Vertical cavity surface emitting lasers: design, characterisation and integration

A thesis by

Abid Khan

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Department of Electronic and Electrical Engineering
University College London
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To my parents and family
Abstract

Vertical cavity surface emitting lasers (VCSELs) are semiconductor lasers with extremely short (~1 wavelength) vertical optical cavities, the cavity being defined by distributed Bragg reflectors (DBRs). These lasers have emission properties distinct from normal waveguide in-plane devices (IPLs). This thesis presents theoretical and experimental results on strained QW InGaAs/GaAs/AlGaAs based VCSELs and integrated laser/modulator devices.

Optical pumping techniques are used to study the sub-threshold emission characteristics of VCSEL (microcavity) structures. These show that the optical properties of the microcavity dictate the structures emission properties. In particular, an incomplete overlap of the QW spontaneous emission spectrum with the mirror high reflectivity stop-band results in the emission of side-modes. Current injected VCSELs, with threshold currents below 5mA and operating between 940nm and 980nm, are also studied. It is demonstrated that graded-index separate-confinement heterostructures may be used to increase the lasers power output and (electrical-optical) conversion efficiency. We present devices exhibiting more than 50mW output.

Through the use of short-period superlattices, inserted into the DBR mirrors, we have achieved threshold voltages below 5 volts. Other methods for the reduction of series resistance within DBRs are investigated. In particular, the use of post-growth annealing of the DBRs. Results show a 50% decrease in the series resistance with the reflectivity of the DBR remaining high.

The devices are successfully modelled by using a transfer matrix approach that allows for the emission spectra, threshold currents and power outputs to be calculated.

The thesis ends by presenting a novel integrated VCSEL and modulator. This device utilises a new reflection-modulator which attains a very high reflectivity. By modulating the (modulator) voltage the cavity photon lifetime of the laser is changed. This scheme is shown, theoretically, to result in improved high speed performance relative to a current modulated device.
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Preface

Semiconductor lasers are currently used as the optical sources in numerous optical systems. Predominantly of the waveguide (in-plane) geometry, these lasers have excellent performance and lifetime characteristics and, because of their relative ease of production, are commercially very successful.

Recently, through advances in crystal growth technologies, a new semiconductor laser possessing surface normal emission and a host of attendant advantages has been realised. This device, known as the vertical cavity surface emitting laser (VCSEL), retains many of the advantages of the waveguide lasers but has major advantages in terms of array production and integration. Also, because of its ultra-short microcavity structure its emission properties are quite unique.

Much of the work presented in this thesis is concerned with the design, optimisation and characterisation of VCSELs. Specifically a set of criteria has been developed that will allow the design of lasers possessing high power outputs, low thresholds, good high speed properties, enhanced functionality or combinations of these characteristics.

In chapter 1 we introduce the VCSEL and attempt, briefly, to bring the reader up to date on some of the major developments. Importantly we discuss why high quality mirrors and optical and electrical confining structures are needed in order to produce VCSELs with threshold currents on a par with waveguide devices. In this chapter we also introduce quantum wells and describe how they can improve the laser operating characteristics. Specifically the use of strain and its advantageous effect upon lasing will be discussed.

Chapter 2 of the thesis introduces a novel transfer-matrix based model that allows the emission spectral properties of a VCSEL to be calculated. The model incorporates the well documented transfer-matrix based model for the calculation of internal electrical fields and this allows for calculation of the simple (measurable) quantities of reflectivity and transmission. By incorporating the effects of refractive index dispersion and material absorption and gain (for the GaAs/InGaAs/AlGaAs material system) the model gives good agreement with experimental data. The development and applicability of this model will be discussed in some detail as it is used throughout the rest of the thesis. This chapter also introduces some of the physics behind distributed Bragg reflectors (DBRs) and microcavities.

The production of distributed Bragg reflectors (DBRs) with low series resistance characteristics is the subject of chapter 3. Through the insertion of short period superlattices and the use of periodic doping profiles we show, in agreement with the work of other groups, that the series resistance may be greatly reduced. This chapter also describes the first attempts to use...
post growth (rapid) thermal annealing techniques to change the series resistance of the DBRs. Such a process, if optimised, may allow for the lateral integration of VC-lasers. In particular the effects of thermal annealing upon the structural, and hence reflection, characteristics of the (MOCVD grown) DBR are studied using a combination of theoretical modelling, secondary ion mass spectrometry and reflection spectroscopy. Interesting and novel results are obtained although the changes in resistance are, unfortunately, considered to be too small to make the technique commercially viable.

Chapter 4 is concerned with the production and characterisation of VCSELs. First, models are used to arrive at the optimum cavity design for the laser. Next, optical injection techniques and photoluminescence (PL) spectroscopy are used to study the sub-threshold emission characteristics of VCSELs. These PL experiments give much information about the lasers and demonstrate that the device may be tested and characterised (in some detail) prior to processing. This is a major industrial advantage over in-plane lasers. Also in chapter 4 the low resistance DBRs of chapter 3 are implemented to produce a range of VCSELs with excellent threshold and power characteristics. Specifically the use of optimised DBRs coupled to a graded index separate confinement heterostructure (GRINSCH) cavity is shown to improve the high power characteristics without affecting the device threshold properties. The (pulsed) light-current and current-voltage characteristics of these lasers are studied. The (L-I) characteristics normally exhibit thermal turn-over due to carrier leakage and gain detuning effects. However, these are shown to be greatly reduced through the use of the GRINSCH structure. The (I-V) characteristics show some very interesting features requiring further investigation.

In chapter 5 we develop a novel integrated VCSEL and modulator. The design and function of this device is studied using modified forms of the models developed in chapter 2. In particular a new modulator, designed specifically for integration with a VCSEL, is demonstrated. This device exhibits some completely novel features in its operation. Furthermore its design relies on novel use of the field profile within the structure. Next, theoretical (small-signal) models are put forward to analyse the integrated device dynamic response. These suggest that such a device, relying on a modulation of the photon lifetime in the structure, is inherently faster than a current injected VCSEL.
Chapter 1

Introduction to vertical cavity surface emitting lasers
1.1 Introduction

The early observations of injection luminescence, and subsequently stimulated emission, from direct-bandgap semiconductors [Nathan et al. '62] have led to the development of a host of different semiconductor lasers and light emitting diodes. The lasers may now be found in a variety of industrial and consumer products performing functions as diverse as information retrieval from compact discs to document printing. Furthermore, by virtue of their compact size and extremely high electrical to optical conversion efficiency, these lasers have found favour in the broad field of telecommunications where they are employed as high speed sources for both long and short haul communications.

Intrinsically linked with the development of these lasers has been an improvement in the production (growth) of semiconductor epi-layers. This has involved advancements in both the basic growth technologies and the various in-situ, and post-growth, characterisation techniques. In particular the emergence of molecular beam epitaxy (MBE) and metal organic chemical vapour deposition (MOCVD), as techniques that allow mono-layer precision to be attained during growth, has allowed the production of lasers with quantum well (QW) active layers. These quantum well structures, when employed as active layers within lasers, have numerous advantages relating to laser performance. Amongst the most important of these advantages, however, is that QWs allow the emission wavelength of a device to be tailored.

Recently, as the various device growth and production techniques have matured, a new (vertical cavity) configuration for the semiconductor laser has been realised. This VC-laser has the distinct advantage that light emission is normal to the substrate. This geometry allows the production of discrete lasers with remarkable performance characteristics. Furthermore, the production of very large area (2D) arrays becomes possible. Distinctly, the improved integration capabilities of this laser, with both optical and electronic components, place it in a unique position when systems applications are considered. This is readily confirmed by the rapid, and intense, research effort applied since the VC-lasers conception.

In this chapter we will introduce, and briefly review, the vertical cavity surface emitting laser (VCSEL), initially from an historical aspect. Some of the device characteristics along with any advantages and disadvantages therein, relative to other semiconductor laser types, will be discussed. In particular we will show how mirrors of very high reflectivity are required to produce VC-lasers with threshold currents of the same order as the best in-plane lasers. Next QWs will be introduced and the advantages of strain alluded to. Finally, having provided the reader with a basic background to VCSEL technology and terminology, the work to be presented in the rest of this thesis will be placed in context.
1.2 Historical background and development of VCSELs

The use of a vertical cavity within a semiconductor laser was originally proposed by Kenishi Iga and co-workers in 1977 [see Iga et al. '88 for review]. Such a cavity geometry offers a number of advantages. Lasers can be produced through a purely monolithic process and tested prior to cleaving into discrete devices. Industrially this is very important because the (post-processing) yields from wafers can be dramatically increased. Obviously the cleaving of laser facets is avoided. Implementation of a vertical cavity also allows the transverse (in-plane) laser dimensions to be reduced allowing, for the first time, the production of large area (densely packed) arrays. Iga also noted that the vertical geometry might lend itself to vertical integration with other optical and electronic components. This, in part, is by virtue of the narrow divergence, circularly symmetric output beam, which couples well to optical components. Spectrally the emission is a single longitudinal mode due to the ultra-short laser cavity length. These latter features should prove invaluable if the lasers are to have a place in modern free-space or fibre-based optical systems as they cannot readily be obtained with waveguide devices.

Early research on VCSELs centred around the technologically important InGaAsP/InP and the well studied GaAs/AlGaAs material systems. Of these, the former was for direct application to the 1.3µm and 1.5µm low attenuation low dispersion (silica based) fibre windows, as used in long-haul telecommunications applications. The latter system was for ~850nm emission. Lasing was achieved, in a pulsed mode, within the InGaAsP/InP system in 1979 [Soda et al. '79]. The device had a threshold current of 900mA and required cooling to 77°K. This was followed by a similar demonstration in the GaAs/AlGaAs system in 1984 [Iga et al. '84]. Room temperature continuous wave (CW) operation of a VCSEL, again in GaAs/AlGaAs, was achieved by 1988 [Koyama et al. '88].

These early VCSELs comprised a bulk active region bounded on one side by a metallic reflector and on the other by a, post-growth deposited, dielectric distributed Bragg reflector
(DBR). Production of these early devices required elaborate processing as the only section of the laser to be grown (initially by MOCVD) was the laser cavity and active layers. Figure 1.1 shows a schematic of one such laser. Following the cavity growth the sample had a metallic reflector deposited on the top surface. This also formed a contact. The substrate was thinned and a DBR of Si/SiO₂ deposited to form the bottom reflector. A bottom contact (to the substrate) completed the device to form a buried heterostructure VCSEL [Iga et al. ‘88] with current injection directly to the active layers. Current injection through the DBR was impossible due to the insulating nature of the SiO₂. Unfortunately, because of the low average mirror reflectivities, combined with the short gain length, these early devices had very high threshold currents.

Fortunately a breakthrough in VCSEL production occurred when semiconductor DBRs were integrated, at the growth stage [see for example Jewell et al. ‘88]. It had previously been demonstrated, by a number of groups, that good quality high reflectivity DBRs could be grown using the techniques of MBE [Van der Ziel et al. ‘75] and MOCVD [Thornton et al. ‘84]. By using these (integrated) reflectors, originally in the GaAs/AlGaAs system, VCSELs could be produced with major improvements in growth accuracy (layer thickness) and material optical quality. Performance enhancements rapidly followed and the threshold currents of the devices dropped by more than an order of magnitude (~40mA) [Tai et al. ‘89]. Furthermore the semiconductor DBRs allowed current to be injected vertically through them. This allowed for great simplifications in processing. Unfortunately a penalty arose in the form of an increased laser operating voltage. This was due to the large series resistances of the semiconductor DBRs, caused by the large number of heterointerfaces in the mirrors forming barriers to current flow. A further detrimental effect following directly from the high series resistance was the increased heat dissipation of the laser. This resulted in low power outputs and thermally induced turn-over of the device light-current characteristics (caused by a detuning of the peak gain and laser Fabry-Perot resonance). This problem has been reduced through the use of heterointerfacial grading [for review see Tai et al. ‘90, Kurihara et al. ‘93] and the reader is referred to chapter 3 for a detailed discussion of this extremely important issue.

A further order of magnitude drop in threshold current was later obtained by using quantum well (QW) active regions (to be discussed) coupled to very high finesse cavities [e.g. Lee et al. ‘90]. Importantly this use of QWs, often with the incorporation of strain, allowed greater control of the lasing wavelength, for example wavelengths between 900nm and 1μm could be readily attained through the use of InGaAs QWs [Jewell et al. ‘89]. Furthermore, by placing the QWs at peaks of the standing wave optical field within the laser cavity a further reduction in threshold current could also be obtained. This technique, referred to as the resonant periodic gain scheme
(RPG, also known as PGS), increases the active region confinement factor and thereby increases the modal gain [Raja et al. '88, '89].

The reader will observe from the above introduction that the initial development of VCSELs was extremely rapid. In fact, fuelled by the many advantages that such a laser configuration offers over the more common (in-plane) semiconductor laser types, a number of other important advances have been made. These recent advances will be briefly discussed.

The use of strained QWs, predominantly in the InGaAs/AlGaAs (~980nm) system, has allowed VCSELs to be produced with threshold current densities falling well below 1kA/cm². This corresponds, for a device of order 10μm diameter, to a threshold current of order ≤ 1mA [Geels et al. '90a]. Such low thresholds, at least on a par with the best in-plane devices, are attributed to the bandstructure changes that occur within the strained QW active layers. Simple scaling arguments, relating to the very small active volume of a VCSEL, also apply.

By combining these QWs with (high barrier) cladding layers, to reduce carrier leakage, simple air-post (index-guided) VCSELs have achieved CW power outputs exceeding 100mW [Young et al. '93]. These devices have threshold current densities still of order 1kA/cm². Through the use of interfacial grading (or insertion of short period superlattices) the operating voltages of these lasers have also dropped and values well below 5 volts are now regularly attained. These operating voltages have also been further reduced through the use of intra-cavity contacts. Such schemes are however complex to implement.

Following the excellent results attained by the GaAs/InGaAs/AlGaAs lasers operating at wavelengths between ~800nm and ~1000nm a number of groups have attempted, and achieved, production of VCSELs with lasing operation at both shorter and longer wavelengths.

At the shorter wavelength end of the optical spectrum, sub- 700nm wavelength operation has been demonstrated using AlGaInP active layers with AlAs/AlGaAs based mirrors [Tell et al. '93]. InAlP/InAlGaP DBRs with InGaP QW active regions have also been proposed [Schneider et al. '93]. These devices, intended for display and optical back-plane (visible) applications, have achieved low threshold currents approaching 3mA (10μm diameter) and output powers of ~1mW. Unfortunately most of these devices operate efficiently only at temperatures below 20°C. Other materials intended for the visible spectrum include the II-VI nitride based elements, however these technologies are at a very early stage in development.

A very high (butt-) coupling efficiency to fibres, due to a narrow divergence single mode output, makes the operation of VCSELs at the telecommunications wavelengths of 1.3μm and 1.5μm highly desirable. It is noted that because of their very short cavities and small dimensions VCSELs may operate up to very high modulation rates, as would also be desirable in a telecommunications system. The early work of Iga demonstrated the first operation of a 1.3μm...
device. Unfortunately its threshold characteristics were very poor (900mA threshold), operation was pulsed and at low temperature. Recently operation of VCSELs at both of these wavelengths has been demonstrated by a number of groups, predominantly using the GaInAsP/InP material system [see for example Uchida et al. '93 and Baba et al. '93 for 1.5μm and 1.3μm operation respectively]. Unfortunately all of these long wavelength lasers suffer, in terms of their manufacture and operation, from problems relating to the nature of the constituent materials. At long wavelengths Auger loss mechanisms become important as the active layer bandgaps are reduced; this increases threshold currents. However, the dominant problem is related to the (indium-phosphide based) materials used to form the DBR mirrors at these (long) wavelengths. The ratio of the refractive indices of these materials (generally InGaAs/InP based) are very low. Therefore a large number of DBR layers (~50 pairs) are required to achieve a high reflectivity. Suitable DBRs are therefore very thick, leading to growth related problems in device manufacture and heating problems in operation. By using dielectric layers (e.g. SiO/SiO₂) high reflectivity DBRs may be deposited, however these cannot carry current and so device manufacture becomes complicated. Recently a number of DBRs have been proposed using strained materials (e.g. AlInAs/GaInAs) and more novel material systems (e.g. AlPSb/GaPSb) to increase the refractive index ratio [see for example Guy et al. '93 and Anan et al. '94 respectively]. Unfortunately the marginal gains obtained are offset by increased problems relating to growth and subsequent (structural) compatibility with the laser active layers. When post-growth deposited Si/SiO₂ based DBRs are used the highly insulating nature of the oxides makes current injection through the mirror impossible and device manufacture is again complicated. It is clear, however, that, even with all of the material problems encountered at these wavelengths, the production and optimisation of these 1.3-1.5μm lasers is of great academic interest and commercial importance.

Another area of intense research, also relating to the use of VCSELs in interconnects and telecommunications applications, is that of high speed modulation. Because of their high finesse ultra-short cavities (giving high photon densities and short photon transit times) and small active volumes (giving a low threshold current) VCSELs are expected to perform well under high rates of applied current modulation. Indeed the high speed current modulation of VCSELs has led to lasers operating at frequencies above 10 GHz [Schtengel et al. '93]. These rates are, at present, limited by device parasitics including the high resistance of the DBRs. Some of the issues relating to the high speed operation of VCSELs are discussed in more detail in chapter 5.

The use of VCSELs as optical interconnects has been studied by a number of groups. Free space interconnects have been implemented within which the narrow divergence output of the VCSEL is utilised directly [Jewell et al. '90] (or with the use of integrated lenses [Craft et al.
for information conveyance. One possible configuration for such a free-space scheme is shown in figure 1.2(a). In this case diffractive optics are used to form a routing plane, see for further (generic) examples [Brenner et al. '88].

Figure 1.2 Two possible interconnect configurations implemented using VCSELs.

Figure 1.2(b) shows a schematic of an interconnect scheme that relies upon internal reflections within a substrate. By using gratings to steer the initially vertical beams from a surface emitting laser (SEL), and then using multiple internal reflections, remote (distant) areas of a chip may be optically addressed [Brenner et al. '88, Jahns et al. '92]. These schemes may prove valuable for the manufacture of optically interconnected microprocessors.

Because the transverse dimensions of a VCSEL may be made very small a large number of lasers may be fabricated from a given wafer. More importantly large area arrays may be manufactured in which each laser is addressable. This is, perhaps, the greatest of all the advantages a VCSEL has over an IPL. Figure 1.3 shows schematics of a linear IPL array and a 2-dimensional VCSEL array. In the IP case the lasers are approximately 300μm long and arrays are fabricated by cleaving bars of say 1cm length. For a VCSEL the transverse dimension is of order 10μm and so many thousands of devices may be produced and individually addressed, obviously the packing density is reduced when contacting is considered.

Figure 1.3 Schematics of in-plane and vertical cavity laser arrays.

Once again research into array technology has produced some remarkable achievements. This research has been driven by the fact that arrays of VCSELs may be used as optical back-
planes (e.g. for neural networks) and as high power (compound) sources (e.g. for optical pumping or cutting).

In its simplest form an addressable array of VCSELs may be fabricated by laying down contacts to each individual laser on a wafer (chip). Such schemes have been implemented by a number of groups in both the GaAs (~850nm) and InGaAs (~980nm) active layer material systems. In the former case arrays as large as 8 ×18, individually addressable, elements have been produced with greater than 2mW output per laser [Vakhshoori et al. '93]. At the longer wavelengths arrays as large as 8 × 8 elements have been produced [Lehman et al. '91]. Unfortunately all such, individually contacted, array schemes are limited in the number of laser elements they may contain. This limitation follows directly from the processing difficulties involved in laying down many, closely spaced, contact tracks. Also the physical size of the resulting laser array chip becomes large as numerous contact pads are laid out. Obviously each laser must have a separate pin on the chip. Array chips with more than 100 pins may therefore be envisaged but these are not desirable. Such arrays are therefore limited to about 100 elements.

A much more elegant scheme for producing VCSEL arrays involves processing laser material such that two sets of orthogonal conducting channels are established. In this way a matrix addressed array architecture is obtained. By applying a suitable bias to a given row and column contact an individual laser may be addressed. This scheme has the major advantage that the number of edge (row and column) contacts, and therefore chip pins, is greatly reduced. Obviously the number of addressable lasers is equal to the product of the number of row and column contacts. Importantly the scheme is readily extendible and very large arrays may be fabricated. To date, arrays of 32 × 32 (1024) elements have been fabricated (in the InGaAs based material system) [Orenstein et al. '91].

By allowing each laser in an array to emit a different wavelength, for example by altering the cavity length of each device at the growth stage (chapter 4), a discretely tuneable source may be fabricated (see figure 1.3). To date arrays have been produced in the GaAs/InGaAs/AlGaAs system (~980nm), producing over 70 distinct wavelengths separated by ~10Å [Hasnain et al. '91]. Notably, each individual laser (20μm wide) retains a low threshold current and produces approximately 1mW of CW power. Such arrays have potential applications in wavelength division multiplexing (WDM) applications and, again, as sources within optical interconnects. In the first case the elements of the array may be used to send information down an optical fibre at a number of wavelengths. This increases the data throughput of the system. In the latter scheme off-chip wavelength selective routing planes (e.g. holograms) may be used for beam steering such that a given chip (using such an array) may selectively make contact with another chip.
In general the packing density of any array is limited by coupling (cross-talk) effects between lasers caused by proximity effects. When two VCSELs are placed in close proximity (~μm) the in-plane optical fields from one device may couple to, and therefore effect, the other. This is due to incomplete lateral optical confinement and is regularly observed for index-guided devices. It is noted that further proximity effects also arise from thermal and electrical cross-talk between devices. This imposes further limits upon packing density.

However there are ways in which the optical coupling between VCSELs may be used to advantage. By placing many, generally small diameter, VCSELs in close proximity the coupling between devices may be enhanced and the resulting laser array may be phase-coupled to emit in what is often referred to as a super-mode [Yoo et al. '90]. In this mode of operation the total power output of the array may be made very large. In fact, pulses (100ns) of 1 watt have been achieved from phase coupled arrays of 10 x 10 lasers [Morgan et al. '93]. An advantage of these phased arrays, over the conventional structures, is that the threshold current per device is reduced, often this is accompanied by a marginal increase in the electrical to optical conversion efficiency of the array. These high power sources, which are cheaper to produce than addressable arrays, may find application as optical pumps and illuminators.

It is unfortunate that all of the above array schemes require a large power throughput as this leads to problems in heat dissipation. Device heating acts directly to limit individual laser performance both in terms of threshold and power output. The problem may be tackled, in part, by the use of improved heat sinking, low resistance DBRs and high-barrier cladding layers around the active layers. However device heating still imposes the ultimate limit upon array size, packing density and total power output.

There has recently been much interest in the use of vertical cavity based devices, including lasers and detectors, for optical logic and optical switching applications. By utilising the high packing densities, low operating powers and integration capabilities of VC- devices, high density, high speed (high overall throughput) optical information processing (for example within an optical neural network) may become viable. A number of groups have already implemented optical (Boolean) logic using VCSELs integrated with photodetectors [Chan et al. '91]. Introduction of these detectors allows for the laser operation to be controlled by external optical inputs. Another device currently attracting much interest, again for optical processing applications, is the smart pixel [Cheng et al. '93, Kasahara '93]. Based on the VCSEL this novel device offers greatly enhanced functionality ranging from simple switching (for a discrete device) to self routing in architectures were many devices are integrated together.

Moving away from the industrially important advantages of VCSELs, it has recently been realised that the ultra-short cavity microresonator structures that go to form VCSELs may allow
tailoring of the fundamental emission properties of the active layers placed therein. Specifically, it has theoretically been shown that the spontaneous emission lifetime of the active layers can be altered and that this effect may be used to develop lasers with thresholds on the order of 10\(\mu\)A. These devices may possess emission noise and spectral characteristics unlike those of any previous laser, as such they may open up new and exciting fields of research.

Finally, an important point to remember is that VCSELs form only one device in a range of vertical surface emitting lasers, generically termed SELs. The other members of this class of laser generally comprise in-plane active regions with the output beam steered, after generation, through 90°. These other lasers have advantages, relative to VCSELs, in terms of the output powers that may be achieved. This stems from the fact that in-plane laser cavities (and active region lengths) may be made as large as desired. Other distinct advantages include the possibility of laser operation at wavelengths that are difficult, because of material constraints, to attain using a vertical cavity (for example 1.55\(\mu\)m). Figure 1.4 schematically shows a range of SELs. Cases (a) and (b) show how a 45° mirror may be etched into an IPL to steer the beam into the vertical direction [(a) Kim et al. ‘90, (b) Takamori et al. ‘90]. Lasers of this type have exhibited output powers approaching 25W, as might be required for optical pumping [Donnelly et al. ‘92]. Figure 1.4 (c) shows an IPL with a grating etched to form a vertical output coupler. Obviously, in this case much of the light is lost because of the poor vertical output coupling efficiency of the grating. Case (d) shows a similar structure but incorporating a circularly symmetric output coupling grating [Fallahi et al. ‘92]. This has the advantage that the output beam is circularly symmetric and of relatively low divergence.

![Diagram of various surface emitting lasers](image)

**Figure 1.4 Various surface emitting lasers.**

Unfortunately all of the above in-plane cavity based SELs suffer from problems relating to their large lateral dimensions, this prevents the fabrication of large area arrays. Also the output beam quality of many of the designs is poor, in cases (a), (b) and (c) the output beam is astigmatic with output strongly dependent upon the quality of the etched 45° mirror and gratings respectively. This limits the potential for integration with other optical components. These lasers
will therefore find application when high powers are required but will not, in the view of the author, compete with VCSELs in the more general area of optical systems.

### 1.3 Fundamentals and technology of VCSELs

During the early period of VCSEL development a number of factors were highlighted as necessary for achieving efficient laser operation. Firstly the laser mirrors need to be of very high reflectivity, the structure as a whole should also have a low background absorption. Next, issues relating to the efficient optical and electrical confinement of photons and electrons within the structure must be addressed. Finally the active layers of the sample should be optimised, this may involve the use of quantum wells (QWs) and the periodic gain concept. These factors, which are still undergoing development, form the basis for all modern VCSELs and, as such, shall be discussed further here.

#### 1.3.1 Mirror performance requirements

In order to examine some of the fundamentals of VCSELs it is appropriate for us to look, briefly, at the in-plane (waveguide) laser (IPL). This device, which is perhaps the most successful (and certainly the most common) laser implementation to date, utilises an optical cavity that is parallel to the substrate. Light emission is therefore in the plane of the wafer, the cavity being defined by two cleaved facets (see figure 1.5).

![Figure 1.5 Schematic of an in-plane (stripe-contact) laser.](image)

Devices of this type are highly optimised and characterised both in terms of their performance and industrial production. Furthermore they are used in an extremely wide range of applications (operating over a wide range of wavelengths ~600-2000nm) where they have demonstrated low threshold behaviour, high electrical-to-optical conversion efficiencies, high powers and exceptional reliability (many 1000’s of hours).
Beyond a simple p-n junction, one of the simplest (generic) structures for an IPL is the stripe geometry double heterostructure (DH) laser, see figure 1.5. This IP-laser is of particular interest because it utilises structures to provide for both optical and electrical (lateral) confinement. By briefly studying its operation we may infer operational criteria for a VCSEL.

Photons (of angular frequency \( \omega \)) travelling within the active layers of any laser will, depending upon the active layers state of electrical injection, either be amplified or absorbed. Obviously the active material will also spontaneously emit radiation, this may be neglected at present. If the active layer has a bandgap energy \( E_g \) and its state of injection can be related to the electron and hole quasi-Fermi levels \( E_{pc} \) and \( E_{pv} \) respectively, the amplification or absorption \((\alpha)\) state of the active layer follows the form of the inequalities given below (positive \( \alpha \) represents gain).

\[
\begin{align*}
\hbar \omega < E_g & \quad \alpha(\omega) = 0 \quad \text{.....(1.3.1)} \\
E_g < \hbar \omega < E_{Fe} - E_{Fv} & \quad \alpha(\omega) > 0 \quad \text{.....(1.3.2)} \\
E_{Fe} - E_{Fv} < \hbar \omega & \quad \alpha(\omega) < 0 \quad \text{.....(1.3.3)}
\end{align*}
\]

The threshold condition, defined to be the point at which the round-trip gain for photons oscillating within the cavity exactly balances the round-trip cavity losses, is expressed in equation 1.3.4 (for the laser of figure 1.5) [Yariv ’89]. In this equation \( \gamma \) is the threshold gain, \( \alpha_{tr}(N_i) \) is the loss within the active layer due to free carriers (and any unpumped gain), \( \alpha_{mol} \) accounts for losses within the n- and p-type cladding layers, \( \alpha_s \) is a summation of all the scattering losses (caused predominantly by surface and interfacial roughness) and \( R \) is the average facet reflectivity.

\[
\left( \gamma - \alpha_{tr}(N_i) \right) \Gamma_a = \alpha_n \Gamma_n + \alpha_p \Gamma_p + \frac{1}{L} \ln \left( \frac{1}{R} \right) + \alpha_s \quad \text{.....(1.3.4)}
\]

The front and rear facet reflectivities, \( R_f \) and \( R_b \) respectively, are given by equation 1.3.5, where \( n_o \) and \( n_s \) are the refractive indices of air and the semiconductor respectively. Reflections in this case are from the semiconductor/air interface which is cleaved, the reflectivity is thus fixed at around 30%.

\[
R = \sqrt{R_f R_b} \quad \text{with} \quad R_{f/b} = \frac{n_0 - n_s}{n_0 + n_s}^2 \quad \text{.....(1.3.5)}
\]

The confinement factors \( \Gamma_n \), \( \Gamma_a \) and \( \Gamma_p \) in this case are for the active-, n-type and p-type regions of the laser respectively. In general the confinement factor for a given layer is given by equation 1.3.6. It represents the fraction of the total field within a structure confined to a given
layer (x). The sum of all the individual layer confinement factors is therefore numerically equal to unity.

\[ \Gamma_s = \frac{\int |E|^2 \, dx}{\int |E|^2 \, dx} \quad \text{where} \quad \sum \Gamma_s = 1 \quad \text{(..1.3.6)} \]

We may calculate the reflectivity necessary for lasing action within a VCSEL by comparing equation 1.3.4 with a similar equation for a VCSEL. We begin by rewriting equation 1.3.4, grouping all loss terms into a general loss \( \alpha_{IP} \) and assigning the active layer a confinement factor \( \Gamma_{IP} \). This gives the equation 1.3.7, where all other terms have there usual meanings and IP refers to the in-plane laser.

\[ \Gamma_{IP} \gamma_{IP} = \frac{1}{L_{IP}} \ln \left( \frac{1}{R_{IP}} \right) \quad \text{....(1.3.7)} \]

Figure 1.6 shows a generic index-guided bottom emission VCSEL composed of two distributed Bragg reflectors (DBRs) and a Fabry-Perot (FP) cavity region. The term index-guiding refers to the fact that light within the laser structure is guided by the (real) refractive index discontinuity at the device side-wall semiconductor/air interface. The theory of DBRs and FP cavities will be dealt with in chapter 2. Note that the cavity indicated in figure 1.6 neglects field penetration effects into the DBRs, this will act to increase the effective optical cavity.

Figure 1.6 Generic (bottom emission) VCSEL.

We assume that in the case of the VCSEL the ratio of the active region length \( L_a \) to the effective cavity length \( L_c \), that is the nominal cavity plus any field penetration into the DBRs, is of the order 1/100. This is in contrast to the factor approaching unity for most IPLs. Interestingly, because of the large index discontinuity within index-guided VCSELs the transverse confinement factor of the structure approaches unity. The volume confinement factor for a VCSELs is thus of order 1%, this is similar to the values found within IPLs. Now, if the
active region of the VCSEL is placed at an antinode of the standing wave optical field within the cavity the active layer modal gain may be effectively doubled. This effect is known as resonant periodic gain (RPG) and has the effect of increasing the active layer confinement factor [Raja et al. '89].

By assigning all of the losses within a VCSEL to the quantity $\alpha_{\text{VC}}$ we may re-express equation 1.3.7 as for a VCSEL, note that we have multiplied throughout by the ratio $L_d/L_t$.

$$2\Gamma_{\text{VC}} \left( \frac{L_s}{L_t} \right) \gamma_t = \alpha_{\text{VC}} + \frac{1}{L_t} \ln \left( \frac{1}{R_{\text{VC}}} \right) \tag{1.3.8}$$

Noting that the product of the factors to the left of $\gamma_t$ is essentially another confinement factor, we may equate equations 1.3.7 and 1.3.8, this gives equation 1.3.9. We have assumed that the VCSEL should have a modal threshold gain similar to the IPL. This will give us a value for the reflectivity consistent with a threshold current equivalent to an IPL.

$$\left[ \frac{1}{L_t} \ln \left( \frac{1}{R_{\text{IP}}} \right) \right]_{\text{IP}} = \left[ \frac{1}{L_t} \ln \left( \frac{1}{R_{\text{VC}}} \right) \right]_{\text{VC}} \tag{1.3.9}$$

Using equation 1.3.9, with $R_{\text{IP}} \sim 30\%$ and $L_{\text{IP}} \sim 300 \times L_{\text{VC}}$, gives a value for $R_{\text{VC}}$ exceeding 99%. This demonstrates the need for very high average mirror reflectivities within VCSELs if they are to have threshold current densities comparable to in-plane lasers, i.e. of order 1mA.

Modern VCSELs are produced in one complete epitaxial growth sequence. This allows very low background loss levels to be achieved and produces more accurate structures. The mirrors in this case are of the distributed Bragg type, discussed in chapter 2. It is a credit to the growth technologies employed that the very high reflectivities required from VCSEL mirrors are now readily achieved. Modern VCSELs now have threshold currents better than many (uncoated) IPLs and threshold current densities falling well below 1 kA/cm² have been recorded.

High reflectivity DBRs are achieved by alternately layering two materials, each a quarter of a wavelength (optically) thick and of differing refractive index, together in a stack. However, in order to achieve the largest refractive index difference, and hence the highest reflectivity, the bandgaps of the two materials must differ widely. Unfortunately, this leads directly to problems of series resistance when current is injected through the mirrors. This high series resistance, brought about by the large number of heterointerfacial barriers (in potential) within the DBR, results in problems relating to heat generation within the VCSEL. The problem may, to some extent, be alleviated through the use of heterointerfacial grading and the insertion of short-period superlattices to increase the tunnelling current through the structure. These resistance reducing
techniques are discussed in detail in chapter 3, it is noted however that a vertical current injection path is highly desirable because it allows VCSEL processing to be greatly simplified.

### 1.3.2 Optical and electrical confinement

A second, but equally important point to consider in the production of VCSELS is that regarding lateral and longitudinal current and optical confinement. To achieve efficient lasing action within a laser a large overlap between the active layer and the optical mode must be achieved in all dimensions. Also, in order to achieve high levels of gain from the active layer very efficient current injection is required. In an un-confined laser current injected into the device will spread laterally such that the current density at the active layer will be small, see figure 1.7. Both optical and electrical confinement is required for laser optimisation.

![Current spreading in an unguided VCSEL](image)

Figure 1.7 Current spreading in an unguided VCSEL.

Ideally both the light and current within the structure should be confined, laterally, to the same active area. The light will then experience the greatest degree of material gain. A number of techniques have been employed to confine both the current and the light. Figure 1.8 shows the basic configurations, note that both top and bottom emission devices are indicated. In the gain-guided examples (a) and (b) the DBR active layers are laterally confined by physically altering (damaging) the material in the region around the contact [see for review Jewell et al. ‘91]. This may be achieved through proton implantation or through the indiffusion of various materials, in both cases the samples are often annealed to reduce damage and improve optical and electrical quality. The result is a well defined channel for current flow, as is shown by the arrows in the figure. A small degree of confinement for the light also occurs due to changes in the refractive indices (both real and imaginary) of the damaged (or intermixed) layers. Ion-implantation, as a current guiding method, has advantages in both VCSEL processing and in the device operating characteristics. Industrially important is the fact that large areas of a wafer can be patterned in a single run. Also, both top and bottom emission lasers can be processed simply with excellent power and threshold characteristics. Some of the highest output powers achieved have been
through the use of gain-guiding, the technique lending itself readily to array production. Note how the planarity of the wafer is retained as etching is avoided. This again has advantages in terms of processing. Further advantages arise from the reduced sidewall recombination that occurs within gain-guided VCSELs.

Figure 1.8 (a,b) Gain-guided and (b,c) index-guided VCSELs.

Figure 1.8(c) and (d) shows two index-guided VCSEL structures. These are the type of laser that will be studied in this thesis. In this case the sample is simply etched to define the path for current flow. The large number of heterointerfaces in the DBRs act to laterally spread current such that a uniform injection profile exists at the active layers. This geometry also has a number of attendant advantages. For case (c) the processing is very simple and allows devices of many sizes to be produced. Simple reactive-ion etching may be used and no implantation facilities are required. Furthermore the resulting device has a large degree of optical guiding due to the large refractive index step between the laser and the surrounding air. Obviously sidewall recombination is a problem in these structures although its effects are greatly reduced through the use of larger diameter mesas and surface passivation techniques.

1.3.3 Quantum well active layers

If, in the growth direction, the thickness of the active layer of a VCSEL is reduced to be of the order of the electron (and hole) de Broglie wavelength then the gain and emission properties
of that active layer are dramatically modified. Injected carriers become strongly (spatially) confined, in the direction of injection, and the layer becomes a quantum well (QW). Specifically its operation as an active layer becomes dominated by quantisation effects. The result is a structure with many characteristics distinct from bulk material and with a range of useful properties, these will be discussed here.

![Schematic showing typical confined energy levels within a GaAs quantum well bounded by AlxGa1-xAs barriers.](image)

**Figure 1.9** Schematic showing typical confined energy levels within a GaAs quantum well bounded by AlxGa1-xAs barriers.

In general, if a semiconductor layer of some material A, with bandgap $E_a$, is sandwiched between two layers of a material B, of larger bandgap $E_B$, then the resultant structure (B-A-B, see figure 1.9) is a quantum well (a potential well for carriers). As a lattice-matched (type I) example take a GaAs layer, typically of order 100Å thick, sandwiched between two AlxGa1-xAs barriers ($x \sim 30\%$). Electrons (or holes) injected into the QW will be confined to certain (fixed) energies in the growth direction, they will behave as if in bulk material in the other two orthogonal directions ($x$, $y$). In the conduction band these confined energy levels are designated the electron levels and given the quantum number $n$ to define their energy ($e_n$). In the valence band the effect of quantisation is to effectively lift the degeneracy between the heavy and light holes ($k_z$ becomes discretised and cannot equal zero in a QW) such that a range of hole energy levels appear, these are designated the heavy (hh$_n$) and light (lh$_n$) hole energy levels. Importantly the QW system takes on a bandgap that is greater than that of the well (thin) material, it is defined by the $e_1$-hh$_1$ energy separation. This fact allows QWs to be used to attain operation at wavelengths that cannot (easily) be obtained using bulk materials. By appropriate choice of barrier and well composition and thickness the $e_1$-hh$_1$ transition wavelength can (practically) be continuously tuned, this opens up many design opportunities for the laser manufacturer.

The effect of confinement upon the carriers, and the transitions that they may undergo, is marked. Firstly the carriers are constrained in their motion in the growth direction to well resolved energy levels. Transitions between these energy levels must obey certain selection
rules, these strongly limit the number of observed transitions. Importantly then, only those (photon induced) electron and hole transitions that occur within the QW between given values of \( n \) are allowed, for example \( e_n \) to \( h_n \) or \( l_n \), this is known as the \( \Delta n=0 \) selection rule. Further selection rules apply to the electron and hole momentum through the \( k_h = k_e \) (\( k \) selection) rule (for undoped QWs). Finally transitions are also dependent upon polarisation, this is the origin of polarisation dependent gain (in general \( TE \) polarised light achieves greater amplification).

The strong spatial confinement of carriers results in an increased overlap of the carrier wavefunctions, this results in an increased probability for transitions and so the QW works well as a laser active region. Furthermore, because of the strong spatial confinement, at low (or zero) injection levels the QW acts as a strong absorber. This is generally through the formation of excitons, hydrogenic (Coulomb force bound) particles comprising electron-hole pairs. Of course this absorption can pose problems during laser operation at low injection, especially when a number of QWs are injected non-uniformly. These excitonic features dramatically alter the absorption spectrum of the QW from that of its constituent bulk materials, the resulting spectrum becomes step-like with well resolved features even at room temperature. Such changes to the absorption spectrum, and their subsequent dependence on applied electric fields, form the basis of operation of numerous passive modulator devices and are discussed in chapter 5.

Another effect, one of extreme importance with regard to lasing, relating to carrier confinement is the change that occurs to the density of states (DOS) function, \( \rho(E) \), of the QW. Notably, the density of states for electrons and holes dictates, directly, the number of transitions, spontaneous or stimulated, that may occur within the QW. It therefore has a direct bearing upon the gain that may be obtained from a QW.

![Figure 1.10 Schematic DOS for an unstrained quantum well.](image)

*Figure 1.10 Schematic DOS for an unstrained quantum well. (parabolic curve is 3D DOS for bulk material \( \times \) well width).*
For bulk material the DOS (strongly dependent upon carrier masses) is parabolic and increases as the square root of the energy \( (E) \), for both carrier types. In a QW this function is strongly modified and takes on a step-like structure, as is shown in figure 1.10 [see for example Holonyak et a. '80]. Some of the possible transitions within a QW, namely those obeying the \( \Delta n=0 \) selection rule, are also shown in this figure.

This new DOS for the QW gives the structure markedly different properties from bulk material, especially relating to its operation as a laser active region. The transparency (no loss) condition for any active material is related directly to the number of states at the bandedge, this number is dependent upon the DOS (occupation of these states is dictated by the carrier Fermi-levels). It follows that a reduced DOS leads to a reduced material transparency level. For bulk material the DOS is a smooth parabolically increasing function of energy, with a low DOS near the bandedge. The transparency injection level for bulk material \( (E_{FC}-E_{FV}=E_g) \) is therefore lower than that for a QW. However, because the DOS of a QW is step-like the bandedge DOS rises very sharply with energy. Once transparency is achieved the large DOS in a QW results in a very large increase in gain with additional carrier injection, QWs therefore have a higher differential gain (with respect to carrier density) than bulk material. This feature makes them useful for high speed applications and will be discussed in chapter 5.

Beyond any modifications to the DOS a number of other useful features arise within QWs, these are due predominantly to the reduced active volume. As mentioned, the increased confinement of carriers forces electrons and hole to be in close spatial proximity (the effect responsible for the appearance of room temperature excitons in unpumped QW material) and this increases their interaction (recombination) probability. It is noted that this confinement makes QWs less sensitive to external temperature effects. In magnitude the electron-hole interaction probability (i.e. the transition rate between the conduction and valence bands) is given by Fermi’s golden rule (see for example Corzine et al. in [Zory '93]), which is again dependent upon the number of populated states. This in turn is dictated by a transition matrix element, the magnitude of which, and hence the magnitude of the achievable gain, is increased through the use of QWs, relative to bulk material. Further increases can be obtained through the use of deeper QWs, i.e. wider gap barrier layers. Unfortunately, unlike bulk material, the step-like DOS causes the gain to saturate rapidly with increasing carrier injection. Care must therefore be taken to minimise the optical losses in a QW based laser in order to keep the threshold gain low.

Although the use of lattice-matched QWs allows for greater flexibility in the design of lasers, especially when operation at wavelengths other than the bulk bandgaps is desired, it is limiting in terms of the range of materials that may be employed. By using QWs comprising
lattice-mismatched bulk material access may be gained to a greatly increased wavelength range. Perhaps more importantly, lattice-mismatched QWs yield performance enhancements relating to the differences in bandstructure and DOS with respect to lattice-matched unstrained QWs. Specifically, lattice-mismatched QWs (in the $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ material system) will be used in all of the devices developed in this thesis (for 980nm operation). We will therefore briefly examine strained QWs along with some of their attendant advantages here.

Through the continued development of growth technologies it is now possible to produce high quality epi-layer structures in which the deposited layer has a different lattice constant to that of the substrate. As an example, bulk $\text{In}_x\text{Ga}_{1-x}\text{As}$ has a lattice constant which varies with indium concentration between that of $\text{GaAs}$ (5.65Å) and that of $\text{InAs}$ (6.06Å). When a thin layer of $\text{InGaAs}$, of any composition, is grown onto a $\text{GaAs}$ substrate the lattice of the $\text{InGaAs}$ layer elastically deforms such that, in the plane of the substrate, the lattice constant takes on the substrate value. The situation is illustrated schematically in figure 1.11. $\text{InGaAs}$ is represented as the shaded squares. When combined with the $\text{GaAs}$ substrate the layer deforms both in and orthogonal to the substrate plane. The $\text{InGaAs}$ lattice is in compression in the plane and the layer is said to be compressively strained. A similar situation arises when the layer lattice constant is smaller than the substrate lattice constant. In this case the layers lattice expands to accommodate the strain and the structure is said to be under tensile strain.

![Figure 1.11](image-url)

**Figure 1.11 Illustration of crystal lattice deformation under strain.**

Evidently the thickness of $\text{InGaAs}$ layer is not a free variable and, as might be expected, very thick layers cannot be grown without dislocations being formed. An interplay between the indium composition and the layer thickness occurs such that the amount of misfit (strain) dictates the maximum layer thickness [O’Reilly ‘89]. If the single layer thickness ($h$) exceeds a certain critical value ($h_c$) then it becomes thermodynamically favourable for the layer to accommodate the strain through the generation of misfit dislocations. Unfortunately, the issues relating to critical thickness are very complex and, to a great extent, not well understood. As an order of magnitude approximation the maximum layer thickness that can be coherently (no relaxation) grown is approximately 100Å for every 1% of strain. For an $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ QW, as
used for operation at 980nm, the strain is approximately 1.4% and so the critical thickness is around 70Å. In actuality an 80Å InGaAs QW can be grown relatively free of any relaxation. Interestingly, multiple quantum wells (MQWs) can be grown to a total thickness exceeding the single layer critical thickness without the onset of strain relaxation, this is due to a distribution of the strain energy. Obviously relaxation and the introduction of dislocations has detrimental effects upon the laser operation as non-radiative recombination centres as well as traps for injected carriers are introduced, this acts to increase the lasing threshold current and reduce the lasers quantum efficiency.

The use of coherently accommodated strain (no defects) has a number of desirable effects on laser operation and performance. Many of these effects follow on from changes that occur to the band-structure of the strained layer, relative to both bulk and unstrained QW material. Firstly, as with the use of QWs over bulk material, the range of wavelengths obtainable increases and, for example, wavelengths longer than the bandgap of the substrate may be attained. These wavelengths are important technologically, as pumps for example, but are also useful because bandedge absorption from GaAs can be avoided allowing greater flexibility in design. By using InxGa1-xAs QWs on GaAs the wavelength range from ~870nm (GaAs Eg ~1.424eV) up to ~1040nm may be obtained with coherently strained material (x ~20-25%). Note that InAs has a critical thickness, on GaAs, of only one or two monolayers (Eg ~ 0.356eV). Figure 1.12 shows the range of emission wavelengths that may be obtained using two different indium composition QWs, and various well widths. It may be seen that a number of wavelengths (between ~900nm and ~950nm) may be obtained using different QW well widths and indium compositions. These structures will have different amounts of confinement and their properties will therefore differ. Increased flexibility in design therefore follows.

![Figure 1.12](image_url)

**Figure 1.12** Theoretical e1-hh1 transition for InGaAs QWs, plotted against well width, [Stavrinou '95].
Note that the wavelength of interest in this work is 980nm. This wavelength corresponds to a pump wavelength for rare-earth (Er) doped fibre. More importantly it is a wavelength at which both GaAs and AlAs, the two materials used to form the VCSEL DBRs, are essentially transparent. This allows very low loss structures to be made. Furthermore, the system allows one to investigate the effect (on threshold) of an appreciable strain while retaining compatibility with Si based detectors.

Strain, incorporated without relaxation, dramatically alters the bandstructure of a QW. In the case of compressive strain the effective (mean) bandwidth (e1-hh1) of the QW increases slightly. More importantly the degeneracy, at zone centre, between the heavy- and light-hole bands in the valence band is lifted (hh and lh are separated by approximately 60meV for 1% strain). The effect of the light-hole band upon the heavy-hole band is therefore greatly reduced, subsequently the heavy-hole band becomes almost parabolic in nature. This results in a greatly reduced in-plane effective mass for the heavy-holes and has the further effect of reducing the DOS in that band. As mentioned earlier, reduction in the DOS lead to reductions in the transparency levels for the QW resulting in threshold reductions for the laser. A further effect, following on from the reduction in hole mass, is an equalisation of the DOS in the conduction and valence bands, this again lowers threshold. Finally, because the interaction between the heavy- and light-hole bands is reduced, the DOS in the valence band becomes more step-like. In lattice-matched material these bands interact strongly, thereby increasing carrier effective masses. This has the effect of increasing the bandedge DOS. The ideal unstrained QW step-like DOS of figure 1.10 is actually modified and contains 'spikes' near the bandedges, these require higher injection levels to reach transparency and threshold is increased. Fortunately the situation is avoided through the use of strain [see for example Corzine et al. in [Zory '93]. It is noted that the use of tensile strain may also prove useful both in terms of the wavelengths obtainable and the effects upon band-structure. Unfortunately this (relatively new) subject is falls beyond the scope of this work.

1.4 Concluding remarks

In this chapter we have introduced the VCSEL and shown how, since its conception, the VC-laser has undergone much intense (and rapid) development. In the main the advances have come from attendant improvements in the growth technologies, the spur being from industry which strongly values the advantages the laser has to offer. These advantages have been
described, specifically the applicability of VCSELs to array production and its integration advantages have been highlighted.

We have discussed how the optimisation of the (integrated) DBRs within the laser is of prime importance. These mirrors must be highly reflective and also of low enough resistance to avoid high operating voltages and heat dissipation. This subject, which is of prime importance in VCSEL production, forms the basis of chapter 3. There we will show how various techniques may be used to reduce the series resistance of DBRs without reducing the optical reflectivity.

The production of efficient lasers has also been shown to depend, critically, upon the use of optical and electrical confining structures. Optically VCSELs may simply be etched into pillars to form cylindrical waveguide devices offering good lateral confinement. In the longitudinal direction the structures design must allow for optimisation of the spatial distribution of the optical fields. Electrically, however, the situation is more complex. Again the pillar structure suffices for lateral confinement. Longitudinal confinement through the use of QW confining structures, however, is expected to yield advantages in terms of the lasers operating characteristics. In chapter 4 of this thesis we will demonstrate, and develop, index-guided VCSELs with strained QW active regions. Specifically we will show how the correct choice of electrical and optical confinement structures results in lasers with excellent operating characteristics in terms of both power output and threshold currents.

Finally, in this chapter we have also discussed how VCSELs have been developed for use in optical systems. In particular we have mentioned that VCSELs may be integrated with other devices to enhance both performance and functionality. This subject, along with the general issues of high speed operation, is dealt with in more detail in chapter 5.

To conclude, VCSELs have undergone much development. This has been led predominantly by industrial (and commercial) issues relating to device power consumption and output. It is evident, however, that under such rapid development research into the lasers more general characteristics, its optimisation for systems use and its integration with other devices have been neglected. More generally, the modelling of the device has also, until recently, been neglected. It is these areas that form the basis for the research to be presented in the rest of this thesis.
Chapter 2

*Transfer matrix model for multilayer structures*
2.1 Introduction

Many optoelectronic devices are produced by growing different materials layered, in planes, to form multilayer stacks (MLS). The function of each individual layer is dictated by its composition and thickness. For example, alternating layers of bulk material, of differing refractive index, may be used to form very high reflectivity mirrors and, subsequently, microcavity structures. By reducing the thickness of a layer to below ~200 Å a quantum well (QW) may be formed. This QW will have complex absorption, gain and emission properties and may be used as an active layer for either light emitting or modulating devices. Moreover, when mirrors and QWs are coupled together the resulting multilayer structure may form the basis of a laser, light emitting diode, detector or modulator. Theoretically determining the optical properties of such multilayer structures is therefore important as it allows quantitative analysis of device performance, this aids directly in device development, design and characterisation.

This chapter begins by describing a transfer matrix based model that allows calculation of the electric and magnetic field profiles within any, arbitrary, multilayer structure. This allows us to determine the reflectance and transmission properties of the structure. Various examples are given but we concentrate particularly on the passive reflector and microcavity elements employed within VCSELs.

Next we extend the model to allow the inclusion of QW gain, emission and absorbing sections. Distinctly, this involves the introduction of models for the carrier injection dependent gain and spontaneous emission spectrum of the QW active layers [Rees '93]. This modified model allows us to calculate the emission spectra, threshold current characteristics and power output characteristics of VCSELs (and LEDs) both below and above threshold. We then implement this model to study the properties of some (generic) VCSELs. Specifically we arrive at a number of design curves relating the laser threshold and output power to the reflectivity of the mirrors. These curves are later used to design very efficient VCSELs.

Finally we further modify the model to allow calculation of the oblique incidence reflection properties of a structure. With these modifications we then, briefly, study the emission patterns of microcavity structures.

Collectively the models detailed in this chapter have been developed primarily as design tools. They are applied with suitable modification within each subsequent chapter of this thesis. In each case any modifications made are indicated within the relevant chapter.
2.2 Transfer matrix model of multilayer structures

Strong interference effects may be observed within material layers of high interfacial quality and with an optical thickness \((n_{\text{layer}} \times d)\) of the order of the wavelength \((\lambda)\) of the incident light. Two particularly important cases arise and are illustrated in figure 2.1.

![Figure 2.1](image)

**Figure 2.1** Reflection from (a) \(\lambda/4\) and (b) \(\lambda/2\) optically thick layers.

Firstly, when the layer optical thickness is \(\lambda/4\) the light reflected from the front and back interface of the layer is in phase and a high reflector results. Secondly, when the layer optical thickness is \(\lambda/2\) the various reflections from the interfaces are in anti-phase, a standing wave is established within the layer and the layer reflection spectrum (from air) exhibits a Fabry-Perot (FP) resonance (a dip in reflectivity).

The collective interference phenomena occurring within a collection of material layers may be computationally studied by solving Maxwell’s equations using the now familiar transfer matrix approach [Macleod 86]. Figure 2.2 illustrates a planar dielectric film on a semi-infinite substrate. Following the notation of Macleod we may denote waves travelling in the direction of incidence as positive (+) and those travelling in the opposite direction as negative (-) going. We assume that no wave is entering from the substrate. It is noted that the infinite substrate assumption is valid for semiconductor devices (substrate ~ 300µm) where the substrate has not been thinned or highly polished. In other cases the substrate may form an extra cavity (the air beyond this layer must then be assigned as 'the substrate').

![Figure 2.2](image)

**Figure 2.2** Illustration of plane wave incident upon a thin film.
The tangential components of the electric (E) and magnetic (H) field vectors at boundary b (figure 2.2) are given by a summation, at that boundary, of the forward and backward travelling waves, thus

\[
E_b = E^+_b + E^-_b \quad \text{....(2.2.1a)}
\]
\[
H_b = H^+_b + H^-_b \quad \text{....(2.2.1b)}
\]

The fields at boundary a are then determined by multiplying the phase factors of the positive and negative going waves (equation 2.2.1) by \(e^{i\delta}\) and \(e^{-i\delta}\) respectively, to account for the additional phase shift from the layer. The phase shift (\(\delta\)) in this case, at normal incidence, is given by equation 2.2.2. Here \(N_i\) is the complex refractive index of the layer, defined through equation 2.2.3, with \(n_1\) the real part of the refractive index and \(k_1\) is the extinction coefficient of the material which is related to the material absorption coefficient (\(\alpha\)) through equation 2.2.4.

\[
\delta = \frac{2\pi N_i d}{\lambda} \quad \text{....(2.2.2)}
\]
\[
N_i = n_1 - i k_1 \quad \text{....(2.2.3)}
\]
\[
\alpha = \frac{4\pi k}{\lambda} \quad \text{....(2.2.4)}
\]

Writing the fields at boundary a in terms of those at boundary b gives

\[
E_a = E^+_a + E^-_a = E_b \cos \delta + \frac{i \sin \delta}{N_i} \quad \text{....(2.2.5a)}
\]
\[
H_a = H^+_a + H^-_a = E_b i N_i \sin \delta + H_b \cos \delta \quad \text{....(2.2.5b)}
\]

This may conveniently be expressed in the form of a matrix

\[
\begin{bmatrix}
E_a \\
H_a
\end{bmatrix} = \begin{bmatrix}
\cos \delta & (i \sin \delta) / N_i \\
i N_i \sin \delta & \cos \delta
\end{bmatrix} \begin{bmatrix}
E_b \\
H_b
\end{bmatrix} \quad \text{....(2.2.6)}
\]

The two-by-two matrix in the above expression, referred to as matrix \(M\), completely specifies the fields within the layer of figure 2.2. More generally the fields within a given layer \(j\) of a multilayer structure containing \(m\) layers may be obtained through multiplication of the matrices, \(M_j\), for all preceding layers within the structure. The fields at the first interface of a structure (\(E_0\) and \(H_0\)) may thus be related to the fields at the last interface (\(E_m\) and \(H_m\)) through

\[
\begin{bmatrix}
E_0 \\
H_0
\end{bmatrix} = M \begin{bmatrix}
E_m \\
H_m
\end{bmatrix} \quad \text{....(2.2.7a)}
\]
\[ M = \prod_{j=1,m} M_j \] ....(2.2.7b)

Consider the representative multilayer structure of figure 2.3, bounded on either side by semi-infinite substrates of refractive index \( n_0 \) and \( n_s \), with waves \( E_0^+ \) incident from the left hand side.

![Figure 2.3 Schematic multilayer structure.](image)

We may define the reflection (R) and transmission (T) coefficients of the structure (relative to the incident waves) through equations 2.2.8 and 2.2.9. In this case the electric field in the last layer is normalised such that \( E_{m+1} = E_m = 1 \), note that \( H_m (=E_m n_s) \) is then equal to \( n_s \). The fields at the first interface, \( E_0 \) and \( H_0 \), are calculated using equations 2.2.7.

\[
R = \frac{|E_0^-|^2}{|E_0^+|^2} = \frac{|E_0 - H_0 / n_0|^2}{|E_0 + H_0 / n_0|^2} ....(2.2.8)
\]

\[
T = \frac{n_s |E_{m+1}^+|^2}{n_0 |E_m|^2} = \frac{4n_s n_0 n_m}{|E_0 n_0 + H_0|^2} ....(2.2.9)
\]

The equations in this section may be used to compute the optical properties of arbitrary collections of material layers. Other, generally simpler, techniques that may be used (for example coupled mode theory) are unfortunately limited because of their inability to treat structures with large perturbations in refractive index or complex asymmetric microcavity structures [Corzine et al. '91]. These other techniques also make the introduction of (QW) sources much more complex. It must be noted that the individual layers will have refractive indices (n) and absorption coefficients (\( \alpha \)) that are dependent on wavelength (\( \lambda \)). This dependence has been accounted for in all the material layers considered within this thesis and the reader is referred to appendix A for further information.

2.3 Application of matrix model to multilayer reflector structures

One of the most important structures employed within modern optoelectronic devices is the distributed Bragg reflector (DBR). This structure provides a normal incidence mirror, the
reflectivity of which may be readily controlled through variation of the number and composition of the individual layers. This section describes the optical properties of such reflectors. The attendant electrical properties are discussed in the following chapter.

Figure 2.4 Theoretical graphs of reflectivity for λ/4 GaAs/AlAs (830Å/696Å) DBR. (a) and (b) show reflection spectrum and peak reflectivity vs. number of periods.

The basic DBR is a simple structure that lends itself readily to the growth and deposition techniques used in device production, for example it may be grown by molecular beam epitaxy (MBE) and thereby integrated directly with an optoelectronic device [see for example Jewell et al. '88, '91]. Simple (abrupt interface) DBRs comprise alternating layers of high (n_{hi}) and low (n_{il}) refractive index material, each with an optical thickness of λ/4, where λ is the design wavelength. In this case reflections from subsequent layers add in-phase such that a very high reflectivity mirror may be produced, see figure 2.1(b). Figure 2.4(a) shows the reflection spectrum for a GaAs/AlAs DBR (designed for 980nm operation) containing 4, 8 and 16 periods, where a period refers to a high (n_{GaAs}=3.52) and low index (n_{AlAs}=2.95) layer pairing. Figure 2.4(b) shows how the peak reflectivity may be controlled by appropriate choice of the number of DBR pairs (N). Furthermore, the peak reflectivity is dictated by the ratio of the refractive indices of the high and low refractive index layers. This ratio also dictates the bandwidth of the DBR (∆λ_{DBR}) (see figure 2.5(a)) which may be expressed, in the limit of high N, through the relation [Macleod '86]

$$\frac{\Delta \lambda_{DBR}}{\lambda} = \frac{4}{\pi} \sin^{-1} \left[ \frac{n_H - n_L}{n_H + n_L} \right]$$

...(2.3.1)
The corresponding transmission spectrum for a DBR, shown in figure 2.5(a), shows strong suppression at wavelengths within the stop-band. This is important for VCSELs within which this filtering effect prevents spontaneously emitted light from exiting the structure at wavelengths close to the main lasing mode (see section 2.4.1).

**Figure 2.5** (a) Reflection and transmission spectrum of $\lambda_{o}/4$ GaAs/AlAs DBR ($\lambda_{o}=980\text{nm}$). (b) Corresponding phase shift experienced by light upon reflection.

This spectrum also shows high transmission at the wavelengths on either side of the stop-band. These windows may thus be used to efficiently optically inject carriers into the active region of un-processed VCSELs such that the emission properties may be determined prior to any complex and expensive processing. This highlights one of the basic advantages of VCSELs, that is the fact that they may be tested at the wafer stage, see chapter 4. Also shown in figure 2.5(b) is the phase shift spectrum [Macleod '86] for light reflected from the DBR, this clearly shows a zero point at the design wavelength of 980nm. This point dictates the wavelength at which high finesse Fabry-Perot cavities may be produced by collections of such mirrors, as described later.

### 2.3.1 Hybrid reflectors

The DBRs within VCSELs must provide the dual function of achieving a very high reflectivity while providing a low resistance path for current, see chapter 3. Conflicts arise when the number of DBR layers is large such that numerous heterointerfaces are introduced resulting in increased DBR resistance.
Hybrid mirrors consist of modified DBRs with a layer of metal deposited on top to boost the total reflectivity of the structure [Fischer et al. '90]. Metallic reflectors, with no DBR, have been studied by other groups [Schubert et al. '90] and have demonstrated very low resistivities. Unfortunately VCSELs containing such reflectors have relatively high threshold current densities (~10kAcm⁻²) due to the limit on reflectivity imposed by the metal.

A metal commonly used in the processing of optoelectronic devices and possessing a high reflectivity in the infra-red region is gold. This may be evaporated onto a suitably modified DBR to boost its reflectivity and also to act as a contact layer, furthermore it may be used as part of a reactive ion etch (RIE) mask during VCSEL manufacture [Geels et al. '90a].

![Figure 2.6](attachment:figure2_6.png)

**Figure 2.6** Reflection from last few interfaces of a DBR with λ/2 GaAs and metal termination. Cases (a) and (b) show reflection planes for a perfect and imperfect conductor [Geels '91].

Figure 2.6(a) shows the effective reflection planes for a GaAs/AlAs λ/4 DBR with the final GaAs layer made λ/2 in optical thickness. The structure is terminated with a metal such that a high reflectivity results for light incident from the left. Case (a) shows termination at a perfect conductor. No electric fields penetrate such a conductor and so the reflection plane of the metal coincides with the GaAs/metal interface. In this case a λ/2 GaAs layer phase-matches the reflections from the metal to those within the DBR whereas a λ/4 layer would introduce a phase slip and cavity effects would result. Figure 2.6(b) shows termination at an imperfect (real) conductor. In this case the fields penetrate to a finite depth, the skin depth, within the metal and hence the plane of reflection shifts into the metal. An additional phase shift is introduced in this case and so the thickness of the last, nominally λ/2, layer must be decreased slightly to phase-match reflections. The phase shift, φ, due to the metal is given by equation 2.3.2. The optical thickness (ξ) of the last GaAs layer, as required to phase-match reflections, is given by equation 2.3.3 [Geels ‘91], where n and k are the real and imaginary refractive indices respectively.

\[
\phi = \tan^{-1}\left(\frac{2n_{GaAs}k_{Al}}{n_{Al}^2 - n_{GaAs}^2 + k_{Al}^2}\right) \quad \text{......(2.3.2)}
\]
Figure 2.7 shows the broad- and narrow-band theoretical reflectivity of a 16 period GaAs/AlAs DBR, designed for 980nm operation. Also shown is the spectrum for a hybrid mirror comprising the basic 16 period DBR with the last GaAs layer thickened to 1177Å and terminated on gold.

\[
\xi = \frac{\lambda - \phi \lambda}{2 \pi 4}
\] ....(2.3.3)

Figure 2.7 Reflectivity of 16 period GaAs/AlAs λ/4 DBR (980nm), incidence is from GaAs.

'Hybrid' is the same mirror with the addition of a phase matching layer and 3000Å Au.

The last GaAs layer thickness, in the hybrid case, is increased in accordance with equations 2.3.2 and 2.3.3, using \( n_{\text{GaAs}} = 3.52 \), \( n_{\text{Au}} = 0.247 \) and \( k_{\text{Au}} = 6.684 \) [See appendix A]. In this case \( \phi \), the phase shift due to the penetration of fields into the metal, is approximately 56°.

Figure 2.7(a) clearly demonstrates broadening of the stop-band when gold is used to boost the DBR reflectivity. The gold reflectivity, on GaAs, is approximately 97% at the wavelengths of consideration (increasing slightly with wavelength) and is maintained over a large spectral range. Thus very broad-band reflectors may be produced using metal/DBR combinations. Figure 2.7(b) shows the corresponding increase in peak reflectivity for a hybrid mirror, the slight shift in peak wavelength is attributed to the dispersive indices of the materials used. In both cases incidence is from GaAs, a common material for the cavity of a VCSEL.

The need for fewer DBR periods and the inherent contacting layer make hybrid DBRs the mirrors of choice for modern VCSELs and as such they are used throughout the work in this thesis. The reader is referred to chapter 3 for further series resistance reduction techniques and to chapter 4 for information on the implementation of hybrid mirrors within VCSELs.
2.4 Application of matrix model to microresonators

Microresonators are currently of interest within optoelectronics and form the functional basis of numerous devices. This section of the thesis presents studies on some of the optical properties of microresonators (microcavities) using the transfer matrix model developed earlier, with modifications where appropriate.

The vertical integration of two $\lambda/4$ DBRs, with a spacer region between them, results in a vertical cavity microresonator, figure 2.8. The term microresonator (microcavity) is used here to describe structures with optical cavities only a small number of wavelengths in length.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig2.8.png}
\caption{Generic Fabry-Perot microcavity structure.}
\end{figure}

If the cavity is of the Fabry-Perot (FP) type then its optical length ($d$) must be an integral number ($m$) of half wavelengths, at the design wavelength ($\lambda_0$), as expressed in equation 2.4.1.

\[ d = m \frac{\lambda_0}{2} \quad \ldots (2.4.1) \]

The reflection spectrum for a FP cavity comprising 18 and 20 period top and bottom DBRs and a $1\lambda$ GaAs optical cavity (a configuration that is similar to many VCSELs) is shown in figure 2.9(a). The spectrum clearly shows the broad stop-band of the DBRs, but this is now modified by the FP resonances introduced by the cavity. Figure 2.9(b) shows the effect on the FP resonance, as indicated in figure 2.9(a), of fixing the bottom DBR reflectivity (~99.7% as seen from the cavity, exit is to GaAs) and varying that of the top DBR. The linewidth of the device decreases as the top DBR reflectivity is increased. The FP resonance within the stop-band of the DBRs (also referred to as the FP mode) relates to the high quality (Q) cavity formed between the two DBRs.
Figure 2.9 (a) Reflection spectrum for high finesse FP microcavity.
(b) Effect of varying $N_{\text{top}}$ on linewidth of structure.

The quality factor ($Q$) is numerically defined as the ratio of the FP resonance central wavelength ($\lambda_0$) to the linewidth ($\Delta\lambda$ - full width at half maximum) of the FP resonance, it is given by equation 2.4.2 [Rogers et al. '90]. This quantity relates the linewidth of the FP mode to the top and bottom DBR reflectivities ($R_{\text{top}}$ and $R_{\text{bot}}$) and to the cavity length ($L_c$). As such it characterises the structure completely.

$$Q = \frac{\lambda}{\Delta\lambda} = 2\pi \left( \frac{L_c}{\lambda} \right) \left[ -\ln \left( R_{\text{top}} R_{\text{bot}} \right) \right]^{-1}$$

For the structure of figure 2.9(a) the top DBR reflectivity is $\sim 99.8\%$ (remembering incidence is from GaAs and exit is to air). This gives a $Q$ factor of $\approx 2500$, implying a linewidth of $\sim 4\text{Å}$. This linewidth is important because, neglecting broadening mechanisms, it dictates the maximum linewidth of emission (or absorption) of any material placed within the cavity. Thus by altering the DBR reflectivities narrow linewidth light emitting devices [Keller et al. '93] may be produced (see also chapter 4). An interesting point to note, and one that will be discussed further in chapter 5, is that the Q of a cavity also determines the photon lifetime within that cavity ($\tau_{\text{ph}}$). This cavity photon lifetime, given by equation 2.4.3 [Corzine '93], in turn determines the rate at which energy is dissipated by the cavity and, as such, dictates the rate at which light emission from the cavity may be modulated. In the case studied above (figure 2.9) the photon lifetime is found to be approximately 1.3ps.
Finally, another very important quantity for microcavity structures is the wavelength separation between FP modes, generally termed the mode spacing. In general the mode spacing \( \Delta \lambda_{\text{spacing}} \) of a FP cavity structure is given by equation 2.4.4, where \( n_{\text{cav}} \) is the refractive index of the cavity medium and \( \lambda_0 \) is the main mode wavelength (i.e. the design wavelength).

\[
\Delta \lambda_{\text{spacing}} = \frac{\lambda_0^2}{2dn_{\text{cav}}}
\]

For a 1\( \lambda \) GaAs cavity equation 2.4.4 suggests a mode spacing greater than 400nm. Thus only a single mode exists within the stop-band of the DBRs (figure 2.9(a)). This is of particular significance when considering the light emission characteristics of microcavity structures and is discussed in greater detail within the next section. It is noted that, due to field penetration into the DBRs, the effective cavity length of a microcavity structure is actually larger than that defined by \( d \) in figure 2.8. Thus the observed mode spacing is regularly less than the values obtained using 2.4.4. The transfer matrix approach to solving for the optical modes of a structure does however return the correct (longitudinal) mode spacing for a structure. This is because it includes the penetration effect. This is important because microcavities with more than one mode within the DBR stop-band may emit in an undesirable multimode fashion, competition between modes may then lead to further complications.

### 2.4.1 Application of gain to microresonator cavities

By placing layers with a positive absorption coefficient into the structure of figure 2.8 we may study the effects of gain \( g \) within a microresonator. For a VCSEL structure this involves the insertion of either bulk, or more commonly quantum well (QW) material, into the cavity region. For the structures developed in this thesis the chosen design wavelength is 980nm and as such QW material (InGaAs based) must be used to provide the gain.

The transmission \( T \) of a structure, at the FP mode \( \lambda \), is known to become infinite if the net gain \( g \times L_g \) equals the losses \( \alpha_s \) within the structure [Hansmann '92]. The gain at this point is defined as the threshold gain \( g_{\text{th}} \). Thus the value of \( g_{\text{th}} \) for an arbitrary structure, may be determined by varying the gain and searching for optical modes with transmission tending to infinity \( T(\lambda, g) \rightarrow \infty \). In the case of a VCSEL, only a single mode is expected to lase at a low injection level, due to the longitudinal mode spacing and finite gain bandwidth. Thus only a
single value of $\lambda$ and $g_n$ should be returned. Knowledge of the threshold gain then allows calculation of the field distributions, at threshold, within microcavity structures.

The electric ($E_j$) and magnetic ($H_j$) fields within a given layer (j) of the structure of figure 2.8 (notation in figure 2.3) are given by summing the forward and backward going waves within that layer. The fields at any, arbitrary, position ($z$) may be determined by further decomposing the structure into a collection of very thin (~10Å) layers and calculating the subsequent fields.

Figure 2.10 Field profile within a $1\lambda$ GaAs cavity.

Figure 2.10 shows the electric field profile (actually $E^2$) within the $1\lambda$ cavity of a microresonator. The field clearly shows strong spatial variations along the cavity. If a gain section (the shaded block in figure 2.10) of length $L_g$ is introduced into this cavity its position and physical thickness will dictate the amount of gain experienced by a propagating light beam. The actual gain will be given by the product of the layer gain ($g$) and the layer confinement factor ($\Gamma_z$) in the growth direction, as given by equation 2.4.5. The confinement factor numerically relates the fraction of power carried in a given layer to the total power within the structure [Corzine et al. '89].

$$\Gamma_z = \frac{\int_0^{z_g \lambda} |E|^2 \, dz}{\int \int_{-\infty}^{\infty} |E|^2 \, dz} = \Gamma_{fill} \Gamma_{enh} \quad \text{(2.4.5)}$$

The confinement factor ($\Gamma_z$) comprises two components. The fill-factor ($\Gamma_{fill}$) is essentially the gain-length to cavity-length ratio and for a cavity completely full of gain material ($L_g = d$) is the only contribution to $\Gamma_z$ (i.e. $\Gamma_{enh} = 1$). However, if $L_g$ is made small ($L_g \ll \lambda$) and the gain layer placed at the anti-nodes of the standing wave, then the effective gain of that layer is increased by the enhancement factor ($\Gamma_{enh}$). This effect, which results in an effective doubling of the interaction between the gain and the light, is commonly referred to as the resonant periodic gain (RPG) scheme [Raja et al. '89]. It is commonly used within VCSELs to reduce the gain required to reach threshold. It is noted here that the position of a QW relative to a DBR dictates
strongly, at a fundamental level, the emission properties of that QW [Rogers et al. ‘90]. For the case of interest within a VCSEL, that is when the QWs are placed at the antinodes of the optical field, the spontaneous emission rate is increased slightly.

Figure 2.11 illustrates the optical field for a microcavity structure comprising a 10 period top and bottom DBR (980nm) and a $2\lambda$ optical cavity, containing $3 \times \text{In}_0.5\text{Ga}_{0.5}\text{As}$ QWs. Each QW is placed in a separate antinode of the standing wave optical field and hence the optical interaction with the QWs is enhanced (through RPG).

The figure clearly shows how the optical field decays exponentially into the DBRs of the structure, the photon density within the structure also follows this profile and can be seen to peak within the cavity. This explains the high photon densities that may be achieved within VCSEL cavities, the photon density directly effects the high speed characteristics of a VCSEL and is discussed in chapter 5.

Given the fields at any, arbitrary, position within a microcavity structure, containing both gain and loss sections, we may calculate the emission spectrum of that structure. The spectrum is calculated by summing the spontaneous emission radiated, at a given wavelength, from each active layer, taking into account the multiple reflections from the various interfaces within the structure [Hansmann ‘92]. The transfer model described above will naturally take into account the gain from each active layer, although re-absorption events are not considered. The total intensity emitted from the top of a structure, at a given wavelength ($I_{\text{top}}(\lambda)$), is given by equation 2.4.6. In this equation the terms $t_{\text{top},j}$, $r_{\text{top},j}$ and $r_{\text{bot},j}$ are the complex transmission and reflection coefficients of the structure extended from subsection $j$ to the top and bottom facets of the structure respectively.
The spontaneous emission ($\rho_j$) radiated from a layer (j) is, in general, related to the carrier injection level and to the photon density within that layer. In the model described here the latter, photon density, dependence is not considered because only the number and wavelength of emitted modes are of importance to this work.

For a given injection level the gain and spontaneous emission characteristics of a given active layer, for example a QW, may be calculated. A description of such calculations is beyond the scope of this thesis and the reader is referred to the excellent book by Zory [Zory '93] on this subject. Figure 2.12 shows the theoretical gain and spontaneous emission, at room temperature, of a single 80Å $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ QW (GaAs barriers), plotted against the number of injected carriers [Rees '93]. This is (nominally) the QW of choice for the work in this thesis and the reader is referred to chapter 1 for further information. A constant broadening lifetime of $1\times10^{-13}$s, at room temperature, has been used for the calculation [Rees '93]. Figure 2.12(a) clearly shows the development of the gain spectrum (gain for TE polarised light) with increasing carrier injection, the predominant contribution to the gain in this case is the QW $e_1$-$hh1$ transition. The corresponding spontaneous emission spectra (b) are seen to posses tails that extend from above 1μm in wavelength down to below 900nm. This will strongly effect the broad-band emission spectrum of a microcavity structure, especially under sub-threshold conditions.

\[
I_{\text{sp}}(\lambda) = \sum_i \frac{|t_{\text{top},i}|^2 (1 + |r_{\text{bot},i}|^2)}{|1 - r_{\text{bot},i}t_{\text{top},i}|^2} \rho_j
\] ....(2.4.6)

Figure 2.12 (a) Gain spectra for an 80Å $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ QW with GaAs barriers.
(b) Spontaneous emission spectra for the same QW.
The peak of the gain spectrum in figure 2.12(a) can be seen to increase with increasing carrier injection. However, the peak gain saturates at high injection, neglecting the influence of higher order transitions, due to band filling effects and this must be accounted for in any calculations. Figure 2.13 shows the corresponding peak of the gain spectrum (at approximately 980nm) plotted against carrier injection level.

![Figure 2.13 Peak gain vs. injection level for 80Å In$_{0.3}$Ga$_{0.7}$As QW.](image)

For a simple FP in-plane laser (IPL) the lasing wavelength corresponds directly to the wavelength of the peak gain. Thus, any changes in the peak gain wavelength, as a result of device temperature changes for example, result in a shift of lasing wavelength and, more importantly, in mode hops. The emission (spontaneous and stimulated) wavelength of a microcavity structure is dictated by the optical mode properties of the device structure, as defined at the device growth stage, and not by the peak gain wavelength. Light that is emitted by the QWs within a microcavity structure at wavelengths not coincident with the FP mode will undergo multiple reflections and ultimately be re-absorbed. It has further been suggested that such spontaneous emission, occurring off the main mode, is suppressed within such structures. Conversely, the spontaneous emission rate for photons emitted at the FP mode may be enhanced by a small factor, this is currently an active area of research and may yield very low threshold lasers [Yamamoto et al. '91, Huffaker et al. '92].

Using the above information we may calculate, again at room temperature, the emission spectrum for a microcavity structure. We take a generic VCSEL structure as an example. The structure consists of a 20 period bottom DBR (on a GaAs substrate) and an 18 period top DBR. The cavity is chosen to be 2λ$_0$ long (λ$_0$ = 980nm) and contains 3 × 80Å In$_{0.3}$Ga$_{0.7}$As QWs with each QW placed at an antinode of the standing optical field within the cavity. The structure is designed to emit through the top 18 period DBR. The threshold gain within this structure, with no optical losses, is approximately 560cm$^{-1}$ (QW injection level ~ 4×10$^{18}$cm$^{-3}$) as determined using the transfer matrix model. The reflection spectrum for this structure is similar to that in
figure 2.9(a), again demonstrating a single FP mode within the DBR stop-bands. The corresponding emission spectra (at threshold), showing emission from both the top and bottom of the device, are given in figure 2.14(a).

![Figure 2.14](image)

**Figure 2.14** (a) Top and bottom emission spectra for 980nm VCSEL at threshold. (b) Emission spectra at various levels of gain (offset for clarity).

These spectra clearly show the single longitudinal mode emission at the FP resonance of the structure. The influence of the DBR stop-band can be seen to strongly impede light emission at wavelengths around the main mode, with the absolute light levels dropping by approximately 5 orders of magnitude from the emission maximum to the emission minima. The inset of this figure shows the wavelength and linewidth of the emission at the FP mode, plotted on a linear scale. The linewidth is seen to be less than 0.01Å (FWHM), this linewidth (Δλ) is artificial in that the model does not account for any broadening (dynamic) effects which would increase Δλ. The spectra also show the appearance of side-bands, at wavelengths corresponding to the edges of the stop-band, and these have been attributed to the tails of the spontaneous emission spectrum from the QWs (see figure 2.12(b)). This spontaneous emission is not strongly reflected from the DBRs (falling outside the DBR stop-band) and so escapes, with the oscillating features of the spectrum dictated by the transmission features of the VCSEL structure. Figure 2.14(b) shows the theoretical lasing spectra for the VCSEL sample at various levels of gain (g_th is the threshold gain). Again single longitudinal mode emission is seen over the range of gain levels, the output power at the mode can also be seen to increase with increasing gain (the effect of gain clamping at threshold is not included). Note that the spectra are offset for clarity, the emission wavelength in all cases is the same. Similar models have been developed by a number of authors [Weber et al. '91, Makino '93] who have extended them to include a true coupling of the
spontaneous emission to the optical modes of the structure. In this model the spontaneous emission is treated as an independent source that is filtered, through multiple interference effects, by the structure. This model is however found to be in good agreement, at threshold, with the models of other groups [Weber et al. '91].

Another useful quantity, for a microcavity structure (e.g. a VCSEL), that may be determined using the transfer matrix model is the optical efficiency ($\eta_{opt}$). This quantity is defined as the fraction of photons emitted within the cavity to the number that exit the structure [Corzine et al. '93] and may be viewed as an output coupling efficiency. The optical efficiency may be calculated through a knowledge of the threshold gain ($G$) within a structure with absorptive losses ($L$) and mirror losses ($T$), remembering that

$$G = L + T$$ .....(2.4.7)

By calculating the threshold gain when $L=0$ the value of $T$ may be determined. A subsequent calculation of $G$ when $L=L$ then gives the quantity $L+T$. The ratio of $T$ to $L+T$ then gives $\eta_{opt}$.

$$\eta_{opt} = \frac{T}{L+T}$$ .....(2.4.8)

Calculating the threshold gain, at a number of different loss levels, for the structure of figure 2.14 (by application of the transfer matrix model) gives the solid curve of figure 2.15(a). The optical loss in this case is applied to each layer within the VCSEL structure. This figure also shows the effect of altering the top DBR reflectivity by changing the number of top DBR GaAs/AlAs pairs ($N_{top}$). This has the effect of changing the output coupling efficiency ($\eta_{opt}$), and threshold, of the VCSEL, thereby affecting the maximum output power of the device.

Figure 2.15(b) shows a calculation of the maximum optical efficiency, neglecting sample defects, scattering and diffraction losses, for the VCSEL considered in figure 2.14 (solid curve). The graph clearly shows how the optical efficiency of the structure depends critically upon the losses within the structure. In reality these losses are due, in part, to structural imperfections, for example dislocations, and free carrier losses, due to dopants. Thus, as discussed in greater detail in chapter 3, the doping in a structure should be concentrated within low field areas of the device. Figure 2.15(b) also shows the optical efficiency curves for VCSELs with different top DBR reflectivities. The figure demonstrates how the use of a lower reflectivity output coupler yields a VCSEL with a higher output efficiency. The light that does not exit the structure, in all of these cases, is absorbed and generates heat which leads to thermal problems within the VCSEL. Thus high power devices are seen to require low reflectivity (high efficiency) output couplers. Unfortunately, when figures 2.15(a) and (b) are studied together it becomes clear that a
lower reflectivity output coupler results in a VCSEL with a higher threshold. Thus compromises between threshold gain and power output must be found. Obviously such compromises are dictated by the application for which the VCSEL has been designed, this is discussed in greater detail in chapter 4.

![Figure 2.15](image)

**Figure 2.15** (a) Threshold gain vs. optical loss in VCSEL with varying top DBR reflectivity.  
(b) Optical efficiency vs. optical loss in VCSEL (loss values are applied to each layer).

Finally, with a knowledge of the optical output efficiency and threshold gain of a structure the output intensity, at a given injection current, may be calculated. Unfortunately this model neglects thermal effects due to parasitic absorption of injected power by the structure and as such overestimates the output power. For an injection current I, injected at the contacts of the structure, the output power from the device is given by equation 2.4.9 [Scott et al. ’93a]. In this equation \( \eta_{\text{inj}} \) is the carrier injection efficiency into the QW, it is generally less than one due to recombination in the surrounding cladding layers. The other symbols have their usual meaning.

\[
P_{\text{out}} = \frac{hc}{e\lambda} \eta_{\text{inj}} \eta_{\text{opt}} (I - I_\text{th})
\]

\[(2.4.9)\]

The threshold current in this equation (\( I_\text{th} \)) is, in its simplest form, given by calculating the threshold gain and then the corresponding threshold carrier density (\( n_\text{th} \)) in the QW (see figure 2.13). Knowledge of the carrier lifetime within the material (generally a few nanoseconds) then allows calculation of the threshold current density (\( J_\text{th} \)) which, intern, determines \( I_\text{th} \).

Generally, however, the current injected into a VCSEL, at threshold, is not directly proportional to the number of carriers reaching the active QW layers. In laser modelling it is often convenient to calculate the threshold gain, using the transfer matrix model, and then
determine the carrier injection level \( (n_{inj}) \) required to attain that gain, using for example figure 2.13. The current injection (I) required at the contacts, to obtain the threshold carrier density, may then be calculated through consideration of the various recombination and leakage effects present within the device. This has been done, in a very satisfactory way, by Scott [Scott et al. '93a] who considers the current density \((J)\) required to give a carrier density \((n)\) within the QW as comprising a number of contributions. Firstly there is the current that leads to the carriers in the QWs that results directly in spontaneous emission (termed \(J_{\text{spon}}\)), this is basically the current derived from figure 2.12(b). Next, some of the injected current is expended in producing spontaneous emission within the barriers of the QW \((J_{\text{bar}})\). Finally some of the injected current is lost to non-radiative losses, these include Auger recombination \((J_{\text{Auger}})\) and carrier leakage over the QW heterostructure \((J_{\text{leak}})\). The total injected current is then given by summing the individual currents (equation 2.4.10) which, as mentioned previously, are determined by the carrier level in the QWs.

\[
J(n) = J_{\text{spon}}(n) + J_{\text{bar}}(n) + J_{\text{Auger}}(n) + J_{\text{leak}}(n) /
\eta_{\text{inj}}
\]

(2.4.10)

In this equation the \(J_{\text{spon}}(n)\) terms, which are given explicitly in appendix B, are taken directly from the work of Scott [Scott et al. '93a], the reader should note the temperature dependence of these terms. The injection efficiency \((\eta_{\text{inj}})\) is taken to be constant and may be used as a fitting parameter. It is generally dictated by material quality and is assumed, in this section, to be 80%.

Given the current density required to achieve a given injection level within the QWs of a structure, neglecting current losses in the device DBRs and contacts, the threshold current and device output power may be calculated. It is noted that this model, unlike the iterative model of Scott [Scott et al. '93a], does not calculate the temperature rise in the device during operation. As such a constant temperature \((T)\) must be specified for the calculation. The threshold gain, as determined in figure 2.15 (using the transfer matrix model and the gain calculation [Rees '93]), for a 3 \times\) QW VCSEL \((N_{\text{top}} = 18, N_{\text{bot}} = 20, \text{cavity length} = 2\lambda, T=350k)\) is approximately 630cm\(^{-1}\) (per QW) for a structure with losses of 10cm\(^{-1}\). The injected carrier density (per QW) is approximately \(3\times10^{10}\)cm\(^{-3}\). This leads, using equation 2.4.10, to a threshold current density per QW of approximately 300 A/cm\(^2\) corresponding to a total current density of 900 A/cm\(^2\). Using these values the (total) output power vs. injection current (L-I) graphs of figure 2.16 may be calculated, where the structure is above threshold and a device diameter of 20\(\mu\)m is assumed.

Figure 2.16(a) shows the L-I graph, at a range of temperatures, for the VCSEL described above. The external differential (quantum) efficiency \((\eta_{\text{ext}})\) in this case is approximately constant with temperature and has a value of .07 mW/mA (in must be noted that this model assumes all of the emitted light is unidirectional). It can be seen that as the temperature of the device
increases the threshold current also increases. This may be attributed to an increase in the carrier density required to reach the threshold gain. The gain attained within a QW, at a given wavelength, decreases with increasing temperature due to a change in the bandgaps of the materials forming the QW, this tends to shift the gain peak to longer wavelengths. Furthermore, there is an increase (~10%) in the current lost to barrier and Auger recombination when the temperature is increased. Finally the leakage current increases dramatically with temperature such that fewer carriers thermalise into the QWs to provide gain. This has been forwarded as one of the mechanisms that act to make the L-I curves for a VCSEL non-linear at high current injection and temperature [Geels '91, Scott et al. '93a].

![Figure 2.16](image)

Figure 2.16 (a) Effect of temperature on the L-I curves of a VCSEL \( (\eta_{\text{inj}}=0.8) \)

(b) Effect on threshold current and slope efficiency of varying \( N_{\text{top}} \) \( (N_{\text{bot}}=20) \).

Figure 2.16(b) shows the L-I curves for a range of VCSELs, similar to those of figure 2.15, with varying output coupler efficiencies (as dictated by the value of \( N_{\text{top}} \)). Increases in the threshold current can be seen to accompany a decrease in the output coupler reflectivity. However, the output slope efficiencies can be seen to increase as the output coupler reflectivity is decreased. Values for \( \eta_{\text{ext}} \) of 0.77 mW/mA, 0.69 mW/mA and 0.65 mW/mA are obtained for the VCSELs with \( N_{\text{top}} \) equalling 16, 18 and 20 GaAs/AlAs pairs. At higher injection currents the VCSEL with \( N_{\text{top}}=16 \) will give a higher output power than for the other two structures, thus the L-I curves for the various VCSELs cross over. This again highlights the way that the VCSEL structure may be altered to fulfil certain requirements, for example low threshold or high output power. In this case the VCSEL with an 18 period top DBR is seen to give both a low threshold current (~3mA) and a good power output conversion efficiency. It must, of course, be remembered that the VCSELs studied here are idealised structures. In reality the injection
efficiency falls far short of the ideal values with many carriers, for example, recombining at the sidewalls of the structure or lost to defects within the thick DBRs. Furthermore carriers may be lost, once in the QWs, to the pumping of undesirable levels that lead in turn to gain at wavelengths away from the main FP mode. Ultimately thermal problems will arise and these will affect the L-I curve dramatically. As the VCSEL heats up the QW gain peak shifts to increasingly longer wavelengths, however the optical FP mode remains relatively localised, this leads to a turn-over in the L-I characteristics and a limit on the power output of the device (see chapter 4). These issues will dramatically alter the ideal linear L-I curves of figure 2.16 and will limit both the external quantum efficiency and the maximum power output of the device. A number of authors have attempted to theoretically study the highly complex thermal properties of, and problems within VCSELs [Nakwaski et al. '93, Scott et al. '93a]. Unfortunately the resulting models are themselves highly complex, and generally structure dependent, and fall beyond the scope of this work. However, the importance of temperature and its effects within VCSELs will be referred to, and commented upon, throughout the experimental work in this thesis.

2.4.2 Transverse mode properties of microresonators

The models described up to this point have concentrated on determination of the longitudinal mode properties of microresonators, specifically concentrating on VCSELs. Generally the operation of a VCSEL is also determined by the transverse (or lateral) structure of the device. For example, for the air-post index-guided VCSELs used within this work, if the device is made large, laterally, then in-plane luminescence may dominate the vertical luminescence. This depopulates the injected QW levels and may prevent population inversion, such that vertical lasing action is inhibited [Iga et al. '88]. We have observed this phenomena in rectangular index guided VCSELs with dimensions exceeding 100μm x 100μm. In this case large amounts of in-plane luminescence are observed, emanating from the sidewalls of the active layers (viewed with a CCD camera through an optical microscope), and lasing is prevented.

Figure 2.17 Square and cylindrical waveguides (expressing notation).
The transverse optical mode structure of a device represents the allowed lateral (orthogonal to growth direction) field distributions that are supported by that structure. In general the lateral modes of a vertical cavity device are dictated, for an air post structure, by the shape, size and effective refractive index of the device mesa, for example the rectangular or cylindrical structures of figure 2.17. By assuming that the microcavity structure can be approximated by a single slab of material with a refractive index \( n_{\text{slab}} = n_{\text{active}} = n_{\text{GaAs}} \approx 3.52, n_{\text{air}} = 1 \) we may calculate the transverse mode structure, assuming that it is dictated only by the above variables. For a square slab, of side length \( w \), the transverse electric field profile may be approximated by equation 2.4.11 [Geels '91]. The measurable intensity is then proportional to the square of the electric field. In this case the fields are set to zero at the mesa edge (this is valid due to the large refractive index discontinuity) and we are essentially fitting half wavelengths of light into the structure, in a manner similar to the longitudinal modes of equation 2.4.1. Thus the \( m_x \) and \( m_y \) in 2.4.11 are analogous to the factor \( m \) in 2.4.1.

\[
E = E_0 \sin\left(\frac{\pi m_x}{w} x\right) \sin\left(\frac{\pi m_y}{w} y\right) \quad \text{.....(2.4.11)}
\]

The transverse mode spacing (\( \Delta \lambda_{\text{trans}} \)) in this case, relative to the longitudinal emission wavelength \( \lambda_0 \), is given by equation 2.4.12 [Geels '91], and is \( \approx 1-2\AA \) for a 10\( \mu \)m mesa.

\[
\Delta \lambda_{\text{trans}} = -\frac{\lambda_0^3}{8w^2n_{\text{eff}}^2} \left( m_x^2 + m_y^2 \right) \quad \text{.....(2.4.12)}
\]

The corresponding intensity distribution \( S(r,\phi) \) within a cylindrical structure, of radius \( a \), is given by equation 2.4.13.

\[
S(r,\phi) \approx (\cos^2 b\phi) J_b^2\left(\frac{ur}{a}\right) \quad \text{.....(2.4.13)}
\]

This equation can be seen to be the solution to the transverse fields within a multimode fibre [Lee '86], within which there is generally some leakage of fields out of the guide. Only the solution for \( r < a \) is given, this is found to give a good representation of the basic lateral modes within a VCSEL [Hasnain et al. '90]. The \( J_b \)'s in this equation represent Bessel functions of the first kind, where \( b \) is the order of the function, \( u \) represents the normalised wavenumber.

Field distributions for the square and circular cross section devices are shown in figure 2.18. The \( \text{TEM}_{0,0} \) solutions (more correctly termed the \( \text{LP}_{0,1} \) for the cylindrical case [Lee '86]) can be seen, in both cases, to peak in the centre of the structure and decay rapidly towards the mesa sidewalls. This is in stark contradiction to the higher order \( \text{TEM}_{1,1} \) (\( \text{LP}_{2,1} \) for cylinder) modes which show a higher intensity away from the structure central axis. These higher order
modes can coexist, within a VCSEL, with the lower order modes and, in extreme cases, compete with them for the available gain. The onset of these higher order modes can be impeded through the use of smaller device diameters. This directly affects the number of sustainable lateral modes. It must be noted that these calculations are included only to demonstrate the possible lateral modes within vertical cavity structures.

Figure 2.18 Theoretical transverse modes, as supported in square and circular mesas.

The above calculations are purely waveguide solutions and as such highlight the sustainable modes within perfect structures. In reality the large number of lateral modes (possibly many hundreds) supported, by say a 50µm VCSEL, are further restricted by the carrier injection (and gain) lateral profile. This is itself dictated by the contacting geometry [Chong et al. '93], and is further complicated by any spatial hole burning within the gain of the device (due to injection geometry and temperature effects) [Wilson et al. '94]. Fortunately, within devices of order 20µm diameter the large series resistances of the DBRs act to spread the injected carriers laterally such that a relatively uniform injection profile exists at the active layer. Furthermore, as the device diameter is reduced the transverse modes become affected by any carrier and photon losses, for example sidewall recombination and scattering at the sample surface. These
mechanisms prevent those modes with high off axis photon densities (e.g. TEM_{1,1}) from reaching threshold, at least at gain levels comparable with the lower order modes.

2.4.3 Oblique incidence properties of DBRs and microcavities

In this section we briefly discuss the reflection properties of multilayer structures placed at some angle ($\theta_i$) to the incident light, this is assumed to comprise only plane waves (see figure 2.2). In this case the phase shift ($\delta$) of light passing through a tilted layer is given by equation 2.4.14. The angle $\theta_i$ refers to the direction of light within the layer and is given through successive application of Snells law of refraction, expressed for the first layer (layer 1) in equation 2.4.15.

\[
\delta = \frac{2\pi N_i d_i \cos \theta_i}{\lambda}, \quad \text{.....(2.4.14)}
\]

\[
N_0 \sin \theta_i = N_1 \sin \theta_i, \quad \text{.....(2.4.15)}
\]

Initially we may study the basic DBRs, introduced in section 2.4. At normal incidence the reflectivity of a DBR is independent of the polarisation of the incident light. This is not the case for a tilted DBR. Denoting waves with electric or magnetic field vectors parallel to the material layers as transverse electric (TE) and transverse magnetic (TM) respectively allows calculation of the reflectance properties of tilted DBRs. Arbitrary polarisations may be constructed through suitable addition of these two polarisations.

![Figure 2.19](image.png)  
**Figure 2.19** Theoretical reflection spectra for 980nm $\lambda/4$ DBR at normal and 45° incidence, showing effect of polarisation on reflectance.
Figure 2.19 shows the reflection spectra for a DBR, for each of the two polarisations, when light is incident at an angle of 45° to the normal (growth direction). A shift in the central wavelength of the stop-band is observed which is different, in magnitude, for each polarisation. Furthermore the DBR peak reflectivity and stop-band width is decreased for TM polarised light, relative to the TE polarisation. The reflection spectrum shift with angle is of prime importance in assessing the performance of a number of devices. For example vertical cavity surface emitting amplifiers, and optical logic elements, often require input beams incident at some angle to the normal [Raj et al. ’93]. Also, the optical pumping of VCSELs is regularly performed at an angle so that more light may be injected into the structure. This utilises the reduced reflectivity for specific polarisations and has the added advantage that any reflected pump beam is removed from the system by the oblique incidence (see chapter 4).

The effect of tilting a FP cavity, for example the structure of figure 2.9(a) (N_{top}=18, N_{bot}=20, d=1\lambda), is to shift the FP resonance to shorter wavelengths. This is demonstrated in figure 2.20 which shows the FP mode wavelength (calculated using the transfer matrix model) plotted against the angle of incidence (TE polarisation is assumed).

![Figure 2.20] FP wavelength vs. angle for microcavity structure.

The FP resonance can be seen to shift very quickly for angles greater than 10 degrees. Again this is important for vertical cavity optical logic devices in which case the incident (off-axis) beam wavelength must be altered to match the shifted FP wavelength. This calculation assumes light incident from outside the structure. It is interesting however to note that light emission from within the structure also emits into these off axis modes. We have studied the longitudinal (on axis) mode case in figure 2.14, where it was shown that the wavelength of emission is dictated by the wavelength of the FP mode. Above threshold only this longitudinal mode is of importance as the dominant photon generation process is stimulated emission. However, below threshold the predominant mechanism is that of spontaneous emission. This emission will occur into any modes that are present, with little angular dependence, and as such
will readily radiate light off-axis [Yamanishi ‘92]. Evidently, no emission from the microcavity structure will occur for spontaneous emission at wavelengths longer than the normal incidence FP mode wavelength. Again the emission will have a linewidth dictated by the quality factor (Q, off-axis) of the cavity. This is of particular importance in the design of narrow divergence microcavity light emitting diodes (LEDs) where this off-axis emission imposes limits on the minimum divergence that may be obtained. This effect may be studied by placing a spontaneous emission source (in this case with a gaussian profile, and a peak intensity of 1) within the microcavity structure of figure 2.9. The resulting emission from the structure has the radiation pattern shown as the solid line in figure 2.21(a), where a QW emission linewidth of 10nm is assumed (similar to a good quality single QW at room temperature). In this case the peak of the QW emission spectrum coincides with the normal incidence FP mode of the structure (980nm).

Because the divergence in this case is due to spontaneous emission occurring at wavelengths coinciding with off-axis FP modes we might expect that a narrowing of the QW emission spectrum will result in a narrower divergence emission pattern. This is indeed the case and is shown by the dashed pattern in figure 2.21, where a spontaneous emission linewidth of ~5nm is assumed (as might be obtained at low temperature).

Interestingly, if the peak of the QW emission is shifted, say by an altering of the QW well-width, to shorter wavelengths then the result is a lobed emission pattern as shown in figure 2.21(b). In this case the solid line is for a QW emitting with a peak at 975nm (linewidth 10nm), the dashed line shows a calculation assuming a linewidth of ~5nm. Yamanishi has used this detuning effect to produce, at low temperature, a variable divergence light emitting diode (LED) [Yamanishi ‘92]. Unfortunately at room temperature the two emission lobes coalesce and the functionality of the device is reduced (as demonstrated by the solid curve in figure 2.21(b)). Thus, without the introduction of narrow band filters to select a fixed FP mode, it seems that
simple one-dimensional optical cavity LEDs will be limited in their divergence performance by the quality (and hence emission linewidth) of their QWs. This will in turn affect LEDs designed to operate at other wavelengths (using different materials) in different ways, dependent strongly upon both the materials forming the cavity and the QWs. Overall, we see that the emission patterns from a microcavity device are dictated by both the optical properties of the cavity and by the emission properties of the QW material. Furthermore, it has been shown that the emission properties (for example the radiative lifetime) of a QW, placed within a microcavity, are influenced strongly by the optical properties of that cavity [Yokoyama et al. '90]. These findings add yet more functional parameters into the design of microcavity devices, thereby increasing their range of possible applications.

2.4.4 Effect of layer thickness variations within microcavities

The production of DBR mirrors places high demands on the growth (deposition) technology employed. Random errors may be introduced into the thicknesses of individual layers because of short term fluctuations in the source fluxes at the sample surface. These may then reduce the peak reflectivity that may be achieved. Also thickness variations between neighbouring layers may occur due to poor control of element flux and/or substrate temperature. Furthermore a systematic variation of thickness, within all layers, often occurs because of the relative orientations of the growth sources and the sample wafer. This leads to a growth geometry dependent wafer uniformity. Further complications may also arise due to thermal transients across the wafer, which further alter growth rates. These factors can, in general, be reduced by sample rotation and growth rate calibration. Some of these factors are studied, and utilised to advantage, in chapter 4 but a brief introduction is given here.

Figure 2.3(a) shows the reflectivity spectrum for a 20 period λ/4 GaAs/AlAs DBR designed for 980nm. Also shown are the shifts in the spectrum when a growth error, or growth non-uniformity, of 2%, 4% and 6% are applied to each layer in the DBR. The percentages refer to the amount subtracted from each layer of the structure.

Such systematic shifts in DBR centre wavelength are regularly observed across an MBE or MOCVD grown wafer and are dependent on the growth system geometry. They are often utilised to allow the selection of useful areas of the wafer. More generally such shifts in centre wavelength, with the shift given by the percentage growth error, are a problem as they limit the number of useful devices that can be extracted from a wafer. Figure 2.22(b) shows how the reflectivity, at the design wavelength of 980nm, varies with growth error. As previously stated,
in chapter 1, a low threshold VCSEL requires approximately 99% reflectivity within each DBR. It can be seen from figure 2.22(b) that, at 980nm, the peak reflectivity falls below this value when the growth error exceeds 4%. This imposes stringent limits on the growth technology when large numbers of devices, emitting with the same output characteristics (i.e. the same threshold current, voltage and wavelength values), are required from a given wafer.

![Figure 2.22](a) Change in reflectivity with growth error (non-uniformity).
(b) Change in reflectivity at 980nm vs. growth error.

A number of authors [Weber et al. ’90, Law et al. ’93] have studied the effect of altering the thickness of a single λ/4 layer from its nominal value. The general conclusion is that small changes (~1%) do not affect the peak reflectivity appreciably. Unfortunately the phase shift of the DBR, see figure 2.5(b), does change such that VCSELs containing these errors undergo a shift in their emission wavelengths of a few angstroms. Such fluctuations, confined to individual layers, are generally random in nature but it has been proposed that these variations impose limits on the ultimate linewidth achievable with VCSELs [Weber et al. ’90]. This is due to the lateral thickness variations that may occur across a single device.

If we now take a full microcavity structure and vary only the thickness of the cavity by some percentage, from its nominal value (d), the FP mode position shifts in wavelength. This is shown in figure 2.23. The percentage shift of the FP mode, relative to the design wavelength, is now only approximately given by the percentage variation in the cavity length. This is because of field penetration into the DBRs, which increases the effective cavity length. This has the effect of decreasing the FP mode shift with changes in d. In general, however, a shift of the cavity resonance is accompanied by a corresponding shift of the DBR reflection spectrum, see figure 2.22 (i.e. the layer variations occur to all layers). The overall effect, if all layers are
altered by the same percentage, is to shift the FP resonance away from the design wavelength by an amount which is again given by the percentage change in thickness.

Figure 2.23 Shift of FP resonance accompanying variations in cavity length.

Again this effect may be used to advantage to select useful devices from a wafer. Unfortunately this shift in FP wavelength is, in general, not accompanied by an equivalent shift in the gain spectrum, thus a detuning between the peak gain and the mode occurs. This results in devices with a greatly reduced power output and, in cases of extreme shift, to devices that cannot lase. For example, if the gain bandwidth of a QW is 20nm, peaking at 980nm, then a 2% layer thickness variation in all of the layers forming the structure will shift the FP mode to 960nm thereby preventing lasing. The corresponding shift in gain due to the QW width change (nominally 80Å, assuming an In0.3Ga0.7As QW, becoming 78Å) will only shift the peak gain by a few nanometres.

2.5 Concluding remarks

In this chapter we have presented a novel model for the calculation of a number of important laser and microcavity parameters, to be used later for VCSEL design and optimisation. This model, developed independently but around the same time as a number of other models [see specifically Weber et al. ‘91 and Hansmann ‘92], is based on the well known transfer matrix solutions to Maxwells equations. Modifications have been applied to allow the inclusion of (spontaneous) sources and gain. The model allows us to calculate the emission spectrum and threshold characteristics of any, arbitrarily complex, VCSEL structure containing distributed QW gain and loss sections. Distinct from previous models we have incorporated a complex model for the spontaneous emission spectrum and gain characteristics of InGaAs QWs under
various levels of carrier injection [Rees '93]. This modification, along with the incorporation of dispersive refractive indices and absorption, has allowed us to accurately calculate the threshold and emission spectral characteristics of VCSELs. It is noted that the model, in calculating the threshold characteristics, accounts for carrier leakage over the active heterostructure, Auger losses and barrier recombination (as derived from empirical fits [Scott et al. '93a]).

In practise, by implementing realistic spontaneous emission spectra, the model has predicted the sub- and above threshold emission spectra of VCSELs. Also it has shown that the emission spectrum is strongly determined by the FP modes of the VC-structure, the Q of the cavity and the position and composition of the QWs within the cavity. Obviously this is a very useful tool in the design, optimisation and characterisation of many emitting devices.

Other, attendant, features of this model are that it allows one to calculate the output efficiencies, simple light-current characteristics, internal field profiles and reflection and transmission properties of VCSELs. These features are very useful as they allow us to design highly efficient output couplers for VC-lasers, obviously this is important for optimisation of threshold currents and output powers. In fact, using these models we have, through optimisation of mirror and cavity design (yielding improved confinement factors), designed and produced VCSELs with threshold currents of order 5mA and with output powers exceeding 80mW (chapter 4).
Chapter 3

Series resistance reduction in distributed Bragg reflectors
3.1 Introduction

This chapter begins by introducing the problems of high series resistance inherent within the GaAs/AlAs Bragg reflectors used to produce VCSELs, and other vertical cavity optoelectronic devices requiring carrier transport through the DBRs. After describing the origins of series resistance in DBRs the chapter details various solutions. In general these involve the growth of grading layers and the use of periodic doping, as employed by the majority of workers in the field. We then proceed to present a novel application of post-growth diffusion to the reduction of the series resistance within DBRs. A 50% reduction in resistance is demonstrated with little degradation of optical properties. We conclude with a discussion of the technique’s applicability to device optimisation and lateral integration.

3.2 Series resistance problems

The vertical cavity configuration for optoelectronic devices has proved essential in the realisation of high device packing densities, within modulator and self electro-optic effect device (SEED) arrays for example [Lentine et al. ‘90], by allowing the use of smaller active volumes and vertical input/output coupling. Furthermore the devices often have enhanced functionality, for example improved light modulation characteristics [Whitehead et al. ‘90], and allow on-wafer testing.

VCSEL devices are of particular interest but, because of their quarter-wave distributed Bragg reflectors (λ/4 DBRs, generally consisting of alternating λ/4 thick layers of GaAs and AlAs), their operating voltages, often many tens of volts, are large in comparison with in-plane lasers (IPLs). Such large voltage drops occur because of the presence of the large number of GaAs/AlAs heterointerfaces. Only about 1.3 volts is contributed by the active layer [Michalzik et al. ‘93]. This high operating voltage results in devices with poor electrical to optical power conversion efficiency and increased heat generation leading to unstable operating wavelengths, reduced optical power output and thermally induced 'turn-over' of the lasers light-current characteristics. These, latter, effects are due to thermally induced detuning of the active layer gain and the laser resonance, carrier leakage problems also arise (these effects are observed in most VCSELs at high current injection, see for example [Scott et al. ‘93b]).

Neglecting defects and sample imperfections, for example the doping dependent strain relaxation observed by Jenichen [Jenichen et al. ‘93], the series resistance of a DBR stack is comprised of four major contributions. First, due to the large number of layers of alternating
material, each of widely different bandgap, there are a large number of discontinuities in the bandstructure of the mirror in the direction of current flow, i.e. the growth direction. This leads to the formation of potential barriers that act to impede current flow. Next, accompanying these bandgap discontinuities are ‘spikes’ in potential, generally localised at the heterointerfaces. These are caused by band-bending and space charge (doping dependent) effects, they act to increase the barriers to carrier transport, see figure 3.1. These two mechanisms are by far the largest contributions to the DBR resistance. Further, there is a contribution to resistance due to the finite (non-zero, doping dependent) resistivity of the individual GaAs/AlAs layers forming the DBR. Finally, because carrier motion within GaAs is in the Γ-valley and that in AlAs is in the X-valley, in momentum space, the carrier must undergo scattering when moving between layers of different material and so energy must be supplied. Unfortunately the above problems are further compounded within the p-type DBR due to the high effective mass and unfavourable band-offset for holes in the valence band of the structure.

A number of researchers [Tai et al. '90, Geels '91 and Kurihara et al. '93] have attempted to study the resistance problem by calculating the bandstructure of the DBRs and the corresponding electrical conduction properties. Given the DBR bandstructure approximate voltage drops, required to pass an electron and hole current through an n- and p-type DBR respectively, may be calculated assuming thermionic and tunnelling contributions to transport at the heterointerfaces. Although full treatment of this problem is beyond the scope of this thesis a brief discussion is offered.

**Figure 3.1** Bandstructure of an undoped (a) and p-doped (b - uniform 5x10¹⁸cm⁻³) DBR. Both structures have a basic period consisting of 600Å GaAs and 800Å AlAs.
Graphs (a) and (b) of figure 3.1 [Snider] show the bandstructure, as a self consistent solution to Poisson’s equations, of an undoped (a) and p-doped (b) GaAs/AlAs DBR. The p-type case is shown since it forms the main contribution to the high voltage operation of a VCSEL.

The bandgap discontinuities for the GaAs/AlAs system, with bandgaps separated by approximately 740meV, are accommodated with band-offsets approaching 65% in the conduction band and 35% in the valence band ($\Gamma_{GaAs}-\Gamma_{AlAs}$) [Duggan et al. '85]. Tai et al. [Tai et al. '90] note that the barrier height at the interfaces is given approximately, for holes for example, by the valence band-offset $\Delta E_v$ which, for the case of a p-type DBR, is in excess of 300meV and much greater than the room temperature thermal energy of 26meV. Also the widths of the interfacial spikes in potential, which are inversely dependent on the doping level, are found to be of order 100Å for a doping level of order $10^{18}$cm$^{-3}$ acceptors [Tai et al. ’90].

Using this information, along with the band diagrams above, simple calculations for the thermionic transport of carriers through the DBR may be performed. The thermionic current flowing over a single potential barrier, comprising interfacial GaAs/AlAs band-edge discontinuity and spikes in potential, is given by the Richardson equation and may be expressed as [Sze '81]

$$J_{thermal} = A^*T^2\left(\exp\left[-\frac{q\phi_B}{k_B T}\right]\exp\left[\frac{qV_{App}}{k_B T}\right] - 1\right)$$  \hspace{1cm} (3.1.1)

where $J_{thermal}$ is the current density, $T$ is the temperature, $q$ the electron charge, $\phi_B$ the barrier height, $k_B$ the Boltzmann constant, $V_{App}$ the applied voltage and $A^*$ (in units of Acm$^{-2}$K$^{-2}$) is the effective Richardson constant given by [Geels '91]

$$A^* = \frac{4\pi q m^* k_B^2}{h^3} \equiv 120 \frac{m^*}{m_0}$$  \hspace{1cm} (3.1.2)

with $m^*$, $m_0$ and $h$ being the effective mass of the carrier, the free electron mass and Planck’s constant respectively. Rearrangement of equation 3.1.1, to give $V_{app}$, allows the graph of figure 3.2 to be calculated. This graph shows the voltages required to pass a given current through a 20 period n- and p-type GaAs/AlAs DBR assuming resistance contributions from only the interfacial potential barriers, at a doping level of $5\times10^{18}$cm$^{-3}$, and thermionic transport. As stated previously these potential barriers, comprising GaAs/AlAs band-edge discontinuity and interfacial spikes in potential, are the main contributors to the DBR series resistance.

Figure 3.2 shows how the high hole effective mass results in (at least) an order of magnitude larger series resistance for the p-type DBR relative to the n-type. Of course the calculation is a ‘best case’ example. In practice, when the above resistance contributions are
coupled to the low mobility of p-type material (again due to the hole mass), the measured series resistances of simple \( \lambda/4 \) p-type DBRs often exceeds the theoretical values shown.

![Figure 3.2](image)

**Figure 3.2** Voltage (theoretical) required to pass current through a 20 period, n- and p-type, GaAs/AlAs DBR assuming only thermionic transport.

The contribution to the voltage drop across a DBR from the GaAs/AlAs layer resistivities is expected to be of order 10mV per layer [Geels '91]. It is strongly influenced by the level of doping within the structure. However the concentration profile of dopants, both n- and p-type, is found to be very dependent on the dopant employed [Kopf et al. '92]. For example beryllium, a common p-type dopant in molecular beam epitaxy (MBE) grown Al\(_{x}\)Ga\(_{1-x}\)As, is found, under certain conditions, to gather at the GaAs/AlAs heterointerfaces during growth [Kopf et al. '92]. The resultant DBR AlAs sections are then found to have a maximum dopant concentration of only \(5 \times 10^{17}\mathrm{cm}^{-3}\), this results in a higher resistance. In contrast carbon, again a p-type dopant, gives a uniform dopant profile with higher incorporation levels across the whole DBR structure and is found to yield a correspondingly lower series resistance structure [Kopf et al. '92]. Similarly silicon, a standard n-type dopant, is found to give uniform doping profiles throughout a DBR. The various doping profiles obtained by a given growth technology are therefore of prime importance in lowering the resistance of DBRs, again this is because dopants directly affect the spikes in potential at heterointerfaces and the bulk resistivities. In the limit of high doping these spikes in potential can be dramatically reduced. Unfortunately such high doping adds to the free carrier absorption losses within a DBR, this acts to reduce the DBRs reflectivity. The use of periodic doping does, to some extent, allow high doping levels to be used without drastically reducing reflectivity. In this case high doping is applied to those areas of a structure
experiencing a low photon density, this reduces the optical losses (to be discussed). Such periodic doping is only a partial solution to the resistance problem and so other methods of reduction must be studied.

3.3 Potential growth solutions to DBR resistance problems

Current methods of reducing the series resistance of p-type DBRs, at the growth stage, include altering the simple GaAs/AlAs structure of the mirror to introduce various degrees of compositional grading [Zhou et al. '91], or superlattice (S/L) pseudo-grading [Tai et al. '90] of the aluminium content at the heterointerfaces. The doping profiles within the DBRs may also be altered to reduce the potential barriers associated with the interface bandgap discontinuities. This may involve the use of δ-doping, that is the insertion of a narrow highly doped layer at the heterointerfaces, or periodic doping (discussed later), to reduce the barriers to current flow. Using the δ-doping scheme Kojima [Kojima et al. '93] has shown that a 50% reduction in the slope resistance of a DBR, in the lower resistance Al$_{0.5}$Ga$_{0.42}$As/Al$_{0.16}$Ga$_{0.84}$As system (designed for 830-850nm), may be brought about with only a slight reduction in the optical performance of the mirror.

By controlling the growth source fluxes and substrate temperature during either MBE or MOCVD (metal organic chemical vapour deposition) growth, an arbitrary Al$_x$Ga$_{1-x}$As composition profile can be achieved. Thus a DBR with either linear or parabolic alloy grading from GaAs to AlAs, over approximately 200Å, may be obtained [Zhou et al. '91]. This type of grading is believed to be the most efficient method of reducing the series resistance [Tai et al. '90] but, unfortunately, all such compositional grading schemes currently suffer from problems relating to alloy composition and its reproducibility. These problems act to reduce the reflectivity of the mirrors.

The most common, and to date most successful, growth solution to the series resistance problem, principally within p-type DBRs, involves the insertion, at the GaAs/AlAs heterointerfaces, of thin layers of varying composition Al$_x$Ga$_{1-x}$As. Generally this scheme is used in conjunction with a periodic doping profile. In its simplest form a single 100-200Å Al$_{0.5}$Ga$_{0.5}$As layer is incorporated at each heterointerface, this is accompanied by a high (5×10$^{18}$cm$^{-3}$) doping level. The bulk (GaAs/AlAs) layers of the stack are doped to a lower level (1×10$^{18}$cm$^{-3}$) and narrowed to account for the optical thickness of the grading layer. This method is found to work well in MOCVD grown p-type stacks [Tai et al. '90, Hopkinson '93] where high doping with a good profile (for example through the use of carbon) may be obtained.

- 68 -
Unfortunately this is not the case for MBE grown p-type DBRs where Be or Zn dopants are more commonly used. Fortunately this method may be used to improve the resistance of MBE grown n-type stacks and as such proves a simple to grow resistance solution.

![Graph of Al composition versus distance in monolayers for (a) a linear superlattice and (b) a parabolic superlattice.](image)

**Figure 3.3** Two types of superlattice grading scheme - see main text. (a) is a linear superlattice and (b) is a parabolic superlattice, both superlattices are shown grading from GaAs to AlAs.

Beyond the insertion of a single AlGaAs layer, the method found to give the lowest reported p-type stack resistances, in the GaAs/AlAs system, requires the insertion, at each heterointerface, of a short period superlattice, figure 3.3. Again the optical thickness of the superlattices must be accounted for in the design of the DBR. Such mirrors have the advantage that during growth both the flux from the growth cells and the substrate temperature may be kept constant, because only binary GaAs and AlAs are deposited. It has been shown through the use of bandstructure calculations [Geels ‘91, Kurihara et al. ‘93] that superlattices of approximately 300Å total thickness result in extremely low interfacial potential barriers, and hence series resistance, when used at every DBR interface. However, the use of more practical 200Å superlattices [Geels et al. ‘90b], along with a high doping concentration within each superlattice, also results in a DBR with a resistance often two orders of magnitude lower than the corresponding abrupt interface DBR. Furthermore the average aluminium concentration can be made to vary either linearly, figure 3.3a [Geels et al. ‘90b], or parabolically, figure 3.3b [Sale et al. ‘92] with the parabolic grading scheme resulting in a shorter superlattice than in the linear case, although the growth must involve deposition of Al$_{0.5}$Ga$_{0.5}$As. Both schemes result in Bragg mirrors which retain a high reflectivity as demonstrated by the low threshold current densities of the VCSELs that incorporate them (for example the 366Acm$^{-2}$ demonstrated by Sale [Sale et al. ...]
At present the linear superlattice structures present the lowest operating voltages, for structures injected through the DBRs, with many devices reaching threshold at a voltage drop of only 2-3 volts (for devices of approximately 10μm diameter) [Shtengel et al. '93].

Note that VCSELs with the top, p-type, DBR replaced by semitransparent metals, which form mirrors with both high reflectivity and low resistivity, have achieved threshold voltages as low as 1.3 volts [Tu et al. '90]. Unfortunately such VCSELs tend to have high threshold currents (40mA for a 20μm device [Tu et al. '90]) and suffer from a high output coupler absorption, this may be attributed to the metal reflector.

Much of the series resistance reduction within superlattice DBRs may be attributed to an increase in the tunnelling, as opposed to thermionic, current at the heterointerfaces of the structure. The tunnelling current flowing through a potential barrier, for example the barrier due to band-bending and the band-offset at a GaAs/AlAs heterointerface, may be expressed through equation 3.1.3 [Tsu et al. '73, Kurihara et al. '93]. Here \( J_{\text{tunnel}} \) is the tunnelling current, \( T_p \) is the tunnelling probability and \( E_f \) and \( E_z \) are the Fermi energy and carrier energy respectively.

\[
J_{\text{tunnel}} \sim T_p \int_0^e \frac{1 + \exp((E_f - E_z)/kT)}{1 + \exp((E_f - E_z - qV)/kT)} dE_z \tag{3.1.3}
\]

It can be seen that the thermal current of equation 3.1.1 depends more strongly on temperature than the tunnelling current of equation 3.1.3. Using this fact Kurihara [Kurihara et al. '93] has shown, by varying the temperature at which the slope resistance of various DBRs is taken (over a 20-120°C temperature range), that within superlattice DBRs the tunnelling current contribution dominates the thermal contribution to carrier transport. In the superlattice grading case the resistance of the DBR is found to depend only weakly on temperature, unlike an abrupt interface structure whose resistance increases more sharply with decreasing temperature.

### 3.3.1 Electrical properties of pseudo-graded DBRs

In the process of developing VCSELs we have examined a number of DBR structures, based mainly on designs from the literature, to select a design compatible with the MBE and MOCVD growth techniques available. Both abrupt and pseudo-graded superlattice DBRs, utilising uniform and periodic doping, have been studied.

Figure 3.4 schematically shows the range of GaAs/AlAs DBRs we have studied as potential solutions to the series resistance problems of p-type DBRs. Case (a) shows an abrupt interface DBR, designed nominally for 980nm operation (GaAs 696Å-AlAs 830Å), grown by MBE and
incorporating a uniform doping level of $1\times10^{18}$ cm$^{-3}$, with Be as the p-type dopant. This sample, like the other MBE grown structures in this section, was grown by solid source MBE on a semi-insulating (001) oriented GaAs substrate along with a 0.5μm p-type buffer layer ($\sim3\times10^{18}$ cm$^{-3}$ for contacting purposes). The growth was carried out by C. Roberts at Imperial College London. Samples (a) and (d) were grown in a Varian 360 while sample (c) was grown in a VG V80H. The growth temperature was chosen to be 620°C which resulted in an average growth rate of 1μm per hour. Sample uniformity was found, through reflectance measurements, to be approximately 10% thickness variation across a 2 inch wafer with the central inch uniform to within 2%. All samples contain 14 periods. Further details of the MBE growth are given in chapter 4.

The corresponding valence bandstructure of this sample (a), shown schematically in figure 3.4, exhibits large barriers (in potential) to hole current flow leading to a series resistance approaching 80 Ohms, this corresponds to a resistivity of $\rho_{\text{abrupt}} \sim 6.3\times10^{-3}$Ω cm$^{-2}$ (all quoted resistances refer to the slope of the linear section of the I-V curve of the device). The devices used for the resistance measurements comprise a circular mesa that has been wet-etched, using a 3:4:3 $\text{H}_3\text{PO}_4$:$\text{H}_2\text{O}_2$:H$_2$O solution, into the p-type buffer layer. Both contacts are Cr/Au with the bottom contact placed onto the p-type buffer layer. Measurements, using probes, are taken with an automated curve-tracer. All devices exhibit a diode like ‘turn-on’ around approximately 0.5 volts and this is attributed, in part, to the diode like nature of the DBR comprising the numerous heterointerfaces and a non-uniform doping concentration. Furthermore, the diode characteristics

![Figure 3.4 Various growth solutions for lowering the p-type DBR series resistance.](image)

*Figure shows growth method and measured series resistances (authors results).*
are due to the Cr/Au contacts which behave 'Schottky-like' due to the materials used, poor alloying and the lack of a heavily doped (~10^{19}\text{cm}^{-3}) GaAs contacting layer above the DBR.

Case (b) of figure 3.4 shows a similar DBR structure to that of case (a) but grown by MOCVD (basic period GaAs 657Å-AlAs 670Å). The details of this structure, grown by J. Roberts at Sheffield University for intermixing studies, are presented in section 3.4.2. The lower resistance of this structure, relative to the MBE case, is attributed to a higher incorporation of dopants, in this case Zn (2\times10^{18}\text{cm}^{-3}), throughout the DBR. This high doping manifests itself as a reduction in the magnitude of the interfacial spikes in potential, the resistivity in this case is found to be approximately $\rho_{\text{MOCVD}} \approx 2.91 \times 10^3 \Omega\text{cm}^2$.

Figure 3.4 (c) shows a DBR with a single 200Å Al_{0.5}Ga_{0.5}As layer separating the main GaAs/AlAs (510Å/608Å respectively) layers with high doping (Be at 5\times10^{18}\text{cm}^{-3}), corresponding to the shaded regions in the diagram, concentrated at the grading layers. The series resistance of this structure, with a resistivity of $\rho_{\text{stepped}} \approx 2.51 \times 10^3 \Omega\text{cm}^2$, is found to be almost one third of the corresponding abrupt-interface MBE DBR. This may be attributed to both a decrease in the interfacial potential barriers and an increase in the tunnelling current due to the intermediate (thin) Al_{0.5}Ga_{0.5}As step layers.

Finally case (d) shows a structure incorporating 180Å short period linear superlattices, see figure 3.3 (a), at each interface between the main GaAs (530Å) and AlAs (630Å) layers. In this case high doping (Be at 5\times10^{18}\text{cm}^{-3}) is applied only at the interfaces where the optical field in the structure is a minimum. This is the periodic doping concept and is found to both reduce the series resistance and maintain high reflectivity through a reduction of free carrier losses [Sugimoto et al. '92]. In combination these schemes result in a structure having the lowest resistivity of all the samples studied, $\rho_{\text{SL}} \approx 1.65 \times 10^3 \Omega\text{cm}^2$. In this case the low resistance is due to the increased tunnelling current through the short-period superlattices. It is noted that this resistivity is higher than many values quoted in the literature, generally approaching 9\times10^3\Omega\text{cm}^2 [Tai et al. '90], this is believed to be because of poor contacting (and sample quality) in our samples. Note that the VCSEL structures studied in chapter 4 of this thesis exhibit low threshold currents and voltages when utilising this type of DBR.

### 3.3.2 Optical properties of (superlattice) graded-interface mirrors

It was briefly mentioned in the previous section that the application of grading layers at the heterointerfaces of a DBR alters the optical properties of the DBR. Specifically the DBR GaAs and AlAs layers must be reduced in thickness to allow for the optical thickness of the grading
layers. The result of introducing grading layers is to reduce the peak reflectivity of a given structure and also to alter the stop-band width. These effects are due to the additional phases of the reflections from the compositionally graded layers perturbing the in-phase reflections from the main (almost $\lambda/4$) GaAs/AlAs layers. Also the introduction of $\text{Al}_{x}\text{Ga}_{1-x}\text{As}$ in to the DBR, or effective $\text{Al}_{x}\text{Ga}_{1-x}\text{As}$ in the case of a superlattice DBR, results in a decrease of the difference ($\Delta n = n_H - n_L$) in the refractive index of the main layers which results in a further decrease of the peak reflectivity of the structure. This may be explained analytically by looking at the equations for the stop-band width ($\Delta \lambda_{DBR}$) and peak reflectivity ($r_{peak}$) of a simple $N$ period quarter-wave DBR, equations 3.3.1 and 3.3.2.

$$\frac{\Delta \lambda_{DBR}}{\lambda} = \frac{4}{\pi} \sin^{-1} \left[ \frac{n_H - n_L}{n_H + n_L} \right]$$  \hspace{1cm} \text{(3.3.1)}

$$r_{peak} = \left( \frac{n_H}{n_L} \right)^N - \left( \frac{n_L}{n_H} \right)^N \quad \left( \frac{n_H}{n_L} \right)^N + \left( \frac{n_L}{n_H} \right)^N$$  \hspace{1cm} \text{(3.3.2)}

In this case both the stop-band width and the peak reflectivity are decreased because of a decrease in the ratio of the high to low refractive indices. This is shown in figure 3.5.

![Figure 3.5](image)

**Figure 3.5** Theoretical reflectivity spectra of an abrupt, linear superlattice-graded and AlGaAs stepped DBR, comprising 16 periods (design is for 980nm).

It is evident from figure 3.5 that the stop-band width of the DBR decreases slightly as the mirror interfaces are graded. Equation 3.3.1 shows that this band-width is dependent upon the difference in refractive indices of the layers forming the DBR. By introducing interfacial grading, equivalent to introducing lower refractive index AlGaAs in to the structure, the
difference in the (average) refractive indices has been reduced. It therefore follows that the bandwidth decreases. From equation 3.3.2 we see that the corresponding peak reflectivity is dictated by the ratio of the refractive indices of the layers forming the DBR. The introduction of interfacial grading reduces this ratio, this results in a decrease of the peak reflectivity. In general this decrease in peak reflectivity may be overcome through the addition of extra DBR periods, unfortunately this adds to the series resistance of the structure.

Note that by using hybrid mirrors, as discussed in chapter 2, the reflectivity of a DBR may be increased without increasing its series resistance. The metal usually deposited as a contact onto the DBR may be used to boost the mirrors reflectivity. The resulting DBR may posses a very high reflectivity and low resistance as only a small number of DBR periods are required.

A final point to note is that the introduction of interfacial grading has the effect of increasing the penetration depth of light into the DBR. This is because the effective refractive indices of the mirror layers have been reduced. The effective plane of reflection from the DBR is moved further into the mirror. Any microresonator formed from the graded DBRs will therefore have an effective cavity length that is increased relative to that of a simple microresonator formed from ordinary abrupt interface DBRs. This increased penetration affects the design of VCSEL structures (discussed in the next chapter) which must account for any resultant changes in the optical mode profile of the complete structure.

3.4 Post-growth grading of DBRs for series resistance reduction

Because of the complex growth sequences required to produce superlattice graded interface mirror stacks, we have examined post-growth (annealing) techniques, for the first time, as possible solutions to the series resistance problem.

![Energy Band Diagram](image)

**Figure 3.6** Schematic energy band-diagram for an undoped (a) and p-doped (b) DBR with compositional Al$_x$Ga$_{1-x}$As interfaces. Reproduced from [Tai et al. '90].
If a GaAs/AlAs (main layers) mirror with true compositionally varying Al$_x$Ga$_{1-x}$As interfaces is modelled theoretically [Tai et al. '90], its bandstructure, shown schematically in figure 3.6, is found to contain, certainly in a doped state, almost no barriers to hole current flow in the form of spikes in potential due to band-bending. It is noted that interface in this case refers to the Al$_x$Ga$_{1-x}$As material, which may have a physical extent of hundreds of angstroms, between the pure GaAs/AlAs layers. The resulting DBR should posses a very low series resistance and, as demonstrated later, retain a high reflectivity, although this will be lower than can be achieved in a superlattice or step-graded DBR (see figure 3.5).

A method for achieving a true aluminium composition grading, and thus a reduction in the series resistance of the DBR, involves the use of post-growth intermixing of the GaAs/AlAs layers through the use of thermally induced diffusion [Khan et al. '93]. Interdiffusion involves the movement of group III atoms such that the layer interfaces within a GaAs/AlAs structure are no longer sharply defined but have a graded profile leading, in the case of a GaAs/AlAs DBR, to a graded bandgap profile and hence a reduced resistance to carrier transport.

Layer intermixing in the GaAs/(Al,Ga)As system has been extensively studied. In particular it has been used in the production of opto-electronic integrated circuits (OEICs) using quantum well (QW) material, as the intermixing of the QWs results in a grading of the interfaces and a blue shift of the spectral properties [Ralston et al. '88, Wada et al. '89]. The use of diffused or implanted impurities, for example Si or Zn, can enhance the rate of this interdiffusion over the intrinsic thermal intermixing that occurs at elevated temperatures, this technique is known as impurity induced layer disordering (IILD) [Coleman et al. '82, Lee et al. '84]. An enhancement can also be achieved by capping the sample with silicon dioxide prior to the anneal. This technique is commonly referred to as impurity free vacancy diffusion IFVD [Ralston et al. '88, Ghisoni et al. '91a]. In this case the enhancement is attributed to gallium vacancies being injected into the sample by the encapsulant. Both of these enhanced intermixing techniques offer, via masking, the possibility of lateral spatial selectivity of the properties of the wafer. IILD has been used for the production of low-loss waveguiding sections and lateral confined buried heterostructure lasers [Werner et al. '90, Thornton et al. '90], while IFVD has been used to passivate the edge of a VCSEL mesa [Hamao et al. '91] and applied to reflection modulator configurations [Ghisoni et al. '91b] where no drop in reflectivity of the DBR was observed.

The work in the remainder of this chapter describes the structural, electrical and optical characterisation of intermixed p-doped DBRs. The intermixing in this pre-doped case (as opposed to impurity injection schemes) is a combination of all of the intermixing mechanisms...
described above, namely intrinsic thermal diffusion, IILD and IFVD (some of the samples use a SiO₂ encapsulant). As such, the intermixing mechanisms are complex.

3.4.1 Interdiffusion in GaAs/(Al,Ga)As heterostructures

Neglecting surface driven effects, for example the arsenic outdiffusion that accompanies the heating of uncapped GaAs to temperatures above 600°C [Donnelly '81], the self-diffusion of group III atoms in undoped GaAs proceeds through native defects such as vacancies and interstitials. The magnitude of this self-diffusion depends directly on the concentration of the native defects [Deppe et al. '88] (the exact nature of which is unclear), and this concentration is dependent on the crystal temperature (T), the crystal quality (dictated by growth conditions) and also on the crystal Fermi-level. Moreover, the number of native equilibrium vacancies is found to increase with temperature as e⁻¹/T on both the group III and group V lattice sites [Kahen et al. '89].

It has been suggested that in the intrinsic case interdiffusion at a GaAs/(Al,Ga)As heterointerface proceeds through the same mechanisms (probably involving the group III vacancy V₃⁻ [Tan et al. '91]) that cause the self-diffusion of Ga in GaAs [Tan et al. '88]. This follows from the fact that the data obtained from a number of authors, studying both self- and interdiffusion mechanisms within III-V materials, fits the empirical formula 3.4.1 [Tan et al. '88]. Here nᵢ is the intrinsic carrier concentration and D_Ga denotes the Ga self-diffusion coefficient.

\[ D_{Ga}(n_i) = 2.9 \times 10^8 \exp(-6eV / k_B T) \text{ cm}^2\text{s}^{-1} \quad \ldots \quad (3.4.1) \]

Furthermore, the Ga self-diffusion coefficient is believed to be similar to that for Al and the interdiffusion coefficient of Ga and Al. Thus, unless otherwise stated, the diffusion coefficient D_Ga is used to represent the Ga self diffusion coefficient or the Ga-Al interdiffusion coefficient.

In general, the extent of intermixing within a sample is strongly influenced by the conditions at the sample surface. The heating of GaAs/AlₓGa₁₋ₓAs structures results, certainly at the 870-960°C temperatures used in this work, in the outdiffusion of As [Donnelly '81] and the formation of surface defects. These surface generated defects, either As rich (e.g. As interstitials) or As poor (e.g. As vacancies) defects depending on As overpressure, may then propagate, at these high temperatures, through the crystal enhancing the self- and interdiffusion coefficients. The amount of As outdiffusion is dependent on As overpressure, generally introduced by placing the sample to be annealed into a sealed ampoule containing elemental As,
and this fact is often used to protect the sample surface during annealing. Furthermore, the Al-Ga self diffusion rates are dependent on the As overpressure. This is because the crystal maintains equilibrium with the surrounding As vapour through the creation (or annihilation) of native defects at the crystal surface which may then alter the Al-Ga diffusion rates. In this case the As rich and As poor defects dictating the Al-Ga diffusion are probably the group III vacancy (V_m) and group III interstitial (I_m) respectively [Deppe et al. '88].

Beyond the use of an As overpressure, to both protect the sample surface and to enhance interdiffusion, various encapsulants may be used. These may be deposited onto the sample prior to annealing, to further protect and enhance or impede intermixing within the sample. Commonly used materials for the cap, and the ones of primary use within this work, are the dielectrics SiO_2 and SiN_x. Both of these materials are in common use within the semiconductor industry where they have been used to encapsulate GaAs/Al_xGa_{1-x}As in attempts to reduce As outdiffusion.

The use of SiO_2, while preventing some of the As outdiffusion problem, is also found to enhance the production of Ga vacancies (V_Ga) at the sample surface, these vacancies then propagate through the crystal enhancing interdiffusion. This is the origin of IFVD. Elemental Ga is believed to be produced at the sample/oxide surface through reactions of the form [Katayama et al. '91]

\[ 3\text{SiO}_2 + 4\text{GaAs} \rightleftharpoons 4\text{Ga} + 2\text{As}_2\text{O}_3 + 3\text{Si} \quad \ldots(3.4.2a) \]
\[ \text{As}_2\text{O}_3 + 2\text{GaAs} \rightleftharpoons \text{Ga}_2\text{O}_3 + 4\text{As} \quad \ldots(3.4.2b) \]

This Ga then diffuses rapidly into the encapsulant. This diffusion process is enhanced by the large thermal mismatch between the sample and capping layer [Katayama et al. '89], the subsequent vacancies generated at the sample/cap interface propagate into the crystal. The production of Ga vacancies may be further enhanced through increases in temperature and cap thickness and is found to be greatly reduced through the use of SiN_x encapsulants [for a full review see Ghisoni '92].

Finally, a large enhancement in the diffusion coefficients of Ga and Al may be brought about through the introduction of dopants into the sample. This is the basis of IILD. Of particular concern here is the enhancement brought about through the p-type dopant Zn. The enhancement of intermixing in GaAs/Al_xGa_{1-x}As brought about by Zn is of interest because it occurs at temperatures below those required for the above mechanisms. Generally the Zn dopant, when used for IILD, is either ion-implanted or elementally introduced into the annealing chamber such that a surface driven mechanism results. In this work the Zn is already present within the sample at concentrations approaching ~10^{18} \text{cm}^{-3}, as opposed to the concentrations of ~10^{19} \text{cm}^{-3} used in implantation and other indiffusion schemes. However it is assumed that the
mechanisms involved in the samples here are the same as those within Zn implanted or Zn capped samples (neglecting sample damage). This assumption is necessary because much of the literature uses the latter methods to introduce Zn. It is well known that the diffusivity of Zn in GaAs is high and strongly dependent on concentration, probably dictated by a reaction between interstitial and substitutional Zn [Ky et al. '93]. The enhancement of intermixing brought about by Zn has been attributed to the generation of group III interstitials (I_{III}) by a 'kick-out' mechanism [Gösele et al. '81] whereby Zn occupying an interstitial site (Zn_{i}^{+}, '+' denotes donor), may occupy a substitutional site (Zn_{s}^{-}, '-' denotes acceptor) through the production of an interstitial group III atom (I_{III}) as expressed by 3.4.3, where h refers to hole.

\[ Zn_{i}^{+} \leftrightarrow Zn_{s}^{-} + I_{III} + 2h^{+} \]  

....(3.4.3)

The enhancement of both self- and interdiffusion may then be attributed to the I_{III} defects. It is noted that another process occurring within Zn doped structures is the dissociative mechanism of Longini [see for example Tan et al. '91, Ky et al. '93] whereby Zn can occupy group III vacancies thereby altering the column III diffusion coefficient. This mechanism may be expressed through the relation

\[ Zn_{i}^{+} + V_{III} \leftrightarrow Zn_{s}^{-} + 2h^{+} \]  

....(3.4.4)

The proceeding discussion only covers a small number of the mechanisms producing intermixing within the GaAs/Al_{x}Ga_{1-x}As system at elevated temperatures. Furthermore, the discussion neglects any interplay between the various mechanisms. This will be discussed further within the context of the DBRs studied in the following sections. However it is clear that a range of capping, annealing and doping schemes can be used to alter the amount of intermixing that occurs within a sample.

3.4.2 DBR structure and rapid thermal processing conditions

Due to the destructive nature of the secondary ion mass spectroscopy (SIMS) characterisation and of the diode processing required for resistance measurements two distributed Bragg reflectors, grown simultaneously, are studied. The growth was by MOCVD on p+ (001) oriented GaAs substrates and consists of a 0.5µm GaAs buffer layer and 14 periods of GaAs and AlAs. The reagents in this case are trimethylgallium (TMG), trimethylaluminium (TMA), arsine (AsH_{3}) with H_{2} as the carrier gas and dimethylzinc as the p-type dopant. X-ray diffraction measurements suggest that wafer 1 (sample number QT435-UP) has layers consisting
of 621Å GaAs and 690Å AlAs, while wafer 2 (sample number QT435-DOWN) has layers of 657Å GaAs and 670Å AlAs. Both wafers are uniformly Zn doped, including buffer layers, to a level of \(2.4 \times 10^{18}\) cm\(^{-3}\) as confirmed by electrochemical C-V profiling.

**Wafer 2**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs</td>
<td>657</td>
</tr>
<tr>
<td>AlAs</td>
<td>670</td>
</tr>
<tr>
<td>GaAs 0.5μm buffer</td>
<td></td>
</tr>
<tr>
<td>GaAs p+ substrate</td>
<td></td>
</tr>
</tbody>
</table>

![Reflectivity graph](image)

**Figure 3.7** Experimental and theoretical reflection spectrum for wafer 2.

Figure 3.7 shows the reflection spectrum obtained from the centre of wafer 2 along with a theoretical spectrum calculated with the transfer matrix based model described in chapter 2, using the x-ray derived thicknesses (note that the effects of absorption and dispersion are included in the calculation).

This, and subsequent spectra, are taken using an automated Bentham M300 monochromator (quarter metre - 0.5nm resolution) with a tungsten-halogen source and a silicon photodiode (figure 3.8). Lock-in detection techniques are used and all spectra are normalised to gold.

![Monochromator set-up](image)

**Figure 3.8** Monochromator set-up used for reflection and photocurrent measurements.
The spectrum of figure 3.7 shows a broad stop-band with a bandwidth exceeding 110nm and a peak reflectivity greater than 98%, with wafer 1 showing very similar characteristics. It is noted that the DBRs, although designed for 980nm operation (GaAs 696Å - AlAs 830Å), have a reflection maxima around 910nm (with a central wavelength of ~875nm) and this has been attributed to a parasitic reaction of the zinc dopant with the alkyl reagents during growth resulting in a uniformly reduced layer thickness. This shift of the reflection spectrum to shorter wavelengths results in the appearance of a ‘kink’ in the stop-band at approximately 870nm which can be readily attributed to the band-edge absorption of the GaAs layers, moreover this kink may allow us to optically monitor the degree of intermixing by observing any shifts or changes in reflectivity, around the 870nm wavelength, due to band-edge changes relating to the introduction of Al. Furthermore, although this shift in wavelength is undesirable, due to the very high uniformity, see figure 3.9, and the similar reflection characteristics of the two wafers, the samples were considered suitable for qualitative experiments.

**Figure 3.9** Optical uniformity of wafer 1 and wafer 2 as deduced from reflection. Plots show wavelength of stop-band edge (short wavelength side) vs. position.
After growth and optical characterisation, the two wafers were cleaved into a number of 5mm × 5mm sections in preparation for rapid thermal processing (RTP) [Singh ‘88]. RTP involves the rapid heating of samples, at ramping rates of approximately 50°C/s, through the use of halogen lamps. This allows annealing times to be reduced to a number of seconds with the retention of large degrees of diffusion. The RTP system used in this study is a commercial AST SHS100_MA system based at the University of Sheffield, with the processing performed by M. Pate and G. Hill [‘92]. The system, shown schematically in figure 3.10, consists of a chamber containing 2 banks of water-cooled halogen lamp heaters, 10 lamps above the sample and eleven below, and gold reflectors to yield more efficient heating.

![Schematic diagram of RTP system.](image)

Figure 3.10 Schematic diagram of RTP system.

Samples are placed upon a silicon wafer, covered with another wafer separated by quartz spacers, and held within a quartz isolation tube. The annealing chamber is continually purged with nitrogen, 10 litres/min for 90s (lamps off) then 2 litres/min during the anneal (lamps on), and the temperature is monitored by an extended range optical pyrometer, calibrated to the silicon wafer emissivity.

![Schematic anneal cycle involving 930°C/30s dwell.](image)

Figure 3.11 Schematic anneal cycle involving 930°C/30s dwell.

The anneal cycle, figure 3.11, involves heating the sample up to the desired temperature, say 930°C, within 20 seconds and then maintaining that temperature for some desired time, for
example 30 seconds. The cooling down is facilitated by an increased nitrogen flow (10 litres/min) and the system as a whole is computer controlled. Previous work by M. Pate, G. Hill and M. Ghisoni [Ghisoni '92] suggests that the annealing conditions obtained from this system are highly controllable and reproducible. Note that the anneal times quoted in this work represent the ‘dwell’ section of the anneal cycle.

Table I shows the various samples used in this study along with their respective annealing temperatures, times and, where applicable, capping layers. The capping layers for samples D-Q, and sample U, were deposited by plasma enhanced chemical vapour deposition (PECVD) and have a nominal thickness of 3000Å. It is important to note that the samples used for the SIMS characterisation (samples B,D) have been capped in a different deposition system (University of Sheffield) to the samples used for the electrical and optical characterisation (University College London) and that in the latter case the refractive index of the SiO₉ layers was found to be slightly larger than the nominal value, suggesting a Si rich cap.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cap</th>
<th>Anneal Temperature (°C)</th>
<th>Anneal Time (s)</th>
<th>Sample</th>
<th>Cap</th>
<th>Anneal Temperature (°C)</th>
<th>Anneal Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
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<td></td>
<td></td>
<td>L</td>
<td>SiO₂</td>
<td>930</td>
<td>240</td>
</tr>
<tr>
<td>B</td>
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<td>900</td>
<td>600</td>
<td>M</td>
<td>SiO₂</td>
<td>930</td>
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</tr>
<tr>
<td>C</td>
<td>None</td>
<td>960</td>
<td>480</td>
<td>N</td>
<td>SiO₂</td>
<td>960</td>
<td>120</td>
</tr>
<tr>
<td>D</td>
<td>SiO₂</td>
<td>960</td>
<td>480</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>SiO₂</td>
<td>870</td>
<td>120</td>
<td>P</td>
<td>SiO₂</td>
<td>960</td>
<td>240</td>
</tr>
<tr>
<td>F</td>
<td>SiO₂</td>
<td>870</td>
<td>240</td>
<td>Q</td>
<td>SiO₂</td>
<td>960</td>
<td>360</td>
</tr>
<tr>
<td>G</td>
<td>SiO₂</td>
<td>870</td>
<td>360</td>
<td>R</td>
<td>None</td>
<td>900</td>
<td>120</td>
</tr>
<tr>
<td>H</td>
<td>SiO₂</td>
<td>900</td>
<td>120</td>
<td>S</td>
<td>None</td>
<td>900</td>
<td>240</td>
</tr>
<tr>
<td>I</td>
<td>SiO₂</td>
<td>900</td>
<td>240</td>
<td>T</td>
<td>None</td>
<td>900</td>
<td>360</td>
</tr>
<tr>
<td>J</td>
<td>SiO₂</td>
<td>900</td>
<td>360</td>
<td>U</td>
<td>SiNₓ</td>
<td>930</td>
<td>240</td>
</tr>
<tr>
<td>K</td>
<td>SiO₂</td>
<td>930</td>
<td>120</td>
<td>V</td>
<td>Reference</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table I The capping and annealing conditions used for the experiments within this chapter. Samples A and V are used as references for the SIMS and electrical studies respectively. Samples A-D are taken from wafer 1, while the remainder are from wafer 2.
3.4.3 Secondary ion mass spectrometry characterisation

Characterisation of the samples from wafer 1 (A-D) using SIMS was performed by G. Beyer at Imperial College London. Because of the high Al content of the DBR samples the SIMS study was performed using Cs$^+$ primaries, this species drastically reduces matrix and oxidation effects [Gao '88] as opposed to the use of oxygen.

In order to calibrate the SIMS depth and Al$_x$Ga$_{1-x}$As profiling an Al$_x$Ga$_{1-x}$As step structure, with $x$ incrementing from 0 to 1 in steps of 0.1 and with a step width of 1000Å, was initially profiled. This sample was grown by MBE at a temperature of 630°C and with a Be doping concentration of $2 \times 10^{18}$ atoms cm$^{-3}$. SIMS depth profiling, in this case, was performed in an Atomika 6500 ion microprobe. The 5keV Cs$^+$ beam was rastered over an area of 250µm $\times$ 250µm at an angle of 75° to the normal (to reduce collisional intermixing), under these conditions the erosion rate in GaAs is approximately 1.2 times faster than that of AlAs thus necessitating the previous depth calibration.

![SIMS depth profiles](image)

**Figure 3.12** SIMS depth profiles ($\log_{10}$ [Ga signal]) for samples A, B, C and D.
Comparing figures 3.12 (C) and (D), it can be seen that the degree of intermixing is greater for the uncapped sample (C). This can be seen more clearly in figure 3.13 which shows the intermixing at the second GaAs layer within the DBR. The second layer is shown because of surface effects due to SIMS bombardment causing problems at the first interface. Graph (a) of figure 3.13 shows SIMS data for uncapped samples (A, B and C) showing that the GaAs/AlAs layers are still well resolved after the anneal, also shown is the expected increase in intermixing with temperature and time. Figure 3.13b shows the intermixing for capped and uncapped samples C and D (annealed at a temperature of 960°C for 480s), in this case the extent of layer intermixing is less for the capped sample.

![Figure 3.13a](image1.png) **Figure 3.13a** Depth profiles of the 2nd GaAs layer after anneal for samples A, B and C (without cap or As overpressure).

![Figure 3.13b](image2.png) **Figure 3.13b** Depth profile of the 2nd GaAs layer after anneal for samples A, C and D (i.e. with and without cap).

These depth profiles show diffusion that is of the same order of magnitude as the broadening of the interfaces caused by SIMS collisional intermixing. In order to quantify the thermally induced diffusion the collisional intermixing effect must be accounted for [Beyer '93]. The broadening due to collisional intermixing can be approximated to an error function such that the SIMS signal intensity, as a function of position \( I(z) \), at a given interface is related to the bulk layer intensity \( I_0 \) through

\[
\frac{I(z)}{I_0} = \frac{1}{2} \text{erfc} \left( \frac{z}{\sqrt{2\delta}} \right)
\]

\[\text{.....(3.4.5)}\]

with erfc being the complimentary error function (1-erf) and \( \delta \) the variance of the corresponding Gaussian function.
A diffusion length $L_D$ may also be defined through the relation

$$L_D^2 = \delta^2 = 2Dt \quad \text{.....(3.4.6)}$$

where $D$ is the diffusion coefficient and $t$ is the anneal time. Combining 3.4.5 and 3.4.6, converting intensity $I(z)$ to concentration $N(z)$, gives

$$N(z) = \frac{1}{2} \frac{z}{\sqrt{\pi Dt}} \text{erfc} \left( \frac{z}{2\sqrt{Dt}} \right) \quad \text{.....(3.4.7)}$$

This equation assumes Fickian (constant $D$) diffusion from a semi-infinite source, as is the case when the bulk GaAs/AlAs layers (~700-800Å) are much larger than the extent of the intermixing (collisional or diffusion ~100Å).

Now, if the intermixing due to diffusion also follows the form of an error function and the collisional and thermal diffusion intermixing mechanisms, characterised by $\delta_{\text{coll}}$ and $\delta_{\text{diff}}$ respectively, are independent then the addition of the two error functions yields a third function describing the observed SIMS signal. This may be expressed as

$$\delta_{\text{diff+coll}}^2 = \delta_{\text{diff}}^2 + \delta_{\text{coll}}^2 = \delta_{\text{SIMS}}^2 \quad \text{.....(3.4.8)}$$

Assuming that the intermixing of the reference sample is purely due to collisional effects, arising from the SIMS, the SIMS data may be fitted to the above error functions and the diffusion coefficients associated with the intermixing in the various samples calculated. The values obtained are given in table II, where it is noted that the coefficients for sample B are near the detection limit ($L_D$~1-2nm) of the SIMS (limited by collisional intermixing).

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\delta_{\text{diff}}$/nm</th>
<th>$D$/10$^{-17}$cm$^2$s$^{-1}$</th>
<th>$\delta_{\text{coll}}$/nm</th>
<th>$D$/10$^{-17}$cm$^2$s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>1.9</td>
<td>3</td>
<td>1.1</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>9.1</td>
<td>86</td>
<td>4.8</td>
<td>24</td>
</tr>
<tr>
<td>D</td>
<td>5.0</td>
<td>26</td>
<td>4.9</td>
<td>25</td>
</tr>
</tbody>
</table>

Table II: Diffusion coefficients and $\delta_{\text{diff}}$ values calculated from SIMS data, corrected for collisional intermixing (the curve fitting is carried out to the 'back' of the second GaAs/AlAs interface. The estimated error of $D$ is approximately ±30%.

For intrinsic thermal intermixing at 960°C (the anneal temperature used for samples C and D) the expected interdiffusion coefficient, calculated using equation 3.4.1, is approximately 9×10$^{-17}$cm$^2$s$^{-1}$. The uncapped sample has a value significantly greater than this, by an order of magnitude, implying that an enhancement over the intrinsic intermixing has occurred. This
enhancement may be readily attributed to the presence of Zn within the DBR structure. As previously stated the presence of Zn is known, via ILD, to increase the rate of interdiffusion of Ga. This enhancement is however suppressed by the presence of a silica encapsulant, as demonstrated in sample D, in which case $D_{Ga}$ is approximately one third of the uncapped value. This is consistent with the results of other workers [Deppe et al. '88] which have shown that the diffusion of Zn, and hence the degree of layer intermixing, is reduced by the presence of gallium vacancies which in the capped case are injected into the system in a manner similar to that described in 3.4.2. Simplistically the $V_{Ga}$ suppress the presence of gallium interstitials which are believed necessary for the diffusion of Zn. If vacancies exist then Zn will preferentially occupy substitutional sites and its diffusion will be reduced. It is noted that the silica capping layer, after depth profiling with Xe, reveals the presence of Ga towards the cap/sample interface. Such a build-up of Ga is consistent with the results of Kuzuhara [Kuzuhara et al. '89] and provides evidence for the presence of the aforementioned Ga vacancies. As an aside, it is further noted that no corresponding indiffusion of Si into the DBR is observed in the SIMS samples.

It can be seen that, in table II, the diffusion coefficient of Ga, in AlAs, is larger than the corresponding coefficient of Al, in GaAs. This is attributed to a higher solubility of Zn, and hence increased mobility of Ga, in AlAs. The effect is eliminated when a silica cap is used and the Zn effect suppressed. The enhancement of intermixing through the injection of $V_{Ga}$, via IFVD type processes, is less than that due to the Zn effect.

Finally, having measured the diffusion coefficients for the various samples a standard error function approach [see for example M. Ghisoni et al. '91] may be used to approximate the depth profiles of the annealed DBRs. The aluminium profile may be expressed as

$$x(z) = x_0 \left[ 1 + \frac{1}{2} \text{erf} \left( \frac{z - L_w / 2}{2 \sqrt{D} t} \right) - \frac{1}{2} \text{erf} \left( \frac{z + L_w / 2}{2 \sqrt{D} t} \right) \right] \quad (3.4.9)$$

where $x(z)$ is the Al concentration, $z$ the position, $D$ the diffusion coefficient, $t$ the anneal time, $L_w$ the initial GaAs thickness, $x_0$ the initial Al concentration and erf(X) represents the error function.

Figure 3.14 shows the theoretical depth profiles for samples A, C and D along with a curve calculated using equation 3.4.1. This curve represents the intrinsic intermixing due to the anneal and comparisons to this clearly demonstrate the enhanced intermixing in cases C and D. The difference between the uncapped and capped samples is quite marked although the interfacial grading in both cases can be seen to extend over a depth greater than 200Å. More dramatic is the difference between the doped and the intrinsic (uncapped) samples. In this case the intermixed
regions differ in extent by well over 100\(\text{Å}\). This demonstrates the strong enhancement of the intermixing due to the Zn dopant.

![Simulated diffusion profiles for various samples.](image)

**Figure 3.14** Simulated diffusion profiles for various samples.

The anneal conditions are 960°C/480s.

### 3.4.4 Electrical characterisation of annealed DBRs

Having observed, through SIMS, the degree of intermixing within the DBRs the resulting changes in the DBR electrical characteristics were studied.

After photoreflectance measurements (described later) samples E-Q, and reference sample V, were prepared for electrical characterisation by etching mesas, using a 3:4:3 \(\text{H}_3\text{PO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}\) solution, to a depth corresponding to the buffer region of the structure. Circular mesas of diameter 300\(\mu\text{m}\) and windowed rectangular mesas of contact area 240,000\(\mu\text{m}^2\), 113,400\(\mu\text{m}^2\), 22,800\(\mu\text{m}^2\) and 7350\(\mu\text{m}^2\) were produced (limited by available masks). The mesas have Cr/Au top and bottom contact pads with the bottom pad deposited onto the exposed buffer layer. The resistance of the resulting diodes was then determined by probing the devices and recording the current-voltage (I-V) characteristics with a Hewlett Packard 4145B semiconductor parameter analyser.

All devices exhibited diode-like turn-on at approximately 1 volt, similar to that observed in the superlattice graded DBRs described earlier. All I-V characteristics were approximately linear for currents in the range 20-100mA. The slope of the linear sections of the I-V curves determines the slope-series resistance.
It is noted that mesas of this size allow only qualitative analysis of the resistance properties of the annealed DBRs due to the small ratio of the resistance change, with anneal, to the underlying resistance. The measurements do however highlight important trends.

Figure 3.15 shows the series resistances versus anneal time for a number of anneal temperatures, as measured for the 300μm diameter SiO₂ capped devices (samples E-Q). The series resistance of the reference sample (sample V) was found to be approximately 12Ω.

![Graph showing change in resistance with anneal temperature and time for SiO₂ capped samples E-Q. Also shown is the SiNₓ capped sample U.](image)

It appears that the anneal process, at the lower temperatures and shorter times, initially increases the series resistance. This has been attributed to a compensation of the p-type Zn dopants by the indiffusion of Si from the capping layer. Although this indiffusion is not observed in the SIMS study the refractive index of the SiOₓ capping layer used for these samples, as previously stated, is slightly above the nominal value for SiO₂ and this implies a Si rich encapsulant. It has previously been observed [Ghisoni '92] that under such conditions Si can be diffused into the structure. As the anneal temperatures and times are increased a maximum in resistance, observed in all the data sets, is reached beyond which a decrease is observed. This local maxima corresponds to the point at which the intermixing effects begin to dominate the Si indiffusion and other thermally induced resistance increasing effects.

In an attempt to eliminate the Si indiffusion and to study the intermixing present in a capped structure (i.e. one with little As outdiffusion) without the introduction of Ga vacancies the series resistance of a sample capped with SiNₓ, sample U, was also studied, it is included in figure 3.15. In this case the series resistance was found to decrease further than the corresponding SiOₓ samples (930°C/240s). This is attributed to the enhanced intermixing
brought about by the Zn without the inhibiting effect of injected Ga vacancies. An important point to note is that a reduced temperature may thus be used to achieve the same degree of intermixing as that which occurs when a SiO$_x$ cap is used. Also the As outdiffusion problem is reduced resulting in retention of sample surface quality (as demonstrated later).

Figure 3.16 displays the forward and reverse bias series resistances of the annealed DBRs (samples I, J and reference sample V) plotted against reciprocal area, with the curves extrapolated to mesa dimensions approaching 50µm. Uncapped samples, R-T, are also shown on the plots.

![Forward bias curves](image1)

![Reverse bias curves](image2)

**Figure 3.16** Series resistance change with device area for capped (I, J) and uncapped (R-T) samples. Forward and reverse bias refers to change in bias polarity.
As in figure 3.15 the series resistance again appears to increase for the low temperature, short anneal time samples. The uncapped samples in this figure consistently show a lower series resistance when compared to samples with an SiO\textsubscript{x} cap. This can in part be attributed to the indiffusion of Si from the cap in the latter cases, but the overriding conclusion is that the uncapped samples, consistent with the SIMS results, have intermixed more.

Figure 3.16 demonstrates the effect, upon the electrical properties of a DBR, of grading the interfaces. A reduction in series resistance of almost 50% has occurred in the uncapped 900°C/360s case (a reduction from ~135Ω to ~75Ω for a 50μm device). This reduction in resistance is found to be capping layer dependent (see also figure 3.15) and these findings suggest that a degree of lateral selectivity may be introduced into the electrical properties of a wafer. Furthermore, because the intermixing is enhanced by the presence of the Zn already within the structure it may be possible to use higher doping at the interfaces to increase the intermixing. This should allow vertical selectivity in the intermixing process. Finally, by optimising the anneal conditions (temperature and time) a further increase in intermixing may be achieved.

### 3.4.5 Optical characterisation of annealed DBRs

The error function approximations to the depth profiles of the annealed DBRs, derived from SIMS, as shown in figure 3.14 may be used to calculate the effect of interdiffusion on the reflection properties of the structures. Using the transfer matrix model described in chapter 2, along with the error function approximated profile, the reflection spectrum of an annealed DBR may be calculated. We approximate the structure to a collection of 1Å layers each of slightly differing Al\textsubscript{x}Ga\textsubscript{1-x}As composition, noting that there is no intermixed Al\textsubscript{x}Ga\textsubscript{1-x}As at the sample surface. Obviously the above approximation will introduce errors into the reflectivity calculation, these are however expected to be small relative to the unknowns relating to the diffusion process. A continuum model (perhaps based upon coupled mode theory) may provide a more accurate solution. In this calculation the intermixing is assumed to be isotropic and depth independent, the effect of index dispersion within the Al\textsubscript{x}Ga\textsubscript{1-x}As is accounted for [Casey et al. '74]. It is noted that the SIMS data itself may be used as the basis for this type of calculation but the noise associated with the data (see figure 3.12), an artefact of the SIMS measurement, makes such a calculation highly unreliable. One other group, [Floyd et al. '94], has recently published purely theoretical work on this type of model. In that case an error function solution to the intermixing of GaAs/AlAs is not used, again the above assumptions are made (using a step size...
much greater than 1 Å) but the further assumption of no doping is also made and as such low diffusion coefficients are assumed. Although the results presented here are in broad agreement with the work of Floyd et al. the new experimental work detailed in this chapter leads to the adoption, in this case, of higher diffusion coefficients.

Figure 3.17 shows the theoretical reflection and phase shift, on reflection, spectrum for wafer 2 before and after annealing, a diffusion coefficient of \(100 \times 10^{-17} \text{cm}^2\text{s}^{-1}\) and an annealing time of 120s has been used. The effects of the GaAs bandedge and surface degradation are not included in this calculation (a background absorption approaching 10 cm\(^{-1}\) is used throughout, derived from a fit to the experimental data).

**Figure 3.17** Theoretical Reflection and phase shift, upon reflection, spectra for wafer 2. Calculation assumes \(D=100 \times 10^{-17} \text{cm}^2\text{s}^{-1}\), \(t=120s\) and an error function diffusion profile.

Figure 3.17 shows that the reflection peak, see also figure 3.18, has decreased slightly and also shifted in wavelength with annealing. Furthermore the stop-band width has decreased slightly, these effects are due to the increase in compositional Al\(_x\)Ga\(_{1-x}\)As within the DBR. This material has a lower refractive index than GaAs such that the \(n_d/n_l\) ratio is decreased and so the reflection properties are altered (see equations 3.3.1, 3.3.2 and figure 3.16). The shift in wavelength, by approximately 5-10nm, is due to the non-linear refractive index change in going from GaAs to Al\(_x\)Ga\(_{1-x}\)As and this may need to be accounted for in the use of intermixing as applied to microcavity structures. The corresponding phase shift spectrum clearly shows the wavelength shift for the annealed structure, points a and b along the zero of the phase shift axis. The points a and b approximately correspond to the wavelengths at which a microcavity, formed from such a DBR, would have its main Fabry-Perot resonance both before and after annealing.
Figure 3.18 theoretically shows the peak of the reflection spectrum for wafer 2 against the parameter \((Dt)^{1/2}\), where D is the interdiffusion coefficient and t the time. This calculation clearly shows that the peak reflectivity, neglecting surface degradation effects, of the DBR is not affected dramatically until the diffusion length \(L_d\) (see equation 3.4.6) of the intermixing atoms becomes an appreciable fraction of the quarter-wave thickness of the DBR. Beyond this point the reflectivity drops rapidly.

![Graph](image)

**Figure 3.18** Theoretical peak reflectivity for wafer 2 plotted against \((Dt)^{1/2}\).

*For clarity \(6 \times 10^8\) corresponds to \(D \sim 300 \times 10^{-17} \text{cm}^2\text{s}^{-1}\) and \(t \sim 120\text{s}\).*

In order to quantify some of the above effects a number of samples, as detailed in table I, have been experimentally studied.

The uncapped annealing of GaAs/AlAs based structures in the absence of an As overpressure generally results in samples with As poor surfaces which are microscopically rough. The use of a cap reduces this As depletion, it is noted that the samples under study here are annealed without any application of an As overpressure other than that present at the sample/cap interface. These experimental optical studies use samples from wafer 2 capped with either SiO\(_x\) or SiN\(_x\) (samples E-Q and sample U, from table I). This wafer was used because it is uniform, over a region of 2cm \(\times\) 4cm, to less than 1 percent, corresponding to a wavelength shift of \(~5\text{nm}\). Figure 3.19 shows the results of reflection spectroscopy of all the SiO\(_x\) capped samples (E-Q) along with the reference sample V. All samples are normalised to gold, the peak reflectivity of which is approximately 98 percent at these wavelengths.

After RTA the samples were chemically etched to remove their capping layers. In all cases the samples appeared slightly milky, as is common in samples with a degree of As outdiffusion.
However all samples subsequently exhibited good reflection spectra with a high reflectivity (greater than 90 percent) and broad stop-band. The As outdiffusion was evidenced by Nomarski microscopy which revealed a slightly pitted sample surface, not uniformly pitted but with pit density increasing towards the sample edges (sample size ~5mmx5mm). This outdiffusion may be due to the poor quality of the capping layer as evidenced by the results described earlier which imply a Si rich cap.

![Graphical representation of reflection spectra](image)

**Figure 3.19** Measured reflection spectra for samples E-Q and reference sample V. Anneal temperatures and times are indicated, measurement is with cap removed.

Figure 3.19 shows that the decrease in reflectivity at low anneal temperatures (870°C samples) and for short times is, in the worst case, approximately 1-2 percent. This decrease in reflectivity increases with corresponding increases in temperature and time and is greater than predicted by the theoretical model, see figure 3.18. The predominant reflectivity reducing mechanism in this case is believed to be that of surface roughening, due to As loss, which has the effect of scattering incident light. It is also possible however that the intermixing effect is changing the reflectivity more than predicted due to the proximity of the GaAs bandedge. This may be seen in the 960°C samples of figure 3.19 which show a large change in reflectivity and a change in the reflection 'profile'. In all of the spectra shown the theoretically predicted decrease in stop-band width is observed, evidencing intermixing, although the shift in wavelength appears to be less than predicted, this is probably due to the shift falling within the wafer non-uniformity error.
Using the data above a diffusion coefficient may be calculated, using figure 3.18, by purely optical means. Unfortunately, because surface degradation effects are not included in the calculation, the diffusion coefficient obtained in this way is greatly overestimated and is approximately six times that obtained with SIMS, a value approaching $600 \times 10^{17} \text{cm}^2\text{s}^{-1}$ being obtained.

Finally, figure 3.20 shows the reflection data, taking account of the gold reflectivity, for the SiO$_x$ capped, 240s annealed DBRs (F, I, L, P) along with curves for the SiN$_x$ capped sample (U) and the reference sample (V).

![Figure 3.20 Reflectivity for SiO$_x$ capped samples F, I, L, P and SiN$_x$ capped sample U. All samples annealed for 240s (870°C, 900°C, 930°C, 960°C). Reference sample is V.](image)

The peak reflectivity, figure 3.19, of the SiN$_x$ capped sample (U, 240s/930°C) is found to decrease by approximately 1.9% while the samples annealed at 870°C, 900°C, 930°C and 960°C have reduced in peak reflectivity by 1.9%, 4.8%, 4% and 10.3% respectively, relative to the reference sample. The SiN$_x$ capped sample (U) retains a peak reflectivity equivalent to the SiO$_x$ capped sample (F) annealed at the lower temperature of 870°C. This is attributed to the high quality of the SiN$_x$ encapsulant which has the effect of reducing As outdiffusion. Furthermore, it is noted that this sample (U) also showed a reduction in series resistance equivalent to that for an SiO$_x$ capped sample annealed at the higher temperature of 930°C, for the longer time of 360s. Thus capping with SiN$_x$ shows all of the resistance reduction benefits of annealing without a cap, due to the lack of Zn diffusion suppressing Ga vacancies in this case, along with the optical advantages gained by preventing As outdiffusion.
3.5 Concluding remarks

This chapter has detailed the series resistance problems inherent in GaAs/AlAs based DBRs. The hole transport is identified as the major contributor (approximately 10-100 times more energy is required relative to electron transport) to the series resistance and thus the p-type DBR has been targeted in the search for potential solutions to this problem.

Uniform bulk section doping along with high periodic doping at heterointerfaces has been studied as a solution to the problem and, in accordance with the findings of other workers [Kopf et al. '92, Kurihara et al. '93], has been found to reduce the series resistance appreciably.

Critically, by increasing the tunnelling current at the heterointerfaces through the use of short period superlattices further, order of magnitude, resistance reductions have been achieved. When coupled to the periodic doping scheme the result is a DBR with good optical and electrical properties. The low series resistance of superlattice graded DBRs, along with the fact that they retain a high reflectivity and are relatively tolerant electrically to temperature variations has already made such DBRs the mirrors of choice in modern VCSELs. The low resistance improves both the continuous-wave (cw) performance, at high injection, and also the high speed response of the device by allowing a small resistance/capacitance (RC) constant. Furthermore, although the initial growth cycle is complex, such DBRs simplify device processing by removing the need for intra-cavity contacts. The phase matching of gold to the DBR, see chapter 2, may allow the use of fewer DBR periods and thus achieve a further reduction in series resistance. These metal layers may also provide a contact layer and act as self aligned etch masks. The above are all real advantages for the industrial manufacture of VCSELs.

The technique of post-growth intermixing has been applied, for the first time, to the series resistance problem within p-type DBRs. Although the gains in series resistance reduction in this case are less than that due to the above schemes, typically less than 50%, such work is necessary in the general characterisation of diffusion if intermixing techniques are to be used to laterally integrate vertical cavity devices.

We have demonstrated a cap dependent layer intermixing of the DBR stack, with little depth dependence, and characterised the intermixing process. The intermixing of the DBR has been shown to increase, relative to SiOx capped DBRs, when a SiNx cap or no encapsulant is used. This has been attributed to the lower number of Ga vacancies in the latter two cases. In the former, silica capped, case the injection of Ga vacancies is believed to decrease the effect of Zn enhanced intermixing. This is seen quantitatively in the interdiffusion coefficients for Ga, derived from SIMS, which are found to be greatly enhanced in the uncapped case.
The electrical characteristics of the DBR are found to improve with intermixing, with reductions in the series resistance attributed to grading of the heterointerfaces of the stack. Uncapped samples have shown a maximum resistance reduction of up to 50%, in both their forward and reverse bias characteristics, this may improve through optimising the anneal cycle. Also, further enhancements may be brought about through the use of high doping, applied at the growth stage, at the interfaces to induce more, and selective, intermixing. We believe that this technique may be applied to pseudo-graded DBRs in which case the intermixing may be performed at a reduced temperature so that the sample is not excessively degraded but the resistance is greatly reduced. Such hybrid schemes may allow the intermixing of VCSEL type structures which contain active regions that might degrade at high anneal temperatures.

The cap selective intermixing may allow the patterning of devices and the formation of ‘channels’ of low resistance through DBRs, this may prove useful in the control of the transverse mode structure of VCSELs allowing for the fabrication of planar arrays and lateral integration. Thus it may be possible to optimise both the lateral and longitudinal electrical properties of the VCSEL through careful use of doping and capping.

Finally, we have experimentally and theoretically shown that the optical properties of annealed DBRs do not degrade appreciably unless the group III atom interdiffusion length becomes a significant fraction of the quarter-wave thickness. The main contribution to optical degradation is believed to be As outdiffusion induced surface roughening. This has been verified by Nomarski microscopy of the sample surface and a theoretical analysis that predicts only small changes in reflectivity with the annealing conditions used (the retention of high reflectivity when a SiNx cap is used adds further evidence to this). The use of an As overpressure might reduce this surface degradation effect. The surface degradation should not however affect the reflectivity of the DBR as viewed from within the substrate and so the technique should find application within bottom emission VCSELs, in which case the sample surface forms only a minor part of the DBR.

To conclude, the use of different capping layers has been shown to greatly alter the electrical and optical characteristics of pre-doped DBRs. This suggests that intermixing may be applied, through careful selection of capping layers and annealing conditions, to the lateral integration of vertical cavity devices. This greatly increases the scope of intermixing techniques and suggests that, with greater characterisation, they may become viable industrial techniques for VC-device integration.
Chapter 4

Characterisation of VCSELS
4.1 Introduction

This chapter details the procedures employed in the design, growth, fabrication and characterisation of VCSELs. By utilising the (theoretical) models for the optical parameters of VCSELs, discussed in chapter 2, a number of device designs are developed. The subsequent molecular beam epitaxial (MBE) growth of these structures is discussed and, as might be expected, is found to be a deciding factor in dictating the operating characteristics of the device. Experimentally, the low threshold device designs are shown to have threshold currents of 5mA (current density of ~1kA/cm²) for 20μm diameter circular air-post devices, containing 3QWs and utilising the periodic gain scheme (PGS) [Corzine et al. ‘89]. These designs use the graded interface (hybrid) DBRs developed in chapter 3 and have operating voltages that fall below 5V, compatible with CMOS drive circuitry. Furthermore, the high power designs (which use novel graded index confinement regions and the principle of off-set gain [Young et al. ‘93]) possess pulsed output powers exceeding 50mW, limited by thermal problems due predominantly to inadequate heatsinking. These threshold currents, output powers and drive voltages compare very favourably with some of the best VCSELs developed, in the literature, to date. A characterisation of the emission spectral and power properties of both optically and electrically injected devices is given, both above and (uniquely) below threshold.

4.2 Design of VCSELs

Transfer matrix models that allow calculation of the optical properties of VCSELs were developed in chapter 2. These models are now employed to arrive at VCSEL designs that are optimised for threshold current and power output. Initially we will discuss the optical design of a VCSEL which essentially involves optimisation of the number of DBR pairs (i.e. the output coupling efficiency) and the laser cavity design. The longitudinal mode structure of the device must be considered and the active region confinement factor must be maximised. This involves optimisation of the number, composition and physical position of the QWs in the cavity of the device. Next, the electrical properties of the device must be considered. The DBR heterointerfaces must be graded, as described in chapter 3, to reduce the VCSEL operating voltages and hence improve the devices thermal and high power characteristics. This electrical optimisation will also involve an improvement in the confinement of the injected carriers to the active (QW) layers. Ultimately, it is important to remember that the electrical and optical issues cannot be completely de-coupled and as such VCSEL design is a truly iterative procedure.
4.2.1 Optical design of VCSELs

As stated in chapter 1, the VCSELs developed within this work are, nominally, for operation at 980nm. The real refractive indices for GaAs, AlAs and In$_{0.2}$Ga$_{0.8}$As at this wavelength are \(n_{\text{GaAs}} = 3.52\), \(n_{\text{AlAs}} = 2.95\) and \(n_{\text{InGaAs}} = 3.62\) respectively (see appendix A). These materials are the main constituents of the VCSELs that will be discussed here. The bandedge related absorption within the GaAs and AlAs layers may be neglected at the wavelengths of interest. Using these indices the basic DBR period (GaAs/AlAs pairing) at 980nm can be seen to comprise 696Å GaAs and 831Å AlAs, the reflectance spectrum is given in figure 2.5 of chapter 2. It must be noted that in reality the lattice constant of GaAs (and AlAs) is approximately 5-6Å, this limits the ultimate precision with which DBR, and hence VCSEL, structures may be designed. In principle single monolayer fluctuations in a given layer may result in ∼1Å shifts in the DBR and lasing wavelength [Weber et al. '90, Law et al. '93]. In practice the errors in the refractive indices are the design limiting problem.

By using two of the above DBRs we may form a microresonator, see for example the generic structure given in figure 2.8 of chapter 2. The cavity of a VCSEL (microresonator) contains QWs which, in the case of 980nm emission, have gain and spontaneous emission characteristics similar to those given in figure 2.12 (chapter 2). The number and position of these QWs within the cavity is of prime importance and strongly dictates the devices threshold characteristics.

\[\text{DBR} \quad \text{QW} \quad \text{DBR}\]

Figure 4.1 Schematics of possible cavity configurations within a VCSEL.
Also shown is the optical field (\(E^2\)) profile within the cavity.

Figure 4.1 shows a number of possible cavity configurations for a VCSEL. Case (a) shows a 1λ cavity containing a single QW at the centre. This is the shortest cavity length of interest in
GaAs/AlAs based VCSELs. Shorter cavities (e.g. $\lambda/2$) have high optical fields concentrated only at the cavity-DBR interfaces and this (practically) leads to growth and doping problems for QWs placed at these positions. Case (b) shows a similar cavity containing 3QWs, each separated by 100Å. In this case all the QWs are placed under the same antinode of the optical field, this is a commonly used configuration [Geels et al. '93]. Finally case (c) shows a cavity utilising the periodic gain scheme (PGS), placing each of the 3QWs at a separate peak of the optical field within a $2\lambda$ cavity. The confinement factor in this last case is found, from transfer matrix calculations of field, to be approximately $\Gamma_c = 0.042$ (a structure containing 20 period top and bottom DBRs is assumed, field penetration effects are included). This is approximately three times larger than the corresponding confinement for the single QW (a) which has a value $\Gamma_c = 0.017$. The relationship is approximate due to the dispersive refractive indices of the materials altering the resonant wavelength, of each structure, slightly (from 980nm).

Interestingly, the slowly varying nature of the fields within the resonant cavity leads to a confinement factor for case (b), 3 QWs (in close proximity) placed at one antinode, that is almost equal to that for case (c), 3QWs placed at separate antinodes.

Given these three cavities we can calculate the threshold currents that will be obtained from VCSELs containing these active layers. We use the models developed in chapter 2. Figure 4.2(a) shows the gain at threshold for VCSELs comprising a fixed 20 period $\lambda/4$ bottom DBR and an $N_{top}$ period top DBR, the reflectivity of which is varied (x-axis). The figure shows the result, on threshold, of using each of the above cavities (Figure 4.1). Note that losses of 10cm$^{-1}$ are assumed for each material layer, this is in accordance with values derived from the literature.

![Figure 4.2](image-url)  
*Figure 4.2 Threshold gain (a) and threshold current density (b) for a range of VCSELs.  
Design wavelength is 980nm and the bottom DBR is fixed at 20 (GaAs/AlAs) pairs.*
The above figure (4.2a) clearly shows the effect of the increased confinement factor in the PGS case (cavity c), demonstrated by an approximately three fold decrease in threshold gain (per QW) in going from a 1QW structure to one with 3QWs. However, this decrease in threshold gain per QW is misleading in that this factor of three reduction does not appear in the total threshold current of the device. The corresponding threshold current density ($J_\text{th}$) of the VCSELs is shown in figure 4.2(b), calculated at $T=70°C$ (which corresponds to the operating, junction, temperature of a VCSEL). In this case the threshold current for the 1QW VCSEL falls below the threshold currents for the 3QW lasers when the top (output coupling) DBR contains more than 19 periods. This is explained in terms of the carrier density within the QWs of the respective VCSELs. In the 3QW structures, where less gain per QW is required to reach threshold, the carrier injection level, per QW, is of order $3\times10^{10}$ cm$^{-3}$. The corresponding injection level in the 1QW case is closer to $7\times10^{10}$ cm$^{-3}$. Thus the total (summed) injected current into the 3QW structures is larger, in the high reflectivity (low loss) regime, than that injected into a 1QW structure. At first sight these graphs appear to favour the single QW laser which seems to be most useful, due to its low threshold (when the top DBR is highly reflective). However the 3QW case is more favourable. This is because it prevents the laser from entering the (detrimental) high carrier injection regime near threshold. For in-plane laser examples of this see Reinhart [in Zory '93]. In the 1QW case the carrier injection level in the QW is high, at threshold, and this leads to high recombination rates due to carrier leakage (contributing almost 50% of the total current) and Auger recombination (contributing approximately 10% of the total current, calculated using the model of chapter 2). The corresponding injection level for the 3QW laser (per QW) is much lower and so the laser enters the high injection regime only well above threshold. Furthermore, another problem with the 1QW device, again relating to the high threshold injection level, is that of gain saturation (see figure 2.13, chapter 2). This will strongly limit the devices output power, especially when coupled to the low output efficiency of the high reflectivity DBRs (see figure 2.15, chapter 2). Thus the power output, and conversion efficiency, of the 3QW devices is expected to be higher. These findings are consistent with the experimental work of Geels [Geels et al. '90a] who shows that the use of single QWs, coupled with very high reflectivity DBRs, leads to VCSELs which possess very low threshold currents (0.7mA, $\sim1kA/cm^2$). Unfortunately, the maximum power output is limited to only tens of microwatts. Such, ultra-low threshold current, low power devices are not believed to be of practical importance, other than in very short distance (for example intra-chip) interconnection applications. More generally a higher power output device is required with a moderately low threshold current, and correspondingly low threshold voltage (i.e. low power consumption). Thus, most of the structures studied here will contain 3QWs.
The graphs of figure 4.2 also show that there are only small differences between the threshold characteristics of the non-resonant and resonant 3QW schemes (b and c respectively of figure 4.1). Therefore both these cavity configurations will be utilised. It is noted that the use of larger numbers of QWs will, in general, increase the total power output of the device. Unfortunately the threshold current will also increase, because of optical and electrical losses introduced by the additional QWs. This increase in threshold is not, in general, offset (linearly) by the increase in output power, and as such the use of 3QWs is found to result in the best overall device characteristics. This finding is again borne out by the work of other groups [Geels et al. '93, Young et al. '93].

Having arrived at suitable cavity designs (cavities b and c of figure 4.1), optimised only in their optical properties (i.e. large confinement factors), we must now choose suitable DBRs to form the light output couplers. These must have a high reflectivity to allow multiple passes through the very thin active layers, to give efficient lasing. They must also allow a useful amount of light to exit the structure (numerically this is also a loss mechanism). The minimum reflectivity of a DBR, to allow lasing, is approximately 99%, as discussed in chapter 1. DBRs, and their effect on threshold, have been studied in detail in chapters 2 and 3 and as such the findings are only briefly reiterated here.

In this thesis we study both top-emission and bottom emission devices (lasers and light emitting diodes, LEDs). Specifically, the VCSELs studied are, for practical reasons (see section 4.5.1), bottom emission devices. In this case the output coupling DBR reflectivity, for light incident from the active layers, is reduced (relative to the earlier calculations) because the mirror does not terminate on air. Furthermore, in reality both DBRs contain short period superlattices (see chapter 3) and doping which decrease the reflectivity further. As such the number of periods used in the actual structures, as shown later, may be slightly higher than the theoretically predicted optimal numbers.

In all of the preceding calculations (here and in chapter 2) the back (non-output coupler) DBR has been fixed at 20 periods. This is because such a DBR offers a peak reflectivity of 99.9% (theoretically), which permits the design of low threshold VCSELs. However, in bottom emission devices the back DBR is often of the hybrid type, as described in section 2.3.1 (chapter 2). In order to achieve the same (99.9%) reflectivity in a hybrid DBR only 16 GaAs/AlAs periods are required (as shown in figure 2.7, chapter 2). Thus, this will be the DBR of choice for the VCSELs in this work.

Having fixed both the back DBR and the optical cavity of the VCSEL we must now tackle the important output coupling DBR. The reflectivity of this DBR is dictated completely by the application for which the device is to be designed. For example a high reflector will result in a
low threshold low output power device, while a low reflectivity DBR will result in a higher threshold device with a greater power output. We will consider both cases but will constrain ourselves to the production of VCSELs with both useful (in a systems view) threshold currents and output powers. The efficiency calculations of figure 2.15(b), chapter 2, show that an output coupling DBR of 18 periods will result in a VCSEL with a high optical conversion efficiency and a low threshold current (approximately 3mA for a 20μm device). Alternatively an output coupler of 20 periods will have a threshold current below 3mA, with only a small reduction in conversion efficiency. The power output in this case will depend critically on the confinement of carriers to the active region (at high injection levels and temperatures). Increasing the reflectivity further gives a lower threshold current but lowers the output power to well below 1mW. The structure thickness (and growth time) also becomes large. In a similar vein decreasing the reflectivity below that achieved with 18 DBR periods increases the optical efficiency, but the threshold increases. Calculations show that in this case only a small increase in the background absorption within the structure yields a very large increase in the threshold current.

4.2.2 Electrical design of VCSELs

When designing VCSELs it must be remembered that the multilayer structure will also carry the current injected into the device when no intra-cavity contacting is used [Wu et al. '87]. The DBRs must therefore be graded at the heterointerfaces and periodically doped, to prevent optical degradation due to free carrier absorption. This (grading) has been discussed previously in chapter 3, there it was shown that the incorporation of superlattices at each GaAs/AlAs interface (coupled to a periodic doping scheme) results in a greatly reduced series resistance. Furthermore the number of DBR pairs must be limited to avoid large device electrical resistance (this is, in part, why a maximum of only 20 periods is used in this work). In this matter, the hybrid DBR serves to reduce the series resistance by reducing the number of DBR layers.

As stated previously, at high carrier injection levels carrier leakage out of the QWs causes the light output versus injected current (L-I) curve of VCSELs to turn over, thereby limiting the high power performance. The quantum wells used in this work are In_{0.2}Ga_{0.8}As based and have GaAs barriers. Using these barriers results, at the laser operating temperature of 50-70°C, in approximately 30% of injected carriers being lost to leakage currents (in a 3QW VCSEL - calculated using the model of chapter 2). The use of Al_xGa_{1-x}As barriers (with x approximately 20%) reduces this carrier leakage problem dramatically, this is due to an increased carrier confinement. However a recent solution to this problem involves surrounding the QWs within
the VCSEL with very high Al content cladding layers (x~50%), leaving the individual QWs barriered by GaAs [Young et al. '93]. This solution has been demonstrated to work well, even at output powers exceeding 100mW. Another possible solution, and the one implemented in this work, is to use graded-index separate-confinement heterostructure (GRINSCH) type cavities. These have been employed to excellent effect in in-plane lasers to aid in both optical and, in this case more importantly, electrical confinement. The composition profiles of figure 4.3 show the above three cavity schemes. Schemes (a) and (b) have been studied extensively by a number of authors [Geels et al. '93, Young et al. '93]. Scheme (c) has been studied thoroughly in the IPL case but only rarely [Wang et al. '92- using GaAs QWs] in the VCSEL configuration. It is shown, in this work, to result in lasers with both a high power output (exceeding 50mW) and good threshold characteristics (current densities below 1kA/cm² for a 3QW device).

![Figure 4.3 Schematics of possible cavity configurations within a VCSEL.]

A point to note is that some of the devices developed for this work utilise the principle of offset gain [Young et al. '93]. This is used in conjunction with the GRINSCH cavities to enhance high power performance. The operating temperature of a VCSEL is approximately 70°C. Thus, for a VCSEL with a room temperature gain maximum at 980nm, coincident with the main Fabry-Perot (FP) mode, the laser will operate inefficiently. This is because, as the laser heats up, a detuning of the peak of the gain spectrum and the FP mode occurs. The offset gain scheme places the gain peak, at room temperature, at a shorter wavelength (~950nm) than the optical FP mode. Thus, as the laser heats up the gain maximum shifts into coincidence with the FP mode and the output of the VCSEL is enhanced.

### 4.3 MBE growth of structures

The technique of molecular beam epitaxy (MBE), and its application to the growth of VCSELs, is both complex and device dependent. A full treatment of the subject is unfortunately beyond the scope of this thesis and the reader is referred to literature [Joyce '85, Tsang '85 (general), Geels '91 (VCSELs)] for detailed information. MBE allows the deposition of material
layers with essentially monolayer thickness control and high interfacial quality. These features make it the default technique for the production of VCSELs which require extremely exacting tolerances during their production (see chapter 2). Other techniques, of which the most common is MOCVD (metal organic chemical vapour deposition), have also been used to produce VCSELs. However, to date, the reduced thickness control has resulted in these techniques being used predominantly for DBR or cavity production. The (single cycle) growth of complete VCSELs is generally, with notable exceptions, not attempted by MOCVD. These other techniques are however at the forefront of long wavelength [Baba et al. '93, Uchida et al. '93], and phosphorous containing short wavelength [Chow et al. '94], VCSEL production.

This section of the thesis briefly describes the procedures employed during the production of VCSELs for this project. The VCSELs in this thesis were grown by C. Roberts, at Imperial College London, using a VG V80H solid source MBE system. The MBE sources comprise Ga, Al (x2), In and As cells, with Be and Si as the p- and n-type dopants respectively. The temperature of each source was monitored by a thermocouple and the corresponding fluxes determined by a beam monitor (ion gauge). The flux from the Ga, Al and As sources was found to be very stable with low flux transients, this has been attributed to the cell design and the use of quick (no-bounce) shutters. Unfortunately the In cell flux was found to suffer from shutter related transients and also to be strongly dependent on the cell temperature. Different cells were tried, but the problem still arose and so a high degree of calibration (of a specific In cell) proved to be the only solution. More generally, in order to grow complete VCSELs the growth rate of each material used must be determined very precisely. This is important since no in-situ optical monitoring has been used in the course of this work.

After the initial bake out procedures, the fluxes of each source, as they impinge at the sample surface, were measured (at a range of cell temperatures) using the beam monitor. This source flux test was performed daily (at a given temperature) and the results checked with previous calibrations. Fortunately the response of the system proved to be highly stable over a period of 5 days. After these flux measurements the As to Ga flux ratio was chosen to be 10:1. Having determined the impinging flux the growth rates for bulk GaAs (growing on a GaAs [001] n' substrate) were determined. In this case reflection high energy electron diffraction (RHEED) was used, it is widely accepted that single oscillations of the RHEED intensity correspond to the growth of a single monolayer. The GaAs growth rate was subsequently set to be 1 monolayer per second (~1μm per hour), requiring a substrate temperature of ~670°C. Both pyrometer and thermocouple measurements were used to determine the substrate temperature, the surface oxide desorption temperature (~590°C) was used as a further calibration. RHEED was also used to monitor the growth rate of InGaxAs (on both GaAs and InAs substrates), unfortunately the
RHEED signal was unclear (highly damped) and so another calibration for the In proved necessary (described later). It is noted that sample rotation was fixed at 1 rotation per monolayer, the 2 inch substrates in all cases were clipped to an In free mount.

Having calibrated the growth rates 10μm layers of GaAs and AlAs were grown, AlAs aids in the removal of oxygen from the growth system. Hall measurements were subsequently performed on the layers to check mobility. The doping level was calibrated through the growth of staircase doped structures which were electrochemically (CV) profiled. Next, standard AlGaAs/GaAs multiple quantum well (MQW) samples were grown to check the material optical quality (using photoluminescence, PL), the temperature in this case is reduced to ~620°C. Optical quality is checked against a reference MQW structure. At this stage the In growth rate was checked by growing a range of MQW samples containing different In compositions (ranging from 0 to 25%). These samples were subsequently characterised using high resolution x-ray diffraction (HRXRD), photoluminescence and photocurrent measurements. This, rather involved, indium calibration proved the most precise way to calibrate the InGa1-xAs growth rate and, as such, proved invaluable in the production of strained QW VCSELs.

Finally, having calibrated the growth rates and In (and Al) composition, DBR structures were grown and checked for their optical properties. The position of the stop-band was then used to fine tune the MBE growth rates. It is important to remember that the growth of QWs, generally taking a few minutes, is distinct from the growth of thick (bulk) material. VCSELs may take many hours to grow. As such, the growth rates must be determined very precisely. A one percent growth error within a QW will not alter the QWs optical response appreciably. However the same error within a DBR will shift the reflectance band by 10nm (nominally λ/4 at 980nm). The diffusion of dopants during such a prolonged growth run may also become an important issue, especially at high doping levels. Only after the demonstration of good optical and electrical devices may the growth of VCSELs commence. As a practical aside, each of the VCSEL samples for this work were grown after a run of general InGaAs and DBR based devices which were studied through photocurrent, reflectance and HRXRD spectroscopy prior to the VCSEL growth. This further aided thickness and indium composition calibration.

Figure 4.4 shows the uniformity with position, across a 2 inch wafer, of one of the DBRs grown using this MBE system. The wavelength scale represents the position (in wavelength) of one of the minima within the reflection spectrum, specifically one on the short wavelength side of the stop-band. The right hand scale represents the shift, relative to the spectrum at the wafer centre, of the reflection minima (it may be taken as a thickness variation). A 0.5nm resolution optical multichannel analyser (OMA) was used to measure the reflection spectra. The sample is seen to be uniform to within 1% over a region approximately 1.5cm in diameter, centred at the
middle of the wafer. This also corresponds (approximately) to a thickness variation of 1%. Beyond this the thickness changes rapidly, the edge to edge variation is approximately 10%.

![Figure 4.4 Uniformity of MBE grown wafer (with sample rotation).](image)

Having described the basic growth and calibration procedure we may now go on to describe some of the actual samples produced for the work in this thesis. The four samples described here are representative both of the VCSELs to be found in the literature and the VCSELs we have developed. The first two samples have been designed predominantly for optical injection measurements. The latter two samples are optimised both electrically and optically. These samples have been selected because they utilise a range of different DBR types, DBR reflectivities and active cavity configurations. This aids comparison and provides for a more thorough understanding of the relative effects of each modification.

The first sample, A (termed MV1733), is a simple structure with a 14 period top and 18 period bottom $\lambda/4$ DBR. The cavity in this case is approximately $2\lambda$ long and contains $20 \times \text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ QWs, the structure is shown in detail in appendix 3. This structure is not optimised, either electrically or optically, and forms the simplest microcavity studied in this work. It is noted that the use of a uniform gain section (UGS) is intended to overcome the high losses due to the low reflectivity of the top (output coupling) DBR. This structure is similar to those used to calibrate and optimise the MBE growth. The use of optical injection, in this case, negates the need for growth of complex graded interface DBRs and facilitates a quick turn-around of characterisation information to the grower.

The second structure, B (SA6M35), comprises a 14 and 20 period top and bottom DBR respectively. Each GaAs/AlAs heterojunction in the DBR is graded using $200\,\text{Å}$ $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$ layers to reduce the structures electrical resistance. The optical cavity for this structure is one wavelength long and contains $3 \times \text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ QWs placed at the antinode of the standing wave optical field. This structure is a progression from the first structure in both optical and electrical
terms. By reducing the number of QWs and increasing the DBR reflectivity the threshold of the
device may be reduced. The electrical properties of DBRs are described in chapter 3. The full
structure is given in appendix C (ii).

The third structure, C (U2040), utilises full short period superlattice grading at each of the
interfaces in the top (p-type) DBR. This DBR comprises 16 periods and is periodically doped,
allowing high doping levels without the introduction of undesirable free carrier absorption. The
top GaAs layer thickness has been increased and the layer has been highly doped to allow
contacting, the metal in this case also boosts the DBR reflectivity (hybrid DBRs are discussed in
chapter 2). A 22 period bottom DBR with 200Å Al$_{0.3}$Ga$_{0.7}$As step grading forms the output
coupler. The optical cavity is 2λ long and utilises the resonant periodic gain (RPG) scheme. The
full structure, which corresponds to the low threshold design discussed earlier, is given in
appendix C (iii). It is noted that the sample rotation for this sample was halted during the growth
of the top GaAs (1350Å) cladding layer in the cavity. This induces a strong variation of cavity
thickness across the wafer, leading to a large shift of the Fabry-Perot (FP) resonance (see chapter
2). The corresponding DBR and QW optical spectra shift relatively slowly (as they are grown
with rotation) and so studies on the effect of detuning the FP resonance from the QW gain peak
can be made.

The final structure, D (U4041), is a complete low threshold high power design. It has full
superlattice grading in both the 18 period top (p-type) and 17 period bottom (n-type) DBRs.
Both the mirrors are periodically doped and the top DBR is of the hybrid type, laser emission is
thus through the substrate. A one wavelength long optical cavity is used with 3 × In$_x$Ga$_{1-x}$As
QWs placed at the centre. A reduced indium fraction for the QW (x~18%) is chosen such the
room temperature gain peak is at approximately 950nm. The peak gain should thus shift to
coincide with the FP resonance during device operation. Full structural details are given in
appendix C (iv). The graded Al GRINSCH cavity can be seen to comprise a collection of
stepped Al$_x$Ga$_{1-x}$As layers (step width ~200Å), with x increasing from 0 to 50%. Final grading to
100% Al is achieved through the use of a short-period linear-superlattice. In reality, the flux
response of the Al growth cell to applied temperature changes is not instantaneous and a blurring
of the steps will occur, an almost linear GRINSCH results. Physically the GRINSCH can be seen
to be slightly parabolic in nature. However, optically the grading is linear (up to 50% Al). It is
noted that the sample rotation for this laser was also halted during the latter part of the cavity
growth, again to induce a strong variation in the FP resonance wavelength.

Figure 4.5 shows schematics of the four structures studied. Note that for samples (C) and
(D) the top DBR layers are slightly thicker than a quarter wavelength to allow for phase
matching of a metallic layer. Full details are given in appendix C.
Table I briefly summarises the structures studied in this thesis. The 3QW cavity refers to a cavity with all of the QWs placed under a single antinode of the standing wave optical field.

<table>
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<th>sample</th>
<th>cavity length</th>
<th>cavity type</th>
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<th>N&lt;sub&gt;bot&lt;/sub&gt;</th>
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<th>designed for</th>
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<tbody>
<tr>
<td>(A) MV1733</td>
<td>2λ</td>
<td>UGS</td>
<td>14</td>
<td>18</td>
<td>top surface</td>
<td>optical studies</td>
</tr>
<tr>
<td>(B) SA6M35</td>
<td>1λ</td>
<td>3QW</td>
<td>14</td>
<td>20</td>
<td>top surface</td>
<td>optical studies</td>
</tr>
<tr>
<td>(C) U2040</td>
<td>2λ</td>
<td>PGS</td>
<td>16</td>
<td>22</td>
<td>substrate</td>
<td>low threshold</td>
</tr>
<tr>
<td>(D) U4041</td>
<td>1λ GRINSCH</td>
<td>3QW</td>
<td>18</td>
<td>17</td>
<td>substrate</td>
<td>high power</td>
</tr>
</tbody>
</table>

Table I Brief summary of the samples studied in this chapter.

Full structural details are given in appendix C.

Figure 4.6 shows a scanning electron micrograph (SEM), in cross section, of the layer structure of sample D. Both the top and the substrate of the sample can be seen. This SEM very clearly shows the multilayer structure of the VCSEL (AlAs layers are the darker lines in the picture). The cavity can be seen as a thicker section of (essentially) GaAs, unfortunately QWs are beyond the resolution of the microscope. A high degree of uniformity between the various
layers is observed and this is further demonstrated by the good reflection characteristics of this sample, shown later. Upon closer examination small, lateral variations in the multilayer structure can be seen. These exhibit themselves as mild ripples within the DBRs. The origin of these ripples is not well understood. They may, in part, be due residual strain in the thick multilayer structure due to the small (non-zero) lattice mismatch between GaAs and AlAs. Ultimately, these ripples will introduce diffraction and scattering losses thereby lowering (slightly) the DBR reflectivity. However, it is important to note that these ripples do not lead to large problems within the device because parallelism of the individual GaAs and AlAs layer interfaces is maintained. It is noted that this effect has been previously observed by Wang et al. [Wang et al. '90] who shows that it may be alleviated, almost completely, by growing the structure on a 4° off-orientation substrate. By reducing the ripples a reduced threshold current has been demonstrated, this reduction may be attributed to the reduced scattering losses within the laser.

Figure 4.6 Scanning electron micrograph of sample C showing DBR layers and cavity.
4.4 Optical injection characterisation

VCSELs do not require cleaving into discrete devices prior to testing. In fact they may be highly characterised at the wafer stage through the use of optical reflectance, transmission and carrier injection techniques. These latter techniques provide much information on the quality of growth of the active layers within a structure. Furthermore they give an essentially complete picture of the emission properties of a wafer. Thus, prior to expensive processing, the emission wavelength and active layer efficiency may be determined. This section of the thesis describes a number of optical injection experiments performed on VCSEL wafers.

4.4.1 Experimental apparatus and method

Because the samples in this work use In$_x$Ga$_{1-x}$As based active regions, any light emitted by the QWs may exit the structure through the GaAs substrate. Attenuation due to the substrate in this case (at 980nm) is well below 1%. The 30% GaAs/air reflection coefficient poses a larger problem however, although anti-reflection coating (for efficient samples) has been proved unnecessary.

The top (transmission mode) diagram in figure 4.7 shows the apparatus used to optically inject light, at normal incidence, into microcavity samples. A collimated laser beam, from a tuneable (Ar ion pumped) Ti-sapphire laser, is focused to a spot of approximately 50-100µm diameter at the sample surface. The resulting photoluminescence from the active layers is then collected, passed through a Bentham M300 monochromator (0.5nm resolution) and detected by a silicon photodetector (with amplifier), lock-in detection techniques are used. Use of a tuneable source allows efficient pumping of the active layers by injecting light below the band-edge of the GaAs layers and (selectively) above that of the In$_x$Ga$_{1-x}$As QWs. In a similar way the reflection maxima in the structures optical response may be avoided, practically this limits the pump wavelengths to between 870 and 900nm. The laser power in this wavelength range is limited, at the sample surface, to approximately 200mW.

The lower (wave-guided mode) diagram in figure 4.7 shows another method of optical pumping. In this case light is injected directly into the active layers of the sample, this geometry is intended to avoid pump beam losses due to reflection from the DBRs. In this case the sample is cleaved to dimensions of approximately 5x5mm. Pump light is then focused directly onto the active layers and the resulting (normal) emission is again collected and passed through a monochromator. The emitted light is collected from an area close to the edge of the wafer, in the
region where the pump beam is incident. It is noted that the very large number of transverse modes in this cleaved wafer will allow in-plane luminescence to dominate.

**Transmission mode**

```
+----------------+       +----------------+
|                |       |                |
| monochromator  |       | top mirror     |
| with Si detector|       | pump beam      |
+----------------+       +----------------+
```

**Wave-guided mode**

```
+----------------+       +----------------+
|                |       |                |
| top mirror     |       | pump beam      |
| substrate      |       |                |
+----------------+       +----------------+
```

**Figure 4.7 Optical pumping apparatus.**

In chapter 2 it was shown that the reflectivity of DBRs is reduced slightly for light incident at some oblique angle. Furthermore the reflection spectrum shifts to shorter wavelengths and the reflectivity for two orthogonal (TE and TM) polarisations becomes non-degenerate. We may use these findings to advantage in the optical pumping of microcavity samples. By injecting light at some angle to the normal (at the sample surface) more of the incident light may be coupled to the active layers of the sample.

**Figure 4.8 Apparatus for optical pumping of samples at 45° incidence.**

Figure 4.8 shows the arrangement used for the oblique incidence optical pumping of microcavities. The sample in this case is clamped onto a rotational stage and placed at an angle of 45 degrees to the incident beam. The resulting (normal) emission is collected and passed to the monochromator and detected in the usual way. An important advantage to be gained from this pumping geometry is the selective removal of the pump beam from the measurement (see...
figure), this avoids detector saturation problems. An increased injection of light coupled to the removal of any pump beam allows this arrangement to measure extremely low light levels.

4.4.2 Luminescence from optically injected VCSELs

In order to study the sub-threshold photoluminescence (PL) from microcavity structures we must first look at the luminescence spectrum of a free standing QW. Previously, in chapter 2, we showed the theoretical spontaneous emission spectrum of an 80Å In$_{0.2}$Ga$_{0.8}$As QW, with GaAs barriers. This calculation assumed essentially un-relaxed (i.e. coherently strained) QWs and a broadening lifetime (at room temperature) of $1\times10^{-13}$s. Figure 4.9 shows the measured room temperature PL from a sample containing (nominally) In$_{0.2}$Ga$_{0.8}$As QWs. The spectra are taken using the transmission mode apparatus. As expected the predominant contribution to the spectra is from the e$_1$-h$_{h1}$ QW transition, some of the features to the short wavelength side of the main peak may be due to contributions from higher order transitions. The 100mW pumped spectrum is seen to have a linewidth slightly exceeding 40nm. This broad linewidth is attributed to thermal broadening, well-width fluctuations and strain relaxation. Both of these spectra exceed the design wavelength (980nm) by approximately 10-20nm. This may, in part, be explained by thermally induced changes to the constituent material bandgaps, due to sample heating (this would explain the shift of the PL peak with increasing pump power). Of course some of the shift may be due to small errors in either (or both) the QW well-width or indium composition.

![Figure 4.9 Room temperature photoluminescence spectra (with pump power) for (nominally) 80Å In$_{0.2}$Ga$_{0.8}$As QWs, pump powers are indicated.](image)

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The PL spectrum from QWs placed within a microcavity, as explained in chapter 2, is strongly influenced by the optical response of the microcavity structure (as exemplified by the reflection and transmission spectra). Importantly light will only exit the structure at wavelengths coincident with either Fabry-Perot (FP) modes or regions of reduced reflectivity (for example at the stop-band edges). More generally it has been argued that PL at wavelengths other than the FP mode, yet within the DBR stop-band, is highly suppressed. Enhancements in the corresponding emission at the FP mode, and also at the stop-band edge, have also been observed.

We may begin to study the emission of QWs in a microcavity by looking at the PL from sample A of table I. This sample contains a 2λ cavity with 20 In$_{0.2}$Ga$_{0.8}$As QWs, termed a uniform gain section (UGS). The top and bottom DBRs contain 14 and 18 periods respectively.

![Graph showing theoretical and measured reflection spectra for sample A.](image)

**Figure 4.10** Reflectance spectrum of sample A (see appendix C (i)).

Figure 4.10 shows the theoretical and measured reflection spectra for sample A. The FP resonance is seen to be in close agreement with the predicted value. A poor agreement with the shape of the high reflectivity stop-band is attributed to a slight mismatch between the top and bottom DBRs, from their nominal λ/4 values. The depth of the FP resonance is artificially low due to the 1nm step size used for both the calculation and measurement. It is noted that the FP resonance for this sample falls close to the DBR stop-band edge. This will affect the emission characteristics of the structure quite dramatically as there will be only a weak suppression of spontaneous emission around the FP mode (in stark contrast with figure 2.14 of chapter 2).

The transmission mode broadband PL from sample A, at two different injection levels, is shown in figure 4.11. A minima, at 900nm, in the reflection spectrum of figure 4.10 is used to inject light efficiently into the structure. This figure clearly shows light exiting the structure at those wavelengths corresponding to low reflectivity (high transmission) in figure 4.10. High
suppression of emission is seen at wavelengths above the FP mode. The effect of GaAs bandedge absorption is evidenced by the equally strong reduction of PL at wavelengths below 890nm. The relatively large PL intensity at wavelengths between 900 and 940nm is attributed to the spontaneous emission spectrum of the QWs being centred at approximately 920-940nm. This has been inferred from the relative amplitudes of the PL at the FP mode and at the transmission maxima between 900 and 940nm. Any residual effects from the pump beam are believed to be minimal due to the narrow pump-laser linewidth and absorption in the QWs. Shifts in the QW spontaneous emission, from the design wavelength of 980nm, are attributed to a lower indium concentration within the QWs than the requested 20%. Interestingly, if the top DBR were removed from this structure then, in transmission, no PL would be observed from the QWs (due to back-reflection by the bottom DBR). The FP mode (due to the two DBRs) can thus be viewed as supplying an optical mode for emission through the structure.

\[ \text{Figure 4.11} \] Transmission mode photoluminescence from sample A. 

*Pump power is indicated, note suppression due to DBR stop-band.*

Closer examination of the emission spectrum at the FP mode, given in figure 4.12(a), reveals structure in the spectrum. The peak of this spectrum is attributed to spontaneous emission that is filtered by the FP resonance. The e1-h1 transition is believed to be centred at approximately 930nm, however, only emission at 980nm is being filtered out. Again the FP mode can be seen to impose limits (in the form of an envelope) upon the emission spectrum. Figure 4.12(b) tracks the peak of the emission at the FP mode as a function of pump power. It can be seen to increase quadratically and this may be attributed to the onset of gain (and oscillation) at these wavelengths. All of the other peaks in the spectrum (those between 900-940nm) increase only linearly with pump power. Ultimately the structure appears to enter the superluminescent (sub-threshold gain) regime. Unfortunately this structure is prevented from
lasing due to the large separation between the peak of the gain spectrum and the FP mode. It is noted that heating effects are also causing the FP mode, in figure 4.12(a), to shift to slightly longer wavelengths. Interestingly a second peak (to the left of the first) is also observed in the emission spectrum of figure 4.12(a), its origin however is not understood.

![Figure 4.12](image)

**Figure 4.12** Transmission mode photoluminescence from sample A. (a) shows PL spectra around FP, (b) shows peak luminescence.

These measurements (figures 4.11 and 4.12) show that the emission spectrum of a device is strongly dependent upon the linewidth (and position) of the FP mode. Furthermore a poor spectral overlap of the spontaneous emission and DBR stop-band results in structures emitting light with strong side-bands. These side-bands can be utilised, in part, to estimate the position (in wavelength) of the spontaneous emission peak and hence deduce the QW composition.

Using figure 4.12(a) and equation 2.4.2 we may calculate the cavity Q for sample A. Unfortunately the linewidth of the spectrometer limits our determination of the FP resonance linewidth ($\Delta \lambda$) to within $\sim 1$nm, the value returned is approximately 4nm. This yields a low value for Q of approximately 250. By rewriting 2.4.2 the average DBR reflectivity may be found. This gives an underestimated, though relatively realistic, value of 95%, verifying the high quality of the DBRs.

In an attempt to optically inject more carriers into the active layers of sample A, the sample was optically pumped using the waveguide geometry of figure 4.8. The emission spectra obtained are given in figure 4.13. These spectra reveal a highly complex, but reproducible, structure. A large number of peaks, each of a similar amplitude, are observed. A possible explanation for these spectra is as follows. The large lateral size of the wafer used for this measurement ($\sim 5 \times 5$mm) leads to a structure with a large number of lateral modes, a theoretically deduced mode spacing of $0.03 \AA$ is not implausible. The incident light excites a large number of
these modes, within the spontaneous emission bandwidth of the QWs, such that the pump power is dissipated. In the normal (measurement) direction the light levels emitted are low. Spontaneous emission at wavelengths both at, and around, the longitudinal FP mode exits the structure due to the finite transmission within the DBR stopbands. This is not normally observed because of the relative magnitudes of the light emitted at the FP mode and that emitted within the stopbands (see figure 2.14, chapter 2). It is observed in this case for two reasons. Firstly the QW spontaneous emission peak is at approximately 940nm, thus the (965-1000nm) wavelengths of interest are in the tail of the emission spectrum (the gain at these wavelengths is only marginal). Secondly, dissipation of the pump power due to the large number of transverse modes. Thus we are observing light exiting a microcavity due to the finite transmission (<1%) of the DBRs. The light levels in this case are extremely low. The rough structure is attributed to imperfections (both longitudinal and transverse (see figure 4.6) [as observed by Ouder et al. '92]) in the sample. These lead to minute fluctuations in the transmission spectra of the DBRs. Interestingly, if the emission peak at 970nm is tracked as a function of pump power it is observed to increase non-linearly, see figure 4.13. Again the on-set of gain (and oscillation) for this mode is evidenced, other modes (believed to be transverse) are also seen to be excited in this way. As might be expected, lasing is not observed in this pumping geometry due to the dissipation of pump power to the multiple transverse modes.

![Figure 4.13](image)

Figure 4.13 Photoluminescence spectra from sample A (sample ~5x5mm).

Pumped in waveguide mode (pump power indicated).

Finally, we may utilise the oblique incidence optical pumping apparatus shown in figure 4.8 to study microcavities. For this measurement we will use sample B. This sample has a cavity of length \(1\lambda\), containing 3QWs placed at the maxima of the standing wave optical field in the cavity (see appendix C(ii)). The top and bottom DBRs contain 14 and 20 DBR periods respectively. Figure 4.14 shows the reflection spectrum, at wafer centre, for this sample. The FP
of the measured spectrum is seen to be in excellent agreement with the theoretical spectrum. The other features of the measured spectrum are shifted to shorter wavelengths, relative to the theoretical spectrum, by approximately 20-25nm. This corresponds to a 2.7% thickness reduction in the DBRs. Excellent agreement is achieved if this thickness variation is accounted for. This shift of the DBRs, with no accompanying shift in the cavity, may be attributed to the higher growth rates employed during the DBR growth.

![Figure 4.14](image1)

**Figure 4.14 Measured and theoretical reflectivity spectra for sample B.**

With the pump beam at 45 degrees incidence all of the reflection features of the sample shift to shorter wavelengths. Unfortunately this forces the minima in reflectivity, on the left of the DBR stopband, to shift to wavelengths below the (doped) GaAs bandedge. By varying the pump beam wavelength (at a fixed power) and monitoring the output power from the sample the most efficient pump wavelength may be found.

Figure 4.15(a) shows the emission spectrum for sample B. It may be compared with that of sample A (shown in figure 4.11). In this case a high suppression of the spontaneous emission, at wavelengths on either side of the main FP mode, is observed. This suggests a better alignment of the spontaneous emission spectrum with the FP resonance. Figure 4.15(b) shows the peak of the spontaneous emission plotted against pump power. In this case a non-linear response is observed. The sample is behaving as an LED (possibly superluminescent) with a thermal turnover at high pump power due to increased de-tuning of the spontaneous emission spectrum peak and the FP resonance. Carrier escape is also believed to be important in this high injection case. Upon closer inspection, the spectrum of figure 4.15(a) can be seen to turn up at 980nm. This suggests that the peak of the spontaneous emission from this sample occurs at a longer wavelength than the main FP resonance.
In order to test this assumption very simple in-plane laser structures were fabricated from the material. This involved the deposition of a Cr/Au stripe, approximately 50μm wide, on the sample surface and a Cr/Au substrate contact. The sample was then cleaved into 300μm long sections. The resulting structure (shown as the inset of figure 4.16) was electrically injected using probes and a pulsed square-wave source. The light output was studied using a 0.5nm resolution fibre coupled optical multichannel analyser (OMA).

Figure 4.16 clearly shows that the peak of the spontaneous emission spectrum for this sample occurs at wavelengths above 1000nm. This is attributed to a higher than desired indium concentration in the QWs. However an appreciable level of emission is apparent at the
wavelengths of interest in figure 4.15(a). Thus again we see that, although the peak of the emission does not coincide with the longitudinal FP mode, the structure filters (to a first approximation) the light. It is important to note that, due to the more central position of the FP mode within the DBR stopband of sample B, no sidemodes are observed close to the main mode.

Importantly then, by using optical injection techniques we have shown that both the QW composition and the position of the FP mode within the DBR stopband must be controlled to a high degree if narrow linewidth (single mode) LEDs and VCSELs are to be produced. Specifically, an increased overlap of the spontaneous emission with the DBR stop-bands has been shown to yield improvements in the output spectra of a microresonator (i.e. no side-bands). Furthermore this improved overlap produces increases in the power output of the main mode. In fact (large area) narrow linewidth (electrically injected) LEDs fabricated, by us, from sample B have demonstrated peak output powers of 0.3mW (CW) with linewidths less than 3nm.

4.5 Electrically injected VCSELs

Having described the optically injected emission characteristics of microcavity structures we now go on to describe the electrical injection characteristics. In this section we will look in detail at the sub- and above threshold spectral and power characteristics of VCSELs, to be compared with those described above in section 4.4. We will then briefly discuss the far-field divergence patterns of the devices. Finally the electrical characteristics of the devices will be discussed and we will show how the current-voltage characteristics may give information on the threshold current of the device.

4.5.1 Fabrication and characterisation of electrically injected VCSELs

Before discussing the electrical injection characterisation results we briefly describe the device fabrication and characterisation procedure. All of the devices for this work have been processed by M. Pate and G. Hill at Sheffield University. The devices are index guided structures resembling cylindrical posts. The (highly simplified) sample processing procedure is as follows. Initially the VCSEL wafer is cleaved into square samples measuring approximately 1cm×1cm. Photoresist is then spun onto the substrate side and, using a simple shadow mask, exposed. This results in a sample with a narrow strip of the substrate exposed (down one side of the sample). A back contact comprising In/Ge/Au, in 20nm/20nm/200nm layers respectively, is
then thermally evaporated onto the substrate and (after removing the resist and undesirable metals) alloyed at 420°C. This alloying ensures a good ohmic contact. Next standard lift-off techniques are used to define a range of circular metal dots on the sample surface. These form the top contacts and also act to enhance the top DBR reflectivity. The dots range in size from 5μm to 200μm and comprise Au/Zn/Au in a 5nm/10nm/500nm ratio. Again these top contacts are alloyed (in this case at 360°C) to become ohmic. The relatively thick (500nm) top Au layer is also used as a self-aligned mask for the next step, that of reactive ion etching (RIE). SiCl₄ is used as the etchant as it has previously been shown to produce good quality (vertical) sidewalls. The etch rates for the samples were approximately 100Å per minute, relatively independent of sample structure. The etch depth for the VCSEL samples was chosen to extend slightly beyond the intrinsic layers, this allows a good degree of carrier and optical confinement within the cavity. Subsequent scanning electron microscopy revealed that the etch depth was approximately four periods into the lower DBR. The sidewalls were relatively vertical with a slight degree of under-cutting, a small degree of roughening was also observed. It is noted that the top Au contacting layer was rough after RIE but did not peel or lift during the etching process, this suggests good adhesion.

![Figure 4.17 Schematic of the VCSEL sample mounting](image)

Finally the samples, which are all bottom emission devices, are bonded onto glass microscope-slide cover-slips using gold epoxy. Each cover slip has a strip of gold evaporated onto it. Figure 4.17 shows the sample mounting geometry and also shows the probes used to electrically inject the sample. Any light emission, in this case, undergoes a degree of scattering and reflection within the cover slips, this is not taken into account in the following measurements and hence the power characteristics are slightly underestimated. A practical point to note is that the probe tips were etched, prior to the measurements, to a tip size of approximately 10μm. Unfortunately this size could not be reduced further and so the minimum device dimension studied is 20μm (diameter).

Each device is electrically pumped using 1μs pulses separated by 100μs. This pulse length is the minimum possible without inducing ringing, due primarily to the non impedance-matched
probes. The current within the device is inferred from the voltage developed across a 10 Ohm resistor placed in series with the laser. The corresponding voltage is measured across the laser and resistor combination. It is noted that oscilloscopes are used for both these measurements so the results are gated and not averaged. Any light emitted from the device is either passed to a calibrated silicon photodetector (power meter) or coupled to a fibre bundle and into a 0.5nm resolution monochromator. This monochromator contains a 1024 element silicon photodetector array interfaced to an analyser unit, collectively the system is referred to as an optical multichannel analyser (OMA). It returns real time (0.3ms per scan) emission spectra over a wavelength range of 650-1010nm.

4.5.2 Spectral characterisation of electrically injected VCSELs

The spectral characteristics of electrically injected VCSELs are expected to be similar to the optically injected (sub-threshold) spectra arrived at in section 4.4.2. In order to study this we look at the emission spectra from sample C. This sample has a $2\lambda$ long optical cavity, utilising the RPG scheme, and has top and bottom DBRs with 16 and 22 periods respectively (see appendix C(iii) for full details). The reflection spectrum for this sample is shown in figure 4.18, which was taken prior to the deposition of the gold contacting layer.

![Reflection spectra for sample C, position on wafer indicated. Variation in FP position dictates the range of obtainable wavelengths.](image)

The solid spectrum in this figure shows the reflection spectrum from the centre of the wafer. It shows a FP resonance placed centrally (~985nm) within a broad stopband. The dotted line in this figure shows a reflection spectrum taken from near to the wafer edge. All of the
spectral features in this case are shifted to shorter wavelengths (see section 2.4.4). Importantly
the wavelength separation between the two FPs gives the range of emission wavelengths that
may be obtained from this wafer. Of course VCSELs processed from different areas of this
wafer will have different emission characteristics, in both spectral and power terms, due to the
detuning of the peak gain and the FP resonance. This will be discussed in detail later.

If we theoretically study the expected emission spectrum from this sample, using the model
developed in chapter 2, we see a spectrum similar to that shown in figure 2.14 of chapter 2. If
however the calculation is performed with a flat spontaneous emission spectrum, i.e. a spectrum
with a finite (fixed) value at all wavelengths, we may (simplistically) study the effect of a
detuned spontaneous emission spectrum on the device output. The term ‘detuned’ in this case
refers to an undesirable separation between the FP resonance of the structure and the peak of the
spontaneous emission spectrum from the QWs. This may occur due to growth errors.

![Figure 4.19 Theoretical emission spectrum for sample C, calculated.
assuming infinitely broad QW spontaneous emission profile.]

Figure 4.19 shows the theoretical spectrum expected from sample C when the spontaneous
emission peak is shifted slightly to shorter wavelengths. The spectrum on the left shows a
desirable single longitudinal mode emission with high suppression of the spontaneous emission
at wavelengths within the DBR stopband. However, unlike the spectrum of figure 2.14, this
spectrum shows a re-emergence of the spontaneous emission at the stopband edges. This is
essentially the effect observed in the optical pumping experiments of the previous section. The
result is the appearance of side-bands (see right hand figure) in the emission spectrum of the
laser due to spontaneous emission escaping at wavelengths of low reflectivity.

Both of these cases, i.e. without and with side-bands, are indeed experimentally observed.
Figure 4.20 shows the measured emission spectrum (pulsed) for a 50µm device fabricated from
VCSEL sample C. A range of injection levels are shown, both below and above threshold
(40mA for this particular device). The linewidths of the spectra are limited by the spectrometer. Each individual spectrum shows a single longitudinal mode emission with an excellent suppression of the spontaneous emission around the main mode. Upon closer examination (using a 0.2nm resolution spectrometer) a number of higher order transverse modes can be seen to contribute to the spectrum above. This exhibits itself as fine structure within the main mode. This spectrum suggests an excellent overlap of the spontaneous emission spectrum with the DBR stop-bands. It must be noted that the sample is taken from a section of the wafer with the FP at approximately 950nm. At 980nm the sample obviously emits with sidebands, the peak of the spontaneous emission occurring at approximately 950nm (due to a small error in indium concentration). In this way the variation of FP resonance with position across the wafer may be used to optimise the emission spectrum and, more generally, the device threshold characteristics.

Figure 4.20 Emission spectra for a 50μm VCSEL, taken from sample C. Spectra show behaviour of device both above and below threshold.

By looking at the emission spectrum of a sample with the same structure as sample C, grown just prior to sample C, but with a greater detuning between the spontaneous emission and FP resonance we may observe the effect of sidebands on a VCSEL. This effect is shown in figure 4.21 which clearly displays a second set of emission peaks (almost 10nm wide) at approximately 900nm. These peaks are seen to coincide well with minima in the corresponding reflection spectra of the sample. The peak of the spontaneous emission in this case is believed to
occur at approximately 930nm. These spectra may be directly compared with those of figure 4.20, in both cases the main mode is centred near 950nm. Closer examination of the spectra in both figure 4.20 and 4.21 reveals a shift in the emission wavelengths with increasing current injection. This is attributed to thermal (heating) effects resulting from the inadequate heatsinking, unfortunately sample heating is evident even under the pulsed conditions used during the measurement.

![Figure 4.21](image)

**Figure 4.21** Emission spectra for a 50μm VCSEL both above and below threshold.

*From a sample with the same structure as sample C.*

Thus the effects observed through optical pumping are rigorously reproduced through electrical pumping. The conclusions drawn earlier, namely that the DBR stopband should completely overlap the spontaneous emission (and obviously gain) spectrum, are therefore reaffirmed. Although of a relatively low amplitude, with respect to the main mode, the sidebands may cause problems in low threshold low power devices. The (total) integrated spontaneously emitted power, in this case, may approximate the power in the main mode. Cross talk may then occur and this will be important in systems that use unfiltered photodetectors which will not discriminate between the side- and main modes. Furthermore, if such (spectrally impure) lasers are used in systems containing diffractive elements, scattering of the side mode power may also lead to cross talk between different areas of the system. Finally the high speed characteristics of
a discrete device may be affected if the spontaneously emitted light has a slower response to the modulated injection current than the stimulated light.

### 4.5.3 Power characteristics of VCSELs

Having studied the spectral properties of VCSELs we now go on to look at the output power characteristics. These are, in general, the most important properties of a device and strongly dictate the applications for which the laser may be viable. We begin by looking at the power output versus current injection (L-I) characteristics of VCSELs of various dimensions fabricated from sample C. The reader will recollect that this sample was designed predominantly for a low threshold current.

Measurements are taken using 1 µs pulses, with a duty cycle of 1:100. Thermal turnover at high injection is still evident. Loss of light due to the reflection from the glass slide (mount) and detector surface is not accounted for.

**Figure 4.22** Pulsed light output vs. current input curves for sample C.

The output power curves for 20, 50 and 100 µm VCSELs processed from wafer C are shown in figure 4.22. It is noted that larger devices (200 µm) did not lase due to the dominance of in-plane luminescence. All of the L-I curves in this figure show a distinct threshold characteristic and a relatively linear L-I curve above threshold. It is noted that none of the
emission spectra for these devices exhibit sidemodes, they are similar to those in figure 4.20. Most of the deviation, at high injection, from a linear L-I curve is due to inadequate heatsinking. The samples are mounted onto glass which has a poor thermal conductivity. Unfortunately the pulse lengths, as discussed earlier, are limited to a minimum of 1µs and this results in a degree of sample heating. Increasing the time between pulses (~100µs) lowers the power reaching the Si photodetector, thereby increasing the noise in the measurement, and has little effect on the turn-over characteristics. Predominantly the turnover in the L-I curves is due to a thermally induced shift in the gain spectrum of the QWs. This leads to a detuning of the peak gain and the FP resonance of the laser. Also, the increased temperature leads to an increase in the carrier leakage problems described earlier. Collectively these effects have been studied in detail, both theoretically and experimentally, by Scott and Geels and the reader is referred to the literature [Scott et al. '93a, Geels et al. '93] for further information.

Some of the important parameters to be derived from figure 4.22 are given in table II. The threshold currents of all devices are seen to be below 100mA. The corresponding threshold current densities are seen to be relatively constant and of order 1kA/cm². A slight increase in the threshold current density of the smallest device is attributed to the larger diffraction losses, sidewall scattering (of photons) and recombination (of electrons) that is known to occur within mesas of smaller diameter. The table also shows the threshold current density per QW. This value is used as a figure of merit, however it must be remembered that this quantity is merely an approximation to the injection level within each QW. Finally the output (conversion) efficiency is also shown. It is seen to increase with device area. This is again attributed to larger losses (for both electrons and photons) within the smaller devices.

<table>
<thead>
<tr>
<th>device size</th>
<th>$I_{th}$ (mA)</th>
<th>$J_{th}$ (A/cm²)</th>
<th>$J_{th}/N_{QW}$</th>
<th>$P_{max}$</th>
<th>output efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>20µm</td>
<td>5.6mA</td>
<td>1783</td>
<td>594 A/cm²</td>
<td>0.29mW</td>
<td>0.033mW/mA</td>
</tr>
<tr>
<td>50µm</td>
<td>20mA</td>
<td>1019</td>
<td>340 A/cm²</td>
<td>4.1mW</td>
<td>0.075mW/mA</td>
</tr>
<tr>
<td>100µm</td>
<td>87mA</td>
<td>1108</td>
<td>369 A/cm²</td>
<td>9.1mW</td>
<td>0.084mW/mA</td>
</tr>
</tbody>
</table>

**Table II** Table showing device characteristics for sample C.

$P_{max}$ is the power output attained at turnover.

Because the lasing wavelength in these samples is approximately 950nm the QWs within the cavity, which was designed for resonant gain at 980nm emission, will not coincide exactly with the antinodes of the standing wave optical field. This offset in wavelength is due to the QW peak gain falling at approximately 950nm, a growth error relating to the indium concentration in the QWs is the cause. The position, in wavelength, of the peak gain is determined by measuring
the thresholds of VCSELs processed from various areas of the wafer (thereby emitting at a range of wavelengths), this is discussed in more detail later.

It is noted that each of the VCSELs produced from sample C also work in a continuous wave (CW - un-pulsed) mode, at room temperature. Unfortunately the lack of heatsinking in this case limits the maximum output power to less than $10 \mu W$, even for the largest $100 \mu m$ devices. Generally it is the thermal turnover and, in some cases, catastrophic failure that ultimately limits the CW power output.

The similarity in threshold current density between the various devices from wafer C leads us to expect that the power output of the devices may also scale simply with the area of the device. For the larger devices this certainly appears to be the case. Figure 4.23 shows the output power density (output power / device area) plotted against the injection current density.

![Figure 4.23 Pulsed light output vs. current input curves for sample C. All curves are normalised to their respective device area.](image)

The $50 \mu m$ and $100 \mu m$ device curves clearly show a similar threshold and output characteristic up to injection densities of $0.02 mA/\mu m^2$, beyond which the two curves diverge. The discrepancy with the $20 \mu m$ device is caused by the increased surface scattering and recombination for that device. Divergence of the curves for the two larger devices may be attributed to the higher transverse modes, in-plane luminescence and the different heat dissipation properties of the $100 \mu m$ laser.

Having looked at the power characteristics at a fixed emission wavelength, we may now use the wafer non-uniformity to study devices emitting over a range of wavelengths. It is noted that, due to the slow dependence of gain on QW well width, the gain spectra for all of the samples is essentially fixed. The varying parameter is thus the FP resonance wavelength which may be tuned across the QW gain spectrum by taking devices from different regions of the wafer.
(see figures 4.4 and 4.18). Figure 4.24(a) shows the measured L-I curves for a number of 50μm VCSELs emitting at a range of different wavelengths (taken from sample C). The figure clearly shows an increase in the threshold current of the devices as the wavelength is increased. A corresponding decrease in the devices maximum power output and conversion efficiency is observed. This effect may be completely attributed to a mismatch between the FP mode and the peak of the QW gain spectrum. This gain maxima, at the pulsed operating temperature of the devices, occurs at approximately 940nm. As the FP resonance passes this wavelength a sharp decrease in output power occurs, this is shown in greater detail in figure 4.24(b). In this way the shape of the QW gain spectrum may be determined [Sale et al. ‘92].

![Figure 4.24](image)

**Figure 4.24** Variation of threshold with position on wafer.

The effect is due to a detuning of the FP and gain peak.

The threshold current variation with emission wavelength, figure 4.24(b), shows a local minima between 940-950nm. Unfortunately, due to wafer uniformity, the lowest attainable wavelength for this sample is ~940nm. It is logical to assume that as the FP resonance passes through the gain spectrum maxima, to the short wavelength side, the threshold current will begin to increase, this has previously been observed by Sale and co-workers [Sale et al. ‘92]. This variation in the power characteristics of devices taken from a single wafer imposes limits upon the reproducibility and integration of VCSELs. For example large area arrays [Orenstein et al. ‘91] are often required with similar characteristics between devices, this will require highly uniform growth. Therefore the yield of a given growth technology will be dictated by its uniformity characteristics. On the plus side, the development of arrays emitting a range of wavelengths, for example for wavelength division multiplexing (WDM) applications, becomes a possibility [Hasnain et al. ‘91]. In this case however the wavelength separation between lasers
must again be small to prevent widely differing characteristics between devices. Overall these findings impose increased tolerances on the growth technology which must not only provide precise layer thicknesses and compositions but must also provide highly uniform layers. It is important to note that a number of dedicated industrial machines may already attain these high and exacting standards.

Having looked at the emission and power dependence of the resonant periodic gain sample (C) we may now study the power characteristics of sample D. This sample has a 3QW active region placed within a graded-index separate-confinement heterostructure, see appendix C (iv) for full details. This (GRINSCH) VCSEL is designed to prevent some of the carrier leakage problems evident in the power characteristics of sample C. The slightly reduced confinement factor in this case, due to the bunching of the QWs, should not degrade the performance (see figure 4.2). Furthermore the reduced output coupler reflectivity and the use of short-period superlattice grading within both n- and p-type DBRs should allow the attainment of higher output powers.

![Graph](image)

**Figure 4.25** Measured reflectivity spectrum for sample D (wafer centre).

*Roll-off on the stop-band is due to the detector and gold response.*

The reflection spectrum for sample D, taken at wafer centre, is shown in figure 4.25. It demonstrates a FP resonance centred within the DBR stopband, the slight roll-off in the stopband reflectivity is an artefact of the measurement. This spectrum suggests that the use of a properly designed GRINSCH does not effect (detrimentally) the basic optical properties of the sample. In this case the FP resonance occurs at ~975nm, this is in excellent agreement with the design wavelength of 980nm (less than 1% discrepancy).
The L-I curves for devices of varying diameter are shown in figure 4.26. It is noted that the lasing characteristics of all devices processed from this sample are of the no-sidemode variety (see figure 4.20). This suggests a high degree of overlap of the spontaneous emission (and hence gain) spectrum with the DBR stop-band. In all cases the devices are taken from the centre of the wafer and are found to emit at wavelengths between 975-970nm, very close to the intended wavelength. Again this demonstrates the highly accurate growth.

![Graphs of L-I curves for different device diameters](image)

Measurements are taken using 1µs pulses, with a duty cycle of 1:100. Thermal turnover at high injection is still evident. Loss of light due to the reflection from the glass slide (mount) and detector surface is not accounted for.

**Figure 4.26** Pulsed light output vs. current input curves for sample D.

In a manner similar to figure 4.22, all of the L-I curves of figure 4.26 exhibit sharp threshold characteristics. Surprisingly, and consistently, all of the devices from sample D demonstrate threshold currents slightly less than their counterparts from sample C. This is probably due to a better calibration of the indium content of the QWs. As an aside, the slightly higher indium content in this sample (intentionally ~19%, compared to ~15-16% (grown) in sample C) may reduce the threshold slightly through alteration of the effective carrier masses in the QWs [Sale et al. '92]. Further, it is noted that due to the large thicknesses of the GaAs spacers (barriers) between the InGaAs QWs in the PGS sample (C) the QWs are not expected to undergo appreciable relaxation. However the 3QWs in sample D, with barriers of only 100Å,
also appear coherently strained (theoretically these QWs are very close to the critical thickness). This is evidenced by the low threshold current density exhibited by all of the samples.

The L-I curves for the two smaller device sizes show a very clear turn-over and power saturation. This is due, predominantly, to a detuning of the gain maxima and FP resonance. The reduced carrier leakage is evident in the much higher output powers achieved with these samples. The 20\(\mu\)m device is now emitting greater than 5mW in a pulse. The 100\(\mu\)m device shows very little thermal turn-over and its output power increases relatively linearly until the device suffers a thermally induced catastrophic failure at an output power approaching 60mW (peak). The highest power achieved by such a device, from this wafer, is 80mW. Inadequate heatsinking is the cause of this failure. It is noted that all of these devices operated CW at room temperature although their power outputs were greatly reduced. The peak power for the 100\(\mu\)m device in this case falls below 100\(\mu\)W (an order of magnitude higher than for sample C devices).

Some of the important parameters for the devices from sample D are given in table III. The threshold current density for VCSELs from this sample is reduced relative to sample C, even though the effective reflectivity of the DBRs is lower. In this case the two larger device dimensions exhibit a current density that falls well below 1kA/cm\(^2\). These reduced threshold values, relative to sample C, must be attributed to an increase in both the growth and processing quality of these devices.

The peak power output of these devices is also greatly enhanced, relative to those from sample C. This is due to a higher output coupling efficiency and also to the GRINSCH structure which reduces the level of carrier escape. The output efficiencies for the 20, 50 and 100\(\mu\)m devices are 4.4, 1.9 and 2.1 times better (respectively) than the corresponding efficiencies of the devices from sample C. Again the efficiency is found to increase with mesa size, while the threshold current density is found to decrease. Thus, increased sidewall recombination and optical scattering at smaller device dimensions may again be attributed as the cause.

<table>
<thead>
<tr>
<th>device size</th>
<th>(I_\text{th}) (mA)</th>
<th>(J_\text{th}) (A/cm(^2))</th>
<th>(J_\text{th} / N_{\text{QW}})</th>
<th>(P_{\text{max}})</th>
<th>output efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>20(\mu)m</td>
<td>4.2mA</td>
<td>1337</td>
<td>446 A/cm(^2)</td>
<td>2.4mW</td>
<td>0.143mW/mA</td>
</tr>
<tr>
<td>50(\mu)m</td>
<td>19mA</td>
<td>968</td>
<td>323 A/cm(^2)</td>
<td>17mW</td>
<td>0.139mW/mA</td>
</tr>
<tr>
<td>100(\mu)m</td>
<td>75mA</td>
<td>955</td>
<td>318 A/cm(^2)</td>
<td>54mW</td>
<td>0.178mW/mA</td>
</tr>
</tbody>
</table>

**Table III** Table showing device characteristics for sample D. 

\(P_{\text{max}}\) is the power output attained at turnover.

This data shows that the difference, in terms of threshold, in using a 3QW RPG and bunched-3QW cavity is marginal. The effect is expected to become more important as the
number of QWs is increased. However, by altering the cavity cladding design and using (for the first time at this wavelength) a GRINSCH structure a large enhancement in the devices power output characteristics may be achieved. This enhancement, as demonstrated, may be attained without a degradation of the devices threshold characteristics and results in devices with a more linear L-I curve. The simpler design, and growth, of sample C may lend it to low power, low threshold, (interconnect) applications. Alternatively the more complex sample D may be applicable to higher power (pumping) applications. Generally however both these sets of devices are on a par with some of the best VCSELs developed in the literature.

4.5.4 Output divergence of VCSELs

Having demonstrated VCSELs with a relatively high optical power output, we now go on to briefly examine the way in which that power exits the device. It is believed that, due to their large diameters, the lasers studied are operating in a multi-transverse mode manner, see figure 2.18. This has been verified for the largest devices by looking at the emission spectra of the lasers. These show a single longitudinal mode emission with very closely spaced (<5Å) emission lines contributing to the main mode. The structure is thus either emitting a combination of high order transverse modes or filamentation is occurring. In this latter case different areas of the structure may lase separately. We have previously observed filamentary output from very large area devices (~200µm - top emission) operating in a sub-threshold LED manner.

![Divergence of output from 50 and 100µm diameter devices.](image)

**Figure 4.27** Divergence of output from 50 and 100µm diameter devices. Devices are from sample C, drive current is approximately 1.5×Ith.

All of the devices studied here have diameters much greater than the emission wavelengths (devices of 20, 50 and 100µm diameter have been studied). This would suggest a low output
divergence angle and the device may be assumed to operate outside the diffraction limit. Figure 4.27 shows the far-field profile of two VCSELs taken from sample C. It is noted that the curves are circularly symmetric (note that the figure is not a polar plot). These curves were taken using a large area silicon photodetector with a slit, approximately 1mm wide, acting as its entrance aperture. The detector was moved around the emitter and the readings recorded. The asymmetry in the curves is due to ambient light from the surroundings. These divergence curves show a narrow, 10 degree full-width at half-maximum (FWHM), emission angle. Surprisingly both the 50 and 100μm devices produce, almost exactly, the same divergence. This verifies the assumption that the devices are not diffraction limited, smaller devices are expected to diverge more (at dimensions below 10μm). Simple Gaussian beam propagation arguments suggest that the beam waist (width) within the active layers of these devices are of the same order of magnitude as the device diameter. This further suggests multi-mode behaviour. Unfortunately, due to the size limitations imposed by the processing and measurement system, single mode (small diameter) devices could not be studied here. However the small divergence angles exhibited by these large devices is still very promising, for example for fibre pumping applications. In fact we have coupled many milliwatts of power (peak- from the largest devices) into a multi-mode fibre (linked to an optical spectrum analyser) with a core diameter of ~60μm. It is noted that some of the divergence observed from these devices is due to multiple reflections, and scattering, within the glass slides onto which the devices are mounted.

4.5.5 Electrical characterisation of VCSELs

One of the most important operational parameters of a VCSEL is the voltage required for it to achieve threshold. In order to reduce this operating voltage the reader will recall (see chapter 3) that we have inserted different types of grading structure into the various DBRs of the lasers. In the case of sample C the top p-type DBR contains short-period superlattices at each interface, periodic doping is also applied. The bottom DBR in this case is step graded using 200Å Al_{0.4}Ga_{0.6}As layers.

Figure 4.28 shows the voltage developed across a device as a function of the current passing through it. It is noted that the voltages quoted are those developed across the device plus a 10 Ohms resistor, in this case the voltage across the resistor is approximately one tenth that across the device. The voltage, for both device sizes, is seen to saturate with current. These two device sizes are shown because they have similar threshold characteristics when scaled with area, see figure 4.23.
We may extend the device area scaling effect further by looking at the sub- and above threshold resistances of the VCSELs. For the devices of figure 4.28 we see that the sub-threshold series resistances are approximately 167 Ohms and 43 Ohms for the 50µm and 100µm devices respectively. Above threshold these resistances become 102 Ohms and 31 Ohms respectively, resistance is calculated as the gradient of the I-V curves. Now the resistance (R) of a device of length (l) and resistivity (ρ) is given by equation 4.5.1.

\[ R = \frac{1}{\rho \cdot A} \]  

\[ \text{(4.5.1)} \]

Using this relationship it may be shown (trivially) that the resistance (R_{50µm}) of the 50µm device and that (R_{100µm}) of the 100µm device are related through the ratio of the reciprocal of their areas. That is to say

\[ \frac{R_{50\mu m}}{R_{100\mu m}} = \frac{\text{Area}_{100\mu m}}{\text{Area}_{50\mu m}} = \frac{2500}{625} = 4 \]  

\[ \text{(4.5.2)} \]

This relationship is indeed confirmed by the I-V curves for the devices taken from sample C. In the case of figure 4.28 the sub-threshold ratio is found to be 3.9, while in the above threshold case it is 3.3. The discrepancy between the above and sub-threshold ratios may be attributed to inaccuracies in the measurement, the gradient fitting and the onset of thermal effects. The sub-threshold resistivity is found to be $3.3 \times 10^3 \Omega \cdot \text{cm}^2$, while the corresponding above threshold value is $2.0 \times 10^3 \Omega \cdot \text{cm}^2$. The series resistance of the device is thus found to drop by a factor of 1.5 when the device attains threshold.

The drop in the series resistance above threshold may be explained as follows. Below threshold the series resistance of the laser comprises contributions (predominantly) from the device contacts, the DBR series resistances and a diode contribution due to the active (intrinsic)
layers. The current-voltage characteristics of a diode are given by the Shockley equation (4.5.3) [Sze '85], where $V_d$ is the voltage across the diode, $T$ is the temperature and $I_s$ is the saturation current (generally the exponential term is much greater than 1). The term $\eta$ in this equation is the ideality factor, numerically it approaches unity for an ideal diode.

$$I = I_s \exp \left( \frac{qV_d}{\eta k_B T} \right) - 1$$ \hspace{1cm} \text{.....(4.5.3)}$$

The total voltage ($V$) across the diode is given by equation 4.5.4, where $R$ represents the parasitic resistances due to the DBRs and contacts.

$$V = V_d + IR$$ \hspace{1cm} \text{.....(4.5.4)}$$

When the laser is above threshold the carrier density saturates, this accompanies the gain saturation (at threshold). Any additional current then contributes, in an ideal situation, to the output of the device (this neglects the importance of carrier leakage). Above threshold then, the contribution to the laser resistance reduces basically to the resistance of the contacts and the DBRs (see chapter 3). This becomes clear if we look at the derivative of the I-V curves [Agrawal '86]. From equations 4.5.3 and 4.5.4 we may calculate the derivative $dV/dI$, both above and below threshold. This gives the relations expressed in equation 4.5.5, the equations are multiplied by the current ($I$) for reasons that will become apparent later (see figure 4.29).

$$I \frac{dV}{dI} = \eta \frac{k_B T}{q} + RI \text{ for } I < I_a$$ \hspace{1cm} \text{.....(4.4.5)}$$

The derivative ($\times I$) is seen to drop, at threshold, to the parasitic resistances of the device [see also Grinberg '94]. Again it must be remembered that these equations are for an ideal device. This drop is seen very clearly in the characteristics of a 50$\mu$m device taken from wafer C. The current-voltage, light-current and differential ($dV/dI$) curves for this device are shown in figure 4.29.

The threshold of this device is seen to be approximately 17mA, importantly the threshold voltage in this case is below 4 volts. The highly linear derivative curve exhibits a sharp kink at an injection current corresponding almost precisely with the threshold current of the device. The gradients of this curve below and above threshold are 170 Ohms and 110 Ohms, in broad agreement with the similar device in figure 4.28. The highly linear nature of the derivative, along with the very sharp kink at threshold, suggests that this device is operating highly efficiently.
Deviations from linearity, seen at higher currents, are due to thermal effects and carrier leakage. For reasons that are not understood the two section of the derivative curve (below and above threshold) are not parallel, also the intercepts in both cases are very close (on the scale indicated) to zero. This is not the case for in-plane devices, for which the ideality factor may be calculated from the intercepts. Knowledge of the ideality factor normally gives information as to the dominant carrier mechanisms occurring within the active layers. It is noted that these characteristics have not been previously demonstrated in the literature for VCSELs, to the author’s knowledge.

![Figure 4.29 IdV/dI curve (pulsed), along with the I-V and L-I curves, for sample C.](image)

The I-V curve for a 100µm device, taken from sample D, is shown in figure 4.30 (curve a). This I-V curve has been taken with the device being injected in a CW (un-pulsed) manner. The curve (a) shows a low threshold voltage, again falling below 5 volts. This suggests that the GRINSCH structure has no detrimental effects on the voltage characteristics of the device. We have previously demonstrated that the threshold current characteristics are also unaffected.

Curve (b) shows the same device having undergone thermally induced damage, due to inadequate heatsinking. This device continues to lase but the threshold voltage has been increased, this is attributed to thermal damage of the contacts. The process is thus irreversible.

We have therefore demonstrated that all of the VCSELs developed in this work operate with threshold voltages below 5 volts. Furthermore the resistance parameters of the devices have been shown to scale very well, both above and below threshold, with area. The derivative of the I-V curves for devices from sample C show distinct kinks at threshold and are highly linear on either side of the kink. However, unlike in-plane lasers the two sections of the derivative curve are not parallel and have an essentially zero intercept.
4.6 Concluding remarks

In this chapter we have used the models developed earlier (in chapter 2) to arrive at VCSEL cavity designs that are optimised in terms of both the number and position of the QWs. Calculations have shown that single QW devices will, in general, suffer from power saturation and carrier leakage problems due to the high threshold injection levels. Structures containing 3QWs are predicted (theoretically) to be the optimum when both power and threshold are considered. The optical models (along with the experimental findings on DBRs from chapter 3) have subsequently been applied to arrive at full VCSEL structures. These structures have consequently been fabricated and studied in detail.

The (reproducible) growth of high quality microcavity devices by the technique of MBE has been achieved. The growth has been noted as the single most important issue in VCSEL development. Specifically the calibration of the indium has been shown to be of extreme importance, this dictates how the gain spectrum and FP resonance are aligned.

Optical pumping, in the sub-threshold regime, has been thoroughly studied as a means of characterising the optical emission of a structure. It has shown that sidemodes may occur in the output of a VCSEL due to leakage of spontaneous emission. This problem is avoided when the DBR stopband completely overlaps the spontaneous emission spectrum of the QWs. The optical pumping techniques have proved useful in determination of growth quality and, due to their simplicity, will prove invaluable to industry. As they are pre-processing techniques they may save VCSEL manufacturers much time and expense, the yield of devices may also increase through early rejection of poor material.
We have developed low threshold PGS VCSELs operating at 950nm with threshold current densities of 1kA/cm$^2$ and threshold voltages below 4 volts. The maximum power output in this case is almost 10mW (pulsed - 100μm device). The emission spectra of these devices have been studied in detail and have also demonstrated the sidemode emission observed by the optical pumping experiments (these sidemodes have been predicted theoretically). Improved growth has achieved complete removal of these sidebands. Furthermore, the current-voltage characteristics of these devices have been studied and have shown anomalies when compared with in-plane devices. Both the light-current and current-voltage characteristics of the devices have been shown to scale very well with device area. The smallest devices exhibit higher threshold current densities and this is attributed to increased sidewall recombination and scattering losses.

Beyond simple GaAs cladded cavities we have also developed novel InGaAs based GRINSCH VCSELs operating around 980nm. These have demonstrated very high power outputs, exceeding 50mW, with threshold current densities well below 1kA/cm$^2$ (for 3QWs). The threshold voltages in this case are still below 5 volts, this is attributed to the use of graded mirrors and periodic doping. The increased power output is attributed to the use of an off-set gain scheme and an increased carrier confinement. All devices operate CW with a highly reduced power output. The lack of heatsinking is highlighted as the power limiting problem.
Chapter 5

Integrated VCSELs and modulators
5.1 Introduction

The integration of VCSELs with other optoelectronic devices is of current interest. Practically, integration may allow the production of discrete lasers with enhanced performance characteristics. However, integration may also allow the development of highly functional smart pixels. The former case might combine a VCSEL with a modulator, this may allow (depending upon the type of modulator) for improved high frequency or tunability characteristics. In the latter configuration the basic VCSEL might be combined with detector, switching and perhaps feedback elements to allow the device to respond to external (optical/electrical) input.

Some of the issues involved in the design of integrated VCSELs will be discussed in this chapter. In particular a novel integrated VCSEL and modulator (developed by ourselves) will be studied in detail. The transfer matrix models developed earlier will be used to examine this device’s optical characteristics and small signal solutions to the laser rate equations will be used to study its dynamic properties. We will show that, by modulating the reflectivity of one of the laser DBRs, enhanced modulation performance may be obtained. The results will be compared with discrete injection-current modulated VCSELs. This device will be used as a means of introducing some of the important issues within device integration.

5.2 The need for integration of VCSELs

A need for optoelectronic integrated circuits (OEICs) [Dagenais et al. ‘90], for use in optical logic and interconnect applications, currently forms the basis for the development of integrated VCSELs. Such OEICs may find application in areas ranging from telecommunications to computing. To date, a number of groups have made considerable advances in the integration of VCSELs with a wide range of optoelectronic and electronic devices. Essentially, the aim of this integration is to enhance the VCSELs functionality and, ultimately, allow the laser to become an integral part of a compact (ideally low cost) and highly functional circuit.

Presently, an increasing problem for both electronic and optoelectronic circuits is that of interconnection (information passing) between elements on the same, or different, circuit boards. Information from an element (for example a processor or memory chip) may need to be passed, at a high data rate, from that element to another, or many other elements. In the ideal case a reconfigurable interconnect would be used, this would allow the active routing of information. Figure 5.1 schematically shows an array (plane) of elements, with each element comprising electronic and optoelectronic circuitry, linked via some routing system to another set of
elements. The interconnect in this case could be VCSEL based with the routing plane comprising refractive or diffractive optical elements, for example microlens arrays or holograms [Craft et al. '92, Brenner et al. '88 respectively]. Light beams (from lasers or LEDs) are used in preference to electrical connections in this case because they allow for a very high degree of cross-connectability, with low cross-talk, between elements.

![Schematic of a routing system linking two array elements.](image)

**Figure 5.1** Schematic of a routing system linking two array elements.

The broader issues of (laterally) integrating VCSELs (and VCSEL arrays) with electronic circuitry, for example silicon based CMOS, for data transmission have been addressed by a number of groups [Jewell et al. '90, Banwell et al. '93]. In these cases the integration is with drive circuitry, this circuitry injection current modulates the lasers.

Distinct from the integration of VCSELs with drive circuitry are the issues of integrating VCSELs vertically, such that only a single growth run is required, with other components to enhance either the devices performance or functionality. These are the devices that will be developed further in this work. In this case the laser structure itself must be altered to allow some property or function (optical or electrical) to be enhanced or performed. Evidently however this may compromise the VCSELs primary function, that of providing an efficient optical source.

An example of an integrated VCSEL, falling into the category of devices providing enhanced laser functionality, is the integrated VCSEL with serial integrated modulator (VCSELM) [Gmachi et al. '93]. By introducing a simple (bulk) modulator diode into the cavity of a VCSEL tuning of the lasing wavelength may be achieved. Application of a forward bias to the modulator causes current to flow (within the modulator) and this changes the refractive index of the modulator material. This effect, predominantly comprising the plasma term, decreases the refractive index and therefore shortens the optical length of the laser cavity. The current flow also alters the temperature of the modulator, through joule heating, and this increases both the
refractive index and the laser cavity length. An interplay between these two effects allows for tuning of the device by a few angstroms.

Another important type of integrated laser/modulator, demonstrated previously using in-plane lasers, results from the integration of a laser with a high speed amplitude (and phase) modulator. The resultant device has a greatly enhanced high speed response. To date such an integrated device has not been developed in a vertical cavity geometry. This is because of complexities regarding the devices design and growth. The integration of a VCSEL and modulator, using a completely new design with novel operating principles, forms the basis of the work in this chapter. It is noted here that such a high speed device is considered highly important for both telecommunications and interconnect applications.

Beyond these enhanced lasers are a range of devices commonly referred to as smart pixels. These are highly functional devices that incorporate elements of feedback and switching. An excellent example of a simple smart pixel results from the integration of a VCSEL with a heterojunction phototransistor (HPT). This results in a laser that may be optically controlled by some external optical input [Chan et al. '91]. Chan [Chan et al. '91] and others have shown that such devices may be used to implement optical logic, for example Boolean arithmetic (using two input beams). Significantly, the high packing densities achieved by basic VCSELs are only marginally compromised in such implementations.

Recently there has been a strong research effort applied in all of the above integration areas. Such integrated devices may point the way to ultra-small, ultra-fast computer processors or, perhaps more realistically, sections of processors. Ultimately optical processing, and routing of information (between highly interconnected elements), may become viable using combinations of both enhanced lasers (tuneable devices for example) and smart pixel devices [Cheng et al. '93, Kasahara '93].

5.3 High speed (dynamic) issues within VCSELs

Pertinent to the integration of VCSELs into OEICs is the issue of how fast, and with what characteristics, the laser might respond to some applied modulation. Ideally the device output characteristics, under high applied modulation rates, should remain highly stable.

Injection current modulation of VCSELs results, as with in-plane lasers (IPLs), in a time dependent shift of the emission wavelength. This effect, commonly referred to as chirp, is due to changes in the refractive indices of the laser active layers caused by the rapidly varying carrier
concentrations. These index changes are, for frequencies greater then 1MHz, predominantly caused by band-filling and plasma effects.

The large carrier densities attained within the active layers of lasers (~10^18 cm^-3 around threshold) give rise to band filling effects [Faist et al. '89] which change the active material bandgaps [Chen et al. '93]. This alters (reduces) the real refractive indices of the active layers (~n_{GaAs} ~ 3.52) by as much as 1%, near threshold. In this way n_{active} \Rightarrow n_{active} - ~0.03, when the injection level is changed by ~1x10^18 cm^-3. Of course the gain above threshold is clamped. The current contributing to gain therefore saturates and additional injected current, in the ideal case, contributes to increasing the lasers power output. Any refractive index changes due to carrier injection effects upon the QW band structure are thus greatly reduced above threshold. Importantly, this effect is dependent upon the structure of the active layers, it is marginally greater for QW active layers.

Under these high carrier injection regimes the plasma effect also becomes important [Hunsperger '91]. It is attributed to the interaction of free carriers with the optical field and may alter the refractive index by ~5x10^3. Magnitudes of the refractive index change (Δn_{plasma}) may be calculated, at a wavelength ω, from equation 5.3.1a. Here n_0 is the refractive index of the unpumped active material (no injected carriers), N is the injection level, q is the electron charge, ε_0 is the free space permitivity and m_r represents the reduced electron-hole (m_e-m_h) effective mass (equation 5.3.1b). The plasma effect is relatively independent of the active layer structure.

\[ \Delta n_{\text{plasma}} = -\frac{Nq^2}{2n_0\varepsilon_0m_r} \frac{\lambda^2}{4\pi^2c^2} \]  
\[ m_r = \frac{m_e m_h}{m_e + m_h} \]

Together, during current modulation above threshold, the band-filling and plasma effects result in changes to the active layer refractive indices of order 10^-2. This corresponds to shifting the lasing wavelength by a few angstroms (more below threshold, ~nm).

One advantage of VCSELs over (simple) in-plane lasers is that the carrier injection induced changes in refractive index are not large enough to cause the laser to hop between longitudinal modes. This is because of the extremely short optical cavity, which results in a large longitudinal mode separation (see chapter 2). The inability of VCSELs to hop between modes limits the wavelength shift, due to chirp (or injection tuning for that matter), to that due to changes in the optical length of the cavity. Mode stability is maintained, as would be desirable in most communications applications. Maximum dynamic shifts in wavelength of 0.7Å have been recorded for InGaAs/GaAs based VCSELs (980nm emission) operating at frequencies between
500MHz-1GHz [Mukaihara et al. '94], at injection levels of $I/I_{th} = 1.1$. These values suggest that the mechanisms quoted above are indeed the main contributors to the wavelength shift.

The small dimensions of VCSELs result in a number of other improvements when high speed modulation, primarily of the laser output amplitude, is considered. Firstly, and perhaps most obviously, the device dimensions (which are generally of order $10\times10\times10\mu m$) may be chosen to minimise capacitance. This lowers the resistance/capacitance (RC) time constant of the laser. The capacitance, $C$, for such a device may be approximated (assuming $A \gg d$) by equation 5.3.2. Here $A$ is the device area, $\varepsilon_0$ is the free space permittivity ($8.85\times10^{-12}\text{Fm}^{-1}$), $\varepsilon_r$ and $d$ are the relative permittivity and thickness of the intrinsic (cavity) region respectively. We may approximate the relative permittivity of the cavity, $\varepsilon_r$, as the square of the (real) refractive index of GaAs ($n_{GaAs} \approx 3.6$) which forms the major contribution to the cavity. Assuming a device diameter of $10\mu m$ and an active layer of thickness $1\mu m$ the capacitance is then found to be of order $1\times10^{-14}$ Farads.

\[ C = \frac{\varepsilon_0 \varepsilon_r A}{d} \] ....(5.3.2)

The corresponding series resistance $R$, which is due primarily to the DBRs, may be reduced through the use of graded heterointerfaces, as discussed in chapter 3, or intracavity contacts. Resistances of order 100 Ohms are obtainable for air post devices of diameter $10\mu m$, however the DBRs are still regarded as the major parasitic contribution to the laser CW and high frequency characteristics.

Choosing $R$ to be 100 Ohms then gives an RC value of $1\times10^{-12}$ s. This value falls below the parasitics introduced by the device contacts and drive circuitry which will limit the device modulation to frequencies of order 100 GHz. In practise these modulation rates are further limited by physical processes relating to carrier and photon transport and interaction mechanisms. These effects, which impose the ultimate limit upon the device modulation, are highly dependent upon the laser structure and upon the method chosen to achieve modulation.

In order to gain further insight into the high frequency response of a current modulated VCSEL we may study (theoretically) the small signal response of the device. We will use data derived from the models developed within chapter 2. This analysis should highlight the main mechanisms contributing to the high speed response of the laser, neglecting the RC parasitics discussed above.

A laser's dynamical response is governed by two rate equations, these dictate the interdependence of the carrier and photon densities within the laser cavity. The basic set of rate equations are given below as equations 5.3.3 and 5.3.4 [Lau, chapter 5, in Zory '93].
\[
\frac{dN}{dt} = \frac{J}{ed} - \frac{N}{\tau_s} - v g(N) S \quad \ldots \quad (5.3.3)
\]
\[
\frac{dS}{dt} = \Gamma v g(N) S - \frac{S}{\tau_{ph}} + \beta R_{sp} \quad \ldots \quad (5.3.4)
\]

In these equations \(N\) and \(S\) represent the carrier and photon densities respectively, \(J\) is the current density, \(d\) the active region thickness, \(v\) the group velocity, \(\Gamma\) the confinement factor and \(\tau_{ph}\) and \(\tau_s\) are the cavity photon lifetime and carrier recombination lifetime respectively. The gain, \(g(N)\), in this case represents the peak of the gain spectrum. In a VCSEL we must be careful to utilise QWs with a peak gain that falls at the Fabry-Perot resonance wavelength of the structure, otherwise a mismatch will result and the above equations will require modification. Finally, \(R_{sp}\) is the spontaneous emission rate and \(\beta\) represents the fraction of the spontaneous emission that enters into the lasing mode. In general these two quantities are considered to be independent of the laser structure. However, as mentioned in chapter 2, they are both enhanced slightly in microcavity structures, where the laser dimensions are greatly reduced. Spontaneous emission lifetimes (of which \(R_{sp}\) is the reciprocal) for QW material in a large cavity (e.g. 100x100x100 \(\mu\)m) are on the order of a few picoseconds. The corresponding value for \(\beta\) is approximately \(1 \times 10^4\). Both of these quantities are altered by up to 10% (maximum) when the cavity dimensions are reduced, in one dimension, to 1 \(\mu\)m. Alterations in these two quantities, due to microcavity effects, are considered negligible in the analysis here. The reader is however reminded that the effects upon the dynamics of a laser, when all of the cavity dimensions are greatly reduced, are not inconsiderable. An enhancement in these quantities may ultimately result in devices with extremely low threshold currents and a greatly enhanced dynamic performance. True digital (on-off) switching may become possible through the elimination of relaxation oscillations, this accompanies the low ultra-threshold.

Given the rate equations, the effect upon the photon density of a small change within the carrier density may be calculated. We use small signal analysis with small signal (time dependent) variations applied to the current \(J\), carrier \(N\) and photon \(S\) densities. Equation 5.3.5(a) gives the time varying injection current, equations 5.3.5 (b,c) give the corresponding time varying carrier and photon densities. The terms \(J_0, N_0\) and \(S_0\) are the steady state values for the three densities while \(j, n\) and \(s\) are the small signal (time varying) parts. Current modulation is applied at the frequency \(\nu (=2\pi\omega)\), \(t\) is the time and \(i\) represents the complex root of \(-1\). Note that small signal solutions are used within this work because the large signal dynamics of both in-plane and VC-lasers are not well understood. In particular the lasers response, in terms of output power, is not a linear function of changes in the injection carrier level. Moreover, if large
changes occur to the injection level the laser may mode hop, heat up or respond in some other, highly non-linear, way.

\[ J(t) = J_0 + j e^{i \alpha t} \quad \text{.....(5.3.5a)} \]
\[ N(t) = N_0 + n e^{i \alpha t} \quad \text{.....(5.3.5b)} \]
\[ S(t) = S_0 + s e^{i \alpha t} \quad \text{.....(5.3.5c)} \]

Following Lau [in Zory '93] we define the quantity \( G \) as the product of the gain, \( g \) (which is in units of \( \text{cm}^{-1} \)), and the group velocity \( v \). This quantity is simply a way of expressing the gain in units of inverse time, as required within a dynamic solution.

\[ G(s^{-1}) = v \left( \text{cms}^{-1} \right) g \left( \text{cm}^{-1} \right) \quad \text{.....(5.3.6)} \]

We may now calculate the small signal response of the photon density, \( s(\omega) \), as a function of the frequency of the applied current modulation. The response is given by substituting equations 5.3.5 into the rate equations 5.3.3 and 5.3.4. By taking derivatives and neglecting terms of order \( x^2 \), where \( x \) is the small signal part of the function (density) \( X \) (either \( J, N \) or \( S \)), we obtain equation 5.3.7.

\[ s(\omega) = \Gamma G' S_0 \frac{j}{\epsilon d f(\omega)} \quad \text{.....(5.3.7a)} \]
\[ f(\omega) = \left( i \omega + \frac{\beta R_{sp}}{S_0} + \frac{\epsilon S_0}{\tau_{ph}} \right) \left( i \omega + \frac{1}{\tau_s} + G' S_0 \right) + \frac{G'}{\tau_{ph} (1 + \epsilon S_0)} \quad \text{.....(5.3.7b)} \]

In deriving this response we have assumed, again following Lau [in Zory '93], that the gain (\( G \)) is a linear function of the injected electron density. This is a valid assumption because, in the small signal regime of interest here, the electron density never fluctuates far from the steady state value. It is noted that the validity of this assumption is reduced if the peak of the gain spectrum is not coincident with the FP mode of the laser. Equation 5.3.8 expresses the linear dependence of the gain upon the carrier density. In this equation \( G_0 \) is the steady state (average) gain, \( G' \) is the differential gain (with respect to carrier density, \( N \)), \( n \) is the small signal carrier density and \( \epsilon \) is the gain compression coefficient.

\[ G(N,n) = \frac{G_0(N) + G' n}{1 + \epsilon S} \quad \text{.....(5.3.8)} \]

We have introduced the gain compression (\( \epsilon \)) factor in equation 5.3.8 for generality, however the origin, and value, of this quantity within a VCSEL is not well known. In this work
we will assume that $\epsilon$ is zero. Importantly, the effect of increasing $\epsilon$ is to damp the resonance within the response curve of the laser. Values of $\epsilon$ falling within the range $10^{15}-10^{17} \text{cm}^2$ have been documented [Zory '93]. In general the amount of gain compression is believed to be structure dependent, its physical origins have been attributed to spectral hole burning and carrier transport effects. The times taken for carriers to diffuse too, and thermalise into, the QW active layers of the laser (and the mechanisms therein) have also been forwarded as further mechanisms contributing to an increased gain compression [Nagarajan et al. '92]. These carrier transport and capture effects may impose the ultimate limit upon the response of carrier injection modulated lasers. It is noted, with respect to the carrier transit and capture times, that the use of GRINSCH cavities (see chapter 4) may result, at low temperatures, in lasers with an enhanced modulation response [Nagarajan et al. '92]. The carrier collection efficiency of such structures is known to be very high [Polland et al. '88]. However, at room temperature the presence of phonons aids the thermalisation of carriers, even within an un-graded cavity, and hence any modulation response improvements in using a GRINSCH are reduced.

Equation 5.3.7 shows how the modulation response of a VCSEL, in common with in-plane lasers, is dictated primarily by the differential gain ($G'$), the photon density ($S_0$) in the cavity and the cavity photon lifetime ($\tau_{ph}$). In the analysis here the other quantities within equation 5.3.7, namely the $\beta$ factor and the radiative and non-radiative lifetimes of the carriers, are assumed to be equal to those values found within in-plane devices. The three quantities $G'$, $S_0$ and $\tau_{ph}$ are singled out because they may all be controlled, especially within the latter two cases, to a higher degree (at the design stage) within a VCSEL. We may study their effects individually.

The peak gain and the differential gain for an 80Å In$_{0.2}$Ga$_{0.8}$As QW (as used throughout this work) are shown in figure 5.2 (a and b respectively), plotted against the steady state carrier density ($N$). Figure 5.2a shows the gain saturation behaviour of the QW with increasing carrier injection. The reader should recall that the threshold gain of the VCSELs in this work is at values of approximately $1000 \text{cm}^2$ (per QW), this occurs at injection densities of between $2-3 \times 10^{18} \text{cm}^3$ (per QW). The differential gain, figure 5.2b, over this carrier density range can be seen to range, in an almost linear manner, over the range $1-4 \times 10^{16} \text{cm}^2$. These theoretical values are found to agree with values reported for in-plane lasers. It is noted that the high differential gains achieved within QWs (which are further enhanced through the use of strain, attributed to lighter carrier masses) suggests that QW based lasers may have a high frequency response extending into the 100GHz regime. Unfortunately, although very high relaxation oscillation frequencies have indeed been measured (~70GHz for a VCSEL [Tauber et al. '93]), the predicted high modulation rates have not been attained. Again, this has been attributed to carrier transport limitations and the effect of a non-zero gain compression coefficient.
Figure 5.2 Theoretical gain and differential gain for an 80Å In0.2Ga0.8As QW, at 300k. Calculations use models described in chapter 2 [see Rees '93].

Given the differential gain we may calculate the modulation response of a VCSEL. This is calculated by taking the real part of the small signal response, as given by equation 5.3.7.

\[ |s(\omega)| = \sqrt{s(\omega)s^*(\omega)} \]  

.....(5.3.9)

All of the modulation response graphs shown in this work have been normalised to the response at very low frequencies (typically 1Hz). The log of the modulation response is shown, on this scale zero represents 100 percent modulation (relative to modulation at 1Hz). Equation 5.3.10 shows how the modulation response, \( R \), is obtained (\( \omega_0 \) corresponds to 1Hz modulation).

\[ R = 20 \log_{10} \left( \frac{|s(\omega)|}{|s(\omega_0)|} \right) \]  

.....(5.3.10)

Figure 5.3a shows the modulation response for a VCSEL calculated using various values of differential gain (the laser is operating within the linear section of the L-I curve). Practically these values of differential gain would be obtained by designing the VCSEL to have a specific threshold gain (current). In this calculation the various parameters are chosen to have the following values: \( \tau_i=4\times10^{-9}s \), \( \tau_{ph}=2.5\times10^{-12}s \), \( \beta=1\times10^{-4} \), \( S_0=3.5\times10^{14}cm^3 \), \( J_{th}=1kAcm^{-2} \), \( d=1\mu m \), \( \Gamma=0.02 \), output power \~1mW. These values originate from the models and experiments of chapters 2 and 4 and also from the literature. It is noted that the thermal transients accompanying the injection current modulation of a VCSEL only have a small effect upon the devices dynamic output characteristics. At frequencies above 1MHz thermal effects are considered negligible.
These modulation response curves (figure 5.3a) show a very flat response up to a frequency of 1GHz. The electron-photon resonance occurs at a frequency of 2GHz for the case where the differential gain is $1.5 \times 10^{16} \text{cm}^2$. As the differential gain is increased the resonance frequency is seen to increase and, in the highest case shown, approaches 5GHz. A number of groups have experimentally studied the high speed performance of VCSELs [Choa et al. ’91, Dziura et al. ’91, Shtengel et al. ’93] and have, to date, found that the resonance frequency falls between 5GHz (index-guided devices) and 14GHz (gain-guided). In all cases the modulation is limited by device and drive parasitics. Broad agreement with the experimental values is thus obtained, remembering that the models developed in this thesis are fitted to index-guided (air-post) lasers.

The small cavity lengths, high reflectivity DBRs and small active volumes employed within VCSELs are expected to result in further improvements in the high speed response of the laser. This performance enhancement is due to the higher cavity photon densities, especially within devices with high power outputs and good electrical to optical conversion efficiencies. Figure 5.3b shows the modulation response of a VCSEL at a range of cavity photon densities. Again the resonance frequency is seen to increase with the photon density. Theoretically the (electron photon) resonance frequency of a laser is expected to scale as the square root of the photon density. Appropriate control of the DBR reflectivity allows the photon density to be optimised.

From figure 5.3 (a and b collectively) we see that the correct choice of DBRs (to control $S_0$ and $G_0$) and active region (to control $G'$) may allow the design of very fast lasers. Exact points on the gain-current curve (and hence $G'$) may be chosen through control of the DBR reflectivity. This, however, effects the lasing threshold and output efficiency, $S_0$ may also be affected. VCSEL (structural) design for high speed operation is therefore an iterative process.
A final point of importance to the modulation response of a VCSEL is control of the cavity photon lifetime ($\tau_{ph}$). In chapter 2 we showed how altering the DBR reflectivity, and hence changing the cavity quality factor (Q), alters the cavity photon lifetime. Of course limits exist upon the control we have over the DBR reflectivities and, in general, we must not allow their values to fall below 99%. These limits are imposed because the VCSEL should retain a low threshold current and a high cavity photon density. Furthermore the laser should operate within the linear section of the L-I and differential gain curves, see figure 5.2b.

Figure 5.4a shows the effect upon the cavity photon lifetime (calculated using the models developed in chapter 2) of altering the average DBR reflectivity, within the above limits. Two cases are shown. Firstly, a single wavelength long cavity is shown. In this case the cavity Q may (theoretically) be controlled over a range extending from $-5 \times 10^3$ to $-5 \times 10^4$. The corresponding cavity photon lifetime may thus be controlled over a range of $\sim 1$-10ps. The second case shows a laser with a cavity two wavelengths long, the longer cavity increases Q. In this case the cavity photon lifetime is seen to increase, this follows directly from the increased cavity transit time.

**Figure 5.4 Injection current modulation (small signal) response of a basic VCSEL.**

(a) Dependence of $\tau_{ph}$ on DBR reflectivity. (b) Varying cavity photon lifetime.

Figure 5.4b shows the dynamic modulation response for a VCSEL with a range of cavity photon lifetimes, as dictated by the DBR reflectivity and cavity length. The resonance frequency, as might be expected, is seen to increase as the cavity photon lifetime is decreased. In the case where the lifetime is 5ps the resonance frequency is almost 10GHz. To achieve these high modulation rates the VCSEL must be made to have a lower reflectivity output coupling DBR. Unfortunately this contradicts the low threshold and high photon density requirements for enhanced modulation response, performance trade-offs therefore exist. It is important to note that the high speed switching behaviour of VCSELs is dominated, and ultimately limited by the
cavity photon lifetime. Such calculations are thus pertinent to the design of devices for gain- and other switching techniques, for ultra-short pulse generation [Wiesenfeld et al. '93]. We will return to the subject of the cavity photon lifetime, and ultimately its dynamic modulation, later in this chapter. In the case just studied the photon lifetime is dictated at the growth stage of the device. However we will show how advantages in modulation performance may be gained through its dynamic modulation.

This section on high speed VCSELs is intended to introduce the reader to some of the issues involved when designing VCSELs for high speed applications. Theoretical design curves have been developed and these show that a number of important parameters may be controlled (optimised) at the device design (growth) stage. Specifically the choice of DBR reflectivity will dictate the output power, photon lifetime, cavity photon density and, most importantly, threshold of the laser. These will directly effect the lasers dynamic behaviour. Optimising for modulation response may, however, conflict with the issues involved in designing an optimised CW device. For example the high DBR reflectivities required to produce low threshold devices with high cavity photon densities (required for high speed) may cause problems when issues of high power output are considered. This is important in a system where both types of laser operation (CW and modulated) may be required from a single device. In such a case the device may operate as a laser with a performance intermediate to a good CW device and a good high-speed device.

5.4 The integrated VCSEL and modulator

In the previous section we saw how VCSELs have a good high speed performance. This, in conjunction with their low threshold current and voltage requirements, makes them ideal sources within telecommunications and, perhaps more importantly, short-haul free-space communications applications. However, vertical integration will be necessary if performance and functionality enhancements are to realised.

As a familiar, but important example of integration for enhanced performance and functionality, we may study the integration of a laser with a modulator. In the in-plane laser case the modulator may be integrated monolithically with the laser and separated from it, laterally, by an air (or implanted/diffused spacer) gap. Figure 5.5 schematically shows the layout of such a device, a photodetector is included in the case shown. Amplitude (and phase) modulation is achieved by reverse biasing the modulator section and utilising absorption changes therein to effect the lasers output light amplitude (and phase). Importantly, the effects of chirp are reduced in this integrated device as the current injection to the active layers of the laser is fixed. The
functionality of the device is further enhanced through incorporation of a photodetector which may be used to monitor the laser output power. By incorporation of feed-back electronics the laser could then be made a highly stable CW or modulated source. Furthermore, although not shown in the figure, such an integrated laser and modulator can be used as the basis of a tuneable source. In that case the laser and modulator would not be separated by an air gap but would form an extended cavity. Refractive index changes within the modulator section, caused by forward or reverse bias effects, would then alter the optical cavity length of the laser and the emission wavelength would shift. This is similar, in principal, to the VCSELMs mentioned earlier. An important difference is that mode hopping, when excessive tuning is applied, may occur in these in-plane devices. This is avoided in VCSELMs because of the ultra-short cavity.

![Figure 5.5](image-url)

**Figure 5.5 Schematic of in-plane laser integrated with a modulator.**
A photodetector is also included, coupled to the back laser facet.

A fundamental problem associated with these in-plane integrated devices is that the various subsections may not, easily, be separately optimised. This is due to the spectral properties of the (common) QWs which will, in general, be optimised for the laser emission wavelength. The problem may, to some extent, be overcome through the use of post-growth intermixing (laterally) of the QWs (see chapter 3). However, in a vertical cavity based device different QW structures may be grown (vertically) to perform specific tasks, the spectral properties of each QW may thus be independently optimised. Unfortunately trade-offs in performance still exist because the laser operation will be affected, to some extent, by the operation of the other devices. Furthermore, in the vertical geometry each device will be optically coupled to some degree. Because of this, issues regarding the effect of one devices operation upon another become very important. In the in-plane case the laser, modulator and photodetector sub-sections may be treated as discrete (physically distinct) and independent devices. Light output from the laser, when backward reflections are eliminated, simply passes to neighbouring devices. In the vertical case the various sub-sections cannot be treated as independent. Thus, the design of vertically integrated devices becomes highly complex. Fortunately the transfer matrix models developed earlier within this thesis, see chapter 2, may be applied to account for this strong coupling. These models show
that, in the vertical geometry, the simple serial addition of existing elements (for example VCSELs and modulators) often results in devices with poor characteristics. For example, the complex interplay of the fields and phases within each device often contrive to produce a laser with a multimode output or with a greatly increased threshold. The rest of this chapter is thus dedicated to producing a modulator/VCSEL combination (generically termed VCSELMs), similar to the in-plane laser case of figure 5.5, in which the CW laser performance is not compromised and the dynamic characteristics are enhanced.

A final point is noted. Given that VCSELs are inherently fast devices the question arises as to the need for integrated laser/modulators. An aside to this question is that of using external modulation. The former question is answered by looking at the types of systems requiring ultra-fast and highly stable sources. We might envisage processing elements, as shown in figure 5.1, linked by optical interconnects. These processing elements, to date, operate at frequencies falling within the hundreds of MHz regime. Links between elements thus need to be no faster than this. Simple VCSELs (or LEDs) may form the basis for this type of (local) interconnect. Given a set of such processing elements connected, for example, in a local area network (LAN) we may wish to connect separate networks. This is shown schematically in figure 5.6. The interconnects between networks will require very high data transfer rates if each network (node) contains more than a few elements. These very high data rates may be attained through the use of a number of VCSELs operating in the 1GHz regime. Alternatively a single very high speed device (exceeding 10GHz) may be used. This has the advantage that the drive electronics are simplified and the issues of multiplexing are reduced. Such VCSELMs, faster and more stable (due to the integrated photodetector) than simple current injected VCSELs, might thus be used at the distribution stage of a network. Such VCSELMs, although marginally more expensive to produce than VCSELs due to increased growth tolerances, may themselves ultimately be fabricated into arrays. This would allow a further increase in the throughput of information.

![Figure 5.6](image)

*Figure 5.6 Schematic of two networks linked by a high data rate interconnect.*

*Interconnects at the local level utilise slower (possibly free space) sources.*
The second issue, that of using an external modulator, is one that depends critically upon the application for which the device is destined. Restrictions on the power consumption of the system must be considered, in such cases numerous lasers may not be practical and external modulation of a single source may be the only option. In the short haul free space (board-to-board) level interconnect schemes of interest here the VCSEL is a suitable option because of its highly compact nature.

5.4.1 Introduction to the quantum confined Stark effect

The modulators developed in this work rely for their operation upon a voltage dependent absorption effect, occurring within QWs, known as the quantum confined Stark effect [Miller et al. '85]. At zero applied electric field the absorption spectrum of a quantum well (QW), assuming no cavity effects, comprises a number of peaks due to the formation of excitons (electron-hole pairs). An underlying staircase structure is due to the density of states (DOS) function of the QW. The QWs energy levels, dependent upon the well and barrier composition and width, dictate the presence and position (in wavelength) of the peaks within the absorption spectrum. Selection rules, which relax under the application of a field, further modify the absorption spectrum such that only ‘allowed’ transitions are observed.

Importantly the absorption peaks are modified by broadening mechanisms. Essentially, the absorption peaks from a set of ideal QWs are reduced (in magnitude) if the QWs contain defects. These defects may be in the form of QW well-width or composition fluctuations. Furthermore, within strained QWs any degree of relaxation will also reduce the absorption. Finally the presence of phonons (or other interacting particles, for example free carriers) will also reduce the peak absorption.

![Figure 5.7 Schematic band structure of quantum well, shown without and with an applied electric field to demonstrate the QCSE.](image)

It is interesting to note that the linewidth of a given peak, dependent upon the broadening mechanisms present, scales (inversely) with the absorption such that the area, within the
absorption envelope, remains constant [Miller et al. ’86]. Thus, by theoretically calculating the area under a given peak and actually measuring the linewidth of that peak we may determine the magnitude of the absorption, this method is used when measured data is not available.

The absorption peak (transition) of greatest interest to us is that due to the exciton associated with the e1-hh1 QW levels. In high quality QW structures this exciton is generally, well resolved. This feature aids considerably within the design process. Figure 5.7 schematically shows the e1 and hh1 levels within a QW. In the unbiased case the wavefunctions for the electrons and holes are centred within the QW and a strong absorption peak results (corresponding to a large spatial overlap between the electron and hole wavefunctions). However, when an electric field is applied, perpendicular to the plane of the QWs, the potential barriers are altered (skewed) and the electron and hole wavefunctions become spatially polarised. The energy levels within the QWs also move to lower (closer) energies. The result, corresponding to a reduced overlap of the electron and hole wavefunctions, is a reduction in the absorption peak and an attendant shift in its wavelength. Collectively these two effects are called the quantum confined Stark effect (QCSE).

Figure 5.8 Absorption and refractive index change for GaAs QWs.
Absorption curves are derived from photocurrent measurements.

Figure 5.8a shows the absorption curves, with applied bias, for an 85Å GaAs QW, with 60Å Al0.31Ga0.69As barriers. The curves are inferred from photocurrent measurements of a PIN device containing 50 QWs, the intrinsic region width is buffered to be ~1μm. The unbiased spectrum clearly shows a well defined exciton (highest peak) attributed to the e1-hh1 resonance, the second peak is the e1-lh1 exciton (other peaks are higher order excitons). Under the application of a bias the spectrum clearly exhibits the QCSE. The e1-hh1 peak decreases in magnitude and also shifts to lower energies (longer wavelengths). A shift exceeding 20nm is
observed with a corresponding decrease in absorption of approximately 20,000 cm\(^{-1}\) (for the QW). It is important to remember that within a device these absorption values will be reduced as the QW barrier must be taken into account.

Two regions of interest are apparent within figure 5.8a, marked \(\lambda_1\) and \(\lambda_2\) respectively. At the wavelength \(\lambda_1\) the QW absorption can be seen to decrease with application of a field. At this wavelength there is an attendant background (continuum) absorption of \(\sim 10,000\text{cm}^{-1}\). At \(\lambda_2\) the reverse happens and an increasing field increases the absorption, from a low initial value. It is noted that both of these wavelengths may thus be modulated, although the device characteristics will be different in terms of insertion loss, modulation depth and chirp.

Accompanying the changes in the absorption, the imaginary part of the refractive index, of the QWs (figure 5.8a) are changes in the real part of the refractive index. The magnitude of these changes may be calculated by application of the Kramers-Kronig transformation. This relates changes in the absorption spectrum of a structure to changes in the real refractive indices, it is given in equation 5.4.1 [Weiner et al. '87, see also Yariv '89].

\[
\Delta n(\omega) = \frac{c}{\pi} \int_{\omega_{\text{lower}}}^{\omega_{\text{upper}}} \frac{\Delta \alpha(\omega')}{(\omega')^2 - (\omega)^2} \, d\omega' \quad \text{(5.4.1)}
\]

In this equation \(\Delta n\) represents the absolute change in refractive index at angular frequency \(\omega\) (wavelength \(\lambda\)), \(\Delta \alpha\) is the QCSE induced absorption change, \(\omega'\) is the scanning variable and \(\omega_{\text{lower}}\) and \(\omega_{\text{upper}}\) are the limits of the integration. Given the absorption spectrum over all wavelengths it would, in principal, be possible to calculate the absolute value of the real refractive index of the QWs. Unfortunately limits must be imposed, for practical reasons, upon the wavelength range of the absorption spectrum. Thus only changes in the refractive index may be calculated. In practise the absorption changes for a QW, with bias, are negligible as we move, in wavelength, far away from the e1-hh1 exciton. It is therefore reasonable to use these distant wavelengths as the integration limits.

Figure 5.8b shows the changes in refractive index (per QW) accompanying the QCSE induced absorption changes of figure 5.8a. Large index changes, of order 0.1, can be seen to occur at wavelengths close to the unbiased e1-hh1 exciton wavelength. Much smaller changes occur at longer wavelengths. These changes in refractive index will lead to changes in the phase of light interacting with the QWs and this will lead, in both active and passive devices, to a chirping (shift) of the operational wavelength. Importantly the amount of chirp is dependent upon the absorption change occurring within the QW, this is itself dependent upon the QW structure (composition and material system).
5.4.2 Development of modulators for integration

A number of groups have developed vertically addressable modulators operating in both transmission and reflection modes [see Woodward et al. '90 and Dobbelare et al. '88 respectively, for InGaAs/GaAs based examples]. It has also been shown that the use of interference effects, as occur within vertical cavity DBR based structures, improves the operational characteristics of these modulators in terms of modulation depth, insertion loss and operating voltage. These latter devices fall under the general heading of asymmetric Fabry-Perot modulators (AFPMs) [Whitehead et al. '90]. Importantly, these modulator devices depend for their operation upon the absorption changes that occur, with bias, within QWs.

Unfortunately the above modulators are, without major modification, difficult to combine with VCSELs. If placed upon a VCSEL, during growth, these devices may give some degree of modulation but they will increase the device growth time, total structure thickness and impose increased tolerances upon the growth technology. Furthermore, especially in the case of AFPMs, the serial integration with a VCSEL may radically alter the VCSEL performance as strong coupling between the cavities of the two devices may occur.

In this section of the thesis we discuss the development of modulators for direct integration into (not serially onto) the structure of a VCSEL. The combined modulator and VCSEL system (VCSELM) gives an enhanced amplitude modulation brought about through a strong, but controlled, coupling of the laser and modulator. This coupling intrinsically links the laser performance to that of the modulator such that the two devices cannot be treated as serial elements, the modelling of such devices is therefore complex and will be discussed in detail. Importantly, this coupling results in the need for only a few QWs and, if implemented correctly, only marginally increases the complexity of growth.

\[ \text{Figure 5.9 Schematic of two different types of VT-DBR.} \]
\[ n_{QW} \text{ represents the refractive index of the QW layers.} \]
The selective placing of MQWs into a DBR structure results, with suitable doping and contacting, in a voltage tuneable DBR (VT-DBR). Two groups, to the authors knowledge, have previously demonstrated QW based VT-DBRs. In the first (GaAs/AlGaAs) case [Fritz et al. '89] operation is at ~830nm while in the second (InGaAs/InP) case [Blum et al. '91] operation is at the 1550nm telecommunications wavelength. In both cases the devices comprised a quarterwave DBR, as described in chapter 2, with all of the high index \( \lambda/4 \) layers replaced by multiple quantum wells (MQWs) of the same optical thickness, see case (a) in figure 5.9. The intrinsic regions in both of these devices extended throughout the DBR resulting in operating voltages of ~3 Volts and ~17 Volts for the 830nm and 1550nm devices respectively. These devices, designed predominantly for external modulation, possess peak reflectivities of approximately 90\%, with voltage control over reflectivity extending to ~10\%. Unfortunately these VT-DBRs, predominantly due to their low reflectivities, may not be efficiently integrated into VCSELs.

We propose replacing a single high-index \( \lambda/4 \) layer within a DBR with MQWs as is shown in case (b) of figure 5.9 [Khan et al. '94, '95]. This is distinct from the above devices because the position within the DBR of the QWs becomes a design variable. The intrinsic layer thickness, and hence the operating voltage, is also considerably reduced. Furthermore the resultant DBR now contains a (novel) semi-transparent DBR section (of \( N_{\text{RTS}} \) periods, see figure 5.9). Provision of this section gives this VT-DBR some remarkable properties. These include a very high reflectivity and a low modulator induced chirp. To investigate the properties and advantages of this DBR we must study its operational principals in greater detail. We use the transfer matrix approach, developed in chapter 2, for all calculations.

![Refractive index profile of VCSEL with possible positions of QWs](image)

**Figure 5.10** Field profile \( (E^2) \) within a VCSEL showing possible positions of QWs.

The position and number of QWs dictates the function of those wells.
Figure 5.10 shows the optical field (at threshold) within a VCSEL of the type described in chapters 2 and 4 (single 80Å In$_{0.5}$Ga$_{0.8}$As QW active region, 980nm operation). The field can be seen to decay exponentially into the DBRs (the substrate is on the right). If the bottom (substrate side) DBR is replaced by a DBR of the type shown in figure 5.9 (a) we can see that the distributed QWs would sample (periodically) the whole of the decaying optical field within the DBR. It can however be seen that the deeper a QW is placed within the DBR, the lower is the field that it will interact with. If we now replace the bottom DBR with a DBR of the type shown in case (b) of figure 5.9, we see that the QWs may be selectively placed to interact with a chosen portion of the optical field profile. Obviously the interaction length is reduced. This reduction may readily be offset by the use of a 3λ/4 (or 5λ/4 etc.) optically thick collection of QWs. In this case the interaction length is increased without affecting the reflective properties of the DBR. In fact, the interaction length is increased by a factor marginally greater than might be expected from simply looking at figure 5.10. A magnified portion of the optical field within a VCSEL is shown in figure 5.11. Also shown is the field profile that results when a section of the lower DBR is thickened to 3λ/4 optical length. The magnitude of the field within the 3λ/4 section does not decay with depth over that section (neglecting oscillations). This effect, which increases the effective interaction length (confinement factor) of the QWs, is due to a phase slip introduced by the additional λ/2 layer. It is important to note that the optical field profile within the VCSEL cavity remains unaffected, the active region confinement factor therefore remains high. In fact, beyond the VCSEL cavity, this modified DBR behaves (in terms of reflection phase) in exactly the same way as a normal DBR. This simplifies VCSEL design.

**Figure 5.11** Effect of $3\lambda/4$ ($\theta=3\pi/2$) phase slip on field profile ($E^2$) within a VCSEL.

*Note how the field profile within the laser cavity remains unaffected.*
If, as in case (a) of figure 5.10, the $3\lambda/4$ QW section is placed very close to the VCSEL cavity the interaction of the QWs with the optical field of the laser is maximised. If the QW absorption is then changed, through QCSE, the VCSELs output will respond in both its amplitude and emission wavelength. Chirp due to the modulator QWs will be a maximum in this case and the structure behaves more like a tuneable device.

Case (b) of figure 5.10 represents a set of QWs placed deeper into the VCSEL bottom DBR. In this case the semi-transparent DBR section acts to reduce the optical field interaction with the QWs. Any changes in the absorption of the QWs (due to the QCSE) now result in amplitude modulation of the reflectivity of the lower DBR, the chirp however is considerably reduced. This is attributed to the increased filtering effect of the semi-transparent DBR. Therefore, by controlling the reflectivity of the semi-transparent (also termed intermediate) DBR the modulator associated chirp may be reduced. Careful control of the relative wavelengths of the VCSEL Fabry-Perot (FP) and the QW zero biased e1-hh1 exciton allows a large degree of amplitude modulation to be retained. Interestingly, this semi-transparent DBR also allows us to utilise areas of the QW absorption spectrum that have been, previously, inaccessible to VT-DBRs. This important finding is discussed later.

Finally case (c) of figure 5.10 shows QWs placed very deep into the lower DBR (far from the laser cavity). This case is of importance because the semi-transparent DBR has its strongest effect in this regime. Any absorption changes within the QWs now have a negligible effect upon the VCSEL performance in terms of both amplitude and wavelength modulation. However there is still some (small) interaction between the QWs and the optical field. A reverse bias applied to these QWs should therefore allow the measurement of photocurrent which, importantly, will be directly proportional to the output power of the laser. Because VCSEL emission is normal to the substrate, the integration of photodetectors (moreover detectors that do not effect laser performance) is a complex issue. Many schemes have been attempted [Choquette et al. '93], generally involving measuring the in-plane luminescence exiting from the laser cavity sidewalls. Unfortunately these do not measure, directly, the vertical power. The scheme proposed here should avoid such integration and measurement problems by effectively de-coupling the photodetector and laser.

It is important to note that the ideas (of placing QWs into precise portions of the optical field within a VCSEL) presented above are, effectively, independent of material system. Importantly, for material systems within which large absorption changes are impossible, the semi-transparent DBR may be suitably modified to enhance performance.

 Recently Miller [Miller '94] has also (theoretically) proposed placing QWs within DBR structures. By utilising the spatially varying fields (see figure 5.10) a wavelength selective
(tuneable) detector may be produced. This is distinct from the integrated devices of interest here. It is however interesting to see the large range of device configurations possible when QWs are introduced into the DBRs.

In order to study how the position and absorption of $3\lambda/4$ thick QWs effects the reflectivity of the DBR we use the models of chapter 2, the generic structure studied appears in figure 5.9 (case b). At 980nm approximately 14 In$_x$Ga$_{1-x}$As QWs (~100Å GaAs barriers) will yield an optical thickness of $3\lambda/4$. Assuming a peak absorption of 5000cm$^{-1}$ (per QW) for the QWs (10cm$^{-1}$ for all other layers) and by varying the position (by changing $N_{\text{mid}}$) of the QWs in the GaAs/AlAs DBR we obtain the graph of figure 5.12a. In this calculation a 26 period DBR is used, this large number is to overcome introduced losses (a flat QW absorption spectrum is used here). Fixing $N_{\text{mid}} = 4$ and varying the absorption per QW (keeping all other factors the same) then gives figure 5.12b. This simple example maps the configuration space for this VT-DBR.

![Graph](image)

**Figure 5.12** (a) Effect of QW position, within DBR (i.e. changing $N_{\text{mid}}$), on reflectivity.

(b) Effect, on reflectivity, of changing the QW absorption (QWs are in period 5).

Together these figures clearly show that increasing $N_{\text{mid}}$ reduces the effects of QW absorption upon the DBR reflectivity. Now, at 980nm the absorption of an In$_x$Ga$_{1-x}$As QW (with the zero-field exciton centred between 940-960nm) may be modulated from almost 0cm$^{-1}$ up to 5000cm$^{-1}$. Recalling that low threshold VCSELs require reflectivities of order 99% we see that by placing the $3\lambda/4$ QWs into period 5 of the DBR ($N_{\text{mid}}=4$) allows us to produce a variable reflectivity DBR that will not, under any biasing condition, prevent the laser from reaching threshold. The small modulation of reflectivity is however enough to modulate the laser output.

In order to fully model the behaviour of the VT-DBR we must look at the real absorption, and associated refractive index, changes that occur within strained QWs (see figure 5.8). To this end a QW PIN diode structure was grown containing $10 \times 80\text{Å}$ In$_{0.11}$Ga$_{0.89}$As QWs (~300Å
GaAs barriers), with the intrinsic region buffered to 1μm (the indium is below the desired value). Normalised photocurrent spectra, with bias, for this device are shown in figure 5.13a. The zero-bias e1-hh1 absorption peak for this sample is estimated to be 20,000cm⁻¹. This high peak absorption is attributed to the excellent interfacial quality of the MBE grown sample. Specifically, the strain is believed to be coherently accommodated (little relaxation), as evidenced by the narrow linewidth.

![Figure 5.13 Photocurrent and refractive index change data for InGaAs/GaAs QW PIN.](image)

The peak absorption (at 0V) is believed to be of order 20,000cm⁻¹.

A good QCSE is observed within this sample, with a resolved exciton shift of almost 20nm. It is clear from these photocurrent spectra that the higher order QW excitons (primarily the e1-lh1) have been shifted to shorter wavelengths, away from the e1-hh1 exciton. This shift is attributed to the effects of strain (see chapter 1). A distinct advantage arises because of this increased separation, relative to the unstrained QW case of figure 5. If we look at the changes in refractive index, as shown in figure 5.13b (calculated via the Kramers-Kronig relation), we see that their magnitudes are reduced. At 950nm the refractive index changes are less than 0.01, the absorption change at this wavelength is ~2000cm⁻¹.

We may use this data to predict the performance of a VT-DBR of the type shown in figure 5.9b. It is important to remember that the voltages quoted in the following (theoretical) figures are taken directly from the measured data (figure 5.13). In reality the 3λ/4 QW intrinsic sections of the VT-DBR are thinner than the 1μm devices used to obtain the absorption data. In figure 5.13 a bias of 1V corresponds to an applied field of 1V/μm (10⁷ V/cm). The intrinsic regions within the VT-DBRs are approximately 0.3μm thick, all voltages quoted should therefore be multiplied by the factor 0.3. This multiplication has not been performed here. An unknown voltage drop occurs across the DBRs, due to the large number of GaAs/AlAs heterojunctions.
(see chapter 3). Simply multiplying by this factor would therefore underestimate the operating voltages (possibly by a large margin).

If we simply place a $3\lambda/4$ (at ~940nm) section of QWs into the second period of a $\lambda/4$ DBR, i.e. replacing the second GaAs layer ($N_{\text{mid}}=1$), we obtain a voltage tuneable DBR with the bias dependent reflection response given in figure 5.14. This calculation assumes that incidence is from GaAs and the lower section of the DBR contains 21 GaAs/AlAs pairs ($N_{\text{bot}}=21$).

![Figure 5.14 Voltage tuneable DBR with second period replaced by $3\lambda/4$ QWs.](image)

A broad stopband dominates the reflection features of this VT-DBR. This is directly attributed to the overall $\lambda/4$ periodicity within the device. At all wavelengths within the stop-band the DBR reflectivity exceeds 80%. For wavelengths above 940nm (see spectra (b)) the reflectivity approaches 99.5% (without applied bias), this is continuously variable down to approximately 95% by application of a bias. In this case, where the effects of the semi-transparent DBR are negligible ($N_{\text{mid}}=1$), the QWs strongly perturb the reflection features of the DBR. It is feasible to construct a VCSEL (operating at ~940nm) with this DBR forming the lower mirror. The resulting device will undergo a strong amplitude modulation but the lasers emission wavelength will be chirped due to the (small) refractive index variations within the modulator QWs (see next section). If desired, the laser can also be forced below threshold by applying sufficient bias to reduce the DBR reflectivity to ~95%. Of course this digital switching will cause large, undesirable, changes in the current within the laser active region.

If the importance of the semi-transparent DBR is increased, by increasing $N_{\text{mid}}$, dramatic changes occur to the VT-DBRs reflection features. If we again look at figure 5.14 we see that the reflection features of this device are dominated, within the stop-band, by the absorption edge of the QW. This step-like (continuum) absorption brings the DBR reflectivity, at wavelengths below 930nm, down to ~92%. Unfortunately this low reflectivity renders the VT-DBR useless.
for VCSEL production at wavelengths below the el-hh1 exciton wavelength. Looking back to figure 5.13 we see that the magnitude of this background (continuum) absorption is approximately 5000-6000cm$^{-1}$. If we now refer back to figure 5.12 we see that, if the $3\lambda/4$ QWs are placed in period 8, or deeper (i.e. $N_{\text{mid}} \geq 8$), the DBR reflectivity becomes greater than 99% even when the absorption is 5000cm$^{-1}$. Any decrease in the DBR reflectivity due to the QW background absorption is thus completely removed. Figure 5.15 clearly shows this effect by increasing $N_{\text{mid}}$ to 8 GaAs/AlAs pairs. The broad-band reflection spectrum, (a), shows an excellent stop-band with reflectivity exceeding 98% at all wavelengths. Importantly the reflectivity at wavelengths below the exciton wavelength is now of order 99.5% (as expected). Of course the effect of the background absorption can be decreased further by increasing $N_{\text{mid}}$, unfortunately the resulting DBRs modulation properties are degraded. The optimum value of $N_{\text{mid}}$ is, quite simply, given as the value required to completely remove the effects of the background absorption. Uniquely, this makes the operation of the VT-DBR completely dependent upon absorption changes occurring within the QWs and independent of the absolute absorption. This allows high reflectivities (and modulation) to be achieved at wavelengths both above and at the (unbiased) exciton wavelength.

![Figure 5.15 Voltage tuneable DBR with ninth period replaced by $3\lambda/4$ QWs.](image)

A number of important features arise in this VT-DBR that require further discussion. We have noted that the broad-band reflection features of this device are like those of a simple DBR. This mirror may thus form the lower reflector for a number of devices. The lateral integration of VCSELs, modulators or narrow linewidth photodetectors, processed (via re-growth) from a single wafer, may therefore be a possibility.

Of more importance are the narrow-band (high reflectivity) features. In its un-biased state this device is expected to give a very high reflectivity DBR (>99.8%) at wavelengths above the
el-hhl exciton (for example $\lambda_2$ in figure 5.15b). This reflectivity is directly compatible with low threshold VCSELs. VCSELs incorporating this DBR will therefore lase efficiently even if the modulator in not-contacted to, this increases the range of devices that may be produced from a single wafer. That is to say both VCSELMs and VCSELs (both optimised) can be fabricated from the same material.

Another feature of this VT-DBR, originating purely through the use of a large $N_{\text{mid}}$, is the modulation that occurs at the el-hhl exciton (marked $\lambda_1$ in figure 5.15b). At zero applied bias the reflectivity at this wavelength is $\sim 98.8\%$. However when a bias is applied the reflectivity increases up to a value of 99.8%. Thus a VCSEL fabricated with a Fabry-Perot resonance at this wavelength will, if current injected to just below threshold, not lase until a bias is applied to the modulator. Alternatively optical inputs might be used to bleach the exciton, again forcing the device to lase. A switching (or latching) function might thus be envisaged for this type of device. Importantly the semi-transparent DBR has allowed us to access a larger wavelength range of operation and thereby achieve advantages in operation and integration (over the example given in figure 5.14).

A final point to note is that lasers fabricated from this VT-DBR will undergo a larger degree of modulator associated chirp (of the emission wavelength) if they operate at $\lambda_1$ rather than $\lambda_2$. This can be seen directly from the refractive index curves of figure 5.13b. Fortunately the chirping effect in both cases is small because of the ‘phase-filtering’ effect of the semi-transparent DBR. Obviously the reflectivity modulation depth achieved by the VT-DBR of figure 5.15 is smaller than that achieved by the device of figure 5.14. This, at first sight, might appear a problem when the device is integrated into a VCSEL. Fortunately the modulator will form an integral part of the laser. As such a modulation of only 0.5% in the reflectivity is enough, when the coupled system is considered, to modulate the laser by many dB [Khan et al. '94]. This point will be discussed again later.

### 5.4.3 Experimental characterisation of voltage-tuneable DBR

In order to experimentally demonstrate operation of a VT-DBR (of the type shown in figure 5.15) a sample was grown using the technique of MBE (see chapter 4). The sample, as grown, is shown in figure 5.16. This structure is designed for operation at wavelengths around 980nm and comprises a semi-transparent DBR of 5 $\lambda/4$ GaAs/AlAs pairs ($N_{\text{mid}}=5$), a $3\lambda/4$ section of QWs and a bottom DBR of 20 periods. A top GaAs $\lambda/4$ layer is added to terminate the structure on air, this would be removed for integration. The structure is doped to form a PIN diode, the intrinsic
region extends slightly into the (passive) DBRs to allow for dopant diffusion during growth. A reduced value of $N_{\text{md}}$ within this device, relative to that used in figure 5.15, is consistent with the reduced absorption present in QWs of this higher indium composition.

![Figure 5.16 VT-DBR (grown).](image)

It is noted that the indium mole fraction grown (and quoted) is slightly higher than the 20% design value, the thicknesses were reproduced to a very high accuracy. The reader is reminded that the growth of this structure is relatively simple when compared to previous VT-DBR designs (see figure 5.9a). No highly precise cavities need to be produced and the structure is relatively forgiving (in its final operation) to thickness errors during growth.

Figure 5.17 shows the experimental reflection spectra, with bias, for this sample. This figure compares directly with figure 5.15 and shows all of the important features predicted therein. It is noted that these spectra, taken using the apparatus described in section 3.4.2 (chapter 3), are normalised to gold, the absolute reflectivity of which is taken from the literature.

![Figure 5.17 Measured reflection curves for VT-DBR.](image)
As predicted the broad-band reflection spectra demonstrate an excellent stop-band with a very high, flat-top, reflectivity. The narrow-band spectra demonstrate both of the desirable modes of operation (marked \( \lambda_1 \) and \( \lambda_2 \)). At \( \lambda_1 \) (~983nm) the reflectivity of the DBR increases with applied bias, corresponding to the case where the VCSEL will be off when the modulator is unbiased. In this case a large amplitude modulation may be achieved (the use of a pre-bias in this case may further enhance the modulation characteristics). Conversely, at \( \lambda_2 \) (~1000nm) the reflectivity of the DBR decreases with applied bias. The reader is directed, in both cases, to the low operating voltages required by this device, this is attributed to the very thin intrinsic region.

Figure 5.18 shows the modulation achieved by this VT-DBR device at a number of different wavelengths. It clearly shows the two operational modes, as evidenced by the positive and negative gradients of the data. For wavelengths between 970-990nm the reflectivity increases with bias, the reverse occurs for wavelengths between 990-1010nm.

![Figure 5.18](image)

**Figure 5.18** Measured change in reflection with applied bias for the VT-DBR.
Changes (relative to 0V) at a number of different wavelengths are shown.

Finally, as described earlier the photocurrent generated by QWs within the VT-DBR might provide a useful means of monitoring the vertical emission of a VCSEL (to produce highly stable sources for example). Experimental photocurrent spectra, as taken from the above device, are given in figure 5.19. The broad-band spectra clearly demonstrate the filtering effect of the DBR structure, this effect has previously been observed within the photocurrent response of QWs within VCSELs [Bae et al. '94]. The narrow-band spectra show a good, narrow exciton feature and a clear QCSE (the spectra are normalised at approximately 930nm). It is interesting to observe that, in this sample, the use of 14QWs with high indium concentrations (and relatively narrow barriers) has not dramatically increased the exciton linewidth (through relaxation).
It is noted that the high optical output powers generated by VCSELs (see chapter 4) may saturate (or bleach through the generation of free carriers) the excitons with the QWs of the VT-DBR. This would prevent the device operating as a photodetector and, ultimately, as a modulator. Therefore the device is currently limited to low power applications. The possibility of Q-switching the laser by utilising this saturation mechanism is noted. This follows from the fact that the cavity Q (see figure 5.4a) is strongly dependent upon the DBR reflectivity which, for this device, depends upon the QW absorption. The reader is referred to the work of Dods [Dods et al. '94] who (theoretically) uses a detuned second cavity to achieve Q-modulation in a manner very similar to that proposed here. A final point to note is that in the examples given here we replace a high index layer of the DBR with QWs. In a similar manner we may also replace a low index layer, for example with InGaAs/AlAs MQWs. This may hold advantages in the higher absorption per QW and the reduced photocurrent which, although limiting the devices detector performance, will allow a lower power consumption device to be produced. Such devices may operate up to higher VCSEL output powers.

![Figure 5.19 Measured photocurrent curves for VT-DBR.](image)

The effects of the semi-transparent DBR are evident.

To summarise, a voltage controlled DBR with a peak reflectivity greater than 99%, compatible with VCSELs, has been demonstrated. this DBR has a very short intrinsic region and hence low operating voltage. Two distinct operational modes are demonstrated. In the first mode the device reflectivity increases with bias, the reverse occurs in the second. the use of a semi-transparent DBR forces the modulation of the two modes to occur around the same baseline (corresponding to a reflectivity of ~99.5%). Possible enhancements in VCSEL performance and functionality have been alluded to.
5.4.4 Performance characteristics of the integrated VCSEL and modulator

By integrating the VT-DBR, described above, into a VCSEL a VCSELM is produced with some enhancements in performance. In order to model the system, as a whole, we use the transfer matrix based laser model of chapter 2 with the inclusion of voltage dependent absorption spectra for the QWs in the modulator. Obviously this includes the associated changes in refractive indices (see figures 5.8 and 5.13). This will allow us to model the modulators effects upon the laser threshold and also any modulator induced chirp. It is important to note at this point that the refractive index changes have all been calculated in a DC regime, thus the values obtained will differ marginally from the AC (high frequency) values.

We begin by defining a generic VCSELM structure, for modelling purposes, as shown in figure 5.20. Any effects upon the threshold current of introducing a 3λ/4 thick section of QWs into the lower DBR may be readily calculated using the transfer matrix model. By fixing the (total) bottom DBR to contain 25 GaAs/AlAs pairs (N_bot = N_bot + N_mid), the top DBR (N_top) to be 16 periods and the operating wavelength (at room temperature) to be 980nm, the threshold curves of figures 5.21 and 5.22, may be calculated. In both cases he active cavity is fixed at 1 wavelength long and contains 3 × 80Å In_{0.3}Ga_{0.7}As QWs.

In figure 5.21 the position of the 3λ/4 QWs is fixed and the absorption within the QWs is varied (note that the effects of the barriers is accounted for in both the active and absorptive layers). This figure may be compared with figure 5.12a. As expected, any reduction in the DBR reflectivity through an increasing absorption leads to a large increase in the lasing threshold. Note that control over the absorption of the QWs at zero bias is achieved by careful selection of the wavelengths of the laser FP resonance and the absorber exciton.

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**Figure 5.20 Schematic of generic VCSELM (VCSEL + VT-DBR).**
Figure 5.21 Threshold of VCSEL vs. loss (at FP wavelength) in absorber section.

In the second figure, 5.22, the loss (per QW) of the modulator is fixed and the position of the 3λ/4 section is altered (to be compared with figure 5.12b). In this case the laser threshold decreases exponentially with the depth of the modulator QWs. This corresponds directly to the exponential nature of the optical field (and its interaction with the QWs) within the DBRs, as shown in figure 5.10.

Figure 5.22 Threshold of VCSEL vs. position of absorber in lower DBR.

The reader will recall that figure 5.12 maps the configuration space for the VT-DBR. In a similar way figures 5.21 and 5.22 map the configuration space for the threshold of the VCSEL. Appropriate control over the laser cavity length, to fix the FP resonance wavelength ($\lambda_{FP}$), and the QW absorber composition, to control the exciton wavelength ($\lambda_{QW}$), allows
optimisation of the VCSELMs threshold characteristics. Careful selection of the parameter $N_{\text{mid}}$ then allows the modulation characteristics to be optimised.

By using design curves similar to the above we may arrive at a structure optimised for 980nm emission. In order to yield a device with a very low threshold we place the zero-biased modulator exciton at a wavelength of 950, this places the laser FP (980nm) well into the tail of the exciton absorption. If the same indium composition is used for the modulator QWs and the active region, as would be the case for optimised growth (fixed cell temperature), the modulator QWs will be 50Å thick (14 QWs with 90Å GaAs barriers then give $3\lambda/4$ optical thickness). The result is an absorption of order $100-1000\text{cm}^{-1}$ at the FP wavelength. Now, if we use the same parameters as used to derive figure 5.21 and 5.22 ($N_{\text{bot}}+N_{\text{mid}}=25$, $N_{\text{top}}=16$, 1λ cavity with 3QWs), we see that the semi-transparent DBR should contain 4 periods ($N_{\text{mid}}=4$) to give a total threshold current density of order 1-2 kA/cm$^2$.

![Figure 5.23 Scanning electron micrograph of a VCSEL.](image)
Figure 5.23 shows a scanning electron micrograph (SEM) of an as-grown VCSELM, grown according to the above parameters (light layers are predominantly GaAs). This SEM clearly shows the top, middle and bottom DBRs separated by the lasing cavity and 3λ/4 QW modulator. The device structure is doped n-i-p-i-n (DBR-active-DBR-modulator-DBR) to provide for current injection into the active layers while allowing electric fields to be applied across the modulator. Evidently the device is a three contact geometry. It is noted that this is the first attempt to grow an integrated VCSEL and modulator for high speed (photon lifetime) modulation operation.

An important characteristic of VCSELs, and one that should be maintained by VCSELMs, is the single longitudinal mode emission. Figure 5.24 shows the theoretical emission spectra for the above VCSELM. The single mode is indeed preserved, however there is an increase in the emission at the sides of the stop-bands of the DBR (termed side-modes, see chapter 2 for details). In this calculation we have assumed spontaneous emission originating from both the active and modulator QWs, as would be observed if the sample were studied using photoluminescence. The side-modes in this case originate predominantly due to the modulator QWs (c1-hh1 at ~950nm), they are reduced if the modulator QWs are not emitting. A high suppression of emission within the DBR stop-bands is also evident. It is interesting to note how light emitted from the top and bottom facets of this device differs in both its spectral and amplitude characteristics. This is attributed to the effect of the modulator and the asymmetry of the structure (as viewed by the emitting sections).

![Figure 5.24](image)

**Figure 5.24** Theoretical emission spectra for VCSELM (at threshold).

The single mode behaviour of the as-grown device is evidenced by the reflection spectrum of the structure, figure 5.25a. This shows a FP resonance centred within the stop-band of the DBRs. Two other FP resonances are also observed within the stop-band but these are very close
to the DBR stop-band edges. The DBR reflectivity at these wavelengths will be reduced relative to the stop-band centre and so the lasing threshold for these modes will be higher than for the main mode. Single mode emission should therefore prevail, as the theoretical spectra show. These higher order modes are attributed to an increase in the effective cavity length of the laser, this may be traced to a corresponding increase in the penetration depth of the optical field into the DBRs due to the $3\lambda/4$ QW section. Photoluminescence from this sample, shown in figure 5.25b, also demonstrates single-mode emission. A high suppression of emission within the DBR stop-band is also observed, as is the appearance of the predicted side-modes (due to the modulator QWs). A final point to note is the excellent agreement between the measured and predicted reflection spectra. This demonstrates that the structures growth tolerances are not dramatically different to those of a VCSEL. Furthermore, in conjunction with the theoretical emission spectra of figure 5.24, it validates our use of the transfer matrix model to examine highly coupled devices containing both gain and loss sections.

![Figure 5.25](image)

**Figure 5.25** (a) Measured and theoretical reflection spectra for VCSELM. (b) Measured photoluminescence from sample.

Having shown that the modulator, if integrated correctly, does not dramatically effect the threshold and emission spectral characteristics of the VCSELM, relative to a VCSEL, we now go on to study the VCSELMs modulation characteristics.

Table I lists some of the parameters for five different VCSELMs. Samples (a-c) have GaAs based active and modulator sections while samples (d) and (e) are InGaAs based. Sample (a) has all of the high index layers within the bottom DBR replaced by GaAs QWs, this configuration represents the VT-DBRs of earlier works [e.g. Fritz et al. '89] (see figure 5.9a). The laser operating wavelengths are approximately 860nm and 950nm for the GaAs and InGaAs based structures respectively. Because the following calculations use the measured absorption and
refractive index change spectra of figures 5.8 and 5.13 the exciton wavelength is fixed. The laser wavelength (dictated by the cavity length) is therefore used to vary the FP-exciton separation. In all cases the FP is placed in the (long wavelength side) tail of the zero-biased exciton. Interestingly the minimum FP-exciton separation that can be tolerated in sample (a) is 29nm. Closer placement results in a laser with greatly increased threshold.

<table>
<thead>
<tr>
<th>Sample</th>
<th>QW</th>
<th>Period in DBR</th>
<th>QW thickness</th>
<th>(\lambda_{FP}-\lambda_{QW})</th>
<th>(N_{bot}+N_{mid})</th>
<th>(N_{top})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>GaAs</td>
<td>All</td>
<td>(\lambda/4)</td>
<td>29nm</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td>(b)</td>
<td>GaAs</td>
<td>(N_{mid}=1)</td>
<td>3(\lambda/4)</td>
<td>14nm</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td>(c)</td>
<td>GaAs</td>
<td>(N_{mid}=4)</td>
<td>3(\lambda/4)</td>
<td>10nm</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td>(d)</td>
<td>InGaAs</td>
<td>(N_{mid}=1)</td>
<td>3(\lambda/4)</td>
<td>25nm</td>
<td>25</td>
<td>16</td>
</tr>
<tr>
<td>(e)</td>
<td>InGaAs</td>
<td>(N_{mid}=5)</td>
<td>3(\lambda/4)</td>
<td>25nm</td>
<td>25</td>
<td>16</td>
</tr>
</tbody>
</table>

Table I Theoretical samples studied.

Figure 5.26 shows the modulator induced chirp (tunability) upon the emission wavelength (main mode - see figure 5.24) of the VCSELs of table I. All curves are normalised to the case were the modulator is un-biased. In all cases we assume that the laser is operating well above threshold and that the modulator does not cause the current flowing through the active layers to change substantially.

![Figure 5.26 Tunability (chirp) of VCSEL due to modulator.](image)

Device (a) clearly demonstrates the highest level of chirp and this is attributed directly to the large number of QWs. If this mechanism is used to tune the laser the tuning range is found to be +5Å and -3Å, corresponding to a good degree of tuning. It is interesting to note that, in all cases, the lasing wavelength undergoes both positive and negative shifts with bias, this can be
seen from the refractive index change curves of figures 5.8 and 5.13. This type of behaviour, showing positive and negative shifts in wavelength, is not uncommon in tuneable lasers and has been seen previously within tuneable VCSELs by a number of groups, using various tuning mechanisms [Hasnain et al. ‘91, Gmachi et al. ‘93].

It is evident from these curves that the degree of chirp is greatly reduced (to ~1 Å) if a single section of QWs is employed, see cases (b-d). It is noted that the curve for sample (e) falls, on the scale shown, upon the zero shift axis. In this case a wavelength shift of order ≤ 0.01 Å is recorded (at all bias levels). This small wavelength shift is due to the reduced refractive index changes that occur within InGaAs based QWs (at this wavelength).

In reducing the modulator induced chirp (by using InGaAs QWs and increasing $N_{mid}$) we also reduce the amount by which we modulate the laser amplitude. Figure 5.27 shows the theoretical modulation depths achieved by the VCSELMs of table I. In all cases the curves are normalised to the unbiased modulator case. Note how the horizontal axis is marked change in absorption, this follows from the fact that the modulator QWs absorption can be offset by increasing $N_{mid}$. Cases (a) and (b) both show good modulation depths. Case (b) shows a larger increase than case (a) because the FP-exciton wavelength separation has been reduced, this is possible because the of the reduced absorber thickness. Case (c) shows the smallest modulation depth and this is due to the larger value of $N_{mid}$. The modulation depth for sample (d) is the largest because of the increased number of QWs fitting into the $3\lambda/4$ optical thickness and because of the effects of the increased top DBR. Note that the modulation curve for sample (e) falls (almost exactly) upon the curve for sample (c).

![Figure 5.27 Modulation depth of VCSELM.](image)

Finally, we now turn our attention to the issue of how the VCSELM device responds to an applied modulation. In this case the lasers injection current will remain fixed and the bias to the VT-DBR will be modulated. This modulation of the DBR reflectivity, which must occur without
allowing the laser to fall below threshold, is distinct from current modulation, as described in section 5.3. Reflectivity modulation within a laser is equivalent to a modulation of the cavity photon lifetime ($\tau_{ph}$), see figure 5.4a. Such a modulation scheme has previously been proposed by Avrutin [Avrutin et al. '93] who further notes that if two (different) modulation schemes could be implemented in tandem then a very flat response curve, over a large frequency range, could be obtained. Practically this may be implemented within the VCSELM by simultaneously applying current and photon lifetime modulation.

To determine the VCSELMs modulation response characteristics we will follow Avrutin [Avrutin et al. '93] and use a small signal analysis. In this case the quantity $\tau_{ph}$ becomes a variable, see equation 5.4.1, with $\delta \tau_{ph}$ being the small signal part.

\[
\tau_{ph}(t) = \tau_{ph0} + \delta \tau_{ph} e^{i\omega t}
\]

Substituting this term into the rate equations given in section 5.3, again assuming that $J$ and $S$ have small signal parts, gives the small signal modulation response of equation 5.4.2. In this equation $\tau_{st}$ and $\tau_{sp}$ are the stimulated and spontaneous recombination lifetimes respectively.

\[
\begin{align*}
\Gamma_{st}^{-1} j - (i\omega + \tau_{d}^{-1} + \tau_{st}^{-1}) S_0 \delta \tau_{ph}^{-1} \\
iomega \gamma - \omega^2 + 2
\end{align*}
\]

\[
\tau^{-1} = S_0 \frac{\partial g}{\partial N} 
\]

\[
\tau^{-1} = \frac{\partial}{\partial N} \left( \frac{N_0}{\tau_{sp}(N_0)} \right) 
\]

\[
\omega_{rel}^2 = \frac{1}{\tau_{st} \tau_{ph}} + \frac{\beta N_0}{S_0 \tau_{d} \tau_{sp}} - \frac{\Gamma S_0 \partial g}{\tau_d \partial S} \approx \frac{1}{\tau_{st} \tau_{ph}} 
\]

\[
\gamma = \frac{1}{\tau_d} + \frac{1}{\tau_{st}} + \frac{\beta N_0}{S_0 \tau_{sp}} - \frac{\Gamma S_0 \partial g}{\partial S} 
\]

The resulting modulation response, normalised to 1Hz, is shown in figure 5.28. Also shown in this figure is the response obtained for a current injection modulated VCSEL. Note that the physical parameters for the two devices are chosen to be the same, the electron-photon resonances for the two lasers therefore align in frequency.

In the current injection modulated case the response curve is flat up to the resonance and then decays as the reciprocal of the frequency squared. The VCSELMs response ($\tau_{ph}$ modulated)
is quite different. On both the low and high frequency side of the resonance the response behaves as the reciprocal of the frequency. This device therefore has an improved response at higher frequencies, 100GHz is shown in the figure. An important point to note about the VCSELM designed here, incorporating the highly reflective VT-DBR, is that it may be operated in both the current and photon lifetime modulation regimes. With the modulator un-biased the VCSELM essentially reverts back to a VCSEL. The flat response of the current injected device may therefore be attained.

![Response vs Frequency Graph](image)

Figure 5.28 Photon lifetime ($\tau_{ph}$) and injection current modulation response.

We have therefore shown that, by integrating a VCSEL with a modulator, enhancements in modulation performance may be achieved. Importantly these enhancements have been achieved without detrimentally changing the lasers CW characteristics. This allows the VCSELM device to operate in systems requiring both CW and high speed devices, possibly removing the need for multiple sources. Finally, as stated previously, the ideas introduced in this section are, as with the VT-DBR, applicable to any material system. By coupling the modulator to the laser only small changes in reflectivity are required to modulate the device. Materials within which large absorption values may nor be attained may therefore still be used to make VCSELMs.

5.5 Concluding remarks

In this chapter we have discussed some of the issues pertinent to the continued development of VCSELs. In particular we have attempted to show how the integration of VCSELs with modulators leads to improvements in performance and functionality. This latter
issue is perhaps the most important because, when coupled to the VCSELs high packing density, it opens up many possible applications areas.

In the course of this work we have developed and demonstrated a novel reflection modulator (the first VT-DBR at 980nm). Both the design and operation of this device have been discussed in detail. Distinctly, the device comprises a single (very thin) section of QWs placed within a DBR, the result being a low voltage (<3V) variable reflectivity mirror. By using the QCSE this VT-DBR achieves a 1% reflection change. However, in contrast to other designs, the VT-DBR also achieves an extremely high reflectivity, allowing direct integration with VCSELs. This device, through the use of a semi-transparent DBR, demonstrates two modes of operation (theoretically predicted). In the first mode the reflectivity of the device is high until a bias is applied. In the second mode the reverse is true. These modes may allow the device, when integrated into a laser, to perform switching functions. Furthermore, the VT-DBR may also be used as a photodetector, this should allow the in-situ monitoring of VCSEL vertical power output. This power monitoring can be implemented without affecting laser operation.

The transfer matrix models developed in chapter 2 have been modified to allow the treatment of structures comprising complex gain and absorbing sections (using measured absorption data). These models, which account for QCSE induced refractive index changes, have allowed us to develop design curves for a range of VT-DBRs and VCSELMs. In particular they have allowed us to calculate the biased reflection response and internal field profiles for VT-DBRs and also the threshold, emission spectra, modulation depth and modulator induced chirp (tuning) for VCSELMs. The models have been compared with grown VT-DBRs and VCSELMs and, in all cases, have demonstrated excellent agreement.

When integrated into a VCSEL the VT-DBR has been shown, theoretically, to produce good modulation characteristics with a low modulator induced chirp. The modulation is enhanced through the fact that the VT-DBR forms an integral (highly coupled) part of the laser (VCSEL). Importantly, the CW behaviour of the compound laser has been shown to remain stable with good spectral and threshold characteristics.

It is intended that the VT-DBR provide a practical means of modulating the cavity photon lifetime of the laser. This scheme, fundamentally different from the more commonly used injection current modulation, is theoretically expected to achieve very high modulation rates. Small signal theories for both current and photon lifetime modulation have been introduced and favourable results obtained.
Conclusions

This thesis has primarily been concerned with the development and subsequent characterisation of vertical cavity surface emitting lasers (VCSELs). In particular a number of studies have been presented comprising both critical evaluations of previous work and some completely novel work. We will briefly summarise the important results here. Also, later we will describe some of the studies that we feel are necessary, to be performed in the future, in order to fully complete, and implement, the work presented in this thesis.

In chapter 2 we presented a novel model for calculation of a number of important laser parameters, as used later for VCSEL design and optimisation. This model, developed independently but around the same time as a number of other models [see specifically Weber et al. '91 and Hansmann '92], is based on the well known transfer matrix solutions to Maxwell's equations. Modifications have been applied to include QW sources, absorbers and gain. Distinct from other models, we have incorporated a complex model for the spontaneous emission spectrum and gain characteristics of InGaAs QWs [Rees '93] under different levels of injection. This, along with the incorporation of dispersive refractive indices, has allowed us to accurately determine VCSEL (and laser/modulator) threshold and emission characteristics both below and above threshold. In calculating these threshold characteristics we account for carrier leakage over the active heterostructure, Auger losses and barrier recombination (as derived from empirical fits [Scott et al. '93]). By studying, and minimising, these contributions to threshold we have been able to design VCSELs with optimised active cavities, this has allowed us to produce lasers with good power and threshold characteristics. Spectrally, the model has shown that an incomplete overlap of the DBR stop-band and the spontaneous emission spectrum will result in VCSELs emitting with side-modes. These modes have indeed been experimentally observed (chapter 4), the emission spectrum characteristics are greatly improved if the overlap is increased.

Another, attendant, feature of the model is that it allows one to calculate the output efficiencies, internal field profiles and reflection and transmission properties of VCSELs. These features are very useful as they allow us to design highly efficient output couplers for the lasers, obviously this is important for optimisation of threshold currents and output powers. Using these models we have, through optimisation of mirror and cavity design (improved confinement factors) produced VCSELs with threshold currents of order 5mA and with output powers exceeding 80mW (chapter 4).

Finally, the model has been applied to designing novel integrated structures incorporating highly coupled loss and gain sections. It has, through the incorporation of experimental absorption
curves and the use of the Kramers-Kronig transformation, predicted, to a very high degree of accuracy, the operation of a novel voltage tuneable DBR and its effect upon the integrated lasers threshold and emission properties.

Chapter 3 of this thesis has been concerned with the development of low resistance DBRs. In particular we have studied how (at the growth stage) the insertion of thin AlGaAs step layers and short-period superlattices at each GaAs/AlAs heterointerface in the DBR effects the mirrors electrical and optical properties. Critically, we have reproduced the findings of other groups [Tai et al. '90, Kurihara et al. '93] and found that the use of short-period superlattices dramatically reduces the series resistance of the problematic p-type DBR. This reduction is further improved through the use of periodic doping profiles. We have subsequently used these graded, periodically doped, DBRs within VCSELs and have achieved lasing with operating voltages falling below 5 Volts.

Chapter 3 has also dealt, for the first time, with the application of post-growth annealing techniques to the reduction of series resistance within abrupt interface GaAs/AlAs DBRs. Here, we have shown that the use of rapid thermal annealing with suitable DBR capping layers allows a reduction of the series resistance of a Zn doped DBR by almost 50%. This value, although too small in absolute terms to be useful for discrete device optimisation, may prove enough to allow lateral current confinement.

We have also studied the structural effects of interdiffusion using the technique of secondary ion mass spectrometry (SIMS). This has shown that the use of a silica cap reduces the GaAs/AlAs interdiffusion coefficient from an uncapped value of $86 \times 10^{17} \text{cm}^2\text{s}^{-1}$ to a value of $26 \times 10^{17} \text{cm}^2\text{s}^{-1}$. Note that in both the capped and uncapped cases the interdiffusion coefficient is higher than would be expected in an undoped (intrinsic) sample annealed under the same conditions, in that case a value of order $9 \times 10^{17} \text{cm}^2\text{s}^{-1}$ would be expected [Tan et al. '88]. Our findings suggest that the underlying enhancement is due to (Zn) dopant enhanced intermixing, mediated through the introduction of (Zn) interstitials. The subsequent reduction of intermixing under silica capping conditions is attributed to the introduction of Zn interstitial suppressing Ga vacancies.

Finally, we have used reflectance spectroscopy and our theoretical models to study the effects of intermixing upon the reflection properties of DBRs. In particular, solutions to the diffusion equation have been used to modify our optical model, these have allowed us to calculate the reflection properties of intermixed DBRs. This has, to our knowledge, only been implemented by one other group [Floyd '94]. There are, however, marked differences in the way we deal with the diffusion process. Broadly the results we obtain are in agreement with that work. However through our experimental studies we have demonstrated that dopants have an important effect upon the diffusion and have included this effect (neglected by other groups) in the calculation. Essentially
this is through the use of an enhanced diffusion coefficient. Our findings suggest that the major reflectivity reducing mechanism is surface degradation (microscopic studies appear to verify this). The intermixing itself does not dramatically effect the reflectivity except in the cases where high anneal temperatures and long anneal times are used. This agrees with our theoretical studies which suggest that strong reductions in reflectivity will only occur when the interdiffusion length becomes appreciable relative to the quarterwave thickness of the GaAs and AlAs layers. These optical, electrical and structural studies are of importance if intermixing is to be applied to any (doped) microcavity based device. More specifically, cap selective intermixing may lead the way to lateral integration through the use of patterning.

Chapter 4 has been concerned with the development and characterisation of strained InGaAs QW VCSELs for operation around 980nm. In this chapter we have applied various optical injection techniques to study the sub-threshold luminescence properties of VCSELs. In particular we have shown how side-modes may appear in the emission spectrum of a VCSEL. These modes are attributed to spontaneous emission and have subsequently been observed for electrically injected devices. The appearance of these modes agrees well with our theoretical studies.

With respect to electrically injected VCSELs, we have produced (MBE grown) devices which use the resonant periodic gain concept (3 QWs) and possess threshold current densities of 1kA/cm². These devices, of order 50µm diameter, compare very favourably with similar lasers reported in the literature. Output powers of order 10mW have been achieved and these are limited by thermal turn-over effects attributed to carrier leakage and to a detuning of the peak gain from the laser resonance (no heat-sinking has been used). We have also observed, by looking at lasers of various cavity lengths, how this detuning of the peak gain and the lasing wavelength effects the laser threshold current. Further, we have shown that the use of a graded index separate confinement heterostructure (GRINSCH) active layer greatly reduces the carrier leakage effects and results in a device with much improved output power. The highest output power we report is of order 50mW, this large increase is due to a greatly reduced carrier leakage. Importantly we also show that the threshold current densities of these high power devices are only of order 950 A/cm² (for 3 QWs), an excellent figure. Note that these GRINSCH devices also have a greatly increased output efficiency, this follows from the improved choice of DBR reflectivity (this has been analysed in detail in chapters 2 and 4).

The electrical characteristics of the VCSELs have been studied in some detail. In all cases the threshold voltages are of order 5 Volts, this leads to a relatively low power consumption laser. More specifically the device electrical characteristics have been shown to scale very well with area (the optical properties also do this). Furthermore, we have demonstrated that, as with in-plane lasers (IPLs), the IxV/dI characteristics of VCSELs exhibit a sharp kink at the lasing threshold.
These characteristics appear, however, to be more complex than those of an IPL and require further investigation.

The final chapter of this thesis has been concerned with the integration and high speed modulation of a VCSEL. Using small signal solutions to the laser rate equations we have shown that the modulation speed of an ordinary VCSEL is dictated by factors relating to the active layer QWs, the cavity photon density and the cavity Q. Furthermore we have shown, following Avrutin [Avrutin et al. '93], that a dynamic modulation of a VCSELs cavity Q (and thereby its cavity photon lifetime) may lead to a laser with exceptional high speed characteristics. In particular the improved modulation response will decay only slowly as the frequency is increased above the electron-photon resonance frequency. Uniquely, this chapter goes on to provide a practical means of achieving a modulation of the cavity Q. This involves the integration of the laser with a reflection modulator. The QW modulator developed by us for this purpose has a complex design, this has been described in detail. In operation the device demonstrates some unique properties [Khan et al. '94]. Firstly, it achieves a reflectivity of order 99%. This is through the use of a novel semi-transparent mirror section. Next, it may be reflection modulated, by application of a bias, through the quantum confined Stark effect (QCSE). Modulation of order 1% may be achieved and the device may be operated in two distinct modes, dependent upon wavelength. The first of these modes achieves a high reflectivity without an applied bias. The second achieves high reflectivity upon the application of a bias, we envisage that this device may be used to switch a VCSEL. In both cases the required bias is only of order 2 Volts, this low voltage is achieved through the use of a very thin QW section. Finally, the device may be used to measure photocurrent, as might be required for monitoring VCSEL power output. A point to note is that the operating principles of this modulator are quite unique, the QWs are designed to coincide with a specific portion of the optical standing field within the structure, this position may be tailored through alteration of the semi-transparent DBR section.

Finally the chapter theoretically studies some of the performance characteristics of the integrated VCSEL and modulator. As with the modulator, this integrated device offers some completely unique features. Firstly, if the modulator is unbiased, the laser/modulator reverts to an ordinary VCSEL which may be current modulated. Next the device may be modulated at very high frequency through the photon lifetime modulation scheme. Finally the modulator may be used to monitor the laser output power. This device therefore has a greatly enhanced performance and, through increased research effort, may find a place in the broad field of telecommunications. More importantly the integration ideas, and models, employed in the development of this device are extendible to other wavelengths and this may open up many other opportunities for the advancement of VCSEL technology.
Future directions

In this final section of the thesis we will briefly comment upon certain aspects of the work that require further investigation. We take each chapter in order.

On the modelling side two essential features have been neglected or treated in an overly simplified manner. Firstly the thermal, heat dissipation, effects that act to turn-over the lasing light-current characteristic have been neglected. These will act to shift the emission wavelength as the VCSEL heats up. Such heating will also act to shift the gain peak away from the lasing resonance and so the lasers output power will be limited. Modelling this effect, perhaps using the method outlined by Scott [Scott et al. '93], will make our model much more accurate. The second, less important but perhaps more interesting effect relates to the QW active layer and its emission (and absorption) characteristics. In our model we assume that the active QW is emitting into free space with a large (continuous) optical mode distribution. In reality the QWs are emitting into an optically confined cavity. This will limit the number of optical modes available for emission and will therefore alter the QWs spontaneous emission rate. The result maybe to alter the lasers threshold current and power output characteristics. This effect is believed, at present, to be small in the one dimensional cavity of a VCSEL, however it may be important when the high speed characteristics of the device are considered. Inclusion of these two effects should enhance the models accuracy and make it an indispensable aid in the design and production of VCSELs and LEDs.

The insertion of short period superlattices and the use of periodic doping has been shown to reduce the resistance of DBRs quite dramatically. Detailed studies have not, however, been carried out upon the dopants used and their spatial distribution after growth. The samples studied in this work have used either Zn or Be as the p-type dopant. However it has recently been shown that carbon may be used to lower the resistance of the DBR further. It is widely accepted that this dopant remains localised (does not travel) during growth, it may therefore be selectively placed (within the DBR) near the heterointerfaces. Furthermore, high doping densities may be achieved through its use. Further studies of this, and other, dopant should yield DBRs of very low resistance, these will be necessary if VCSELs with very low threshold input powers and high output powers are to be produced. The current trend towards devices operating at ever decreasing power levels adds further fuel to this argument.

Extending the doping studies into the field of intermixing may also prove useful. We have already shown that the Zn dopant dramatically enhances intermixing between GaAs and AlAs. The use of other dopants may further enhance this mixing. In any case, by selectively doping a
structure (during growth) the longitudinal electrical properties of the sample may be improved. As demonstrated, further control of the intermixing may be achieved through the use of capping layers. A detailed study of all the available capping layers is therefore required. Furthermore a study of patterning, and the lateral electrical confinement it achieves, is necessary if diffusion is to be used to laterally integrate microcavity devices.

By using carrier confining GRINSCH structures we have shown that the carrier leakage properties of a VCSEL may be improved. Further work is required to find the best GRIN-structure such that the highest possible output powers may be achieved. Such structures may prove vital if VCSELs are to produce the powers necessary to optically pump solid-state or fibre-based sources. Moreover, if VCSELs are to be used in long-haul telecommunications application they will need to produce high powers. Studies may therefore also be required to test if the GRINSCH structure improves the dynamic response of the laser.

Beyond carrier leakage the lasers we have produced for this work are further limited, in terms of output power, simply by the lack of heat-sinking. Obviously this problem needs to be addressed. A range of techniques exist for the mounting of IPLs and these same techniques may be readily applied, with modification, to the VC-laser.

Regarding the integrated laser/modulator, although we have grown integrated structures we obviously need to demonstrate the operation of the device. Importantly the feasibility of the photon lifetime modulation scheme needs further study. If realised this device will have great potential in high speed communication. Measurements of the modulation and its associated noise characteristics will follow. The novel physics of a photon lifetime (cavity Q) modulated laser will also require further study.

Finally, at present the DBRs of a VCSEL are passive and perform only a reflection role. We have shown that a modulator may be integrated into the DBR without affecting the DBRs, and hence lasers, characteristics. This idea may be extended to allow other devices to be integrated into the VCSELs DBR without compromising the laser performance. These devices may, or may not, be coupled to the laser. However they will enhance the functionality of the laser and increase the integration possibilities. Using such techniques smart-pixel type devices may be envisaged with the VCSEL comprising many vertical (interdependent) subsections. This important field of integration obviously requires much research to develop it to an industrially viable level.
Appendix A

Knowledge of the real part of the refractive index (n) of a material is of prime importance if the effects of that material on the optical properties of a structure are to be determined. A number of curve fits have been arrived at, by us, using published refractive index data. These are given here for reference.

The refractive index of GaAs (n_{GaAs}), at room temperature, for wavelengths between 800-1100nm, is found to be approximated well by the equation (A1.1) of Blakemoore [Blakemoore '82].

\[ n_{GaAs} = 7.1 + \frac{3.78}{\sqrt{1-0.18x\left(\frac{1.239852}{\lambda}\right)^2}} \]  

...(A1.1)

The refractive index of AlAs (n_{AlAs}), over the same spectral range, is given by equation A1.2, which is a fit to data from the reference [Landolt et al. '82, '89].

\[ n_{AlAs} = -2.5 \times 10^{-4} \lambda + 3.2 \]  

...(A1.2)

The refractive index of Al_{x}Ga_{1-x}As, at a given wavelength, is calculated as a parabolic interpolation [Casey et al. '74] between the indices of GaAs and AlAs, at that wavelength. It is given by

\[ n_{AlGaAs} = 0.4(1-x)^2 + (n_{GaAs} - n_{AlAs} - 0.4)(1-x) + n_{AlAs} \]  

...(A1.3)

The refractive index of InAs [Landolt et al. '82, '89] has the wavelength dependence of equation A1.4. The refractive index of In_{x}Ga_{1-x}As is taken as a linear interpolation between the indices of InAs and GaAs at the desired wavelength.

\[ n_{InAs} = -1.2074 \times 10^{-3} \lambda + 5.1822 \]  

...(A1.4)

Finally the refractive index of gold is calculated from equation A1.5, which is a curve fit to the data in [Palik '85]. k_{Au} is the imaginary coefficient.

\[ n_{Au} = 8.39334 \times 10^{-2} - 8.09271 \times 10^{-5} \lambda + 2.52477 \times 10^{-7} \lambda^2 \]  

...(A1.5)

\[ k_{Au} = -3.05320 + 1.14275 \times 10^{-2} \lambda - 1.52222 \times 10^{-6} \lambda^2 \]  

...(A1.5)
Appendix B

Scott [Scott et al. '93] has developed a number of curve fits, using VCSELs that are very similar to the structures within this work, to allow calculation of some of the factors contributing to the current injected into a device. The current injected into a device will, in general, only in part go towards the injection of carriers into the QWs within the device. More generally some of the current will be lost to non-radiative recombination and leakage mechanisms. The curve fits of Scott allow the calculation of the current injection (at the contacts) required to produce a given carrier density within the QWs of a device.

Although this work uses the model of Rees [Rees '93] to calculate the gain and spontaneous emission within a device, Scott’s equations for gain give a good empirical fit to the data and so are included here for completeness.

The gain, per QW, as a function of carrier density (n) and temperature (T) is given by equation B1.1, where \( n_0 \) is a carrier density of \( 1 \times 10^{18} \) cm\(^{-3}\).

\[
g\text{(cm }^{-1}) = A(T)\ln\left(\frac{n / n_0 - 0.41}{B(T)}\right) \quad \text{.....(B1.1)}
\]

\[
A(T) = \begin{cases} 
46963.3 + 371.56T - 0.941029T^2 + 0.000799276T^3 & \text{(T < 430k)} \\
535 + 2.48T + 0.0041T^2 & \text{(T > 430k)} 
\end{cases}
\]

\[
B(T) = 2.723 - 0.02417T + 0.0000647867T^2
\]

The current density (J) required to support a carrier density n, in the QW, is given by summing the current lost to spontaneous emission, within the QW (J\(_{\text{sp}}\)) and the barriers (J\(_{\text{bar}}\)). Also the current lost to non-radiative Auger recombination (J\(_{\text{Auger}}\)) and to carrier leakage over the heterostructure (J\(_{\text{leak}}\)) must be considered. The following relationships are given by Scott.

\[
J_{\text{sp}} = A(T)\left(\left(1 + B(T)(n / n_0)\right)^{1/2} - 1\right)^2 \quad \text{.....(B1.2)}
\]

\[
A(T) = 68.5 - 0.277 + 0.000817T^2
\]

\[
B(T) = 6.11 - 0.022T + 0.000022T^2
\]

\[
J_{\text{bar}} = 0.0979\left(n / n_0\right)^3 \quad \text{.....(B1.3)}
\]
\[ J_{\text{Auger}} = (C_{s0} \exp(A_n T + B_n T^2)) + \left( C_{po} \exp(A_p T + B_p T^2) \right) \left( \frac{n}{n_0} \right)^3 \]  

\[ C_{s0} = 2.51 \times 10^{-3} \text{ A/cm}^2 \]
\[ C_{po} = 12.5 \times 10^{-3} \text{ A/cm}^2 \]
\[ A_n = 8.71 \times 10^{-3} \text{ k}^{-1} \]
\[ A_p = 1.05 \times 10^{-3} \text{ k}^{-1} \]
\[ B_n = -3.66 \times 10^{-6} \text{ k}^{-2} \]
\[ B_p = -7.74 \times 10^{-6} \text{ k}^{-2} \]

The leakage current is dependent upon the quasi-Fermi level separation \((\Delta E_{\text{fcv}})\) and the bandgaps of the materials forming the barriers of the material \((E_{gb})\), in this case \(\text{Al}_{x}\text{Ga}_{1-x}\text{As}\).

\[ J_{\text{leak}} = J_0 \exp \left( \frac{E_{gb} - \Delta E_{\text{fcv}}(n,T)}{k_B T} \right) \]  

\[ E_{gb} = E_{\text{GaAs}}(T) + 1.247x \]
\[ E_{\text{GaAs}}(T) = 1.519 - \frac{5.4 \times 10^{-4} T^2}{204 + T} \]
\[ \Delta E_{\text{fcv}} = E_{\text{GaAs}}(T) - 0.05857 + (0.00465 + 0.00622(T / 300)) \left( \frac{n}{n_0} \right) - \left( \frac{0.294}{\left( \frac{n}{n_0} \right) + 1} \right) \]

\(J_0\) is a fitting parameter, a value of 250 fits the experimental data in this work. \(k_B\) is Boltzmann's constant and \(x\) is the Al mole fraction within the barrier layers.

It is important to note that the QWs used within the VCSELs of Scott (the data from which is used to derive the curve fits above) are nominally 80Å \(\text{In}_{0.2}\text{Ga}_{0.8}\text{As}\) and, as such, are the same as those used within this work.
**Appendix C (i)**

*Sample A (MV1733).* This sample was designed specifically as a test structure for optical injection. Design and growth in this case (only) were by K. Woodbridge at Philips, Redhill. As such the DBRs are not graded in any way, this dramatically simplifies growth (as does the small number of DBR periods). The structure is for top emission and contains a uniform gain cavity (uniform gain scheme, UGS). It may be viewed as the simplest of VCSEL structures, in this case the increased single pass gain (2\(\lambda\) optical cavity) is intended to overcome the low reflectivity (high output coupling efficiency) DBRs.

![Structure diagram](image.png)

The thickness of this structure is approximately 5.4\(\mu\)m, neglecting the buffer layer. Structures of this type have been used to characterise (and calibrate) the MBE growth system.
**Appendix C (ii)**

**Sample B (SA6M35).** This sample is again a preliminary structure. The cavity in this case is one wavelength long and contains 3QWs in a non-resonant configuration.

The DBRs are 200Å Al$_{0.5}$Ga$_{0.5}$As step graded in an attempt to provide some series resistance reduction. This scheme allowed this device to be electrically injected to perform as a narrow linewidth light emitting diode. Note that the doping has been extended into the cavity in this case. The physical thickness of this structure is approximately 5.7μm, neglecting the buffer layer.
Appendix C (iii)

Sample C (U2040). This sample utilises the resonant periodic gain scheme (RPG). The sample is designed for bottom (substrate) emission, this is also the case for sample U4041. As such the top GaAs layer is thickened and heavily doped to accept the metal contact that will also boost the top DBR reflectivity. Note that the lower (n-type) DBR is step graded, using 200Å Al\textsubscript{0.5}Ga\textsubscript{0.5}As layers. The n-type DBR poses less of a series resistance problem than the p-type DBR and so step grading, in conjunction with a high overall doping concentration, should suffice to produce a low voltage device.

Note that the short period superlattice (S/L) grading applied to the p-type DBR in this sample, and also to sample U4041 (next page), is shown here only in a schematic format, as used by Geels [Geels '91]. In reality the minimum layer thickness is dictated by the lattice constants of the material layers. The superlattices actually grown are thus approximations to this. The thickness of the structure in this case is approximately 6.5μm, neglecting the buffer layer.

<table>
<thead>
<tr>
<th>Doping Level</th>
<th>Phase Matching Layer</th>
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<tr>
<td>1x10\textsuperscript{16} cm\textsuperscript{-3}</td>
<td>Ga\textsubscript{As} 2Å</td>
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<tr>
<td>3x10\textsuperscript{19} cm\textsuperscript{-3}</td>
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<td>7x10\textsuperscript{19} cm\textsuperscript{-3}</td>
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<table>
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<tr>
<td>Ga\textsubscript{As} 2Å</td>
<td>Ga\textsubscript{As} 2Å</td>
</tr>
</tbody>
</table>
Appendix C (iv)

Sample D (U4041). This sample comprises a GRINSCH cavity region with 3x80 Å In_{0.185}Ga_{0.815}As QWs (e1-hh1 ~ 950nm, at T=300°k), designed to utilise the offset-gain scheme.

doping level

<table>
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<tbody>
<tr>
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<tr>
<td>S/L B</td>
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<td>GaAs 530Å</td>
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<td>S/L A</td>
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<tr>
<td>AlAs 631Å</td>
<td>AlAs 6Å</td>
</tr>
<tr>
<td>S/L B</td>
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<tr>
<td>GaAs 100Å</td>
<td>AlAs 12Å</td>
</tr>
<tr>
<td>In_{0.185}Ga_{0.815}As 80Å</td>
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<td>AlAs 14Å</td>
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<td>In_{0.185}Ga_{0.815}As 80Å</td>
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<td>GaAs buffer 0.5µm</td>
<td>GaAs 10Å</td>
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</table>

Other layers doped 1x10^{18} cm^{-3}

- 192 -
References


- 194 -


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Publications


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