A STUDY OF GaSb-BASED RESONANT CAVITY PHOTODETECTORS

A thesis by

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to my mother and father
ABSTRACT

The design and modelling of resonant cavity-enhanced [RCE] photodetectors, where the active region is incorporated between two mirrors, has been considered using GaSb as the cavity material grown on GaAs substrates. These type of structures offer the possibility of highly efficient, wavelength selective photodetectors whilst allowing the use of much thinner active regions as compared to the conventional non-resonant structures. The antimonide material system has a carrier concentration of $1 \times 10^{16}$ cm$^{-3}$ when undoped which presents a problem when considering photodiodes which require large active regions in order to achieve high efficiency; and hence the use of a resonant cavity structure is advantageous.

Schottky and p-n structures have both been considered as potential diodes. In the form of conventional non-resonant devices these are then used as reference structures for the cavity detectors. Non-resonant p-n$^+$ junction structures showed the best efficiency measurements with $\eta$~10% at -1V reverse bias and a corresponding $D^*(\lambda=1700\text{nm})=4.93 \times 10^9$ cmHz$^{1/2}$W$^{-1}$, the highest $D^*$ in this structure was $1.46 \times 10^{10}$ cmHz$^{1/2}$W$^{-1}$ at 0V.

Quarter-wave mirror stacks have been grown, using MBE, with measured reflectivities $>95\%$ at 1.68$\mu$m using GaAs/AlAs layers. Bulk GaSb was grown on top of the DBR by MOCVD to form the cavity; and the air-semiconductor interface was used as the top reflector. Measured optical spectra show an increase in the photocurrent by a factor of $\sim$4 at $\lambda=1748\text{nm}$ and by a factor of $\sim$3 at $\lambda=1631\text{nm}$ over non-resonant structures with the same active region thickness. The best quantum efficiency for an RCE structure was measured at $\lambda=1631\text{nm}$ where $\eta$~10% at -0.3V reverse bias with $D^*=1.71 \times 10^9$ cmHz$^{1/2}$W$^{-1}$ and the best $D^*$ was achieved at the same wavelength where $D^*(\lambda=1631\text{nm})=4.49 \times 10^9$ cmHz$^{1/2}$W$^{-1}$ at a bias of 0V. The main limit to the achievement of high $\eta$ and $D^*$ is the poor dark current characteristics of all the structures considered in this thesis. Reduction of this parameter should, hopefully, result in an increase in the signal-to-noise ratio and an improvement in $\eta$ and $D^*$. 

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## ABSTRACT

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The uses of semiconductor photodetectors are numerous ranging from missile guidance to alarm systems and heat detectors. To date these photodetectors have been designed using Si and Ge at wavelengths below 1.5μm and mercury-cadmium telluride (CMT) and the lead-salt family at wavelengths greater than 2μm. Of the III-V semiconductors the main emphasis, in the research community, has been on the design of detectors for the 1.3μm and 1.55μm communication wavelengths utilizing mainly the InGaAs material system. However there are many other applications where III-V semiconductor detectors can be utilized and one of these is in the design of gas sensors for the detection of noxious pollutants such as CO from car exhausts and CH₄ from land-fill sites. This type of optical sensor would consist of a photodetector and an LED where the presence or absence of a gas would be detected by the magnitude of the detector output signal at a specific wavelength corresponding to an absorption band of the gas being detected.

As many of these gases have strong absorption bands in the infrared region [λ>1.5μm] the design of a photodetector would require a suitable semiconductor material system which could cover the wavelength[s] of interest. Much of the work presented in this thesis is concerned with the design and characterization of an optical photodetector based on the III-V semiconductor GaSb with the possibility in mind of it being used eventually in a gas sensing system. To this end the photodetector design used is such that many of the criteria such as high quantum efficiency and narrow spectral response required for a photodetector used in such an application can be maximized.

Chapter 1 provides a brief introduction to various aspects of photodetector design and performance criteria. The photoconductive and photovoltaic modes of operation are discussed along with a brief consideration of different photodetector types and the merits as well as the disadvantages of each type. The various applications using semiconductor photodetectors are considered expanding on that of gas sensing. In chapter 2 we discuss in detail the various figures of merit used to characterize photodetectors and various ways of maximizing these theoretically. Two of the most important figures of merit for photodetectors in general are the quantum efficiency and the noise response which in turn effects the specific detectivity [D*]. The quantum efficiency is discussed with consideration of detector structures and semiconductor both of which greatly influence this parameter. The ultimate detection limit is the noise response which in semiconductor detectors can be determined by the quality of the material used as well as the photodetector structure. Many of the performance criteria are theoretically derived in order to provide an idea of the dependencies of this parameters.
OVERVIEW

Photodetector structures are considered in detail in chapter 3. Three main types are discussed, the p-n, p-i-n and the Schottky barrier junction. The advantages and disadvantages of each are considered especially from the point of view of utilizing the GaSb material system. From these considerations as well as the application of gas sensing, we briefly introduce a novel structure based on the resonant cavity effect which overcomes [theoretically] some of the problems encountered in using these conventional detector types. Chapter 4 introduces some of the commonly used material systems used in photodetector design at the present time from the point of view of the material quality, ease of growth, wavelength ranges the materials cover and a review of detector characteristics of photodetectors designed using these various materials.

In chapter 5 we discuss in detail the theory of resonant cavity photodetector structures. This structure where the absorbing region of the photodetector is placed between two mirrors causes the incident light to undergo multiple passes through this absorbing region and hence causes an increase in the quantum efficiency of the photodetector at the resonant wavelengths. A transfer matrix model is used to derive the design equations used in the theoretical analysis of this cavity effect and these equations are then used in the theoretical consideration of some of the figures of merit discussed in chapter 3. The design, growth and characterization of distributed Bragg reflectors [DBRs] is the subject of chapter 6. Calculations of the reflectivities achievable with different mirror designs is possible through the use of various models available in the department again based on the transfer-matrix based model. GaAs/AlAs-based reflector stacks are designed for various wavelengths and characterized in order to determine their reflectivity and hence their usefulness in a cavity structure.

We then go onto discuss the GaSb material system in detail in chapter 7. From a detailed literature survey as well as from experimental studies we found the main problem hindering the production of a good photodetector is the high background doping seen in GaSb resulting in a carrier concentration of the order of \(10^{16}-10^{17}\) cm\(^{-3}\) regardless of the growth method used. GaSb-based photodetector structures are designed, grown and characterized electrically in order to study their suitability as possible detector structures. Current-voltage characterization are used to ascertain various parameters of these photodetectors such as calculation of the dark current and reverse breakdown voltage. Various models are presented to explain the measured dark current characteristics. In chapter 8 we consider the design, growth and operation of a resonant cavity detector structure utilizing the reflector stacks designed in the previous chapter. The photocurrent is seen to be enhanced at the resonant wavelength for the cavity structures when compared with non-resonant reference structures. This suggests that these cavity structures are capable of high quantum efficiencies as well as being wavelength selective, two factors required in the design of a detector for gas-sensing.
OVERVIEW

The GaSb epilayers were grown by Dr N. Mason, University of Oxford, using MOCVD; the GaAs/AlAs DBRs were grown by Dr. R. Grey, University of Sheffield, using MBE; wafer processing was done at the University of Sheffield by Dr. G. Hill and at University College London by D. Prescott; software both for the modelling of possible device structures and the interfacing of equipment were written by the author as well as the optical and electrical measurements presented in the final chapters.
The interest in infrared [IR] photodetectors in applications such as telecommunications and infrared imaging for military use has led to the development of new semiconductor-based photodetectors. The fact that these detectors are compact in size, highly efficient in converting optical signals into electrical and have a fast response speed means that they are favoured for the above applications over other detector types such as thermal. The wavelength range over which a device functions is determined by its material structure. Along with the improvement in appropriate material systems, research into IR semiconductor photodetectors has concentrated on different structures in order to optimise the appropriate detector characteristics.

This chapter will give a brief history of the development of IR detectors and the materials used in their design. In designing any device it is important to know the basic parameters by which the device will be judged and a brief discussion of these will be provided for the photodetector. The basic physics of photodetectors from the point of view of the absorption mechanism and various photon effects which are used to detect the incident light are discussed. We also introduce some of the common detector structures and briefly compare their structures. Finally, some applications of photodetectors [mainly IR] are tabulated and the application of gas sensing is considered.
1.1 HISTORY

Infrared [IR] detectors [Kruse et al., 1962] had their beginning with the blackened thermometer used by Sir William Herschel [1738-1822] when he discovered infrared in 1800. Whilst studying the heating effect produced by different parts of the solar spectrum, he established that it contained some form of radiant energy which was not visible to the human eye. At the time it was widely believed that the spectrum of the sun only covered the narrow range which could be seen. Herschel used thermometers and found that those placed outside the visible region of the spectrum of a prism, just beyond the red, showed the greatest heating power. He called this spectral range infrared and all IR detectors thereafter were of the thermal type. It wasn't until the discovery of the transistor in 1947 that large scale research was carried out on the detecting properties of semiconductors and photon detectors came into their own. Table 1-1 shows a brief history of IR detectors from 1800 until the middle of the 20th century.

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
<th>Scientist</th>
</tr>
</thead>
<tbody>
<tr>
<td>1800</td>
<td>Discovery of infrared radiation [IR]</td>
<td>Sir William Herschel</td>
</tr>
<tr>
<td>1830</td>
<td>Invention of radiation thermocouple</td>
<td>L. Nobilli</td>
</tr>
<tr>
<td>1833</td>
<td>Invention of thermopile</td>
<td>M. Melloni</td>
</tr>
<tr>
<td></td>
<td>Experimental validation of a fundamental law of thermal radiation:</td>
<td>L. Richie</td>
</tr>
<tr>
<td></td>
<td>A material which is a good emitter of IR radiation is an equally good absorber</td>
<td></td>
</tr>
<tr>
<td>1840</td>
<td>Demonstration of the existence of IR absorption and transmission by noting rate of evaporation of alcohol from blackened paper</td>
<td>Sir John Herschel</td>
</tr>
<tr>
<td>1859</td>
<td>Theoretical validation of Richie's experimental findings</td>
<td>G. Kirchoff</td>
</tr>
<tr>
<td>1862</td>
<td>Verification of Maxwell's classical theory of electromagnetic radiation</td>
<td></td>
</tr>
<tr>
<td>1879</td>
<td>Conclusion was reached that the rate at which heat was transferred from one body to another was proportional to the difference of the fourth power of their absolute temperature</td>
<td>Stefan</td>
</tr>
<tr>
<td>1880</td>
<td>Discovery that photographic plates were sensitive to 2μm</td>
<td>W. Abney</td>
</tr>
<tr>
<td>1881</td>
<td>Invention of the bolometer</td>
<td>S. Langley</td>
</tr>
<tr>
<td>Date</td>
<td>Event</td>
<td>Scientist</td>
</tr>
<tr>
<td>----------</td>
<td>----------------------------------------------------------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>1884</td>
<td>Theoretical derivation of Stefan's 1879 experimental results:</td>
<td>Boltzmann</td>
</tr>
<tr>
<td></td>
<td>Stefan-Boltzmann Law</td>
<td></td>
</tr>
<tr>
<td>1887</td>
<td>Production of very long wavelength IR radiation by electrical means</td>
<td>H. Hertz</td>
</tr>
<tr>
<td>1917</td>
<td>Design of thallous sulphide photoconductive detector sensitive to 1.2μm</td>
<td>Case</td>
</tr>
<tr>
<td>1920's-</td>
<td>Development of PbS cells-wavelength extended to 4μm</td>
<td></td>
</tr>
<tr>
<td>1940's</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1947</td>
<td>Development of the Golay cell</td>
<td>Golay</td>
</tr>
<tr>
<td></td>
<td>Discovery of the transistor</td>
<td>William Shockley, John Bardeen, Walter Brittain</td>
</tr>
<tr>
<td>1952</td>
<td>Semiconducting properties of InSb revealed</td>
<td>H. Welker</td>
</tr>
<tr>
<td>1958</td>
<td>Potential of Hg_{1+x}Cd_{1-x}Te as an IR detector material discovered</td>
<td>Lawson and co-workers at the Royal Radar Establishment</td>
</tr>
<tr>
<td>1950's</td>
<td>Long wavelength IR detectors studied using impurity doped Si and Ge</td>
<td></td>
</tr>
</tbody>
</table>

The real work into materials for present day IR photodetectors [Willardson et al., 1981] began in the middle of this century. Although radar technology came of age during this time, IR technology was still in its infancy, consisting principally of active infrared image converters and single element PbS cells [Cashman et al., 1946]. In the decade following the war, the lead salt family, including PbS, PbSe and PbTe, were exploited [Cashman, 1959]. PbSe and PbTe being used in missile guidance and also in thermal imaging for the 3-5μm range as they have absorption edges near 5μm at 77K. It was during the latter part of the 1950’s that Reike et al., published a paper which reported the use of InSb, one of the newly discovered III-V semiconductor compounds, in thermal imaging. Dopants of Ge were also discovered with excitation energies which were also useful for thermal imaging, mainly Ge:Au and Ge:Hg [Levinstein et al., 1959]. Ge:Hg had the advantage that it responded throughout the 8-12μm atmospheric window [Gebbie, 1951], but required cooling to around 30K. InSb operated at 77K but operated in 3-5μm interval only and hence the need arose for a new material which would combine 8-12μm response and 77K operation.
Gray Sn was considered \( E_g = 0.1 \text{eV} \) but it was found that it was semi-metallic and unstable at room temperature. HgSe \([\text{Blue et al.}, 1962]\) and HgTe \([\text{Hornon et al.}, 1958]\) were considered but it was found that they were both semimetallic. It wasn’t until 1959 that the III-V semiconductor Hg_{1-x}Cd_xTe [CMT] was considered as a potential candidate for IR detectors especially in the 8-14\(\mu\text{m}\) region \([\text{Lowson et al.}, 1959]\). From this early work, progress in IR detector material research has progressed rapidly to the present day where many of these materials are now widely used in commercial devices. The II-VI and IV-VI semiconductors are in principle well adapted to detector design because of their direct band gaps. Their position with respect to other semiconductors can be seen in fig. 1.1 which gives values of the room temperature band gap vs. lattice constant. The IR region is covered by PbS, PbTe, PbSe and the alloys PbSnTe, PbSnSe, CdHgTe and ZnHgTe which allow the wavelength limit to be extended to 3\(\mu\text{m}\). The CMT alloy is the basis for a variety of IR detectors and a lot of research has been carried out on this material system.

![Energy gap vs lattice constant for several semiconductor types](image)

**Figure 1.1** Energy gap as a function of lattice constant for several semiconductor types

### 1.2 PHYSICS OF PHOTODETECTORS

The function of a photodetector is to convert incoming modulated light energy into modulated electrical current. Light incident on a semiconductor photodetector is absorbed, and if the photon energy is greater than the bandgap energy, electron-hole pairs will be generated. These carriers, created within a region of high electric field called the depletion region [absorber region], will be swept out by the application of an applied reverse bias, which results in a photo-generated current which is collected by external electrical circuitry.

In photomultipliers, vacuum photodetectors, and phototubes, electrons are excited by photons over the energy barrier, or work function, of the material and become free electrons in a process called the external photoeffect \([\text{Streetmon, 1990}]\). Semiconductor photodiodes operate on a
principle known as the internal photoeffect where the electrons and holes excited by the photon to higher energy levels remain within the material and contribute to the photocurrent. The incident photon absorbed by the semiconductor generates a free electron that is excited from the valence to the conduction band, while a hole is generated in the valence band, fig. 1.2. The carriers created in the depletion region drift in opposite directions as they are separated by the electric field and carriers created within a diffusion length of the depletion region diffuse to the edges of the region and are collected. Under reverse bias, the carrier drift [Singh, 1994] in the electric field induces a photocurrent in the load resistor.

\[ \alpha(h\omega) \equiv 3 \times 10^6 \left( \frac{m_e^*}{m_0} \right)^{3/2} \left( \frac{h\omega - E_g}{h\omega} \right)^{1/2} \text{[cm}^{-1}] \] \[ \text{[1.2.1]} \]

When a semiconductor does not have a direct bandgap, vertical \( k \) transitions are not possible, and the electrons can absorb a photon only if a phonon [or lattice vibration] participates in the process, as in fig. 1.3[b]. Such processes are not as strong as the ones which do not involve a phonon. The absorption coefficient for indirect bandgap materials is typically a factor of 100 smaller than the indirect bandgap semiconductors for the same value of photon energy above the bandgap \( [h\omega - E_g] \).
Figure 1.3 Band to band absorption in direct and indirect semiconductors. [a] an electron in the valence band "absorbs" a photon and moves into the conduction band. Momentum conservation ensures that only vertical transitions are allowed. [b] In indirect semiconductors a phonon must participate to take an electron from the top of the valence band to the bottom of the conduction band. This is a comparatively weak process.

Table 1-2 Bandgaps for some semiconductor photodetector materials at 300K

<table>
<thead>
<tr>
<th></th>
<th>Bandgap [eV] at 300K</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Indirect</td>
</tr>
<tr>
<td>Si</td>
<td>1.14</td>
</tr>
<tr>
<td>Ge</td>
<td>0.67</td>
</tr>
<tr>
<td>GaAs</td>
<td>-</td>
</tr>
<tr>
<td>InAs</td>
<td>-</td>
</tr>
<tr>
<td>InP</td>
<td>-</td>
</tr>
<tr>
<td>GaSb</td>
<td>-</td>
</tr>
<tr>
<td>In_{0.53}Ga_{0.47}As</td>
<td>-</td>
</tr>
<tr>
<td>In_{0.14}Ga_{0.86}As</td>
<td>-</td>
</tr>
<tr>
<td>GaAs_{0.88}Sb_{0.12}</td>
<td>-</td>
</tr>
</tbody>
</table>

Materials like GaAs, InGaAs, InP have strong optical absorption at the bandedges because the optical absorption can occur without a phonon participation. On the other hand, Si and Ge have an indirect bandgap, and the absorption strength is weak near the bandedge. However this does not mean that these materials cannot be used as detectors just that they have larger interaction lengths than the direct bandgap materials. The two most widely used, but, often misleading effects used in photodetectors for the detection of radiation are the photoconductive and photovoltaic.
1.2.1 PHOTOCONDUCTIVE MODE

Photoconductive detectors [Gupta, 1984] produce a current in response to incident light and the term photoconductive itself refers to operation with an external reverse bias. The simplest of all photoconductive detectors are composed of a bulk semiconductor which has a large surface area and two ohmic contact points. When a charge carrier is generated in the material in the presence of an incident energised photon, and at least one member of the pair is mobile, the device conductivity will be increased. The bias applied to the device then causes an increased current to flow until the pair recombine. Photoconductive gain will be present if one member of the pair is more mobile than the other, so that on average more than one member of the mobile carriers can flow through the device before recombination occurs. Recombination may occur in the device, or, if the less mobile carrier is first "swept out", will occur when the less mobile carrier reaches a contact.

Photoconductors are relatively easy to construct but they are slow in their operation. They require external voltage sources and in most cases must be cryogenically cooled to minimise the effect of thermally generated charge carriers. The major benefit of the photoconductive mode is that it is the photogenerated current which constitutes the measured output signal and not the voltage drop across the diode as in the photovoltaic mode. Hence, the output signal is a linear function of the incident light flux. Photoconductive operation results in higher response speed than photovoltaic. Due to the wide depletion layer and, consequently, higher electric field, the transit time for charge carriers to reach the contacts is reduced. The main disadvantage is the increased noise due to the ever present leakage current. Some of the more common photoconductors are PbS, PbSe, InSb, and Hg$_{1-x}$Cd$_x$Te [R. B. Emmons et al., 1975].

1.2.2 PHOTOVOLTAIC MODE

Photovoltaic detectors are p-n junction detectors which operate with no applied external bias. They are operated open circuit. The electron-hole pairs which are generated separate and drift to opposite sides of the depletion layer. Since the electrons are pulled to the n-side and holes to the p-side, a photoinduced reverse current flows through the diode from the n-side to the p-side. The effect of this is to lower the energy barrier with respect to its equilibrium value and hence more majority carriers are able to cross the junction creating forward current through the diode. Since the diode is open-circuit, the photocurrent must exactly balance the forward current. No net current flows and the drop in the energy barrier is seen as a forward voltage across the ends of the diode. It is this signal which is measured and gives this mode of operation its name, photovoltaic.
CHAPTER 1 Introduction

The main disadvantage of the photovoltaic mode as mentioned above lies in the relation between the incident signal and the output signal, namely that it is non-linear. Also, since charge carriers are only detected when they drift, influenced by the internal electric field, to their respective contacts, speed of response depends on diode thickness and is generally slow. The main benefit is low noise due to the absence of leakage current. The photovoltaic effect, as has already been mentioned, generates a voltage in the absence of any electric field. It is also possible, however, to detect the radiation by applying a bias voltage to the p-n junction in the reverse direction and detecting the change in current between dark and irradiated conditions. This type of detector is then termed the photodetector or photodiode and has given rise to a confusion in the terminology. By definition, the photovoltaic effect is obtained without bias, it is the open-circuit voltage obtained with irradiation. But, junction detectors are frequently operated under reverse bias so that the observed photosignal is a photocurrent rather than a photovoltage. In this case they are said to be in the photoconductive mode even though the configuration is not that of the photoconductor already discussed. These photodiodes will be discussed in more detail in Chapter 3.

1.3 IMPORTANT PERFORMANCE CRITERIA

Photodetectors are characterised by various figures of merit which provide a means of comparing the optical and electrical properties of different detectors. The most important of these are:

High efficiency at the operating wavelength:
The quantum efficiency is defined as the fraction of incident photons which are absorbed by the photodetector and generate electrons which are collected at the detector terminals.

Speed of response or sufficient bandwidth [telecommunications] in order to accommodate the information.

Minimum additional noise introduced by the detector:
There will always be background radiation which will interfere with the detector output but dark currents and leakage currents, which are a property of the material, need to be minimised in order that the signal-to-noise ratio [SNR] is as high as possible. If the detector provides internal gain, as in avalanche photodiodes or where an amplifier is used, the gain mechanism needs to be as noise free as possible.

Detector stability is important when changes in ambient conditions occur. Sensitivity and noise will vary with a change in ambient temperature and hence compensation to account for these effects needs to be considered in many applications.
Many of these performance criteria will be discussed in more detail in Chapter 2. The properties of photodetectors are strongly influenced by the choice of the semiconductor material system. For the device active layer [depletion region], a material with an appropriate bandgap has to be chosen in order to be able to absorb photons in the wavelength range desired. Fig. 1.1 shows the various materials used for optical devices. For example, for telecommunications the wavelength of 1.3 and 1.55μm can be detected by using Ge or a suitable alloy of InGaAs. For infrared imaging, the 3-5μm range is required and this can be utilised by using the III-Vs InAsSb and InGaSb or the II-VI, HgCdTe. The maximum wavelength for which a material will absorb is determined by its bandgap energy. For photon wavelengths, $\lambda_0 > \frac{hc}{E_g}$, where h is the Planck’s constant and c is the speed of light in a vacuum, then the material will be transparent. In the case of InP, for example, this long wavelength cut-off occurs at 0.92μm. For photons with energies greater than the bandgap of the semiconductor material the light absorption is dependent on the material absorption coefficient, $\alpha$. In direct bandgap materials, transitions can occur between the conduction band minimum and the valence band maximum with the same wavevector. Indirect materials, where the conduction band minimum is not at the same value of the wavevector as the valence band maximum, require a phonon to conserve momentum in addition to the photon of energy $> E_g$. The active layer must be thick enough, of the order of $1/\alpha$, to absorb the light and create electron-hole pairs. Hence, the aforementioned detector requirements translate into particular material requirements [Stillman et al., 1982]:

[i] An energy gap smaller than the photon energy which must be detected and preferably a direct bandgap with a high absorption coefficient. Under these conditions, the photoexcited carriers encounter the least competition from thermally activated carriers, a situation that helps achieve low dark current and good sensitivity to weak light signals.

[ii] High quality, low defect density material and junctions. This lowers the leakage and dark current.

[iii] High purity so that the depletion width is as large as possible. A large depletion region is essential for low device capacitance and hence high quantum efficiency.

Additionally, the detector structure must be designed so as to optimise each of the detector requirements. Trying to achieve many of the above becomes more and more difficult the longer the operating wavelength, mainly, due to poor material technology, processing and surface passivation, and a general lack of knowledge about material parameters. These are some of the fundamental drawbacks to device design of any kind at wavelengths which require the use of semiconductors other than GaAs and Si.
1.4 PHOTODETECTOR TYPES

The two main detector types which are commonly used in the infrared at the present time are thermal and photon detectors. Thermal detectors will not be covered in this thesis, nevertheless, it is important to have an understanding of the difference between the two types. The basic distinction between photon and thermal detectors exists in the manner in which they respond to radiation. Photon detectors essentially measure the rate at which quanta are absorbed, whereas thermal detectors measure the rate at which energy is absorbed. Photon detectors require the incident photons to have more than a certain minimum energy before they can be detected. Hence they are selective in that they respond only to those photons of sufficiently short wavelengths. Their response at any wavelength is proportional to the rate at which photons of that wavelength are absorbed and hence as the wavelength decreases the response decreases below that corresponding to the minimum energy.

Thermal detectors respond only to the intensity of absorbed radiant power and not to the spectral content of it. Thus they respond equally well to radiant energies of all wavelengths. These statements are only ideal. In practice most photon detectors have a quantum efficiency which depends on wavelength and so their response does not simply increase with wavelength but in most cases deviates from this. Neither do all thermal detectors possess responses which are completely independent of wavelength. Table 1-3 shows the different types of thermal and quantum detectors with respect to their spectral response and operating temperature.

<table>
<thead>
<tr>
<th>Types of Detectors</th>
<th>Spectral Response [μm]</th>
<th>Operating Temp. [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Type</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermopile</td>
<td>Golay cell, TGS, LiTaO₃</td>
<td>No wavelength</td>
</tr>
<tr>
<td>Bolometer</td>
<td></td>
<td>300</td>
</tr>
<tr>
<td>Pneumatic</td>
<td></td>
<td>300</td>
</tr>
<tr>
<td>Pyroelectric</td>
<td></td>
<td>300</td>
</tr>
</tbody>
</table>

Table 1-3 Thermal and Photon Detectors
### Types of Detectors

<table>
<thead>
<tr>
<th>Types of Detectors</th>
<th>Detectors</th>
<th>Spectral Response [μm]</th>
<th>Operating Temp. [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intrinsic Type</strong></td>
<td>PbS</td>
<td>1-3</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>PbSe</td>
<td>1-4.5</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>HgCdTe</td>
<td>2-12</td>
<td>77</td>
</tr>
<tr>
<td><strong>Quantum Type</strong></td>
<td>Ge</td>
<td>0.9-1.8</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>InAs</td>
<td>1-3</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>InSb</td>
<td>2-5.5</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>HgCdTe</td>
<td>2-12</td>
<td>77</td>
</tr>
<tr>
<td><strong>Extrinsic Type</strong></td>
<td>Ge:Au</td>
<td>1-10</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>Ge:Ag</td>
<td>2-14</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>Ge:Cu</td>
<td>2-30</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>Ge:Zn</td>
<td>2-40</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>Si:Ga</td>
<td>1-17</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>Si:As</td>
<td>1-23</td>
<td>4.2</td>
</tr>
</tbody>
</table>

In choosing the type of photodetector, the speed of response, noise, and quantum efficiency are all parameters which have to be considered. The material plays an important part for as well as dictating the wavelength range it also decrees performance and the cost. The more mature technologies such as Si, Ge and GaAs usually mean lower cost devices and good performance. For longer wavelengths, materials with less well developed technologies have to be used and these typically have more involved fabrication processes and more-difficult to control dark currents. Hence in choosing an appropriate detector structure all of the above have to be taken into account.

#### 1.4.1 PHOTOCONDUCTOR

The photoconductor is not a junction detector but simply a slab of semiconductor with a pair of ohmic end contacts. When the material is illuminated, electron-hole pairs are generated and the electrical conductivity of the material increases. The greater the photon flux, the greater the increase in conductivity. When voltage is applied to the contacts, the electrons and holes move in opposite direction, resulting in a photocurrent. The anode and cathode may be placed on opposite ends of the semiconductor or both on top in an interdigitated pattern [Emmons, 1975].

Photoconductive detectors have photoconductive gain, defined as the flow of electrons per second from the device divided by the generation of electron-hole pairs within the device. The generation
per unit volume of electron-hole pairs within the slab is [assuming the device is thick enough to absorb all incident light $d \gg \alpha$]

$$g = \eta \frac{\phi}{l wd}$$

[1.4.1]

where $\eta$ is the quantum efficiency and $\phi$ is the photon flux illuminating the device of volume $l wd$. If the electron velocity is greater than that of holes, the electron reaches the side of the photoconductor before the hole. Continuity of current requires that another electron enter the device through the external circuit and it again travels more quickly than the hole. One photon, then, can cause several electrons to move through the device until recombination occurs. The device gain is expressed as

$$G = \frac{\tau_m}{\tau_e}$$

[1.4.2]

where $\tau_m$ is the excess carrier recombination lifetime and $\tau_e$ is the electron transit time [J. Müller, 1981]. Gain may be larger than 1. Photoconductive detectors have the advantage of photoconductive gain and ease of fabrication over p-n or p-i-n junction devices [see next section] but lack their speed capabilities. The transit time in a photoconductor is set by the peak velocity of the fastest carrier compared with p-i-n’s where it is limited by the slowest carrier.

1.4.2 p-n PHOTODETECTOR

The p-n junction is formed by doping layers of semiconductor material n-type and p-type. When a photon is absorbed, it creates an electron-hole pair as in the photoconductive device. Here, the electric field is formed only in the depletion region of the device and only carriers generated there, or near there [within a diffusion length [Müller, 1981]], have the ability to be moved in a specific direction. The device is usually operated under reverse bias and normally one side is more heavily doped than the other [$p^+\text{-}n$ or $n^+\text{-}p$] such that the depletion region extends further into the more lightly doped side. Electrons are moved to the n-region and holes drift to the p-region under the influence of the electric field. Carriers can be created in each of three different regions. If we take the p-n homojunction as an example and discuss briefly the optical detection process we can then apply the same principle to all the detector structures. The basic detection process is illustrated by fig. 1.4 which shows a reverse-biased p-n photodiode.
Electron-hole pairs generated at greater than the diffusion length from the depletion region diffuse around and eventually recombine not contributing to the photocurrent. Carriers created within a diffusion length of the depletion region may be collected. Electrons from the p-side will move across the depletion region toward the n-side and holes from the n-side will be transported to the p-side. Response time of a p-n junction device is faster than a photoconductive device due to the strong electric field in the depletion region giving carriers a greater velocity. Carriers within a diffusion length are also collected but much later than those in the depletion region.

1.4.3 HETEROJUNCTION

Heterojunctions are fabricated by growing a material [a] of bandgap $E_{ga}$ on a material [b] of bandgap $E_{gb}$. The lattice constants of the two materials must match very closely else dislocations and lattice imperfection will result. These generate interface states, recombination centres, electrically weak channels, and sources of thermal and temporal degradation.
Figure 1.5 depicts the band structures of an n-n⁺ and p⁺-n heterojunction for $E_{gx}>E_{gh}$ [Anderson et al., 1962]. Both junction types apply to commonly used heterojunction diode designs. Heterojunction photodiodes take advantage of the different bandgap energies. The semiconductor which forms the surface layer must have a wider band gap so that there is negligible absorption. As the light enters the narrower-bandgap material at a heterojunction, the absorption becomes strong, and this corresponds with the region where the electric field is high. Provided that the recombination velocity at the heterojunction is not excessive high quantum efficiency can be obtained. Photodiodes are very sensitive to crystal imperfections such as dislocations and trap centres. They raise the dark current and act as recombination centres for the optically generated carrier and hence diminish the quantum efficiency. Such defects will accumulate predominantly at the heterojunction, where the lattice is strained most since a small mismatch or contamination may be unavoidable during growth.

Careful fabrication of the heterojunction is required in order to reduce defects at the interfaces such as misfit dislocations. Lattice matching is therefore an important criterion for the materials used to form the interface. It is often not possible to obtain good lattice matching with the semiconductor materials required to provide detection at a specific wavelength and, hence, in reality lattice mismatched junctions have to be tolerated.

1.4.4 p-i-n PHOTODETECTOR
A p-i-n detector is typically formed by growing an intrinsic [lightly doped] layer on top of a highly doped n⁺ substrate and growing a p⁺ layer on top of the intrinsic layer. In practice the i region is approximated by either a high resistivity p [π] layer or a high resistivity n [ν] layer. Because of the low doping in the i region most of the potential will drop across this region. The p-i-n has advantages over the p-n junction device in that a wider depletion region can be obtained with the application of a small bias as compared to a similar bias applied to a p-n junction due to this low-doped i region. This then results in a lower capacitance and RC time constant [Gowor, 1984] The transit time however will increase. Typically p-n and p-i-n structures are heterojunctions, that is to say that they are composed of two different semiconductor materials, for example Al$_{0.27}$Ga$_{0.73}$As/GaAs for use at 680-880nm. The higher bandgap material [AlGaAs] sits on top, where light incident at $\lambda_0 = \hbar c/E_g$ is not absorbed but passes through to the intrinsic layer, which under bias is depleted of carriers as they are swept out continuously. This top transparent layer is called the window layer. The heterojunction window layer of the higher bandgap material allows for the photons to pass through and be collected in the i layer below. The
p-n junction of the device is placed away from the surface and thus reduces surface recombination.

1.4.5 SCHOTTKY BARRIER PHOTODETECTOR

A thin metal layer deposited on a semiconductor can form a Schottky barrier. If made thin enough the metal is transparent to the incident light. The depletion region is formed at the surface. Schottky devices are thus used for detectors of UV, where most of the light is absorbed close to the semiconductor surface. If we compare these devices from the point of view of applied electric field we can see that as well as the structure they also differ in the way this field is applied across the junction, see fig. 1.6. The electric field across the depletion region of the p-i-n structure is constant [ideally] whereas that in the p'-n junction falls off with distance into the n-region due to the higher doping and hence the fact that not all of it will be depleted by the applied bias.

Figure 1.6 Comparison of electric field profiles of various p-n homojunction structures; [a] p-n junction with both sides having the same doping level, [b] p'-n junction with p-side more heavily doped than the n-side, and [c] p'-i-n' structure with "i" and π lightly p-doped layer.

All the photodetector structures that have been discussed thus far have been based on inter-band absorption, fig. 1.7, where the absorption of a photon takes place between the energy levels of the conduction band and the valence band. Since the absorption of a photon, in this case, creates both an electron and a hole, the semiconductor does not need to be doped. As well as inter-band absorption there is also the possibility of intra-band absorption, fig. 1.7, [Gunapala et al., 1994; Chiu et al., 1983; Coon, 1984; Levine et al., 1987] using quantum well structures in semiconductors.
1.4.6 INTERSUBBAND ABSorption PHOTODETECTORS

The idea of intra-band absorption structures is to 'engineer' small bandgaps in wide bandgap semiconductors such as GaAs. The position of the energy levels or subbands in the quantum well are determined mainly by the height and the width of the well. Hence, by tailoring the quantum well structure, it should be possible to adjust the energy levels so that low energy IR photons can induce an intersub-band transition between the ground state and the first excited state of the quantum well, as in fig. 1.7.

Operation of these types of photodetectors is based on intersub-band transitions which can occur between two quantum well states. The carriers are excited from the filled ground state to the upper lying states [n-type] in the well where they can tunnel out to the continuum [continuous energy level above the quantum well] and in the presence of an electric field produce a photocurrent. This is known as bound-to-bound transition, fig. 1.8[b]. After absorption of an IR photon, electrons tunnel out of the wells, and since the mobility of these hot electrons is different from those confined in the wells, photoconductivity is observed. The main disadvantage of this is that the barriers must be thin enough to ensure the efficient tunnelling of the photoexcited electrons, but at the same time there would be large dark currents preventing high detection efficiency. By reducing the quantum well width it is possible to push the first excited state into the continuum and hence to excite the carriers from the ground state to the extended states in this continuum. This is known as bound-to-continuum transition, fig. 1.8[a] and the major advantages of this are that the barriers can be made as large as possible since the photoexcited electrons do not have to tunnel through the barrier to reach the continuum. This reduces the dark current due...
to tunneling and hence increases the quantum efficiency. Intersub-band photodetectors can be realised in larger bandgap materials such as GaAs/AlGaAs and InGaAs/InP which have a well developed technology rather than the narrow bandgap materials required for such long wavelengths which have growth and processing problems. In reality the use of these types of structures is limited by various problems.

They exhibit high dark current due to the fact that these detectors have to be doped in order to introduce electrons into the well for tunnelling to occur. Increasing the doping density in the wells leads to higher quantum efficiency but also leads to an increase in the dark current. These types of photodetectors also require sophisticated processing due to the fact that the incoming photons must strike the surface at the Brewster's angle [West et al., 1985] of the quantum well materials to allow coupling between the incoming radiation and the electrons that undergo such transitions. Many groups [Andersson et al., 1991; Sheng, 1991] have used gratings on top of the detector which deflect the light away from the direction normal to the surface. The gratings can be made by either depositing fine metal strips on top of the quantum well structure or etching grooves in a cap layer. These types of photodetector structures are an alternative to the conventional interband absorption ones but they are more complicated in practice to grow and to process.

1.5 APPLICATIONS
Photodetectors are used in a variety of applications which are too numerous to mention. Some common applications of IR photodetectors are shown in Table 1-4.
Many of the uses are military especially for the 8-14μm transmission window. For the detector designed in this thesis we are mainly interested in applications which cover the 2-5μm wavelength region. One such application is that of gas sensing of atmospheric pollutants. Table 1-5 shows some of these gases along with the wavelengths where they exhibit strong absorption bands. The absorption characteristics are defined mainly by the vibrational energy levels within a molecule. The quantized molecular vibrations occur at energies determined by the strength of the chemical bond, the mass of the atoms and the nature of the vibration. Vibrational modes can be classified as involving stretching, where the atoms move along the bond resulting in change in bond length,
or involving deformation or bending. In the latter case the molecules move perpendicular to the bond and hence require less energy. Although the masses of the bonded atoms influence the absorption wavelength, the neighbouring atoms and the surrounding environment will also have an effect. In general, a particular chemical group will not have a fixed wavelength for maximum absorption but will absorb radiation in a characteristic wavelength band, commonly referred to as the 'fingerprint' region [Herzberg, 1944]. For example, CH₄ has two strong absorption bands at 1.68μm and 3.39μm, though the one at 3.39μm is two orders of magnitude stronger than that at 1.68μm [Chon et al., 1984]. Designing a sensor which operates at both these wavelengths will provide an indication of which gas is present.

<table>
<thead>
<tr>
<th>NO₂</th>
<th>SO₂</th>
<th>CO₂</th>
<th>CO</th>
<th>H₂S</th>
<th>Hydrocarbons</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ[μm]</td>
<td>I</td>
<td>λ[μm]</td>
<td>I</td>
<td>λ[μm]</td>
<td>I</td>
</tr>
<tr>
<td>2.10 → M</td>
<td>2.0 → M</td>
<td>2.06 → M</td>
<td>2.30 → S</td>
<td>2.64 → S</td>
<td>3.03–3.51</td>
</tr>
<tr>
<td>2.41 → S</td>
<td>2.69 → S</td>
<td>2.77 → S</td>
<td></td>
<td></td>
<td>3.30–VS</td>
</tr>
<tr>
<td>3.09 → S</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.43</td>
</tr>
<tr>
<td>3.44 → VS</td>
<td></td>
<td></td>
<td>3.73 → S</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.75 → M</td>
<td></td>
<td></td>
<td>3.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.84 → M</td>
<td>4.0</td>
<td></td>
<td>4.12 → M</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.50 → M</td>
<td></td>
<td>4.26 → VS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.34</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The gas sensor under consideration would consist of a light source such as a light-emitting diode or laser and a photodetector which would be broad-band [if a laser is the light source] or wavelength selective [if LED is used depending on the range of wavelengths over which it operates]. The presence of a gas would be indicated by attenuation of the detector output signal. Absorption of this radiation follows the Beer-Lambert law which states that the transmittance $T$ of radiation through an absorbing medium decreases exponentially by the products of the extinction coefficient $k$, the concentration $c$ and the path length $l$:

$$T = \exp(-kcl)$$ \hspace{1cm} [1.5.1]

The extinction coefficient is dependent upon the wavelength of the radiation and the properties of the gas molecule. Hence, the gas concentration and its extinction coefficient [or its absorption per path length] would influence the strength of the detector output signal and how far apart the source and the detector would have to be placed in order to obtain a measurable reading from the detector. If a sensor is designed such that the width of the laser line output is less than or equal to the width of the absorption band of the gas under test then this fingerprint region could be detected by a broad-band detector. The converse is also true by using an LED and a wavelength selective detector which has an output signal bandwidth less than or equal to the absorption band of the gas.
Chapter 2

IMPORTANT FIGURES OF MERIT FOR PHOTODETECTORS

2.1 Introduction

2.2 Spectral Response and Responsivity

2.3 Quantum Efficiency

2.4 Speed of Response

2.5 Noise

2.5.1 Thermal [Johnson] Noise

2.5.2 Shot Noise

2.6 Detectivity [D*]

2.7 Summary

2.1 INTRODUCTION

As with most devices there is no unique set of characteristics which can be used to describe the "ideal" infrared detector, just as there is no "ideal" structure which will satisfy all the demands placed upon it by application needs. Classification of detectors is usually dependent on the mode of operation and the performance of individual detectors is described in terms of certain figures of merit and it is necessary to define these if a quantitative idea is required of the detector operation. These parameters provide an indication of detector performance and some of these have already been mentioned in Chapter 2 and will be expanded upon in this chapter.

Initially we will consider the spectral response of the detector which describes the change of the detector signal with wavelength and provides an indication of the range of wavelengths over which the detector has an appreciable response and also where the signal is greatest. This leads onto one of the most common figures of merit used for many devices, the quantum efficiency. This gives a measure of how much of the incident light energy is converted into electrical energy so providing an idea of how efficient the detector is. The factors that govern the speed of response of the detector are then discussed and guidelines provided for achieving high speed detection. The problem of noise which is inherent in all semiconductor devices in one form or another is then discussed which, finally, leads onto the most important parameter used to compare
photodetectors, the detectivity \([D^*]\). This is derived theoretically for both the photoconductive and photovoltaic modes of operation.

## 2.2 SPECTRAL RESPONSE AND RESPONSIVITY

The spectral response is possibly the most basic of all the figures and it describes the manner by which a detector changes its output signal in response to changes in wavelength of the input signal. For example, photon detectors ideally exhibit a spectral response which rises linearly with increasing wavelength, peaks, and then drops sharply to zero. This is because their response is generally proportional to the photon arrival rate for energies greater than the semiconductor absorption edge. Thermal detectors, on the other hand respond to the radiant power rather than the photon rate, and hence exhibit ideally a spectral response which is wavelength independent see fig. 2.1.

![Spectral Response Diagram](image)

**Figure 2.1** Comparison of detector response of thermal and photon type detectors

The wavelength of peak operation depends on the end application. Long-haul communications have an operating wavelength at 1.55\(\mu\)m, whereas for methane detection it is 3.39\(\mu\)m. As far as semiconductors are concerned being able to access the wavelength of interest depends on the material employed and also on the external conditions such as temperature as both these will affect the operational wavelength. A figure of merit associated with the spectral response is the responsivity which is a measure of the dependence of the signal output of a detector upon the input radiant power [Kruse, 1980], and hence it is important to specify the nature of the source. The usual convention for IR detectors is to speak of a black-body responsivity, \(R[T, f]\) and a spectral responsivity, \(R[\lambda, f]\), where the former represents the output signal in response to input radiation from a black-body at absolute temperature, \(T\), with signal measured at frequency, \(f\) and the latter represents the output signal measured at a frequency \(f\) in response to monochromatic radiation of wavelength, \(\lambda\), modulated at frequency \(f\). The responsivity is usually given by

\[
R = \frac{i_d}{\Phi} \quad \text{or} \quad \frac{v_d}{\Phi} \quad \text{[2.2.1]}
\]
where \( i_d = \text{output current of detector} \) and \( v_d = \text{output voltage} \).

The photon generated current can be derived by considering what happens when a beam of light of wavelength \( \lambda \) irradiates a photodetector. The rate of incident photons arriving at the photodetector is given by

\[
\eta_p = \frac{\Phi}{W_{ph}} \tag{2.2.2}
\]

where \( \Phi = \text{total light flux} \) and \( W_{ph} = \text{energy of a single photon} \).

The rate of photoelectron production is obtained by multiplying the incident photon rate by the quantum efficiency. Hence

\[
\eta_e = \frac{\eta \Phi \lambda}{hc} \tag{2.2.3}
\]

The generated photocurrent is therefore given by

\[
i_{ph} = \left( \frac{\eta \Phi \lambda}{hc} \right) q \tag{2.2.4}
\]

\[ R = \frac{\eta q}{hc} [\text{A/W}] \tag{2.2.5} \]

The responsivity depends strongly on the material and detector structure. Additionally it changes considerably with wavelength and it is a consequence of the wavelength dependence of the optical absorption that the responsivity is high only over a narrow range of wavelengths. Hence, careful consideration has to be given to the choice of detector type as well as to the detector material and its construction to achieve optimal responsivity. If the quantum efficiency was equal to unity, then a narrow bandgap material would, theoretically, have higher values of responsivity according to equation 2.2.5. Hence InSb \([E_g=0.17eV]\) should have a higher value of responsivity, assuming the same incident light power, than GaAs \([E_g=1.42eV]\), for example. In reality this is far from true as will be seen in the next section.

### 2.3 Quantum Efficiency \([\eta]\)

When optical power hits the diode window it will, in general, not be completely absorbed in the semiconductor and generate electron-hole pairs. Additionally not all the photogenerated carriers will contribute to the photocurrent, \(i_{ph}\). The ratio of the number of carriers contributing to the current and the number of photons hitting the diode surface per second is denoted the quantum efficiency \([\eta]\), where
The quantum efficiency describes how close to ideal a given photodetector gets. Both $\eta$ and the responsivity are functions of diode material, geometry, wavelength and temperature [Müller, 1981]. The quantum efficiency approaches 1 if all the optical power is absorbed in the lightly doped region of a p-i-n diode [see Chapter 3]. The carriers would then be separated immediately after their generation by the applied electric field and swept out of this depletion region. Hence this "i" region must be large compared to the light penetration depth, $1/\alpha$, and the drift time of these carriers must be short compared to their lifetime. However, there are a variety of physical which contribute to a reduction in the quantum efficiency or responsivity, respectively:

Due to the high refractive index, $n_s$, of semiconductors some of the light incident on the semiconductor surface will be reflected at the air-semiconductor interface. The reflectivity, $R$, is given by

$$R = |r|^2 = \frac{(n_s - n_o)^2 + k_s^2}{(n_s + n_o)^2 + k_s^2}$$

where $k_s = \frac{\lambda}{4 \pi \alpha}$

$r = \text{reflection coefficient, } \alpha = \text{absorption coefficient, } k_s = \text{imaginary part of the refractive index, } \lambda = \text{wavelength of operation, } n_s = \text{refractive index of semiconductor and } n_o = \text{refractive index of air}$

Since $n_s$ is usually between 3 and 4 for most semiconductors, about a third of the incident light is reflected. These reflection losses can be avoided by choosing an appropriate antireflection coating.
[ii] Referring to fig. 2.2, for a double homojunction structure, when light at a usable range of the semiconductor [with a high $\alpha$] falls on the detector it will be absorbed in the top, highly doped contact layer $[w_t]$. As there is no electric field in this layer, the generated minority carriers diffuse toward the depletion region of the diode. Depending on the thickness of this top layer, $w_t$, and the absorption coefficient, $\alpha$, a fraction of the intensity will be absorbed there

$$\frac{\Phi_1}{\Phi_0} = (1 - R)(1 - e^{-\alpha w_t})$$

where $R$ is the reflectance of the air-semiconductor interface and is $-0.3$ for no antireflection coating and 0 for an antireflection coating.

In the case $1/\alpha<<w_t$, most of the light is absorbed in this top layer and hence there may be a considerable reduction in the quantum efficiency due to recombination which will be made worse if the thickness of this layer is not small compared to the diffusion length

$$L_D = (D_n\tau_n)^{1/2}$$

$D_n$ = diffusion coefficient of electrons and holes respectively
$\tau_n$ = lifetimes of electrons and holes

Only those minority carriers will reach the depletion layer, before they recombine, which are generated approximately within a diffusion length of the junction. As both $D$ and $\tau$ can be very small for highly doped materials [$\sim 1 \times 10^7$/s and $10^2 - 10^5$ s] $L_D$ is of the order of a micron. Due to the abrupt end of the crystal lattice at the semiconductor surface, accompanied by dangling bonds and surface states, all semiconducting materials exhibit a surface recombination where the minority carriers recombine at an increased rate at the surface. This phenomenon can be
described by a surface recombination velocity which depends strongly on the semiconductor material, surface preparation and passivation. If this velocity is high enough a concentration gradient will develop toward the surface, which in the limiting case of \( v_{sr} \to \infty \) and \( L_D > w_t \) will make at least half of the carriers generated within the top layer recombine at the surface. For semiconductor materials with extremely small light penetration depths at the desired wavelength, as seen in direct bandgap materials, this top layer has to be extremely thin. This solution is not always practicable as a non-injecting contact requires a minimum thickness. Other solutions would be the use of a Schottky contact or a heterojunction [see Chapter 3].

[iii] the most desirable situation exists when almost all the light is absorbed within the depletion region. The fraction of power absorbed there is given by

\[
\frac{\Phi_1}{\Phi_0} = \eta = ((1 - R) e^{-aw_t})(1 - e^{-aw_i}) \quad \text{[2.3.5]}
\]

\( \frac{\Phi_1}{\Phi_0} \) is large when \( w_t \) is small compared to the light penetration depth

[iv] If the sum of \( w_t + w_i \) is not large compared to \( 1/\alpha \), the light will penetrate into the substrate and again will generate minority carriers which have to diffuse to the drift [i] region. The absorbed intensity takes the form

\[
\frac{\Phi_0}{\Phi_0} = ((1 - R) e^{-\alpha(w_t + w_i)})(1 - e^{-aw_i}) \quad \text{[2.3.6]}
\]

If the substrate thickness is large compared to \( 1/\alpha \) all of the remaining light is absorbed there \( [e^{-aw_t} = 0] \). The absorption of optical power in the substrate and the associated recombination loss might be tolerated due to:

[a] if \( w_t + w_i \gg 1/\alpha \), then the light entering the substrate is decreased considerably

[b] due to the relatively thick substrate, surface recombination is not significant.

It seems obvious that \( w_t \) has to be as small as possible and \( w_i \) as large as possible but in practice this can lead to difficulties and so a compromise has to be reached.

Carrier lifetime is normally much greater than the carrier transit time across the depletion layer so that a negligible fraction of carriers generated there are lost by recombination. Carriers generated within a diffusion length of the depletion layer edges may be collected over a period of the order of the recombination lifetime as a result of diffusion. Should these become an appreciable fraction of the total, the quantum efficiency would be reduced by the recombination that does occur, and
the frequency response of the diode would be impaired. It is important, then, that the minimisation of \( w_i \) and the maximisation of \( w_o \) should not be dependent on the effective extension of the depletion layer by the diffusion regions at either end. The p-n junction should be formed close to the surface, and the depletion layer width should be much greater than the attenuation distance. Hence \( w_i \ll 1/\alpha << l_d \), where \( l_d \) = diffusion length. If the first of these conditions is not met, surface recombination causes the quantum efficiency to be reduced. The surface recombination velocity should always be minimised, but when \( \alpha \) is large it may be necessary to resort to Schottky or heterojunction barrier diodes [see Chapter 3].

One of the key factors that determines \( \eta \) is the absorption coefficient, fig. 2.3. For Ge, Si and III-V compound semiconductors, the curves shift toward longer wavelengths as the temperature increases. For some IV-VI compound [e.g. PbSe] the opposite happens as the bandgap increases with increasing temperature. Since \( \alpha \) is a strong function of the wavelength, for a given semiconductor, the wavelength range in which appreciable photocurrent can be guaranteed is limited. The long wavelength cut-off, \( \lambda_{oc} \), is established by the \( E_g \) of the semiconductor i.e. 1.7\( \mu \)m for Ge and 1.1\( \mu \)m for Si. For wavelengths longer than \( \lambda_{oc} \), the values of \( \alpha \) are too small to give appreciable absorption. The short wavelength cut-off comes about because the value of \( \alpha \) for short wavelengths are very large \( [\geq 10^6/cm^{-1}] \) and the radiation is absorbed very near the surface where the recombination time is short. The photocarriers thus recombine before they can be collected in the p-n junction.

Fig. 2.4 shows some typical plots of quantum efficiency versus wavelength for some IR photodetectors with responsivity curves superimposed. In the UV and visible region, metal-semiconductor photodiodes show good quantum efficiencies. In the near IR Si photodiodes with
AR coatings can reach 100% quantum efficiency near 0.8 and 0.9μm. In the 1-1.6μm region, Ge photodetectors, III-V ternary photodetectors [GaInAs] and III-V quaternary photodetectors [e.g. InGaAsP] have shown good quantum efficiencies.

![Graph of Quantum Efficiency and Responsivity](image)

**Figure 2.4** Quantum efficiency and responsivity for IR photodetectors [S. M. See, 1981]

### 2.4 SPEED OF RESPONSE

The time response of a photodetector depends on wavelength, semiconductor material, diode geometry and load impedance of the external circuit. Fig. 2.5 shows a typical photodiode response to an optical pulse.

![Graph of Photodetector Response](image)

**Figure 2.5** Photodetector response to an optical pulse

Besides the form of the optical pulse three phenomena shape the electrical response, namely the carrier drift time in the depletion region, carrier diffusion in the non-depleted region, and, the RC time constant of the circuit impedance and the diode capacitance.

[i] Carrier Drift Time

The speed of response of a photodiode is fundamentally limited by the time it takes photogenerated carriers to drift across the depletion region. Whenever an electron or hole of
charge $q$ drifts with constant velocity through the depletion region of the photodetector, it gives rise to a conduction current $[i_d]$ in the electrical circuit during its drift time $[t_d]$

$$i_d = \frac{q}{t_d} \text{ .................................................. [2.4.1]}$$

The distance that the carrier has to travel and the drift velocity, $v_d$, determine $t_d$. The velocity, $v_d$, depends on the applied electric field strength, $F$, as

$$v_d = \mu F \text{ .................................................. [2.4.2]}$$

$\mu$ is the carrier mobility until it reaches the drift saturation velocity, $v_s$, at the drift saturation field strength, $F_s$. Whereas $\mu$ varies considerably with semiconductor material and doping concentration and is different for electrons and holes, as does $F_s$ [10$^4$-10$^5$V/cm] their drift saturation velocities approximate [0.5-1x10$^5$cm/s] for electric field strengths exceeding 10$^5$V/cm.

If the carriers are generated at one edge of the depletion, i, layer or are injected from the highly doped contact regions, they have to transverse all of the depletion layer, $w_i$. The drift time then is

$$t_{d,s} = \frac{w_i}{\mu_{p,n} F} \text{ for } F < F_{p,n} \text{ .................................................. [2.4.3a]}$$

and

$$t_{d,s} = \frac{w_i}{\mu_{p,n}} \text{ for } F \geq F_{p,n} \text{ .................................................. [2.4.3b]}$$

From equations 2.4.1 and 2.4.2 it is evident that a high electric field strength results in a short drift time and a high conduction current. If the drift region is not intrinsic, the electric field strength there is not constant, and the drift velocity may vary accordingly. For optimum design of a fast photodetector the doping of the depletion layer should stay below a concentration which keeps the electric field at the p-n junction below the breakdown field strength of the material while still sustaining $F_s$ at the opposite end of the drift region. Otherwise, part of the generated carriers will travel through a region of only a few or even no field strength and slow the frequency response considerably. A field strength above 2x10$^4$V/cm in Si gives maximum [saturated] carrier velocities of approximately 10$^5$cms$^{-1}$. Thus the transit time through a depletion layer width of 10$\mu$m is around 0.1ns.

[ii] Diffusion Time Constant

Carriers which are generated within the highly doped contact regions or in the absorbing but undepleted region have to diffuse to the drift region before they can contribute to the drift current. If an appreciable part of the optical power is absorbed there, this carrier diffusion will cause a
time spread of the carriers reaching the drift zone. This is a relatively slow process where the time
taken, $t_{\text{diff}}$, for carriers to diffuse a distance $d$ is written as

$$t_{\text{diff}} = \frac{d^2}{2D_c} \quad [2.4.4]$$

where $D_c$ is the minority carrier diffusion coefficient. For example, the hole diffusion time
through 10\,\mu m of Si is 40\,ns whereas the electron diffusion time over a similar distance is 8\,ns.

[iii] The RC Time Constant
In addition to the delay mechanism inside the diode, the imbedding network and diode housing in
combination with the diode impedance may limit the time response of the diode. The main
elements governing the time response are the depletion layer capacitance of the diode and the
series and load resistances, $R_s$ and $R_l$.

$$t_{\text{RC}} = (R_s + R_l)C_d \quad [2.4.5]$$

The depletion layer capacitance is given by $C_d = \varepsilon_r A/W$, where $A$ is the area of the diode and $\varepsilon_r$ is
the permittivity of the material. Hence a small depletion width, $W$, increases the junction
capacitance. This capacitance must be minimised in order to reduce the RC time constant which
also limits the detector response time. If we consider what is required to obtain a high speed yet
efficient photodetector we can see that a compromise has to be made in the thickness of the
deployment layer between high speed [thin depletion layer] or high quantum efficiency [thick
deployment layer], see table 2-1.

Table 2-1 Design criteria for fast and sensitive photodetectors

<table>
<thead>
<tr>
<th>Property</th>
<th>Short time response</th>
<th>High $\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift [depletion] Layer</td>
<td>Short [drift time]</td>
<td>Long [$w_r&gt;&gt;1/\alpha$]</td>
</tr>
<tr>
<td></td>
<td>Long [capacitance]</td>
<td></td>
</tr>
<tr>
<td>Drift Layer Doping</td>
<td>Low</td>
<td>Low [recombination]</td>
</tr>
<tr>
<td>Top Contact Layer</td>
<td>Thin</td>
<td>Thin</td>
</tr>
<tr>
<td>Surface Recombination</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Substrate Recombination</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Area</td>
<td>Small [capacitance]</td>
<td>Large</td>
</tr>
</tbody>
</table>

2.5 NOISE
The ultimate detection capability of any detection system is limited by random fluctuations of the
voltage and current that occur at its output terminals, both in the presence and absence of an
optical signal. The problem lies in the need to recognise the signal as something more than one of
the random fluctuations and an understanding of such phenomena is basic to any attempt to realise the ultimate performance of any detection system. The noise appearing in an IR system originates in a variety of sources and their individual contributions depends on wavelength, diode design and material, and electrical circuit.

Variations in the concentration and motion of the current carriers in the semiconductor give rise to fluctuations in the electrical output of the detector. The ability to detect the presence or absence of a signal rests upon the ability to discriminate against noise. Depending upon the application, most photodiodes seem to be limited by thermal or shot noise.

2.5.1 THERMAL [JOHNSON] NOISE
This is due to the random motion of electrical charges and it may be observed in the absence of an external bias. The carrier density fluctuations cause resistance variations which are observed as noise at finite bias currents. A derivation of this noise was put forward by Nyquist in the early part of this century [H. Nyquist, 1928] and this derivation has been covered by Kruse, 1980. The thermal noise current for a photodetector is given by

\[ I_{\text{N,th}} = \left( \frac{4kT B}{R} \right)^{1/2} \]  \[\text{[2.5.1]}\]

where \( B \) = bandwidth and \( R \) = resistance of the semiconductor detector.

2.5.2 SHOT NOISE
The electrons which make up the device current are discrete particles carrying discrete charge. When current flows in a device, the electrons are distributed in energy and momentum according to some distribution function. As a result, all electrons do not travel with the same velocity and energy and it is assumed that the variation in the number of electrons coming in during a time interval \( \Delta t \) is given by a Poisson distribution. This type of noise is referred to as shot noise [also photon noise or quantum noise], and is generated in a detector whenever random independent events occur. It can arise from the photon stream impinging upon a detector, or the current flowing in the detector resulting form electron-hole pair generation since both events involve discrete particles.

Shot noise also refers to the noise generated by the discreteness of the field. It can be classed into two types: [i] that due to the signal radiation alone and [ii] that due to the background radiation only. From the derivation by Singh, 1994, the shot noise is calculated to be
where $I$ is the detector average current and always exhibits a random fluctuation about its mean value as a result of the statistical nature of the quantum detection process. This fluctuation is exhibited as shot noise and is composed of all the currents which contribute to the photodetector current, namely photogenerated currents of the signal and diode reverse dark current. The dark current is that current which is generated when there is no intended optical signal and this too has shot noise associated with it. This may comprise some photogenerated current, $I_B$, arising from the background radiation entering the diode as well as the junction saturation current, $I_S$. $I_S$ is composed of three parts:

[i] the generation-recombination current in the drift region [depletion region]

$$i_{gr} = \frac{A n_i W_i}{\tau_i}$$  \hspace{1cm} [2.5.3]

where $W_i$ is the thickness of the depletion layer and $n_i$ is the intrinsic carrier concentration in the depletion layer and $\tau_i$ the minority carrier lifetime. To reduce this current $\tau_i$ needs to be as large as possible and this requires high quality, defect free material.

[ii] the minority carrier diffusion current of the highly doped contact regions which form the potential barriers in the p-i-n diode

$$i_d = A n_i \left[ \frac{1}{N_D} \left( \frac{D_p}{\tau_p} \right)^{1/2} + \frac{1}{N_A} \left( \frac{D_n}{\tau_n} \right)^{1/2} \right]$$  \hspace{1cm} [2.5.4]

where $N_{D,A}$ are the donor, acceptor concentrations in the $n^+$ and $p^+$ regions respectively, $\tau_{p,n}$ are minority carrier lifetimes of holes and electrons and $D_{p,n}$ are the diffusion coefficients of holes and electrons.

[iii] the reverse current flowing across the surface and periphery of the diode $i_{ls}$. This current is commonly called the surface leakage or leakage current. As it depends strongly on diode preparation, material and geometry there seems to be no definite expression for it.

The various contributions to the saturation current will be considered in detail in chapter 7 in relation to electrical results obtained on GaSb-based p-n$^+$ heterojunctions.

Hence to obtain a total low dark current, $i_d = i_{gr} + i_d + i_{ls}$, the minority carrier lifetimes should be as long as possible and the doping concentrations in the contact regions should be as high as possible to limit the diffusion current. The doping of the drift region should be as low as possible for a small generation-recombination current. As both $i_{gr}$ and $i_d$ are proportional to the volume of the different regions ($AW_i, A(D/\tau)^{1/2} = ALD/\tau$) a low dark current requires the smallest diode

$$I_{N,Sh} = (2q\overline{I}B)^{1/2}$$  \hspace{1cm} [2.5.2]
geometry possible with respect to the quantum efficiency. A small leakage current demands good passivation, low surface recombination velocity, and restricted peripheral regions. As \( i_a \) flows across the periphery of the diode, it varies approximately as the square root of the area.

The total noise current is therefore given by

\[
I_{N,\text{Total}} = I_{N,\text{Th}} + I_{N,\text{Sh}} \tag{2.5.5}
\]

Therefore

\[
I_{N,\text{Total}} = \left( \frac{4kTB}{R} \right)^{1/2} + (2q \bar{I} B)^{1/2} \tag{2.5.6}
\]

where \( \bar{I} = \) photodiode current.

If we consider the usual form of the diode equation [S. M. Sze, 1981]

\[
I = I_s \left( e^{qV/kT} - 1 \right) \tag{2.5.7}
\]

where \( I_s = \) reverse bias saturation current, then if we differentiate with respect to the voltage

\[
\text{Conductance}, \quad G = \frac{\delta I}{\delta V} = R^{-1} = \frac{\delta}{\delta V} \left[ I_s \left( e^{qV/kT} - 1 \right) \right]
\]

\[
\therefore R^{-1} = \frac{qI_s}{kT} e^{qV/kT}
\]

Hence

\[
R = \frac{kT}{qI_s} e^{-qV/kT} \tag{2.5.8}
\]

If equation 2.5.8 is substituted into that for the thermal noise current, then

\[
I_{N,\text{Th}} = \left( 4qB I_s e^{qV/kT} \right)^{1/2} \tag{2.5.9}
\]

Substituting equation 2.5.8 into the equation for shot noise current, then

\[
I_{N,\text{Sh}} = \left[ 2qB I_s \left( e^{qV/kT} - 1 \right) \right]^{1/2} \tag{2.5.10}
\]

Hence the total noise current [assuming it depends only on the thermal noise and on shot noise] is

\[
I_{N,\text{Total}} = \left[ \left( 2qI_s \left( e^{qV/kT} - 1 \right) + 4qI_s e^{qV/kT} \right) B \right]^{1/2} \tag{2.5.11}
\]

The form of equation 2.5.11 which is eventually used will depend on the mode of operation of the photodetector. This will be discussed in more detail in the next section but it will be mentioned here as it is important in the derivation of an important figure of merit, the specific detectivity \( D^* \).

\[ i \] \( V=0 \)

\[
I_{N,\text{Total}} = \left( 4qI_s B \right)^{1/2} \tag{2.5.12}
\]
The diode noise current is equal to the thermal noise current at zero bias. This is the photovoltaic mode of operation. At zero bias both the internal resistance of the photodiode and the device detectivity take particularly simple forms. From equation 2.5.8, the internal resistance of the device is determined by a knowledge of its zero bias junction saturation current. In this case the limiting device noise is the thermal noise associated with the internal resistance, equation 2.5.1.

\[ I_{N,\text{Total}} = (2qI_{S}B)^{1/2} \] \[ \text{[2.5.13]} \]

The diode noise current is equal to the shot noise current since the thermal noise current is too small to make any useful contribution. This is the photoconductive mode of operation and this is the form of noise which is most commonly used.

\[ I_{N,\text{Total}} = \left( \frac{4qI_{S}B}{T} \right)^{1/2} \] \[ \text{[2.5.14]} \]

Using equations 2.5.9 and 2.5.10, we can calculate the magnitudes of the various noise currents, using \( I_{S} = 10\text{nA} \), \( B = 1\text{Hz} \) and \( T = 300\text{K} \). From fig. 2.6 and table 2-2, when \( V>0 \), the total noise current is equal to the combined values of the thermal and shot noise currents. At \( V = 0 \), the total noise current is equal to the thermal noise current, as the shot noise current is much smaller in magnitude and at \( V<0 \), the total noise current is equal to the shot noise current. The eventual mode of operation is important when considering detector design as it effects the noise current and as a consequence the detecting capabilities of the detector. Fig. 2.6 shows the magnitude of the respective noise currents with respect to the applied bias. As can be seen at zero bias, thermal noise current dominates, whereas at large reverse bias shot noise dominates. In forward bias the picture is more complicated with both types of noise current contributing to the total noise current.
Figure 2.6 Graph showing the variation of the magnitude of the noise currents with applied bias. A log scale is used due to the small values of the noise currents but the shot noise and total noise currents are negative at \( V<0 \) [see Table 2-2]

Table 2-2 Chart showing the variation of noise currents with bias for GaSb

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<thead>
<tr>
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<tbody>
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</table>
2.6 SPECIFIC DETECTIVITY \([D^*]\)

This is probably the most important figure of merit, along with the responsivity used to distinguish between photodetectors at this time. Because the performance of infrared detectors is limited by noise, it is important to be able to specify a signal-to-noise ratio in response to the incident radiant power. An area independent figure of merit is \(D^*\), the specific detectivity, the units of which are cmHz\(^{1/2}\)/W\(^{-1}\). This is a figure of merit used to compare all infrared detectors and gives an idea of the detecting capabilities. The higher the value of \(D^*\) the better the detector. In order to derive the equation for \(D^*\) it is important to know some other figures of merit.

[i] Detectivity, \(D\): This is defined as the signal-to-noise ratio per unit radiant power and is the reciprocal of the noise equivalent power. Some confusion has arisen over the term detectivity and in many cases it is used to mean \(D^*\).

\[
D = \frac{1}{\text{NEP}} \quad \text{[Hz}^{1/2}\text{W}^{-1}]....................................................................................................................[2.6.1]
\]

[ii] Noise Equivalent Power, \(\text{NEP}\): This has largely been superseded by \(D^*\) but is still used in certain cases and is defined as the incident light level which produces a photocurrent equal to the noise level.

\[
\text{NEP} = \frac{\bar{I}}{R} \quad \text{[W]}....................................................................................................................[2.6.2]
\]

where \(\bar{I}\) is the noise current and \(R\) is the responsivity. The NEP is determined from the signal-to-noise ratio and the detecting capability of the detector improves as the NEP decreases. The signal-to-noise ratio \([\text{SNR}]\) is defined as the signal power at the output of the detector divided by the average noise power.

**Derivation of \(D^*\)**

The signal-to-noise ratio \([\text{SNR}]\) can be written as:

\[
\left(\frac{S}{N}\right)_{\text{power}} = \frac{I_{\text{signal}}^2 R_{\text{eq}}}{I_{\text{noise}}^2 R_{\text{eq}}}....................................................................................................................[2.6.3]
\]

where \(R_{\text{eq}}\) is the combination of all the resistances in the photodiode and the electrical circuit. \(I_{\text{signal}}^2 R_{\text{eq}}\) is the signal power and \(I_{\text{noise}}^2 R_{\text{eq}}\) is the noise power.

From equation 2.3.1

\[
I_{\text{signal}}^2 = \left(\frac{q\eta P_{\text{opt}}}{h\nu}\right)^2....................................................................................................................[2.6.4]
\]
From equation 2.5.11

\[ I_{\text{noise}} = \left[ 2qB_1(e^{\frac{qV}{kT}} - 1) + 4qB_1e^{\frac{qV}{kT}} \right] \] .......................................................................................[2.6.5]

Hence substituting equation 2.6.3 into equation 2.6.5

\[ \frac{S}{N} = \frac{\left( \frac{q\eta P_{\text{opt}}}{h\nu} \right)^2}{2qB_1(e^{\frac{qV}{kT}} - 1) + 4qB_1e^{\frac{qV}{kT}}} \] .......................................................................................[2.6.7]

The minimum optical power required to obtain a given signal-to-noise ratio is

\[ (P_{\text{opt}})_{\text{min}} = \left( \frac{S}{N} \right) \frac{\hbar^2\nu^2}{q^2\eta^2} \left[ 2qB_1(e^{\frac{qV}{kT}} - 1) + 4qB_1e^{\frac{qV}{kT}} \right] \] .......................................................................................[2.6.8]

The noise equivalent power [NEP] is given by \( \text{NEP} = (P_{\text{opt}})_{\text{min}} \) when \( S/N = 1 \) and \( B = 1 \text{Hz} \)

\[ \text{NEP} = \frac{\hbar\nu^2}{q\eta^2} \left[ 2qB_1(e^{\frac{qV}{kT}} - 1) + 4qB_1e^{\frac{qV}{kT}} \right]^{1/2} \] .......................................................................................[2.6.9]

Detectivity, \( D = \frac{1}{\text{NEP}} \)

\[ D = \frac{q\eta\lambda}{\hbar\nu^2(e^{\frac{qV}{kT}} - 1) + 4qB_1e^{\frac{qV}{kT}}} \] .......................................................................................[2.6.10]

Hence the specific detectivity, \( D^* = DA^{1/2} \) in units of cmHz^{1/2}W^{-1}

\[ D^* = \frac{\eta\lambda}{\hbar\nu^2(e^{\frac{qV}{kT}} - 1) + 4qB_1e^{\frac{qV}{kT}}}^{1/2} \] .......................................................................................[2.6.11]

Equation 2.6.11 is the general equation for a photodetector limited mainly by dark current.

\( V<0: \) Photoconductive Mode

From equation 2.5.13, \( I_{N,\text{Total}} = 2qI_S \)

\[ D_{\text{pc}} = \frac{\eta\lambda}{\hbar\nu^2(\frac{q}{2J_0})^{1/2}} \] .......................................................................................[2.6.12]

\( V>0: \) Photovoltaic Mode

From equation 2.5.12, \( I_{N,\text{Total}} = 4qI_S \)

\[ D_{\text{pv}} = \frac{\eta\lambda}{2h\nu^2(\frac{J_0}{q})} \] .......................................................................................[2.6.13]
CHAPTER 2 Important Figures of Merit for Photodetectors

where \( J_0 = \text{current density [A/cm}^2\)\]

The equation for \( D^* \) for the photovoltaic mode gives a lower value for the specific detectivity than that for the photoconductive mode assuming the other parameters are equal and the photoconductive mode is the one that is used more often in infrared detectors.

2.7 SUMMARY

The figures of merit which have been derived in this chapter are required in the design of efficient photodetectors and are used in the characterisation of all detector types in general. The maximisation of parameters such as the responsivity, \( \eta \) and \( D^* \) depend on the minimisation of parameters which will reduce the detector output signal be it a actual structure problem or an external circuit problem. The equations derived in this chapter for the various characteristics can be used to define the performance of a photodetector in order to obtain an idea of its detecting capabilities before it is grown.

As seen from the equations for \( \eta \) and the detector speed of response, there has to be a trade-off between the two. If a highly absorbing device is required, then the absorber region has to be as large as possible which in turn will increase the response of the detector by increasing the drift and diffusion times. But, it will result in a decrease in the RC time constant by keeping the junction capacitance small. The effect of this large depletion region width will depend on which of these time phenomena are limiting. The noise current can be due to a variety of reasons as was mentioned and to obtain a highly efficient detector this needs to be reduced such that the signal/noise ratio is large. Its influence on the NEP means that any small increase in the noise current will result in a large decrease in \( D^* \), as will be seen later in the thesis, thereby reducing the performance of the photodetector.

It has also been shown that depending on the mode of operation of the photodetector, two different forms of the equation involving \( D^* \) can be derived. Of the two, the mode of operation giving the highest value of \( D^* \) [2.6.12] should ideally be used [if possible]. To this end, the rest of this thesis is concerned with various photodetector structures and materials, in order to try and optimise these parameters.
Chapter 3

A COMPARISON OF SOME COMMON JUNCTION PHOTODETECTORS

3.1 Introduction
3.2 The p-n Junction
  3.2.1 Depletion Layer Width, Junction Capacitance and Response Time
3.3 The p-i-n Junction
  3.3.1 Mode of Operation
3.4 The Schottky Barrier Junction
  3.4.1 Mode of Operation
3.5 Summary

3.1 INTRODUCTION
Having considered the requirements demanded of photodetectors in the previous chapter, these will be applied and compared for different detector structures which are the basis of this chapter. There are many different detectors which can be utilised to achieve efficient detection in the infrared region. The three most common structures employed at the present time are the p-n junction, p-i-n junction and the Schottky barrier junction. The choice of any of these is dictated by many criteria such as high sensitivity at the wavelength of operation, room temperature operation, high speed and low noise properties. Most or all of these criteria are usually common to most applications. In reality, the choice of detector structure also depends to a great extent on the material chosen [as we shall see in Chapter 4] and how advanced the technology is. Ease of growth, processing and material quality will all influence the choice of detector structure.

This chapter begins with the p-n junction structure and discusses its mode of operation as well as the derivation of equations for the electric current and depletion region width in p-n junctions. These equations are generally common to most junction detector structures. This then leads onto the p-i-n junction structure which differs from the p-n junction in that it has a tailored depletion or “i” region. The two structure are compared along with the Schottky barrier junction structure.
The advantages of the Schottky-type structure are considered. Finally, we briefly introduce a fourth detector structure which is not widely used for photodetectors but more in modulators and vertical cavity lasers, the resonant cavity structure. This uses the principle of light enhancement via multiple reflection using the fact that the detector is incorporated between two mirrors which allow the light to undergo multiple passes. This will be covered in more detail in Chapter 5 theoretically. In this chapter we consider the advantages of the resonant cavity structure over the structures mentioned.

3.2 THE P-N JUNCTION

This is the basis for most infrared detectors and various methods are used in the manufacture of the p-n junction. Most commercial detectors [see Chapter 5] use diffused junctions though nearly all of the III-V detectors in research at the present time are grown by one of the epitaxy methods. When light impinges upon a semiconductor and generates electron-hole pairs, the detector performance depends upon collecting these carriers and thus changing the conductivity of the material or generating a voltage signal. In the absence of an electric field or a concentration gradient, the electron-hole pairs will recombine with each other and not generate a detectable signal. To collect the electron-hole pairs generated by the light one needs an electric field. This can be generated by either simply applying a bias across an undoped semiconductor or by using a p-n diode. The former choice leads to the photoconductive detector [see Chapter 1] in which the electron-hole pairs change the conductivity of the semiconductor. The p-n structure is widely used as a detector and exploits the built-in electric fields present at the junction together with an applied reverse bias to collect the electrons and holes.

![Diagram of p-n photodiode showing depletion and diffusion regions](image)

Fig. 3.1 shows a reverse-biased p-n [homojunction] photodiode with both the depletion region and diffusion regions. Under the influence of an electric field the mobile charge carriers are swept to their majority sides. The width of the depletion region is therefore dependent upon the doping.
concentrations for a given applied reverse bias. Photons may be absorbed in both the depletion region and the diffusion region, indicated by the absorption region in fig 3.1. The absorption regions position and width depends upon the energy of the incident photons and on the material from which the photodiode is fabricated. In the depletion region the carrier pairs separate and drift under the influence of the electric field, whereas outside this region the holes diffuse towards the depletion region in order to be collected. The diffusion process is very slow compared to drift and thus limits the response of the photodiode [Chapter 2]. It is therefore important that the photons are absorbed in the depletion region. Thus it is made as long as possible by decreasing the doping in the n-type material.

The current-voltage [I-V] characteristics of an ideal junction are shown in fig 3.2. For forward bias, the applied voltage reduces the height of the potential barrier allowing many more majority carriers from the neutral region to diffuse across the junction, thus giving rise to large diffusion currents. The diode current due to the flow of minority carriers from the neutral region are reduced by the reduction in the electric field across the depletion region. In reverse bias, the junction barrier is enhanced in magnitude. This leads to fewer majority carriers being of sufficient energy to pass over the barrier. Both the hole and electron components of diffusion current are negligible due to this large barrier [(V_D + V_f) where V_D is the built-in potential and V_f is the applied reverse bias] and the only current is a relatively small generation current which is due to the drift of generated carriers across the junction and is termed the dark current.

An applied forward bias, V = V_f, increases the probability that a carrier can diffuse across the junction by the factor $e^{V_f/kT}$. Hence, the diffusion current under forward bias is given by its equilibrium value multiplied by $e^{V_f/kT}$. Similarly for reverse bias, the diffusion current is the equilibrium value reduced by the same factor with $V = -V_r$. Since the equilibrium diffusion current

**Figure 3.2 I-V characteristics of a p-n junction**

Hence, at $V = 0$ [equilibrium] the diffusion and generation components of the current cancel and

$$I = I_{diff} - I_0 = 0.................................................................[3.2.1]$$

An applied forward bias, $V = V_f$, increases the probability that a carrier can diffuse across the junction by the factor $e^{V_f/kT}$. Hence, the diffusion current under forward bias is given by its equilibrium value multiplied by $e^{V_f/kT}$.
is equal in magnitude to the generation current, $I_0$, the diffusion current with applied bias is $I_0e^{VAT}$. The total current, $I$, for an ideal diode is then the diffusion current minus the generation current, $I_0$ [in the absence of incident light]:

$$I = I_0\left[e^{\frac{V}{kT}} - 1\right] \quad \text{[3.2.2]}$$

However in practice, the diode behaviour is somewhat different from the ideal case. The most obvious deviation is that at sufficiently large values of reverse bias, breakdown occurs. Reverse breakdown occurs by two mechanisms:

[a] Zener effect [Singh, 1994] which is due to quantum mechanical tunnelling. This usually occurs in heavily doped junctions which lead to narrow depletion layers and therefore high junction fields. In effect, the energy bands on the two sides of the junction become “crossed” so that filled states in the valence band of the p-side are aligned with empty bands in the conduction band of the n-side. Electrons, therefore, tunnel from the p- to n-side and in the process vastly increase the dark current.

[b] Avalanche breakdown [Sze, 1981; Streetman, 1990] occurs in lightly doped junctions with wide depletion layers and involves impact ionisation of the host atoms by energetic carriers. Neither breakdown mechanism is destructive to the diode in itself, however Joule heating due to too large reverse current may damage the device.

The second deviation arises from our having ignored such factors as carrier generation and recombination within the depletion region in the ideal diode equation, 3.2.2. This leads in some cases to the p-n junction, especially at low current, having a current-voltage relationship of the form

$$I = I_0\left[e^{\frac{V}{nkT}} - 1\right] \quad \text{[3.2.3]}$$

where $n$ is termed the ideality factor of the diode and normally varies between 1 and 2 depending on the semiconductor and the temperature. It determines the departure from the ideal diode characteristic and can be predicted from the forward biased semilog plot of the I-V curve of fig. 3.2. If $V$ is positive and greater than a few $kT/q$ [$kT/q = 0.0259V$ at room temperature], the exponential term is much greater than unity. The current thus increases exponentially with forward bias. When the diode is reverse biased, the exponential term in equation 3.2.3 approaches zero, and the output current, $I$, varies linearly with the light intensity and hence

$$I = -I_0 \quad \text{[3.2.4]}$$

where $I_0$ is termed the reverse saturation current [see Chapter 2]. Another reason why diodes do not exhibit ideal diode characteristics is due to surface effects. These will be covered in more detail in section 3.4, but these are due primarily to ionic charges on or outside the semiconductor

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surface that induce image charges in the semiconductor, hence forming surface channels or surface-depletion layer regions and thereby giving rise to surface leakage currents. Reasons for the high dark current and premature junction breakdown will be discussed in greater detail in chapter 7 in relation to the electrical characterisation of GaSb photodiode structures.

3.2.1 DEPLETION LAYER WIDTH, JUNCTION CAPACITANCE AND RESPONSE TIME

In most optical detection applications the detector's speed of response is important. If the photodiode is to respond to a series of light pulses 1ns apart, for example, the photogenerated minority carriers must diffuse to the junction and be swept across to the other side in a time much less than 1ns. The carrier diffusion step in this process is time consuming and should be eliminated if possible. Therefore, it is desirable that the width of the depletion region \( W \) be large enough so that most of the photons are absorbed within \( W \) rather than in the neutral \( n \) and \( p \) regions. When an electron-hole pair is created in the depletion region, the electric field sweeps the electron to the \( n \)-side and the holes to the \( p \)-side. Since this carrier drift occurs in a very short time, the response of the photodiode can be quite fast. It is desirable to dope at least one side of the junction lightly so that \( W \) can be made large. The equations for the penetration of the depletion region into the \( p \) and \( n \) sides have been derived in various texts [S. M. Sze, 1981; B. G. Streetman, 1990] and only the results will be presented here:

\[
x_{p\theta} = \left( \frac{2eV_0}{q} \left[ \frac{N_d}{N_a(N_a + N_d)} \right] \right)^{1/2} \tag{3.2.4}
\]

\[
x_{n\theta} = \left( \frac{2eV_0}{q} \left[ \frac{N_a}{N_d(N_a + N_d)} \right] \right)^{1/2} \tag{3.2.5}
\]

where

\( N_d \) = concentration of donors, \( N_a \) = concentration of acceptors, \( W \) = depletion region width,

\( x_{p\theta} \) = penetration of depletion region into \( p \) material, \( x_{n\theta} \) = penetration of depletion region into \( n \) material, and \( V_0 \) = applied voltage

Equations 3.2.4 and 3.2.5 predict that the transition region extends further into the side with the lighter doping. If \( N_a < N_d \), \( x_{p\theta} \) is large compared with \( x_{n\theta} \). Also the transition width \( W \) varies as the square root of the potential across the region. Hence an applied voltage can increase or decrease the potential across the depletion region, thus aiding or opposing the equilibrium electric field. Figure 3.3 shows the variation of depletion depth with change in carrier concentration for different values of applied bias. The smaller the values of carrier concentration the less the value
of the applied bias to deplete a certain thickness of active region. For example, if the depletion region thickness was 1 μm and the carrier concentration was $1 \times 10^{16} \text{cm}^{-3}$, then to deplete this we would need an applied bias of greater than 6V, whereas if the carrier concentration had been $5 \times 10^{15} \text{cm}^{-3}$, this would be depleted with ~2V.

![Graph of carrier concentration vs. depletion region width for various values of applied bias. The material used is GaSb which has $\varepsilon_r = 15.7$ [Sze, 1980] and $N_d = 1 \times 10^{19} \text{cm}^{-3}$](image)

The appropriate width for $W$ is chosen as a compromise between sensitivity and speed of response. If $W$ is wide, most of the incident photons will be absorbed in the depletion region. Also, a wide $W$ results in a small junction capacitance thereby reducing the RC time constant of the detector circuit. On the other hand, $W$ must not be so wide that the time required for drift of photogenerated carriers out of the depletion region is excessive.

$$C_j = \frac{\varepsilon A}{W} = \frac{2}{q \varepsilon_0} \left[ \frac{1}{N_a} + \frac{1}{N_d} \right] \frac{1}{\sqrt{\frac{2}{q \varepsilon_0} \left( V_0 + \sum \text{applied voltage} \right)}}$$  \[3.2.6\]

where $A$ is the diode junction area and $V_0$ is the sum of the built-in voltage and the applied voltage. Assuming that the area of the device is $10^4 \text{cm}^2$, we can see from figure 3.4 that the larger the depletion depth, the smaller the capacitance. This has important consequences when considering the response speed as a small capacitance is desirable in order to reduce the RC time constant, see section 2.4, which implies a large depletion width, figure 3.4. But, in order to minimise the drift time of carriers through the depletion region, the thickness of this region needs to be small which implies a large capacitance. Depending on which factor is limiting, the correct choice has to be made if high-speed photodiodes are required.
The speed of response of a photodetector is ultimately limited by the time the photogenerated carriers take to sweep across the depletion region. The electric field in the depletion region is usually greater than $2 \times 10^4 \text{V/cm}$, at which the carriers attain the scattering-limited [saturated] velocity of $\sim 10^7 \text{cm/s}$ [in Si]. Hence for $W = 10 \mu\text{m}$, the transit time can be as short as 0.1ns. In order to achieve high quantum efficiency the depletion-layer width must be wider than $1/\alpha$. Also, if $W$ is not sufficiently wide, the photocarriers generated beyond the depletion region would have to diffuse back into that region before they can be collected. Since the carrier diffusion times, see chapter 2, can be quite long [for example, the hole diffusion time through 10\mu m of Si is 40 ns], it is important, not only from the consideration of high quantum efficiency but also of high speed, to have a diode structure with a sufficiently wide depletion layer. If we consider the structure of fig. 3.5 then we can see what the influences are on photocurrent production when the absorber region material has a high background doping.

The carriers generated in $W_D$ by the incident light will be separated by the electric field, drift to their respective sides [electrons to the n-side and holes to the p-side] where they are collected as
photocurrent. Those minority electrons generated on the p-side in a length \( L_n \) will have to diffuse to the depletion region where they will then drift to the n-side and be collected as photocurrent. This diffusion of carriers is a much slower process than drift and hence if carrier diffusion forms the greater part of the photocurrent then the device speed will be reduced. The probability of these minority carriers recombining before reaching the depletion region is dependent on the diffusion length, \( L_n \), which is a product of the diffusion coefficient, \( D_n \), and the recombination time \( \tau_n \). The diffusion coefficient is dependent on the mobility of the carrier and this decreases as the carrier concentration increases. So, for a higher background doping of the absorber region the diffusion length will be smaller. One convenient method of controlling the width of the depletion region is to build a p-i-n photodetector. This has the same mode of operation as the p-n junction photodiode but the "i" region is lightly doped and "reaches through" to the heavily doped substrate at the normal operating voltage.

### 3.3 THE p-i-n JUNCTION

The "i" region need not be truly intrinsic, as long as the resistivity is high. When this device is reverse-biased, the applied voltage appears almost entirely across the intrinsic region, fig. 3.6 If the carrier lifetime within the "i" region is long compared with the drift time, most of the photogenerated carriers will be collected by the n' and p' regions.

At longer wavelengths where the light penetrates more deeply into the semiconductor material a wider depletion region is necessary and hence a p-i-n detector is the obvious choice. As the donor and acceptor impurity concentration are low, only a small reverse bias is needed to increase the width of the depletion region until we reach full depletion. The p-i-n diode has a very fast response time, nanoseconds or less, and is beginning to replace the basic photodiode as the 'standard photodetector'.
3.3.1 MODE OF OPERATION

The mode of operation is the same as that for the p-n junction photodiode except that p-n photodiodes have a lower response speed than the p-i-n photodiode due to the larger contribution of diffusion current. They are also a lot less efficient due to the incomplete depletion of the active region as compared to the p-i-n photodiode.

![Diagram]

Figure 3.7 Cross-sectional view of a p-i-n photodiode, [b] energy band diagram under reverse bias and [c] optical absorption

Since the diode is in reverse bias, the diode dark current, $I_d$, is independent of the applied bias. The photocurrent, $I_{ph}$, is mainly due to the carriers generated in the depletion region that are collected. The maximum current that can be collected [assuming that the intrinsic region is larger than the diffusion length of holes or electrons] is given by

$$I_{ph} = qA \int_0^W G(x) dx$$  \[3.3.1\]

where $W =$ depletion width, $A =$ area of device, $G(x) =$ electron-hole generation rate

If we account for the fact that as photons penetrate a material, their intensity decreases through absorption, see fig. 3.7, then the generation rate is given by

$$G(x) = \alpha \Phi_0 e^{-\alpha x}$$  \[3.3.2\]

where $\Phi_0$ is the photon flux at $x = 0$, see fig. 3.7[c]. From equations 3.3.1 and 3.3.2 the photocurrent is given by

$$I_{ph} = qA \Phi_0 \left(1 - e^{-\alpha W}\right)$$  \[3.3.3\]

If we take into account the reflectivity of the incident light from the front surface, then

$$I_{ph} = qA \Phi_0 \left(1 - R\right)\left[1 - e^{-\alpha W}\right]$$  \[3.3.4\]
Hence the rate of ratio of photocurrent density to the incident light flux [the detector quantum efficiency] is,

\[ \eta = \frac{I_{ph}}{A\Phi} = (1 - R)(1 - e^{-\alpha W}) \]  

[3.3.5]

If we consider the quantum efficiency as a function of both \( \alpha \) and \( d \), fig. 3.8, then as \( d \) and \( \alpha \) increase so does \( \eta \) for all the curves shown in fig. 3.8. The curves increase more steeply the greater the value of \( \alpha \) and eventually saturate at larger values of \( \alpha d \) such that large quantum efficiencies can be obtained for this depletion region [\( >2 \mu \text{m} \)] and large absorption coefficients [\( >1 \times 10^4 \text{ cm}^{-1} \)].

![Graph showing quantum efficiency as a function of depletion region width for various values of absorption coefficient.](image)

**Figure 3.8** Detector quantum efficiency as a function of depletion region width for various values of absorption coefficient.

Therefore, for high quantum efficiency one must have a small \( R \) [use of an antireflection coating] and a long \( W \). However, if \( W \) is too long the electron transit time that controls the device speed becomes too long, reducing the response of the device. High speed devices have \( W \) of about a micron or less and can operate at speeds in excess of 10GHz [J. Müller, 1981]. When direct or indirect bandgap materials far from the threshold are used, values of the absorption coefficient may be very large, \( \alpha > 10^6 \text{ m}^{-1} \). Good photodiode design then requires a very thin and heavily doped [therefore highly conducting] surface layer. Problems then arise from the proximity of the free surface with its relatively high surface recombination velocity. A large proportion of the carriers generated in the surface layer recombine at the surface rather than diffuse to the contact at the periphery or into the depletion layer. As a consequence, the quantum efficiency is impaired. One type of photodiode which can be used to minimise this problem is the Schottky barrier photodiode which will be discussed in the next section.
3.4 THE SCHOTTKY-BARRIER JUNCTION

The metal-semiconductor junction structure is useful for detectors operating in the visible and UV region of the electromagnetic spectrum where the absorption coefficients of most of the common semiconductors, [see fig. 2.3], are very high, which corresponds to an effective absorption length of $1/\alpha \sim 0.1 \mu m$ or less. They provide the possibility of designing photodiodes where most of the incident light is absorbed near the surface of the semiconductor. Generally, these types of devices seem fairly simple in construction and metal-i-n diodes and metal-n [or p] diodes are possible, but in practice, though the concept may be simple, it can be difficult to form good Schottky junctions in many materials [Rhoderick et al., 1988].

In practical Schottky diodes, the disruption of the crystal lattice at the surface produces a large number of surface states located in the forbidden bandgap. The situation at the surface of a crystalline solid is different from that prevailing in the bulk. Due to the absence of neighbouring atoms, the equilibrium positions adopted by the surface atoms differ from those corresponding to the perfect crystal lattice, and the surface is said to be relaxed or reconstructed. Dangling bonds give rise to localised states on the surface of the semiconductor with energy levels lying in the forbidden bandgap. These surface states are usually continuously distributed in the bandgap. On clean surfaces of covalent semiconductors the density of surface states equals the density of surface atoms. Adsorbed layers of foreign atoms may considerably reduce this density by completing the broken covalent bonds. The surface states modify the charge in the depletion region and so affect the barrier height. As a result the barrier height becomes independent of the metal work function and is said to be "pinned" by the surface states. This model of Fermi-level pinning was proposed by Bardeen [Bardeen, 1947] and explained the limited success of the proposition that Schottky barrier heights were due to this pinning mechanism by surface states. Much of the current interpretation of Schottky barriers is based on this Fermi-level pinning model but it is still unclear on the identification of the physical origin of the interface states responsible for the Fermi-level pinning at the metal-semiconductor interfaces.

3.4.1 MODE OF OPERATION

The Schottky diode has characteristics that are essentially similar to those of the p-n junction diode except that for many applications it has a much faster response. If we consider the ideal case, where there are no surface states in the bandgap of the semiconductor near the surface region, fig. 3.9, and if we assume that $\phi_m > \phi_s$ [$\phi_m$ is the work function of the metal and $\phi_s$ is the workfunction of the semiconductor], then when the junction between the two systems is formed, the Fermi level should line up at the junction and in the absence of any current remains flat. To
ensure the continuity of the vacuum level and keep the Fermi level flat, the Fermi level must move deeper into the bandgap from the semiconductor at the interface region. This involves electrons moving from the semiconductor to the metal side. Since the metal side has a very large electron density, the metal Fermi level does not change when a small fraction of electrons are added or taken out. As electrons move to the metal side, they leave behind positively charged, fixed ions, and a dipole region is formed in the same way as for the p-n diode.

In the ideal Schottky barrier, the height of the barrier at the metal-semiconductor junction is defined as

\[ q \phi_h = q \phi_m - q \chi_s \]  \hspace{1cm} [3.4.1]

where \( \chi_s \) is the electron affinity. The electrons coming for the semiconductor into the metal face a barrier denoted by \( q \phi_{bi} \). This is called the built-in potential of the diode and is given by

\[ q \phi_{bi} = q \phi_m - q \phi_s \]  \hspace{1cm} [3.4.2a]

\[ q \phi_{bi} = q \phi_s - q \phi_m \]  \hspace{1cm} [3.4.2b]

The height of the potential barrier can be altered by applying an external bias as was the case in the p-n diode, and the junction can be used for rectification. In practice, the Schottky barrier height is almost independent of the metal employed, as can be seen from table 3-1 which shows barrier heights of various semiconductors using a selection of metals.
Table 3-1 Schottky barrier heights [in volts] for several metals and p-type semiconductors.
The barrier is seen to have a weak dependence upon the metal used

<table>
<thead>
<tr>
<th>Schottky Metal</th>
<th>n-Si</th>
<th>p-Si</th>
<th>n-GaAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>0.7</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Ti</td>
<td>0.5</td>
<td>0.61</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>0.67</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Au</td>
<td>0.79</td>
<td>0.25</td>
<td>0.9</td>
</tr>
<tr>
<td>Ag</td>
<td></td>
<td>0.88</td>
<td></td>
</tr>
<tr>
<td>Pt</td>
<td></td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>PtSi</td>
<td>0.85</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>NiSi₂</td>
<td>0.7</td>
<td>0.45</td>
<td></td>
</tr>
</tbody>
</table>

From fig. 3.10, the distribution of interface states may be characterised by a neutral level $\phi_0$ having the properties that states below it are neutral if filled and above it are neutral if empty.

![Figure 3.10](image)

Figure 3.10 At a real metal-semiconductor interface, there are a large number of interface states in the bandgap region. If the interface density is high, the Fermi level is "pinned" at $\phi_0$ and the Schottky barrier is determined by $\phi_0$ and the material bandgap.

If the density of bandgap states near $\phi_0$ is very large, then the addition or depletion of electrons to the semiconductor does not alter the Fermi level position and the Fermi level is said to be "pinned". The Schottky barrier height is then given by

$$q\phi_b = E_g - q\phi_0$$

[3.4.3]

and is almost independent of the metal used. The detailed mechanism of interface state formation and Fermi level pinning is quite complex and beyond the scope of this thesis but a good description of various pinning mechanisms can be found in the thesis of S. Walters, 1989.

Once the Schottky barrier height is known, the depletion width and the depletion junction capacitance can be evaluated in the same as for a p-n junction. The problem is identical to that for a p'-n junction diode since there is no depletion in the metal side. We can assume the depletion...
approximation; there is no mobile charge in the depletion region and the semiconductor is neutral outside the depletion region. Then the solution of Poisson's equation [S. M. Sze, 1981] gives

$$W = \left( \frac{2\varepsilon (V_{bi} - V)}{qN_d} \right)^{1/2}$$

for \(N_d > N_i\) ........................................................................................................[3.4.4]

and the corresponding junction capacitance is

$$C = \frac{\varepsilon A}{W} = \frac{\varepsilon A}{W} \left[ \frac{qN_d}{2(V_{bi} - V)} \right]^{1/2}$$

........................................................................................................[3.4.5]

The current flow across a Schottky barrier can involve a number of different mechanisms with the most important being thermionic emission in which electrons with energy greater than the barrier height \([V_{bi} - V]\) can overcome the barrier and pass across the junction. As an electron enters the semiconductor through a contact and travels towards the junction, its path in the neutral region is determined by the drift-diffusion process. The net current at an applied bias, [Singh, 1994] \(V\), is

$$I = I_{sm} - I_{ms} = I_s \left[ e^{qV/kT} - 1 \right]$$

........................................................................................................[3.4.6]

where \(I_{sm}\) is the current flow from the semiconductor to the metal and \(I_{ms}\) is the current flow from the metal to the semiconductor.

The saturation current in the Schottky barrier turns out to be much higher than that in a p-i-n diode with similar built-in voltage. This results in a turn-on voltage for the forward bias conduction state occurring at a very low applied bias, but also results in a high reverse current. The electrons in the semiconductor side see a variable potential barrier as the applied bias changes while the current from the metal side remains essentially unchanged. If the barrier height is small [and comparable to a few kT] then the saturation current can be high. To avoid this, Schottky diodes with large barrier heights need to be used. In a real device the I-V characteristics have the form

$$I = I_s \left( e^{qV/kT} - 1 \right)$$

........................................................................................................[3.4.7]

where the ideality factor \(n\) is very close to 1 for the Schottky diode since the device has very little minority carrier participation and the recombination current is low.

**Advantages/Disadvantages of Schottky Diodes**

Although the choice between Schottky diodes and p-n junctions for device applications is usually dictated by purely technological considerations, it sometimes happens that both of them are technologically feasible, and the choice between them has then to be made by reference to their
electrical and optical properties. If we consider the growth and processing, then there a number of advantages offered by a Schottky barrier photodiode: [i] the act of forming the barrier can be a low-temperature process that does not degrade material properties, [ii] no diffusion or ion implantation is necessary to form the barrier, and, [iii] device can be made using semiconductors available in just one doping type. On the other hand, some common problems with these structures are: [i] the metal contact layer can reduce the amount of light coming from or entering into the semiconductor. This effect can be reduced by using thinner metal thicknesses or by using the metal in a grid pattern, [ii] many MIS devices have to rely on fixed charge in the interfacial layer for aiding barrier formation and in some cases this may degrade under illumination.

In practice, the barrier height of a Schottky diode is likely to be appreciably less than that of a p-n junction made from the same semiconductor. In the case of Si, for example, the lowest possible value of $\phi_m$, which occurs when the p-side of the p-n junction is very lightly doped, is about 0.8eV, while it is easy to make Schottky diodes with barrier heights in the range 0.5-0.6eV. Hence the saturation current density of a Schottky diode is likely to exceed that of a p-n junction made from the same semiconductor by a factor of $10^7$ or more, i.e. for the same current density the forward voltage drop across a p-n junction will exceed that across a Schottky diode by at least 0.4V. This makes the Schottky diode especially suitable for use as a low voltage, high current rectifier. Conversely, since the reverse saturation current is also larger, a Schottky diode is not as suitable as a p-n junction for use as a high-voltage, low current rectifier. There are other differences associated with p-n and Schottky junctions mainly to do with minority carrier injection [Rhoderick et al., 1988] in forward bias but these are of interest when operating these structures as bipolar transistors and light-emitting diodes which is beyond the scope of this thesis. Schottky junction photodiodes are used as low voltage, high current rectifiers. They can carry out all the rectification and switching functions of a p-n diode but at a very high speed. They are used in high-speed applications, in both digital and microwave systems. The speed of these sorts of detectors are limited by the RC time constant.
### Schottky Diode
- Weak temperature dependence of Schottky barrier as the reverse current is due to majority carriers that overcome the barrier.
- Forward current due to majority injection from the semiconductor.
- Small turn-on voltage.
- Switching speed controlled by thermalization of "hot" injected electrons across the barrier - few picoseconds. Speed is not dependent upon minority charge extraction via diffusion or recombination.
- Essentially no recombination in depletion region.
- Ideality factor - 1.0.
- The thermionic emission process has shown a current density of the order of $10^7$ A/cm² in Si and GaAs. Hence, for a given applied bias the current is higher than for a p-n diode.

### p-n Diode
- Strong temperature dependence as the currents are controlled by the diffusion process of minority carriers. Reverse current due to minority carriers diffusing to the depletion region.
- Forward current due to minority carrier injection from the n- and p-sides.
- Forward bias needed to make the device conducting is quite large.
- Switching speed controlled by recombination of minority injected carriers. Can be orders of magnitude slower than Schottky diodes.
- Ideality factor - 1.2-2.0 due to recombination in the depletion region.
- Lower saturation current density by four orders of magnitude.

---

**Figure 3.11** A comparison of some important properties of p-n and Schottky photodiodes.

Schottky barrier MS photodiodes which rely on absorption in the semiconductor have been studied for Ge and GaSb. The Ge devices have been shown to be minority carrier devices which serve as effective photodiodes. The GaSb devices have the advantage that GaSb is a direct bandgap material whereas Ge is indirect gap, hence GaSb devices have stronger absorption. Metal-semiconductor GaSb photodiodes have been reported with quantum efficiencies $>35\%$ [H. Nogoo et al., 1981]. Since more carriers are created in the barrier region for GaSb diodes, there
is less reliance on diffusion of minority carriers into the barrier. This increased reliance on drift in the barrier directly as opposed to diffusion into the barrier should give better high-speed response. Due to the superior high-speed response of devices which collect the photocurrent by drift directly, metal/lightly doped n/n structures are always advantageous because the barrier will extend further into a lightly doped region. The question of whether to design a device for collection by drift or diffusion is one that must considered taking into account the material used as the semiconductor and by considering the device application. If the semiconductor has a large diffusion length and if speed of response is not a consideration [it is not in solar cells but is in detectors] then collection by diffusion is attractive. If the semiconductor has a poor diffusion length or if speed of response is a consideration then collection by drift is the approach to be used.

From the detector structures that have been considered it is important to know what characteristics are required and hence which type of structure will meet all or some of these. For high quantum efficiency it is necessary to have a large depletion region in order to be able to generate as many carriers as possible and also to be able to deplete this region in order to maximise the chances of collecting as many of these carriers. For high speed photodiodes a thin depletion region is required in order to reduce the carrier drift time if this is the dominating mechanism, or a thick depletion region is required in order to minimise the junction capacitance if the RC time constant dominates. A trade-off therefore has to be reached between these two. These are not the only factors which influence the choice of diode structure, the semiconductor material employed also has a significant effect as shall be seen in the Chapter 4.

One of the main reasons for considering the final structure which will be discussed in this chapter is due to the material system, namely GaSb [see chapter 7] which will be used in the design of the photodetectors considered later in this thesis. From the previous structures, one of the most important requirements for efficient detectors is the low doping of the active or absorber region. This low doping allows the use of low values of bias in order to be able to fully deplete it and the lower the bias the larger the active region thickness that can be employed. But, not all materials have ideal material properties and GaSb falls into this category. These properties will be discussed in more detail in Chapter 5 of this thesis but, briefly, undoped GaSb grows p-type with a carrier concentration >10^{16} cm^{-3}. This will limit the active region thickness that can be used and hence also the quantum efficiency that can be achieved with the conventional detector structures. As a means of getting around this problem, the final structure considered is that of a resonant cavity detector.
The concept behind this is based on the Fabry-Perot effect and has been used for modulators and VCSELs for many years with some success. Only recently, in the last decade or so, has it been applied to detectors. It is based on the fact that the photocurrent can be enhanced in a detector by incorporating the active region in between two mirrors. The structure is designed in such a way that the incident light undergoes multiple passes in the active region hence causing an effective increase in the thickness of this region and so causing an enhancement in the photocurrent. It allows the use of thinner active regions whilst still having a high quantum efficiency. Conventionally a thinner active region implies reduced efficiency due to incomplete absorption of the incident light.

The advantages of this type of structure over conventional non-resonant structures are mainly due to the absorber region and where it is placed in the structure. The use of such thin active regions means that high speed diodes are possible and the effect that the absorber region is placed in between two mirrors means that the light will undergo multiple passes and hence increased absorption, when compared to the absorption achieved using the same value of active region thickness with a conventional non-resonant structure. Cavity structures also provide wavelength selectivity which may be an advantage for certain applications. Disadvantages of this type of structure are the complexity in the structure due to the additional mirrors either side of the absorber region and the increased accuracy required in the cavity thickness and in the mirror growth in order for the detector to operate at the resonant wavelength. These will be discussed in more detail in chapter 5.

3.5 SUMMARY

In this chapter we have introduced the most important detector configurations in use at the present. The carrier generation processes which occur in the structures have been discussed and equations derived for the detector current as well as for the depletion region width and capacitance, both of which influence the properties mentioned in chapter 2 such as $\eta$ and response speed. We have also considered the advantages and disadvantages of all the structures looked at in this chapter in relation to each other and also on their own merit.

In practice, when considering photodetectors and suitable structures, other factors will influence the choice such as the material system used, chapter 4, the ease of growth and processing, the application and so on. The equations considered here can help to predict some of the more important properties of the photodetector and comparisons can be made, from these results,
between the different configurations to decide which is best suited to the requirements. The resonant cavity structure has only briefly been introduced at the end of this chapter as it will be discussed in chapter 5 where various theoretical models will be used to predict the performance of various cavity designs.
CHAPTER 4 Photodetectors using other Material Systems

Chapter 4

PHOTODETECTORS USING OTHER MATERIAL SYSTEMS

4.1 Introduction

4.2 Growth Methods
   4.2.1 MBE [Molecular Beam Epitaxy]
   4.2.2 MOVPE [Metal-Organic Vapour Phase Epitaxy]

4.3 Silicon

4.4 Germanium

4.5 Impurity doped Si and Ge

4.6 The Lead Chalcogenide Family

4.7 Mercury Cadmium Telluride [MCT]

4.8 III-V Semiconductors
   4.8.1 InGaAs

4.9 Literature Review
   4.9.1 Commercial Infrared Photodetectors

4.10 Summary

4.1 INTRODUCTION

In semiconductor detector design, the choice of material system depends on the availability and ease of growth. Photodetectors using the group IV semiconductors, Si and Ge, have been extremely successful and are extensively available. For commercial applications these tend to consist of bulk material with diffused junctions. The success story has also been repeated in the last decade or so with the III-V semiconductor material InGaAs for the longer wavelength regions.

In this chapter we begin with a description of two common growth methods used to grow the photodetectors described in latter chapters, MBE and MOCVD. We shall consider the advantages and disadvantages of each method. Next we discuss different semiconductor material systems which are used in photodetector design. The first of these is Si [0.4-1 μm], mainly due to the fact that it has some of the best properties for highly efficient photodetectors and is nearly the ideal material for detector design at the present time. For the 1-1.6 μm region Ge reigns supreme,
although InGaAs is rapidly gaining ground and has a better D* in the wavelength region of operation of Ge, and with the addition of impurities, the wavelengths of operation of both Si and Ge can be increased to beyond 2μm. Other materials used in photodetector design in 2-5μm region are the II-VI material, HgCdTe, and the IV-VI materials, PbSe and PbS. HgCdTe is also used in the 8-14μm transmission window especially for thermal imaging purposes.

The lead-salt materials and HgCdTe are only briefly covered in this chapter as there is numerous literature available on these. The III-V materials are rapidly gaining popularity for many applications especially at the communications wavelengths 1.3 and 1.55μm. The most popular of these are the GaAs-based and InP-based materials for the 0.8-0.9μm region and the 1-1.6μm region, respectively. We shall consider InGaAs as an example of semiconductor detectors showing what can be achieved with the III-Vs.

4.2 GROWTH METHODS

We are mainly interested in two epitaxial growth processes, namely molecular beam epitaxy [MBE] and metal-organic vapour phase epitaxy [MOVPE]. In this project MBE was used to grow the mirror structures considered in chapter 6 for eventual use in the resonant cavity detector structure and MOVPE was used to grow the active regions in the eventual detector structures. A brief description of both methods will be followed by the disadvantages and advantages of each.

4.2.1 MBE [MOLECULAR BEAM EPITAXY]

![Figure 4.1: Evaporation cells inside a high vacuum chamber directing beams of elements and dopants onto a substrate](image)
Elemental sources are evaporated at a controlled rate onto a heated substrate under ultra-high vacuum [UHV] conditions. The substrates are initially etched and polished and then loaded into a preparation chamber where initial outgassing occurs. From this they are then moved into the growth chamber and positioned such that they are at the crossover point of all the various molecular and atomic beams. The elemental compounds are heated along with any dopants in separate cylindrical cells and collimated beams of the constituents escape into the vacuum and are directed onto the surface of the substrate. Depending on the nature of the Group V element present in the substrate, an overpressure of this element when growing prevents the substrate from incongruent melting caused by the loss from the surface of the more volatile Group V atoms. The rate at which these atomic beams strike the surface can be closely controlled. Abrupt changes in doping or crystal composition can be obtained by controlling the shutters in front of the individual beams. The atoms have a surface mobility dependent on surface mobility and they move about the crystal until they find a site on which to locate.

**Advantages [R. Grey, 1996]:**

[a] characterisation techniques such as RHEED [reflection high energy diffraction] can be used to monitor the growing surface. Auger Spectrometry can be performed either in the growth chamber or in the preparation chamber. This would normally be done during growth halts but could be carried out as the growth proceeds. It is also possible to use several techniques to determine the growth rate, in particular RHEED intensity oscillations, so allowing better control and reproducibility especially for very thin layers;

[b] very abrupt interfaces are possible in both matrix elements and dopants although diffusion of Be is fairly rapid. Layers can be grown, theoretically, down to partial monolayers, although controlled growth of continuous layers is probably limited to a minimum of 3-4 monolayers;

[c] the low growth temperatures used in MBE growth provide improvements in several ways: diffusion is reduced, low temperature growth of materials is possible [it is possible that relaxation processes are delayed at the lower temperatures];

[d] MBE is believed to provide AlGaAs based materials which are more suitable for transport devices;

[e] only high purity elemental sources are used in MBE, reducing the possibility of introduced contaminants.

**Disadvantages:**

[a] MBE systems [in common with other growth processes] normally rotate the sample during growth to provide optimum thickness uniformity from a distribution of cells. The temperature measurement is difficult as a result but this does not prevent accurate control of the sample
CHAPTER 4 Photodetectors using other Material Systems

temperature. One difficulty that rotation provides is the generation of particulates but the samples are mounted face down so that the particulate cannot contaminate the growth surface;
[b] the difficulty in ramping Knudsen cell temperatures to vary the flux in structures needing graded composition or doping. These cells have a high thermal mass and because they run at relatively low temperatures it is difficult to change the source temperature rapidly;
[c] the need to open up the UHV environment each time the elemental sources need to be replenished. The system requires approximately 2 weeks for the loading/bakeout cycle so is time consuming.

4.2.2 MOVPE [METAL-ORGANIC VAPOUR PHASE EPITAXY]
This makes use of reactions occurring between the vapours of volatile chemical compounds when they are heated together. These reactions produce chemically active species that interact either in the vapour phase or on a solid surface of the substrate to produce an epitaxial layer. Vapours from metal-organic compounds are used and in order to produce good material this requires that the concentration of the reactants is controlled in the vapour phase. Most of the literature describing MOVPE growth describes the growth of GaAs. We shall also consider this as it provides an idea of the reactions involved.

Typical starting materials for the growth of GaAs would be trimethylgallium [TMGa] and arsine [AsH₃]. The TMGa is a liquid at room temperature and is held in a stainless steel bubbler. H₂ is passed into the liquid TMGa and the bubbles of hydrogen become saturated with the TMGa vapour and this vapour is then transported to the reaction cell. The reaction takes place in a cell containing a graphite block called a susceptor which holds the GaAs substrate. The substrate is cleaned and polished before growth and etched in order to remove regions of the crystals that are damaged during the cutting and polishing. Material grown on substrates that have not been etched will result in defects which can extend up from the substrate and cause traps. The susceptor is and substrate are heated under AsH₃ to 800°C and the temperature switched to the growth temperature and the TMGa switched into the reactor cell to begin the growth of the epitaxial GaAs.

Advantages:
[a] the ability to grow highly pure semiconductor layers
[b] the development of safer and purer precursors which allow the growth of compounds at lower temperatures with lower impurity levels
[c] the possibility of scale-up to produce large areas of semiconductor material suitable for VLSI

Disadvantages:
[a] the use of toxic and pyrophoric materials on a large scale
[b] the difficulty of growing uniform quantum wells with abrupt interfaces over large areas
[c] the lack of any suitable in-situ characteristic method as in MBE ion order to provide information about the crystal quality

4.3 SILICON

Si is the material with the most advanced technology and due to its abundance and the relatively easy preparation of extremely pure, high quality single crystals, it is also the least expensive material with a nearly perfect lattice. Additionally the fabrication of all kinds of semiconductor devices is well advanced as is the surface passivation and stabilisation. Its electrical and thermal properties are excellent [Sze, 1981] and hence as far as devices go it is the preferred material of choice even though other materials may promise better performance. In the 0.4-1μm range Si is the best material for photodetectors. Above this range the light penetration depth 1/α is too short [<0.2μm] to allow a high quantum efficiency; above 1μm, 1/α increases beyond 0.1nm, and thus high-speed diodes with good quantum efficiency are no longer feasible. Table 4-1 summarises data of commercially available p-i-n photodiodes. Their time response usually exceeds 1ns both for pulse rise and fall time and peak quantum efficiencies of 60-80% are typical. The Si photodiode is one of the simplest forms of photodetectors and most commercial photodetectors use the form of fig. 4.2. SiO₂ is used to define the diode area as well as providing surface passivation and sometimes acting as an antireflection [AR] coating.

![Figure 4.2 Typical Si p-i-n photodetector structure](image)

The relatively large light penetration depths in the 0.8-0.9μm wavelength region [1-30μm] require drift regions of 30-100μm and hence bias voltages of 30-200V. The diffused contacts are usually a few microns thick to avoid carrier injection from the contact and to keep the electric field strength at the curved periphery sufficiently low to prevent breakdown there [Berz et al, 1979; Sze et al, 1966]
### CHAPTER 4 Photodetectors using other Material Systems

Table 4-1 Data of commercially available Si p-i-n photodiodes for $\lambda < 1\,\mu m$

<table>
<thead>
<tr>
<th>$\lambda_p$ [nm]</th>
<th>Hamamatsu</th>
<th>Siemens</th>
<th>RCA</th>
<th>Valvo</th>
<th>Quantrad</th>
<th>Centronic</th>
<th>EG&amp;G</th>
</tr>
</thead>
<tbody>
<tr>
<td>850</td>
<td>850</td>
<td>900</td>
<td>830</td>
<td>900</td>
<td>950</td>
<td>900</td>
<td></td>
</tr>
</tbody>
</table>

| Bias [V] | 50 | 20 | 45 | 10 | 60 | 80 | <180 |

| $R@\lambda_p$ [A/W] | 0.45 | 0.55 | 0.6 | 0.4 | 0.5 | 0.47 | 0.5 |

| QE @ $\lambda_p$ [%] | 65 | 80 | 83 | 60 | 65 | 65 | 65 |

| $I_d$ [mA] | 4 | 0.15 | 10 | 0.1 | 100 | 5 | 3 |

| $D^* @ \lambda_p [10^{12} \, cmHz^{1/2} W^{-1}]$ | 1.4 | 4.4 | 0.45 | 0.65 | 1.4 | 1.1 |

| Rise Time [ns] | 0.8 | 1 | 3 | 0.2 | 7 | 1 | 3 |

4.4 GERMANIUM

One of the main reasons for including Ge in this thesis is the fact that it is the detector that has been used as a reference for all our devices. It is a good comparison for bulk GaSb-based detectors as at the wavelength of operation in these devices [1.72$\mu m$] Ge has some of the best characteristics of any of the detectors at room temperature. The absorption edge of Ge is near 1.6$\mu m$ at room temperature, so its absorption coefficient is large [$\geq 10^4$ cm$^{-1}$] over the entire wavelength range [Sze, 1981]. Due to its small band gap Ge, in principle, covers the total wavelength range 0.8-1.7$\mu m$ which is especially useful for optical communications. As compared to Si it suffers from several severe drawbacks, which limit its practical applications to wavelengths greater than 1$\mu m$:

[i] The light penetration depth is $\sim 1\mu m$ up to wavelengths of 1.5$\mu m$. This allows a short drift region and a correspondingly fast time response on the one hand, but impairs the quantum efficiency, because much light is absorbed in the top layer of p-n junction diodes. Ge Schottky diodes, on the other hand, exhibit a reverse current characteristic which is too poor for a photodetector.

[ii] Surface recombination is very pronounced in Ge, which further reduces the quantum efficiency.
[iii] The dark current in Ge is fairly high due to its low band gap energy and high intrinsic carrier concentration. Therefore the thermal generation of electron-hole pairs is high. The dark current of Ge usually exceeds that of Si diodes by four orders of magnitude, see tables 4-1 and 4-2.

[iv] Surface and leakage currents are high as there is no stable and effective natural surface passivation as with SiO$_2$ for silicon.

All these restrictions considerably impair the performance of Ge diodes. Table 4-2 shows some important characteristics for commercial Ge photodetectors. As can be seen the dark current is in microamps as compared to Si photodetectors, see [table 4-1] where it is in nanoamps. This would in turn reduce the $D^*$ values of these photodetectors especially when compared to Si photodetectors at their respective operating wavelengths. Most commercial detectors have short light penetration depths and hence depletion layer widths of 3-10μm are sufficient to absorb the optical power up to wavelengths approaching 1.6μm.

<table>
<thead>
<tr>
<th></th>
<th>Rofin</th>
<th>Judson Infrared</th>
<th>Optitron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_p$ [μm]</td>
<td>1.45</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Bias [V]</td>
<td>10</td>
<td>9</td>
<td>30-45</td>
</tr>
<tr>
<td>$R@\lambda_p$ [A/W]</td>
<td>0.7</td>
<td>0.4</td>
<td>0.73</td>
</tr>
<tr>
<td>QE @ $\lambda_p$ [%]</td>
<td>73</td>
<td>33</td>
<td>60</td>
</tr>
<tr>
<td>Id [μA]</td>
<td>6</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>NEP @ $\lambda_p$ [$10^{-12}$cmHz$^{1/2}$/W]</td>
<td>3</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Rise Time [ns]</td>
<td>50</td>
<td>0.5</td>
<td>0.22</td>
</tr>
</tbody>
</table>

4.5 IMPURITY-DOPED SI AND GE PHOTODETECTORS

There has been considerable research in both Si and Ge to try and extend the operating wavelengths by the addition of impurity atoms to the crystals [Bratt, 1981], see [table 4-3]. The properties of these detectors result more from the characteristics of the impurity atoms rather than the host crystal. Impurity ionisation energies in silicon range from 0.04-0.55eV giving long wavelength cut-offs from 2 to 31μm. This large wavelength of sensitivity has been one of the key factors in the continuing research into these detector types. The first studies in impurity photoconductivity in Si were carried out in the early 1950’s. The energy levels of group III and V
impurities in these materials were already known due to the intensive work that had gone on a
decade earlier leading to the development of the transistor in 1948. Si was selected in the early
stages over Ge because there was little interest in detectors that detected out to 120μm. The main
goal was to find detectors that were highly sensitive in the 3-5 and 8-14μm atmospheric window
regions. The first results on photoconductivity in impurity Si were reported in 1952 by Burstein
and co-workers in 1953 and Rollins and Simmons in 1952. There has been a resurgence in the
efforts to develop these long wavelength Si detectors since they offer the capability of integration.

Table 4-3 Si and Ge dopants and their wavelengths of operation

<table>
<thead>
<tr>
<th>Impurity Atom</th>
<th>λₚ [μm]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge:In</td>
<td>4.3</td>
<td>R. A. Messinger, 1971</td>
</tr>
<tr>
<td>Ge:Zn⁺</td>
<td>2.5</td>
<td>J. Henman, 1973</td>
</tr>
<tr>
<td>Ge:Zn⁻</td>
<td>1.4</td>
<td>J. Henman, 1973</td>
</tr>
<tr>
<td>Ge:S</td>
<td>1.8</td>
<td>C. T. Sah, 1971</td>
</tr>
<tr>
<td>Ge:Hg</td>
<td>10</td>
<td>R. A. Chapman, 1965</td>
</tr>
<tr>
<td>Ge:Cu</td>
<td>23</td>
<td>W. Kaiser, 1954</td>
</tr>
<tr>
<td>Ge:Au</td>
<td>2</td>
<td>L. F. Johnson, 1960</td>
</tr>
<tr>
<td>Si:B</td>
<td>23</td>
<td>G. Burstein, 1956</td>
</tr>
<tr>
<td>Si:Al</td>
<td>15</td>
<td>G. Burstein, 1956</td>
</tr>
<tr>
<td>Si:Ga</td>
<td>15</td>
<td>G. Burstein, 1956</td>
</tr>
<tr>
<td>Si:In</td>
<td>4.3</td>
<td>R. A. Messinger, 1971</td>
</tr>
</tbody>
</table>

As with Si, research has also been carried out to try and extend the wavelength of Ge to cover the
longer wavelength regions. It has impurity ionisation energies which range from 0.01-0.35eV
[3.5μm to 120μm]. The first studies were also carried out in the 1950’s and Burstein et al., 1954,
were successful in making IR detectors of Ge:Au and Ge:Cu. Ge was much more widely
researched at this point due to the better sensitivity that could be obtained from Ge than Si. This
was due to the longer photocarrier lifetimes as Ge could be made more pure than Si with respect
to compensating donor and acceptor atoms. Ge:Au was used as a very sensitive detector for the 3-
5μm region but lost out subsequently to PbSe and InSb. These detectors are available
commercially nowadays, see [table 4-4], mainly beyond 5μm, although as has been mentioned the
research into similar Si detectors is increasing mainly due to the fact that Si offers higher
impurity concentrations, resulting in higher absorption of radiation per unit path length, as well as
lower dielectric constant and better developed device technology.
4.6 THE LEAD CHALCOGENIDE FAMILY

Most fundamental studies have been devoted to the compounds PbS, PbTe, PbSe and to the ternary alloys PbS_{1-x}Se_{x}, Pb_{1-x}Sn_{x}Te and Pb_{1-x}Sn_{x}Se. All these materials are direct energy gap semiconductors. Doping is easily realised by deviation from stoichiometry leading to high carrier concentrations up to \(10^{19}-10^{20}\text{cm}^{-3}\). By careful annealing it is possible to lower the extrinsic carrier concentration into the \(10^{14}-10^{16}\text{cm}^{-3}\) range [Meingaillais et al., 1970]. Measured lifetimes are usually lower by an order of magnitude than the theoretical estimates, for intrinsic recombination, as compared to small bandgap CMT. Hence extrinsic recombination due to point centres and extended defects appears to be significant [Lischko, 1978]

Background noise-limited detectivity has been obtained in the 4-6\text{µm} wavelength range using epitaxial PbSe Schottky barrier diodes cooled at 77K [Hohuke, 1974]. Despite the extensive research, most of the efforts to develop epitaxial detectors for the medium and long wavelength ranges have concentrated on the CMT alloys because

[i] the high average carrier concentration \([-10^{17}\text{cm}^{-3}]\) in the lead salts causes diode leakage
[ii] high dielectric constants give large resistance capacity [RC] diode time constants, and
[iii] the large thermal expansion coefficient leads to a strong thermal mismatch with respect to alternative substrates, such as GaAs and Si.
It has been shown that these drawbacks could be partially overcome by growing a special buffer layer on a Si substrate [Zogg et al., 1985]. Plastic deformation of the buffer layer is invoked to explain the strain relief when cooling down from growth to room temperature. The lead-chalcogenide films are then grown by MBE. It appears that the best PbTe on silicon sensors are at the level of CMT detectors with comparable cut-off wavelengths. The Pb_{1-x}Sn_{x}Se devices are a factor of 2-5 below [Zogg et al., 1991].

4.7 CADMIUM MERCURY TELLURIDE [CMT]
The Hg_{1-x}Cd_{x}Te alloy is one of the most thoroughly studied semiconductors outranked only by GaAs and Si. The research began in the 1950's when W. D. Lawson and co-workers, 1959, at the Royal Radar Establishment at Malvern discovered that Hg_{1-x}Cd_{x}Te alloys were semiconductors with bandgaps that could be varied from 0.0 to 1.605eV as x increased from 0.17 to 1.0. From then on progress was rapid. By 1965 CMT photoconductive IR detector technology had advanced sufficiently that prototype detectors could be made for thermal imaging systems. In the 1970's Hg_{1-x}Cd_{x}Te detector technology matured especially for the 8-12μm range, x=0.2. Other compositions suitable for use in the 1-3, 3-5, and 14-30μm range were also investigated. The demonstration of long-wavelength photoconductivity in these alloys has led the way for subsequent development of IR detectors and these have found widespread use in applications in military, space and industrial systems [Broudt et al., 1981].

There is a continuous range of solid solutions between CdTe and HgTe all having a zincblende lattice. The lattice constant varies from 4.481Å for CdTe to 4.463Å for HgTe. A lot of attention has focused on the compositions around x=0.2-0.3 which corresponds to the 2 regions of long wavelength IR [8-12μm] and medium IR [3-5μm]. As far as the growth is concerned, the present trend is toward highly homogenous and perfect materials grown by epitaxy. Presently, CMT epilayers are most frequently fabricated using liquid-phase epitaxy [LPE], where CdTe or a lattice-matched alloy [CdZnTe, CdSeTe] are used as the substrate and this has provided materials with low dislocation densities, carrier concentrations and good composition [K. H. Hermann, 1978]. However, at the growth temperatures used [450-500°C], chemical interdiffusion produces graded interfaces and hence sharp heterojunctions are not feasible. To achieve these abrupt device/substrate heterojunctions, epitaxial growth of CMT has been driven to lower temperatures, using chemical vapour deposition or molecular beam techniques. These methods also offer the possibility of being able to grow layers on heterosubstrates, such as GaAs or Si. Despite the large lattice mismatch good electrical properties have been reported [Broudy et al., 1981; Lange et al., 1988; Zogg et al., 1986; Flanders et al., 1990; Sporken et al., 1990]. These techniques minimise
CHAPTER 4 Photodetectors using other Material Systems

interdiffusion but they are more sensitive to wafer quality at the surface. Additionally, the fast diffusion of Hg along dislocation centres has resulted in a demand for minimisation of extended defects. The small dependence of the lattice constant on the Cd molar fraction, x, of CMT has made it relatively easy to grow epitaxial layers or heterostructures across the wide IR spectral range of 1-14µm without the severe lattice-matching constraints usually found.

The attractions of using CMT as a detector material are quite obvious. The energy gap can be adjusted between 0 and 1.6eV and hence they can be used for IR detectors in all three wavelength regions of interest; 1-3µm, 3-5µm, 8-14µm. Also the detectivities [see table 4-5] of MCT detectors are very high and can usually reach background limited performance [BLIP] at higher operating temperatures [>77K] due to the longer lifetime of the photoinduced minority carriers and lower dark currents [Shen, 1993]. Despite achievements in material and device quality, CMT has one of the most serious technological problems of any material in mass production. Difficulties still exist due to lattice, surface and interface stabilities. Shortcomings such as mechanical softness and sensitivity to elevated temperatures are fundamental and there is no way to improve the material in these respects. Other problems such as a high density of Shockley-Read-Hall trap centres [Szc, 1981], which cause tunnelling leakage current and dark current, and the non-uniformity of the detectivity and response wavelength are not fundamental but are problems related to compositional inhomogeneity and defects. However these may also be caused by native defects due to the weakness of the Hg-Te chemical bond and hence may be quite difficult to solve. The difficulties encountered with CMT has made it desirable to examine other material systems in the search for a viable alternative.

4.8 III-V SEMICONDUCTORS

As an alternative to the well-studied detector materials already mentioned the III-V's are now coming into their own. They are not, as yet, widely available as commercial IR detectors apart from InSb and, lately, InGaAs. Various III-V semiconductor alloys are under active investigation for use as detector materials for longer wavelength applications. An attractive feature of these alloys is that their bandgaps depend upon composition, hence it is possible to optimise detector performance by choosing a composition which places the absorption edge just above the wavelength of operation, thereby ensuring high quantum efficiency and speed of response with minimum dark current. Experimental photodetectors have been made using various III-V alloys, including GaAs, AlGaAs, InGaAs, GaAsSb, GaAlSb and InGaAsP. GaAs is the best researched of all the III-V's and is used extensively in many devices. The III-V's used in the near IR still have growth and surface passivation problems which have yet to be solved and considerable
research at present is focused on ternary and quaternary-alloy materials and photodiodes. p-n photodiodes made with III-V materials, notably InGaAs on GaAs or InP, have been studied as an alternative to Ge photodiectors for the 1-1.8μm region. Initial studies carried out on III-V materials for lasers promised good p-i-n diodes.

4.8.1 InGaAs

Due to its ability to respond over the entire 1-1.6μm range and the relative ease with which high purity material can be prepared the GaInAs homojunction photodiode has received a lot of attention. Mesa geometries have been described with front illumination, fig. 4.3[a], through a thin p-region [Pearsall et al., 1978; Popuchon et al., 1978; Leheny et al., 1979], window layer [Holsen, 1981], or with rear illumination, fig. 4.3[b], through the InP substrate [Popuchon et al., 1978; Burrus et al., 1981]. Planar geometry devices with front or rear illumination have also been reported [Susa et al., 1979; Forrest et al., 1982]. The use of rear illumination through an InP wide bandgap window layer offers a key advantage. All the photons will be absorbed within the n-type depletion region if it is made sufficiently large. This eliminates the surface recombination that occurs when some of the light is absorbed in the p-InGaAs region of a top-illuminated structure and increases the quantum efficiency close to the bandgap. Rear-illuminated devices, may be faster since carriers are generated directly in the depletion region and are not required to diffuse there from the p-layer [Lee et al., 1981]. Restriction of the junction region to the smallest possible area minimises both the photodiode capacitance and dark current. In the case of the planar device, the junction is formed by diffusion through a mask and the junction of a mesa device may be formed by diffusion or during epitaxial growth by suitable doping.

Figure 4.3 [a] Mesa and [b] planar geometries of InGaAs p-i-n photodiodes. Illumination may be either through a thin p-region or through the transparent InP substrate.

-78-
The design parameters of a GaInAs p-i-n photodiode can be determined from the graphs of fig. 4.4, 4.5 and 4.6. Fig. 4.4 shows the depletion region width as a function of the carrier concentration for varying values of applied bias. For a 1μm of active region, if the applied bias is to be <10V, then the carrier concentration has to be less than \(1 \times 10^{16}\) cm\(^{-3}\). Obviously the larger the active region the greater the quantum efficiency of the detector, fig. 4.5.

![Figure 4.4 Depletion region thickness as a function of the applied bias and the carrier concentration for In\(_{0.53}\)Ga\(_{0.47}\)As](image)

A large depletion region thickness results in a reduced junction device capacitance, fig. 4.4, where the junction capacitance \(C = \varepsilon A/W\) is for a junction area of \(10^{-4}\) cm\(^2\), and hence a slower device response speed due to the transit time constant being increased but does give high quantum efficiency, assuming an absorption coefficient of \(\alpha = 10^4\) cm\(^{-1}\). From this it can be seen that design of a p-i-n diode with \(\eta > 90\%\) and capacitance less than 0.5pF requires a depletion layer width greater than about 2μm. Devices with these characteristics have been reported by [R. F. Leeney et al., 1981; R. G. Denton et al., 1981]. Hence a trade-off has to be reached between a highly efficient device and hence a large absorption region or a fast response and therefore a thinner absorption region.
When designing a photodetector it is useful to know what sort of applied voltages the device can tolerate and this depends, as can be seen from fig. 4.6, on the carrier concentration of the active region. Fig. 4.6 assumes that breakdown is due to avalanche breakdown which is the breakdown mechanism which sets an upper limit to the reverse bias voltage. From Sze, 1981, a general expression has been derived for this breakdown voltage which covers all semiconductors:

$$V_B = 60 \left( \frac{E_G}{1.1} \right)^{3/2} \left( \frac{N_D}{10^{16}} \right)^{3/4}$$  \[\text{[4.8.1]}\]

where $N_D$ is the carrier concentration of the depletion region and $E_G$ is the room temperature bandgap in eV. This has been plotted for InGaAs and a GaInAsP compositions. The breakdown voltage is large when the carrier concentration is very small [of the order of $10^{14}$ cm$^{-3}$] but as the carrier concentration increases the breakdown voltage drops rapidly and is less than 10V for a carrier concentration of $10^{17}$ cm$^{-3}$.
The maximum speed of the p-i-n photodiode, section 2.4, depends only on junction capacitance and depletion width as long as the carrier diffusion effects are avoided as in a properly designed rear-illuminated junction. By designing a photodiode with a contact area of 25µm, a junction capacitance of 0.1pF can be achieved, which in a high speed 50Ω circuit will give a circuit time-limited response of only 5ps. The transit time contribution for W=2µm is about 20ps. Such high-speed mesa geometry InGaAs p-i-n photodiodes have been demonstrated [T. P. Lee et al., 1981].

For the planar geometry of fig. 4.3[b] care must be taken to prevent illumination of the undepleted n-region surrounding the depletion region. If this should occur, a slower response will result due to hole diffusion to the depletion region.

Nishida et al., in 1979 were the first to show that special device structures employing wider gap junctions and using a narrow gap junction as the absorption region only, could be used to significantly reduce the dark current. The major application for this concept is for APDs, which operate at large reverse bias voltages near breakdown. Another adaptation of this idea is for p-i-n photodiodes designed to be operated at low bias voltages [0-10V [Capasso et al., 1980; Pearsall et al., 1981]]. One such heterostructure [Pearsall et al., 1981] consists of a p' layer of InGaAs grown on low-doped n-InP. Dopant diffusion leads to a junction in the InP layer close to the heterointerface. A 50-fold reduction in dark current over a homostructure has been demonstrated. At 14V the maximum quantum efficiency of 60% is obtained. Using this structure, the room temperature dark current for a photodiode of 200µm diameter is 10⁻¹⁰A, and at 60°C, the current is 4nA, under an operating bias of 1V [Pearsall et al., 1981].

4.9 LITERATURE REVIEW
4.9.1 COMMERCIAL INFRARED PHOTODETECTORS

<table>
<thead>
<tr>
<th>Detector</th>
<th>Type</th>
<th>( \lambda_0 ) [µm]</th>
<th>Operating Temp. [K]</th>
<th>Responsivity [V/W or A/W]</th>
<th>Response Time</th>
<th>Detectivity ([D^*] ) @ ( \lambda_0 ) cmHz(^{10^9})W⁻¹</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge</td>
<td>APD</td>
<td>0.8-1.7 ([\lambda_p = 1.55])</td>
<td>300</td>
<td>0.8A/W</td>
<td>2µs</td>
<td>Gain, ( M = 10 ) at 0.86µm</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>PV</td>
<td>([\lambda_p = 1.4])</td>
<td>77</td>
<td>0.75A/W</td>
<td></td>
<td>( 8 \times 10^{15} )</td>
<td></td>
</tr>
</tbody>
</table>
## CHAPTER 4 Photodetectors using other Material Systems

| Detector | Type | $\lambda_0$ [\(\mu\m)] | Operating Temp. [K] | Responsivity [V/W or A/W] | Response Time | Detectivity $|D^*| @ \lambda_p$ cm Hz$^{0.5}$/W$^{-1}$ |
|----------|------|------------------------|---------------------|--------------------------|--------------|---------------------------------|
| InGaAs   | PV   | 0.8-1.65 ($\lambda_p = 1.5$) | 300                | 40V/W @ 1500nm          | 85ps         | 5x10$^{12}$                     |
|          | PV   | 1.2-2.6 ($\lambda_p = 2.4$) | 300                | 1A/W                    | 0.3-10ns     | 5x10$^{11}$                     |
| MCT      | PC   | 3-5 ($\lambda_p = 4.5$)   | 77                 |                          | 1\(\mu\)s    | 8x10$^{11}$                     |
|          | PC   | 3-6 ($\lambda_p = 3.6$)   | 77                 |                          | 0.4-6\(\mu\)s| 1.5x10$^{11}$                   |
|          | PC   | 3-5 ($\lambda_p = 4.4$-4.6) | 77                 | 4x10$^5$V/W            | 10\(\mu\)s    | 1x10$^{11}$                     |
| PbSe     | PC   | 2.9 ($\lambda_p = 3.8$)   | 196                | 1.6x10$^5$V/W          | 14-20\(\mu\)s| 1.5x10$^{10}$                   |
|          | PC   | 3-5 ($\lambda_p = 5$)     | 77                 | 2x10$^5$V/W            | 60-100\(\mu\)s| 3x10$^9$                        |
| PbS      | PC   | 1-4 ($\lambda_p = 2.2$)   | 77                 | 1.3x10$^5$V/W          | 5ms          | 1.5x10$^{11}$                   |
|          | PC   | 1-4 ($\lambda_p = 2.7$)   | 228                | 1.3x10$^5$V/W          | 1ms          | 3x10$^{11}$                     |
|          | PC   | 2.9 ($\lambda_p = 2.7$)   | 196                | 5x10$^5$V/W            | 2-5ms        | 3x10$^{11}$                     |
| InSb     | PV   | 1-4.5 ($\lambda_p = 5$)   | 77                 | >2A/W                   | 0.1-1\(\mu\)s| 1x10$^{11}$                     |
| PbTe     | PV   | 3-6 ($\lambda_p = 4.8$)   | 77                 | 6x10$^5$V/W            |              | 1x10$^{11}$                     |
CHAPTER 4 Photodetectors using other Material Systems

The material systems that have been mentioned in this chapter are used in the design of IR photodetectors which are commercially available. Table 4-5 lists some of these along with various detector characteristics which allows a comparison of the different types. The data is taken from various manufacturers and these are some of the best available commercially. Generally, for the individual photodetectors the various characteristics do not differ greatly from manufacturer to manufacturer. The two main detector types are photovoltaic and photoconductive with the p-n junctions being diffused junctions rather than epitaxially grown. The photodetectors composed of III-V semiconductors tend to be photovoltaic detectors and others such as PbSe, PbS and MCT tend to be photoconductive types. If we consider the operating parameters then:

[1] The response time: [usually taken as the time for the photodetector output signal to rise from 0-63% of its final value] is shortest in InGaAs where Speirs Robertson have measured it to be 85ps at room temperature in their detector, and Optilas have measured it to be ~10ms. These figures are over 3 orders of magnitude better than all the other detectors tabulated. The slowest response time is obtained for PbS where it is in milliseconds. If we compare this to the PbSe detector, the PbS is ~2 orders of magnitude slower than the PbSe. Discounting InGaAs, there is no trend in response speed between the remaining photodetectors in terms of whether they are photoconductive or photovoltaic types.

[2] D*: the highest D* has been obtained is by Hamamatsus Ge photodetector, where $D^* = 8 \times 10^{13} \text{cmHz}^{-1/2} \text{W}^{-1}$ at 77K. This is nearly two orders of magnitude better than most of the others. But, InGaAs at room temperature has $D^* = 5 \times 10^{12} \text{cmHz}^{-1/2} \text{W}^{-1}$ which would improve if this was also cooled to 77K. No figures are available for the $D^*$ of InGaAs at 77K. The worst operating properties are those of the PbSe photodetector where $D^* = 3 \times 10^9 \text{cmHz}^{-1/2} \text{W}^{-1}$ which is two orders of magnitude lower than that obtained with the other photodetectors, with the exception of Ge. If we compare PbSe and $\lambda = 5 \mu m$ with InSb at $\lambda = 5 \mu m$ we can see that the $D^*$ for InSb is two orders of magnitude better than that of the PbSe and hence would be a better choice at this wavelength.

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<table>
<thead>
<tr>
<th>Detector</th>
<th>Type</th>
<th>$\lambda_0$ [\mu m]</th>
<th>Operating Temp. [K]</th>
<th>Responsivity [V/W or A/W]</th>
<th>Response Time</th>
<th>Detectivity $[D^*]@\lambda_p$ cmHz$^{1/2}$W$^{-1}$</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>InAs</td>
<td>PV</td>
<td>1-3.1</td>
<td>77</td>
<td>1A/W</td>
<td>1\mu s</td>
<td>6x10$^{11}$</td>
<td>1</td>
</tr>
</tbody>
</table>

$M$=manufacturer

1=Hamamatsu UK Ltd; 2=Speirs Robertson; 3=Optilas; 4=Infrared Associates Inc.; 5=Judson Infrared Inc.; 6=Metax Ltd.; 7=Infrared Engineering Ltd.
[3] Temperature: the temperature for the photodetector range vary from room temperature to 77K, though those that operate at longer wavelengths [>2μm] have better detecting properties at the lower temperatures. Cooled detectors are offered in various types depending on how the detecting element is cooled. For operation at 77K, dewars are required which can make them expensive as well as bulky and may not be appropriate for some applications. At higher temperatures, thermoelectric coolers are used especially for the lead-salt photodetectors. These offer a cheaper alternative as well as making them less cumbersome.

4.10 SUMMARY
As yet, epitaxially grown photodetectors of the type mentioned in chapter 2 are not easily available commercially with the exception of InGaAs which is mostly used at an operation wavelength of 1.55μm. The main disadvantages with all of these photodetectors, especially for the 2-5μm wavelength region, is the fact that they have to be cooled to achieve efficient detection and high speed. They also have very high dark currents which can be reduced by cooling. As the majority are dewar-cooled and for the application of gas-sensing mentioned, where a portable sensor is required, they would be difficult to use, though multiple Peltier coolers could be used.

Cost is also another factor which is a disadvantage in most cases as many of these can cost thousands of pounds. When compared to Ge and Si at the shorter wavelengths which operate at room temperature, are highly efficient and have fast response speeds as well as only costing hundreds of pounds, then there is still a long way to go in the improvement of these photodetectors at the longer wavelengths. It could be that due to material systems used and hence the associated higher dark currents, lower absorption coefficients, difficulty in obtaining good materials and so on that these may be inherent problems which maybe difficult to improve. The photodetectors of table 4-5 may always have poorer characteristics compared to those of the group IV materials especially Si. But with the use of InGaAs it may be possible to equal and maybe better Ge over the wavelength region 1.5-1.7μm.
Having considered all the various aspects which influence photodetector design we now consider in detail a structure briefly mentioned in chapter 3, the resonant cavity photodetector. This offers a novel solution to problems encountered in the use of GaSb [chapter 7] as a detector absorber region. We begin this chapter by considering reasons for using the cavity type structure over the conventional structures discussed in the previous chapter. The equations used in the modelling of these structures are derived and analysed in detail. From this we then go on to discuss quantitatively the thickness and placement of the active region as well as considering the mirrors forming the cavity. We conclude with an analysis of output characteristics relevant to cavity photodetectors and discuss ways of optimising these parameters.

5.1 INTRODUCTION

The quantum efficiency of conventional photodetector structures [for one pass of the incident light through the active region] is limited by the absorption coefficient of the active layer, \( \alpha \), thickness of the active region, \( d \), and the reflection of the incident light from the front air/semiconductor. This is shown in equation 5.1.1

\[
\eta = (1 - R_p) \times (1 - e^{-\alpha d})
\]  

[5.1.1]

\( R_p = 0 \) for an ideal antireflection coating and is normally 33\% for most semiconductors [3<\( n \)<4], see chapter 6. If we consider the graphs of figures 5.1 and 5.2 which plot the variation of active
region [depletion depth] with carrier concentration of the active region and variation of absorption coefficient of the active region with external quantum efficiency, respectively, then we can use these to calculate some design parameters for these conventional photodetectors.

![Figure 5.1: Depletion depth vs. carrier concentration for GaSb active region with varying voltage](image1)

**Figure 5.1** Depletion depth vs. carrier concentration for GaSb active region with varying voltage

![Figure 5.2: External quantum efficiency vs. absorption coefficient for a non-resonant detector structure showing the dependence on depletion depth](image2)

**Figure 5.2** External quantum efficiency vs. absorption coefficient for a non-resonant detector structure showing the dependence on depletion depth

For an absorption coefficient of $5 \times 10^{5} \text{ cm}^{-1}$ and with a depletion depth of $1.5 \mu \text{m}$ the maximum external quantum efficiency $[\eta]$ which can be achieved is $\sim 35\%$, with no antireflection coating. With an AR coating on top of the structure the reflection at the front surface is minimised. For an ideal antireflection coating where $R_{t} = 0$, then for the previous parameters the quantum efficiency is $\sim 53\%$. To deplete $1.5 \mu \text{m}$ requires a reverse bias greater than $10 \text{V}$ at a carrier concentration of $10^{18} \text{cm}^{-3}$. This is difficult from the point of view of GaSb photodetectors as the dark current
increases rapidly above ~2V, see chapter 7. A more realistic bias voltage would be ~4V reverse bias which corresponds to a depletion depth of 0.7μm. With an absorption coefficient of 5x10^5 cm^-1, the quantum efficiency is ~20% for no AR coating and ~29% with a perfect AR coating. To design diodes with quantum efficiencies comparable to Si or Ge requires active region thicknesses of ~12μm for the same absorption coefficient and carrier concentration. This is not an achievable target for most III-Vs and especially not for GaSb.

It would be useful if the η could be enhanced in some way whilst still keeping the active layer thickness low. One way in which this can be achieved is to employ a multi-pass detection scheme where a single active layer is incorporated into a resonant cavity. This employs the Fabry-Perot effect where the single layer serves many times in generating photocarriers. The active layer is integrated between two mirrors [top and bottom] and at the resonance condition the incoming light interferes constructively with the reflected component from the bottom mirror. The resulting resonant cavity effect enhances the internal optical field amplitudes. At the resonance wavelength of the cavity, the effective optical path length is increased due to the multiple reflections from the mirrors. Hence, this results in an increase in quantum efficiency relative to the structures without mirrors.

Fig. 5.3 shows a schematic of a simple RCE detector design with front and back reflectors. These reflectors are usually composed of alternating layers of semiconductor materials designed such that high reflectance is achieved at the wavelength of operation. These types of mirrors are termed distributed Bragg reflector [DBR] stacks and are advantageous from the point of view that the whole device can be grown monolithically. The bandgap of the semiconductor material used in the DBRs has to be larger than the active region material in order to avoid absorption problems. Other materials, aside from semiconductors, can also be used in the design of these reflectors and these include dielectric materials and also metals such as Au and Ag. The reflectors will be discussed in detail in Chapter 6.

![Figure 5.3 Simple schematic of the RCE detector. The front and back reflectors consist of alternating semiconductor layers having larger bandgaps than the active region.](image-url)
By using the structure of fig. 5.3, the quantum efficiency of an optically thin detector can be improved considerably over a restricted spectral range by the use of a highly reflecting back mirror and a suitably designed front mirror. In the next section we shall consider some important equations needed for designing and predicting the spectral response of these resonant photodetectors which will provide some guidelines in their design.

5.2 LITERATURE REVIEW

The cavity effect has been mainly applied to devices which consist of modulators and vertical cavity surface emitting lasers [VCSELs]. Resonant cavity photodetectors have been designed and characterised in the shorter wavelength regions [$\lambda<1\mu m$] using the GaAs-based material system. Table 5-1 lists the photodetectors which have been published which utilise the cavity scheme.

Table 5-1 Comparison of photodetectors utilising the resonant cavity structure. The enhancement refers to the increase in photocurrent when comparing a resonant cavity device with a non-resonant cavity device with the same active region thickness. [APD, avalanche photodiode; M-S-M, metal-semiconductor-metal; HPT, heterojunction phototransistor]

<table>
<thead>
<tr>
<th>Type</th>
<th>$\lambda_p$ [\mu m]</th>
<th>Active Region</th>
<th>Reflectors</th>
<th>Enhancement</th>
<th>$\eta$ [%]</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPT</td>
<td>0.9</td>
<td>0.1\mu m In$<em>{0.05}$Ga$</em>{0.95}$As</td>
<td>air/semiconductor interface [30%]</td>
<td>GaAs/AlAs [90%]</td>
<td>6.4</td>
<td>43</td>
</tr>
<tr>
<td>Schottky</td>
<td>1.52</td>
<td>0.475\mu m Ga$<em>{0.47}$In$</em>{0.53}$As</td>
<td>Al</td>
<td>Al$<em>{0.48}$In$</em>{0.52}$ As/Al$<em>{0.17}$Ga$</em>{0.83}$In$_{0.53}$As</td>
<td>50</td>
<td>A. Chin et al., 1991</td>
</tr>
<tr>
<td>APD</td>
<td>0.84</td>
<td>0.09\mu m In$<em>{0.05}$Ga$</em>{0.95}$As</td>
<td>air/semiconductor interface [30%]</td>
<td>GaAs/AlAs [&gt;90%]</td>
<td>49</td>
<td>R. Kuchbhotla et al., 1991</td>
</tr>
<tr>
<td>HPT</td>
<td>0.93</td>
<td>In$<em>{0.12}$Ga$</em>{0.88}$As/ GaAs MQWs</td>
<td>GaAs/AlAs [70%]</td>
<td>GaAs/AlAs [99%]</td>
<td>Optical Gain &gt;600</td>
<td>R. P. Bryan et al., 1991</td>
</tr>
<tr>
<td>HPT</td>
<td>1.28</td>
<td>0.35-0.38\mu m InGaAs</td>
<td>Au</td>
<td>InAlAs/In GaAlAs</td>
<td>Current gain</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>1.52</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>$\lambda_p$ [µm]</td>
<td>Active Region</td>
<td>Reflectors</td>
<td>$R_F$</td>
<td>$R_B$</td>
<td>Enhancement</td>
</tr>
<tr>
<td>------</td>
<td>-----------------</td>
<td>---------------</td>
<td>------------</td>
<td>------</td>
<td>------</td>
<td>-------------</td>
</tr>
<tr>
<td>M-S-M</td>
<td>0.83</td>
<td>0.5µm GaAs</td>
<td>air/semicond -uctor interface</td>
<td>0.5µm GaAs</td>
<td>Al, Ga, As/Al, Ga, As</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>p-i-n</td>
<td>0.87</td>
<td>0.12µm In$<em>{0.05}$Ga$</em>{0.95}$As</td>
<td>air/semicond -uctor interface</td>
<td>GaAs/AlAs</td>
<td>GaAs/AlAs</td>
<td>90%</td>
</tr>
<tr>
<td>p-i-n</td>
<td>0.13</td>
<td>InGaAs</td>
<td>dielectric</td>
<td>dielectric</td>
<td>dielectric</td>
<td>52</td>
</tr>
<tr>
<td>p-i-n</td>
<td>0.94</td>
<td>3xInGaAs/GaAs MQWs</td>
<td>12xGaAs/AlAs</td>
<td>16xGaAs/AlAs</td>
<td></td>
<td>80</td>
</tr>
<tr>
<td>n$^+$/p</td>
<td>1.63</td>
<td>1.47µm u-GaSb</td>
<td>air/semicond -uctor interface</td>
<td>18 period GaAs/AlAs</td>
<td>GaAs/AlAs</td>
<td>D*=$4.5\times10^{10}$ cm$^{-2}$Hz$^{-1}$W$^{-1}$ at 0V</td>
</tr>
<tr>
<td></td>
<td>1.65</td>
<td>1.47µm u- GaSb</td>
<td></td>
<td></td>
<td></td>
<td>D*=$2.3\times10^{10}$ cm$^{-2}$Hz$^{-1}$W$^{-1}$ at 0V</td>
</tr>
<tr>
<td></td>
<td>1.75</td>
<td>0.92µm u- GaSb</td>
<td></td>
<td></td>
<td></td>
<td>4</td>
</tr>
</tbody>
</table>

The best $\eta$ of 80% was obtained by Daryanani et al., 1992, at a wavelength of ~0.94µm using GaAs/AlAs front and back reflectors with three InGaAs/GaAs MQWs used in the active region. The longest wavelength photodetector [not including the one designed in this thesis] was designed for operation at 1.52µm [Chin et al., 1991] and was a Schottky-type photodetector. This consisted
of a metal front mirror [Al] and a AllnAs/AlGaInAs DBR as the back reflector. The absorber region was ~0.5 μm thick of GaInAs and a η of 50% was obtained with this structure. Various clever designs have been tried to try and improve both η and the response speed such as using a triple absorber region [Huong et al., 1993] where they divided a single InGaAs active region into three segments to alleviate the problem of strain mismatch. This structure also achieved significant enhancement as compared to one whole absorber region in the cavity. Sverdlov et al., 1993, found that using thin absorption layers reduced the generation component of dark current which is of interest in photodetector design as this is one of the limitations in achieving highly efficient detectors. The generation current arises from the thermal generation of carriers in the depletion region and the generation current density can be expressed as

\[ J_g = q \frac{n_i}{\tau_{\text{eff}}} W \]  

\[ n_i \] is the intrinsic carrier concentration, \( W \) is the width of the depletion region and \( \tau_{\text{eff}} \) is the effective generation-recombination lifetime. To reduce this current \( n_i \) needs to be as small as possible [intrinsic], \( \tau_{\text{eff}} \) needs to be large [this is difficult to improve due to the technological limitations on the material quality] and \( W \) needs to be as small as possible. The RCE scheme provides a possible way of reducing \( W \) without sacrificing the quantum efficiency of the photodetector due to the fact that the net absorption in the layer placed into the cavity is enhanced due to the accumulation of optical energy at Fabry-Perot resonances. The final reference [F. Mansoor et al., 1995 and R. Grey et al., 1996] concerns RCE detectors designed in our study which will be discussed in detail in the rest of this thesis. These are the longest wavelength RCE photodetectors to date and the best efficiency that we have achieved is \( \eta = 10\% \) at \( \lambda = 1.63 \mu m \) with a \( D^*[\lambda = 1.63 \mu m, V = 0V] = 4.5 \times 10^{10} \text{cmHz}^{1/2}/\text{W} \). There are no published values of \( D^* \) in the literature for the detectors of table 5-1.

5.3 DESIGN EQUATIONS

A derivation of the design equations is given in Appendix A.

![Figure 5.4 Reflected, transmitted and absorbed beams in a cavity structure](image)
For an absorbing cavity, fig. 5.4, we can apply the conservation of energy and
\[ A + T + R = 1 \] \[ 5.3.1 \]
where \( A \) is the absorptance of the cavity and is given by \( I_s / I_r \), \( R \) is the reflectance and is given by \( I_s / I_i \), and \( T \) is the transmittance and is given by \( I_s / I_s \). \( I_s \) is the total absorbed intensity, \( I_r \) is the total reflected intensity, \( I_s \) is the total transmitted intensity and \( I_i \) is the incident intensity. At resonance

\[ T = \frac{(1 - R_f)(1 - R_b)e^{-ad}}{(1 - \sqrt{R_f}R_b e^{-ad})^2} \] \[ 5.3.2 \]
\[ R = \frac{(\sqrt{R_f} - \sqrt{R_b} e^{-ad})^2}{(1 - \sqrt{R_f}R_b e^{-ad})^2} \] \[ 5.3.3 \]
\[ A = \frac{(1 + R_b e^{-ad})}{(1 - \sqrt{R_f}R_b e^{-ad})^2} \times (1 - R_f)(1 - e^{-ad}) \] \[ 5.3.4 \]

Inspection of this equation shows that \( A \) can be made equal to unity if
\[ R_f = e^{-2ad} \] \[ 5.3.5 \]
As well as the transmittance being made equal to zero the reflectance also needs to be made equal to zero. Hence, using equation 5.3.3
\[ 0 = (\sqrt{R_f} - \sqrt{R_b} e^{-ad})^2 \]
\[ R_f = R_b e^{-2ad} = R_b \text{' matching condition} \] \[ 5.3.6 \]
This states that the value of the front mirror [for maximum absorption] has to be made equal to the attenuated value of the back mirror reflectivity. The general from of equation 5.3.4 is given by 5.3.7 where the two only differ in the fact that the denominator of equation 5.3.7 has an extra term \( \cos[2\beta L + \varphi_f + \varphi_b] \) which takes into account the quantum efficiency at off-resonance.

\[ \eta = \frac{1 + R_b e^{-ad}}{1 - 2\sqrt{R_f R_b e^{-ad} \cos(2\beta L + \varphi_f + \varphi_b) + R_f R_b e^{-2ad}}} \times (1 - R_f)(1 - e^{-ad}) \] \[ 5.3.7 \]

Cavity Enhancement Effect

where \( \beta = 2\pi n / \lambda \) [\( n \): refractive index; \( \lambda \):wavelength at resonance].

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CHAPTER 5 Theory: Resonant Cavity-Enhanced [RCE] Photodetectors

This equation has also been derived using various methods in Kishino et al., 1991; Chin et al., 1991; Ünlü et al., 1992; Daryanani et al., 1993.

5.3.1 ANALYSIS OF EQUATION 5.3.7

The expression \(2\beta L + \varphi_f + \varphi_b\) is the phase delay which is present due to the double pass of the incident light through the detector structure. \(\varphi_f\) and \(\varphi_b\) denote the phase shifts [K. Kishino et al., 1991] due to light penetrating into the multiple layer top and bottom mirror regions, respectively. For ideal mirrors with no phase shift, the \(\varphi_f\) and \(\varphi_b\) terms vanish and we are left with \(\cos(2\beta L)\).

The quantum efficiency is enhanced periodically at the resonant points which are determined by

\[2\beta L + \varphi_f + \varphi_b = 2m\pi\] ...........................................................

where \(m = [1, 2, 3, 5, \ldots]\). At this point the field amplitude of the light between the two end mirrors is a maximum due to the constructive interference of the forward and backward travelling waves, resulting in an increased quantum efficiency. At the off-resonance points

\[2\beta L + \varphi_f + \varphi_b = (2m + 1)\pi\] ...........................................................

the field amplitudes of the light between the two mirrors will decrease due to the destructive interference of the forward and backward travelling waves and this results in suppressed quantum efficiency.

If \(R_b = 0\) in equation 5.3.7, then the equation reduces to that for a conventional photodetector given by equation 5.1.1. In this case we are left with the term inside the bracket becoming unity and hence \(\eta = (1 - R_f)(1 - e^{-ad})\). It is the cavity enhancement effect which needs to be maximised in order to maximise the structure. At the resonance points, from equation 5.3.1.1, \(2\beta L = 2m\pi\) and hence the cavity length for resonance to occur is given by

\[L = \frac{m\lambda}{2n}\] ...........................................................

This gives \(\cos(2\beta L + \varphi_f + \varphi_b) = 1\) and hence the peak quantum efficiency is given by

\[\eta_{\text{peak}} = \left\{ \frac{1 + R_b e^{-ad}}{(1 - \sqrt{R_f R_b} e^{-ad})^2} \right\} \times (1 - R_f)(1 - e^{-ad})\] ...........................................................

From equation 5.3.1.3, the position of the resonant peak depends on the cavity length and on the refractive index of the cavity material.

In order for the resonant cavity structure of fig. 5.3 to operate as a detector we want maximum absorption in the active region, \(d\), where \(d = L\), which would be the case if there were no buffer or
spacer layers. The condition for maximum reflectance corresponds to the condition of minimum reflectance from the detector. In effect the structure of fig. 5.3 can be considered as a mirror stack with an absorbing region. Despite the fact that alone the front and back mirrors are both highly reflecting with the addition of the active region which is $\lambda/2n$ thick, the total reflectivity of the whole structure is zero. This would be the case if the light reflected from the mirror is out of phase with that reflected at the back mirror and the active region and equation 5.3.6 is obeyed.

5.4 DESIGN CRITERIA

Cavity Thickness

As was seen from equation 5.3.1.3, the cavity thickness is dependent on the refractive index of the material used for the cavity and the wavelength of operation. As mentioned in chapter 1, the wavelength considered for the resonant cavity detectors in this thesis is 1.68$\mu$m [CH$_4$ absorption]. Using GaSb as the cavity material, the refractive index linearly interpolated from [Palik, 1981] is given to be $\approx$3.89. In fig. 5.5 we plot the variation of $d$ with integer $m$ as the light will interfere constructively at 1.68$\mu$m every $m=2nd/\lambda$.

![Graph](image)

Figure 5.5 Variation of cavity thickness with resonance peak spacing [m]

From the graph of fig. 5.5 we can determine the value of cavity thickness which will give resonance at the required wavelength. This will occur every $m=1, 2, 3$... Factors which will influence the choice of cavity thickness have all been discussed in the previous section but to summarise:

[a] the material used for the active region has a background doping associated with it. Ideally this is required to be low such that ‘intrinsic’ material results. The lower the carrier concentration the
larger the cavity region that can be depleted with reasonable values of bias, hence the more efficient the detector.

[b] Ideally the cavity thickness should be in the high light intensity part of the graph of light penetration depth, as in fig. 5.6[a]. This would ensure more efficient reflection due to the greater power. As the back mirror is assumed to be an ideal reflector, there is no danger that the remaining light intensity would penetrate into the mirror and cause diffusion current. This would not be the ideal choice if this was a conventional detector structure as the rest of the intensity would penetrate into the substrate, see Chapter 2, and minority carriers will be generated which would result in a diffusion current which may reduce the quantum efficiency. Hence, as mentioned in the previous section the maximum thickness of the cavity region should be \( d = \frac{1}{\alpha} \), fig. 5.6[b].

![Figure 5.6 Light penetration depth in a resonant cavity semiconductor assuming the R_s=1 and neither mirror is absorbing: (a) the effective cavity region, 2d, is small and hence receives the benefit of higher light power, (b) the effective cavity region, 2d, is equal to 1/\alpha and hence not all of the region will receive the benefit of the higher light intensity](image)

There is one exception to the rules for cavity thickness already mentioned and this is when the cavity is very thin, of the order of \( \leq 0.1 \) \( \mu m \). As well as being highly absorbing these are also useful as high speed devices [Chin et al., 1990, 1991]. This has been discussed in appendices B and C.

**Mirror Reflectivities**

Ideally, the back mirror reflectivity should be 1 or near enough such that all the light is reflected back into the cavity and none is lost through transmission. This is quite difficult to achieve in reality even with metal mirrors. Using equation 5.3.6, we can match the front mirror reflectivity to the back mirror reflectivity. Figures 5.7 and 5.8 consider various parameters which will
determine the value of the mirror reflectivities. Fig. 5.7 shows the variation of $R_f$ as a function of $R_b$, for various values of cavity thicknesses, where $\alpha = 5 \times 10^3 \text{cm}^{-1}$. Fig. 5.8 shows what happens to the front mirror reflectivity as the absorption coefficient changes where $R_b = 1$. We assume that the cavity thicknesses lie in the range $\frac{\lambda}{2n} \geq d \leq \frac{1}{2\alpha}$. 

From Fig. 5.7, the greater the value of $R_b$, the greater the front mirror reflectivity has to be for the matched condition to be satisfied. For $d = 0.5 \mu m$, $R_f \sim 60\%$, when the back mirror is an ideal reflector. At a cavity thickness of $1 \mu m$, the matched front mirror reflectivity is $\sim 37\%$. For an ideal back reflector, the higher the absorption coefficient the lower the front mirror reflectivity required. For $\alpha = 5 \times 10^3 \text{cm}^{-1}$, $d = 0.5 \mu m$, the front mirror reflectivity is equal to $\sim 60\%$, whereas for
\( \alpha = 1 \times 10^4 \text{cm}^{-1} \), the front mirror reflectivity is \(-39\%\). Obviously the value of \( \alpha \) is dependent on the material used in the cavity. Once the condition for matching has been met, then we can consider what the structure reflectivity is depending on the back mirror, fig. 5.9.

![Figure 5.9](image)

**Figure 5.9** The total structure reflectivity, \( R_T \), as a function of \( R_f \) for various back mirror reflectivity \([R_b']\).

When front and back mirror reflectivities are equal, there is zero net structure reflectivity. For example at \( R_f = 0.8 \), \( R_b' = 0.8 \), the total structure reflectivity, \( R_T \) is zero. Either side of \( R_f = 0.8 \), the reflectivity increases and this increase in the structure reflectivity results in a decrease in the detection efficiency due to loss of incident light at the detector surface. The other factor which also influences the overall reflectivity is the angle of incidence of the light as it enters the structure. The total structure selectivity can only reach zero when \( \sin 2[\sigma] = 0 \), i.e. when \( \sigma = m\pi \), fig. 5.10. Hence, at \( m = 0, 1 \) \([\sigma = 0^\circ \text{ and } 180^\circ]\) the structure reflectivity is zero.

![Figure 5.10](image)

**Figure 5.10** Incident light angle dependency of the total structure reflectivity for \( \sigma = 0^\circ, \pi \), \( 1^\circ, 2^\circ \text{ and } 5^\circ \), \( R_b' = 1 \).
When the light is at an angle off-incidence, the structure reflectivity does not go to zero. The larger the angle the greater the reflectivity of the structure. At an incident angle of 5°, the reflectivity is ~50% at $R_b=0.8$. Even at smaller angles of incidence ($\sigma=1^\circ$), the total structure reflectivity is ~4% which would still result in some loss of detector efficiency.

If we consider the front surface reflectivity for a unity back mirror as a function of $\alpha$, and relate this to the cavity thickness through the factor $m$, equation 5.3.1.3, we can see that the greater $m$, the smaller the value of the front surface reflectivity, fig. 5.11, for the same $R_b$ and a certain $\sigma$. Since $d \propto m$, then the larger the value of $m$ the deeper the cavity. Since the resonance effect occurs at every $m=0, 1, 2, \ldots$, then at these points the absorption in the cavity will be enhanced. This enhancement is seen more clearly in fig. 5.12 in the next section.

![Graph](image)

**Figure 5.11** Variation of front mirror reflectivity with absorption coefficient for various values of the integer $m$.

### 5.5 MODELLING OF DETECTOR CHARACTERISTICS

#### Quantum Efficiency

The wavelength dependence of the quantum efficiency can be seen in fig. 5.12 where $\eta$ is calculated for $R_b=1$ and $R_c=0.9$. The resonant maxima are very narrow at the shorter wavelengths and the width increases as we go to longer wavelengths [see chapter 6 and appendix D]. It can be seen that the quantum efficiency is enhanced periodically at the resonant points, determined by $2\beta L+\phi_1+\phi_2=2m\pi$ [$m=1, 2, 3, \ldots$].

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Fig. 5.13 shows the quantum efficiency for three curves where $R_F = R_b$, 0.34 and 0.9 for $R_b = 1$, $d = 0.647 \mu m$ and $\alpha = 5 \times 10^3 \text{cm}^{-1}$. The reason for the values for $d$ and $\alpha$ will become clear later in this chapter. Also shown in both cases is the maximum value attainable for a conventional photodetector, given by $1 - e^{-\alpha d}$. For $R_F = 0.9$ in fig. 5.13, the quantum efficiency is ~50% at the resonant points.

In reality, the resonance peaks would not all have the same efficiency, as in the model we are assuming that the absorption coefficient and reflectance of the mirrors is the same over the entire wavelength range [$\alpha = 5 \times 10^3 \text{cm}^{-1}$]. This is not the case due to a wavelength dependence of both $R$ and $\alpha$, where

$$\alpha = \frac{4\pi k}{\lambda}$$

[5.5.1]

where $k$ is the extinction coefficient. This was discussed in Chapter 2. Therefore, the efficiency will be greatest at the point where $\alpha$ is greatest, as long as the other parameters stay the same.
From fig. 5.13, we can see that the quantum efficiency is equal to 1 when the front and back mirrors are matched. Also plotted are curves for $R_f = 34\%$, $90\%$ and for a non-resonant structure, where $R_b = 0$ and $R_f = 34\%$. For $R_b = 1$, $R_f = 0.34$, the resonance peaks are much broader than that for $R_f = R_b$ and the quantum efficiency has dropped from $\sim 1$ to $\sim 0.8$. The thinnest resonance peak occurs for $R_f = 1$, $R_b = 0.9$ i.e. when both mirror reflectivities are high. But the efficiency is very low as the front mirror is overcompensated for the back mirror. At $R_b = 0$, there is no resonance and equation 5.37 reduces to that for a non-resonating detector. The width of the resonance peaks is important when considering the finesse [Kishino et al., 1991] of the cavity. The higher the finesse, the narrower the linewidth at resonance and the more wavelength selective the detector. The equation for the finesse is derived in appendix D [linewidth] and is given by

$$F = \frac{FSR}{\Delta \lambda_{1/2}} = \frac{\pi (R_f R_b)^{1/4} e^{-\alpha d/2}}{1 - \sqrt{R_f R_b} e^{-\alpha d}} \tag{5.5.2}$$

where $FSR$ is the free spectral range and refers to the wavelength spacing between resonant peaks. $\Delta \lambda_{1/2}$ is the full width of the resonant peak at half maximum and is a measure of the wavelength selectivity of detection, fig. 5.14 [a] and [b].
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Figure 5.14 Variation of finesse of cavity with active region thickness for [a] unity back reflector, [b] 90% back mirror reflectivity, and various values of front mirror reflectivity. The finesse is greatest for small values of active region thickness and high front and back mirror reflectivities.

If we choose \( m = 3 \) for a cavity with \( \alpha = 5 \times 10^5 \text{cm}^{-1} \), the thickness is calculated to be 0.647 \( \mu \text{m} \). This can be depleted with \(-4 \text{V}\) at a carrier concentration of \(10^{16} \text{cm}^{-3}\) [characteristic of good GaSb]. In fig. 5.15, we consider various values of \( R_b \) with matched values of \( R_f \).

Figure 5.15 Optimised values of front mirror reflectivity as a function of back mirror reflectivity. The maximising condition is \( R_f = R_0 e^{-\alpha d/2} \).

The graph of fig. 5.16 is linear with the maximum value of \( R_f \) occurring at \( R_b = 1 \). From this we can choose various values of \( R_f \) depending on the back mirror reflectivity which can be grown realistically. This then leads onto fig. 5.16 where the quantum efficiency is plotted as a function of \( R_f \) for various value of \( R_b \). The greatest efficiency is reached when the \( R_b = 1 \) and \( R_f = 54\% \). The lower the back mirror reflectivity, the lower the efficiency due to the transmission of light through

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the back mirror and hence the incomplete total reflection, at the back mirror, of the forward travelling wave in the cavity.

![Figure 5.16 Quantum efficiency as a function of the front mirror reflectivity for varying back mirror reflectivities. The cavity thickness is taken to be 0.647μm and the absorption coefficient is 5x10^3 cm^-1](image)

It can be seen from fig. 5.16 that the curves peak at \( R_f= R_b \). If the front mirror reflectivity is overcompensated, then the quantum efficiency drops as can be seen from the right hand side of fig. 5.16 and the same is true for undercompensating \( R_f \). At \( R_b=0 \), the quantum efficiency is greatest when no light is reflected from the front surface, i.e. \( R_f=0 \), and drops linearly the greater the front surface reflectivity. Thus, for a conventional detector, an AR coating is necessary in order to reduce this front surface reflectivity.

The origin of such drastic enhancements of the quantum efficiency as has been modelled in the previous graphs is due to the enhanced amplitude of the internal field inside a resonant cavity. This amplitude enhancement can be evaluated by the internal optical power increment factor to the incident power. This factor is identical to the right-hand term in equation 5.3.7, except for the \([1-e^{-\alpha d}]\) term, and hence expresses the absolute improvement of the quantum efficiency by the cavity effect over an identical conventional detector, \([R_f=R_b=0]\), with the same active layer thickness.

The internal optical power increment factor at resonance for \( R_f=0.9, 0.7, 0.5, 0.34 \) for \( R_b=1 \) and for \( R_b=0 \), \( R_f=0.34 \) has been calculated in fig. 5.17[a], and for \( R_b=0.9 \) with the same values of \( R_f \) in fig. 5.17[b]. The absorption in the cavity is taken to be \( 5x10^3 \) cm^-1. For small values of active
region thickness the increment factor exceeds 10 and can reach 100 or more at the higher top and bottom mirror reflectivities and result in a reasonably high quantum efficiency for very small values of the cavity thickness. The internal optical power, at a low value of \( d \), can be greatly enhanced by increasing the front and bottom mirror reflectivities. On the other hand, with increasing \( d \), this increment factor decreases rapidly, especially for the high values of \( R_f \) and \( R_b \), resulting in the increment factor becoming less than unity.

The absorption term \([1 - e^{-\alpha d}]\) increases with increasing \( d \), while the internal power increment factor decreases as shown in fig. 5.17[a] and [b]. Therefore, \( \eta \) is a maximum at a certain \( d \) and decreases with increasing thickness to the conventional value determined by the top mirror reflectivity, i.e., \( \eta_{d=\infty} = 1 - R_f \). For a thick absorption region, most of the light is absorbed before it reaches the bottom mirror and hence the cavity effect is removed. For conventional detectors without the cavity effect, high quantum efficiency [\( >90\% \)] can be realised only for very thick active layers [5-6\( \mu \)m], see fig. 5.19. This shows the maximised quantum efficiency using equation 5.2.6 as a function of \( d \).

**Figure 5.17** Internal optical power increment factor in resonant cavities with various front mirror reflectivities for [a] \( R_b=1 \), and [b] \( R_b=0.9 \), as a function of cavity thickness, \( d \). The power increment factor for a non-resonant structure is also plotted where \( R_b=0 \) and \( R_f=0.34 \).

Figure 5.18 shows \( \eta \) at resonant modes as a function of \( d \) for \( \alpha=5\times10^3 \text{cm}^{-1} \) for varying \( R_f \) and \( R_b=1 \). The \( \eta \) for the no reflector case [\( R_b=0 \)] is also shown. When the two curves of \( R_b=0 \) and 1.0 for \( R_f=0.34 \) are compared to each other, it can be seen that the cavity enhancement improves \( \eta \) from \(-18\%\) to \(90\%\) [a factor of 5] for 0.6\( \mu \)m thick absorption layer.
In the case of RCE detectors, when $R_s = 0.99$, a maximum quantum efficiency exceeding 90% can be easily realised for very thin active layers of 0.1-0.2 μm thickness [$\alpha = 5 \times 10^3 \text{cm}^{-1}$] as shown in fig. 5.19. This fact is helpful when considering improvements in the high-speed performance, see Chapter 2, of detectors because the electronic transit time along the depletion absorption region may eventually govern the high frequency performance.

If we consider the diagram of fig. 5.20 which shows the various processes that occur in a resonant cavity structure, then it can be seen that that incident light undergoes reflection, absorption and transmission depending on how the cavity is designed. The cavity has a refractive
index, $n$, absorption coefficient, $\alpha$, thickness, $d$, and front and back mirror reflectivities $R_f$ and $R_b$, respectively.

Figure 5.20 Schematic showing passage of a beam of light incident on a cavity structure of thickness $d$ with front and back mirrors of reflectivity $R_f$ and $R_b$, respectively.

Plotting the transmittance, reflectance and absorptance as a function of $d$ gives the curves of figures 5.21 [a]-[d].

Figure 5.21 Passage of incident light through an absorbing cavity structure with unity back reflector and $\alpha=5 \times 10^4 \text{ cm}^{-1}$. The transmittance, reflectance and transmittance of the light are plotted as a function of cavity region thickness, $d$, for various values of front mirror reflectivity, [a] $R_f=0.9$, [b] $R_f=0.7$, [c] $R_f=0.34$, and [d] $R_f=0, R_b=0$ [ideal non-resonant detector]. The back mirror is a unity reflector in [a], [b], and [c].
As the front mirror reflectivity decreases, the peak absorptance shifts to larger values of cavity thickness as does the minimum of the reflectance curve, graphs [a]-[c] in fig. 5.21. As $R_f$, $R_b$ and $\alpha$ are fixed for each graph, the only parameter that can be varied in order to match the mirrors and hence maximise the structure is $d$. The greater the value of the front mirror reflectivity, the thinner the active region required in order to satisfy equation 5.3.6. The transmittance in all the graphs of [a]-[c] of fig. 5.21 is zero for all values of active region thickness as the back mirror is a unity reflector and hence no light will be transmitted through the back of the cavity. Graph [d] of fig. 5.21 shows the reflectance, transmittance and absorptance of the incident light in a non-resonant structure where $R_b=0$ and $R_f=0$ [AR coating]. The reflectance is zero due to the ideal AR coating which stops any reflection from the front surface. The absorptance increases as the active region thickness increases and at 3$\mu$m, it is $\sim$80%. As the cavity thickness increases the transmittance decreases from a maximum at 0.01$\mu$m to $\sim$20% at 3$\mu$m. As the absorptance increases the transmittance decreases. Comparing graph [d] with those of [a]-[c], we can see that the resonant cavity structures show a great improvement in the absorptance at smaller values of active region thickness where these types of structure are most effective. A non-resonant detector requires a very thick absorber layer in excess of 10$\mu$m, to absorb 99% of the incoming light even with a perfect anti-reflection coating. The secondary recombination of photo-generated carriers while drifting through such a thick depletion region will then limit $\eta$ introducing an additional difficulty for achieving very high $\eta$ [>99%].

Considering a more realistic value for the back mirror reflectivity, graphs [a]-[c] of fig. 5.21 are repeated in fig. 5.22 with the same parameters except that $R_b=0.9$. The absorptance has now dropped for each of the graphs due to the transmittance of the light through the back of the structure. The best absorptance is obtained for graph [c] where it is $\sim$90% at $\sim$1$\mu$m, as this value of $R_f$ provides the best match to the value of $R_b$ at 1$\mu$m. If we consider $d=0.01\mu$m and compare the transmittance and reflectance we can see that the transmittance decreases as the reflectance increases at this cavity thickness.
Figure 5.22 Passage of incident light through an absorbing cavity structure with a 90% back reflector and $\alpha=5\times10^5\text{cm}^{-1}$. The transmittance, reflectance and transmittance of the light are plotted as a function of cavity region thickness, $d$, for various values of front mirror reflectivity, $[a] R_f=0.9$, $[b] R_f=0.7$, and $[c] R_f=0.34$.

5.6 SUMMARY

This chapter has examined in detail the resonant cavity junction structure which was previously introduced. A qualitative comparison has been made between the resonant structure and the non-resonant structure at the start of this chapter by examining the equation for $\eta$ for a non-resonant structure. To this end a general expression for $\eta$ for a resonant cavity photodetector has been derived by consideration of the reflectance and transmittance of the light in such a structure. The reflectance, transmittance and absorptance have been derived for both a lossless cavity and one which is absorbing assuming that the main absorption mechanism is due to band-to-band absorption.

From these derivations it was found that $\eta\text{RCE}$ depended on the front and back mirror reflectivities, the cavity thickness and the absorption coefficient. To maximise the efficiency the back mirror has to be as close to unity as possible and the front mirror has to satisfy equation 5.3.6. Using the derived equations various cavity structures were modelled giving the following results.
[a] Under the resonance condition, the enhanced amplitude of the internal optical fields results in a drastic enhancement in the absorption in the cavity and hence $\eta$. Off-resonance wavelengths are rejected from the cavity and hence RCE photodetectors can provide wavelength selectivity.

[b] The higher the back mirror reflectivity, the better $\eta$. Even for very thin layers the efficiency can be made nearly equal to unity if the back mirror is made a unity reflector and the matching condition is satisfied. The higher the values of the front and back mirrors the better the finesse of the cavity and the more selective the photodetector, though this may at the expense of $\eta$.

[c] For a cavity thickness of the order of $\lambda/2n$ or less, the SWE becomes significant and an effective absorption coefficient has to be considered. This resulting enhanced absorption even for very thin absorber regions is dependent on their placement in the cavity.

Finally we have considered some work on published cavity type photodetectors and compared the $\eta$ of these as well as the type of structure used. Using the resonant cavity structure to enhance the detector efficiency is all well and good but we still need to have a material system for the absorber region with some reasonable properties. The cavity structure cannot alone provide efficient detectors. The next chapters discuss various aspects of the RCE detector design beginning with Bragg reflector stacks in chapter 6, electrical characterisation results of the GaSb/GaAs heterojunction on both the non-resonant and resonant cavity structures in chapter 7 and optical results on the resonant cavity photodetector in chapter 8.
6.1 INTRODUCTION

Photodetectors using GaSb as the active region present some problems mainly due to the native acceptor. The growth of p-i-n structures has not, as yet, been possible with this material system because of the resulting high carrier concentration. The possibility of using a resonant-cavity structure to overcome these limitations [chapter 6] will be considered and fundamental to the construction of these resonant cavity detectors are the mirrors on either side of the detecting region. These reflectors are composed of materials which do not absorb [ideally] at the operation wavelength of the detector. Depending on the cavity structure, the back mirror is always designed to be highly reflecting in order to reduce the transmittance of the incident light. The front mirror is designed to be have a reflectivity as close as possible to the attenuated value of the back mirror reflectivity. Ideally, these DBRs should be lattice-matched to the active region and to the substrate in order to reduce the dislocation density. The use of GaSb as the absorber material determines the materials which can be used for the Bragg stack from the point of view of lattice-matching. The obvious choice would be antimonide-based stacks such as AlGaSb/GaSb but we are also limited by the growth facilities available to us and currently Al cannot be used in the MOVPE chamber.

As will be seen in chapter 7 it was possible to achieve good junction characteristics with the GaSb/GaAs heterojunction and hence it was decided to use GaAs/AlAs as the material systems
for the Bragg stacks. In this chapter we consider the theory and principles of operation of these Bragg stacks. One of the main problems in the design of these reflector structures is the lack of knowledge of material parameters, such as refractive index, required for the designs. This is especially true at the longer wavelengths [\( \lambda > 1.6 \mu m \)]. This problem is considered in the design of the various mirror structures. Five different GaAs/AlAs stacks were grown operating at different wavelengths and the design, growth and characterisation of these will be discussed.

6.2 OPERATION OF DBRs

In designing the mirrors various factors must be taken into account. In most cases, they must be highly reflecting at the operating wavelength. It should also, ideally, be possible to grow the mirrors and the active region monolithically in order to avoid problems with post-growth deposition such as degradation of the growth surface which could result in a poor interface between the mirror and the active region. This may not always be possible depending on the type of materials used and the availability of growth facilities. In addition, the mirrors should not interfere with the electrical properties of the device. If they have a large resistance, the operating voltage of the device would be increased [Khan, 1995] and is one reason why the thickness of the mirrors should be kept small.

There are a few different types of mirrors which can be utilised in the cavity design. Metal mirrors, such as Au and Ag, offer a high reflectivity over a wider wavelength range. Au, for example, has a reflectance greater than 99% between 1.6-5 \( \mu m \) [Melles Griot, 1995]. These mirrors cannot be epitaxially grown within the structure and hence require post-growth processing which, though feasible, may make the device design more complicated. Due to the high extinction coefficient of these metals, there is always a phase change on reflection at the metal interface which would require the growth of a phase matching layer [Khan, 1995], and this may make the structure more complicated.

DBRs can also be used as highly reflecting coatings. These consist of alternating layers of materials of different refractive index with the material being either dielectrics [e.g. SiO\(_2\)/SiN\(_x\)] or semiconductors [GaAs/AlAs]. Dielectrics can be designed to have high values of reflectivity with only a few layers due to the large refractive index difference between the materials. But, these again require post-growth processing as these materials cannot be easily grown monolithically with the rest of the detector structure.
The DBR [Born et al., 1969; Macleod, 1986] works on the principle that light reflected from a material of higher refractive index than the incident medium will undergo a $\pi$ phase change and that the reflected light from each interface in a multilayer stack will have an additional phase change due to the path length. Constructive interference of reflected beams will occur when the layer optical thickness is given by

$$t = \frac{\lambda}{4n} \quad [6.2.1]$$

where $n$ is the refractive index of the material. A typical DBR with $F$ layers is shown in fig. 6.1.

![Diagram of DBR stack](image)

**Figure 6.1** Multilayer stack consisting of alternating layers of high and low refractive indices (even number of layers)

The reflection from any one of the layers is very low but that from a structure employing many layers of alternating high and low refractive indices will yield large reflectivities due to constructive interference of the reflected light beam. The reflectivity $R$ is given by

$$R = \left[ 1 - \left( \frac{n_1}{n_0} \right)^{2N} \right]^2 \quad [6.2.2a]$$

This is true for an even number of layers, $F$. For an odd number of layers [Guy, 1983]

$$R = \left[ 1 - \left( \frac{n_1^2}{n_0^2} \right)^{2N} \right]^2 \quad [6.2.2b]$$

From equation 6.2.2, the reflectance of the multilayer stack can be seen to depend on the refractive index difference between the DBR materials [$\Delta n = n_1-n_2$] and on the number of layer pairs [2 layers = 1 period], $N$, of the stack. Fig. 6.2 shows the variation of reflectance, $R$, with
the number of periods of the stack. The refractive indices used here for modelling purposes, taken from Palik, 1991, are $n_1=3.3615$ [GaAs], $n_2=2.888$ [AlAs], $n_0=1$ [air] and $n_s=3.3615$ [GaAs]. These values correspond to the refractive indices for GaAs and AlAs, at 1.68μm. The precise values of $n$ have been calculated by linear interpolation between $\lambda_1$ and $\lambda_2$ where $\lambda_1>\lambda_0>\lambda_2$ [$\lambda_0$ is the operating wavelength]. The general equation used for calculating $n_1$, $n_2$, and $n_s$ is

$$n_i = n_1 - \left[ \frac{\lambda_0 - \lambda_1}{\lambda_2 - \lambda_1} \right] \times (n_1 - n_2)$$

[6.2.3]

where $i=1, 2, s$ and $n_1>n_0>n_2$. The errors in this way of calculating $n$ will be discussed later in this thesis.

![Figure 6.2](image)

Figure 6.2 Reflectance of a MLS as a function of number of periods for $n_0=1$ and $n_0=3.83$

[refractive index of GaSb at 1.68μm]

If we consider the limits of the graph at $N=0$ and $N>20$ [i.e. where the curve begins to saturate as it approaches 1.0] and re-write equation 6.2.3 in simpler terms, then

$$R = \frac{1 - ab^{2N}}{1 + ab^{2N}}$$

[6.2.4]

where $a = \left( \frac{n_s}{n_0} \right)$ and $b = \left( \frac{n_1}{n_2} \right)$

From fig. 6.2, the graph saturates at large values of $N$. As $N$ increases $ab^{2N} \gg 1$, hence $\left[1-ab^{2N}\right] \to -ab^{2N}$ and if $N$ is large enough $ab^{2N} \to 0$. The converse is true for $\left[1+ab^{2N}\right]$ where $\left[1+ab^{2N}\right] \to ab^{2N}$ for large values of $N$ and as $N$ increases, $ab^{2N} \to \infty$. Eventually, if $N$
is large enough, \[ \left( \frac{1 - ab^{2N}}{1 + ab^{2N}} \right) \rightarrow 1 \] and the curve saturates, fig. 6.2. At the other extreme where \( N = 0 \), \( b^{2N} = 1 \) and equation can then be written as \( R = \left( \frac{1 - a}{1 + a} \right)^2 \) and hence the reflectance is solely dependent on the refractive indices of the input and exit media. If \( n_0 = 1 \) [entry medium is air] and \( n_s = 3.3615 \), then, from fig. 6.2 at \( N = 0 \), the reflectance is \(-30\%\). If the entry medium is not air but a semiconductor, say GaSb, where \( n_0 = 3.89 \) at 1.68\( \mu \text{m} \) [Palik, 1991], then the reflectance is \(-0.4\%\). The difference is due to the larger \( \Delta n \) in the first case [\( \Delta n = 2.615 \)] as compared to the second case [\( \Delta n = 0.4685 \)]. The reflectance will be greater for a larger value of \( \Delta n \).

Detailed theory of multilayer films can be found in many texts [Pedrotti et al., 1992; Macleod, 1986] where Maxwell’s equations are solved using the transfer matrix approach of Born and Wolf, 1984. The overall transfer matrix related the electric and magnetic fields at one boundary to those at another in a multilayer film. Software programs have been written in the department to compute the reflectivities of DBRs [Guy, 1995; Geele, 1992].

**Example 1**

We can illustrate the theory with some examples of various structures. If we consider a multilayer reflector stack where all the reflected beams are in phase, fig. 6.3. The structure is that of a GaAs/AlAs stack with GaAs being the high refractive index layer and AlAs the lower refractive index layer. The input medium is air and the exit medium is a GaAs substrate. At the design wavelength of 1680nm, the bandgap of both these materials is non-absorbing which makes them ideal candidates.

![Multilayer stack](image)

With air as the incident medium, as the light goes from air to a higher refractive index material \( [n=3.3615] \), the reflected ray suffers a \( \pi \) phase change at this first interface. The second ray will
pass through a quarter-wave layer before leaving the medium. Hence it will have suffered a phase change of $\pi$ due to the total path length being $\lambda/2$. Depending on whether the 2nd layer has a higher or lower refractive index than the first layer, this second ray will also experience a phase change on reflection at the second interface. The final ray reaching the last interface of the stack will have a path of $F\lambda/2$ [where $F$ is the total number of layers in the stack] before reflection and $F\lambda/2$ after reflection. Hence, it will have a total phase change due to its path length of $F\pi$. It may, in addition, have a phase change on reflection depending on the refractive index of the medium. This is better illustrated in fig. 6.4 which shows the phase changes at the various interfaces for an even number of layers.

![Figure 6.4](image)

**Figure 6.4** Phase changes on reflection for the structure of fig. 6.3. The number of layers is even.

Using the transfer matrix model, the reflectivity of the multilayer stack of fig. 6.3 can be plotted as a function of wavelength, fig. 6.5. This shows the dependence of the reflectance on wavelength for various values of $N$.

![Figure 6.5](image)

**Figure 6.5** Variation of reflectance of a multilayer stack [MLS] with wavelength. Three curves are plotted for $N=2$, $N=6$ and $N=18$.
Also plotted, in fig. 6.6, is the reflectance spectra of the multilayer stack of fig. 6.3 with N=18 along with the phase shift of the stack on reflection.

Figure 6.6 Reflectance spectra and phase shift of MLS of fig. 6.4 with N = 18

Points to note about figures 6.5 and 6.6 are:

[i] The reflectance spectra consists of a large, central maxima called the stopband, which is centred at the design wavelength, in this case \( \lambda_0 = 1.68 \mu \text{m} \). As mentioned previously, the peak reflectivity of this stopband is dependent on the refractive index difference and the number of periods, N, of the stack. The refractive index difference also determines the bandwidth of the stopband, \( \Delta \lambda \) of fig. 6.5, which increases with increasing \( \Delta n \) and approaches a constant for high values of N. The stopband width, \( \Delta \lambda \), is given by [Macleod, 1986]

\[
\frac{\Delta \lambda}{\lambda_0} = \frac{4}{\pi} \sin^{-1} \left[ \frac{n_H - n_L}{n_H + n_L} \right]
\]

where \( \lambda_0 \) is the wavelength at which peak reflectivity occurs and \( n_H \) and \( n_L \) are the high and low values of refractive index, respectively.

[ii] The oscillations, or sidebands, on either side of the stopband occur due to the incomplete destructive interference of the reflected light from each interface. For example, the first sideband to the left of the stopband occurs at \( \sim 1540 \text{nm} \) and the reflectivity is \( \sim 58\% \). This is due to the fact that light reflected from each interface, though not totally in phase with each other as at the centre of the stopband, is not totally out of phase either, and the amplitude of the reflected waves still add up to give some reflectance.

[iii] The sidebands to the left of the central maxima are narrower than those on the right. This phenomena is not due to the physical structure or growth of the reflector stack but rather is due to the fact that the oscillations are equally spaced in energy rather than wavelength. The linewidth of the bands varies as \( \lambda^2 \) [appendix D], hence if \( \lambda \) is small then the linewidth is narrower compared
to longer wavelengths. There is no dependence if the spectra are plotted as a function of the wavenumber \( \text{cm}^{-1} \). We can see the wavelength dependence of the oscillations from fig. 6.7 which plots the spectra of fig. 6.3 over a larger wavelength range. At the smaller wavelengths the stopbands are much narrower than at the longer wavelengths.

![Modelled spectra of M2 plotted over a wavelength range of 500-5000 nm in order to show the dependence of the oscillations on wavelength](image)

**Figure 6.7**

If we consider fig. 6.6, which also shows the variation of phase with wavelength, then at the design wavelength [centre of the stopband] the phase shift is zero. This implies that at this point the reflected light at each interface of the stack is in phase [constructive interference] and hence maximum reflectance occurs. Either side of the design wavelength the phase shift is non-zero and hence due to all the reflected rays of light not being in phase totally, the reflectance will be reduced at these points. A phase shift of non-zero at the centre wavelength, may arise due to problems with the growth or poor design, has important implications from a device design point of view which is discussed later in this chapter.

Some important points to note about the transfer matrix model used in this thesis are

[a] any absorption in the semiconductor materials used in the MLS is not taken into account. The absorption at the design wavelength may be negligible but over the wavelength range of say the graph of fig. 6.5 this may not be the case and a lot of discrepancies between modelled and measured reflectance spectra arise because of this problem.

[b] the refractive indices of the layers of the stack are only correct at the wavelength of operation. The model assumes them to be constant over the entire wavelength range considered. For example, in fig. 6.5, \( n_1 \) and \( n_2 \) are correct at 1.68\text{\mu m} \) but nowhere else. The graphs of fig. 6.8[a]
and [b] show the variation of refractive index with wavelength [E. D. Polik, 1991] for GaAs and AlAs, respectively, over the wavelength range 1-5μm.

![Figure 6.8 Values of refractive index as a function of wavelength for [a] GaAs and [b] AlAs](image)

The refractive index is not constant but is wavelength dependent and decreases as the wavelength increases. In reality, the spectra of these reflector stacks would not be considered over such a large wavelength range and are usually only measured over a range slightly more than the width of the stopband. Even for such a well characterised system as GaAs, the refractive indices have only been measured for a few wavelengths and it is difficult to find a specific n for intermediate wavelengths except by linear interpolation. Considering fig. 6.5 and plotting the refractive indices of GaAs and AlAs over the region of the stopband for the graph of N=18 [1600-1780nm], then it can be seen that the refractive index difference between 1600 and 1780nm is only 0.007 for GaAs, fig. 6.9[a], and 0.014 for AlAs, fig. 6.9[b]. At 1680nm, n_{GaAs} is 3.3615 and there is a difference of +/-0.2% between this value and those at the two wavelengths extremes [1600 and 1780nm] and a difference of +/-0.1% for AlAs, where n_{AlAs} is 2.888 at 1680nm.
The reflectance, fig. 6.10, over this wavelength range varies from ~0.9951 at 1600nm to ~0.9947 at 1780nm, which is a difference of $4 \times 10^{-5}$ between these two extremes. This corresponds to a difference of $\pm 0.2\%$ between the reflectance at 1600nm to that at 1680nm and at 1780nm.

In the comparison of the modelled and measured reflectance spectra of the multilayer stack considered in this thesis it will be assumed that the values of the refractive indices are constant over the wavelength range of the stopband as it is not possible, as yet, to vary the refractive index in the various multilayer models used.
Example 2

If we consider a second example where the entry medium is a semiconductor rather than air then \( n_0 \) would increase. If we still consider the structure of fig. 6.3 and say that \( n_0 < n_1 \), then the structure of fig. 6.4 would still provide high reflectivity as the reflected light from the interfaces is in phase with that reflected from the \( n_0/n_1 \) interface and the \( n_0/n_2 \) interface. If on the other hand, \( n_0 > n_1 \) and the same structure was considered then the phase change at the first interface will be 0. The second beam will undergo a \( \pi \) phase change due to its path length. Both these rays will be out of phase and hence destructive interference will occur. This is illustrated in fig. 6.11.

![Figure 6.11](image-url)

**Figure 6.11** Phase changes on reflection where the light reflected from the \( n_0/n_1 \) interface is out of phase with that reflected from the rest of the structure.

In order to rectify this phase problem, the structure of fig. 6.12 needs to be used where the first layer has a refractive index of 2.888 and the total number of layers \( F \) odd.

![Figure 6.12](image-url)

**Figure 6.12** Reflector stack structure with \( n_0=3.83 \) and refractive index of the first layer being 2.888 with the total number of layers being odd.

This then means that there is 0 phase change at the \( n_0/n_1 \) interface, \( 2\pi \) phase change at the \( n_1/n_2 \) interface and \([F-1]\pi\) phase change at the \( n_f/n_s \) interface [for \( F \) odd], fig. 6.13.
The reflectance spectra of fig. 6.4, fig. 6.11 and fig. 6.13 are plotted in the graph of fig. 6.14. This shows the variation of reflectance with wavelength for \( N=10 \) for each structure. The greatest reflectance, curve A in fig. 6.15, is achieved by the structure of fig. 6.4 where the first layer has a refractive index of 3.3615 and the entry medium is air. Curve C in fig. 6.15 uses the same structure as fig. 6.4 but the refractive index of the entry medium is now higher, 3.892 [\( n_{\text{air}} \) at 1.68\( \mu \text{m} \)]. Due to the fact that the light reflected from the \( n_0/n_1 \) interface is now out of phase with that reflected from the rest of the structure, the reflectivity is reduced from \(-96\%\) for A to \(-80\%\) for C. Curve B, in fig. 6.14, is the same structure as fig. 6.11 with \( n_0=3.892 \), but in this case the structure has been modified to take into account the higher refractive index of the entry medium. The maximum reflectivity in curve B occurs at \(-90\%\). This is slightly less than that of curve A due to the fact that the difference between the refractive indices of the entry and exit mediums is greater for curve A than for curve B and as the reflectivity is dependent on this difference, this would account for the slightly reduced reflectivity. To increase the reflectivity the number of periods of the stack would have to be increased for the same values of refractive indices.
From the aforementioned device considerations, various reflector stacks were designed to be incorporated, eventually, into resonant cavity structures to be used as wavelength selective detectors, chapter 5. They were designed to have central stopband wavelengths corresponding to strong absorption lines of various gases. All use GaAs/AlAs as the semiconductor materials for the individual layers of the multilayer stack.

**Why GaAs/AlAs?**

[1] Growth of Bragg stacks using this material system is fairly standard.

[2] Lack of alternative facilities for growth of better lattice-matched systems, such as GaSb/Al[Ga]Sb.

[3] Good electrical characteristics seen with GaAs/GaSb heterojunctions [chapter 7].

**MBE Growth**

The reflector stacks were grown using molecular beam epitaxy at the University of Sheffield by Dr. Robert Grey. The basics of MBE growth have already been discussed in chapter 4. Errors may be introduced into the thickness of the individual layers of the DBR due to the fluctuations in the source fluxes at the sample surface. A systematic variation of the thickness, within all the layers often occurs due to the relative orientation of the growth sources and the sample wafer. This leads to a growth geometry dependent wafer uniformity. Complications may also arise due to thermal transients across the wafer, which further alter the growth rate. It is hoped, with MBE, that these can be reduced by sample rotation and growth rate calibration.
6.3 DBR DESIGN AND MODELLING

Five different reflector stacks were modelled all operating at different wavelengths. Most of the wavelengths chosen correspond to an absorption band of a pollutant gas. These are given in table 6-1.

<table>
<thead>
<tr>
<th>Wavelength [µm]</th>
<th>Reason for choice of wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.55</td>
<td>Communications wavelength. Low loss region of Si fibres</td>
</tr>
<tr>
<td>1.68</td>
<td>Strong absorption band for CH₄</td>
</tr>
<tr>
<td>2.2</td>
<td>Absorption band for NO₂</td>
</tr>
<tr>
<td>2.77</td>
<td>Strong absorption band for CO₂</td>
</tr>
<tr>
<td>3.39</td>
<td>Strong absorption band for CH₄</td>
</tr>
</tbody>
</table>

The structures and the refractive indices of the GaAs/AlAs reflector stacks are given in tables 6-2 and 6-3.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Operating Wavelength [µm]</th>
<th>nₐlₐₐs</th>
<th>nₐ₃₃₃</th>
<th>Δn</th>
<th>Number of Periods</th>
<th>Total Thickness [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>1.55</td>
<td>2.909</td>
<td>3.3737</td>
<td>0.4647</td>
<td>20</td>
<td>5.32</td>
</tr>
<tr>
<td>M2</td>
<td>1.68</td>
<td>2.888</td>
<td>3.3615</td>
<td>0.4735</td>
<td>18</td>
<td>5.24</td>
</tr>
<tr>
<td>M3</td>
<td>2.2</td>
<td>2.875</td>
<td>3.333</td>
<td>0.458</td>
<td>15</td>
<td>5.5</td>
</tr>
<tr>
<td>M4</td>
<td>2.77</td>
<td>2.869</td>
<td>3.318</td>
<td>0.449</td>
<td>15</td>
<td>6.21</td>
</tr>
<tr>
<td>M5</td>
<td>3.39</td>
<td>2.864</td>
<td>3.309</td>
<td>0.445</td>
<td>13</td>
<td>6.68</td>
</tr>
</tbody>
</table>

Table 6-3 lists the structures of the DBRs of table 6-2. The thicknesses of the individual layers were measured using X-ray diffraction [Schroder, 1990]. In all cases the error in the growth was quoted to be +/-30-40Å of the total layer thickness. The carrier concentration was measured by using C-V profiling where the layers are etched using a suitable enchant and the carrier concentration ascertained from the etch depth, area and capacitance of the layer being etched.
### Table 6-3 Structures of the distributed Bragg reflectors stacks

<table>
<thead>
<tr>
<th>Sample</th>
<th>Thickness [Å]</th>
<th>Dopant</th>
<th>Carrier Concentration [cm⁻³]</th>
<th>Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 [λᵣ = 1.55µm]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layer 1</td>
<td>2296 [λ/2n]</td>
<td>n-type</td>
<td>1x10¹⁸</td>
<td>n⁺ GaAs:Si</td>
</tr>
<tr>
<td>Layer 2</td>
<td>1332 [λ/4n]</td>
<td>n-type</td>
<td>1x10¹⁸</td>
<td>n⁺ AlAs:Si</td>
</tr>
<tr>
<td>Layer 3</td>
<td>1148 [λ/4n]</td>
<td>n-type</td>
<td>1x10¹⁸</td>
<td>n⁺ GaAs:Si</td>
</tr>
<tr>
<td>Layer 4</td>
<td>1332 [λ/4n]</td>
<td>n-type</td>
<td>1x10¹⁸</td>
<td>n⁺ AlAs:Si</td>
</tr>
<tr>
<td>Buffer</td>
<td>2500</td>
<td>n-type</td>
<td>1x10¹⁸</td>
<td>n⁺ GaAs:Si</td>
</tr>
<tr>
<td>Substrate</td>
<td></td>
<td>n-type</td>
<td></td>
<td>n⁺ GaAs:Si</td>
</tr>
<tr>
<td>M2 [λᵣ = 1.68µm]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layer 1</td>
<td>2498 [λ/2n]</td>
<td>n-type</td>
<td>2.35x10¹⁸</td>
<td>n⁺ GaAs:Si</td>
</tr>
<tr>
<td>Layer 2</td>
<td>1454 [λ/4n]</td>
<td>n-type</td>
<td>3.15x10¹⁸</td>
<td>n⁺ AlAs:Si</td>
</tr>
<tr>
<td>Layer 3</td>
<td>1249 [λ/4n]</td>
<td>n-type</td>
<td>2.35x10¹⁸</td>
<td>n⁺ GaAs:Si</td>
</tr>
<tr>
<td>Layer 4</td>
<td>1454 [λ/4n]</td>
<td>n-type</td>
<td>3.15x10¹⁸</td>
<td>n⁺ AlAs:Si</td>
</tr>
<tr>
<td>Buffer</td>
<td>2500</td>
<td>n-type</td>
<td>2.35x10¹⁸</td>
<td>n⁺ GaAs:Si</td>
</tr>
<tr>
<td>Buffer</td>
<td>2500</td>
<td>n-type</td>
<td>2.35x10¹⁸</td>
<td>n⁺ GaAs:Si</td>
</tr>
<tr>
<td>Substrate</td>
<td></td>
<td>n-type</td>
<td></td>
<td>n⁺ GaAs:Si</td>
</tr>
<tr>
<td>M3 [λᵣ = 2.2µm]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layer 1</td>
<td>3300 [λ/2n]</td>
<td>n-type</td>
<td>2.35x10¹⁸</td>
<td>n⁺ GaAs:Si</td>
</tr>
<tr>
<td>Layer 2</td>
<td>1913 [λ/4n]</td>
<td>n-type</td>
<td>2.5x10¹⁸</td>
<td>n⁺ AlAs:Si</td>
</tr>
<tr>
<td>Layer 3</td>
<td>1650 [λ/4n]</td>
<td>n-type</td>
<td>2.35x10¹⁸</td>
<td>n⁺ GaAs:Si</td>
</tr>
<tr>
<td>Layer 4</td>
<td>1913 [λ/4n]</td>
<td>n-type</td>
<td>2.5x10¹⁸</td>
<td>n⁺ AlAs:Si</td>
</tr>
<tr>
<td>Buffer</td>
<td>2500</td>
<td>n-type</td>
<td>2.35x10¹⁸</td>
<td>n⁺ GaAs:Si</td>
</tr>
<tr>
<td>Substrate</td>
<td></td>
<td>n-type</td>
<td></td>
<td>n⁺ GaAs:Si</td>
</tr>
<tr>
<td>M4 [λᵣ = 2.77µm]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layer 1</td>
<td>4174 [λ/2n]</td>
<td>n-type</td>
<td>1x10¹⁸</td>
<td>n⁺ GaAs:Si</td>
</tr>
</tbody>
</table>
In all the structures the first GaAs layer is of thickness $\lambda/2n$, rather than the more usual $\lambda/4n$. The reason for this is that these stacks have been designed for eventual use in a resonant cavity detector structure. The refractive index of the entry medium will not be air but will be the semiconductor material of the active region [GaSb in this case]. Hence, the phase changes on reflection of all the layers and that of the active region of the detector structure must be such that the total reflectivity of the whole structure is zero, see example 2.

The phase changes of the one of the structures [M2] has been considered with both air and GaSb as the incident mediums, fig. 6.15. Air is considered as the entry medium as these DBRs will be characterised after growth before the GaSb is grown on top.
In case [a] of fig. 6.15, the phase change of the reflected light at the \( n_0/n_1 \) interface is \( \pi \) since the light goes from a medium of low refractive index to one of high refractive index. At the \( n_1/n_2 \) interface, the second ray suffers a phase change of \( 2\pi \) due to the pathlength, \( \pi \) before reflection and \( \pi \) after reflection. Hence the first and second rays are out of phase with each other. The final ray will undergo a phase change of \( [n+2]\pi \), \( [n+1]\pi \) before reflection at the \( n_2/n_3 \) interface and \( [n+2]\pi \) after reflection. The phase changes of the whole structure after the \( n_0/n_1 \) phase change give a high reflectivity but as this one interface is out of phase with the rest of the structure this lowers the total reflectivity. This is seen more clearly in the graphs of figures 6.16 [a]-[e]. In case [b] of fig. 6.15, the phase change of the reflected light at the \( n_0/n_1 \) interface is now \( 0 \) which is now in phase with the rest of the structure. This now gives the curves of higher reflectivity in figures 6.16 [a]-[e]. In all cases of the reflectance spectra exhibiting the highest values of \( R \), GaSb [bulk] is considered as the entry medium although at the longer wavelengths [above the GaSb bandedge] this would not be suitable due to the low absorption coefficient. At these wavelengths GaInSb would be more suitable and \( n \) is expected to be similar in the modelled spectra of figures 6.16 [a]-[e] we wanted to convey to the reader is the improvement in the reflectance spectra by using a higher value of entry medium refractive index which will always be the case no matter what the semiconductor is that we use due to the refractive indices of most semiconductors being in the range 3-4.

The alternative to making the first layer \( \lambda/2n \) thick would have been to use AlAs as the first layer and use a structure similar to that of fig. 6.13. AlAs as the first layer presents a problem due to the instability of the Al which tends to oxidise when exposed to air [N. Mason, private
communication, 1995] and hence gives a poor surface for growth by causing pitting of the surface. This would not be such a problem if the detector structure was to be grown monolithically, but, in this case, the active region will be grown on top after optical characterisation of the mirror stack and hence the time lapse would cause a degradation of the Bragg stack surface. It was recommended that we use GaAs as the first layer of the reflector stack to try and reduce this problem.

Figure 6.16 Reflectance spectra for an 18 period GaAs/AlAs stack with both GaSb and air as the entry media centred at [a] 1.55μm, [b] 1.68μm, [c] 2.2μm, [d] 2.77μm and [e] 3.39μm.

From the data of table 6-4, the width of the central stopband for both types of incident medium is increasing with longer wavelength despite the fact that the refractive index difference of the layers for the different samples is decreasing with wavelength, table 6-2. But, the width of the stopband is also dependent on the wavelength and as this increases, the width of this stopband will increase and this explains the values obtained in table 6-4. The reflectance at the centre of the stopband in both cases for n₀=air or GaSb drops as the wavelength increases, mainly due to the fact that the
N is decreasing in order to keep the thickness of the stacks small and also from table 6-2 the change in refractive indices of the layers is also decreasing.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Reflectance at centre of stopband for (n_0=\text{air})</th>
<th>Reflectance at centre of stopband for (n_0=\text{GaSb})</th>
<th>Bandwidth at FWHM of (\lambda_0) ([n_0=\text{air}]) nm</th>
<th>Bandwidth at FWHM of (\lambda_0) ([n_0=\text{GaSb}]) nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>0.96</td>
<td>0.99</td>
<td>205</td>
<td>184</td>
</tr>
<tr>
<td>M2</td>
<td>0.95</td>
<td>0.98</td>
<td>237</td>
<td>205</td>
</tr>
<tr>
<td>M3</td>
<td>0.85</td>
<td>0.96</td>
<td>344</td>
<td>278</td>
</tr>
<tr>
<td>M4</td>
<td>0.84</td>
<td>0.96</td>
<td>432</td>
<td>350</td>
</tr>
<tr>
<td>M5</td>
<td>0.73</td>
<td>0.92</td>
<td>588</td>
<td>434</td>
</tr>
</tbody>
</table>

### 6.4 LITERATURE REVIEW: LONG WAVELENGTH BRAGG STACKS

<table>
<thead>
<tr>
<th>Operation Wavelength [(\lambda_0)] (\mu)m</th>
<th>Material System</th>
<th>Number of Periods</th>
<th>(\Delta n)</th>
<th>Reflectance at (\lambda_0) %</th>
<th>Comments</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.57 (\mu)m (\text{AlPSb/GaPSb}) InP substrate</td>
<td>8</td>
<td>0.542</td>
<td>84</td>
<td>MBE</td>
<td>H. Shimomura et al., 1994</td>
<td></td>
</tr>
<tr>
<td>1.6 (\mu)m (\text{AlPSb/GaPSb}) InP substrate</td>
<td>20</td>
<td>0.542</td>
<td>99</td>
<td>MBE</td>
<td>T. Anan et al., 1994</td>
<td></td>
</tr>
<tr>
<td>1.65 (\mu)m (\text{InP/In}<em>{0.53}\text{Ga}</em>{0.47}\text{As}) InP substrate</td>
<td>25</td>
<td>0.43</td>
<td>99</td>
<td>MOCVD</td>
<td>D. G. Deppe et al., 1990</td>
<td></td>
</tr>
<tr>
<td>1.74 (\mu)m (\text{GaAs}<em>{0.65}\text{Sb}</em>{0.35}/\text{AlAs}<em>{0.56}\text{Sb}</em>{0.44}) InP substrate</td>
<td>10</td>
<td>0.5</td>
<td>98</td>
<td>MBE Stopband width=271.5 nm</td>
<td>O. Blum et al., 1995</td>
<td></td>
</tr>
<tr>
<td>1.92 (\mu)m (\text{AlSb/GaSb}) GaAs substrate</td>
<td>10</td>
<td>0.77</td>
<td>98</td>
<td>MBE</td>
<td>G. Tuttle et al., 1993</td>
<td></td>
</tr>
<tr>
<td>1.68 (\mu)m (\text{GaAs/AlAs})</td>
<td>18</td>
<td>0.473</td>
<td>95</td>
<td>MBE</td>
<td>F. Manso-</td>
<td></td>
</tr>
</tbody>
</table>
Much of the work has concentrated on the antimonide-based material system due to the advantage of a large refractive index ratio. Wide bandwidth, high reflectance mirrors are possible with a fewer number of periods at these longer wavelengths. The small number of references is due to the fact that much of the DBR work, to date, has concentrated mainly on structures designed to operate at 1.55\,µm utilising GaInAsP and AlGaInAs alloys lattice-matched to InP [Guy et al., 1995]. The major disadvantage of these when compared to the antimonide-based system is the larger number of periods required in order to achieve high reflectivity due to the smaller refractive index ratios.

The longest wavelength AlSb/GaSb reflector stack to date is that grown by Tuttle et al., 1993, which shows a peak reflectance of 98\% at $\lambda=1.92\,\mu$m. only ten periods were used giving a total stack thickness of 3\,µm. The stack is 0.6\% mismatched which imposes an upper limit on the individual layer thicknesses that can be grown without inducing misfit dislocations though these dislocations are thought to have a negligible effect on the optical properties of these Bragg stacks.

One interesting concept using InGaAs/InP on InP substrates was that proposed by Deppe et al., 1990, where the mirror was doped high n-type in order to reduce absorption in these stacks as under normal circumstances mirrors made from this material system are absorbing. The high doping is thought to shift the absorption bandedge to longer wavelengths [Guy et al., 1995]. The longest wavelength GaAs/AlAs Bragg stacks are those that have been discussed in this chapter [M2 and M3], also see Mansoor et al. in 1995. M2 achieved >95\% reflectivity albeit with a larger number of periods than many of the antimonide-based Bragg stacks such as Tuttle et al. in 1993. The larger number of periods required when using GaAs/AlAs in order to achieve highly reflecting Bragg stacks is due to the smaller refractive index difference in this material system as compared to many of the antimonide-based systems listed in table 6-1.

Table 6-7 references DBRs grown for operation at wavelengths greater than or equal to 1.6\,µm.
6.5 OPTICAL CHARACTERISATION

The reflectance and transmittance of the multilayer stacks were measured using the experimental set-up of fig. 6.16. A Newport Ge photodetector and a Hamamatsu InSb photodetector were used as the reference detectors in the optical measurements. Broad-band light from a 150W quartz-halogen light source was focused onto the CVI monochromator. The light was then focused onto the output of the slit via various optics inside the monochromator. CaF₂ lenses were used as this material provides over 95% transmittance between 1-6μm, which is better than conventional glass lenses which are only 90% transmitting between 0.3-1.5μm and the transmittance drops rapidly and are <30% transmitting at 2.5μm. The light from the quartz-halogen light source was chopped at a frequency of ~318Hz. An EG&G lock-in amplifier was used to measure the reading from the detector. The whole system was computer-controlled using an icon-based programming package called Lab-View which allows easier interfacing of the various instruments to the PC. The reflectivity measurements for the DBRs were normalised to a Au mirror [assumed to be over 99% reflecting between 1.5-5μm].

![Experimental set-up used to measure the reflectance and transmittance of the various devices](image)

It is important to note that whilst the greatest care was taken in the measurements of all the devices considered in this thesis, inaccuracies can still arise due to the nature of the set-up. The degree of accuracy with which the lens holders, sample holders and detector stage could be moved in the x, y, and z directions was difficult to control as these were not mounted on motorised stages but instead relied on human movement. Hence, when changing samples the stability of the rest of the set-up could not be guaranteed as a slight movement in any direction of the lenses, sample stage, or detector stage resulted in an error in the actual reading of the output signal. This error varied between 1-5% of the actual reading and was unavoidable in the measurements due to the limits of the instrumentation used.

The five reflector stacks designed and grown were characterised optically and some electrically. All the stacks were designed with the idea in mind that they would be incorporated eventually into
a cavity structure, with a suitably designed active region. Due to the time span that elapsed in the growth and characterisation of these stacks to the eventual regrowth of the absorber region and the processing and characterisation of the final cavity structure, only M2 was incorporated into a cavity to form the RCE detector. Hence, in the results in the next section this is the most characterised of the five stacks and the results from these will be discussed in detail.

**M2**
The stack was grown as a 2" wafer with one half of the stack characterised optically and the other half kept by the University of Sheffield to have some X-ray measurements and capacitance-voltage measurements [to ascertain the carrier concentration of the Bragg stack] carried out. The half of the reflector stack characterised optically was split into the grid of fig. 6.18 and each section was tested.

![Characterisation grid for sample M2](image)

*Figure 6.18 Characterisation grid for sample M2*

The wafer was mapped in order to ascertain the reflectivity at various points of the wafer and to obtain an idea of the growth uniformity. It is hoped that the reflectance will be uniform over the area of the wafer but this is not always the case. The spectra of fig. 6.19 shows a reflectance spectrum from near the centre of the stack [A3] which is centred at ~1.68μm. Also shown is a modelled spectrum using the parameters given in tables 6-2 and 6-3.
Figure 6.19 Measured and modelled reflectivity spectrum of M2.

Considering the measured spectra, we can see that the modelled and measured spectra show good agreement. For the theoretical curve, an 18 period DBR should yield a stopband centred at 1680nm with a reflectivity of 94%, with air as the incident medium, and a stopband width at 80% of 210nm. The measured result yields a 194nm wide bandwidth at 80% centred at 1694nm and a reflectivity of ~96%. This was one of the best reflectivity spectra that was measured for this wafer. Some interesting points to note about the graph are:

[a] the dip at 168μm has shifted slightly to the left when compared to the model making the central maxima slightly asymmetrical

[b] the half of the spectra to the left of 168μm has shifted to the right

[c] two of the sidebands, one on either side of the central maxima have dropped in reflectivity when compared to the modelled spectra. The one on the left-hand side is in the wavelength range 1500-1550nm and the one on the right-hand side is in the wavelength range 1900-2000nm.

In order to analyse these results several important points have to be taken into account. Firstly, the value of the reflectivity depends on the refractive indices of the layers and the number of periods of the mirror stack. Secondly, the position of the central maxima depends on the thickness of the layers and hence the refractive index. The thickness of these layers is not accurately known once they are grown. As previously mentioned from X-ray data, for M2, we are quoted a layer thickness with an error of +/-30-40Å for each of the layers which corresponds to a 3% error in the growth of each layer. We also do not know if the refractive indices of these layers is correct. We assume a linear interpolation of the data, as there are no references for values of the measured refractive indices at 1.68μm. Modelling the error in the growth thickness of the reflector stacks for M2, fig. 6.20, we can gain an idea of the error in the optical spectra.
Decreasing each of the layers by 40Å causes a graded stack to be produced. This causes a shift in the central maxima to a shorter wavelength. Increasing the layers by 40Å/layer causes a shift in the opposite direction to longer wavelengths.

Figure 6.20 Reflectance spectra showing the variation of the stopband wavelength with increasing and decreasing layer thicknesses: $A=0Å$, $B=+10Å$ and $C=−10Å$ [a] reflectance spectra over a large wavelength range [1400-2000nm], and [b] same spectra over a shorter wavelength range [1600-1850nm].

The grading of the layers as seen from curves B and C of fig 6.20 causes an asymmetry of the reflectance spectra which is clearer in fig. 6.20[b]. Fig. 6.21 considers the phase shift of the curves of fig. 6.20. Curve A has a phase shift of 0° at 1680nm, curve B has a phase shift of ~11° at 1680nm and curve C has a phase shift of ~13° at 1680nm.

Figure 6.21 Phase shift of the central stopband of reflector stacks with graded layers: $A=0Å$, $B=+10Å$ and $C=−10Å$.

Due to the fact that the width of the central stopband in M2 is so broad, the reflectance of the stacks is still greater than 85% despite the shift of curves B and C of fig. 6.21. This is no problem.
as long as the mirror is not used in a resonant cavity devices. If it is to be used in a device, then
this additional phase will cause a problem when considering the cavity design of the device. From
chapter 4 it was seen that the cavity has to be some multiple of $m\lambda/2n$ in order for resonance to
occur and, for the detector, maximum absorption of the incident light. If there is a phase change
in the DBR due to layer thickness variations then this introduces an extra thickness, called the
light penetration depth, which has to be added onto the actual cavity thickness. The resonant
wavelength of the device depends on this cavity thickness and if the cavity is too long then the
wavelength of resonance will also be too long. This will result in a non-optimised device as most
devices are grown monolithically where it is assumed that the mirrors suffer no phase shift and
hence the cavity thickness will be that designed for. If the centre wavelength of the mirrors and
that of the cavity do not coincide then this will result in a broadening of the resonance linewidth.

If we now consider points [a]-[c] made about the spectra of fig. 6.19 in turn, then, from various
modelling using the multilayer program, we can come to some answers for the difference in the
two curves. The slight asymmetry of the stopband can be attributed to a thickness gradient of say
$\pm 10\AA$/layer. This type of behaviour has also been observed by other groups [Lambert et al.,
1994; Boets et al., 1987; Thornton et al., 1984], and for the MLS in question the thickness of the
layers were not measured to any great degree of accuracy and hence we cannot conclusively say
that the thicknesses used in the model are the same as those in the actual stack itself. Using the
transfer matrix model and decreasing all the layers of the MLS by 10Å showed good agreement
with measured spectra of fig. 6.19. This type of gradient in the reflector stack layers can
deteriorate the optical quality of the mirrors by introducing this type of asymmetry into the Bragg
reflection band and thereby reducing the width of the band and the reflectivity.

The drop in the sidebands of the measured spectra when compared to the calculated spectra is
difficult to explain. As stated, the model is only valid over the range of the stopband and outside
of this the refractive indices vary by amounts which are significant enough to make a difference
to the reflectivity spectra. Ideally, it should be possible to take the refractive index dispersion into
account. This may explain the variation of the measured spectra and the model below 1600nm
and above 1780nm.

Ideally the growth technique would produce a sample which gave uniform measurements over the
whole wafer. However, this is fairly difficult to achieve. To this extent, the wafer of M2 was
mapped according to the grid of fig. 6.22. From the reflectance measurements, the wavelength of
the central stopband was noted for each section and a pattern, corresponding to fig. 6.23 was established.

![Diagram of wafer mapping variation of wavelength of the central stopband with distance over the wafer half.](image)

**Figure 6.22** Wafer mapping variation of wavelength of the central stopband with distance over the wafer half. The distance $L_1 - L_2$ is ~5cm and distance from the wafer centre to the wafer edge is ~2.5cm.

The pattern follows concentric circles around the wafer, such that those spectra which corresponded to the desired wavelength of 1.68µm and agreed with the modelled spectra all occurred in a semicircle within a radius of 1.5cm from the green dot. Those spectra where the central stopband wavelength was too long all occurred in a cluster near the centre of the wafer and on either side of the red line and where the wavelength of the centre stopband was too short, all these spectra occurred at the edges of the wafer. The spectra of fig. 6.23 shows four plots corresponding to the colours of the grid of fig. 6.22. The reflectance at the centre of the stopband width and the bandwidth at 80% is tabulated in table 6-6.

![Graph showing variation of wavelength of central stopband over the wafer.](image)

**Figure 6.23** Variation of wavelength of central stopband over the wafer.
The shift in wavelength to the left of 1.68µm is due to a gradual grading of the layers, a decrease in each layer by tens of angstroms. The larger the shift to the left the greater the decrease/layer. This also causes a reduction in the reflectivity of the overall stack by a few percent. A shift to the right of the central stopband is attributed to an increase in each layer by tens of angstroms, the larger the grading the greater the shift. This also causes an increase in the overall reflectivity due to an increase in the thickness of the layers.

Table 6-6 Reflectance and bandwidth calculations of the curves of fig. 6.23

<table>
<thead>
<tr>
<th>Curve</th>
<th>Wavelength at stopband centre [(\lambda_0)] nm</th>
<th>Reflectance at (\lambda_0) %</th>
<th>Bandwidth at (\lambda_0) nm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1684</td>
<td>96</td>
<td>199</td>
</tr>
<tr>
<td></td>
<td>1715</td>
<td>97</td>
<td>203</td>
</tr>
<tr>
<td></td>
<td>1650</td>
<td>93</td>
<td>182</td>
</tr>
<tr>
<td></td>
<td>1640</td>
<td>92</td>
<td>179</td>
</tr>
</tbody>
</table>

The reflectance has dropped at the shorter wavelengths and increased at the longer wavelengths over the region of the sideband which agrees with our theory about a grading of the layers. The variation of the wavelength of the central stopband with distance from the two flats of the wafer [wafer edge and wafer flat, fig. 6.23] are seen in figures 6.24 and 6.25. From fig. 6.24, the central wavelength varies between 1600-1700nm near to the wafer centre but the further away from this we go the shorter the wavelength of the central stopband. From fig. 6.25, it can be seen that both near the wafer flat [0.6cm] and furthest away [>4.2cm] the wavelength of the central stopband shifts to shorter wavelengths.

Figure 6.24 Variation of centre wavelength of stopbands over the wafer measured from the wafer centre
The shift of +/-50nm either side of 1680nm corresponds to a +/-3% error in the growth of the layer thicknesses of M2. Such systematic shifts in the DBR centre wavelength, as has been observed, are quite common in MBE and MOCVD grown wafers and are dependent on the growth system geometry. Such non-uniformities in the growth are a problem as they limit the number of useful devices which can be extracted from a single wafer.

### M1, M3, M4, and M5

Table 6-6 summarises some important features from figures 6.26-6.29 which show the modelled and measured reflectance spectra. All the measured reflectance spectra were taken from a point near the centre of a 2” wafer, fig. 6.18. The trend in wafer non-uniformity for all the DBRs was similar to M2 and hence will not be covered again.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>183</td>
<td>171</td>
<td>97% at 1.55μm</td>
<td>98% at 1.57μm</td>
</tr>
<tr>
<td>M3</td>
<td>262</td>
<td>262</td>
<td>83% at 2.2μm</td>
<td>82% at 2.2μm</td>
</tr>
<tr>
<td>M4</td>
<td>339</td>
<td>-</td>
<td>84% at 2.77μm</td>
<td>56% at 2.61μm</td>
</tr>
<tr>
<td>M5</td>
<td>396</td>
<td>-</td>
<td>74% at 3.39μm</td>
<td>65% at 3.3μm</td>
</tr>
</tbody>
</table>

Considering the measured and modelled spectra for each of the structures:
Figure 6.26 Measured reflectance spectra of M3 designed for a central wavelength of 2.2 μm. Also shown is the calculated reflectance curve.

Figure 6.26

The central maxima to the right of 2.2 μm shows very good agreement with the modelled spectra whilst that to the left of 2.2 μm has shifted slightly to the shorter wavelengths. The reflectance dip is now at ~2116 nm and the reflectance has also dropped slightly. This gives an asymmetry to the spectra. The causes of the wavelength shift and the asymmetry has already been discussed.

Figure 6.27 Measured reflectance spectra of M1 designed for a central wavelength of 1.55 μm. Also shown is the calculated reflectance curve.

Figure 6.27

The measured reflectance spectra shows a stopband which is asymmetric about the centre of the stopband. The stopband width is also narrower than the model and the whole spectra has shifted slightly to longer wavelengths. Reasons for these discrepancies have already been cited for Bragg stacks M2 and M3. Both M3 and M1 are possibilities for future cavity structures as long as the
surface is still suitable for growth. For M1, GaSb [bulk] could still be used as the absorber region as the absorption coefficient at this wavelength is of the order of \(10^4\text{cm}^{-1}\).

Figure 6.28 Measured reflectance spectra of M4 designed for a central wavelength of 2.77\(\mu\text{m}\). Also shown is the calculated reflectance curve.

Figure 6.29 Measured reflectance spectra of M5 designed for a central wavelength of 3.39\(\mu\text{m}\). Also shown is the calculated reflectance curve.

Figure 6.28 and Figure 6.29
These two graphs are much more difficult to explain as the measured reflectance spectra do not match the model at all. In both cases the modelled spectra are much wider and of higher reflectivity. It could be that the refractive index difference was over-estimated in both cases hence the narrower bandwidth. The curve of fig. 6.28 as well as having shifted to a shorter wavelength also has a large dip in the centre of the stopband. One possible reason for this dip could be the presence of a layer which is not \(\lambda/4\)\(\text{n}\) thick situated in the middle of the reflector stack, causing a cavity-type structure to form. The presence of this layer causes there to be some destructive interference between the light reflected from this layer and that from all the other layers. This
assumption agreed well modelled data computed using the multilayer programs and gave reasonable agreement with the measured spectra of fig. 6.28.

The curve of fig. 6.29 is very asymmetric and the stopband is very narrow. Once again the reasons cited previously could be the explanation. As we have no way, here at UCL, of measuring the actual layer thicknesses, say, by using TEM [Transmission Electron Microscopy], we do not actually know how thick the layers were. SEM [Scanning Electron Microscopy] measurements were carried out on structures M4 and M5 and from the photographs the individual layers looked to be of equal thickness, though the pictures were rather grainy. It was not possible to ascertain the actual thickness of the individual layers to any great degree of accuracy as the pictures were not of a high enough resolution. Whether the discrepancy between the modelled spectra and the measured is due to an error in the refractive indices, growth or both is uncertain. Regrowth of these stacks is being undertaken.

6.6 CONCLUSIONS

In this chapter we have considered the derivation of equations required for Bragg stack design. The reflectivity for a multilayer structure has been stated and analysed. The reflectance has been seen to depend on the difference in refractive indices between the two layers making up one period of the stack and the number of periods used. The greater these two parameters, the higher the value of the reflectance of the mirror. The theory of Bragg stacks is then illustrated with two examples where different designs are considered in order to provide an idea of how they operate.

From this initial study of the theory of these structures, this was then applied to the design of the reflectors which were grown and characterised. These were composed of GaAs/AlAs and grown on GaAs:Si substrates. The stacks were heavily doped n-type of the order of $2 \times 10^{11}$ cm$^{-3}$ with the aim in mind of using them as the n$^+$ region in a p-n$^+$ cavity structure. Of the five stacks the best results were obtained on the lower wavelength stacks. For M2 [Mansoor et al., 1995] the maximum measured reflectivity was measured to be 96% at 1694nm. The modelled and measured reflectivity spectra show good agreement near the centre of the wafer but growth non-uniformity causes a shift of ~200nm in the spectrum across a 2" wafer and a drop of 25% in peak reflectivity towards the edges of the wafer. Bragg stack M3 [Mansoor et al., 1995] is the longest wavelength GaAs/AlAs reflector grown to date and this had a maximum reflectance of ~83% at 2.2µm. This was slightly reduced from the modelled data. This also exhibited growth non-uniformities with ~250nm shift in the spectrum over the 2" wafer and a 15% drop in reflectance towards the edges. The growth non-uniformities followed a similar trend in all the stacks.
7.1 INTRODUCTION

Having considered various junction structures in chapter 3, this chapter goes on to show some electrical results obtained on two junction structures already considered theoretically: the p-n\(^+\) heterojunction [p-GaSb/n\(^-\)GaAs] and the Schottky barrier junction [metal/p-GaSb]. The design and growth of high quality junctions is important in determining the output characteristics of a photodiode. To this end the absorber region needs to be as defect free as possible, within the limits of the growth, in order to obtain a highly efficiency detector. The p-n\(^+\) heterojunction, despite the large lattice mismatch between the active region and the substrate, shows good electrical characteristics in comparison to other structures of this type. The dark current and breakdown voltage of the structures are calculated and quantitative analysis is made of the dark current. Schottky junctions are considered as an alternative to the heterojunction in order to avoid the problems of poor interfaces. Electrical results from some of these structures present some interesting points, although the strong rectification of early samples proved difficult to repeat.

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Initially we consider the antimonide-based material system and possible ternaries and quaternaries which can be utilised in the 2-5μm wavelength region. We then go onto look at the problems with the binary GaSb as a possible detector active region. The electrical characteristics of GaSb-based Schottky and heterojunctions are discussed in detail both theoretically and experimentally.

7.2 THE GaSb MATERIAL SYSTEM

GaSb is a basic binary component of AlGaSb, InGaSb and InGaAsSb compound semiconductors. It has a bulk bandgap at room temperature of 0.72eV [Landolt-Börnstein, 1982] and a cubic lattice constant of 6.095Å [Landolt-Börnstein, 1982]. It is barely a direct bandgap semiconductor since the L-valleys are only 0.07eV and the X-valleys only 0.29eV above the Γ valley [Milnes et al., 1993]. As we are limited by the use of the elements In, As, Ga and Sb in order to reach the 2-5μm region, this does not leave many options as far as lattice-matched systems are concerned. If we consider the ternary antimonide-based systems InGaSb\textsubscript{1-x} and In\textsubscript{1-x}As\textsubscript{x}Sb, then only InAsSb is lattice-matched to GaSb at one point which corresponds to x=0.91 (λ=4.2μm). With regards to other substrates such as GaAs and InP the ternaries cannot be lattice-matched. The degree of lattice mismatch between InAsSb and substrates such as GaSb and GaAs is shown in the graph of fig. 7.1.

![Graph showing lattice mismatch of InAsSb with GaAs and GaSb substrates](image)

**Figure 7.1 Lattice mismatch of In\textsubscript{1-x}Sb with GaAs and GaSb substrates**

The mismatch between In\textsubscript{1-x}As\textsubscript{x}Sb and two various substrates decreases linearly with increase in the As content of the ternary. From Krijn [Krijn, 1991], the quadratic expression

\[ T_{ABC}(x) = xB_{AB} + (1-x)B_{AC} + x(x-1)C'_{AB} \]  

[7.2.1]

was used to calculate \( E_g \) when the ternary alloy is of the form \( AB_xC_{1-x} \). The constant \( C' \) is known as the bowing parameter for \( E_g \) and was found by Krijn to be 0.38 for In\textsubscript{1-x}As\textsubscript{x}Sb and 0.42 for In\textsubscript{1-x}Ga\textsubscript{x}Sb.
The substrates being considered here are GaSb or GaAs. GaSb substrate because it offers the closest lattice-match for both InAsSb and InGaSb and GaAs because it offers the lowest defect density material of all the III-V substrates. The growth of GaSb on GaAs shows an 8% mismatch between the lattice constants of the two material systems which may present a problem from the point of view of there being a large number of dislocations extending into the epilayer. Buffer layers will need to be incorporated between the substrate and the active region in order to reduce the dislocations extending into the active region. The reduction of these is important in order to prevent recombination centres from occurring and thereby reducing the efficiency of the detector. One way is the use of a step graded buffer layer between the substrate and the active layer where the bottom layer is lattice-matched to the substrate and the top layer to the active region. It seems to be more effective than a continuous buffer layer in decreasing dislocation densities because the dislocations bend at the step interface and do not propagate along the growth direction. It is not clearly known what effect a large number of dislocations arising from a poor interface has on the
electrical and optical properties of these material systems. It would be useful to compare these epitaxial layers with a similar dislocation-free material but this is not, as yet, possible.

Another useful material system is $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{Sb}_{1-y}$, the bandgap of which covers the 1.43-0.17eV wavelength range. Lattice-matched to InP substrates the energy bandgap is nearly fixed, 0.74-0.78eV. But lattice-matched to GaSb, the energy bandgap varies between 0.73 and 0.29eV [1.7-4.3μm]. It has received little attention because it is known to have a very large miscibility gap [Dolićinov, 1978] when grown by LPE, with a critical temperature estimated to be 1467°C. This restricts the range of solid alloys [Koboyashi et al., 1979] which can be grown. The use of MBE which is kinetically controlled and hence is useful for the growth of metastable alloys [N. Koboyashi et al., 1982] has resulted in the growth of GaInAsSb alloys lattice-matched to GaSb substrates with $\lambda=2.1\mu$m. For the 2-4μm region, InGaAsSb lattice-matched to GaSb and InAs are useful. From Tsang et al., 1984, the lattice constants of $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{Sb}_{1-y}$ alloys are related to the lattice constants of the constituent binary compounds by Vegards Law. The condition for lattice-matching to GaSb is [Eglosh et al., 1991]

$$y = \frac{0.91(1-x)}{(1 + 0.05x)}$$

[7.2.2]

The bandgap of $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{Sb}_{1-y}$ alloys at 300K, as estimated from the bandgaps of the ternary alloys [Eglosh et al., 1991] is given by

$$E_g(x,y) = 0.18 + 0.131x - 0.4y - 0.122xy + 0.415x^2 + 0.58y^2 + 0.021x^2y + 0.62xy^2$$

[7.2.3]

Simultaneous solution of equations 7.2.2 and 7.2.3 yields the curve of bandgap as a function of Ga content, as shown in fig. 7.4 for alloys lattice-matched to GaSb. At the two extremes of the x-axis, for $x=0$, $y=0.91$ and the bandgap energy is equal to that of InAs$_{0.91}$Sb$_{0.09}$ which corresponds to a wavelength of 4.2μm. For $x=1$, $y=0$ the bandgap energy is equal to that of GaSb, 0.72eV [1.73μm].
II. ELECTRICAL STUDY OF GaSb-BASED PHOTODETECTOR STRUCTURES

Figure 7.4 Change in bandgap for varying Ga content. The inset shows the change in \( y \) for varying \( x \) for the quaternary according to the equation

\[
y = 0.91(1-x)/(1+0.05x)
\]

The smallest energy gap among the III-V compound semiconductors occurs in the alloy of the InAs\(_x\)Sb\(_{1-x}\) material system, see fig. 7.1 [Wooley et al., 1964]. From this it should be possible to fabricate detectors with cut-off wavelengths as large as 9 \( \mu \)m at 77K. InAs\(_{0.9}\)Sb\(_{0.09}\) lattice-matched to GaSb corresponds to \( \lambda = 4.2 \mu \)m at 300K. The InAsSb alloy system spans the wavelength range 3-5 \( \mu \)m. The lattice mismatch of the ternary on InAs becomes severe enough to limit the crystal growth for \( x > 0.15 \), and considerable mismatch exists for lower \( x \) [von der Ziel et al., 1985]. For InAs\(_{0.9}\)Sb\(_{0.09}\) grown by LPE the GaSb substrate tends to go into solution unless the ternary melt is highly super-cooled resulting in a very rapid and relatively low quality growth [Gertner et al., 1979]. The use of MBE and MOVPE avoids many of these problems.

**GaSb: Disadvantages as a detector material**

The potential development of antimonide-based devices has been hindered by the technical difficulty encountered in solving two major problems. Both of these are growth related and until further research is made into solving these the progress in antimonide-based structures will be slow. The problems are:

1. Controlling the residual p-type doping level: Epitaxially grown antimonide-based materials always grow p-type with a hole concentration of the order of \( 10^{14} - 10^{17} \) cm\(^{-3}\). The reason for the high doping is due to a deviation from stoichiometry which has been attributed to an Sb vacancy on an Sb site. However, the form of this defect centre has been suggested [von der Meulen, 1967] to be more complex, such as an antisite defect of the form Ga\(_{\text{Sb}}\)V\(_{\text{Ga}}\). This Ga\(_{\text{Sb}}\)V\(_{\text{Ga}}\) defect can be created in two ways:

   [1] one of the nearest Ga atoms fills a vacant Sb site leaving behind a Ga vacancy.
[ii] the presence of a Ga atom on an Sb site facilitates the formation of an adjoining Ga vacancy. The native lattice defect is a combination of a Ga vacancy and a Ga atom on an Sb site which acts as a doubly ionisable acceptor. Various methods have been suggested to try and reduce the background carrier concentration such as low temperature growth, growth from Sb-rich solutions, and compensation doping the p-GaSb by gradually adding small amounts of n-type dopant to the p-GaSb in order to balance out the carrier concentration.

Takeda et al., 1984, and Noda, 1984, have demonstrated that the background concentration of undoped Al_{0.1}Ga_{0.9}Sb was reduced by the growth from Ga-rich solutions below 400°C [V. Takeda et al., 1984]. The carrier concentration of bulk GaSb was also reduced by the growth from Sb-rich solutions [Effene et al., 1964; Reid et al., 1966]. They realised that the origin of the p-type background carrier concentration of Sb-rich solution growth is the same native defect as found in Ga-rich solution growth. Using Sb-rich solutions at low growth temperatures strongly reduces the native defect related to Sb vacancies. For GaSb an order of magnitude increase in the carrier concentration [10^{15} \text{cm}^{-3} \text{ to } 10^{16} \text{cm}^{-3}] causes ~7-fold increase in the voltage required to deplete this thickness.

[2] The growth of high quality, epitaxial material on a suitable substrate especially when the operating wavelength required is >2\mu m. In the case of depositing high quality epitaxial material on GaAs substrates, then, this has been attempted many times [Lee et al., 1986; Haywood et al., 1988; Chidley et al., 1991; Turner et al., 1993; A. Boroldi et al., 1994]. All attempts to deposit heteroepitaxial layers of GaSb on GaAs even if a low level of residual doping could be achieved always report a lower quality material as compared to the one homoepitaxially deposited on GaSb [Lee et al., 1986; Chidley et al., 1991]. The authors have found that ramping the temperature under an As flux optimised the switching sequence between GaAs and GaSb. In this case the mismatch which separates the Ga-As and Ga-Sb bond lengths is abruptly relaxed and good quality GaSb can be homogeneously deposited.

The crystal behaviour of the GaSb/GaAs system exhibits features associated with heterostructures with a large lattice mismatch. The density of threading defects has been measured at the level of the interface and is at least two orders of magnitude smaller than that in the 4% mismatched GaAs/Si system [Roche et al., 1991]. In propagating through the active region these dislocations form non-radiative recombination centres and accelerated the diffusion of impurities along their lines. The origin of threading dislocations is thought to be the misfit
CHAPTER 7 Electrical Study of GaSb-based Photodetector Structures

dislocations which relieve the lattice mismatch induced strain. It is important to inhibit the propagation of the misfit dislocations in the epilayer by confining them to the interface [Bourret et al., 1992].

7.3 LITERATURE REVIEW: COMPARISON OF ANTIMONIDE-BASED PHOTODETECTORS

Table 7-1 summarises results on long wavelength antimonide-based photodetectors. There are very few published papers on antimonide-based photodetectors for the longer wavelength regions and I have only include those where the operating wavelengths are greater than 1.6μm.

<table>
<thead>
<tr>
<th>Detector Type</th>
<th>Structure</th>
<th>λ [μm]</th>
<th>η [%]</th>
<th>D* [cmHz^1/2W^-1]</th>
<th>Comments</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-n</td>
<td>p-n GaSb′Te substrate; p-Ga0.57In0.18As0.17Sb0.38; LPE</td>
<td>2.2</td>
<td><a href="mailto:67@0.1V">67@0.1V</a>; 43@0V;</td>
<td>7×10^7@0V; Rear illumination. Dark current ∼50-100μA at -1V;</td>
<td></td>
<td>A. K. Srivastava, 1986</td>
</tr>
<tr>
<td>p-n</td>
<td>GaInAsSb/GaSb heterojunction</td>
<td>2.4</td>
<td>40% [1.75 - 2.25μm]</td>
<td>8.8×10^5</td>
<td>Capacitance is ∼10pF at -1V. Very high dark current</td>
<td>Tournié et al., 1991</td>
</tr>
<tr>
<td>p-n</td>
<td>p'-GaSb substrate; 0.6μm GaSb buffer; 4μm p-In0.53Ga0.47Sb absorbing region; n'-In0.53Ga0.47Sb; MOVPE</td>
<td>2.55</td>
<td>43@2.6μm</td>
<td></td>
<td></td>
<td>F. Pascal - Delannoy, 1992</td>
</tr>
<tr>
<td>Schottky</td>
<td>n'-GaSb; n-GaSb; Au Schottky [100-150Å]; LPE</td>
<td>1.6</td>
<td>37@0V</td>
<td>Assumes that α=2×10^6cm^-1 at 1μm and 1×10^6cm^-1 at 1.25μm</td>
<td></td>
<td>Y. Nagao et al., 1981</td>
</tr>
<tr>
<td>p-n'</td>
<td>GaSb substrate; 3μm p-InGaSb; 1μm p-InGaSb; LPE</td>
<td>2.2</td>
<td>61</td>
<td></td>
<td></td>
<td>A. Aardvark et al., 1993</td>
</tr>
</tbody>
</table>
### Table 7.1: Electrical Properties of Gasb-Based Photodetector Structures

<table>
<thead>
<tr>
<th>Detector Type</th>
<th>Structure</th>
<th>λ [μm]</th>
<th>η [%]</th>
<th>D* [cmHz(^{1/2})]</th>
<th>Comments</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>In varies 28-40%; MOVPE</td>
<td>p-n&lt;sup&gt;+&lt;/sup&gt;</td>
<td>1.7</td>
<td>10</td>
<td>3.5x10&lt;sup&gt;9&lt;/sup&gt; @ -1V</td>
<td>4-fold enhancement in the photocurrent</td>
<td>F. Mansoor et al., 1995</td>
</tr>
<tr>
<td></td>
<td>n&lt;sup&gt;+&lt;/sup&gt;-GaAs substrate; 0.92μm p-GaSb; MOVPE</td>
<td>0.8</td>
<td></td>
<td>3x10&lt;sup&gt;10&lt;/sup&gt; @ 0V</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In 1981 Nagao et al. reported a GaSb Schottky diode with an external quantum efficiency of ~35% at zero bias voltage without an antireflection coating over a broad wavelength range up to 1.6 μm. They suggested that surface leakage current, tunnelling current and avalanche breakdown respectively dominated the reverse characteristics with increasing bias. GaInAsSb photodiodes operating in the 2-3 μm range have been grown by LPE [Low et al., 1981], as well as GaInAsSb/GaAsAsSb avalanche photodiodes with separate absorption and multiplication regions [Gouskov et al., 1991]. The first uncooled high efficiency GaInAsSb/GaSb p-n heterojunction photodiode was reported by Srivastava et al. in 1986. This was grown by LPE with a net acceptor concentration in the depletion region of 3-4×10^{15} cm^{-3}. The room temperature external quantum efficiency of this device was 67% at 2.2 μm with an applied bias of 0.1V and the D*{[2.2μm]} = 7×10^9 cmHz^{1/2}W^{-1}.

In 1991 Toumie et al. also reported an LPE grown GaInAsSb/GaSb heterojunction photodiode which exhibited a long wavelength threshold of 2.4 μm. From 1.75-2.25 μm, they report a η of 40% and D*{[2.2μm]} = 8.8×10^9 cmHz^{1/2}W^{-1} which is comparable to that by Srivastava et al., 1986, in 1986. The cooled photodiode exhibited a significant improvement in device performance. The photodiode reported by Toumie et al., showed a D*{[2.4μm]} = 2.1×10^11 cmHz^{1/2}W^{-1} at a temperature of 200K due to the improved dark current characteristics of diodes in reverse bias at such low temperatures. Pascal-Delannoy et al., in 1992, reported a GaInAs-based diode grown by MOVPE operating at 2.55 μm. This exhibited a peak quantum efficiency of 43% at 2.6 μm.

7.4 ELECTRICAL RESULTS
The previous section has discussed some of the problems involved with using GaSb and as can be seen many of them are growth-related. From the point of view of detector structures the main problem is that of the high doping which limits the type of structures that can be used. p-i-n junctions are difficult with a material with such a high carrier concentration as the intrinsic region will be doped 10^{16}-10^{17} cm^{-3}. The use of a p-n+ heterojunction with GaAs acting as the n+ region is possible and various devices have been grown using this configuration. As well as this, the use of a Schottky-type structure offers some solutions such as the use of only one semiconductor material. As the p-n junction is formed between a metal and the p-GaSb this avoids the problem of a poor interface as in the heterojunction between the GaSb epilayer and the GaAs substrate due to the large mismatch between the lattice constants of the two materials. The ideal choice would be to grow the p-GaSb epilayer on a GaSb substrate and this has been attempted by our collaborators at Oxford [Hordvork et al., 1993]. They grew various homojunctions structures and
the best results were obtained on a structure where the p-n junction was away from the epilayer/substrate interface, though even for this the dark current was of the order of ~0.1mA at 1V reverse bias. This could be attributed to the poor quality of the GaSb substrate which has a higher defect density than a GaAs substrate. The results obtained by Aardvark et al., 1993, were similar to the ones we obtained on homojunctions and hence will not be commented on further.

**Characterisation System**

The electrical characterisation will mainly consist of current-voltage measurements carried out using a Hewlett-Packard 4.612A Characterisation System, fig. 7.5. A voltage is applied to the top and bottom contacts of the device, via probes, and the current is measured using a suitable meter. Various parameters can be calculated from the I-V measurements such as the ideality factor, the series resistance, the dark current and the breakdown voltage. Capacitance-voltage measurements can also be made where a graph of $1/C^2$ as a function of applied voltage can be used to calculate the doping in the depletion region as well as the depletion region width.

![Diagram of Characterisation System](image)

**Figure 7.5 The electrical characterisation system used to measure the current-voltage characteristics of the diode structure**

**Junction Structure**

Table 7-2 lists the structures which have been grown and characterised as possible detector structures. Structure A has both a Schottky front junction and a p-n back junction.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Junction Type</th>
<th>Front Contact</th>
<th>Back Contact</th>
<th>Substrate</th>
<th>Absorbing Layer</th>
<th>Capping Layer</th>
<th>Buffer Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>n'-p heterojunction</td>
<td>Al [400μm]</td>
<td>In/Ge/A u</td>
<td>GaAs:Si</td>
<td>u-GaSb &lt;250Å</td>
<td>GaAs:Si 400°C</td>
<td>u-GaSb</td>
</tr>
</tbody>
</table>

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7.4.1 SCHOTTKY-BARRIER JUNCTION \([Al/n-GaAs:Si \text{ CAP/p-GaSb EPILAYER}]\)-STRUCTURE A

It would be an advantage to be able to make Schottky contacts to p-GaSb as this would avoid the need to dope the material. Schottky diodes have been made to n-GaSb [Nagao et al., 1981; Chin et al., 1980; Sukegawa et al., 1978] but the main limitation to both these devices has been the high dark current. To date only ohmic contacts have been made to p-GaSb due to the low barrier height of ~0.2eV. The Fermi level is pinned 0.2eV above the valence band edge due to the large density of surface states. We investigated various methods of enhancing the barrier height to carrier transport. Many other groups have used various principles, incorporating insulators [Schmidt et al., 1988], highly doped surface layers [Pearton et al., 1989], and other semiconductors [Cheeks et al., 1991; Woldrop et al., 1988]. Since u-GaSb grows p-type when not intentionally doped, these methods have concentrated on increasing the hole barrier. The large arsenide/antimonide valence band offset suggested the use of an interfacial layer of GaAs between the metal and the GaSb. The band diagram is shown in fig. 7.6 with band offsets calculated from the model solid theory of Van der Walle, 1989, assuming complete relaxation of the strain. From this it can be seen that the barrier to holes is significant.
Sample A had the structure shown in fig. 7.7 where the GaAs cap thickness was <250Å. This thickness was chosen as the GaAs grown at 560°C was found to be p-type with a carrier concentration of $2 \times 10^{17}$ cm$^{-3}$. At this concentration and thickness the GaAs should be fully depleted which may not be the case for a thicker layer. The ~8% mismatch between the GaSb/GaAs lattice constants results in the epilayer being highly dislocated [Chicley et al., 1989]. The cap appears to act as an insulator and enhances the barrier to hole conduction.

The structure of fig. 7.7 was considered. The metal/GaAs cap/GaSb absorber layer acts like a MIS [metal-insulator-semiconductor] type junction. The cap was added in a second growth run. Between the substrate and the p-GaSb active region is a buffer layer grown at 400°C. When growing on substrates with a large mismatch it is usually necessary to grow a low temperature buffer layer to improve the initial growth conditions [Nishimura et al., 1991]. It presents a good surface for growth and stops the dislocations from propagating too far into the active region.
From the I-V characteristics, fig. 7.8, there is rectification on both sides. The forward bias represents the depletion of the GaSb active region under the GaAs capping layer and the reverse bias represents depletion of the p-n junction at the back.

![Image of I-V characteristics](image)

**Figure 7.8 I-V characteristics of sample A. The inset shows the log I-V plot and the energy band diagram of this device.**

Breakdown occurs at around 4V reverse bias and the dark current is less than 10μA up to -2V. From the energy band diagram it has been calculated [L. Ponnompolom, 1992] that the valence band offset is 0.81eV compared to the conduction band offset which is 0.31eV and it is believed that it is the high valence band offset between the GaAs and GaSb which causes good rectification. Some of the devices showed ohmic characteristic and one reason for this could be due to the fact that the top metal contact may have diffused down to the p-GaSb through the cap. Since the cap is <250Å this is entirely possible.

Capacitance-voltage measurements were carried out on sample A and showed a carrier concentration of $10^{17}$ cm$^{-3}$ for the GaSb active region. At this order of carrier concentration and for a reverse bias of 4V, the depletion region can be calculated to be 800Å [0.08μm]. The theoretical external quantum efficiency near the bandedge can be calculated to be ~2.6% using the fact that ~33% of the incident light would be reflected at the front surface.

The zero bias barrier height and ideality factor can be calculated from the forward bias I-V data. In the case of structure A when the front junction is forward biased, the back junction is reverse biased. This makes the calculation of the ideality factor and barrier height more complicated. Butcher et al., 1993, show a similar problem in their GaAs diodes. These showed that forward-biased Schottky diodes on n-type epilayers were accompanied by depletion from the substrate metallisation, while forward biasing barriers on n-type epilayers reverse-biased the junction.
between the epitaxy and the n-type substrate. A similar effect was observed in sample A where depletion of active layer under the top contact is accompanied by depletion of p-n junction between the active layer and the substrate.

It is usual to measure ideality factors from the forward biased I-V data, but this is not possible in this case as explained. Butcher et al., 1993, calculated the ideality factors in both forward and reverse bias using a graph similar to fig. 7.9.

![Figure 7.9 Plot of ln(I) as a function of the applied voltage to calculate the ideality factor for both the back and front junctions of structure A](image)

For the front Schottky contact the ideality factor was calculated to be 1.124 and for the back p-n junction the ideality factor was calculated to be 1.109. This indicated that the transport mechanism which causes the current to flow for the front junction dominates over the back junction. In forward bias the diffusion current dominated over the drift current.

The Schottky resulting from device A was not found to be repeatable and only one device gave this result. This was not promising from the point of view of growing structures and using them as Schottky detectors. The main reason for the other devices exhibiting non-Schottky contacts could be due to the top metal contact diffusing down through the cap layer and hence making an ohmic contact to the epilayer. One very important point which came about due to looking at the I-V characteristics of structure A is the comparatively good characteristics of the back n⁺-p junction. This result was repeatable in all the devices measured and it was decided to investigate this further.
7.4.2 HETEROJUNCTION [p-GaSb/n'-GaAs:Si SUBSTRATE]-STRUCTURES A, B, C, D, E, AND F

The 6 samples presented in the final chapters were selected on the basis that they showed the best optical and electrical characteristics of the many samples studied for this project. Structures A and B represent the best Schottky and p-n junction [n'-GaAs substrate/p-GaSb absorber region] devices. The quantum wells shown in the schematics of fig. 7.10 are irrelevant as we are only interested in the Schottky contact in structure A and the back p-n junction in structure B and hence any effects due to the quantum wells are not seen as we cannot deplete that far into either structure. Structures C and F represent the best control samples for the best resonant cavity structures D and E. All four are p-n+ junction type structures.

![Schematics of the structures of samples A, B, C, D, E, F](image)

The structures for the six samples are shown in fig. 7.10 above. Structure A has already been discussed in relation to Schottky contacts but in this section we are only interested in the back p-n heterojunction. Structures A and B include a low temperature buffer layer grown at 400°C in order to improve the initial growth conditions. Structures D and E are resonant cavity structures and structures C and F are heterojunction structures grown in the same run as the resonant cavity structures but on a GaAs substrate [C/D and E/F]. Structures C and D are compared to each other as are structures C and F as they were grown under similar conditions. The reverse bias I-V results are shown in the graph of fig. 7.11 and in table 7-2.
Figure 7.11 Reverse bias I-V characteristics for heterojunctions A, B, C, D, E, and F

Table 7.2 Dark current characteristics of samples A, B, C, D, E, and F at various values of applied bias.

<table>
<thead>
<tr>
<th>Sample</th>
<th>I_d at -2V [μA]</th>
<th>I_d at -1V [μA]</th>
<th>I_d at -0.5V [μA]</th>
<th>I_d at -0.3V [μA]</th>
<th>I_d at -0.1V [μA]</th>
<th>I_d at 0V [μA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5.74</td>
<td>0.853</td>
<td>0.853</td>
<td>0.175</td>
<td>0.0353</td>
<td>0.0003</td>
</tr>
<tr>
<td>B</td>
<td>8.69</td>
<td>0.489</td>
<td>0.489</td>
<td>0.0099</td>
<td>0.0018</td>
<td>0.0002</td>
</tr>
<tr>
<td>C</td>
<td>30</td>
<td>3.02</td>
<td>0.159</td>
<td>0.034</td>
<td>0.006</td>
<td>0.0001</td>
</tr>
<tr>
<td>D</td>
<td>10060</td>
<td>1990</td>
<td>640</td>
<td>360</td>
<td>110</td>
<td>1.304</td>
</tr>
<tr>
<td>E</td>
<td>8240</td>
<td>650</td>
<td>30</td>
<td>4.28</td>
<td>0.167</td>
<td>0.0006</td>
</tr>
<tr>
<td>F</td>
<td>7800</td>
<td>1100</td>
<td>110</td>
<td>30</td>
<td>4.72</td>
<td>0.081</td>
</tr>
</tbody>
</table>

Structures A and B

Structures A and B show very similar I-V characteristics with breakdown occurring at ~4V reverse bias and dark current being less than 10μA up to -2V [Hordvark et al., 1993]. From C-V measurements on sample B it was calculated that the carrier concentration was ~1.2x10^{16} cm^{-3} which is characteristic of high quality GaSb [S. K. Haywood et al., 1988]. If we assume that the GaAs cap, for A and B, is fully depleted under all conditions then from the capacitance measurements, at -2V, we can calculate the depletion width to be ~0.5μm for this structure. If we are depleting from the back p-n junction then we would not see any effect due to the 80Å In_{0.4}Ga_{0.6}Sb well as the depletion region does not extend into this region. This well would not be seen if any optical measurements were to be done on this sample at room temperature and hence we can assume the absorber region to be bulk GaSb. The same can be said for structure A where
the Ga$_{0.17}$In$_{0.83}$Sb well is under the GaAs cap so any depletion from the back p-n junction would not reveal the presence of this well as we cannot deplete that far.

Initially, in order to validate the fact that we were depleting into the GaSb, the GaSb epilayer was etched off in structure B and Schottky contacts were formed on the substrate. The GaSb epilayer was etched by 4,5-dihydroxy-1,3-benzene-sulphonic acid, disodium salt monohydrate, 0.1M in water which stops etching at the GaAs:Si substrate when used in the dark [R. Aved et al., 1993]. A C-V measurement showed that the surface carrier concentration of the etched part was 2.5x$10^{18}$cm$^{-3}$, characteristic of doped GaAs and was within the manufacturers specifications. Later, it was ascertained from optical measurements that we were depleting into the GaSb as the photocurrent increased with applied reverse bias. The larger barriers presented to both holes and electrons at the heterojunction appear highly favourable to the diode characteristics at this back junction.

**Structures C and D**
Structure C has lower dark current than structure D and breakdown occurs at $\sim$3.5V. There is 3 orders of magnitude difference in their dark current. A probable reason for this could be that the structure C is grown monolithically whereas structure D was grown in two stages. Due to the fact that the surface may have become contaminated [the DBRs were not kept under vacuum conditions] this could mean that the initial conditions for growth of the GaSb epilayer were poor and hence results in the poorer electrical characteristics.

**Structures E and F**
The I-V characteristics are very similar to structure D in that the breakdown is soft [there is no clear distinction between the low dark current region and the point at which the dark increases significantly]. The dark current is high even at 0.5V reverse bias where it is $>30 \mu$A. This increases to $>5$mA at -2V and up to -1V the dark current of structure E is better than that of structure F. This is in contrast to that observed with structures C and D where the epilayer grown on the GaAs substrate showed the lower dark current characteristics. In the case of structure E, the DBRs were kept in a vacuum until they were ready for growth of the epilayer. This non-contamination of the growth surface could account for the better electrical characteristics of structure E as compared to F.

Reasons as to why the structure grown on the DBR exhibits better electrical characteristics than that grown on the GaAs substrate in the case of E/F, whereas the situation is reversed between
C/D, are unclear. The fact that the dark current increases as we go to the latter structures could be due to the changing growth conditions. Overall, the dark current is high for all 6 structures taking into account the low operating voltages [V<-4V in all cases].

Origins of the dark current could be due to a number of factors which will be discussed theoretically in the next section. These results will then be compared to measured data in order to ascertain the sources of dark current and to try and present some solutions to reducing this parameter.

### 7.5 THEORETICAL MODELS FOR DARK CURRENT

Generally, in p-n junctions the dark current is assumed to be the sum of bulk and surface components. The bulk components consist of diffusion current, generation-recombination current, and tunnelling current. The surface effects are due primarily to ionic charges on or outside the semiconductor surface that induce image changes in the semiconductor and cause formation of surface channels or surface depletion layer regions. Once a channel is formed it modifies the junction depletion region and gives rise to surface leakage current. It is difficult to predict the surface component of dark current accurately as it is dependent on surface preparation, contacts and material quality. For the bulk component, the diffusion and generation-recombination components of dark current can be represented by the general equation

\[ I_d = I_a A \exp\left[ -\frac{E_g}{nkT} \right] \]  \[ \text{[7.5.1]} \]

where \( n \) is a constant called the ideality factor and depends on the origin of the dark current. Generally, the current originating within the depletion region of the diode will vary exponentially as one half of the bandgap \( [n=2] \) and the diffusion component varies exponentially as the bandgap \( [n=1] \). If we consider the p-n heterogeneous junction then:

#### [1] Diffusion Current \([I_{diff}]\)

This arises due to thermally generated minority carriers diffusing from the n^-region into the p-region and is given by

\[ I_{diff} = I_s \left( e^{\frac{qV}{kT}} - 1 \right) \]  \[ \text{[7.5.2]} \]

where \( V \) is the applied voltage and the negative in the case of reverse bias. \( I_s \) is termed the saturation current and is given by

\[ I_s = q\alpha_n^2 \sqrt{ \frac{D_n}{\tau_n} } \frac{A}{N_A} \]  \[ \text{[7.5.3]} \]
where $n_i$ is the intrinsic carrier concentration and is given as being of the order of $10^{14}$cm$^{-3}$ in Landolt-Börnstein, 1982, $\tau_n$ is the minority carrier diffusion lifetime in the p-material and $A$ is the device area. $D_n$ is the minority carrier diffusion constant and is calculated using the Einstein relation [Singh, 1994]

$$D_{n,p} = \frac{kT}{\mu_{n,p}q}$$

[7.5.4]

where $\mu$ is the carrier mobility and is dependent on the carrier concentration. Carrier mobility decreases with increasing carrier concentration.

For the heterostructures characterised in this chapter, we can calculate the diffusion component of dark current. The minority carrier diffusion constant for minority electrons in the p-region is $D_n=77.62$cm$^2$/s for $\mu_n=3000$cm$^2$/Vs [Landolt-Börnstein, 1982]. At reverse biases greater than a few $kT/q$, $I_{diff}=I_s$, and hence we can discount the term in parenthesis in equation 7.5.2. Plotting the diffusion current as a function of the minority carrier lifetime, fig. 7.12, we can see it decreases with decreasing minority carrier lifetime. Hence the slower the minority carriers in diffusing from the n-region to the p-region the smaller the contribution of this component to the dark current. Varying the carrier concentration of the p-region shows that the greater diffusion current occurs for the lighter doped epilayers. In these cases the minority carriers [electrons in this case] diffusing into the p-region will have less holes to recombine with and hence the result in a greater diffusion current.

![Image]

Figure 7.12 Diffusion component of dark current as a function of the minority carrier lifetime for various depletion region carrier concentrations


The current due to the generation and recombination of electron-hole pairs in the depletion region is given by
where $\tau_{\text{eff}}$ is the effective carrier lifetime. The generation-recombination current is proportional to the depletion region width, $W$, and reducing this is important in decreasing the generation-recombination current component of dark current. The low voltage dependence of the term in the parenthesis arises due to the generation and recombination of carriers via traps situated near the middle of the bandgap. Due to a lack of measurements of the value of the effective carrier lifetime for p-GaSb we have plotted $I_{g-r}$ as a function of the applied reverse bias for various values of $\tau_{\text{eff}}$ [$\tau_{\text{eff}}=1\text{ms}-1\text{ns}$].

Figure 7.13[a] shows the variation of the generation-recombination current with applied bias for various values of effective recombination lifetime at $N_a=1.2 \times 10^{16}\text{cm}^{-3}$ for the p-n$^+$ heterojunction. The smaller the effective carrier lifetime the greater the generation-recombination current contribution to the dark current. Figure 7.13[b] shows the generation-recombination current for $N_a=1 \times 10^{17}\text{cm}^{-3}$. If we compare figs. 7.13[a] and [b] then, for the same applied bias and $\tau_{\text{eff}}$, the generation-recombination current is least in fig. 7.13[b]. This is due to the dependence of the generation-recombination current on the depletion region width. Reduction of this parameter would reduce this component of the dark current. The higher carrier concentration of the depletion region in the model of fig. 7.13[b] will give a smaller depletion region width in this case and hence the generation-recombination will also be less. The use of a structure, such as the resonant cavity structure, where the depletion region width can be kept small yet still allowing high quantum efficiency is one way of reducing this dark current component. The larger $W$ the greater the area for generation-recombination centres to exist.

![Figure 7.13](image-url)
[3] Tunnelling Current [\(I_{\text{tunn}}\)]

Two forms of tunnelling current exist, band-to-band and that due to traps and defect levels in the energy gap. Band-to-band tunnelling current in reverse-biased, direct bandgap semiconductors is given by [Stillman et al., 1982; Forrest et al., 1980; Ando et al., 1980; Pearsoll, 1980]

\[
I_t = \frac{A\sqrt{2m^*q^3FV}}{4\pi^2\hbar^2E_g^{1/2}} \exp \left[ \frac{\xi \sqrt{m^*E_g^{3/2}}}{q\hbar F} \right] \frac{\xi}{\psi} \frac{m^*E_g^{3/2}}{q\hbar F} \]

where \(F\) is the applied electric field at the junction, \(E_g\) the bandgap of the semiconductor and \(m^*\) the reduced effective mass. \(P\) is the tunnelling probability and becomes more significant for narrower bandgap materials. \(\xi\) depends on the detailed shape of the tunnelling barrier and is given as 1.11 for a triangular barrier and 1.88 for a parabolic barrier. The parameter \(\psi\) depends on the initial and final states of the tunnelling carrier. For a p-n junction the electric field is not constituent and for abrupt p-n junctions the electric field results in parabolic energy bands. As the tunnelling current has a strong electric field dependence then it becomes significant at high electric field. It is assumed that due to this dependence most of the tunnelling takes place close to the junction edge the electric field is highest

\[
F_{\text{m}} = \frac{2V}{W} = \left( \frac{2qN_{D,A}}{\varepsilon_s} \right)^{1/2} \]

To reduce the electric field, the operating voltage needs to be kept low and the depletion width large. To have a large depletion width, the carrier concentration needs to be kept as low as possible.
Tunnelling is also possible via states [traps or defects] within the forbidden energy gap. This defect-assisted tunnelling is expected to retain the same functional form as the band-to-band tunnelling except the tunnelling probability is modified in equation 7.5.6. Riben et al., 1966, gives the tunnelling probability for a carrier tunnelling from an impurity level to the conduction band as

$$P = \exp \left( \frac{\xi V m^* E_T^{3/2}}{qF} \right)$$

where $E_T$ is the energy level of the trap. Due to $E_T > E_g$, trap-assisted tunnelling will be greater than band-to-band tunnelling, equation 7.5.6. In lattice-mismatched structures such as ours the number of defects will be high and hence trap-assisted tunnelling could be a plausible explanation for the high dark currents observed especially in the latter structures [D, E, and F] where soft breakdown is seen over the entire voltage range in reverse bias. In all cases the various contributions to the dark current need to be verified experimentally [Sze, 1981] by measuring the I-V characteristics as the temperature of the device is varied, but due to the time limit this was not possible.

### 7.5.1 BREAKDOWN PHENOMENA

When a sufficiently high field is applied to a p-n junction, the junction “breaks down” and conducts a very large current. The breakdown occurs due to carrier multiplication [number of holes and electrons that can participate in current flow increases]. There are two main breakdown mechanisms associated with reverse I-V characteristics and these are tunnelling and avalanche.
Tunnelling (Zener Breakdown) [Sze, 1981]:
This breakdown is due to the quantum mechanical process of tunnelling. At strong electric fields, the electrons in the valence band can tunnel into an unoccupied state in the conduction band and vice versa. As the electric field is increased (reverse-biased) the effective barrier that an electron in the valence band has to overcome to go into the conduction band starts to decrease. Once this tunnelling probability becomes significant there are so many free carriers that the diode effectively shorts out. The Zener tunnelling depends upon the depletion width and the applied bias; the wider the width the lower the bias. If the junction is made from heavily doped materials, the Zener tunnelling could start at a reverse bias of a few tenths of volts. This has already been discussed in relation to the tunnelling current in the previous section.

Avalanche (Impact ionisation):
In the impact ionisation process an electron scatters with an electron in the valence band via the coulombic interaction and knocks it out into the conduction band. The initial electron must provide enough energy to bring the valence band electron up into the conduction band. Thus the initial electron should have energy slightly larger than the bandgap (measured from the conduction band minimum). In the final state we now have two electrons in the conduction band and one hole in the valence band. Thus the number of current-carrying charges has multiplied and the process is called avalanching. The current in the device, once avalanching, is dependent on the carrier ionisation coefficients. These depend upon the bandgap of the material. The narrower the bandgap energy the lower the electric field needed to initiate avalanche. This breakdown mechanism imposes an upper limit on the reverse bias for most diodes. A critical breakdown field can be defined at which point avalanching will start. The breakdown voltage at which the maximum electric field equals the critical electric field is given by

\[ V_b = \frac{\varepsilon_s F^2_{\text{crit}}}{2qN_{a,s}} \] [7.5.1.2]

where \( \varepsilon_s \) is the semiconductor permittivity, \( F_{\text{crit}} \) is the critical electric field, \( N_{a,s} \) is the carrier concentration of the less lightly doped side of a one-sided abrupt junction or of the intrinsic region of a p-i-n structure.

The avalanche breakdown voltage is given by the semi-empirical expression [Sze, 1981]:

\[ V_b = 60 \left( \frac{E_g}{1.1} \right)^{3/2} \left( \frac{N_{A,D}}{10^{16}} \right)^{-3/4} \] [7.5.1.3]

where \( E_g \) is in eV and \( N_{A,D} \) is in cm\(^{-3}\).
Figure 7.15 Avalanche breakdown voltage as a function of the carrier concentration for GaSb

Considering fig. 7.15, at a carrier concentration of $\sim 1 \times 10^{16}$ cm$^{-3}$ [as measured for structure B], avalanche breakdown occurs at $\sim 30$V reverse bias. Hence, if the measured value for $N_S$ is correct for structure B then avalanche breakdown can be ruled out according to the modelled data. The highest breakdown voltage is $\sim 4$V reverse bias observed in A, C and also B, and for this to be attributed to avalanche breakdown then the carrier concentration of the p-GaSb epilayer has to be of the order of $\sim 1 \times 10^{17}$ cm$^{-3}$. Such a carrier concentration cannot be ruled out.

7.5.2 COMPARISON OF $I_d$ TO THEORETICAL MODELS

In this section we shall try and attempt to fit our measured data to the model for dark current. At low voltage the current at 300K could be associated either to a generation-recombination mechanism or to a diffusion mechanism. For $V \leq 1$V reverse bias, the dark current of structures A, B, and C lies in the range 1μA-100μA. From fig. 7.12, for $N_S \sim 1 \times 10^{16}$ cm$^{-3}$, a fit can be made to this assuming that the minority carrier lifetime, $\tau_n > 1$μs. Assuming a carrier concentration of these epilayers of $\sim 1 \times 10^{17}$ cm$^{-3}$, then for the same voltage range the minority carrier lifetime falls within the range, $10^{-4}s < \tau_n < 10^{-3}s$. In fig. 7.16 we plot the dark current for structures A, B, and C and the theoretical generation-recombination current for the p-n GaSb/GaAs heterojunction as a function of applied bias. In fitting the curves we have used $n_i = 1 \times 10^{14}$ cm$^{-3}$ [Lödolt-Börnstein, 1982]. $W$ was calculated using equations 3.2.4 and 3.2.5 and $\tau_{eff}$ was fitted to the measured data.
Figure 7.16 Dark current of GaAs-GaSb p-n+ heterojunction photodiode showing the contribution of the generation-recombination current at $V \leq 1.0V$

From fig. 7.17 the value of $\tau_{\text{eff}}$ which gave the best fit was in the range 1-10$\mu$s. It was not possible to measure $\tau_{\text{eff}}$ and $\tau_n$ for our heterojunctions. Very few values are given in literature for these two parameters and as they are dependent on the material quality it would be inaccurate to use these. Bougnot et al., 1988, have used $\tau_{\text{eff}} = 10^{-10}s$ to obtain a fit to the dark current for $V \leq -1V$ for their p-n GaSb homojunction. Their measured dark current is 3 orders of magnitude higher than that measured for structures A, B, and C. As $I_{\text{gen}}$ is inversely dependent on $\tau_{\text{eff}}$, then, in order to reduce the contribution of this dark current component, it is necessary to increase this parameter such that the generation of carriers is reduced.

Figure 7.17 Dark current of reverse-biased GaAs-GaSb p-n+ heterojunction photodiode where $I_d$ is the measured dark current, $I_{\text{nom}}$ is the theoretical band-to-band component of dark current, $I_{\text{gen}}$ is the generation-recombination component of dark current at two values of effective carrier lifetime.
If we plot the sum of the tunneling current and the generation-recombination current and compare with the measured dark current obtained for structures A, B and C, fig. 7.18, then the greatest discrepancy between the measured and the theoretical data arises in the 1-3V region. At biases greater than 3V reverse bias, a good fit is obtained using the band-to-band tunnelling model assuming that the carrier concentration is of the order of $1 \times 10^{17} \text{cm}^{-3}$, fig. 7.18. For $-1V < V < 3V$ the dark current is greater than the model for band-to-band tunnelling and could be a combination of trap-assisted tunnelling and surface leakage current. For a lower carrier concentration, such as $\sim 1 \times 10^{16} \text{cm}^{-3}$, the dark current cannot be explained by band-to-band tunnelling at biases greater than -1V reverse and once again could be due to a combination of tunnelling [band-to-band and trap-assisted] as well as surface leakage current due to the non-passivation of all these devices.

![Graph showing dark current vs. reverse bias](image)

**Figure 7.18** Measured dark current of structures A, B, and C. The sum of the theoretical tunneling current and the generation-recombination current [for $\tau_{eff} = 1 \mu s$ and $\tau_{eff} = 10 \mu s$], seen separately in fig. 7.17, are also shown.

The soft breakdown at for structures D, E, and F over the entire wavelength range with the corresponding high dark current, fig. 7.11, may be explained as being mainly due to tunnelling current, probably trap-assisted. From the band diagram of fig. 7.6 it can be seen that for the back heterojunction the barrier to tunnelling is relatively thin and once this junction is reverse-biased the tunnelling barrier will become even thinner making it easier for electrons to tunnel from the GaAs conduction band to the GaSb valence band. If there are energy states in the bandgap then this probability for tunnelling to occur is increased even further.

**7.6 DISCUSSION**

The GaSb-based diode structures studied in this chapter all suffer from the problem of poor electrical characteristics despite the structure. The fact that the dark current is lower in some
structures than in others could be explained by the varying growth conditions day-to-day. The main contribution to the dark current seems to be from tunnelling current attributable to the short distance the electrons have to tunnel at the back p-n heterojunction. Reduction of the dark current is important in attaining highly efficient detectors and some possible solutions are:

[i] The use of small area devices: the dark current components considered in the models are all directly proportional to the area of the device and hence the smaller this parameter the smaller these contributions to $I_d$. The main problem to this is that due to the equipment used in the eventual optical measurements the spot size from the light source could only be focused down to $\sim 400\mu m$. Hence, even though the dark current was reduced at the smaller areas only the $400\mu m$ mesas were of significance.

[ii] Operation of the devices at low temperatures: the devices were cooled to 77K and it was found that the dark current was reduced by about an order of magnitude in all cases. Many of the commercial photodetectors are cooled for this very reason. This is one option for reducing $I_d$ but it would depend on the eventual application as cooling to 77K requires bulky dewars, though the use of thermoelectric coolers could be a possibility.

[iii] One interesting structure which was grown by accident was a p-GaSb epilayer on an n-GaAs substrate [semi-insulating]. If the high dark current in these heterojunctions is due mainly to band-to-band tunnelling [as looks likely at voltages greater than 3V reverse bias] then the results obtained from this p-n heterojunction are of interest. The measured dark current for this p-n heterojunction was measured to be of the order of nA's over the entire voltage range in reverse bias. It could simply be that as the GaAs is low doped there are not as many electrons available for tunnelling across the p-n junction and hence the dark current is reduced as a result of this. If this is the case then the incorporation of a low doped layer before the growth of the p-GaSb epilayer in these heterojunctions would be a way of reducing the dark current and is currently being considered.

7.7 CONCLUSIONS
In this chapter we have considered the GaSb material system and the advantages and disadvantages of its use as a photodetector material. From the electrical characterisation it became clear that the devices, though rectifying, showed poor electrical characteristics. The dark current was high in all cases up to breakdown and many of the latter structures [D, E, and F] exhibited soft breakdown over the entire voltage range. The values obtained agreed well with
those obtained by other groups, see literature review in this chapter, and the problem of high dark current seems to be the normal for antimonide-based devices in general.

The best results were obtained from structures A, B, and C where the breakdown occurred at -4V and the dark current was <10μA up to -2V. The high carrier concentration as well as the large lattice mismatch between the lattice constants of the active region and the substrate are a probable cause of this high noise in all the devices. Non-passivation of these devices is another reason which would cause the dark current to be high as well as causing premature breakdown. Models to predict the causes of the dark current were used and the main contribution was concluded to be the tunnelling current due to the defect levels in the bandgap acting as both generation-recombination centres and trap centres. The close proximity of the bands at the p-n+ heterojunction presents a small barrier to the tunnelling of carriers and this would decrease even further with the an applied reverse bias.

In addition to the above work, GaSb-based Schottky barrier structures were also considered and showed similar electrical results as were seen from the back heterojunction. The Schottky contact was made to the p-GaSb with the use of an interfacial layer of thin, highly dislocated GaAs. A MIS structure was formed and though the results could not be subsequently repeated these initial results looked promising. But, due to the low yield it was decided that the p-n+ heterojunction was the best option for possible optical GaSb-based photodetectors.
Chapter 8

OPTICAL RESULTS: RCE PHOTODETECTOR

8.1 INTRODUCTION
The improvement in quantum efficiency obtained for a resonant cavity structure over a non-resonant structure, in theory at least, provides a solution to some of the problems encountered with the GaSb material system in chapter 7. To prove some of the hypotheses presented in chapter 5, we consider now the growth of the GaSb epilayer on the GaAs/AlAs DBRs characterised in chapter 6. Initially, to prove the principle of resonance with GaSb, we grew layers of bulk GaSb of various thicknesses on the DBR and compared the characteristics of these devices with some corresponding non-resonant structures grown in the same growth run on GaAs substrates. The characterisation consists of reflectance and photocurrent measurements in order to obtain quantitative values for the quantum efficiency and the specific detectivity.

8.2 STRUCTURE DESIGN
To briefly summarise, the structures developed within this work, are designed, nominally, to operate at a wavelength corresponding to a gas absorption line [chapter 1]. In the case of the devices that will be considered in this thesis, the design wavelength is chosen to be 1680nm which corresponds to a strong absorption line of CH₄. The material for the absorber region is GaSb and the materials for the DBRs are GaAs and AlAs. At 1.68μm n_{AlAs}=2.889, n_{GaAs}=3.3615,
n_{GaSb}=3.892, and \( \alpha_{1.68 \mu m} = 5 \times 10^3 \text{cm}^{-1} \), see chapter 6, and these parameters will be used in the design of the structure considered.

The structure that will be modelled is shown in fig. 8.1. The back mirror is highly reflecting and consists of 18 period of GaAs/AlAs, [Monsoor et al., 1995], grown on a GaAs substrate. The design and characterisation of this structure have already been covered in chapter 5.

![Figure 8.1 Schematic of RCE detector structure. The structure is a p'-n junction with the DBR being heavily doped n-type and the GaSb being p-type of the order of 10^{16} \text{cm}^{-3}](image)

The cavity thickness, \( d \), is designed to be some multiple of \( m \lambda/2n \) and, as seen in chapter 5, a thickness of 0.647\( \mu \)m was chosen as this corresponds to \( m=3 \). It was concluded from the modelling carried out in chapter 4 that this thickness could be adequately depleted with \(~4\text{V}\) of reverse bias if the carrier concentration of the GaSb was in the low \( 10^{16} \text{cm}^{-3} \). Due to the complexities of the growth it was decided that the front mirror, in these initial structures, should be the air-semiconductor interface, thereby making the structure less complicated. This would give a front mirror reflectivity of \(~34\%\) for the value of the refractive index considered above. The back mirror reflectivity is required to be as highly reflecting as possible and M2 was highly reflecting in the centre of the wafer [F. Monsoor et al., 1995].

Modelling the reflectance as a function of wavelength for the resonant cavity structure for operation at 1.68\( \mu \)m gives the spectra of fig. 8.2. This shows reflectance spectra for the structure shown in fig. 8.1 with no absorption and for \( \alpha=5000 \text{cm}^{-1} \). Also shown is a spectra for the DBR as was seen in chapter 6. With no absorption, fig. 8.2[A], there is a small dip in the spectra at the operating wavelength and the reflectance is \(~95\%\). This dip is due to the destructive interference of the light reflected from the front mirror and the light reflected form the cavity and the back mirror. With an increase in the absorption, fig. 8.2[B], the reflectance drops to \(~4\%\) as more of
the incident light is absorbed. The reflectance spectra of fig. 8.2[C] is plotted to show the reflectance of a Bragg reflector stack which is not incorporated into a cavity and is lossless.

![Reflectance Spectra](image)

**Figure 8.2** Spectra showing reflectance as a function of wavelength for various structures

A: resonant cavity structure with $\alpha=0\text{cm}^{-1}$; B: resonant cavity structure with $\alpha=5000\text{cm}^{-1}$; C: Bragg reflector stack

As well as the absorption coefficient causing the reflectance of a cavity structure to be minimised, the thickness of the cavity region also influences the reflectance. The graph of fig. 8.3 plots the thickness of the cavity by representing it as the integer $m$ which has been derived in chapter 5. As $m$ increases the reflectance decreases due to the thickness of the cavity also increasing according to equation 5.3.1.3 in chapter 5. At $m=4$, the reflectance is nearly zero as more of the incident light is absorbed and the conditions for minimum reflectance in a cavity are satisfied. The absorption coefficient used in the modelling for fig. 8.3 is taken to be $5\times10^5\text{cm}^{-1}$ with a unity back reflector and a front reflector of 34% to simulate the air-semiconductor interface.
From the results of fig. 8.2, we can model the effect of increasing the absorption coefficient of the cavity on the reflectance spectra. The reflectance decreases, fig. 8.4, as the absorption coefficient increases up to $\alpha=9000\text{cm}^{-1}$ and then increases again as the absorption coefficient increases further such that at $\alpha=2\times10^5\text{cm}^{-1}$, the reflectance has increased to $\sim18\%$ from being zero at $\alpha=9\times10^3\text{cm}^{-1}$. This is due to the fact that the front mirror is overcompensated at $\alpha=2\times10^5\text{cm}^{-1}$ and the equations for optimising the cavity given in chapter 5 are not satisfied. This increase in reflectance will mean a corresponding decrease in the quantum efficiency of the detector structure.
Table 8-1 list the designs of the various structures grown. In the case of the resonant cavity structures, reflector stack M2 was used as the back mirror. In all cases the cavity thickness was designed to be some multiple of $\lambda/2n$ where $\lambda=1.68\mu$m. $d=0.647\mu$m was a thickness which we thought would be a good one for an initial structure, D, as we could, in theory, fully deplete this with $-4$V reverse bias at an assumed carrier concentration of $\sim2\times10^{16}$cm$^{-3}$. Non-resonant structures were grown in the same growth run with the same absorber region thickness but on GaAs:Si substrates. The second RCE detector structure, E, was also designed to have the same cavity thickness and was grown on stack M2 in order to try and improve on D. Table 8-1 lists the structures and the designed and actual absorber region thicknesses. As can be seen there is a discrepancy between the values of this thickness and analysis of these structures from the measured results will be discussed in detail in the following sections.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cavity Thickness designed</th>
<th>Measured Cavity thickness [polaron at Oxford]</th>
<th>Calculated Cavity Thickness [from Reflectance Measurements]</th>
<th>Layer</th>
<th>Dopant</th>
<th>Carrier Concentration [cm$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>0.647$\mu$m</td>
<td>1$\mu$m +/- 10%</td>
<td>0.92$\mu$m</td>
<td>GaSb</td>
<td>p-type</td>
<td>$\sim2\times10^{16}$</td>
</tr>
<tr>
<td>Layer 1</td>
<td>n' GaAs:Si</td>
<td>n-type</td>
<td>2.35x10$^{18}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layer 2</td>
<td>n' AlAs:Si</td>
<td>n-type</td>
<td>3.15x10$^{18}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layer 3</td>
<td>n' GaAs:Si</td>
<td>n-type</td>
<td>2.35x10$^{18}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layer 4</td>
<td>n' GaAs:Si</td>
<td>n-type</td>
<td>2.35x10$^{18}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layer 5</td>
<td>n' AlAs:Si</td>
<td>n-type</td>
<td>3.15x10$^{18}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buffer</td>
<td>n' GaAs:Si</td>
<td>n-type</td>
<td>2.35x10$^{18}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Substrate</td>
<td>n' GaAs:Si</td>
<td>n-type</td>
<td>NaAlAs:Si</td>
<td>n-type</td>
<td>3x10$^{18}$</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.647$\mu$m</td>
<td>1$\mu$m +/- 10%</td>
<td>0.92$\mu$m</td>
<td>GaSb</td>
<td>p-type</td>
<td>$\sim2\times10^{16}$</td>
</tr>
<tr>
<td>E$_i$/E$_2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 8-1

**Structures of the resonant cavity and non-resonant cavity devices where E$_i$, E$_2$ refers to wafer E [device 1 and device 2]**
Phase changes at reflection for the resonant cavity structures of table 8-1

If we assume that the cavity is some multiple of $m\lambda/2n$, then from fig. 8.5, we can calculate the phase changes on reflection at each interface.

**Table 8-1**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cavity Thickness designed</th>
<th>Measured Cavity Thickness [polaron at Oxford]</th>
<th>Calculated Cavity Thickness [from Reflectance Measurements]</th>
<th>Layer</th>
<th>Dopant</th>
<th>Carrier Concentration [cm⁻³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td>0.647μm</td>
<td>1.51μm +/- 10%</td>
<td>1.47μm</td>
<td>GaSb</td>
<td>p-type</td>
<td>~2x10¹⁶</td>
</tr>
<tr>
<td>Layer 2</td>
<td></td>
<td></td>
<td></td>
<td>n' GaAs:Si</td>
<td>n-type</td>
<td>2.35x10¹⁸</td>
</tr>
<tr>
<td>Layer 3</td>
<td></td>
<td></td>
<td></td>
<td>n'AlAs:Si</td>
<td>n-type</td>
<td>3.15x10¹⁸</td>
</tr>
<tr>
<td>Layer 4</td>
<td></td>
<td></td>
<td></td>
<td>n'GaAs:Si</td>
<td>n-type</td>
<td>2.35x10¹⁸</td>
</tr>
<tr>
<td>Layer 5</td>
<td></td>
<td></td>
<td></td>
<td>n'AlAs:Si</td>
<td>n-type</td>
<td>3.15x10¹⁸</td>
</tr>
<tr>
<td>Buffer</td>
<td></td>
<td>n'GaAs:Si</td>
<td></td>
<td></td>
<td></td>
<td>2.35x10¹⁸</td>
</tr>
<tr>
<td>Substrate</td>
<td></td>
<td>n'GaAs:Si</td>
<td></td>
<td></td>
<td></td>
<td>3x10¹⁶</td>
</tr>
</tbody>
</table>

**Figure 8.5** Phase changes on reflection for a resonant cavity structure with $d=m\lambda/2n$. The phase change at the $n_0/n_1$ interface is $\pi$ and that at all the other interfaces is $[\pm \pi]$, where $i$ is an even number.
From fig. 8.5, the phase change of the reflected light at the \( n_0/n_1 \) interface is \( \pi \) since the light goes from a medium of low refractive index to one of high refractive index. At the \( n_1/n_2 \) interface, the second ray suffers a phase change of \( 2m\pi \) due to the pathlength, \( m\pi \) before reflection and \( m\pi \) after reflection, where \( m=1, 2, 3, \ldots \). Hence the first and second rays are out of phase with each other. At the \( n_2/n_3 \) interface, the third ray undergoes a phase change of \( 2m\pi+2\pi \) which is in phase with the second ray but out of phase with the first ray. The final ray suffers a phase change of \( 2m\pi+[F+1]\pi \) where \( F \) is the total number of layers. Hence destructive interference will occur due to the phase changes if the reflected light at the interfaces being out of phase with that at the \( n_0/n_1 \) interface. If the cavity was lossless then the reflectance spectra would resemble that of fig. 8.2A. If the cavity was both absorbing and equation 5.3.6 was obeyed, where the mirrors are matching, then the reflectivity would drop to zero as in fig. 8.2B.

8.3 OPTICAL CHARACTERISATION

The optical set-ups to measure the photocurrent and the reflectance have been mentioned in chapter 6. The optical set-up used to measure the photocurrent is that of fig. 8.6. A Newport Ge photodetector is used as the reference detector in all the optical measurements.

The sample is mounted onto a holder which in turn is connected in series with a 100k \( \Omega \) Light is incident from the monochromator and is focused onto the photodetector. The bias circuit is clamped onto a rotational and x-y-z movement stage. The photocurrent that is produced is collected across the resistor and is then read by the lock-in amplifier. The light has to be focused more finely in the case of the photocurrent due to the fact that the devices are 200-400\( \mu m \) in diameter and for efficient
light collection it is required that the whole of the incident light beam is focused onto the detector window rather than overlapping onto the contact itself. The bias circuit that is used is shown in fig. 8.7.

The bias circuit consists of a large resistor in series with the photodetector. The bias from the voltage source is applied across both this resistor and the photodetector under test and the photocurrent is measured across the large resistor by the lock-in amplifier. The resistance of the detector has to be larger than that of R in order that the bias falls across the photodetector. The large resistor in series is there to limit the current through the detector to prevent any damage. When designing a circuit for photodiode operation it is important to know whether we want photoconductive or photovoltaic operation; in other words do we need linearity and high speed or low noise and high responsivity. The diodes designed for this thesis are operated in the photoconductive mode [see chapters 2 and 3], fig. 8.7, which means that the detector output signal will be a linear function of the incident light signal.

**Measurement Responsivity and Quantum Efficiency**

Both of these parameters require a measurement of the photocurrent. In order to ascertain what the responsivity is we need to know the total amount of light incident on the photodetector from the light source as the responsivity is given by

\[
R = \frac{I_{ph}}{\Phi} \tag{8.3.1}
\]

where \(I_{ph}\) is the photocurrent from the device under test and \(\Phi\) is the power output from the light source. \(\Phi\) has to be measured using some reference detector which we have to take to be the ideal detector over the wavelength range we are interested in. The values for the \(\eta\) of the GaSb photodetector under test should be quoted with reference to the detector they were compared with. In this case it is a Ge detector which is used. From equation 2.2.5

\[
\Phi = \frac{h c I_{ph}}{q \lambda} \tag{8.3.2}
\]

for the reference detector. The lock-in is used to measure the photocurrent from the Ge photodetector directly, and using this in equation will give the power incident on the detector under test. From this the \(\eta\) can be measured by using the equation

\[
\eta = \frac{R}{\frac{h c}{q \lambda}} \tag{8.3.3}
\]
\[ \eta = \frac{Rq\lambda}{hc} \] \hspace{1cm} [8.3.3]

All these equations have been derived in chapter 2. Having calculated \( \eta \) this then leads onto a measure of the specific detectivity, \( D^* \) using either equation 2.6.12 or 2.6.13 depending on the situation under which the measurements were made and what the limits to the detector noise are.

**Experimental Errors**

[a] Placement of the detector under test and the reference detector such that both are in the same place in the set-up. The distance of these from the light source has to be the same in order to say with any conviction that the same amount of light falls on both of these else an error will result in the measurement of the responsivity due to a variation in the power falling on the detectors.

[b] Alignment of the devices under test such that light is incident at right angles to the plane of the detector. If the angle is off-incidence then this could result in loss of efficiency, see chapter 5. The use of a rotating stage should reduce this problem though it can’t be guaranteed to eliminate it.

[c] The light source needs to be constant over the wavelength range and over the time which it is used. Ideally, a black body should be used where the power output is constant with wavelength as long as the temperature is constant. In this case we used a quartz-halogen lamp which varies with the time over which it is in use. A feed-back circuit which regulates the current through the light source such that it increased or decreased in order to keep the power constant is required. In the case of the experiments considered in this chapter this was not the case and hence one had to be careful that the measurements were made in as short a space of time as possible such that the variation in the power output was kept to a minimum.

**8.3.1 REFLECTANCE MEASUREMENTS**

The reflectance spectra of D and E are shown in the graph of fig. 8.8. The spectra for structure D shows resonance at a wavelength of 1748nm which is not very clear from the fig. 8.8 and is more discernible in the photocurrent spectra which is shown later in the chapter. The reflectance at this wavelength is \( \sim 30\% \). At the wavelength for which this structure was designed for, \( \lambda=1680\text{nm} \), the reflectance is \( \sim 58\% \). For structure E, the resonance minima occurs at a wavelength of 1650nm which is closer to the value desired for the operating wavelength and the reflectance at resonance is \( \sim 8\% \). At a wavelength of 1680nm, the reflectance for E is measured to be \( \sim 39\% \).

E exhibits a lower reflectance than D and this is due to the fact that both have different values of cavity thickness. This in turn changes the point at which resonance will occur and also the value of the reflectance due to the fact that the absorption coefficient of the material used in the cavity
region varies with wavelength. D has a resonance wavelength greater than the corresponding wavelength for the bandgap of GaSb \([E_g = 0.72\text{eV}, \lambda \sim 1.73\mu\text{m}]\). It was seen in chapter 2 that the absorption coefficient drops rapidly when the wavelength exceeds the wavelength corresponding to the bandgap energy of the semiconductor. Since D shows resonance at 1748nm, then the absorption coefficient will be decreased. The structure was designed to have minimum reflectance at \(\lambda=1680\text{nm}\) which corresponds to \(\alpha=5000\text{cm}^{-1}\) and the cavity thickness was designed to be some multiple of \(\lambda/2\text{n}\). This is not the case with structure D; instead the cavity is some multiple of \(\lambda/2\text{n}\) for \(\lambda=1748\text{nm}\). This then requires a larger front mirror in order to match the front and back mirrors as the value of \(\alpha\) has decreased at this longer wavelength.

The situation, as far as minimisation of the structure reflectance is concerned, is better in the case of structure E where the reflectance is lower. The wavelength is still not that which was designed for, but has now shifted to the left of 1680nm to \(\lambda=1650\text{nm}\). This corresponds to an increase in the absorption coefficient from the value of \(\alpha\) at \(\lambda=1680\text{nm}\). The reflectance is low because the mirrors are more closely matched at 1650nm despite both having approximately the same reflectivity as D. The only parameters which have changed are \(\alpha\) and the cavity thickness. The cavity thickness now corresponds to some multiple of \(\lambda/2\text{n}\) where \(\lambda=1650\text{nm}\).

![Figure 8.8 Reflectance spectra of samples D and E (resonant cavity devices) showing the different wavelengths at which resonance occurs](image)

Fig. 8.9 plots the measured reflectance spectra of both D and E as well as the measured Bragg stack on which these cavities were grown. As can be seen the reflectance of the Bragg stack is still high over the resonance wavelengths corresponding to D and E. Hence the back mirror
reflectivity for wavelengths at which resonance occurs for structures D and E will still be constant.

![Reflectance spectra showing samples D and E and comparing these to the reflectance spectra of the Bragg reflector of M2](image)

**Figure 8.9** Reflectance spectra showing samples D and E and comparing these to the reflectance spectra of the Bragg reflector of M2

As was stated in table 8-1 the thickness of the GaSb absorber region was both measured and calculated from the reflectance spectra. The calculated values for the epilayer thickness was modelled using the multilayer model mentioned in both chapters 5 and 6. The best fit to D was obtained by using a value of cavity thickness equal to 920nm for the cavity thickness and an absorption coefficient of 1400cm⁻¹, see fig. 8.10. This value of absorption coefficient agreed with measured values obtained on a GaSb epilayer. In order to optimise the device for a wavelength of 1748nm, i.e. to achieve zero reflectivity, the front mirror reflectivity needs to be ~75%. For a structure designed for operation at 1680nm, the value of the front mirror for the structure is ~53% which is much closer to the value for the air-semiconductor interface.
The best fit for structure E was obtained using a value of cavity thickness equal to 1470nm with a value of the absorption coefficient of ~5400cm\(^{-1}\) at \(\lambda=1650\)nm, see fig. 8.11. This also agrees well with measured values obtained on low doped GaSb epilayers. Zero reflectance of the structure requires a front mirror reflectivity of ~17% for \(\alpha=5400\)cm\(^{-1}\), \(R_b=98\)% and \(d=1470\)nm. This low value of the front mirror reflectivity means that the air-semiconductor reflectivity (~34%) needs to be reduced. The use of a dielectric mirror with a suitable refractive index would be an option to try and obtain this sort of reflectivity.
8.3.2 PHOTOCURRENT MEASUREMENTS
Before considering the photocurrent results for the resonant cavity and non-resonant cavity detectors it has to be remembered that the resonant cavity detector structure was grown in two stages with the DBR grown initially by MBE and the GaSb epilayer grown at a later stage [MOVPE] once the DBR had been characterised, whereas, the non-resonant structure was grown monolithically. Despite the DBR being cleaned before growth of the epilayer the problem of the initial contamination will result in a structure which will be inferior to one which is grown monolithically. As was seen in chapter 7 the dark current of the resonant cavity structure was very high as compared to that of the non-resonant cavity structure and this would result in a poorer S/N ratio, hence effecting the optical characteristics considered in the following sections.

C and D
One of the most important measurements as far as optical detectors are concerned is the measurement of the photogenerated current or photocurrent. The detection efficiency can be calculated from a knowledge of the photoelectron generation \( n_e \) to the incident photon rate \( n_p \) where

\[
\eta = \frac{n_e}{n_p}
\]

The ideal situation for a photodetector with no internal gain would be one photoelectron for one photon. In practice, this is not usually the case for reasons already mentioned in previous chapters. Measurements of the photocurrent have been carried out for the structures mentioned in table 8-1 and will be discussed in the next section. These then leads onto calculations of the quantum efficiency and the specific detectivity \( D^* \).

In operation, the RCE photodetector should achieve enhanced absorption of the incident optical signal due to the multiple pass detection scheme. Each reflection from one of the cavity mirrors results in the generation of electron-hole pairs as the light traverses the absorbing layer. In essence, the mirror scheme permits the absorbing layer to be "reused" many times by recirculating the optical signal. As mentioned in chapter 5, the characteristic of Fabry-Perot cavities is that resonance is achieved at specific wavelengths for which the round trip phase shift is a multiple of \( 2\pi \) and the spacing between the maxima is determined by the cavity length. We can see this enhancement in the photocurrent spectra of fig. 8.12 for structure D.
Figure 8.12 Measured photocurrent spectra with applied bias for sample D. The photocurrent reaches a peak at a reverse bias of -0.3V and then drops as the bias is further increased.

The effect of the cavity can be seen just beyond the bandedge and occurs at a peak resonance wavelength of ~1748nm. It is difficult to see this in this spectra due to the oscillations that occur below 1600nm. It is easier to see this enhancement in Figure 8.13 which shows five graphs measured at different values of applied bias. Plotted are both the resonant cavity photocurrent spectra and their corresponding reference detector [C] photocurrent spectra. At 0V, the enhancement in the photocurrent at $\lambda=1748$nm for the cavity structure can be seen quite clearly. Where the curve for the non-resonant structure falls off beyond the bandedge wavelength, that of the cavity structure increases before falling off. At 0V, where the distinction between the two curves is clearest, there is approximately a 4-fold increase in the photocurrent at the resonance wavelength for the cavity structure [D]. As the bias increases, the distinction between the photocurrent spectra for the two structures decreases as does the enhancement factor at the resonant wavelength. At $V_R=-0.3V$, the photocurrent spectra for the RCE detector structure has dropped below that of the non-resonant structure everywhere except over the region of the resonant peak and eventually, at $V_R=-1.0V$, the photocurrent values of the conventional structure is much greater than that of the RCE detector structure.
If we consider fig. 8.12 again we can see that the photocurrent increases up to -0.3V and then drops rapidly as the bias is increased further. For the non-resonant structure, fig. 8.14, the photocurrent increases steadily up to -0.5V before falling as the bias is further increased. The value of the photocurrent is greater in the non-resonant structure and one explanation for this could be the lower dark current of this device over the non-resonant device which gives a higher signal-to-noise ratio [S/N]
Superimposing the spectra for both the reflectance and the photocurrent for the resonant cavity structure D, gives the graph of Fig. 8.15. The maxima in the photocurrent at 1748nm corresponds to a minima in the reflectance spectra at the same wavelength. The lower the reflectance the greater the photocurrent as long as the dark current is also low. The reflectance is determined by the total cavity thickness, whereas the value of the photocurrent is determined by the thickness of the depletion region and hence the bias. As was stated in chapter 1 the carriers are collected more efficiently in a region of high field which is fully depleted. The thinner this depletion region, as compared to the total absorption region, the less the amount of photocurrent which will be collected and this thickness is also determined by the background concentration of the material of the active region as well as the amount of bias which can be applied.

**Figure 8.15 Reflectance and photocurrent spectra for sample D**

**E and F**

Structures E and F were characterised in a similar way to D and C. From the reflectance spectra of A3 it was seen that the resonance wavelength occurred at 1650nm, Fig. 8.8, and that the
reflectance at this wavelength was ~8%. Figure 8.16 shows the photocurrent spectra for the resonant cavity structure, E, with applied bias. The minimum value of voltage that can be applied with a corresponding increase in the photocurrent is ~0.2V reverse bias. The photocurrent for structure E₂, fig. 8.17, shows resonance at around 1631nm and was an order of magnitude greater than that for structure E₁ and this will become more significant in the values for the quantum efficiency of these structures calculated later in this chapter.

![Figure 8.16](image1.png)

*Figure 8.16 Photocurrent spectra of sample E₁ with applied bias. The maximum value of bias which could be applied was -0.2V before the photocurrent dropped due to the increase in dark current of the detector*

![Figure 8.17](image2.png)

*Figure 8.17 Photocurrent spectra of sample E₂ with applied bias. The maximum value of bias which could be applied was -0.3V before the photocurrent dropped due to the increase in dark current of the detector*

Figure 8.18 shows the photocurrent spectra of the corresponding non-resonant structure, F, with applied bias. In this case the maximum value of voltage which can be applied is -1V.
If we compare the photoresponse of both E and F, Fig. 8.19, for the same value of applied bias, then the enhancement at -0.1V is about 3-fold for the RCE structure over the conventional structure. Although only -0.1 V reverse bias could be applied across structure E, the magnitude of the photoresponse at this value of applied bias was still greater than that for the non-resonant structure [F] at 1 V reverse bias, despite the higher voltage. At the lower values of applied bias [$V_R$ < -0.3 V] the dark current of the RCE detector [E] is approximately an order of magnitude lower than that for the non-resonant structure. Hence, the S/N ratio is better for the resonant cavity structure which could account for the higher photoresponse.

**Figure 8.18** Photocurrent spectra of non-resonant detector, A4, with applied bias. Maximum valued of bias which could be applied with a corresponding increase in the photocurrent was 1V reverse bias.

**Figure 8.19** Photocurrent spectra of structures E and F, resonant and non-resonant detectors respectively, showing the enhancement in the photocurrent at ~1650nm for the resonant cavity device.
Superimposing the photoresponse and reflectance spectra for structure $E_1$, fig. 8.20, and $E_2$, fig. 8.21, we can see that the maxima of the photocurrent responds to the minima of the reflectance spectra at the resonance wavelengths. This should ensure that the photoresponse is highest at this point even if it may not be the maximum possible.

**Figure 8.20** Reflectance and photocurrent spectra for structure $E_1$. From the spectra it can be seen that where the reflectance is a minimum the photocurrent is a maximum.

**Figure 8.21** Reflectance and photocurrent spectra for structure $E_2$. From the spectra it can be seen that where the reflectance is a minimum the photocurrent is a maximum.
8.3.3 QUANTUM EFFICIENCY AND DETECTIVITY [D*]

Table 8-2: Measured values of $\eta$ and $D^*$ for no applied bias

<table>
<thead>
<tr>
<th>$\lambda_p$ [nm]</th>
<th>C</th>
<th>D</th>
<th>$E_1$</th>
<th>$E_2$</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>$%$</td>
<td>0.8</td>
<td>0.44</td>
<td>0.68</td>
<td>3.61</td>
<td>0.36</td>
</tr>
<tr>
<td>$D^*$ [cmHz$^{1/2}$W$^{-1}$]</td>
<td>2.8x10$^{10}$</td>
<td>2.39x10$^{8}$</td>
<td>2.33x10$^{10}$</td>
<td>4.49x10$^{10}$</td>
<td>1.08x10$^{7}$</td>
</tr>
<tr>
<td>$I_d$ [$\mu$A]</td>
<td>0.0006</td>
<td>1.304</td>
<td>0.000589</td>
<td>0.00438</td>
<td>0.081</td>
</tr>
</tbody>
</table>

Table 8-3: Measured values of $\eta$ and $D^*$ for an applied bias corresponding to the best $\eta$

<table>
<thead>
<tr>
<th>$V_R$</th>
<th>C @ -1V</th>
<th>$E_1$ @ -0.1V</th>
<th>$E_2$ @ -0.3V</th>
<th>F @ -1V</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_p$ [nm]</td>
<td>1700</td>
<td>1650</td>
<td>1631</td>
<td>1700</td>
</tr>
<tr>
<td>$%$</td>
<td>10</td>
<td>1.06</td>
<td>10</td>
<td>0.82</td>
</tr>
<tr>
<td>$D^*$ [cmHz$^{1/2}$W$^{-1}$]</td>
<td>3.49x10$^{5}$</td>
<td>1.52x10$^{5}$</td>
<td>1.16x10$^{9}$</td>
<td>1.5x10$^{7}$</td>
</tr>
<tr>
<td>$I_d$ [$\mu$A]</td>
<td>3.02</td>
<td>0.167</td>
<td>25</td>
<td>1100</td>
</tr>
</tbody>
</table>

Tables 8-2 and 8-3 show the measured $\eta$ and $D^*$ with no applied bias and with an applied bias, respectively; the latter gives the best $\eta$. $D^*$ at 0V is calculated using equation 2.6.13 and that for $V<0V$ using equation 2.6.12. The highest $\eta$ can be seen in table 8-3 since the applied voltage results in a correspondingly higher photocurrent for all the structures. However, due to the fact that the dark current is least at 0V, the $D^*$ value is higher under these conditions [Table 8-2] than when the detector is reverse-biased. The best $\eta$ is obtained for structures $E_1$ [resonant cavity] and C [non-resonant] where it is $\sim 10\%$ in both cases. At these values of $\eta$ the specific detectivity is greater in the case of structure C due to the lower dark current and the longer wavelength at which maximum response occurs in this structure. Structure D is not included in table 8-3 as the dark current at $V>0V$ was too high and the photocurrent spectra was too noisy for any accurate measurements to be made. The highest value of $D^*$ was obtained from structure $E_2$ where $D^*$ [$\lambda=1631$nm]=4.49x10$^{10}$cmHz$^{1/2}$W$^{-1}$ at 0V. The dark current is of the order of nanoamps at this point.
In order to gain a clearer picture of what is happening in these structures we can calculate some theoretical parameters and use these as a measure of what can be achieved with these detectors with a few improvements. Assuming that the carrier concentration of the p-GaSb is of the order of \( \sim 10^{16} \text{cm}^{-3} \), we can calculate the theoretical depletion region widths, table 8-4, and the theoretical quantum efficiency possible for both the resonant and non-resonant structures.

**Table 8-4** Depletion widths for the various structures at different values of applied bias.

<table>
<thead>
<tr>
<th>Sample</th>
<th>( W_d@-2.0\text{V} ) [( \mu \text{m} )]</th>
<th>( W_d@-1.0\text{V} ) [( \mu \text{m} )]</th>
<th>( W_d@-0.5\text{V} ) [( \mu \text{m} )]</th>
<th>( W_d@-0.3\text{V} ) [( \mu \text{m} )]</th>
<th>( W_d@-0.1\text{V} ) [( \mu \text{m} )]</th>
<th>( W_d@0\text{V} ) [( \mu \text{m} )]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C, D, E, F</td>
<td>0.49</td>
<td>0.39</td>
<td>0.32</td>
<td>0.3</td>
<td>0.26</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Comparing the theoretical depletion region widths of table 8-4 with theoretical absorber region thickness for each structure we can calculate the fraction that has been depleted depending on the applied bias.

**Table 8-5** Fraction of the absorber region which is depleted with various values of the applied voltage for the five samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>( W_R/W_d@-2.0\text{V} ) [%]</th>
<th>( W_R/W_d@-1.0\text{V} ) [%]</th>
<th>( W_R/W_d@-0.5\text{V} ) [%]</th>
<th>( W_R/W_d@-0.3\text{V} ) [%]</th>
<th>( W_R/W_d@-0.1\text{V} ) [%]</th>
<th>( W_R/W_d@0\text{V} ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C, D</td>
<td>53</td>
<td>42</td>
<td>35</td>
<td>32.6</td>
<td>28</td>
<td>27</td>
</tr>
<tr>
<td>E, F</td>
<td>33</td>
<td>27</td>
<td>22</td>
<td>20</td>
<td>18</td>
<td>17</td>
</tr>
</tbody>
</table>

Structures C and D should, theoretically, exhibit the greater \( \eta \) than E, F due to the larger fraction of the absorber region which is depleted. From the calculated values of the depletion region width from table 8-4, the quantum efficiency and specific detectivity can be calculated. If we consider tables 8-2 and 8-3, then we can redo these again but with the calculated values.

**Table 8-6** Calculated values of \( \eta \) and \( D^* \) for 0V.

<table>
<thead>
<tr>
<th>V=0V</th>
<th>C</th>
<th>D</th>
<th>E₁</th>
<th>E₂</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_p ) [nm]</td>
<td>1700</td>
<td>1748</td>
<td>1650</td>
<td>1631</td>
<td>1700</td>
</tr>
<tr>
<td>( \eta ) [%]</td>
<td>7</td>
<td>22</td>
<td>62</td>
<td>64</td>
<td>7</td>
</tr>
<tr>
<td>( D^* ) [\text{cmHz}^{1/2}\text{W}^{-1}]</td>
<td>5.46x10¹¹</td>
<td>4.16x10¹⁰</td>
<td>2.12x10¹²</td>
<td>7.92x10¹¹</td>
<td>1.99x10¹⁰</td>
</tr>
<tr>
<td>( I_d ) [( \mu \text{A} )]</td>
<td>0.0001</td>
<td>1.304</td>
<td>0.000589</td>
<td>0.00438</td>
<td>0.081</td>
</tr>
</tbody>
</table>
Table 8-7 Calculated values of $\eta$ and $D^*$ for an applied bias corresponding to the best $\eta$

<table>
<thead>
<tr>
<th>$V_R$</th>
<th>$C @ -1V$</th>
<th>$E_1 @ -0.1V$</th>
<th>$E_2 @ -0.3V$</th>
<th>$F @ -1V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{np}$ [nm]</td>
<td>1700</td>
<td>1650</td>
<td>1631</td>
<td>1700</td>
</tr>
<tr>
<td>$\eta$ [%]</td>
<td>10</td>
<td>64</td>
<td>70</td>
<td>10</td>
</tr>
<tr>
<td>$D^*$ [cm$^{1/2}$Hz$^{1/2}$W$^{-1}$]</td>
<td>3.49x10$^7$</td>
<td>1.31x10$^{11}$</td>
<td>1.016x10$^{10}$</td>
<td>1.83x10$^8$</td>
</tr>
<tr>
<td>$I_L$ [$\mu$A]</td>
<td>3.02</td>
<td>0.167</td>
<td>25</td>
<td>1100</td>
</tr>
</tbody>
</table>

Table 8-2/Table 8-6

If we could achieve the theoretical depletion region width for the various structures, then from table 8-6 we should be able to achieve a quantum efficiency of $\sim$7% for both C and F. In reality we find that for C, $\eta$=0.8% and hence we are only achieving $\sim$10% of the predicted efficiency. In the case of structure F, this is halved and only 5% of the predicted efficiency is achieved. The measured $D^*$ of structure C and F are an order of magnitude less than their predicted values. It is higher for structure C due to the much lower dark current of this structure at no applied bias. In the case of the non-resonant structures, the predicted quantum efficiency is nearly two orders of magnitude higher than that measured with a corresponding difference in the $D^*$ values for D, E$_1$, and E$_2$.

Table 8-3/Table 8-7

The best non-resonant cavity efficiency achieved is that by structure C where it is $\sim$10% at 1700nm at a bias of -1V. This agrees with the predicted value. The best resonant cavity detector efficiency is that obtained from structure E$_2$ where it is $\sim$10% at $V$=-0.3V. The predicted value is $\sim$70% and the predicted $D^*$ is an order of magnitude greater than the measured. Hence, in this case we are only achieving $\sim$14% of the predicted efficiency. This is explained by the inadequate depletion of the absorber region which suggests that the carrier concentration in this region is higher than that used to calculate the values of table 8-4. This high carrier concentration [p-type] will also result in an increase in the recombination of carriers, decrease the diffusion length in the n-region and hence decrease the depletion region width.

Using the best current density achieved [$J_0=8.6x10^{3}$A/cm$^2$ for structure C] and the best measured efficiency [$\eta=10%$ for structures C and E$_2$] we can predict the best $D^*$ which could be achieved at the various wavelengths considered in this chapter, table 8-8. The $D^*$ in all cases is of the order of 8x10$^{11}$cmHz$^{1/2}$W$^{-1}$ taking into account the dependence of $D^*$ on wavelength.
Table 8-8 Calculating $D^*$ using the best measured values for $J_0$ and $\eta$ from all of the devices considered in this thesis [both resonant and non-resonant structures]

<table>
<thead>
<tr>
<th>$\lambda$ [nm]</th>
<th>Best $J_0$ [A/cm$^2$]</th>
<th>Best $\eta$ [%]</th>
<th>Best $D^*$ [cmHz$^{1/2}$W$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1631</td>
<td>8.6x10$^{-8}$</td>
<td>9.96</td>
<td>7.88x10$^{11}$</td>
</tr>
<tr>
<td>1650</td>
<td>8.6x10$^{-8}$</td>
<td>9.96</td>
<td>7.97x10$^{11}$</td>
</tr>
<tr>
<td>1748</td>
<td>8.6x10$^{-8}$</td>
<td>9.96</td>
<td>8.44x10$^{11}$</td>
</tr>
</tbody>
</table>

We can plot the data of tables 8-2/8-6 and 8-3/8-7 in the graph of fig. 8.21 along with the best predicted, table 8-8.

Figure 8.22 Measured and predicted $D^*$ values for the various photodetector structures

$D^*$,table [8-2]........D*calc [table 8-6]......D*best [table 8-8]

Comparing the data of fig. 8.22 with $D^*$ of commercial IR photodetectors, fig. 8.23, then at the wavelengths we have measured in this project, the comparable photodetectors are InGaAs and Ge. InGaAs at wavelengths below 1.8μm has $D^*\sim 5x10^{12}$cmHz$^{1/2}$W$^{-1}$ and is not included in this graph.
Comparing figs. 8.22 and 8.23, our best measured device [E₂], at 25°C, is between than InSb [-196°C] not as good as Ge at room temperature. We are 2 orders of magnitude below InGaAs at the present time. The best that we can achieve [table 8-8] with η~10%, is better than PbS [-77°C], InAs [-196°C] and Ge [25°C]. If we could achieve the predicted quantum efficiency for structure E₁ of ~62% then we could achieve D* equal to current InGaAs photodetectors over a similar wavelength range. Cooling our structures would result in at least an order of magnitude decrease in the dark current [chapter 7] and this would cause about the same order of magnitude increase in D*.

8.4 DISCUSSION

The operating characteristics of the resonant cavity detector is very sensitive to various parameters, such as the cavity depth, absorption coefficient, and the refractive index. Accurate knowledge of all these is required in order to predict the eventual performance of the grown photodetectors and to be able to improve on these.

8.4.1 FACTORS EFFECTING RCE DETECTOR CHARACTERISTICS

From the point of view of the modelling of these detectors it is important to know accurately the wavelength at which maximum reflectivity occurs as at this point the phase of the DBR will be zero. Hence, the thickness of any cavity grown can be accurately determined to be mλ/2n. If the phase is not zero, then there will be an extra length to be taken into account due to the penetration of the light into the mirrors. This results in a much more complicated structure as the cavity has to be increased by this distance in order to have the structure operating at the required...
wavelength. This can be rectified if the mirror is first grown, characterised and then has the cavity grown on top but if the structure is grown monolithically [as is the usual case] then the growth has to be accurate at the first attempt.

From fig. 5.15 which plots the value of the front mirror reflectivity as a function of the back mirror reflectivity assuming that $d=0.647\mu m$ and $\alpha=5\times10^6 cm^{-1}$, it was calculated that for an ideal back reflector [$R_b=1$], the front mirror needs to be $\sim53\%$ reflecting in order to maximise the structure of fig. 8.1. This in turn should give an external quantum efficiency of 100%, theoretically. A smaller value of front mirror reflectivity results in a drop in the theoretical $\eta$. For the maximised structure, the cavity enhancement over a non-resonant structure is $\sim$4-fold and is about the same for the non-maximised structure [$R_f=0.34$], for $d=0.647\mu m$. Hence, for a unity back reflector the difference in $\eta$ between the two cases is not significant and, therefore, it would not be detrimental to use the air-semiconductor interface as the front mirror. The problem arises if the back mirror is not a unity reflector, as is highly likely.

A second problem that may arise is an incorrect cavity length. The cavity length is calculated from $m\lambda/2n$, where $n$ is the refractive index of the absorber material. If this is not known accurately then the cavity length will be wrong and hence the resonance may occur at an incorrect wavelength. As was explained in the previous chapter, only calculated data is available for the refractive indices for GaSb at $\lambda=1.68\mu m$. If we consider a variation of $n$ by $+/\sim10\%$ of $n=3.892$, then we can see how much difference this makes to the operating wavelength, fig. 8.24 and we have also calculated the new wavelength of operation using the new refractive index value.

![Figure 8.24](image)

**Figure 8.24** Variation of cavity thickness, $d$, and operating wavelength, $\lambda_o$, with $+/\sim10\%$ refractive index change
A +/-10% change in the refractive index corresponds to a +/-13% change in the operating wavelength and +/-11% change in the cavity thickness. The larger the change in the refractive index from the initial value the greater the change in the two parameters. Even a small percentage change in the refractive index will cause a change in the cavity thickness and consequently a deviation of the operating wavelength from the design wavelength. These variations in the cavity thickness are more significant the higher the cavity finesse [the thinner the linewidth of the resonance peak] as there is less room for error in the wavelength of operation. For a low finesse cavity [broader linewidth] there is more tolerance for error in the cavity thickness as the linewidth may cover a range of wavelengths. Obviously, for the application of gas sensing, the higher the detector finesse the better due to the narrowness of the absorption lines of the gases [Herzberg]. As was seen in chapter 5, high values of finesse require high front and back mirror reflectivities. High values of $R_f$ and $R_b$ does not necessarily mean that the structure is optimised and hence there will be a corresponding change in the quantum efficiency. It has to be clear when designing these resonant cavity structures what the important criteria are for the application that the detector will be used in. This point is illustrated in fig. 5.13 where the higher finesse structure has a quantum efficiency of ~40% whereas the optimised structure [with a lower finesse] is 100% efficient.

The final parameter which determines the detector characteristics is the absorption coefficient. This has been measured for low background doped p-GaSb to be $5 \times 10^3 \text{cm}^{-1}$ at $\lambda \sim 1.7 \mu m$ [accounting for experimental error] using the experimental set-up of fig. 6.17. A variation in $\alpha$ will have an effect on the front mirror reflectivity, the quantum efficiency and the finesse of the cavity. This is easier to see in the graphs of figures 8.25-8.26 which shows these parameters as a function of a +/-10% change in $\alpha$, similar to fig. 8.24 but with $\Delta \alpha$ instead of $\Delta \lambda$.

![Figure 8.25](attachment:figure.png)

*Figure 8.25* Dependence of front mirror reflectivity on percentage change in $\alpha$ for varying back mirror reflectivities.
A +/-10% error in the absorption coefficient causes a change of ~+/-7% in the front mirror reflectivity for a certain value of the back mirror reflectivity. This percentage error in the front mirror reflectivity can usually be tolerated in reality when measuring the optical characteristics of these devices due to the fact that it is also difficult to obtain structures grown to exactly the specified cavity length.

![Figure 8.26 Variation of \( \eta \) with a +/-10% change in the absorption coefficient for various back and front mirror reflectivities](image)

Due to unavoidable errors which can occur in the growth and in characterising these devices it is important that when designing these structures the parameters used are known as accurately as possible in order for there to be an increased chance that the structure will be as close to what is hoped for. If, initially there is an error in the design due to unknown parameters, such as in the case of these structures where a lot of the parameters have been taken from calculated data rather than measured data, then there is the possibility that the parameters used will be inaccurate. In some cases these inaccuracies can be taken into account. For example, an error in the value of the cavity thickness can be rectified by growing the front mirror after characterisation of the cavity and back mirror in order to ascertain what the actual, thickness is and then decreasing or increasing the cavity in order to get the cavity thickness correct before deposition of the front mirror. This is not ideal but is one option until growth non-uniformities can be reduced and/or improved upon. As far as \( \alpha \) and \( n \) are concerned these need to be measured for the actual material used in the cavity region for that particular device as both parameters vary from material to material.
8.4.2 ETCHING OF THE TOP LAYER IN ORDER TO REDUCE THE CAVITY THICKNESS

One way to obtain the desired wavelength and reduce the cavity thickness at the same time is by etching the surface layer. The cavity region can be tuned, by the use of a suitable etchant, which changes the cavity length and causes resonance to occur at the desired wavelength. This is possible if there is no front mirror required for the structure or if the front mirror is to be grown later. This offers a possible solution to the problems of incorrect growth of the cavity thickness as has been seen in the structures designed in this thesis.

If we consider structure D which had a cavity thickness of ~920nm, we can model the reflectance spectra for this as the cavity thickness is gradually reduced, fig. 8.27, in order to see the effect of the etching on the reflectance and the wavelength of the structure.

![Figure 8.27 Modelling of structure D showing (a) the effect of reducing the cavity thickness but keeping the absorption coefficient constant where $\alpha=1400\text{cm}^{-1}$, and (b) the effect of both reducing the cavity thickness and using measured values of $\alpha$ corresponding to the resonance wavelength](image)

Structure D was etched in order to obtain the desired wavelength. The device was etched with 0.1M NaOH for ~1h and then characterised optically. The resultant spectra can be seen in fig. 8.28 which shows the reflectance spectra of structure C before and after etching. There is a shift of ~50nm to shorter wavelengths which corresponds to an etch depth of ~0.05μm as measured by a tally-step after etching. The resonance wavelength after etching is ~1690nm and the reflectance is the same as before etching, though the spectra of the curve after etching is different to that before with the dip occurring closer to the centre of the stopband in the etched structure and the sidebands having higher reflectances at their peaks.
Figure 8.28 Etched reflectivity spectra of structure D. There is ~50nm shift in the resonance wavelength between the original structure and the etched structure.

Figure 8.29 Modelled data for the measured etched and non-etched curves of fig. 8.28 using a value of $a = 1.65 \times 10^3 \text{cm}^{-1}$ for the etched structure in order to obtain a good fit to the measured reflectance value.

Etching of the surface layer also offers the possibility of having an array of detectors all operating at different wavelengths by appropriate recessing of the cavity. Hence on the one wafer, there is the prospect of being able to operate the structure at different wavelengths for various applications, such as the diagram of fig. 8.30 illustrates.
Figure 8.30 Resonant cavity structure offering the possibility of operation at four different wavelengths by suitable etching of the cavity region, where \( L \) is the cavity thickness and \( \lambda \) is the wavelength of operation.

8.5 CONCLUSIONS

In this final chapter, we have concentrated mainly on the optical characterisation of the RCE detector structure and compared these to the corresponding non-resonant heterojunction structures grown in the same growth run. From the optical spectra [both reflectance and photocurrent] it was ascertained that resonance was possible using GaSb albeit the design wavelengths were not quite those designed for. It became clear, especially from the theory, that the back mirror needed to be as close to unity as was possible in order to maximise the absorption in the cavity region and to allow the use of the air-semiconductor as the front mirror. The complexity of growing a front mirror on a structure which had already been grown in two stages was not an ideal situation and hence was decided against. The problem of high carrier concentrations in the absorber region coupled with the low breakdown and high dark currents of these RCE detector structures limited the detector characteristics which could be obtained if the absorber region could be fully depleted and the dark current reduced.

Modelling of the quantum efficiency and \( D^* \) agreed well for the measured results for the non-resonant structure C but not in the case of the RCE detectors. Due to the limited reverse bias which could be applied across these structures, the best measured quantum efficiency was \( \sim 10\% \).

The best \( D^* \) occurred at no applied bias [lower dark current] and was \( D^*[\lambda=1631\text{nm}]=5\times10^{10}\text{cmHz}^{-1}\text{W}^{-1} \), limited by the low quantum efficiency. Higher quantum efficiencies occurred at higher values of reverse bias but the dark current also increased thus reducing the \( D^* \). With an order of magnitude improvement in the dark current our RCE detector structures would be comparable of current InGaAs detectors at similar wavelengths.
CONCLUSIONS

This thesis has discussed in detail various types of photodetectors in general and the resonant cavity-enhanced photodetector in particular. From a study of currently available commercial photodetectors it was decided that many of the operating characteristics could be improved upon especially in the 1.6-2μm wavelength region. The use of the GaSb-based material system provided some problems which needed to be solved in order to access the desired wavelength[s] of operation. The use of the resonant cavity structure was one such solution and hence was investigated both theoretically and experimentally.

From the results obtained in this thesis we can conclude that:

The use of GaSb as the absorber region in conventional detector structures, though theoretically possible, in reality is a problem until the problems of antisite defects resulting in a high carrier concentration in undoped GaSb can be solved. The growth and characterisation of Schottky barrier diodes resulted in the first Schottky contacts to p-GaSb ever published. The electrical characteristics showed good rectification with breakdown at ~4V and dark current <10μA up to -2V though this result could not consequently be repeated on any other similar structures.

The p-n⁺ heterojunction resulted in more reproducible results. The electrical characteristics showed favourable results and were similar to that obtained for the Schottky structures. The heterojunctions were characterised optically and showed η~10% at λ=1700nm, with D*[λ=1700nm, V=0V]~3x10¹⁰cmHz¹/²W⁻¹. These initial results look promising as future optical detectors as an order of magnitude reduction in the dark current would make a D* value equal to that of current InGaAs detectors achievable.

We have designed, demonstrated and investigated the resonant cavity photodetector structure [RCE]. The idea has already been cited in literature though its use has mainly been limited to the design of photodetectors for operating wavelengths less than 1μm using the GaAs-based material systems. The structure was attractive as it provides the option of using smaller absorber regions without sacrificing the quantum efficiency, an idea that is very attractive for a material such as GaSb where the thickness of the absorber is limited due to the high carrier concentration. We demonstrated the first long wavelength [λ>1.6μm] GaSb RCE photodetectors operating at λ~1.63μm, λ~1.65μm, and λ~1.75μm.

We also demonstrated the first long wavelength GaAs/AlAs Bragg reflector stacks with Bragg wavelengths at λveyor=1.68μm and λveyor=2.2μm. These exhibited high reflectivities with
CONCLUSIONS

$R_{1.63\mu m} > 95\%$ and $R_{2.2\mu m} > 85\%$ and were designed for eventual use in the RCE detector structures with the GaAs/AlAs material system being chosen due to the good electrical characteristics obtained with the p-GaSb/n^-GaAs heterojunction. The problem of regrowth on these Bragg stacks was not great as initially feared and measured results showed $\eta \sim 10\%$ with the best $D^*[\lambda=1.63\mu m, 0V] \sim 5 \times 10^{10} \text{cmHz}^{1/2}\text{W}^{-1}$.

We have tried to evaluate, critically, the problems that have been encountered with the RCE detector design, the most notable of which being the poor electrical characteristics resulting in a much reduced S/N ratio for the photodetectors. Various solutions have been put forward for reduction of this parameter and implementation of these should result in a much reduced dark current with a corresponding increase in the $D^*$. 

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Finally, we need to consider the work discussed in this thesis from the point of view of future direction.

[1] Reduction of the dark current: reducing this parameter is one of the key factors in improving the overall detection properties of the photodetectors [both RCE and non-resonant detectors]. There are various solutions to this problem:

[i] Surface passivation might help to reduce the surface leakage current. This was attempted with limited success using the III-VI GaS material [Pérotin, 1994] and it was found that these MIS structures allowed no depletion into the active region.

[ii] Cooling the photodetector in order to reduce the thermal generation of electron-hole pairs.

[iii] The use of buffers in order to reduce the diffusion of impurities from the heavily doped regions either side of the absorber region as well as improving the initial growth conditions for the epilayer.

[iv] Eventual use of GaSb substrate and better lattice-matched mirrors in order to reduce the number of dislocations which are acting as traps for the carriers.

[v] The use of a low doped surface layer before the GaSb active region [see chapter 7] in order to reduce the band to-band tunneling current since this appears to be one of the major causes of high dark current for V>-3V in all the devices characterised in this thesis.

[2] Etching the RCE detector [as mentioned in the last chapter] in order to attain the correct wavelength for the application of interest and also to try and reduce the absorber region thickness so that we can depleted it all with a reasonable amount of bias. There is no point in having a larger absorber region than can be depleted [especially with RCE structures] due to the problem with diffusion currents which as well as being slow will also impair the quantum efficiency.

[3] Deposition of a front mirror on the RCE structures already grown in order to try and improve the η and also to narrow the linewidth at resonance. The use of dielectric mirrors would be one solution to this problem as they can be deposited after growth.
FUTURE WORK

[4] GaInSb/Ga[In]Sb MQWs to try and access the longer wavelength regions and not suffer a
mismatch penalty as would be the case when using bulk absorber regions. This means using
strain-balanced MQW structures.

The lattice constant of the buffer is designed to be between that of the well and the barrier. The
strain in the well is balanced by the strain in the barrier and hence the overall strain in the
structure is reduced [P. Stavrinou, 1995]

[5] Investigation of other RCE detector structures:

Light incident through the substrate which has to be non-absorbing at the wavelength of interest.
A highly reflecting Au back mirror and a MLS lower reflectivity front mirror. This should ensure
that the back mirror will have \( R > 98\% \) without the need for 1/4 wave stacks where it would be
difficult to achieve such a high value of \( R \) without having a lot of layers.

[i]

[ii]
In order to ensure that the substrate does not interfere with the incident light, the substrate can be etched off and a contact made to a thin contact layer below the absorber region. The disadvantage with this structure is that etching off the substrate leaves behind a very thin device which may crack due to the lack of the larger substrate layer.

If it was possible to grow the whole structure monolithically than this would be ideal as one could use lattice-matched mirrors either side of the absorber region. One possibility would be the use of epitaxial lift-off [Demeester, 1993] a technique gaining wide-spread interest especially in the field of VCSELs, which would be ideal for a material such as ours where it is difficult to grow a device without incurring lattice-mismatch penalties.
APPENDIX A
DERIVATION OF EQUATIONS USED IN RCE DETECTOR DESIGN

If we consider two mirrors with a lossless cavity in between, fig. A1.1, where $R_t$ is the reflectivity of the top mirror and $R_b$ is the reflectivity of the bottom mirror, cavity thickness $d$, and refractive index $n$, then

\[ T+R=1 \quad \text{[A1.1]} \]

\[ T = \frac{1}{I_1} \quad \text{and} \quad R = \frac{1}{I_1} \]

where $I_j$ is the total reflected light intensity, $I_i$ is the total transmitted light intensity and $I_o$ is the total incident light intensity. If the incident ray is expressed as $E_0^{\text{inc}}$, the successive rays can be expressed by appropriately modifying both the amplitude and the phase of the initial wave. Referring to fig. A1.1

\[ E_1 = E_0 t_1 t_2 e^{\text{inc}i} \quad \text{[A1.2a]} \]

\[ E_2 = E_0 t_1 t_2 r_1 r_2 e^{\text{inc}i} \quad \text{[A1.2b]} \]

\[ E_3 = E_0 t_1 t_2 r_1 r_2 e^{\text{inc}i} \quad \text{[A1.2c]} \]
and so on where $\delta$ is the phase difference between successive beams and is given by

$$\delta = \frac{4\pi nd \cos \alpha}{\lambda_0}$$

Therefore,

$$E e^{i\delta} = E_1 + E_2 + E_3 + \ldots.$$

$$E = E_0 t_1 t_2 [e^{-i\delta} + r_1 r_2 e^{-i2\delta} + \ldots]$$

$$E r_1 r_2 e^{-i\delta} = E_0 t_1 t_2 r_1 r_2 e^{-i\delta} [e^{-i\delta} + r_1 r_2 e^{-i2\delta} + \ldots].$$

$$E - E r_1 r_2 e^{-i\delta} = E_0 t_1 t_2.$$

$$E = \frac{E_0 t_1 t_2}{(1 - r_1 r_2 e^{-i\delta})}.$$  \[A1.5\]

The transmittance of the resultant beam is proportional to the square of the amplitude, $E$, which is complex, and is given by $|E|^2 = EE^*$. Hence

$$EE^* = \frac{t_1 t_2}{\left(1 - r_1 r_2 \left[e^{i\delta} + e^{-i\delta}\right] + r_1^2 r_2^2\right)}.$$  \[A1.6\]

where $e^{i\delta} + e^{-i\delta} = 2 - 4 \sin^2(\delta/2)$ and hence using $t_1 = [1 - R_1]^{1/2}$ and $t_2 = [1 - R_2]^{1/2}$

$$T = \frac{|E|^2}{E_0^2} = \frac{(1 - R_1)(1 - R_2)}{\left(1 - \sqrt{R_1 R_2}\right)^2 + 4\sqrt{R_1 R_2} \sin^2(\delta/2)}.$$  \[A1.7\]

From equation A1.1, $R$ can be calculated to be

$$R = \frac{\left(\sqrt{R_1} - \sqrt{R_2}\right)^2 + 4\sqrt{R_1 R_2} \sin^2(\delta/2)}{\left(1 - \sqrt{R_1 R_2}\right)^2 + 4\sqrt{R_1 R_2} \sin^2(\delta/2)}.$$  \[A1.8\]

For an absorbing cavity, assuming there are no losses at the surface of the detector, the conservation of energy applies, and equation A1.1 is modified to be

$$A + T + R = 1.$$  \[A1.9\]

where $A$ is the absorptance of the cavity and is given by $A = \frac{I_A}{I}$ where $I_A$ is the total absorbed intensity. Equations A1.7 and A1.8 have to be modified to take into account the absorption in the cavity and hence there is an $e^{-i\delta}$ term which has to be taken into account as the light traverses the cavity. At resonance where $\delta = 2m\pi$ [m is an integer], then
\[ T = \frac{(1 - R_t)(1 - R_b)e^{-at}}{(1 - \sqrt{R_t R_b} e^{-at})^2} \] \hspace{1cm} [A1.10]

\[ R = \frac{(\sqrt{R_t} - \sqrt{R_b} e^{-at})^2}{(1 - \sqrt{R_t R_b} e^{-at})^2} \] \hspace{1cm} [A1.11]

\[ A = \frac{(1 + R_b e^{-at})}{(1 - \sqrt{R_t R_b} e^{-at})^2} x (1 - R_t)(1 - e^{-at}) \] \hspace{1cm} [A1.12]
APPENDIX B

THE STANDING WAVE EFFECT [SWE]

In appendix A we have derived equations for resonant cavity design. In general, these are valid for all detector structures except in the case of very thin active regions where \( d<\lambda/2n \) where a phenomena called the standing wave effect [SWE] has to be taken into account. In an ideal cavity the energy would not be lost on reflection from the back mirror nor absorbed in the transmitting medium. This implies that both the forward and backward traveling waves are in phase and hence their respective amplitudes add up by the principle of superposition to be double that of the single amplitude. There will be points along the wave where the amplitude will be a maximum and a minimum and these are referred to as the antinodes and the nodes respectively of the wave. Unlike traveling waves, standing waves transmit no energy. All the energy in the wave goes into sustaining the oscillations between nodes, at which points forward and backward waves cancel. This is called the standing wave effect, SWE, [S. M. Ünlü, 1992].

However, since the mirrors are not perfect reflectors and the transmitting medium generally absorbs some of the wave energy, the wave amplitude decreases with distance. Unless the source continues to replace lost energy, the amplitude also decreases with time. In this case, the two waves do not cancel exactly at the nodes nor do they add to the maximum at the antinodes and so the resultant wave will then include a traveling wave component that carries energy to the mirror and back. The introduction of a relative phase between the waves, such as would be expected on reflection, leads to a phase angle component in the sine and cosine factors in the wave equation [see ref]. The nodes will then be displaced although their separation remains \( \lambda/2 \).

In the case of thin active layers \( [d<\lambda/2n] \), the standing wave effect [SWE] becomes significant [M. S. Ünlü et al., 1991]. The SWE can be accounted for by considering an effective absorption coefficient, \( \alpha_{\text{eff}} \) in equation 5.3.7 to substitute for the original absorption coefficient. Under the first-order perturbation approximation, assuming a constant absorption coefficient, \( \alpha \), within the cavity region, the effective absorption coefficient can be written as [Ünlü et al., 1991]

\[
\frac{\alpha_{\text{eff}}}{\alpha} = \text{SWE} \tag{B1.1}
\]

with the coefficient of the SWE given by

\[
\text{SWE} = 1 \pm \frac{\sin \beta d}{\beta d} \tag{B1.2}
\]
where $\beta$, the wavenumber, is the same as before and the (+) and (-) signs correspond to the cases where the centre of the active region is at the standing wave maximum and minimum respectively. These cases represent the extremes of the standing wave effect and are illustrated in fig. B1.1. Equation 5B1.2 is valid assuming an ideal bottom mirror, $R_b=1$, $\varphi_1 = 0$, $\varphi_2 = 0$, matched top mirror reflectivity and the active region is in the centre of the cavity.

\[
I = \frac{1}{1 - \left\{\sin(pd)/pd\right\}}.
\]

Figure B1.1 Dependence of the standing wave effect on the cavity thickness. The extremes of the SWE are shown

In obtaining equation B1.2 it is assumed that the resonance condition in the cavity is satisfied and that the bottom mirror is a unity reflector. This effect for thin active regions will be discussed in appendix C where we consider the traversal of the light through a thin active region. From fig. B1.1, we can calculate the SWE depending on the cavity thickness and substituting this SWE value into equation B1.1, the effective absorption coefficient can be calculated. For $d=0.01\mu m$, the SWE is equal to 2 and hence $\alpha_{eff}=2\alpha$. When $d=\lambda/4n$ [0.11\mu m] for $\lambda=1.68\mu m$, the SWE ranges between 0 and 2 resulting in drastic variations in the device photosensitivity at different wavelengths. For $d=\lambda/2n$ [0.216\mu m], the SWE is nearly unity. The maximum deviation for thicker active regions occurs at $d=3\lambda/4n$ [0.32\mu m] and ranges from 0.8 to 1.2. Therefore, for active layers thicker than one period of the standing wave [$d>\lambda/2n$], the effective absorption coefficient is within ±20% of the actual absorption coefficient. The situation for thinner active regions is slightly more complicated mainly due to the problem of where to place the absorber region in the cavity. From literature [S. L. Drayononi et al., 1992; F. Huang et al., 1993], when this type of structure has been used the absorber region needs to be placed in the middle of the cavity corresponding to an antinode of the standing wave in order to gain maximum effect from using this type of structure.
APPENDIX C

TRAVERSAL OF LIGHT THROUGH A THIN CAVITY REGION: UTILIZATION OF THE MODEL PRESENTED IN APPENDIX A

Utilizing the equations introduced in appendix A and B and considering fig. C1.1, we can look at the passage of a beam of light of initial amplitude $S_0$ as it traverses an absorbing medium of thickness $d$ enclosed on either side by reflectors, $R_f$ and $R_b$.

Figure C1.1 Transversal of the incident light through an absorbing cavity bounded on either side by reflectors

As the beam passes through the absorbing region, its amplitude will be attenuated by $e^{-\alpha d}$. At the back mirror there is no loss due to the reflection as $R_b$ is assumed to be a perfect reflector, but at the front mirror there will be some loss as this is not a perfect reflector since it has to be matched, using equation 5.3.6, to the back mirror in order for the device to be maximised. For an absorption coefficient of $\alpha=5\times10^7 \text{cm}^{-1}$, the light penetration depth is 2µm. This value of $\alpha$ is used because this is the absorption coefficient of GaSb at 1.68µm both from measured data and from literature [Londert-Bornstein, 1982]. Hence if this $\alpha$ is substituted into $e^{-\alpha d}$, then at 2µm the original signal has fallen to 37% of the final signal. Table C1-1 considers the signal at it traverses the cavity for various cavity thicknesses for the structure of fig. C1.2.
We can see from table C1-1 that for $-0.5\mu m \leq d \leq 1\mu m$, the signal suffers a double pass through the structure of fig. C1.2 before it reaches $0.37S_0$. For $d=-0.5\mu m$, the number of passes increases before it reaches $0.37S_0$ and for $d>1\mu m$ the number of passes is reduced before this limit is reached. Using the calculated values for the number of passes, a new front mirror reflectivity can be calculated [$R_f'$] for the smaller cavity thicknesses. Using equation 5.3.6, we get an overcompensated value for the front mirror reflectivity which would then result in the front mirror reflectivity not being equal to the attenuated value of the back mirror reflectivity and hence, instead of the total structure reflectivity being zero, as required for maximum absorption, there would be some reflectance at the front surface and this would reduce the absorption in the cavity. This will be discussed further in the next section.

Assumptions used in the model to calculate the data for table C1-1 are: [i] back reflector is an ideal mirror and reflectivity is 1, and [ii] there is no absorption in the reflector. From fig. C1.2

### Table C1-1: Calculation of the output signal as it traverses an absorbing medium of $\alpha=5x10^4\text{cm}^{-1}$ for various cavity thicknesses

<table>
<thead>
<tr>
<th>$d$ [(\mu m)]</th>
<th>0.02</th>
<th>0.1</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_fR_bS_0e^{-20d}$</td>
<td>0.98</td>
<td>0.9</td>
<td>0.61</td>
<td>0.37</td>
<td>0.22</td>
<td>0.14</td>
</tr>
<tr>
<td>$S_0e^{-20d}$</td>
<td>0.99</td>
<td>0.95</td>
<td>0.78</td>
<td>0.61</td>
<td>0.47</td>
<td>0.37</td>
</tr>
<tr>
<td>$R_fS_0e^{-20d}$</td>
<td>0.99</td>
<td>0.95</td>
<td>0.78</td>
<td>0.61</td>
<td>0.47</td>
<td>0.37</td>
</tr>
<tr>
<td>$R_f^2S_0e^{-20d}$</td>
<td>0.98</td>
<td>0.9</td>
<td>0.61</td>
<td>0.37</td>
<td>0.22</td>
<td>0.14</td>
</tr>
<tr>
<td>$R_fR_fS_0e^{-20d}$</td>
<td>0.96</td>
<td>0.82</td>
<td>0.37</td>
<td>0.14</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>$R_f^2R_bS_0e^{-20d}$</td>
<td>0.95</td>
<td>0.78</td>
<td>0.29</td>
<td>0.08</td>
<td>0.02</td>
<td>0.00</td>
</tr>
<tr>
<td>$R_f^2R_b^2S_0e^{-40d}$</td>
<td>0.95</td>
<td>0.78</td>
<td>0.29</td>
<td>0.08</td>
<td>0.02</td>
<td>0.00</td>
</tr>
<tr>
<td>$R_f^2R_b^2S_0e^{-40d}$</td>
<td>0.94</td>
<td>0.74</td>
<td>0.22</td>
<td>0.05</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>$R_f^2R_b^2S_0e^{-40d}$</td>
<td>0.92</td>
<td>0.67</td>
<td>0.14</td>
<td>0.02</td>
<td>0.002</td>
<td>0.00</td>
</tr>
<tr>
<td>Number of passes</td>
<td>50</td>
<td>10</td>
<td>2</td>
<td>2</td>
<td>1.3</td>
<td>1</td>
</tr>
<tr>
<td>$S=0.37S_0$</td>
<td>0.61</td>
<td>0.61</td>
<td>$R_f$</td>
<td>$R_f$</td>
<td>0.37</td>
<td>0.37</td>
</tr>
<tr>
<td>Effective cavity thickness $[d']$ before</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S=0.37S_0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX C

and table C1-1, it can be said that equation 5.3.6 is valid, the exception being very small values of \( d \) \([d \leq 0.1\mu m \text{ for } \alpha = 5 \times 10^3 \text{ cm}^{-1}]\) where there is an extra enhancement factor of 2 in the exponential term which then becomes \( e^{-\alpha d} \).
The phase difference between successive beams traversing a path of length \( d \) with refractive index \( n \) is given by:

\[
\delta = \frac{2\pi}{\lambda} (2nd \cos \theta) \quad \text{[D1.1]}
\]

At normal incidence \( \cos \theta = 1 \), hence

\[
\delta = \frac{4\pi nd}{\lambda} \quad \text{[D1.2]}
\]

If we consider the traversal of a light beam through a resonant cavity structure, then the transmittance \( T \) \cite{Pedrotti, 1992},

\[
T = \frac{1}{1 + \left( \frac{4r^2}{(1 - r^2)^2} \sin^2 \left( \frac{\delta}{2} \right) \right)} \quad \text{[D1.3]}
\]

Using \( \cos \delta = 1 - 2 \sin^2(\delta/2) \)

\[
T = \frac{1}{1 + \left( \frac{4r^2}{(1 - r^2)^2} \sin^2 \left( \frac{\delta}{2} \right) \right)} \quad \text{[D1.4]}
\]

The coefficient of finesse is given by

\[
F = \frac{4r^2}{(1 - r^2)^2} \quad \text{[D1.5]}
\]

Hence

\[
T = \frac{1}{1 + F \sin^2 \left( \frac{\delta}{2} \right)} \quad \text{[D1.6]}
\]

Maximum transmission occurs at \( \sin^2(\delta/2) = 0 \)

\[
\Rightarrow \sin \frac{\delta}{2} = 0
\]

\[
\frac{\delta}{2} = \pm 0, \pm \pi, \pm 2\pi, \ldots
\]

At these points get maximum transmission and minimum reflectivity. At 50% of the maximum signal

\[
T = \frac{I_i}{I_i} = \frac{1}{2}
\]
\[
T = \frac{1}{1 + F \sin^2(\delta/2)} = \frac{1}{2}
\]

If at the half maxima \(\delta = \delta_{1/2}\), then
\[
2 = 1 + F \sin^2(\delta_{1/2}/2)
\]
\[
1/F = \sin^2(\delta_{1/2}/2)
\]
\[
\delta_{1/2} = 2 \sin^{-1}\left(\frac{1}{\sqrt{F}}\right) = \text{Half-width half maxima}
\]

Full-width half maxima
\[
[FWHM] = 2\delta_{1/2} = 4 \sin^{-1}\left(\frac{1}{\sqrt{F}}\right)
\]

Coefficient of finesse, \(F = \left(\frac{2r}{1 - r^2}\right)^2 = \frac{4R}{(1 - R)^2}\)

from \(R = r^2\)
\[
\Rightarrow R = \sqrt{R_r R_b} e^{-2\alpha d} = \sqrt{R_r} e^{-\alpha \delta} \text{ for a resonant cavity structure with and back mirrors}
\]
\[
F = \frac{4\sqrt{R_r R_b} e^{-\alpha d}}{(1 - \sqrt{R_r} R_b e^{-\alpha d})^2}
\]

FWHM = \(4 \sin^{-1} \frac{1}{\sqrt{F}} \equiv \frac{4}{\sqrt{F}}\)

FWHM_{phase} = \(\frac{4\pi}{\sqrt{F}} = \frac{2(R_r R_b)^{1/4} e^{-\alpha d/2}}{1 - \sqrt{R_r} R_b e^{-\alpha d}}\)

Finesse of the cavity in terms of phase, \(\phi\),
\[
\phi = \text{distance between adjacent maxima}/\text{FWHM}
\]
\[
\phi_{\text{phase}} = \frac{2\pi}{\text{FWHM}} = \frac{\pi (R_r R_b)^{1/4} e^{-\alpha d/2}}{1 - \sqrt{R_r} R_b e^{-\alpha d}}
\]

**LINEWIDTH [in terms of the wavelength]**

Using equation [D.2], \(\delta = 4\pi d/\lambda\) and differentiating with respect \(\lambda\)
\[
\frac{\Delta \delta}{\Delta \lambda} = \frac{4\pi d}{\lambda^2}
\]
\[
\Rightarrow \Delta \delta = 4\pi d \frac{\Delta \lambda}{\lambda^2}
\]
\[
\Rightarrow \Delta \lambda = \frac{\Delta \delta \lambda^2}{4\pi d}\]
\[ \Rightarrow \Delta \lambda = \frac{2\delta_{1/2} \lambda^2}{4\pi nd} \]

Using equation D1.9, \( \Delta \lambda = \frac{\lambda^2 \sin^{-1}\left(\frac{1}{\sqrt{F}}\right)}{\pi nd} \)

\[ \text{FWHM}_{\text{wavelength}} = \frac{\lambda^2}{\pi nd\sqrt{F}} \] \[\text{[D1.16]}\]

Therefore the FWHM in terms of the wavelength can be deduced by substituting equation 11.11 in equation D1.16

\[ \text{FWHM}_{\text{wavelength}} = \left(\frac{\lambda^2}{\pi nd}\right)\left(\frac{1 - \sqrt{R_r R_b e^{-\alpha d}}}{2(R_r R_b)^{1/4} e^{-\alpha d/2}}\right) \] \[\text{[D1.17]}\]

LINEWIDTH [in terms of the wavenumber, cm\(^{-1}\)]

Wavenumber, \( \sigma = \frac{1}{\lambda} \) \[\text{[D1.18]}\]

Using equation D1.2 and differentiating with respect to \( \sigma \)

\[ \frac{\Delta \delta}{\Delta \sigma} = 4\pi nd \]

\[ \Delta \sigma = \frac{\Delta \delta}{4\pi nd} \]

Using equation D1.9 where \( \Delta \delta = 2\delta_{1/2} = 4\sin^{-1}\left(\frac{1}{\sqrt{F}}\right) \)

\[ \text{FWHM}_{\text{wavenumber}} = \frac{1}{\pi nd\sqrt{F}} \]

\[ \therefore \text{FWHM}_{\text{wavenumber}} = \left(\frac{1}{\pi nd}\right)\left(\frac{1 - \sqrt{R_r R_b e^{-\alpha d}}}{2(R_r R_b)^{1/4} e^{-\alpha d/2}}\right) \] \[\text{[D1.19]}\]

From equations D1.13, D1.17 and D1.19 it can be seen that when considering the transmittance [same is true for the absorptance and reflectance] the linewidth is dependent on the wavelength when \( T, R \) or \( A \) are plotted as a function of wavelength and are independent when plotted as a function of phase and wavenumber. Hence, when plotted as a function of the wavelength the spectral lines should increase in width as we go to longer wavelength due to the \( \lambda^2 \) dependence of FWHM\(_{\text{wavelength}}\)
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