O-band InAs Quantum Dot Light Sources Monolithically Grown on Si

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Abstract: We discuss our recent progress made in the direct growth of 1.3 µm InAs/GaAs quantum dot (QD) light-emitting sources on Si substrates for Si photonics.

OCIS codes: (230.5590) Quantum-well, -wire and -dot devices; (250.5960) Semiconductor lasers; (250.5300) Photonic integrated circuits

1. Introduction

The availability of Si-based lasers is the key technology for the whole Si photonics industry. However, the indirect bandgap of Si is a severe limitation, and, despite recent advances, all-Si-based lasers will not, in the foreseeable future, outperform their III-V counterparts. Much effort has been directed toward hybrid integration of III-V lasers with Si photonics platforms. Although impressive results have been achieved, in the longer term, large-scale integration of photonics circuits will rely on the monolithic integration of laser sources on Si[1]. The superiority of III-V quantum dot (QD) structures has attracted considerable attention over the last few decades for semiconductor lasers to achieve ultimately superior device performance [2], and has recently attracted increasing attention for monolithic III-V/Si integration due to their enhanced tolerance to defects [3].

In this paper, we first report our recent progress in the direct growth of 1.3µm InAs/GaAs QD lasers on Si substrates. We then move on to discuss the first study of post-growth fabrication and prototyping of various Si-based InAs/GaAs QD light-emitting sources by utilizing the focused ion beam (FIB) technique.

2. 1.3 µm QD lasers grown on Si substrates

To date, the fundamental road block limiting monolithic integration has been the large material dissimilarity between III-Vs and Si substrates. This discrepancy results in various types of defects, including antiphase boundaries (APBs), threading dislocations (TDs), and microcracks, which all generate non-radiative recombination centres and dramatically degrade the promise of III-V materials. To overcome this obstacle, the growth of a GaAs nucleation layer (NL) was first explored to reduce the density of TDs by effectively confining defects at the interface between the GaAs buffer and Si substrate. As a result, an electrically-pumped InAs/GaAs QD laser epitaxially grown on a Si substrate was demonstrated for the first time at 1.3 µm under pulsed operation at room temperature (RT) with a threshold current density of 725 A/cm^2, an output power of 26 mW and lasing up to 42°C [4]. Soon after, a new type of AlAs NL was developed to further reduce the TDs within the GaAs epilayer on Si substrates. AlAs NL was found to be more effective in terms of confining defects within the AlAs/Si interface region and, consequently, fewer defects propagated into the GaAs buffer. The Si-based InAs/GaAs QD laser with an AlAs NL was demonstrated with a threshold current density of 650 A/cm^2 at RT and lasing up to 63°C [5]. To further minimize the impact of various types of defect, the combined strategies of an AlAs NL, InGaAs/GaAs DFLs [6], *in situ* thermal annealing [7] and using InAs QDs as the laser active regions have been developed to achieve high-quality III-V epilayers with a low density of threading dislocations on the order of 10^5 cm^{-2}. Based on this achievement, we have simultaneously achieved CW lasing up to 75 °C, with an ultralow CW threshold current density of 62.5 A/cm^2, a high output power exceeding 105 mW at RT and a long-extrapolated lifetime of over 100,158 h [8].

In our previous work mentioned above, to prevent the formation of APBs, off-cut Si (001) wafers have been used. While this approach can be successfully used for the annihilation of APBs, it compromises full compatibility with standard microelectronics fabrication, where on-axis Si (001) substrates are typically used. To overcome this barrier, the APB free epitaxial GaAs film with a small root-mean-square (RMS) surface roughness was first deposited on a 300-mm standard industry-compatible on-axis Si (001) substrate by metal-organic chemical vapor deposition (MOCVD). In doing so, an effective Si wafer preparation, as well as a two-step process, have been used [9]. The QD laser structure was then grown on this APB-free GaAs/Si (001) virtual substrate by molecular beam epitaxy (MBE). Electrically-pumped CW 1.3 µm InAs/GaAs QD lasers monolithically grown on on-axis Si (001) substrates without any intermediate buffer layers have been realized for the first time with a threshold current density of 425 A/cm^2 and single facet output power of 43 mW. Under pulsed operation, lasing operation up to 102 °C has been realized, with a threshold current density of 250 A/cm^2 and single facet output power exceeding 130 mW at RT [10].

3. Post-fabrication of III-V Light Sources on Si by FIB Technique

While optical lithography using photoresist is the dominant patterning technique, as it allows the patterning of an entire 300 mm (and larger) wafer in a short time with high yield, due to the need for expensive masks and repeated processing, development of new devices is costly and time-consuming. It is therefore attractive to use prototyping technologies that enable rapid and flexible fabrication of nanophotonic components, ranging from micro- to nanometer scales. Among these approaches, FIB is an interesting alternative as it allows photoresist-free and direct writing, which enables the post-fabrication of devices with a more complex topography such as ridge waveguides and laser facets. Also, FIB technology has been widely used for photonics applications, including fabrication of grating couplers and various waveguides.

To this end, the first study of post-fabrication and prototyping of various Si-based light emitting sources has been demonstrated by utilizing the FIB technique, with the intention of expediting the progress toward large-scale and low-cost photonic integrated circuits monolithically integrated on a Si platform. Lasing characteristics for silicon-based lasers with FIB-created facets and as-cleaved facets were compared, and the initial results reveal that there was no obvious deterioration between these two facet realization approaches. Various Si-based light emitting sources, such as lasers, superluminescent diodes (SLDs) [11] and LEDs, were then realized by effectively reduced facet reflectivity using focused Ga^{+} ion beam milling of the front facet of the edge emitting Si-based InAs/GaAs QD laser [12].

4. Conclusion

We have discussed our recent progress in III-V lasers monolithically grown on Si substrates with offcut and standard industry-compatible on-axis Si (001) substrates. We have also reported the first studies of post-fabrication of various Si-based III-V QD light sources by means of FIB for use in Si photonics.

5. Reference

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