Optical Gain and Absorption of 1.55 μm Emitting InAs Quantum Dot Lasers Directly Grown on (001) Silicon

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Abstract: Broad-area InAs quantum dot lasers and segmented contact devices have been fabricated using monolithically grown InAs/InAlGaAs/InP active structures on nano-patterned (001) silicon substrates. The device optoelectronic properties, optical gain and absorption have been studied and compared to structures with a nominally identical active region, grown on a native indium phosphide substrate.

1. Introduction

Quantum dot (QD) laser structures have been considered as promising candidates for the realization of monolithic integration of III-V laser active structures grown directly on (001) silicon, due to physical advantages such as less sensitivity to material defects and higher operation temperature, whilst providing broad optical gain bandwidth. Considerable progress has been made in recent years in achieving 1.3 μm QD lasers on silicon [1, 2], which rely on epitaxial structures with InAs QDs incorporated into GaAs-based alloys (≈ 4% lattice mismatch to silicon). For applications in future optical communication and sensing industries utilising silicon photonic integration technology there is increasing demand to push the lasing spectra of silicon based QD lasers into the 1.55 μm band. To realise an efficient, compact QD laser for these applications, requires achieving high-quality growth of InAs QD active regions and the overall laser structure whilst incorporating InP-based materials. These have larger lattice mismatch, ≈ 8% with silicon, which inevitably introduces more material defects during growth. Only recently have both optically pumped and the more alluring electrically pumped silicon-based 1.55 μm QD lasers been reported [3, 4]. However, a more delicate growth technique and refined laser structure design must be developed to enhance device performance to meet the requirements for practical use.

We report the first optical gain and absorption measurements of 1.55 μm InAs QD laser structures grown on silicon (001) substrates and compare to a nominally identical laser structure grown on a native InP substrate. These results can be used to further understand and optimise the laser structure design and inform future material growth.

2. Experimental Setup

To achieve high quality growth and overcome the large lattice mismatch between Si and InP, a Si (001) substrate fully patterned with nano V-grooves is used. The Si (111) surfaces exposed by the nano V-grove pattern has been shown to be effective in trapping and terminating defects [4, 5, 6]. A GaAs buffer and InGaAs/InP superlattice layers were grown to filter threading dislocations and planarize the surface. The active region was formed by three layers of InAs QDs with InAlGaAs barriers and InP cladding layers (Figure 1a). Differential contrast imaging (DIC) of the as-grown wafer surface however reveals considerable surface morphology and defects remain (Figure 1b).

Broad-area co-planar stripe lasers and non-lasing segmented contact devices were fabricated using standard photolithography and inductively coupled plasma etching techniques. The mesa width was defined to be 100 μm wide and etched ≈ 3 μm to the InP n-contact layer. 50 μm wide p-contact and n-contact metals were deposited to

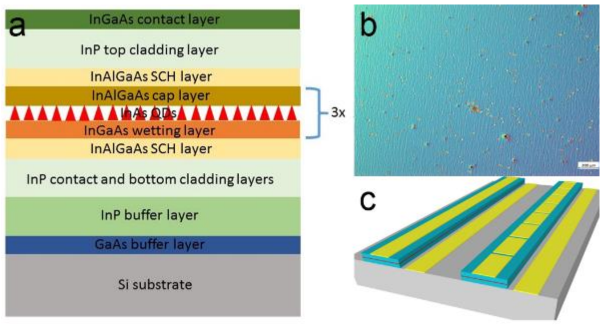

Figure 1: (a) Epitaxial structure of 1.55 μm InAs QD laser growth on Si. (b) Wafer surface imaged in differential interference contrast mode (Si substrate). (c) Schematic diagram of broad-area lasers and segmented contact devices.

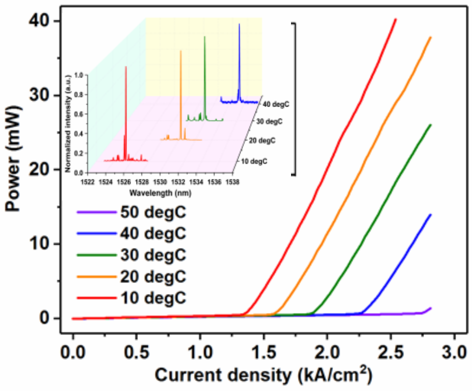

Figure 2: Power-Current curves of a 2.1 mm cavity length stripe laser measured at temperatures between 10 °C and 50 °C. Also shown (inset) is the lasing spectra between 10 °C and 40 °C exhibiting a red shift from 1526 nm to 1536 nm.

form top and bottom contact respectively. For the segmented contact devices each contact was defined to be 292 μm in length with 8 μm intercontact spacing. Lasing and non-lasing segmented contact devices with cleaved, uncoated facets were mounted on TO headers and wire-bonded.

3. Results and Discussion

Broad-area stipe lasers with a cavity length of 2.1 mm were driven using a pulsed current source with a 1 μs pulse duration and a repetition rate of 5 kHz to avoid self-heating. The average power emission from a single facet was measured and converted to peak average power, accounting for emission from both facets of the device (Figure 2). Increasing the temperature from 10 ℃ to 50 ℃ increased the threshold current density from 1.36 kA cm^{-2} to 2.8 kA cm^{-2}. The lasing wavelength was measured at $\approx$ 10% above the device threshold current at each temperature (Figure 2, inset). The lasing wavelength peak exhibited $\approx$ 10 nm redshift from 1525.3 nm to 1535.3 nm due to the increase in temperature, whilst the laser linewidth broadened from 7.1 GHz to 11.1 GHz.

To better understand the optical properties of the material, and directly compare to a nominally identical laser structure grown on a native InP substrate, the optical gain and absorption of each wafer was measured using the segmented contact method [7] at 20 °C and 40 °C. Figure 3 shows the optical gain and absorption spectra for the Si substrate sample as a function of injection current density, with a maximum measured net gain of $\approx$ 14 cm^{-1} at a current density of 2.67 kAcm^{-2}. A large internal optical loss, $\alpha_i \approx$ 20 cm^{-1} at 20 °C was measured at longer wavelengths and a similar value was recorded for the sample grown in InP. Increasing the sample temperature to 40 °C resulted in a significant increase in the value of α_i for both samples, resulting in a decrease in the peak net gain (Figure 4), and thus the large increase in threshold current density with temperature observed in Figure 2. It should be noted that the similarities between the peak net gain against current density (Figure 4) for each sample indicate that the high threshold current densities observed in both is therefore likely due to the laser structure design, rather than any defects introduced due to the growth on Si substrate.

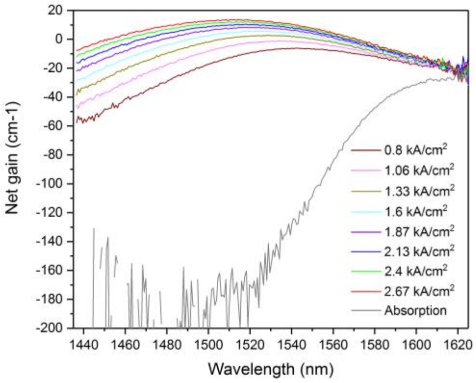

Figure 3: Optical gain and absorption spectra at 20 °C for the laser structure grown on Si substrate.

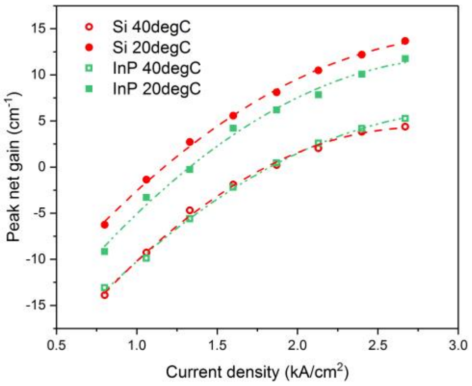

Figure 4: Peak net gain against current density for the laser structures grown on Si and InP substrates at 20 °C and 40 °C. Fits to the curves are shown as dashed/dot-dashed lines.

4. Conclusion

We present the first report of optical gain and absorption measurements of 1.55 μm InAs QD laser structures grown on silicon (001) substrates. A comparison of the laser, optical gain and absorption characteristics to a nominally identical structure grown on a native InP substrate indicates the device performance is currently limited by the laser active structure design, rather than the introduction of defects due to growth on the silicon substrate.

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5. References

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