Monolithic Growth of InAs Quantum Dots Lasers on (001) Silicon Emitting at 1.55 µm

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***Abstract*—Broad-area 1.55 µm InAs quantum dots (QDs) lasers were fabricated based on monolithic growth of InAs/InAlGaAs/InP active structures on nano-patterned (001) silicon substrates. Device optoelectronic properties and materials' optical gain and absorption features were studied to provide experimental support for further optimizations in laser design.**

Keywords—InAs Quantum Dots, Defects, Monolithic Growth, 1.55µm laser diodes.

I. INTRODUCTION

Quantum dot (QD) laser structures have been considered as promising candidates for the realization of monolithic integration of III-V laser active structures 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). There is also a strong motivation to push the lasing spectra of silicon-based QD lasers into the 1.55 µm band to meet the growing demand in silicon photonic integration technology, for application in future optical communication and sensing industry. To realize such a QD laser, requires the achievement of high-quality growth of InAs QD active regions and the overall laser structure, utilizing InP-based materials. These have larger lattice mismatch ~8% with silicon, inevitably introducing more material defects. 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.

In this paper, we have used the same material published in [4] and fabricated broad-area stripe lasers and multi-segmented contact devices to study the optoelectronic and material properties, this includes the temperature dependent light-current (L-I) features together with lasing spectra, and the first investigation of the optical gain and absorption of this 1.55 µm InAs QD laser structure grown on silicon. These results can be used to further optimize the laser structure design and future material growth.

II. MATERIAL AND DEVICE

To overcome the large lattice mismatch between InP and Si, (001) silicon fully patterned with nano V-grooves was chosen as the substrate for growth. The Si (111) surfaces and initial III-V materials grown on them have been shown to be effective in trapping and terminating defects [4-6]. A GaAs buffer and InGaAs/InP superlattice layers were subsequently grown to filter out threading dislocations and smooth the surface. Finally, the active region was formed by three layers of InAs QDs surrounded by InAlGaAs quantum-barriers, and sandwiched by InP cladding. The whole epi-structure is shown in Figure 1a. Nevertheless, surface morphology and particles can be observed by a global view of optical microscope under the differential intensity contrast (DIC) mode (Figure 1b).

Broad-area co-planar stripe lasers and multiple segmented contact devices (Figure 1c) were fabricated by using photolithography and inductively coupled plasma etching, where the mesa width was defined as 100 µm wide and etched down to the InP contact layer, yielding a mesa height of ~3 µm. 50 µm wide p-contact and n-contact metals were deposited on top of and at the bottom of the mesa, respectively. For segmented contact devices, each contact was 292 µm in length and separated by 8 µm inter-contact gaps. After lapping and cleaving, chips were mounted and wire-bonded onto the TO headers.

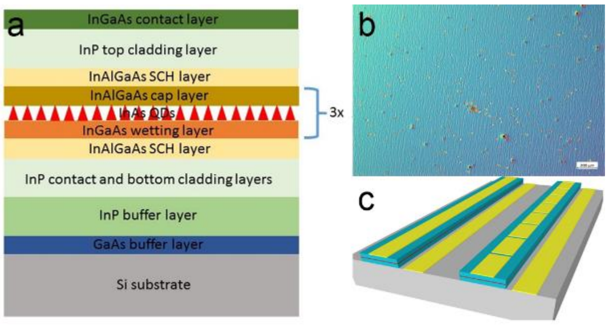

Figure 1, (a), structure of 1.55 µm InAs QD laser growth on silicon, (b), material surface imaged by DIC mode, (c), diagram of broad-area devices.

III. RESULTS AND DISCUSSIONS

Figure 2 gives the temperature dependent light-current (L-I) curves of a stripe laser with a cavity length of 2.1 mm, the inset plot shows the threshold current density at each corresponding temperature. The laser was driven by a pulsed current source with 1 µs pulse duration and 5 kHz duty cycle, and laser power in the plot was converted from CW average power measured by the integrating sphere to peak average power in the pulse for emission from both facets. With the temperature increased from 10℃ to 50℃, the corresponding threshold current density increased from 1.36 kA/cm^2 to 2.8 kA/cm^2. This high threshold current density was at least partially caused by material defects, each acting as an individual parallel current channel, as well as nonradiative recombination centers.

The laser beam emitted from the front facet was focused and coupled into a multi-mode optical fiber which was connected to an optical spectral analyzer. Figure 3 shows the normalized lasing spectra measured at 10℃ to 40℃. The laser drive current density was 1.42 kA/cm^2, 1.74 kA/cm^2, 2.1 kA/cm^2 and 2.56 kA/cm^2 respectively, which is approximately 10% above the corresponding threshold current density at each temperature. The lasing peak exhibited a ~10 nm redshift from 1525.3 nm to 1535.3 nm due to the increasing operation temperature, whilst the laser linewidth broadened from 7.07 GHz to 11.1 GHz.

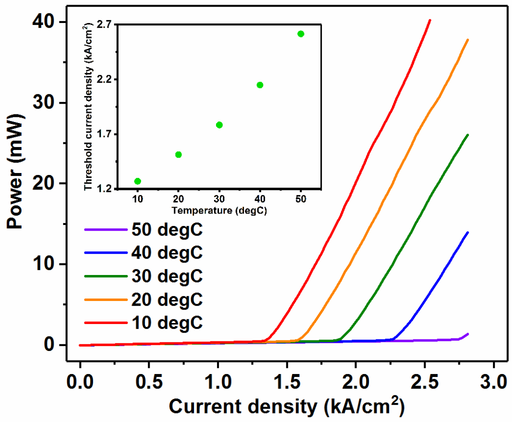

Figure 2, L-I curves of a 2.1 mm length stripe laser measured at different temperature. Inset, threshold current density at each measured temperature.

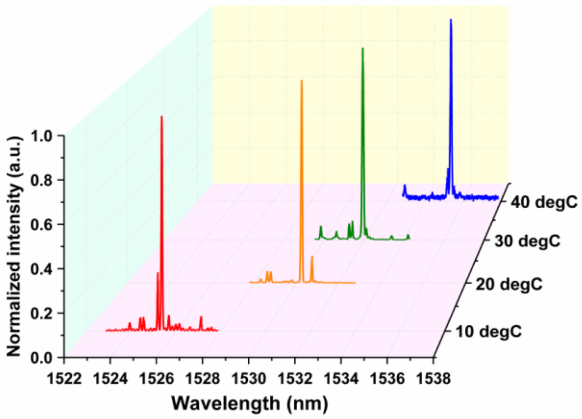

Figure 3, lasing spectra measured from 10℃ to 40℃, redshift in lasing spectra and broadening in laser linewidth were observed with increasing temperature.

To better understand the material optical properties of these 1.55 µm InAs QD laser structures on silicon, segmented contact devices were fabricated to study the optical gain and absorption. Devices consisted of 10 equal-length segmented contacts, where the back 8 contacts are connected to ground. By comparing the amplified spontaneous emission (ASE) spectrum measured when the first segmented contact section is electrically driven to the spectrum of ASE signal measured when two segmented contact sections are driven together, the net optical gain (single pass) can be obtained, as shown in equation (1)

$$G = \frac{1}{L}\ln\left[\frac{I(2L)}{I(L)} - 1\right] \quad (1)$$

Where, L is the length of each segmented contact section, I(2L) is the ASE signal measured from section 1 and 2 together, and I(L) is the ASE signal measured only from section 1. Similarly, the material's modal absorption can be obtained from ASE signal measured from section 1 and section 2 individually, as shown in equation (2).

$$A = \frac{1}{L}\ln\left[\frac{I(s1)}{I(s2)}\right] \quad (2)$$

Where I(s1) and I(s2) are the ASE signals measured when electrically driving sections 1 and 2 respectively. [7]

Figure 4 gives the room-temperature optical gain and absorption spectra measured as a function of the injection current density. The plotted absorption spectrum was measured when driven with a current density of 2.05 kAcm^{-2} per section. At the long wavelength range, the absorption corresponds to the internal loss α_i, which was about 20 cm^{-1}. The maximum gain of 10 cm^{-1} at a current density of 2.05 kAcm^{-2} is at 1518 nm. Generally, this silicon-based 1.55 µm QD laser structure exhibited a high internal optical mode loss, which was due to the large amount of defects generated during growth. This can also explain the high threshold current density of the stripe laser mentioned above.

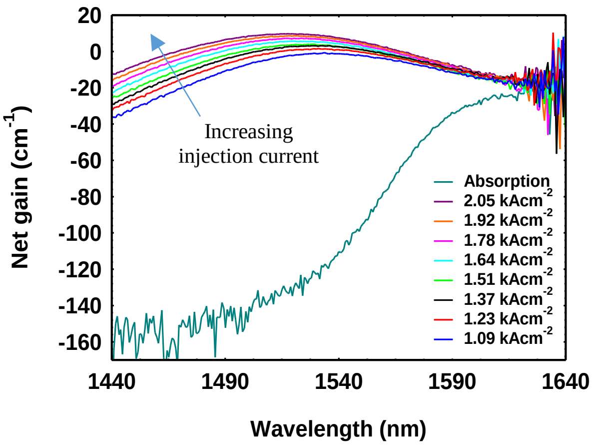

Figure 4, Optical gain and absorption spectra measured at 21 ^{0}C with injection current density from 1.09 kAcm^{-2} to 2.05 kAcm^{-2}.

IV. SUMMARY

We have demonstrated the fabrication of 1.55 µm InAs QD lasers and non-lasing multiple segmented contact devices grown on silicon. Temperature dependent laser performance has been characterized up to 50˚C, but low optical gain and high internal optical loss necessitate a further optimization of both the QDs active layers and the InP buffer on Si. These results will contribute to further improvements in growth technique and more efficient laser structure design.

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