InAs/GaAs Quantum Dot Lasers Monolithically Integrated on Group IV Platform

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Abstract—III-V quantum dot lasers monolithically integrated on silicon platform attracts intensive interests due to its advantages on providing a promising solution for reliable and efficient light source to integrated on photonics and electronics circuits. Compared to wafer bonding technique, monolithic integration its more attractive for large scale, low cost and streamline fabrication. In this paper, we give a brief review on our recent progress of III-V quantum dot lasers monolithically integrated on 4° offcut and exact (001) Si substrates for the silicon photonic integration.

I. INTRODUCTION

Monolithic integration of III-V reliable and efficient electrically pumped continues wave (CW) semiconductor laser on silicon platform is an ultimate solution for producing complex Si based optoelectronics integrated circuits. Directly epitaxial growth for III-V semiconductor material on silicon substrate gives a promising solution to provide a low cost, large scale and high yield on-chip light source. However, large material dissimilarities between group IV and group III-V materials cause many significant challenges for monolithic integration. For example, large material mismatch, thermal expansion ecoefficiency difference and polar on non-polar growth which cause various types of defects including threading dislocations (TDs), microcracks and antiphase boundaries (APBs). These may generate non-radiative recombination centres which will dramatically decrease the performance of fabricated devices. To overcome these challenges, many approaches including dislocation filter layers (DFLs) and thermal annealing (TA) have been considered in our results in order to improve device performance. Considering the active region, quantum dot structure attracts extensive research interests in past several decades for the monolithic integration of III-V on Si. It has been widely used as active layers in semiconductor lasers due to the advantages of low threshold current density (J_{th}), insensitive to TDs, and high temperature stability. In this paper, we will give a review of our recent progress on III-V quantum dot lasers monolithically integrated on Si platform.

II. QUNATUM DOT LASERS MONOLITHICALLY INTEGRATED ON OFFUCT SILICON SUBSTRATE

In this work, InAs/GaAs quantum dot lasers structure was directly grown on 4° offcut to [011] Si substrate using solid-source molecular beam epitaxy (MBE) system to prevent the formation of APBs. In our previous work, we have reported the first electrically pumped InAs/GaAs quantum dot laser directly grown on Si substrate by using a optimized GaAs nucleation layer on Si and a InGaAs/GaAs strained layer superlattice (SLS) as DFLs [1]. After that, we consistently improve the devices performance in our following works. Eventually, due to the high-quality GaAs film we realized on offcut Si substrate by applying combined strategies as AlAs nucleation layer, optimized InGaAs/GaAs DFLs and in-situ thermal annealing. A high performance 1310 nm InAs/GaAs quantum dot laser monolithically grown on offcut Si substrate with record low threshold current density 62.5 A/cm^2 at room temperature (RT) has been demonstrated [2]. The maximum output power of single facet is about 105 mW and the maximum operation temperature is up to 75°C under CW mode. We will give a more detailed description in the following two sessions.

A. Epitaxial structire

The epitaxial structures of quantum dot lasers were deposited by Veeco solid-source MBE GEN 930. After the preparation of offcut Si substrate, a thin film of AlAs nucleation layer was deposited on Si substrate by migration enhanced epitaxy (MEE) technique at relative low temperature about 350°C. As AlAs nucleation layer suppressed the three-dimensional growth, a good interface was formed for the following growth. After this, GaAs buffer was formed by three-step growth technique in different growth temperature. First, 30 nm GaAs was deposited at the same temperature as AlAs; then, 170 nm GaAs film was formed afterwards at higher temperature 450°C; at the end, 800 nm high temperature GaAs was deposited at 590°C. After depositing the GaAs buffer, 10 nm $In_{0.18}Ga_{0.82}As$/10 nm GaAs SLS was used as DFLs to further reduce the threading dislocation density (TDD). Four repeats of DFLs were performed on GaAs buffer and each DFL included five periods of SLS and separated by 300 nm GaAs. In-situ thermal annealing was performed in each DFL after the formation of five periods of SLS. This will help to increase the mobility of TDs and then lead to the annihilation before the subsequently growth. Fig. 1 (a) (b) give a clear explanation on the TDD according to the different position of epitaxial structure. Most of the TDs were stopped at first 200 nm of the buffer layer. However, TDD is still at the level of 10^9 cm^{-2} at position 1. After four repeats of DFLs, the TDD was clearly reduced and down to the level of 10^5cm^{-2} after the last 300nm GaAs space layer. We successfully demonstrated a high-quality buffer for the following laser structure growth. Subsequently, a typical InAs/GaAs DWELL laser structure will be deposited on well optimized low TDD GaAs virtual substrate on Si.

B. Device performance

To date, we achieved low threshold current density and high optical output power quantum dot lasers on offcut Si substrate.

Fig. 2 (insert) gives an AFM image of typical uncapped quantum dots layer grown under same condition with the laser devices. Good uniformity with $3\times10^{10}cm^{-2}$ quantum dot density is obtained. Fig. 2 also provides a photoluminescence (PL) image measured of the uncapped quantum dot layer which emitting at ~1300 nm with full-width at half maximum (FWHM) ~ 29 meV. Broad area lasers were fabricated based on the laser structure we developed. Eventually, we demonstrated a high reliability, high performance electrically pumped continuous wave 1.3 µm QD laser on 4° offcut Si (001) substrate with J_{th} of 62.5 A/cm^2 at room temperature and maximum operating temperature 75°C at CW mode. Fig. 3 shows the light-current-voltage (LIV) characteristic measurement for our InAs/GaAs quantum dot laser monolithically grown on Si. High optical output power of 105mW was observed under injection current density of 650 A/cm^2.

III. QUANTUM DOTS LASER MONOLITHICALLY INTEGRATED ON EXACT (001) SILICON SUBSTRATE

Based on our previous discussion, we have successfully demonstrated the III-V quantum dot lasers grown on offcut Si substrate to prevent the formation of APBs. However, although the offcut substrate can annihilate the APBs caused by polar III-V materials grown on non-polar group IV materials, it is not fully compatible to the industrial standard fabrication. Therefore, most recently, we have demonstrated the 1.3µm electrically pumped CW quantum dot lasers on exact Si (001) substrate which is industrial compatible. A J_{th} down to 425 A/cm^2 at room temperature with maximum operation temperature 36 °C under CW mode was achieved [3]. Detailed Epitaxial structure and devices performance will be discussed in following sessions.

A. Epitaxial structure

The schematic diagram of our epitaxial structure on exact (001) Si substrate is shown in Fig. 4. 400 nm GaAs buffer was grown in steps by MOCVD on an 300 mm diameter industrial standard Si (001) substrate without offcut. Firstly, a 40 nm thin film GaAs nucleation layer was deposited at low growth temperature (400-500°C). Then, a 360 nm GaAs buffer was grown at higher temperature (600-700°C) [4]. Eventually, as the AFM image shown in Fig. 5 (a), an APB free GaAs surface and small root mean square (RMS) surface roughness of ~0.86 nm were achieved. Afterwards, sample was moved to MBE chamber for the following laser structure growth. 600 nm GaAs buffer was deposited firstly and following by five repeats of DFLs consist of five periods of optimized InGaAs/GaAs SLS separated by 300 nm GaAs. Then, a InAs/GaAs quantum dot laser structure was deposited on it started with 1.4 µm n-type AlGaAs cladding layer and ended with 300 nm p-type GaAs contact layer. The active region consists of five repeats of undoped InAs/GaAs DWELL structure separated by 50 nm GaAs space layers.

B. Device performance

These quantum dot laser samples grown on exact (001) Si substrate were fabricated into broad area lasers and took various relative measurements. Fig. 5 (b) shows the room temperature PL comparison for these two samples. They present comparable emission intensity at ~1285 nm with ~32 meV FWHM. The intensity of GaAs based quantum dots sample is about 1.3 times greater than Si (001) based sample. The surface morphology investigation was done by AFM for an uncapped InAs quantum dots layer grown on same condition with laser structure Fig. 6 presents the 1 × 1 μm^2 AFM image of uncapped InAs QDs grown on Si (001) substrate which shows good uniformity and the dot density are $\sim3.5\times10^{10}cm^{-2}$. The LIV characteristic comparison is presented in Fig. 7, the J_{th} is 210 A/cm^2 and 425 A/cm^2 for GaAs based, and Si based lasers respectively. The slope efficiencies are calculated as 0.12 W/A and 12.7% for GaAs based devices and 0.068 W/A and 7.2% for the Si based devices. From Fig. 8, the maximum output power of single facet is 43 mW achieved under 1332 A/cm^2 injection current density at CW mode and only small rollover presented. For pulsed mode, the maximum output power is 134 mW under $2kA/cm^2$ injection current density. Fig. 9 presents the emission spectrum under different injection current density under CW mode. When the injection current density increases to $425A/cm^2$, typical lasing behavior presented. Fig. 10-11 show the light-current (LI) characteristic under pulsed and CW mode respectively. Under pulsed mode, the characteristic temperature T_0 is ~32K between 16°C to 102°C. And for CW mode, lasing operation was observed when heatsink heated up to 36°C.

IV. CONCLUSION

We reviewed the recent results about III-V quantum dots lasers monolithically integrated on offcut Si and exact (001) Si substrate in this paper. They all present promising potential for high efficient and reliable on-chip light source for Si based optoelectronics integrated circuits.

ACKNOWLEDGMENT

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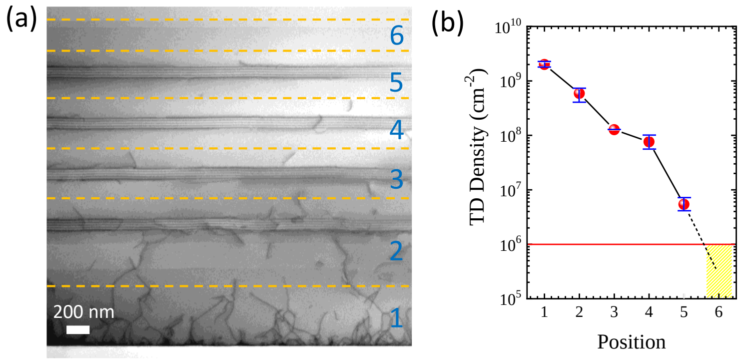

Fig. 1. (a) Bright-field scanning TEM image of DFLs; (b) Dislocation density measured at different positions in (a).

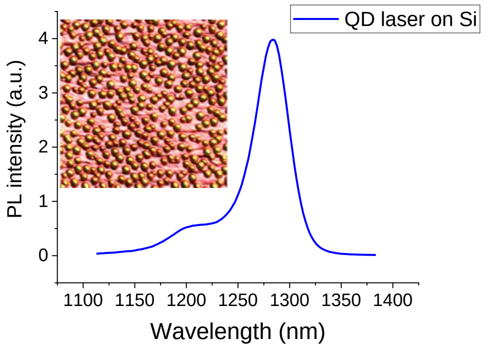

Fig. 2. PL spectrum for QD grown on Si emitting at ~1300nm; Inset: representative AFM image of uncapped QD grown on Si

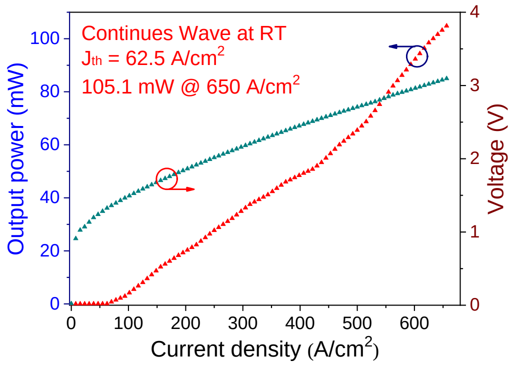

Fig. 3. LIV characteristics for a 50 μm × 3200 μm InAs/GaAs QD laser grown on Si substrate under CW operation at 18 °C.

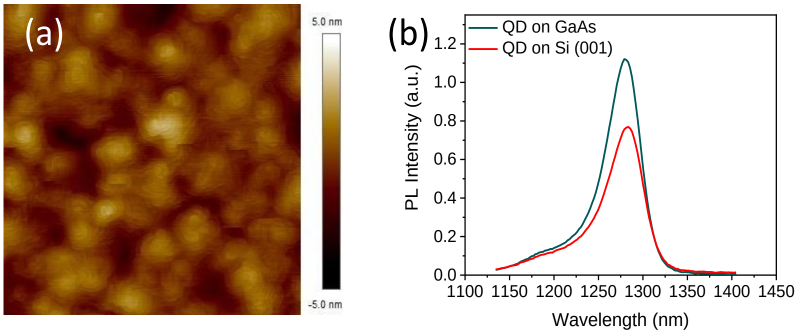

Fig. 5. (a) 5 × 5 μm^2 AFM image of a 400 nm GaAs buffer direct grown on exact Si (001) substrate; (b) Room temperature PL comparison of InAs/GaAs QD laser structure grown on exact Si (001) and GaAs substrate.

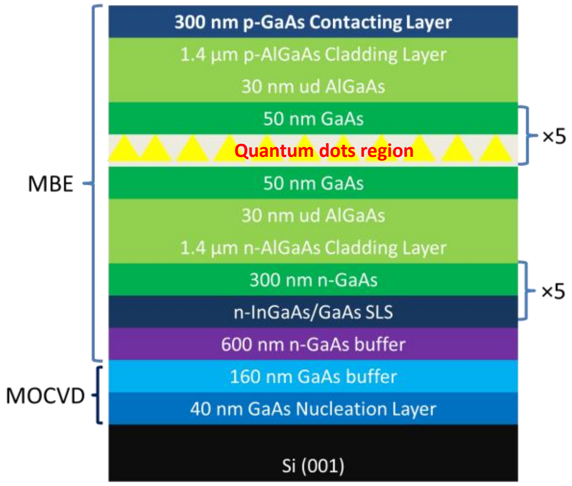

Fig. 4. The schematic diagram of the QD laser structure grown on the on-axis Si (001) substrate.

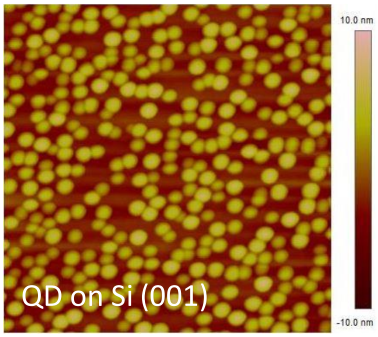

Fig. 6. 1 × 1 μm^2 AFM image of uncapped InAs QDs grown on exact Si (001) substrate.

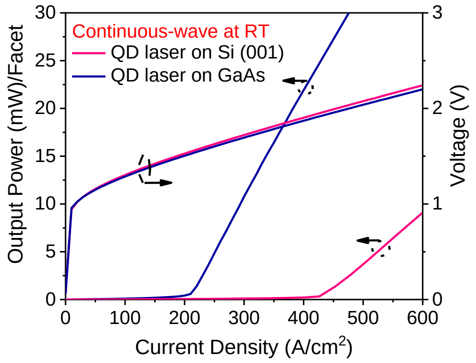

Fig. 7. LIV characteristic comparison of a InAs/GaAs QD laser grown on Si (001) and native GaAs substrate at room temperature under CW operation.

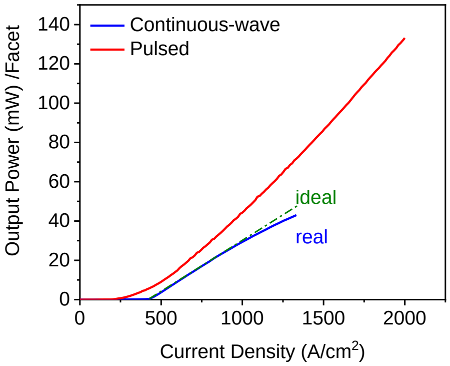

Fig. 8. LI comparison of InAs/GaAs QD laser grown on Si (001) substrate under CW and pulsed conditions at room temperature.

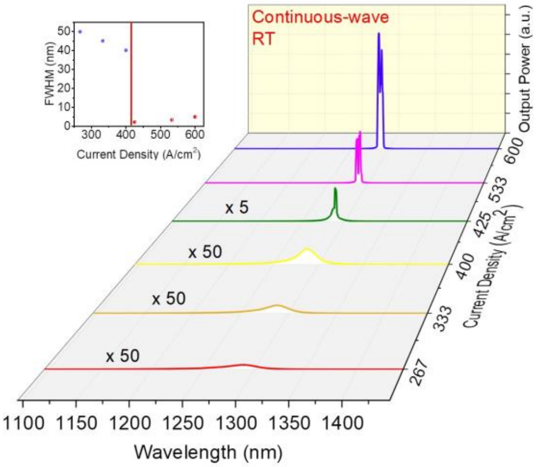

Fig. 9. Emission spectra for InAs/GaAs QD laser on Si (001) substrate at various injection current densities at room temperature. The inset shows the FWHM change as a function of injection current density.

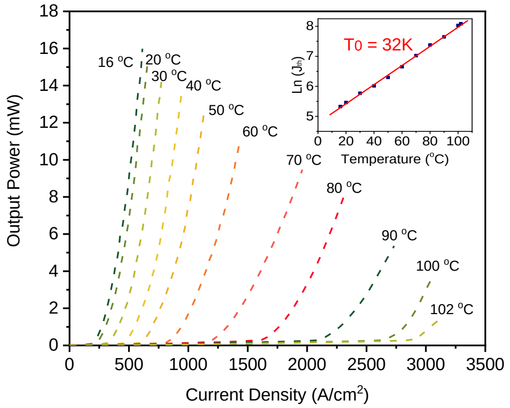

Fig. 10. Single facet LI curve for a InAs/GaAs QD laser grown on Si (001) substrate at different heat sink temperatures under pulsed condition. The inset shows the natural logarithm of current density against temperature in the ranges of 16 – 102°C.

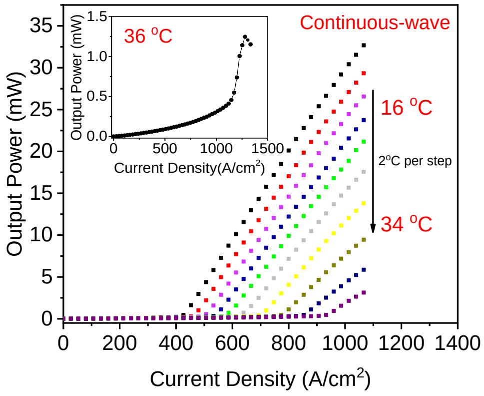

Fig. 11. Single facet LI curve for the same InAs/GaAs QD laser on Si (001) as a function of temperature under CW operation. The inset shows the LI curve for this QD laser at a heat sink temperature of 36°C.