III-V Quantum Dot Lasers Monolithically Grown on Silicon

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Abstract: We review the direct growth of III-V quantum dot laser on Si substrates. A low threading dislocation density, on the order of 10^5 cm^{-2}, for III-V epilayer on Si has been achieved.

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I. Introduction

Over the past few decades, the increasing demands of the high-throughput system have always been a puzzle for modern Datacenters and Data industries, which needs novel methods to bridge between the large bandwidth and low power consumption. There seems to be an unbroken "wall" between the conventional copper interconnection and the high-throughput systems [1], which copper interconnection introduce extra heat and cooling cost to the system. The integration of optical interconnects on a Si platform is believed to be one of the most promising methods to meet this demand [2-6]. An efficient and reliable laser source still remains problematic despite great efforts have been devoted to Si-based light generation and modulation technologies. Group IV semiconductors, such as silicon and germanium, have been put forward to serving as the light-emitting source in integrated circuits. However, the indirect bandgap property of group IV materials, in which a phonon participates in the recombination process, makes them naturally incapable of accomplishing efficient radiative recombination. Although electrically pumped Ge/Si laser has been demonstrated, the threshold current density is extremely high (~280 kA/cm^2) [7]. While III-V materials are direct bandgap and are believed to be one of the promising materials to realize efficient and reliable laser. Additionally, III-V materials have the advantage that they can be tailored for III-V emitters operating at various wavelengths. [1,3] Therefore, the integration of III-V compound semiconductors on Si platform is an attractive technology for a high efficiency but low-cost laser. Although heterogeneous integration technique has been well-established, monolithic integration still reminds the opportunity of low-cost and dense integration of III-V photonic components on Si platform. However, monolithic integration technique faces fatal challenges because of the distinct material properties between III-V semiconductors and group IV materials, such as lattice constant, thermal expansion coefficient, and chemical polarity. These differences introduce various types of defects during the epitaxial growth of III-V materials on Si substrate, including antiphase boundaries (APBs), threading dislocations (TDs), and micro-cracks, all of which could serve as non-radiative recombination centers. These non-radiative recombination centers will dramatically lower the laser performance.

Several techniques have been proposed to overcome the defects generated by the heteroepitaxial growth of III-V materials on Si substrates. Ge, which has a similar lattice constant as GaAs. Thus, direct growth of III-V lasers on Ge substrate is a significant pre-step for monolithic integration of III-V lasers on Ge/Si substrates since the epitaxial growth of Ge-on-Si is well-established. We have demonstrated the first QD laser grown on Ge substrates, with lasing at a wavelength of 1305 nm and a low threshold current density of 55.2 A/cm^2 [8]. Based on this result, we have also described the first III-V QD laser diode monolithically grown on Ge-on-Si substrates. Room temperature PL at a wavelength of 1.29 μm with full-width half maximum (FWHM) of ~30 meV has been achieved [9].

Although Ge buffer seems like an excellent approach for monolithic integration of III-V laser on Si substrates, this intermediate Ge layer would restrict the application on the integration of Si platform due to the large optical absorption at telecommunications wavelength. Thus, technologies for direct growth of III-V epilayer on Si substrate need to be put forward.

II. QD lasers monolithically grown on offcut Si substrate

According to the previous researches, we have proven the Si (100) wafer with 4° miscut-angle oriented towards the [110] plane would suppress APBs due result from the formation of double-layer steps as shown in figure 1(a) [10]. Except for this 4° miscut-angle substrates, several strategies have been used in order to decrease the density of TDs in the III-V epilayer. A 6 nm AlAs layer, known as a nucleation layer, has been grown by migration-enhanced epitaxy (MEE) on the Si substrate, as shown in figure 1(b), followed by a 1 μm GaAs buffer layer grown by the three-step growth technique. Finally, 4 sets of InGaAs/GaAs strained layer superlattice (SLSs) defect filter layers (DFLs) were formed before the laser structure. In situ thermal annealing of SLSs was performed aiming at improving the annihilation efficacy of TDs [10,11]. As a result, a high quality III-V epilayer on Si substrate with a low density of TDs at the order of 10^5~10^6 cm^{-2}.

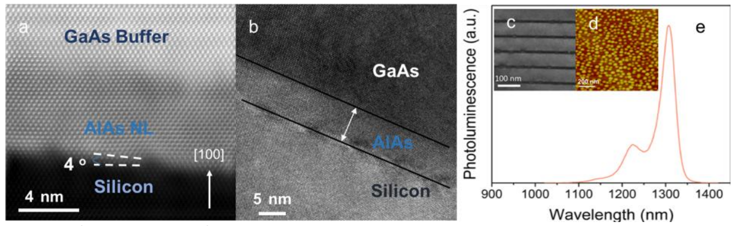

Figure.1. (a) High-resolution TEM of AlAs/Si interface. (b) High-resolution TEM image showing the nucleation layer. (c) TEM cross section image of five-layer quantum dot. (d) 1×1 μm^2 AFM image of InAs/GaAs quantum dots. (e) PL of InAs/GaAs quantum dots

Based on the pre-structure on the Si substrate, a standard p-i-n laser structure was grown at optimized conditions with the following order: a 1.4 μm n-doped AlGaAs cladding layer, followed by a 140 nm undoped AlGaAs, a five-layer InAs/InGaAs/GaAs dots-in-well (DWELL) active region [10], another 140 nm undoped AlGaAs layer, a 1.4 μm p-doped AlGaAs cladding layer, and finally a 300 nm highly doped GaAs as the contact layer. A high resolution bright-field scanning transmission electron microscope (TEM) measurement was performed to characterize the QD active region [12]. An active region without noticeable defects can be observed in the TEM measurement, indicating the TDs generated at the III-V/Si surface have been annihilated efficiently due to the strategies employed during the pre-structure. A typical atomic force microscopy (AFM) was also used to characterize the uncapped InAs/GaAs QDs grown on the III-V epilayers. A dot density of ~3.0×10^{10} cm^{-2} with good uniformity could be derived from AFM, which resulted in a strong room temperature photoluminescence (PL) emission at ~1300 nm with a narrow linewidth of ~29 meV has been achieved [12].

Broad-area lasers were fabricated following the standard lithography, wet etching and metallization techniques as described in [12]. The light-current (LI) characteristics of a typical InAs/GaAs QD laser under continuous-wave (c.w.) operation at room temperature was shown in figure 2(a). An extremely low threshold current density of 62.5 A/cm^2 and a high output power of over 52.5 mW has been achieved. The c.w. lasing spectrum was measured with an injection current density of 225 A was shown in figure 3(b). Moreover, the c.w. lasing in the ground state was maintained until 75 °C. As for the pulse mode, the silicon-based laser lased up to 120 °C [12].

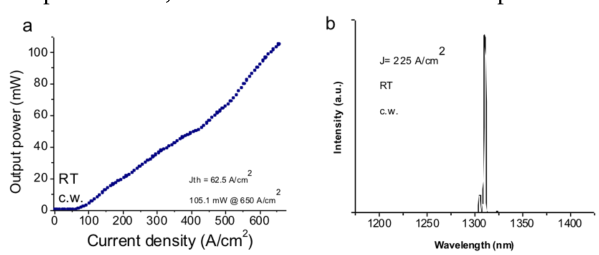

Figure.2. (a) LIV characteristics for an InAs/GaAs QD laser under c.w. operation at room temperature (b) The emission spectrum of QD laser under c.w. mode with a 225 A/cm^2 injection current at room temperature

III. QD laser on on-axis Si Substrate

Si (100) substrate with a 4° miscut-angle, mentioned in the previous works, has been introduced to suppress the formation of APBs when growing polar materials on unipolar materials [10-12]. The offcut Si substrate makes it possible to grow a high quality III-V epilayer directly on the cost of the full compatibility with standard microelectronics fabrication. In this part, a first electrically pumped c.w. InAs/GaAs QD laser directly grown on, CMOS compatible, on-axis Si (100) substrate has been demonstrated, through the cooperation of the Metal-Organic Chemical Vapor Deposition (MOCVD) and Molecular Beam Epitaxy (MBE) machines.

The whole QD laser structure could be divided into two parts as shown in figure 3(a). The first part comprised a thin GaAs nucleation layer and a GaAs buffer layer. Both the nucleation layer and buffer layer were grown by MOCVD [13]. The second part was the InAs/GaAs QD laser grown by MBE at the following sequence under the optimized condition: a GaAs buffer layer with the thickness of 600 nm, 4 sets of InGaAs/GaAs SLSs DFLs, five layers of DWELL structure sandwiched by a 50 nm GaAs spacing layer, surrounded by 30 nm undoped AlGaAs guiding layer with the upper and lower 1.4 μm p-doped and n-doped AlGaAs cladding layer, finally a 300 nm p-doped GaAs contacting layer [14]. The GaAs buffer layer directly grown on the on-axis Si substrate by MOCVD and the InAs/GaAs QDs grown by MBE were characterized through AFM measurements as shown in figure 3(b) and (c). A small root-mean-square (RMS) roughness for the 400nm GaAs directly grown on Si (100) of 0.86 nm was calculated through a typical 5×5 μm^2 AFM image. Additionally, an APB-free GaAs film layer has been achieved by the MOCVD [12]. The AFM image of InAs/GaAs QD indicates a good dot uniformity has been achieved with a typical dot density of 3×10^{10} cm^{-2}. The room-temperature PL spectrum of the InAs/GaAs QD is shown in figure 3(d), where the wavelength emission at ~1285 with a narrow linewidth of 32 meV.

A LI characteristic measurement of a typical InAs/GaAs QD laser grown on exact Si (100) substrate under c.w. operation at room temperature is shown in figure 3(e). A current threshold density of 425 A/cm^2 and a single facet output of 43 mW were observed with an injection current density of 1.3 kA/cm^2. The c.w. lasing spectrum was measured with an injection current density of 533 A/cm^2 as the figure 3(f) shown, where the lasing peak located at 1288 nm.

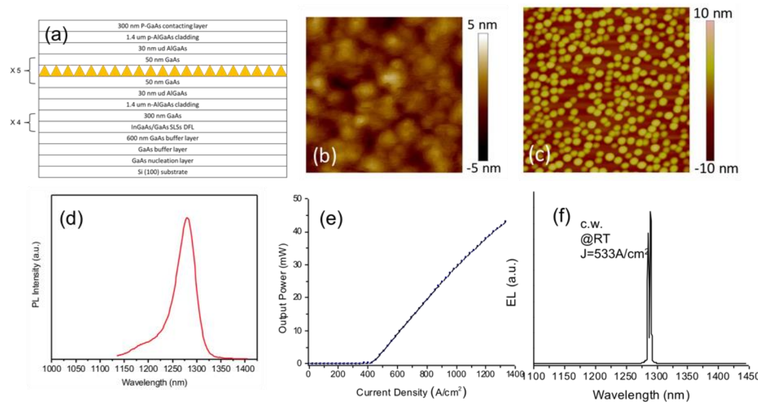

Figure.3. (a) Scheme of the layer structure grown on Si (100) substrate. (b) A typical 5 × 5 μm^2 AFM image of 400 nm GaAs. (c) 1 × 1 μm^2 AFM image of InAs/GaAs quantum dots grown on (001) Si substrate. (d) PL of InAs/GaAs QD on exact Si substrate. (e) LIV characteristic for InAs/GaAs QD laser on exact Si substrate (f) Emission spectrum of QD laser with an injection current density of 533 A/cm^2.

IV Conclusion

We have reviewed our recent progresses in III-V quantum dot laser directly grown on Si substrates including the offcut Si substrate and on-axis Si substrate.

V References

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