Silicon-based III-V Quantum Dot Materials and Dsevices

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Abstract: III-V Quantum-dot (QD) materials and lasers directly grown on Si platform are the most prospective candidate to realize on-chip optical sources for Si photonics. The recent progress made in this field are discussed.

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

1. Introduction

To meet the requirement of increased data throughput between silicon processors in modern information processing Si photonics has been under intensive investigation in recent years. As Group-IV materials have the indirect bandgap, the abundant non-radiative recombinations make Group-IV materials to be inefficient for the optical light sources. On the other hand, III-V compounds have direct bandgap, and hence have been utilized with a wide range of high-performance emitters, such as laser diodes. The integration of III–V laser diodes on Si platform will, thus be the most practical way of obtaining on-chip light sources on Si platform. In addition, in comparison with the well-established wafer bonding integration technologies, monolithic growth of III-V epitaxy materials on Si platform is more promising for low-cost and high dense integration in the long term. Self-assemble III-V quantum dots (QDs) with three-dimensional carrier confinement have been intensively promoted in order to achieve high-performance III-V laser devices, in term of better defects tolerance, lower threshold current density and temperature-insensitive operation [1,2]. Very recently, the pioneering work of monolithic integration of III-V QD lasers on Si substrates have been demonstrated [1-8]. In this paper, we will present the growth of III-V quantum dot materials and devices on Ge, Ge-on-Si, and Si substrates for silicon photonics [1-8].

2. III-V QD lasers grown on Ge, and Ge-on-Si substrates

An alternative to direct growth of GaAs on Si substrate is to use an intermediate epitaxial layer which creates near-GaAs lattice constant but has few defects. Because Ge is very closely lattice-matched (only 0.08% mismatch) to GaAs, Ge-coated Si (Ge/Si) layers were widely employed as a "virtual substrate" for subsequent GaAs growth. Therefore, the growth of III-V QDs on Ge was first exploited. Ge and Ge-on-Si substrates (100)-orientated with 6^o offcut towards the [111] planes were used in our experiments. The thickness of the Ge wafer was 350 mm. The substrate temperature was then increased to 650 ^{o}C and held at that temperature for 20 min. The Ge substrate was then cooled to 380 ^{o}C for the growth of III–V epitaxial layers. The Ga prelayer was used for the initial nucleation of GaAs buffer layer. To ensure total Ga coverage on the Ge substrate, 1.08-monolayer Ga was first deposited. After deposition of Ga prelayers, 20 monolayers of GaAs were grown by migration-enhanced epitaxy using alternating Ga and As_4 beams, followed by the addition of the III–V buffer layer at higher temperature. QD laser devices containing five InAs/InGaAs dot-in-well (DWELL) layers were then grown at optimized conditions as on GaAs substrates, with each layer consisting of 3.0 monolayers of InAs grown on 2 nm of $In_{0.15}Ga_{0.85}As$ and capped by 6 nm of $In_{0.15}Ga_{0.85}As$. The InAs/GaAs quantum-dot lasers grown on Ge substrate shave been demonstrated with lasing at 1305 nm at room temperature and lasing operation between 20 and 60 ^{o}C [1]. To form the Ge-on-Si virtual substrate, 2-μm Ge layer was grown using chemical vapour deposition on phosphorus-doped (100)-oriented Si substrates with a 6^o offcut toward [111] planes. The threading dislocation density in Ge epitaxial layer is about $5 \times 10^6/cm^2$. The optimized InAs/GaAs DWELL laser structures were fabricated on Ge/Si. The cw lasing was demonstrated for the devices on Ge-on-Si substrates [7].

3. III-V QD lasers directly grown on Si substrates

InAs/GaAs QD laser structures were directly grown on phosphorus-doped Si substrates by a solid-source molecular beam epitaxy (MBE) system. The (001)-silicon wafer with 4° miscut-angle oriented towards the [011] plane was used to suppress antiphase domains (APDs). The combined strategies of an AlAs nucleation layer, InGaAs/GaAs dislocation filter layers (DFLs), *in situ* thermal annealing and using QDs as active regions are applied to realize the high quality GaAs-on-Si laser structure with low defects [2]. Figure 1 (a) shows light-current-voltage (LIV) measurement of this high performance QD laser on Si with a low threshold current density of 62.5 A/cm^2 and a room-temperature output power exceeding 105 mW under c.w. operation. The maximum lasing operation is up to 120 °C under pulsed condition. Figure. 1(b) shows the ageing data for this InAs/GaAs QD laser on silicon. The device was aged in auto current control mode at 26 °C under 210 mA of constant applied current. A sub-linear mode model is employed to fit the aging and an extrapolated lifetime of over 100,158 h was determined [2].

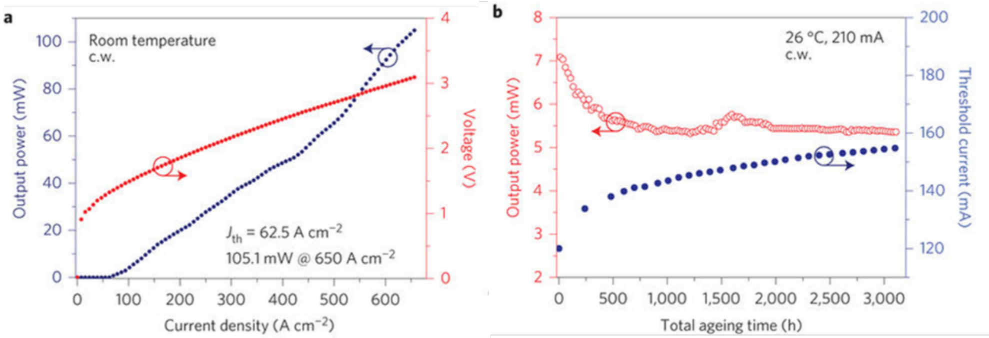

Fig. 1 (a). LIV curve of InAs/GaAs QD lasers on off-cut Si substrate under c.w. operation at room temperature; (b) Aging test of Si-based QD laser at a constant heatsink temperature of 26°C and 210 mA driving current.

4. Conclusion

In conclusion, we have demonstrated the practical InAs/GaAs QDs lasers on Ge, Ge-on-Si, and Si substrates with high power and long lifetime at 1300 nm. These results could ultimately form the basis for the monolithic integration of 1300-nm InAs/GaAs QD lasers on Si platform, as well as for the integration of other III-V devices on Si substrates in order to realize the long-dreamed of III-V/Si optoelectronic integrated circuit.

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