III-V Quantum Dot Lasers Epitaxially Grown on Si

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***Abstract*—We review our recent developments, through several approaches, in the direct epitaxial growth of III-V quantum dot lasers on silicon substrates.**

Keywords—semiconductor lasers; silicon photonics; monolithic integration

I. Introduction

Monolithic integration of semiconductor lasers on silicon platform is the ultimate solution for creating complex optoelectronic circuits, which is the key to chip-to-chip and system-to-system communications. The direct epitaxial integration of III–V semiconductor materials on Si or Ge is one of the most promising approaches for the fabrication of electrically pumped light sources on a Si platform, promising low-cost, high-yield and large-scale deployment of silicon photonics [1, 2]. However, monolithic integration technique faces significant challenges because of the large material dissimilarity between III–V and Group IV materials, such as lattice mismatch, thermal expansion coefficient differences, and polar versus nonpolar surfaces [2, 3]. These differences tend to produce various types of defects, such as, antiphase boundaries (APBs), threading dislocations (TDs), and microcracks, which all generate nonradiative recombination centers and dramatically undermine the promise of III–V materials. Recently, quantum dots (QDs) structure is becoming widely used in active layer in semiconductor lasers due to their advantages of low threshold current density and temperature insensitive operation [4, 5]. Also, QD structures have attracted increasing attention for the monolithic III-V/Si integration due to their enhanced tolerance to defects and special capability of filtering the APBs and threading dislocations [6, 7]. In this paper, we review our recent progress made in the direct growth of III-V QD lasers on Si substrates.

II. Quantum Dot Lasers Monolithically Grown on Group IV Substrates

A. QD lasers on Ge and Ge-on-Si substrates

As techniques for fabricating low-defect Ge buffer layers on silicon substrates have been systematically developed and high-quality Ge/Si wafers are commercially available, direct epitaxial growth of III-V materials on Ge substrates is an essential step towards the monolithic integration of III-V lasers on a Ge/Si substrates. Here, firstly, we describe the first QD laser realised on Ge substrates [8]. To fabricated the laser, a single-domain GaAs buffer layer was first grown on the Ge substrate using the Ga prelayer technique [8]. A long-wavelength InAs/GaAs QD structure was then fabricated on the high-quality GaAs buffer layer. Lasing at a wavelength of 1,305 nm with a low threshold current density of 55.2 A/cm^2 observed under continuous-wave (c.w.) current operation at room temperature [8]. Based on techniques developed for growing III-V QD laser on Ge, we then report the first room-temperature c.w. operation of III-V QD laser diodes monolithically grown on a Ge-on-Si substrate. Room-temperature lasing at a wavelength of 1.28 μm has been achieved with threshold current densities of 163 A/cm^2 and 64.3 A/cm^2 under continuous-wave and pulsed conditions for ridge-waveguide lasers with as cleaved facets, respectively. This Ge-on-Si technique was then taken up by A. Liu, *et al.,* at UCSB, who have now published high temperature c.w. lasing operation as well as preliminary yield and reliability data [9, 10].

B. QD Lasers on Si Substrates with Offcut

Although the Ge-on-Si approach delivers excellent laser performance, for direct integration with silicon, such an intermediate Ge layer restricts the range of silicon circuits to which it can be applied and limits the efficient light coupling from the Ge layer to silicon waveguide due to the large optical absorption coefficient of Ge at telecommunications wavelengths. To bypass the need for the absorptive Ge intermediate buffer layer, in our previous work, we realized the first electrically pumped 1.3-μm InAs/GaAs QD lasers grown on silicon substrates by optimizing the initial growth temperature of GaAs nucleation layer (NL) and inserting InGaAs/GaAs strained layer superlattices (SLSs) that serves as dislocation filter layers (DFLs) [11]. Following this work, the performance of Si-based QD lasers has been consistently improved due to the efficient reduction in the defect density [12-14]. However, a high-performance long-lifetime electrically pumped c.w. III-V QD laser monolithically grown on silicon substrates has not yet been demonstrated. In this paper, due to the realization of high-quality GaAs films on silicon by applying the combined strategies of an offcut silicon substrate [11-14], an AlAs nucleation layer [15], InGaAs/GaAs DFLs [16, 17], *in situ* thermal annealing [18], we demonstrate experimentally high-performance 1310 nm InAs/GaAs QD lasers directly grown on silicon, with a record low threshold current density of 62.5 A/cm^2 at room temperature, high power of over 100 mW and high-temperature c.w. operation up to 75 ^{o}C. Significantly, a large number of operating hours with negligible power degradation has been demonstrated for III–V lasers directly grown on silicon substrates [15].

C. QD Lasers on on-axis Si (001) Substrates

In our previous work mentioned above, Si (001) wafers with an offcut of 4° to the [011] plane have been used to prevent the formation of APBs while growing polar III-V materials on non-polar group-IV substrates [11-18]. Although the offcut could be successfully used for annihilation of APBs, it compromises full compatibility with standard microelectronics fabrication, where on-axis Si (001) substrates are typically used [19-20]. To this end, in the final part of this paper. We report on the first electrically pumped c.w. InAs/GaAs QD lasers monolithically grown on on-axis Si (001) substrates without any intermediate buffer layers [21]. A 400 nm APB free epitaxial GaAs film with a small root-mean-square (RMS) surface roughness of 0.86 nm was first deposited on a 300 mm standard industry-compatible on-axis Si (001) substrate by metal-organic chemical vapor deposition (MOCVD). The QD laser structure was then grown on this APB-free GaAs/Si (001) virtual substrate by molecular beam epitaxy (MBE). Room-temperature c.w. lasing at ~1.3 µm has been achieved with a threshold current density of 425 A/cm^2 and single facet output power of 43 mW. Under pulsed operation, lasing operation up to 102 °C has been realized, with a threshold current density of 250 A/cm^2 and single facet output power exceeding 130 mW at room temperature.

III. CONCLUSION

We have reviewed our recent progress in III-V lasers monolithically grown on Ge substrates, Ge-on-Si substrates, silicon substrates with offcut and standard industry-compatible on-axis Si (001) substrates.

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