Low threshold InAs/InP quantum dot lasers on Si

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***Abstract*—We have developed low threshold InP-based L-band quantum (QD) lasers monolithically grown on Si substrates for photonic integration. To overcome the fundamental challenges of growing high-density, high uniformity QDs on InP-based material system, QD thickness in combination with a modified indium flush technique was adopted, resulting in a low threshold current density of 1.35 kA/cm^2 and pulsed lasing up to 100 °C. These results represent progress in C-/L-band QD laser development on Si, highlighting the potential for high-performance semiconductor light source for long-haul telecommunication applications.**

Keywords*—*L-band, quantum dots, photonic integration, MBE, telecommunication.

I. INTRODUCTION

Si-based C- and L-band InAs/InP QD lasers have emerged as promising candidates for high-speed, long-haul optical communication and eye-safe optical sensing, especially with the increasing data demand driven by AI advancements [1-3]. These lasers are promising light sources thanks to their discrete density of states and defect tolerance, offering advantages over conventional quantum well lasers, including low threshold current density (J_{th}), temperature stability, optical feedback tolerance, and ultrafast gain recovery [4]. However, despite their potential, the development of InAs/InP QD lasers has lagged behind their O-band InAs/GaAs counterparts, primarily due to challenges associated with material properties and growth dynamics.

The relatively low lattice mismatch of ~3.2% in the InAs/InP system, compared to ~7.2% in InAs/GaAs, results in weaker strain energy during Stranski-Krastanov growth, leading to a broader size distribution of QDs. This non-uniformity necessitates stringent growth optimisation to achieve high-quality, uniform QDs, which are essential for sufficient optical gain and low threshold current density (Jth) [5]. Additionally, InAs/InP QDs often exhibit insufficient gain, high J_{th}, and limited high-temperature performance, further hindering their practical deployment. Another challenge is the formation of elongated nanostructures, or quantum dashes, along the [1$\bar{1}$0] direction due to the surface diffusion anisotropy of indium adatoms on (001) InP substrates.

To address these limitations, in this work we present the QD growth optimisation in molecular beam epitaxy (MBE) via a combination of the QD deposition thickness and a modified indium flush technique, where an $In_{0.359}Al_{0.323}Ga_{0.318}As$ stressor was inserted above the QDs, controlling the strain accumulation as well as the dot morphology. Different strategies of adopting stressor layers were compared. Seven-layer QD lasers on Si fabricated using optimised growth conditions demonstrated improved performance.

II. EPITAXIAL GROWTH AND FABRICATION

First, single-layer InAs/InP QD structures were grown on n-type (001) InP substrates using a Veeco GEN 930 MBE system equipped with valved arsenic and phosphorus cracker sources to compare the effects of deposition thickness of QD and stressor layer. For each QD layer, 6.5 or 6.8 monolayer (ML) of InAs was directly grown on $In_{0.528}Al_{0.238}Ga_{0.234}As$ at 485 °C with a growth rate of 0.42 ML/s and an As_2/III ratio of 18, followed by a 10 second growth interruption under As_2 pressure to stabilise QD formation and reduce island size dispersion. Then, a modified indium-flush technique was applied, where 0 ~ 2.2 nm $In_{0.359}Al_{0.323}Ga_{0.318}As$ stressor layer was deposited upon the dots, following $In_{0.528}Al_{0.238}Ga_{0.234}As$ deposition and a temperature elevation to 515 °C under As_2 overpressure. This modified indium-flush technique ensures the high-quality stacking of the QDs by manipulating the morphology of and the strain around the QDs. Then, QD laser structures on Si were grown on Si based on the optimised QD growth conditions. The schematic epitaxial structure of the seven-layer QD laser is shown in Fig. 1(a). The low defect density InP/Si template was first grown by metal-organic chemical vapor deposition (MOCVD) using the dislocation filter layers described in an earlier work [6]. Then, seven-layer QD stack separated by 33 nm $In_{0.528}Al_{0.238}Ga_{0.234}As$ and sandwiched by 200 nm n- and p-type $In_{0.528}Al_{0.238}Ga_{0.234}As$ and 300 nm n- and p-type $In_{0.524}Al_{0.476}As$ was grown in MBE, and followed by MOCVD growth of the top p-type InP cladding layer and InGaAs contact layer. The seven-stack InAs/InP QD Fabry-Pérot lasers were fabricated with ridge widths of 5 μm and 50 μm. The ridge waveguides were defined using conventional photolithography, followed by wet chemical etching and passivated with a 400 nm SiO_2 layer.

III. RESULTS

The optical As shown in atomic force microscope (AFM) images Fig.1 (c) and (d), an increase in deposition thickness results in uniform dot shape and a high QD density of over 520/μm^2. However, even at the QD thickness of 6.5 ML, the emission wavelength is out of the range of L-band. Through the manipulation of the $In_{0.359}Al_{0.323}Ga_{0.318}As$ stressor layer in combination of the QD deposition thickness, the emission wavelength can be effectively shifted to L-band without degrading the PL intensity. This modified indium-flush technique will also contribute to the alleviation of strain build up in multi-layer QD structure growth.

The fabricated lasers were characterised under pulsed injection (1 % duty cycle, 1 μs pulse width) to minimise self-heating effects. Fig. 2(a) shows the temperature-dependent light-current (*L*-*I*) curves for InAs/InP/Si QD lasers with 2000 μm × 5 μm cavity, which can lase up to 100 °C. Fig. 2(b) presents the L-I curves for 50 μm cavity width with varied cavity lengths from 500 μm to 2000 μm. The 2000 μm device exhibited the lowest J_{th} of 1.35 kA/cm^2, corresponding to a J_{th} per QD layer of 197 A/cm^2.

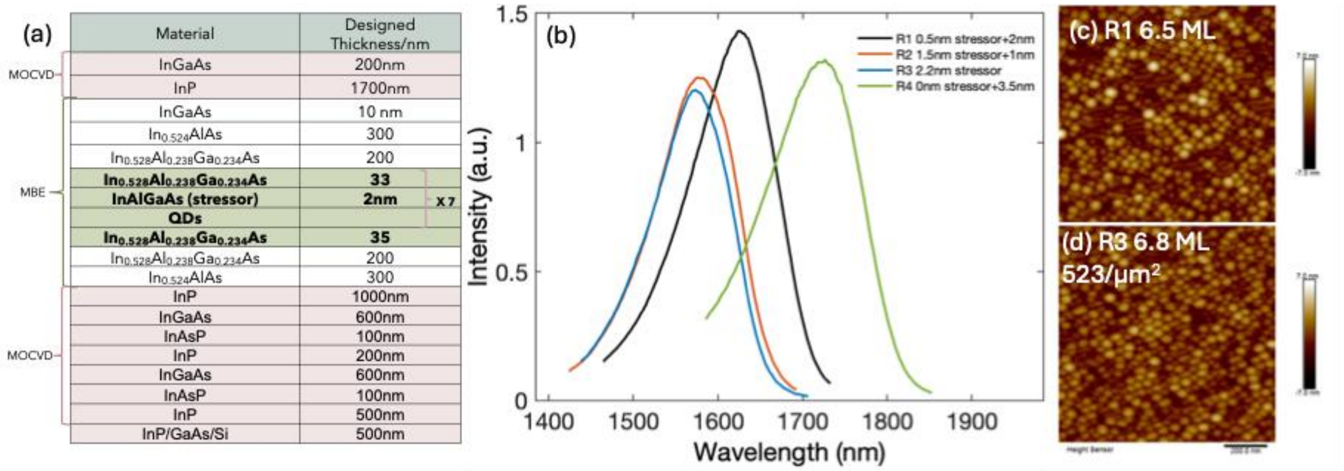

Fig. 1. (a) Schematic epitaxial structure of the InAs/InP QD laser on Si. (b) PL spectra of InAs/InP QDs with different capping layers. (c) and (d) AFM images of 6.5 ML and 6.8 ML InAs deposition, respectively, with the latter showing a high dot density of 523/μm^2.

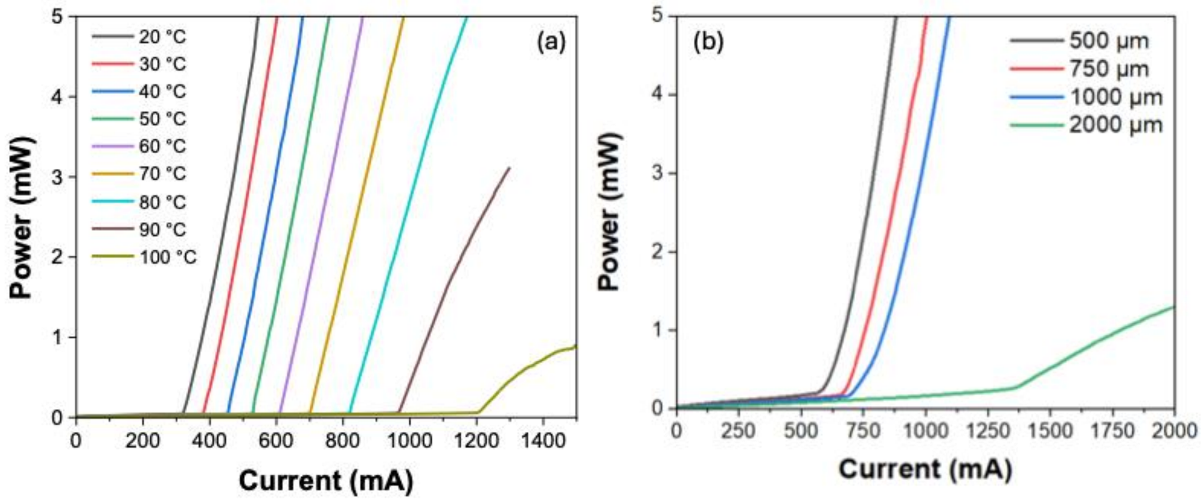

Fig. 2. (a) Temperature-dependent current versus power L-I curves under pulsed injection for 2000 μm × 5 μm cavity InAs/InP QD lasers on Si. (b) Current versus power L-I curves under pulsed injection for 50 μm cavity width InAs/InP QD lasers on Si with varied cavity lengths from 500 μm to 2000 μm.

In conclusion we presented high-performance InAs/InP QD lasers on Si emitting at L-band with improved QD density and high uniformity. Theses QD lasers on Si show promise as optical sources in silicon-photonic integrated platforms. Acknowledgement

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