High performance and reliable 1.3 μm InAs quantum dot lasers epitaxially grown on Si

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Abstract: 1.3 μm InAs quantum dot lasers on Si show a CW threshold current of 4.8 mA and extrapolated lifetimes of ten million hours at 35 °C and ~65,000 hours at 60 °C.

I. INTRODUCTION

Silicon photonics has shown tremendous advances over the past decades for various important applications such as telecom, data centers, sensors and on-chip optical interconnects [1]. While high performance passive components have been demonstrated, monolithic integration of efficient, scalable and reliable light sources on Si is still challenging. Recently, epitaxially grown III/V quantum dots (QD) have shown promise as a potential light source on Si [2]. Compared to conventional quantum well lasers grown on Si, QD lasers have several advantages due to their efficient carrier captures into individual QDs, which reduces non-radiative recombination rates. Extensive research on QD lasers has been conducted using intentional (4-6 °) offcut Si substrates and have made significant advances in performance (continuous-wave threshold current of ~16 mA) as well as device lifetimes (~100,000 hours) [2, 3]. However, in order to fully benefit from the established Si CMOS foundries, high performance QD lasers have to be demonstrated on-axis (001) Si with excellent device reliability. Here, we present 1.3 μm QD Fabry-Perot lasers grown on CMOS-compatible on-axis (001) Si with a record-low CW threshold current of 4.8 mA, a maximum CW operation temperature of 85 °C, and lifetimes of more than ten million hours at 35°C, which were enabled by reduced threading dislocation density (7×10^6 cm^{-2}) in the lasers. We also show for the first time high temperature (60 °C) aging results on unintentionally doped (UID) and p-modulation doped (pMD) QD lasers on Si.

II. TECHNICAL WORK PREPARATION

QD lasers were grown on on-axis (001) Si substrates by molecular beam epitaxy [4]. The Si substrates have a 45 nm-thick pseudomorphic GaP layer to avoid formation of antiphase domains that can arise from the polar/non-polar III/V-Si interface. The InAs QDs used here has a density of ~5×10^{10} cm^{-2} as shown in Figure 1(a) and is embedded in InGaAs quantum wells. The epitaxial laser structure is illustrated in Figure 1(a). The high lattice mismatch between GaAs and Si was tackled by growing high quality GaAs buffer layer [5]. Five QD layers separated by 37.5 nm either UID or p-MD GaAs barriers were grown in a GaAs/AlGaAs graded-index separate confinement heterostructure [6]. Then, the epi materials were processed to deep-etched narrow ridge-waveguide lasers. Fabry-Perot cavities were formed by facet cleaving as shown in Figure 1(b).

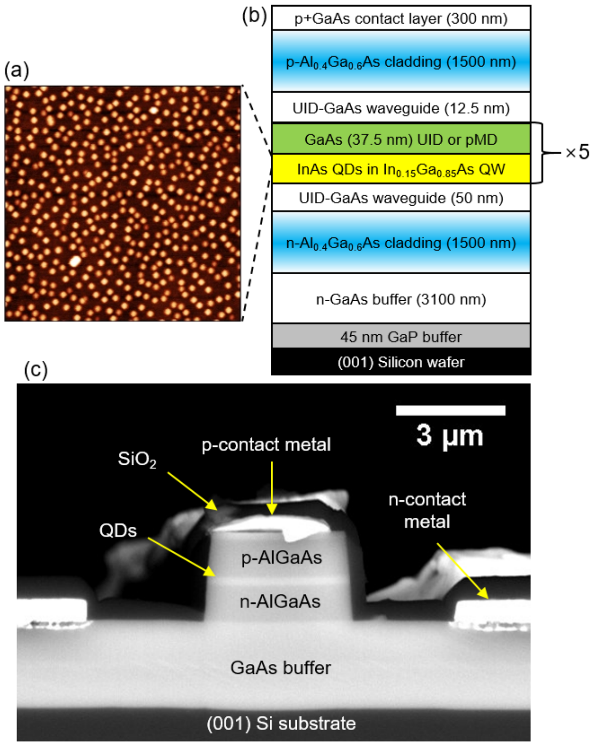

Figure 1 (a) Atomic force microscopy image of uncapped QDs. (b) Schematic of QD laser grown on Si. (c) Cross-sectional scanning transmission electron microscopy image of QD laser monolithically integrated on Si.

Figure 2(a) shows a CW threshold current of 4.8 mA at 20 °C from a 2.5×1174 μm^2 laser with high reflectivity (99%/60%) films applied on both facets. Its corresponding current density is 163 A/cm^2. The peak wall-plug-efficiency of the laser is 16% at 37 mA. The UID lasers lased CW up to 85 °C and the characteristic temperature (T_0) was 31 K. To improve the thermal

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performance, we have also fabricated pMD QD lasers by partially doping the GaAs barriers ($p=5\times10^{17}$ cm^{-2}). While the threshold current densities of the pMD lasers are higher than UID ones up to 40 °C due to increased free carrier absorption, they reveal improved T_0 (~85K) in the range of 20-80 °C and lower threshold current densities above 40 °C as shown in Figure 2(b). Note that the pMD lasers lased CW up to 107 °C.

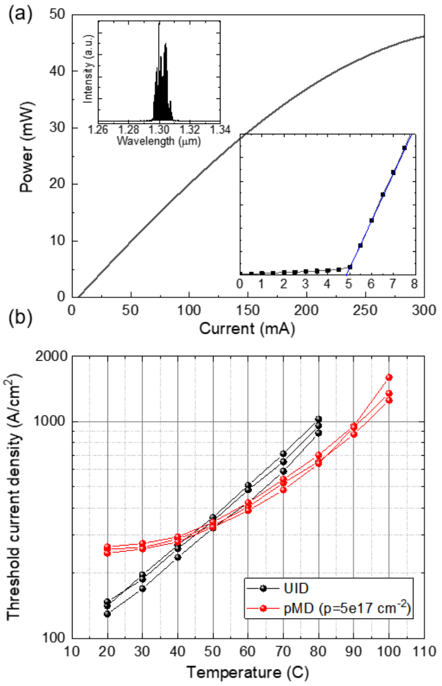

Figure 2(a) CW light-current curve at 20 °C. Right inset shows a zoom-in graph and left inset shows spectra with multi longitudinal modes. (b) Threshold current density vs. temperature of UID and pMD QD lasers.

Laser reliability test was performed at Intel Corp. by wirebonding QD lasers on AlN carriers after applying HR films on a facet. Lasers were aged at 2× their initial threshold current at aging temperatures of 35 or 60 °C under CW current injection. Light-voltage-current measurements were periodically performed at 35 °C to monitor the laser degradation rates. Figure 3(a) shows four different UID lasers that were aged at 35 °C. Note that no further threshold current increase was observed after the initial ~200-hr aging. Using a non-linear fitting [3], we have attempted to extrapolate the laser lifetimes, which are more than 10 million hours (~100 years).

We have also tested the QD lasers at 60 °C to investigate its viability for practical applications such as data centers, on-chip sensors. Figure 3(b) shows increases in the bias current to produce 10 mW output power from two UID and two pMD lasers. We find that pMD lasers (red circles) show superior reliability than the UID lasers even though they were all aged at the identical aging condition (60 °C, 2× thresholds). The extrapolated times to double the bias current for 10 mW power for UID lasers are ~2,500 hours while those for pMD lasers are ~65,000 hours. We speculate that faster carrier captures to QDs in pMD lasers reduce non-radiative recombination enhanced dislocation climbs in GaAs barriers than UID lasers, which results in superior reliability at elevated temperature operation.

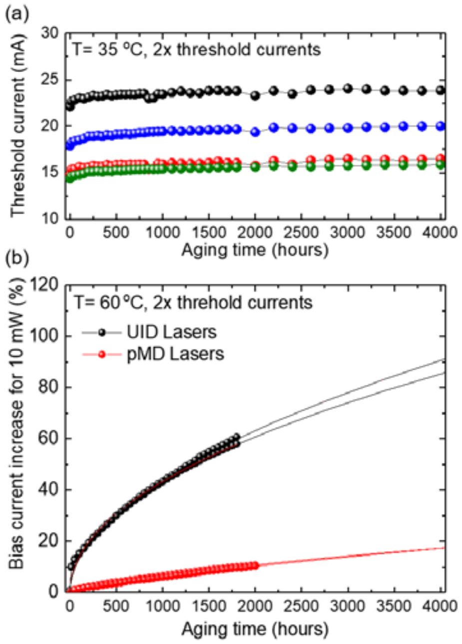

Figure 3(a) Threshold current vs. aging time at 35 °C for UID QD lasers on Si. (b) Bias current increase for 10 mW output power vs. aging time. Solid lines are non-linear fittings. Aging temperature was 60 °C. LIVs were taken at 35 °C after cooling from 60 °C.

III. CONCLUSIONS

Here, we demonstrated low threshold current and highly reliable quantum dot lasers epitaxially grown on CMOS-compatible Si substrates. The results are promising for efficient, scalable, and reliable lasers monolithically integrated on Si-based photonic integrated circuits.

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