Low Threshold Epitaxial InAs Quantum Dot Lasers on On-Axis GaP/Si (001)

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***Abstract* — We report 1300 nm continuous wave lasing on an on-axis GaP/Si (001) virtual substrate operating up to 60°C with record low threshold current of 27 mA. Ridge and broad area lasers were fabricated with seven layers of p-modulation doped quantum dots and as-cleaved facets.**

High performance III-V lasers epitaxially integrated on a silicon substrate are needed to meet the techno-economic demands of future chip-scale optical interconnects[1]. The principle challenge of epitaxial integration is overcoming the inherent mismatch (lattice, thermal expansion, and polarity) between III-V materials and Si that leads to high densities of defects including threading dislocations, stacking faults, and antiphase domains[2]. Past results have shown the promise of InAs quantum dots as a defect tolerant gain medium that could offer a path toward high performance, high reliability lasers on silicon[2-4]; however, until recently[5-7], these results were limited to miscut silicon substrates which are incompatible with the CMOS manufacturing infrastructure that is the key enabler of economical chip-scale integration. Here we report record low thresholds, high output powers, and high temperature operation for a III-V laser on on-axis (001) silicon.

The epitaxial laser structure was grown on a commercially available GaP/Si (001) template purchased from $NAsP_{III/V}$ GmbH. The as-received template consisted of a 775 µm thick (001) on-axis p-doped Si substrate, with 200 nm thick n-doped Si homo-epitaxial buffer and a subsequent 45 nm thick n-doped GaP layer, all grown by metalorganic chemical vapor deposition (MOCVD). On this template a GaAs buffer and graded-index separate-confinement heterostructure were grown by molecular beam epitaxy. The layer stack is shown in Fig. 1(a). The active region consisted of seven layers of p-modulation doped InAs quantum dots in $In_{.15}Ga_{.85}As$ quantum wells. Identical epitaxial structures were grown on GaAs substrates for a direct comparison of laser performance.

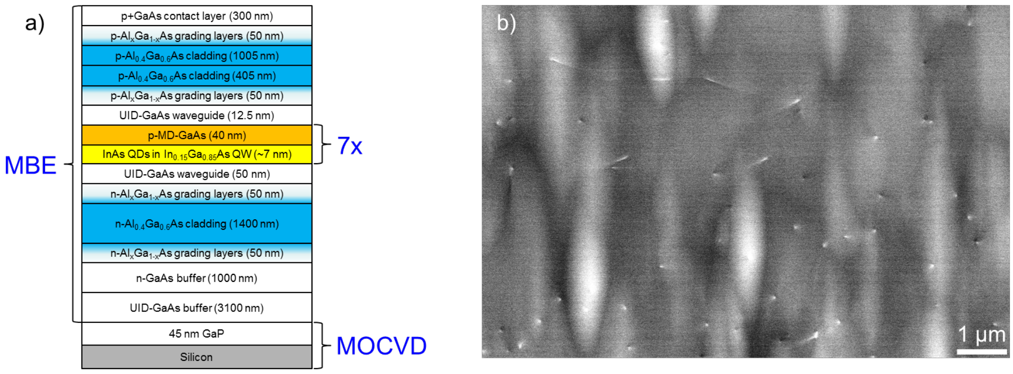

Figure 1. (a) Schematic of the laser structure. (b) Electron channeling contrast image of the uid-GaAs buffer surface. Pinpoints indicate threading dislocations.

Electron channeling contrast imaging (ECCI) was used to image the dislocation density of the material stack after the MBE buffer but before laser growth (Fig. 1(b)) revealing a dislocation density of $\sim 7 \times 10^7$ cm^{-2}. Photoluminescence measurements taken on the as-grown laser epi on Si and GaAs are shown in Fig. 2(a) revealing a relative intensity of 93% for the laser on Si relative to GaAs and nearly identical peak wavelength (1286 nm) and full-width at half-maximum (34 meV) of the ground state emission peak.

The material was processed into deeply etched lasers with varying stripe widths using standard dry etching and metallization techniques. The lasers utilized a Pd/Ti/Pd/Au p-contact on top of the etched mesa and Pd/Ge/Au n-contact metal deposited on the exposed n-GaAs layers adjacent to the ridge. Laser cavities were formed by thinning the substrate through mechanical polishing to 150 µm and then cleaving. Broad area lasers with lengths up to 3.1 mm and widths of 20 and 50 µm and ridge lasers with lengths from 400 to 1600 µm and widths from 2 to 10 µm were fabricated.

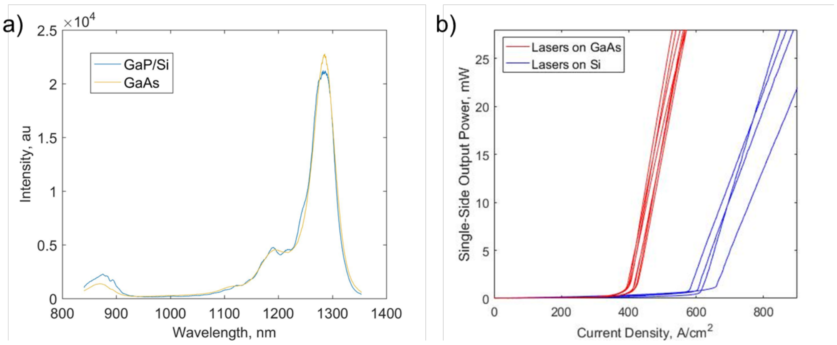

Figure 2. (a) Photoluminescence of as-grown laser material on GaAs and Si substrates. (b) Light output versus bias current density for 50x3100 µm² broad area devices on GaAs and Si showing a 1.5x increase in threshold.

As cleaved laser results are shown in Fig. 2(b) and Fig. 3(a-d). Fig. 2(b) shows a direct comparison of 3100x50 µm² broad area lasers on GaAs and Si. The lowest threshold current densities are 396 A/cm² (57 A/cm² per layer) and 577 A/cm² (82 A/cm² per layer) for lasers on GaAs and Si, respectively. Ridge lasers showed a minimum threshold of 27 mA for a 5x850 µm² device and maximum single facet output power of 88 mW for a 10x1350 µm² device. These thresholds outperform the previous record[6] set with 95%/55% high reflectivity coatings despite utilizing as-cleaved facets. The full breakdown of device results on Si is shown in Fig. 3(a-b). Ground state lasing at 1300 nm was confirmed for a 2.5x750 µm² as shown in Fig. 3(c). One 5x850 µm² device was measured at elevated temperatures (Fig. 3(d)). CW lasing is clearly visible up to 60°C from the ground state at lower currents. This is the highest reported temperature for CW operation on on-axis Si without facet coatings. The kink and second rise in the LI curves is due to excited state lasing. All data shown is of as-cleaved devices with no facet coatings.

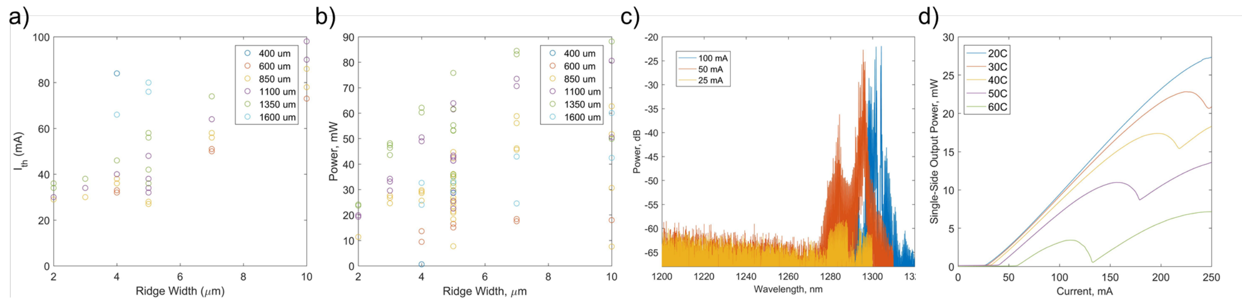

Figure 3. Scatterplots of (a) threshold current and (b) single facet output power for laser ridges of varying width and length grown on Si. (c) Lasing spectra of a 2.5x2.5x750 µm² ridge above threshold. (d) Power output versus bias current at elevated temperature for a 5x850 µm² device.

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