Sub-mA threshold 1.3 μm CW lasing from electrically pumped micro-rings grown on (001) Si

Yating Wan[1,2], Justin Norman[3], Qiang Li[2], M. J. Kennedy[1], Di Liang[4], Chong Zhang[4], Duanni Huang[1], Alan Y. Liu[3], Alfredo Torres[1], Daehwan Jung[3], Arthur C. Gossard[1,3], Evelyn L. Hu[5], Kei May Lau[2] and John E. Bowers[1,3]

1 Department of Electrical and Computer Engineering, University of California Santa Barbara, Santa Barbara, California 93106, USA
2 Department of Electronic and Computer Engineering, Hong Kong University of Science & Technology, Clear Water Bay, Hong Kong
3 Materials Department, University of California Santa Barbara, Santa Barbara, California 93106, USA
4 Hewlett Packard Labs, Hewlett Packard Enterprise, 1501 Page Mill Road, Palo Alto, California 94304, USA
5 School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA
eekmlau@ust.hk bowers@ece.ucsb.edu,

Abstract: We demonstrate the first electrically pumped quantum-dot micro-ring lasers epitaxially grown on (001) silicon. Continuous-wave lasing around 1.3 μm was achieved with ultra-low thresholds as small as 0.6 mA and maximum operation temperatures up to 100°C.

OCIS codes: (230.5590) Quantum-well, -wire and -dot devices; (140.5960) Semiconductor lasers; (140.3948) Microcavity devices; (160.3130) Integrated optics materials

1. Introduction

In the transition from traditional copper wire connections to high speed optical connections, cost is a crucial design criterion and #1 factor for large-scale commercial applications [1]. Currently, direct hetero-epitaxial growth of III–V laser structures on Si using quantum dots (QDs) as active region holds great potential for low-cost, high-yield, long-lived device operation at high temperature[2]. Competitive work is being conducted in switching from miscut Si substrates towards the so-called "exact" (001) Si substrates that are standard in microelectronics fabrication [3-5]. Using a special GaAs-on-Si template with no additional Ge buffers or substrate miscut, our group recently developed *optically pumped* micro-lasers with ultra-low thresholds and excellent temperature characteristics [6-8]. Here, we report the first *electrically pumped* InAs/InGaAs QD micro-ring lasers epitaxially grown on (001) Si. Using QDs as active medium to effectively minimize surface recombination and mitigate the influence of dislocations arising from lattice-mismatched growth, we have produced tiny lasers with ultra-low thresholds down to 0.6 mA in the 1.3 μm band. CW operation at elevated temperature up to 100°C was obtained in larger devices.

2. Experiments and results

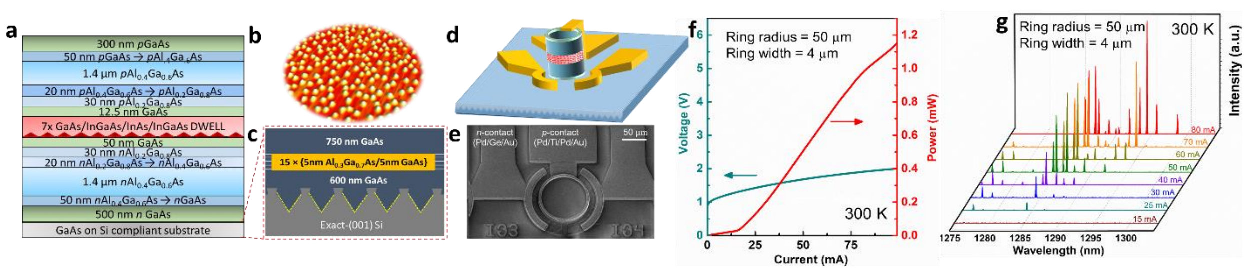

Fig. 1. (a) Schematic of the epi-layer structure; (b) AFM image of a single QD layer with a dot density of 6×10^{10} cm^{-2}; (c) schematic of the GaAs on Si compliant substrate, (d) schematic of the fabricated micro-ring laser, (e) top-view SEM image of a fabricated micro-ring. (f) Measured LIV curve and (g) emission spectra of a typical micro-ring laser with a radius of 50 μm under CW operation at room temperature.

The complete epitaxial structure is shown in Fig. 1(a). The crystalline GaAs-on-Si template contains coalesced GaAs in-plane nanowires inside Si V-grooves, with fifteen periods of $Al_{0.3}Ga_{0.7}As$/GaAs (5/5 nm) superlattice inserted in the middle as dislocation filters (Fig. 1(c)) [9]. Two GaAs/$Al_xGa_{1-x}As$ graded index separate confinement heterostructure (GRINSCH) structures were used with seven InAs/InGaAs quantum dot-in-a-well (DWELL) active layers. The density of the quantum dots is roughly 6×10^{10} cm^{-2} (Fig. 1(b)). The laser material was processed into deeply-etched ring structures with radii ranging from 5 to 50 μm and ring waveguide width ranging from 2 to 7 μm. The 4 μm dry-etched mesa allows strong lateral optical confinement and therefore preserves the excellent cavity modes to enable lasing. After sidewall passivation with 1 μm-thick PECVD SiO_2, metallization with Pd/Ti/Pd/Au and Pd/Ge/Au layer stacks were used to form the *p*- and *n*-contacts, respectively. The *n*-contact was probed from laterally displaced pads while the current was injected from the *p*-contact on top of the ring mesa, as depicted in the schematic

(Fig. 1(d)) and scanning electron microscope (SEM) image (Fig. 1(e)) of a fabricated device. A typical CW, light-current-voltage (LIV) characteristic of a micro-ring laser with a radius of 50 µm and a mesa width of 4 µm is shown in Fig. 1(f). A low lasing threshold around 15 mA was measured, corresponding to a threshold current density (J_{th}) of 1.2 kA/cm^2. Multiple longitudinal mode lasing (Fig. 1(g)) was observed with the primary lasing peak at ~1.3 µm that aligned with the material gain peak from the room temperature photoluminescence measurement. The measured free spectral range (FSR) of 1.4 nm agrees well with the theoretical calculation for the fundamental transverse mode.

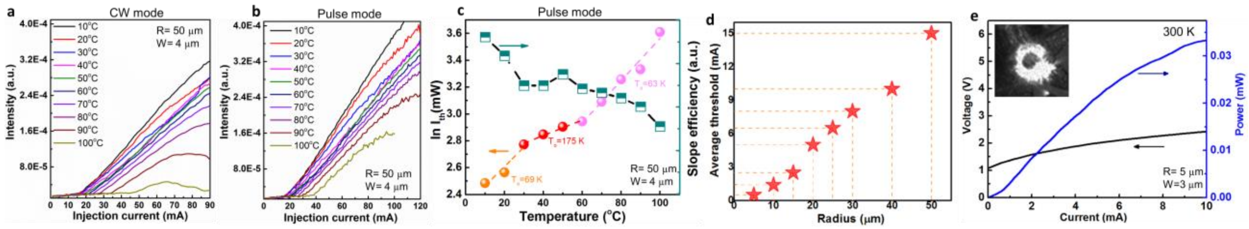

Fig. 2. Measured LI curves of a micro-ring laser with a radius of 50 µm as a function of the heatsink temperature under (a) CW operation and (b) pulsed condition; (c) temperature dependent threshold current and slope efficiency vs. heatsink temperature, the dashed lines represent the linear fit to the experimental data. (d) Average threshold as a function of outer ring radius. (e) Measured LIV curve from a micro-ring laser with a radius of 5 µm. Inset: infrared image of the laser cavity above threshold.

Fig. 2(a) and (b) show the L-I characteristics from the same micro-ring laser at various heatsink temperatures ranging from 10 to 100 °C under CW and pulsed operation mode, respectively. For pulsed measurement, we use 0.5% duty cycle and 5 µs pulse width. Fig. 2(c) shows the lasing thresholds and relative slope efficiencies as a function of operating temperature under pulsed operation. The characteristic temperature T_0 was extracted to be 69 K between 10 and 30 °C, 175 K between 30 and 50 °C, and 63 K between 60 and 100 °C. Scaling the size of the micro-rings leads to reduction of the laser thresholds. Fig. 2(d) summarizes the threshold powers obtained from a series of micro-ring lasers with different radii (5-50 µm) and ring width (3-4 µm). An ultra-low threshold of ~0.5 mA was measured for a device with a radius of 5 µm and ring width of 3 µm, as shown in the LIV curve in Fig. 2(e). The inset presents the infrared image of the laser cavity above threshold. The bright spots with interferometric fringes appeared in the ring cavity. The spatially concentrated mode profile is indicative of the dominance of the mode oscillation in the micro-ring.

3. Conclusions

In conclusion, we demonstrate high-performance electrically-pumped QD micro-ring lasers grown on exact (001) Si substrate, achieving small footprint, low power consumption, and high temperature operation. These are the smallest electrically-pumped micro-ring lasers, demonstrating lasing up to 100 °C under CW operation. In addition, these lasers have much lower thresholds than previously reported lasers which were epitaxially grown on Si.

4. References

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