Various microcavity lasers monolithically grown on planar on-axis Si (001) substrates

Zhaoyu Zhang
School of Science and Engineering
The Chinese University of Hong Kong, Shenzhen
Shenzen, China
zhangzy@cuhk.edu.cn

Yaoran Huang
School of Science and Engineering
The Chinese University of Hong Kong, Shenzhen
Shenzen, China
yaoranhuang@link.cuhk.edu.cn

Taojie Zhou
Department of Electronic and Electrical Engineering
University College London, London
London, UK
taojie.zhou@ucl.ac.uk

Mingchu Tang
Department of Electronic and Electrical Engineering
University College London, London
London, UK
mingchu.tang.11@ucl.ac.uk

Siming Chen
Department of Electronic and Electrical Engineering
University College London, London
London, UK
siming.chen@ucl.ac.uk

Huiyun Liu
Department of Electronic and Electrical Engineering
University College London, London
London, UK
huiyun.liu@ucl.ac.uk

***Abstract*— With exponential growth in data traffic and limitations of Moore's Law, electronic integrated circuits have reached a bottleneck period. Photonic Integrated Circuits (PICs) are seemed as candidate for solving the problem of data transmission. Moreover, robust laser sources are significant building block for PICs design. Here, we demonstrate several InAs/GaAs quantum dot microcavity lasers monolithically grown on planar on-axis Si (001) substrates, including microdisk cavity [1], 2D Photonic Crystal with L3 defects cavity [2], 1D Photonic Crystal nanobeam cavity, bandedge Photonic Crystal cavity, bound states in the continuum (BIC) cavity, etc.**

Keywords—microcavity lasers, PICs, quantum dot material, Si substrates

I. EXTENDED ABSTRACTS

The recent development of data transmission speed of electronic integrated circuits has been reaching a bottleneck due to electron tunnelling and huge power consumption. However, Si-based Photonic Integrated Circuits not only offer advantages such as high modulation speed, low power consumption, low thermal effects, large integration capacity, but also can be made with the same fabrication technique as CMOS-based electronic integrated circuits [3-5]. Silicon photonics technology has monolithically integrated optical components such as modulators, waveguides, beam splitters, detectors, etc. But monolithically integrated the light source of the core component, that is, semiconductor laser is still a tricky challenge, due to the conjunction of large thermal expansion coefficients, lattice, and polarity mismatches between the Si substrate and III-V layer [6-8]. Despite several techniques have been used in heterogeneous integration of microcavity lasers on Silicon or Silicon on insulator (SOI) substrates, such as wafer bonding, transfer printing, etc [9-11]. The monolithic integration is still the efficient way for a higher yield, higher density and higher scalability for III-V microcavity lasers integrated on CMOS compatible Silicon substrates. By optimizing the III-V materials buffer layer and complex epitaxial technology, great efforts have been made to achieve a low defect density and CMOS compatible III-V/Si virtual substrate [12]. In addition, using zero-dimensional III-V quantum dots (QDs) as gain material provide various advantages, including less sensitivity to defects, low lasing threshold, high performance at room temperature and long lifetime [13]. Due to the reduced non-radiative recombination rate, the realization of high-quality QDs insensitive to defects as a gain material is the best solution for high-efficiency light-emitting sources monolithically grown on Si substrates [14].

Here, we demonstrate several kinds of InAs/GaAs quantum dot microcavity lasers fabricated on CMOS-compatible on-axis Si (001) substrates, all the lasers' pumping condition is CW optically pumped using a 632.8 nm He-Ne laser with focus spot size of ~ 3 μm at room temperature.

1. **Microdisk lasers** [1]. Fig.1.(a) presents the measured lasing spectra of ultra-small microdisk lasers with diameter ~ 1.1 μm and 1.4 μm. The L-L curve and full width at half maximum (FWHM) shows in Fig.1.(b), which presents ultra-low threshold of the first excited state is 2.9 ± 0.4 μW. From Fig.1.(a), we can also find the mode selection by changing the diameter of microdisk cavity, owing to its large free spectral range (FSR) and well-separated resonant peaks.
2. **2D Photonic Crystal with L3 defects lasers** [2]. The measured spectra under various pumping powers of a single mode Photonic Crystal laser with a = 310nm and r/a = 0.27 is shown in Fig.2.(a). The collected intensity (L-L) and the FWHM of the lasing peak at ~ 1306 nm under various pumping powers are shown in Fig.2.(b), which exhibit the

evidence of the lasing with a clear kink of L-L curve and the spectral linewidth narrowing effect.

3. **1D Photonic Crystal nanobeam lasers**. The ultra-small physical volume of ~ 0.64 λ^3 (λ = 1313nm) is obtained. The nanobeam cavity measured spectra shows single mode at ~ 1313nm with pumping threshold of ~ 0.8 μW. The FWHM of nanobeam cavity is below 1 nm when it reaches threshold. Due to the paper haven't been published yet, we would not show the figure of measured spectra.
4. **Bandedge Photonic Crystal lasers**. With the designed band gap, we have three bandedge point M_1, M_2, X_1 with low group velocity. Under the pumping condition, we obtained relative high pumping threshold of ~ 4 μW, as well as large linewidth of ~4 nm. With low side mode suppression ratio (SMSR) and relative large full width at half-maximum (FWHM), we still need to optimize fabrication process.

In conclusion, all these kind of microcavity lasers show a major advance towards large-scale, low-cost integration of laser sources on the Silicon platform.

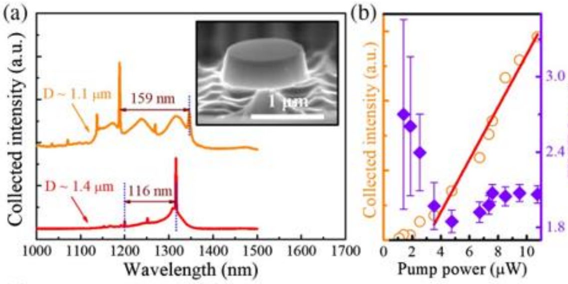

Fig.1.(a) Measured lasing spectra of the microdisk lasers with diameter ~ 1.1 μm and 1.4 μm. (b) L-L curve and FWHM of lasing peak ~ 1189 nm of the sub-wavelength scale microdisk laser with D ~ 1.1 μm.

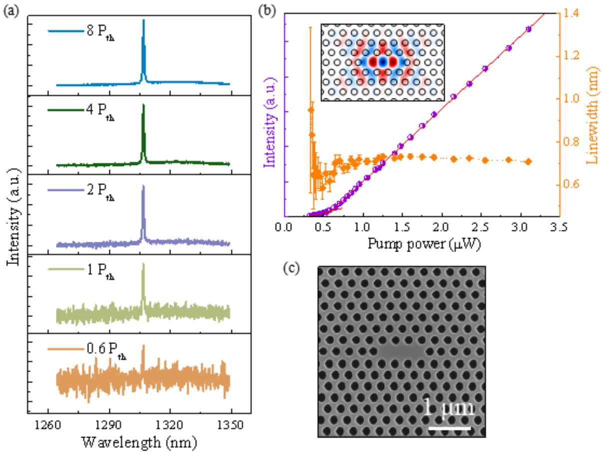

Fig.2.(a) Measured spectra under various input pumping powers of the PC laser with a = 310 nm and r/a = 0.27. (b) Collected L-L curve and line width of the lasing peak at 1306 nm. The inset shows the calculated Ey field profile of the fundamental mode. (c) Top-view SEM image of the fabricated PC cavity.

REFERENCES

[1] Taojie Zhou, Mingchu Tang, Guohong Xiang, Xuan Fang, Xiu Liu, Boyuan Xiang, Suikong Hark, Mickael Martin, Marie-Leonor Touraton, Thierry Baron, et al. "Ultra-low threshold InAs/GaAs quantum dot microdisk lasers on planar on-axis Si (001) substrates," Optica, 6(4): 430-435, 2019.

[2] Taojie Zhou, Mingchu Tang, Guohong Xiang, Boyuan Xiang, Suikong Hark, Mickael Martin, Thierry Baron, Shujie Pan, Jae-Seong Park, Zizhuo Liu, et al. "Continuous-wave quantum dot photonic crystal lasers grown on on-axis Si (001)," Nature Communications, 11(1): 1-7, 2020.

[3] Sun, C. "Single-chip microprocessor that communicates directly using light," Nature 528, 534-538, 2015.

[4] Soref, R. "The pass, present, and future of silicon photonics," IEEE J. Sel. Top. Quantum Electron. 12, 1678-1687, 2006.

[5] Komljenovic, T. et al. Photonic integrated circuits using heterogeneous integration on silicon. Proc. IEEE 106, 2246-2257, 2018.

[6] Z. Wang, K. Van Gasse, V. Moskalenko, S. Latkowski, E. Bente, B. Kuyken, G. Roelkens. "A III-V-on-Si ultra-dense comb laser," Light: Science & Applications 6, 16260, 2017.

[7] Beeck, Camiel Op De, et al. "Heterogeneous integration of III-V semiconductor amplifiers and lasers on silicon nitride via micro-transfer printing," Optica, 7, no.5, 2020.

[8] Van Campenhout, Joris, et al. "Electrically pumped InP-based microdisk lasers integrated with a nanophotonic silicon-on-insulator waveguide circuit." Optics Express 15, no.11: 6744-6749. (2007).

[9] Tanabe, K., Nomura, M., Guimard, D., Iwamoto, S. & Arakawa, Y. "Room temperature continuous wave operation of InAs/GaAs quantum dot photonic crystal nanocavity laser on silicon substrate," Opt. Express 17, 7036-7042, 2009.

[10] Ryota Katsumi, Yasutomo Ota, Alto Osada, Takeyoshi Tajiri, Takuto Yamaguchi, et al. "In situ wavelength tuning of quantum-dot single-photon sources integrated on a CMOS-processed silicon waveguide," Appl. Phys. Lett. 116, 041103, 2020.

[11] Monat, C, et al. "Continuous-wave operation of photonic band-edge laser near 1.55 μm on silicon wafer, Opt. Express 15, 7551-1557, 2012."

[12] Li Q. &Lau, K. M. Epitaxial growth of highly mismatched III-V materials on (001) silicon for electronics and optoelectronics. Prog. Cryst. Growth Charact. Mater. 63, 105-120, 2017.

[13] Liu, S. et al. "High-channel-count 20Ghz passively mode-locked quantum dot laser directly grown on Si with 4.1 Tbit/s transmission capacity," Optica 6,128-134, 2019.

[14] M. Tang, et al. "Integration of III-V lasers on Si for Si photonics," Prog. Quantum Electron. 66, 1-18, 2019.