Monolithically integrated microcavity lasers on silicon

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Abstract—In recent years, due to the limitation of Moore's Law, traditional electronic integrated circuits have been unable to meet the requirements of exponential growth of data traffic. An optical interconnect paradigm with higher density of processing units and lower energy consumption is urgently needed. Highly integrated III-V lasers on silicon are promising candidates for ultra-compact light sources of the next generation on-chip optical interconnect. Here, we present various InAs/GaAs quantum dot microcavity lasers monolithically grown on silicon, including micro-disk lasers, 2D Photonic Crystal lasers with L3 defects, 1D Photonic Crystal nanobeam lasers, Photonic Crystal bandedge lasers, topological corner state lasers, Dirac-vortex topological lasers and vortex lasers based on bound states in the continuum (BIC).

Keywords-microcavity lasers; PICs; quantum dot material; Si substrates

I. Introduction

Ultra-dense integration of transistors on integrated circuit (IC) enables modern high-performance computing capacities on a single chip. However, due to the limitation of electron tunnelling and large power consumption, the development of electronic integrated circuits in data transmission has been greatly hindered, hence a more efficient on-chip optical inter-connection method is needed. Highly integrated III-V lasers based on silicon are good candidates for ultra-compact light sources of the next generation Photonic Integrated Circuits (PICs), which has a broad prospect in the processing, encoding and transmission of analog signals [1-3].

Up to now, many optical components such as waveguides, optical combs, beam splitters have been integrated on silicon, however, achieving highly integrated light source on silicon is still a huge challenge [4-6]. The past two decades have witnessed numerous efforts towards III-V lasers integrated on silicon platform, such as co-packing, hybrid integration, wafer bonding, etc [7-9]. However, these techniques require cumbersome fabrication processed to align III-V wafer to fabricated passive photonic devices on silicon, which is not completely CMOS-compatible in the current IC fabrication industry. In contrast, monolithically integrated III-V lasers on silicon is a state-of-the-art scheme that has been extensively studied, owing to its lower-cost, larger integration capacity, CMOS-compatible fabrication, and scalability properties [10]. To achieve efficient III-V/Si platform with low defect density and CMOS compatibility properties, numerous efforts have been made to advance complex epitaxial technology and III-V buffer layer [11]. In addition, zero-dimensional quantum dots (QDs) monolithically grown on silicon as gain material with reduced temperature sensitivity, low threshold and less sensitivity to defects have been extensively investigated in recent years, which is a promising solution for next generation high-efficiency light sources [12].

Here, we present various InAs/GaAs quantum dot microcavity lasers monolithically grown on silicon, and all the devices are continuous (CW) optically pumped at room temperature using a 632.8 nm He-Ne laser with focus spot size of ~ 3 μm.

II. RESULTS AND DISSCUSIONS

1. **Microdisk lasers** [13]. As shown in the lasing spectra and inset SEM image in Fig.1.(a), the ultra-small microdisk lasers with diameter ~ 1.1 μm and 1.4 μm are demonstrated, showing large free spectral range (FSR) and well-separated resonant peaks. The L-L curve and full width at half maximum (FWHM) of lasing peak ~ 1189nm of the microdisk laser with D ~ 1.1 μm are shown in Fig.1.(b), which presents the threshold of the first excited state as low as ~ 3 μW.
2. **2D Photonic Crystal with L3 defects lasers** [14]. Top-view SEM image of the fabricated Photonic Crystal cavity is shown in Fig.2.(a). From the collected L–L curve and linewidth of the lasing peak at 1306 nm shown in Fig.2.(b), a lasing threshold ~ 0.6 μW is shown, and the inset shows Lorentzian curve fitting of measured data just below the threshold, indicating a linewidth ~0.68 nm.
3. **1D Photonic Crystal nanobeam lasers** [15]. The ultra-compact InAs/GaAs QD 1D PhC nanobeam lasers monolithically grown on silicon are presented, exhibiting a low lasing threshold of ~ 0.8 μW and ultra-small physical volume of ~ 0.64 $\lambda 3$ (λ = 1313nm). The tilted SEM image of the nanobeam laser and some characterization data of the laser are shown in Fig.3.
4. **Photonic Crystal bandedge lasers** [16]**.** The InAs/GaAs QD square lattice photonic crystal bandedge lasers monolithically grown on silicon are shown. Three bandedge point M1, M2, X1 with low group velocity are obtained with the designed bang gap. As shown in Fig.4, an ultra-low lasing threshold in the multi-mode lasing operation is presented, as well as relatively large linewidth of ~4 nm. The results need subsequent optimized fabrication process and structure design to realize single mode lasing emission.
5. **Vortex lasers based on bound states in the continuum (BIC).** The InAs/GaAs QD BIC lasers monolithi-cally grown on planar on-axis Si (001) substrate. In this work, we did some numerical simulations to analyze the properties of BIC modes, and the BIC modes and the vorticity of the laser beam are also verified experimentally.
6. **Topological corner state lasers.** In the work, we experimentally demonstrated topological corner state lasers with InAs/GaAs QD materials monolithically grown on planar on-axis Si (001) substrate, obtaining single-mode laser emission at a telecom wavelength. The excellent laser performance and unique topological properties are expected to play an important role in topology and quantum electrodynamics.

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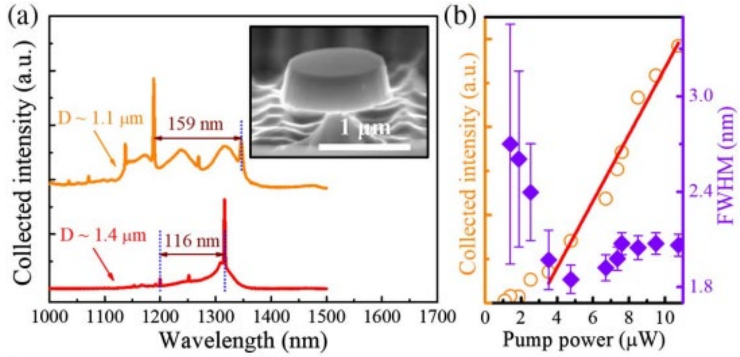

Figure 1. (a) Measured lasing spectra of the microdisk laser with D ~ 1.1 μm and ~1.4 μm. Inset: SEM image of the microdisk laser. (b) L-L curve and FWHM of lasing peak ~1189 nm of the sub-wavelength scale microdisk laser with D ~ 1.1 μm, showing the lasing threshold of ~3 μW.

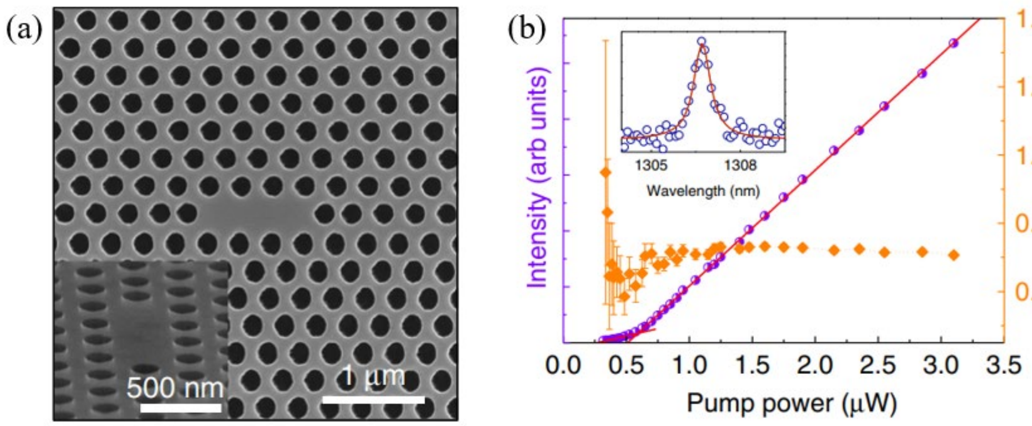

Figure 2. (a) Top-view SEM image of the fabricated Photonic Crystal cavity. (b) Collected L–L curve and linewidth of the lasing peak at 1306 nm

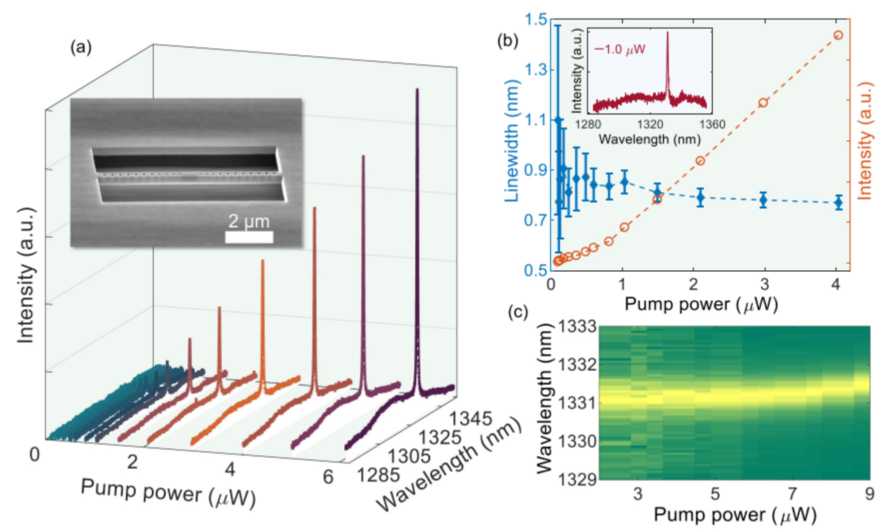

Figure 3. (a) Power-dependent emission spectra of a more compact single-mode PhC nanobeam laser on silicon. The structural parameters are W = 530 nm, a_0 = 346 nm, r_s/a_0 = 0.26. Inset: A tilted SEM image of the fabricated nanobeam laser. (b) Collected L-L curve and linewidth of the lasing peak at ~ 1331 nm, indicating a lasing threshold ~ 0.9 μW. (c) The lasing wavelength under various input pump powers.

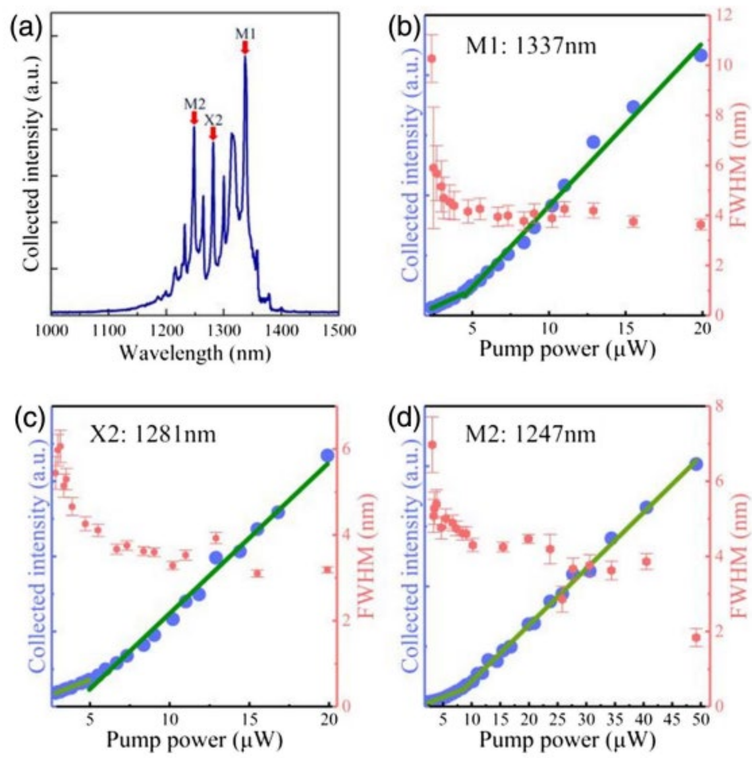

Figure 4. (a) Emission spectrum of the fabricated photonic crystal bandedge laser, the pump power is 49.2 μW. Lasing modes of M1, X2, and M2 can be determined by the spectral positions. (b)–(d) The L-L curve and FWHM as a function of input power for three lasing modes M1, X2, and M2, respectively.

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