Optofluidic Assembly of InGaAsP Microdisk Lasers on Si Photonic Circuits with Submicron Alignment Accuracy

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Abstract: We demonstrate optofluidic assembly of pre-fabricated InGaAsP microdisk lasers (6 μm diameter, 200 nm thickness) on silicon photonic circuits with sub-micron alignment accuracy. The laser output is successfully coupled to the integrated silicon waveguide.

OCIS codes: (230.4685) Optical microelectromechanical devices; (250.5300) Photonic integrated circuits

1. Introduction

Silicon photonics is an attractive platform for electronic-photonic integrated circuits [1, 2]. Passive nanophotonic circuits and electro-optic modulators can be directly integrated with complementary metal-oxide-semiconductor (CMOS) circuits using standard Si foundry processes. However, on-chip semiconductor lasers have been lacking. Silicon Raman lasers have been demonstrated, but they still require external lasers for optical pumping [3, 4]. Direct epitaxial growth of III-V semiconductor lasers on silicon substrates offers another option for heterogeneous integration, but the growth temperature (> 400 ^{o}C) is usually too high for post-CMOS processing [5]. Hybrid lasers and heterogeneously-integrated lasers using low-temperature wafer-bonding techniques have been realized [6, 7]. However, the planarity required for wafer bonding presents a challenge for post-CMOS integration as the silicon waveguides are buried underneath many (up to ten) layers of electrical interconnects.

In this paper, we propose a novel optofluidic assembly technique to integrate pre-fabricated III-V microdisk lasers on fully-processed CMOS wafers. This room-temperature optofluidic assembly process is realized using lateral-field optoelectronic tweezers (LOET) [8]. We have shown that the optofluidically-assembled microdisk lasers on Si exhibited similar characteristics as the lasers on native InP substrates [9]. In this paper, we report on the integration of microdisk lasers and Si nanophotonic circuits. Light from 200-nm-thick InGaAs/InGaAsP multi-quantum-well (MQW) microdisk lasers is successfully coupled to the sub-micron waveguides on silicon-on-insulators (SOI). Single mode operation at room temperature has been observed. Threshold pump power is 0.6 mW (pulsed).

2. Device fabrication and assembly

The microdisk laser consists of three 7-nm-thick InGaAs quantum wells separated by 10-nm-thick InGaAsP barrier layers (bandgap wavelength λ_g = 1.2 μm). The MQW layers are sandwiched between two symmetric InGaAsP optical confinement layers (λ_g = 1.1 μm). The total thickness of the microdisk laser is intentionally kept very thin (200 nm) so that output light can be evanescently coupled to the Si waveguides. The lasers were grown by metalorganic chemical vapor deposition (MOCVD) on an InP substrate. Microdisk lasers with 6 μm diameters were fabricated by lithography and wet chemical etching (Br_2/methanol). They are completely released from their native InP substrate by selective etching, and then suspended in ethanol solution.

The silicon waveguides are fabricated on SOI. The waveguides are 850 nm wide and 100 nm thick. A 200-nm-thick oxide layer is grown on top of the waveguides and determines the evanescent optical coupling between the waveguides and the assembled microdisk. To perform optofluidic assembly, an LOET structure with a 0.8-μm-thick amorphous silicon (a-Si) photoconductor is patterned around the waveguides and the pedestals, as shown in Fig. 1a (schematic) and 1b (SEM). The detailed fabrication process of the LOET structure is shown in Fig. 2. Using optically-induced dielectrophoresis (DEP), the microdisk lasers suspended in ethanol are attracted by projected light patterns on LOET. We used optical patterns created by a computer-controlled digital projector to transport and align microdisks to the waveguides with an applied AC voltage of 1 to 10 Vpp at 200 kHz [10]. Once the disk is aligned to the waveguides, the applied voltage is increased to 20 Vpp to hold the disks during the drying process. After drying, the a-Si layer is removed by xenon difluoride etching in room temperature. The SEM image of the assembled microdisk laser with integrated waveguides is shown in Fig. 1c. Sub-micron alignment accuracy between the microdisk laser and the waveguides has been achieved.

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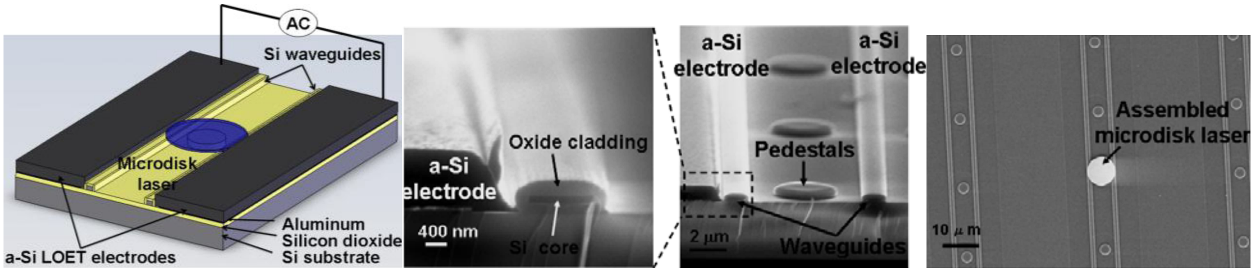


(a) **(b)** **(c)**

Fig. 1. (a) Schematic of lateral-field optoelectronic tweezers (LOET) with integrated silicon waveguides. (b) Scanning electron micrograph of the integrated LOET device. A magnified view of the sub-micron silicon waveguide (850 nm wide × 100 nm thick) is shown on the left. (c) Assembled InP-based MQW microdisk laser shows a good alignment to the waveguides.

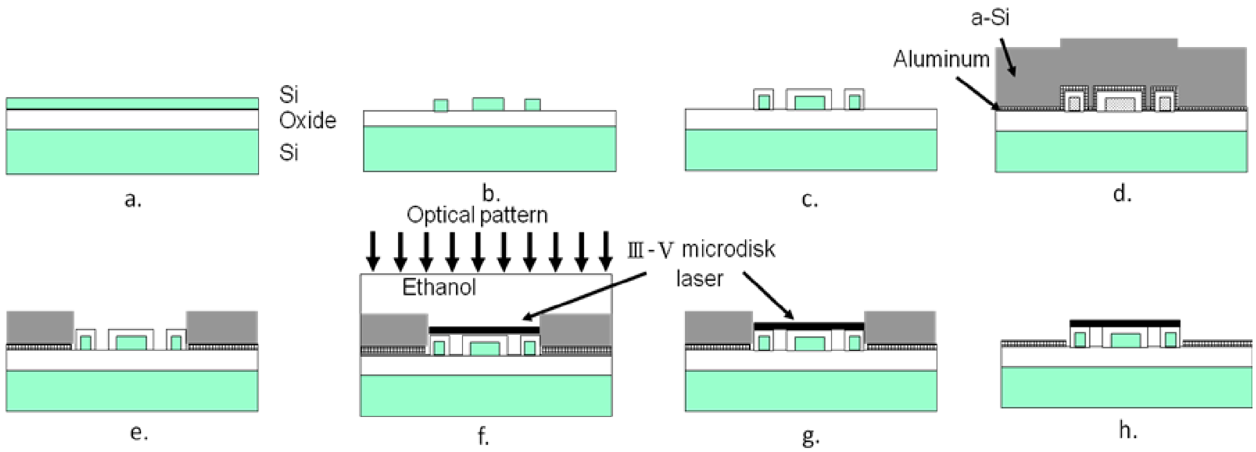
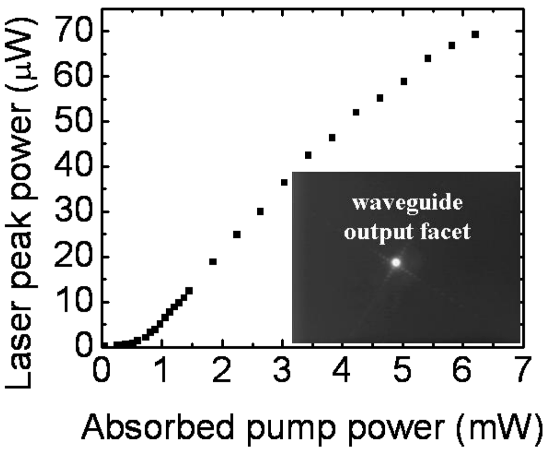


Fig. 2. Fabrication and assembly process flow. (a) The fabrication starts with an SOI wafer with 3-μm-thick buried oxide and 250-nm-thick Si device layer. (b) Patterning of the Si waveguides and pedestals. (c) Thermal oxide is grown to control the evanescent optical coupling between the waveguides and the assembled microdisk laser. (d) Deposition of aluminum and a-Si layers. (e) Patterning LOET electrodes by etching a-Si and aluminum. (f) Assembly of III-V microdisk lasers onto the waveguides in ethanol by projecting optical patterns from a computer-controlled projection display. (g) Assembled microdisk laser after the solution has evaporated. (h) Removal of the a-Si layer by xenon difluoride etching to avoid interference with the optical modes in the microdisk and waveguides.

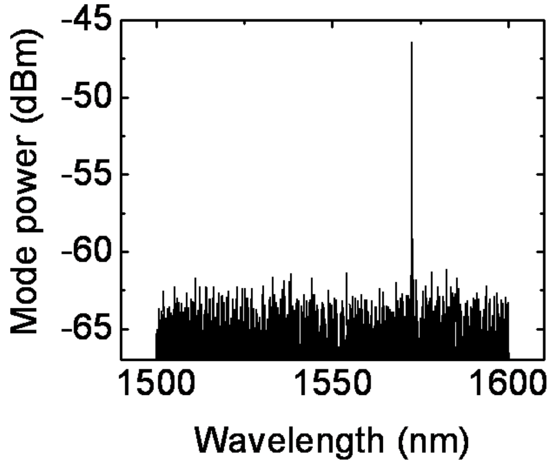
3. Microdisk laser measurements

The assembled microdisk lasers are optically pumped at room temperature using a 635-nm diode laser with 0.3-μs pulses and 1% duty cycle. The pump beam is focused onto the microdisk through a 25× objective. The emitted light is evanescently coupled to the waveguides on SOI. For testing purposes, the SOI chip is cleaved and a single-mode lensed fiber is used to collect the output light from the waveguide. An infrared camera with a 60× objective is also used to examine the laser output at the cleaved waveguide facet, as shown in the inset of Fig. 3a.

The measured laser output versus pump power (L-L curve) is shown in Fig. 3a. The actual optical power absorbed by the InP-based epitaxial MQW structure (approximately 40%) results in an effective threshold peak pump power of 0.6 mW for a 6-μm-diameter microdisk. The external quantum efficiency of the laser coupled to the waveguide is 3.5%. A maximum laser output power of 90 μW is obtained with 8.8 mW pump power. The measured optical spectrum is shown in Fig. 3b. Single mode operation is observed with a peak wavelength of 1572.6 nm. The measured linewidth is 23 pm, which is limited by the resolution bandwidth of the optical spectrum analyzer. At high pump powers, a second whispering gallery mode with 15-dB suppression is observed. The free-spectral range of the fundamental modes is 37.4 nm, which is consistent with theoretical calculations.



(a)



(b)

Fig. 3. (a) Peak laser power versus peak absorbed optical pump power (L-L curve). The threshold pump power of this 6-μm-diameter microdisk laser is about 0.6 mW. The inset shows the infrared camera image at the waveguide output facet. (b) Lasing spectrum with the linewidth of <23pm (limited by the equipment resolution) under pulsed excitation with 0.6 mW peak pump power. The lasing wavelength is at 1572.6 nm.

4. Conclusion

We have successfully assembled InGaAsP microdisk lasers onto silicon photonic circuits using a post-CMOS optofluidic assembly technique at room temperature. This integrated microdisk laser exhibits an effective threshold pump power of 0.6 mW and a maximum output power of 90 μW under pulsed-mode optical excitation. This process can potentially be used to integrate the much needed on-chip lasers on fully processed CMOS wafers.

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