An Optically-Pumped Silicon Evanescent Microring Resonator Laser

Di Liang\textsuperscript{a}, Marco Fiorentino\textsuperscript{b}, Alexander W. Fang\textsuperscript{a}, Daoxin Dai\textsuperscript{a}, Ying-Hao Kuo\textsuperscript{a}
Raymond G. Beausoleil\textsuperscript{b}, John E. Bowers\textsuperscript{a}

\textsuperscript{a} Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106, USA
\textsuperscript{b} HP Laboratories, Palo Alto, CA, 94304, USA

Abstract – We demonstrate an optically-pumped hybrid silicon evanescent microring laser fabricated by a self-aligned process. Low threshold carrier densities ($<$2.5$\times$10$^{18}$ cm$^{-3}$) are measured for both 15 and 25 $\mu$m diameter devices. Lasing up to 50 $^\circ$C is achieved with 0.1 nm/$^\circ$C wavelength red shift rate.

I. INTRODUCTION

Semiconductor ring resonator lasers are simple but very powerful components, which can be readily integrated with other optoelectronic devices and don’t require gratings or facets for optical feedback. Both optically-pumped Fabry-Perot lasers and electrically-driven racetrack ring resonator lasers have been demonstrated recently on the hybrid Si evanescent platform\cite{1,2}, demonstrating the capability to integrate on-chip light sources and photodetectors for optical interconnect applications. However, the reported racetrack waveguide geometry limited bend radii to 150 $\mu$m, leading to a long cavity length (~2.6 mm), ultimately resulting in high threshold currents (~175 mA). A much compact, electrically-driven, InP-based microdisk laser has also been demonstrated in a similar hybrid integration platform, showing sub-mA thresholds\cite{3}. In this paper we demonstrate a microring laser with small diameters of 15 and 25 $\mu$m on the hybrid Si evanescent platform, resulting in a device footprint decrease of 1000X over distributed feedback Si evanescent lasers\cite{4}. A self-aligned, deep dry-etch process is developed to allow patterning III-V gain material in a ring geometry and Si disk resonator in a single lithography step, allowing for tight bend radii. By using a 980 nm Ti:Sapphire pump source, an optically-driven laser is achieved. The measured threshold carrier density ($<$2.5$\times$10$^{18}$ cm$^{-3}$) indicates low cavity losses.

II. DEVICE DESIGN AND FABRICATION

Fig. 1(a) shows the layout of the devices. Resonator diameters are 15 (inset a) and 25 $\mu$m with a waveguide width of 2.5 $\mu$m. The resonators are coupled to 1 $\mu$m-wide, 20 $\mu$m-long straight SOI bus waveguides. The coupling gap $s$ between resonator and SOI bus waveguide varies between 50 nm and 500 nm. The height $h$ of the Si pedestal in the coupling region is either 150 nm (shallow etch) or 0 nm (deep etch). The bus waveguide width is extended to 1.5 $\mu$m through 100 $\mu$m long tapers to minimize sidewall roughness-induced transmission loss\cite{5}. The two ends of bus waveguides are then brought to the same side through four $R=100$ $\mu$m bends, allowing for simultaneous measurement of the combined outputs. The last straight portion of the bus waveguide is 7$^\circ$ off the normal of the output facets to minimize reflections. The total length of bus waveguide in the

First author e-mail: dliang@ece.ucsb.edu. This work was supported by HP Research Innovation Award.

Fig. 1. Mask layout of optically-pumped device. Inset a: SEM top-view of a finished 15 $\mu$m diameter ring resonator laser. b: SEM image of a well-aligned waveguide joint; c: SEM side-view of deeply dry-etched 15 $\mu$m diameter ring resonator laser and bus waveguide. (b) BPM mode profile simulation for the hybrid resonator structure of 15 $\mu$m in diameter. Schematic conduction bandgap of the III-V epitaxial layer structure is shown in the inset.
layout is 2262 μm.

Fig. 1(b) is the schematic device cross-section with a BPM simulated optical mode for a 15 μm diameter resonator. Inset (b) of Fig. 1 shows the III-V epitaxial layer conduction band diagram. In this structure an InAlGaAs separated confinement heterostructure (SCH) and multiple quantum wells (MQWs) are sandwiched by the upper InP cladding and a thin layer of InP which will be used as n-type contact layer electrically-pumped devices. A two-period InGaAsP/InP superlattice bonding layer is interposed between the bottom InP layer and the SOI to protect the active region from any bonding-induced defects at the interface. The total active region and top Si layer are 145 nm and 350 nm thick, respectively, resulting in MQW and Si waveguide layer confinement factors of 5.5% and 51.7%, respectively.

Device fabrication starts with patterning the 1.5 μm-wide SOI bus waveguide section (dark red portion in Fig. 1(a)) by conventional projection lithography and Cl₂/BCl₃-plasma dry etch. We then use low-temperature O₂ plasma-assisted direct bonding to transfer the III-V epitaxial layer onto the SOI substrate. The InP substrate and InGaAs etch stop layer are then removed and a 400 nm layer of plasma-enhanced chemical vapor deposition (PECVD) SiO₂ is deposited. Electron-beam lithography (EBL) is used to define the outer circumference of the resonator, (i.e., forming a disk resonator temporarily), 1 μm-wide bus waveguide section and two 100 μm-long tapered waveguide sections (shallow red portion in Fig. 1(a)). The EBL pattern is transferred to the SiO₂ hardmask layer through a Cl₂/BCl₃-plasma dry etch. A deep, highly-anisotropic InP dry etch process (N₂/Cl₂, 200 °C) was developed to etch through the entire 1.9 μm thick III-V epitaxial layer to Si layer as shown in Fig. 1(a) inset c. Special care is required to align the EBL-defined bus waveguide section with previously patterned SOI bus waveguide section (Fig. 1(a) inset b) which is invisible after III-V epitaxial layer transfer. The disk and bus waveguide pattern are finally transferred to Si layer using another Cl₂/BCl₃-plasma dry etch. A shallow Si etch (remaining Si thickness h=150 nm) and a deep Si etch (h=0), both leading to negligible bending loss, are chosen to study the optimal coupling condition. A 1-μm PECVD SiO₂ (n=1.45) layer is deposited to passivate the dry-etched surface and also fill the directional coupler region. A second optical projection lithography step is used to define the inner circumference of the resonator, and following the dry etch stops right above the InAlGaAs SCH layer. The remaining active region in the disk center is removed by selective H₂SO₄-based wet etch, followed by protecting the resonator region in the last photolithography step and complete III-V removal elsewhere to realize the final ring resonator structure in Fig. 1(b). The device chip with shallow Si etch is coated with a layer of SU8 polymer to protect waveguides during facet polishing.

III. DEVICE MEASUREMENT

A 980 nm Ti:Sapphire pump source is used to deliver up to 500 mW pump light through a single-mode fiber to the devices. Light emitted by the ring is measured either by collecting scattered light through a second fiber or by collecting light output from the polished bus waveguide facets through a lens.

Fig. 2 shows light-light (LL) characteristic of D=15 μm resonators with deep- and shallow-etch (i.e., h=0 nm and h=150 nm, respectively) Si directional couplers. The carrier density is calculated from,

\[ N = \frac{\Gamma P \tau}{h V_{MQW}} \tag{1} \]

where \( \Gamma \) is the pump power absorption efficiency, \( T \) is the transmission of pump light (\( T=0.72 \) for deep-etch case, \( T=0.8418 \) for shallow-etch case due to additional SU8 surface encapsulation). \( P, \tau, h \) and \( V_{MQW} \) are the pump power, injected carrier lifetime (\( \tau=10^{-9} \) sec), single photon energy (\( \lambda=980 \) nm), and MQW volume, respectively. For the deep-etch case, no coupling to the bus waveguide is observed due to strong lateral confinement in the resonator. Therefore, we measured scattered radiation. We measured the peak power of the laser line using an optical spectrum analyzer with up to 0.02 nm resolution, thus amplified spontaneous emission (ASE) is not observed in Fig. 2. The effective pump power at the threshold is 45.28 mW, corresponding to a low carrier density of \( 2.6 \times 10^{18} \text{ cm}^{-3} \), indicating low cavity losses. The spectrum (Fig. 2 inset) obtained at 52 mW pump power shows a peak wavelength of 1567.18 nm and full width at half maximum (FWHM) is 0.098 nm, other modes are suppressed by at least 30 dB (limited by instrument sensitivity). In contrast to the deep-etched case, shallow etch reduces the lateral optical confinement in the resonator, leading to a much stronger coupling to the bus waveguide. The waveguides’ output is collimated with an anti-reflection (AR) coated asphere, passed through a filter to eliminate pump light and measured with a large area detector. Total output power in Fig. 2 is obtained by
taking into account 70% free-space filter transmission, 30.5% waveguide facet reflection, and a conservative 5 dB/cm SOI bus waveguide transmission loss into account. Waveguide output collection efficiency from the lens is not included so the actual laser output powers are higher than reported values in this paper. For coupling gap $s = 50, 150$ and 250 nm the resonators are overcoupled, which inhibits carrier population inversion in the measurement range. For $s = 500$ nm lasing is observed with a higher threshold of 70 mW.

The same trend is shown in Fig. 3(a) for shallow-etched 25 μm devices where laser threshold increases with decreasing gap width $s$. As expected coupling strength is poorer for D=25 μm than D=15 μm devices with same directional coupler parameters. Lasing threshold reduces down to 42.78 mW for a coupling gap of 250 nm. The corresponding threshold carrier density is even lower, compared to that of D=15 μm devices, primarily due to smaller side-wall roughness-induced scattering loss for large bend. We measure up to 22 μW for 137 mW pump power; at higher power we observe device damage. Fig. 3(b) shows the change in threshold behavior as we change the temperature of the stage holding the laser. As expected the threshold power increases with temperature but we can still observe lasing up to 50 °C.

IV. CONCLUSION

We fabricated and tested compact, optically-pumped microring resonators with diameters of 15 and 25 μm on a hybrid Si evanescent platform. These devices show low threshold carrier densities, indicating low cavity losses. We observed lasing up to 50 °C with a wavelength red shift rate of ~0.1 nm/°C. Detailed studies in coupling and thermal performance are under way. We are currently fabricating electrically-pumped devices. We envision that these devices could be used as key components for complementary metal-oxide semiconductor-compatible optical interconnects.

ACKNOWLEDGMENT

The authors thank Ms. Hui-Wen Chen for technical assistance, and Dr. Matthew N. Sysak, Dr. Richard Jones and Dr. David A. Fattal for valuable discussions.

REFERENCES