Si Microring Resonator Switch Based on III-V/Si Hybrid MOS Optical Phase Shifter Using Ultrathin InP Membrane

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Abstract *We demonstrate ultralow-power Si microring resonator switch based on taperless III-V/Si hybrid MOS optical phase shifter using ultrathin InP membrane. Owing to electron accumulation at the InP MOS interface, we successfully achieved optical switching with 0.3 pW, enabling large-scale integration without thermal crosstalk.*

Introduction

Photonic integrated circuits (PICs) based on Si photonics have attracted a lot of attention to meet the demand for global data traffic and high-performance computing. In particular, for communication and computing systems based on wavelength division multiplexing (WDM), a PIC based on Si microring resonator[1] (MRR) switches, such as a switch matrix PIC[2] or a microring weight bank[3], has been investigated since a compact Si MRR is suitable for large-scale integration. To tune an MRR, a thermo-optic (TO) phase shifter has been employed, while its large power consumption and high thermal crosstalk hinder the realization of a large-scale PIC based on an MRR. A carried-induced Si optical phase shifter is another phase shifter for a MRR, while its large free-carrier absorption is an issue. To solve these problems, a III-V/Si hybrid metal-oxide-semiconductor (MOS) optical phase shifter is applicable[4]. Owing to the large carrier-induced refractive index change of the III-V semiconductor, the III-V/Si hybrid MOS optical phase shifter exhibits high modulation efficiency with low attenuation[5]. Also, since it works by carrier accumulation of the III-V/Si hybrid MOS capacitor, the power consumption is extremely low[6], resulting in no thermal crosstalk. However, due to the necessity of a 50-µm-long III-V taper for smooth coupling between the hybrid waveguide and Si waveguide, it was difficult to integrate the III-V/Si hybrid MOS optical phase shifter with a Si MRR. Previously, we reported a racetrack resonator modulator based on the hybrid MOS optical phase shifter where we still used III-V tapers, resulting in large circuit size[7]. In this paper, we propose a MRR switch based on taperless III-V/Si hybrid MOS optical phase shifter using an ultrathin InP membrane and a SiO_2-embedded Si waveguide shown in Fig. 1. Owing to the small mode mismatch between the hybrid and Si waveguides, the smooth transmission between the two waveguide can be obtained even with no taper[8], enabling small-size and high-Q MRR switch. We numerically designed the MRR switch with the III-V/Si hybrid optical phase shifter and successfully demonstrated the proof-of-concept device using a 50-nm-thick InP membrane, exhibiting ultralow power switching.

Numerical analysis

To find an optimal structure at a 1300 nm wavelength, we numerically analysed the MRR switch based on a III-V/Si hybrid MOS optical phase shifter shown in Fig. 2(a). The total thickness of the p-type Si layer was defined to be 300 nm. The width and height of the Si rib were 550 nm and 150 nm, respectively. The n-type III-V layer was assumed to be bonded on the Si waveguide with a 5 nm gate dielectric. The doping concentration of p-Si and n-InP was assumed to be 5×10^{17} cm^{-3}. The radius of the ring waveguide was assumed to be 10 µm. At first, we evaluated the optical loss of the ring structure by calculating radiation loss of the ring waveguide and coupling loss between the Si ring waveguide and the III-V/Si hybrid ring waveguide using Lumerical MODE. Figure 2(b) shows calculated radiation loss, coupling loss, and total optical loss

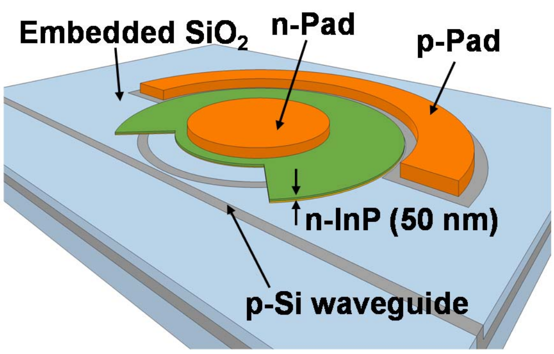

Fig. 1: Schematic of MRR switch based on taper-less III-V/Si hybrid MOS optical phase shifter using ultrathin InP membrane.

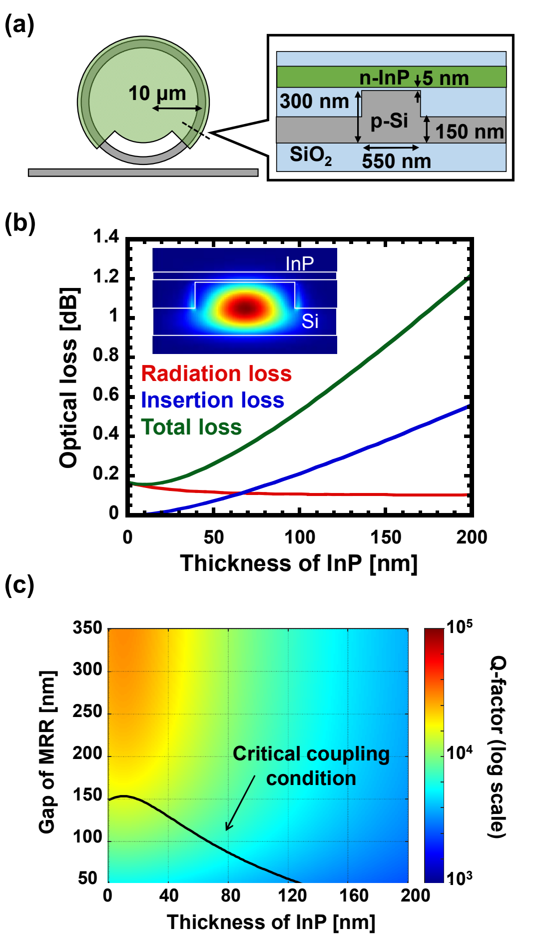

Fig. 2: (a) Schematic of MRR switch based on III-V/Si hybrid MOS optical phase shifter. (b) Calculated optical loss of the ring waveguide, (c) Q-factor and the critical coupling condition of the MRR switch.

of the ring structure. The Inset of Fig. 2(b) shows the mode profile of the III-V/Si hybrid bend waveguide. As the thickness of InP becomes thicker, the radiation loss becomes lower owing to the higher optical confinement, while the insertion loss becomes higher due to the mode mismatch, and the total optical loss also becomes higher. When the thickness of InP was 50 nm, the mode mismatch was sufficiently suppressed even without a taper sturcture. As a result, the total optical loss was evaluated to be 0.3 dB, applicable for a high-Q MRR. Next, using the attenuation coefficient of the ring waveguide obtained from Fig. 2(b) and the self-coupling coefficent between the bus waveguide and the ring waveguide obtained from the supermode analysis[9], we analyzed the Q-factor and the critical coupling condition of the ring resonator switch with varied thicknesses of InP and the gaps of the MRR[1]. Figure 2(c) shows the calculated Q-factor and the critical coupling condition of the MRR switch. From this result, by choosing a 50-nm-thick InP and 120-nm gap, the

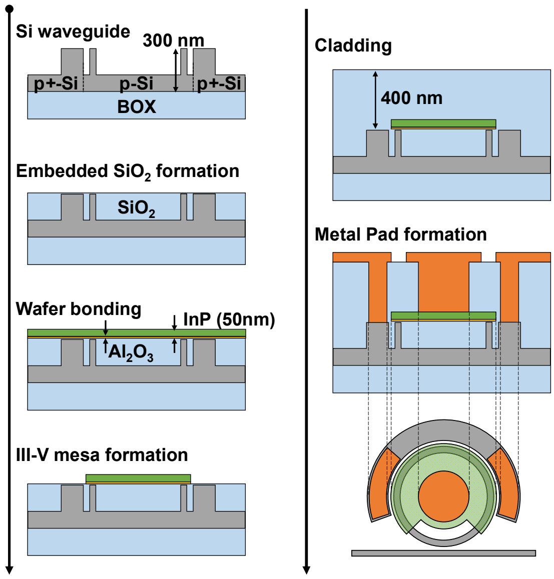

Fig. 3: Fabrication procedure of MRR switch based on III-V/Si hybrid MOS optical phase shifter.

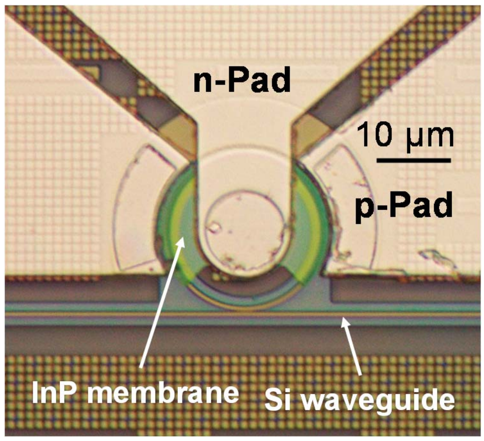

Fig. 4: Microscopy image of fabricated MRR switch integrated with III-V/Si hybrid MOS optical phase shifter.

MRR switch with Q-factor of 10^4 is expected to be obtained.

Fabrication

We fabricated the MRR switch with the III-V/Si hybrid MOS optical phase shifter according to the obtained design, where the thickness of the Si waveguide, the thickness of the InP membrane, the gap of the MRR were 300 nm, 50 nm, and 150 nm. The width of Si waveguide was 550 nm. Figure 3 shows the fabrication procedure. After forming p-type Si rib waveguides and grating couplers for a 1300 nm wavelength, a SiO_2 cladding was deposited by chemical vapor deposition (CVD). Then, chemical mechanical polishing (CMP) was used to planarize the surface of SiO_2 to form the SiO_2-embedded Si waveguides. The thickness of SiO_2 that remained on the top of the Si waveguide after CMP process was approximately 4 nm. A n-type 50-nm-InP membrane was bonded on the Si waveguide via

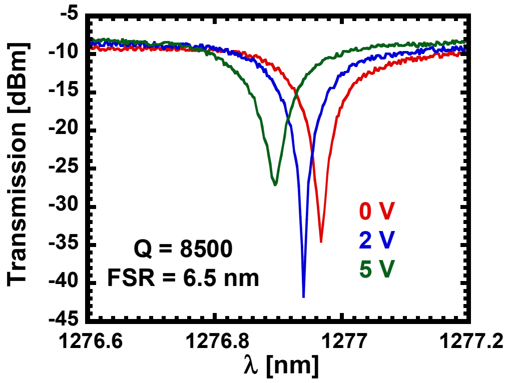

Fig. 5: Output spectra of fabricated MRR switch with varied gate voltages.

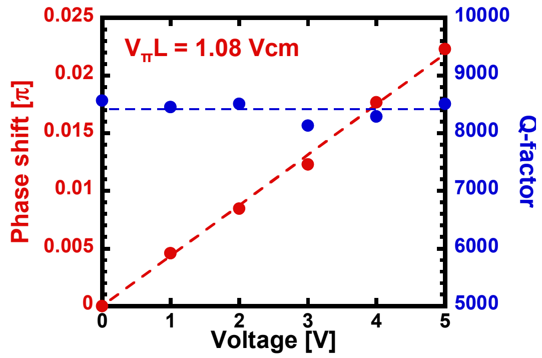

Fig. 6: Phase shift and Q-factor of the MRR switch as a function of gate voltage.

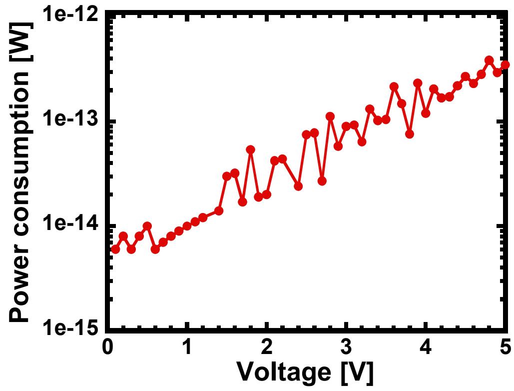

Fig. 7: Power consumption of the MRR switch.

4 nm Al_2O_3. By electron-beam (EB) lithography and wet etching, an InP mesa was formed. A SiO_2 cladding was deposited by CVD. Finally, the electrode pads composed of a Ni/Ti/Pt/Al metal stack was formed by sputtering and lift-off process. Figure 4 shows a plan-view microscopy image of the fabricated MRR switch. The 50-nm-InP membrane was successfully bonded on the MRR. Compared with the racetrack resonator modulator[7], the size of waveguide is 10 times smaller, which is advantage for large-scale integration.

Measurement

We evaluated the MRR switch based on III-V/Si hybrid MOS optical phase shifter. Figure 5 shows the measured output spectra. The Q-factor and FSR of the MRR were 8500, and 6.5 nm, respectively. When the applied gate voltage was 2V, the extinction ratio of the MRR was more than 30 dB, which indicated the MRR switch met the critical coupling condition. These characteristics agreed with the results of the numerical analysis. Since the peak of MRR was blue-shifted by applying voltage, the charrier-induced phase shift of the hybrid MOS optical phase shifter was successfully obtained. Figure 6 shows the phase shift and Q-factor of the MRR switch obtained from Fig. 5. Owing to the low free-carrier absorption of InP, the Q-factor of the MRR switch did not change while applying gate voltage. The modulation efficiency of the phase shifter was calculated to be 1.08 Vcm. The equivalent oxide thickness (EOT) was estimated to 20 nm from the modulation efficiency. By reducing EOT and employing InGaAsP instead of InP[8], the modulation efficiency can be improved to be 0.11 Vcm. Figure 7 shows the power consumption of the MRR switch. An optical signal at a 1276.98 nm wavelength can be switched when the gate voltage was swept from 0 V to 5 V. For switching, the power consumption was approximately 0.3 pW, which is more than 10^7 times smaller than that of the MRR switch based on the TO effect. Thus, the thermal crosstalk of the fabricated MRR switch can be eliminated, enabling dense integration of MRR switches.

Conclusions

We successfully demonstrated an MRR switch based on a III-V/Si hybrid MOS optical phase shifter using an ultrathin InP membrane. Owing to the ultrathin InP membrane, the III-V/Si hybrid waveguide can be integrated with a Si waveguide without any taper structures. As a result, ultralow-power switching was achieved using optical phase shift induced by electron accumulation at the InP MOS interface. Thanks to the ultralow-power operation, the thermal crosstalk is expected to be negligible, enabling high-density integration. Therefore, the demonstrated MRR switch is applicable to large-scale WDM-based PICs.

Acknowledgements

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