Tunable High Quality-Factor Silicon Microring Resonator Driven by High-Mobility Transparent Conductive Oxide

Wei-Che Hsu, Cheng Zhen, and Alan X. Wang*
School of Electrical Engineering and Computer Science, Oregon State University, Corvallis, Oregon 97331, USA
*Corresponding Author: * wang@oregonstate.edu*

Abstract: We demonstrated a silicon microring resonator driven by a titanium-doped indium oxide capacitor with 10 nm hafnium oxide insulator, achieving a high quality-factor of 11,700 with a high electro-optic tunability of 120 pm/V.

OCIS codes: (130.7408) Wavelength filtering devices; (140.4780) Optical resonators

1. Introduction

Silicon microring resonator (MRR) plays a pivotal role in integrated photonic circuits as tunable optical filters and optical modulators due to its compact size. However, most active Si MRRs are driven by reversed PN junctions, which only provide a low electro-optic (E-O) tunability of 40 pm/V [1]. To address this challenge, MRRs with a heterogeneously integrated III-V compound metal-oxide-semiconductor (MOS) capacitor on Si waveguide presented a higher tunability of 55 pm/V [2]. Recently, our group demonstrated an indium-tin-oxide (ITO)-gated Si MRR, which achieved an ultra-high tunability of 271 pm/V using a narrow microring waveguide with a hafnium oxide (HfO_2) insulator [3] along with nanocavity [4] and electro-absorption modulators [5]. However, the quality factor (Q-factor) is limited to 1,000 due to the high optical loss from the ITO gate. To improve the Q-factor of the tunable MRR, high-mobility transparent conductive oxide (TCO) materials are essential to lower the optical loss from the gate as they can reduce the free carrier optical absorption [6]. Titanium-doped indium oxide (ITiO) is one of the high mobility TCO materials and it can achieve $105 cm^2V^{-1}s^{-1}$ mobility by a simple RF sputtering process [7]. In this paper, we demonstrated a tunable Si MRR with a heterogeneously integrated ITiO/HfO_2/Si MOS capacitor, which has a high Q-factor of 11,700 with high tunability of 120pm/V. A higher Q-factor of 22,000 is feasible by our further analysis.

2. Design and Fabrication

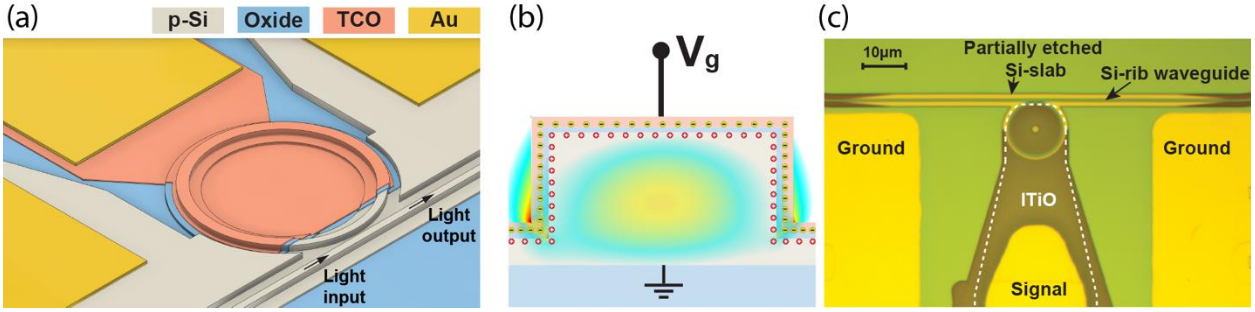

Fig.1 (a) 3D schematic of a tunable Si microring resonator. (b) The cross-sectional schematic in the active region. With the negative V_g, it induces the carrier accumulation in the ITiO and Si layers. (c) Optical image of the fabricated ITiO-gated MOS microring resonator. The ITiO gate, highlighted by the white dashed line, covers the microring's active region except for the coupling region to the bus waveguide.

Fig. 1(a) shows the 3D schematic of the tunable Si MRR, which is designed with a TCO/insulator/Si MOS capacitor. In the active region, the p-type Si (p-Si) rib waveguide serves as the bottom substrate of the MOS capacitor, and the slab makes the connection with the ground Au electrodes. As shown in Fig 1(b), when a negative bias (V_g) is applied, electrons accumulate in the TCO layer and holes accumulate in the p-Si layer. These accumulated carriers at the interfaces will reduce the Q-factor and blue shift the resonance wavelength of the MRR. In this work, a tunable Si MRR with a heterogeneously integrated ITiO/HfO_2/Si MOS capacitor was fabricated on a silicon-on-insulator (SOI) wafer, as shown in Fig. 1(c). First, MRRs with waveguide grating couplers are patterned by two steps of electron beam lithography (EBL) and reactive ion etching (RIE), which have a 250 nm thick p-Si rib waveguide with 50 nm slab. The MRRs have a radius of 6 μm with a waveguide width of 400 nm. Next, a 10 nm HfO_2 layer is formed by atomic layer deposition (ALD), and the HfO_2 on the Si contact region is etched by hydrofluoric acid (HF). After that, 8 nm ITiO is deposited by RF sputtering at room temperature, followed by a liftoff process and patterned by EBL with the dual layers of resists (PMMA/ZEP520A). Finally, the Ni/Au electrodes are thermally evaporated and patterned by regular photolithography.

3. Results and Discussion

Fig. 2 (a) shows the transmission spectra of the tunable MRR with different V_g. When a negative V_g is applied to the ITiO gate, the resonance wavelength has a blue shift. At V_g=0V, it has a large extinction ratio (ER) of -17 dB since this tunable MRR is designed under critical coupling condition. The resonance wavelength shifts and Q-factors are measured and plotted in Fig. 2 (b). The resonance wavelength shift is almost linearly proportional to the V_g. The tunable MRR has a high initial Q-factor of 11,700 (V_g=0V) and the Q-factor gradually degrades as the negative V_g increases. The Q-factor is still higher than 7,500 when it has a cumulative resonance wavelength shift of 600 pm. From our characterization, the mobility of ITiO in this work is only around 25 $cm^2V^{-1}s^{-1}$. To further improve the device performance, we achieved a mobility of 66 $cm^2V^{-1}s^{-1}$ by adding substrate heating at 450°C during the ITiO sputtering process. Integrating such high mobility ITiO with the Si MRR is currently under development. Fig.2 (c) shows the simulated results to achieve a higher Q-factor with high mobility ITiO. The initial Q-factor of the Si MRR is expected to be 22,000 and the final Q-factor is around 12,000 with cumulative resonance wavelength shifting of 600 pm.

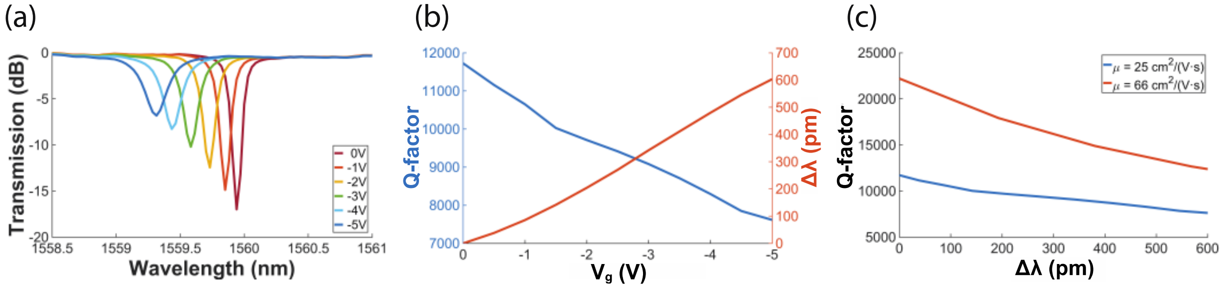

Fig. 2 (a) Normalized transmission spectra of ITiO-gated MOS Si MRR with different V_g. (b) Experimental Q-factor (blue line, left y-axis) and the resonance shift (Δλ) (red line, right y-axis). (c) Comparison of Q-factor between different free carrier mobilities. The blue line is the current experimental result, and the red line is the simulation result with a mobility of 66 $cm^2/(Vs)$.

4. Conclusion

In conclusion, we demonstrated a tunable Si MRR driven by ITiO MOS capacitor. It achieved a high Q-factor of 11,700 with a high E-O tunability of 120 pm/V. With optimized fabrication process to integrate higher mobility ITiO, the tunable Si MRR can be improved to a higher Q-factor of 22,000, which will enable high-efficiency on-chip wavelength division multiplexing silicon photonic integrated circuits.

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