Ge Ring Modulator Based on Carrier-injection Phaser Shifter Operating at Two Micrometer Band

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Abstract *We demonstrated proof-of-concept Ge ring modulator by carrier injection on the Ge-on-insulator (GeOI) platform. Owing to the strong optical confinement in Ge rib waveguide, the optical modulation with 13 dB extinction ratio was obtained by optical phase shift induced by 1 mA current injection.*

Introduction

Mid infrared (MIR) photonics has been attracting the scientific attentions for its great potential in communication and sensing. Particularly, Ge is emerging as a promising material for MIR photonics for its large transparency window from 2 to 15 μm wavelength [1]. Furthermore, Ge possesses 10 times larger free-carrier absorption than Si at the MIR spectrum. We have demonstrated carrier-injection optical modulator based on the free-carrier absorption in Ge using the Ge-on-insulator (GeOI) photonic platform [2, 3]. However, the power consumption of the absorption modulation was rather high as compared with the phase modulation scheme, obstructing the practical application of Ge modulators.

In this work, we present a proof-of-concept Ge ring modulator operating at 2-μm band by integrating a lateral PIN junction for carrier injection. As a result, phase modulation is successfully demonstrated by current injection of 1 mA with the modulation depth of 13 dB. The numerical analysis of the optical phase shift reveals that the presented GeOI modulator has approximately ten times greater phase modulation efficiency than a Ge-on-Si modulator, owing to the strong optical confinement in a Ge waveguide on the GeOI platform.

Design and fabrication

Figure 1 shows a schematic of a Ge ring resonator consisting of Ge rib waveguides fabricated on a GeOI wafer with a 250-nm-thick Ge layer. To achieve a single-mode Ge rib waveguide at a 2 μm wavelength, the waveguide width and rib height are designed to 500 nm and 150 nm, respectively. A lateral PIN junction is formed along the ring waveguide for carrier injection. The distance between the p^+- and n^+-regions was designed to be 2.7 μm to avoid absorption from the doped regions.

To investigate the feasibility of the Ge ring modulator based on phase modulation, we pefrome the numerical analysis of the trasmission spectrum. The radius of the Ge ring resonator is assumed to be 45 μm. The simulated spectrum can be represented using the following equation [4],

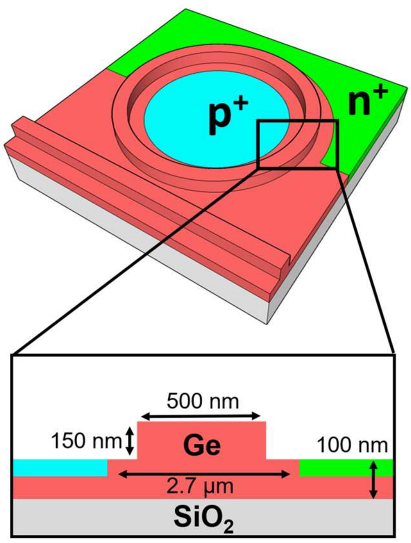

Fig. 1: Schematic of the Ge ring modulator.

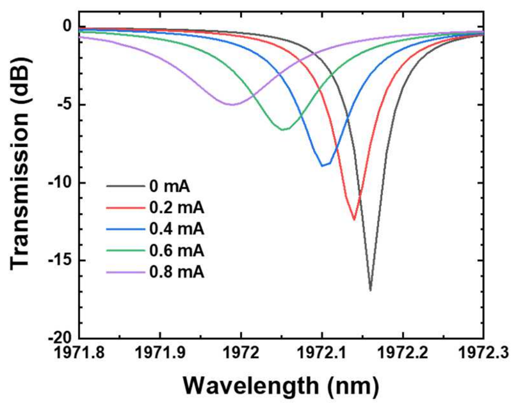

Fig. 2: Simulated transmission spectra of the Ge ring modulator.

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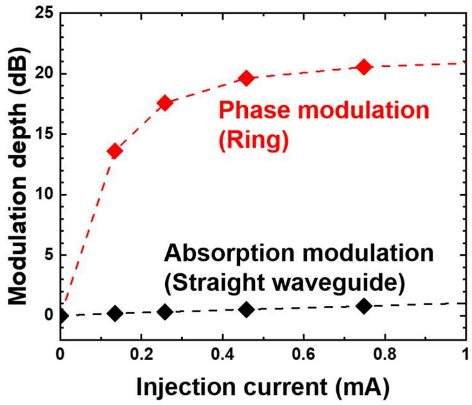

Fig. 3: Comparison of modulation depth between Ge ring modulator and Ge absorption modulator with same active region.

$$T = T_0 \frac{(a\Delta a)^2 - 2ra\Delta a \cdot \cos(\beta L_r + \Delta\beta L_a) + r^2}{1 - 2ra\Delta a \cdot cos(\beta L_r + \Delta\beta L_a) + (ra\Delta a)^2}$$

where T_0 is the initial input power, a is the single-pass amplitude transmission associated with the propagation loss of the Ge ring waveguide, r is the transmission coefficient, here we set $r = a$ for critical coupling in our simulation. Note that a is experimentally extracted from the propagation loss of 15 dB/cm measured by the cut-back method of the Ge passive waveguide, and β is the propagation constant. L_a is the active length for the PIN junction, which is approximately 141 µm for half of the circumference. Through Lumerical DEVICE and MODE simulations, the change of absorption Δa and the change of the propagation constant $\Delta\beta$ associated with carrier injection are obtained for the 2-µm band in conjunction with the free-carrier effect model in Ge [5]. Figure 2 shows the calculated transmission spectra of the Ge ring modulator. With the increase in the injection current, the blue shift of the resonance peak is observed due to the free-carrier plasma dispersion effect. Note that, since Ge possesses 10 times greater free-carrier absorption than Si, the Q factor degrades from ~21,000 to ~16,000 when the injection current is increased from 0 to 0.8 mA. As shown in Fig. 3, the modulation depth of the Ge ring modulator can reach 20 dB with 0.8 mA injection current. As compared with the absorption modulation in the Ge waveguide with the same device length, the phase modulation in the Ge ring resonator enables remarkably efficient optical modulation. This simulation result shows the superiority of the phase modulation in a Ge ring resonator.

According to the numerical analysis, we fabricate the Ge ring modulator on a GeOI wafer. The fabrication procedure is illustrated in Fig. 4. A GeOI wafer is fabricated by direct wafer bonding and Smart-cut™ as described in [6]. After patterning and etching of markers for electron-

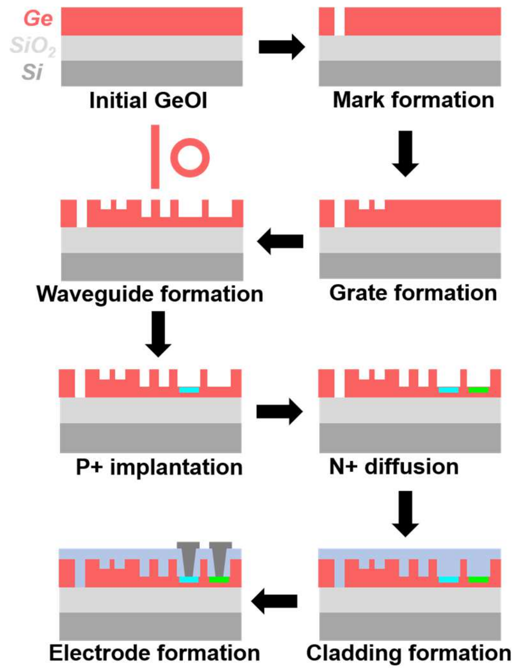

Fig. 4: Fabrication process flow of the Ge ring modulator

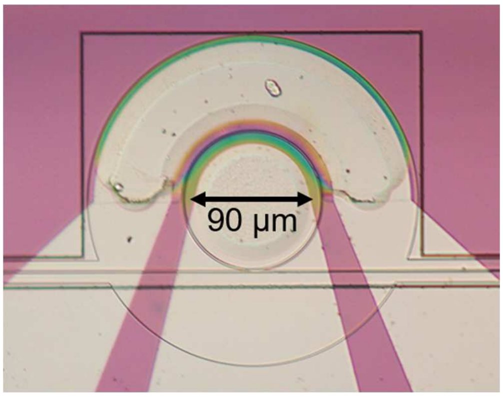

Fig. 5: Optical microscope image of the Ge ring modulator.

beam (EB) lithography, grating couplers are formed by reactive ion etching (RIE) with CF_4 gas. A Ge rib waveguides are also etched by dry etching. Then, a P^+-region is formed by boron ion implantation, and N^+-region is formed by solid diffusion of phosphorus from spin-on-glass [5]. After the formation of SiO_2 cladding by plasma enhanced chemical vapor deposition (PECVD), contact via is opened by BHF wet etching, and Ni/Al electrodes are formed by sputtering and lift-off. Figure 5 shows the optical image of Ge ring modulator with a radius of 45 µm.

Experimental evaluation

First we evaluate the transmission spectrum of the fabricated Ge ring resonator by an amplified spontaneous emission source operating at 2-µm band. Light is coupled from a cleaved optical fiber to the Ge waveguide through a Ge grating, and

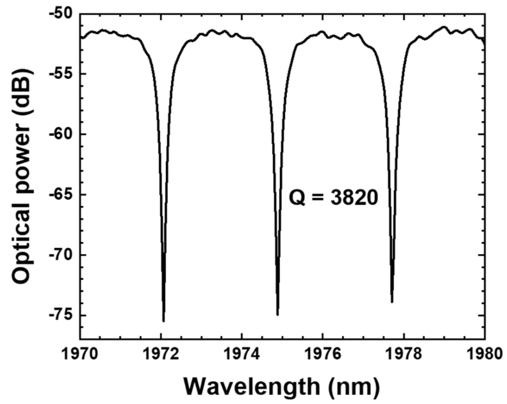

Fig. 6: Transmission spectrum of the fabricated Ge ring modulator.

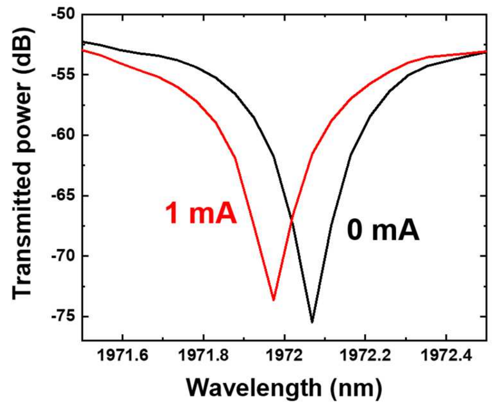

Fig. 7: Phase modulation of the Ge ring modulator by injecting current of 1 mA.

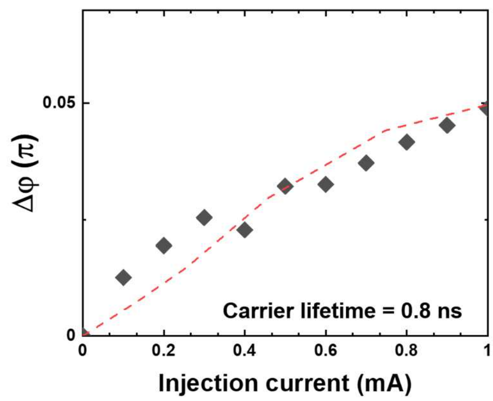

Fig. 8: Measured optical phase shift as a function of injection current of the Ge ring modulator.

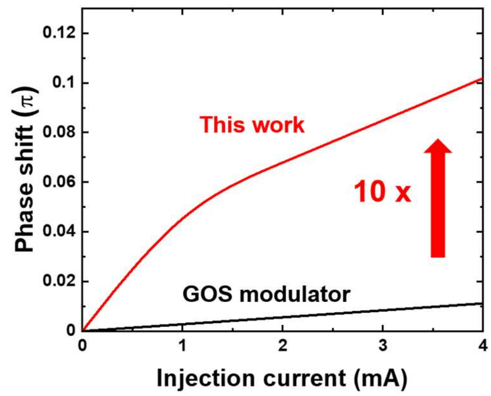

Fig. 9: Benchmark of the phase modulation efficiency.

the output is coupled again to another optical fiber, and detected by an optical spectrum analyzer. As shown in Fig. 6, the resonance peaks of the Ge ring resonator are clearly observed with Q factor of 3820. As compared with our simulation, the degraded Q factor might be due to the imperfect fabrication process. Then, we apply forward bias to the formed PIN junction integrated along the ring waveguide. Figure 7 shows the modulation result. We observe the clear blue shift of the resonance wavelength associated with carrier-induced optical phase shift in the Ge waveguide. The modulation depth of 13 dB is obtained when the injection current is 1 mA. Figure 8 shows the measured optical phase shift as a function of the injection current. By assuming that the free carrier lifetime of the Ge membrane is 0.8 ns, we find that the experiment result is in good agreement with the numerical analysis. Finally, we benchmark our result with the Mach-Zehnder (MZ) modulator on a Ge-on-Si (GOS) platform [7], as described in Fig. 9. Our GeOI device shows nearly 10 times greater phase modulation efficiency than the GOS device when the injection current is 4 mA thanks to the strong optical confinement in the GeOI waveguide.

Conclusions

We successfully demonstrate the proof-of-concept Ge ring modulator operating at 2-μm band on the GeOI MIR photonic platform. By injecting 1 mA current, we successfully achieve high modulation depth of 13 dB by carrier-induced optical phase shift in the Ge waveguide. The strong optical confinement of the GeOI platform enables an efficient carrier-injection optical phase shifter, promising for 2-μm band data transmission.

Acknowledgements

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References

[1] R. Soref, “Mid-infrared photonics in silicon and germanium”, *Nat. Photonics*, vol 4, pp. 495–497, 2010.

[2] J. Kang, M. Takenaka, and S. Takagi, "Novel Ge waveguide platform on Ge-on-insulator wafer for mid-infrared photonic integrated circuits," *Opt. Express,* vol. 24, no. 11, pp. 11855-11864, 2016.

[3] Z. Zhao et al., "Efficient Mid-Infrared Germanium Variable Optical Attenuator Fabricated by Spin-on-Glass Doping," *J. Light. Technol.,* vol. 38, no. 17, pp. 4808-4816, 2020.

[4] W. Bogaerts et al., “Silicon microring resonators”, *Laser Photonics Rev.*, vol. 6, no. 1, pp. 47-73, 2012.

[5] M. Nedeljkovic, R. Soref, and G. Z. Mashanovich, “Predictions of Free-Carrier Electroabsorption and Electrorefraction in Germanium”, *IEEE Photonics J.*, vol. 7, no. 3, p. 2600214, 2015.

[6] J. Kang, X. Yu, M. Takenaka and S. Takagi, “Impact of thermal annealing on Ge-on-Insulator substrate fabricated by wafer bonding,” Materials Science in Semiconductor Processing, vol. 42, Part 2, pp. 259-263, 2016.

[7] Tiantian Li et al., "Ge-on-Si modulators operating at mid-infrared wavelengths up to 8 μm," *Photon. Res.* Vol. 7, no. 8, pp. 828-836, 2019.