Mid-infrared Non-volatile Compact Optical Phase Shifter Based on $Ge_2Sb_2Te_5$

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Abstract *We demonstrated a low-loss, non-volatile optical phase shifter based on phase-change material, $Ge_2Sb_2Te_5$ operating at a 2 μm wavelength. Using a 10-μm-long phase-change phase shifter, we obtained a 0.7π phase shift at 2 μm with approximately 10 times smaller loss per phase shift than at 1.55 μm.*

Introduction

Mid-infrared silicon photonics has attracted increasing attention as a new platform for communication[1], sensing[2], deep learning[3], and quantum computing[4]. An optical phase shifter, which controls the phase of light propagating in a waveguide of a photonic integrated circuit (PIC), is one of the most essential building blocks of a programable PIC. In particular, a low-loss and non-volatile optical phase shifter is strongly desired to realize deep learning and quantum computing using a programable PIC.

Phase change materials (PCMs) have been widely used in various applications such as optical discs and phase change random access memory (PCRAM) because they have a reversible, non-volatile, stable, and fast phase transition property. Among phase change materials, $Ge_2Sb_2Te_5$, commonly known as GST, is a representative PCM which has large optical property contrast in the visible range and fast crystalline-amorphous transition as well as excellent stability of the amorphous state. Since GST holds the large contrast changes in refractive index and extinction coefficient at near-infrared wavelengths and has complementary metal-oxide-semiconductor (CMOS) compatibility, several studies have reported non-volatile compact optical switches operating at the wavelength of 1.55 μm mainly utilizing the significant change in optical absorption along with the phase transition of GST[5]-[7]. The large optical absorption of GST in the near-infrared range, however, prevents realizing optical phase shifters operating at a 1.55 μm wavelength based on GST.

In this study, we propose a non-volatile optical phase shifter using GST operating at MIR wavelength. At a 2 μm wavelength, the optical absorption of GST in the amorphous state is almost negligible, and that in the crystalline state is fairly small compared with the near-infrared range. As a result, the optical loss required for the π phase shift can be significantly reduced. This result suggests the first step toward a low-loss optical phase shifter based on PCMs.

Numerical analysis of phase-change phase shifter

The inserted figures in Fig. 1 show the cross-sectional structures of the phase-change phase shifters. The strip waveguide sizes were designed to be 220 × 500 nm for 1.55 μm wavelength and 220 × 600 nm for 2 μm wavelength, respectively. A 10-nm-thick GST layer was supposed on the top of the waveguide. The complex refractive indexes of amorphous and crystalline GST at 1.55 μm were

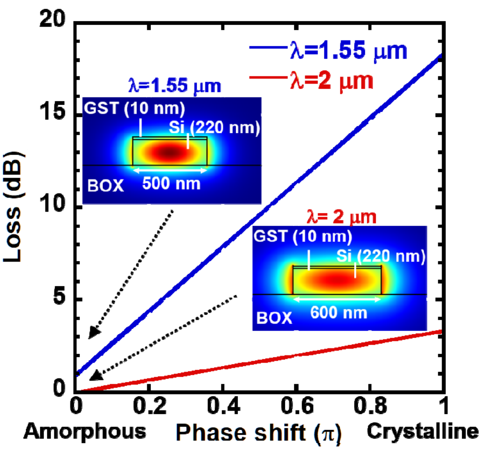

Fig. 1: Simulated relationship between phase shift and loss of phase-change phase shifter operating at the wavelengths of 1.55 μm and 2 μm.

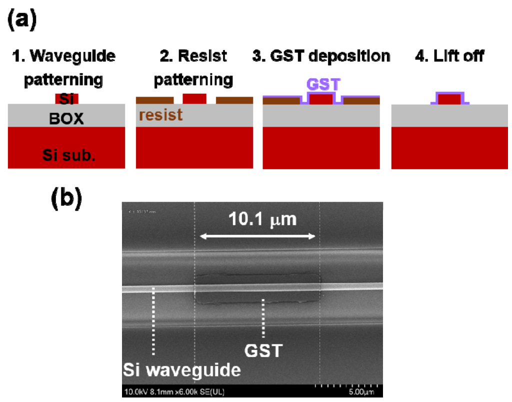

Fig. 2: (a) Fabrication procedure of phase-change phase shifter on SOI wafer. (b) SEM image of fabricated phase-change phase shifter.

4.46+0.127i and 7.14+1.12i, respectively and those at 2 μm were 4.14+0.00i and 6.77+0.232i, respectively. These values were obtained by FTIR measurement. We simulated the effective refractive index of the fundamental electric (TE) mode of the waveguides with amorphous and crystalline GST using finite element mode solvers. Then we calculated the loss of phase-change phase shifters as a function of the phase shift as shown in Fig 1. The length of each phase shifter for a π shift was as short as 10.7 μm and 11.1 μm in the case of 1.55 μm and 2 μm, respectively. The loss in the case of 1.55 μm increased with the increase of phase shift and reached larger than 18 dB when GST was the crystalline state. In contrast, the loss in the case of 2 μm was around 3 dB even when the GST was the crystalline state, which is 30 times smaller than that of 1.55 μm. Thus, we can conclude that a phase shift based on the phase transition of GST at the wavelength of 2 μm is promising for realizing a non-volatile compact optical phase shifter.

Fabrication of phase-change phase shifter

To experimentally examine the loss and the phase shift of phase-change phase shifter operating at 2 μm, we fabricated straight waveguides and asymmetric Mach-Zehnder interferometers (AMZIs) with different lengths of phase-change phase shifters. Figure 2(a) shows the fabrication procedure. After patterning waveguides with grating couplers on 220 nm SOI wafer by electron-beam (EB) lithography and dry etching with CHF_3 and SF_6, EB resist was deposited and patterned by EB lithography. A 10-nm-thick GST layer was deposited by sputtering and patterned by a lift-off process. A scanning electron microscope (SEM) image of a fabricated phase-change phase shifter is shown in Fig. 2(b). GST was successfully patterned as designed.

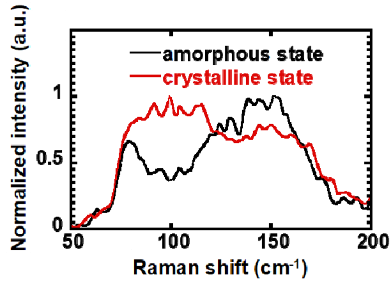

Fig. 3: Raman spectra of amorphous and crystalline GST.

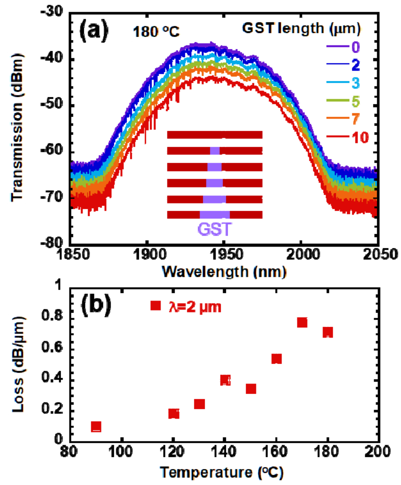

Fig. 4: (a) Transmission spectra of straight waveguides with different length of phase shifters measured at 180 °C. (b) Loss per unit length of phase shifters with increasing heating-up temperature.

Evaluation of phase-change phase shifter

We evaluated the transmission spectrum of straight waveguides and AMZIs to extract the loss and the phase shift. An ASE optical source was coupled into a waveguide via a grating coupler. The output was coupled again to an SMF using a grating coupler and measured by an optical spectrum analyser. As-deposited GST was in amorphous and was gradually crystallized by placing the chip on a hotplate for 5 minutes at an increasing temperature from 120 °C to 180 °C. The phase transition was confirmed by Raman spectroscopy as shown in Fig. 3. The Raman spectrum of amorphous GST showed a broad main peak at around 150 cm^{-1} and the peak position shifted to 110 cm^{-1} after crystallization, which is consistent with previous reports[8][9].

Figure 4(a) shows the transmission spectra of the straight waveguides with different lengths of phase shifters measured at 180 °C. The change in the loss per unit length of the phase shifter with increasing heating-up temperature is shown in Fig 4(b). Since the chip was heated up to 90 °C during the lift-off process, the initial

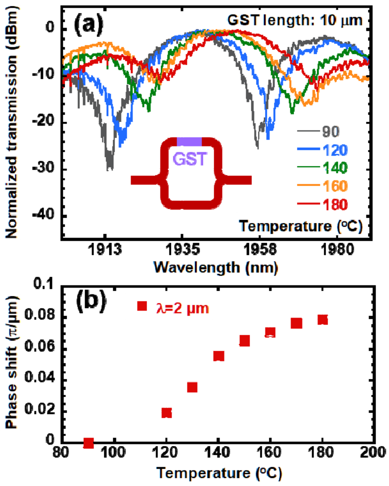

Fig. 5: (a) Transmission spectra of the AMZIs with a 10-μm phase shifter measured after heating up at different temperatures. (b) Phase shift per unit length of phase shifters with increasing heating-up temperature.

temperature was 90 °C. As the heating-up temperature increased, GST was partially and gradually crystallized, and the loss increased. We attribute the loss of the phase shifter with amorphous GST to partial crystallization during fabrication, fabrication variation, and/or the surface oxidation of GST. Note that all the spectra were measured at room temperature after cooling the chip, ensuring the non-volatile operation of phase shifters.

Figure 5(a) shows the transmission spectra of the AMZIs with a 10-μm phase shifter measured after heating up at different temperatures. The change in the phase shift per unit length of the phase shifter with increasing heating-up temperature is shown in Fig. 5(b). As with the loss, the phase shift increased according to the gradual crystallization of GST.

Figure 6 shows the measured relationship between phase shift and loss at 2 μm. At 2 μm, approximately 0.7π phase shift was obtained with a 10-μm phase shifter, while the loss increased by 5 dB. The slope of loss at 2 μm

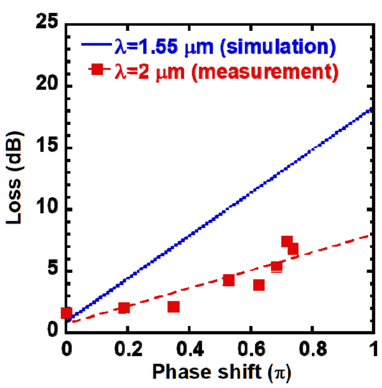

Fig. 6: Measured and simulated relationship between phase shift and loss of phase-change phase shifter operating at the wavelength of 1.55 μm and 2 μm.

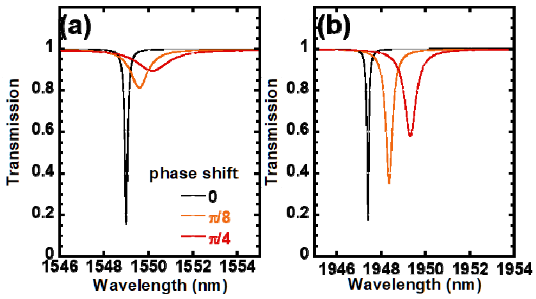

Fig. 7: Simulated transmission spectra of MRRs with phase-change phase shifter operating at (a) 1.55 μm and (b) 2 μm.

was 7.3 dB/π, which was approximately 10 times smaller than at 1.55 μm.

To show the superiority of the GST-based optical phase shifter at 2 μm, we numerically analysed micro-ring resonators with 20-μm-radius with a phase-change phase shifter. Figure 7 shows the simulated transmission spectra of MRRs with phase-change phase shifter operating at (a) 1.55 μm and (b) 2 μm. The length of the phase shifter was 1.4 μm and 1.7 μm in the case of 1.55 μm and 2 μm wavelengths, respectively. Since the loss in the case of 2 μm is fairly small compared with 1.55 μm, the π/4 shifted spectrum still showed the sharp resonance peak. Therefore, the GST-based optical phase shift is more suitable for tuning an MRR at 2 μm.

Conclusions

We have demonstrated the non-volatile compact optical phase shifter based on GST operating at a 2 μm wavelength. Owing to the small optical absorption of GST in the MIR range, the loss of phase-change phase shifter operating at 2 μm was significantly smaller than that of 1.55 μm. As a result, we can utilize the very large refractive index constant of GST without severe loss. By optimizing an operating wavelength and PCMs, we expect a further reduction in optical loss accompanying phase shift. Therefore, the optical phase shifter based on PCM at MIR wavelengths is quite promising for various range of applications.

Acknowledgement

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