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A new design of 1×2 optical switch with silicon waveguide and phase change material

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Abstract. On chip photonics devices relying on the weak, volatile thermo-optic or electro-optic effect of silicon usually suffer from high energy consumption and low refractive index coefficient. In this paper, we designed a 1×2 phase change optical switch. The device is implemented in two silicon waveguides system using an overcladding layer of the phase change data storage material $Ge_2Sb_2Te_5$ (GST), which exhibits high contrast in its optical properties upon transitions between its crystalline and amorphous structural phases. The switch shows cross-state and bar-state corresponding to amorphous GST (a-GST) and crystalline GST (c-GST), respectively. The characteristic parameters of the switch were carefully designed and simulated by three-dimensional finite-difference time-domain (3-D FDTD) method. As the simulation result, the insert loss was less than 0.5 dB. The crosstalk was -16 dB for cross-state and -29 dB for bar-state at 1550nm.The device performance can be further optimized and the low consumption phase change optical switch can be expected for future optical communication networks.

1. Introduction

Optical switch is an extremely important part of optical communication network, and its switch selectivity is one of the important functions of optical network communication. In particular, waveguide-based optical switches are drawing more and more attention as integrated with other optical devices. Traditional optical switches are mainly electro-optical (EO) switches and thermo-optical (TO) switches, which need to consume excess energy [1, 2]. Moreover, traditional optical switches are very sensitive to temperature changes, which leads to potential stability problems.

One solution to overcome these problems is to use exotic materials with much larger refractive index modulation. Phase change materials (PCMs) can switch reversibly between the covalent-bonded amorphous phase and the resonant-bonded crystalline phase. These two phases exhibit high contrast in the electrical resistivity and optical constant over a wide wavelength range in the infrared spectral region [3]. A widely used phase change material, $Ge_2Sb_2Te_5$ (GST), has a "self-holding" feature, which means that it does not need a continuous static power supply to maintain its state. GST has several outstanding characteristics, such as high optical contrast between amorphous and crystalline state [4], nanosecond phase change time [5], compatibility with Complementary Metal Oxide Semiconductor (CMOS) manufacturing process [6] and high scalability [7], which are the great advantages of phase change material applied to photonic chips. Therefore, GST is a good material choice to realize non-volatile on-chip micro-photonic devices. Although there are some optical switches which fabricated with PCMs [8, 9, 10], they bring great losses.

In this paper, we present a 1×2 phase change optical switch based on a 220-nm-thick Si waveguide, which offers low power consumption. The switch is composed of two waveguides system, one of which covered with a thin GST film. The 1×2 optical switch is the basic "building blocks" for creating large-scale on-chip optical switching chips. In order to achieve a lower insert loss and high extinction ratio phase change optical switch, the FDTD was used to study the field profile and the light propagation of the hybrid waveguide with a-GST and c-GST.

2. Experimental

The structural diagram of 1 × 2 optical switch is shown in Fig. 1(a). The optical switch was fabricated on a silicon-on-insulator (SOI) wafer with a 220-nm-thick silicon layer on the top of a 3-μm-thick buried oxide layer. The switch consisted of two waveguides system, and one of the waveguides was covered by a thin GST film. The Si waveguide was 500nm wide and 220nm high. The width of the GST was 460nm.The 30-nm-thick GST film was patterned on the waveguide by lift-off process. Fig. 1(b) shows the cross-sectional diagram of the phase change optical switch.

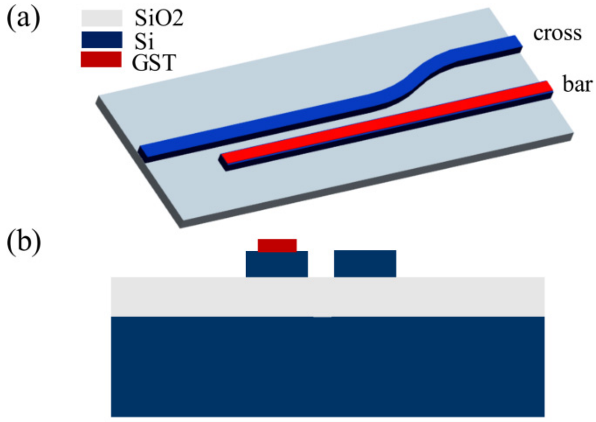

Fig.1. (a) Structure of a 1×2 phase change optical switch with Si waveguide and GST film, (b)The cross-section of the switch.

The 30-nm-thick GST film was deposited on Si (100) wafer by DC magnetron sputtering using a stoichiometric target at room temperature. The film was annealed at 190°C for 10 min in the N2 gas by using rapid thermal annealing for crystallization. We verified the states by ellipsometer and X-ray diffraction (XRD) measurement of GST.

3. Results and discussion

3.1. Properties of GST

Fig. 2(a) shows that there is high contrast of optical constant in the wide spectral region (especially in C-band communication wavelength) between the a-GST and c-GST. In addition, the optical constant of GST influences the effective index of the waveguide. XRD spectra in Fig. 2(b) indicate the transition from a-GST to fcc c-GST after rapid annealing at 190°C [11]. For amorphous state, there are no characteristic peaks, but for fcc crystalline GST, there are four characteristic peaks.

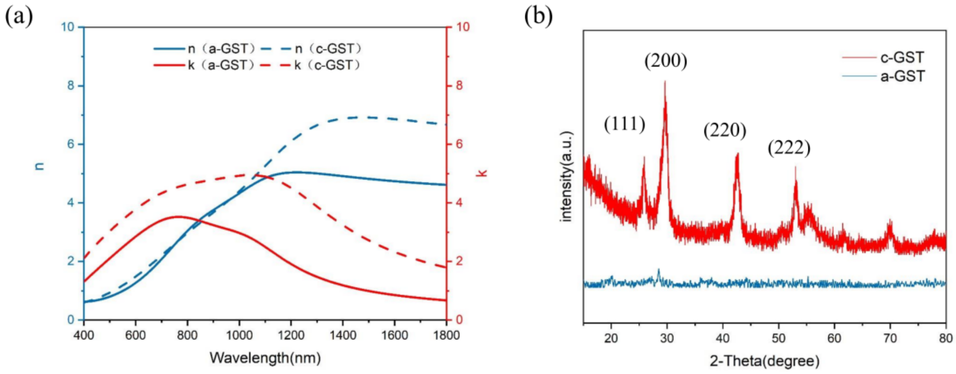

Fig.2. GST characterization. (a) complex refractive index of a-GST and c-GST as a function of wavelength, (b) XRD data of a-GST and c-GST.

The difference of GST refractive index is due to the arrangement of atoms in different crystal states. Fig. 3(a) (b) shows the structures of a-GST and c-GST, respectively. The arrangement of atom is disordered for a-GST. The fcc crystalline GST presents a rocksalt-like structure, in which the anion sublattice is occupied by Te atoms, and the cation sublattice is randomly occupied by Ge/Sb atoms and vacancies as shown in Fig. 3 (b) [12].

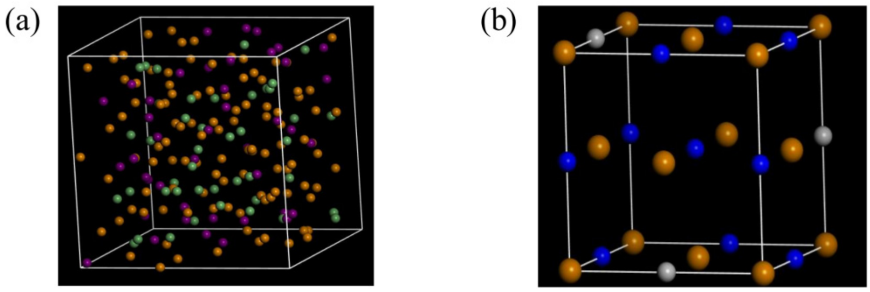

Fig.3 Structures of (a) a-GST, (b) c-GST (fcc crystalline GST). The orange, green, and purple balls represent Te, Ge, and Sb atoms, respectively, and the blue balls represent that both Ge and Sb atoms may occupy the sites.

3.2. Modal intensity profile

3-D FDTD was employed to simulate the phase-change optical switch. For all practical waveguides with two-dimensional constraints, their eigenmode are classified as quasi-TE and quasi-TM modes. Fig. 4 shows the electric field distribution of the fundamental quasi-transverse electric (TE) mode in the waveguide when GST is in amorphous and crystalline states respectively. It can be seen that when GST is at amorphous state , the TE mode is bound in the Si waveguide. While GST is at crystalline state, the TE mode moves up. Due to the small extinction coefficient of a-GST in the C-band (1525nm-1565nm), the light attenuation of a-GST at the top of the waveguide is small, indicating that most of the optical mode in the waveguide remains unchanged and the evanescent coupling with GST is weak. On the other hand, c-GST has a large complex refractive index in C-band. This results in a strong overlap between crystalline GST with high absorption and light field, which leads to a strong attenuation of light signal and a huge loss of light signal. The evanescent coupling between GST and silicon waveguide depends on the crystallization of GST.

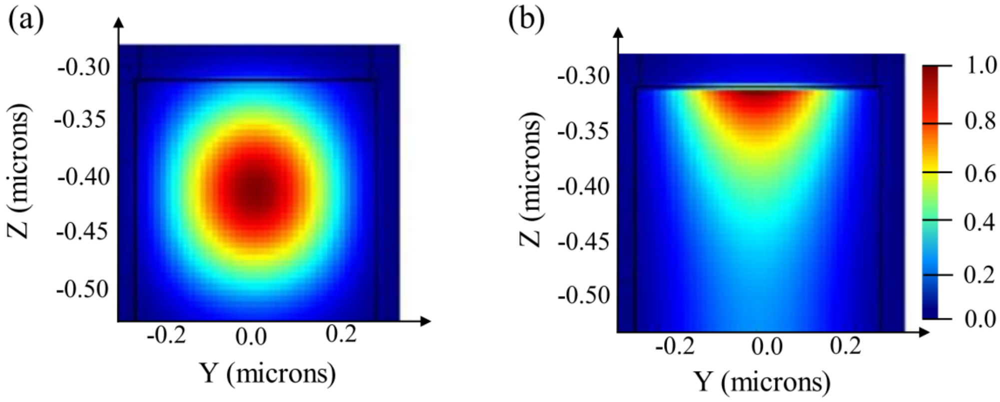

Fig.4. (a) Modal intensity profiles of Si waveguide loaded with a-GST, (b) Modal intensity profiles of Si waveguide loaded with c-GST

The complex refractive index of crystalline and amorphous GST varies greatly, which leads to the change of effective refractive index in Si-GST waveguide. For the modal solution, when GST is in amorphous phase, the effective index of the hybrid waveguide written as (ne1+i*ke1), while in crystalline phase, the effective index written as (ne2+i*ke2). The mode absorption loss α for each state can be calculated from the imaginary part of their effective index ke as

$$\alpha = 2 \times 10\log e \times (\frac{2\pi ke}{\lambda})$$

In the formula above, ke is the effective extinction coefficient of different crystal states, and the wavelength λ is 1.55μm.

Table 1 The simulated modal solution parameters

	n_e	k_e	Mode loss(dB/μm)
a-GST	2.59952	0.01406	0.4952
c-GST	3.14701	0.26009	9.1576

3.3. Propagation image in FDTD simulation

In order to determine the switching operation, 3-D FDTD was used to simulate the optical transmission of the designed parameters. Fig. 5 shows the light transmission when GST is in amorphous state and crystalline state, respectively. When GST is in low-loss amorphous state, the structure of the normal silicon waveguide and a GST-on-silicon waveguide can meet the phase-matching condition for TE polarization, leading to the cross-state. However, when GST transformed to crystalline state with larger mode loss, phase-matching condition is changed for the interface coupling between GST and Si waveguide which leading to the bar-state. Fig. 6 shows the partial enlarged view of Fig. 4, which shows the cross-state and the bar-state, respectively. From the enlarged figure, it can be seen that there are certain mode losses for both cross-state and bar-state. Fig. 7 shows the mode profile of 1×2 optical switch when GST at amorphous state and crystalline state.

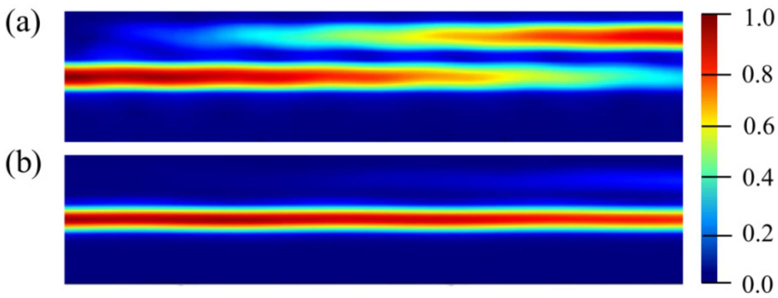

Fig.5. FDTD simulation optical field intensity distribution in the optical switch at the (a) amorphous (b) crystalline states.

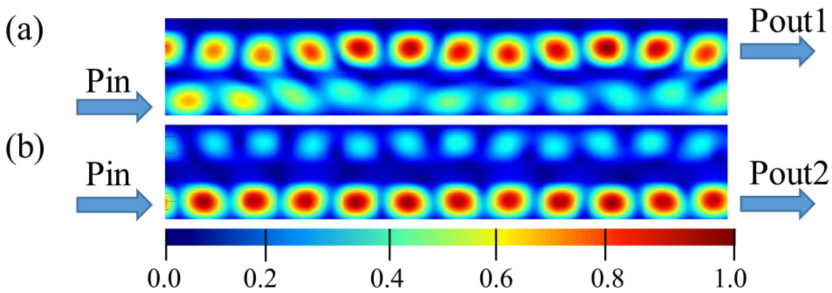

Fig. 6. The partial enlarged view of Fig. 4. (a) cross-state(b)bar-state.

Fig. 8 shows the transmission spectral response of the phase change optical switch simulated by FDTD. The insert losses of the amorphous state and the crystalline state were less than 0.5 dB in the wavelength range from 1530 nm to 1575 nm. At the amorphous state, the crosstalk of the optical switch in the wavelength range of 1530 nm to 1575 nm was from -19 to -15 dB. At the crystalline state, the crosstalk of the optical switch in the wavelength range of 1530 nm to 1575 nm was from -30 to -27 dB.

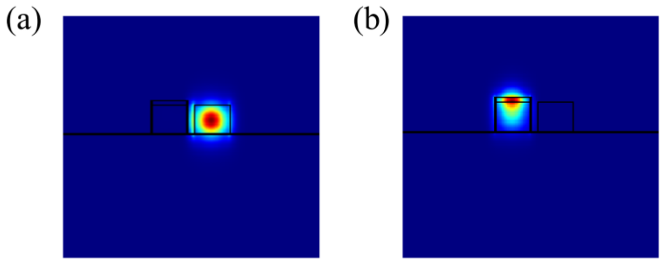

Fig. 7. The mode profile of the 1×2 optical switch when GST at (a) amorphous state (b)crystalline state.

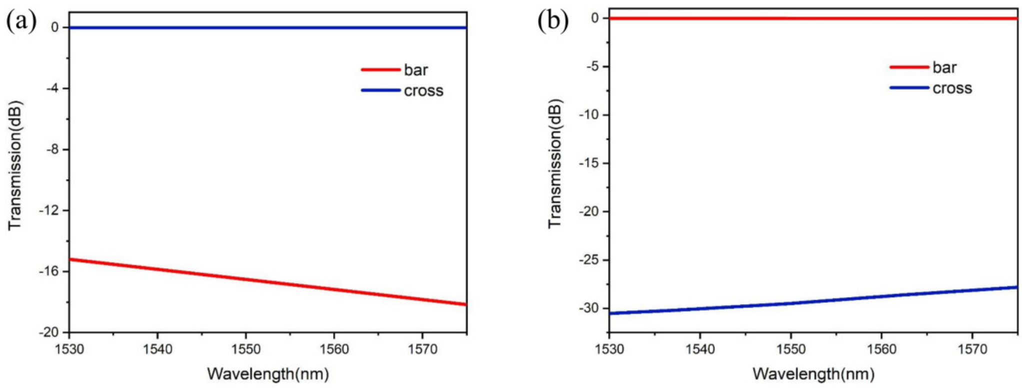

Fig. 8. The transmission spectra of the optical switch when GST at (a) amorphous state (b) crystalline state.

4. Conclusion

GST is a great material for optical switches due to its non-volatile high refractive index between amorphous and crystalline states. We have designed a compact 1×2 directional coupling optical switch with Si waveguide and a 30-nm-thick GST layer. Switching operation was demonstrated by 3D-FDTD method. As the simulation result, we have realized that the optical contrast of GST thin film can be used to reversibly turn the switch between two well-defined states. The switch shows cross-state and bar-state corresponding to amorphous GST (a-GST) and crystalline GST (c-GST), respectively. The insert loss was less than 0.5 dB. The crosstalk was -16 dB for a-GST and -29 dB for c-GST, respectively. More on chip photonics devices can be expected with PCMs, which would have a wide application prospect for future optical communication networks.

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