Ultrafast non-volatile 1x1 optical switch using phase change material Sc$_{0.2}$Sb$_2$Te$_3$

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Abstract. Phase change materials are widely used in photonic devices due to their extremely large optical properties. Phase change optical switches use the difference in refractive index between amorphous and crystalline states to achieve “on” and “off”. In this paper, we design a Si-Sc$_{0.2}$Sb$_2$Te$_3$ (SST) hybrid waveguide 1x1 optical switch. The finite element method was used to optimize the structural parameters of the device and the modal distribution of TE polarization was calculated. The transmission performance of the device is simulated by the FDTD method. In this case, a very compact, 2 µm long SST shows a large extinction ratio of more than 12 dB and over 100 nm bandwidth operation.

1. Introduction
Optical switch is an extreme component of photonics. Photonic devices based on SOI have great application prospects. For example, MZI interferometer$^{[1]}$, ring resonant cavity$^{[2]}$, optical switch$^{[3]}$, etc. Among them, optical switches including electro-optic (EO) switch$^{[4]}$, thermo-optic (TO) switch$^{[5]}$ and phase change optical switch$^{[6]}$ are widely studied and applied in the field of communication. Compared with EO switch and TO switch, phase-change optical switch has the advantages of all-optical$^{[7]}$, nonvolatile$^{[8]}$ and ultra-compact$^{[9]}$.

Phase change materials (PCMs) have great contrast between amorphous and crystalline states. For example, optical refractive index, electrical conductivity. The reversible transition between the two states makes phase-change materials the most promising candidates for photonic chips. PCMs possess the “self-holding” characteristics$^{[8]}$, and can maintain the state without extra energy. Therefore, the PCMs hybrid optical waveguide can realize non-volatile on-chip storage. The most typical phase change material used in optical switches is Ge$_2$Sb$_2$Te$_5$(GST). Phase change optical switch based on GST has been extensively studied for its outstanding characteristics such as high cycle number$^{[10]}$, good data retention capability$^{[11]}$, and nanosecond crystallization time$^{[12]}$. However, the nanosecond crystallization time of GST still restricts the key problem of photonic chip. In recent years, a new type
of phase change material Sc\(_{0.2}\)Sb\(_2\)Te\(_3\) (SST) has been studied\(^{[13]}\), which can implement the picosecond scale crystallization time without pre-programming. It is a promising candidate to improve the phase transition speed. However, research on the application of this phase-change material to devices has only studied in phase-change RAM\(^{[14]}\). The study of photonic devices combined with SST did not find. Here, we propose an optical switch that combines SST with an optical waveguide.

In this paper, we present a 1x1 optical switch based SST hybrid Si waveguide, which composes 220 nm Si claded 30 nm-thick SST film. It performs a large extinction ratio ~12 dB and stable in a wide range of 100 nm.

2. **Structure and design**

Figure 1 (a)-(b) shows the structure of the SST-based hybrid waveguide. The input source in the waveguide is TE polarized and propagates from one side of the silicon waveguide along the axial direction of the waveguide. The 1x1 optical switch geometric parameters of the are as follows: \(W_{Si}=220\) nm, \(L_{sst}=2\) µm, \(W_{sst}=450\) nm, The height of SST is defined as \(H_{sst}\), and \(H_{sst}=30\) nm. The cross section of the phase change material at the junction with the waveguide is shown in Figure 1 (b).

![Figure 1](image_url)

Figure 1. Structure diagram of device.(a) Schematic diagram of 1x1 optical switch based on silicon waveguide and phase change material SST. (b) cross-section of optical switch.

3. **Results and discussion**

3.1 **Properties of SST**

In order to characterize the properties of the material, we calculated and tested the refractive index and XRD of the SST film.

Figure 2 (a) shows the refractive index and extinction coefficient of the material using the principle of ab initio calculation from 250 nm to 2000 nm. As can be seen, SST has a large optical contrast of \(n\) and \(k\), the real and imaginary parts of the refractive index, respectively. In the amorphous state, the refractive index coefficient \(n\) and the extinction coefficient \(k\) are relatively small. In the crystalline state, the index of refraction is bigger. The phase change optical switch uses this characteristic to turn the input signal “on” and “off”. Figure 2(b) Shows X-ray diffraction patterns of SST films in the amorphous and crystalline states. Amorphous films are deposited by magnetron sputtering. Crystallization is obtained by isothermal annealing of the deposited film at 190°C for 10min. As can be seen from the figure, not only the amorphous peak but also the characteristic crystalline peak (0015) appears in the XRD pattern of the deposited film. However, the Sb\(_2\)Te\(_3\) film has an unstable amorphous phase \(^{[15]}\). We infer that this is due to doping with a small amount of Sc, and this feature still exists. It confirms that the deposited film has some grains and makes the SST film more conducive to crystallization. Whereinto, the characteristic peaks of crystal state are (009), (0015), (1010), (110), respectively.
3.2 **Analysis of light propagation**

Here we use FDTD to demonstrate the light field information of the optical switch based on the SST hybrid waveguide. The center wavelength of the incident light is at 1550 nm. The refractive index of SST extracted from Figure 1(a) at 1550 nm as $n_{\text{a-SST}} \approx 3.72+1.36i$ and $n_{\text{c-SST}} \approx 5.95+2.94i$. Meanwhile, the TE polarization mode distribution of the waveguide cross section is calculated using COMSOL.

In order to compare the control effects of the two phase states on light, Figure 3(a) shows the optical field intensity distribution along the transmission direction of the waveguide when SST is amorphous. At this time, the refractive index of the a-SST ($n=3.72$) is similar to that of the silicon ($n=3.48$) waveguide. The fundamental mode distribution is shown in Figure 3(c), which is basically constrained in the Si waveguide and the small extinction coefficient makes the absorption loss of this device small, so the transmittance becomes larger, and the "on" in the optical switch is realized. When SST is crystalline, its refractive index is much larger than that of Si, and the extinction coefficient is significantly increased, resulting in a strong coupling with the Si waveguide. In the case, the mode as shown in Figure 3(c) in the waveguide appears to move up to SST due to the change of effective refractive index. As the thickness of the SST film increases, the more the mode shifts.

At the communication wavelength of 1550 nm, the extinction ratio (ER) and insertion loss (IL) of SST is calculated by the formula $\text{ER} = \text{IL}_{\text{on}} - \text{IL}_{\text{off}}$, $\text{IL} = 10 \log \left( \frac{T_{\text{input}}}{T_{\text{output}}} \right)$. The IL of 30 nm-thick SST film in the amorphous and crystalline states are < 4 dB and ~16 dB, respectively. The ER is 12.1 dB. In the wavelength range of 1500~1600 nm, and the extinction ratio of optical switch is >12 dB (See Figure 3(d)). It can be seen that the optical switch based on SST has a great extinction ratio and 100 nm broadband operation can be achieved.

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**Figure 2.** SST characteristics. (a) refractive index and extinction coefficient of crystalline and amorphous Sc$_{0.2}$Sb$_2$Te$_3$. (b) XRD patterns of amorphous (deposited) and crystalline (190°C annealed) SST films.
Figure 3. Schematic diagram of simulation. (a) Electric field distribution diagram of light transmission of a-SST and (b) c-SST using FDTD. (c) cross-section of TE polarization mode for SST in the amorphous and crystalline. (d) amorphous and crystalline insertion loss (IL) and extinction ratio (ER).

4. Conclusion
In summary, we have designed a 1x1 phase change optical switch based on a novel phase change material. Optical switching operation of a 30 nm-thick SST hybrid Si waveguide was demonstrated using the FDTD. The mode distribution and effective refractive index of fundamental mode TE polarization were calculated by COMSOL. After optimization, the optical switch has a large extinction ratio ~12 dB. The operation can be stable over a wavelength range of about 100 nm. This provides a reference for the future application of SST in photonic devices.

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