MID-INFRARED NON-VOLATILE SILICON PHOTONIC SWITCHES USING $Ge_2Sb_2Te_5$ EMBEDDED IN SOI WAVEGUIDE

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Nadir Ali
Department of Physics
Indian Institute of Technology Roorkee
Roorkee, India 247667
nadir.dph2016@iitr.ac.in

Rajesh Kumar
Department of Physics
Indian Institute of Technology Roorkee
Roorkee, India 247667
rajeshfph@iitr.ac.in

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ABSTRACT

We report designs and simulations of nonvolatile photonic switches for emerging optical communication window around 2 $\mu$m wavelength. The switches are designed making use of CMOS compatible $Ge_2Sb_2Te_5$ phase change material embedded with in the silicon-on-insulator strip waveguide. The wavelength of operation is 2.1 $\mu$m. In a $1 \times 1$ waveguide switch, active material $Ge_2Sb_2Te_5$ is substituted in partially and fully etched silicon region of the waveguides. By optimizing the dimensions of active region, we show that a $1 \times 1$ switch of only 920 nm in active length can exhibit high extinction ratio of 34.04 dB when phase of $Ge_2Sb_2Te_5$ is altered from amorphous to crystalline and low insertion loss of 0.49 dB in ON state. The second device is a two waveguide $1 \times 2$ directional coupler switch where one of the silicon waveguides is partially etched and substituted with a 20 nm thick $Ge_2Sb_2Te_5$ in etched silicon region. The altering of $Ge_2Sb_2Te_5$ phases allows switching of the propagating mode from bar state to cross state and vice-versa. Simulations results show that the directional coupler switch has an extinction ratio of 18.59 dB with insertion loss of 1.90 dB for cross state. Device state is changed by injecting voltage pulses into the active region of the waveguide through the indium tin oxide electrodes deposited on top of the active region. Due to its nonvolatile nature, $Ge_2Sb_2Te_5$ consumes energy only during he phase transformation, and hence the energy consumption for the devices is of the order of sub nJ which is lower than the volatile electro-optical and all-optical switches.

Keywords Optical switching devices · electro-optical switches · directional coupler switches · integrated optics devices · phase change materials

1 Introduction

The internet data traffic over the fiber optic communication system has been increasing at an exponential rate which is estimated to be around 40% each year, because of widespread use of social networking, cloud computing and video streaming. Handling of this tremendous data relies on the underpinning infrastructure based on optical fibers, which is rapidly approaching its projected ultimate transmission capacity limit (1). Researches have proposed many solutions to avoid such capacity limitations. A radical solution proposed is to shift the optical communication wavelength to the $2 \mu$m wavelength region (2). The main reason for such a proposal is to have optical fibers with zero absorption loss by guiding light in air core and minimizing Rayleigh scattering loss by having higher wavelength of operation as the Rayleigh scattering has $\lambda^{-4}$ dependence. In fact such fibers have been developed though total propagation loss still need further improvement (3,4). These fibers have many attractive properties for optical communications such as low latency, ultra-low optical non-linearity, and low attenuation around 2 $\mu$m region. Moreover, with the experimental demonstration of high bandwidth thulium doped fiber amplifier (5), the 2 $\mu$m has emerged as a promising band for future optical communication. A range of different photonic components such as photo-detectors (6), lasers (7), modulators (8), and switches (9) operating around 2$\mu$m are required for the
realization of a complete optical transmission links. The optical switches are indispensable to control the flow of light within the optical network and needs to be realized in this band with high performance metrics. Also, the success of photonics technology will require replacing today’s individual discrete photonic components with integrated silicon based photonics (10, 11). Silicon (Si) is optically transparent at optical communications wavelengths, and it can be used to fabricate nanoscale waveguides and passive devices using the same CMOS manufacturing technology that has been used to make electronic integrated circuits (12).

Recently, a well-known phase change material Ge$_2$Sb$_2$Te$_5$ (GST) has drawn considerable attention owing to its good phase change behavior between amorphous (a-GST) and crystalline (c-GST) phases and large refractive index and absorption coefficient difference between these two phases. These properties provide a possibility for realizing GST based ultra-compact active optical devices (13). In addition, CMOS compatibility and high scalability of GST material makes it a good candidate for the application in the Si photonic integrated circuits (14, 15). Another interesting property of GST is the self-holding bistability i.e. no sustaining power is required for maintaining the two phases (16). The GST can be switched among its two phases using different approaches such as optical (17), electrical (18) or thermal pulses (19) with transition time of sub-nanoseconds (20).

At communication wavelength of 1.55 µm, GST based optical devices have high optical insertion losses in the range of 2-3 dB because of high extinction coefficient (k = 0.12) of GST in the amorphous phase (21, 22, 23, 24). Fortunately, GST possesses much lower values of extinction coefficient in the wavelength region of 1.8-2.2 µm and has a minimum at 2.1 µm (9). Therefore, GST based active optical components with low optical attenuation and ultra-compact footprint can be realized in the Mid-IR region, and these switches in the Mid-IR region remains to be explored.

![Figure 1: Schematic structure of GST based 1 × 1 waveguide switch with cross-section view and modal profile of active waveguide. (a) Switch with GST substituted in fully etched silicon waveguide, and (b) GST substituted in partially etched silicon waveguide.](image)

The most common approach for the designing of 1 × 1 optical switch is to cover Si waveguide with GST cladding (16, 21, 22, 23). Although this approach is relatively convenient from fabrication point of view, but the light-matter interaction between the guided mode and the GST is weak because only the evanescent field of the propagating mode interacts with the GST (25, 26, 27). In another approach, fixed thickness GST layers are embedded in doped Si channel waveguides (9, 28). In this configuration, the guided mode directly interacts with the GST, but due to small thickness of the GST layer the devices footprints are quite large.

There are many features of the GST-Si hybrid waveguides based structures remain to be studied. For example, a good trade-off between the extinction ratio and insertion loss can be achieved by optimizing the GST structure and its geometrical parameters. The power consumption of the GST based optical active devices can also be reduced by optimizing GST dimensions. In this paper, we propose a simple and effective design of GST-Si waveguide for the realization of 1 × 1 and 1 × 2 switches and consider optimization of the GST dimensions.

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The rest of the paper is organized as follows. In section II, we introduce the design of single mode Si waveguide at 2.1 μm, and describe the proposed 1 × 1 waveguide switch and 1 × 2 directional coupler switch. The various parameters evaluated to investigate the switches performance are also described in section II. The third section presents the results obtained by performing electromagnetic and thermal simulations. Also, the switching method, and the voltages and energy needed for the GST phase transformation are reported in section III. Finally, the conclusions are presented in section IV.

2 Designs and Simulations

The devices designed here are 1 × 1 waveguide switch and 1 × 2 directional coupler switch. Both devices are designed using single mode silicon-on-insulator strip waveguide having a cross-section of 800 nm × 400 nm (w × h) and operating at 2.1 μm.

2.1 1 x 1 photonic waveguide switch

The schematic in Fig.1 shows Si-based 1 × 1 photonic waveguide switch. The active material GST is substituted with two different ways in the Si waveguide as shown in cross-section view of Fig.1(a) and (b). In the Fig.1(a), the Si waveguide is completely etched in the middle and substituted with GST. The height of the GST is denoted as h_{GST} and width is same as Si waveguide. Whereas in Fig.1(b), the GST is substituted within the partially etched region of Si waveguide. In etched part, h_{GST} and h_{Si} denote heights of the GST layer and the partially etched Si layer, respectively. For both cases, l_{GST} is the length of the GST substituted within the Si waveguide. The electric field profile with amorphous and crystalline phase of GST substituted in fully and partially etched Si waveguide is shown in Fig.1(a) and (b), respectively. Switch static performance is optimized by varying dimensions of the GST layer. Static performance is evaluated in terms of IL and ER. These parameters are calculated by obtaining transmission of the device for both of the GST phases. In our case, insertion loss is defined for the ON state as IL = 10 log(T_{ON}), and extinction ratio as ER = 10 log(T_{ON}/T_{OFF}), where T_{ON} denotes transmission when GST is amorphous phase and T_{OFF} denotes transmission when the GST is in crystalline phase. For electrically controlled switching performance indium-tin-oxide (ITO) electrodes of thickness 50 nm are placed on the top of the GST and on the either side of the active waveguide region of length l_{GST} for the phase transformation of GST from a-GST to c-GST and vice-versa (23). The ITO is chosen as an electrode material as its deposition temperature is around 300 °C. This temperature is compatible with CMOS process and hence ITO as an electrode material can be introduced in CMOS fabrication process (29).

2.2 1 x 2 directional coupler switch

Figure 2 shows the designed 1 × 2 photonic directional coupler switch, which, for simplicity only depicts the active region of directional coupler consisting of two parallel coupling waveguides. The cross sectional view of the two waveguides is depicted in Fig.2(b), where one of the Si waveguides is partially etched and substituted with 20 nm thick GST into it. The gap between the two parallel waveguide is labelled as g. By starting the value of g from 50 nm and
obtaining the optical power transmission for both phases of GST, we calculated the characteristic parameters such as coupling ratio (CR) = \( P_{\text{cross}}/(P_{\text{cross}} + P_{\text{bar}}) \); excess loss (EL) = \( 10 \log \left(\frac{P_{\text{i}}}{P_{\text{cross}} + P_{\text{bar}}}\right) \); and insertion losses IL, \( IL_{\text{cross}} = 10 \log \left(\frac{P_{\text{i}}}{P_{\text{cross}}}\right) \) and \( IL_{\text{bar}} = 10 \log \left(\frac{P_{\text{i}}}{P_{\text{bar}}}\right) \), where \( P_{\text{i}} \) denotes the input power and \( P_{\text{bar}} \) and \( P_{\text{cross}} \) denotes the output power for bar and cross state of the switch, respectively. As in the previous case, ITO electrodes are used for applying voltage pulses for the phase transformation of GST.

For the results to follow, the electromagnetic simulations are performed using finite integration method solver CST Microwave studio with perfectly matched layer boundary conditions. The indices of GST are taken as 4.05 + i0.006 (a-GST) and 6.80+ i0.40 (c-GST) \((28)\), the index of ITO as 1.84 + i0.019 \((30)\), and the indices of \( \text{SiO}_2 \), Si and air are set to 1.45, 3.48 and 1, respectively at the wavelength of 2.1 \( \mu \)m. Thermal simulations are performed using co-simulation in Multiphysics module of CST microwave studio software which are based on finite element method. Open boundary conditions are used for the thermal simulations. Materials properties used for the thermal simulations are taken from \((31; 32; 33)\) and are enlisted in Table I.

### 3 Analysis and Results

Optical and thermal simulations are carried out to analyze the switches static and dynamic performance.

#### 3.1 Optical Simulations

For optical simulations, we used an electromagnetic equation solver based on finite integration technique. Figure 3(a) shows IL values of switch as a function of \( h_{\text{GST}} \) and \( l_{\text{GST}} \) for the switch structure of Fig. 1(a). As can be seen from Fig. 3(a) the variation of IL values is quite large for \( h_{\text{GST}} <80 \) nm, corresponding to the propagation of guided mode through the air column which results in large scattering and reflection at the interfaces of air-Si, GST-Si and air-GST. The maximum ER obtained is limited to \( \sim 14 \) dB as can be seen from Fig. 3(b). The negative values of ER for \( h_{\text{GST}} <40 \) nm and \( l_{\text{GST}} >540 \) nm are because c-GST with higher refractive index provides slightly better guidance...
than a-GST phase. While both phases of GST have negligible absorption for $h_{GST} < 40$ nm. Accordingly, we selected the dimensions of GST for which the ER is maximum and performed 3D time domain simulation to calculate the propagating mode electric field profile of the switch. Figure 4 illustrate the ON and OFF state of switch corresponding to the maximum ER of $\sim 14$ dB and IL of 1.36 dB with GST of volume $1020 \text{ nm} \times 800 \text{ nm} \times 240 \text{ nm}$ (length $\times$ width $\times$ height $l \times w \times h$).

For obtaining low IL and high ER, we propose an improved design of switch with partially etched Si waveguide substituted with GST as shown in Fig. 2(b). Figure 5 illustrates the IL and ER for the improved switch design as a function of $l_{GST}$, $h_{GST}$ and $h_{Si}$. The $h_{GST}$ and $h_{Si}$ are varied such that the total height ($h_{GST} + h_{Si}$) is always equal to 400 nm. As can be seen from Fig. 5(a), the IL is decreased by $\sim 14$ dB. And at the same time the maximum ER is increased to $\sim 34$ dB as depicted in Fig. 5(b). Also, the back reflection from Si-GST interfaces is low in this configuration with -16.71 dB in a-GST and -28.73 dB in c-GST as compared to -11.98 dB and -26.73 dB, respectively in the previous case. The optimized dimensions of GST are $920 \text{ nm} \times 800 \text{ nm} \times 260 \text{ nm}$ ($l \times w \times h$), which corresponds to the maximum ER of 34.04 dB with low IL of 0.49 dB. The electric field profile for the optimized dimension of switch for ON and OFF state is shown in Fig. 6(a) and (b), respectively.

In case of $1 \times 2$ directional coupler switch, we plotted the output power emerging from the bar and cross port as

![Electric field profile with optimized values of GST dimensions incorporated in fully etched silicon waveguide](image)

**Figure 4:** Electric field profile with optimized values of GST dimensions incorporated in fully etched silicon waveguide for (a) a-GST and (b) c-GST.

![Contour plots of (a) IL and (b) ER as a function of $h_{GST}$, $h_{Si}$ and $l_{GST}$ for GST incorporated partially etched silicon waveguide switch.](image)

**Figure 5:** Contour plots of (a) IL and (b) ER as a function of $h_{GST}$, $h_{Si}$ and $l_{GST}$ for GST incorporated partially etched silicon waveguide switch.
Figure 6: Electric field profile of partially etched silicon waveguide substituted with optimized values of GST dimensions for (b) a-GST and (c) c-GST.

Figure 7: (a) Normalized power as a function of device length $l_{GST}$ with $g = 100$ nm (as one example). Optical power distribution (top view) of $1 \times 2$ directional coupler switch for (b) amorphous and (c) crystalline phases of GST.

a function of device length $l_{GST}$. Using these plots, coupling length $l_c$ are obtained for different values of $g$. The calculated normalized optical power with value of $g = 100$ nm for both phases of the GST is plotted in Fig[7](a). In amorphous phase, the light launched from Si waveguide couples to the a-GST-Si waveguide after traveling a distance equal to the coupling length $l_c = 52 \mu m$ with a coupling ratio of 85.56 %. However, in crystalline phase, almost all the light remains in the Si waveguide for $l_{GST} = l_c$, and coupling ratio is just $\sim 1\%$. We calculated the performance parameters of the switch after analyzing the simulation results listed in Table 2. In this table, coupling length is calculated for only amorphous phase, and gap, CR, EL, and IL are calculated for both amorphous and crystalline phases. As can be seen clearly from the table that in both phases the CR decreases as value of gap increases. This is due to the dependence of power transmission along the device length on the optical phase matching and absorption in material. These two factors are also responsible for the ripple behaviour in output power shown in Fig[7](a). We selected the optimized value of $g$ by considering device fabrication limitations and performance. The switch corresponding to the optimized value of $g = 100$ nm provide ER of 18.59 dB in cross state and 8.33 dB in bar state with GST of volume 52 $\mu m \times 20$ nm $\times 800$ nm ($l \times w \times h$). The insertion loss is 1.90 dB and 1.33 dB for the cross and bar state, respectively.

3.2 Thermal Simulations

In this section we present the thermal response of the devices with optimized GST dimensions. By applying the voltage pulses into the active region of waveguide, we obtained corresponding energy values required for the complete GST phase transformation. The phase transition of GST involves two processes viz. crystallization and amorphization. First, we performed the analysis of $1 \times 1$ waveguide switch. We started with amorphous phase of GST and transformed
Table 2: Calculated Parameters of $1 \times 2$ Directional Coupler Switch With Amorphous and Crystalline Phases of GST.

| Gap (nm) | Coupling length ($\mu$m) | Amorphous | | Crystalline | |
|---|---|---|---|---|---|
| g | l_c | CR | EL (dB) | IL_{cross} (dB) | IL_{bar} (dB) | CR | EL (dB) | IL_{cross} (dB) | IL_{bar} (dB) |
| 50 | 36 | 92.00 | 1.07 | 1.77 | 9.83 | 1.04 | 1.13 | 20.02 | 1.18 |
| 75 | 42 | 91.64 | 1.08 | 1.52 | 11.92 | 1.60 | 1.23 | 18.95 | 1.33 |
| 100 | 52 | 85.56 | 1.1 | 1.90 | 9.66 | 1.10 | 1.13 | 20.49 | 1.33 |
| 125 | 56 | 79.78 | 1.22 | 2.24 | 8.18 | 0.83 | 1.18 | 22.06 | 1.28 |
| 150 | 65 | 73.88 | 1.41 | 2.72 | 7.22 | 0.57 | 1.39 | 23.91 | 1.37 |
| 175 | 73 | 57.14 | 1.54 | 3.95 | 5.10 | 0.27 | 1.41 | 26.75 | 1.39 |
| 200 | 82 | 47.05 | 1.66 | 4.76 | 4.42 | 0.19 | 1.53 | 28.43 | 1.48 |

Figure 8: Spatial thermal distribution of temperature rise in $1 \times 1$ waveguide switch for the process of (a) crystallization and (b) amorphization.

...it into crystalline phase. This process of crystallization requires a voltage pulse of 100 ns duration to raise the GST temperature above 140 °C but below 540 °C, that is the melting temperature of GST [34]. In our simulation, a 100 ns duration 5 V pulse is applied through the ITO electrodes, which raised the temperature to 210 °C, i.e.; above 140 °C but below 540 °C. The energy consumption corresponding to the applied voltage is 19.7 nJ. The spatial temperature distribution of switch for the process of crystallization is shown in Fig.8(a). By analyzing the three dimensional thermal profile of GST, we concluded that the whole GST region temperature rises above the transition temperature. The process of amorphization requires a 10 ns voltage pulse to raise the GST temperature above the melting temperature of 546 °C [35]. We applied a 7 V pulse of 10 ns duration, which increased the maximum temperature of GST to 962 °C, well above the 546 °C. We observed that complete GST region temperature rose to 645.6 °C, and energy consumed during the proces is 22.9 nJ. Spatial thermal distribution of temperature for the process of amorphization is shown in Fig.8(b).

For $1 \times 2$ directional coupler switch same procedure is used for transition of GST as used in $1 \times 1$ waveguide switch. The voltage induced temperature rise in directional coupler switch of 100 nm gap and coupling length of 52 $\mu$m is simulated. For the process of crystallization, we applied a voltage pulse of 17 V which rose the average temperature of the GST to 572.4 °C, well above the melting temperature of GST. The value of energy obtained for the applied voltage pulse is 36.08 nJ. For the reverse process, we employed a voltage pulse of 7 V for the time duration of 100 ns, which rose temperature to 159 °C as required for the process of crystallization. The energy consumed corresponding to the applied voltage is 388.9 nJ. The thermal profiles for the processes of crystallization and amorphization are shown in Fig.9(a) and (b), respectively.
4 CONCLUSIONS

In summary, we proposed and theoretically analyzed ultra-compact, low-loss electro-optic switches using phase change material Ge$_2$Sb$_2$Te$_5$ substituted in silicon strip waveguide operating at Mid-IR wavelength of 2.1 $\mu$m. This work lead to conclusion that an energy efficient 1 $\times$ 1 waveguide switch with good trade-off between the ER and IL can be achieved by optimizing the GST cell. We achieved high ER of 34.08 dB with low IL of 0.46 dB with nanoscale GST dimensions of 920 nm $\times$ 800 nm $\times$ 260 nm (l $\times$ w $\times$ h). The energy consumption per switching cycle is 42.6 nJ, and due to the self-holding nature of GST, the switch states are self-sustained without static power. The designed 1 $\times$ 2 directional coupler length of 52 $\mu$m is compact in comparison to the previously reported GST based three and four waveguide directional coupler switches. Simulation results show that the directional coupler switch has an ER of 18.59 dB in the cross state and 8.33 dB in the bar state. The IL is 1.90 and 1.33 dB for the cross and bar states, respectively. Our devices are easy to be implemented using the standard CMOS fabrication process. This work will be helpful for the experimental realization of GST based hybrid ultra-compact and non-volatile electro-optical switches for communication applications around 2 $\mu$m.

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