Non-Volatile, Reconfigurable, Zero-Static Power Optical Routing for Transistor-Laser-Based Electronic-Photonic Processing

Kaidong Peng, Aditi Udupa, and Lynford L. Goddard

*Photonic Systems Laboratory, Department of Electrical and Computer Engineering, Micro and Nanotechnology Laboratory, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA *lgoddard@illinois.edu*

Abstract: The ever-growing data traffic requires greater transmission bandwidth and better energy efficiency in chip scale interconnects. The emerging transistor-laser-based electronic-photonic processing platform stands out for its high electrical-to-optical efficiency. Because transistor lasers operate best at 980 nm, efficient optical interconnects at this wavelength need to be developed for such energy-efficient computing platforms. Phase change materials (PCMs) are good candidates for achieving non-volatile, reconfigurable, zero-static power optical switching. Having bi-stable states under room temperature, a PCM has its permittivity significantly different between its crystalline and amorphous phases. The authors propose to develop a reconfigurable 1 x 2 optical switch by utilizing low loss GeTe PCM to pave the way for the transistor-laser platform at 980 nm. The non-volatility of the proposed device will open up opportunities for other interesting applications such as non-volatile optical memory and the optical equivalence of the field programmable gate array (FPGA).

1. Introduction

A transistor laser is a transistor with a quantum well base that can emit electrical and optical signal outputs simultaneously [1]. Operating at near-infrared 980 nm, transistor lasers are highly energy-efficient in electrical-to-optical conversion. Transistor-laser-based electronic-photonic processing platforms are promising in reducing the energy consumed per processing operation by 100x over existing technology platforms. Thus, it is necessary to develop various other photonic devices to work with transistor lasers. Different physical mechanisms, including electro-absorption, quantum confined Stark effect (QCSE), acousto-optic, magneto-optic, and electro-optic effects, have been studied to achieve optical switching. Particularly, electro-optic modulation is one of the fastest methods, with demonstrated speeds as high as 160 Gbps [2]. Aside from high speed switching for modulation purposes, energy efficient, reconfigurable, and non-volatile optical routing topologies are also desirable for a number of other applications. Optical non-volatile memories will be a key component in the establishment of all-optical computing systems. Moreover, circuit repurposing provides great flexibilities in circuit design and rework.

Unlike high speed modulators, non-volatile switching elements are expected to maintain their state stably for an extended period of time. For very large-scale information systems and data centers, most switching methods described above are impractical in terms of power consumption. Phase change materials (PCMs) such as GeTe and $Ge_2Sb_2Te_5$ [3,4] are good candidates for zero-static power switching. A PCM typically has bi-stable states under room temperature, and its permittivity is significantly different between its crystalline and amorphous phases. Even if it demands a certain amount of activation energy to transform states, the time-averaged power due to activation becomes effectively zero. $Ge_2Sb_2Te_5$ has been investigated extensively to achieve non-volatile switching at 1550 nm because of its larger index contrast between its two structural states [4, 5]. For the 980-nm transistor laser platform, GeTe has lower loss and is thus preferable. Table 1 shows the Complex permittivity values of GeTe and $Ge_2Sb_2Te_5$ at 980 nm.

Table 1: Complex permittivity ε_r of $Ge_2Sb_2Te_5$ and GeTe at 980 nm. Data Courtesy of M. Wuttig.

Material	Crystalline	Amorphous
$Ge_2Sb_2Te_5$	$29.146 + 52.486i$	$20.056 + 8.590i$
GeTe	$36.507 + 52.183i$	$1.598 + 5.702i$

2. Device Design

We propose to use the GeTe PCM as a thin film patch on top of the silicon nitride (Si_3N_4) microring resonators to develop such reconfigurable, non-volatile optical switching elements at 980 nm. From Table 1, although GeTe has lower loss at 980 nm, its loss especially in the crystalline state is still too high to be used directly as the core material of a waveguide. Thus, GeTe is applied as a thin film on top of the Si_3N_4 waveguide. In addition, a very thin layer of SiO_2 is introduced between the Si_3N_4 waveguide and the GeTe film. The strength of the interaction between the GeTe film and the Si_3N_4 core on the mode profile can be controlled by adjusting the SiO_2 spacer thickness. Si_3N_4 waveguides are used instead of Si waveguides because Si is absorbing below 1100 nm [6]. The dimension of the Si_3N_4 core underneath the GeTe is chosen to be 900 nm x 400 nm based on the previous work of our colleague Shaneen Braswell. These Si_3N_4 waveguides are reasonable in size and have good optical confinement.

The indium-tin-oxide (ITO) metal heater design described in [7] is adapted to our device structure to transform GeTe from one PCM state to the other. Figure 1(a) provides a comprehensive view of the cross section of the design that incorporates the current-driven method setup. Benzocyclobutene (BCB) is used as the planarization polymer and applied onto the sample surface before the deposition of the ITO heater and Au metal contacts. This is to level the ITO and metal contacts across the features and promote good thermal conductivity and current flow at the junctions. The ITO heater is placed under and in direct contact with GeTe to transform the GeTe between states. The gold pads deposited on both sides of the ITO are used as electrical contacts. The GeTe layer is coated by a thin layer of sputtered SiO_2 to prevent ablation and oxidation of the GeTe. Figure 1(b) presents the top view of the add-drop ring resonator design. The dimensions of the different materials used in this design are presented in Table 2.

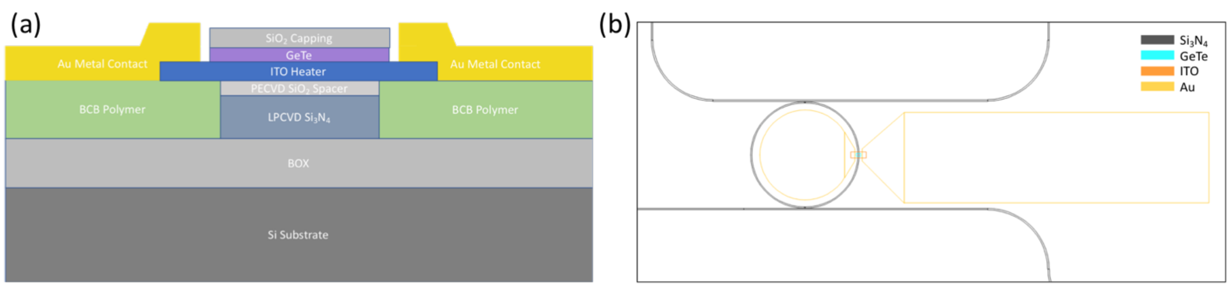

Figure 1: (a) Cross-section view of the current-driven design with an ITO heater and Au metal contacts. (b) Top view of the add-drop ring resonator design with GeTe and the current-driven setup.

Table 2: Geometrical parameters of Si_3N_4, ITO, GeTe, and Au metal contacts (Units: μm).

Material	Width	Length	Thickness
Si_3N_4	0.9	Varies	0.4
GeTe	3	2	0.015
ITO	10	4	0.03
Au Rectangle	200	60	0.4

3. Simulation Results

2D-axisymmetric effective index simulations of the fundamental TE and TM modes for the cross-section design shown in Figure 1(a) are first carried out using Comsol. The derived optical values are then utilized to determine some of the geometrical parameters listed in Table 2. Because the refractive index of GeTe is much higher than that of the Si_3N_4, the GeTe film has to be thin enough to avoid creating an optical mode inside the GeTe film. The mode profile of such a non-ideal device, which has a GeTe thickness greater than 20 nm, is shown in Figure 2. In the amorphous state, the mode is clearly confined in the GeTe layer instead of the Si_3N_4 core. This is undesirable because the large mode mismatch at the interface results in very minimal coupling. Therefore, we choose 15 nm GeTe and 20 nm SiO_2 spacer underneath to be the design from simulations. Figure 3 shows the fundamental TE and TM mode profiles of the GeTe incorporated geometry when GeTe is crystalline and amorphous, respectively.

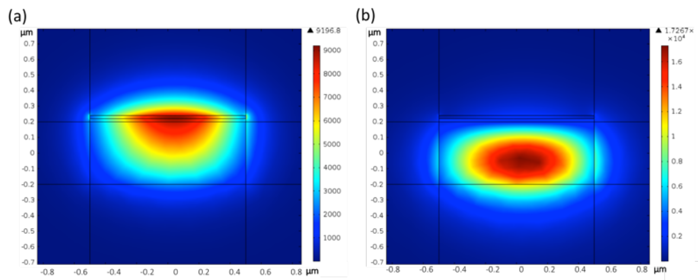

Figure 2: The mode profiles of the GeTe incorporated geometry for the fundamental TE mode with a 20-nm GeTe thickness in the (a) amorphous and the (b) crystalline state.

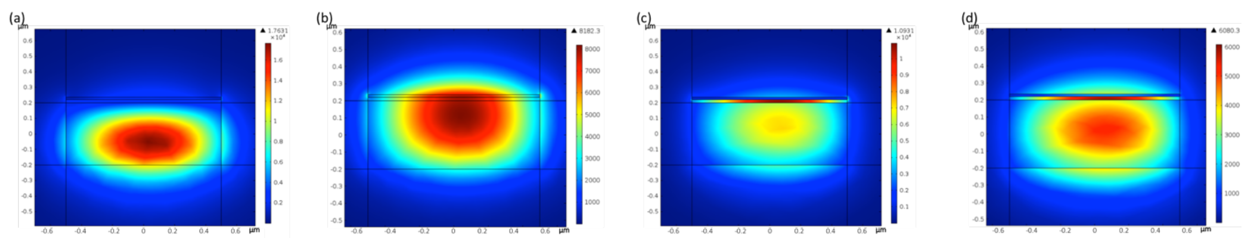

Figure 3: The mode profiles of the GeTe incorporated geometry for the fundamental (a) TE and (c) TM mode when GeTe is crystalline, and for the fundamental (b) TE and (d) TM mode when GeTe is amorphous, respectively.

When GeTe is in the crystalline state, the mode profile is more pushed away from the top of the Si_3N_4 core. This behavior is analog to a metallic waveguide, because the high refractive index of crystalline GeTe is close to that of a metal. When GeTe is in the amorphous state, the energy density of the mode profile is nearly evenly distributed from the Si_3N_4 core to the GeTe thin film. This is because the refractive index of the amorphous GeTe is low and more similar to that of a dielectric material. The difference in the mode profiles between the two bi-stable states of the GeTe results in a difference in the effective index of the structure. Table 3 shows the effective index and the attenuation constant of this structure in the two structural states of GeTe.

Table 3: Numerical values of refractive index and attenuation coefficient of the GeTe incorporated structure at 980 nm in crystalline and amorphous states.

Mode	Effective Index	Attenuation Constant
TE Amorphous	1.876	$5.162 \cdot 10^{-2}$
TE Crystalline	1.746	$2.361 \cdot 10^{-2}$
TM Amorphous	1.791	$6.850 \cdot 10^{-3}$
TM Crystalline	1.824	$2.917 \cdot 10^{-2}$

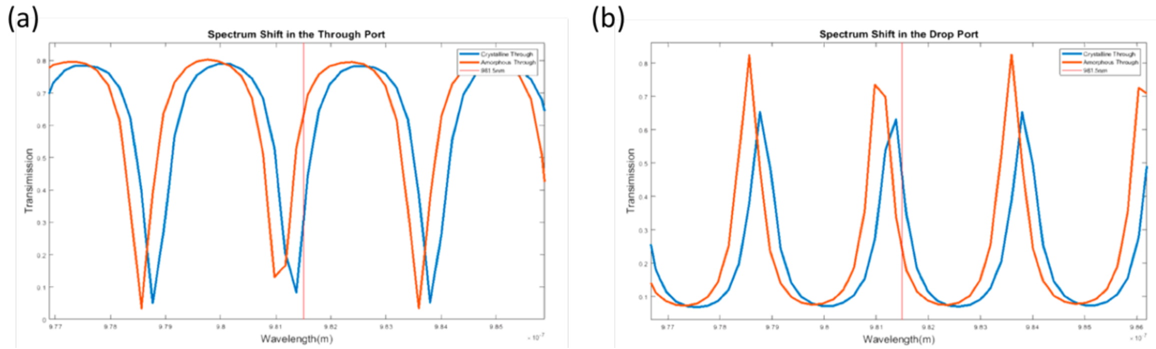

Figure 4: Shift in spectra of the proposed device at the (a) through and the (b) drop ports when GeTe is amorphous and crystalline near 980 nm.

3D FDTD simulations of the complete device design shown in Figure 1(b) are done in Lumerical. Figure 4 shows the spectra of the drop and through ports when GeTe is in its amorphous and crystalline states. Simulations suggest that less than 2.5 dB of loss can be achieved at the outputs. From Figure 4, the output spectra are indeed shifted when the GeTe patch is transformed from the amorphous state to the crystalline state. However, even if the GeTe patch is designed to be L_π long, the shift in the spectra is much smaller than π phase shift because of the reflections at the interfaces on the ring. Although the shift in the spectra is less than π, there is still a clear contrast at the output ports between the two structural states of GeTe. Overall, numerical simulations have demonstrated the feasibility of this approach.

4. Conclusions

In this work, a non-volatile, zero-static power, reconfigurable 1 x 2 optical switch at 980 nm was designed using the GeTe PCM. The large contrast in optical properties between the amorphous and the crystalline GeTe allows for a shift in the mode profile and hence effective index of the GeTe incorporated geometry between the two material states. FDTD simulations shows a shift at the output ports with loss less than 2.5 dB. Device fabrication should be carried out in the future to experimentally verify this design.

5. Acknowledgments

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