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# Non-volatile silicon photonic devices enabled by phase change material

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## ABSTRACT

*We review our recent research progress on silicon-$Ge_2Sb_2Te_5$ hybrid photonic devices. The optical transmission can be varied by 20 dB using micron-length GST. The inherent "self-holding" feature of GST make it attractive for low-power applications.*

**Keywords:** *silicon photonics, optical switch, optical memory, microring resonator*

## 1. INTRODUCTION

Phase change materials (PCMs) traditionally used in electrical memories have attracted considerable research interest in integrated photonics due to their high contrast in optical properties after phase transitions. They are one of the most promising candidates to overcome some of the fundamental limitations of today's silicon photonic devices. The commonly used PCMs include chalcogenide compounds (e.g., $Ge_2Sb_2Te_5$, GeTe, AgInSbTe) and transition metal oxides (e.g., $VO_2$, $NbO_2$). Different PCMs can exhibit distinct characteristics, including volatility, refractive index contrast before and after phase change, phase transition speed, etc.

Compared with other PCMs, $Ge_2Sb_2Te_5$ (GST) is the most mature one with fast crystallization speed, large optical and electrical contrast, and good reversibility between amorphous and crystalline states. At 168 °C, the GST film changes from amorphous to face-centered cubic (FCC) crystal structure. At 300 °C, the GST film changes from the FCC structure to the hexagonal structure (HEX). The amorphous GST film exhibits semiconductor characteristics, while the FCC and hexagonal crystalline films exhibit semi-metallic and metallic properties, respectively. The resistivity of the three phases changes greatly, resulting in distinct optical properties, i.e., the material refraction index. Usually electrical or optical pulses are used to heat GST to induce reversible phase transition between the amorphous and crystalline states. During the crystallization process (refractive index changes from low to high), it is necessary to apply a weak and wide pulse to locally heat up the GST. When the temperature of the material is between the crystallization temperature and the melting point, the GST will crystallize. On the other hand, during the amorphization process (refractive index changes from high to low), a strong and narrow pulse is applied to heat the GST to a temperature beyond the melting point of the material to break down the chemical bond. After a rapid cooling quenching process, the atoms in the phase change material in the molten state are less likely to be re-bonded and therefore form a short-range ordered, long-range disordered amorphous state.

High-quality GST film deposition is a key step in device fabrication. The thin film preparation methods include evaporation, sputtering, laser pulse deposition, etc. The basic requirement for thin film cladding on waveguide is high uniformity, smooth surface, correct material composition. In optical device operation, the optical signal must interact with GST, and therefore the optical power should not be high to induce phase change.

Here, we review our recent progress on Si-GST hybrid photonic devices in which the phase change is induced either by optical pulses or by electrical pulses [1-9]. The inherent "self-holding" feature of GST makes it attractive for ultra-compact Si-GST hybrid devices for applications in optical memristive switches, optical memory, and neuromorphic computing.

## 2. DEVICES AND RESUTLS

Fig. 1(a) shows a silicon asymmetric Mach–Zehnder interferometer (AMZI)-coupled ring resonator with GST integrated in the ring waveguide for all-optical resonance tuning [1]. The advantage of using an AMZI coupler lies in the fact that it is easier to achieve critical coupling by selecting a proper operation wavelength, and thereby a large switching extinction ratio can be achieved. The phase change of GST is enabled by applying a series of optical pump pulses. The pump pulse is chosen to be in the over-coupling regime, so that it can interact with the GST without suffering the narrow band filtering effect of the ring resonator. The probe light is chosen at the critical coupling wavelength which gives the maximum optical transmission contrast between the amorphous and crystalline states.

By controlling the power of the optical pulses, it is also possible to partially crystallize the GST, thereby increasing the tuning freedom. The all-optical switch achieves a transmission contrast of more than 20 dB with 2 μm long GST section, as shown in Fig. 1(b).

Fig. 1(c) shows the time response of the output transmission upon a phase change. It demonstrates that four and six distinguishable intermediate levels can be easily obtained by controlling the width of pump pulses and the number of pump pulses to realize partial crystallization of GST.

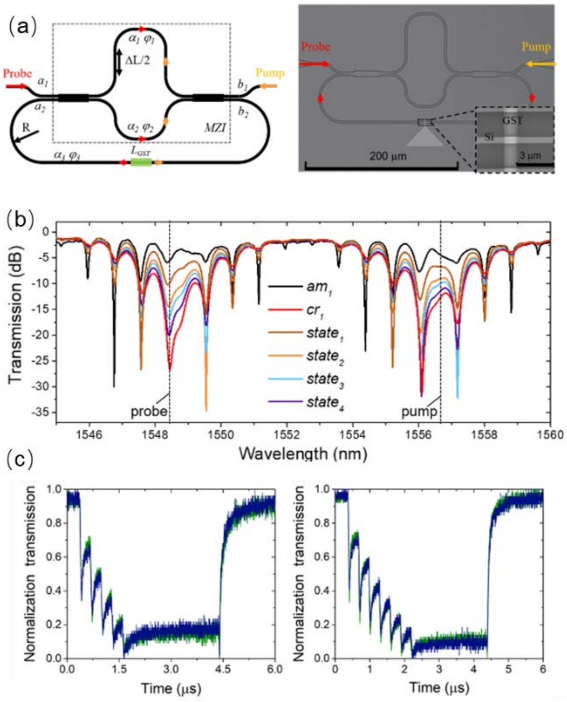

Fig. 1. (a) Schematic structure and SEM image of the AMZI-coupled ring resonator integrated with GST. (b) Intermediate transmission spectra when the GST is partially crystallized. (c) Temporal response of the device when a sequence of crystallization pulses followed by a single re-amorphization pulse is applied.

All-optical synapses can be formed based on GST-loaded microring resonators [2]. The optical transmission can be gradually increased (long-term potentiation, LTP) or decreased (long-term depression, LTD) due to phase change of GST in response to neuron spikes.

Fig. 2(a) shows the concept of optical synapses. When the GST changes from the amorphous state to the crystalline state, the GST-covered silicon waveguide has a higher light absorption loss. The optical transmission of the waveguide covered by GST can be effectively modulated by changing the GST phase state. The resonant effect of the microring resonator can amplify small changes to a detectable level.

We implemented three photonic synaptic structures (synapses I, II, III) based on microring resonators. Fig. 2(b) shows the experimental results. The first microring resonator works in the over-coupling regime for amorphous state and near the critical-coupling regime for the crystalline state. In this synapse, the crystallization of GST produces the synaptic LTD effect (weight decreasing). The second microring resonator (synapse II) works near the critical coupling regime for the amorphous state and in the under-coupling regime for the crystalline state. The crystallization process of synapse II produces the synaptic LTP effect (weight increasing). The third microring resonator device (synapse III) can realize both effects. the transmission level first drops and then rises, indicating that both the LTP and LTD effects can be generated at the same wavelength.

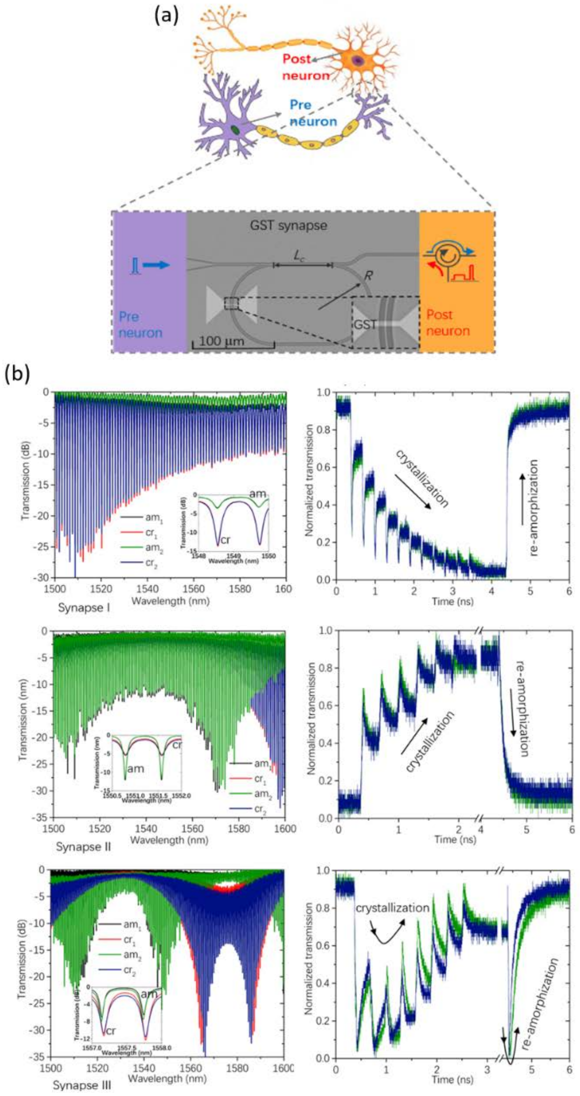

Fig. 2. (a) Structure of the neuron and synapse. Inset: illustration of the photonic synapse and the scanning electron microscope image of the device. (b) Measured transmission spectra of the all-optical synaptic devices over two phase-change cycles and temporal responses of the synaptic devices.

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In the above two devices, the phase change is enabled by optical pump pulses. In electrically reconfigurable photonic circuits, however, the phase change should be triggered by electrical pulses. We designed an electrically-driven Si-GST hybrid waveguide as shown in Fig. 3(a) [3]. A μm-sized GST is sandwiched between two electrodes made of a highly-doped silicon layer and an ITO layer. The active tuning is realized by applying electrical pulses to the GST to raise the temperature high enough to induce phase change.

Fig. 3(b) shows the change in transmission of over 20 dB upon repeated switching between the crystalline and amorphous states of the GST. It indicates the electrically-driven GST has good reversibility and high optical transmission contrast. The co-existed effects such as phase-change, free-carrier generation, and thermo-optic effects induced by the electrical pulses make the optical waveform more complex than the electrical waveform.

Multi-level electrical switching can also be realized by controlling the degree of crystallization using a sequence of set and reset electrical pulses, as shown in Fig. 3(c). The number of switching levels is currently limited by the noise of the photodetector.

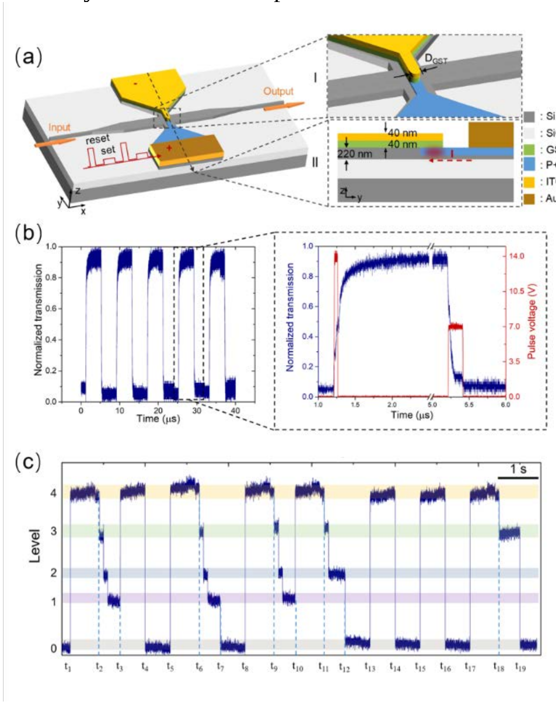

Fig. 3. (a) Schematic structure of the GST-loaded silicon waveguide. (b) Temporal response of the device with the 1-μm-long GST changed between amorphous and crystalline states. (c) Multi-level operation of the device showing the dynamic response to a sequence of set and reset pulses.

## 5. CONCLUSION

Most of the tunable silicon photonic devices demonstrated so far are volatile, which means that a voltage source is needed to maintain the device state. A non-volatile tuning method with a memory function is highly desirable to reduce static power consumption. The GST phase change can be induced by using a series of light pulses. When the GST is integrated in a ring resonator, the transmission contrast can be significantly amplified by the resonance effect. We obtained a 20 dB transmittance contrast between the amorphous and crystalline GST states in a ring resonator with a 2-μm long GST. Multi-level transmission can also be obtained by controlling the partial crystallization degree of the GST material. The phase change can also be triggered by using an electrical pulse based on the electrothermal effect. We implemented an optical memristive switch based on a silicon MMI structure with a nano-sized GST on top. The light transmission can be tuned in a controllable and repeatable manner with a maximum transmission contrast of more than 20 dB. These efforts are an important step toward implementing non-volatile photonic devices that consume significantly less power than traditional thermo-optic or electro-optic silicon photonic devices.

## 4. ACKNOWLEDGMENTS

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