Supplementary material

Miniature Multi-Level Optical Memristive Switch Using Phase Change Material

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S1. Fabrication process flow

The device was fabricated in an SOI wafer with a 220-nm-thick silicon layer on top of a 2-μm-thick buried oxide layer. The silicon waveguides were patterned by electron-beam lithography (EBL, VistecEBPG-5200+) with positive-tone resist (ZEP-520A). The waveguides were then etched by inductively coupled plasma (ICP, SPTS DRIE-I) with SF_6 and C_4F_8 gases. Next, a positive-tone 2-μm-thick electron-beam resist, PMMA, was coated and patterned to open the doping window for the following boron ion implantation. The ion implantation energy and dosage were 10 KeV and 3×10^{15} ions/cm^2, respectively. The wafer was then annealed at 1100°C for 15 seconds to activate the dopants. A double layer PMMA was spin-coated on the sample and a second EBL was performed to define the GST deposition window on top of the MMI. A stack of 30-nm/30-nm GST/ITO was deposited using a magnetron sputtering system followed by a lift-off process. The sputtering conditions are 15 sccm Ar and 30 W RF power for GST, 25 sccm Ar and 200 W DC power for ITO. Subsequently, the wafer was immersed in the buffered oxide etchant (BOE) for 15 seconds to remove the native oxide. A stack of metal layers composed of 20-nm-thick Cr and 100-nm-thick Au were deposited with evaporation to contact with the P^{++}-doped silicon region.

S2. Experimental setup

Figure S1 shows the experimental setup used for device characterization. The input light was continuous-wave light (CWL, Agilent, 81600B) at the 1550 nm wavelength. The power was fixed to a low level of -6 dBm so that the device spectrum could be measured without changing the phase of GST. The polarization of the input light was set to transverse electric (TE) polarization by using a manual fiber polarization controller (Thorlabs, CPC900). Light was then coupled into and out of the device through on-chip apodized grating couplers. The electrical pulses were generated from an arbitrary waveform generator (Agilent, 81150A) and applied to the Au electrodes via a pair of metal probes. The output light from the device can be switched for both static and dynamic measurements. Straight silicon waveguides were also measured as references. In the transmission spectrum measurement, the probe light after the device was directly detected by an optical detector. For the dynamic response measurement, the probe light after the device was further amplified by an erbium-doped fiber amplifier (EDFA, Amonics, AEDFA-23-B-FA) followed by an optical tunable filter (Dicon, TF-1550-3.2-9). The amplified optical signal was finally converted into an electrical one by a 1-GHz-bandwidth photodiode (Thorlabs, DET01CFC) and measured by an oscilloscope.

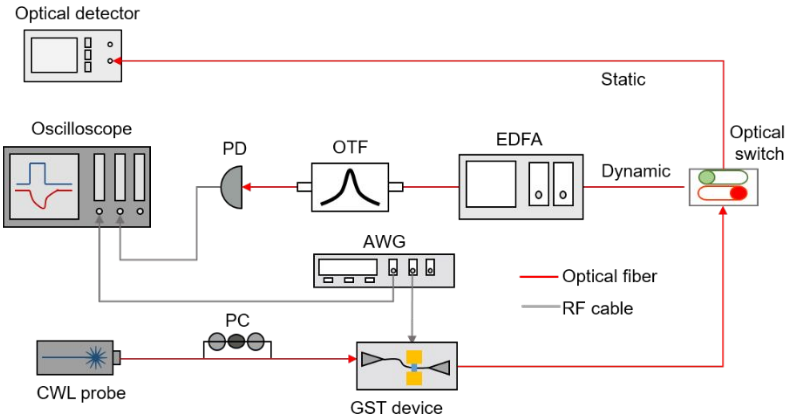

Figure S1. Experimental setup for device characterization. CWL: continuous-wave laser; PC: polarization controller; AWG: arbitrary waveform generator; EDFA: erbium-doped fiber amplifier; OTF: optical tunable filter; PD: photodiode.

S3. Transmission contrast

In Figure S2, we used a device with 1-μm-diameter GST to show the transmission spectra of the memristive switch for two phase-change cycles (two crystalline states and two amorphous states) over the wavelength range of 1500 nm to 1600 nm. The initial GST was crystalline (OFF-state), exhibiting low optical transmission. The re-amorphization (ON-state) of GST was then achieved by using a single 20-ns-wide Write pulse with a peak power of 520 mW. The device transmission loss was reduced from 11 dB to 1 dB at the 1550 nm wavelength. The crystallization of GST was performed by applying a single 100-ns-wide Erase pulse with a peak power of 90 mW. The original crystalline state was reached after one round of Write/Erase cycle. Both states can be maintained with good retention during the switching operation. The transmission contrast is defined as the output transmission difference between the amorphous and crystalline states. The insertion loss is defined as the transmission loss at the amorphous state. A switch with a low insertion loss and a high transmission contrast is highly demanded. This device exhibits a transmission contrast of 10 dB and an insertion loss of 1 dB. It should be noted that the device performance is affected mainly by two factors, namely, the degree of amorphization/crystallization and the size of GST.

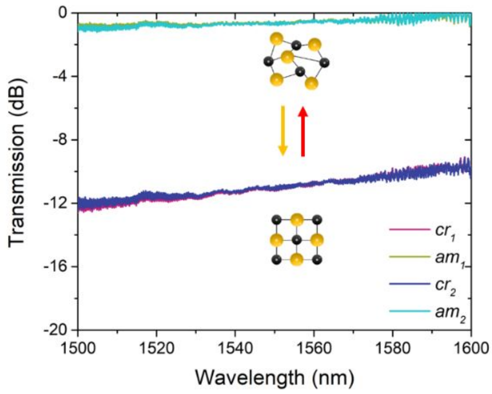

Figure S2. Measured transmission spectra of the device with 1-μm-diameter GST over two phase-change cycles.

S4. GST size effect on operation speed

The phase change is essentially enabled by resistive Joule heating to raise the GST temperature above the melting or crystallization point. Although experiments have shown that the phase change can be triggered by pulses with nanosecond and even sub-nanosecond durations, the amorphization process, however, requires higher heating energy, leading to a longer cooling time. Therefore, the response is slower for the Write process than for the Erase process.

Figures S3 (a) and (b) present the transmission dynamic responses to the Write and Erase pulses for three devices with different GST sizes. Although the Write pulse (duration 20 ns) is narrower than the Erase (100 ns duration), the response of the Write process is slower, as manifested by the slow rising tail after the electrical pulse. Moreover, for larger sizes of GST, the response time becomes longer. During the Erase process, the response time is comparable to the duration of the electrical pulse and is not sensitive to the GST size.

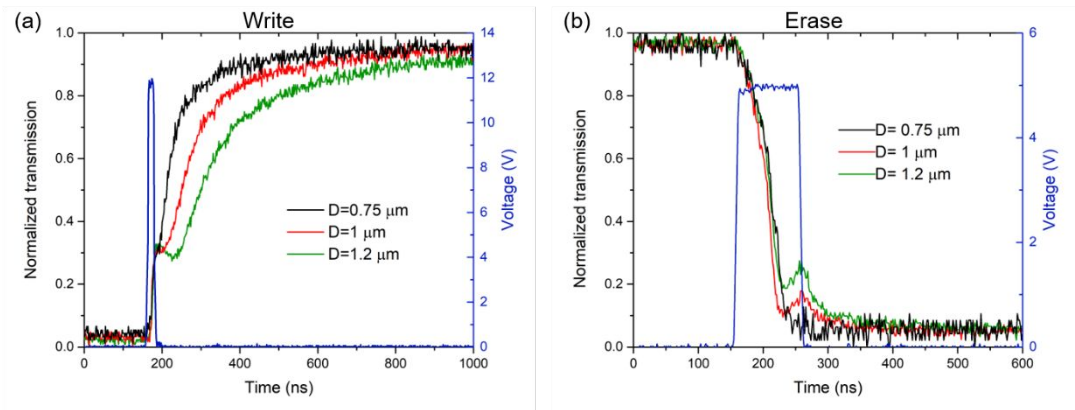

Figure S3. Transmission dynamics during (a) the amorphization and (b) the crystallization processes. The excitation electrical pulse energy is high enough to initiate the phase transition for different sizes of GST.

S5. All-optical phase change

Besides the electrical drive, the phase change of our device can also be driven by an optical pump pulse. Figure S4 shows the bi-directional pump & probe setup used to measure the all-optical switching. The pump laser light was firstly modulated by an electro-optic modulator (MZER-LN-20-40dB) driven by an arbitrary waveform generator (Agilent, 81150A) to generate optical pump pulses. The power of the pump pulses was high enough to heat the GST to its phase transition temperature. The probe laser light used to detect the optical transmission was a continuous-wave light at the 1550 nm wavelength with a low optical power of -6 dBm. The device that we measured has 1-μm-diameter GST.

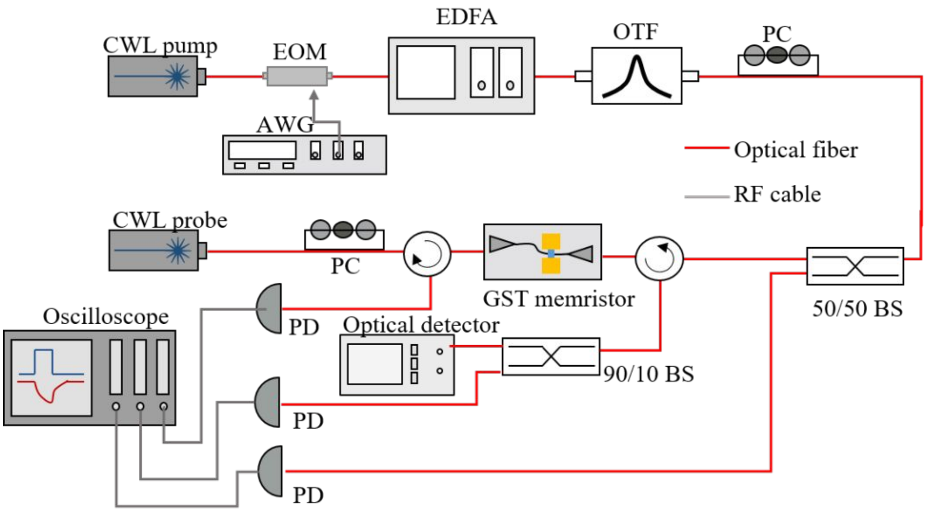

Figure S4. Experimental setup for all-optical switching. CWL: continuous-wave laser; EOM: electro-optic modulator; AWG: arbitrary waveform generator; EDFA: erbium-doped fiber amplifier; OTF: optical tunable filter; PC: polarization controller; PD: photodiode; BS: beam splitter.

Figure S5(a) shows the dynamic response of the probe light transmission during the GST crystallization process. The power of the optical pump pulse is fixed to 20.2 mW with increasing pulse width from 30 ns to 120 ns. The corresponding pump pulse energy increases from 0.61 nJ to 2.43 nJ. When the pulse energy is less than 0.61 nJ, the transmission first drops with the incoming of the pump pulse. Then, after the pump pulse, the transmission recovers to its original level. Over the duration of the pump pulse, the GST has no phase change. More optical energy is absorbed by GST to raise its temperature to the phase transition point when the pump pulse energy is further increased. Thus, GST is gradually crystallized. Figure S5(b) shows the transmission change as a function of pump pulse energy. It has a relatively linear response when the pulse energy is increased beyond the crystallization threshold energy.

Figure S5(c) shows the dynamic response of the probe light transmission for the amorphization process. The width of the optical pump pulse is fixed to 20 ns while the optical pulse power is increasing. When the energy of the optical pump pulse is high enough to heat up the GST to the melting temperature (~650 ^{o}C), the subsequent rapid quench makes GST amorphous, raising the optical transmission. The degree of amorphization is well controlled by carefully setting the pump pulse energy. Figure S5(d) shows that the transmission change has an almost linear response to the pulse energy.

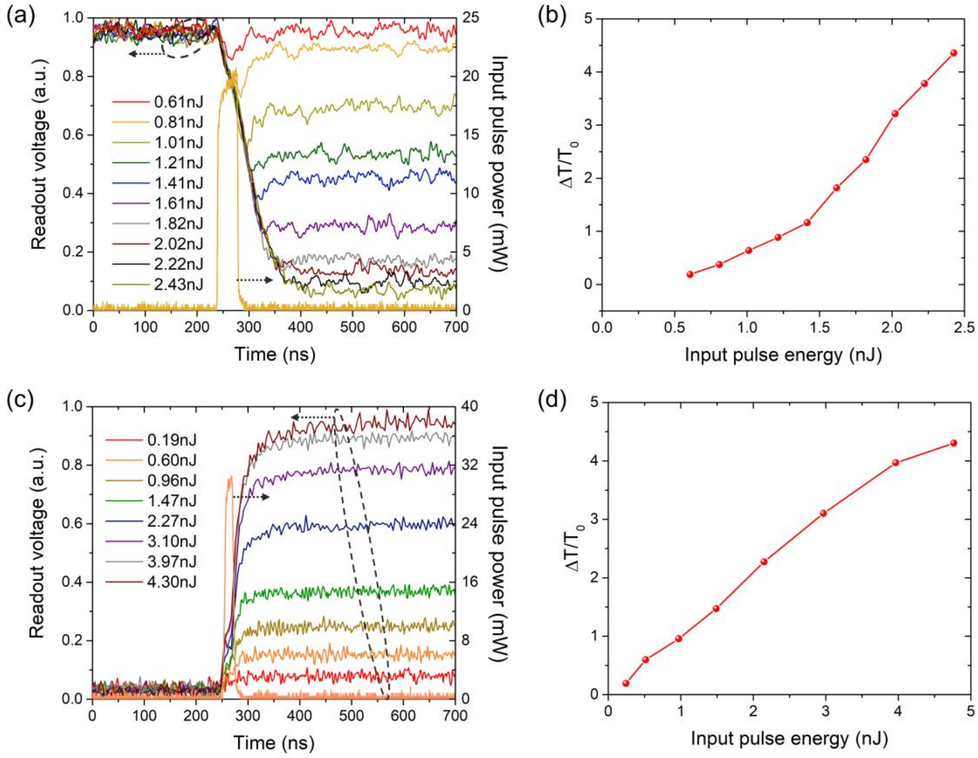

Figure S5 (a, b) Dynamic response of optical transmission during the crystallization process. (a) The input optical pulse has a fixed power and a varying duration. (b) The maximum transmission change varies with the pulse energy. (c, d) Dynamic response of optical transmission during the amorphization process. (c) The input optical pulse has a fixed duration and a varying power. (d) The maximum transmission change varies with the pulse energy.