

Nanoscale Optoelectronic Memory with Nonvolatile Phase-Change Photonics

Nathan Youngblood^{1,2,†,*}, Nikolaos Farmakidis^{1,†}, Xuan Li¹, and Harish Bhaskaran^{1,*}

¹University of Oxford, Department of Materials, Parks Road, Oxford OX1 3PH, UK

²Univ. of Pittsburgh, Dept. of Electrical and Computer Engineering, 3700 O'Hara St., Benedum Hall, Pittsburgh, PA 15261, USA

[†]These authors contributed equally to this work, *corresponding email: nay32@pitt.edu and harish.bhaskaran@materials.ox.ac.uk

Abstract: Waveguide-integrated plasmonic nanogap electrodes bridged by GST form a phase-change memory cell addressable in both the optical and electrical domains. Our hybrid memory cell reduces the footprint and switching energy by 100× and 2× respectively over prior works.

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1. Introduction

Phase-change chalcogenides, such as $\text{Ge}_2\text{Sb}_2\text{Te}_5$ (GST), are promising materials for both optical and electrical memory [1–4] with applications ranging from rewritable data storage [1, 2] to non-von Neumann computing [3, 4]. Key to the success of GST is a large contrast in both its optical and electrical properties ($\Delta n \sim 2$ and $\Delta \sigma \sim 10^3$) when switched between the amorphous and crystalline states. Additionally, GST is robust for billions of programming cycles and can reliably store data for over ten years at a time at room temperature [1]. While GST has separately enabled data storage and computation in both optical and electrical domains, no integrated device has been demonstrated which combines the advantages of both domains into a single memory cell. Here, we demonstrate a plasmonic waveguide-integrated, nonvolatile memory cell that can be programmed and read out both optically and electrically—enabling both optoelectronic memory and electro-optical conversion at the nanoscale.

2. Device design and fabrication

The concept of the hybrid optoelectronic memory cell is illustrated in Fig. 1A with a false-color SEM image of the fabricated device shown in Fig. 1B (blue material between Au electrodes is GST). In this device, both optical and electrical pulses can be used to either crystallize or amorphize the GST between the Au electrodes which modulates both the optical absorption and electrical conductance (see Fig. 1C). Once programmed, the memory cell can then be read out both optically and electrically. The tapered region between the waveguide and plasmonic nanogap converts the optical field from the waveguide to a plasmonic metal-dielectric-metal waveguide mode. Fig. 1D shows the cross-sectional mode profile in the nanogap for the case of both amorphous and crystalline GST. Enhanced light-matter interaction in the nanogap due to mode confinement and the reduced switching volume of the GST leads to a reduction in the minimum optical pulse energy required to observe a nonvolatile change in optical transmission (Fig. 1E). This is a 2× reduction of the minimum switching threshold over previous demonstrations of GST-based optical memory [2]. The field enhancement within the nanogap has the added benefit of increasing the optical sensitivity to small changes in the GST due to electrical switching (see Fig. 2).

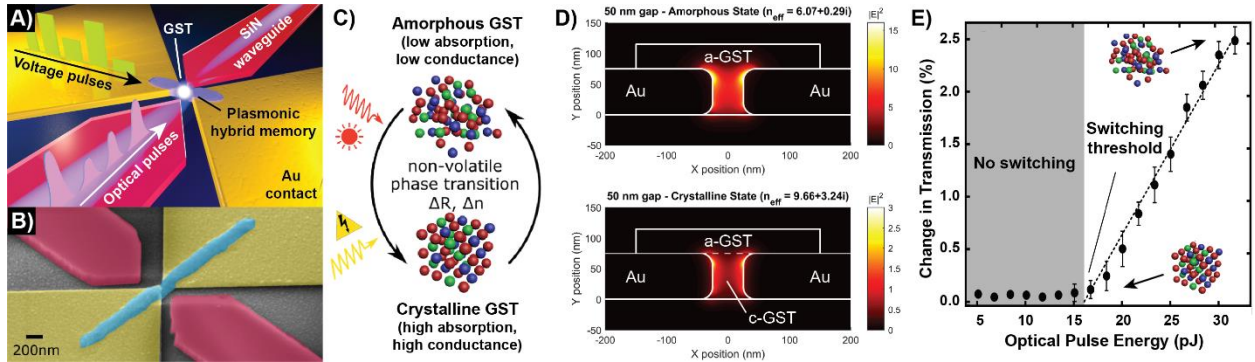


Figure 1: A) 3D illustration of plasmonic nanogap optoelectronic memory device. B) False color SEM image of a fabricated memory cell illustrated in A). C) A structural transformation between the amorphous and crystalline phases caused by either optical or electrical excitation results in a change in both the optical and electrical material properties. D) Cross-sectional simulations of the mode profile in the nanogap. E) The e-field enhancement and smaller switching volume of the plasmonic nanogap results in a low optical switching energy compared to previous work.

3. Experimental results

We have demonstrated the mixed-domain capabilities of our memory cell by using both optical pulses and electrical voltage pulses to switch between the crystalline and amorphous states. In Fig. 2A, we send sequential optical write and erase pulses to amorphize or crystallize the GST between the nanogap electrodes. We use a rectangular optical pulse (7.5 mW peak power for 8 ns) to reach an amorphous state and a piece-wise pulse (7.5 mW for 8 ns + 3 mW for 400 ns) to return to the crystalline state. We have used this optical programming scheme previously to encode multi-bit information in evanescently-coupled GST memory cells [5]. Interestingly, we see that the optical transmission increases when the GST is in a low-resistance (i.e. crystalline) state. We attribute this to the significant change in effective refractive index of the plasmonic mode (see Fig. 1D) which reduces the scattered and reflected light between the nanogap and plasmonic mode converter when GST is in the crystalline state, despite higher optical absorption.

In Fig. 2B, we see a similar trend when using voltage pulses to switch the state of the GST. We use rectangular voltage pulses (350 mV for 10 ns) to amorphize and triangular pulses (350 mV with a 5 ns/500 ns rise-fall time) to crystallize the GST. However, since the electrical resistance is dependent on forming and breaking conductive paths between the left- and right-hand Au contacts, a much smaller volume of GST can be switched between the amorphous and crystalline states while still achieving high on-off ratios (blue trace in Fig. 2B). The optical transmission, on the other hand, depends on the overlap between the optical mode and the volume of material switched. The fact that a measureable change in optical transmission can also be observed during the electrical switching of these nanoscale domains is a testament to the enhanced light-matter interaction in our device due to the nanogap. In Fig. 2C, we show that controlling the optical pulse amplitude (8 ns pulse width) can lead to multi-level data storage in our devices. Due to the stochastic nature of forming and breaking conductive paths, the electrical resistance (blue) shows a much more variable dependence on the optical pulse energy than the optical transmission (red).

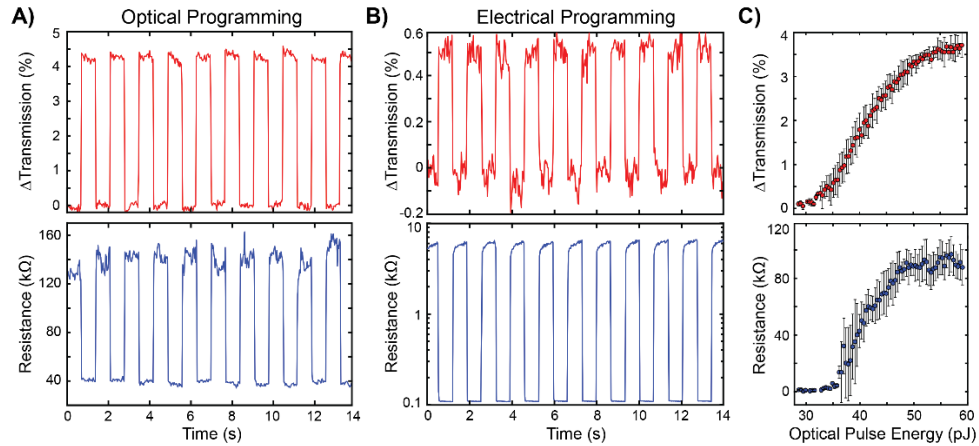


Figure 2: Simultaneous change in the optical transmission and electrical resistance read out during **A)** optical and **B)** electrical write/erase pulses. **C)** Change in nonvolatile transmission and resistance state as a function of optical pulse energy, allowing multi-level data storage in our nanogap device. Optical read out is less stochastic than electrical read out due to a dependence on the ratio of crystalline-to-amorphous volume, rather than a dependence on the conductive path between electrodes.

4. Conclusions

We have fabricated a nonvolatile plasmonic memory cell integrated on a waveguide that is fully addressable in both the optical and electrical domains. Our hybrid approach to optoelectronic memory uses plasmonics to overcome the limits of diffraction while using low-loss waveguides to route light to and from the nanoscale memory cell. Additionally, we are able to benefit from enhanced light-matter interaction in our device to reduce the optical switching energy while increasing sensitivity. The ability to control nonvolatile phase-change materials in both optical and electrical domains is expected to enable new devices for next generation memory and computation while reducing the footprint and power consumption of electrical-optical conversions.

5. References

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