Non-Volatile and Ultra-Compact Photonic Memory

(Student paper)

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ABSTRACT

In this work, we propose a non-volatile and ultra-compact photonic flash memory by utilizing a transparent conducting oxide (TCO) as a floating gate. The memory acts as a non-volatile electro-absorption switch and exploits the epsilon-near-zero regime (ENZ) of the TCO floating gate for enabling the switching between two states with low and high optical losses. Our simulation shows that, by means of applying +11 V and –11 V voltage pulses, the memory is programmed or erased, respectively. Additionally, for a 5-µm-long device, the memory features negligible insertion losses and an optical extinction ratio of 35 dB with an inherent broadband wavelength operation due to its non-resonant response. This device could pave the way for developing high-density photonic memory banks on the silicon photonics platform.

Keywords: optical memory, non-volatile, epsilon-near-zero, transparent conducting oxides, silicon photonics.

1. INTRODUCTION

The current lack of memory effect in the silicon photonics platform is one of the main drawbacks in comparison with electronic circuits. Recently, all-optical memories utilizing phase-change materials have been demonstrated to tackle the von Neumann bottleneck [1–2], but optoelectronic conversion is still required in most systems. Hence, on the electro-optic side, there have been some proposals relying on the same concept as that of electronic flash memories either by exploiting the silicon plasma dispersion effect [3–6] or by integrating 2D materials such as graphene [7] to induce the optical change. However, approaches relying on weak electro-optic effects impose a trade-off between the use of resonant, narrow band and relatively compact devices or non-resonant broadband but large footprint devices. On the other hand, the integration of atomically thin materials, such as graphene, by keeping their quality is challenging which increases the difficulty for high yield and large volume manufacturing.

Conversely, transparent conducting oxides, such as indium tin oxide (ITO) or Al-doped zinc oxide (AZO), exhibit an epsilon-near-zero regime in the near-infrared spectra. This effect can be electrically tuned by carrier injection and has been exploited for ultra-fast, high-energy efficient and ultra-compact electro-optic photonic modulators [8–10].

In this work, to the best of our knowledge, we propose for the first time the use of transparent conducting oxides for non-volatile photonic memories based on a floating gate. The photonic memory is electrically programmed/erased and optically read. Furthermore, our device features an ultra-compact footprint and a non-resonant broadband optical response by exploiting the ENZ state of the TCO floating gate.

2. DESIGN

Figure 1(a) illustrates the functionality of the non-volatile photonic memory. By applying either a positive or negative voltage pulse to the control gate, the photonic mode switches between a low-loss and high-loss state induced by the ENZ regime of the TCO floating gate. The ENZ state of the TCO floating gate is achieved by accumulating electrons via the Fowler-Nordheim quantum effect on the tunneling oxide layer.

The cross-section of the structure is depicted in Fig. 1(b) and consists of a standard 500 nm × 220 nm silicon strip waveguide electrically grounded. A 6-nm-thick Al_2O_3 layer on top of the waveguide is used as the tunneling oxide which has the capacity to handle breakdown voltages reaching 30 MV/cm [11]. The floating gate is formed by a 5-nm-thick ITO layer with a low free carrier density. A high-κ material for the blocking oxide is necessary in order to lower the programming/erasing voltages and improve the retention time. Thus, we choose a 5-nm-thick TiO_2 layer ($\varepsilon_{DC} = 80$) as the blocking oxide. The control gate is also formed by a 10-nm-thick ITO layer deposited at the same conditions as the ITO floating gate. The use of a TCO instead of a metal contributes to reduce the insertion losses due to the refractive index mismatch. Finally, the structure is surrounded by a SiO_2 cladding. Atomic layer deposition (ALD) can be used to form the Al_2O_3, ITO and TiO_2 layers and plasma-enhanced chemical vapour deposition (PECVD) to clad the structure with SiO_2.

From the electrical point of view, the memory acts as two capacitors in series when applying voltage pulses and as two parallel capacitors connected to a floating voltage induced by the accumulated charge when the control gate is grounded. Further details of the electrical model used in this work can be found in [7].

Once the floating gate is electrically programmed, it forms two accumulation layers in the ITO floating gate interfaces. These accumulation layers are reported to be between 1-5 nm [12]. Since our ITO floating gate layer is 5-nm-thick, we calculate the volumetric charge density (N_e) by averaging the surface charge density to the ITO floating gate thickness. Hence, by applying the Drude model we map ITO free carrier density to its refractive index in order to compute the optical modes and obtain the corresponding propagation losses for both memory states.

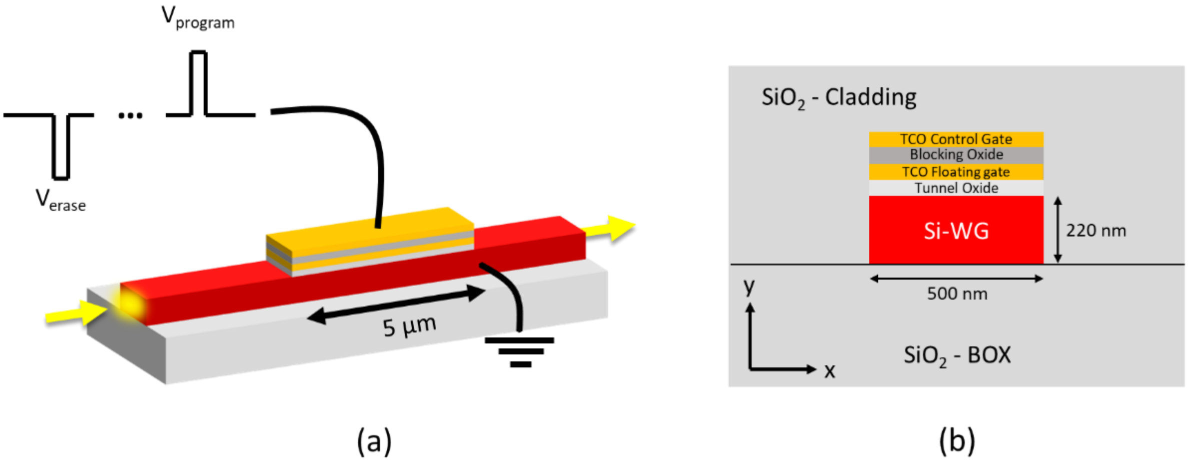

Figure 1. (a) Schematic of the ultra-compact (5µm-long) non-volatile photonic memory. The device shows a non-volatile electro-absorption switch when the memory is either programmed or erased by applying a positive or negative voltage pulse, respectively. (b) Cross-section of the memory. Tunneling and blocking oxide layers are made of Al_2O_3 and TiO_2, respectively. We choose ITO as the TCO for the floating and control gate with the following Drude parameters: $\varepsilon_\infty = 3.9$, $\Gamma = 5\times10^{13}$ rad/s, $m^* = 0.35m_e$ and $N_0 = 10^{19}$ cm^{-3}.

3. RESULTS

Figure 2(a) shows the temporal response of the memory when a pattern of programming and erasing square pulses are applied. From our simulations, the ENZ state of the ITO floating gate is attained at +11 V, hence we set this value as the programming voltage. In a similar way, the erase-pulse amplitude is found at –11 V, since for voltage amplitudes below –11 V the floating gate is fully discharged. The duration of both pulses is set at 10 µs with a 10 ns of rise and fall times.

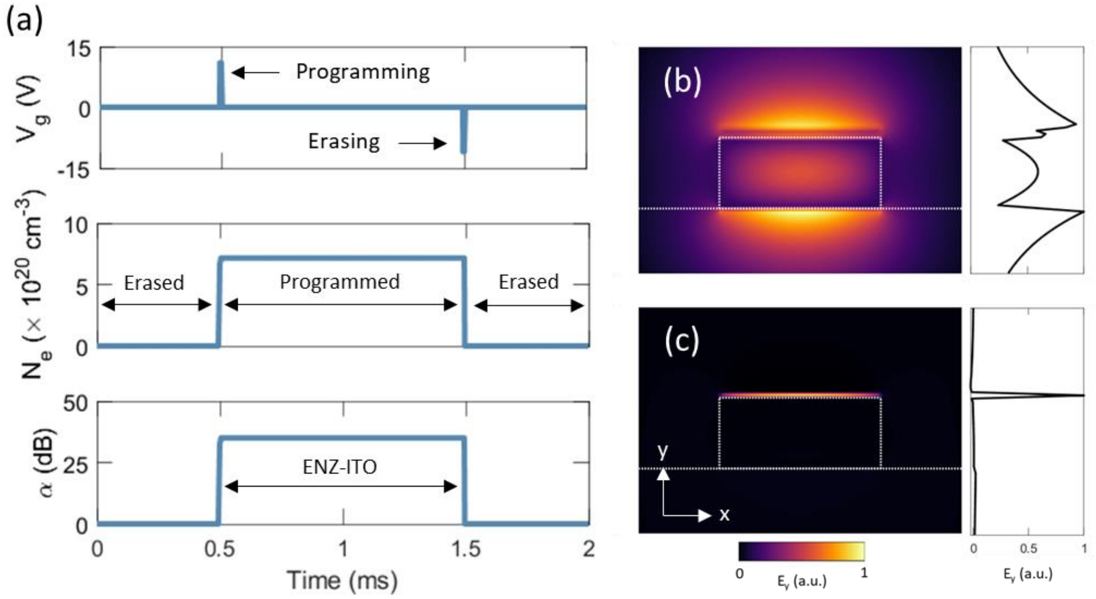

Figure 2. (a) Simulated temporal response of the device on the application of a programming (+11 V) and erasing (–11 V) voltage pulse pattern. When the program pulse is applied, the electron carrier density, N_e, of the ITO floating gate raises to ~6.5×10^{20} cm^{-3} (ENZ state) and induces 35 dB of optical losses, α, on the optical mode. (b) and (c) depict the E-field spatial distribution of the optical mode at $\lambda = 1550$ nm for the erased and programmed states, respectively.

When a programming pulse is applied to the control gate, the Fowler-Nordheim current flows through the tunnel oxide towards the ITO floating gate, which is switched to the ENZ state due to carrier accumulation. Once the programming pulse is removed, the ITO ENZ state is kept since the remaining electric field induced by the accumulated carriers is not strong enough to induce a significant leakage current. In addition, electrical simulations predict retention times of years. On the other hand, by applying the erasing pulse, the floating gate is discharged and the ITO returns to its former state. Hence, we obtain a non-volatile absorption optical switch with optical losses going from a negligible value to 35 dB for the erased and programmed memory, respectively.

The influence of the ENZ can be clearly seen on the photonic mode profiles. When the ITO floating gate has a low free carrier density [see Fig. 2(b)], it acts as a low-loss dielectric layer like the control gate and thus we obtain a typical transversal magnetic (TM) photonic mode. However, when the ITO floating gate is in the ENZ regime [see Fig. 2(c)], the optical mode is fully confined within the floating gate because the value of its absolute permittivity is almost zero. Along with this, the ITO imaginary refractive index increases turning into a highly lossy material. This combination of both strong optical confinement and optical loss variation is achieved thanks to the ENZ behaviour inherent to ITO.

4. CONCLUSIONS

In this work, a non-volatile photonic memory is proposed based on the integration of transparent conducting oxides like ITO in a silicon compatible structure. The proposed device is electrically driven and optically read. The key benefit of utilizing ITO as a floating gate is that the epsilon-near-zero regime can be exploited to achieve an ultra-compact footprint with large optical extinction ratios, negligible insertion losses and broadband response. Furthermore, the control electrical pulses have a low voltage, ultra-short duration and retention times of years have been predicted.

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