Integrated graphene/ferroelectric based plasmonic random access memory

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Abstract
Using ferroelectric domains in lead zirconate titanate (PZT: PbZr$_{0.3}$Ti$_{0.7}$O$_3$), we propose and simulate a graphene/ferroelectric-based integrated plasmonic random access memory (P-RAM). The proposed P-RAM poses bistable behavior between two transmission levels when the polarization of the ferroelectric film is switched via tuning an applied bias. Simulation results show that when a voltage applied to a 500-nm long P-RAM is swept from $-1.5$ V to $+6$ V and vice versa, the possible extinction ratio is about 18 dB. This integrated P-RAM, operating at a wavelength of 7 µm, can be used as a memory by measuring two distinct levels of transmission. The proposed integrated memory device, also functioning as a latching plasmonic switch, does not require any external unit for generating the required plasmonic wave. In the ON state, the wavelength of the plasmonic mode propagating across the memory unit is $\sim$156 nm. Its corresponding propagation length ($\sim$5.57 µm) is longer than two-and-a-half times the entire P-RAM length. This proposed integrated P-RAM of footprint 2 µm$^2$ that does not suffer from coupling loss is a promising device for applications in the storage of information and the development of future plasmonic chips. To obtain the presented numerical results, we solve the full Maxwell equations, by the 3D finite element method using the COMSOL multiphysics.

1. Introduction

The signaling speed and the frequency bandwidth are two well-known obstacles, obstructing the further advent of semiconductor electronics. Instead, photonic chips with fundamentally higher information-transport capacity and inherently less heat production are potential alternatives that can overcome the said obstacles. However, the optical diffraction limit can prevent the integration of conventional photonic devices. Nonetheless, the advent of the plasmonic devices with subwavelength feature size, overcoming the optical diffraction limit, has shown promising behavior for the fabrication of high speed integrated optical chips [1–5].

A single sheet of graphene with tunable optical conduction, formed on a suitable dielectric layer, is shown to be capable of confining surface plasmons while propagating at the interface with a low plasmonic loss that is suitable for various applications [6–11]. Meanwhile, a recent experimental investigation has shown that at cryogenic temperatures, the propagation length of the plasmons at its interface with a dielectric can increase to 13 µm [12]. Moreover, recent studies have demonstrated that a graphene/ferroelectric heterostructure can be a promising plasmonic platform, whose carrier concentration can be modulated efficiently via electrical modulation of the ferroelectric layer polarization [13, 14].

Nonvolatile plasmonic switches are electrically controllable plasmonic switches with a memory effect, emerging as key elements of the future low power plasmonic integrated circuits and information storage. Emboras et al [15] demonstrated the first hybrid plasmonic memristor with optical readout functionality, based on electrically controlled formation/annihilation of a conductive path in a metal/insulator structure.
integrated with an optical waveguide. They have shown that electrically controlled silver ions diffused into Si and trapped in the defect states formed the conductive path and led to a low switching speed with a low extinction ratio. In this line of research, Hoessbacher [16] have shown the possibility of higher switching speed and extinction ratio, using gold ions diffusion into a SiO$_2$ layer to form a conductive path within the insulator and hence a plasmonic metal–insulator–metal waveguide.

Moreover, there are numerous reports on the electrical nonvolatile memories, based on graphene/ferroelectric structure, operating by modulation of the graphene conductivity via electrically controlling the ferroelectric polarization [17–21]. Kim et al [22] have demonstrated electrically programmable graphene-based logic gates using ferroelectrics. In this manuscript, we have proposed a plasmonic random access memory (P-RAM), acting as a plasmonic latching switch. The new proposed P-RAM benefits from the effect of the lead zirconate titanate (PZT: PbZr$_{0.3}$Ti$_{0.7}$O$_3$) ferroelectric polarization on the graphene layer. Using minor hysteresis loops of ferroelectric material, a reversible nonvolatile switching between the high transmission (latching-ON) state and the low transmission (latching-OFF) state of graphene surface plasmons can be realized. To the best of our knowledge, this is the first instance of introducing an integrated P-RAM based on electrically gated graphene/ferroelectric, acting as a latching plasmonic switch, which has been reported to date. The operation of the proposed P-RAM is based on the polarization switching of the ferroelectric domains in the PZT by applying an external voltage across it, changing the magnitude and direction of the polarization, and benefiting from the bidirectional interdependency of the graphene doping level and the polarization of the ferroelectric material. The hysteretic behavior of the polarization in the PZT film leads to a bistable switching transmission when the P-RAM bias is swept appropriately. Due to the fast polarization switching of PZT, the proposed P-RAM benefits from a high writing speed and a large extinction ratio.

2. Device structure and operation principle

A three dimensional schematic of the proposed integrated P-RAM structure is illustrated in figure 1. The proposed device consists of two blocks including a surface plasmon generating unit (Zone I) integrated with the P-RAM unit (Zone II). The input unit is one of the advantages of this integrated P-RAM making it needless to an external bulky unit for generating the required input plasmonic wave that imposes an unavoidable coupling loss at the input. As can be observed in this figure, a PZT ferroelectric film is topped by a graphene layer, whose interface can serve as a plasmonic waveguide. The Ge grating on top of the graphene in Zone I is used for exciting the surface plasmons at the graphene/PZT interface, under an appropriate illumination and biasing condition. To excite surface plasmons at the PZT/graphene interface in Zone I, we consider a TM-polarized plane wave of wavelength $\lambda$—i.e. far away from those of the optical phonons in graphene and PZT—incident upon the grating. The applied bias $V_{G1}$ is a control voltage that can be tuned to adjust the graphene chemical potential ($\mu_C$) in Zone I, and hence the excitation wavelength of the surface plasmons ($\lambda_{SP}$) as desired. As indicated in the figure, the plasmonic wave generated in Zone I is readily coupled to the graphene/PZT interface in Zone II that also acts as a plasmonic waveguide. The applied gate voltage $V_{G2}$, in Zone II, can be swept appropriately to switch the PZT polarization there and hence control the propagation loss of the plasmonic modes, as desired for the P-RAM operation. Moreover, the step at the interface of the two zones is devised in the underlying SiO$_2$ platform to isolate the two adjacent zones, electrically.

![Figure 1. A 3-D schematic of the proposed graphene/PZT based P-RAM. The external voltages $V_{G1}$ and $V_{G2}$ are applied to the gold contacts on the p$^+$-Si in Zones I and II to control the excitation of surface plasmons and their propagation, in the respective zones.](image-url)
According to the Kubo formalism the graphene optical conductivity, $\sigma$, in the absence of an external magnetic field is defined as [25]:

$$
\sigma = -\frac{i e^2 }{\pi \hbar^2} \left\{ \frac{1}{(\omega + i 2 \Gamma)^2} \int_0^\infty d\delta \left( \frac{\partial f(\delta)}{\partial \delta} - \frac{\partial f(-\delta)}{\partial \delta} \right) \delta \right. 
- \int_0^\infty \frac{d\epsilon}{(\omega + i 2 \Gamma)^2} \frac{f(-\delta) - f(\delta)}{4(\delta/\hbar)^2} \right\},
$$  \hspace{1cm} (1a)

where $\omega$, $E$, $b$, $f$ $(s)$ and $\Gamma$ represent the optical beam angular frequency, the carrier energy, the reduced Planck’s constant, the Fermi–Dirac distribution, and the free carriers scattering rate in graphene. Moreover, $k_B$, $T$, $e$, $\mu_e$, and $v_F$ are the Boltzmann constant, temperature, the electron charge, free carriers mobility in graphene, and the electron Fermi velocity in graphene. The first and the second terms in equation (1) correspond to the intraband and interband transitions. Note that since the wavelength of the input optical signal is assumed well beyond the optical phonon cut-off wavelength in graphene (i.e. $\lambda \geq 6 \mu m$), we ignore the scattering term related to the electron–optical phonon coupling in graphene [24]. Furthermore, $\mu_C$ depends on the graphene carrier concentration ($N_0$) as:

$$
\mu_C = \sqrt{\pi N_0 \hbar^2 v_F}.
$$  \hspace{1cm} (2)

Moreover, $N_0$ in graphene that can be modulated by an externally controlled field effect. Here, $V_{G1}$ and $V_{G2}$, as mentioned earlier, control the upward/downward ferroelectric domains in the PZT, and hence $N_0$ in the respective regions. The effective permittivity of the graphene in the given structure is defined by

$$
\varepsilon_G = \varepsilon_b + i \sigma / \varepsilon_0 \omega \Delta,
$$  \hspace{1cm} (3)

where $\varepsilon_0$, $\Delta$, and $\varepsilon_b$ are the free space permittivity, the thickness of the graphene layer, and the effective permittivity of the background medium.

### 3. Simulation results and discussions

To investigate the plasmonic behavior of graphene/PZT heterostructure in the proposed device, we have solved Maxwell equations numerically, using the 3D finite element method (FEM) by COMSOL multiphysics. Moreover, all the geometrical and physical parameters used in simulations are given table 1, while the p$^+$-Si layers are considered to be uniformly doped.

The plasmonic wave propagation along the graphene/PZT interface can be characterized by the structure effective refractive index real part, Re $(n_{eff})$, and imaginary part, Im $(n_{eff})$, which mainly depend on the incident wavelength and the graphene chemical potential via graphene dispersion relation (3). For this purpose, first, we present the wavelength dependence of Re $(\varepsilon_G)$ and Im $(\varepsilon_G)$, for $\mu_C = 0.4, 0.6, \text{and } 0.8 \text{ eV}$, as illustrated in figure 2(a). This figure shows that for all given $\mu_C$ values, Re $(\varepsilon_G)$ is a large negative number over the range of $6 \mu m < \lambda \leq 10 \mu m$, while $+1 \leq \text{Im} \ (\varepsilon_G) < +6$. Moreover, at any given $\lambda$, Re $(\varepsilon_G)$ increases significantly as $\mu_C$ decreases by an increment of 0.2 eV, whereas a similar incremental drop in $\mu_C$ increases Im $(\varepsilon_G)$ rather insignificantly. These behaviors indicate that the formation and propagation of plasmonic waves at the graphene/PZT interface are conceivable. To find the strength of the plasmonic mode confinement and the corresponding propagation loss at the graphene/PZT in the proposed structure, we have numerically calculated Re $(n_{eff})$ and Im $(n_{eff})$, solving the full Maxwell equations. Figures 2(b) and (c) illustrate the results, showing that at any given wavelength, Re $(n_{eff})$ and Im $(n_{eff})$ both decrease with an increase in $\mu_C$. These behaviors indicate an inherent trade-off between the surface plasmons field confinement and the corresponding propagation loss along the graphene/PZT heterointerface. In other words, for the input optical signal of $\lambda_0 = 7 \mu m$, going from $\mu_C = 0.4$ to 0.8 eV, the plasmonic mode wavelength increases from $\lambda_P \equiv \lambda_0 / \text{Re}(\varepsilon_G) \approx 70 \text{ to } \sim 147 \text{ nm}$ and the corresponding mode propagation length also increases from $L_p \equiv \lambda_0 / 2\pi \text{ Im}(n_{eff}) \approx 1 \text{ to } \sim 6.8 \mu m$. This trade-off can be attributed to the relation between the rate of the free carriers in graphene and its chemical potential—i.e. $\Gamma \propto \mu_C^{-1}$, as given in equation (1b). To put it simply, as a decrease in $\mu_C$ strengthens the plasmonic mode confinement, the graphene free carriers scattering rate also increase, enhancing the plasmonic loss.

Next, we study the surface plasmons excitement in Zone I. As we have mentioned earlier, this input unit makes the proposed P-RAM needless to an external bulky unit for generating the required input plasmonic
wave, minimizing the total loss. While exciting the graphene surface plasmons, the incident light wave vector should be conserved. This condition can be satisfied by various configurations [28–30]. Technically, the simplest configuration that is compatible with the proposed P-RAM is the grating configuration with a period of $\Lambda$, satisfying the phase matching equation [28]:

$$\text{Re}(\beta(\lambda_0)) = \frac{2\pi}{\lambda_0} \sin \theta = \frac{2\pi}{\Lambda},$$  

(4)

where $\lambda_0$ and $\theta$ are the center wavelength and angle of the incident light beam, and $\beta \equiv n_{\text{eff}} k_0$ and $k_0 = 2\pi/\lambda_0$ are the surface plasmons and free space wavevectors. Similar to the case under study, for a normally incident light beam ($\theta = 0$), the plasmonic waves can be excited if the plasmonic wavelength, $\lambda_p$, satisfies $\lambda_p = 2\pi/\text{Re}(\beta) = \Lambda$.

Now, we present the numerical results for the transmission spectra through the output $O_1$ versus $\mu_C$ and the wavelength of the incident light beam, for different gratings of pitches $\Lambda = 100, 120, 140,$ and $160 \text{ nm}$, as illustrated in figures 3(a)–(d). As can be observed, in each transmission profile there are two minima. For any given $\mu_C$, the strong trace denotes the first surface plasmon mode excited at the graphene/PZT interface and the weak trace represents the second plasmonic mode.

Moreover, a comparison of the four spectra in figure 3 reveals, for any given incident $\lambda_0$ in the wavelength range of interest, as the pitch size decreases a smaller chemical potential and hence a smaller gate voltage is required to excite the surface plasmons. This is following the data shown in figure 2(a). Furthermore, for a given $\mu_C$, the same comparison reveals that an increase in the pitch size increases the incident wavelength that can excite the plasmonic wave. This is also following the data shown in figure 2(a) and equation (3).

Now, as a practical example, we consider a structure with a pitch size of $\Lambda = 100 \text{ nm}$ and adjust $V_{G1}$ to maintain the chemical potential of the graphene layer on top of the left zone ($L_1$) at $\mu_{G1} \approx 0.55 \text{ eV}$ that is feasible for the proposed gate configuration. Now, we incorporate the ferroelectric behavior of the underlying PZT layer in the operation of the proposed graphene/PZT based P-RAM. For this purpose, first, we elaborate on the ferroelectric characteristics of PZT, according to the experimental results reported by Ricinschi et al [31]. It is known that ferroelectric materials have spontaneous electric polarization, which can be reversed utilizing an external electric field. The operation of our proposed P-RAM is based on the minor loop characteristic of PZT, corresponding to non-180° domain reorientation control of the ferroelectric domains that is achievable by exerting an electric field cycle with asymmetric amplitudes. It will be shown that the utilized minor loop characteristics lead to asymmetric plasmon transmission and two stable transmission states at zero applied voltage consequently. Unlike the minor loop, the transmission major loop does not show bi-level plasmonic property at $V_{G2} = 0$. This is because we presumed graphene with no background doping with a symmetric bandstructure is transferred to the PZT layer with a symmetric hysteresis loop. Figure 4(a) displays the calculated modulation of carrier concentration ($N_0$) in graphene.
Figure 2. (a) Re ($\varepsilon_G$) (left axis) and Im ($\varepsilon_G$) (right axis), (b) Re ($n_{eff}$), and (c) Im ($n_{eff}$) the incident light wavelength, $\lambda$, for $\mu_C = 0.4$ eV (solid line), 0.6 eV (dashes), and 0.8 eV (dots).

Figure 3. The vertical transmission through $O_I$ (figure 1) with a grating of pitch size (a) 100 nm, (b) 120 nm, (c) 140 nm, and (d) 160 nm versus the incident wavelength and the graphene chemical potential. The two minima in each figure signify the first and second plasmonic modes at the graphene/PZT interface in the left zone.

versus $V_{G2}$, corresponding to the reported polarization–electric field (P–E) characteristics of the PZT layer [31], including major and minor hysteresis loops. By applying an external voltage across the PZT layer, an electric field is formed across the layer that depends on the PZT film thickness. The size of $N_0$ is determined by the ferroelectric gating in the proposed graphene/PZT heterostructure via:

$$N_0 = \alpha P(V_G)/e,$$

where $\alpha$ is the electric coupling between the ferroelectric dipoles and the graphene free carries, and $P$ is the voltage-induced ferroelectric polarization [20], showing an interdependency between graphene charge concentration and the PZT layer polarization. For an ideal ferroelectric/graphene interface $\alpha \sim 1$. However, due to the existence of interface non-idealities and the upper limit in the carrier concentration of graphene as a 2D material, $\alpha$ degrades down to 30%–40%, practically [20].

Figure 4(b) shows the transmission coefficient at the output $O_{H}$ versus $V_{G2}$ for the wavelength of $\lambda_0 = 7 \mu m$, achieved by dividing the output power emerging from $O_{H}$ to the input signal power, for $L_{H} = 0.5 \mu m$ (figure 1). The pink solid curve represents the transmission profile of the plasmonic wave for
the minor loop of PZT and the transition depicted by blue dashes corresponds to the PZT major loop, shown in figure 4(a).

As can be observed from the blue dashes, the major loop leads to a symmetric hysteresis characteristic and does not show a memory behavior because it has only one stable state at $V_{G2} = 0$. Nonetheless, the pink solid curve shows that the minor loop that is realized by exerting asymmetric electric field span results in an asymmetric hysteresis characteristic with two stable transmission states at $V_{G2} = 0$. Successful realization of four different stable states, including ON, OFF, Latched ON (as the bit ‘1’ in binary information), and Latched OFF (as the bit ‘0’), are shown for the proposed P-RAM in this figure. Moreover, the pink solid curve shows that as $V_{G2}$ is spanned from 6 V to −1.5 V, the proposed P-RAM is turned OFF with an extinction ratio of $\sim$18 dB and a latching extinction ratio of $\sim$3.5 dB, indicating high gate controllability for the proposed device. Notice that the proposed device consumes power only when it switches from the ON state to the OFF state. The plasmonic loss for the ON state of the device with $L_H = 0.5 \mu m$ is $\sim$1 dB.

To see how the plasmonic zone length ($L_H$) affect the P-RAM characteristics, we set $L_H = 1 \mu m$ and repeat the calculations. Figure 5(a) compares the asymmetric hysteresis characteristic of the transmission versus $V_{G2}$ for $L_H = 0.5 \mu m$ (solid curve) and $1 \mu m$ (dots), for $\lambda_0 = 7 \mu m$. A comparison of the curves in this figure shows that as $L_H$ increased from 0.5 to $1 \mu m$, the extinction ratio is also doubled to 36 dB. Fig. 5(b) displays the plasmonic field distribution at the graphene/PZT heterointerface in an OFF state ($V_G = −1.5 V$, resulting in $\mu_C = 0.26 eV$) and figure 5(c) shows similar results in the ON state ($V_G = 6 V$, resulting in $\mu_C = 0.83 eV$), both calculated for $L_H = 0.5 \mu m$. In the OFF state the surface plasmons excited in Zone I are strongly quenched in Zone II, due to the significant damping in plasmonic wave induced by the reduction in $N_0$ in that region under the bias $V_{G2} = −1.5 V$. On the contrary, in ON state the excited plasmon in the Zone I couples to Zone II, propagating across it with a wavelength of $\lambda_{PI} \sim 156 nm$ and propagation length of $L_P \sim 5.57 \mu m$, moving out from $O_{II}$. The propagation length is more than two-and-a-half times longer than the entire device length.

To elaborate on the device performance, we study the dynamic behavior of the proposed P-RAM. Figure 6 shows the switching performance of the P-RAM with $L_H = 0.5 \mu m$. The pink solid step-wise curve represents the gate signaling ($V_{G2}$)---i.e. the stepwise pulses of amplitudes −1.5, 0, and $+6 V$ with the same duration of 100 ns. These amplitudes are chosen according to the ON, OFF, Latched ON (i.e. the bit ‘1’) and Latched OFF (i.e. the bit ‘0’) states of the pink solid curve in figure 4(b). The blue dashes in figure 6 represent the corresponding transmission step response through $O_{II}$. The polarization switching mechanism in PZT and the dynamic behavior of the proposed P-RAM is calculated using Kolmogorov–Avrami–Ishibashi (KAI) model [32]. This model expresses that the polarization switching mechanism of a ferroelectric material under an applied electric field includes four stages: (i) nucleation of domains, (ii) longitudinal growth of domains, (iii) transverse growth of domains, and (iv) conglutination of domains until the complete reversal of the polarization. In the KAI model, the volume fraction of the switched domains, $f$ in a ferroelectric versus time ($t$) is given by [32, 33]:

$$f(\text{switched}) = 1 - \exp (-t/t_0)^n,$$

where $t_0$ is the characteristic switching time and $n$ is the dimensionality of the nucleating domains. According to [32] for a 150 nm thick PZT ferroelectric film $t_0 = 500 ns$ and $n = 2.5$ figure 6 reveals that despite the short duration of pulses, a good latching switching behavior is observed. The latching extinction ratio is $18 dB$ versus a time duration of about $100 ns$, which is more than three orders of magnitudes faster than the previous reports on plasmonic latching switches [15, 16]. It is noteworthy that the proposed P-RAM
can switch far faster than the calculated switching speed, by the expense of more power consumption. It has been proved in the experimental reports on PZT that an increase in the applied bias (electric field) enhances the polarization switching speed of PZT to a few hundreds of ps switching timescales and improves the dynamic behavior of the presented latching switch \[32, 34].

The reading mechanism for the proposed P-RAM can be achieved by detecting the graphene surface plasmons, employing techniques such as the use of thermoelectric effect with an AFM tip [35] or the nonlinear nature of the hydrodynamic equations of motion that describes transport in graphene [36] and various proposed structures [37, 38].

An inherent advantage of the proposed P-RAM lies with its near-zero coupling loss that is the consequence of the integration of its memory unit with a grating coupler acting as a required plasmonic wave generator, making it needless to a bulky external plasmonic driver. Hence, this miniaturized Integrated P-RAM with a footprint of 2 μm² can be a promising candidate for the next-generation volatile/nonvolatile plasmonic memories, for information storage and low power circuit switching applications. However, a major drawback of this memory device is its relatively low latching extinction ratio (∼3.5 dB). Nonetheless, this extinction ratio can be increased by increasing the length of the memory section (LII) with the same factor. Another drawback is its voltage swing (7.5 V) that can be reduced at the expense of lowering the device speed, by reducing the PZT thickness.

Figure 5. (a) Output performance of the proposed P-RAM with \( L_{\text{II}} = 0.5 \ \mu \text{m} \) (solid) and \( L_{\text{II}} = 1 \ \mu \text{m} \) (dotted), showing extinction ratios of 18 and 36 dB respectively. Electric field profile of the (b) OFF state for \( \mu_{C} = 0.26 \ \text{eV} \) and (c) ON state for \( \mu_{C} = 0.83 \ \text{eV} \). The white arrows in parts (b) and (c) show the direction of the electric field. In the ON state, the plasmonic wavelength in Zone II is about 136 nm.
Figure 6. Dynamic response of the proposed P-RAM (blue dashes) to the step-wise $V_{G2}$ pulses (pink solid curve), corresponding to OFF, Latched ON (bit 1), ON, and Latched OFF (bit 0) states.

4. Conclusions

In conclusion, we demonstrated a novel design for a latching plasmonic switch based on the ferroelectricity-induced tuning of the optical properties of graphene. We have numerically simulated the proposed structure, using the 3D FEM in the COMSOL multiphysics environment. The device shows bistable plasmonic behavior with an extinction ratio of 18 dB for a 1.5 $\mu$m long device, at the wavelength of 7 $\mu$m. The proposed device consumes power only when the state of the switch is changed between +6 V and −1.5 V. In the ON state (i.e. at $V_{G2} = 6$ V), the plasmonic mode propagates across the memory unit with the wavelength of $\lambda_P \sim 156$ nm and propagation length of $L_P \sim 5.57$ $\mu$m that is more than two-and-a-half times longer than the entire device length. The proposed structure with a 2 $\mu$m$^2$ footprint can serve as a miniaturized high-performance low power P-RAM with the inherent plasmon-based short length that is favorable for high integration level of photonic circuit applications and benefiting from the integration-compatible fabrication process. The relatively low latching extinction ratio (≈3.5 dB) of this latching plasmonic switch that can be increased by increasing the length of the memory section with the same factor is one of its limitations. Another major drawback of the proposed P-RAM lies with its relatively large voltage swing (7.5 V). This voltage swing can be reduced at the expense of lowering the device speed, by reducing the PZT thickness.

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Conflict of interest

The authors declare no conflicts of interest.

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