Switching terahertz waves with gate-controlled active graphene metamaterials

S. H. Lee[1], M. Choi[2], T.-T. Kim[1], S. Lee[1], M. Liu[3], X. Yin[3], H. K. Choi[2], S. S. Lee[1], C.-G. Choi[2], S.-Y. Choi[4], X. Zhang[3,5], and B. Min[1]

[1]Department of Mechanical Engineering
Korea Advanced Institute of Science and Technology (KAIST)
373-1, Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea
[2] Electronics and Telecommunications Research Institute (ETRI)
Daejeon, 305-700, Republic of Korea
[3]Nanoscale Science and Engineering Center, 3112 Etcheverry Hall
University of California, Berkeley, California 94720, USA
[4]Department of Electrical Engineering, KAIST
Daejeon, 305-701, Republic of Korea
[5]Material Science Division
Lawrence Berkeley National Laboratory
1 Cyclotron Road, Berkeley, California 94720, USA
Fax: +82-42-350-3274; email: bmin@kaist.ac.kr

Abstract

In this paper we demonstrate an electrically controllable light-matter interaction in a gate-controlled active graphene metamaterial, which shows an electrically controlled memory effect as well as the modulation of terahertz waves in the extreme subwavelength-scale.

1. Introduction

The extraordinary properties of graphene, such as its continuously gate-variable ambipolar field effect and the resulting steep change in resistivity, provided the main thrusts for the rapid advance of graphene electronics [1]. The gate-controllable electronic properties of graphene provide a route to efficiently manipulate the interaction of low-energy photons with massless Dirac fermions, which has recently sparked keen interest in graphene photonics such as plasmonics and metamaterials [2-6]. However, the electro-optic tuning capability of unpatterned graphene alone is still not strong enough for practical optoelectronic applications due to its nonresonant Drude-like behaviour. In this paper, we experimentally demonstrate that substantial gate-induced persistent switching and linear modulation of terahertz waves can be achieved in a 2D artificial material integrated with atomically thin, 2D graphene layer, referred to as an active metamaterial [7]. The gate-controllable light-matter interaction in the graphene layer can be greatly enhanced by the strong resonances and the corresponding field enhancement in the metamaterial. Although the thickness of the embedded single-layer graphene is more than ‘six’ orders of magnitude smaller than the wavelength ($< \lambda/1{,}000{,}000$), the one-atom-thick layer, in conjunction with the metamaterial, can modulate both the amplitude of the transmitted wave by up to 47% and its phase by more than 32.2° at room temperature. The controllable light-matter interaction, as well as the memory effect in the active graphene metamaterials, present immense potential for a myriad of important applications, particularly in active control of terahertz waves in the extreme subwavelength-scale, such as fast terahertz modulators, tunable transformation-optics devices, electrically controllable photonic memory, and reconfigurable terahertz devices.

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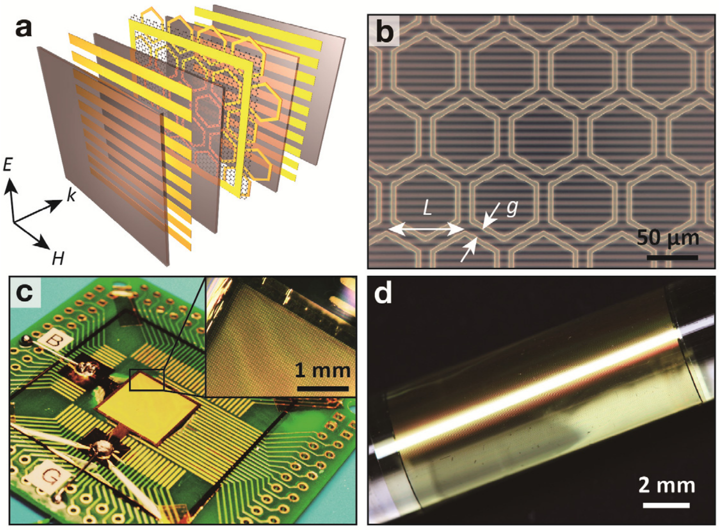

Fig. 1: (a) Schematic rendering of a gate-controlled active graphene metamaterial composed of a single atomic layer of graphene deposited on a layer of hexagonal metallic meta-atoms (a unit cell of L = 60 µm, g = 5 µm, and total device thickness d = 4.2 µm) and top/bottom electrodes (periodicity = 6 µm, metal width = 4 µm) embedded in a dielectric material (polyimide). (b) Optical micrograph of the fabricated gate-controlled active graphene metamaterial without the top electrode giving a clear view of the hexagonal meta-atoms. (c) Fully integrated gate-controlled active graphene metamaterial attached to a drilled printed circuit board (PCB) for THz-TDS measurement (B: connected to bottom electrode, G: connected to graphene layer). Inset: Magnified view of the gate-controlled active graphene metamaterial. (d) Optical image of the fabricated large-area metamaterial wound around a glass rod, showing its high degree of flexibility.

2. Active modulation and memory operation in the graphene metamaterials

The structure of a fully integrated, gate-controlled, active terahertz graphene metamaterial is depicted in Fig. 1. Functionally, the device is a combination of an array of meta-atoms, an atomically thin graphene layer transferred conformally onto the metamaterial layer, and an array of metallic wire gate electrodes within a polyimide hosting medium. Terahertz time-domain spectroscopy (THz-TDS) was employed to measure amplitude and phase changes in terahertz waves transmitted through the active graphene metamaterial with variations in the applied gate voltage V_g. The measured and simulated transmission spectra of the single-layer graphene metamaterial clearly show the gate voltage dependent resonant features (Fig. 2a-f): As increasing $|\Delta V| = |V_{CNP} - V_g|$, (1) the resonant frequency (f_0) is red-shifted due to the increase in the real part of complex conductivity of graphene; (2) the width of resonance is broadened caused by additional Joule losses from the *metallic* graphene layer; (3) the on-resonance transmission, $T(f_0)$, increases for the SLG metamaterial as a result of weaker resonant strength of meta-atoms with increasing real part of complex conductivity of the graphene layer; and (4) the off-resonance transmission is supressed due to the gate-induced broadband electro-absorption in the graphene layer. The measured relative changes in transmission ($-\Delta T/T_{CNP}$) and phase change ($\Delta\phi$) reaches approximately -90% ($-\Delta T/T_{max} \simeq$ -47%) and 32.2°, respectively. It is noteworthy that this huge modulation is realized solely by the inclusion of a graphene layer of infinitesimal thickness (< λ/1,000,000) into the metamaterial of deep subwavelength-scale thickness (~λ/100). Moreover, a large degree of *broadband* modulation at the off-resonance frequencies (0.1–0.6 and 1.2–2.5 THz) is possible. For a quantitative comparison with experimentally observed phenomena, the transmission spectra of active graphene metamaterials were calculated by a finite element analysis with Kubo's formula. All of the gate voltage dependent resonant features were excellently reproduced in the simulations with the following parameters; scattering time τ = 16 fs and carrier density at the conductivity minimum $n_0 = 4 \times 10^{11}$ cm^{-2}. More interestingly, the active graphene metamaterials show hysteretic behaviour (Fig. 2g) in the transmission of terahertz waves, which is indicative of persistent photonic memory effects. Figure 2h shows a flip-flop photonic memory operation in transmission at resonant frequency. Here, the 'write (set)' and 'erase (reset)' inputs were implemented by applying a short

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pulse signal of the gate voltage. The state of the transmission of the graphene metamaterial was read at zero gate voltage. The measured retention time of the active graphene metamaterial was proportional to both the magnitude and the pulse width of the applied gate voltage. With the given gate voltage pulses (±300 V for 1 sec), the retention time is estimated to be around 20 min.

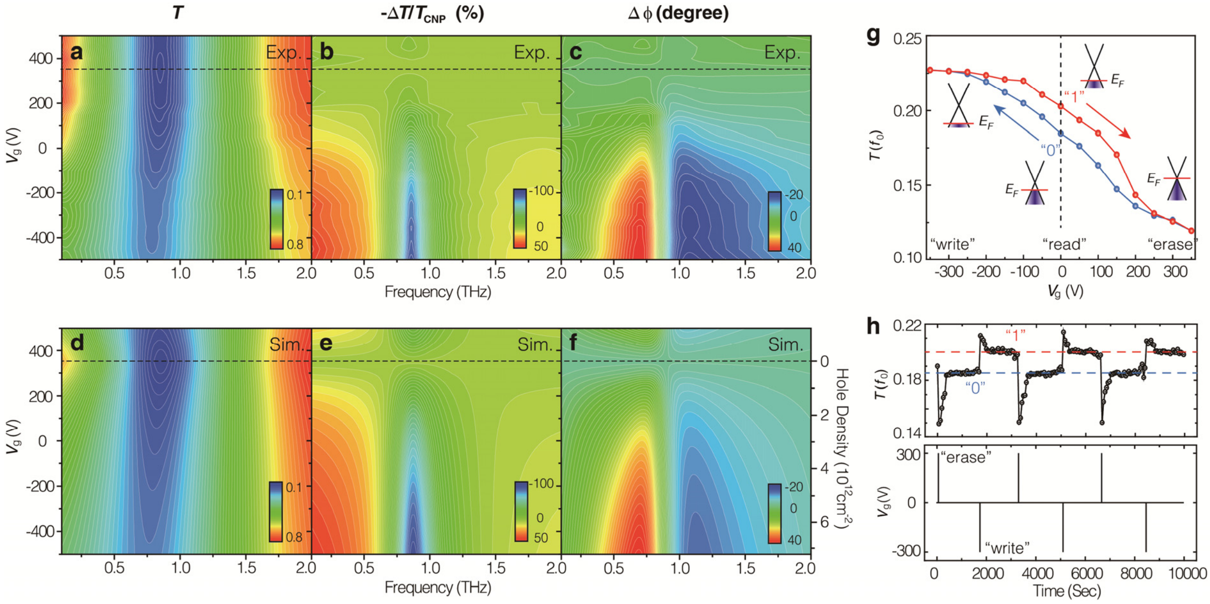

Fig. 2: Measured spectra of (a) transmission (T), (b) relative change in transmission ($-\Delta T/T_{CNP}$), (c) phase change ($\Delta\phi$) plotted as a function of gate voltages. (d)-(f) Simulated results with a single layer graphene approximation are plotted, corresponding to (a), (b), and (c), respectively. A fitting parameter for scattering time is set to 15 fs. (g) Hysteresis behaviour of on-resonance transmission for a cyclic change of the gate voltage (with a sweeping rate of 50 V/min). (h) Binary memory operation in the transmission (top panel) and gating pulse signal (pulse width = 1 sec, lower panel). The observed memory retention time is estimated to be around 20 min**.**

3. Conclusion

In conclusion, we experimentally demonstrated gate-controlled active graphene metamaterial which showed substantial terahertz modulation and photonic memory effect. Benefitting from the controllable light-matter interaction, the active graphene metamaterials are expected to provide a myriad of important applications, particularly in the dynamic control of terahertz waves, tunable transformation-optics devices, and photonic memory devices.

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