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Efficient terahertz modulator based on photoexcited graphene

Maixia Fu [a, b], Xinke Wang [a], Sen Wang [c], Zhenwei Xie [d], Shengfei Feng [a], Wenfeng Sun [a], Jiasheng Ye [a], Peng Han [a], Yan Zhang [a, *]

[a] Department of Physics, Capital Normal University, Beijing Key Lab for Metamaterials and Devices, Key Lab of Terahertz Optoelectronics, Ministry of Education, and Beijing Advanced Innovation Center for Imaging Technology, Beijing 100048, China
[b] College of Information Science and Engineering, Henan University of Technology, Key Laboratory of Grain Information Processing and Control, Ministry of Education, Zhengzhou, Henan 450001, China
[c] Department of Physics, Harbin Institute of Technology, Harbin 150001, China
[d] Nanophotonics Research Center, Shenzhen University, Shenzhen 518060, China

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ABSTRACT

An efficient terahertz (THz) modulator consisting of a single-layer graphene on a silicon substrate has been investigated using an external 450 nm continuous-wave laser with a low photoexcitation power. Upon photoexcitation, both transmission and reflection are measured using a THz time-domain spectroscopy. The experimental results show that the modulation depth of the transmission can reach 74% for the proposed modulator under external photoexcitation. The difference between the transmission through the sample and bare silicon substrate can reach a maximal value of 49.3% with a pump power of 420 mW, which indicates that the modulation effect of graphene is dominant with minimal contribution from the silicon substrate. The analyses of the strong attenuation of the transmitted THz waves reveals that an enhanced absorption of the THz wave takes place, which is shown to be rooted in the increase of the doping level in graphene, the accumulation of the photo-induced carrier at the interface of the graphene and silicon substrate, as well as the scattering between carriers, phonons and defects. The results of this study imply promising applications for the development of high-performance THz modulators and absorbers.

Terahertz (THz) technology has attracted the spotlight of scientific interest because of its important applications in astronomy, security and communications [1–3]. Great efforts, including the use of optically-driven semiconductors, the resonance of metamaterial structures, the thermally-activated phase transition materials, and superconductors, have been devoted to the efficient modulation of THz waves [4–8]. However, to date, the existing THz modulators exhibit some limitations in terms of fabrication complexity, modulation depth, and efficiency. Therefore, an active THz modulator with high modulation depth and ease of processing and operation is highly desirable.

Graphene, as a two-dimensional material with a hexagonal lattice, has attracted great interest from scientists. Since its discovery in 2004, a wide range of experiments have evidenced its interesting physical properties, such as anomalous quantum Hall effect, extremely high carrier mobility and absorption that can be saturated [9,10]. Thus far, experimental studies have confirmed that a pristine graphene monolayer has a constant absorption of 2.3% across the infrared and visible range [11–14]. Intraband transitions dominate in the THz range, which results in a tunable optical conductivity that can be described using the Drude model [15–17]. Although the thickness of a continuous single-layer graphene is only one-atom thick, the modulation effect for THz waves induced by a continuous single-layer graphene is still remarkable in the THz region [18,19]. Recently, an active graphene-silicon hybrid diode for THz waves was realized with a simultaneous 532 nm CW laser optical pump and external electrical excitation [20]. Here, it is shown that a continuous single-layer graphene on top of silicon (SLGOS) is highly suitable for efficient modulation of THz waves using only a 450 nm CW laser excitation.

In this paper, we report on an efficient optically-driven THz amplitude modulator, which is fabricated with only SLGOS. Both transmission and reflectance properties were measured using a THz time-domain spectroscopy system (THz-TDS) under external excitation using CW laser irradiation with a wavelength of 450 nm.

* Corresponding author.
E-mail address: yzhang@cnu.edu.cn (Y. Zhang).

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A substantial transmitted THz-wave attenuation is observed under different powers of external laser excitation, which suggests a potential application as a THz amplitude modulator. The analyses indicate that an enhanced absorption is the main reason for the acquired modulation. In a similar structure, Weiset al. realized a THz modulation by using femtosecond laser excitation with a wavelength of 780 nm, and an amplitude modulation depth of 99% can be obtained with an appropriate pump power [21]. However, the maximum difference between the transmission through the bare silicon and the sample was only 18%, because the silicon substrate used was intrinsically phosphor-doped and the optical response of graphene was almost negligible as the pump power was increased to more than 40 mW. Wen et al. demonstrated an all-optical THz modulator based on SLG on a germanium substrate that could be modulated by a 1.55 mm (CW) laser with a modulation depth of 94% [22]. However, the maximum difference between the transmission through the germanium substrate and sample was only 30% with a pump power of 800 mW. Compared with the previous reports, an appropriate modulation depth of 74% is obtained for the present samples, particularly, the difference between the transmission through the sample and silicon substrate can reach a maximal value of 49.3% with a pump power of 420 mW. Hence, the effect of graphene is dominant and the silicon substrate dynamics contribute minimally to the THz modulation.

Our measurements were conducted with a THz-TDS under an external CW laser optical excitation. The experimental setup for transmission measurement is schematically illustrated in Fig. 1(a). A femtosecond Ti: sapphire amplifier system, with a repetition rate of 1 kHz and a central wavelength of 800 nm, was used as the light source. The THz wave generated by a ⟨110⟩ ZnTe crystal was normally incident on the SLGOS. The pump beam was provided by an external semiconductor CW laser with a wavelength of 450 nm and was obliquely incident on the sample. The SLGOS samples were commercially available and prepared by the chemical vapor deposition (CVD) method. To weaken the modulation effect of silicon substrate and ensure a high THz transmission, the substrate used was selected as an undoped high-resistance silicon, which possesses a high resistivity of R ≈ 5000 Ω cm and a thickness of 500 μm. Raman spectroscopy was used to evaluate the quality of the graphene sample, as illustrated in Fig. 1(b). The G band and the 2D band were positioned at 1584 cm^{-1} and 2693 cm^{-1}, respectively. Comparing the typical Raman peaks of graphene that are positioned at 1580 cm^{-1} (G band) and 2670 cm^{-1} (2D band), both the G band and the 2D band of the measured sample were blue-shifted, indicating hole doping for graphene. The full wave at half maximum (FWHM) of the 2D band was approximately 30 cm^{-1}. The ratio of the intensity of 2D band, I (2D), and the G band, I (G), was I (2D)/I (G) ≈ 4. Thus, the graphene film used was predominantly single-layered [23]. There was also a weak D peak positioned at 1351 cm^{-1}, showing the presence of defects for the used graphene.

The transmission of the SLGOS sample was firstly measured without external photoexcitation. The THz wave transmitted through the SLGOS sample and a bare silicon substrate were recorded as $E_{sam}(t)$ and $E_{sub}(t)$, respectively, as shown in Fig. 2(a). The inset of Fig. 2(a) shows a magnified view of the peaks, which more clearly shows the THz transmission of the SLGOS sample and silicon substrate. Considering that the thickness of the single layer

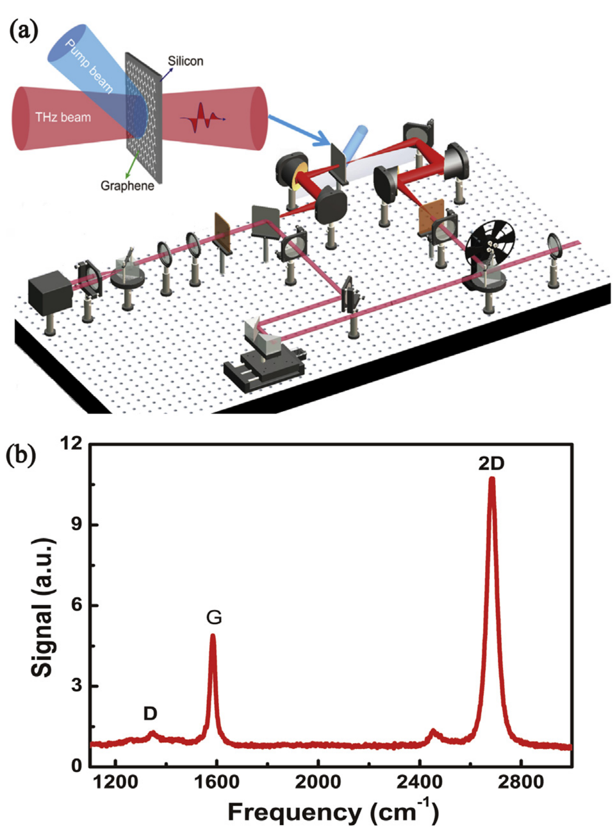

Fig. 1. (a) Schematic of the experimental setup. (b) Raman spectrum of the SLGOS sample.

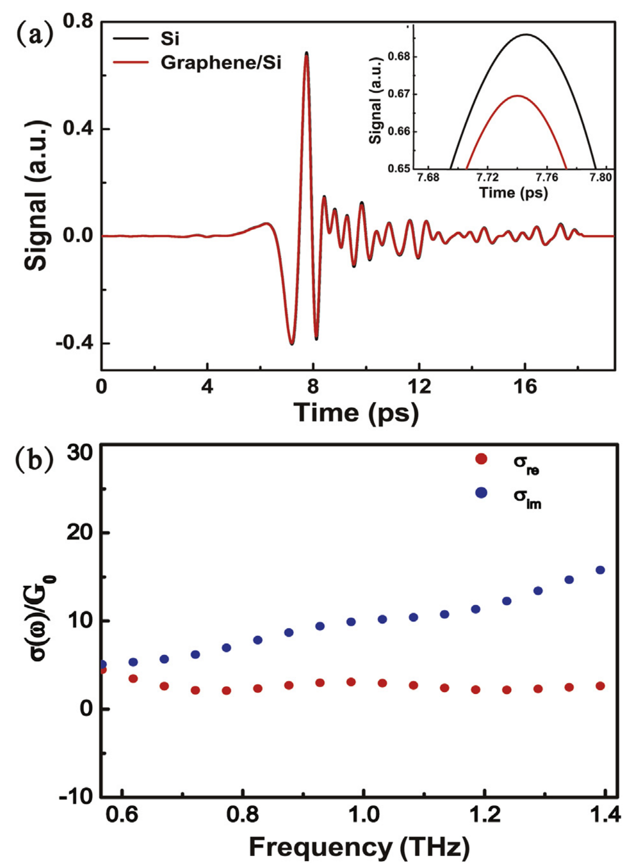

Fig. 2. (a) Measured THz waveforms transmitted through the SLGOS sample (red) and bare high resistance silicon substrate (black). The inset shows the corresponding a magnified view of the peaks. (b) Experimental complex conductivity of the SLGOS sample. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)