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Tuning the optical modulation of wideband terahertz waves by the gate voltage of graphene field effect transistors

Dainan Zhang [a, b], Dandan Sun [b], Qiye Wen [b], Tianlong Wen [b, *], James Kolodzey [a], Huaiwu Zhang [b]

[a] *Department of Electrical and Computer Engineering, University of Delaware, Newark, DE 19716, USA*
[b] *State Key Laboratory of Electronic Thin Films and Integrated Devices, University of Electronic Science and Technology of China, Sichuan Chengdu 610045, China*

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ABSTRACT

In this paper, a broadband terahertz wave was optically modulated by laser signal using a graphene field effect transistor. The modulation speed and depth were tuned by varying the gate voltage. The modulating laser and gate voltage together can trigger both inter- and intra-band transitions in graphene. The laser light penetrates through graphene into the p-Si substrate forming a thin loss layer at the graphene/p-Si interface, while the gate voltage tuned the intra-band transitions in graphene by changing the carrier density of states and the Fermi level. The change in carrier concentration, density of states, and mobility in the loss layer directly affected the optical conductivity and refractive index, and thus the modulation depth. Modulation depth of the whole device is between 28.5% and 39.3% at modulation frequencies from 100 kHz to 1.0 MHz.

1. Introduction

Terahertz (THz) wave modulators are important components of the terahertz technology systems that control the intensity of terahertz wave by modulating signals [1]. The THz modulators have many applications such as wireless THz wave communication system [2] and THz wave imaging [3]. The metamaterial modulators have large modulation depth and speed. However, their fabrication process is complicated and costly, and their modulation is narrow band [4]. Due to its novel properties such as zero energy band-gap, high carrier mobility, and broadband optical absorption, graphene has been used in a variety of fields, such as supercapacitors [5], photodetectors [6], electron emission [7], and nanocomposites [8]. It also attracted much attention for THz and optical electromagnetic wave modulation devices [9–13]. Compared with metamaterial modulators, graphene based THz modulators are more robust and much less expensive for fabrication, and their modulation is wideband. However, their modulation depth and speed are inferior to metamaterials. Here we explore the possibilities to improve the modulation speed and depth of graphene based THz modulator by using electrical and optical modulating signals for inexpensive and wideband applications.

In 2011, Zhang's group demonstrated the first prototype of an optical modulator based on graphene [14]. This modulator was composed of a silicon waveguide covered by an alumina thin film and then a graphene monolayer, which was then connected with a gold electrode by a thin layer of silicon. The optical absorption and transmission were controlled by tuning the Fermi level of the graphene through the gate voltage. The modulation depth was as large as 0.1 dB/μm at wavelengths from 1.35 to 1.60 μm. In 2012, a reflection plane modulator was designed and prepared for the first time [15]. The modulator was composed of a tantalum pentoxide (Ta_2O_5) dielectric sandwiched by a graphene monolayer and a metallic silver thin film, where the silver thin film served as a reflection mirror as well as a back gate electrode. The thickness of Ta_2O_5 dielectric can strongly affect the Fermi level and thus the light absorption. In the same year, a new type of optical modulators based on field effect transistor (FET) was demonstrated [16]. Low resistance silicon was used as substrate and SiO_2 as gate dielectric. It was found that the optical conductivity of the graphene was independent (linearly dependent) with gate bias at low (high) carrier concentrations.

* Corresponding author.
E-mail addresses: qywen@uestc.edu.cn (Q. Wen), halong@uestc.edu.cn (T. Wen), kolodzey@udel.edu (J. Kolodzey).

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Recently, a graphene based FET (GFET) THz wave modulator was prepared using the gate voltage as the modulating signal [17]. Here the intra-band transition of graphene dominates since the energy of THz waves is insufficient to activate the inter-band transition. The Modulation depth of this GFET can be as high as 16% with THz wave frequencies from 570 to 630 GHz. Lee and coworkers designed a THz wave modulator based upon a graphene metamaterial [18]. Polyimide was used as the substrate, where a monolayer graphene was put on top of a hexagonal metamaterial. The modulator operated at 0.68 THz and achieved a maximum modulation depth of 90%. However it was of narrow band.

Although GFET has been demonstrated effective to modulate THz waves [17,19], the modulation depth and speed are still low, deterring their application in THz technology. Here, we designed a GFET with a structure of Graphene/SiO_2/p-Si (GOS) to modulate THz waves to achieve large modulation depth and quick switching speed by tuning the optical modulation with a gate voltage. The modulation mechanism will be discussed, including the inter-band and intra-band transition of carriers and the Fermi level splitting of the p-Si substrate, which leads to the optical conductivity variation and thus affects the transmittance of THz wave. This work firstly explores the possibility of achieving better THz wave modulation performance by applying a gate voltage to a graphene field effect transistor. In contrast to the optical modulation of THz waves by a graphene/silicon hetero-structure in Refs. [13], here we apply a gate voltage to the GOS to tune the optical modulation. The applied gate voltage can effectively affect the inter- and intra-band transitions of electrons during optical modulation, and change the electron transfer between the silicon and graphene, which thus can affect the modulation of THz wave by the GOS.

2. Experimental part

2.1. Fabrication of GFET

Graphene was fabricated by chemical vapor deposition (CVD) method in a tube furnace. Copper foil (~25 μm) was firstly heat treated at 1005 °C for 1 h under hydrogen gas flow (~10 sccm). A mixture gas of methane (~1 sccm) and hydrogen (~50 sccm) was then flown through the copper foil at 1005 °C for 20 min. Upon cooling, graphene was formed on the copper foil. Fig. 1 shows the process to transfer graphene from copper foil onto the SiO_2/Si substrate, where SiO_2 thin films (~300 nm) were fabricated by thermal oxidization. The copper was cut into 10 mm × 10 mm pierces and spin-coated with polymethyl-methacrylate (PMMA). The copper pierces were dissolved with an etching solution of iron chloride. After copper foil completely dissolved, the graphene was attached on PMMA and floated on the etching solution, which was then transferred onto SiO_2/Si substrate. The substrate was rinsed completely by D.I. water. The sample was then dried in air. Finally, the PMMA was dissolved by acetone, and the graphene was successfully transferred on the silicon oxide substrate, as shown in Fig. 1. To fabricate GFET, the electrode of gate, source and drain was made by gold evaporation.

2.2. THz wave modulation test

A home-built time domain spectroscopy (TDS) system was used for static modulation test. The THz wave was generated by interaction of a 1550 nm fs laser (*Calmar Laser*) with a photoconductive antenna. The detecting femtosecond laser pulse was controlled by a delay line. The time domain spectroscopy was measured at different gate voltage in transmission and reflection mode. The frequency domain spectroscopy was obtained by Fourier transformation of the time domain spectroscopy of the measured THz pulse. For dynamic modulation test, a continuous THz wave source was used. The intensity of transmitted THz wave was detected by a Schottky diode intensity detector (Virginia Diodes). During measurement, the gate voltage of the GFET was controlled by a function generator. The responding waveform of the transmitted THz wave was then recorded at different frequency.

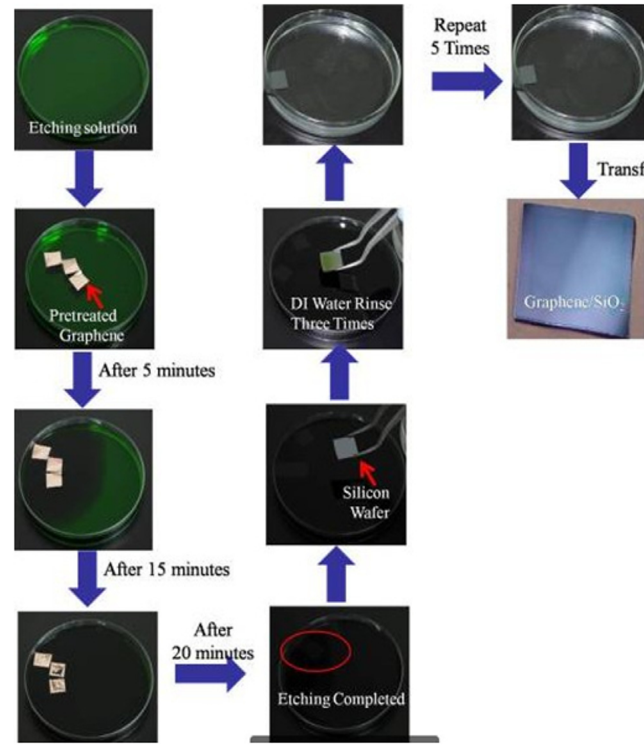

Fig. 1. The transfer process of graphene from copper foil to SiO_2/Si substrate.

3. Result and discussion

Inter- and intra-band transitions are two types of electron excitations in graphene [20–23]. Inter-band transitions can be excited by infrared/visible light, where absorption varies from 0.0% to 2.3% by tuning its Fermi level. Intra-band transitions dominate in the THz range, where optical conductivity can be well described by Drude model [17]. In this model, the optical conductivity of the graphene in THz range can be tuned by Fermi level and the carrier density of states. Here the GOS structure modulates the THz wave by an incident laser signal, and the modulation depth and speed is tuned by the gate bias, where geometry is shown in Fig. 2(a) and (b) for reflection and transmission respectively.

The optical conductivity of graphene can be expressed by:

$$\sigma(\omega_T) = \sigma_{\text{inter}}(\omega_T) + \sigma_{\text{intra}}(\omega_T) \tag{1}$$

where σ_{inter} and σ_{intra} are the contributions from the inter- and intra-band transitions respectively, and ω_T is the angular frequency of the THz wave. If neglecting the Fermi level splitting in p-Si substrate and only considering a monolayer graphene, the dynamic optical conductivity $\sigma(\omega)$ is a constant and equal to $e^2/4\hbar$ (2.3%) in the visible and infrared range when photon energy ($h\nu$) is larger than twice the Fermi level (E_F) [21]. By tuning the Fermi level, inter-band transitions can be switched on and off at $h\nu = 2E_F$ [24,25]. However, laser beam does not only go through the graphene films but also penetrates into the p-Si substrate to activate electron–hole