Active Terahertz Modulations Based on Graphene-silicon Hybrid Structures

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***Abstract*—With simultaneous optical and electrical excitations, we experimentally demonstrate an active modulation of transmitted terahertz waves through a graphene-silicon hybrid structure. A large transmission modulation of 83% was observed. Meanwhile, a "diode" behavior was found in such a structure, where terahertz waves transmits when biased with a positive voltage while attenuates under a low negative voltage.**

I. Introduction

As a two-dimensional version of graphite, graphene has attracted a lot of attention from physicists, engineers and material scientists over the past few years. In terahertz regime, graphene is also one of the most prosperous materials in modulating the propagation properties of the terahertz wave. Several modulation routes have been applied to achieve high modulation, such as applying external voltage to tune the Fermi level in graphene [1], using optical pump to excite carrier in the substrate [2]. Here, we present the impact of dual excitation behaviors of a graphene-silicon hybrid film where we achieve enhanced modulation of the terahertz waves at low voltage bias and low fluence photoexcitation.

II. Results

The proposed device is schematically illustrated in Fig. 1. A large-area graphene monolayer was first grown on copper by chemical vapor deposition (CVD) using methane and hydrogen. A thin layer of poly-(methyl methacrylate) (PMMA) was then coated onto the monolayer. In the next step, two layers of graphene were transferred onto a 510-μm-thick *N*-type silicon substrate in sequence by using wet etching method to remove the copper and PMMA, respectively [3]. The entire sample area is 1×1 cm^2. Two square metallic rings were carefully placed onto both the graphene and silicon sides as two electrodes in order to bias the graphene on silicon. Meanwhile, a continuous wave (CW) green laser (532 nm) was used to illuminate the sample.

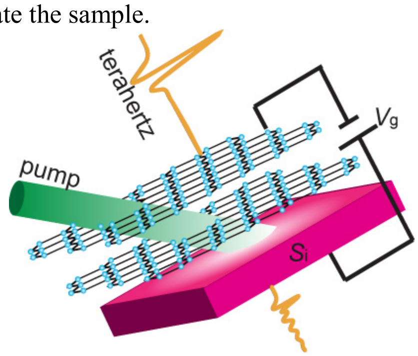

Fig. 1. Illustration of the hybrid structure. The double-layer graphene on the silicon substrate was photoexcited with green light and biased with voltage V_g.

A terahertz time-domain spectroscopy (THz-TDS) system was used to measure the transmission spectra of the sample under different optical pump illumination power P and bias voltages V_g at normal incidence. As a reference, an identical bare piece of silicon without the graphene layer was photoexcited with the same optical power but without bias voltage.

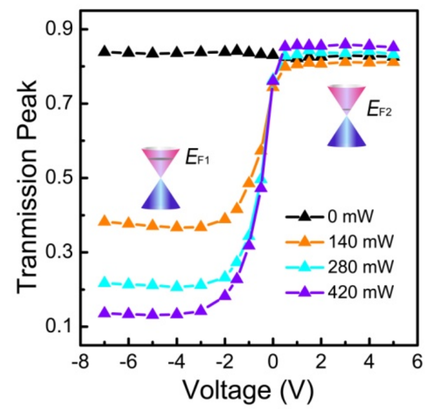

Fig. 2. Gate voltage-dependent, normalized time-domain transmission peaks of the double-layer graphene on silicon substrate at different laser photoexcitation power. Insets: schematic diagram of the Fermi levels. Upon photoexcitation, the Fermi level is near the Dirac point in the conduction band at the positive bias while the Fermi level moves away from the Dirac point to the higher conduction band at negative bias.

Figure 2 represents the normalized peak values of the time-domain signals from the sample biased from -7 V to 5 V under different CW optical illumination power P = 0, 140, 280 and 420 mW, respectively. Without photoexcitation, the applied bias voltage did not cause any significant change in the terahertz transmission. However, when the biased graphene-silicon hybrid film was photoexcited, the graphene-silicon hybrid film transmits the terahertz waves when biased with a positive voltage while blocks the wave when biased with a negative voltage, resembling the characteristic of a typical semiconductor based electronic diode that allows passage of current only for positive bias and blocks the current when negatively biased. Thus the proposed graphene-silicon hybrid film could function as a "diode" for the terahertz waves. Under the illumination power of 140 mW, modulation depth of up to 51% was achieved when the bias was changed from 0 to -3 V. With further increase in the illumination power P to 420 mW, the modulation depth was increased to a maximum value of 83% when -4 V bias was applied. The modulation depth is defined as: $M = \left|(t_{\text{peak},V_g} - t_{\text{peak},V_0})/t_{\text{peak},V_0}\right|$, where t_{peak,V_0} and t_{peak,V_g} are the normalized time-domain transmission peaks for zero and V_g gate voltages, respectively.

As a control experiment, we also prepared another sample in which the double-layer graphene was transferred onto a silicon substrate with a 300-nm-thick top SiO_2 layer. Thus, the graphene film was separated from the silicon substrate by the SiO_2 spacer. When the same experiment condition was repeated with this control sample, we did not observe any modulation effect, as shown in Fig. 3. Previous work with the SiO_2 spacer layer reported that tens of volts of applied bias would cause small modulations (lower than 20%) on the transmitted terahertz waves [4-6]. In our experiment, however, the low voltage bias did not result in any obvious modulation on the transmission signal. Therefore, the observed "diode" characteristics could be attributed to the variation in hybrid graphene-silicon interface.

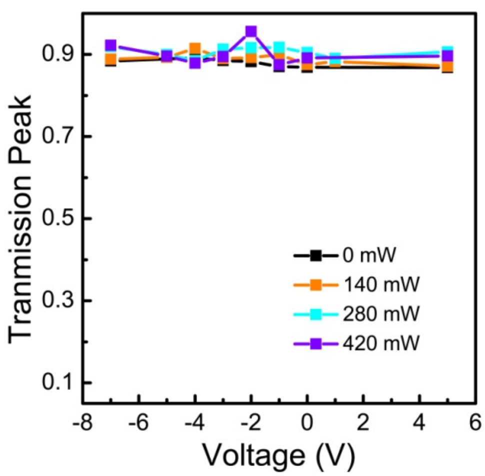

Fig. 3. Gate voltage-dependent, normalized time-domain transmission peaks of the double-layer graphene on SiO_2-Si substrate at different laser photoexcitation power.

Based on the experimental results in Fig. 2, we could interpret the graphene-silicon interface as that of an electronic PN junction. Since the silicon substrate used here is an *N*-type semiconductor, the graphene would act as a *P*-type material in this configuration. When the graphene-silicon hybrid sample was photoexcited by the green laser, a photo-conductive silicon layer was generated beneath the graphene layer where the electron density was enhanced due to carrier generation. However, the amount of photoexcited carriers generated in the graphene layer was much smaller due to small optical absorption [2]. Thus, a density difference was formed at the graphene-silicon interface. As a result, the electrons would first diffuse from the photo-conductive silicon layer into the graphene film until an equilibrium was reached, resulting in the formation of a depletion layer with lower conductivity in the photo-conductive silicon layer (the graphene layer is quite thin). With the injection of the diffusion electrons, the holes in the graphene (CVD graphene is weakly hole-doped) recombined with electrons and then an increased number of empty electron states were filled, hence the initial Fermi level of the graphene under photoexcitation was in the conduction band at zero bias. Meanwhile, the graphene conductivity was increased, leading to attenuation of the terahertz transmission. At positive bias, the depletion layer became thinner. Beyond a threshold bias (~ 0.5 V), the electrons formed a current flow in the electronic circle and thus became hard to accumulate in graphene. Therefore, a small enhanced transmission was observed when the voltage was increased from 0 to 0.5 V, and there was no obvious change in the transmission when the bias voltage was further increased from 0.5 to 5 V. The corresponding position of the Fermi level E_{F2} is shown in the right inset of Fig. 2. On the other hand, when the negative bias voltage was applied, the diffusion of carriers was weakened, while the depletion layer was broadened. The PN junction behaved as a parallel plate capacitance. More electrons would be injected into the graphene layer as the negative bias increased, which shifted the Fermi level E_{F1} further away into higher conduction band (left inset of Fig. 2). Meanwhile, the conductivity of graphene further increased which led to higher attenuation of the terahertz wave. Further increase in the negative bias gave rise to a saturation in the carrier density of the graphene layer. Thus, the terahertz transmission remained constant on any further increase in the negative bias up to -7 V. We found a saturation point in the terahertz transmission peak at the bias voltage of -3 V for all the three different photoexcitation power. At the saturated voltage bias, the transmission could only be tuned by varying the photoexcitation pump power where a larger power would result in a smaller transmission.

III. Summary

In summary, we have experimentally demonstrated a graphene-silicon hybrid film that behaves as an efficient "diode" for the terahertz waves under simultaneous CW photoexcitation and DC bias voltage. The "terahertz diode" achieves a large modulation depth of up to 83% at a small negative gate bias voltage of -4 V. The active tuning behavior of the graphene-silicon hybrid film would enable promising applications in terahertz technology, such as communications, plasmonic engineering and graphene-based metamaterials.

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