Graphene-based Broadband THz Modulators

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While the Terahertz (THz) frequency provides untapped potential for both photonics and electronics in imaging, spectroscopy, and wireless communications, to manipulate a THz beam is still difficult due to lack of efficient devices in this frequency regime. Recently graphene-based modulators have been promoted[1] and reported from 570 to 630 GHz.[2] Here we demonstrate electrically controlled graphene-based optical wide band modulators from 100 GHz to 1.5 THz at room temperature. The modulation depth, or relative transmission change, reached about ~ 20% for single layer graphene devices.

The modulation of the light intensity is achieved by controlling the beam absorption through graphene layer. In high frequency (visible and infrared) regime, the absorption process is dominated by the carrier interband transitions, and the absorption for single layer graphene is a constant ~2.3% with the optical conductivity equal to $e^2/4\hbar$, roughly independent of optical frequency and Fermi energy level. In contrast to the high frequency regime, however, intraband transitions prevail in the THz regime. As a result, the optical absorption hence optical conductivity is not constant anymore, and subject to light wavelength and Fermi level that is electrically controllable.

We engineered two kinds of graphene-based THz modulators. Sample structures are shown in Figure 1 and 2. Figure 1 shows an AlGaN/AlN/GaN 2DEG-based electrically tuned optical modulator with the conventional metal gate being replaced by a graphene gate. Figure 2 shows a back gated graphene on SiO_2/Si structure. The experiments were performed using LakeShore's THz time domain spectrometer (THz-TDS). For the Graphene/AlGaN/AlN/GaN device, the modulation depth is about 13% at 20 V bias, while for the Graphene/SiO_2/Si sample, the modulation depth is up to 20% at -90 V bias, as shown in Figure 3 and 4, respectively. These results demonstrate a new type of electrically tunable high performance optical modulator in THz regime.

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[1] B. Sensale-Rodriguez, *et al.* Appl. Phys. Lett. **99**, 113104 (2011); R. Yan, *et al.* Opt. Express **20**, 28664 (2012)

[2] B. Sensale-Rodriguez, *et al.* Nat. Commun. **3**, 780 (2012); Nano Lett. **12**, 4518 (2012)

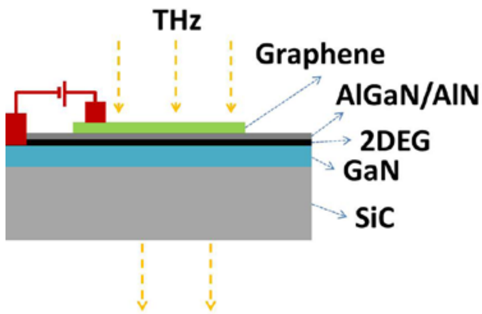

Figure 1. Schematic of double 2DEGs based optical modulator. When the bias is applied, the 2DEG at the interface of AlN/GaN and 2DEG/2DHG in graphene layer will be tuned simultaneously. As a result, the optical absorption and conductivity hence the modulation depth are electrically controlled. The voltage is applied as shown. Dimensions are not scaled.

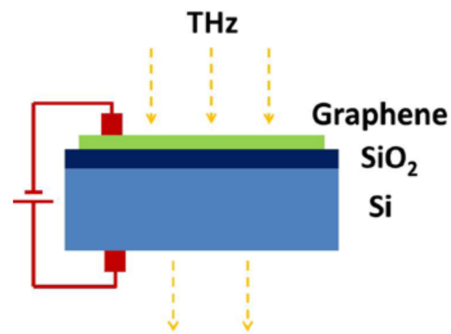

Figure 2. Schematic of graphene based optical modulator. Graphene are transferred to the 300 nm thick SiO2 layer on lightly doped Si substrate. When bias is applied, the Fermi level of graphene is adjusted. As a result, the interband transition hence the optical absorption are electrically controlled. The voltage is applied as shown. Dimensions are not scaled.

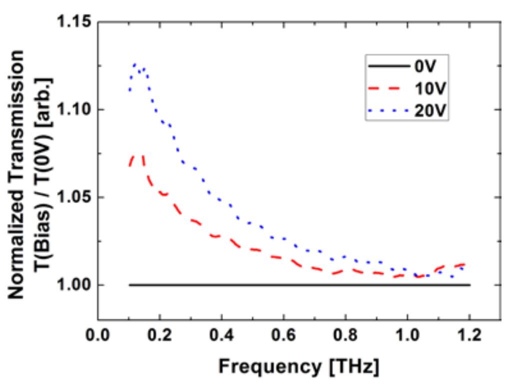

Figure 3. Measured relative transmission intensity for the sample structure shown in Figure 1 at three bias conditions: 0V, 10V, and 20V at room temperature. The intensity is normalized to the 0V bias transmission. Data have been smoothed.

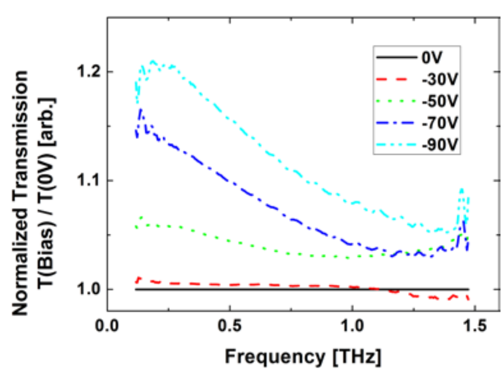

Figure 4. Measured relative transmission intensity for the sample structure shown in Figure 2 at varous bias conditions at room temperature. The intensity is normalized to the 0V bias transmission. Data have been smoothed.