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Plasma resonances effect in terahertz modulator based on double graphene layer

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ABSTRACT

A modulator of terahertz radiation based on a double graphene-layer (GL) heterostructure utilizing the variation of the GL absorption and the resonant excitation of plasma oscillations is proposed. The dynamic operation and the modulation properties are substantiated using the developed device model. It is shown that the excitation of plasma oscillations in double GL structure can bring about the resonant increase of the modulation depth when the modulation frequency approaches the resonant plasma frequency. In addition, the modulation depth exhibits a sharp maximum whose position corresponds to the plasma resonance. This opens up the possibility to use the double-GL structures for effective modulation of THz radiation.

1. Introduction

Graphene, a two-dimensional semiconductor with zero bandgap, has attracted growing attentions due to its outstanding and intriguing properties [1]. Because of its highest carrier mobility, graphene has stirred up particular interest for high-speed electronics and is considered as a promising replacement for silicon for integration [2,3]. The features of the energy spectrum of electrons and holes in graphene layers (GLs) result in great investigation in theoretic and application areas in recent years [4–6]. Lots of optoelectronic devices, especially the modulators, have been proposed and studied [7–12]. By changing the controlling voltage, one can effectively change the electron and hole densities and the Fermi energy, hence the intraband and interband absorptions in GLs. The rise in the electron (hole) density decreases the interband absorption, and simultaneously increases the intraband absorption which associated with the Drude mechanism. Because of the coupling between two graphene layers, Terahertz modulator constructed by double layer graphene can reaches higher modulation depth, greater modulation range [13,14] and lower insertion loss.

As a significant physical theoretics, plasmon excitation reveals unusual behaviors in conventional semiconductor fields. Researchers demonstrated that the excitation of surface plasmon resonance of AgNPs can be used to make hierarchical patterns of submicrometer scale features [15]. An optimal substrate design for SERS have also been proposed and attested that the efficient collective plasmon oscillation is a straightforward approach for achieving great SERS enhancement [16]. In addition, the applications of plasmonic resonances in optical fields have been well considered and obtained numerous outstanding results [17,18]. Compare with the above, plasmonic properties of double graphene layer have also attracted particular interest in recent years. For example, double layer structures can act as plasmonic modulators [19], and plasma resonances can affect the characteristics of optical modulators, resulting in greater modulation depth [20]. Most recently, a unique method that utilizes a metal reflector to enhance the terahertz electric field is proposed to provide very high modulation depth, even up to 100% and a low insertion loss [21]. To our best knowledge, the modulation properties of plasma oscillations in terahertz modulators in double graphene have not been studied yet.

In this paper, we propose a terahertz modulator based on a double-GL heterostructure utilizing the resonant excitation of plasma oscillations by incoming terahertz radiation. The GLs are separated by relatively thick barrier and the structure is integrated with an optical waveguide. Using the developed device model we analyze the modulator operation and calculate its characteristics. It is demonstrated that at high modulation frequencies, the modulation signals can excite the electron–hole plasma oscillations and the plasma effect can result in several-fold increase of the modulation depth, when the modulation frequency approaches the plasma frequency.

2. Equations of the model

The structure of terahertz modulator considered in this paper is depicted in Fig. 1, with the assuming that each GL is connected to one side contact and separated from the opposite contact.

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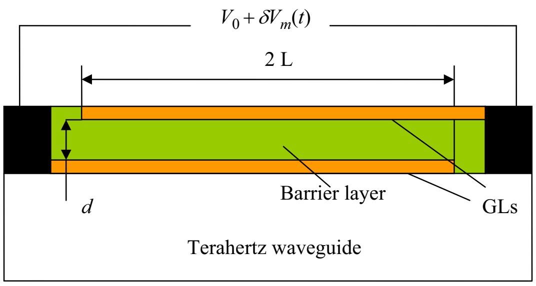

Fig. 1. Schematic view of a terahertz modulator based on a double-GL heterostructure.

The voltage applied between these contacts $V_m = V_0 + \delta V_m$, where V_0 and δV_m are the bias and modulation components. We set $\delta V_m(t) = \delta V_m \exp(-i\omega t)$, where ω is the modulation frequency that is much smaller than the frequency of the incident terahertz radiation Ω. The two highly conducting side contacts can be acted as a slot line enabling the propagation of the modulation signals. In addition, the side contacts can also be connected to or a part of terahertz antenna.

With the light wave propagating along the waveguide, the absorption coefficient is determined by the real part of the double-GL conductivity $\mathrm{Re}\sigma_\Omega$ at the frequency Ω

$$\beta_\Omega = \frac{4\pi \mathrm{Re}\langle\sigma_\Omega\rangle \Gamma_\Omega}{c\sqrt{k}}, \tag{1}$$

where c is the speed of light in vacuum and k is the dielectric constant of the waveguide material, and the symbol $\langle\ldots\rangle$ means the averaging accounting for the distribution of the optical field $E_\Omega(x,y)$ in the waveguide. Thus,

$$\langle\sigma_\Omega\rangle \Gamma_\Omega = \frac{\int_{-L}^{L} \mathrm{Re}\sigma_\Omega |E_\Omega(x,0)|^2 dx}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} |E_\Omega(x,y)|^2 dxdy}, \tag{2}$$

where

$$\Gamma_\Omega = \frac{\int_{-L}^{L} |E_\Omega(x,0)|^2 dx}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} |E_\Omega(x,y)|^2 dxdy}$$

is the mode overlap factor and $2L$ is the GL length, which is approximately equal to the spacing between the side contacts as shown in Fig. 1.

As has been attested, interband transitions dominate in the infrared/visible range while intraband transitions dominate in the terahertz range [22]. Hence, when only terahertz light propagates, intraband transitions are the primary processes to be considered while the interband transitions can be neglected. Additionally, the electron and hole momentum relaxation time in our assumption is associated with the scattering due to disorder and acoustic phonons, so its energy dependence is given by $\tau^{-1} = \nu(\varepsilon/T_0)$, where ν is the characteristic scattering frequency at the Dirac point. Under these considerations, the real part of the conductivity of two GLs at $\Omega >> \nu_0$ can be presented as [23]

$$\mathrm{Re}\sigma_\Omega = \frac{e^2}{4\hbar}\frac{8\nu}{\pi\hbar\Omega^2}\frac{(\mu_+^2 + \mu_-^2 + \pi^2 T^2/3)}{T} \tag{3}$$

where μ_+ and μ_- are the GL Fermi energies in the upper and lower GLs, respectively. T is the temperature, and e is the electron charge. When the applied voltage varies slowly, $\mu_+ = \mu_- = \mu$, where μ obeys the following equation:

$$2\mu + \Delta = eV_m \tag{4}$$

here, Δ is determined by the electric field between GLs and the thickness d of the barrier layer between GLs. As a matter of fact, at sufficiently fast variations of the voltage, i.e., at large modulation frequency, the spatial distributions of the electron and hole densities cannot follow the variation of the applied voltage, and the Fermi energies depend on the coordinate x.

The Fermi energies in GLs are determined by the following equation:

$$|\Sigma_\pm| = \frac{2}{\pi\hbar^2 v_F^2}\int_0^\infty \frac{\varepsilon d\varepsilon}{1+\exp(\varepsilon - \mu_\pm/T)} \tag{5}$$

where $v_F = 10^8\ cm/s$ is the characteristic velocity of electrons and holes in GLs. With the formula of the Fermi energies, and the consideration of the spacing between GLs rather smaller than $2L$, one can get the following formulas which combine the densities $\Sigma_\pm$ and the electric potentials of GLs $\varphi_\pm$:

$$\frac{4\pi e\Sigma_\pm}{k} = \mp\frac{(\varphi_+ - \varphi_-)}{d}, \tag{6}$$

where k is the dielectric constant. The positive values correspond to the case when a GL is filled by holes, whereas the negative values correspond to the filling by electrons.

3. Modulation characteristics

Under the condition that the control voltage V_m varies slowly, one can set

$$\varphi_\pm = \pm\frac{V_m}{2}, \tag{7}$$

so,

$$\Sigma_\pm = \mp\frac{kV_m}{4\pi ed},\ \mu_\pm = \mu, \tag{8}$$

where μ is governed by $V_m/\overline{V} = \int_0^\infty (\xi d\xi/1+\exp(\xi-\mu/T))$, and

$$\overline{V} = \frac{8ed}{k}\left(\frac{T}{\hbar v_F}\right)^2 \tag{9}$$

If $d = 10\ nm$, $k = 7(Al_2O_3)$, and $T = 300\ K$, from Eq. (9) we obtain $\overline{V} \approx 25 mV$.

When the bias voltage V_0 is sufficiently large, the electron and hole systems in GLs become degenerate, and Eq. (9) yields

$$\mu \approx T\sqrt{\frac{2V_m}{\overline{V}}} = \hbar v_F\sqrt{\frac{kV_m}{4ed}}, \tag{10}$$

therefore, taking into account Eq. (4), one can get

$$\Delta \approx eV_m - 2T\sqrt{\frac{2V_m}{\overline{V}}} = eV_m - \hbar v_F\sqrt{\frac{kV_m}{ed}} \tag{11}$$

Thus, combining Eqs. (1), (3) and (8), we arrive at the following formula for the absorption coefficient:

$$\frac{\beta_\Omega}{\overline{\beta}_\Omega} = \frac{32\nu T}{\pi\hbar\Omega^2}\left(\frac{V_m}{\overline{V}} + \frac{\pi^2}{12}\right), \tag{12}$$

where $\overline{\beta}_\Omega = 2\pi\alpha\Gamma_\Omega/\sqrt{k}$, ν is the characteristic collision frequency of electrons and holes, and $\alpha = e^2/c\hbar \approx 1/137$ is the fine structure constant.

The relationship between intensities of output I_0 and input radiation I_{00} can be expressed as $I_0 = I_{00}\exp(-\beta_\Omega H)$, where H is the length of double-GL in the direction of radiation propagation. Then the ratio of I_0 and I_{00} can be presented as

$$\frac{I_0}{I_{00}} = \exp\left[-\overline{\beta}_\Omega H\frac{16\nu T}{\pi\hbar\Omega^2}\left(\frac{V_m}{\overline{V}} + \frac{\pi^2}{12}\right)\right] \tag{13}$$

Eq. (13) describes the variation of the output radiation I_0 caused by relatively slow variations of the applied voltage V_m. With this equation, one can estimate the modulation depth m_0 in the case of relatively slow modulation: $m_0 = 1 - \exp(-\overline{\beta}_\Omega H)$.

We make an assumption that V_0 is sufficiently large to form the degenerate electron and hole systems in the pertinent GLs. In this

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