Exceptional Tunability of THz Reflectance in Graphene Structures

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***Abstract*— We propose and demonstrate a graphene-based device achieving extraordinary control of terahertz (THz) wave reflectance. The advantages of graphene based switchable THz devices include low cost, facile fabrication and excellent tunability, thus promising for THz system applications.**

I. INTRODUCTION AND BACKGROUND

GRAPHENE, an intrinsically two-dimensional material, has recently gained much interest due to its peculiar electrical and optical properties. In the THz range, where its optical properties are mainly determined by intraband transitions, its optical conductivity closely follows the electrical one – well described by the Drude model. Therefore, in contrast to the IR/Vis range where absorption by graphene at normal incidence is 0 – 2.3% and weakly dependent on the Fermi level, the THz absorption or optical conductivity of graphene is proportional to its carrier concentration. Exploiting this phenomenon, electrical control of THz transmittance was recently demonstrated in graphene/SiO_2/Si structures [1]-[2]. Up to ~ 20% intensity transmittance modulation has been reported with a low attenuation (< 5%), which is introduced by the minimum conductivity of graphene. This is a remarkable result since the active device basically consists of an atom-thick graphene sheet only.

Our analysis [1] showed that the observed intensity transmittance modulation of near 20% is owing to absorption in graphene entirely, and also further suggested that absorption by graphene can be much augmented if the THz field at graphene is enhanced utilizing cavities. In this work we employ one of the simplest cavity designs and demonstrate experimentally 64% intensity modulation of THz reflectance in graphene/SiO_2/Si/metal reflective structures. This extraordinary control of THz radiation is comparable to the best THz modulation reported in the literature, which are typically attained in metamaterial structures [3]. Particularly interesting, our theoretical analysis also indicates that, in these reflective structures, it is possible to completely turn the reflection off thus achieving 100% reflectance modulation.

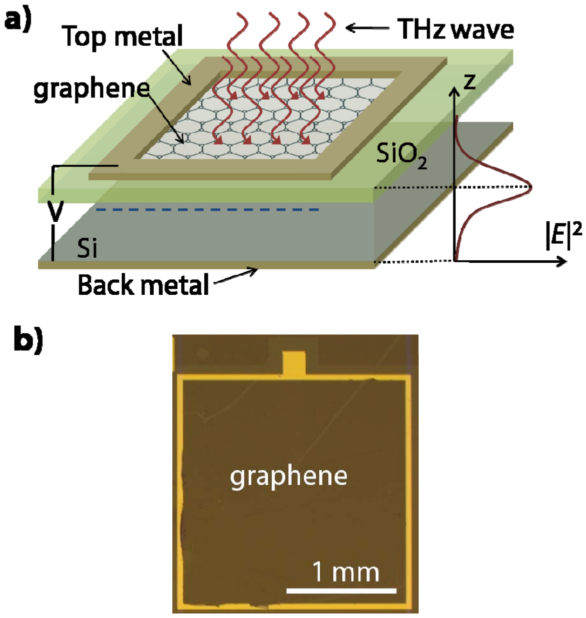

Fig. 1. a) Schematic of the device structure and THz intensity distribution in the device. When the substrate thickness is an odd multiple of a quarter wavelength of the incoming THz radiation (as depicted in the figure), the THz intensity at graphene is at maxima. b) Optical image of a scaled prototype device showing 2mm x 2mm graphene with a top ring metal contact.

II. DEVICE DESIGN AND FABRICATION

A. *Device structure*

The devices demonstrated in this work consist of graphene/SiO_2/Si/metal reflective structures, as depicted in Fig. 1a-b). The only difference between this reflection mode device and the previous transmission mode device is the bottom metal contact. In the transmission mode device, a back ring contact was used. In the reflection mode device, the ohmic contact covers the entire backside, also acting as the reflector.

Assuming the Si substrate is highly resistive, i.e. no free carrier absorption in Si, the THz reflectance can be calculated based on the ABCD matrix formalism [2]. The associated reflectance is given by:

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$$R = \left| \frac{Ae^{-j\varphi} + Ce^{j\varphi}}{Be^{-j\varphi} + De^{j\varphi}} \right|^2 , \qquad (1)$$

and

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \frac{1}{2n_s} \begin{pmatrix} 1+n_s - Z_0\sigma & n_s - 1 - Z_0\sigma \\ n_s - 1 + Z_0\sigma & 1 + n_s + Z_0\sigma \end{pmatrix}, \qquad (2)$$

where $\varphi = 2\pi d / \lambda$, d is the substrate thickness, λ the THz wavelength in the substrate, n_s the substrate refractive index ($n_s = 3.42$ for Si), Z_0 the vacuum impedance ($Z_0 = 377\Omega$), and σ the graphene conductivity. To derive Eqn. (1) we have neglected the effect of mobile carriers accumulated at the Si/SiO$_2$ interface [1] since the THz absorption is low due to their low mobility (much smaller than that of carriers in the capacitively coupled graphene layer). Moreover, normal incidence is assumed in both the theoretical and experimental work.

From Eqn. (1) and (2), it can be easily seen that the dependence of THz reflectance with frequency, therefore φ, has two extreme cases:

- $\varphi = m\pi$, where $m = 0,1,2,\ldots$. This case corresponds to the substrate thickness being an even multiple of a quarter-wavelength of the incoming THz radiation. Under this situation, $R = 1$ regardless of the graphene conductivity.

- $\varphi = (m+1/2)\pi$, where $m = 0,1,2,\ldots$. This case corresponds to the substrate thickness being an odd multiple of a quarter-wavelength of the incoming THz radiation. Under this situation, the reflectance is minimal and strongly depends on the graphene conductivity:

  $$R = \left| (1 - Z_0\sigma) / (1 + Z_0\sigma) \right|^2 . \qquad (3)$$

  As a result, by electrostatically tuning the Fermi level in graphene [4], reflectance can be effectively modulated.

The operation mechanism is intrinsically broadband in the previously demonstrated graphene transmission mode modulators, however, THz transmittance becomes frequency dependent due to cavity effects when the substrate is optically thick [2]. At frequencies exhibiting maximal transmittance and also maximal transmittance modulation, the substrate thickness is an even multiple of a quarter wavelength of the THz beam. At these frequencies, the dependence of transmittance with conductivity is given by [1]:

$$T = \left| 2 / (2 + Z_0\sigma) \right|^2 \qquad (4)$$

Based on this analysis, one can plot the calculated reflectance for the reflection mode modulator and the calculated transmittance for the transmission mode modulator as a function of graphene conductivity, using Eqn. (3) and (4), respectively. As shown in Fig. 2, a unique feature of the reflectance based modulator is that zero reflectance, i.e. total absorption, of THz radiation can be potentially achieved. At $\sigma = 1/Z_0 = 2.7\,mS$, the reflectance is zero. For graphene conductivities larger than this critical value, the graphene layer itself starts to reflect THz beams, thus leading to an increase in reflectance. The achievable reflectance modulation for a typical conductivity swing in large-area CVD graphene (e.g. 0.2 to 1 mS [1], the grey shaded region in Fig. 2) can be thus ~ 4 times larger than the attainable transmittance modulation in transmission mode modulators.

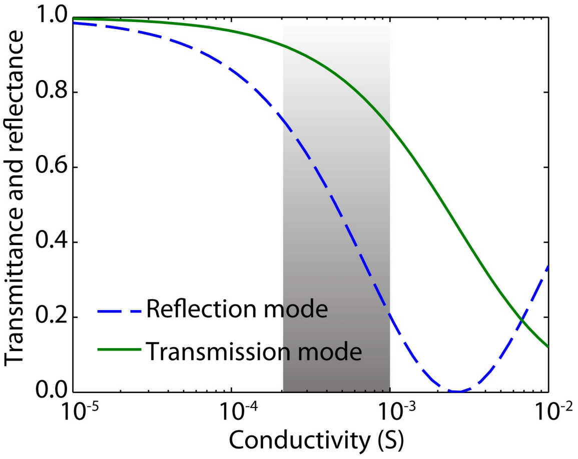

Fig. 2. Calculated transmittance/reflectance versus graphene conductivity for the graphene based transmission/reflection mode THz modulators. It is noteworthy that total THz absorption can be achieved in reflection mode devices. The region highlighted in gray corresponds to a graphene conductivity swing between 0.2 and 1mS.

The superior modulation in this reflectance based structure can be physically understood in terms of field enhancement in the graphene active layer. When the device is designed so that the Si thickness is an odd multiple of a quarter-wavelength of the incoming THz radiation, the intensity of the electric field maximizes and exhibits 4 times enhancement in the graphene layer due to the back metal reflector (see Fig. 1a). A similar structure was also recently explored to improve IR modulation employing graphene [5], but achieving small modulation (~ 4%), because of the weak tunability of graphene optical response at IR frequencies.

B. *Sample fabrication*

The graphene employed in this work was grown on copper by the chemical vapor deposition (CVD) approach [6]. The Si substrate is *p*-type with a resistivity ρ of ~ 1000 Ω.cm. A 70-nm thick SiO$_2$ was grown thermally on the Si substrate. Graphene transfer was realized by means of poly(methyl methacrylate) (PMMA) and wet etch methods. Metal contacts to the graphene and back side of the Si substrate (Ti/Au) were deposited by e-beam evaporation.

III. RESULTS

The device was characterized using a CW THz spectroscopy and imaging setup [7], consisting of a 570-630 GHz VDI (Virginia Diodes Inc.) CW THz source and a zero bias Schottky diode broadband intensity detector. The setup was arranged for reflection measurements. The THz reflectance was measured as a function of frequency for different voltages applied between the top graphene and back metal (reflector), as shown in Fig. 3. At the resonance frequency of the structure (~ 620 GHz), a strong modulation of 64% is observed because of the field enhancement in the graphene active layer, which is >3X larger than that achieved in previously demonstrated graphene-based transmission mode modulators [1], [8]. By improving the graphene quality, modulation depths approaching 100% can be attained as anticipated from the theory presented above.

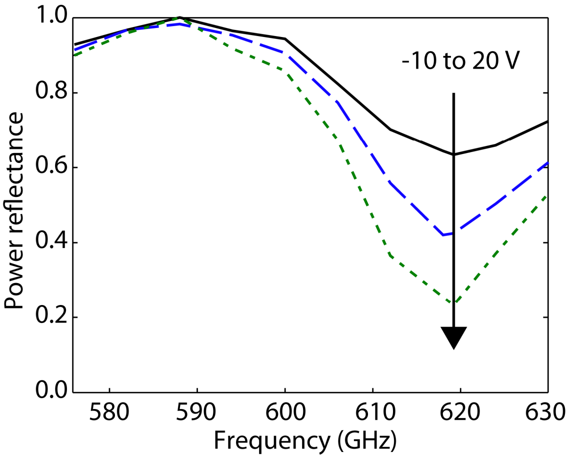

Fig. 3. Measured power reflectance as a function of frequency for different voltages between the top graphene and back metal.

IV. CONCLUSION

We have demonstrated that extraordinary control over THz reflectance can be achieved in a graphene-based device, therefore showing the enormous potential of graphene as an active material in structures manipulating THz waves.

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