Unique prospects for graphene-based terahertz modulators

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The modulation depth of two-dimensional electron-gas (2DEG) based terahertz (THz) modulators using AlGaAs/GaAs hetero-structures with metal gates is inherently limited to <30%. The metal gate not only attenuates the THz signal but also severely degrades modulation depth. Metal losses can be significantly reduced employing an alternative material with tunable conductivity. Graphene presents a unique solution to this problem due to its symmetric band structure and extraordinarily high hole mobility. In this work, we show that it is possible to achieve a modulation depth of >90% while simultaneously minimizing signal attenuation to <5% by tuning the Fermi level at its Dirac point. © *2011 American Institute of Physics*. [doi:10.1063/1.3636435]

The terahertz (THz) electromagnetic spectrum has long been recognized as an important region for scientific research. However, due to the lack of devices, circuits and systems for effective THz signal generation, detection, and modulation, this region remains the least explored and developed of the electromagnetic spectrum. The past decade witnessed a substantial increase in THz research activities.[1] Electrically tunable THz modulation is one of the actively pursued subjects due to its importance in applications such as communications, imaging, and spectroscopy. Kleine *et al.*[2,3] demonstrated a THz modulator operating at room temperature (RT) by employing a semiconductor two-dimensional electron-gas (2DEG) structure. Though RT operation is a significant advance compared to typical devices that operate at cryogenic temperatures, poor modulation depths (MDs) of 3%–4% have been reported so far. Consequently, the principal direction of the RT modulator research turned towards metamaterial approaches,[4–6] with up to 52% modulation recently reported.[5] However, these metamaterial-based devices have several comparative disadvantages. For example, they are intrinsically narrowband and usually have a polarization-dependent response.[6] There has been a little discussion in the literature on the fundamental performance limits of 2DEG-based THz modulators. In this work, we show that the modulation depth of previously proposed AlGaAs/GaAs 2DEG THz modulators is inherently limited to be <30% due to the adverse effect of the metal gate; however, by employing graphene in place of the metal gate, modulation depth >90% is achievable.

Graphene, a single layer of carbon atom with honeycomb structure, has attracted intense attention in the physical, chemical, and biological sciences since its discovery in 2004.[7] Although its optical properties have been extensively explored, however, to date there are only a few studies of graphene-based THz devices in the literature including emitters[8] and detectors.[9] In this work, we present a proposal of graphene-based THz modulators.

The structure of a generic 2DEG-based electrically driven THz modulator is shown in Fig. 1(a). Since THz transmission through a conducting media is a function of its conductivity, modulation of THz transmission can be achieved by electrically tuning the 2DEG density using a metal gate. In this work, we investigate the performance benefits of replacing the metal gate by a single-layer of graphene, as shown in Fig. 1(b). We also consider the use of two sheets of graphene separated by an insulator, taking advantage of the facile fabrication and low cost of large area graphene grown using chemical vapor deposition. When the Fermi level is at the Dirac point of both graphene layers, THz transmission approaches 100%; while when electron and hole sheets of charges are formed in the top and bottom graphene layers under appropriate bias conditions, transmission approaches zero.

Figure 2(a) shows the schematic of a general structure with N conductive sheets with sheet conductivity σ_i separated by dielectric materials with optical refractive index n_i. To model THz transmission through this structure, the wave-transfer matrix theory is employed.[10] Each conductive interface is represented by an S_i or M_i matrix and each dielectric interlayer is represented by an $\tilde{S}_i$ or $\tilde{M}_i$ matrix. Shown in Eq. (1) are the definitions of the S- and M-matrix and their relationship to the electric field vector of the incident (+) and reflected (−) waves at the two ports of an optical system as sketched in Fig. 2(b)

$$\begin{pmatrix} E_2^{(+)} \\ E_1^{(-)} \end{pmatrix} = \begin{pmatrix} t_{12} & r_{21} \\ r_{12} & t_{21} \end{pmatrix} \begin{pmatrix} E_1^{(+)} \\ E_2^{(-)} \end{pmatrix} = S \begin{pmatrix} E_1^{(+)} \\ E_2^{(-)} \end{pmatrix},$$

$$\begin{pmatrix} E_2^{(+)} \\ E_2^{(-)} \end{pmatrix} = \frac{1}{t_{21}} \begin{pmatrix} t_{12}t_{21} - r_{12}r_{21} & r_{21} \\ -r_{12} & 1 \end{pmatrix} \begin{pmatrix} E_1^{(+)} \\ E_1^{(-)} \end{pmatrix} = M \begin{pmatrix} E_1^{(+)} \\ E_1^{(-)} \end{pmatrix},$$

$$M = M_N \times \tilde{M}_{N-1} \times M_{N-1} \times \ldots \times \tilde{M}_1 \times M_1. \quad (1)$$

Since the metal gate thickness (∼5 nm) and the effective thickness of the 2DEG (on the order of nanometers) are several orders of magnitude smaller than the THz beam wavelength (e.g., 500 μm at 600 GHz), both layers can be treated as zero thickness conductive sheets. In this analysis, the metal gate is modeled with a constant sheet conductivity $\sigma_{s,m}$, and

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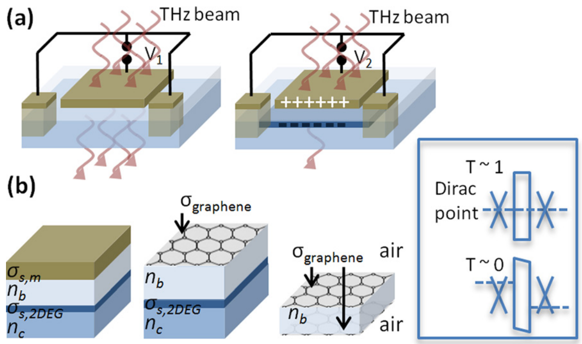

FIG. 1. (Color online) (a) Operating principle of a 2DEG-based THz modulator. (b) Layer structures of traditional metal-gate/2DEG and proposed graphene/2DEG and graphene/graphene THz modulators. Shown in the box are the schematic energy band diagrams of a graphene/insulator/graphene modulator.

the 2DEG is represented as a variable conductive layer with an associated sheet conductivity $\sigma_{s,2DEG}$. Additionally, it is assumed that at the frequency of the THz beam, optical sheet conductivity equals the DC electrical conductivity. Under normal incidence, the Fresnel coefficients in the S-matrix for a zero thickness conductive layer located between two dielectric materials with refractive indexes of n_i and n_j, respectively, are given by[11] $t_{ij} = 2n_i/\Delta$ and $r_{ij} = (n_i - n_j - Z_0\sigma_s)/\Delta$, with $\Delta = n_i + n_j + Z_0\sigma_s$, where σ_s is the sheet conductivity of the conductive layer and $Z_0 = 377\ \Omega$ is the wave impedance of vacuum. For the generic structure shown in Fig. 2(a), one can see that the dielectric interlayers can induce Fabry-Perot cavity type oscillatory behavior as a function of layer thickness and frequency. The wave transmission property intrinsic to the conductive sheets can be obtained independent of the cavity effect, for instance, in a structure where the sum of all dielectric interlayer thicknesses is much smaller than the beam wavelength. In this case, one can ignore the phase change of the wave in the dielectric interlayers, i.e., the $\tilde{S}$ and $\tilde{M}$ matrices. The beam transmission through the generic structure can thus be derived using the wave-transfer matrix analysis as

$$T = 4n_0n_N \times \left[n_0 + n_N + Z_0\sum_{i=1}^{N}\sigma_i\right]^{-2}. \tag{2}$$

For the 2DEG THz modulator structures considered in Fig. 1(b), the beam transmission is given by

$$T_{metalgate} = 4 \times [2 + Z_0\sigma_{s,m} + Z_0\sigma_{s,2DEG}]^{-2},$$
$$T_{graphenegate} = 4 \times [2 + Z_0\sigma_{s,m} + Z_0\sigma_{s,graphene}]^{-2}. \tag{3}$$

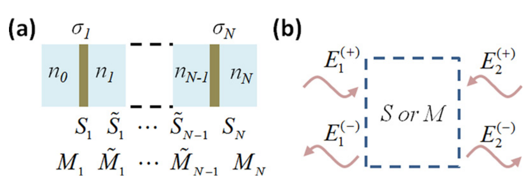

FIG. 2. (Color online) (a) Definition of parameters in a generic structure with N conductive sheets separated by dielectric interlayers. (b) Definition of the electric field vectors of incident and reflected waves at two ports of a generic optical system.

The MD of the modulators, defined as $(T_{\sigma=0} - T_\sigma)/T_{\sigma=0}$, is therefore found to be

$$MD_{metalgate} = 1 - \left[1 + \frac{Z_0\sigma_{s,2DEG}}{(2 + Z_0\sigma_{s,m})}\right]^{-2},$$
$$MD_{graphenegate} = 1 - \left[1 + \frac{Z_0\sigma_{graphene}}{2}\left(1 + \frac{\mu_{2DEG}}{\mu_{graphene}}\right)\right]^{-2}. \tag{4}$$

It has been assumed that the graphene conductivity can be tuned to be ~ 0 to simplify the analytical expressions since the minimum conductivity of graphene ($4e^2/h$) introduces a beam attenuation of $<5\%$ using Eq. (3). Two key observations are evident from inspection of Eq. (4): (1) A metal gate with sheet conductivity generally greater than that of the 2DEG adversely lowers the MD in addition to introducing significant beam attenuation and (2) the maximum MD is limited by the maximal tunable 2DEG and graphene sheet conductivity.

Also assumed in Eq. (4) is that the conductivities of the graphene gate and the 2DEG channel are tuned to their minimum or maximum values simultaneously. To meet this requirement, graphene minimum conductivity should be achieved at or below the threshold bias region of the HEMT. Above the threshold condition, a 2DEG is induced in the semiconductor channel and the opposite charge with the same concentration, a 2D hole gas (2DHG), is induced in graphene. The simultaneous tuning requirement makes graphene the best candidate for the tunable conductive pair in 2DEG-based THz modulators, as the hole mobility in graphene is comparable to the electron mobility due to its symmetric and conical band structure. Furthermore, the graphene electron mobility is among the highest for a given 2DEG concentration in all 2DEG systems, while the hole mobility in conventional semiconductors is generally orders of

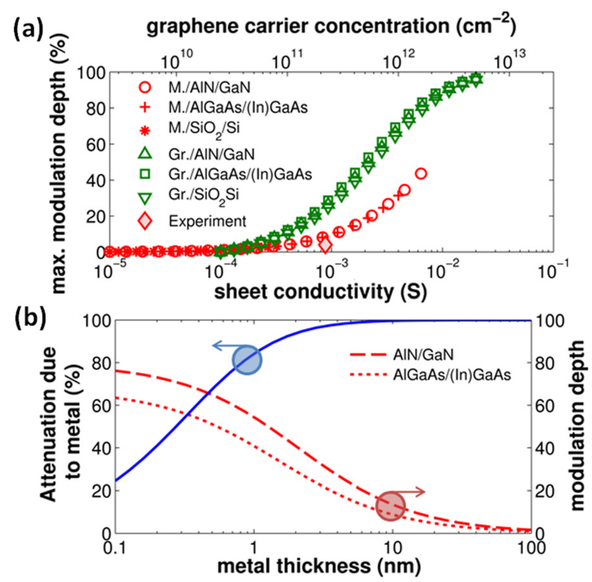

FIG. 3. (Color online) (a) Calculated achievable modulation depth for several modulator structures. (b) Calculated beam power attenuation introduced by the metal and maximum modulation depth for metal/AlN/GaN and metal/AlGaAs/GaAs modulators as a function of Cr gate thickness.

TABLE I. Material systems compared in Fig. 3 and their 2DEG properties at two carrier concentrations estimated from the literature.

	$n_s = 5 \times 10^{12}$ cm^{-2}		$n_s = 2 \times 10^{13}$ cm^{-2}			
	μ (cm^2/V s)	σ (mS)	μ (cm^2/V s)	σ (mS)	$\mu_{2DEG}/\mu_{graphene}$ (5×10^{12} cm^{-2})	$\sigma_{2DEG,max} + \sigma_{graphene,max}$ (mS)
Al(InGa)N/GaN (Refs. 13 and 14)	2000	1.6	2000	6.4	2/25	26.4
SiO_2/Si (Ref. 15)	200	0.16	100	0.32	0.2/25	20.16
AlGaAs/(In)GaAs (Ref. 16)	5000	4	—	—	5/25	24
Graphene (Refs. 17 and 18)	25 000	20	2500	8	—	40

magnitude smaller than that in graphene. Likewise, a graphene-graphene pair can be used for 2DEG THz modulators as shown in Fig. 1(b). It is also worth noting that optical absorption in graphene in the THz range is dominated by intraband transitions, and its optical conductivity closely follows the electrical.[12]

Based on Eq. (4), the attainable MD as a function of sheet conductivity is presented in Fig. 3(a) for metal-gate/2DEG and graphene/2DEG modulators. Various material parameters used in the calculation are listed in Table I. To facilitate the evaluation, mobility and conductivity values are compared at two carrier concentrations: (1) 5×10^{12} cm^{-2} since the highest conductivity reported in AlGaAs/(In)GaAs and graphene 2DEGs is around this concentration and (2) 2×10^{13} cm^{-2} representing a typical value for the highest carrier concentration in Al(InGa)N/GaN, SiO_2/Si and graphene 2DEGs.

For the metal/2DEG modulators, a beam power attenuation of 90% due to the metal gate is assumed to agree with the experimental results reported by Kleine *et al.*[2,3] Using the maximum values of the 2DEG conductivity, MD of up to 5%, 30%, and 45% is expected in SiO_2/Si, AlGaAs/(In)GaAs, and Al(InGa)N/GaN based metal/2DEG modulators, respectively. It is evident that the higher the maximum 2DEG conductivity, the higher the achievable MD. Also shown in Fig. 3(a) is the MD observed in Kleine's experiment.[2,3] For the graphene/2DEG modulators, a constant ratio of $\mu_{2DEG}/\mu_{graphene}$ at 5×10^{12} cm^{-2} is used as a parameter (Table I).

To further illustrate the adverse effect of the metal gate, we show in Fig. 3(b) the calculated beam attenuation and the resultant maximum achievable modulation depth as a function of the chromium gate thickness using a Cr bulk conductivity of 8×10^6 S/m. Beam attenuation quickly increases from ~30% to ~100% when the Cr thickness is increased from 0.1 nm to 10 nm; consequently, the achievable modulation depth drops from near 70% to 10%. In practice, it is challenging to reduce the beam attenuation to be lower than 90% using the conventional metal gate (in stark contrast to beam attenuation <5% introduced by the typical minimum conductivity in graphene).

In conclusion, we have presented an analytical study on the current limits of performance of 2DEG-based THz modulators, and how incorporating graphene as a "tunable metal" gate holds promise for significant improvements. A single layer graphene can be nearly transparent when its Fermi level is tuned at the Dirac point and block almost 100% THz beam when tuning to its maximum conductivity. By adopting graphene in 2DEG THz modulators, negligibly low beam attenuation and near 100% modulation depth are achievable, offering advantages including RT, broadband, and polarization-independent operation.

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