Simulative Study on Electronically Tunable Metal Gated and Graphene Gated Terahertz Modulator based on Modulation Depth

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Received: 14-September-2016; Accepted: 31-January-2017; Published: 1-February-2017

Abstract: Two dimensional electron gas (2DEG) based High Electron Mobility Transistor (HEMT) has been considered as the basic structure of the THz modulator, where three different metals, namely Ni, Zn and Al of 1 nm thickness, have been considered as the gate material of the HEMT. For graphene gated 2DEG based THz Modulator, 1 nm width of graphene layer and different 2DEG materials are considered for simulation. Electronically tunable conductivity of the graphene gate is simulated in the range of -50 V to 50 V. Then beam attenuation of the metal-gated THz modulator is studied and its effect on the modulation depth is simulated. After that, intensity transmittance of the both metal and graphene gated THz modulator is simulated as a function of the metal and 2DEG sheet conductivity. Finally, the modulation depth of both metal and graphene gated THz modulator has been studied in terms of the conductivity of 2DEG sheet and graphene gate respectively. After analyzing these studies, graphene based THz modulator has been recommended as a suitable and efficient modulator for the modulation of incident THz radiation for its higher modulation depth than the metal gated modulators, and suggested to be very useful for long distance communication purpose.

Keywords: THz, graphene, modulator, transmittance, attenuation.

1. Introduction

The Terahertz (THz) frequency range is the region of the electromagnetic spectrum lying between the microwaves and the infra-red (IR). Since both electrical and optical phenomena are significant at these frequencies THz is considered as the melting pot between electronics and photonics. Terahertz radiation is also called waves, tremendously high frequency T-rays, T-waves, T-light, T-lux or THz, which consists of electromagnetic waves, defined between the frequency range 300 GHz and 3 to 30 THz [1]. THz technology has recently turned into a major field of scientific research. In 2004, Kleine-Ostmann et al. demonstrated a THz modulator operating at room temperature by employing a semiconductor two dimensional electron gas (2DEG) structure with poor modulation depth of 3-4% [2] [3]. Recently, it was found that graphene can be superior to semiconductors when used as a gate material of electrically driven THz modulator for its excellent electronically tuning property such as conductivity and high frequency properties, which can achieve high modulation depth [4] [5]. In this research work, Modulation Depth of electronically tunable metal and graphene gated THz modulator has been simulated for gates of different metals and 2DEG sheets respectively. To study the comparisons between modulation depth of these two different gated THz modulators, changing some material properties like primarily optical conductivity. Moreover, frequency selective surfaces incorporating microwave transistors or diodes as switches can also
modulate the THz transmittance. In this kind of modulators, electronically tuning the conductivity of the frequency selective surface, transmittance of incident THz radiation can be modified which performs THz modulation. In this kind of modulators, meta-material structure can be used to perform efficient modulation where, the change of conductivity and therefore free carrier absorption in a small semiconductor active region located in between a periodic metallic pattern, i.e. a frequency selective surface structure (FSS), translates into an extraordinary control of the terahertz transmission (modulation depth ~80%) for frequencies close to the structure intrinsic resonance [1].

1.1 2DEG and HEMT in THz Modulation

Carrier concentration in semiconductor is altered by electric injection or depletion of charge carriers to achieve THz modulation. In the last decade the use of two-dimensional electron gases (2DEGs) in semiconductors has proven useful for control of THz waves and the high electron mobility transistor (HEMT) is an often used architecture. Modulation of the incident signal on the modulator can be performed by changing the 2DEG sheet conductivity. For efficient manipulation of terahertz signal, switchable meta-materials can also be useful [6] [7]. At the interface of hetero-structure, a triangular quantum well forms where the charge carriers are restricted in one direction whereas the carriers can move freely in other two directions of the well, called 2DEG [8][9]. Electronically, THz modulation involves high mobility homogeneous 2DEG where, by tuning the conductivity of the 2DEG, incident THz signal can be modulated. The tuning is performed electrically by using semi-transparent metallic gate and the field effect. This arrangement is generally performed by a special field-effect transistor, called HEMT. The modulation process using this principle can be switched very rapidly and efficiently, because, a homogeneous two-dimensional electron gas modulator has a strongly frequency-dependent transmission function, which at frequencies of around 1 THz only changes the transmission by only around 1 percent. Thus, fast and strong modulation can be achieved using 2DEG based electrically tuned THz modulator [10] [11].

1.2 Metal gated THz Modulator

A generic electronically driven metal gated THz modulator is shown in Fig.1. THz transmission can be achieved by modulating the conductivity of 2DEG density using a gate since transmission of THz signal through any conductive media depends on the conductivity of that media. Traditionally in 2DEG modulators metal is used as gate material. Here THz transmission is tuned by applying a voltage between the metal gate and 2DEG. Transmission of THz signal is inversely proportional to 2DEG density because of enhanced absorption and reflection [4].

In this 2DEG-metal THz modulator, HEMT is very essential because here channel is formed with intrinsic crystal which causes high mobility and charge density at RT(room temperature) which produces fast conduction at THz frequency and with using meta-material structure, enables switching speed up to 10 MHz [12]. In metal-2DEG THz modulator, the effective thickness of 2DEG and thickness of metal is several orders of magnitude smaller than the THz beam wavelength, so it can be considered that both 2DEG and metal gate are zero thickness conductive sheet. Modulation depth (MD) of the metal-2DEG modulator vary with the variation of sheet conductivity of 2DEG, which is related by the equation of MD of metal gated modulator given by:

\[
MD = 1 - \left[ 1 + \frac{2\sigma_{2DEG}}{2 + \frac{\sigma_{2DEG}}{\sigma_{metal}}} \right]^{-2} = \frac{T_{\sigma=\sigma} - T_{\sigma=0}}{T_{\sigma=0}}
\]

Here, 2DEG is represented as a variable conductive layer with sheet conductivity \(\sigma_{2DEG}\), 2DEG. \(T_{\sigma}\) and \(T_{\sigma=0}\) denotes transmittance of the incident THz signal at a certain value of 2DEG sheet conductivity and at zero conductivity respectively and wave impedance at vacuum is denoted by \(z_0\). Beam transmission of metal-gated modulator is given by [4]:

\[
\]
Fig. 1. 2DEG based electrically driven modulator

1.3 Graphene gated THz modulator

Graphene is the single atomic thick layer of hexagonal lattice shaped carbon atoms. Due to excellently electronically tuning property of graphene conductivity and high frequency properties, graphene gated THz modulators can achieve large modulation depth[13][14]. THz wave transmission through graphene involves 2 processes: Intra-band transition and inter-band transition. Red arrows of Fig. 3(a) shows intraband transition and long arrows (green) shows inter-band transition. At the visible and infrared portion of the incident electromagnetic spectrum on graphene based modulator, interband transition in graphene dominates and than conductivity of graphene becomes less dependent on fermi energy in graphene. It shows excellent transmission of visible and infrared signal through graphene. But in THz portion of electromagnetic spectrum, intraband transition dominates and then tuning the conductivity of graphene using gate voltage, the fermi energy level can be varied and transmission of THz signal can be well controlled and modulated [15][16][17]. A schematic diagram of graphene based THz modulator is also shown on Fig. 2(a). When the gate voltage of modulator is zero, the fermi level lies at the dirac point of all graphene layers, which results minimum insertion loss or signal attenuation. When a gate bias is applied, two-dimensional hole gases (2DHGs) are induced in the graphene layers which are connected to the positive power supply and two-dimensional layers connected to the negative power supply. Due to the symmetric band structure of graphene, density of states of electrons and holes and both carrier mobility is identical. So in stacked graphene layer structure in modulator, shown on Fig. 2(b), each layer contributes equally to THz modulation. In this figure, it is shown that at zero gate voltage, Fermi level is at dirac point resulting unity THz transmission and with applying gate bias, Fermi level moves up or down to valence or conduction band which leads near zero transmission [17]. Conductivity of graphene in modulator can be varied by varying modulating frequency. Graphene conductivity as a function of frequency is given by [18]

\[
\sigma(\omega) = \frac{\sigma_Q}{\sigma_0} \left( \frac{2}{\pi \tau} + \frac{1}{\tau} \right)^{-1} \left( 1 + e \left( \frac{2E_F - \hbar \omega}{2k_B T} \right) \right)^{-1}
\]

Here, \( \tau \) is the momentum relaxation time of the charge carriers in graphene (2 fs considered) and \( \sigma_Q \) is the quantum conductivity for graphene arising from interband transition. Here, dirac fermion velocity of graphene is 106 m/s. Conductivity of graphene as a function of modulating frequency can be shown by above equation. Extracting the graphene sheet conductivity from this equation, we can show the frequency dependence of transmittance through the graphene-2DEG modulator. Also we can show the variation of transmittance with graphene sheet conductivity. Finally, the transmittance
variation as a function of sheet conductivity, we can measure the MD of graphene-2DEG based modulator from the following equation [4]

\[
MD = 1 - \left[ 1 + \frac{Z_0 \sigma_{\text{graphene}}}{2} \left( 1 + \frac{\mu_{\text{2DEG}}}{\mu_{\text{graphene}}} \right) \right]^{-2} \tag{4}
\]

Here, \( \mu_{\text{2DEG}} \) and \( \mu_{\text{graphene}} \) is mobility of charge carriers in different 2DEG sheets considered in the THz modulators and mobility in graphene layer respectively.

Fig. 2. Conical band diagram of Graphene and schematic diagram of Graphene based modulator and multiple graphene layers in modulator structure

2. Simulations

In this work, metal-2DEG based THz modulators of three different high conductive gate metals- Nickel (Ni), Zinc (Zn) and Aluminium (Al), is considered to simulate the maximum modulation depth (MD) with varying the sheet conductivity of 2DEG. Concentration of electrons at the 2DEG sheet of these three different metal gated THz modulators is considered, \( n_s = 5 \times 10^{12} \text{ cm}^{-2} \) and 1 nm thickness of metal gates are chosen for simulation. Than the metal gate is replaced by Graphene and the variation of the modulation depth (M.D) of graphene-2DEG based THz modulators with varying the conductivity of graphene sheet is simulated, for different 2DEG materials. Here three different graphene-2DEG based THz modulators are considered: Graphene/Al(InGa)N/GaN, Graphene/AlGaAs/GaAs and Graphene/SiO2/Si, with 2DEG carrier concentration of \( 5 \times 10^{12} \text{ cm}^{-2} \).

2.1 Electronically Tuning Conductivity of Graphene upto ±50 Volt :

In Graphene gated THz modulator, conductivity of graphene can be electronically tuned using a gate voltage. Here the variation of the conductivity of graphene is simulated for gate voltage upto ±50 Volt in Fig. 3. It has been observed from the simulation curve that, varying gate voltage from -50 V to 0, the conductivity of graphene decreases gradually and increasing gate voltage from 0 to 50 V, the conductivity increases. When gate is unbiased, the fermi energy level of graphene is at the dirac point which represents zero conductivity. Applying a positive gate voltage, the mobility of the carriers in the graphene increases and results increase of graphene conductivity. When a THz signal is incident on graphene based THz modulator, the energy of the photons of the THz signal is not very high to drive interband transition. As a result, intraband transition dominate the absorption of the THz radiation. Then the conductivity as well as fermi energy and the available density of states for intraband transitions is tuned by applying gate voltage across the graphene gated modulator, which increases the conductivity of graphene and reduces the transmittance of incident THz signal. Thus the change of transmittance with the conductivity modulates the input signal of the THz modulator.

2.2 Beam Attenuation at Zn Gated THz Modulator and effect on modulation depth:
Attenuation of the transmitted THz signal in the metal-2DEG based THz modulator with the variation of the gate metal thickness is studied from Fig. 4(a). In this case, a thin Zn gate of 1 nm width has been considered as:

![Graph showing Electronically tuning the conductivity of graphene in graphene gated THz modulator](image)

**Fig. 3.** Electronically tuning the conductivity of graphene in graphene gated THz modulator

Gate metal and then the thickness of the Zn gate is increased to realize the effect of attenuation of transmitted carrier signal of the modulator, i.e THz signal. We also observe the effect of attenuation on the modulation depth (MD) of the metal based modulator with varying the metal thickness from the simulation curve shown on Fig. 4(b). From the simulation of Fig 4(a), we observe that, increasing the thickness of the metal gate (Zn), the attenuation of transmitted electromagnetic signal rises sharply and then becomes nearly constant. It is seen from the simulation curve, at certain thickness of the metal gate, used as Zn in this work, the THz carrier signal of the modulator face a constant attenuation which causes undesired reflection and absorption of the incident signal. When a THz signal transmitted in the metal gated modulator, the low energy photons of the signal face certain absorption. Increasing the thickness of the gate material, the absorption of the photons of the THz signal rises which results the reduction of transmittance of the signal through the modulator and affects modulation process.

The effect of attenuation with increasing the metal gate thickness is simulated in terms of MD of the metal-2DEG based modulator and it is shown on Fig. 4(b), where it has been noticed that, due to constant attenuation of the incident THZ wave at the modulator, the modulation depth decreases gradually.
2.3 Signal Transmittance at THz Modulators for Different Metal Gates and 2DEG Sheets:

In metal-2DEG THz modulators, the variation of transmittance of THz carrier signal with varying 2DEG sheet conductivity is also studied and it is compared with the transmittance of graphene-2DEG based modulators. The simulation curves are shown:
On Fig. 5(a). To study the transmittance of the metal based THz modulators, 1 nanometer (nm) thick Zinc (Zn) and Nickel (Ni) gated THz modulators are considered and in case of graphene-2DEG modulators, two different 2DEG sheets are considered shown in Fig. 5(b). It is studied from Fig. 5(a) and 5(b) that, the variation of transmittance with conductivity in graphene based THz modulators are much higher than that of the metal based modulators. Modulation depth of a modulator is related to the transmittance of the electromagnetic signal which can be tuned by varying the conductivity. Change of transmittance with conductivity is defined as modulation depth. The calculation of the difference in the transmittance of Zn/2DEG THz modulators from Fig. 5(a) are given below:

\[
MD_{\text{metal \ gate}} = \frac{T_{\sigma=0} - T_{\sigma=0.01}}{T_{\sigma=0}} = 0.072 - 0.035 \times 100\% \approx 52 \%
\]

The calculation of the difference in the transmittance of Graphene/SiO2/Si modulator from Fig. 5(b) are given below:

\[
MD_{\text{graphene \ gate}} = \frac{T_{\sigma=0} - T_{\sigma=0.01}}{T_{\sigma=0}} = 0.9 - 0.15 \times 100\% \approx 84\%
\]

From analyzing the calculation of transmittance for metal and graphene gated THz modulators, it can be said that, as the change of transmittance in graphene-2DEG THz modulators are larger than the metal-2DEG based modulators, found from the simulation curve of Fig. 5(a) and 5(b), so very high MD in graphene based modulators (above 80%) can be obtained than metal gated modulators.

![Fig. 5(a). Transmittance at metal gate as a function of graphene sheet conductivity](image-url)
Fig. 5(b). Transmittance at graphene gate as a function of graphene sheet conductivity

Fig. 6(a). Simulation curve of modulation depth for metal gated THz modulator

2.4 Modulation Depth for metal gated and Graphene gated THz Modulator:

Finally, the Modulation depth of metal gated THz modulators for different metal gates is simulated in terms of the conductivity of 2DEG sheet, shown on Fig 6(a). Variation of modulation depth of graphene-2DEG based THz modulators with varying the conductivity of graphene sheet is also studied in Fig 6(b). Here we observe that, for metal gated THz modulator, In metal-2DEG THz
modulators, modulation depth has been obtained between 30% to 50%, whereas for graphene gated THz modulator, the modulation depth has been found between 80% to 90%.

3. Results

Studying the simulation results of the comparison between electronically tunable metal and Graphene gated THz modulators, it can be proposed that, Graphene-2DEG based THz modulator is more efficient and suitable for the modulation of incident THz radiation. Than metal-2DEG based 2DEG modulator for having higher maximum modulation depth (MD), 80%-90% obtained from the simulation. Thus the simulation proves graphene gated THz modulator as a efficacious device for long distance communication purpose.

![Fig. 6(b). Simulation curve of modulation depth for graphene gated THz modulator](image)

4. Conclusions

A study on the electronically tunable metal gated and graphene gated THz modulator based on Modulation depth has been performed in this research work. For the comparison between the both THz modulators, intensity transmittance and beam attenuation of the modulators, gated by different materials, have been studied. 2DEG based HEMT has been considered as the structure of the both metal and graphene gated THz modulators. The electronically tuning conductivity of graphene gate is observed for a gate voltage ranged between -50 to 50 V. For the simulation of transmittance, beam attenuation and modulation depth of metal-2DEG based THz modulators, three different metals - Ni, Zn and Al, have been considered and for these metals, modulation depth of the THz modulators in terms of 2DEG sheet conductivity has been simulated for 1 nm thick metal gate. After that, the gate material is replaced by Graphene and the modulation depth of the graphene-2DEG based THz modulator has been studied with varying graphene conductivity. Three different 2DEG sheet has been considered for the graphene gated THz modulators- AlGaAs/(In)GaAS, Al(InGa)N/GaN and SiO2/Si. From the simulation, above 80% modulation depth has been obtained for all the graphene gated THz modulators, whereas for metal based THz modulator, 30 to 50% modulation depth has
been found. After analyzing and comparing all these simulations, the Graphene gated Terahertz (THz) modulator has been proposed as a suitable and efficient device for its large percentage of modulation depth. Using the Graphene based THz modulator, highly efficient continuous-wave terahertz (THz) photoconductive antennas and antenna array can be designed and implemented in future for high contrast THz modulation and long distance communication with best performance [19].

References


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