Terahertz plasmon resonances in GaN and graphene

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Abstract

The plasmon resonance and tunability have been investigated in GaN-based and graphene device, the good agreement between theory and experiments indicate the potentially advantages of GaN device for filling the terahertz (THz) gap. Stronger resonant absorption will lead to the hydrodynamic rectifying of THz radiation in wide spectrum region, paving the way for self-coupling and detection of THz radiation in multiple quantum systems.

I. Introduction

In the last decade, terahertz (THz) technology has attracted great interest due to its inherent advantage in the applications of biomedical imaging, security imaging and nondestructive evaluation/quality control [1] [2]. Conventional detection techniques covering the spectral region of infrared and microwave rely on the narrow-gap materials or fast electron response in the field effect transistor. However, at THz band, the frequency is far beyond the fastest electron response and below the material's gap energy. To sense the THz radiation, detectors available now include bolometers, Schottky diodes and photoconductive detectors[3][4]. However, these detectors are not frequency-agile and bulky, which require mechanical motion of external optics to generate spectral information [5]. Achieving the appropriate performance without using highly sophisticated technologies would be extremely advantageous.

Recently, a new detection mechanism utilizing hydrodynamic nonlinearity of plasma wave (plasmon) in the two-dimensional (2D) channel of field effect transistors (FETs)/high electron mobility transistors (HEMTs) has been proposed [6]. Since the first demonstration of 2D plasmons and their capability for THz detection, several kinds of plasmonic devices have been explored and plasmon nonresonant/resonant phenomena are observed in the experiment [6-11]. Of particular interests, these results pave a route to realize large area focal-plane array THz camera. In order for improving the performance of plasmonic devices further, more advanced device structures embedded with antenna are developed such as grating-coupled large area detector array [12], multiple detectors connected in series or parallel [2, 13,14], and membrane substrate detectors with defect electrode [15,16].

The plasma waves in FETs have a linear dispersion, $\omega=sk$, where s is the wave velocity. The plasma wave velocity $s=(e^2n/m^*C)^{0.5}$ depends on the carrier density as controlled by the gate voltage and the gate-to-channel capacitance per unit area $C=\varepsilon/4\pi d$. Most of previous work focus on the GaAs or InP based material system with deep-submicron meter gate-length operating in the THz/sub-THz regime (the sheet electron density in the channel of GaAs sample is usually around 10^{12}cm^{-2})[9][10]. This paper aims to explore the potential properties of plasmon resonance in larger area GaN and graphene device, such as electrical tunability, resonant strength and its application in the plasmon-quantum emitter and detection system.

II. Device Description and Simulations

Figs. 1 (a) and (b) show the structure of grating-gated single-channel (SC) and graphene FETs. For GaN device, the structure can be grown on *c*-plane sapphire or SiC substrate by either metal organic chemical vapor deposition or molecular beam epitaxy [11]. The grating-gate can be served both as the electrodes controlling the sheet electron density and polarizer for the incident waves. The AlN/GaN device in Fig. 1(a) consists of 2μm GaN buffer layer and 5nm AlN barrier layer. The sheet electron density in the channel can exceeds 3×10^{13}cm^{-2}. As referring to the graphene device, either mechanical cleavage or (chemical vapor deposition) CVD grown on substrate such as SiO_2 or SiC can be performed with high material quality [12]. Graphene device usually has larger mobility than other III-V material system, which is benefiting from its two-dimensional properties and zero effective mass.

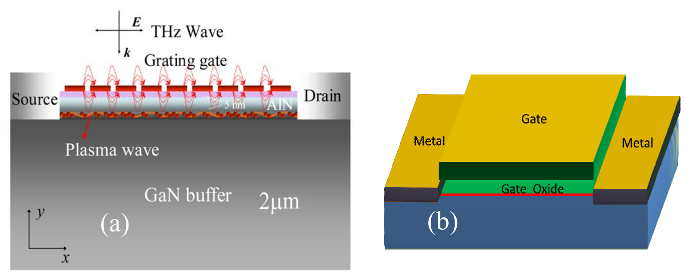

Fig.1. Schematic of device structures: (a) grating-coupled single-channel AlN/GaN HEMT; (b)Graphene device.

III. Results and Discussions

Theoretically, the electron mass in graphene is infinitesimal, while its mobility can reach 10^6 cm^2/Vs. If graphene is electrically doped or chemically doped, the interband transition is suppressed by Pauli blocking, so that the Landau damping can be neglected at THz band. In both the graphene and GaN HEMT, the electron density can be tuned to a high value.

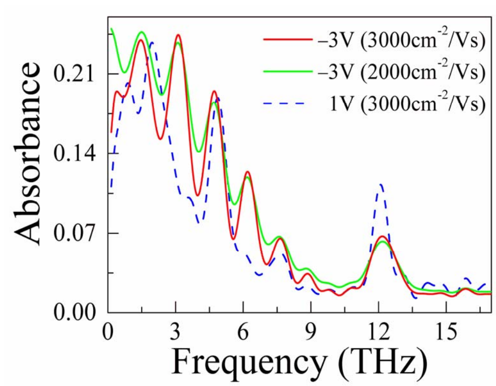

Fig. 2. Plasmon resonances in AlN/GaN HEMTs under different gate voltage.

Fig. 2 displays the plasmon resonance in GaN HEMT by using FDTD method as developed in our previous works [11-14]. We found that the plasmon resonance can be excited up to 6th order, indicating the resonant quality factor exceeds 5 even with small mobility values. When applying appropriate gate voltage to tune the frequency, the electric-field strength is enhanced at resonant frequency due to the

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long range Coulomb interaction. The high electric-field strength is benefit for improving responsivity of photodetection system or the emission efficiency of quantum dot and excitons system. Such results demonstrate potential advantages against other III-V material for higher THz frequency detection and room temperature operation.

In order to compare better between graphene and GaN for THz plasmonics. Here, we study the tunability of AB-stacking and monolayer graphene as shown in Fig. 1(b)[15]. The simulated fundamental resonant frequency versus Fermi energy is shown in Fig.3. We can see that the plasmon resonance frequency is comparable with GaN device at low Fermi level, however, in AB graphene device, the frequency is higher than GaN and monolayer graphene ones. In Fig. 3, the simulated date are fitted by the analytical method, the good agreement between these results indicate almost $E_F^{1/2}$ dependence of resonant frequency. While the AB device contains wider tunability than monolayer device, such deviation is caused by the different of energy dispersion between monolayer and AB stacking layers.

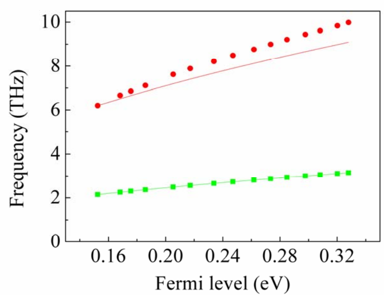

Fig.3. Simulated fundamental resonant frequency of monolayer graphene and AB-stacking bilayer graphene versus Fermi energy. Red circle: simulated fundamental resonant frequency of AB-stacking bilayer graphene. Green square: simulated fundamental resonant frequency of monolayer graphene. Red line: calculated fundamental resonant frequency of AB-stacking bilayer graphene supposing that it fulfills $\omega_p \propto E_F^{1/2}$. Green line: calculated fundamental resonant frequency of monolayer graphene supposing that it fulfills $\omega_p \propto E_F^{1/2}$.

III. Conclusions

A finite-difference method is employed to describe the local response of plasmonic oscillation in AlN/GaN and graphene device. The results indicate wide tunable resonance of these devices for THz detection. Due to different energy dispersions, the tunability of plasmon resonance exhibit different properties. We find AB stacking device can be tuned to frequency higher than 10THz, while below 10THz the GaN device will be the good choice. Such results propose hybrid design of these two materials.

Acknowledgements

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