Metamaterial Terahertz Bandpass Filters: A Comparison between Metallic and Graphene-based Structures

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Abstract— Metamaterial-based optoelectronic devices including Terahertz filters play a definitive role in advancement of THz technology. In this article we present a design procedure to obtain voltage-dependent carrier density control in a GaN-based heterostructure with a Schottky gate configuration which serves as the substrate for a THz bandpass filter (BPF). The introduced structure consists of a cross shaped metallic layer on the AlGaN/GaN heterostructures. Then, we investigate tuning of transmission properties and the tunability of the filter. An overall tunability of about 103 GHz in the resonance frequency was obtained by varying the applied voltage from −8 V to 2 V. Also, a plasmonic metamaterial based on the graphene cross-shaped structure is studied and a comparison has been performed between the optical properties of graphene-based cross-shaped structure and the original structure.

1. INTRODUCTION

Among different THz passive devices, THz wave band pass filters with multi frequency operations are crucial elements to enhance the efficiency in applications such as astronomy, terahertz signal processing, imaging, communications, and biomedical and chemical sensors [1, 2]. On the other hand, the exciting possibilities of artificially designed metamaterials with sub-wavelength scale, customizable electromagnetic (EM) properties and ability to control them at unit cell level, make them promising candidate for development of versatile THz components [3, 4]. However, due to the resonant nature of metamaterials, their operation has been confined to a narrow spectral range. The performance of metamaterial-based THz wave BPFs could be extended tremendously if their response is dynamically tuned. In this article we mainly focus on the active tuning of the filtering characteristics of metallic and graphene based structures.

2. RESULTS AND DISCUSSION

The considered metallic structure consists of a cross shaped metallic layer on the AlGaN/GaN heterostructures as illustrated in Figure 1. The transmission properties of the designed structure at different bias voltages have been depicted in Figure 2.

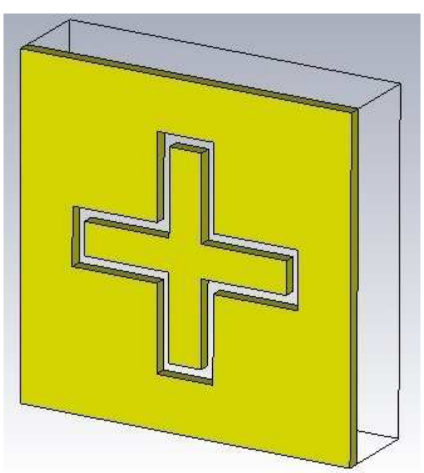

Figure 1: Cross-shaped THz BPF considered for study.

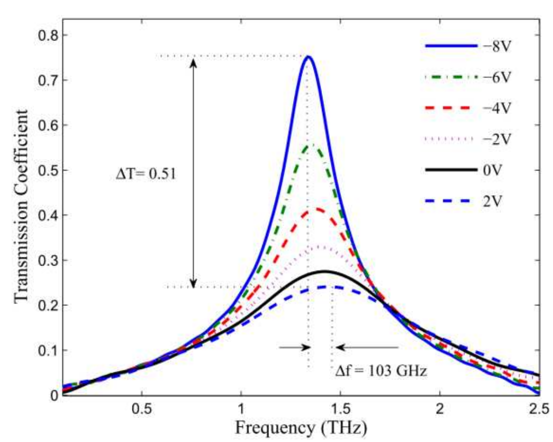

Figure 2: Transmission characteristics of the THz-BPF as a function of applied bias voltage.

To explore the active tuning of this structure, we have reduced the thickness of metal parts to 0.2 μm and the metallic part has been embedded on an $Al_xGa_{1-x}N/GaN$ heterostructures with relative thickness of 20 nm and 0.35 μm for $Al_xGa_{1-x}N$ and GaN layers, respectively as the substrate. In order to enable voltage-controlled conductivity of the substrate, metallic parts are electrically connected with 1 μm wide metallic (copper) connections which make the structure sensitive to polarization of THz wave. All simulations have been done for normal incidence. The array and substrate effectively form a Schottky diode, where dielectric properties of the substrate can be controlled by controlling the carrier density via applied gate voltage. An electric signal affects the high-frequency conductivity as well as the dielectric constant of the substrate in critical areas near the designed meta-molecules and thus, affects their resonant response. A self-consistent Schrödinger-Poisson approach has been utilized to obtain the energy subbands and the Fermi level in which the voltage-dependent sheet carrier density for $Al_xGa_{1-x}N/GaN$ structure has been included through

$$N_s = \frac{\varepsilon(x)}{e(d_d + d_i)}\left(V_a - V_{th} - \frac{E_f(x)}{e}\right) \tag{1}$$

where $\varepsilon(x)$ is the dielectric constant, E_f is the Fermi level, d_d and d_i are doped and undoped AlGaN thickness, and V_a and V_{th} stand for applied voltage and threshold voltage respectively, given by

$$V_{th}(x) = \phi^b(x) - \Delta E(x) - \frac{eN_d d_d^2}{2\varepsilon(x)} - \frac{\sigma(x)}{\varepsilon(x)}(d_d + d_i) \tag{2}$$

The threshold voltage depends on the conduction band discontinuity between $Al_xGa_{1-x}N/GaN$ denoted by $\Delta E(x)$, φ^b as the Schottky barrier at metal/AlGaN interface, dopant concentration, N_d, and the polarization induced charge density, $\sigma(x)$, at $Al_xGa_{1-x}N/GaN$ interface. Depending on the dopant concentration and Al mole fraction and consequently, the Fermi level, one may assume several confined energy levels, n, to obtain the total sheet carrier concentration inside the well through

$$N_s = \sum_{n=1}^{n=n_0} \frac{mk_bT}{\pi\hbar^2} \ln\left(1 + \exp\left((E_f - E_n)/k_bT\right)\right) \tag{3}$$

Plasma frequency of the (2DEG) can be then defined by $\omega_p = (N_s e^2/\varepsilon_0 m^*)^{0.5}$ where $m^* = 0.22\,\mathrm{m}$ is the effective electron mass in GaN and m is the free-electron mass.

As illustrated in Figure 2, an overall tunability of about 103 GHz in the resonance frequency was obtained by varying the applied voltage from −8 V to 2 V.

It is noteworthy to mention that graphene-based THz filters are more flexible to achieving tunability, and the continuous forms of graphene can be transferred to a flat substrate and the carrier concentration of each layer in a graphene-based multi-layer filter can be dynamically tuned.

The surface conductivity of graphene that contains the effect of interband and intraband transitions has been calculated through the local limit of random-phase approximation (RPA). The surface conductivity depends on the temperature, the intrinsic carrier relaxation time, τ, and the

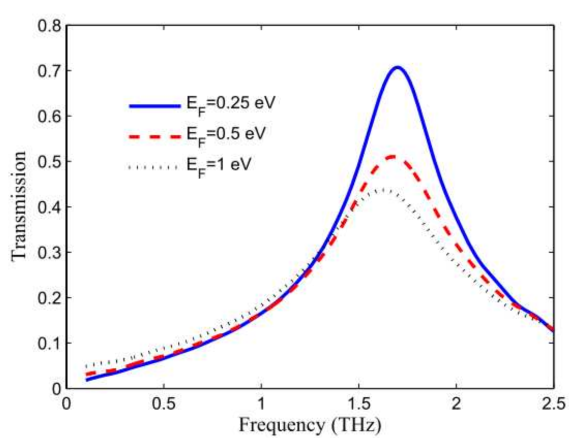

Figure 3: Transmission characteristics of the THz-BPF based on graphene as a function of Fermi energy.

Fermi level (which depends on the external bias voltage). Obtained results show considerable resonance strength and dynamically controllable feature.

Figure 3 shows the obtained transmission characteristics for the graphene-based THz filter which has the same structure as the metallic (copper) filter designed in this study. Beside the resonance shift which arises from the difference in the dielectric function of the copper and graphene at THz frequencies, a similar behavior is seen in graphene-based filter with varying the Fermi energy. As it is clear from Figure 3, increasing the voltage-induced Fermi energy increases the electron density and consequently, shorts the gap in the structure resulting in the reduced transmission of the structure.

The surface conductivity of graphene that contains interband and intraband transitions can be calculated through [5]

$$\sigma_s(\omega) = \frac{2e^2 k_b T}{\pi \hbar^2} \frac{i}{\omega + i\tau^{-1}} \log\left[2\cosh\left(\frac{E_F}{2k_b T}\right)\right] + \frac{e^2}{4\hbar}\left[H\left(\frac{\omega}{2}\right) + \frac{4i\omega}{\pi}\int_0^\infty \frac{H(\varepsilon) - H(\varepsilon/2)}{\omega^2 - 4\varepsilon^2} d\varepsilon\right], \quad (4)$$

where

$$H(\varepsilon) = \frac{\sinh\left(\hbar\varepsilon/k_b T\right)}{\cosh\left(E_F/k_b T\right) + \cosh\left(\hbar\varepsilon/k_b T\right)}, \quad (5)$$

Here, T is the temperature and E_F is the Fermi energy.

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