CARBON 82 (2015) 229–237

Available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/carbon

Tunable terahertz graphene metamaterials

Xiaoyong He

Mathematics & Science College, Shanghai Normal University, No. 100 Guilin Road, Shanghai 200234, PR China

ARTICLE INFO

Article history:
Received 9 August 2014
Accepted 22 October 2014
Available online 28 October 2014

ABSTRACT

Using graphene metamaterial (MM) patterns, the tunable resonant properties of graphene–SiO_2/Si ($GSiO_2Si$) structures deposited on flexible polymer substrates have been theoretically investigated in the terahertz regime. This study shows that the tuning mechanism of the $GSiO_2Si$ structure mainly depends on dipolar resonance, which is different from the conventional metallic MM structure based on the LC resonance. For graphene MM structures, the resonant transmission curves can be tuned over a wide range by controlling applied electric fields. The modulation depth of transmission is about 80%. As the Fermi level of the graphene layer increases, the resonant transmission become stronger, and the resonant dips significantly shift to higher frequency.

1. Introduction

Recently, terahertz (THz) science and technology have made rapid development in the aspects of sources [1–3] and detectors [4], but compared to the well-established neighboring infrared and microwave wave bands, the THz regime is still in need of fundamental advances. A great challenge in developing the THz technology further is that it is very difficult to find suitable materials to respond to the THz radiation strongly. Fortunately, this problem can be alleviated to a large extent with the help of metamaterials (MMs), that is, the composite materials designed to manifest exotic electromagnetic phenomena not observed in natural materials [5]. Their response to light is determined by their structures rather than by their composition. MMs provide a promising platform for the investigation of many phenomena, such as negative refractive index [6], super-focusing [7], and extraordinary transmission [8]. The most common unit cell structures for MMs include split-ring resonators (SRRs) [9,10], electric SRRs (eSRRs) [11], and H-shaped structures [12,13]. For actively controlled MMs, the responses can be tuned by using an external stimulus. Based on the MM structure, active THz modulators have been proposed over the past several years. For instance, an active MM switcher/modulator operated at THz frequencies has been suggested by Chen et al. [5], which can be designed to work at specific frequencies and exhibit good amplitude modulation of narrowband devices. By incorporating semiconductors in the critical regions of metallic SRRs, frequency-agile MM devices were produced, which operate as broadband THz modulators because of the causal relation between the amplitude modulation and the phase shift [14–16].

Recently, the investigation of active MM devices significantly benefits from the rapid development of graphene optoelectronics. With the merits of high carrier mobility and strong interaction with light by using the doping or regular structured patterning in broad-frequency regimes [17,18], graphene has attracted considerable attention for both fundamental physics and its enormous applications [19,20]. It can be regarded as an alternative to metallic materials and a good candidate for modulating MM and surface plasmon (SP) devices [21,22]. Graphene SPs exhibit strong confinement and relatively long propagation lengths [23–25]. Furthermore, graphene can also provide ultra-wideband tunability through electrostatic field, magnetic field, or chemical doping [26–28]. Presently, some research has been carried out to develop novel graphene MM devices [29–35]. For instance, on the basis

E-mail address: xyhethz@hotmail.com
http://dx.doi.org/10.1016/j.carbon.2014.10.066
0008-6223/

of the graphene–dielectrics–metal layer structure, a tunable MM absorber can be achieved [30]. With the integrated graphene layer, the substantial gate-induced switcher has also been shown [32], manifesting the persistent photonic memory effects simultaneously. Valmorra et al. proposed the production of transmission modulators by using hybrid graphene/MM structures; that is, the metallic eSRRs directly evaporated on the top of the large-area single graphene layer, and the modulation depth can reach about 12% [35].

As one of the key devices, a THz modulator is highly required to meet the need for short-range wireless THz communication or ultrafast interconnections. For current state-of-the-art semiconductor modulators [13,36–38], there still exist many problems, such as the small modulation depth and the need for cryogenic temperatures. Therefore, further improvements of the performance characteristics are required for the practical applications. By depositing graphene patterns on the SiO_2/Si layers, we suggest the graphene–SiO_2–Si ($GSiO_2Si$) structure based on the flexible substrate to realize dynamically control of the propagation waves. Because the permittivity of the graphene layer can be varied via the applied electric fields or chemical doping, the transmission of the $GSiO_2Si$ structure can be conveniently modulated. Therefore, the tunable transmission properties of the proposed $GSiO_2Si$ structure were explored in the THz regimes, including the influences of the Fermi level of the graphene layer, the operation frequency, the thickness of the substrate, and the different kinds of MM unit cell patterns. The results show that the transmission of the proposed $GSiO_2Si$ structure can be modulated conveniently in a broadband range.

2. Theoretic model and research method

Fig. 1(a) shows the sketch of the side view of the graphene MM structures, depositing on top of the SiO_2/doped-Si layers. The thickness of the SiO_2 layer is 30 nm, and the thickness of the doped Si layer is 1 μm. To reduce the influence of the substrate, the flexible polymer material was adopted, which is made from the polyimide layer. Fig. 1(b–d) shows the top views of the geometry for several kinds of unit cell structures, the eSRRs resonators (Fig. 1b), the H-shaped structure (Fig. 1c), and the cross-shaped structure (Fig. 1d). The period lengths along the x and y directions are p_x and p_y, respectively. The sub-wavelength MM structures are made of monolayer graphene. The normal incident waves transmit through the graphene MM structure along the z direction.

Graphene can be considered as a two-dimensional material and is described by surface conductivity σ_g, which is related to the radiation frequency ω, chemical potential μ_c (Fermi level, E_f), environmental temperature T, and relaxation time τ. The conductivity of the monolayer graphene can be obtained from the Kubo formula [39]:

$$\sigma(\omega,\mu_c,\tau,T) = \sigma_{\mathrm{inter}} + \sigma_{\mathrm{intra}} = \frac{je^2(\omega - j\tau^{-1})}{\pi\hbar^2} \times \left[\frac{1}{(\omega - j\tau^{-1})^2}\int_0^\infty \frac{\partial f_d(\varepsilon)}{\partial\varepsilon} - \frac{\partial f_d(-\varepsilon)}{\partial\varepsilon}d\varepsilon - \int_0^\infty \frac{f_d(-\varepsilon) - f_d(\varepsilon)}{(\omega - j\tau^{-1})^2 - 4(\varepsilon/\hbar)^2}d\varepsilon\right] \quad (1)$$

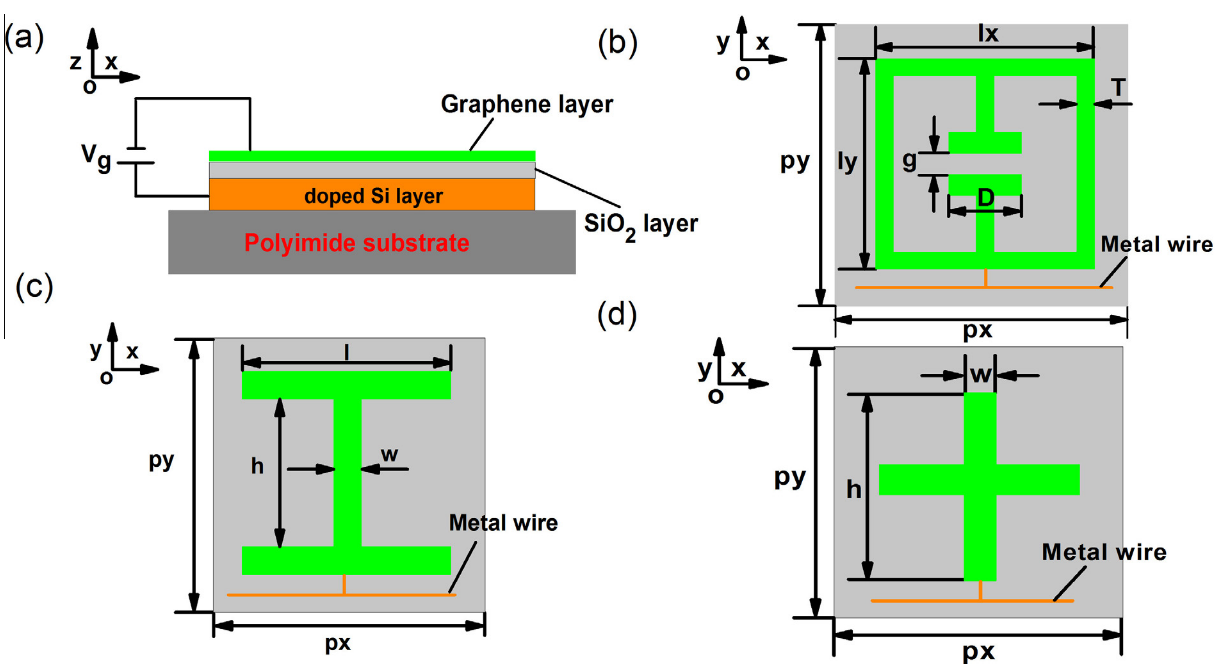

Fig. 1 – (a) The side view of the $GSiO_2Si$ structure. The graphene unit cell structures are deposited on the SiO_2/Si layers, the thickness of the SiO_2 layer is 30 nm, and the doped Si layer is used to apply the gate voltage with the thickness of 1 μm. The substrate is the polyimide layer. (b–d) The top views of the geometry and dimension of the several kinds of MM unit cell structures, which have been connected by using the metallic wire. (b) The eSRR structure, $l_x = l_y = 36$ μm, $g = 2$ μm, $D = 10$ μm, $T = 4$ μm; (c) the H-shaped structure, $w = 6$ μm, $h = 36$ μm, and $l = 48$ μm; and (d) the cross structure, $w = 6$ μm and $h = 36$ μm. The periodic lengths along the x and y directions are both 60 μm. The green-shaded regions indicate the graphene layer, and the gray layer is SiO_2. (A color version of this figure can be viewed online.)