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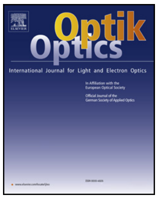

Original research article

Tunable multi-band terahertz absorber based on a one-dimensional heterostructure containing semiconductor

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ABSTRACT

The absorption properties of a simple layered heterostructure composed of semiconductor and dielectric are analyzed by transfer matrix method. The numerical results indicate that such a structure can serve as a tunable multi-band terahertz perfect absorber. This phenomenon is due to the photon localization in the semiconductor layer at particular wavelengths and the presence of the damping factor of semiconductor layer. The number of the absorption peaks can be tuned by changing the thickness of the semiconductor layer. Moreover, the influences coming from the incident angle and the temperature of semiconductor on the absorption properties are also numerically studied.

1. Introduction

During the past two decades, the terahertz (THz) radiation, which refers to the frequencies from 0.1 THz to 10 THz, has attracted significant attention for its potential intriguing applications in spectroscopy, security imaging, short-range and high-speed communications [1]. Recently, the THz perfect absorber, which is an important aspect of THz technology, has also aroused people's attention for its wide use in various technologies such as photonic radiation detectors, spectroscopic imagers, sensors, and so on. Up to now, a wealth of efforts have been paid on achieving high-performance THz absorbers and great progress has been made.

For different aims, THz absorbers have been fabricated as a narrow peak, multi-band peaks and a broad band [2–10]. At first, much attention has been paid on THz absorber with a narrow absorption peak. For example, in 2008, a narrow band THz resonant absorber with an absorbance of 0.96 at 1.6 THz was proposed by Tao et al. [2]. Also, several efforts have been made on absorber with multi-band absorption peaks due to its important role in multispectral detection and sensing [11–13]. For instance, a dual band terahertz metamaterial absorber with two distinct absorption peaks at 0.45 and 0.92 THz was demonstrated by Wen et al. in 2009 [3]. Later, Cui et al. have proposed a terahertz triple-band metamaterial absorber, which works at 0.5, 1.03, and 1.71 THz with absorption rates of 96.4%, 96.3%, and 96.7%, respectively [4]. It has been demonstrated that a four-band polarization insensitive terahertz metamaterial absorber can be achieved by four square metallic rings and a dielectric layer on top a metallic ground plane [5]. Those elegant works mentioned above are benefit from the rapid development of metamaterial structures manufacturing technique, and also from the deep understanding of mechanisms of coupling the THz wave into the structures.

Recently, researchers have introduced a novel class of absorbers which are realized by one-dimensional heterostructure containing graphene [14–17]. Because of the tunability of the electromagnetic parameters of graphene, the properties of the absorption

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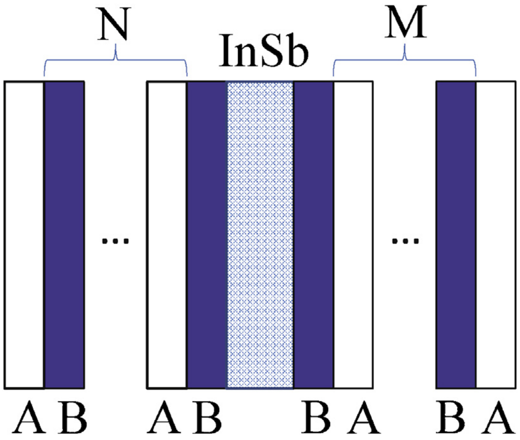

Fig. 1. Schematic of the one-dimensional semiconductor-dielectric heterostructure.

peak can be adjusted. For example, Deng et al. have investigated the THz absorption properties of graphene-based heterostructures, and found that such a structure can lead to perfect THz absorption and the position of the absorption peak moves toward higher frequencies by varying the chemical potential of graphene [17]. In fact, the absorber based on one-dimensional structure has been studied for many years due to its simple structure. Within visible and near-infrared region, a broad and robust absorption band for a wide range of incidence angles and for both polarizations can be realized using a one-dimensional metallic-dielectric quasi-periodic structure [18]. A one-dimensional multilayer structure which has high solar absorption efficiency has been achieved [19]. Generally speaking, such absorbers can be fabricated using proven thin-film technologies, while the THz absorbers utilizing metamaterial structures should be fabricated by using lithography or etching methods. In fact, a plenty of works which focus on photonic heterostructures for realizing efficient absorbers have been achieved [20–23]. However, the work frequency range of such absorbers is within the visible range. Up to now, few studies have been carried on the THz absorber with its absorption peak properties (both positions and number) can be tuned. It is worth to note that Fekete et al. have proposed a one-dimensional heterostructure containing semiconductor (GaAs), which exhibited many useful functions for controlling the THz waves [24].

In this paper, we proposed a tunable multi-band THz absorber based on a one dimensional layered heterostructure composed of semiconductor and dielectric. With the rapid development of THz technology, the purpose of this work is to meet the increasing demand for high-performance tunable multi-band THz absorber. The reasons why we choose one-dimensional semiconductor-dielectric heterostructure are for its low cost and simple structure. The rest of the paper is organized as follows: In Section 2, we give the model and the numerical formulations that will be used in our calculation. The results and discussions are then presented in Section 3. Finally, a conclusion is given in Section 4.

2. Model and numerical method

The schematic of the proposed one-dimensional heterostructure structure denoted as $(AB)^N InSb(BA)^M$ is shown in Fig. 1, where A and B represented Si and SiO$_2$, respectively. N and M are the periods. Within THz range, the refractive indices are $n_A = 3.3$(Si) and $n_B = 2.25$(SiO$_2$) [25]. At THz frequency, the relative dielectric function of InSb is complex-valued and temperature-dependent which can be simply described by the Drude model and can be written as follows [26]:

$$\varepsilon(\omega,\, T) = \varepsilon_\infty - \frac{\omega_p(T)^2}{\omega^2 + i\omega\gamma(T)}, \tag{1}$$

where ε_∞ denotes the high-frequency permittivity. ω is the angular frequency of the incident THz wave, T is the temperature in Kelvin, and γ is the damping factor depended on temperature. The plasma frequency $\omega_p(T) = \sqrt{\frac{N(T)e^2}{\varepsilon_0 m^*}}$ depends on the intrinsic carrier density N, the electronic charge e, the vacuum permittivity ε_0, and the effective mass m^* of free carriers. The intrinsic carrier density N also depends on temperature and can be expressed as $N(T) = 5.76 \times 10^{20} T^{1.5} \exp\left(-\frac{0.26}{2k_B T}\right)$, where k_B is the Boltzmann constant, and N is in unit of m^{-3}. In fact, for certain temperatures, the data of plasma frequency and damping factor can be found in Refs. [27,28] and are given in Table 1. Unfortunately, a general analytical expression for the damping factor is not available due to the complexity of real situations [27]. In this paper, we would like to use the data presented in Table 1.

In order to calculate the absorption properties for such a multilayered structure, the transfer matrix method is used. Consider the one-dimensional semiconductor-dielectric heterostructure with interfaces normal to the z axis. Let a plane wave be incident from air into the heterostructure at an incident angle θ with $+z$ direction. According to transfer matrix method, the electric and magnetic fields of adjacent layers can be related via a transfer matrix [29,30]