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Mid-infrared broadband absorber of full semiconductor epi-layers

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ABSTRACT

We demonstrate mid-infrared dual channel near-perfect absorbers based on full semiconductor epi-layers theoretically. Strong absorption (>99.9%) is observed at 25.04 THz. Through introducing composite grating and controlling the thickness of the dielectric layer, we can get a broadband absorption with absorptivity above 80% at the range from 8 μm to 12 μm with a good incidence angle tolerance. The structure investigated in this paper shows a broadband, all-semiconductor, plasmonic architecture, which is of great importance for many applications such as bolometers, cloaking, imaging devices and also can be used in enhancing interaction of mid-infrared radiation with integrated semiconductor optoelectronic elements.

1. Introduction

In recent years, perfect absorber, which has wide applications in sensor, thermal emitter, thermal cloaking and so on, has aroused great interest. Perfect absorber based on metamaterials can be realized by minimizing the transmission and reflection of the metamaterials simultaneously through maximized losses and impedance matching respectively [1]. The first perfect absorber was realized in the microwave range by using a resonator and wire structure [2]. Subsequently, with the introduction of plasmonic resonator structures, such as discs and strips [3,4], the frequency range was expanded to optical frequency. Today, resonant perfect absorbers have been demonstrated in various frequency bands of the electromagnetic spectrum including microwave, THz, infrared, and visible [5–15].

Nowadays, tunable perfect absorber, multiband and broadband perfect absorber based on metamaterials have become research hotspots and attract great attention [16–25]. Many modulation and tuning mechanisms have been proposed and applied to control both the strength and resonance frequency of a metamaterial electromagnetic response including optical excitation, mechanical actuation, thermal or electrical control [26–30]. Broadband absorber, as another pursuit goal of many researchers, can be obtained through introducing multi-layered gradually varied electric ring resonator (ERR) structure [31–34]. All of the resonance absorption peaks induced by multi-layered gradually varied ERR are close to each other, thereby forming a broadband perfect absorber. Although it has been verified by virtual of multi-layered gradually varied ERR structure, these structures often suffer from the difficulties of either alignment or fabrication, leading to the impracticality in practical application. Therefore, the development of a simple structured broadband absorber in the mid-IR range is one critical problem that needs to be solved urgently.

Recently, highly doped semiconductors, as a kind of artificial plasmonic materials in the mid-IR region, have been studied [35–39]. Similarly to the behavior of traditional plasmonic metals such as Au or Ag at visible region, highly doped semiconductors designed with subwavelength structures can support Surface Plasmon Polaritons (SPP) and Localized Surface Plasmon Resonance (LSPR) in the mid-IR region and be potentially used in all-semiconductor active mid-IR plasmonic devices. According to the Ref. [39], we know that the permittivity of the highly doped semiconductors can be described accurately by the Drude model in a quite broadband region (including $\omega \geq \omega_p$ where $\varepsilon_m \approx 0$ and $\varepsilon_m > 0$), which is not applicable for metal because of the existence of interband transitions at the frequencies near and greater than the plasma frequency (ω_p). So it also makes us have access to study the special optical property of the plasmonic materials near their plasma frequency by using heavily doped semiconductors. In this paper, we present an all-semiconductor mid-infrared dual channel near-perfect absorber, whose absorptivity observed at 25.04 THz is more than 99.9%. Through introducing composite grating and adjusting the thickness of the dielectric layer, we

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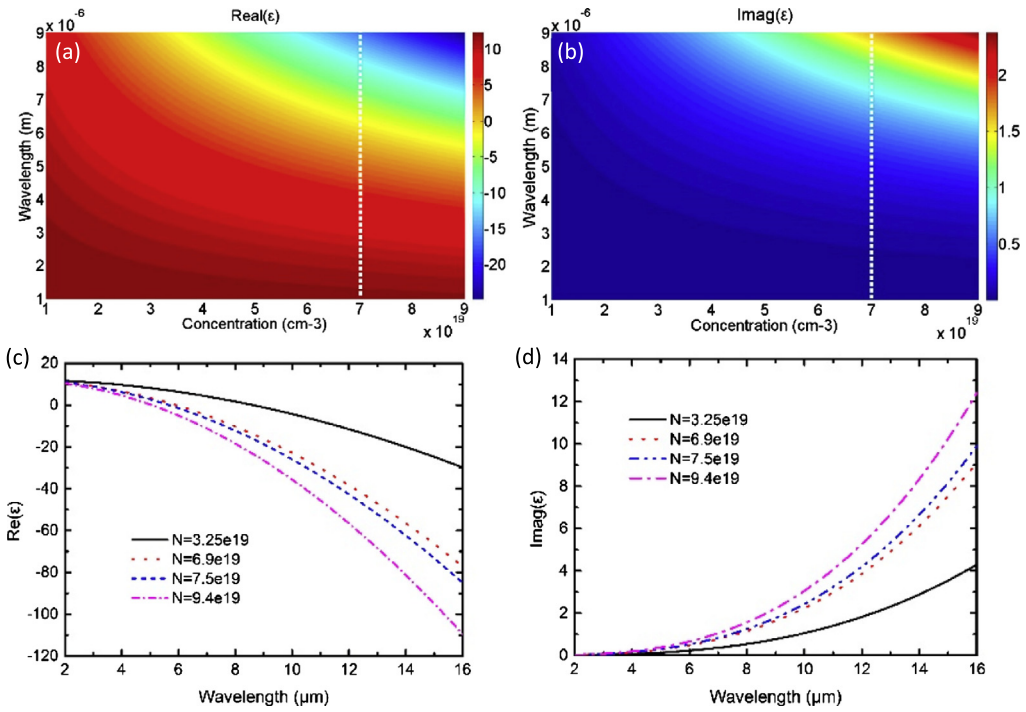

Fig. 1. The real part (a) and imaginary part (b) of ε as a function of doping (N) and wavelength (λ) for InAs. The real part (c) and imaginary part (d) of ε as a function of wavelength (λ) for InAs at $N = 3.25\text{e}19$, 6.9e19, 7.5e19 and 9.4e19 (cm^3).

can get a broadband absorption with absorptivity above 80% at the range from 8 μm to 12 μm.

2. Materials and methods

In the typical metal–dielectric–metal (M–D–M) structure, by tuning the amplitude and frequency location of the electric and magnetic resonances it is possible to match the impedance $z(\omega) = \sqrt{\mu(\omega)/\varepsilon(\omega)}$ of the perfect absorber to free space, thus minimizing the reflectance at a specific frequency. On the other hand, making the lower metallic ground plane thicker than the penetration depth of light in the IR range will make the transmission of the perfect absorber zero. These two conditions lead to high absorption in narrow band.

Here, we try to achieve a metallic response at mid-infrared wavelength, such that the dielectric constant of the doped semiconductor can be written as $\varepsilon = \varepsilon' + i\varepsilon''$. We consider a Drude model for doped semiconductors given by [40]:

$$\varepsilon(\omega) = \varepsilon_\infty \left[1 - \frac{\omega_p^2}{\omega^2 + \tau^{-2}} + i\frac{\omega_p^2 \tau^{-1}}{\omega(\omega^2 + \tau^{-2})}\right], \tag{1}$$

where ε_∞ is the high-frequency dielectric constant, and $\omega_p = \sqrt{Nq^2/(\varepsilon_\infty \varepsilon_0 m_e)}$ is the plasma frequency. $\tau = \mu_n m_e/q$ is the average collision time of the electrons. N, q and ε_0 are the semiconductor electron doping concentration, fundamental charge and free space permittivity, respectively. m_e is the electron effective mass, which is often smaller than the free-electron mass m_0, and μ_n is the electron mobility, which depends on material, doping concentration (N), and the temperature (T). The electron mobility μ_n for most semiconductor materials can be expressed by employing the empirical-fit relationship [41]

$$\mu_n = \mu_{\min} + \frac{\mu_{\max}(300\text{ K})(\frac{300\text{ K}}{T})^{\theta_1} - \mu_{\min}}{1 + [\frac{N}{N_{\text{ref}}(300\text{ K})(\frac{300\text{ K}}{T})^{\theta_2}}]^a}, \tag{2}$$

where $\mu_{\min}$ is the minimum of mobility for heavy doping, $\mu_{\max}$ (300 K) is the maximum of mobility for light doping. N_{ref} (300 K), θ_1, θ_2 and a are the fitting parameters. At room temperature ($T = 300$ K), $\mu(N)$ can be simplified as $\mu(N) = \mu_{\min} + (\mu_{\max} - \mu_{\min})/[1 + (N/N_{\text{ref}})^a]$. We use published effective mass, high frequency dielectric constant, and the fitting parameter of electron mobility for indium arsenide (InAs) in simulation [40]. Fig. 1(a) and (b) show the real part and imaginary part of ε as a function of doping concentration (N) and wavelength (λ) for InAs by Eq. (1). Dashed lines show the position where the doping concentration is 7e19 (cm^3). Without special instructions, the simulation is based on such a doping concentration in this paper. Then choosing different doping concentrations, with $N = 3.25\text{e}19$, 6.9e19, 7.5e19 and 9.4e19 (cm^3), we can get the permittivity of InAs as the function of wavelength respectively. The results are shown in Fig. 1(c) and (d), which match with the experimental data in Ref. [42]. The deviation is from the change of the effective mass m_e, which depends on the doping concentration, and will cause a misfit between the simulation results and the experimental data.

Based on the theory above, we design a sandwich $\text{InAs}_{\text{doped}}$–InAs–$\text{InAs}_{\text{doped}}$ structure where the doped InAs can be treated as metal, which can be achieved by Molecule Beam Epitaxy and photolithography. The width and the period of the upper layer grating are $w = 0.4$ μm and $p = 1$ μm, and the thickness of every layer is $t_1 = 0.22$ μm, $t_2 = 1$ μm and $t_d = 0.22$ μm (shown in Fig. 2(a)). By employing finite-difference time domain (FDTD) method and choosing the doping concentration $N = 7\text{e}19$ (cm^3), incident light normal to the grating with the electric field parallel to the direction of period, we can attain the reflectance and transmission spectrum of this MDM structure and then obtain the absorptivity by $A(\omega) = 1 - R(\omega) - T(\omega)$. As shown in Fig. 2(b), there are two resonant modes at $\lambda = 8.07$ μm (mode A) and $\lambda = 11.98$ μm (mode B) respectively. Mode A is caused by the plasmonic resonance, which is similar with the experimental result in Ref. [39] by Law etc. In Ref. [39], the reflection dip is at ~7.75 μm with similar MDM structure and $N = 6.9\text{e}19$ (cm^3), which can further prove our theoretical data and simulation credible. Besides, there is another mode B at longer wavelength, which is a horizontal guided mode from the Fabry–Perot resonance. Fig. 2(c) and (d) give the