Optically tunable metamaterial based on semiconductor superlattice

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Abstract

In this work we theoretically analyze new type of tunable metamaterial for terahertz optics based on semiconductor superlattice. We show that the signs of the dielectric function tensor components of suggested metamaterial can be optically manipulated by incident light of the visible or near-infrared spectrum. Density of the photon states in the metamaterial is controlled by the incident light intensity.

1. Introduction

In recent years, there is a great deal of attention devoted to metamaterials. Metamaterials are novel synthetic materials with properties which are usually not appropriate to the natural materials. Due to their unique properties, metamaterials have many potential applications in the optoelectronics, medicine, telecommunications, and in other branches of science and industry [1].

In the common case electromagnetic properties of the metamaterials are anisotropic and described by a tensorial dielectric function. Signs of the main components of the tensor (signature) determine the shape of equal-energy surface in **k**-space. Depending on the signature, the shape can be an ellipsoid, one- or two-sheeted hyperboloid. Manipulation of the tensor components gives the opportunity to manipulate the shape of the equal-energy surface and, therefore, to manipulate the density of the photon states in the material.

Tunable metamaterial is a quite topical problem. Some models of tunable metamaterials are discussed in [1],[2],[3]. Here we suggest new type of the optically tunable metamaterial for terahertz optics based on the semiconductor superlattice (SL).

2. Model

Let us consider undoped periodic semiconductor SL of quantum wells. Within effective medium approximation, dielectric function of the SL is a tensor with three non-zero diagonal components:

$$\widehat{\varepsilon}(\omega) = \begin{pmatrix} \varepsilon_{\perp}(\omega) & 0 & 0 \\ 0 & \varepsilon_{||}(\omega) & 0 \\ 0 & 0 & \varepsilon_{||}(\omega) \end{pmatrix}. \quad (1)$$

Frequency dependence of each tensor component we describe within Drude-Lorentz approximation:

$$\varepsilon_s(\omega) = \varepsilon^{\infty}\left(1 - \frac{\Omega_s^2}{\omega(\omega + i\gamma_s)}\right); \quad s = \perp, ||; \quad (2)$$

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Here ε^{∞} is a material permittivity, $\gamma_{\perp,||} = 1/\tau_{\perp,||}$ is an inverse scattering time of transversal and longitudinal electron momentum which is responsible for free carrier absorption. For the sake of simplicity, we put $\gamma_{\perp} = \gamma_{||} = \gamma$. $\Omega_{\perp,||}$ is a transversal and longitudinal plasma frequency of electron-hole plasma. In Eq.(2) we do not take into account interband and intersubband transitions. It is justified if operating frequency is less than width of the minigaps in the charge carrier spectrum of the SL. Usually, holes in semiconductors more heavier than electrons. It is why, in the first approach, we ignore contribution of holes into the plasma frequency of electron-hole gas. Transversal and longitudinal electron plasma frequency are determined as follows:

$$\Omega^2_{\perp,||} = \frac{e^2}{\pi^2\hbar^3}\sum_i \iiint f_i(\mathbf{p})\frac{\partial^2 E_i(\mathbf{p})}{\partial p^2_{\perp,||}}d^3p. \tag{3}$$

Here i is a number of electron miniband, $\mathbf{p}$ is electron momentum, $p_{\perp}$ and $p_{||}$ are electron momentum components across and along to the SL layers, $E_i(\mathbf{p})$ is the energy of electrons, $f_i(\mathbf{p})$ is the distribution function of electrons in the i-th miniband. This equation is quite common and determines dependence of $\Omega_{\perp}$ and $\Omega_{||}$ on the electron spectrum, temperature, and chemical potential of electrons (electron concentration). Energy spectrum of electrons in a SL is anisotropic and depends on the i, $p_{\perp}$ and $p_{||}$ as follows: $E(i, p_{\perp}, p_{||}) = E_i(p_{\perp}) + \frac{p^2_{||}}{2m^*_{||}}$. Here $m^*_{||}$ is in-plane effective electron mass.

The idea of the tunable metamaterial is following. Due to the anisotropic energy spectrum of the carriers in the SL, longitudinal and transversal plasma frequencies are different ($\Omega_{\perp} \neq \Omega_{||}$). The signs of the components of the dielectric function tensor depend on the relation between $\Omega_{\perp,||}$ and ω. If $\omega < \Omega_{\perp,||}$ then $\varepsilon_{\perp,||} < 0$. If $\omega > \Omega_{\perp,||}$ then $\varepsilon_{\perp,||} > 0$. Manipulation of $\varepsilon_{\perp,||}$ is possible by means of the manipulation of free electrons concentration in the conduction band. For example, free electrons concentration in the conduction band can be manipulated by photo-excitation with external light source, temperature or by electron injection. Here we analyze the case of photo-excitation with external light source.

3. Results

As an example, we consider SL of quantum wells with following parameters (see subfigure in Fig.1a). Depth of the quantum well is 0.2 eV, its thickness is 9 nm, barrier thickness is 4 nm. In-plane effective mass of electrons we set as $m_{||} = 0.05m^*_e$. Such parameters are close, for example, to $GaAs_{0.2}Sb_{0.8}$/GaSb superlattice.

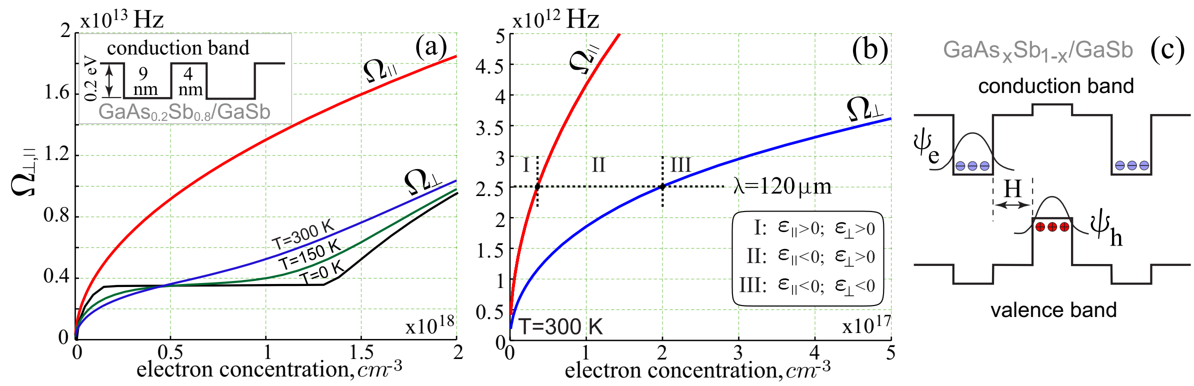

Fig. 1: (a) Dependence of the longitudinal and transversal plasma frequencies, $\Omega_{||}$ and $\Omega_{\perp}$, in the quantum well SL on the free electron concentration in the conduction band for different temperatures. Parameters of the SL is shown on the subfigure. Contribution of holes into $\Omega_{||}$ and $\Omega_{\perp}$ is ignored. (b) Zoom-in image of Fig.1a for T=300 K. (c) SL of spatially separated quantum wells for electrons and holes.

In Fig.1a we show dependence of $\Omega_{\perp,||}$ on the free electron concentration in conduction band for different temperatures. One can see that $\Omega_{\perp}$ has a staircase behavior at low temperatures. The plateau corresponds to the situation when chemical potential lies in the minigap of the electron spectrum. The plateau smears out as the temperature increases. Longitudinal plasma frequency does not have implicit dependence on the temperature and depends only on the total electron concentration in the conduction band.

At room temperature (see Fig.1b) for the frequency 2.5 THz, signature [1] of the tensor changes from (+,+,+) to (+,–,–) at n=4·10^{16} cm $^{-3}$, and changes from (+,–,–) to (–,–,–) at n=2·10^{17}cm^{-3}.

Optical power, P, necessary to provide non-equilibrium electron concentration n in the conduction band can be estimated as follows:

$$P = l \cdot n \cdot \hbar\omega/\tau. \tag{4}$$

Here $\hbar\omega$ is energy of the incident photon which is about 1 eV, l is film thickness and τ is a lifetime of electron-hole radiative recombination which is usually about 10^{-8} sec. Substitution of these parameters into (4) yields $P \sim 30\ kW/cm^2$ for the film of 100 μm thickness and n ∼2·10^{17}cm^{-3}. It is enormous power unfit for applications. The optical power, P, can be essentially reduced if to suppress electron-hole radiative recombination. It is possible by means of spatial separation of electrons and holes. For suppression of electron-hole radiative recombination one can use SL of spatially separated quantum wells (Fig.1c). Such SL can be fabricated using, for example, solid solution of $GaAs_xSb_{1-x}$ with corresponding spatial variation of x. Our estimation shows that spatial separation $H \sim 3$ nm (Fig.1c) increases τ from 10^{-8} to 10^{-4} sec. This estimation correspond with experimental data [4],[5]. Therefore, P in this case is about 3 W/cm^2 for the film of 100 μm thickness and n ∼2·10^{17}cm^{-3}. It is a quite reasonable value for applications.

4. Conclusion

In this work we proposed the idea of optically tunable metamaterial for terahertz optics based on semiconductor superlattice with spatially separated quantum wells for electrons and holes. We show that the tensor signature of the dielectric function and, therefore, density of the photon states can be manipulated optically by the incident light of visible or near-infrared spectrum with intensity about several W/cm^2.

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[1]For short we consider notation $(\pm, \pm, \pm)$ where the first sign corresponds to the sign of $\varepsilon_{\perp}$ and the second and third signs correspond to the sign of $\varepsilon_{||}$.

