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Generation of Terahertz Radiation by a Photoconductive Antenna

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We report on the first principle calculations of photocarriers kinetics in a photoconductive antenna excited by an ultrashort optical laser pulse. The solution of non-equilibrium Boltzmann equation is used to derive the expression for the irradiated electric field. The analysis reveals the important role of non-uniform photocarrier distribution inside the active layer in the formation of the terahertz radiation from the emitter in both collinear and anti-collinear directions.

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1. Introduction

The time-domain coherent THz spectroscopy of condensed matter has got considerable attention during the last decade due to great perspectives of its applications in many areas of science and technology. A critical component of the coherent THz spectrometer is a THz emitter. Up to now the most popular THz emitters are semiconductor based photoconductive antennas excited by ultrashort pulses of visible or near-infrared lasers. The physical principle of such emitter employs the short current pulse in biased semiconductor with small lifetime of nonequilibrium carriers created by the laser pulse [1]. The current pulse radiates the THz electromagnetic waves. The large-aperture photoconductive antennas were studied experimentally and theoretically in many papers [2–4]. However, in the most of the published works the analysis of the THz emission was performed in frame of simplified approaches which did not take into account the propagation of a short pump pulse through a semiconductor etc. We have developed a model describing the emitted THz field based on the solution of the Boltzman semiconductor and Maxwell equations for a photoconductive THz emitter and demonstrate the application of this model for low-temperature (LT)-GaAs photoconductive antennas.

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2. Calculation of THz emission field for large-aperture emitters

Let us consider a large-aperture photoconductive emitter excited by a short light pulse with the energy of quantum exceeding the band energy of the material. We will assume that the excitation is uniform and propagates in y-direction. Also we will suppose that the bias field is uniform too, directed in z-directed and is considerably stronger than the electric field of THz radiation. The symmetry of the task allows one to consider the set of Maxwell equations for THz radiation fields $\boldsymbol{E}(\boldsymbol{r},t)$ and $\boldsymbol{H}(\boldsymbol{r},t)$ in one-dimensional representation. After Fourier transforms we will get the following wave equation for the Fourier component of electric field:

$$\frac{\mathrm{d}^2 E_z^\omega}{\mathrm{d}y^2} + \frac{\omega^2}{c^2}\varepsilon E_z^\omega = -\mathrm{i}\omega\mu_0 J_z^\omega, \tag{1}$$

where ε, μ_0 have usual meaning, c and ω are light velocity in vacuum and frequency of the THz radiation, J_z^ω is the Fourier component of the density of photoinduced current. The photocurrent density can be calculated from the nonequilibrium distribution function $f_{\mathrm{e,h}}$ of free carriers

$$J_z(t,y) = \frac{\hbar e}{4\pi^3}\int k_z[f_\mathrm{e}(\boldsymbol{k},t,\boldsymbol{r})/m_\mathrm{e} - f_\mathrm{h}(\boldsymbol{k},t,\boldsymbol{r})/m_\mathrm{h}]\mathrm{d}\boldsymbol{k}, \tag{2}$$

where $\boldsymbol{k}$ is the electron wave vector, m_e and m_h are the effective masses of free electrons and holes, respectively. From (2) it is clear that in approximation of $m_\mathrm{e} \ll m_\mathrm{h}$ we may omit the second term in (2). The holes are assumed to form a homogeneous background for recombining electrons. Omitting index e of f_e for convenience, the distribution functions of electrons is found from the Boltzmann equation [5, 6]:

$$\frac{\partial f}{\partial t} + \frac{\hbar\boldsymbol{k}}{m}\frac{\partial f}{\partial \boldsymbol{r}} + \frac{e}{\hbar}\boldsymbol{E}\frac{\partial f}{\partial \boldsymbol{k}} = -\Gamma(f-\tilde{f}) + \gamma f + G(t,y)\frac{\pi^2\delta(k-k_0)}{k_0^2}, \tag{3}$$

where Γ is the inverse time of the momentum relaxation, γ is the inverse lifetime of the nonequilibrium electrons in the conduction band, $k_0^2 = 2(\hbar\omega_0 - E_\mathrm{g})$ $m_\mathrm{e}m_\mathrm{h}/[\hbar^2(m_\mathrm{e}+m_\mathrm{h})]$ is the module of the wave vector of photoexcited electrons, E_g is the forbidden gap, $\hbar\omega_0$ is the quantum energy of pump. The pump generation rate $G(y,t)$ is

$$G(t,y) = \frac{\alpha(1-R)I_0}{\hbar\omega_0}\exp(-\alpha y)\exp\left(-\left(t-\frac{y}{\nu_0}\right)^2/2\Delta^2\right), \tag{4}$$

where I_0, α, R are the pump intensity, absorption coefficient and reflection coefficient of semiconducting layer at the frequency of pump, ν_0 is the group velocity of pump, Δ is duration of pump pulse. Equation (4) takes into account finite absorption of the external pump pulse source in the layer that leads to the nonuniform current density along y-axis. The Fourier component of the current density, J_z^ω, obtained from (2) and (3), can be written as

$$J_z^\omega = \frac{e^2}{m_e} E_0 [\gamma(k_0) - \mathrm{i}\omega]^{-1} [\Gamma(k_0) + \gamma(k_0) - \mathrm{i}\omega]^{-1} G\omega(\omega, y), \tag{5}$$

where

$$G_\omega(\omega, y) = \frac{\alpha(1-R) I_0 \Delta}{\hbar\omega_0} \exp(-\alpha y) \exp\left(-\frac{\omega^2 \Delta^2}{2}\right) \exp\left(\mathrm{i}\omega \frac{y}{\nu_0}\right).$$

The external electric field at frequency ω is the sum of two terms, the solutions of homogeneous and inhomogeneous wave equation. In the case of $\alpha d > 1$ using the boundary continuity conditions for $\boldsymbol{E}$ and $\boldsymbol{H}$ vectors finally we obtain for the THz electric field at output and input surfaces of the emitter, respectively:

$$E_\omega(\omega, d+) = -\left(\frac{\mu_0}{\varepsilon_0}\right)^{1/2} A(\omega) \left(1 - \mathrm{i}\frac{\omega N}{\alpha c}\right)^{-1} \left(1 + \mathrm{i}\frac{\omega \delta n}{\alpha c}\right)^{-1}$$
$$\times \frac{\left(1 - \mathrm{i}\frac{\omega(n_0 + n_c)}{\alpha c}\right) 2n}{(n + n_c)^2} \exp\left(\mathrm{i}\frac{\omega}{c} nd\right) \left[1 - r^2 \exp\left(\mathrm{i}\frac{\omega}{c} 2nd\right)\right]^{-1}, \tag{6}$$

$$E_\omega(\omega, 0-) = -\left(\frac{\mu_0}{\varepsilon_0}\right)^{1/2} A(\omega) \left[1 - r^2 \exp\left(\mathrm{i}\frac{\omega}{c} 2nd\right)\right]^{-1}$$
$$\times \left[\frac{\left(1 - \mathrm{i}\frac{\omega N}{\alpha c}\right)^{-1}}{n + n_c} + \frac{\left(1 + \mathrm{i}\frac{\omega \delta n}{\alpha c}\right)^{-1} r}{n + n_c} \exp\left(\mathrm{i}\frac{\omega}{c} 2nd\right)\right], \tag{7}$$

where $n_0 = c/\nu_0$, $n = \sqrt{\varepsilon}$, $n_c = \sqrt{\varepsilon_c}$ — are refractive indices of the material and surroundings, respectively,

$$\tau^{-1} = \gamma,\ \tau_p^{-1} = \Gamma + \gamma,\ \delta n = n - n_0,\ N = n + n_0,\ r = (n - n_c)/(n + n_c),$$

$$A = \frac{e^2}{m_e} E_0 \frac{(1-R) I_0 \Delta}{\hbar\omega_0} \tau\tau_p \exp\left(-\frac{\omega^2 \Delta^2}{2}\right) (1 - \mathrm{i}\omega\tau)^{-1} (1 - \mathrm{i}\omega\tau_p)^{-1}.$$

The wave form of the electric field in a far field zone is calculated using diffraction integral [7]. Figures 1 and 2 show the wave forms calculated for forward and

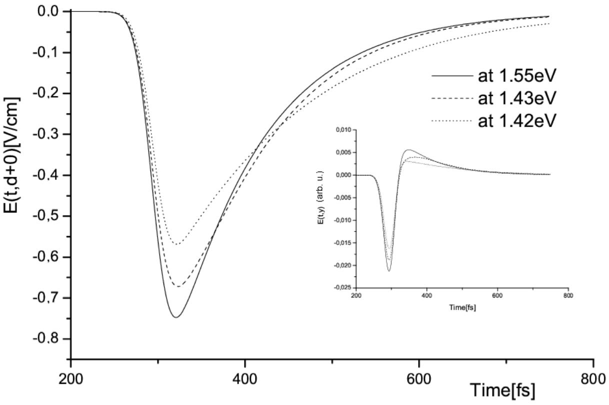

Fig. 1. Theoretical wave forms forwardly emitted from the slab of LT-GaAs .The inset shows these wave forms in far field zone. Pulse duration is 15 fs, $I_0 = 1$ MW/cm^2. The parameters: $\tau = 100$ fs, $\tau_p = 70$ fs, $n = 3.5$, $n_0 = 3.65$ are taken from literature.

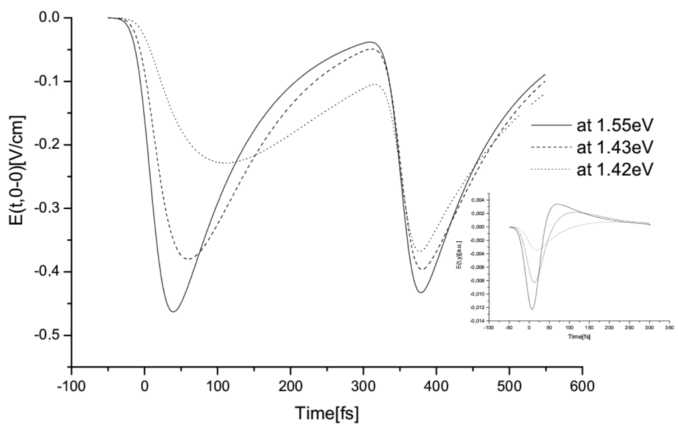

Fig. 2. Theoretical wave forms backwardly emitted from the slab of LT-GaAs. The inset shows these wave forms in far field zone. The same data as in Fig. 1 was used.

backward emitted THz radiation from a semiconductor emitter. It is seen that the details, the spectral content and the field amplitude of the wave forms, strongly depend on the choice of pump quantum energy $\hbar\omega_0$. For the backward emitted THz field, the spectral content of the THz wave forms is very sensitive to the sum of the time of flight of the pump and time of flight of the THz pulse on the scale of α^{-1}. For the forward emitted THz pulse the important parameter is the difference of the time of flight of the pump and time of flight of the THz pulse on the scale of α^{-1}. The generation mechanism is, therefore, the composite product of two localized sources of THz radiation. If $ad > 1$, the generation is restricted to the input boundary of the emitter, whereas at $ad < 1$, the generation also occurs at the output boundary. Such scenario, to some extent, is similar to the mechanism of THz generation at nonlinear wave conversion discussed in [8].

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