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Electron-deformation mechanism of photoexcitation of hypersound in semiconductors in a dc electric field

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***Abstract*. The effect of a dc electric field on photoexcitation of a hypersonic pulse in a semiconductor via an electron-deformation mechanism is studied. The profiles of acoustic pulses are simulated for different directions of the electric field.**

Keywords: *optoacoustics, semiconductors, electron-deformation mechanism.*

1. Introduction

The rapid recent development of the methods for generating short laser pulses opened up broad prospects for exciting short acoustic pulses. Such hypersonic pulses are of considerable scientific interest because they allow one to perform defectoscopy of various materials with high time and spatial resolution. Photoexcitation of hypersonic pulses in semiconductors has been studied by several research groups. It is known that in semiconductors both thermal and non-thermal mechanisms of sound generation can operate [1]. It was shown that, in the absence of piezoelectric effect, the electron-deformation mechanism of hypersound generation dominates. In this case, an acoustic pulse is generated due to the deformation potential of electrons and holes. Note that the duration of an acoustic pulse during the time that is much shorter than the recombination time of an electron – hole plasma is determined by diffusion processes in the plasma [2, 3].

At the same time, it follows from experiments [4] that an external electric field can affect the profile of an acoustic pulse in a semiconductor. A dc electric field applied to a germanium single crystal caused the time shift of an acoustic pulse. A piezoelectric generation of sound in semiconductors under the condition of a diffusion spatial charge separation and in an external electric field was studied in paper [5]. It was shown, in particular, that an external electric field can reduce the velocity of plasma propagation inside the sample from its surface, resulting in the shortening of the acoustic pulse. The aim of this paper is to study in detail the effect of an electric field on the electron-deformation mechanism of photoexcitation of an acoustic pulse in semiconductors.

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2. Generation of an acoustic pulse in semiconductors

Consider a free (unloaded) semiconductor surface irradiated by a laser beam. A photon absorbed upon an interband transition in a surface layer generates an electron – hole plasma (EHP) (Fig. 1).

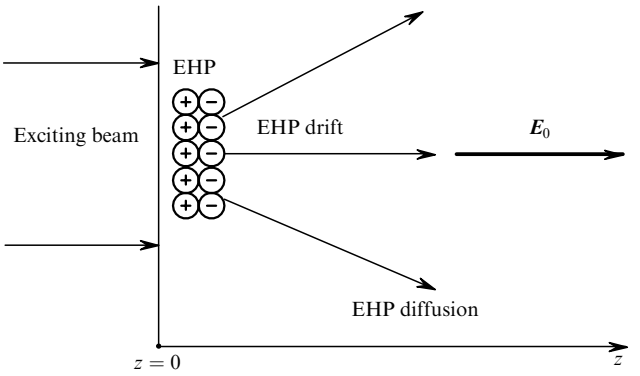

Figure 1. Photogeneration and propagation of the EHP in a surface layer of a semiconductor.

Because the laser beam diameter is much greater than the depth of the EHP propagation in the experiment, we can consider the photogeneration of acoustic pulses by using a one-dimensional geometry. The photogeneration of sound along the z axis ($z \geqslant 0$) via the electron-deformation mechanism in a semiconductor is described by the wave equation [6]

$$\frac{\partial^2 u}{\partial t^2} - c_s^2 \frac{\partial^2 u}{\partial z^2} = \frac{d}{\rho}\frac{\partial n}{\partial z}, \tag{1}$$

where u is the mechanical displacement; d is the total deformation potential of electrons and holes; ρ is the semiconductor density; n is the concentration of the photoinduced EHP; and c_s is the sound speed in the semiconductor.

It is convenient to seek the solution of Eqn (1) by using the Fourier transformation in time and the Laplace transformation in space:

$$\tilde{u}(\omega, z) = \int_{-\infty}^{+\infty} u(t, z) e^{i\omega t} dt, \quad \hat{u}(\omega, p) = \int_0^{\infty} \tilde{u}(\omega, z) e^{-pz} dz. \tag{2}$$

It follows from (2) that

$$\hat{u}(\omega,p) = -\frac{d}{2\rho c_s^2}\left[\hat{n}\left(\omega, \mathrm{i}\frac{\omega}{c_s}\right) - \hat{n}\left(\omega, -\mathrm{i}\frac{\omega}{c_s}\right)\right], \tag{3}$$

where $\hat{n}(\omega,p)$ is the Laplace transformation of the concentration spectrum of the EHP.

The time dynamics of the density of the photoinduced EHP is determined by the drift of carriers along the direction of the electric field E_0 and by their diffusion inside from the photoexcited surface $z = 0$ (Fig. 1). Photoinduced electrons and holes form a packet of free carriers, its diffusion velocity being determined by the ambipolar diffusion coefficient D related to the densities n_e and n_h and the diffusion coefficients D_e and D_h of electrons and holes, respectively, by expression [7]

$$D = \frac{n_e + n_h}{n_h/D_e + n_e/D_h}.$$

The mobility μ of a packet of charge carriers is determined by the mobilities μ_e and μ_h of electrons and holes:

$$\mu = \frac{n_e - n_h}{n_h/\mu_e + n_e/\mu_h}. \tag{4}$$

It follows from (4) that a packet of free carriers in a semiconductor with the intrinsic conductivity does not move in an external electric field. At the time scale of ~ 1 ns that we consider, no spatial charge separation occurs in semiconductors containing impurities at the concentration of no less than 10^{14} cm^{-3}, which is typical for samples used in optoacoustic experiments. Therefore, we assume that the plasma of photogenerated carriers is neutral.

Consider a weakly alloyed n-type semiconductor, in which the density n of photoinduced charge carriers greatly exceeds their density in the absence of radiation. When the electric field E_0 is applied along the z axis, the drift velocity of the packet is $V = \mu E_0$. The dynamic equation for photoinduced carriers has the form [6]

$$\frac{\partial n}{\partial t} = D\frac{\partial^2 n}{\partial z^2} + V\frac{\partial n}{\partial z} + \frac{W}{h\nu_{las}}, \tag{5}$$

where $h\nu_{las}$ is the photon energy; $W = (1-R)\alpha W_0 f(t)\mathrm{e}^{-\alpha z}$ is the volume density of the absorbed energy; R is the reflection coefficient of the semiconductor surface; W_0 is the energy density of the exciting pulse; and α is the absorption coefficient. The envelope $f(t)$ of a laser pulse is usually a Gaussian

$$f(t) = \exp\left(-\frac{t^2}{\tau_{las}^2}\right),$$

where τ_{las} is the exciting pulse duration.

The boundary conditions are determined by the absence of the EHP flow through the semiconductor–air interface:

$$D\frac{\partial n}{\partial z} + Vn = 0 \quad \text{for } z = 0. \tag{6}$$

By using transformations (2), we can represent the solution of Eqn (5) with the boundary condition (6) in the form

$$\hat{n}(\omega,p) = \frac{(p/p_D)\hat{W}(\omega,p_D) - \hat{W}(\omega,p)}{h\nu_{las}D[p^2 + (V/D)p + \mathrm{i}\omega/D]}, \tag{7}$$

where

$$p_D = \frac{-V + (V^2 - 4\mathrm{i}\omega D)^{1/2}}{2D};$$

$$\hat{W}(\omega,p) = \frac{(1-R)\alpha W_0 \tilde{f}(\omega)}{\alpha + p}.$$

Therefore, the displacement spectrum of the surface $z = 0$ of a semiconductor in the case of the electron-deformation mechanism of sound generation, obtained with the help of transformations inverse to (2), has the form

$$\begin{aligned}\hat{u}(0) = {} & \frac{d(1-R)\alpha W_0}{2\rho c_s^2 h\nu_{las}}\frac{1}{p_D D} \\ & \times\left\{\frac{p_\omega}{(\alpha + p_D)[p_\omega^2 + (V/D)p_\omega + \mathrm{i}(\omega/D)]}\right. \\ & + \frac{p_\omega}{(\alpha + p_D)[p_\omega^2 - (V/D)p_\omega + \mathrm{i}(\omega/D)]} \\ & - \frac{p_D}{(\alpha + p_\omega)[p_\omega^2 + (V/D)p_\omega + \mathrm{i}(\omega/D)]} \\ & \left. + \frac{p_D}{(\alpha - p_\omega)[p_\omega^2 - (V/D)p_\omega + \mathrm{i}(\omega/D)]}\right\},\end{aligned} \tag{8}$$

where $p_\omega = \mathrm{i}\omega/c_s$.

An acoustic pulse is quite often excited in experiments on the semiconductor surface and then propagates inside the semiconductor and is detected on the opposite surface. A change in the pulse profile during its propagation is determined by the diffraction and absorption of sound. The resulting displacement spectrum of the acoustic pulse is a product of the initial spectrum $\tilde{u}(0)$ and the coefficient taking into account absorption and diffraction of hypersound [8]:

$$K(\omega,z) = \exp\left[-\gamma z(\omega/2\pi)^2\right]\frac{\exp\{-r^2/[a^2(1 + \mathrm{i}z/L_d)]\}}{1 + \mathrm{i}z/L_d}, \tag{9}$$

where γ is the absorption coefficient of sound; a is the radius of the acoustic beam for $z = 0$ at the 1/e level; and $L_d = \omega a^2/(2c_s)$ is the diffraction length of the frequency component ω.

3. Analysis of simulation results

Germanium single crystals have been well studied by optoacoustic methods and are widely used in radioelectronics. We studied the generation of hypersonic pulses in crystalline germanium plates oriented along the [111] direction, in particular, in a dc electric field [2–4]. Below, we used in calculations the following parameters of a crystal germanium: $c_s \approx 5.5 \times 10^5$ cm s^{-1}, $D \approx 65$ cm^2 s^{-1}, and $\alpha \approx 1.4 \times 10^4$ cm^{-1} [9, 10]. Hypersound was excited by 1064-nm, 100-ps, 1.17-eV pulses from a neodymium laser.

Profiles of an acoustic pulse on the germanium plate surface $z = 0$ calculated from (8) and normalised to the

maximum value are presented in Fig. 2a. One can see that the pulse profile noticeably changes when the drift velocity of a carrier packet in the plasma becomes comparable with the sound speed in germanium ($V \sim 10^5$ cm s^{-1}). The duration of the acoustic pulse decay decreases when the sign of the electric field changes and the drift of the free carrier packet is directed toward the superconductor surface. When the drift is directed from the excited surface, the duration of the pulse decay increases.

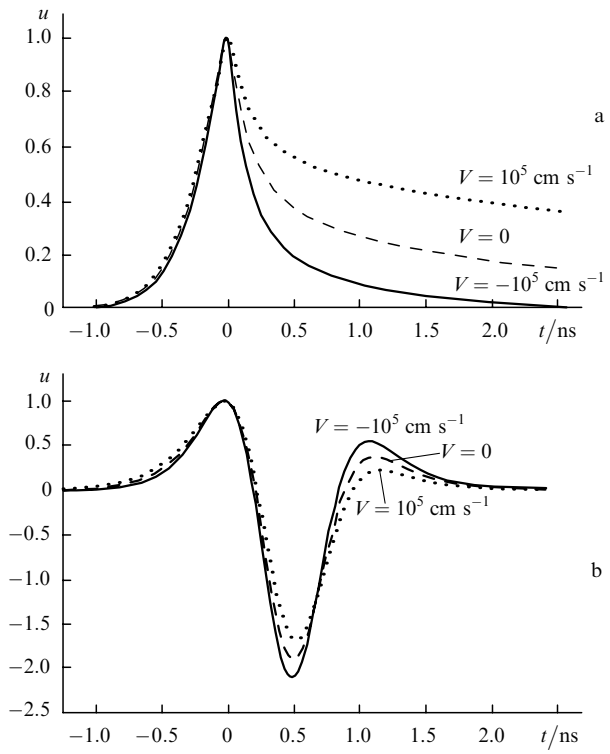

Figure 2. Normalised profiles u of photogenerated acoustic pulses for different drift velocities V for $z = 0$ (a) and 1000 μm (b).

The profile of an acoustic pulse changes during its propagation in a semiconductor plate [see (9)]. The pulse propagation in the [111] direction in germanium [11] was simulated using the following parameters: $z = 1000$ μm, $a = 20$ μm, $\gamma = 2.8$ cm^{-1} GHz^{-2}. The profiles of acoustic pulses normalised to the first maximum are presented in Fig. 2b. One can see that the differences between the acoustic pulse profiles in the presence of an electric field and in its absence are preserved upon pulse propagation in a semiconductor. Note that the EHP drift at velocities $V \leqslant c_s$ affects the leading edge of an acoustic pulse substantially weaker than its trailing edge. Therefore, all our conclusions [2, 3] about the supersonic expansion of the EHP based on the analysis of the hypersonic pulse front are also valid in this case.

We neglected so far the influence of an acoustic pulse on the dynamics of EHP propagation. However, preliminary estimates [12] show that the amplitude of acoustic pulses can increase in the presence of a dc electric field and a drift of carriers. This effect can be especially strong at low temperatures. The study of this effect is outside the scope of this paper, and it should be investigated separately.

The conditions under which an external electric field can substantially affect the photogeneration of an acoustic pulse in a semiconductor can be achieved at temperatures ~ 300 K. This was demonstrated in experiments [4] where the ~ 200-ps shift of an acoustic pulse was observed in moderate electric fields ~ 100 V cm^{-1}.

Therefore, by applying an electric field, we can decrease the expansion of an EHP, thereby achieving a more compact localisation of sound sources in a semiconductor. This leads to the shortening of acoustic pulses, which can be important for experiments on laser optoacoustics of semiconductors.

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