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Analytical model of terahertz generation in AlGaAs/GaAs $p-i-n$ diode

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An analytical model describing the dynamics of photoelectrons excited by femtosecond optical pulses in an AlGaAs/GaAs $p-i-n$ diode is presented. A change in the reverse bias causes a change in the terahertz generation mechanism. The waveform of the photocurrent (amplitude, duration, maximum position) depends significantly on both the reverse bias and the level of optical excitation, as well as on the energy of the laser radiation quantum. At sufficiently high values of the internal electric field strength, terahertz generation in a heterostructure $p-i-n$ diode is caused by the acceleration of electrons over several hundred femtoseconds to a velocity significantly exceeding the saturation velocity („velocity overshoot“), followed by a sharp drop associated with the transition of electrons from the central valley to the side valleys.

Keywords: terahertz electromagnetic radiation, $p-i-n$ diode, femtosecond laser excitation, photoelectron dynamics.

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The results of an experimental study and Monte Carlo simulation of the process of generation of terahertz (THz) radiation by heterostructure $p-i-n$ $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$/GaAs diodes under excitation by femtosecond optical pulses were presented in [1]. It was found experimentally that the amplitude and the time position of the THz-pulse peak depend on the magnitude of reverse voltage, the excitation level, and the wavelength of optical radiation. The same correlation was observed for the photocurrent dynamics calculated by the Monte Carlo method (see Figs. 3 and 4 in [1]). The obtained results were used to demonstrate that when the reverse bias applied to $p-i-n$ $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$/GaAs diodes is varied, the THz- generation mechanism changes. There is no analytical model that would characterize this evolution of the THz-pulse delay with a change in reverse bias applied to $p-i-n$ diodes. A simplified hydrodynamic model characterizing the transient dynamics of photoexcited carriers was proposed in [2]. But, it will be demonstrated below that this model does not provide a complete explanation of the experimental data from [1].

in the present study, we propose an analytical model of the process of THz generation by heterostructure $p-i-n$ $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$/GaAs diodes under excitation by femtosecond optical pulses. It differs from the above-mentioned model [2] in that the effective mass and the relaxation times of electrons in momentum and energy depend on the energy. The simulation results obtained with this analytical model are qualitatively consistent with the experimental data [1].

A heterostructure $p-i-n$ $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$/GaAs diode irradiated with a delta-shaped optical pulse is considered. The variation of photocarrier density within the i-layer thickness is neglected. Electrons and holes are produced as a result of interband optical absorption in the i layer. Moving in an electric field, they form a subpicosecond photocurrent pulse. Since the effective mass of an electron is much lower than the effective mass of a hole, we will take into account the dynamics of photoelectrons and consider holes to be stationary. As photoelectrons move in the electric field, electrons and holes in the i layer get separated, producing an electric field that screens the original internal field. With the above assumptions, the analytical model based on the momentum and energy balance equations is presented in the following form:

$$\frac{dv}{dt} = \frac{q}{m_\varepsilon^*}E - \frac{v}{\tau_p}, \tag{1}$$

$$E = E_0 - \frac{qn}{\varepsilon\varepsilon_0}\int\limits_0^t v\,dt, \tag{2}$$

$$\frac{d\epsilon}{dt} = qEv - \frac{\epsilon - \epsilon_L}{\tau_\epsilon}, \tag{3}$$

where q is the elementary electron charge, E is the electric field, E_0 is the initial electric field strength, v is the velocity of a photoelectron, ε is the dielectric constant, ε_0 is the permittivity of vacuum, n is the electron density, ϵ is the energy of a photoelectron, and ϵ_L is the initial energy of a photoelectron. Effective electron mass m_ε and relaxation times in momentum τ_p and energy τ_ϵ depend on electron energy ϵ. Let us assume first that they are independent of energy, as was done in [2]. The processes of scattering of electrons off

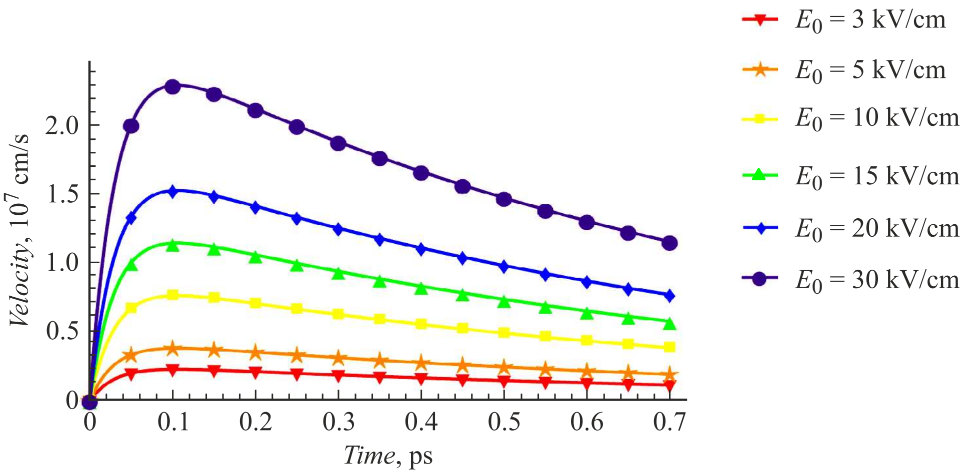

Figure 1. Dynamics of photoelectron velocity at a low excitation level ($n = 10^{14}\,\mathrm{cm}^{-3}$).

intervalley phonons and their transitions to lateral valleys are then neglected, and Eq, (1) may be transformed as

$$\frac{d^2v}{dt^2} = -\omega_p^2 v - \frac{dv}{dt}\frac{1}{\tau_p}, \quad v(t=0) = 0, \quad \left.\frac{dv}{dt}\right|_{t=0} = \frac{qE_0}{m_\varepsilon},$$

$$\omega_p^2 = \frac{q^2 n}{\varepsilon\varepsilon_0 m_\varepsilon^*}. \tag{4}$$

where ω_p is the plasma frequency and n is the photoelectron density.

The solution of Eq. (4) may be presented in analytical form

$$v(t) = \frac{qE_0}{m_\varepsilon \omega_p'} e^{-\frac{t}{2\tau_p}} \sin \omega_p' t,$$

$$\omega_p' = \sqrt{\omega_p^2 - \frac{1}{4\tau_p^2}}. \tag{5}$$

It follows from the solution of this equation that the nature of electron motion depends on the ratio between the plasma frequency and the pulse relaxation frequency: motion may proceed in both ballistic ($2\omega_p\tau_p > 1$) and hydrodynamic ($2\omega_p\tau_p < 1$) regimes. The model considered here is inapplicable to steady-state motion of an electron with its velocity reaching the saturation level. Therefore, it is important to note that Eqs. (1)−(3) and expression (5) derived from them characterize the motion of an electron only at the initial stage (i.e., within the first few picoseconds after its production).

With a low density of photoexcited electrons ($n < 10^{14}\,\mathrm{cm}^{-3}$), the electric field is screened in a hydrodynamic regime with a characteristic time determined by Maxwell relaxation time $\tau_M = \left(\omega_p^2\tau_p\right)^{-1} \propto 10^{-11}$ s. At the initial (ballistic) stage of motion, an electron accelerates under the influence of the electric field; after that, it moves in a drift regime with a velocity proportional to the electric field strength (Fig. 1). With an increase in photoexcitation intensity ($n = 10^{15}\,\mathrm{cm}^{-3}$) (Fig. 2), the electric field screening time decreases to several picoseconds, and an electron moves mostly in a quasi-ballistic regime within this time interval. At high excitation levels ($n = 10^{16}\,\mathrm{cm}^{-3}$) with the $2\omega_p\tau_p > 1$ condition satisfied, screening is effected in a collisionless regime and plasma oscillations of electrons emerge (Fig. 3).

The amplitude of the terahertz electric field in the far field is proportional to the time derivative of surface current: $E_{\mathrm{THz}} \propto dJ/dt$. In the present case of instantaneous photoexcitation, $E_{\mathrm{THz}} \propto dv/dt$. Therefore, the temporal position of a THz-pulse will be correlated with the time dependence of the electron velocity: the electron velocity maximum will be aligned with the moment of sign inversion of the THz-field. It follows from expression (5) that the time needed for photoelectrons to reach maximum velocity is determined by condition $\cos(\omega_p' t) = (2\omega_p\tau_p)^{-1}$ and does not depend on the applied electric field. It follows that the delay of a THz-pulse generated by a $p{-}i{-}n$ diode relative to the optical pulse will remain constant within the simplest

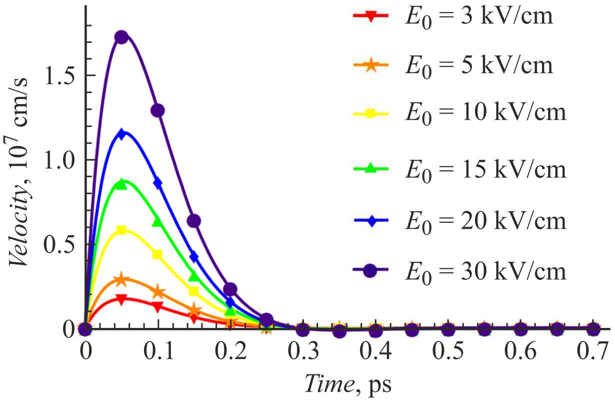

Figure 2. Dynamics of photoelectron velocity at a moderate excitation level ($n = 10^{15}\,\mathrm{cm}^{-3}$).

model [2], which takes into account the screening effect only.

To explain the experimentally observed dependence of the time shift of the THz-pulse maximum on the applied bias [1], one needs to take into account the dependences of parameters τ_p, τ_ϵ, and m_ε on the photoelectron energy, which were detailed in [3,4]. The electron velocity decreases in this case not only due to screening of the electric field, but also due to transitions of photoelectrons from the Γ valley to the L valley. Equations (1)–(3) were solved numerically in the Mathematica package. Figure 4 shows the time dependences of the electron velocity for photoelectron density $n = 10^{15}\,\mathrm{cm}^{-3}$and different values of the reverse bias of a $p-i-n$ diode.

Calculations reveal that the time needed for photoelectrons to reach their maximum velocity (delay time) depends on the applied reverse bias in a non-monotonic manner. In weak electric fields ($< 20\,\mathrm{kV/cm}$), intervalley transitions are lacking, and relaxation of the photocurrent is attributable to the screening effect. An increase in reverse bias leads in this case to an increase in delay. This behavior of the delay time may be attributed to an electron mobility reduction and, accordingly, an increase in screening time with an increase in electric field strength. In strong electric fields where an electron has enough time to reach the threshold energy of intervalley transitions before the electric field „collapses,“ the delay time decreases with increasing bias voltage. In addition, the results demonstrate that the velocity of photoelectrons and, consequently, THz generation in the heterostructure $p-i-n$ $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$/GaAs diode with high levels of the electric field strength in the i layer are governed by the acceleration of electrons at the ballistic stage of their motion in the electric field to a velocity exceeding significantly the saturation one. The velocity reaches its maximum in a few hundred femtoseconds („velocity overshoot“) and then drops sharply due to the intervalley transition of electrons.

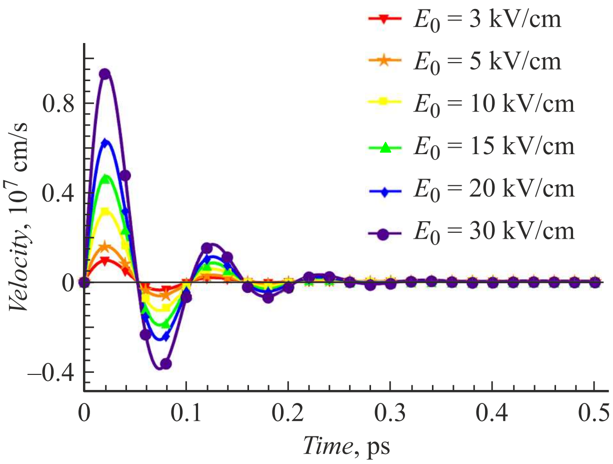

Figure 3. Dynamics of photoelectron velocity at a high excitation level ($n = 10^{16}\,\mathrm{cm}^{-3}$).

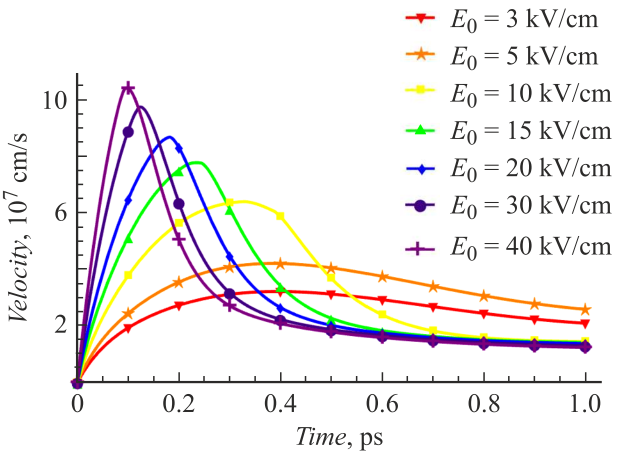

Figure 4. Dynamics of photoelectron velocity calculated with account for the dependence of parameters τ_p, τ_ϵ, and m_ε on the photoelectron energy ($n = 10^{15}\,\mathrm{cm}^{-3}$).

Thus, the proposed model was applied in the analysis of mechanisms of photocurrent formation and, consequently, THz generation in a $p-i-n$ diode and provided an explanation for the non-monotonic variation of the position of the THz-pulse maximum with reverse bias magnitude, attributing it to a change in mechanisms responsible for the relaxation of photocurrent.

Conflict of interest

The authors declare that they have no conflict of interest.

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