Technical Physics Letters, 2026, Vol. 52, No. 5

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Dynamics of photoexcited charge carriers in the i-layer of an AlGaAs/GaAs heterostructure $p-i-n$ diode

© V.N. Trukhin[1], V.L. Malevich[2,3], X. Fan[4], V.I. Mustafin[1], V.S. Kalinovski[1], E.V. Kontrosh[1]

[1] Ioffe Institute, St. Petersburg, Russia
[2] Belarusian State University of Informatics and Radioelectronics, Minsk, Belarus
[3] Stepanov Institute of Physics, Belarusian Academy of Sciences, Minsk, Belarus
[4] ITMO University, St. Petersburg, Russia
E-mail: valera.truchin@mail.ioffe.ru

Received December 18, 2025
Revised January 28, 2026
Accepted January 29, 2026

We investigated the dynamics of photoexcited carriers in the i-layer of a $p-i-n$ diode using dynamic emission terahertz spectroscopy with sub-picosecond resolution. Depending on the photoexcitation intensity and electric field strength, electric field screening in the depleted i-region can occur in ballistic or diffusion-drift regime. The slow stage of electric field screening is due to the transport of photoexcited electrons through the depleted i-layer and their subsequent escape into the n-region. The dynamics of electric field recovery in the depleted region of a $p-i-n$ diode are determined by the drift of holes following the escape of electrons from the i-layer and the recharging of the $p-i-n$ diode capacitance via the external circuit, as well as the relaxation of charge carriers captured during the drift process into deep impurity levels in GaAs.

Keywords: terahertz radiation, $p-i-n$ diode, dynamics, screening.

DOI: 10.61011/TPL.2026.05.63292.20605

The Terahertz (THz) range of electromagnetic radiation covering frequencies from 0.1 to 10 THz (which correspond to wavelengths from 3.0 to 0.03 mm), is of great interest for multiple applications. These include non-invasive imaging of hidden objects [1], spectroscopic analysis of materials [2], nanoelectronics [3], diagnostics of various substances [4], pharmaceutical quality control [5] and space research [6]. Despite broad application prospects, the use of the THz range is still limited due to the lack of compact, efficient sources of radiation. Currently the most widely used basic THz-emitters are photoconductive antennas and bulk semiconductors, such as InAs, excited by ultrashort laser pulses. Promising approaches to improving THz-sources are related to using metasurfaces to enhance plasmonic effects and heterostructure $p-i-n$ diodes [7,8].

$p-i-n$ diodes based on heterostructures III-V compounds are of special interest. Their operating principle is based on the unique ability to accelerate photo-injected electrons in the i-region under high electric fields to velocities significantly exceeding the saturation velocity, followed by a sharp deceleration due to interval intervalley scattering from the central Γ valley into the satellite L valleys. To improve the efficiency of THz-emitter based on heterostructural $p-i-n$ diodes, detailed analysis and quantitative estimation of ultrafast dynamics of photo-excited charge carriers in the i-region of the structure are required. This paper presents the results of the experimental study of the dynamics of photoexcited carriers in the i-area of $p-i-n$ diode using dynamic emission THz spectroscopy.

The experimental samples of heterostructure $Al_xGa_{1-x}As$/GaAs $p-i-n$ diodes were grown by molecular-beam epitaxy on n-GaAs (001) substrates. The studied structure included Bragg grating AlAs/GaAs, a 1.5-μm-thick undoped i-GaAs layer, layer p-$Al_{0.2}Ga_{0.8}As$ with thickness of 1.5 μm ($p = 5 \cdot 10^{20}\,cm^{-3}$), layer p-$Al_{0.8}Ga_{0.2}As$ with thickness of 0.1 μm ($p = 5 \cdot 10^{19}\,cm^{-3}$) and contact layer p^+-GaAs. Chips of $p-i-n$ diodes were formed on the grown epitaxial plate using photolithography.

The studied samples were excited by ultrashort optical pulses (with a duration of 15 fs) generated by Ti-sapphire laser, at a repetition rate of 80 MHz and a central wavelength of 800 nm. The waveforms of the THz pulse generated by $p-i-n$ diode when excited by an optical pulse were detected using the method of electro-optic gating in reflection geometry. As noted above it was already noted, the dynamics of photoexcited electron-hole plasma was studied using dynamic emission THz spectroscopy. This method is based on the study of the effect of non-equilibrium plasma excited in the studied sample at the efficiency of THz-generatiion. Photoexcited electrons and holes being spatially separated under the action of the electric field in i-layer, form polarization that screens this field. Since the amplitude of the THz pulse is nearly proportional to the electric-field strength, measuring the dependence of the THz-generation efficiency dependence on the delay time between the optical pumping pulse exciting the electron-hole plasma, and the probe optical pulse, whose THz signal is detected, makes it possible to investigate the transport of charge carriers and dynamics of electric field screening with subpicosecond time resolution.

The study of temporal dynamics of THz-generation efficiency change after excitation of the electron-hole plasma in the i-region of $p-i-n$ diode found that the efficiency of THz-generation determined by the value of the THz-pulse amplitude value reduces after the generation of the electron-hole plasma, and then it is restored (Fig. 1). The process of restoration of THz-generation efficiency is characterized by longer times that the times of its recession.

Time dependences of recession and restoration of the THz-generation after photoexcitation by the pumping pulse have both a fast and a slow components (Fig. 1 and 2). The fast recession of THz-pulse amplitude after the start of plasma excitation happens at time interval of around 0.3 ps and depends on the excitation level. The subsequent slow recession occurs for the time that takes about 5 ps (Fig. 2) and hardly depends on the excitation level, i. e. on the concentration of photo-excited charge carriers and the value of reverse bias (Fig. 2, *a* and *b*). Such dynamics can be explained as follows. As it was noted, the value of THz-generation efficiency at low level of excitation is proportionate to the value of the electric field. After development of the electron-hole plasma in i-layer by a femtosecond optical pumping pulse, non-equilibrium carriers are spatially separated, and a space charge arises, which screens the electric field of the external field and the built-in field. Neglecting the spatial nonuniformity of the photocarrier distribution in i-layer, the dynamics of field screening when excited by the instantaneous optical pulse may be described by the following equations

$$\frac{dv}{dt} + \frac{v}{\tau_p} = \frac{qE}{m}, \tag{1}$$

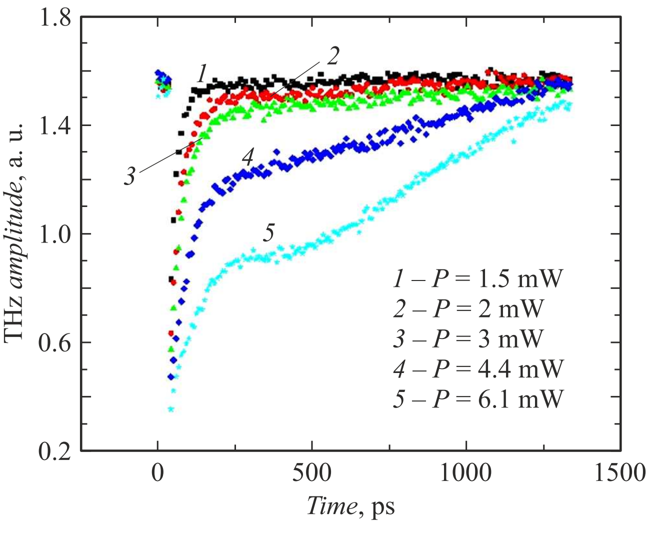

Figure 1. Dependence of THz-pulse amplitude on time of delay between the pumping pulse and pulse generating the THz-emission (bias voltage $V_s = -8$ V, P — average power of optical pumping pulse).

$$E = E_0 - \frac{qn}{\varepsilon\varepsilon_0}\int_0^t v\,dt, \tag{2}$$

where q — elementary charge of electron, v — electron velocity, E —electric field strength, E_0 — initial electric field strength, m and τ_p — effective mass and t pulse relaxation time of electrons, n — electron concentration, ε — dielectric permittivity, ε_0 — dielectric permittivity of vacuum.

From (1), (2) by simple transformations we obtain the equation for the field

$$\frac{d^2E}{dt^2} + \frac{1}{\tau_p}\frac{dE}{dt} + \omega_p^2 E = 0, \tag{3}$$

where $\omega_p = (ne^2/m\varepsilon\varepsilon_0)^{1/2}$ is the plasma frequency. Equation (3) describes both collisionless and Maxwellian screening regimes in the absence of the external-circuit effect. At a later time, when the carrier transport occurs in the diffusion-drift regime, the dynamics of electric field generation starts to be exposed to the external circuit. Taking into account the voltage drop across the resistance of the external circuit R, the equation for the total current can be written as

$$\varepsilon\varepsilon_0\frac{dE}{dt} + nqv = \frac{U - Ew}{RS}, \tag{4}$$

where S and w — irradiated area of irradiated surface and width of i-layer, U — potential difference, including the voltage of the external source and the voltage induced by the built-in electric field. Substituting in (4) the expression for velocity $v = -q\tau_p E/m$, we obtain the equation for the intensity of the electric field in the form of

$$\frac{dE}{dt} + \left(\tau_M^{-1} + \tau_{RC}^{-1}\right)E = \frac{U}{w\tau_{RC}}, \tag{5}$$

where $\tau_{RC} = RC$ — time constant of the external circuit, $C = \varepsilon\varepsilon_0 S/w$ — diode capacity, $\tau_M = \left(\omega_p^2\tau_p\right)^{-1}$ — Maxwell relaxation time.

For the first several hundreds of femtoseconds after the development of the electron-hole plasma the screening occurs in the ballistic regime. Solving equation (3), we obtain that the dependence of the electric field value on time is described by expression $\exp(-t/2\tau_p)\cos\left(t\sqrt{\omega_p^2 - 1/4\tau_p^2}\right)$. The specific time of electric field change at the ballistic stage of electron motion is defined as ω_p^{-1}. This time decreases with the increasing concentration of photo-carriers and with the excitation levels used here is 200−300 fs. Note that the screening dynamics may depend on the intervalley transitions of electrons. In the strong electric fields the electron may accumulate energy exceeding the threshold energy for the transitions to the satellite valleys of the conduction band ($\Delta = 0.29$ eV, GaAs, 300 K), for the shorter time than the screening time. This situation occurs at low concentrations of photoelectrons, when the condition $\omega_p\sqrt{2m\Delta}/eE < 1$ is met.

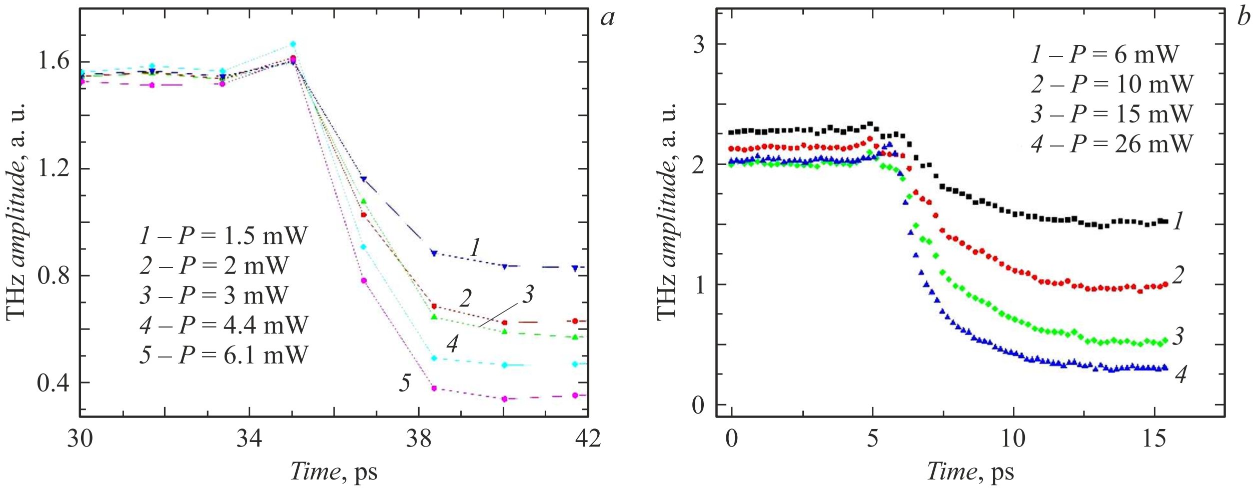

Figure 2. Dynamics of THz-pulse amplitude recession depending on time of delay of the optical pulse generating THz-emission relative to the pumping pulse. $V_s = -8$ (a) and -2.5 V (b).

When the electron transport mechanism transitions from ballistic to diffusion-drift, the dynamics of electric field screening are determined by the Maxwell relaxation time $\tau_M = \left(\omega_p^2\tau_p\right)^{-1}$. When the Maxwell relaxation time is determined, note that in the strong electric fields (> 10 kV/cm) some electrons are in satellite L valleys, which are characterized by mobility that is lower by approximately an order of magnitude compared to the mobility of electrons in the central valley.

The slow stage of electric field screening, the duration of which hardly depends on the concentration of photo-excited electrons and is around 5 ps, depends on the processes of transfer of photo-excited electrons and holes via the depleted i-layer and is mainly determined by the escape of electrons into the n-region and further into the external circuit. In strong electric fields (> 20 kV/cm) the electron velocity in GaAs reaches the saturation velocity of 10^7 cm/s within a few hundred femtoseconds and depends only slightly on the field strength. The time at which electrons reach n-region depends on the time of flight through the depleted area ($w = 1.5\,\mu$m), which is 5–10 ps. The process of electric field reduction also consists of two phases: fast, characterized by time ~ 100 ps, and slow, the time of which may reach 1 ns. The fast phase of electric field reduction depends on the recharge time τ_{RC} through the external circuit, which is around 400 ps ($R = 50\,\Omega$, $C \sim 8$ pF), and hole transit time flight through the depleted i-region. You can estimate the time of flight as follows. The screening effect causes decrease of the electric field of i-layer. The average intensity of this field after all electrons leave the depleted area may be presented as $E_0 - new/\varepsilon\varepsilon_0$, where E_0 — field intensity prior to photoexcitation. Holes with mobility μ_p leave the depleted area for the time $w/\mu_p\left(E_0 - new/\varepsilon\varepsilon_0\right)$, which, as you can see, increases with the increasing concentration of the photo-excited carriers. Thus, the experimentally observed decrease in the rate of recovery of THz generation efficiency as the photoexcitation level increases is due to the increased transit time of holes through the depleted i region. The subsequent slow recovery of THz generation happens at longer times (of the order of nanoseconds). This process might be related to the recharging through the external circuit and relaxation of the charge carriers captured during the time of drift to the lower deep impurity levels.

To conclude, note that this paper experimentally investigated the dependence of THz-generation efficiency in the heterostructure $p{-}i{-}n$ diode on the delay time between the optical pumping pulse exciting the electron-hole plasma and the probe optical pulse, the THz-signal from which is recorded. Based on the obtained results, the dynamics of nonequilibrium charge carriers and electric field is determined in the i-layer of $p{-}i{-}n$ diode with subpicosecond time resolution. After development of the electron-hole plasma, the spatial separation of photoexcited electrons and holes takes place, which causes polarization that screens the electric field in the depleted i-region. At this stage, the electrons move in ballistic regime and, over a time of 200–300 fs, gain enough energy to transition from the Γ valley to the L valley. The subsequent screening of the internal electric field occurs in the diffusion-drift regime and is characterized by the Maxwell relaxation time. The slow stage of electric field screening, the duration of which hardly depends on the concentration of electrons and is around 5 ps, depends on the processes of transfer of photo-excited electrons via the depleted i-layer and their escape into the n-region and further into the external circuit. After the electrons leave i-layer, the subsequent dynamics of internal electric field reduction in the depleted area of $p{-}i{-}n$ diode depends on the drift of holes and them exiting into area p-AlGaAs, and also recharging timle τ_{RC} of the capacitance of $p{-}i{-}n$ diode via the external circuit. The final stage of electric field reduction in i-layer is caused by the relaxation of the charge carriers captured in process of drift to the deep impurity levels in GaAs.

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by M.Verenikina