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The physical topological modeling of single radiation effects in submicron ultrahigh-frequency semiconductor diode structures with taking in account the heating of an electron-hole gas in the charged particle track

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Abstract

The local nonequilibrium quasi-hydrodynamic model, based on the system of hyperbolic equations of charge carrier transport is devised. The electron temperature in the track of a heavy charged particle for various semiconductors is determined. A theoretical analysis of transient ionization processes in Mott diodes under the heavy charged particles and laser pulses simulating impact them is carried out. The effect of heating the electron-hole plasma in the track of the ion and the laser pulse on the relaxation of the photocurrent pulse is shown. Comparison of the calculated estimate of the cross section of single failures under the influence of a neutron flux with experimental data shows the adequacy of the proposed approach.

Keywords: cosmic rays, heavy ions, hot nonequilibrium charge carriers, submicron semiconductor devices

1. introduction

The reducing of the topological norms of microelectronic products leads to an improvement in their characteristics to a decrease in the switching energy of elements of digital integral circuits and a decrease in the flight time of the working area of analog devices. This reduces power consumption and further increases the number of elements on a chip in digital integrated circuits, as well as improves the gain and noise performance of analog devices at increasingly high frequencies. On the other hand, a decrease in the switching energy of digital elements and a decrease in the inertia of analog semiconductor devices reduces the threshold energies for the occurrence of single radiation effects, leading to failures of microelectronic products [1].

2. The mathematical model

It was experimentally and theoretically shown [2] that a decrease in the size of microelectronic elements leads to an increase in fault tolerance and a decrease in resilience, which is of a probabilistic nature. This gives rise to interest in the study of single radiation effects in submicron structures. The dimensions of modern semiconductor structures and the time span of carrier's active area close to the characteristic time of formation of the ionized region in the track of the primary recoil atom and its geometrical dimensions. Classical models of charge carrier transport [3-5] are based on the local equilibrium approximation. This means that the space-time change in the macro-parameters of the system should be smooth on the scale of its relaxation to the equilibrium state [6]

$$L \sim \Psi / \frac{\partial \Psi}{\partial x} >> l, \quad (1)$$

$$T \sim \Psi / \frac{\partial \Psi}{\partial t} >> \tau, \quad (2)$$

where is Ψ – the macro parameter of the system - the transfer potential (for semiconductors, this is the electron or hole concentration), τ – relaxation time of the system to the equilibrium state, $v = \sqrt{a/\tau}$ – speed of propagation of disturbances in the environment, a – transfer coefficient (here it means the electron and hole diffusion coefficients), $l = v\tau$ – dimensional microscale at which the relaxation of the system to thermodynamic equilibrium occurs (correlation length), V – traveling wave speed, $L = a/V$ – macroscale – characteristic size of the front of the traveling wave, $T = a/V^2$ – characteristic time of macro-changes of the system.

In the case of semiconductors, propagation speed of disturbances can be equal to the average speed of movement of charge carriers. In the Table 1 is shown the characteristic values of the propagation velocity of disturbances and the relaxation time of electrons for Si and GaAs at room temperature in comparison with the space-time characteristics of the ionized region of the track of a heavy charged particle.

Table 1. Typical values of the propagation velocity of disturbances and the relaxation time of electrons for Si and GaAs at room temperature in comparison with the space-time characteristics of the ionized region of the track of a heavy charged particle

Semiconductor	Si	GaAs
effective mass [7], m0	0.328	0.067
diffusion coefficient [7], cm2/s	37.5	212.5
propagation velocity, ×107 cm/s	1.9	4.2
relaxation time, fs	100	100
correlation length, nm	20	40
The radius of the nucleus of an ionized region in the track of a heavy charged particle [8], nm	5	5
traveling wave speed, ×107 cm/s	7.5	42.5
The duration of the front of the disturbance impulse, fs	6.7	1.2

How can be seen from the Table 1, the conditions of local equilibrium for submicron semiconductor structures under the heavy charged particles impact are not satisfied [9], because of the classical local equilibrium transport theory is valid if the characteristic rate of this process is much less than the rate of propagation of disturbances in the medium, while the relaxation time, during which equilibrium is established in small but macroscopic regions, turns out to be much less than the process under consideration [6].

The local nonequilibrium quasi-hydrodynamic model of charge carrier transport is formulated through correction of flow of particles and, in the linear approximation, is written in the form:

$$\frac{\partial}{\partial x}\left(\varepsilon\varepsilon_0 \frac{\partial \phi}{\partial x}\right) + q(N_d - N_a - n + p) = 0, \quad (3)$$

$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial j_n}{\partial x} - R + G, \quad (4)$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\frac{\partial j_p}{\partial x} - R + G, \quad (5)$$

$$\frac{\partial (nW_n)}{\partial t} = -\frac{\partial S_n}{\partial x} - j_n \frac{\partial \phi}{\partial x} - W_n R - n\frac{W_n - W_0}{\tau_{en}} + W_e G, \quad (6)$$

$$\frac{\partial (pW_p)}{\partial t} = -\frac{\partial S_p}{\partial x} - j_p \frac{\partial \phi}{\partial x} - W_p R - p\frac{W_p - W_0}{\tau_{ep}} + W_h G, \quad (7)$$

$$j_n = -q\mu_n n \frac{\partial \phi}{\partial x} + qD_n \frac{\partial n}{\partial x} - \tau_{scn}\frac{\partial j_n}{\partial x}, \quad (8)$$

$$j_p = -q\mu_p p \frac{\partial \phi}{\partial x} - qD_p \frac{\partial p}{\partial x} - \tau_{scp}\frac{\partial j_p}{\partial x}, \quad (9)$$

$$S_n = -\mu_n n W_n \frac{\partial \phi}{\partial x} - D_n \frac{\partial (nW_n)}{\partial x} - \tau_{scn}\frac{\partial S_n}{\partial x}, \quad (10)$$

$$S_p = -\mu_p p W_p \frac{\partial \phi}{\partial x} - D_p \frac{\partial (pW_p)}{\partial x} - \tau_{scp}\frac{\partial S_p}{\partial x}. \quad (11)$$

where is q – charge of an electron, $\varepsilon\varepsilon_0$ – absolute dielectric permeability of semiconductor, φ – electric field potential, N_a – concentration of acceptors, N_d – concentration of donors, n and p – electron and hole concentration, μ_n and μ_p – electron and hole mobility, D_n, and D_p – electron and hole diffusion coefficient, W_n and W_p – electron and hole average energy, W_e and W_h – radiation-generated electron and hole average energy, τ_{en} and τ_{ep} – electron and hole relaxation time, τ_{scn} and τ_{scp} – average time scattering of electrons and holes, j_n and j_p – density of the electric current of electrons and holes, S_n and S_p – density of stream of energy of electrons and holes, G and R – generation and recombination coefficients of charge carriers, x – coordinate, t – time.

From the point of view of mathematical calculations, usage of current densities and energy flows of electrons and holes with a retarded component leads to a change in the type of differential equations from parabolic to hyperbolic, describing the propagation of a disturbance with a finite velocity.

3. The results of the calculations

For calculating the instant initial distribution of hot radiation-generated charge carriers in a submicron structure, an algorithm, based on the Monte Carlo procedures, was developed [10]. Using the empirical pseudopotential method [11], the band structure and density of states of charge carriers in Si, GaAs, and ZnTe in the band energy range no less than a bulk plasmon were calculated. At the first step, the probability density of the transfer of a given energy from a plasmon to a valence electron p(ΔE) was calculated using the formula [12]

$$p(\Delta E) \propto \frac{1}{\frac{5B\left(\Delta U_{peak}-1\right)^{\frac{3}{2}}\left(B\Delta U_{peak}+1\right)^{\frac{3}{2}}}{\sqrt{\frac{\Delta E}{E_g}-1}}+\left(B\frac{\Delta E}{E_g}+1\right)^{\frac{5}{2}}}, \tag{12}$$

where is ΔE – the amount of energy transferable to the pair electron-hole, E_g – band gap, B and ΔU_{peak} – model parameters, which are shown in Table 2.

Table 2. Model parameters [12]

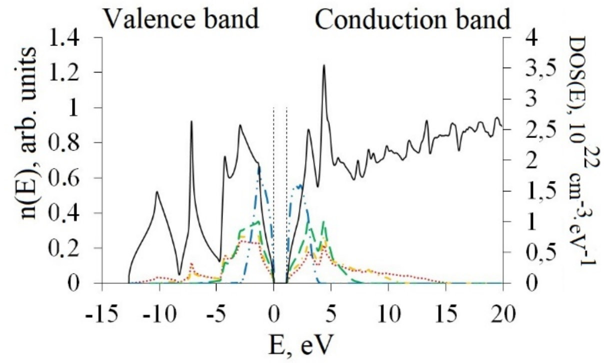
	Si	GaAs	ZnTe
E_g, eV	1.12	1.42	2.24
B	0.1	0.3	0.12
ΔU_{peak}	2.5	2.5	1.84

At the second step, the probability density of generating an electron-hole pair at the set points of the Brillouin zone was calculated in proportion to the product of the densities of states, considering the law of conservation of energy [12]

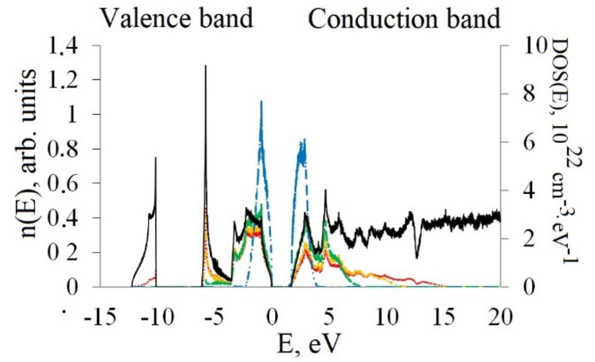
$$p(E_h, E_e|\Delta E) \propto \rho_v(E_h)\rho_c(E_e), \tag{13}$$

$$E_e = \Delta E - E_h - E_g, \tag{14}$$

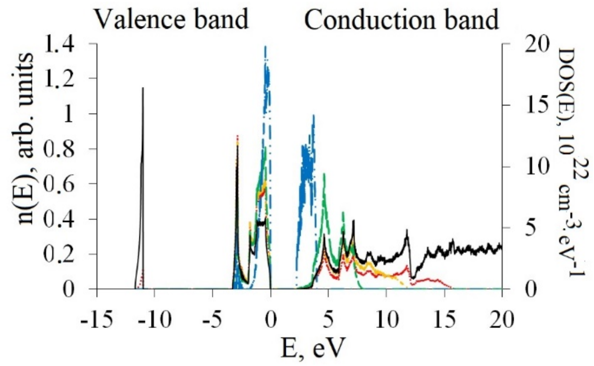
Where is $\rho_v(E_h)$ and $\rho_c(E_e)$ – density of states of holes in the valence band and electrons in the conduction band. The initial energy distributions of hot nonequilibrium charge carriers in the track of a heavy charged particle in Si, GaAs and ZnTe are shown in Figure 1:



a)



b)



c)

Figure 1. Initial energy allocations of hot nonequilibrium charge carriers in the track of a heavy charged particle in a) Si, b) GaAs, c) ZnTe. The red line is the maximum transmitted energy of 16 eV, the yellow line is the maximum transmitted energy of 12 eV, the green line is the maximum transmitted energy of 8 eV, the blue line is the maximum transmitted energy of 4 eV. The density of states is plotted along the additional axis (the black line)

From formula (12) it follows that the probability density of the transfer of a high energy valence electron decreases proportionally to $\Delta E^{-2.5}$, that is, hot nonequilibrium electrons and holes are concentrated near the bottom of the conduction band and the top of the valence band, respectively. If average the obtained energy spectra by the probability density of energy transfer to the valence electron the temperature of the electron gas in the track of a heavy charged particle can be obtained: in Si T_e = 5230 K, in GaAs T_e = 6650 K, and in ZnTe T_e = 10460 K.

One of the perspective devices for millimeter-wavelength equipment which is resistant to ionizing radiation from outer space, is an uncooled GaAs Mott diode with a reduced effective height of the potential barrier at the metal-semiconductor interface [13]: the thickness of the weakly alloyed i-layer (the active area of the diode) – is 100 nm, the impurity concentration in the active area is $1.0 \cdot 10^{14}$ cm^{-3}, he impurity concentration in the substrate is – $5.0 \cdot 10^{17}$ cm^{-3}, the layer concentration of donors in the δ-layer – $8.8 \cdot 10^{12}$ cm^{-2}, the distance from the δ-layer to the boundary with the metal is 4.7 nm. The lifetime of nonequilibrium charge carriers was set equal to 10 ns [7], which is much longer than the duration of the exciting effect.

The results of numerical modeling of the transient ionization process in a sub-micron Mott diode are shown in Figure 2. A disturbance was considered, the duration of which was set equal to 1 ps, 0.1 ps, and 0.01 ps. At times, exceeding several picoseconds, the results of calculations with using the local equilibrium and local nonequilibrium models coincide. It means, that for describing the "slow" processes in comparison with the relaxation time, will be sufficient to use the traditional local equilibrium diffusion-drift or quasi-hydrodynamic model.

Figure 3 shows the dependences of the durations of the leading edge of the pulse and the pulse itself, as well as the maximum amplitudes of the photocurrent on the duration of the ionizing radiation pulse, which varied within 0.01-4000 ps. The leading edge of the photocurrent pulse calculated using the local equilibrium model is much shorter than for the local nonequilibrium model. This shows an unusually high speed of movement of charge carriers. Because of various models of the leading edge, which are several times longer than the relaxation time, the carrier flux rates are equalized. The duration of the trailing edge of the pulse, therefore, the duration of the response to the action of ionizing radiation practically does not depend on the model used in the calculations: local equilibrium or local nonequilibrium.

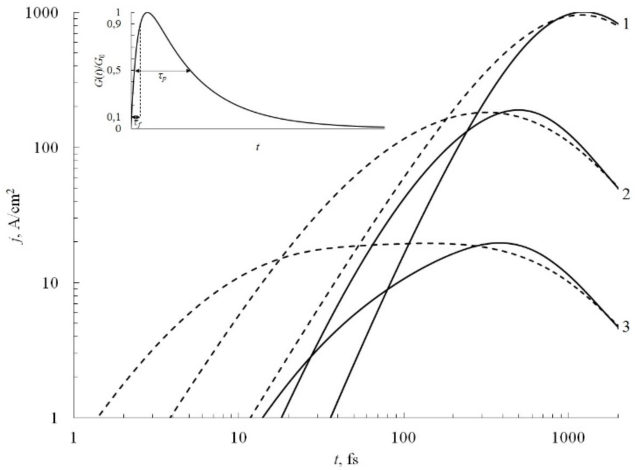


Figure 2. Transient ionization process in a Mott diode under the influence of a pulse of ionizing radiation with a duration of: 1 – 1; 2) 2 – 0.1 и 3 – 0.01 ps;
(- - -) – locally equilibrium model; (—) – locally nonequilibrium model. The inset shows the pulse shape of ionizing radiation: τ_p – is the pulse duration,
τ_f – is the duration of the leading edge of the pulse

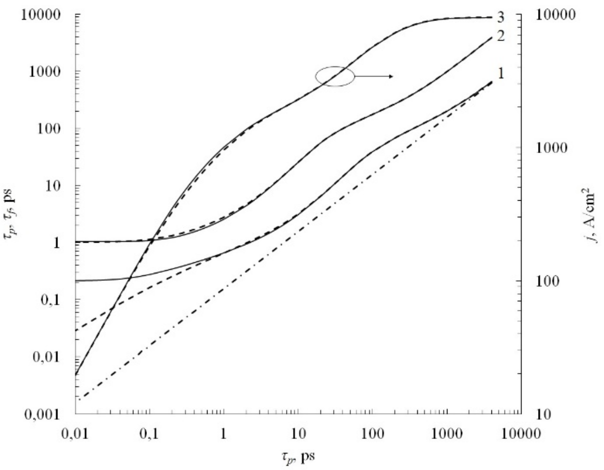


Figure 3. Duration of the leading edge of the pulse (1) and the photocurrent pulse (2), the maximum amplitude of the photocurrent (3) depending on the duration of the ionizing radiation pulse: (- - -) – locally equilibrium diffusion-drift model; (—) – locally nonequilibrium diffusion-drift model; (- · - · -) – duration of the leading edge of the ionizing radiation pulse

The space-time distribution of the electron concentration in the working area of the Mott diode is shown in Figure 4. The terminal velocity of propagation of charge carriers in semiconductors, limited by the ballistic limit, leads to the formation of electron waves in a self-consistent electric field. The amplitude of these waves is determined by the rate of increase in the concentration of nonequilibrium charge carriers, and the frequency is determined by the size of the area of the strong field (i-layer) and by ballistic transport conditions. In general, this process is like the formation of domains in the Gunn diode.

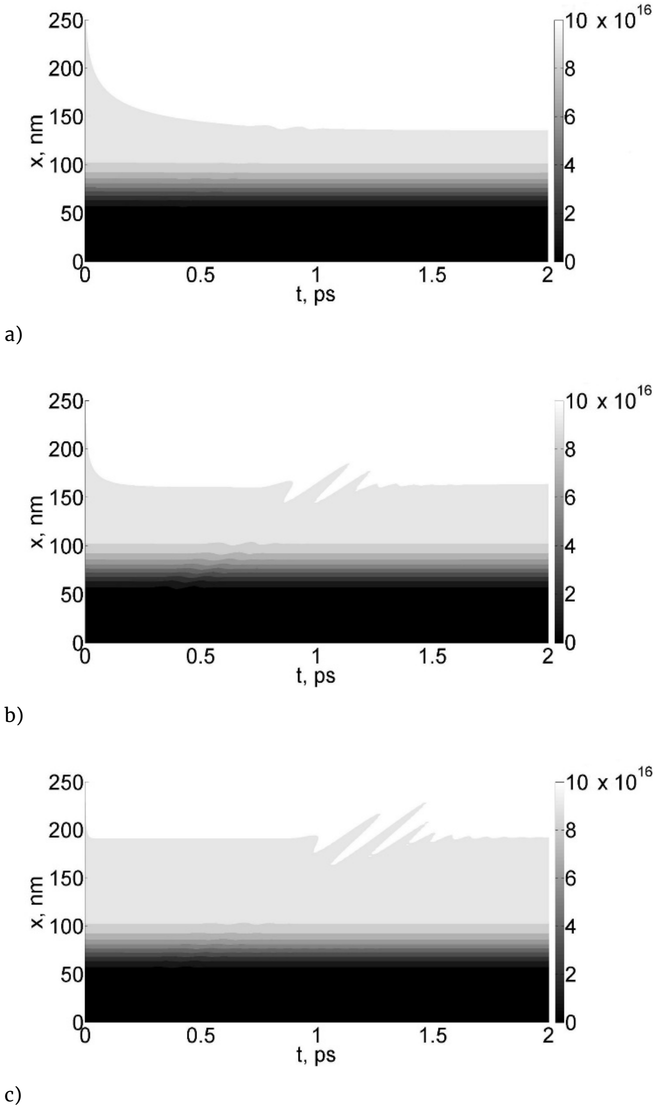


Figure 4. The space-time distribution of the electron concentration in the working area of the Mott diode (local nonequilibrium model) under the influence of an ionizing radiation pulse with a duration of: a) 1 ps; b) 0.1 ps; c) 0.01 ps

Simulation methods based on laser irradiation are widely used to predict the failure stability under the heavy charged particles of outer space impact. The physical validity of this approach lies in the ability to generate nonequilibrium charge carriers by a laser pulse in the local volume of a semiconductor. At the same time, even though the spatial-temporal distribution profiles of nonequilibrium charge carriers differ significantly under the influence of laser radiation and during the ion passage, in most semiconductor devices, due to the processes of ambipolar diffusion, by the beginning of the formation of the electric reaction of low-frequency structures after times of about 100 ps, the differences in the ionization structure practically disappear. These conditions, however, are not fulfilled for ultrahigh-frequency structures, in which "hot" charge carriers play an important role, and an electric reaction is formed within a few picoseconds after exposure to a heavy charged particle of outer space. Figure 5 shows the transient ionization process when an arsenic ion passes through a weakly alloyed region of a Mott diode with an energy of 200 MeV, which corresponds to the maximum possible linear energy transfer of 26 MeV·cm^2/mg and is the worst case when protons are scattered in GaAs. The effect of a pulse of a titanium-sapphire laser with a duration of 10 fs with a wavelength of 870 nm (without heating the electron gas) and 670 nm (with heating the electron gas by 0.24 eV) was also simulated. It was obtained, that short-wave irradiation makes it possible to correctly describe the leading edge of the current pulse, and the long – wave one-the rear, which is due to the difference in the dynamics of heating and relaxation of the energy of unequal charge carriers in the track of a charged particle and when exposed to a femtosecond titanium-sapphire laser pulse with a tunable wavelength. When an arsenic ion passes through a conducting substrate, the transient ionization process is correctly described by the standard diffusion model [14] and is simulated by a picosecond laser pulse with a wavelength of 870 nm (Figure 6).

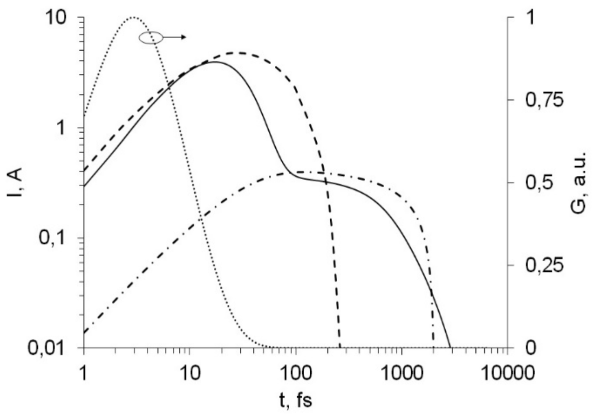


Figure 5. Transient ionization process in the i-layer of a Mott diode under the impact of an As ion with an energy of 200 MeV (—); a laser pulse with a duration of 10 fs and a wavelength of 870 nm (-·-·-); a laser pulse with a duration of 10 fs and a wavelength of 670 nm (- - -); he form of a laser pulse (·····). he normalized coefficient of generation of unequal carriers in the track of a charged particle or a laser pulse is deposited along the auxiliary axis.

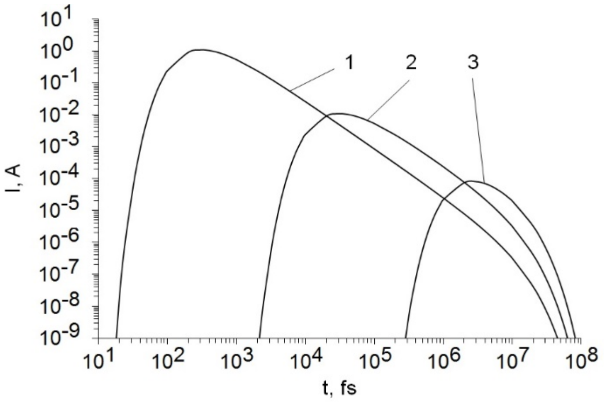


Figure 6. The transient ionization process in the n-layer of the Mott diode when exposed to an As ion with an energy of 200 MeV, the ion track passes perpendicular to the axis of the structure at a distance of: 1 - 0.2 microns;
2 - 2 microns; 3 - 20 microns from the metal contact

4. Conclusions

1. The local nonequilibrium quasi-hydrodynamic model based on a system of hyperbolic charge carrier transfer equations is proposed. The developed approximation allows to consider the inertia of the electron-hole plasma and expand the limits of applicability of this description to the characteristic space (5 nm) and time (0.2 ps) scales of inhomogeneity of the concentration and temperature of charge carriers in the track of a heavy charged particle.
2. The electron temperature in the track of a heavy charged particle is determined. It is 5230 K for Si, 6650 K for GaAs and 10460 K for ZnTe. The results are in good agreement with the experimentally determined electron temperature in amorphous carbon for the energy of the incident ion of 5 MeV/nucleon, which lies in the range of 7500-55000 K.
3. The simulation of the transient ionization process in an ultrahigh-frequency Mott diode is done. Damped waves of electron concentration in a self-consistent electric field of the terahertz frequency range which due to the ballistic limit of the velocity of charge carriers in a semiconductor are obtained.
4. A theoretical comparison of the effect of a heavy charged particle of outer space and a laser pulse on an ultrahigh-frequency Mott diode is done. When a charged particle enters the region of the strong field of the Mott diode (i-layer), it is possible to simulate correctly either the leading edge or the trailing edge of the transient ionization process by a laser pulse, which is due to the difference in the dynamics of heating and relaxation of the energy of non-equal charge carriers in the track of a charged particle

and when exposed to a femtosecond titanium-sapphire laser pulse with a tunable wavelength.

Conflict of interest

The authors declare that they have no conflicts of interest.

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