# Ionization of impurity centers by hot Auger electrons and characteristics of charge relaxation process in compensated gallium arsenide

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A study was made of the ionizing effect of an electric field on impurity levels 0.2–0.4 eV deep in semi-insulating gallium arsenide crystals excited by weakly absorbed light at 77°K. The characteristics of the field effect (a low threshold independent of the level depth and saturation in higher fields) were in conflict with the usual ideas on impact ionization. All the observations were explained qualitatively and quantitatively on the basis of ionization of impurities by hot Auger electrons, whose cooling rate could be altered by an electric field during the relaxation stage following an intervalley $X$–$\Gamma$ transition. An analysis of the experimental data yielded parameters of the intervalley transition [transition time $\tau_{1-2}(E)$ and valley coupling constant $D_{12}$].

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Investigations of the mechanism of carrier recombination in chromium-compensated gallium arsenide revealed the presence of impurity complexes and a considerable influence of the interimpurity interaction effects on equilibrium[1] and non-equilibrium[2] processes. Some of the experimental results indicated a high probability of the Auger capture of electrons and holes by a deep acceptor level located approximately in the middle of the forbidden band, which was accompanied by the transfer of energy to an electron bound to the nearest donor.[2,3] The most characteristic feature of the Auger processes was known to be the generation of relatively energetic ("hot") electrons capable of ionizing deep impurity levels. We detected the ionizing action of hot electrons by investigating the thermally stimulated conductivity (TSC) at various excitation rates. We found that the number of electrons accumulating at traps varied nonmonotonically with the duration and intensity of excitation and this was the expected manifestation[4] of the ionization of impurities by hot electrons. We discovered a nontrivial effect of considerable enhancement of the trap ionization process in relatively weak (~100 V/cm) electric fields,[5] which differed considerably in respect of its characteristics from the usual field ionization effects. We analyzed these characteristics and found that they were a consequence of the association of the effect with hot Auger electrons and reflected the features of the process of electron energy relaxation in the many-valley conduction band of gallium arsenide.

## §1. INFLUENCE OF AN ELECTRIC FIELD ON THE IONIZATION OF IMPURITIES BY HOT ELECTRONS

Ionization of the $E_c - 0.2$–$0.4$ eV traps was investigated by the TSC method in crystals of standard semi-insulating GaAs:Cr (see Refs. 4 and 5). These levels were filled with electrons in the course of low-temperature (77°K) illumination of a sample. The duration (30–60 sec) and intensity of excitation were selected to ensure maximum population of the levels. After a dark interval, which could range from 10 sec to 15 min without altering the results, a sample was heated at a uniform rate and the time dependence of the excess conductivity was used to find the number of electrons captured by the local levels. The depth of these levels was deduced from the positions of the TSC peaks, and from the rising parts of the TSC curves; the two methods gave similar results. An electric field was applied at the end of the excitation period, i.e., after the impurity levels were largely filled. This eliminated the effects associated with the process of filling the energy levels, namely, the influence of the field on the electron capture cross sections.

In the investigation of the field dependence of the ionization, the TSC was excited near the fundamental absorption edge (corresponding to the maximum photocurrent). Moreover, since an earlier study showed that the field effect only occurred during illumination or immediately after its end, the dependence of the effect on the nature of the excitation after preliminary filling of the levels by excitation with light corresponding to the photocurrent maximum was investigated by applying the field in conjunction with a change from excitation in the fundamental region to the impurity region selecting the light intensity in all cases so as to ensure the same photocurrent. Figure 1 shows the dependence of the field ionization of two impurity levels on the wavelength of light $\lambda$ exciting a sample during the action of the field [curve 5 applies to the $E_c - 0.28$ eV level, and curve 6 to $E_c - 0.4$ eV; $n_t(\mathscr{E}, \lambda)$ is the number of electrons remaining at the levels after the end of illumination and application of the field, whereas $n_t^0(\lambda)$ is the number which remains after the same excitation regime but without the field]. We can see that the presence of the field reduces $n_t$ considerably and that this reduction depends on $\lambda$.

The spectrum of the optical–field quenching of the TSC is compared in Fig. 1 with the photocurrent spectra obtained under monochromatic (curve 1) and combined (curve 3) excitation conditions (in the latter case, the monochromatic excitation is acting simultaneously with the interband excitation that creates the initial

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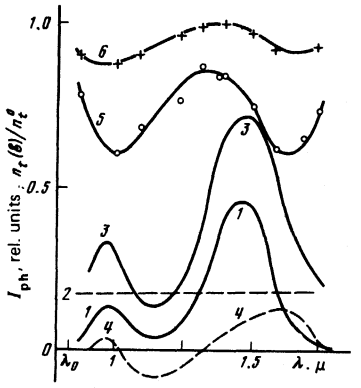


FIG. 1. Spectra of the photocurrent (1, 3, 4) and optical–field quenching of the TSC: 1) photocurrent excited by monochromatic light $I_{ph}(\lambda)$; 2) photocurrent due to interband excitation $I_{ph}(\lambda_0)$; 3) photocurrent due to combined excitation $I_{ph}(\lambda_0+\lambda)$; 4) nonadditivity $\Delta I_{ph}=I_{ph}(\lambda_0+\lambda)-I_{ph}(\lambda_0)-I_{ph}(\lambda)$; 5) $n_t(\mathscr{E})/n_t^0$ for levels of depth 0.28 eV; 6) the same for levels of depth 0.4 eV. A field $\mathscr{E}=200$ V/cm of frequency $\nu=25$ kHz was applied for 1 min.

photocurrent represented by curve 2); curve 4 shows the nonadditivity of the interband and monochromatic excitations. The region of negative nonadditivity near $\lambda=1.1-1.3$ $\mu$ (quenching of the interband photocurrent by impurity-absorbed light) corresponds to preferential generation of the minority carriers (holes).[2,6] In the regions of positive nonadditivity (near 1 and 1.6 $\mu$), illumination results in electron accumulation at donor levels participating in the recombination at impurity complexes; this alters the rate of recombination[2,3] and increases the probability of Auger capture processes involving electrons bound to donors. It is clear from Fig. 1 that the effect of the field on the population of the impurity levels is greatest in the same spectral regions.

The mechanism of the action of the field on the level populations may generally be associated either with the direct ionization by the field, hot electrons, light, or heat, or it may be due to the change in the population of the levels caused by holes (which may be created optically or injected by the field). The results obtained allow us to decide between these possibilities.

*a) Hold effects.* We can immediately exclude the influence of the injected holes because of the considerable length of the sample (~0.5 cm) compared with the hole diffusion and drift length ($10^{-3}$–$10^{-4}$ cm). The role of the optically created holes should be greatest in the photocurrent quenching region but the influence of the field does not exhibit a maximum; the long-wavelength maximum of the influence of the field (at $\lambda=1.6$ $\mu$) lies in the region where light effectively generates only electrons.[2,6] Consequently, holes do not play an important role in the processes observed in our experiments.

*b) Ionization effects.* The lack of dependence of the TSC on the duration of the dark interval preceding heating (mentioned above) shows that there is practically no thermal ionization of impurities in the absence of the field; since the field does not increase the temperature significantly, the result is not due to thermal ionization. We can also exclude the direct participation of light in the ionization process because all the characteristic features of the effect are still observed at the beginning of the dark interval following illumination (during this interval, electrons are liberated from shallow traps and are recaptured). The application of an electric field up to 2 kV/cm at the end of the dark interval and during the heating stage does not affect the TSC, which excludes direct field ionization of impurities. Thus, ionization can only be caused by hot electrons whose ionizing action is enhanced by the field. The identity of the characteristics of the effect during and immediately after illumination shows that the appearance of these electrons is not associated with the direct influence of light but with the carrier capture process; the identity of the spectral regions of the greatest influence of the field on the TSC with the regions of positive nonadditivity of the photocurrent (Fig. 1) is evidence of the Auger origin of hot electrons.

Filling the impurity levels with electrons in the presence of ionizing electrons can be described by the following relationship (which ignores thermal ionization, i.e., applies at low temperatures):

$$nv_nS_n(N_t-n_t)-\gamma n_t=0, \tag{1}$$

where $n$ is the density of free electrons; $v_n$ is their velocity; $S_n$ is the capture cross section of the impurity levels; $N_t$ and $n_t$ are, respectively, the density of these levels and of the electrons present at these levels; $\gamma$ is the probability of ionization which can be represented in the form

$$\gamma=n_iv_iS_i; \tag{2}$$

$n_i$ is the number of electrons with energy sufficient for ionization; $v_i$ is the velocity of these electrons; $S_i$ is the ionization cross section. We shall estimate $\gamma$ on the assumption[1)] that $n_i\approx nt_E/\tau$ ($t_E$ is the time during which electrons have enough energy for ionization and $\tau$ is the total electron lifetime in the conduction band); if $n=10^{10}$ cm$^{-3}$, $\tau=10^{-6}$ sec (experimental values), $t_e\approx10^{-11}$ sec (Ref. 7), $v_i\approx10^7$ cm/sec, and $S_i\approx10^{-12}$ cm$^2$ (this is the value obtained in Ref. 8 for similar levels in silicon), then $\gamma=nt_Ev_iS_i/\tau\approx1$ sec$^{-1}$, i.e., the ionization of impurities should occur in 1 sec. We can see that the mechanism of ionization by the Auger electrons can be very effective under our experimental conditions (see above).

The steady-state electron population of the impurity levels is obtained from Eqs. (1) and (2):

$$n_t/N_t=[1+\gamma(nv_nS_n)^{-1}]^{-1}, \tag{3}$$

where the ionization probability $\gamma$ should depend on the electric field $\mathscr{E}$. The nature of this dependence governs the field dependence of the ionization of levels (Fig. 2).

The main characteristics of the field influence on the ionization of impurity levels are as follows: 1) a pronounced and low threshold $\mathscr{E}_0$; 2) an approximately linear dependence of the effect, i.e., of $[n_t^0-n_t(\mathscr{E})]/n_t^0$

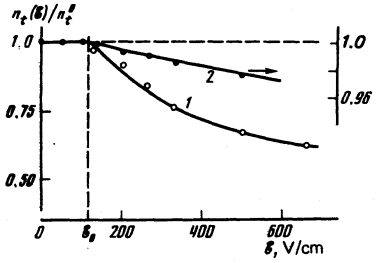


FIG. 2. Dependence of the populations of levels of depth 0.24 eV (curve 1) and 0.4 eV (curve 2) on the field amplitude. Frequency 100 kHz. The continuous curves are the theoretical dependences,

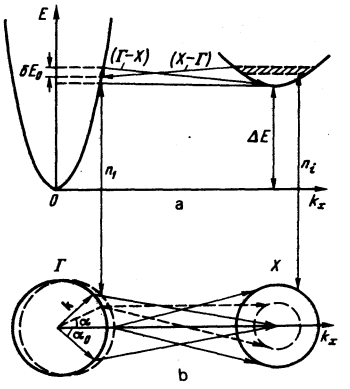


FIG. 3. Intervalley electron transition scheme. The dependences $E(k)$ are given at the top (Fig. 3a) and the constant-energy surfaces near the $\Gamma$ and $X$ points of the Brillouin zone are given at the bottom (Fig. 3b).

on the field $\mathcal{E}$ near the threshold; 3) weakening of this dependence in strong fields (approach to saturation); 4) independence of the threshold of the level depth.

A feature of fundamental importance is the very low threshold field ($\mathcal{E}_0 = 120$ V/cm) compared with the field causing significant heating of the electrons in GaAs (~3 kV/cm, which is the threshold of the Gunn effect). Therefore, it is essential to consider whether the effect under consideration is related to inhomogeneities as well as to fields much higher than the average value. Obviously, the influence of such inhomogeneities should decrease on increase in the frequency of the voltage applied to the sample because of the shunting of the inhomogeneities by the capacitative current; complete suppression of their influence occurs when the frequency exceeds the reciprocal of the Maxwellian relaxation time $\tau_M^0$ of the low-resistivity parts of the sample. This condition is satisfied under the experimental conditions (Fig. 2); the value of $\tau_M^0$ was found from the frequency dependence of the ohmic conductivity.

The above features of the influence of the field on the impurity ionization process are in conflict with the usual ideas on impact ionization.[9,10] They show directly that the ionizing effect is produced not by the electrons heated by the field from a low initial energy but by the electrons which already have high energy at the moment of their appearance in the conduction band and which are capable of ionizing all the levels mentioned above (these are the Auger electrons). The ionizing power $\gamma$ of the latter electrons is proportional to the time they spend in the high-energy state. The rise in $\gamma$ in the presence of a field should increase the time for which the energy $E \gtrsim 0.4$ eV is retained (population of the levels deeper than $E_c - 0.4$ eV is independent of the field). Bearing in mind the structure of the conduction band of GaAs, it is natural to assume that a field confines the electrons to any one of the upper ($X$ or $L$) valleys, whose bottom is located $\Delta E \approx 0.4$ eV above the bottom of the $\Gamma$ valley (Fig. 3).

Thus, in the first approximation, the mechanism of the field effect is independent of the nature of the deep impurity levels. It is interesting that a similar influence of the field on the ionization of impurity levels was also observed by us for samples of GaAs:O and GaAs:Fe. Clearly, the same effect occurs[11,12] in GaAs:Cr and GaAs:O.

## §2. DEPENDENCE OF THE ELECTRON COOLING TIME ON THE ELECTRIC FIELD

The energy of the Auger electrons, governed by the depth of the acceptors relative to the band edges ($E_c - 0.8$ eV, $E_v + 0.7$ eV), from which the binding energy of an electron at the nearest donor (~0.2 eV, according to Ref. 2) is subtracted, should amount to 0.5–0.6 eV. According to the current ideas,[13-15] electrons of this energy in GaAs can reach the side valleys (for example, the $X$ valleys—Fig. 3) in a time of $\sim 10^{-13}$–$10^{-14}$ sec, where the energy $\hbar\omega_{X-X}$ is rapidly dissipated by intervalley transfer accompanied by phonon emission. The cooling rate decreases rapidly on approach to the energy level $E = \Delta E + \hbar\omega_{X-X}$; the corresponding "region of slow relaxation" is shown shaded in Fig. 3a. An electron is transformed from this region to the valley $\Gamma$, emitting a phonon of energy $\hbar\omega_{X-\Gamma}$, i.e., after this transition, the electron energy is $\sim\Delta E$ ($X-\Gamma$ transition in Fig. 3); transitions accompanied by phonon absorption at 77°K can be ignored because an electron cannot return from the $\Gamma$ to the $X$ valley in the absence of the field. Relaxation in the $\Gamma$ valley is accompanied by the emission of optical phonons with a small wave vector $\mathbf{k}$ and the cooling rate increases on reduction in energy; immediately after the $X-\Gamma$ transition, the relaxation time in the central valley becomes $\tau_\Gamma \approx 10^{-12}$ sec (Ref. 15). In the first approximation, we can assume that the ionizing action is governed by the number of electrons $n_i$ which are in the slow relaxation region of the valley $X$: according to Ref. 7, the electrons spend up to $\sim 10^{-11}$ sec in this region. It is important that these electrons are capable of ionizing only the levels whose depth is less than $\Delta E + \hbar\omega_{X-X} \approx 0.4$ eV.

The electric field is capable of altering the value of $n_i$ if, in a time $\tau_\Gamma$, the field increases the electron energy in the valley $\Gamma$ by an amount $\delta E_0$ necessary for the return $\Gamma-X$ transition (Fig. 3a); as a result of this

process, some of the electrons return to the valley $X$. It should be noted that $\delta E_0$ may be somewhat smaller than $\hbar\omega_{X-\Gamma}$: the value of $\delta E_0$ depends on the difference between $\hbar\omega_{X-X}$ and $\hbar\omega_{X-\Gamma}$, and on the ratios of the probabilities of the $X-X$ and $X-\Gamma$ transitions in the slow relaxation region. The relationship between the field $\mathscr{E}$ and the increase in energy in this field $\delta E$ are found by calculating the change in the electron quasimomentum $P$: $\delta P = e\mathscr{E}\tau_\Gamma$. If we ignore the conduction band nonparabolicity[2] and assume approximately that $E \approx P^2/2m$ ($m_1 \approx 0.07\, m_0$ is the electron mass at the bottom of the valley $\Gamma$), we find that $\delta E = P\delta P \cos\alpha/m_1$, where $\alpha$ is the angle between the vectors $\mathscr{E}$ and P (the direction of P in Fig3b is governed by the direction of k; to be specific, the field $\mathscr{E}$ is assumed to be parallel to the $0k_x$ axis); the threshold field $\mathscr{E}_0$ can be found if we assume that $\delta E = \delta E_0$ and $\cos\alpha = 1$. Then,

$$\mathscr{E}_0 = \frac{m_1\delta E_0}{Pe\tau_\Gamma} \approx \frac{\delta E_0}{e\tau_\Gamma}\left(\frac{m_1}{2\Delta E}\right)^{1/2}; \tag{4}$$

here, allowance is made for the fact that, immediately after the $X-\Gamma$ transition, the electron energy is approximately equal to $\Delta E = P^2/2m_1$. If we take the experimental value $\mathscr{E}_0 = 120$ V/cm (Fig. 2), we find from Eq. (4) that $\delta E_0 = 0.015$ eV, which is slightly less than the energies of longitudinal acoustic (0.02 eV) and optical (0.029 eV) phonons with limiting values of k in GaAs.

If only a small proportion of the $X$-valley electrons can ionize the traps, the conditions for the exchange of electrons between the $\Gamma$ and $X$ valleys are

$$\left.\begin{aligned} \frac{dn_i}{dt} &= G_i - \frac{n_i}{\tau_{X\Gamma}} + n_1 w, \\ \frac{dn_1}{dt} &= \beta\frac{n_i}{\tau_{X\Gamma}} - \frac{n_1}{\tau_\Gamma} - n_1 w, \end{aligned}\right\} \tag{5}$$

where $\tau_{X\Gamma}$ is the $X-\Gamma$ transition time; it follows from our discussion of the cooling mechanism that $\tau_{X\Gamma} \approx t_E$. The quantity $n_1$ is the number of electrons in the right half of the central constant-energy sphere in the $k$ space corresponding to the condition $E = \Delta E$ (Fig. 3b); these are the electrons which are heated by the field, whereas the electrons in the left half are cooled; $w$ is the probability of the $\Gamma-X$ transition for these electrons; $\beta$ is the proportion of the electrons in the right half of the central sphere after the $X-\Gamma$ transition ($\beta \gtrsim 0.5$);[3] $G_i$ is the rate of generation of hot electrons (by the Auger capture process).

Under steady state conditions, we have $dn_i/dt = dn_1/dt = 0$ and it then follows from Eq. (5) that

$$n_i = \frac{n_i^0}{1-\beta[1+(w\tau_\Gamma)^{-1}]^{-1}},$$

where $n_i^0 = G_i t_E = n_i$ for $\mathscr{E} = 0$. Assuming also that $\gamma$ is proportional to $n_i$, we find from Eq. (3) that the number of electrons at the impurity levels deduced from from the TSC is

$$n_i = \frac{N_i}{1+A\{1-\beta[1+(w\tau_\Gamma)^{-1}]^{-1}\}^{-1}}, \tag{6}$$

where $A = n_i^0 v_i S_i / n v_n S_n = \text{const}$. The relative change in the level populations is given by

$$\frac{n_i}{n_i^0} = \frac{1+A}{1+A\{1-\beta[1+(w\tau_\Gamma)^{-1}]^{-1}\}^{-1}}, \tag{7}$$

and since the maximum effect occurs for $A \gg 1$, it follows that

$$n_i/n_i^0 \approx 1-\beta[1+(w\tau_\Gamma)^{-1}]^{-1}. \tag{8}$$

Before determining the field dependence of $w$, we shall consider the field dependence of the number of electron states participating in a $\Gamma-X$ transition. For $\mathscr{E} = \mathscr{E}_0$, the excess electron energy above the bottom of the valley $X$ corresponds to $\hbar\omega_{X-\Gamma}$ and the final states after the $\Gamma-X$ transition can only lie in the region of $k$ space near the point $X$ (Fig. 3a). At higher values of $\mathscr{E}$ and $\delta E$, the transition $\Gamma-X$ ends in a spherical layer of radius $k_2 \approx \hbar^{-1}[2m_2(\delta E - \delta E_0)]^{1/2}$, where $m_2$ is the effective mass of an electron in the valley $X$ (Fig. 3b) and the thickness of the layer is found by differentiating $k_2$ with respect to $\delta E$. We can then assume quite accurately that the number and energy $\hbar\omega_{X-\Gamma}$ of the phonons are the same for transitions to all the parts of the $k$ space considered above. It follows that the energy intervals of the electrons participating in the intervalley transitions are not affected by the $\Gamma-X$ and $X-\Gamma$ transitions; the corresponding intervals in the $k$ space change in accordance with the dependences $E(k)$. In view of the slight relative change in the electron energy in the valley $\Gamma$ as a result of field heating, we can assume constancy of the thickness ($dk_1$) of the spherical layer participating in the $\Gamma-X$ transitions in the valley $\Gamma$.

The probability of the $\Gamma-X$ transitions from a given range of energies in the valley $\Gamma$ is proportional to the product of the volumes of the regions in the $k$ space corresponding to the initial and final states. The total probability of the $\Gamma-X$ transitions per unit volume in 1 sec is given by the integral of this product over all the states capable of participating in these transitions (i.e., those whose energy increases by $\delta E \geqslant \delta E_0$):

$$\begin{aligned} w &= \text{const}\int_\alpha 2\pi k_1 \sin\alpha k_1 d\alpha \cdot 4\pi k_2^2 dk_2 \\ &= c\cdot 2\pi k_1^2 \int_0^{\alpha_0} \sin\alpha d\alpha \left(\frac{\mathscr{E}}{\mathscr{E}_0}\cos\alpha - 1\right)^{1/2}, \end{aligned} \tag{9}$$

where the limit $\alpha_0$ is governed by the condition $\mathscr{E}\cos\alpha_0 = \mathscr{E}_0$; $c$ is a constant proportional to the matrix element of the $\Gamma-X$ transition. Integration of Eq. (9) gives

$$\begin{aligned} w &= \frac{4}{3}\pi k_1^2 c \frac{\mathscr{E}_0}{\mathscr{E}}\left(\frac{\mathscr{E}}{\mathscr{E}_0} - 1\right)^{3/2} \\ &= B\frac{(\mathscr{E}-\mathscr{E}_0)^{3/2}}{\mathscr{E}\mathscr{E}_0^{1/2}}. \end{aligned} \tag{10}$$

Substituting the above expression in Eqs. (7) and (8), we find the field dependence of the impurity-level populations. We shall use it to analyze the experimental data (Fig. 2). Allowing for the relatively strong effect in the case represented by curve 1 in Fig. 2, we shall compare the experimental results with Eq. (8). Curve 1 in Fig. 2 is calculated using this equation and assuming that $\beta = 0.86$ and $B = 0.45 \times 10^{12}$ sec$^{-1}$; the same parameters were used later to calculate curve 2 in Fig. 2, employing Eq. (7); the parameter $A$ governing the vertical scale of the curves was 0.052 (the parameters $\beta$ and $B$ apply to the intervalley transitions and should be the same in all cases, whereas $A$ is an

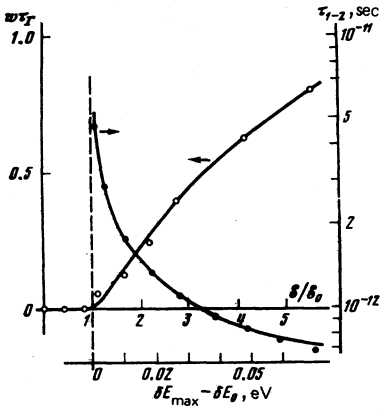


FIG. 4. Field and energy dependences of the intervalley transition probability and time. Explanations in text.

individual characteristic of an impurity). A comparison of the experimental points with the theoretical curves shows that the dependences obtained describe correctly the laws governing the effect in question.

Figure 4 shows the dependence of $w\tau_\Gamma$ on $\mathcal{E}$, plotted on the basis of Eq. (10). The points are deduced from the experimental values of $n_t/n_t^0$ in Fig. 2 using Eq. (8). These data can be employed in finding the energy dependence of the time $\tau_{1-2}$ of the intervalley transition $\Gamma-X$. The values of $w$ (Fig. 4) representing the total probability of a transition for all the electrons in the central half-sphere of the $k$ space with energies from $E_1 \approx \Delta E$ to $E_1 + \delta E_{max} = E_1 + \delta E_0 \mathcal{E}/\mathcal{E}_0$, have to replaced with the probabilities $w' = \tau_{1-2}^{-1}$, corresponding to a unit energy interval, and allowance has to be made for the number of electrons which actually participate in the transitions. This can be done by assuming, first of all, that all the electrons participating in the $\Gamma-X$ transition have the maximum energy $E_1 + \delta E_{max}$; then, substituting $k_2 = \hbar^{-1}[2m_2(\delta E_{max} - \delta E_0)]^{1/2} = \text{const}$ in Eq. (9), we obtain $w_1 = cS_1(\mathcal{E}/\mathcal{E}_0 - 1)^{1/2}$, where $S_1$ is the area of the part of the half-sphere for which $\mathcal{E}\cos\alpha \geq \mathcal{E}_0$, i.e., that part in which electrons may be transferred to the valley $X$. The conversion from $w_1$ to $w'$ is made on the assumption that the electrons with this energy occupy all the half-sphere: $w' = w_1 2\pi k_1^2/S_1$. Comparing $w_1$ and $w'$ with Eq. (10), we find that

$$w' = 1.5w(1-\mathcal{E}_0/\mathcal{E})^{-1}.$$

The values of $\tau_{1-2} = 1/w'$, obtained with the aid of this equation for various values of $\delta E_{max}$, are represented by black dots in Fig. 4; the calculations were based on the values of $w$ given in this figure. The curve passing through the black dots in Fig. 4 is calculated using a formula[15] for the $\Gamma-X$ transitions accompanied by phonon emission:

$$(\tau_{1-2})^{-1} = \frac{D_{12}^2 m_2^{3/2}}{2^{1/2}\pi\hbar^3\rho\omega_{\Gamma-X}}(E - \hbar\omega_{\Gamma-X} - \Delta E)^{1/2}, \quad (11)$$

where $\rho$ is the density of the crystal. We can see from Fig. 4 that the theoretical curve fits the data very well. In a quantitative comparison, the value of the coupling constant $D_{12}$ in Eq. (11) is assumed to be $1.4 \times 10^8$ eV/cm, which is of the same order as the value adopted in Ref. 15. Our estimate depends strongly on the value of $\tau_\Gamma$; if the real value of $\tau_\Gamma$ is found to be less than $10^{-12}$ sec, the constant $D_{12}$ has to be reduced correspondingly.

Thus, our field enhancement of the ionization of impurity levels in optically excited semiinsulating gallium arsenide is unexpected and provides a very strong argument for Auger processes involving bound carriers occurring in GaAs:Cr.

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[1)] This is justified on condition that the Auger capture processes determine the electron lifetime; the recombination rate $n/\tau$ is then equal to the rate of generation of the ionizing electrons.

[2)] The use of a more accurate formula $\hbar^2k^2/2m_1 = E(1 + 0.933E/E_g)$ gives results which are 25% different in respect of the threshold energy of the $\Gamma-X$ transition $\delta E_0$ and in respect of the proportionality coefficient in the dependence $w(\mathcal{E})$, as discussed below. The nature of the dependence $w(\mathcal{E})$ and, consequently, of $n_t(\mathcal{E})$ is not affected.

[3)] We can expect the value of $\beta$ to be quite close to 0.5 (corresponding to an isotropic distribution of electrons in the central valley). In the case when the exchange of electrons between adjacent parts of the valleys in the $k$ space is more probable (for example, because of some features of the phonon distribution function), we have $\beta > 0.5$.

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# Avalanche ionization produced in solids by large radiation quanta and relative role of multiphoton ionization in laser-induced breakdown

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The generalized solution of the diffusion kinetic equation for avalanche ionization is generalized to include the region of short radiation pulses of $10^{-9}$–$10^{-11}$ sec. A solution of the differential-difference quantum kinetic equation is obtained and it is shown that in the case of large radiation quanta the dependences of the critical field on the frequency and on the pulse duration are substantially altered. The relative roles of avalanche and multiphoton ionization in laser-induced breakdown of transparent dielectrics are analyzed.

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We have previously investigated,[1-3] by solving the quantum-kinetic equation for the conduction-band electrons in the diffusion approximation, the process of avalanche impact ionization as one of the principal mechanisms of breakdown of transparent dielectrics in a strong electromagnetic field. We determined thereby the principal regularities of this process, namely, the dependence of the critical field $E_c$ on the initial lattice temperature $T_0$ on the frequency $\Omega$, and on the duration of the radiation pulse, in a wide range of the indicated parameters. It was shown in particular that the diffusion approximation provides a rather good description of the process up to field frequencies satisfying the condition $\hbar\Omega \ll I$, where $I$ is the effective ionization potential, and that this approximation leads to a relation of the type

$$E_c^2 \propto \Omega^2 + \nu_{eff}^2, \qquad (1)$$

where $\nu_{eff}$ is the effective frequency of the hot-electron collisions. The frequency dependence of $E_c(\Omega)$ was subsequently[5] refined for high frequencies by solving a quantum-kinetic difference equation. It turned out that the $E_c(\Omega)$ dependence can be quite weaker in the indicated region than in the diffusion case described by relation (1).

The derived regularities[1-4] have made possible purposeful experimental investigations[4,5] aimed at determining the role of the electron avalanche in laser-induced breakdown of real crystals. It was shown that the dependences of the breakdown thresholds on the radiation frequency and on the temperature, observed for a number of the optically most durable samples of alkali-halide crystals agree with the theoretical predictions and lead to a reasonable estimate, $\nu_{eff} \approx 6 \times 10^{14}$ sec$^{-1}$, of the frequency of the electron–phonon collisions. Some experimental results, however, particularly on the temperature dependence of the breakdown thresholds at low and high radiation frequencies, were not fully explained. It was assumed, in particular, that the disparity between the observed temperature dependences of the breakdown threshold and that predicted by the theory of avalanche impact ionization for high-temperature laser radiation ($\lambda = 0.53\ \mu m$) may be due to the effective inclusion of another carrier-generation mechanism, namely multiphonon ionization.

These facts have prompted us to investigate theoretically in greater detail the development of avalanche impact ionization for large radiation quanta and to analyze the relative role of the mechanisms of impact and multiphoton ionization in laser-induced breakdown of transparent dielectrics. The relative contribution made to the carrier generation by these two processes, characterized respectively by the electron-avalanche development constant $\gamma$ and by the rate $W_n$ of $n$-photon carrier generation, should be essentially determined by the dependence of $\gamma$ and $W_n$ on the intensity and frequency of the electromagnetic radiation. It follows from an analysis and multiphoton transitions (see, e.g., Ref. 6), that in the entire investigated range of pulse durations $t_p$ ($10^{-7}$–$10^{-11}$ sec) we have $W_n \propto E^{2n}$ if $n \lesssim 10$. As to the avalanche development constant $\gamma$, it can have a stronger dependence on the frequency for wide-band dielectrics. Thus, in the case of laser breakdown in the nanosecond pulse range, as shown in Refs. 1–3, $\gamma$ depends exponentially on the radiation intensity. On going to the picosecond band, the $\gamma(E)$ dependence can be weaker.

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