Role of intervalley scattering in electron recombination in silicon

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It is shown that intervalley scattering in n-silicon leads to the appearance of maxima on the plot of the coefficient of phonon-induced electron recombination against the electric field.

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Most known data on phonon recombination of carriers in semiconductors have been satisfactorily explained[1] on the basis of the theory of cascade recombination[2] with participation of long-wave acoustic phonons. Although recombination with participation of optical and short-wave acoustic phonons has been considered in the literature,[2-5] no special experimental studies of this question have been made. Yet this question is of interest, for if the energy $\hbar\omega$ of a high-energy phonon exceeds the recombination level E_R, then recombination with participation of such phonons on attracting centers should have an unusual field dependence. In fact, to be able to recombine with the $\hbar\omega$ radiation, the carrier must have an energy at least equal to $\hbar\omega - E_R$. If the average thermal energy kT is less than this distance, then noticable recombination will occur only when the electrons are heated. Instead of the ordinary decrease of the recombination with increasing field, a maximum of the recombination should be observed in this case in a certain field interval.

We report here some experimental and theoretical data on the effect of intervalley scattering on recombination of electrons on the levels of phosphorus and silicon under conditions of partial freezing-out of electrons on these levels ($T = 27.1$ K).

We investigated the dependences of the electron concentration and of the time of decrease of the additional excitation from the donor levels of the carriers on the electric field. It was assumed that both the stationary concentration and the indicated time depend on all the processes of generation and recombination in accordance with the well known equation

$$\frac{dn}{dt} = A_T(N_D - N_A - n) - B_T(N_A + n)n + A_J(N_D - N_A - n)n + B_J(N_A + n)n^2.$$

As shown in Ref. 6, the coefficients A_T, B_T, A_J, and B_J can be determined by measuring the stationary concentration and the time of decrease of the concentration of the nonequilibrium carriers in two crystals with different doping levels. The concentrations of the donors and acceptors were determined in our samples by careful Hall measurements and were equal to

$N_D^I = 4.5 \cdot 10^{14}\,\mathrm{cm}^{-3}$; $N_A^I = 9.7 \cdot 10^{12}\,\mathrm{cm}^{-3}$;

$N_D^{II} = 0{,}58 \cdot 10^{14}\,\mathrm{cm}^{-3}$, $N_A^{II} = 4 \cdot 10^{12}\,\mathrm{cm}^{-3}$.

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To determine the stationary concentration of the electrons in the heating fields, we measured the current–voltage characteristics of the conductivity of samples cut in the $\langle 111 \rangle$ direction. The electron concentration was calculated from these characteristics, using the data on the field dependence of the drift velocity, obtained in Ref. 7 by the time-of-flight method. For weak heating fields, a correction was introduced for the difference between the concentrations of the scattering centers and the different crystals. The lifetime of the electrons was measured by the method of applied pulses described in Ref. 5.

Figure 1 shows the measured lifetimes of the electrons and the obtained dependences of their concentration in the conduction band on the electric field. The behavior of the phonon part of the electron recombination, which is of interest to us and is characterized by the coefficient B_T, is shown by curve 1 of Fig. 2. It is seen that when

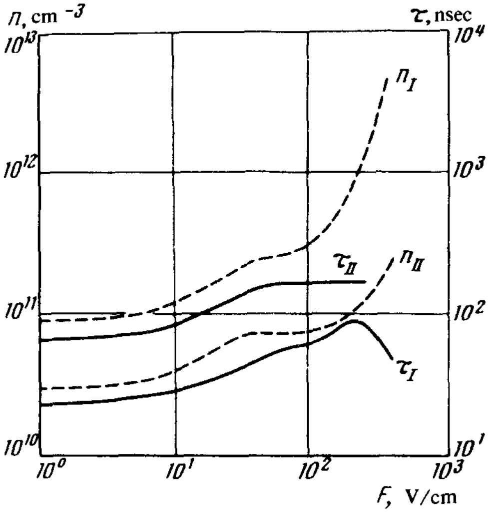

FIG. 1. Dependence of the stationary concentration of the electrons and of the time of decrease of the nonequilibrium carriers on the electric field; I, II—samples with different N_D and N_A, whose values are given in the text.

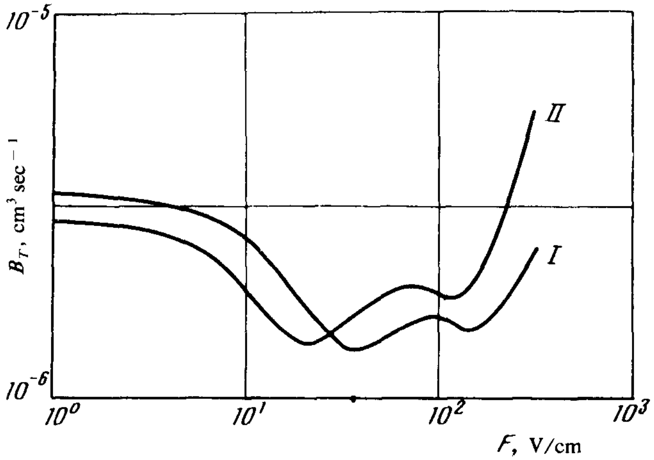

FIG. 2. Dependence of the combined phonon-recombination coefficient B_T on the electric field; I—obtained from the experimental data of Fig. 1, II—calculated theoretically.

the heating of the electrons sets in the phonon recombination first decreases, to fields on the order of 30 V/cm, and then again increases and reaches a maximum in a field of approximately 90 V/cm, and subsequently grows rapidly for a second time in fields stronger than 150 V/cm. It is natural to attribute such a complicated behavior of B_T to the presence of two groups of high-temperature phonons, which interact with the electrons in the silicon and lead to intervalley transfers of the latter.

To confirm this point of view, we calculated the phonon part of the electron recombination on the phosphorus levels using the Lax model[2] and including in the sticking function the correction given in Ref. 8 for the averaging of the probability of the phonon emission over the electron trajectory near the recombination center. In the calculation of the integrals that determine B_T, it was assumed, in accordance with the Lax model, that the ground and weakly excited levels make no noticable contribution to B_T, and the integration was carried out only starting with the excitation energy of the phosphorus level $E_R = -10.9$ meV. The distribution function of the "hot" electrons was approximated by the Budd function[9] for electron energies lower than $\hbar\omega$, when the scattering is only by the long-wave acoustic phonons and the charged impurities, and by the function obtained by Reik and Risken[10] for electron energies exceeding $\hbar\omega$. The results of the calculations for the B_T components determined by the recombination with participation of the long-wave acoustic and intervalley phonons with energies $\hbar\omega_1 = 220$ K and $\hbar\omega_2 = 720$ K are shown in Fig. 3 (the data are normalized to the values at $F = 0$). Figure 3 demonstrates clearly the difference between the field dependences of the recombination with participation of acoustic and high-energy intervalley phonons. The total value of B_T is obtained by adding these compo-

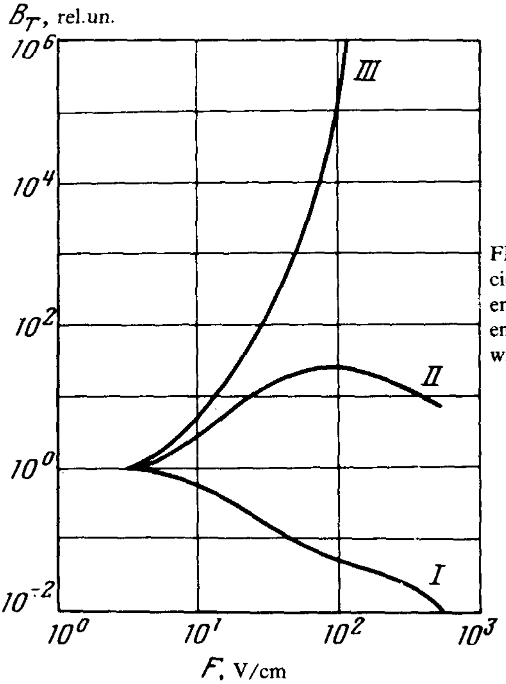

FIG. 3. Dependence of the components of the coefficient B_T on the electric field for recombination with emission of long-wave acoustic phonons (I), with emissions of phonons having $\hbar\omega_1 = 220$ K (II), and with emission of phonons having $\hbar\omega_2 = 720$ K (III).

nents, multiplied by a normalization factor [it was assumed that the ratio of the constants of the interaction of intervalley and acoustic phonons with the electrons are equal to $W_{720\ \mathrm{K}}/W_{ak} = 2$ and $W_{220\ \mathrm{K}}/W_{ak} = 0.2$ (Ref. 11)]. The results are shown in Fig. 2, curve 2. It is seen that the initial decrease of B_T with changing field gives way to an increase due to the advent of intervalley phonons of the acoustic branch with energy $\hbar\omega_1 = 220$ K and by a second rapid increase at 150 V/cm because of the intervalley phonons of the optical branch with $\hbar\omega_2 = 720$ K.

Taking into consideration the approximate character of the employed distribution function, the theoretical curve can be taken to be in fair agreement with the experimental data, thus demonstrating the important role of recombination with participation of intervalley phonons in silicon under conditions of partial freezing-out of the electrons.

[1] V.N. Abakumov, V.I. Perel', and I.N. Yassievich, Fiz. Tekh. Poluprovodn. **12**, 3 (1978) [Sov. Phys. Semicond. **12**, 1 (1978)].

[2] M. Lax, Phys. Rev. **119**, 1502 (1960).

[3] Yu.A. Bykovskiĭ, V.F. Elesin, and V.V. Zuev, Fiz. Tekh. Poluprovodn. **3**, 1713 (1969) [Sov. Phys. Semicond. **3**, 1442 (1970)].

[4] J. von Borzeskowski and J. Scholz, Phys. Status Solidi B **79**, 525 (1977).

[5] M. Asche and O.G. Sarbey, Phys. Status Solidi A **31**, 27 (1975).

[6] M. Asche and O.G. Sarbey, Phys. Status Solidi B, in press.

[7] C. Canali, C. Jakoboni, F. Nava, G. Ottaviani, and A. Alberigi-Quaranta, Phys. Rev. B **12**, 2265 (1975).

[8] V.N. Abakumov and I.N. Yassievich, Zh. Eksp. Teor. Fiz. **71**, 657 (1976) [Sov. Phys. JETP **44**, 345 (1976)].

[9] H. Budd, Phys. Rev. **140**, A2170 (1965).

[10] H.G. Reik and H. Risken, Phys. Rev. **124**, 777 (1961).

[11] M. Asche, B.L. Boichenko, V.M. Bondar, and O.G. Sarbey, Phys. Status Solidi B **44**, 173 (1971).