On a Possible Mechanism for the Increase in the Conductivity of Atomic Semiconductors in a Strong Electric Field

F. G. BASS

(Submitted to JETP editor March 30, 1956)
J. Exptl. Theoret. Phys. (U.S.S.R.) 32, 863-865 (April, 1957)

We investigate the effect of a decrease of the electron recombination rate in a strong electric field on the conductivity of atomic semiconductors.

As IS WELL KNOWN, the conductivity of a semiconductor increases in a strong electric field. Various investigators explain this phenomenon by the increase in the conduction electron concentration due to collision ionization[1], the Stark effect, the tunnel effect[2], *etc.* Davydov and Shmushkevich[3] have indicated the possibility that the conduction electron concentration may be caused by a decrease in the coefficient of recombination which, in turn, is due to a decrease in the probability of electron trapping in impurity centers. In the same work, however, it was noted that this situation can cause effects only in external fields comparable with the internal atomic fields.

In addition, however, the recombination coefficient depends not only on the probability of electron capture by an impurity center, but also on the concentration of electrons about the impurity center and on the diffusion of electrons to the impurity center[4]. The last two factors may be altered by electric fields which are much weaker than the internal atomic ones.

In strong electric fields, when accounting for Coulomb interactions, the electron energy distribution is Maxwellian with a temperature depending on the electric field and differing from the phonon temperature.

The energy distribution function of the electrons, and the temperature Θ of the electron gas are given by the following formulas[5]:

$$f = 2\pi^{-1/2}(k\Theta)^{-3/2}e^{-\varepsilon/k\Theta}\sqrt{\varepsilon},$$
$$\Theta = {}^1/_2 T\left(1+\sqrt{1+(M/3m)(eEl/kT)^2}\right) \qquad (1)$$

Here ε is the electron energy, $M = kT/c^2$ is the effective mass of the phonon, k is Boltzmann's constant, T is the temperature of the phonon gas, m is the electron effective mass, e is the electron charge, l is the mean free path, and c is the velocity of sound. It is seen from Eq. (1) that

$$\Theta = T\left\{1+\frac{1}{12}\left(\frac{eEl}{kT}\right)^2\frac{M}{m}\right\} \quad \text{when } \frac{M}{3m}\left(\frac{eEl}{kT}\right)^2 \ll 1,$$
$$\Theta = \frac{1}{2\sqrt{3}}\sqrt{\frac{M}{m}}\frac{eEl}{kT} \quad \text{when } \frac{M}{3m}\left(\frac{eEl}{kT}\right)^2 \gg 1. \qquad (2)$$

In order to calculate the recombination coefficient, we make use of a formula derived by Pekar[4], namely

$$\beta = \beta_1 e^{-eV(r_0)/k\Theta}\left[1+\frac{\beta_1}{4\pi D}e^{-eV(r_0)/k\Theta}\int_0^{1/r_0} e^{eV(x)/k\Theta}dx\right], \qquad (3)$$

where β_1 is the capture probability, V is the potential of the impurity center, r_0 is a certain effective cutoff radius, and D is the diffusion constant. In this formula, the common temperature T of the electrons and lattice is replaced by the temperature of the electron gas in the presence of an electric field. In order for this replacement to be possible, a stationary state corresponding to the temperature Θ must be established. For this to happen, the electron must have to go over to a stationary state before recombination, which means that the mean free path must be several times less than the distance between impurity centers. This condition is not a new restriction on the calculation we are here making, since it lies at the basis of the derivation of Eq. (3).

In addition, in order that the formula be applicable, it is necessary that drift motion due to the external field E be negligible close to the impurity center compared with diffusion toward the center. This condition is satisfied if the external field E is much less than the field of the impurity center at $r = r_0$. Let $V(r) \approx e/\kappa r$ (where κ is the dielectric constant). In this case the condition that Eq. (3) be applicable reduces to the inequality $E \ll e/\kappa r_0^2$; setting $r_0 \sim 10^{-6}$ cm and $\kappa \sim 5$, we obtain $E \ll 10^6$ cgs electrostatic units. Effects due to the electric field will be observable at $\sqrt{M/m}\, eEl/kT \sim 1$, and with $T \sim 300°$ and $l \sim 10^{-6}$ cm, we have

$$E \sim \sqrt{m/M}\, kT/el \sim 0{,}2 \text{ cgs esu}$$

Thus the present considerations are meaningful in the field interval $0.2 \leq E \ll 10^6$ cgs esu.

If the impurity levels are nowhere near depleted, the electron concentration in the conduction band is given by the equation[1]

$$N = (\bar{\alpha}/2\beta) + \sqrt{(\bar{\alpha}/2\beta)^2 + N'/\beta}. \qquad (4)$$

Here N is the electron concentration in the conduction band, $\bar{\alpha}$ is the mean coefficient of collision ionization, and N' is the number of electrons per unit time which enter the conduction band due to thermal excitation; $\bar{\alpha}$ can be calculated by averaging the cross section for collision ionization with the distribution function of Eq. (1)[1]. Simple calculation leads to the expression

$$\bar{\alpha} = \frac{2\alpha_0 \sqrt{\varepsilon_0/k\Theta}}{\sqrt{\pi}} \int\limits_{\varepsilon_0/k\Theta}^{\infty} \frac{e^{-u}}{u}\, du, \qquad (5)$$

where α_0 is a constant in the formula for the collision ionization cross section, and ε_0 is the separation between the impurity level and the conduction band. If, as is the case for usual fields, $\varepsilon_0/k\Theta \gg 1$, then

$$\bar{\alpha} = 2\alpha_0 \sqrt{k\Theta/\pi\varepsilon_0}\, e^{-\varepsilon_0/k\Theta}. \qquad (5')$$

Let us now assume that electrons enter the conduction band primarily due to collision ionization. In this case N'/β can be ignored in the radical of radical of Eq. (4). Combining Eqs. (3)-(5) we obtain the following expression for the conduction electron concentration:

$$N = \frac{\alpha_0}{\beta_1} \sqrt{\frac{2k\Theta}{\pi\varepsilon_0}}\, e^{-\varepsilon'/k\Theta} (1 + F),$$
$$F = \frac{\beta_1}{4\pi D} e^{-eV(r_0)/k\Theta} \int\limits_0^{1/r_0} e^{eV(x)/k\Theta} dx. \qquad (6)$$

Here $\varepsilon' = \varepsilon_0 + |eV(r_0)|$. If $F \ll 1$, then

$$N = (\alpha_0/\beta_1) \sqrt{2\kappa\Theta/\pi\varepsilon_0}\, e^{-\varepsilon'/k\Theta}. \qquad (6')$$

As the electric field is increased, N first increases as e^{aE^2}, and then as $\sqrt{E}$.

The conductivity σ is defined by the expression

$$\sigma = (4\sqrt{2}\,\alpha_0 e^2 l / 3\pi\beta_1 \sqrt{m\varepsilon_0})\, e^{-\varepsilon'/k\Theta}. \qquad (7)$$

For small fields $\sigma \sim e^{aE^2}$, and for large fields it approaches saturation.

In order to investigate the dependence of N on Θ for $F \gg 1$, the form of V must be given. If V is a Coulomb potential, then N and σ become

$$N = (3\alpha_0 k\Theta\varkappa \sqrt{m} / 4\sqrt{2}\,\pi e^3 l \sqrt{\varepsilon_0})\, e^{-\varepsilon_0/k\Theta}, \qquad (8)$$
$$\sigma = (\varkappa\alpha_0 / 2\pi^{3/2}) \sqrt{k\Theta/\varepsilon_0}\, e^{-\varepsilon_0/k\Theta}. \qquad (9)$$

In this case, the change of recombination in an electric field plays practically no role.

If $N' \gg \bar{\alpha}^2/4\beta$, then for $F \ll 1$ we obtain

$$N = \sqrt{N'/\beta_1} \exp\{-|eV(r_0)|/k\Theta\}, \qquad (10)$$
$$\sigma = (2/3 e^2 l \sqrt{2N'/\pi\beta_1 mk\Theta}) \exp\{-|eV(r_0)|/k\Theta\}. \qquad (11)$$

Here the variation of N and σ with the field is the same as in Eqs. (7)–(9), and the effect is due entirely to the decrease in the recombination rate caused by the electric field.

If $F \gg 1$, on the other hand, $N \sim \Theta^{1/4}$, and $\sigma \sim \Theta^{-1/4}$ and hardly depend on the field.

In conclusion I should like to express my gratitude to M. I. Kaganov for a discussion of the results of the present work.

[1] N. L. Pisarenko, Izv. Akad. Nauk SSSR, Ser. Fiz. **3**, 631 (1938).

[2] F. F. Vol'kenshtein, *Electric Conductivity of Semiconductors*, Gostekhizdat, 1947.

[3] B. I. Davydov, I. M. Shmushkevich, J. Exptl. Theoret. Phys. (U.S.S.R.) **10**, 1042 (1940).

[4] S. I. Pekar, *Investigations in the Electron Theory of Crystals*, GTTI, 1951.

[5] B. I. Davydov, J. Exptl. Theoret. Phys. (U.S.S.R.) **7**, 1069 (1937).

Translated by
E. J. Saletan
184