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ON THE THEORY OF THE SWITCHING EFFECT IN CRYSTALS

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The temperature and compensation dependences of the critical electric field at which the switching effect in some partly compensated crystalline semiconductors occurs is found on the basis of the model in which the screening of ionized donors and delocalization of electrons by an applied electric field play an important role. A rough criterium is found which enables to establish whether the proposed mechanism can occur at a lower electric field than that due to the impact ionization. According to this criterium the proposed model is realistic for crystals with sufficiently low carrier mobilities this, however, was not yet experimentally confirmed.

I. INTRODUCTION

In many smiconductors and dielectrics distinguished by a small electric conductivity at low electric fields the transition to the high conductivity state can be observed at some critical field E_c. We shall not consider here various structures with a hight resistivity basis, where the metioned trasnsition can be due to the injection of the carriers from contacts, nor shall various thermal instabilities leading to the switching effect be considered. These causes can be excluded by a properly chosen experiment. Thus we restrict our considerations only to electronic bulk effects in crystals. Then the transition connected with the rapid increase of the concentration of conduction electrons is usually interpreted as an impurity breakdown caused by the impact ionization of impurities by electrons with a sufficiently high energy gained from the electric field. This impurity breakdown can be observed at temperatures $T < \varepsilon_i/k_B$, where ε_i is the ionization energy of the impurity and k_B is the Boltzmann constant. According to Sclar and Burstein [1], the critical field E_c^i for the impact ionization of shallow donor levels is approximately given by the formula

$$E_c^i \approx \frac{w}{\mu}\left(\frac{2\varepsilon_i}{k_B T}\right)^{1/2}, \tag{1}$$

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where w is the sound velocity and μ is the mobility of electrons from the conduction band. This formula was also used by **Abdulina-Zavarickaja** [2] for the interpretation of the temperature and magnetic field dependences of the critical field E_c^i in germanium at low temperatures, and also by **Oliver** [3], who investigated the electrical properties of GaAs at low temperatures and high electric fields. Although the simple formula (1) can give only the rough estimation of the critical field it can serve us as a guide for the interpretation on the current voltage characteristics of the S-type in some crystalline semiconductors observed first in Ge by **Rediker** and **McWharter** [4] and later also in ohter crystals like GaAs [5], CdS [6], CdSe [7].

The impact ionization alone is not sufficient for the occurrence of the S-type characteristic. The condition must also be fulfilled that the initial rapid increase of the concentration of conduction electrons will continue even if the electrical field is lowered. According to formula (1) this is possible at a constant temperature if with the increasing number of the conduction electrons their mobility increases or the ionization energy decreases or both effects occur simultaneously. **Crandal** [5] has experimentally shown that the increase of the electron concentration at the low temperature impurity breakdown in GaAs is accompanied by an increase of their mobility and has given the theoretical explanation of this effect considering the screening influence of the conduction electrons on various scattering processes.

Now it is evident that the impact ionization together with the screening influence of the conduction electrons can explain the switching effect in some crystals. However, as again we can see from formula (1), the lower the electron mobility is, the higher is the value of the critical electric field at a given temperature and impurity ionization energy. Therefore the question arises, whether another mechanism leading to a rapid increase of the conduction electrons in the bulk of the crystal with low carrier mobilities is not possible, which could occur at a lower critical field than the critical fiield corresponding to the impact ionization. The aim of this paper is to give the theory of the switching effect in crystalline semiconductors with a low value of carrier mobilities based on another mechanism than the impact ionization, i. e. on the screening of impurities by the conduction electrons and the direct release of localized electrons by the applied electric field. We shall consider a semiconductor of the n-type with shallow donor levels, partly compensated at low temperatures, and we shall suppose that the priming carrier concentration is created by the Poole-Frenkel effect. We wish to remark that **Sandomirsky** et al. [8] have shown in a phenomenological way that the decrease of the donor-ionization energy with an increasing concentration of the conduction electrons due to the Poole-Frenkel effect (or injection) can really lead to the S-type current-voltage characteristic. In paper [9] we have pointed out in another way the possibility

of the switching effect in some crystals due to the screening of donors by the conduction electrons and to their ionization by the applied electric field. In this paper we deal with an elaboration of the model proposed in [9] to such a form that it enables to gain the temperature and compensation dependences of the critical field at which the transition from a low to a high conductivity state starts in partly compensated samiconductors with shallow donor levels. We give also a rough criterium which enables to decide whether or not the proposed mechanism in the given crystal is more probable that the impact ionization. We point out briefly the influence of the magnetic field on the value of the critical electric field. Finally we discuss the possibility of the generalization of the model for the case of various donor-like impurities present in the crystal. Although our model has a common idea with that of **Sandomirsky** et al. [8], our approach and the solved problems are quite different from those in the above mentioned paper.

II. THE DEPENDENCE OF THE IONIZATION FIELD ON THE SCREENING PARAMETER

We shall suppose that the potential energy of an electron in the field of the singly charged donor screened by the conduction electrons is of the form

$$V(r) = -\frac{e^2}{4\pi \in r} \exp(-\varkappa r), \tag{2}$$

where $\in$ is the static dielectric constant of the crystal and $\varkappa$ is the screening parameter. The ground-state energy of an electron with potential energy (2) can be approximately expressed (see Appendix) by the relation

$$-\varepsilon/\varepsilon_0 = (1 - \varkappa a_0) \exp(-\varkappa a_0), \tag{3}$$

where $\varepsilon_0 = e^2/8\pi \in a_0$ is the magnitude of the binding energy for $\varkappa = 0$, and $a_0 = 4\pi \in \hbar^2/m^* e^2$ is the radius of the first Bohr orbit in the crystal.

If a uniform electric field E is applied in the z-direction, the potential energy in the z-direction is given by

$$U(z) = -\frac{e^2}{4\pi \in z} \exp(-\varkappa z) - ezE. \tag{4}$$

The maximum of this function is at the point z_0, which can be found from the condition $\mathrm{d}U/\mathrm{d}z = 0$. Denoting $U(z_0) = -W$, and $z_0/a_0 = \zeta_0$, the equations

$$\frac{E}{E_0} = \frac{16 \exp(-\varkappa a_0 \zeta_0)}{\zeta_0^2} (\varkappa a_0 \zeta_0 + 1), \tag{5}$$

with $E_0 = \varepsilon_0/8a_0e$, and

$$-\frac{W}{\varepsilon_0} = \frac{2\exp(-\varkappa a_0\zeta_0)}{\zeta_0}(\varkappa a_0\zeta_0 + 2), \tag{6}$$

hold.

If the electric field is so strong, $E = E_c$, that $-W/\varepsilon_0 = -\varepsilon/\varepsilon_0$, i. e. if

$$\frac{2\exp(-\varkappa a_0\zeta_0)}{\zeta_0}(\varkappa a_0\zeta_0 + 2) = (1 - \varkappa a_0)\exp(-\varkappa a_0), \tag{7}$$

then the electron can no longer be localized accordint to the classical picture in the z-direction, as it is also seen from Fig. 1.

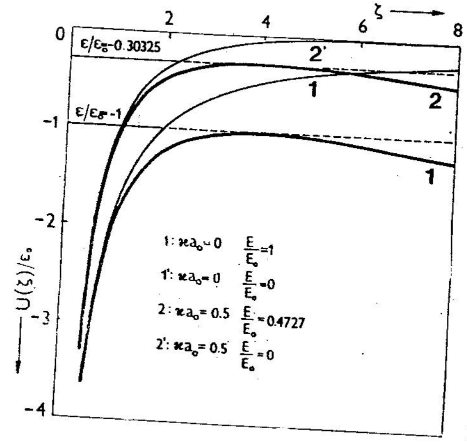

Fig. 1. The effect of the screening and of the app,ied electric field on the potential energy of an electron in the vicinity of the singly charged donor. The horizontal lines correspond to the ground-state energy of localized electron at zero electric field.

The problem of an electron ih the Coulomb field of a positive charge and in the applied uniform electric field was discussed in detail by Dow and Redfield [10] in connection with the ionization of an exciton by the electric field. In our case, due to the screening, the problem is mathematically more complicated especially if we realize that the screening parameter is also field dependent, as we shall see later. Therefore we shall be satisfied with the classical criterium for the ionization field, expressed by Eq. (7). From (7) we can determine ζ_0 for avrious values of $\varkappa a_0$. Substituting ζ_0 together with the corresponding $\varkappa a_0$ into (5) we get the dependence of E_c/E_0 on $\varkappa a_0$. We consider the field E_c determined in this way as the critical field at which all the donors should be ionized and thus the transition to a higher conductivity state occurs. The result of the numerical computations are given in Table 1.

Table 1

$\varkappa a_0$	0.00	0.10	0.15	0.20	0.25	0.30	0.35
E_c/E_0	1.0000	0.9585	0.9146	0.8612	0.8014	0.7376	0.6713
$\varkappa a_0$	0.40	0.42	0.44	0.46	0.48	0.50	0.52
E_c/E_0	0.6045	0.5777	0.5510	0.5248	0.4984	0.4727	0.4473
$\varkappa a_0$	0.54	0.56	0.58	0.60	0.62	0.64	0.66
E_c/E_0	0.4220	0.3972	0.3731	0.3490	0.3256	0.3027	0.2803
$\varkappa a_0$	0.70	.75	0.80	0.85	0.90	0.95	1.00
E_c/E_0	0.2370	0.1884	0.1397	0.0993	0.0588	0.0255	0.0000

III. THE TEMPERATURE AND COMPENSATION DEPENDENCES OF THE CRITICAL FIELD

We shall use the Debye-Hückel expression for the sreening parametr, i. e.

$$\varkappa^2 = \frac{e^2 n}{\epsilon\, k_B T}, \tag{8}$$

where n is the concentration of the conduction electrons, which in a general case depends on temperature and, due to the Poole-Frenkel effect, alto on the electric field strength E. Taking into account the screening of the trapping centres according to (2) with the Debye-Hückel screening parameter (8), Berezin et al. [11] have found for the field dependence of the concentration of the conduction electrons due to the Poole-Frenkel effect an expression which we shall use in the form

$$(na_0^3)^{1/2}\ln\left(\frac{na_0^3}{n_0a_0^3}\right) = \frac{E}{E_0}\left(\frac{b}{4\pi}\right)^{1/2}, \tag{9}$$

where $b = \varepsilon_0/2k_BT$, and n_0 is the concentration of conduction electrons at the zero electric field. In the case of partly compensated semiconductors with N_D donors and N_A acceptors in a unit volume, when for the compensation ratio $K = N_A/N_D$ the inequality

$$K \gg \frac{1}{2N_Da_0^3}(2\pi b)^{-3/2}\exp(-2b), \tag{10}$$

holds, we can use for n_0 the relation (see e. g. [12])

$$n_0a_0^3 = \frac{1-K}{4K}(2\pi b)^{-3/2}\exp(-2b). \tag{11}$$

From (8) it follows

$$na_0^3 = \frac{\varkappa^2a_0^2}{16\pi b}. \tag{12}$$

Substituting (11) and (12) into (9) we get

$$\frac{E_c}{E_0} = \varkappa a_0\{1 + \frac{1}{2b} \ln [\varkappa^2 a_0^2 \frac{K}{2(1 - K)} (2\pi b)^{1/2}]\}. \tag{13}$$

If we substitute into (13) for a given $\varkappa a_0$ the corresponding value of E_c/E_0 according to Tab. 1, we get the dependence of E_c/E_0 on K and b. The plot of E_c/E_0 versus $1/b \sim T$ vor various K is shown in Fig. 2.

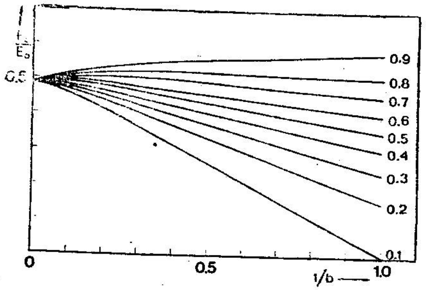

Fig. 2. The computed temperature $1/b \sim T$ depencences of the critical electric field E_c for various compensation ratios K (the numbers on the right-hand side).

According to (13) E_c/E_0 as function of b reaches a maximum

$$\left(\frac{E_c}{E_0}\right)_{\max} = \varkappa a_0\left(1 + \frac{1}{4b_m}\right), \tag{14}$$

where

$$b_m = \frac{2e}{\pi(\varkappa a_0)^4} \frac{(1 - K)^2}{K^2}, \qquad e = 2.7183\ldots.$$

For strongly compensated semiconductors ($K > 0.84$) the critical electric field increases with increasing temperature in the ragne $b > 1$. However, the larger the value of the compensation ratio is, the smaller is the possible change of the electron concentration due to the ionization of donors. Therefore the case where $b_m \gg 1$ is more interesting. Then for temperatures $T > T_m = \varepsilon_0/2k_B b_m$ the critical field decreases with increasing temperatures and this decrease is more rapid the lower the compensation ratio is, (however, we must remember the condition (10) for K). For temperatures $T < T_m$ with decreasing temperature E_c/E_0 decreases to the value $E_c/E_0 = \varkappa a_0 \doteq 0.488$, which corresponds to $T = 0$ independently from K. Therefore for an approximative estimation of the critical field we can use the simple formula

$$E_c \approx \frac{\varepsilon_0}{16 a_0 e} = \frac{\pi \in \varepsilon_0^2}{2e^3}. \tag{15}$$

If we compare this formula with the approximate formula for the critical field in the case of impact ionization given in the introduction, we get the following criterium regarding the mobility of the conduction electrons, which must be fulfilled in order that the proposed mechanism may occur at a lower electric field than the impact ionizations:

$$\mu < \frac{4e^3 w}{\pi \in \varepsilon_0^2} \left(\frac{\varepsilon_0}{2k_B T}\right)^{1/2}. \tag{16}$$

For example with $\varepsilon_0 = 0.16$ eV, $\in = 10 \in_0$, $w = 5 \times 10^3$ ms^{-1}, $T = 77$ °K, this condition gives $\mu < 500$ cm^2/Vs, and with the same values, but with $T = 4.2$ °K, we get $\mu < 2000$ cm^2/Vs.

The compensation is in favour of our model since it causes the lowering of the ionization energy of donors and at the same time reduces the electron mobility at low temperatures when the scattering on the ionized donors is dominant. If we take into account this lowering of the donor ionization energy, then it is necessary to substitute ε_0 in the above relations by

$$\varepsilon_d = \varepsilon_0 - \alpha(N_{D+})^{1/3}; \tag{17}$$

where N_{D+} is the concentration of ionized donors (at very low temperatures and low electric field $N_{D+} = N_A$). Formula (17) has been recently cnofirmed experimentallv by Woodburg and Aven [13] for the II—VI compounds, which perhaps may be suitable for the experimentai verification of formula (13).

The magnetic field can influence the value of E_c given by (45) only through the dependence of the donor ionization energy on the magnetic field B. The plot of $\varepsilon_0(B)/\varepsilon_0$ versus $\hbar\omega_c/2\varepsilon_0$ according to Larsen's [14] results is in Fig. 3, where the dashed line corresponds to the case where only the rise of the bottom

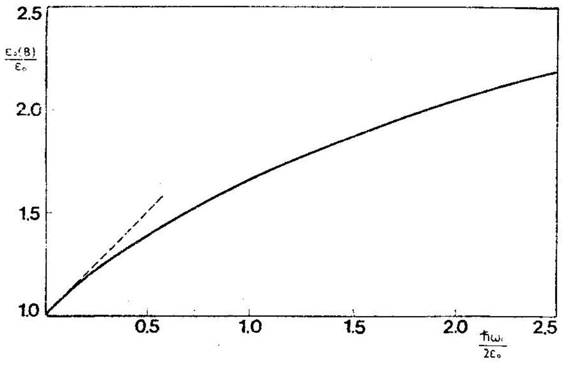

Fig. 3. The magnetic field dependence of the donor ionization energy. $\omega_c = eB/m^*$.

of the conduction band by $\hbar\omega_c/2$ is considered. This gives a good approximation for $\hbar\omega_c/2\varepsilon_0 < 0.2$ (for $\varepsilon_0 = 0.01$ eV, $m^* = 0.1\ m_e$ the linear approximation is good up to $B = 3.6$ T). Therefore in a not too hight magnetic field we can approximate the magnetic field dependence of the critical electric field by the relation

$$E_c(B) = E_c(0)\left(1 + \frac{e\hbar}{2m^*\varepsilon_0}B\right)^2, \tag{18}$$

independently of the orientation of the magnetic field.

The concentration n_c which corresponds to the field E_c is given by the relation (12), if we use again the $\varkappa a_0$ corresponding to E_c/E_0 according to Tab. 1. Since for $\varkappa a_0 = 1$, $E_c = 0$, there holds

$$a_0^3 n_c(0) = \frac{1}{16\pi b}. \tag{19}$$

The electric field causes the decrease of the concentration of the conduction electrons, which is necessary in order that electrons may no more be trapped by ionized donors. There holds

$$n_c(E_c)/n_c(0) = \varkappa^2 a_0^2. \tag{20}$$

From this relation the dependence of $n_c(E_c)/n_c(0)$ on E_c/E_0 follows, which is plotted in Fig. 4.

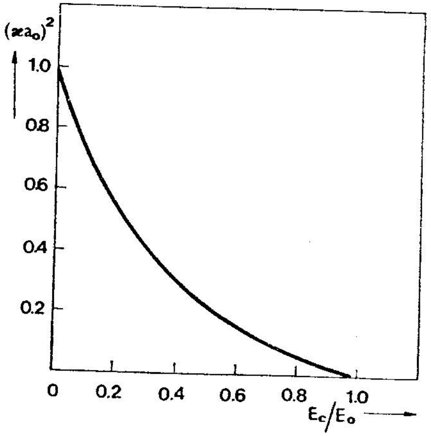

Fig. 4. The dependence of $(\varkappa a_0)^2 = n_c(E_c)/n_c(0)$ on E_c/E_0.

IV. THE SWITCHING EFFECT

Suppose that

$$a_0^3 n_c(E_c) < a_0^3 N_D(1 - K) < \frac{1 - K}{64}. \tag{21}$$

The last inequality, $a_0^3 N_D < 4^{-3}$, is the condition under which the Mott [15] transition at the zero electric field cannot yet occur. When the appllied electric field reaches the value E_c at a given b, the concentration of the conduction electrons will change from the value $n_c(E_c)$ to the value $N_D(1 - K)$ because the already ionized donors will not be able to trap the conduction electrons again. The plots of $a_0^3 n_c(E_c)$ versus 1/b for the various compensation ratios are shown in Fig. 5. The horizontal lines correspond to the particular values

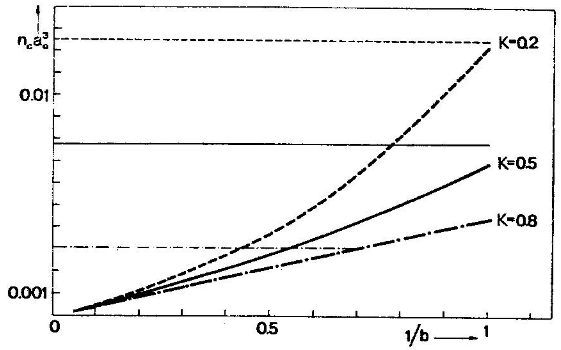

Fig. 5. The plot of $n_c a_0^3$ versus 1/b for various K. The horizontal lines correspond to particular values of $(1 - K)/64$, which is the upper limit for $N_D a_0^3(1 - K)$.

of $(1 - K)/64$. From Fig. 5 it can be seen that the higher the value of $1/b$ is, (i.e. the higher the temperature is) and the larger the compensation ratio is the lower is the possible change of the concentration of the conduction electrons. With the increasing concentration of the conduction electrons their screening effect rises, i. e. the donor level approaches the conduction band and in accordance with Fig. 4 the value of the critical field E_c decreases. Therefore after the switch-on to the state with a higher electron concentration, say n_c', this state can remain until the electric field is lowered below the value $E_c' < E_c$ corresponding to n_c' according to the relation (20). This is the reason why the current-voltage characteristic can be of the S-type.

The proposed model can be generalized for cases of various donor-like impurities. Assume that various donors with ionization enegies $\varepsilon_1 < \varepsilon_2 < \varepsilon_3$, with the corresponding Bohr radii $a_1 > a_2 > a_3$ and with concentrations $N_{D1} < N_{D2} < N_{D3}$ are present in the crystal. For the illustration that such an assumption is reasonable we give in Table 2 the values of the ionization energies of various donors in germanium together with the corresponding Bohr radii and computed as well as experimentally determined values of donor concentrations at which the Mott transition occurs.

Table 2

Host	Donor	ε_0[eV]	a_0[Å]	N_c[cm^{-3}] calcul.	N_c[cm^{-3}] empir.
Ge	Sb	0.0096	46.4	0.9×10^{17}	0.95×10^{17}
	P	0.0120	37.5	1.3×10^{17}	2.5×10^{17}
	As	0.0127	35.2	1.4×10^{17}	3.5×10^{17}

N_c is the concentration of donors at which the Mott transition occurs.

All the values in Tab. 2 are taken from the paper by **Bergren** [16]. In Fig. 6 there are the computed dependences of n_c on E_c at 4.2 °K from various donors in germanium with the use of the values from the Tab. 2, and the mechanis is shown which leads to the increase of the conduction electrons concentration. In our case there corresponds to the lowest ionization energy 0.0096 eV the value of $n_c a_0^3$ equal approximately to 0.0003 and since $a_0 = 4.64 \times 10^{-7}$ cm, the concentration $n_c \doteq 3 \times 10^{15}$ cm^{-3}. To this value of n_c there corresponds according to Fig. 6 $E_c \doteq 2.2 \times 10^3$ V/cm. At this field strength the electron concentration increases from n_c to N_{D1} $(1 - K)$. If this latest value is equal or larger than the concentration n_{c2} which is necessary for all the donors of type 2 to be ionized at the field E_{c1}, then the concentration will continue to increase to the value $N_{D1}(1 - K) + N_{D2}$. If this value is equal or larger than $n_{c3}(E_{c1})$, the electron concentration can reach the value $N_{D1} + N_{D2} + N_{D3} - N_A$. This mechanism can work for an arbitrary number of donor levels. The magnitutde of the critical field E_{c1} is determined by the first partly occupied level below the conduction band and the change of the concentration of the conduction electrons dependes on the total number of the uncompensated donors. This cascade increase of the electron concentration can by responsible for the changes of the electric conductivity of several orders, which is observed in some semiconductors.

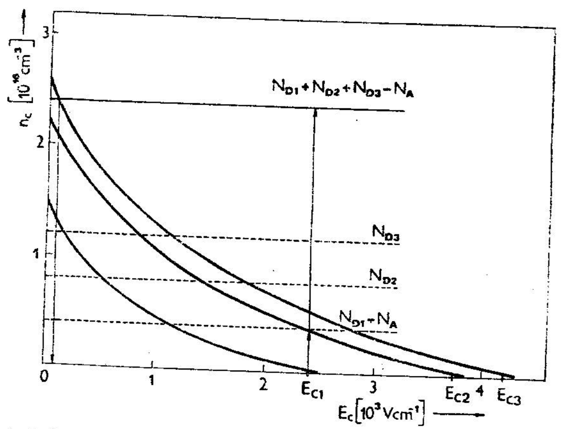

Fig. 6. The computed dependences of n_c on E_c for variozs donors in germanium at 4.2 °K, and the cascade mechanism of the increase of the conduction electrons concentration.

We illustrated our considerations on germanium at 4.2 °K, because we could use the known necessary data and we can compare our conclusions with experiments on the low temperature breakdown which had been done on this material. **Bannaja** et al. [17] investigated the threshold field in rather pure n-germanium with a total concentration of impurities $N_A + N_D - 10^{13}$ cm^{-3} as a function of the compensation ratio at 4.2 °K. In their experiments E_c varied from 3 V/cm at $K = 0.1$ up to 22 V/cm at $K = 0.96$. Such pure material is distinguished by a high electron mobility at 4.2 °K so that the impact ionization can occur at threshold fields in the mentioned range. On the other hand **Zabrodskij** et al. [18] investigated the impurity breakdown on heavily doped and compensated germanium with a total concentration of impurities $\sim 10^{19}$ cm^{-3} and for the threshold field at 4.2°K they have found the value ~ 450 V/cm. This value is already comparable with the value following from our model especially if we take into account the lowering of the ionization energy of shallow levels from which the process can start due to the compensation, as it was mentioned in connection with the relation (17).

V. CONCLUSIONS

The main result of this paper is the relation (13) for the temperature and compensation dependences of the critical electric field at which the transition to a higher conductivity state should occur in a partly compensated crystalline semiconductor with shallow donor levels and low electron mobility at sufficient low temperatures. This formula has been derived for the n-type semiconductor with discrete donor levels separated from the conduction band. On principle the basic ideas of the model are applicable also to the p-type semiconductors, which perhaps may be more suitable for the experimental verification of the model since as a rule the holes have a much lower mobility than the electrons. However, the computation of the acceptor levels is usually not so simple as in the case of donors because the valence bands have more complicated structures than the conduction bands. Hence for the p-type semiconductors probably some modification of formula (13) would be necessary.

Although the results of this paper are not yet experimentally verified the criterium (17) is given which can help in the choice of crystals in which the proposed mechanism of the switching effect should occur at a lower electric field than the impact ionization.

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APPENDIX

The Schrödinger equation for stationary states of an electron with the potential energy (2) is not analytically solvable. Therefore approximating and numerical methods were used [19—22] to find the energy levels of the- bound eigenstates. However, for aur goal we need a formula giving the ground-state energy as a function of the sreeening parameter $\varkappa$. The approximating formula (3) which we have used can be found by the semiclassical method. Starting from the Lagrangian

$$L = \frac{m^*}{2}(\dot{r}^2 + r^2\dot{\varphi}^2) + \frac{e^2}{4\pi \in r}\exp(-\varkappa r) \qquad (A1)$$

and using the quantum condition

$$\oint \frac{\delta L}{\delta \dot{\varphi}} \mathrm{d}\varphi = 2\pi\hbar n, \qquad (A2)$$

we gêt for the ground state energy ($\dot{r} = 0$, $n = 1$)

$$\varepsilon = -\frac{e^2}{8\pi \in r_0}(1 - \varkappa r_0)\exp(-\varkappa r_0), \qquad (A3)$$

where r_0 is determined by the equation

$$a_0 = r_0(1 + \varkappa r_0)\exp(-\varkappa r_0). \qquad (A4)$$

Table A1

$1/\varkappa a_0$	$-\varepsilon/\varepsilon_0(3)$	$-\varepsilon/\varepsilon_0[22]$
∞	1.0000	.0000
100	0.9801	0.9801
50	0.9606	0.9606
20	0.9036	0.9036
10	0.8143	0.8141
7	0.7429	0.7424
5	0.6550	0.6536
4	0.5841	0.5818
3	0.4777	0.4737
2	0.3033	0.2962
1.4	0.1399	0.1351
1	0.0000	0.20057

Using the approximation $r_0 \doteq a_0$ we get from (A3) the relation (3). How good the formula (3) is can be appreciated by comparison of the values computed according to (3) with accurate numerical solutions of the corresponding Schrödinger equation for 1*s* states for various values of $1/\varkappa a_0$ obtained by Rogers et al. [22] (see Table A1).

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