Quasibreakdown in the impurity Hubbard band system of noncompensated silicon

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It was found that in a crystalline silicon the impurity conductivity abruptly increases with electric field E at $E>E_c$, where E_c is a certain threshold value of the field. This increase—"the quasibreakdown" (QB)—was observed only in materials with extremely low compensation: $K<10^{-3}$. The dependence $\sigma(E)$ in the QB region is approximated well by the expression $\ln \sigma \sim (-1/E)$. The weak magnetic field can supress the QB completely. It is suggested that QB is a hopping conductivity through the localized states of the upper Hubbard band tail which is stimulated by an electric field. © *1995 American Institute of Physics.*

1. Lately the conductivity of noncompensated, shallow-impurity doped silicon has recently been studied extensively.[1-4] This conductivity has a number of very interesting features which are connected mainly with the fact that the upper Hubbard band (UHB—the D^- band or A^+ band in the n- and p-type Si, respectively) has a decisive influence on the conductivity.

The present paper briefly describes the main results of an experimental study of noncompensated silicon conductivity σ at liquid-helium temperatures in a strong electric field E. A large number of samples of n- and p-type Si, with impurity concentration $N\approx 10^{16}-10^{17}$ cm^{-3} and compensation $K\approx 10^{-5}10^{-3}$, was tested at temperatures $T=4.2-18$ K.

2. The results of the measurements are shown in Fig. 1, which gives the profiles of $\sigma(E)$ for Si:B samples ($N\sim 6.5\times 10^{16}$ cm^{-3}, $K\simeq 10^{-4}$—curve *1* and $N\sim 3.6\times 10^{16}$ cm^{-3} $K=1.5\times 10^{-4}$—curve *2*) obtained at $T=4.2$ K. As we can see from the following discussion, $\sigma(E)$ can be written as follows:

$$\sigma(E)=\sigma_T(E)+\sigma_E(E). \tag{1}$$

The first term predominates in a weak E and the second term is dominant in a strong E; σ_T depends only slightly on E. In contrast, σ_E increases sharply with E. We call this increase a quasibreakdown (QB). The critical field E_c, at which the QB begins, determined for sample 2 from the condition $\sigma_T(E_c)\approx\sigma_E(E_c)$, is roughly 180 V/cm. In sample *1* the conductivity σ_T at 4.2 K is very small ($\sigma_T<10^{-11}$ S/cm). We did not measure its conductivity. We see from curve *1* that for this sample the critical field is $E_c(4.2\text{ K})\lesssim 170$ V/cm. The conductivity $\sigma_T(E)$ was studied earlier in Refs. 1–3. We will not consider σ_T here. We will stress here a point which is esential for the following discussion: σ changes

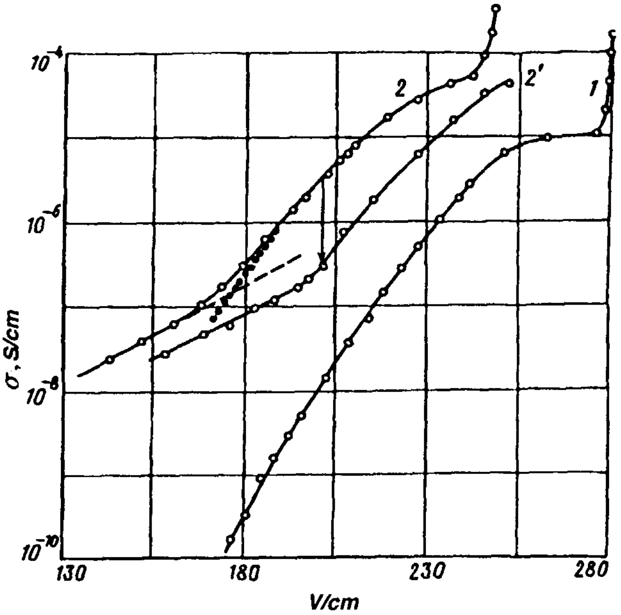

FIG. 1. The dependence $\sigma(E)$ for Si:B at 4.2 K for samples with N and K: *1*—6.5×10^{16} cm^{-3}, $K\approx10^{-4}$; *2(2')*—3.6×10^{16} cm^{-3}, $K\approx1.5\times10^{-4}$. *1* and *2*—$H=0$; *2'*—$H=10$ kOe.

with the magnetic field H only slightly, and this change is isotropic. (Here we always speak about weak fields, $H\leq10$ kOe.) The subject of this paper is the conductivity σ_E which corresponds to the QB.

We will point out the most important results:
—at $E>E_c$ (and also at $E<E_c$) the Hall voltage V_H could not be measured $V_H\approx0$;
—E_c increases with K;
—in a transverse magnetic field QB moves to a stronger E range: E_c increases with H. The curve *2'* in Fig. 1 gives the $\sigma(E)$ in $H=10$ kOe for sample *2*. The vertical arrow in Fig. 1 shows the change of σ for sample *2* at $E\approx200$ V/cm in a magnetic field $H\approx10$ kOe. The conductivity decreases by an order of magnitude: there is a large, positive magnetoresistance (PMR). The longitudinal magnetoresistance in such an H is smaller by several factors.

Thus, the transverse H can suppress the QB completely. Using this property of H, it is possible to separate σ_T and σ_E at $E\approx E_c$, where they are comparable. Figure 1 shows the values of σ_T (the shaded line) and σ_E (the dotted line) which were obtained in this manner.

3. Let us proceed to the discussion of our results. First of all, it is necessary to stress that QB is not an ordinary impurity breakdown when free carriers appear. The fact that $V_H=0$ when QB exists is evidence of their absence (holes in our case). The impurity breakdown (the vertical parts of the curves) arises at $E=E_b=280$ V/cm and 250 V/cm for samples *1* and *2*, respectively. The Hall voltage appears at these E. The field E_c is essentially lower than E_b, and the dependence $\sigma(E)$ in the QB region is much smoother than that at the impurity breakdown. We recall that at $K \ll 1$ E_b is virtually independent of K (Ref. 5). The field E_c increases with K. At $K \approx 10^{-3}$ the field E_c reaches E_b and the electric field region in which QB can be observed vanishes.

This is an important point which explains why QB has not been detected until materials with very small K appeared.

Thus the QB represents a heretofore unknown new phenomenon which is characteristic of crystalline semiconductors with an extremely small compensation.

4. At present, theoretical and experimental studies[3,4,6] show evidence that in noncompensated crystalline semiconductors doped with shallow impurities the UHB tail and the tail of the lower Hubbard band (LHB—the ground-state band) overlap each other. At $T=0$, the Fermi level ε_F lies in the region of the overlapped tails. The density of unoccupied localized states rapidly increases with $\varepsilon - \varepsilon_F$. We assume that the QB detected by us is a variable hop conductivity through the UHB tail states, which is stimulated by an electric field.

The nature of the phenomenon is the following. In a field E the Fermi level ε_F inclines. An electron with energy $\varepsilon < \varepsilon_F$ (in terms of n-type material) can jump from under the Fermi level to an unoccupied state of UHB tail, making an activationless hop. This hop and the subsequent hops along the unoccupied states give rise to an electric current.

Such a mechanism was first proposed by Shklovskiĭ.[7] In his paper he assumed the density of states to be constant. In this case the hops take place in the direct vicinity of the Fermi level. The dependence $\sigma(E)$ has the form $\ln \sigma \sim (-E^{-1/4})$.

In our previous study[8] the theory of this phenomenon was developed for the case in which the density of unoccupied states increases rapidly with ε.

The main results are as follows:
—if E is strong enough, hops against the field predominate. The situation becomes one-dimensional;
—there is a certain level $\varepsilon_E(E)$—the "transport level," along which an electron with energy ε_E hops, maintaining its average energy constant. Because of this circumstance, the electrons accumulate near the ε_E level. On the other hand, the level ε_E lies essentially higher than ε_F. The density of states near ε_E is much greater and therefore the mean hop length is considerably shorter than that near ε_F. That is why the conductivity in strong E is completely determined by hops along the ε_E level. Thus, the stimulated conductivity can be considered as a multistep electric breakdown in the system of impurity Hubbard bands of a crystal.

In order to obtain analytical expressions, the one-dimensional density of unoccupied states in Ref. 8 is used in the form

$$g(\varepsilon) = g_F \exp((\varepsilon - \varepsilon_F)/\varepsilon_0), \tag{2}$$

where g_F is the density of states at the Fermi level, and ε_0 is a constant. The strong field condition is

$$\alpha(E) \equiv eE/g_F \varepsilon_0^2 \gg 1. \tag{3}$$

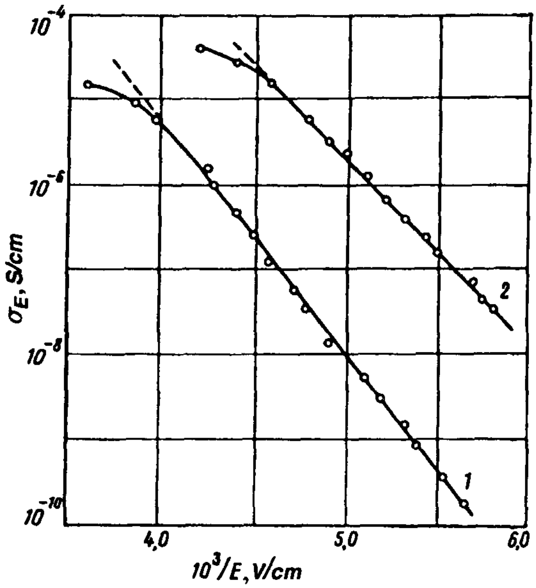

FIG. 2. The σ_E curves for samples *1* and 2 in Fig. 1 are redrawn as 2 function of $1/E$.

For ε_E and the typical hop length x_E the expressions obtained are

$$\varepsilon_E=\varepsilon_F+\varepsilon_0 \ln \alpha, \quad x_E=(\varepsilon_0/eE)\ln 2, \tag{4}$$

and for $\sigma(E)$

$$\ln \sigma=-\beta(2\varepsilon_0/eEa). \tag{5}$$

Here a is the radius of the localized state, and $\beta=\beta(E)\simeq 1$ is the function which weakly (logarithmically) depends on E.

The origin of the dependence (5) is obvious. If E increases, the level ε_E moves up to a region with a higher $g(\varepsilon)$. The typical hop length x_E decreases in accordance with the second equation in (4), and the hopping probability $\nu[\nu\sim\exp(-2x_E/a)]$ increases according to the law: $\ln \nu \sim -1/E$.

In Fig. 2 the σ_E curves for samples *1* and *2* from Fig. 1 are drawn as functions of $1/E$. We see that with a great degree of accuracy the function $f(1/E)\equiv\ln \sigma_E$ can be considered linear when σ_E changes by five orders of magnitude (sample *1*) and by three orders of magnitude (sample *2*), respectively. This result is a convincing argument in favor of the model developed in Ref. 8.

It may seem strange that the dependence $\ln\sigma_E \sim -1/E$ holds throughout a very large interval of σ_E. Indeed, a special form, (2), of the density of states was used to obtain this dependence. It can be shown however, that for this dependence to exist the expression (2) must not be true in the whole interval $\varepsilon_F<\varepsilon<\varepsilon_E$, but only in the region $\Delta\varepsilon$ in which the level ε_E lies at the given values of the electric field. In our case $\Delta\varepsilon \lesssim \varepsilon_0$, while $\varepsilon_E-\varepsilon_F$ is equal to several ε_0.

At very strong E the dependence $\sigma(E)$becomes weaker. This behavior is apparently connected with the fact that ε_E is already in the region in which the dependence $g(\varepsilon)$ is smoother.

From the slope of the curves in Fig. 2 we evaluate ε_0, assuming $\beta = 1$ and $a = 10^{-6}$ cm (a is the radius of the A^+ state in Si:B). For samples *1* and 2 we find it equal to ~4 meV and ~3 meV, respectively. The order of the values is the same as that of the characteristic energy scale of the impurity band in the limit $K \to 0$ (for example, ε_3, the activation energy of the hopping conductivity through LHB, is on the order of several meV).

The field E_c is defined by the condition $\alpha(E_c) = 1$. At $\alpha \ll 1$, the level ε_E lies near ε_F: $\varepsilon_E - \varepsilon_F \ll \varepsilon_0$. At $\alpha \gg 1$, the level ε_E " comes off" ε_F and goes upward to the region in which the density of states is large. (The values of E_c, which are obtained from the experimental curves *1* (shown above) in section two, are obviously slightly overestimated.) Assuming $E_c \simeq 150$ V/cm and $\varepsilon_0 \simeq 4$ meV, we find from the condition $\alpha(E) = 1$ that $g_F \simeq 10^4$ meV^{-1}·cm^{-1}.

On the other hand, the density of states (three dimensional) at the level ε_F in the LHB is on the order of N_c/ε_3, where $N_c = KN$ is the concentration of the compensating impurity.[9] The corresponding one-dimensional density of states $N_c^{1/3}/\varepsilon_3$ is an order of magnitude greater than g_F.

Thus the values ε_0 and g_F obtained from the analysis of experimental data seem reasonable.

Let us discuss now the effect of H on QB. In terms of the results of Ref. 9, the fields $H \leqslant 10$ kOe are weak for Si. In weak H an additional term, $\Delta\xi$, appears in the exponent of the hopping conductivity. Within an accuracy of a factor close to 1 we have

$$\Delta\xi = \frac{r^3 d}{12\lambda^4} \overline{\sin^2 \theta} \,. \tag{6}$$

Here r is the typical hop length, $\lambda^2 = \hbar c/eH$ is the magnetic length, and θ is the angle between **H** and the hop direction. The bar over the term means averaging over the direction of the hops.

At small values of E the directions of the hops are isotropic: $\overline{\sin^2\theta} = 1/3$. Here $\Delta\xi$ does not depend on the angle between **H** and **E**. The small anisotropy of MR arises only because of the pre-exponential factor. Substituting $r \approx N^{-1/3}$, we find $\Delta\xi \ll 1$ at $H = 10$ kOe: MR is negligible.

In our case at 10 kOe the transverses MR is large: σ decreases by an order of magnitude. The longitudinal MR is lower by several factors. This is evidence of the directional nature of the hopping activity. The condition of the QB at **H**⊥**E** therefore implies $\Theta = \pi/2$ and $r \approx x_E$. At $E = 200$ V/cm and $\varepsilon_0 \approx 3$ meV the length $x_E \approx 10\ N^{-1/3}$. Then $\Delta\xi \approx 3$ and $\sigma(H)/\sigma(0) \approx 10^{-1}$, which agrees with the experiment. In these fields the dependence $\ln(\sigma(H)/\sigma(0)) \sim -H^2$ is observed, as it should be.

Thus, the model of the variable hopping length conductivity through the D^- band tail states, which is stimulated by the electric field, explains the main pecularities of the QB fairly well.

We assume that the $E_c(K)$ dependence is connected with a decrease in the probability that an electron can reach the ε_E level upon an increase in the concentration of the recombination centers.

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