Negative differential resistance in the hopping-conductivity region in silicon

D. I. Aladashvili, Z. A. Adamiya, K. G. Lavdovskiĭ, E. I. Levin, and B. I. Shklovskiĭ
Tbilisi State University

(Submitted 9 March 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **47**, No. 8, 390–392 (25 April 1988)

A negative differential resistance has been observed in the hopping-conductivity region in slightly compensated *p*-Si. The basic features of this effect agree with the model of a capture of electrons at the "dead ends" of an infinite cluster of acceptors which is responsible for a hopping ohmic transport.

An exponential decrease in the hopping conductivity with increasing electric field E was predicted in Ref. 1. This effect should result in a negative differential resistance. The case studied in Ref. 1 was that in which a given small number of electrons are moving by the hopping mechanism among randomly arranged neutral impurities, whose energy spread does not greatly exceed the temperature T. A situation of this sort arises in the saturation region of hopping conductivity, e.g., in very slightly compensated *p*-type silicon, which is the material we have studied. We know that the electrons in this material in the region of the so-called ϵ_3 conductivity, and at sufficiently low temperatures T, are for the most part localized at those rarely encountered acceptors which are very close to ionized donors. The density (n) of electrons which are activated to typical acceptors and which implement the hopping transport among them is exponentially small. As the temperature is raised, however, nearly all of the electrons detach from donors, and the dependence $n(T)$ weakens; i.e., a saturation region of the hopping conductivity arises.[2] In this region, the ideas of Ref. 1 are applicable, but the equations derived in Ref. 1 refer to fields which are so strong that impurity breakdown occurs in the samples which we studied. Below we examine the origin of the negative differential resistance in more moderate fields.

A hopping ohmic transport is known[2] to be determined by an infinite cluster of acceptors separated by distances which do not exceed $r_c + a/2$, where $r_c = 0.87R$ is the percolation radius, $R = N_A^{-1/3}$ is the density of acceptors, and a is the localization length of an acceptor. The correlation length of the infinite cluster (the typical period of its network) is

$$L_0 = {}^1/_3\,(2r_c/a)^{\nu} R, \qquad (1)$$

where $\nu = 0.88$ is a critical index. The longest of the dead ends of the infinite cluster, which are not exponentially rare (see 1 and 2 in Fig. 1), are of the same length. Under the condition $eEL_0 \ll kT$, Ohm's law holds, since an electron at a dead end can freely leave it. In the case $eEL_0 \gg kT$, the probability for moving away to the left from a dead end of type 1 is smaller by a factor of $\exp(eEL_0/kT)$ than the probability for an arrival. Let us assume that an escape to the right from a dead end of this sort can occur only as a result of a hop with a length greater than r_c by an amount $\Delta r \gg a$. A

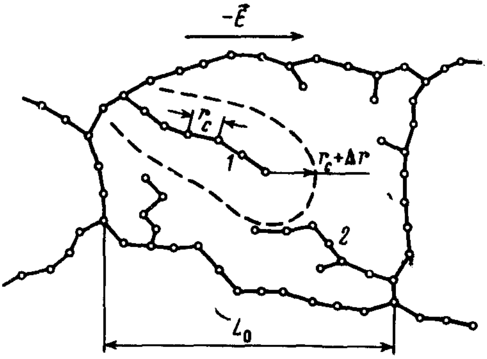

FIG. 1. Fragment of an infinite cluster responsible for a hopping conductivity. The dashed line is the boundary of the region which produces the "insulation" around dead end 1.

dead end of this sort is thus a trap for an electron. After leaving one trap, the electron reaches another, etc. Under the condition $eEL_0 \gg kT$, a large fraction of the electrons—a fraction which increases with the field—is at traps at all times. The conductivity thus falls off with increasing field. To calculate the conductivity, we need to calculate the probability $W(x)$ for the appearance of a trap which has a length x along the field and which has some "insulation" Δr of such a magnitude that the times for escape to the right and to the left are identical; i.e., $2\Delta r/a = eEx/kT$. It is easy to show that we have $w(x) = \exp[-(x/L_0)\times(eEx/2kT)^{\nu}]$. The contribution from traps of length x to the average electron retardation time $\bar{\tau}$,

$$\tau(x) = \tau_0 W(x) \exp(eEx/kT), \tag{2}$$

has a sharp extremum in x. Calculating (2) at the point of the maximum, $x = x_m$, and using $\sigma(E) \propto \bar{\tau}^{-1}$, we find

$$\sigma(E) = \sigma(0)\exp[-(\beta eEL_0/kT)^{1/\nu}) \approx \sigma(0)\exp[-eEL_0/2kT]. \tag{3}$$

(The latter expression can be found by using the approximation $\nu = 1$.) Expression (3) obviously leads to a negative differential resistance at $E > 2kT/eL_0$. This expression is valid only at a sufficiently small degree of compensation $K = N_D/N_A$, and in fields E which are not very strong, so that the traps which are important to expression (3) are not clogged with electrons. Expression (3) furthermore holds only in the saturation region of the hopping conductivity, since as the temperature is lowered, and the states at the acceptors close to donors fix the Fermi level to themselves, the number of electrons at the skeleton of the infinite cluster (this number determines the conductivity) becomes independent of E. In addition, the field extracts from the Fermi level a number of electrons exactly equal to the number caught at traps.

We turn now to the experimental data. We have observed a decrease in the cunductivity σ with increasing E in weakly compensated samples of n- and p-type silicon doped with Sb, P, and B at a major-dopant concentration $(5\text{–}15)\times 10^{16}$ cm^{-3} and also in a Si⟨Ga⟩ sample with $N_A = 4\times 10^{17}$ cm^{-3}. The initial part of the $\sigma(E)$ curve, where a decrease in $\sigma(E)$ by as much as a factor of two was observed, is described fairly well by expression (3) with a length $L_0 \approx 7\ R$. Estimate (1) yields the same,

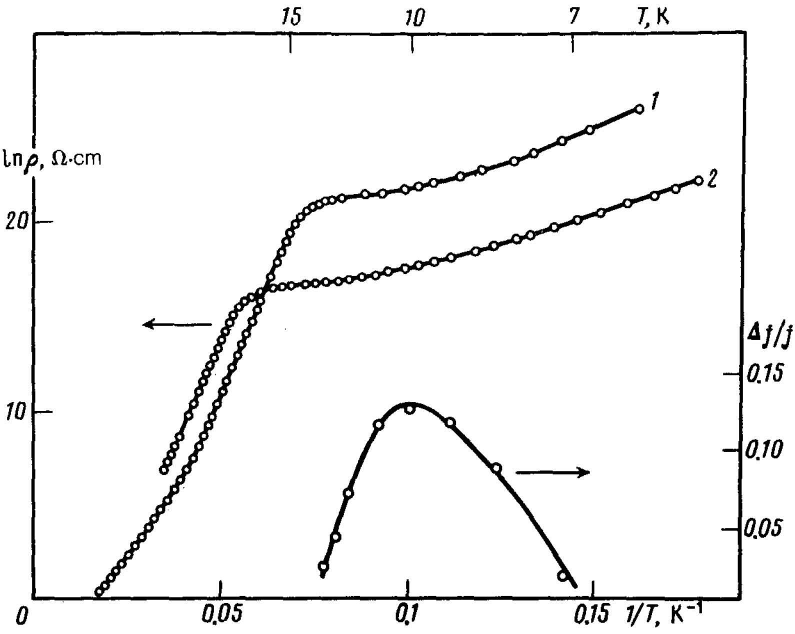

FIG. 2. Resistivity of samples 1 and 2 (scale on the left) and relative amplitude of the current oscillations near the threshold in sample 1 (scale on the right), versus the reciprocal temperature.

value. With a further increase in E, to the point of impurity breakdown, σ varies only slightly. This result may be due to a clogging of dead ends. A slight decrease (up to 30%) in σ has been observed previously[3] in weakly compensated Ge. Current saturation in Si⟨Ga⟩ with $N_A < 4\times 10^{17}$ cm^{-3} was reported in Ref. 4.

In two Si⟨B⟩ samples ($N_{A1} = 5.9\times 10^{16}$ cm^{-3}; $K_1 = 4\times 10^{-5}$; $N_{A2} = 5.5\times 10^{16}$ cm^{-3}; $K_2 = 5\times 10^{-3}$) we observed not only a decrease in σ with increasing E but also a negative differential resistance. Figure 2 shows the temperature dependence of the resistivity of these samples. Hopping conductivity occurs at $T < 13$ K in sample 1 and at $T < 17$ K in sample 2. Figure 3 shows the current density j measured as a function of E at $T = 10$ K during a slow increase in E over time for sample 1, in which the negative differential resistance was most prominent. At $E < 39$ V/cm, the dependence $j(E)$ agrees approximately with expression (3). In strong fields, we observe oscillations in the current, which imply the onset of an instability associated with the N-shaped local current-voltage characteristic of the sample. The oscillations fade away as the temperature is raised, as the hopping conductivity gives way to a band conductivity, and also as the temperature is lowered, and we leave the saturation region. These results agree with the arguments presented above. Figure 2 shows the oscillation amplitude near the threshold field, $\Delta j/j$, as a function of E. The threshold field for the onset of the oscillations is essentially independent of the temperature.

The amplitude of the oscillations was far lower in sample 2 than in sample 1. This result can be explained in a natural way on the basis that the former sample was

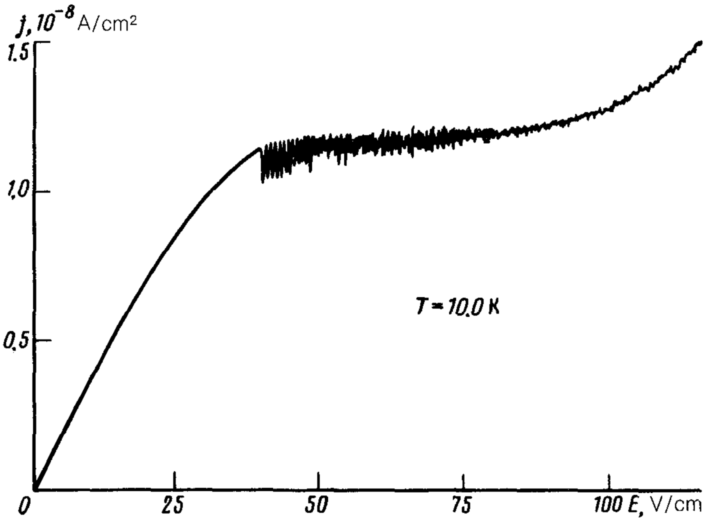

FIG. 3. Behavior of the current density as E is increased slowly over time for sample 1 (the total duration of the sweep is 10 min).

compensated to a significantly greater extent, so that the traps should have been clogged with electrons, as mentioned above.

We wish to thank E. M. Gershenzon, L. B. Litvak-Gorskaya, and A. P. Mel'nikov for furnishing sample 1. We also thank M. I. D'yakonov, M. S. Kagan, Z. S. Kachlishvili, Sh. M. Kogan, M. E. Levinshteĭn, G. E. Pikus, and A. S. Furman for useful discussions.

[1] Nguyen Van Lien and B. I. Shklovskiĭ, Solid State Commun. **38**, 99 (1981).
[2] B. I. Shklovskiĭ and A. L. Efros, Electronic Properties of Doped Semiconductors, Nauka, Moscow, 1979.
[3] A. G. Zabrodskiĭ and I. S. Shlimak, Fiz. Tekh. Poluprovodn. **11**, 736 (1977) [Sov. Phys. Semicond. **11**, 430 (1977)].
[4] R. Baron and M. H. Young, Solid State Electron. **28**, 204 (1985).

Translated by Dave Parsons