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MECHANISM OF LOW-TEMPERATURE IMPURITY BREAKDOWN IN COMPENSATED SEMICONDUCTORS AND OF SWITCHING IN AMORPHOUS SEMICONDUCTORS

A. G. Zabrodskii, S. M. Ryvkin, and I. S. Shlimak
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The mechanism of switching in amorphous semiconductors has not been uniquely identified to this day. On the other hand, a switching effect was in fact observed also in crystalline semiconductors. As is well known, low-temperature breakdown in doped and compensated semiconductors has an S-shaped current-voltage characteristic[1)]. The explanation of this effect is based on the fact that the breakdown is due to impact ionization of shallow impurities [1], and that after the start of the breakdown the electrons become redistributed in an even shallower level, ionization from which is more probable, as a result of which the voltage needed to maintain the breakdown is smaller than the ignition voltage E_{ig}. It was proposed, in particular, that the excited state of the shallow impurity center can be regarded as this level.

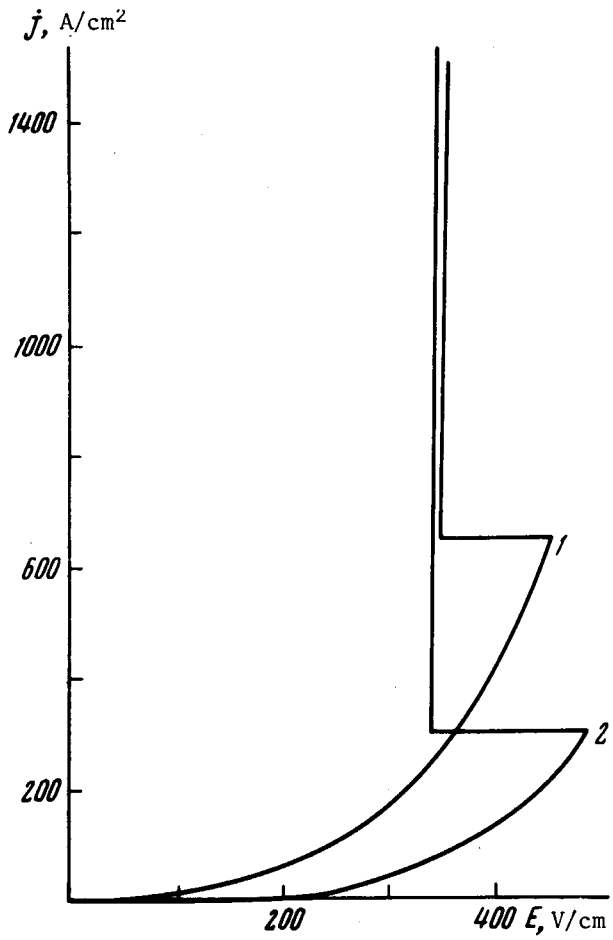

Fig. 1. Current-voltage characteristics of one of the SDC germanium samples: 1) 4.2°K, 2) 2.2°K.

It will be shown below that there is an analogy between these switching phenomena in crystalline and amorphous semiconductors. The experiments were performed by us on samples of strongly doped and compensated (SDC) germanium. In addition to being of independent interest (switching in SDC semiconductors has not been investigated before), the mechanism of switching in these samples is expected to be common also to a number of amorphous structure, owing to the similarity between the spectra of the electronic states in these systems [3].

At first glance, the mechanism of impact recombination in SDC and in amorphous semiconductors should call for too strong fields, owing to the great depth of the Fermi level. Thus, estimates [4] show that for a level of depth 0.1 - 0.2 eV the field should be of the order of 10^5 - 10^6 V/cm. In weakly doped crystalline semiconductors, however, when the shallow impurities are fully compensated by deep ones and no impact ionization is observed, it is still possible to effect this ionization by filling the shallow impurity centers (e.g., by illumination). This effect has first been described in [5] and is known as induced impurity breakdown. We shall show that an analogous phenomenon can take place in SDC and amorphous semiconductors. Indeed, at low carrier temperatures the carriers are localized in these semiconductors in the deepest wells of the potential relief, and charge

transport is with the aid of tunnel hopping of the carriers from one well to another; the states over which the hops take place lie in a narrow energy band Δ near the Fermi level. Wells of lower depth, which form a statistically continuous energy spectrum of states above the Fermi level, remain empty in a weak electric field. In a sufficiently strong field, however, when the electron potential-energy drop over the length of the hop eER begins to exceed Δ, these states begin to be filled effectively, and when a certain carrier density n_0 is reached at relatively shallow levels the development of impact ionization from these levels becomes possible. This process is analogous to induced impurity breakdown, the only difference being that the upper levels are filled not by light but by the electric field itself. The proposed model should give rise to certain characteristic features of the switching. Thus, at low temperatures E_{ig} should depend little on the temperature. The switching delay time τ_d is determined then by the time τ_0 needed to reach the density n_0, and should therefore exceed appreciably the characteristic hopping time τ_h.

Experiments performed on a group of SDC Ge samples with total impurity concentration $\sim 10^{19}$ cm^{-3} and with different degrees of compensation have confirmed these assumptions. The values of E_{ig} for all the investigated samples in the interval 1.4 - 4.2°K decreased little with increasing temperature (Fig. 1). Measurements with pulses have made it possible to determine τ_0 as the minimum time during which E_{ig} does not differ from its dc value E^0_{ig} (Fig. 2). For samples with different degrees of compensation, the variation of τ_0 correlated with the variation of τ_h, so that the ratio τ_0/τ_h for all samples was of the order of 10. At $\tau < \tau_0$, there is no time for a concentration n to "accumulate" on the shallow levels within the time of the pulse, so that the breakdown can be produced only at a higher voltage $E_{ig} > E^0_{ig}$. Since the potential-energy drop over the length of the hop increases linearly with the field, one should expect the increase of E_{ig} at small deviations from E^0_{ig} to be proportional to the decrease of τ_d, i.e., $E_{ig} \sim 1/\tau_d$. For the same reason, E^0_{ig} should increase linearly with increasing depth of the Fermi level. It is seen from Figs. 2 and 3 that these relations are well confirmed by experiment.

Thus, impact ionization proceeds from a group of relatively shallow levels. Within this group, however, one can distinguish shallow states for which the probability of impact ionization is largest. The number of such states is statistically maximal, so that the "freezing out" of the free carriers after the start of the breakdown occurs predominantly for these states. If the carrier lifetime with respect to their further relaxation to deeper states exceeds the time needed for impact ionization to develop, then the ionization can proceed subsequently even from the shallowest levels, thereby making the conditions more favorable for maintenance of the breakdown, and ensuring that the current-voltage

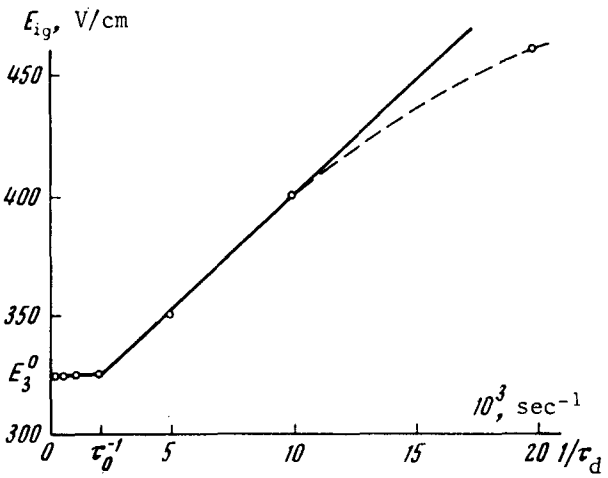

Fig. 2. Dependence of E_{ig} on τ_d for one of the samples.

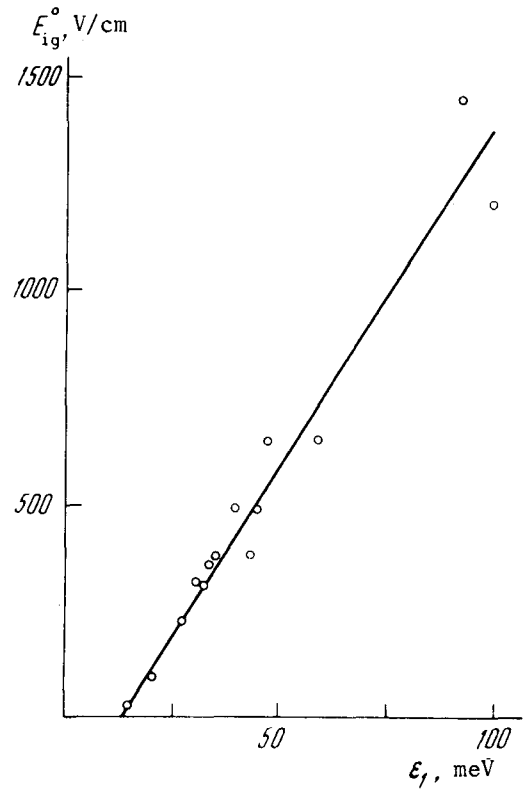

Fig. 3. Plot of E^0_{ig} against the depth of the Fermi level at T = 1.4°K.

characteristics become S-shaped, i.e., the switching effect. With increasing temperature, when the carrier relaxation from the shallower to the deeper wells is accelerated because of transitions over the barrier, the S-shape should become straighter. Temperature investigations have shown that in SDC Ge samples the S-shapes begin to straighten out at $T > 5°K$, and there is no S-shape at all at $T = 25°K$. This makes it possible to estimate the effective depth of the shallowest states, the overfilling of which is responsible for the switching, at several millielectron volts.

In weakly doped semiconductors, the presence of a compensating impurity raises the levels of certain ions of the main impurity considerably above the neutral-atom levels. After the breakdown, the electrons "freeze out" from the conduction band. This phenomenon can be particularly noticeable in the presence of correlation in the placements of the main and compensating impurity ions, when the energy of the Coulomb interaction of the impurities is much higher than at the average distance.

[1)] Breakdown with an S-shaped characteristic will henceforth be called "switching," for in this case two different values of the current can correspond to one value of the voltage.

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CONCERNING SUPERCONDUCTIVITY IN THE SODIUM-AMMONIA SYSTEM

I. M. Dmitrenko and I. S. Shchetkin

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The resistivity of sodium-ammonia solutions with concentrations 1 - 12 at.% Na was investigated in the temperature interval 20 - 240°K. The results suggest that this system may be superconducting.

The possibility that a sodium-ammonia system may be superconducting has been frequently suggested [1, 2] because anomalously low resistivities have been observed in it [2 - 5], and from this point of view this is one of the most promising systems. However, owing to the lack of experimental facts, the question of superconductivity in sodium-ammonia solutions remains open.

We present here the results of an investigation of the resistivity of sodium-ammonia solutions with concentrations 1 - 12 at.% Na in the temperature intervals 20 - 80, 78 - 240, and 20 - 240°K. We measured about 300 samples with different geometries; the samples were either frozen in capillaries or frozen between cover glasses.

The temperature dependence of the resistance at 3.2% sodium concentration is shown in Fig. 1. Similar curves were obtained also for other compositions[1)].

In the 20 - 80°K range, the resistance increases very slowly with temperature. Near the nitrogen point, a sharp increase of the resistance is observed (by approximately two orders of magnitude) followed by a flattening into a plateau. With further temperature rise, the samples go over into the dielectric phase, which spans the interval 120 - 160°K (II). A new transition to the conducting state occurs above 160°K (III). The resistance maximum at 195°K is connected with the transition of the sample to the liquid phase.

We note that in temperature regions I and III the temperature dependence of the resistance is described by a single function