Transport phenomena in germanium bicrystals in the region of nonmetallic conductivity

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The electrical conductivity $\sigma_\square$ of germanium bicrystals with angle of inclination $7 \leqslant \theta \leqslant 25°$ in the temperature range $0.3 \leqslant T \leqslant 5$ K is studied. It is established that as T increases, the logarithmic drop in the electrical conductivity is replaced by a sharp exponential dependence at $\sigma_\square = \sigma_{\min}$. For lower values of $\sigma_\square$, $\sigma(T) = \sigma_0 \exp[-(T_0/T)^{1/2}]$, where T_0 is a characteristic temperature equal to 10–750 K.

As is well known, conducting layers with hole-like, isotropic, metallic conductivity appear at the joining surfaces of germanium bicrystals with angles of inclination $\theta = 20$–$25°$.[1] As the angle of inclination θ is reduced, the electrical conductivity of the surface layers in Ge bicrystals decreases and becomes increasingly more isotropic, and at a conductivity of

$$\sigma_\square \approx \sigma_{\min} \approx \frac{e^2}{2\pi\hbar} \simeq 4 \times 10^{-5}\ \Omega^{-1}, \tag{1}$$

where e is the electron charge, and $\hbar$ is Planck's constant), the two-dimensional metallic conductivity is replaced by a thermal activation conductivity, $\sigma_\square \sim \exp(-W_a/kT)$, where W_a is the activation energy.[2]

The two-dimensional metal–insulator transition discovered[2] in Ge bicrystals was studied in the temperature range $1.6 \leqslant T \leqslant 6$ K. The region in which the two-dimensional semi-metallic conductivity has been investigated was recently[3] extended to a temperature $T = 0.02$ K. In this letter we are studying the electrical conductivity of Ge bicrystals at $T < 1.5$ K in the region of nonmetallic conductivity.

The investigations were performed on bicrystals with an angle of inclination θ varying from 7 to 25°. The samples were cut out of ingots in such a way that current

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could flow either parallel or perpendicular to the rows of edge atoms which appear due to the sectioning of the atomic planes by the joining surface of the bicrystal.[4] The samples had the form of a parallelepiped with dimensions $\sim 2\times 2\times 7$ mm and with a conducting surface area of $\sim 2\times 7$ mm. The ohmic contacts for the surface hole layers were prepared by fusing-in indium. Since the resistance of the Ge crystal was very high, the current flowed only along the layer adjacent to the joining surface of the Ge bicrystals. The electrical conductivity was studied in the region where the current depended linearly on the applied voltage.

In the course of the experiment, we measured the conductivities $\sigma_{\parallel}$ and $\sigma_{\perp}$, as well as the Hall coefficient R_H at $T=4.2$ K. The value of $\sigma_{\perp}$ was measured for samples in which the chains of edge atoms extended from one current contact to the other; the value of $\sigma_{\parallel}$ was measured for samples in which the rows of edge atoms were oriented perpendicular to the line connecting the current contacts. The results of the measurements of $\sigma_{\parallel}$ and $\sigma_{\perp}$ at $T=4.2$ K are shown in Fig. 1 as the dependence $\eta=\sigma_{\perp}/\sigma_{\parallel}=f(\sigma_{\perp})$. It is evident from these data that for high values of the electrical conductivity, $\sigma_{\square}>1\times 10^{-4}\,\Omega^{-1}$, the conductivity of the bicrystals is isotropic, and for small values the electrical conductivity measured across the rows of edge atoms is an order of magnitude lower than that measured along them. This process apparently reflects the tendency for a transition to occur to conditions of quasi-one-dimensional conductivity in Ge bicrystals at small values of the angle of inclination θ.

In samples with anisotropic conductivity the Hall's coefficient remains essentially constant, $R_H=(1.6\pm 0.1)\times 10^{6}$ cm^2/C, and does not depend on the condition under which the current flows along or across the rows of edge atoms.

In the region of high isotropic conductivity, the quantity R_H decreases with increasing σ, which is typical for metallic conductivity. Under these conditions the

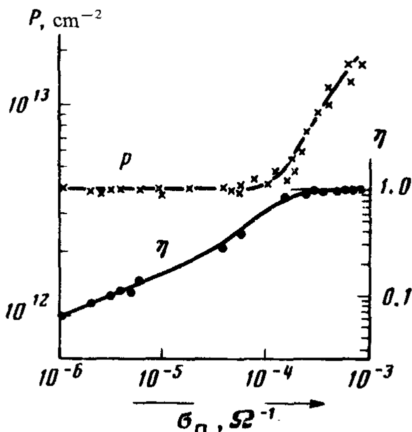

FIG. 1. ● — Dependence of the coefficient $\eta=\sigma_{\perp}/\sigma_{\parallel}$ on the conductivity $\sigma_{\perp}$; $\times$ — dependence of the hole density on the conductivities $\sigma_{\parallel}$ and $\sigma_{\perp}$.

relation

$$p = \frac{1}{R_H e} \ . \qquad (2)$$

can be used to calculate the hole density. The results of the calculation of $p = f(\sigma)$ at $T = 4.2$ K are shown in Fig. 1, together with the dependence $\eta(\sigma)$. [At low electrical conductivities, relation (2) is correct only in order of magnitude.]

In the region of interest to us $\sigma_\square < \sigma_{\min}$, the conductivity seems to occur in hops from one localized state to another, and the probability of such hops is proportional to

$$\exp\left(-\frac{R}{R_0}\right)\exp\left(-\frac{W_a}{kT}\right), \qquad (3)$$

where R_0 is the localization length, and R is the length of a hop.

The magnitude of the activation energy in Ge bicrystals is determined by several factors. The most important factor could be the Coulomb interaction,[5] whose "precursor" is the logarithmic increase of the Hall coefficient,[6] $R_H \sim \ln T$, observed in Ge bicrystals on the metallic side of the insulator–metal transition.[3]

Under conditions when the Coulomb interaction is large, the magnitude of the activation energy is $W_a = e^2/\kappa R$,[7] where κ is the dielectric constant, and optimization

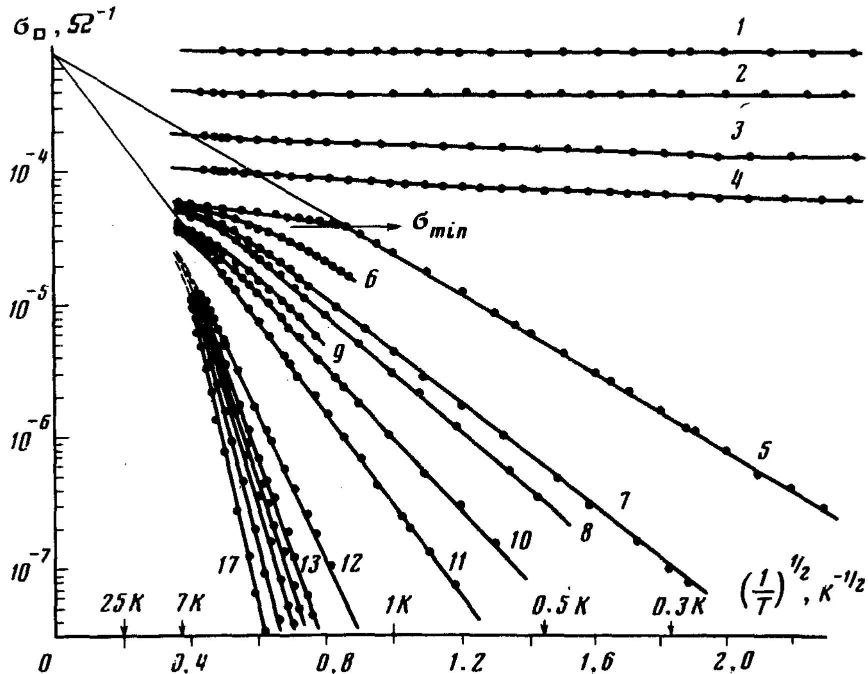

FIG. 2. Temperature dependences of the conductivities $\sigma_\parallel$ and $\sigma_\perp$ in Ge bicrystals. Curves 1, 2, 3, 4, 6, and 8–11 refer to $\sigma_\parallel$; curves 1, 2, 5, 7, and 12–17 refer to $\sigma_\perp$.

of relation (3) gives

$$\sigma(T) = \sigma_0 \exp\left[-\left(\frac{T_0}{T}\right)^{1/2}\right], \tag{4}$$

where σ_0 is the preexponential factor, and $T_0 = (4e^2/k\kappa R_0)$ is the characteristic temperature.

The same dependence (4) can also be obtained without invoking the "Coulomb gap," if the high probability (in Ge bicrystals) for a transition to a quasi-one-dimentional conductivity is taken into account. The Mott mechanism of hopping conductivity[8] under these conditions leads to an activation energy of $W_a = 1/N_0R$, where N_0 is the state density approximately equal to $m/\pi^2\hbar^2n$, m is the effective mass of carriers, and n is their linear density. Optimization of relation (3) under these conditions gives the dependence (4), where the characteristic temperature is $T_0 = 4/kN_0R_0$.

Near the metal–insulator transition dependence (4), according to Ref. 9, is also valid under conditions when the conductivity is due to suboptimal hops.

In order to clarify this behavior, the results of the measurements of the specific surface electrical conductivity, $\sigma_{\parallel}$ and $\sigma_{\perp}$, in Ge bicrystals are shown in Fig. 2 as the dependences $\log\sigma = f(T^{-1/2})$. The 17 experimental curves represent three families, one of which clearly refers to metallic conductivity, while the other two refer to nonmetallic conductivity.

As is evident from these data, the break in the semimetallic conductivity in Ge bicrystals at low T is very sharp. As soon as the conductivity $\sigma_{\square}$ reaches the value $\sigma_{\square} = \sigma_{\min}$, as a result of a logarithmic decrease of the electrical conductivity with decreasing T, the dependence $\sigma(T)$ exhibits a steep break and, beginning at some temperature, decreases exponentially. The dependences $\sigma_{\square} = \sigma_0 \exp[-(T_0/T)^{1/2}]$ in this case form two families of straight lines, to which the samples (5–11) with conductivity

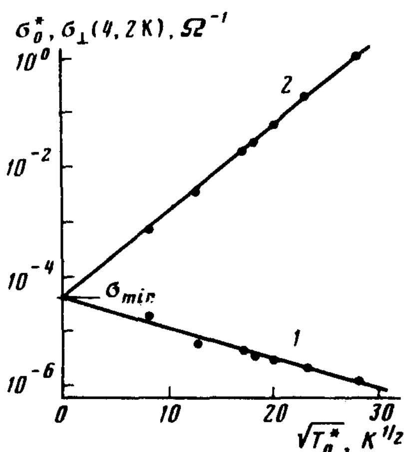

FIG. 3. 1) Relation between the values of the electrical conductivity $\sigma_{\perp}$ (at $T = 4.2$ K) and the values of the characteristic temperature T_0^* (for curves 12–17); 2) relation between σ_0^* and T_0^* (for curves 12–17).

$\sigma_\square$ close to σ_{min} at $T=1$–3 K belong, the samples (12–17), for which in this region of T the electrical conductivity is several times lower than σ_{min}, belong to the second family.

For samples in the first group the characteristic temperatures are in the range $10 \leqslant T_0 \leqslant 70$ K, and the preexponential factor is approximately the same for all samples:

$$\sigma_0 \approx (12 \div 18)\,\sigma_{min} \approx (2 \div 3)\frac{e^2}{\hbar},\ \Omega^{-1}. \tag{5}$$

For samples in the second group the characteristic temperatures are an order of magnitude higher, $150 \leqslant T_0^* \leqslant 750$ K; the preexponential factor σ_0^* sharply increases with T_0^* and, as is evident from the data shown in Fig. 3, can be represented in the form

$$\ln \frac{\sigma_0^*}{\sigma_{min}} = 0{,}36\sqrt{T_0^*}. \tag{6}$$

The behavior observed in Ge bicrystals cannot be attributed to the suboptimal hops,[9] since the experimentally determined values of σ_0 and σ_0^* greatly exceed the value $\sigma_0 \approx \sigma_{min}$ predicted by the theory.[9]

As far as the Mott[8] and the Coulomb gap[5] models are concerned, for them only qualitative estimates of the magnitude of the preexponential factor σ_0 are available, and a comparison of the measured values of T_0 with the values computed according to Refs. 5 and 8 does not lead to a preference of one or the other model.

To determine which of the mechanisms plays the main role in Ge bicrystals, additional investigations, especially those of the dependence of $\sigma_\square$ on the intensity of electric and magnetic fields, must be carried out.

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