Two-dimensional conductivity of the intergrowth surface of germanium bicrystals at ultralow temperatures

B. M. Vul and É. I. Zavaritskaya
P. N. Lebedev Physics Institute, Academy of Sciences of the USSR

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Investigations of electrical conductivity down to $T = 20$ mK have established that for specimens for which $\sigma_{\square} < \sigma_{min} = e^2/h$ the electrical conductivity σ has a hopping character and $\sigma \sim \exp[-(T_0/T)^{1/3}]$. For $\sigma_{\square} \gg \sigma_{min}$, the electrical conductivity has a weak temperature dependence: in the temperature range $0.1 \leqslant T \leqslant 4.2$ K, σ varies as $\ln T$ and at still lower temperatures $\sigma = \text{const}$.

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The electrical conductivity of a layer contiguous to the intergrowth surface (100) of germanium bicrystals was investigated at temperatures ranging from 4.2 K to 20 mK in bicrystals with inclination angles varying from 9 to 25°. In this case, the electrical conductivity is determined by transport of holes in thin layers about 30 Å thick.[1]

For two-dimensional conductivity, the transition from metallic to activated conductivity occurs at

$$\sigma = \sigma_{min} \approx e^2/h \approx 4 \times 10^{-5} \quad \Omega^{-1},$$

where e is the electron charge, and h is Planck's constant. Below this value of σ, the concept of electrical conductivity of a degenerate electron gas is no longer applicable. In this case, conduction occurs by jumps from one localized state to another. This process, examined by Mott for a three-dimensional medium, leads to the dependence

$$\sigma \sim \exp[-(T_0/T)^{1/4}],$$

where T_0 is a quantity with the dimensionality of temperature.[2]

An analogous analysis for a two-dimensional medium yields the result that with an activation energy W the probability of a hop over some distance R is proportional to

$$\exp\left(-\frac{R}{R_0}\right)\exp\left(-\frac{W}{kT}\right), \tag{1}$$

where R_0 is the average length of a hop and k is Boltzmann's constant. In the two-dimensional case, the activation energy W and the distance R at temperature T are related by

$$W(T)\pi N_0 R^2(T) = 1, \tag{2}$$

where N_0 is the density of states, which is independent of energy in the two-dimensional case.

The magnitude of a hop corresponding to maximum conductivity is given by

$$R_m = \left(\frac{2R_0}{\pi N_0 kT} \right)^{1/3}. \tag{3}$$

Then, the density of the current passing through the specimen in an electric field E is

$$J = J_0 \exp\left[- \frac{3R_m}{2R_0} \right] \mathrm{sh} \frac{eER_m}{kT}, \tag{4}$$

where

$$J_0 = 4\pi e\sqrt{n}\, W/h$$

n is the surface density of holes, and $2\pi W/h$ approximately equals the frequency of oscillations of the charge in a potential well W.

In sufficiently weak electric fields, when $eER_m/kT \ll 1$, the current density

$$J = 4\pi \, e^2/h \sqrt{n} \frac{W}{kT} R_m E \exp\left[- \frac{3R_m}{2R_0} \right], \tag{5}$$

hence it follows that the electrical conductivity

$$\sigma = \sigma_0 \exp\left[-(T_0/T)^{1/3} \right], \tag{6}$$

where

$$T_0 = \frac{27}{4R_0^2 \pi N_0 k}; \qquad \sigma_0 = \frac{e^2}{h} \frac{4\pi\sqrt{n}}{(2R_0)^{1/3} (\pi N_0 kT)^{2/3}}. \tag{7}$$

The temperature dependence of the electrical conductivity for specimen No. 1 with σ equal to $1.4\sigma_{\min}$ at $T = 4.2$ K is shown in Fig. 1. As is evident from these data, as the temperature decreases, the electrical conductivity of the specimen is equal to $\sigma_{\min}$ at $T = 1.3$ K. Below this temperature, σ as a function of T satisfies well the dependence (6) down to the lowest temperatures, equal to 0.15 K for these measurements. It

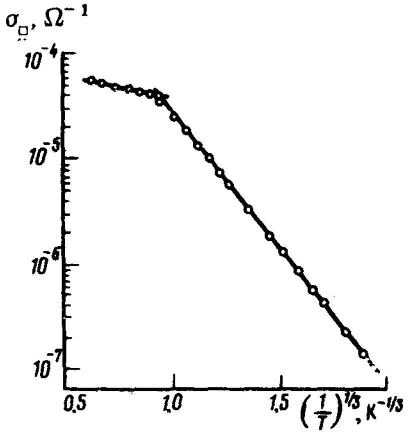

FIG. 1. Dependence of the electrical conductivity $\ln \sigma = f(T^{-1/3})$ for specimen No. 1, prepared from a bicrystal with angle $\theta = 9°$.

TABLE I.

No.	$\sigma_{\square}$ (4.2K) (exp)	T_0, K (exp)	σ_0, Om^{-1} (exp)	R_0, cm	at T = 0.2 K		
					R_m/R_0	R_m, cm	W, meV
1	5.5×10^{-5}	190	8×10^{-3}	1.0×10^{-6}	6.6	6.6×10^{-6}	0.66
2	4.0×10^{-5}	310	6×10^{-3}	0.77×10^{-6}	7.8	6.0×10^{-6}	0.78
3	1.6×10^{-5}	1000	10×10^{-3}	0.43×10^{-6}	11.4	4.9×10^{-6}	1.14

follows from the slope of the straight line that for this specimen $T_0 = 190$ K; the value $\sigma_0 \approx 8\times10^{-3}$. Analogous results were obtained for two other specimens, whose data are presented in Table I.

To estimate the quantities R_0, R_m, and σ_0, we assumed that the density of states $N_0 = 4\pi m/h^2$, while the mass of the hole density of states $m = 2.9\times10^{-28}$, as in a single crystal, because of the weak distortion of the crystal lattice.

Assuming that the average temperature is equal to 1 K and that the surface density of holes $n \simeq 4\times10^{12}$ cm^2, we obtain from relation (7) $\sigma_0 = (7\text{–}9)\times10^{-3}\ \Omega^{-1}$, which agrees well with the measured values $\sigma_0 = (6\text{–}10)\times10^{-3}\ \Omega^{-1}$.

The measurements presented above concern regions in which the current depends linearly on the applied voltage, produced in fields of the order of several mV/cm at $T = 0.4$ K. As the temperature is increased, the region in which Ohm's law is valid becomes larger, encompassing high field intensities. At $T = 4.2$ K, σ was found to be independent of E for specimen No. 1 up to 2 V/cm, but in this case the conductivity

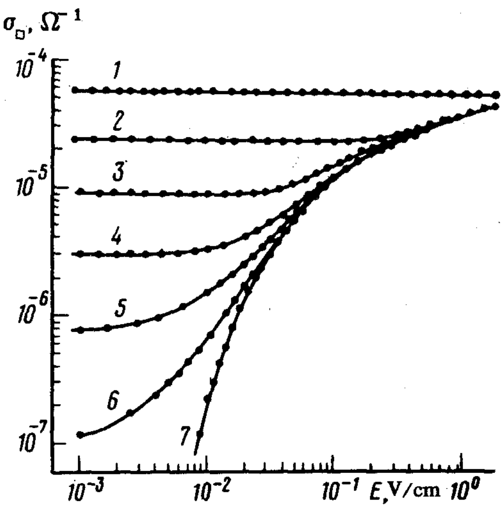

FIG. 2. Dependence of the electrical conductivity σ on the electric field intensity E for specimen No. 1 at different temperatures: 1—4.2 K; 2—1.0 K; 3—0.6 K; 4—0.4 K; 5—0.25 K; 6—0.15 K; 7—0.10 K.

was not a hopping conductivity. The dependence $\sigma = f(E)$ for specimen No. 1 for different T is shown in Fig. 2. As is evident from these data, in the region of hopping conductivity, for $T \leqslant 1$K the nonlinear field dependence becomes even stronger as the temperature decreases. In this case, the dependence of J on E is much stronger than is implied by relation (4). This problem will be examined in a subsequent publication.

For specimens with electrical conductivity in the temperature interval studied

$$\sigma_{\square} >> \sigma_{min}$$

the quasimetallic two-dimensional conductivity decreases when the temperature decreases from T_0 to T by an amount

$$\Delta\sigma = \sigma_{\square}(T_1) - \sigma_{\square}(T) = C\frac{2e^2}{\pi h}\ln\frac{T_1}{T} \quad , \tag{8}$$

where C is a coefficient of the order of unity.[3]

Typical results obtained for bicrystals with electrical conductivity $\sigma_{\square}(4.2\text{ K}) \gg \sigma_{\min}$ are shown in Fig. 3. For a specimen in which at $T = 4.2$ K the electrical conductivity is ten times greater than $\sigma_{\min}$, a distinct logarithmic temperature dependence with decreasing temperature is observed down to 0.1 K. In another specimen, with even higher conductivity, $\sigma_{\square}(4.2\text{ K}) = 25\sigma_{\min}$, the logarithmic dependence is observed down to 0.2 K. An analogous dependence occurs for the other five specimens, whose electrical conductivity at $T = 4.2$ K varies from $20\sigma_{\min}$ to $3\sigma_{\min}$. For most specimens, the constant $C \simeq 0.3$ and for two specimens, the quantity C was twice as high.

At lower temperatures, $T < 0.1$ K, the conductivity no longer depends on the

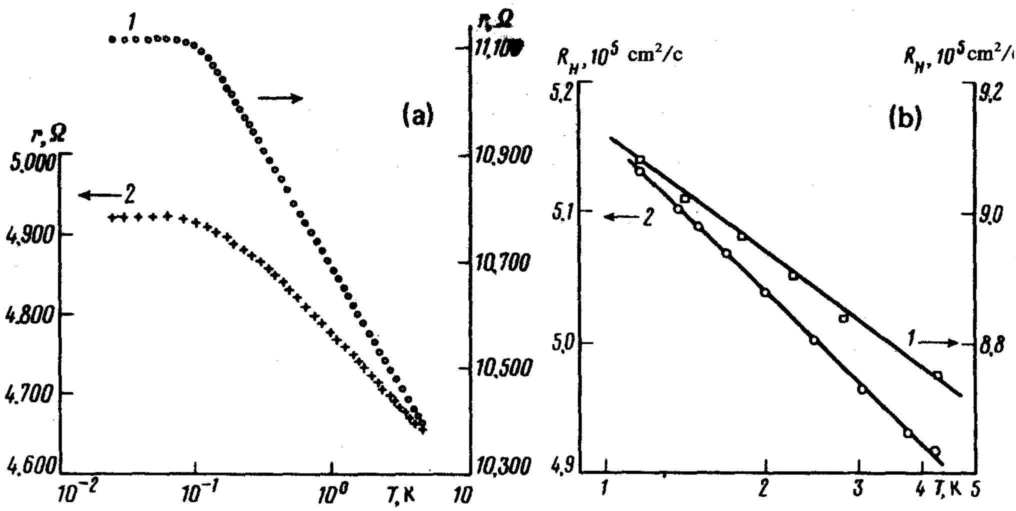

FIG. 3. (a) Temperature dependence of the resistance for bicrystals with inclination angles $\theta = 20$–25: 1) specimen No. 4, with resistivity $\rho = 2$ kΩ at $T = 4.2$ K; 2) specimen No. 5 with resistivity $\rho = 1.2$ kΩ at $T = 4.2$ K; b) temperature dependence of Hall's coefficient: 1) specimen No. 4 and 2) specimen No. 5.

temperature and remains essentially constant for each of the specimens down to the lowest temperature that we can attain $T \simeq 20$ mK. The transition from the logarithmic dependence to a constant occurs at the temperature $t = 0.10$–0.15 K, independent of the starting electrical conductivity of these specimens. A variation of the current density from 10^{-5} to 10^{-7} A/cm did not affect the measurements of σ, which eliminates the possibility of current-induced heating of the specimens. In the specimens studied, the electron gas is strongly degenerate, while the degree of disorder is very low, which is manifested in the very small change in the electrical conductivity, less than 7%, in the temperature range 4.2 to 0.1 K; at still lower temperatures, the effect of lattice defects decreases.

In addition to the investigation of electrical conductivity, we have measured the temperature dependence of Hall's coefficient R_H in individual specimens in magnetic fields with intensity $H_1 = 10$ kOe and $H_2 = 20$ kOe. The intensity of magnetic field did not affect the magnitude of Hall's constant. The results of measurements of $R_H = f(\ln T)$ in the temperature range from 4.2 K to 1.2 K are shown in Fig. 3b. As is evident from these data, in the temperature range studied, Hall's coefficient increases by 3.8% for one specimen and by 4.4% for the other. According to the data in Fig. 3a, the resistance of these specimens increases in the same temperature range approximately by 1.9 and 2.2%.

The theoretical relation between the relative changes in ρ and R_H was investigated in Ref. 4.

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