Minimum of metallic conductivity in a two-dimensional system

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(Submitted January 20, 1977)
Pis'ma Zh. Eksp. Teor. Fiz. **25**, No. 4, 204–207 (20 February 1977)

We investigated the electric conductivity of conducting layers produced at the boundary of germanium bicrystals, as a function of the grain disorientation angle $7 \leq \theta \leq 30°$. A transition from metallic conduction to activation conduction is observed at $\theta \lesssim 10°$. It is established that the transition corresponds to $\sigma_{\min} \approx 4 \times 10^{-5}\ \Omega^{-1}$, in agreement with the theoretical estimate $\sigma_{\min} \simeq e^2/h$ for a two-dimensional system.

PACS numbers: 73.25.+i

In recent years, interest in the properties of thin layers has greatly increased because of their extensive use in semiconductor microelectronics. Thin layers can be regarded abstractly as two-dimensional media, and the extent to which this abstraction is valid under given conditions must be verified only by comparison with experiment.

The electric conductivity of a degenerate electron gas in a two-dimensional system is

$$\sigma = ne\mu = 2\pi \frac{e^2}{h^2} (pl), \tag{1}$$

where $n = 2(\pi p^2/h^2)$ is the electron density, $\mu = (el/mv) = (el/p)$ is the carrier mobility, p is the electron momentum at the Fermi level, l is the mean free path, and m is the effective mass.

If it is assumed that

$$pl > p\Delta l > h/2\pi ,$$

then the minimum value of the electric conductivity of a degenerate electron gas in a two-dimensional system is

$$\sigma_{\min} \approx \frac{e^2}{h} = 3.9 \times 10^{-5}\ (\Omega)^{-1} \tag{3}$$

and does not depend on the material.[1]

Thin layers imitating a two-dimensional system can be explained by various methods. In[2] such layers were investigated in MIS structures of silicon field-effect transistors. These investigations have shown that the minimum values of the conductivity depend on the surface state and range from 3×10^{-5} to $10^{-3}\ \Omega^{-1}$ for different samples.

In our case we investigated thin highly-conducting layers produced on the grain boundaries of bicrystals grown by the Czochralski method on a double

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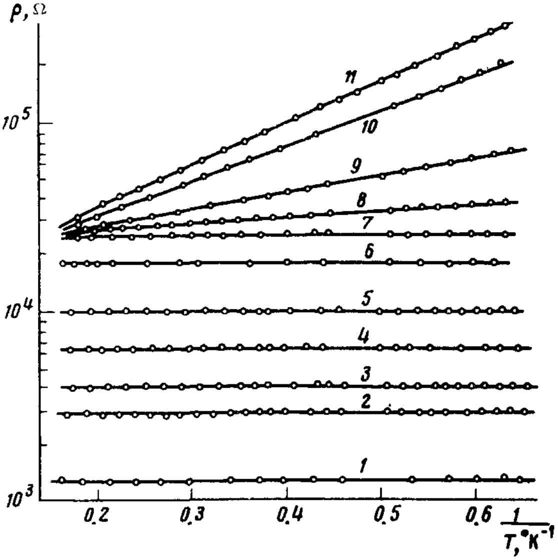

FIG. 1. Temperature dependence of the resistivity of samples with different disorientation angles θ.

seed. It is known that in this case there is produced a two-dimensional grid of edge dislocations, the distance between which is $D=[b/2\sin(\theta/2)]$, where **b** is the Burgers vector and θ is the disorientation angle.[3] The dislocation plane in germanium is a negatively charged surface of partially-filled bonds, with adjacent layers several dozen angstroms thick and having p-type conductivity.[4]

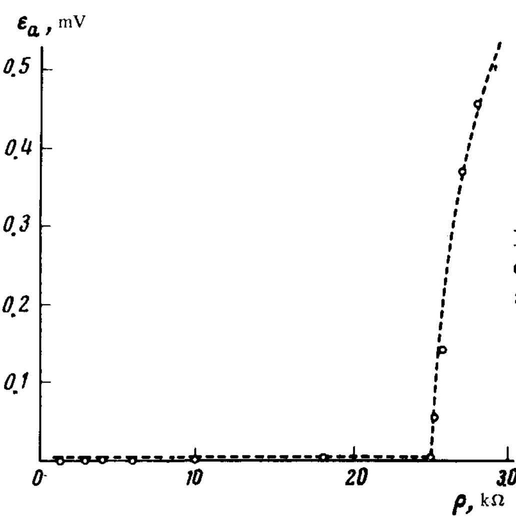

FIG. 2. Dependence of the "activation energy" ϵ_a on the sample resistivity at $T=6$ °K.

We present here the results of the investigation of structures obtained on the basis of n- and p-type germanium with different initial electron and hole densities and with different disorientation angles $7 < \theta < 30°$ relative to the [100] directions. The samples were rectangles 10 mm long and 1×2 mm in cross section, with dislocation rows along the long side of the samples. The contacts were made of indium. They were ohmic for the dislocation-boundary region with p-type conductivity, and of the barrier type for the shunting n-Ge layers on both sides of the boundary. At low temperatures, $T < 4\,°\mathrm{K}$, this precaution was unnecessary, since the resistance of the adjacent layers exceeded $10^9\,\Omega$ and their contribution to the conductivity could be neglected.

The dependence of the resistance on the temperature in the region $1.5 \lesssim T \leq 6\,°\mathrm{K}$ is shown in Fig. 1 for some of the investigated samples. The lower family of straight lines (1—6) corresponds to disorientation angles $10 \leq \theta \leq 30°$, and the family of lines (7—11) corresponds to angles $7 \leq \theta \leq 10°$. It is seen from these data that at low temperatures the resistance of the samples varies with the disorientation angle, ranging from 1 kΩ to 1 MΩ. When the resistance of a sample drops below a certain critical value, it becomes independent of temperature in the region $T < 10\,°\mathrm{K}$; samples with large resistance have a "thermal activation" conductivity. This result follows most clearly from the data shown in Fig. 2, which shows the dependence of the "activation energy" ϵ_a on the sample resistance.

As seen from these data, in our case there is a rather abrupt transition from the temperature-independent electric conductivity to the temperature-dependent conductivity at a value $\sigma \approx 4 \times 10^{-5}\,\Omega^{-1}$. Thus, the experimentally obtained value of σ_{min} agrees sufficiently well with the value calculated in elementary fashion in accordance with (3), and the thin layers of p-type conductivity obtained at the bicrystal boundary can be regarded from the point of view of the electric conductivity, with sufficient accuracy, as two-dimensional medium.

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