The Hall effect on the surface of germanium crystals cleaved in liquid helium

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When germanium crystals are cleaved in liquid helium the freshly formed surface captures, on the broken bonds, electrons from the near-surface germanium layer, leaving holes in the valence band. Measurements of the Hall effect show that the concentration of free holes in the near-surface layer and, accordingly, the electron concentration on the surface are approximately 10^{13} cm $^{-2}$. The hole mobility is $\mu \sim 300$ cm^2/V sec. The overall physical picture is the same as that observed on the interface of germanium bicrystals.

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In an earlier paper we have reported the findings of a study, at $T = 4.2$ K, of the surface electrical conductivity of germanium after cleavage of the crystals in liquid helium.[1] In the present paper we report measurements of the Hall effect under the same experimental conditions as in Ref. 1.

The measurements have shown that, irrespective of the conductivity type of the initial crystal and the concentration of impurities in it, the surface electrical conductivity of germanium is due to the motion of holes. Hall emf measurements were conduct-

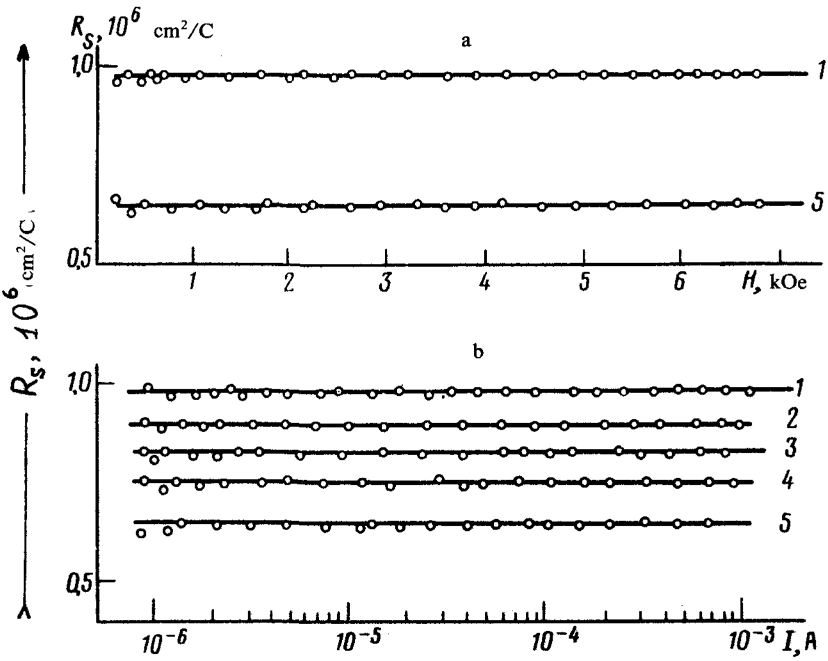

FIG. 1. Dependence of the Hall constant on: a—the magnetic field strength at $I \approx \text{const} = 50\ \mu A$, b—current at $H = \text{const} = 2$ kOe (numbers at the curves identify the samples).

ed on 14 Ge samples of the n and p types with various donor and acceptor concentrations in the range $10^{14} - 3 \times 10^{15}$ cm^{-3}. The results of the measurement of the Hall coefficient R_s for five of these samples are presented in Fig. 1; for the remaining samples the data were similar to those shown in the figure, lying within the same range of R_s. The observed values of R_s were independent of the sample characteristics prior to cleavage.

Experimental data on the Hall mobility $\mu = R_s \sigma_s$ for various samples are given in Fig. 2. All of these data refer to samples which after cleavage were subjected to an intermediate heating at $T_n \approx 40$ K.

From the results of Fig. 1 it follows that the Hall coefficient

$$R_s = r/eP_s \tag{1}$$

does not depend on the magnetic field intensity in the range $100 \leqslant H \leqslant 7000$ Oe or on the current in the range $10^{-6} \leqslant J \leqslant 10^{-3}$ A.

Under our conditions one can assume the Hall factor $r = 1$. Then the hole concentration is

$$P_s = (6\text{–}10) \times 10^{12}\ \text{cm}^{-2},$$

as on the interface of germanium bicrystals.[2]

At such high concentrations the scattering of holes occurs mainly on the charged

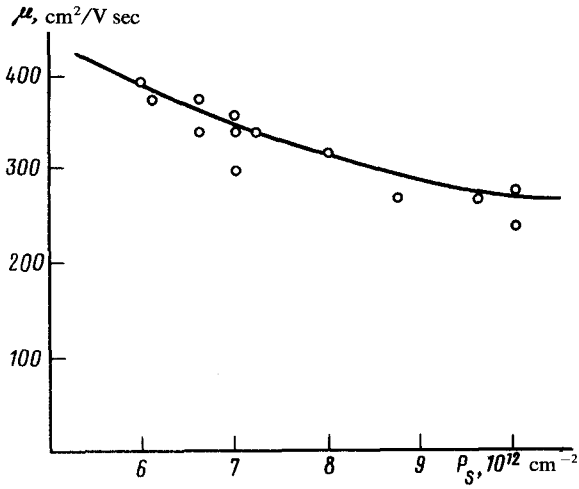

FIG. 2. ●—Dependence of mobility of holes on their concentration; the curve is the value of μ_{theor}, calculated according to (2), multiplied by 2.

centers. From a mobility calculation under these conditions for a two-dimensional model,[3] we have

$$\mu = \frac{\kappa h \sqrt{P_s}}{2\sqrt{2}\pi e m^* N_i} \left(\operatorname{arc\,tg} \frac{\kappa h^2 P_s}{4\pi e^2 m^* \sqrt{N_i}} \right)^{-1}, \tag{2}$$

where κ is the dielectric constant, h the Planck constant, e the electron charge, m^* the effective mass of the carriers, P_s the concentration of the carriers, and N_i the concentration of the scattering centers.

In a first approximation we can assume that at the germanium surface, as in the bulk, $\kappa = 16$, the effective mass of the holes is $m_h^* = 0.4\ m_0$, and the concentration of the scattering centers is $N_i \approx P_s$. Then the calculated values will be roughly one-half of the measured Hall values, which, under our crude assumptions, can be regarded as satisfactory agreement.

Directly after the crystal cleavage in liquid helium the additional conductivity σ_s introduced by the freshly formed smooth surface is not discernible against the background of the bulk conductivity. The intermediate heating in helium vapor makes it possible to reveal the effect of the newly formed surface.

After heating the sample to 40 K and keeping it at this temperature for 1–2 min, its surface electrical conductivity measured at $T = 4.2$ K attains values $\sigma_m \approx 4\times 10^{-4}$ Ω^{-1} and the surface current exceeds the bulk current by 10^5–10^6 times. If the intermediate heating is conducted at $T_n < 40$ K or is not maintained for a sufficiently long time the surface conductivity σ_s does not reach σ_m, although it does increase with increased duration of the heating. When the samples are stored in liquid helium these intermediate values of σ_s remain unchanged for many hours. Measurements of the Hall effect on surfaces with electrical conductivity

$$0.1\,\sigma_m \leqslant \sigma_s \leqslant \sigma_m$$

show that the hole concentration in that case does not differ from the limiting value of P_m to any significant degree.

It can be assumed, therefore, that the growth of the surface conductivity with increasing duration of the intermediate heating is caused by processes similar to annealing of defects, and leads to an enhancement of the mobility of the carriers.

The limiting value of the surface conductivity $\sigma_m \approx 4\times 10^{-4}\ \Omega^{-1}$ is determined, as with germanium bicrystals, by the motion of holes with the concentration $P_s = (6\text{–}10)\times 10^{12}\ \text{cm}^{-2}$ and mobility $\mu = 400 - 250\ \text{cm}^2/\text{V sec}$.

The findings suggest that the overall physical picture of the phenomena under study is largely the same as that observed on the interface of germanium bicrystals.[2] In the latter case, however, no intermediate heating is necessary since the bicrystal growth takes place at a substantially higher temperature than T_n.

The electrons from the valence band of germanium are trapped on the broken bonds which arise, in the former case, in cleavage of the crystal and in the latter case, during crystal growth on a double seed with a large dip angle. The conductivity of the cleavage surface of the crystal, like that of the interface of two crystals in germanium, is due to the near-surface motion of holes which remain vacant down to very low temperatures.

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