Hall investigation of germanium surfaces cleaved in liquid helium

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The conductivity σ_s of channels produced on germanium surfaces cleaved in liquid He is distributed nonuniformly on the cleaved surface. Warming at $30 < T < 60$ K homogenizes σ_s. The effective mobility and concentration of free holes in the channels, which can be determined from the Hall measurements, differ from the true mobility and concentration as long as σ_s is inhomogeneous.

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In the first papers[1,2] on the investigation of Ge surfaces cleaved in liquid helium recently published, the contributions of the effective mobility μ and concentration Γ of the free charge carriers to the surface conductivity σ_s have not been separated. A knowledge of these parameters allows us to understand more fully the physical processes occurring on such surfaces. In this paper we determine the values of μ and Γ using the Hall current method.[3]

The samples were prepared from an antimony-doped (2×10^{14} cm^{-3}) and gold-doped (4×10^{14} cm^{-3}) germanium with a resistivity $\rho > 2\times10^5$ Ω cm at 77 K and $\rho > 10^9$ Ω cm at 4.2 K. The samples are shown in Fig. 1. The contacts were established by melting indium.

The samples were cleaved in liquid He. The Hall measurements were performed by placing the samples in a superconducting solenoid ($H = 1.43\times10^4$ Oe). All measurements were carried out at 4.2 K after heating the cleaved samples in a helium vapor. The heating temperature T_H was gradually raised. Figure 1 shows typical results of the measurements. Immediately after cleavage and heating to $T_H < 30$ K the sample's conductivity σ increased negligibly, but did not depend on the length of time it was held in liquid He. The sample's conductivity σ increased irreversibly by a factor of $\sim 10^6$ when it was heated to $30 < T_H < 60$ K. After the sample was exposed to air and subsequently immersed in liquid He, its conductivity σ returned to the value it had prior to cleavage. This led us to assume that the observed variation of the sample's conductivity is attributable to the physical processes that change the conductivity σ_s of the channels formed on the cleaved surfaces. The values of σ_s (curve 1) per unit surface of the cleaved sample are plotted along the Y axis in Fig. 1.

The direction of flow of the Hall currents corresponded to the hole conductivity of the surface channels. Curves 2 and 3 in Fig. 1 represent the effective Hall mobility and concentration of the free holes in the channels. At $\sigma_s < 5\times10^{-5}$ Ω^{-1} the Hall measurements could not be performed because of the large nonequivalent potentials of the contacts for measuring the Hall current. The nonequivalent potentials indicated that the conductivity σ_s was distributed nonuniformly on the cleaved surface. The

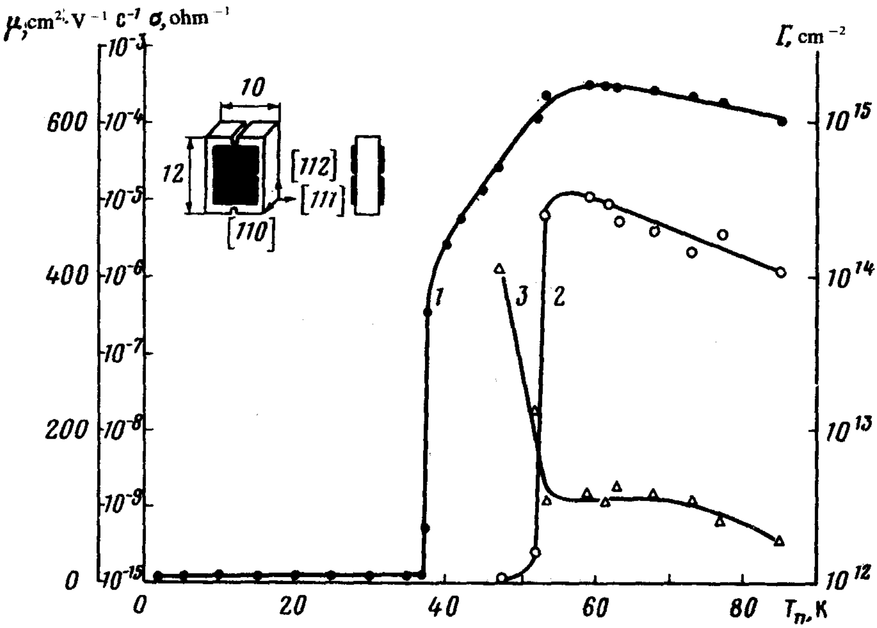

FIG. 1. Samples for measuring the Hall current (size in mm). The conductivity σ_s of the surface channel (1), Hall mobility μ (2), and its effective hole density Γ (3) are plotted as a function of the heating temperature T_H of the cleaved sample.

nonuniformed distribution of σ_s was investigated using special samples shown in Fig. 2. The distribution of the voltage drop V along the cleaved surface, obtained as a result of gradually increasing T_H, is also shown in Fig. 2. We can see that the distribution of V is almost linear and σ is uniform on the cleaved surface only after the sample is heated to $T_H \approx 60$ K. At this temperature the $\sigma_s(T_H)$ and $\mu(T_H)$ dependences reach their maximum values and the $\Gamma(T_H)$ dependence reaches a plateau (Fig. 1).

Thus, the conductivity of the surface channels is nonuniform in the region of rapid increase of $\sigma_s(T_H)$ (curve 1 in Fig. 1). The Hall measurements of μ and Γ in the channels with a nonuniform conductivity may give values that differ substantially from the true drift mobility and the average concentration of the free charge carriers.[4,5] A sharp variation of the $\mu(T_H)$ and $\Gamma(T_H)$ dependences at $T_H \sim 40-50$ K (curves 2 and 3 in Fig. 1) apparently is attributable to the fact that as the homogeneity of the channel increases with increasing T_H, the values of μ and Γ determined from the Hall measurements approach those values actually obtained in the channel. At $T_H > 60$ K the surface channel is homogeneous, and the use of Hall method gives correct results.

The value of σ_s did not change noticeably in the samples heated to $T_H \sim 80$ K as the temperature was raised from 4.2 to 80 K. The hole gas in the surface channels, therefore, is degenerate. The values of σ_s, μ, and Γ in such channels at 77 K are close to those obtained for cleaved Ge in liquid nitrogen in a high vacuum.[6] This led us to assume that the channels formed on cleaved Ge surfaces in liquid He and N in a high

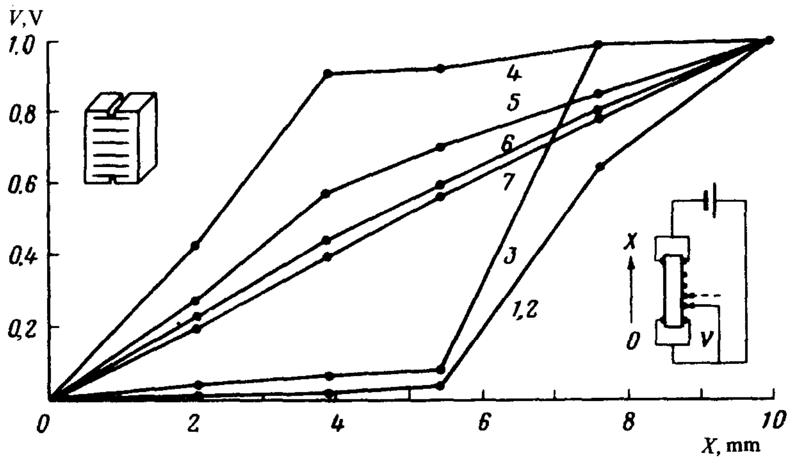

FIG. 2. Samples for recording the voltage distribution on the cleaved surface. Dependence of V and the X coordinate along the surface were recorded after the samples were heated. 1, 4.2°; 2, 13°: 3, 37°; 4, 45.5°; 5, 53°; 6, 55.5°; 7, 80°.

vacuum are the same. The cleaved surface produced acceptor-type energy states in which a negative charge Q_{ss}, which induces a hole-enriched channel in the surface region, is localized.

The effects observed on the surfaces cleaved in liquid helium can be accounted for in the following way. As a result of cleaving the sample, the newly formed surfaces develop mechanical stresses. Judging by the diversity of profiles of the cleaved samples, the magnitude of these stresses is different at different points on the surface. These stresses can affect the characteristics (energy state or density, or both) of surface states in such a way that immediately after cleavage the small charge localized in them Q_{ss} will be distributed nonuniformly along the cleaved surface. According to Q_{ss}, the small conductivity σ_s of the channel is also distributed nonuniformly. As the heating temperature of the sample is raised, the stresses gradually vanish and the increasing Q_{ss} is distributed with greater uniformity along the surface. This increases σ_s and sharply changes μ and Γ determined from the Hall effect (curves 1–3 in Fig. 1 for $T_H < 60$ K). At $T_H \sim 60$ K, Q_{ss} after reaching a maximum is distributed uniformly along the cleaved surface.

It was mentioned in Ref. 1 that the SHF conductivity increases appreciably immediately after Ge cleavage in liquid He. According to our data and those obtained elsewhere,[2] a noticeable σ_s appears only after heating the samples at $T_H > 30$–40 K. Such discrepancy confirms the validity of the proposed model for a nonuniform surface. The presence of conducting islands on the surface may affect the SHF absorption. However, for the appearance of conductivity with a direct current, the islands must be sufficiently large, overlap each other and produce a conducting chain between the contacts of the sample.

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