Localization of electrons on the cleavage surface of germanium in liquid helium

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The surface conductivity on the cleavage surfaces of germanium crystals in liquid helium, in rarefied helium and in ultrahigh vacuum has been investigated. It has been established that the transfer of electrons from the valence band to the surface occurs as a result of adsorption of impurity atoms, amounting to about 1% of the monolayer.

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It has been established that the cleavage surfaces of germanium in liquid helium can be changed from a weakly conducting state to a state with metallic conductivity by rapidly warming them in helium vapor at $T_i \approx 35$ K.[1]

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The purpose of our work was to investigate the processes of appearance and disappearance of surface conductivity in germanium as a function of the annealing conditions of freshly cleaved surfaces.

The annealing was accomplished in several ways: 1) in helium vapor above the liquid, as described previously[1-3]; 2) in an atmosphere of helium gas at pressures ranging from a few Torr to several tens of Torr in a container, as in Ref. 4; and 3) in an evacuated container completely immersed in liquid helium. Before the crystal was cleaved, all the elements inside the container were heated to a temperature higher than the temperature T_i of the subsequent annealing of the cleavage surface. The pressure in the container under these conditions must be lower than 10^{-12} Torr.[5]

The results of measurements of the surface conductivity σ_s at $T=4.2$ K, after an intermediate annealing at a temperature T_i in helium vapors, are shown in Fig. 1. As seen from the presented data, three regions are clearly discernible in the $\sigma_s=f(T_i)$ dependence: I—a steep increase of σ_s after annealing at $T_i\approx 35$ K, II—temperature independence of σ_s at $35\leqslant T_i\leqslant 50$ K and a monotonic decrease of σ_s at $50<T_i<80$ K, and III—a steep decrease of σ_s at $T_i>80$ K.

As seen in Fig. 1, after the annealing at $T_i\approx 90$ K, the conductivity decreases almost discontinuously to such a small values as to make them indistinguishable from the background bulk conductivity $\sigma\sim 10^{-8}$ ohm^{-1}.

In addition to measuring the surface resistivity ρ_s, we have also measured the Hall effect in the interval $2\ \text{k}\Omega\leqslant\rho_s\leqslant 50\ \text{k}\Omega$.

The hole density reached a maximum value p_m in different samples within the limits

$$6\times 10^{12}\leqslant p_m\leqslant 1\times 10^{13}\ \text{cm}^{-2}.$$

During successive warmings in helium vapor at $T_i\approx 35$ K, we were able to mea-

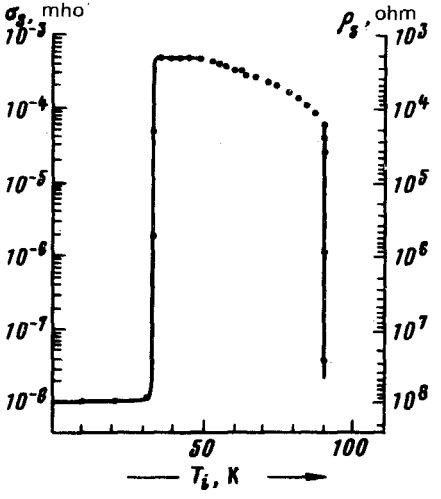

FIG. 1. Dependence of the surface conductivity σ_s at $T=4.2$ K on the temperature T_i of the intermediate annealing in helium vapor (each point was obtained after warming for 5 minutes).

sure in region I the values $p_s = 0.7\, p_m$ at a resistivity $\rho_s = (30\text{–}40)$ kΩ. The results of a measurement of the dependence $p_s = f(\rho_s)$ in regions II and III are shown in Fig. 2. A comparison of these data with those in Fig. 1 shows that the monotonic decrease of σ_s in region II is determined primarily by the gradual decrease in the density of free holes, whereas a steep decrease of the conductivity σ_s in region III occurs at an almost constant hole density $p_c = 2 \times 10^{12}$ cm^{-2}.

The results of measurements of $\sigma_s = f(T_i)$, obtained by using various annealing methods, are presented in Fig. 3. As seen from these data, a high surface conductivity σ_m is reached at $T_i \cong 35$ K after annealing in helium vapor (curve 1), at $T_i \approx 70$ K after annealing in rarefied helium (curve 2), and only a slight increase of σ_s is observed after annealing in a high vacuum up to $T_i \sim 120$ K.

Measurements of the Hall coefficient simultaneously with the σ_s measurements showed that a slight increase of the conductivity σ_s in rarefield helium is accompanied by a monotonic increase in the hole density from 2×10^{12} to p_m.

The results of measurements of the dependence $p_s = f(\rho_s)$ are also shown in Fig. 2; a comparison of the curves shows that they are identical to those obtained previously for a decrease in σ_s. The dependences $p_s = f(\rho_s)$ are therefore the same, regardless of the annealing conditions and the direction of variation of the conductivity σ_s.

It follows from the obtained data that the germanium surface has a certain critical density,

$$p_c = (2 \pm 0.2) \times 10^{12} \text{ cm}^{-2},$$

above which the hole mobility increases sharply, and the holes can be regarded as a degenerate gas.

The two abrupt transitions–insulator to metal (in region I) and metal to insulator (in region III)–shown in Fig. 1 are the result of the existence of this critical density. If the hole density, which increases gradually, exceeds the value p_c, the conductivity will increase sharply; as the hole density is reduced gradually, the conductivity σ_s decreases smoothly until the hole density decreases to the value p_c. In this case the free holes become bound, and the conductivity decreases discontinuously, which gives rise to the metal-dielectric transition.

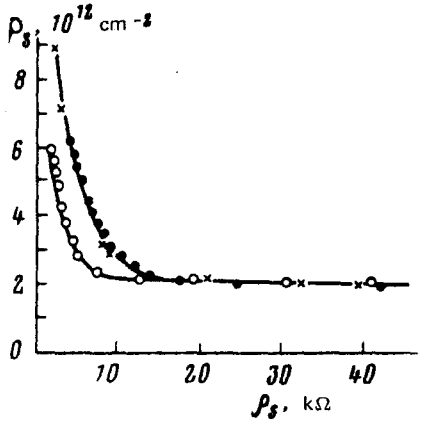

FIG. 2. Dependence of the surface density of holes on the resistivity ρ_s. • ○–Values obtained as a result of increase of the resistance in regions II and III, ×–as a result of decrease of the resistance in rarefied helium in region I.

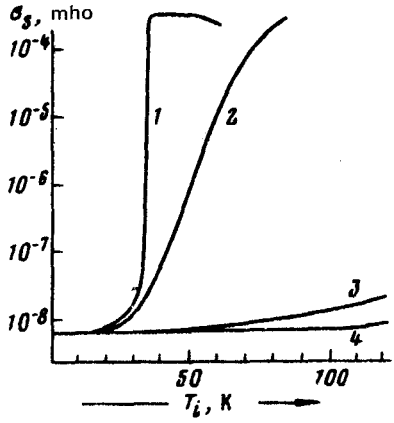

FIG. 3. The dependence $\sigma_s = f(T_i)$ measured at $T = 4.2$ K. 1–Values obtained after heating in helium vapor (pressure, 1 atm), 2–after heating in rarefied helium (pressure, a few Torr), 3 and 4–after heating in a vacuum.

Investigation of the temperature dependence of the surface conductivity $\sigma_s = f(1/T)$ in the temperature region $1.0 \leqslant T \leqslant 4.2$ K showed that the minimum metallic conductivity amounts to $\sigma_{min} \approx 4 \times 10^{-5}$ ohm^{-1}, in good agreement with the theoretical estimate $\sigma_{min} = e^2/h$ for the two-dimensional model.[6] Therefore, the described transitions from a nonconducting state to a conducting state and vice versa are two-dimensional metal-to-insulator transitions.

It follows from the results of measurements in ultrahigh vacuum that the broken bonds formed during the crystal cleavage and heating to 150 K cannot account for the appearance of surface conductivity. The broken bonds apparently are reconstructed on the surface without leaving the levels, thereby preventing the transfer of electrons to them from the valence band.

On the other hand, it follows from the results of measurements in helium vapor that, after an intermediate heating at $T_i \approx 40$ K, the valence electrons can be transferred to the surface on which free holes can appear. An adsorption of impurity atoms on the surface apparently must occur in this process.

The effect of helium can be inferred from the results of measurements in the rarefied gas. In these experiments a fairly large amount of helium was present in the container, and the increase of surface conductivity as a function of T_i should have had a steeper rise. The slow increase of σ_s observed in the experiment apparently is attributable to the fact that the few impurities in the helium rather than the helium atoms are gradually adsorbed on the surface; this coats the surface with foreign atoms whose layer thickness is of the order of one percent of the monolayer.

Our measurements in helium at different pressures showed, therefore, that the process of surface conductivity on cleavage surfaces of germanium crystals is more complex than has been assumed previously.[3]

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