Surface conductivity of germanium cleaved in liquid helium

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After the cleaving of germanium in liquid helium the surface conductivity for the mirror-smooth (111) cleavage surfaces is $\sigma < 10^{-9}$ ohm^{-1}, whereas for defect surfaces it can reach values of $\sigma \sim 10^{-5}$ ohm^{-1}. After intermediate warming at $T \geqslant 40$ K the surface conductivity at $T = 4.2$ K increases irreversibly and suddenly, regardless of the state of the surface, reaching a value of $\sigma = (3\text{–}5) \times 10^{-4}$ ohm^{-1}, just as in the case of germanium bicrystals.

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Considering the high chemical inertness of helium, one could expect that when a crystal is cleaved in liquid helium, the surrounding medium will have practically no effect on the properties of the surface and in this way one could determine the properties of a "clean" surface.

Germanium crystals, *n*- and *p*-type, with an impurity concentration of 5×10^{13} to 5×10^{15} cm^{-3} were cleaved along the (111) cleavage plane. Contacts were made by indium fusion and were placed as shown in Fig. 1. All conductivity measurements were made in liquid helium at $T = 4.2$ K.

Before cleaving the conductivity of the samples was determined by the bulk properties of the germanium and had a value of 10^{-8} to 10^{-10} ohm$^{-1}\cdot$ cm^{-1}, depending on the amount of impurities. After cleaving in liquid helium the freshly formed flat surface, if it was mirror-smooth, contributed nothing at all to the conductivity of the samples, and the surface conductivity could be ignored. However, after an intermediate warming in helium vapors to a temperature of about 40 K the surface conductivity increased suddenly and irreversibly.

The conductivity measurement results at $T = 4.2$ K for samples that had been cleaved in helium are shown in Fig. 1 as a function of the intermediate warming temperature T_{int}. Each point on the curves was obtained after heating the sample to T_{int} followed by cooling to 4.2 K. As seen from the data shown in Fig. 1, intermediate warming to $T_{\text{int}} \lesssim 30$ K does not affect the conductivity of well-cleaved samples. An abrupt increase in conductivity occurs for heating in the interval $35° \leqslant T \leqslant 45$ K.

For $T_{\text{int}} > 40$ K the surface conductivity is

$$\sigma_s = (3 - 5) \cdot 10^{-4} \text{ Ohm.}^{-1}$$

which is ten times greater than the minimum metallic conductivity value in a two-dimensional medium. The value of σ_s does not depend on the type of conductivity and the impurity concentration in the original crystal, nor on the cleaving quality, and is equal to the conductivity of germanium bicrystals with large inclination angles. It remains constant for several hours, as long as there is liquid helium in the cryostat.

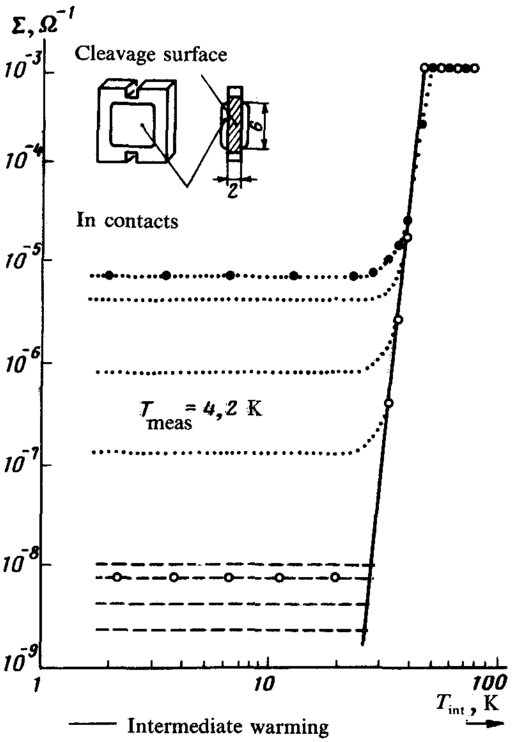

FIG. 1. Conductivity, measured at $T = 4.2$ K, as a function of the intermediate warming temperature T_{int}, ○—on a sample with mirror surface, ●—with a rough surface. (The sample dimensions and the contact arrangement are given in the upper part of Fig. 1).---is the volume conductivity of germanium with different impurity concentrations, —is the surface conductivity of well-cleaved samples,·····is the surface conductivity of samples with defect surfaces.

If a sample with a freshly cleaved surface is removed from the cryostat, and then the measurements are repeated in liquid helium, its properties depend on the length of its exposure to air. A brief exposure, less than 30 sec, leads to an increase of the surface conductivity to values of $\sigma \sim 1 \times 10^{-4}$ ohm^{-1}, but a longer exposure—in excess of 2 minutes—leads to its complete disappearance. Two effects are obviously superimposed here—warming and contamination.

The measurement results shown in Fig. 1 were obtained in weak electric fields. In stronger fields, $E \gtrsim 5$ V/cm, as is known, impact ionization of the impurities occurs in germanium. The $I(E)$ relationship for a freshly cleaved n-Ge sample is represented by curve 1 in Fig. 2. Just as before cleaving an abrupt current increase, due to impact ionization, begins in a field $E \approx 5$ V/cm. The I vs. E curves of the sample before and after cleaving coincide within the entire region of currents studied from 10^{-9} to 10^{-2} A.

If these same measurements are made on a sample after cleaving and intermediate warming to $T_{int} = 50$ K, then, as seen from the measurement results shown in this same Fig. 2, the current through the sample is a sum of the volume current, caused by impact ionization, and the surface current, increasing proportionally to the applied voltage. The linear dependence of the surface current on the voltage is maintained to fields that exceed the breakdown value by a factor of two. It is obvious that impact ionization of the impurities has no influence on the surface current value. The same

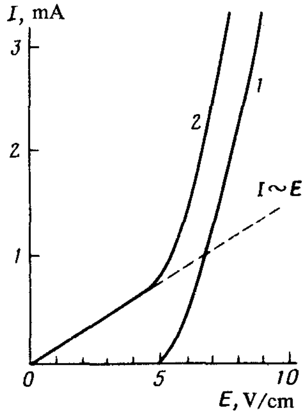

FIG. 2. $I(E)$ relationship in an n-Ge sample at $T = 4.2$ K. 1—for freshly cleaved sample, 2—after intermediate warming to 50 K (the $I \sim E$ relationship for $E > 5$ V/cm is obtained by subtracting curve 1 from curve 2).

results were obtained on p-type samples. Thus, the considerable increase in the density of free electrons or holes during breakdown does not affect the value of the surface conductivity that we are measuring.

The data presented on the conductivity of freshly cleaved germanium surfaces apply to samples with a mirror-smooth surface along the (111) cleavage plane. In the case of a rough uneven surface having steps and other defects which are formed during the cleavage of samples that have been oriented insufficiently precisely, a high conductivity is observed immediately after cleavage in the liquid helium. Depending on the type of surface imperfection, the conductivity has values from 10^{-7} to 3×10^{-5} ohm^{-1}. On some such surfaces the conductivity in the helium increases slightly with time, starting from the moment of cleavage. On all samples with a defect surface considerable residual photoconductivity is observed after illumination with visible light. After an intermediate warming above 40 K the conductivity of the samples is the same for surfaces with a rough and a mirror-smooth surface.

For ideal cleavage of germanium along the (111) plane one paired valence bond is broken at each surface atom. It is extremely probable that the free bonds formed during cleaving in liquid helium are paired to adjacent atoms, forming a double-bond surface that is sufficiently strong to be preserved at $T = 4.2$ K and does not contribute to transport phenomena.

The breaking of these bonds, occurring on the surfaces having an imperfect structure with step and other dislocation-like defects and also during the intermediate warming, lead to the appearance of a surface conductivity, the nature of which is apparently similar to the conductivity on the joining plane of germanium bicrystals.[1]

[1]B.M. Vul and E.I. Zavaritskaya, Zh. Eksp. Teor. Fiz. **76**, 1089 (1979) [Sov. Phys. JETP **49**,551 (1979)].