Electrical conductivity of a cleaved (111) face of germanium

V. Yu. Aristov, V. I. Tal'yanskiĭ, and A. A. Kharlamov
Institute of Solid State Physics, Academy of Sciences of the USSR

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The electrical conductivity of the germanium (111) face formed by cleavage at liquid-helium temperature in high vacuum increases sharply and irreversibly after heating to $T \sim 70$ K. The temperature at which this irreversible increase occurs is strongly dependent on the medium in contact with the crystal. It is suggested that the observed effect results from an irreversible restructuring of the (111) face.

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It has been reported previously[1-3] that the surface electrical conductivity of germanium (111) faces cleaved in liquid helium increases irreversibly to $\sigma \sim 10^{-4}$ mho when the crystals are heated to $T \sim 40$ K. We have suggested[2] that this irreversible increase in surface conductivity results from structural changes at the (111) face.

Cleaving the crystal in liquid helium is believed to produce an atomically clean surface. If the crystal is subsequently heated in gaseous helium, however, there is still the possibility that a gaseous impurity resulting from "defrosting" will affect the electrical properties of the surface. In this letter we are reporting an attempt to determine the role played by this impurity atmosphere. We have made a comparative study of the temperature dependence of the conductivity of germanium (111) faces formed by cleavage in liquid helium and in high vacuum, at $p = 10^{-9}$ Torr. For the measurements in high vacuum the germanium crystals were placed in a helium cryogenic pump, where the crystals were cleaved and the temperature dependence of their conductivity was measured.

The germanium samples used in Refs. 1-5 were doped with shallow centers, so that the volume conductivity which arose upon heating prevented direct measurement of the temperature of the surface conductivity. All the measurements were thus taken at $T = 4.2$ K, and only the irreversible change in the surface conductivity after a heating and recooling could be measured. This change was measured for various values of the temperature reached during the heating step. In the present experiments we have attempted to avoid this procedure by using gold-doped n-type germanium with $N_{Au} = 3 \times 10^{15}$ cm^{-3} and $N_{Sb} = 5 \times 10^{15}$ cm^{-3}. The volume conductivity of these crystals can be ignored essentially up to $T \sim 100$ K, so that the temperature dependence of the surface conductivity can be measured directly.

The procedure for forming the (111) surface by cleavage was similar to that described in Ref. 2. The samples had dimensions of $1.5 \times 2 \times 8$ mm. Contacts for the electrical measurements were fabricated by thermocompression bonding of gold to two opposite faces of the sample. These contacts were ohmic over the temperature

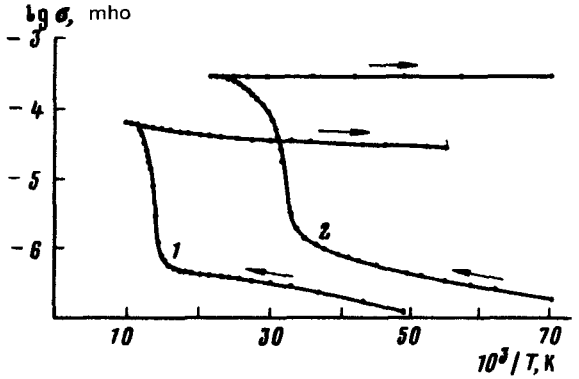

FIG. 1. Temperature dependence of the electrical conductivity of the germanium (111) face after low-temperature cleavage. 1–In high vacuum (cleavage at $T = 18$ K); 2–in a helium atmosphere (cleavage at $T = 4.2$ K).

range studied, from 4.2 to 100 K.

The experimental results are shown in Figs. 1 and 2. Figure 1 shows the temperature dependence of the surface conductivity in the case of low-temperature cleavage in high vacuum (curve 1) and in helium (curve 2). Shown here is the temperature dependence as the sample is heated immediately after the cleavage and also the reverse path, corresponding to the cooling of the samples after the irreversible increase in the conductivity. The most important result of these measurements is that in the high-vacuum case the irreversible conductivity increase occurs near $T = 70$ K, while in the helium case it occurs near $T = 40$ K. Figure 2 shows the results found after crystals were cleaved at temperatures above 70 K in high vacuum. In this case the surface conductivity arose instantaneously and then remained constant, if the sample was held at a constant temperature. Before the cleavage, the conductivity at these tem-

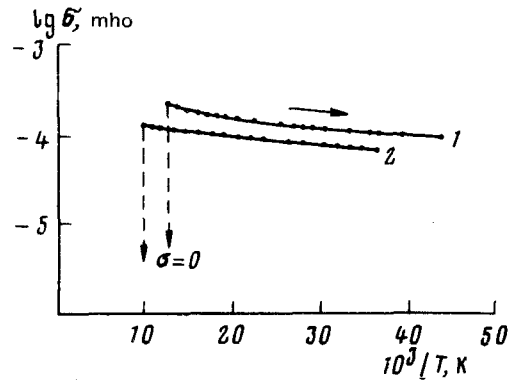

FIG. 2. Temperature dependence of the electrical conductivity of the germanium (111) face after high-temperature cleavage in high vacuum. 1–Cleavage at $T = 80$ K; 2–cleavage at $T = 100$ K.

peratures was so low as to be negligible in comparison with the surface conductivity that arose (a nominal value of the conductivity before cleavage is indicated in Fig. 2). The temperature dependence of the surface conductivity, as shown by curves 1 and 2 in Fig. 2, is similar to that of the surface conductivity after heating in high vacuum (the reverse path of curve 1 in Fig. 1). After the irreversible increase in the surface conductivity resulting from the heating (curve 1 in Fig. 1) and after the high-temperature cleavage (curves 1 and 2 in Fig. 2) in high vacuum, the temperature dependence of the surface conductivity reflects some sort of activation process, although the conductivity was essentially independent of the temperature in the experiments in the helium atmosphere (the reverse path of curve 2 in Fig. 1).

The present measurements show that the results of Refs. 1-5 were affected by the adsorption of some gases from the gaseous helium atmosphere. Hydrogen was apparently adsorbed in substantial amounts in Refs. 1-5, since hydrogen begins to "defrost" at temperatures above $T = 20$ K—i.e., in the temperature range in which the surface conductivity increased irreversibly in Refs. 1-5. Unfortunately, we cannot completely rule out the possibility that adsorption is also having an effect in the present experiments, but we believe that another mechanism, not involving adsorption, may be responsible. As in Ref. 2, we may suggest that different surface structures form on the germanium (111) face, depending on the cleavage temperature. We believe that different surface conductivities can correspond to these different surface structures and that the effects observed in the present experiments may result from a restructuring of the (111) face. The results of the present experiments seem to point to such a structural transition. We intend to pursue the matter by simultaneously studying the structure and electrical properties of the same germanium (111) face without disrupting the ultrahigh vacuum.

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