Electrical conductivity of a low-temperature two-dimensional medium

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(Submitted 3 December 1982)
Pis'ma Zh. Eksp. Teor. Fiz. **37**, No. 2, 87–89 (20 January 1983)

The surface conductivity $\sigma_\Box$ of the (111) face of a germanium crystal has been studied over the temperature (T) interval from 1.2 to 4.2 K. At $\sigma_\Box \lesssim (e^2/h)$ the surface conductivity $\sigma_\Box$ varies in proportion to $\exp(-\epsilon/kT)$, where e is the electron charge, h is the Planck constant, and ϵ is the activation energy. At $\sigma_\Box \gtrsim (e^2/h)$ the behavior of the conductivity is described by $\Delta\sigma = \sigma_\Box(T_1) - \sigma_\Box(T) \simeq (e^2/4h)\ln(T_1/T)$ as the temperature is lowered from $T_1 = 4.2$ K to 1.2 K. In the transition region the $\sigma_\Box(T)$ dependence agrees quite well with both descriptions.

PACS numbers: 73.25. + i

Two-dimensional electrical conductivity at low temperatures has recently attracted considerable interest; a review[1] of the electronic properties of two-dimensional systems published in April 1982 covers more than 2000 articles. There is special interest in the nature of the metal-insulator transition, which has been the subject of many theoretical and experimental studies of metal-insulator-semiconductor structures and thin metal films.

 0021-3640/83/020105-04$01.00

We report here a study of the conductivity in the two-dimensional system formed near the (111) face of a germanium single crystal. The samples are prepared from n-type crystals with a room-temperature resistivity of 20–40 Ω cm. Fresh surfaces are prepared by cleaving the crystals in liquid helium and holding them there for up to 10 days, a time sufficient for the entire program of measurements for each sample.

Immediately after the crystals are cleaved in liquid helium, the surface conductivity is so low as to be indistinguishable against the volume resistance, on the order of 10^8–10^9 Ω. The surface properties are changed by intervals of heating in helium vapor at various temperatures and for various times.[2] After the first heating interval, for 3–5 min at $T_i \simeq 40$ K, the surface conductivity reaches a maximum value

$$\sigma_\square \simeq 4\times 10^{-4}\ \Omega^{-1} \quad \text{at} \quad T = 4.2\text{K}. \tag{1}$$

In the subsequent heating intervals, the sample is raised to $T_i \simeq 85$ K, with the result that the surface conductivity gradually decreases.

The conductivity $\sigma_\square$ is measured after each heating interval with the sample immersed in liquid helium, at the normal saturation vapor pressure of the helium and at a reduced pressure, so that the temperature can be changed from 4.2 to 1.15 K. Figure 1 shows the results of the measurements of $\sigma_\square = f(1/T)$. We see that the T dependence of $\sigma_\square$ in this temperature interval is described by

$$\sigma_i = A_i \exp\left(-\frac{\epsilon_i}{kT}\right), \tag{2}$$

where i is the curve label, ϵ_i is analogous to an activation energy, k is the Boltzmann constant, and A_i is determined by extrapolating the line $\log\sigma = f(1/T)$ to the ordinate axis.

Figure 2 shows ϵ_i vs A_i. We see that ϵ_i increases with decreasing conductivity. Extrapolation of the linear part of the $\epsilon_i(A_i)$ curve at values $\epsilon_i \geqslant kT$ to the abscissa axis yields

$$\sigma_\square \simeq \sigma_{min} \approx e^2/h \simeq 4\times 10^{-5}\ \Omega^{-1}, \tag{3}$$

where $\sigma_{\min}$ is the minimum metallic conductivity.

The same value, $\sigma_\square \simeq \sigma_{\min}$, can be found by extrapolating to the abscissa axis in Fig. 2 if we plot along this axis the values of $\sigma_\square$ measured for an arbitrary T over the temperature interval studied.

Simple calculations show that the transition from a conductivity of one type, "metallic," to another type, "activated," occurs in a two-dimensional medium at the conductivity value e^2/h, which is independent of the properties of the material. According to the experiments, however, a sharp transition of this type is not observed, and the value $\sigma_{\min} \simeq e^2/h$ can be obtained only through an extrapolation, as shown in Fig. 2.

The temperature dependence of the conductivity at values $\sigma_\square > e^2/h$ is attributed to a "weak" localization and an interaction of electrons. Regardless of the initial physical arguments, it is concluded that the conductivity decreases with decreasing temperature in proportion to $\ln T$. This dependence has been the subject of many

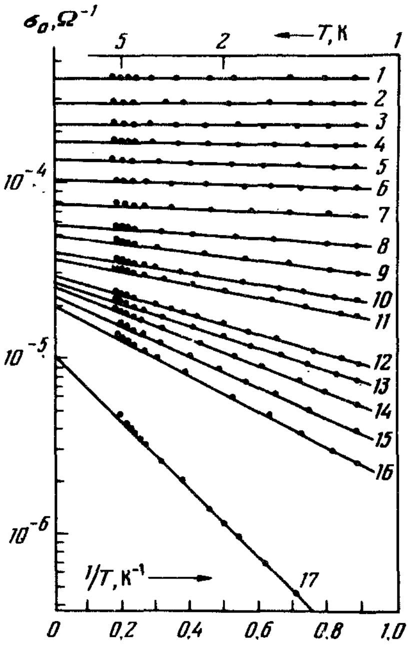

Fig. 1.

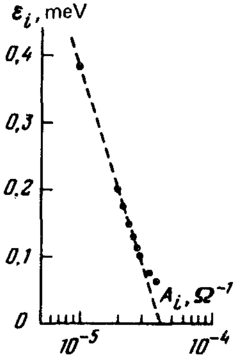

Fig. 2

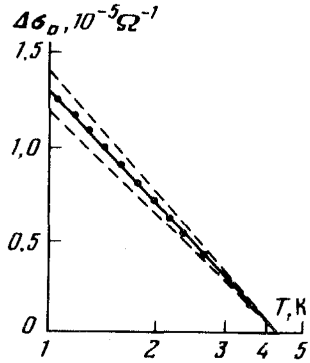

Fig. 3

Fig. 1. Temperature dependence of the surface electrical conductivity $\sigma_\square$ after the sample is heated in helium vapor. The curve label increases with increasing number of heating events.

Fig. 2. The "activation energy" ϵ_i vs the coefficient of the exponential function, A_i.

Fig. 3. Temperature dependence of $\Delta\sigma = \sigma_\square(4.2\text{K}) - \sigma_\square(T)$ for one of the samples. The temperature scale is logarithmic. The dashed lines are the boundaries of the region containing the fan of lines calculated from the experimental data (1–15) in Fig. 1.

recent theoretical papers, which are reviewed in Ref. 1. In particular, it follows from Eq. (5.10) in Ref. 1 (p. 527) that as the temperature is reduced from T_1 to T the quasimetallic two-dimensional conductivity decreases by an amount

$$\Delta\sigma = \sigma_\square(T_1) - \sigma_\square(T) = C\frac{e^2}{\pi^2\hbar}\ln\frac{T_1}{T}, \quad (4)$$

where the coefficient C is defined in various ways, depending on the initial assumptions.[3,4]

Values of $\Delta\sigma = \sigma_\square(4.2\text{ K}) - \sigma_\square(T)$ were determined from the data in Fig. 1. It can be seen from the data in Fig. 3 that as the temperature is lowered from 4.2 to 1.15 K the conductivity of germanium decreases by approximately the same amount,

$$\Delta\sigma \simeq (1.2\text{–}1.3)\times 10^{-5}, \quad (5)$$

regardless of the absolute value of the surface conductivity at $T = 4.2$ K over the interval from 40×10^{-5} to $2\times 10^{-5}\ \Omega^{-1}$.

The change $\Delta\sigma$ caused by the temperature change corresponds to (4) with the coefficient $C = 0.37 \pm 0.03$.

The coefficient C in (4) thus remains the same not only at high values of the conductivity—at metallic levels—but also at values of $\sigma_\square(4.2\ \mathrm{K})$ half as large as $\sigma_{\min}$.

Comparison of the results in Figs. 1, 2, and 3 shows that at $\sigma_\square < \sigma_{\min}$ the conductivity is described by an activation law with comparatively low binding energies ϵ_i, on the order of kT. At $\sigma_\square > \sigma_{\min}$ the changes in the conductivity are determined by the effects discussed in Refs. 3 and 4. At intermediate values, the two types of behavior overlap. Where different T dependences of σ overlap for a bounded temperature interval, the choice between them must be based on physical considerations. At $\sigma_\square \simeq \sigma_{\min}$, the experimental results should evidently be interpreted on the basis of the theory of Refs. 3 and 4.

The particular conditions chosen for these measurements have certain advantages for studying the conductivity in disordered media. In a one-dimensional medium, it is not possible to circumvent localization centers, while in a three-dimensional medium the probability becomes quite high, so that experiments at low temperatures, under conditions such that the motion may be regarded as two-dimensional, tends to bring out the basic behavior of the electronic phenomena. Furthermore, in a two-dimensional medium the state density does not depend on the electron energy. This circumstance simplifies the calculations and introduces the quantity e^2/h as a measure of the conductivity; this quantity is independent of the properties of the medium, determined exclusively by fundamental constants.

We wish to thank B. L. Al'tshuler, A. G. Aronov, A. I. Larkin, and D. E. Khmel'nitskiĭ for a discussion of these results.

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Translated by Dave Parsons
Edited by S. J. Amoretty