Temperature dependence of Hall's coefficient at the cleavage surface of germanium in liquid helium

É. I. Zavaritskaya
P. N. Lebedev Physics Institute, Academy of Sciences of the USSR

(Submitted 8 February 1984)
Pis'ma Zh. Eksp. Teor. Fiz. **39**, No. 7, 311–314 (10 April 1984)

The temperature dependence of Hall's coefficient R_H and of the electrical conductivity $\sigma_\square$ in the temperature interval $1.15 \leqslant T \leqslant 4.2$ K in a two-dimensional semimetallic system formed at the cleavage surface of germanium is studied. It is shown that the temperature corrections to Hall's coefficient ΔR_H increase with decreasing T proportionally to $\ln T$, just as $\Delta\sigma$ in this region of T, and their ratio satisfies the condition $(\Delta R_H/R_H) = -\alpha(\Delta\sigma/\sigma)$, where $1 < \alpha \leqslant 2$. This situation indicates that the interelectronic interaction[3] is the dominant contribution to the transport of holes at the cleavage surface of germanium.

Experiments have shown[1] that in the two-dimensional system formed at the cleavage surface of germanium single crystals the conductivity $\sigma_\square$ decreases logarithmically with decreasing temperature, and the quantity is

$$\Delta\sigma \equiv [\sigma_\square(T_1) - \sigma_\square(T)] \simeq 1\times10^{-5} \ln\frac{T_1}{T}, \quad \Omega^{-1}, \tag{1}$$

irrespective of the initial electrical conductivity σ_0 in the range

$$2\times10^{-5} \leqslant \sigma_0 \leqslant 40\times10^{-5}, \quad \Omega^{-1},$$

where $\sigma_0 \equiv \sigma_\square$ (4.2 K) is the resistivity at $T_1 = 4.2$ K.

The results of the measurements[1] agree well with both the localization theory[2] and the interaction theory.[3] The quantum correction to the semimetallic conductivity in a two-dimensional medium, according to Refs. 2 and 3, has the form

$$\Delta\sigma = C\frac{e^2}{\pi h}\ln\frac{T_1}{T}, \quad \Omega^{-1}, \tag{2}$$

where e is the charge of an electron, h is Planck's constant, and C is a constant which depends on the starting assumptions of the theory, but in both cases can assume a value $C \simeq 0.8$, for which relations (1) and (2) coincide. Under these conditions it is impossible to determine which of the physical effects, that of Ref. 2 or that of Ref. 3, actually plays a role in the transport of carriers at the cleavage surface of Ge.

It is known, however, that the contributions to Hall's coefficient from these effects are markedly different. If localization dominates,[2] then the decrease of $\sigma_\square$ is related to the decrease in the mobility of the carriers, rather than to their concentration, and Hall's coefficient does not depend on T.

Under conditions when interelectronic interaction is important,[3] Hall's constant contains an additional term, ΔR_H, which, just as $\Delta\sigma$ in relation (2), varies logarithmically with decreasing T, and the following relation is satisfied:

$$\frac{\Delta R_H}{R_H} = -2\frac{\Delta\sigma}{\sigma}\ . \tag{3}$$

Under these conditions it is important to investigate Hall's coefficient R_H and the dependence $R_H = f(T)$. The results of these measurements are presented in this paper.

The starting germanium crystals were of n type with room-temperature resistivity 200–400 Ω·cm. The crystals were cleaved in liquid helium. The properties of the surface were changed by intermediate annealing in helium vapor at different temperatures T_i and durations of heating.[4] After the first annealing at $T_i = 400$ K the surface conductivity reached the maximum value σ_0 $(3\text{–}4)\times 10^{-4}\ \Omega^{-1}$. Subsequent annealings performed at $T_i \approx 85$ K, led to a gradual decrease of the surface conductivity.

The electrical conductivity $\sigma_\square$ and Hall's coefficient R_H were measured after each annealing for specimens immersed in liquid helium. the measurements were performed at temperatures ranging from 1.15 to 4.2 K.

After each of the 18 successive annealings, the electrical conductivity of the cleavage surface assumed a new value, which did not differ very much from the preceding value. In this manner the following interval was filled:

$$6\times 10^{-7} \leqslant \sigma_0 \leqslant 4\times 10^{-4}\ ,\ \Omega^{-1}\ .$$

Measurements of Hall's coefficient were performed after the first 16 annealings of the surface, in magnetic fields H up to 20 kOe. The relation between the quantities σ_0 and R_H at $T = 4.2$ K is denoted by the dashed curve 1 in Fig. 1a.

From the dependence $R_H = f(\sigma_0)$, shown in Fig. 1a, it follows that the decrease of the surface conductivity in the range $5\times 10^{-5} \leqslant \sigma_0 \leqslant 30\times 10^{-5}\ \Omega^{-1}$ observed after the annealings is due primarily to the decrease of the carrier concentration. In this interval of σ_0 the concentration decreases more than fourfold, and the mobility of holes decreases by approximately a factor of 1.5 from 240 to 170 cm^2/V·s. At $\sigma_0 < 5\times 10^{-5}$ Ω^{-1} the decrease in the conductivity is caused by the sharp decrease of the mobility, $\mu = R_H\sigma$, with the hole concentration remaining essentially constant, $p_c \simeq 1.9\times 10^{12}$ cm^{-2}.

Measurements of Hall's coefficient in the temperature range $1.15 \leqslant T \leqslant 4.2$ K showed that the quantities $(R_H)_i$, while not revealing an appreciable dependence on the magnetic field intensity and the current density, increase with decreasing temperature in proportion to the logarithm of T, as predicted in Ref. 3, but the coefficient of proportionality between the quantities $\Delta R_H/R_H$ and $\Delta\sigma/\sigma$ is not a constant quantity, which is evident from the dependences of the relative quantities, shown in Fig. 1,

$$\frac{\Delta R_H}{R_H} \equiv \frac{R_H(1.15\text{K}) - R_H(4.2\text{K})}{R_H(1.15\text{K})};\quad \frac{\Delta\sigma}{\sigma} \equiv \frac{\sigma_\square(4.2\text{K}) - \sigma_\square(1.15\text{K})}{\sigma_\square(4.2\text{K})};\quad \alpha = \frac{\Delta R_H}{R_H} \Big/ \frac{\Delta\sigma}{\sigma}$$

on the starting electrical conductivity σ_0.

These dependences have a break at some characteristic magnitude of the electrical conductivity, $\sigma_0 \simeq 4\times 10^{-5}\ \Omega^{-1}$, which agrees with the minimum metallic conductiv-

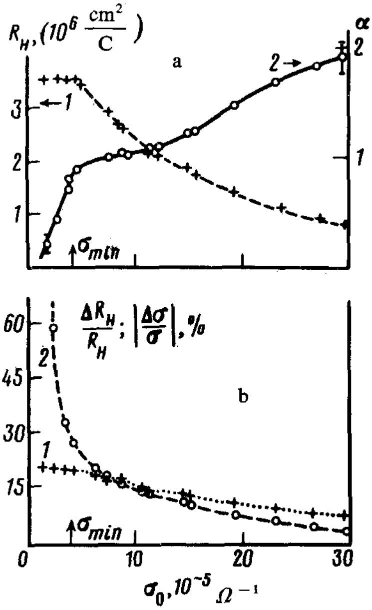

FIG. 1. Dependence of the surface electrical conductivity σ_0 at $T = 4.2$ K. a) Hall's coefficient R_H (+); the coefficient $\alpha = (\Delta R_H/R_H)/(\Delta\sigma/\sigma)$ (O); b) corrections to Hall's coefficient $(\Delta R_H/R_H) = [R_H(1.15\ \text{K}) - R_H(4.2\ \text{K})]/[R_H(1.15\ \text{K})]$ (+); corrections to the electrical conductivity $\Delta\sigma/\sigma = [\sigma_\square(4.2\ \text{K}) - \sigma_\square(1.15\ \text{K})/\sigma_\square(4.2\ \text{K})]$ (O).

ity, $\sigma_{\min} \simeq e^2/h$, predicted by Mott.[5] The entire interval of σ_0 studied by us separates, in accordance with Mott's concept ion, into two regions: a semimetallic region with $\sigma_0 \geqslant \sigma_{\min}$ and a nonmetallic region with $\sigma_0 < \sigma_{\min}$.

In the region of semimetallic conductivity the temperature correction to the electrical conductivity is

$$\Delta\sigma \simeq \frac{e^2}{\pi h} \ln\frac{T_1}{T} \simeq 1\times10^{-5}\ \ln\frac{T_1}{T},\ \Omega^{-1}, \qquad (4)$$

and the correction to Hall's coefficient is

$$\frac{\Delta R_H}{R_H} = -\alpha\frac{\Delta\sigma}{\sigma}, \qquad (5)$$

where $1 < \alpha \leqslant 2$. In this case the measured values of $\Delta\sigma$ are in agreement with those of Ref. 3, up to electrical conductivities $\sigma_0 \simeq 0.5\sigma_{\min}$, and the values of α agree with the "double-slope rule" predicted in Ref. 3 only under conditions of strong degeneracy, with $\sigma_0 \geqslant 3\times10^{-4}\ \Omega^{-1}$. With decreasing σ_0, the quantity α decreases, but these variations of α are small and do not exceed a factor of two in the entire region of semimetallic conductivity down to $\sigma_0 \simeq \sigma_{\min}$. The corrections to Hall's coefficient, ΔR_H and $\Delta R_H/R_H$, increase under these conditions.

It follows from these data that the interelectronic interaction plays an appreciable

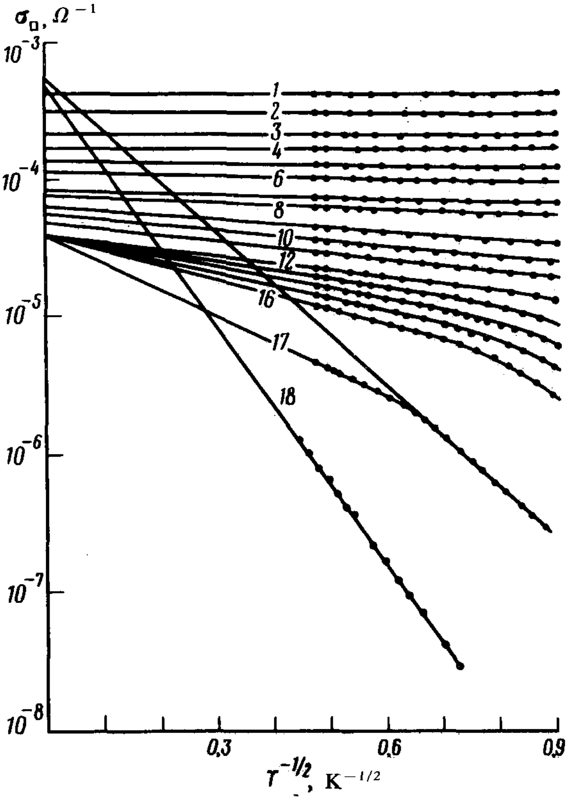

FIG. 2. Temperature dependence of the surface conductivity $\sigma_\square$ after annealing of specimens in helium vapor. The higher the number of the curve, the larger is the number of annealings to which the specimen was subjected.

role not only in the region of metallic conductivity but also for values of $\sigma_0 < \sigma_{\min}$, when the electrical conductivity is realized by "hops" from one localized state to another. The probability of such hops is proportional to

$$\exp\left(-\frac{L}{L_0}\right)\exp\left(-\frac{W_a}{kT}\right), \tag{6}$$

where L_0 is the localization length of the wave function, L is the hopping distance of an electron, and W_a is the activation energy.

Under conditions when Coulomb interaction dominates, we would have $W_a \simeq e^2/\kappa L$, the length of the optimum hop would be $L_c = (e^2 L_0/\kappa T)^{1/2}$, and the temperature dependence of the electrical conductivity would be[6]

$$\sigma = \sigma_e \exp[-(T_0/T)^{1/2}], \tag{7}$$

where σ_e is a preexponential factor, κ is the dielectric constant, and $T_0 = 4e^2/\kappa L_0$.[7]

To reveal regularities of this type, the results of the measurements of the surface conductivity are represented in Fig. 2 as the dependence $\log\sigma_\square$ as a function of $1/\sqrt{T}$.

As is evident from these data, the 18 experimental curves form three families, rather than two, as expected for a sharp boundary corresponding to $\sigma_{\min}$.

The first group of curves (1–11), which corresponds to the region of semimetallic conductivity, is described by the dependence (4).

The last two curves (17 and 18) refer to the region of "strong" localization, which is characterized by the dependence (7), where $\sigma_e \simeq 10^{-3}\ \Omega^{-1}$, and the effective temperature T_0 reaches values of 100–200 K.

The curves (12–16) form the "intermediate" region, which simultaneously satisfies the conditions of semimetallic conductivity (4) and conductivity which can be described by the dependence

$$\sigma = \sigma_{\min} \exp[-(T^*/T)^{1/2}] \tag{8}$$

with an effective temperature T^* of the order of 2–6 K.

This dependence, which has been observed in specimens $\sigma_0 = (2\text{–}4)\times 10^{-5}\ \Omega^{-1}$, corresponds to the very narrow range of energies lying next to the interface between the localized and delocalized states in the hole energy spectrum. The "intermediate" region is presumably attributable to transient conditions corresponding to a transition from a double spin degeneracy, characteristic for the region of metallic conductivity, to a single degeneracy which occurs when there is a localization.

These systematic features can be analyzed in greater detail by extending the studies involving $\sigma_\Box$ to lower as well as higher temperatures.

The authors than B. M. Vul for his constant interest in this work and for his support, A. I. Larkin and D. E. Khmel'nitskiĭ for a discussion of the results, and V. N. Zavaritskiĭ for assistance in the experiment.

[1] B. M. Vul, É. I. Zavaritskaya, and V. N. Zavaritskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **37**, 87 (1983) [JETP Lett. **37**, 105 (1983)].

[2] P. W. Anderson, E. Abrahams, D. C. Licciardello, and T. V. Ramakrishnan, Phys. Rev. Lett. **42**, 673 (1979); Phys. Rev. Lett. **43**, 718 (1979).

[3] B. L. Al'tshuler and A. G. Aronov, Zh. Eksp. Teor. Fiz. **77**, 2028 (1979) [Sov. Phys. JETP **50**, 968 (1979)]; B. L. Al'tshuler, A. G. Aronov, and P. A. Lee, Phys. Rev. Lett. **44**, 11288 (1980).

[4] B. M. Vul, É. I. Zavaritskaya, and V. I. Zavaritskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **34**, 371 (1981) [JETP Lett. **34**, 353 (1981)]; *ibid.* **35**, 209 (1982) [*ibid.* **35**, 259 (1982)].

[5] N. F. Mott and E. A. Davis, Electronic Processes in Noncrystalline Materials, Clarendon Press, Oxford, 1979.

[6] B. I. Shklovskiĭ and A. L. Éfros, Élektronnye svoĭstva legirovannykh poluprovodnikov (Electronic Properties of Doped Semiconductors), Nauka, Moscow, 1979.

[7] A. I. Larkin and D. E. Khmel'nitskiĭ, Zh. Eksp. Teor. Fiz. **83**, 1140 (1982) [Sov. Phys JETP **56**, 647 (1982)].

Translated by M. E. Alferieff
Edited by S. J. Amoretty