Negative magnetoresistance in *n*-type germanium and its analysis based on quantum theory of this effect

T. A. Polyanskaya and I. I. Saĭdashev
A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR

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A comparison of the experimental and theoretical data shows that the effect of interelectronic repulsion on magnetoresistance must be taken into account. The interaction constant of electrons and the relaxation time of the wave function, which turned out to be close to the decay time of single-electron excitations, are examined.

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A new theory, whose explanation of negative magnetoresistance in strongly doped semiconductors is linked with the effect of the magnetic field on quantum corrections for the conductivity, was proposed in Refs. 1–4. The unknown parameters of the theory are the electron-electron interaction constant g and the relaxation time of the wave function of an electron τ_ϕ.

In this letter we present new experimental data of a study of negative magnetoresistance in germanium doped with antimony. The experimental procedure was described elsewhere.[5] We have measured the dependence of magnetoresistance of Hall emf on the intensity of the magnetic field H in the range $(30\text{-}5)\times 10^4$ G, and used these values to calculate the variation of conductivity in the magnetic field $\Delta\sigma_e(H) = \sigma_e(H) - \sigma_e(0)$. The quantum correction for the conductivity $\Delta\sigma_q(H)$ was calculated as the difference

$$\Delta\sigma_q(H) = \Delta\sigma_e(H) - \Delta\sigma_c(H), \tag{1}$$

where $\Delta\sigma_c(H)$ is the classical part of the permeance calculated in the approximation $\epsilon_F/kT \gg 1$ (ϵ_F is the Fermi energy). The experimental dependences (1) were compared with the theoretical dependences calculated for the case of noninteracting electrons[2]

$$\Delta\sigma_f = a_f c_q \sum_i D_i\, f(b_i H\tau_\phi/\hbar) \tag{2}$$

and with allowance for electron-electron interaction[3]

$$\Delta\sigma_\phi = a_\phi c_q \sum_i D_i\, \phi\,(b_i H/2\pi kT), \tag{3}$$

where $c_q = (e^2/2\pi^2\hbar)\sqrt{\hbar c/eH}$, $a_f = 1 - \beta(g)$, $a_\phi = -g$, and the $f(x)$, $\phi(x)$, and $\beta(g)$ functions are given in Refs. 2, 3, and 4, respectively. D_i and b_i are determined by the diffusion-coefficient tensor, and the summation is carried out over the four ellipsoids of the isoenergentic surface of germanium.[3] In the calculations g and τ_ϕ remained free

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parameters.

Figure 1 shows the experimental curves 1 for the samples with an electron density in the range $3.7 \times 10^{17} - 5 \times 10^{18}$ cm^{-3}. This figure also shows the $\Delta\sigma_f(H)$ curves for the case of noninteracting electrons 2. The values of τ_ϕ, which were used in their calculation, are shown in Fig. 2a. The coefficient a_f (curve 2) turned out to be equal to 0.4-0.5 for all the samples. As is evident in Fig. 1, the permeance observed experimentally is described well by the theory, which ignores the interaction between electrons[2] in a magnetic field $0.03 < H < 3$ kG, within a broad range of variation of $\Delta\sigma_q$ [2-3.5 orders of magnitude (see Fig. 1)]. However, at $H > 3$ kG the experimental permeance increases slower with the magnetic field than that predicted theoretically for noninteracting electrons. We can assume that this discrepancy is associated with the electron repulsion. The interaction constant in this case is $g > 0$, and the conductivity associated with the interaction 3 decreases with increasing mag-

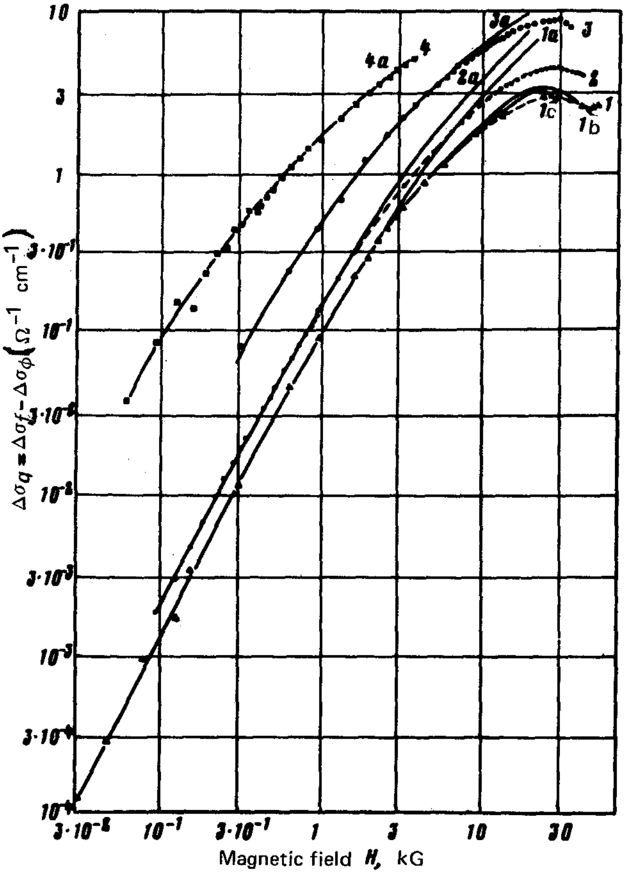

FIG. 1. Variation of conductivity $\Delta\sigma_q(H)$ in a magnetic field (dotted and dashed curves) for samples with densities $n = 1/eR_H$ (10^{17} cm^{-3}). 1–3.7, 2–5.5, 3–11, 4–52, measured at $T = 4.2$ K. The theoretical curves (straight lines) for $\Delta\sigma_f(H)$. 1a–4a, $\Delta\sigma_f(H) + \Delta\sigma_\phi(H)$; 1b–$a_\phi = -0.25$; 1c–$a_\phi = -0.3$.

netic field ($\Delta\sigma_\phi < 0$). Figure 1 shows the theoretical curves $\Delta\sigma_f(H) + \Delta\sigma_\phi(H)$, calculated for the sample with a density $n \sim 3.7 \times 10^{17}$ cm^{-3} for the values $a_\phi = -0.25$ and -0.3. As is evident in this figure, a much better agreement between theory and experiment can be obtained within the range of the magnetic fields 3-30 kG by assuming that the electrons repel each other and by taking into account the corresponding effect of $\Delta\sigma_\phi(H)$ on the variation of the conductivity with the magnetic field. The coefficients $a_\phi(3)$ and $a_f(2)$ obtained by us are difficult to compare, since the $\beta(g)$ dependence for the positive values of g ($g > 0.1$) was not analyzed in Ref. 4.

The experimental values of τ_ϕ (Fig. 2a) were compared 1) with the damping time of single-electron excitations in the presence of defects that limit the length of the mean free path of an electron, $\tau_{ee}^{(2)} \equiv \tau'_\phi \sim T^{3/2}/\epsilon_F^2$ (Ref. 6) and 2) with the relaxation time of the wave function under the conditions of a quasielastic electron-phonon interaction τ''_ϕ.[3] In our case, $\tau''_\phi \sim \tau_{\rm ph}$, since the following inequality is correct: $\tau_{\rm ph} s\epsilon_F/v_F > 1$, where $\tau_{\rm ph}^{-1}$ is the electron-phonon collision frequency, s is the velocity of sound, and v_F is the velocity of an electron with an energy ϵ_F.

Figure 2a shows the values of τ'_ϕ and $\tau_{\rm ph}$, which were calculated for the samples under investigation. We can see that the experimental values of τ_ϕ in the region of low electron densities are close to the values of τ'_ϕ, and for electron densities $n \sim 5 \times 10^{18}$ cm^{-3} ($\epsilon_F \sim 200$ K) they are close to the value of $\tau_{\rm ph}$. The dashed curve in Fig. 2a represents the sum $\hbar/\tau'_\phi + \hbar/\tau_{\rm ph}$, which describes well the behavior of the experimental curve $\hbar/\tau_\phi(\epsilon_F)$.

The temperature dependence τ_ϕ was estimated from measurements of the magnetoresistance of a sample with a density $n \sim 5.5 \times 10^{17}$ cm^{-3} in the temperature range 1.8-4.2 K in weak magnetic fields (Fig. 3). As $H \to 0$ $\Delta\rho/\rho_0 \sim H^2$, as predicted theoretically. Since the effect associated with the interaction, as $H \to 0$, is small with respect to the parameter $\sim (\hbar/2\pi kT\tau_\phi)^{3/2}$, we can disregard it, and we have $-\Delta\rho/\rho_0 H^2 \approx \Delta\sigma_f/\sigma_0 H^2 \sim \tau_\phi^{3/2}$.[2,3] The temperature dependence of $\hbar/\tau_\phi$ obtained in this manner

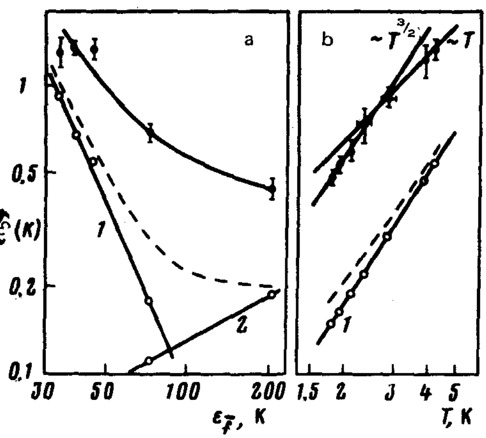

FIG. 2. (a) Dependence of the inverse relaxation time $\hbar/\tau$(K) on the Fermi energy ϵ_F(K) and (b) on temperature T(K). (•)–experimental values ($\hbar/\tau_\phi$), ○–theoretical values. 1–$\hbar/\tau'_\phi$, 2–$\hbar/\tau_{\rm ph}$; the dashed curves represent the sum ($\hbar/\tau'_\phi + \hbar/\tau_{\rm ph}$).

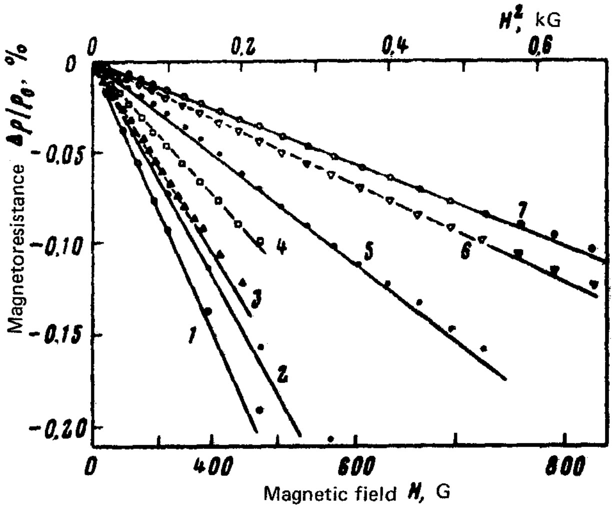

FIG. 3. Dependence of the magnetoresistance on the magnetic field squared, measured at the following temperatures T(K): 1–1.8, 2–1.9, 3–2.1, 4–2.3, 5–2.8, 6–3.9, and 7–4.2.

is shown in Fig. 2b, together with the calculated dependence $\hbar/\tau'_\phi(T)$ for the same sample, which turned out to be close to the experimental value.

In summary, we can draw the following conclusions from the study conducted by us. 1) The new theory of negative magnetoresistance[2,3] is in good agreement with the results of the experiment; moreover, a contribution to the magnetoresistance due to interelectronic repulsion has been observed in the region of magnetic fields $H > 3$ kG (Ref. 3); 2) the relaxation time of the wave function, τ_ϕ, and its temperature and density dependences are comparable with the decay time τ'_ϕ of single-electron excitations[4] for electron densities $n < 10^{18}$ cm^{-3} and with the relaxation time due to electron-phonon interaction[3] for $n > 10^{18}$ cm^{-3}.

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