Negative magnetoresistance of compensated germanium with deep impurities

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A negative magnetoresistance of compensated germanium with deep charged impurities has been observed during photoexcitation. The effect is attributed to an Anderson localization of conduction electrons in the Coulomb potential of charged impurities.

1. In the present experiments we studied n-type germanium crystals containing copper and compensated with antimony in such a manner that the upper level of the copper ($E_c - 0.26$ eV) was approximately half-filled. The copper concentration was $\sim 10^{15}$ cm^{-3}. At low temperatures T the resistance of these samples is very large, so that the conductivity is produced by impurity illumination through a germanium filter at room temperature. The sample is in a gas-exchange helium optical cryostat between the pole tips of an electromagnet, which can produce magnetic fields H up to 4 KOe. Auxiliary coils produce an alternating field $\tilde{H} = 8.7$ Oe. We measure the direct current through the sample, i, and the alternating current $\tilde{i}$, caused by a modulation of the magnetic field. Under the condition $\tilde{H} \ll H$ the alternating current is $\tilde{i} = \tilde{H} di/dH$, and from the dependence $\tilde{i}(H)$ we find the H dependence of the relative magnetoconductivity, $[i(H) - i(0)]i(0)$.

At $T \lesssim 20$K the magnetoresistance is negative. Figure 1 shows $\tilde{i}/i$ versus H at various values of T; Fig. 2 shows corresponding curves of the magnetoconductivity reconstructed from the curves in Fig. 1. Let us examine the basic features of these curves. From Fig. 2 we see that there is a region of classically weak fields H [$\mu H/c \ll 1$;

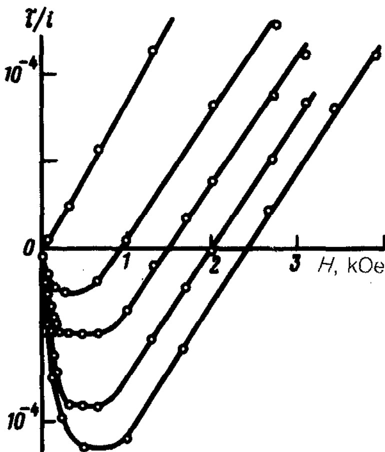

FIG. 1. $\tilde{i}/i$ versus the magnetic field at various temperatures T, K: 1—10.9; 2—12.6; 3—15.2; 4—10.4; 5—32.

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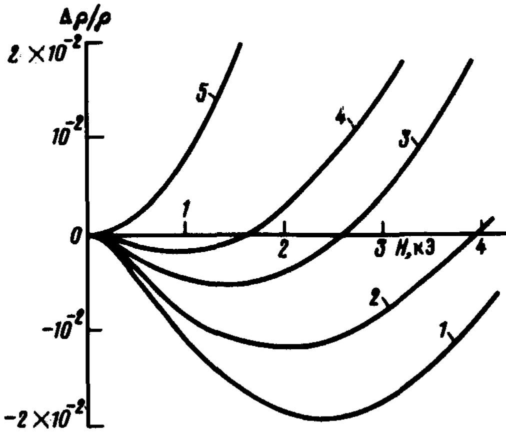

FIG. 2. Magnetoresistance versus the magnetic field. T, K: 1—10.9; 2—12.6; 3—15.2; 4—20.4; 5—32.

the mobility μ found from the magnetoresistance reaches a maximum $\sim 6.5\times 10^3$ $cm^2/(V\cdot s)$ at $T\approx 70$ K], in which the magnetoconductivity is negative. The value of the field at which the magnetoresistance changes sign, H_c, decreases with increasing temperature. There is a corresponding decrease in the maximum value of the negative magnetoresistance. The differential magnetoconductivity di/dH (Fig. 1) is negative at small values of H, and with increasing H it goes onto a linearly increasing region, where the sign changes.

2. A negative magnetoresistance has been observed repeatedly in heavily doped semiconductors and metals (see, for example, Ref. 1 and the bibliography there). It is presently attributed to either a decrease in the quantum corrections to the conductivity in a magnetic field[2] or a shift in a magnetic field of the mobility threshold upon a metal-insulator transition.[3,4] In our case, the negative magnetoresistance is observed in a classical semiconductor, in which the Fermi level is deep in the energy gap, and the conductivity results from the photoexcitation of electrons into the conduction band, where they have a Boltzmann energy distribution. Even in this case, however, there is a mobility threshold for the electrons in the conduction band, determined by the condition $\lambda\sim l$ (λ is the wavelength of the electron, and l is the mean free path) or, equivalently, $e_\lambda\sim h/\tau$, where τ is the mean free time. Electrons with an energy $\epsilon<\epsilon_\lambda$ are localized and do not participate in the conductivity; as the temperature is lowered, and the relation $kT<\epsilon_\lambda$ becomes satisfied, the only photoexcited carriers which participate in the conductivity are those that make up an exponentially decreasing fraction with $\epsilon>\epsilon_\lambda$. The strong impurity scattering due to multiply charged copper ions (Cu^{2-} and Cu^{3-}) maintains the condition $\lambda\sim l$ for electrons with $\epsilon\gtrsim kT$ at rather high values of T. A localization of electrons occurs in the small-scale Coulomb potential of the charged impurities, since at low values of T there is no large-scale potential when the deep impurity is half full.[5]

The existence of a mobility threshold is confirmed by the temperature dependence of the conductivity σ shown in Fig. 3. Below ~ 100 K, the electron density is controlled by the optical excitation of electrons from impurities, and σ increases with

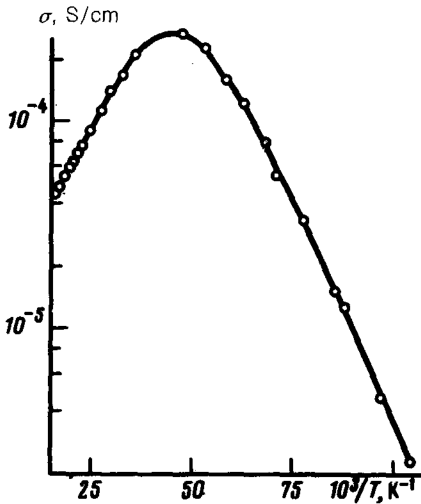

FIG. 3. Temperature dependence of the conductivity of the sample.

decreasing T because of the decrease in the probability for trapping by repulsive copper ions.[6] At $T \lesssim 20$ K we observe an exponential decrease in σ with an activation energy ~ 8 meV. This activation region cannot be attributed to a freezing out of electrons at shallow donors (antimony), since the low density of free carriers, $n(\sim 10^{10} - 10^{12}\ \mathrm{cm}^{-3})$, means that the attachment to antimony should begin at far lower T. A necessary condition here is $n \approx n_1$, where $n_1 = N_c \exp(-\epsilon_D/kT)$ is the Shockley-Read factor, and ϵ_D is the donor ionization energy. This condition yields $T \lesssim 5$ K for the freezing out of antimony. There is also direct experimental proof that the low-temperature activation region is unrelated to the antimony: The activation energy decreases with increasing electric field.

We attribute the activated decrease in the conductivity to the freezing out of photoexcited electrons below the localization energy ϵ_λ. An exponential region can be seen on the $\sigma(T)$ curve only if the temperature dependence of the lifetime essentially disappears at $T \lesssim 20$ K. The reason may be that at low T the distance from a free electron to the impurity center is limited by the mean distance between impurities.

As was shown in Refs. 3 and 4, the localization energy ϵ_λ should decrease in a magnetic field, leading to a decrease in σ and thus a negative magnetoresistance. On the other hand, electrons with $\epsilon > \epsilon_\lambda$ make a positive contribution to the magnetoresistance. The competition between these two mechanisms determines the resultant magnitude of the magnetoresistance. As the magnetic field is increased, the H dependence of the negative magnetoresistance should weaken,[2] and the magnetoresistance should change sign.

The region of a liner increase in $\tilde{i}$ in "strong" fields H (Fig. 1) is due exclusively to the positive contribution to the magnetoresistance from electrons with $\epsilon > \epsilon_\lambda$. In this case the slope of the region should correspond to the mobility of electrons with $\epsilon \approx \epsilon_\lambda$. Indeed, if we determine μ from this slope, using the expression $\tilde{i}/i\tilde{H} = d[r_M(\mu H/c)^2]/dH$ (with $r_M = 1$), we find $\mu \approx (6.2 - 6.7) \times 10^3\ \mathrm{cm}^2/(\mathrm{Vs})$.

This result corresponds to the mobility of electrons which was determined in the same sample from the magnetoresistance at liquid-helium temperature. On the other hand, the same results can be used to find the estimate $\epsilon_\lambda \sim h/\tau = he/\mu m \approx 6$ meV. This result is close to the observed activation energy.

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