Anomalous magnetoresistance of plastically deformed germanium

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The observation of an anomalous positive magnetoresistance in single crystals of strongly deformed germanium is reported. The results are discussed within the framework of the weak-localization and electron-electron interaction theories.

Disordered systems of different dimensionality have been extensively investigated in recent years. Experimental work on this class of substances was greatly stimulated by the creation of the theory of weak localization of electrons (WLE) and the theory of electron-electron interaction (EEI), which explained the nature of the anomalous magnetoresistance (AMR) in semiconductors and metals as well as a number of other phenomena.[1]

In this paper we will attempt to determine whether quantum coherent phenomena (WLE, EEI) affect the kinetic electronic properties of strongly deformed Ge, which has an appreciable dislocation dc conductivity at low temperatures.[2]

For this purpose, we measured the dc resistance (R) of specimens of strongly plastically deformed Ge in the temperature (T) range 0.6–10 K for different magnetic field intensities H (from 0 to 20 kOe). The measurements were performed in a setup in which He^3 was evacuated. The temperature was determined with a semiconducting resistance thermometer and from the He^3 vapor pressure. The magnetic field was created with a superconducting solenoid. Highly pure crystals of p-type Ge with a fine acceptor concentration $\simeq 10^{12}$ cm^{-3} were used. The plastic deformation was realized by compression along the $\langle 100 \rangle$ direction, under conditions of dynamic loading with a velocity of 10–20 μm/min at $T = 750\,^\circ\mathrm{C}$ in a vacuum of $\sim 10^{-2}$ mm Hg, to a degree of deformation $\epsilon = 25$–40%.

An investigation of the temperature dependent $R(T)$ at $H = 0$ showed that the law $R(T) \sim T^{-y}$, where $y \simeq 0.1$, is satisfied for the indicated degrees of deformation in the temperature range 0.6–10 K. It should be noted that the functional dependence of $R(T)$ agrees with the data in Refs. 2–4, but the minimum value of y obtained in Ref. 3 was 0.5. This difference could be related to the specific characteristics of the dislocation structure and the density and distribution of dislocations.[1)]

We shall now describe the results of investigations of the transverse magnetoresistance $R(H)$. To measure $R(H)$, a signal proportional to the magnetic field was supplied to the horizontal axis of an automatic plotter and a signal proportional to the voltage on the specimen, from which we subtracted the voltage in the absence of a magnetic field at the given temperature and constant measuring current $I = 9$ μA, was supplied to the vertical axis. The curves obtained in this manner, which reflect the change in the resistance in a magnetic field $\Delta R(H) = R(H) - R(0)$ at different values of T for a Ge specimen with $\epsilon = 27\%$, are shown in Fig. 1.

We note the following characteristics of these curves.

1. The sign of the magnetoresistance is positive for all values of H.

2. An appreciable positive magnetoresistance (PMR) is observed for small $H \sim 10^2$ Oe (see also Fig. 2). As H is raised, an inflection appears on the curves, after which the dependence $\Delta R(H)$ weakens and gradually moves toward the asymptotic region.

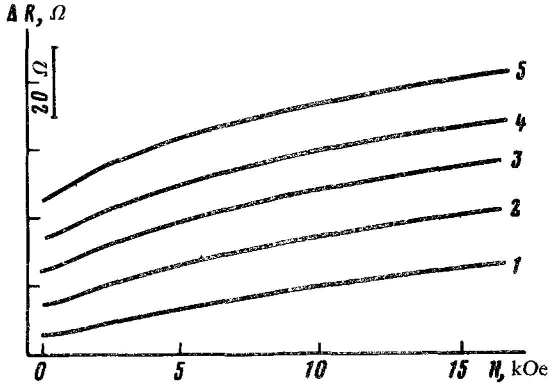

FIG. 1. Magnetoresistance of a Ge specimen with $\epsilon = 27\%$ ($R_{4.2\,\mathrm{K}} = 395\,\Omega$, $\rho_{4.2\,\mathrm{K}} = 6.3\,\Omega\cdot\mathrm{cm}$) at different temperatures. 1) $T = 2.4$ K, 2) 1.47 K, 3) 1.0 K, 4) 0.75 K, 5) 0.6 K. For clarity, the curves are displaced along the vertical axis.

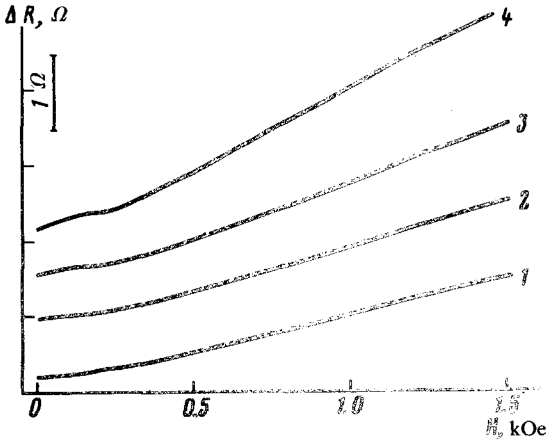

FIG. 2. Magnetoresistance of a Ge specimen with $\epsilon = 38\%$ ($R_{4.2\,\mathrm{K}} = 196\ \Omega$, $\rho_{4.2\,\mathrm{K}} = 5.8\ \Omega\cdot\mathrm{cm}$) in weak fields at the following temperatures. 1) $T = 2.25$ K, 2) 1.92 K, 3) 1.3 K, 4) 0.65 K.

3. As the temperature is lowered, the absolute value of PMR increases. In addition, the dependence $\Delta R\,(H)$ becomes stronger in weak fields ($H < 10^3$ Oe) and in stronger fields ($H \sim 10^4$ Oe) the slope of the curves $\Delta R\,(H)$ is nearly independent of the temperature.

As ϵ is increased, all the characteristic features of the curves $\Delta R\,(H)$ remain, but for weak fields (~ 10–10^3 Oe) a "fine structure" is sometimes observed on the curves (see Fig. 2, which shows the data for a Ge specimen with $\epsilon = 38\%$).

Let us discuss the results obtained. According to Ref. 2, the low temperature dc conductivity in strongly deformed Ge is related to the motion of holes along a system of disordered intersecting dislocation lines. In this case the following processes, which determine the dependence of $R\,(T)$ and of PMR of the specimens investigated, can occur in principle: Anderson localization, classical conductivity and magnetoresistance, as well as WLE and EEI. The weak power-law dependence of $R\,(T)$ and the shape of the curves $\Delta R\,(H)$ indicate that there is no Anderson localization.[6,5] Within the framework of the classical models (under conditions such that Hall's constant remains the same in strongly deformed Ge at low temperature[2]) it would appear that the observed growth of $R\,(T)$ is due to a decrease of the mean free path. If it is assumed that the magnetic field affects the carrier trajectories, the dependence $\Delta R\,(H)$ would then have to weaken with decreasing temperature [and increasing $R\,(T)$], which contradicts our experimental data (see curve 2, in Fig. 1). On the other hand, it is precisely the appearance of AMR in the region of classically weak fields (10^1–10^4 Oe) and its temperature dependence that agree with the experimental results obtained in semiconductors in other cases, for example, in Refs. 8 and 7, and can be explained in terms of WLE and EEI. For this reason, because of the generality of the theory of quantum coherent phenomena,[1] it is useful to use this theory to discuss AMR in plastically strongly deformed Ge.

According to Ref. 1, the characteristic magnetic fields H^0, in which the magnetoresistance reaches its asymptotic level, usually differ considerably in the case of WLE and EEI, and in particular $H^0_{\mathrm{EEI}} \gg H^0_{\mathrm{WLE}}$. Based on the experimental results obtained, this makes it possible for us to concentrate at first on the theory of WLE in analyzing the observed AMR. Comparison of the curves $\Delta R\,(H,T)$ obtained on the basis of the theory of WLE in semiconductors,[1] shows that the sign of the magnetoresistance, its temperature dependence, the asymptotic behavior of the curves at $H \sim 10^4$ Oe, and the temperature-independence of the slope of $\Delta R\,(H)$ in these fields are in qualitative agreement with the predictions of the theory for noninteracting electrons in the two-dimensional case,

$$G(H) - G(0) = c_2 \frac{e^2}{2\pi^2\hbar} f_2\left(\frac{4DeH}{\hbar c}\,\tau_\phi\right), \tag{1}$$

$$f_2(x) = \begin{cases} x^2/24 & x \ll 1 \\ \ln x & x \gg 1 \end{cases}.$$

Here $G(H) = 1/R^{\square}(H)$ is the conductivity "on a square" in a magnetic field, τ_ϕ is the relaxation time of the phase of the wave function due to inelastic collisions, D is the coefficient of diffusion of electrons, and $c_2 = -1/4$ for p-Ge, corresponding to PMR.

The temperature dependence of $\Delta R\,(H)$ in the limit of weak fields, according to (1), is determined by the temperature dependence of $[\tau_\phi(T)]^2$ with constant coefficient of diffusion D. Under the assumption that $\tau_\phi \sim T^{-p}$, we determined the values of p from experimental data for weak fields (Fig. 3): $p = 0.47$ and 0.37 for specimens with $\epsilon = 27\%$ and 37%, respectively. The dependence $\tau_\phi \sim T^{-0.5}$ was obtained theoretically in Ref. 9, where the elastic scattering due to electron-electron interaction was examined in the one-dimensional case. If the proximity of the experimental values of p to 0.5 is not accidental, then we can assume that in plastically deformed Ge the different dimensionality of the dislocation structure is manifested in different processes [change in R in a magnetic field, temperature dependence of $\Delta R\,(H)$]. In addition,

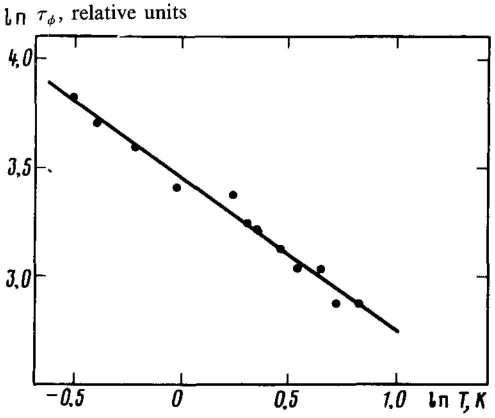

FIG. 3. Temperature dependence of the phase relaxation time τ_ϕ for a Ge specimen with $\epsilon = 27\%$.

quantum coherent phenomena (WLE, EEI) apparently also affect the temperature dependence of dislocation conductivity in the absence of a magnetic field. We plan to analyze these problems in greater detail in the future.

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1)The results of an electron-microscope study of the dislocation structure of deformed Ge will be presented in subsequent publications.

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