Dislocation Hall effect in germanium

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The Hall emf was measured down to 4.2 K in the region of dislocation conductivity of a germanium sample that was plastically strained severely. A dislocation conductivity model is discussed.

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Previously,[1] we reported the observation of a low-temperature *dc* conductivity in plastically strained, *p*-type germanium. This conductivity differs from the conductivity produced by free current carriers in that it has a weak temperature dependence and no Hall effect. We assumed that these peculiarities are due to the presence of a specific dislocation conductivity (*DC*). The existence of conductivity along the dislocations has been confirmed in observations of the peculiarities of *uhf* conductivity in *n*- and *p*-type germanium with dislocations.[2,3] It was found that the *uhf* conductivity of germanium samples, which contain an ordered system of dislocations, also has a very weak temperature dependence at low temperatures, is anisotropic and its anisotropy corresponds to that of the dislocation structure (*D* structure). The absence of Hall effect in crystals with an ordered dislocation structure made it impossible to determine the type of current carriers in such quasi-one-dimensional dislocation conductivity. However, knowledge of the sign and magnitude of the Hall *emf* is very important for understanding the structure of electron-energy spectrum and the electrical conductivity mechanism in semiconductors with dislocations.

Because of this, we have assumed that if a system of dislocations with a high density is produced in a crystal and if the mobility of the current carriers along the dislocations is sufficient, then it will still be possible to produce a measurable net Hall *emf* and, consequently, to determine the sign of the current carriers of the dislocation conductivity by applying the required magnetic field. The experiments, whose results are reported below, were set up in this manner.

The *dc* electrical properties were measured in germanium that was severely plastically strained at 750°C. Preliminary electron-microscopic studies showed that the *D* structure of our samples is very complicated and, in general, is a developed system of dislocations whose degree of connectedness increases with increasing degree of deformation δ. High-purity *n*- and *p*-type germanium with donor and acceptor densities $N_d = 3\times10^{12}\text{cm}^{-3}$ and $N_a = 1\times10^{12}\text{cm}^{-3}$, respectively, was used for the most part.

The main result of the measurements shows that a Hall *emf*, which is easily measurable down to 4.2 K, appears in severely strained samples ($\delta = 50$–70%) and that after the strain all the samples, regardless of the original type of conductivity, exhibit hole-type conductivity in the entire temperature range in which the Hall *emf* was measured. These results are shown in Fig. 1.

Curves 1-4 represent n-type samples with a 10-45% strain. As the temperature is decreased from 300 K, the density of the holes in the valence band decreases; this is manifested by an increase of the Hall coefficient with a certain activation energy ξ_a. The Hall coefficient, which is characterized by anomalous behavior in the temperature range $50 \lesssim T \lesssim 100$K and intermediate strain $\delta = 16$–45%, is dependent on the magnetic field intensity $\mathscr{H}$ (it decreases drastically with increasing $\mathscr{H}$ from 0.05 to 0.7 T), and with a further decrease in temperature ($T < 50$K) the Hall *emf* decreases rapidly and ceases to be measurable. This corresponds to the discontinuity of the curves 1–4 in Fig. 1.

A different picture is observed for n- and p-type samples for 50–70% strain (curves 5, 6, and 7). The $R\,(1/T)$ curve rises at temperatures above 50 K, but the Hall coefficient remains the same with further decrease of temperature, becomes independent of the temperature, and can be easily measured to a temperature of 4.2 K. It behaves normally in this temperature region, does not depend on the intensity of either the electric or magnetic field and, as mentioned above, its sign corresponds to hole conductivity. The sign of the thermo emf, measured in the sample 5 to 4.2 K, also corresponds to hole-type conductivity.

It must also be noted that as the strain increases from 10% to 70% in the band-conductivity region ($T > 50$K), the activation energy $\mathscr{E}_a$, as follows from the data of Fig. 1, decreases from 0.07 eV in the sample 1 to 0.03 eV in the sample 6.

The dependences of conductivity on the strain and temperature are shown in Fig. 2 for these samples. It can be seen that the conductivity increases with increasing strain, but its temperature dependence becomes weaker and disappears almost com-

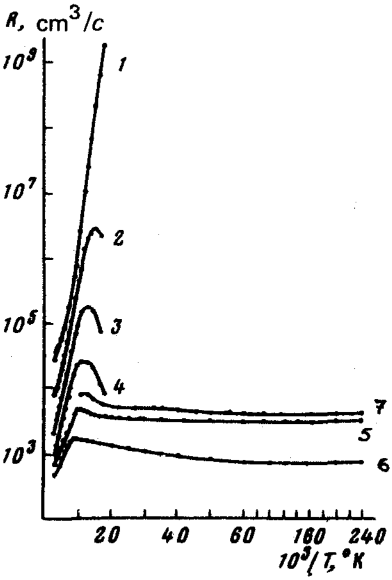

FIG. 1. Temperature dependence of the Hall coefficient in strained samples of n-type germanium with $N_d = 3\times10^{12}\text{cm}^{-3}$ and with different degrees of strain δ: 1, 10%; 2, 16%; 3, 35%; 4, 45%; 5, 50%; 6, 70% and in a p-type sample 7 with $N_a = 1\times10^{12}\text{cm}^{-3}$ and $\delta = 56\%$ for a magnetic-field intensity $\mathscr{H} = 0.7T$.

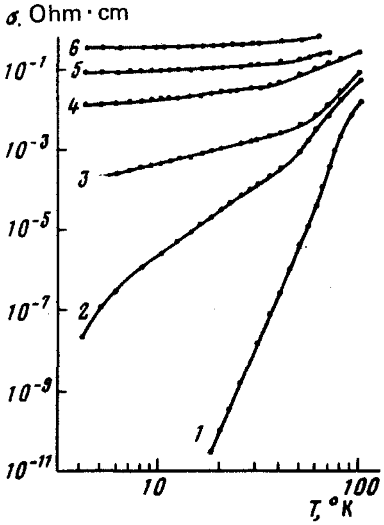

FIG. 2. Temperature dependence of electrical conductivity in the samples 1–6.

pletely at $\delta = 70\%$. We note that the temperature dependence of the Hall coefficient is similar to that of the *DC* for *p*-type samples with $N_a = 1 \times 10^{12} \text{cm}^{-3}$ and $\delta = 10$–70%.

Proceeding to a discussion of the obtained results, we assume that they can be explained systematically within the framework of the *DC* model on the basis of the dislocation energy spectrum suggested in Refs. 4 and 5. This energy-spectrum scheme is based on the fact that the band of electron energies E_1 of the dislocation broken

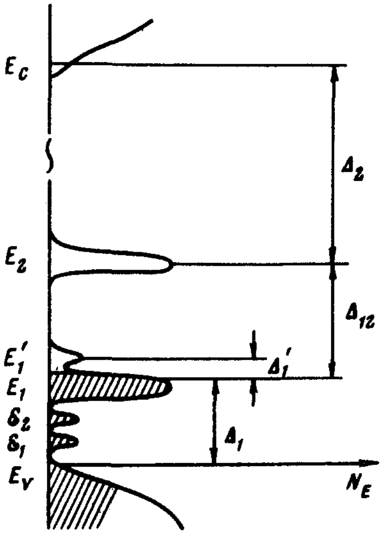

FIG. 3. Energy diagram of *D* states in germanium according to Refs. 4 and 5. Here N_E is the density of states, $\Delta_1 = 0.07$ eV, $\Delta_1' < 0.03$ eV, $\Delta_{12} = 0.18$ eV, and $\Delta_2 = 0.49$ eV.

bonds and the band of energies E_2 of the extra electrons trapped in these bonds are separated by an energy gap Δ_{12}. However, there are electron states in the dislocations whose energies lie below E_1 — these are electrons that are localized at singular sites along the dislocations, such as breaks, bends and crossing points. By analogy with E_1 and E_2, they form the ϵ_1 and ϵ_2 states for the intrinsic and captured electrons (Fig. 3). The number of such states is strongly dependent on the characteristics of the dislocation structure, i.e., on the degree and type of strain. For a severe strain with $\delta = 50$–70% the number of singular sites at the dislocations — dislocation defects (*DD*) — is much greater than the number of donors in our samples. This means that all the donor electrons and some of the electrons from the E_1 band are captured in the ϵ_2 states and the holes are formed in the E_1 band. Since these holes are the current carriers of the *DC*, we can see the corresponding sign of the Hall coefficient. Since the Fermi level decreases somewhat as a result of capture of electrons from the E_1 band to the ϵ_2 state, we can see a decrease of the band-conductivity activation energy with increasing strain. However, the Fermi level remains in the forbidden band, in contrast to the conductivity along the boundary of a germanium bicrystal.[6]

The temperature dependence of the *DC* can be described by empirical formulas of the type $\sigma \sim T^y$ with $y = 0.15$–1.5. We can formulate from this dependence the *DC* (jump, band, etc.) just as in the physics of three-dimensional disordered systems,[7] but a dearth of experimental data for the dislocation structure and for the electrical properties frees us to limit ourselves to a qualitative picture.

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