Peculiarities of electrical conductivity of plastically deformed *n*-type germanium

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A minimum in the temperature dependence of the electrical conductivity when direct current is applied perpendicular to the dislocations was observed in a plastically deformed *n*-type germanium at 35 K. This effect is attributable to the presence at the same temperature of a maximum in the electron filling coefficient of the dislocations.

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In this paper we investigate the dc conductivity of plastically deformed *n*-type germanium with a concentration of uncompensated donors $N_d = 2.4 \times 10^{13}$ cm^{-3} and with a fairly well-ordered, anisotropic structure of 60° dislocations of density $N_d \approx 2\text{–}7 \times 10^6$ cm^{-2}. We have shown experimentally[1] that such samples have non-conducting cylinders surrounding the dislocations (D cylinders).

Under conditions such that Ohm's law holds we determined the electrical conductivity parallel ($\sigma_{\parallel}$) and perpendicular ($\sigma_{\perp}$) to the main direction of dislocations in the temperature interval 4.2–300 K.

As follows from Fig. 1 the conductivity of the strained samples depends on the

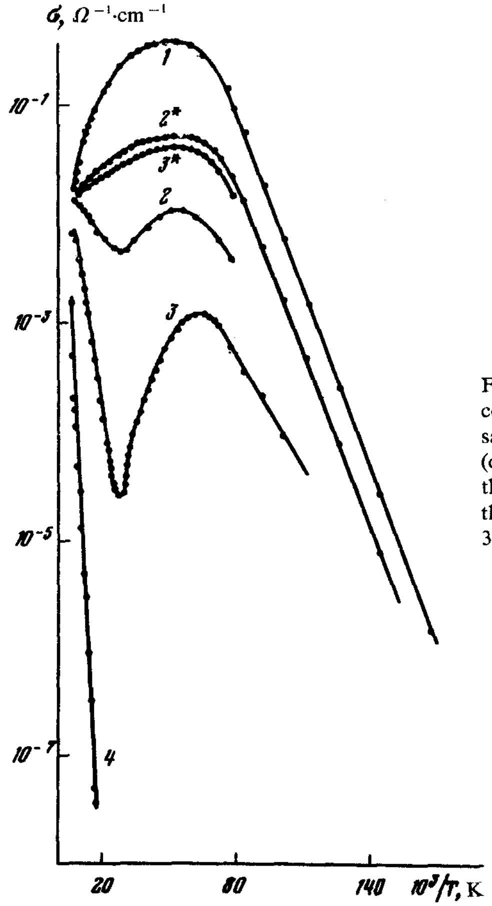

FIG. 1. Temperature dependence of the electrical conductivity in the control (1) and strained (2–4) samples when the electric field is directed along (curves 2* and 3*) and perpendicular (curves 2–4) to the main direction of the dislocation. The density of the dislocations in samples 2–4 is 3.0×10^6 cm^{-2}, 3.8×10^6 cm^{-2}, and 5.2×10^6 cm^{-2}, respectively.

direction of the electric field relative to the direction of the dislocations. The anisotropy **σ**, which is noticeable at $T\approx240$ K, increases with decreasing temperature. At elevated temperatures the difference between $\sigma_{\parallel}$ and $\sigma_{\perp}$ can be observed with increasing N_D. The temperature dependence of the conductivity σ_0 of the control sample is qualitatively similar to the $\sigma_{\parallel}$ conductivity. The appearance of a minimum at $T\approx35$ K is a characteristic feature of $\sigma_{\perp}(T)$. A clear minimum in $\sigma_{\perp}(T)$ was observed in the samples in which the D cylinders occupied more than a fraction $\epsilon=\frac{1}{2}$ of their volume. For $\epsilon\approx0.8$–0.9 the depth of the minimum is about two orders of magnitude (curve 3 in Fig. 1). In sample 4 the conductivity $\sigma_{\perp}$ decreases sharply at high temperatures and at $T=50$ K it reaches a value of $\sim10^{-9}$ Ω·cm, i.e., at low temperatures the sample is a dielectric. At $N_D>6\times10^6$ cm^{-2}, however, the conductivity is inverted in the samples.

Notice that there are two other peculiarities of $\sigma_{\perp}$, not previously observed in germanium in the temperature range 20–60 K. 1) The dependence of $\sigma_{\perp}$ on the rate N of temperature variation of the samples during the measurements for $v>1$ deg/min, and an almost total absence of this dependence for $\sigma_{\parallel}$. For example, with a cooling

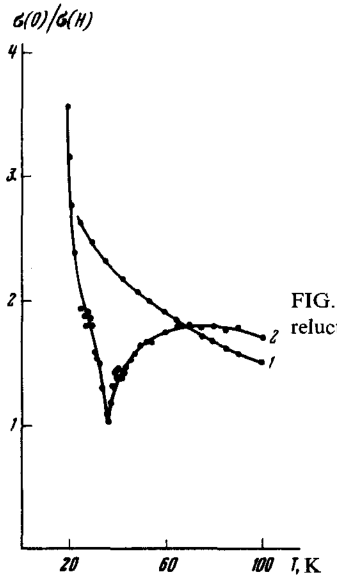

FIG. 2. Temperature dependence of the coefficient of relative transverse reluctance $K_{\perp}$ (curve 1) and $K_{\parallel}$ (curve 2) for sample 3.

rate $v = 1$ deg/min, $\sigma_{\perp}$ for sample 3 at 35 K is twice as large as the $\sigma_{\perp}$ obtained when $v = 5$ deg/min. 2) The presence of a minimum at 35 K in the temperature dependence of the relative reluctance coefficient $K_{\perp} = \sigma_{\perp}(0)/\sigma_{\perp}(H)$ in the samples, with a deep minimum in $\sigma_{\perp}(T)$ (Fig. 2) as a result of the monotonic increase of $K_{\parallel} = \sigma_{\parallel}(0)/\sigma_{\parallel}(H)$ in the same temperature interval. A 7-kG magnetic field was directed perpendicular to the dislocation lines and to the electric field

At 35 K the samples with $\epsilon \approx 0.5$–0.6 also have a minimum in the temperature dependence of the Hall electron mobility. At $\epsilon > 0.6$ the Hall effect could be measured reliably only at $T \gtrsim 60$ K.

The sizable value of $\sigma_{\parallel}$ at the temperatures investigated, the electrical breakdown at 4.2 K in ~ 2 V/cm field along the dislocations, and the negative values of the Hall coefficient indicate that only a fraction of the volume of samples 2 and 3 is occupied by the D cylinders, i.e., the conductivity is produced by the free electrons outside of the cylinders.

As shown by Read[2] and Logan *et al.*,[3] D cylinders placed perpendicular to the direction of motion of the electrons serve both to bend the current lines (the so-called bending effect) and to decrease the mean free path of the electrons because of their collision with the D cylinders. Estimates show that at $T \approx 35$ K the effect of these collisions on $\sigma_{\perp}$ is $\leqslant 20\%$ in our samples. Therefore, the deep minimum in $\sigma_{\perp}(T)$ cannot be attributed to the scattering of electrons by dislocations. Thus, according to Read[2]

$$\sigma_{\parallel} = \sigma_0 (1 - \epsilon), \tag{1}$$

$$\sigma_{\perp} = \sigma_0 (1 - \epsilon) \, g(\epsilon), \tag{2}$$

where $g(\epsilon)$ is a monotonically decreasing function which takes into account the distortion of the electron trajectory, whose explicit shape depends on the specific dislocation structure. The distribution of dislocations in our samples represents an intermediate case between the regular structure and randomly situated dislocations. This prevents us from using for quantitative calculations either the result of Read,[2] who gives the function $g(\epsilon)$ for a hexagonal dislocation network, or the result of Last and Thouless,[4] who investigated how the conductivity of a medium with a random distribution of the holes depends on the concentration of the holes. In any case, however, for the values of ϵ close to unity $g(\epsilon)$ must be small [for example, for an ideal D structure[2] $g(0.8) = 0.1$ and $g(0.91) = 0$]. Thus even a small change of the radius of the D cylinders sharply alters the conductivity. Therefore, as Eq. (2) shows, the minimum in $\sigma_\perp(T)$ can be attributed to the nonmonotonic dependence of $\epsilon(T)$, or specifically, to the presence of a weak maximum in $\epsilon(T)$ at $T = 35$ K.

Since ϵ is proportional to the coefficient f of occupation of the dislocation by the electrons, we can assume that at 35 K a maximum exists in the temperature dependence of f. Accordance to existing ideas,[2] however, f increases monotonically with decreasing temperature. We can therefore assume that in plastically deformed n-type germanium at 35 K a new physical process causing the required reduction of f is in effect. One such process is the rearrangement of the spectrum of the D states due to, say, a phase transition in the D-electron system.

In view of these considerations we can qualitatively explain the two properties (1) and (2).

In conclusion, we note that effects analogous to those examined in this letter might account for the Hall mobility anomalies in plastically deformed p-type germanium.[5]

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[1]A.I. Kolyubakin, Yu.A. Osip'yan, and S.A. Shevchenko, Zh. Eksp. Teor. Fiz. **7**, 9 (1979).
[2]W.T. Read, Phil. Magn. **45**, 775 (1954); **46**, 111 (1955).
[3]R.A. Logan, G.L. Pearson, and P.A. Kleinman, J. Appl. Phys. **30**, 885 (1959).
[4]B.J. Last and D.J. Thouless, Phys. Rev. Lett. **27**, 1719 (1971).
[5]Yu.A. Osip'yan and S.A. Shevchenko, Pis'ma Zh. Eksp. Teor. Fiz. **18**, 256 (1973) [JETP Lett. **18**, 153 (1973)].