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ZEEMAN EFFECT ON ACCEPTOR CENTERS AND NEGATIVE MAGNETORESISTANCE IN TELLURIUM

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Experimental data are presented to show that the negative magnetoresistance in tellurium has no noticeable anisotropy and does not differ significantly from the negative magnetoresistance in other semiconductors. On the other hand, it is shown theoretically that the Zeeman splitting of acceptor states in tellurium is essentially anisotropic and is practically nonexistent at H ' C_3. Thus, the Toyozawa's theory of negative magnetoresistance does not hold for tellurium.

Negative magnetoresistance of semiconductors was first observed in tellurium [1] and was subsequently investigated in detail both in tellurium [2, 3] and in many other semiconductors. The negative magnetoresistance effect is usually explained with the aid of Toyozawa's mechanism [4], namely the decreased scattering of carriers with spin flip by the magnetic moments of the localized electrons, owing to the splitting of the impurity levels in the magnetic field. According to [5], we have then

$$-\frac{\Delta\rho}{\rho} \sim M^2 \sim B_j(x), \tag{1}$$

where $B_j(x)$ is the Brillouin function, $x = j\mu_B gH/kT$, and $\mu^* = jg\mu_B$ is the effective magnetic moment. For a number of semiconductors, the negative magnetoresistance is approximately described by formula (1), and in this case μ^* is usually much larger than for free carriers (see, e.g., [5, 6]).

In the present communication we present experimental data, together with their quantitative analysis, which show that negative magnetoresistance in tellurium does not differ from that in other semiconductors, for H either parallel or perpendicular to C_3, and the dependence of the negative magnetoresistance on H and T in weak magnetic field is described approximately by formula (1). It follows from the theoretical calculations presented below, however, that the character of the Zeeman splitting of the impurities in tellurium is essentially different from that in other semiconductors, and cannot explain the negative magnetoresistance.

Theory. The structure of the valence band of tellurium is shown schematically in Fig. 1. Its characteristic feature is the absence of spin degeneracy of the holes [7]. The impurity levels corresponding to the extrema at the points $K_0 \pm \kappa_0$ split into symmetrical and antisymmetrical states [8]. According to [3], this splitting equals $2\Delta = 0.16$ meV at an ionization energy $E_i = 1.47$ meV. Each of these levels is doubly degenerate because of invariance and the time reversal that connects the points K_0 and $-K_0$. Calculation shows that the splitting of the impurity levels in a longitudinal magnetic field is described by the formula

$$E = \pm\left[\left(\frac{1}{2} G\mu_B H_z\right)^2 + \Delta^2 \pm G\mu_B H_z|\delta|\right]^{1/2}. \tag{2}$$

Here G is a constant that determines the relative shift of the bands at the points κ_0 and $-\kappa_0$ in a field $H \| C_3$, and $G = 5$ according to [9]; δ is a constant that determines the mixing of the

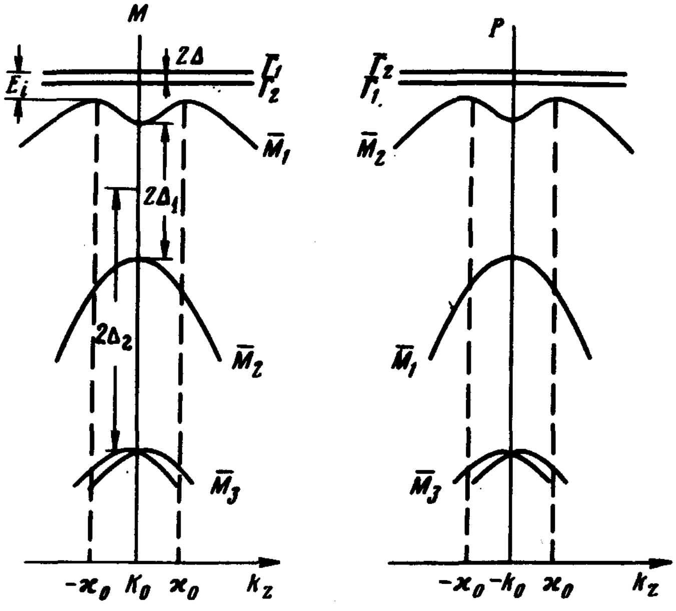

Fig. 1. Structure of valence band and of acceptor states in tellurium.

symmetrical state in K_0 - $\Gamma_1(M)$ and the antisymmetrical one in $-K_0$ - $\Gamma_1(P)$ (and vice versa) as a result of the impurity potential: $\delta/\Delta = (\kappa_0/K_0)^2\varepsilon \approx 0.1$ (ε is the dielectric constant). In a weak field, the splitting of each of the degenerate states is linear in H_z and the corresponding g factor is equal to $g_{\parallel} = G(\delta/\Delta) \cong 0.5$. At $\delta = 0$ we have $g = 0$, owing to the absence of a relative shift of the bands at the points K_0 and $-K_0$ at $H \parallel C_3$ [7]. At $H \perp C_3$, the splitting of the impurity center coincides with the shift of the bands at the points K_0 and $-K_0$, and is equal to

$$E = \pm\Delta \pm \gamma(H_+^3 + H_-^3). \tag{3}$$

An estimate shows that $\gamma \cong g\mu_B(g\mu_B/2\Delta_1)^2$; according to [7, 9] we have $g \cong 10$ and $2\Delta_1 \cong 0.2$ eV, i.e., $\gamma \cong 3\times10^{-7}$ meV/kOe^3.

In tellurium there are two possible channels for the scattering of holes by an acceptor center, one without a change in the state of the center itself, and the other with a transition of the impurity electron into a Kramers-conjugate state. Owing to the absence of spin degeneracy of the valence band, the probability of the second mechanism (which in principle can lead to negative magnetoresistance) is decreased by an amount $\Delta_2^2/(\Delta_2^2 + B^2\kappa_0^2)$, which is equal to 0.6 [7].

Experiment. Figure 2 shows the experimental data on the negative magnetoresistance of tellurium for a sample with $p = 4.6\times10^{16}$ cm^{-3} at $J \perp C_3$, $H \parallel C_3$, and $H \perp C_3$. For comparison, the figure shows also a plot of $\Delta\rho/\rho$ for an n-GaAs sample with $n = 6\times10^{16}$ cm^{-3}. These data demonstrate the low anisotropy of the negative magnetoresistance in tellurium, with a general resemblance to the negative magnetoresistance in cubic n-GaAs. The same figure shows the derivative $\partial\rho/\partial H = f(H)$, obtained by modulating the magnetic field at a depth 15 Oe. Measurement of $\partial\rho/\partial H$ permits a comparison of the experimental $\rho(H)$ with formula (1) without using the region of strong magnetic field, where the role of the Lorentz component $(\Delta\rho/\rho)_L$ becomes stronger. In the given sample, owing to the strong degeneracy, the value of $(\Delta\rho/\rho)_L$ in the region of the minimum of $\partial\rho/\partial H$ did not exceed 0.1%. We note that it was precisely the difficulty with separating $(\Delta\rho/\rho)_L$ which had previously hindered the quantitative interpretation of the negative magnetoresistance in tellurium. In Fig. 3, the results of such measurements are compared with theoretical relation $-\partial\rho/\partial H \sim [B_{1/2}^2(x)]'$. The value of μ^* was chosen to make the epxerimental and theoretical curves coincide at the maximum, namely for Te $\mu^* = 9\mu_B$ at $H \parallel C_3$ and $\mu^* = 11\mu_B$ for $H \perp C_3$. For n-GaAs we have $\mu^* = 13\mu_B$, which is close to the value $\mu^* = 10\mu_B$ cited in [10] for a sample having approximately the same concentration.

Thus, experiment shows no significant anisotropy of the negative magnetoresistance in Te; such an anisotropy is called for by the Toyozawa mechanism as a result of the strong anisotropy of the g-factor. In addition in the Toyozawa mechanism at $H \perp C_3$, when the splitting is proportional to H^3, the plot of $\rho(H)$ should be entirely different than at $H \parallel C_3$, something likewise not observed in the experiment[1)].

Since the negative magnetoresistance of Te does not differ from that of many other semiconductors, both in the character of the anisotropy and in the form of the dependence on the magnetic field, the universality of the Toyozawa mechanism is doubtful. To explain the negative magnetoresistance in Te, at any rate when $H \perp C_3$, it is apparently necessary to take into account the quantization of the electron spectrum.

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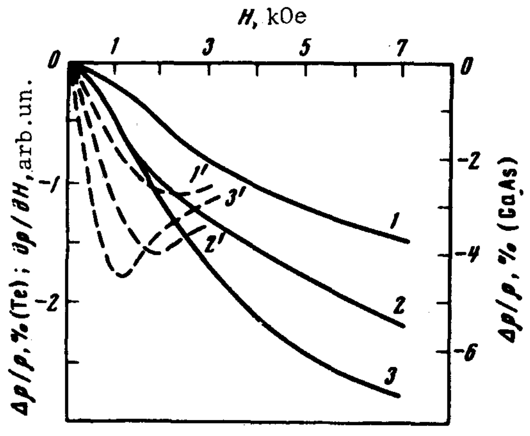

Fig. 2

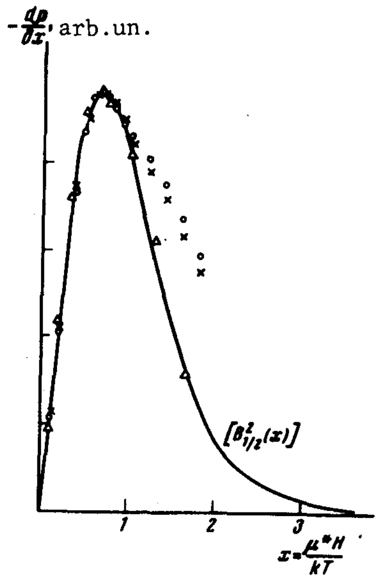

Fig. 3

Fig. 2. Plot of $\Delta\rho/\rho$ against the magnetic field intensity: 1 — Te, $H \perp C_3$, $T = 2.2°K$; 2 — Te, $H \parallel C_3$, $T = 2.2°K$; 3 — n-GaAs, $T = 1.6°K$. The dashed curves show the plots of $\partial\rho(H)/\partial H$.

Fig. 3. Plot of $\partial\rho(x)/\partial x$: O — Te, $H \perp C_3$, $T = 2.2°K$; Δ — Te, $H \parallel C_3$, $T = 2.2°K$; χ — n-GaAs, $T = 1.6°K$. Solid curve — derivative of the square of the Brillouin function $[B^2_{1/2}(x)]'$.

supplying the GaAs sample.

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1) Takita et al. [3], without presenting a quantitative analysis, also point to difficulties in explaining the negative magnetoresistance of tellurium by means of the Toyozawa theory.

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