

Weak localization under lifted spin-degeneracy conditions (two-dimensional layer on a tellurium surface)

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The first observation of anomalous magnetoresistance of two-dimensional holes on the (0001) surface of Te is reported. The results are interpreted on the basis of the theory of weak localization, which was modified to include the properties of the band spectrum of Te: lifted spin degeneracy and trigonal distortion of the Fermi surface.

It has become clear in recent years that the anomalous magnetoresistance (AMR) of a material with metallic conductivity in the region of classically weak magnetic fields is, in many cases, due to weak localization of noninteracting particles.¹ In the theory of weak localization, time reversal symmetry (t symmetry) is extremely important. From this point of view, it is interesting to investigate AMR in tellurium, since the manifestation of t -symmetry in Te has a number of important features.²

The galvanomagnetic properties of Te specimens, on whose (0001) surfaces a hole accumulation layer (AL) was created, were investigated in the temperature range 0.38–4.2 K. The magnetic field H was oriented perpendicular to the surface. The experimental procedure, including the method used to create an AL with a hole density of $p_{AL} \sim 10^{12} \text{ cm}^{-2}$, is described in Ref. 3. The experimentally determined properties of carriers and proof of the two-dimensionality of their motion were also presented in this paper. For specimens with $p_{AL} < 10^{12} \text{ cm}^{-2}$, the effect of a controlling voltage U_g , which decreased p_{AL} at $U_g > 0$, on the AMR was also studied in the MDP capacitor geometry.

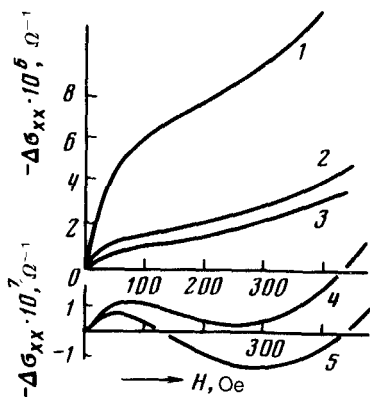


FIG. 1. Anomalous magnetoresistance of specimens with different conductivities.

$1-p_{AL} = 2.10^{12} \text{ cm}^{-2}$, $T = 0.44 \text{ K}$, $\sigma(0) = 2.5 \text{ k}\Omega^{-1}$ 2,3,4,5- $p_{AL} < 10^{12} \text{ cm}^{-2}$, $T = 0.38 \text{ K}$, $U_{g3} < U_{g3} < 0 < U_{g4} < U_{g5}$, $\sigma(0) = 1.5, 1.3, 0.7, 0.6 \text{ k}\Omega^{-1}$ respectively.

Figure 1 shows the typical dependences of the magnetoconductivity $\Delta\sigma(H) = \sigma(H) - \sigma(0)$ for different values of $\sigma(0)$, while Fig. 2 shows $\Delta\sigma(H) \text{ cm}^{-2}$ at different temperatures. We see that AL on a Te surface can have both positive and

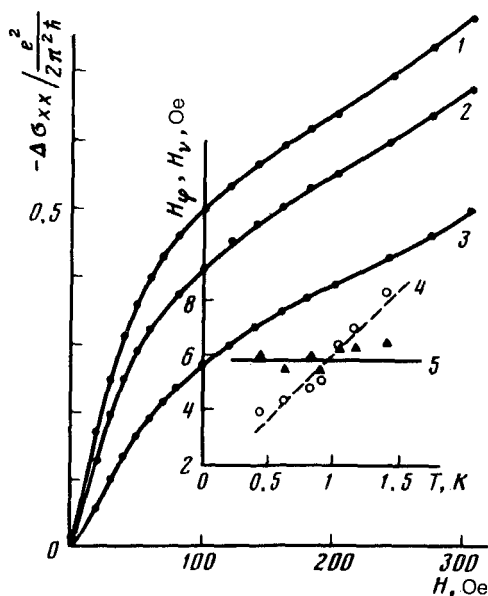


FIG. 2. Anomalous magnetoresistance at different temperatures. Curves 1, 2, and 3 show the experimental values at $T = 0.44, 0.83$, and 1.4 K , respectively; the points show the calculation using (1). The experimental values of H_ϕ (○) and H_v (▲) are shown in the inset. Curves 4 and 5 in the inset show the linear approximation to the temperature dependence of H_ϕ and H_v .

negative magnetoresistance (PMR and NMR), depending on the magnitude of $\sigma(0)$, the temperature, and the magnetic field. An increase in the carrier density in AL and a decrease in temperature lead to predominance of PMR and vice versa. These characteristics cannot be explained by the classical conductivity theory.

In interpreting the AMR within the framework of the theory of weak localization, it is important to take into account the characteristics of the spectrum of holes in AL of tellurium. In Te the strong spin-orbit interaction completely removes the spin degeneracy. Holes fill two valleys, which are centered at the corners of the Brillouin zones \mathbf{H} and \mathbf{H}' .² Because of the trigonal symmetry of Te, and because of the absence of a center of inversion, the points \mathbf{H} and \mathbf{H} are related only by the t symmetry operation; under time reversal, the states of the valley \mathbf{H} go over to the valley \mathbf{H}' and vice versa.

The holes in AL are located in the field of the confining potential. The quantization of the motion along the C_3 axis, perpendicular to the surface, leads to the formation of levels.³ Motion parallel to the surface transforms the levels into two-dimensional bands with a spectrum $E_i(\mathbf{k}) \simeq \epsilon_i(|\mathbf{k}|) \pm \gamma|\mathbf{k}|^3 \cos 3\phi_k$, where i is the number of the level, and k is a component of the quasi-momentum perpendicular to C_3 , measured from the points \mathbf{H} or \mathbf{H}' , γ is a parameter of the (small) trigonal distortion of the Fermi surface of Te,² ϕ_k is the angle between \mathbf{k} and the C_2 axis, and the levels in the valleys \mathbf{H} and \mathbf{H}' have different signs. The number n of filled bands is determined from the condition $\epsilon_n(0) < E_F$; $n = 3$ for $p_{AL} = 2 \times 10^{12} \text{ cm}^{-2}$.³

The quantum correction to the conductivity of noninteracting particles^{1,4} is determined by the sum $C_{HH}^i = C_{HH'}^i$ of cooperons, which are comprised of wave functions of the i th level of the same valley \mathbf{H} or \mathbf{H}' , as well as $C_{HH'}^i = C_{HH}^i$ cooperons, which are nondiagonal with respect to the valleys ($i = 1, \dots, n$). At times longer than the impurity transition time between levels of a single valley, summation over levels reduces to averaging of the cooperon parameters. The expression for the magnetoconductivity has the form

$$\frac{\Delta\sigma(H)}{\sigma_0} = f_2\left(\frac{H}{H_\phi + H_v + H_\gamma}\right) + \frac{1}{2}f_2\left(\frac{H}{H_\phi + 2H_v}\right) - \frac{1}{2}f_2\left(\frac{H}{H_\phi}\right), \quad (1)$$

where $\sigma_0 = e^2/2\pi^2\hbar$, $f_2(x) = \ln x + \psi(1/2 + 1/x)$, and ψ is the digamma function. Equation (1) coincides with the expression obtained in Ref. 1. The fields H_ϕ , H_v , H_γ are determined, respectively, by the relaxation time of the phase τ_ϕ ,^{1,4} the intervalley transition time τ_v , and the time τ_γ : $H_\alpha = \hbar c/4eD\tau_\alpha$, where D is the diffusion coefficient, and $\alpha = \phi$, v , and γ . The quantity

$$1/\tau_\gamma = 2\gamma^2 \sum_{i=1}^n \tau_i \nu_i k_{Fi}^6 / (\hbar^2 \sum_{i=1}^n \nu_i), \quad (2)$$

where τ_i , ν_i , k_{Fi} are, respectively, the impurity momentum relaxation time, the density of states, and the Fermi momentum of the band of the i th level. The time τ_γ determines the damping of cooperons C_{HH}^i and $C_{HH'}^i$, which is related to the asymmetry of the spectrum: $E_i(\mathbf{k}) \neq E_i(-\mathbf{k})$. The intervalley transitions play the same role as spin-flip resulting from spin-orbit scattering as in the case of Ref. 1.

Figure 2 is a comparison of the experimental data and Eq. (1), in which a term $\propto H^2$ was added in order to take into account the small classical PMR. The best agreement is obtained for $H_v = 5-7$ Oe, $H_\gamma = 100-130$ Oe, $H_\phi (0.38 < T < 1.4) = A_\phi T + H_\phi(0)$.

The dependence $H_\phi(T)$ can be explained by the temperature dependence of the phase disruption time due to the interaction of carriers with Nyquist fluctuations: $\tau_\phi \approx \tau_\phi^{(N)} = \hbar\sigma/\pi\sigma_0 T \ln(\sigma/\sigma_0)$.⁴ Using the previously found parameters of AL,³ we obtain $A_\phi^{(N)} = 2.5$ Oe/K, which is quite close to the observed value. The final small value of $H_\phi(0)$ is apparently related to weak spin scattering.

A calculation of the quantity H_γ using (2), with allowance for the data of Ref. 3 and $\gamma \approx 2 \times 10^{-20}$ meV·cm³ gives 65 Oe. Keeping in mind the approximate nature of the value of γ (Ref. 5) and the sensitivity of H_γ to the properties of the specimen, especially the concentration, we consider that the agreement is satisfactory.

Relations (1) and (2) permit interpreting qualitatively the dependence of the AMR on the surface density. A decrease in the density increases the time τ_γ . As a result, the first term in (1), which is responsible for the negative magnetoresistance, increases. In addition, a decrease of the time $\tau_\phi^{(N)} \propto \sigma/T$, which accompanies a decrease in density, leads to a decrease of the sum of the two last terms (1) which determine the positive magnetoresistance. An increase in temperature leads to the same effect. In our opinion, these two circumstances explain the observed transition from positive to negative magnetoresistance which accompanies a decrease in the surface density or increase in temperature.

Thus the theory of weak localization of noninteracting particles describes completely satisfactorily the experimental results. In the future, we hope to refine, by means of a detailed study of AMR, the value of the parameter of the band structure of tellurium γ .

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