Distinctive features of the weak localization of 2D holes on the tellurium (10$\bar{1}$0) surface: role of energy-spectrum anisotropy

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The conductivity of a system of 2D holes in an accumulating quantum-well layer on the (10$\bar{1}$0) surface of a tellurium crystal has been studied at temperatures of 1.3–4.2 K. In weak magnetic fields there is an anomalous positive magnetoresistance. The latter is interpreted in a modified theory of a weak localization of particles which do not interact with each other. The modification consists of incorporating an anisotropy of the tellurium band spectrum. Phase relaxation of the wave function of the particles in the course of intervalley transitions plays a special role in the weak localization of 2D holes on the tellurium surface.

Quantum corrections to the conductivity of 2D holes on a tellurium surface have been observed previously in a study of a 2D layer on the (0001) crystallographic plane at ultralow temperatures.[1] The effect has been interpreted on the basis of a theory of a weak localization of particles which do not interact with each other.[2] It has proved necessary to take into account the features of the band spectrum of tellurium:[3] the lifted spin degeneracy, the multivalley nature of the valence band, and the trigonal distortion, proportional to $\gamma k_{\perp}^{3}$, of a Fermi trajectory on the (0001) plane. It has been found that the value of the coefficient γ actually determines the sign and magnitude of the anomalous magnetoresistance of a 2D layer on this plane.[1,4]

In the present letter we are reporting a study of kinetic effects in classically weak magnetic fields in a 2D hole layer produced on the tellurium face with the crystallographic indices (10$\bar{1}$0), on which there is no trigonal distortion of the Fermi trajectories of holes. Since the dispersion relation of the tellurium valence band contains a term which is linear in the quasimomentum, $\xi = Ak_z$, the Fermi trajectories of 2D holes on this plane are dumbbell-shaped except at very low energies.[3] A study of Shubnikov–de Haas oscillations in this system has reliably revealed two 2D subbands with a total hole concentration $\simeq 4.5 \times 10^{12}\ \mathrm{cm}^{-2}$ and also a magnetic breakdown of the thin section of the dumbbell-shaped trajectory in a 2D subband with a low Fermi energy.[5,6]

An accumulating layer was produced on the (10$\bar{1}$0) surface by the same technique as in Ref. 1. The experiment was carried out on an automatic apparatus with a steady-state magnetic field, which provided a high resolution at a reduced noise level.[6]

Figure 1 shows the conductivity of a sample with an accumulating layer on the (10$\bar{1}$0) surface versus the strength of a magnetic field directed perpendicular to this

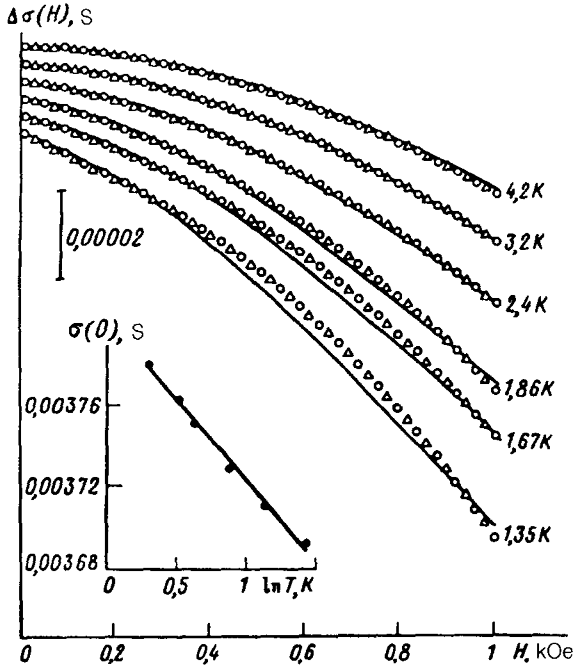

FIG. 1. Change in conductivity in a magnetic field of a tellurium sample with a 2D layer on its $(10\bar{1}0)$ surface at various temperatures. Curves—Experimental; △—calculated from (1) with $H_{v}=H_{\gamma\beta}$; circle—calculated from (1) with $H_{v}\neq H_{\gamma\beta}$. The inset shows the temperature dependence of the conductivity of the same tellurium sample. ●—Experimental; solid curve—linear approximation. The conductivity is expressed per unit area.

surface, at liquid-helium temperatures. In weak transverse magnetic fields, we see a positive magnetoresistance (the conductivity decreases in the magnetic field). This magnetoresistance increases with decreasing temperature. This effect is characterized as anomalous since its magnitude is much greater than that of the classical magnetoresistance calculated from the mobilities found for 2D holes in Ref. 6. The conductivity of the test sample falls off logarithmically with the temperature (see the inset in Fig. 1).

The observed behavior of the conductivity of the 2D layer as a function of the magnetic field and the temperature is characteristic of quantum corrections to the resistance, in particular, a weak localization of particles which are not interacting with each other.

To reach an understanding of the specifics of the manifestation of the weak-localization effect in tellurium in a 2D hole system on the $(10\bar{1}0)$ surface, we need to take a detailed look at the anisotropy of the band spectrum of tellurium.

The strong spin–orbit coupling in tellurium completely lifts the spin degeneracy. The extrema of the valence band lie at the vertices of a hexagonal prism of the

Brillouin zone of tellurium: the points M and P, which are sent into each other by the operation of time reversal. The wave functions at these extrema are superpositions of states with angular-momentum projections $M_z = \pm 3/2$ onto the z axis, which runs parallel to the threefold C_3 axis. This circumstance is responsible for the pronounced anisotropy of the Fermi surfaces of the holes in tellurium and, correspondingly, the difference between the Fermi contours of 2D holes on different crystallographic surfaces.

The weak-localization correction to the conductivity is determined by the sum $C_{MM} = C_{PP}$, of cooperons consisting of the wave functions of the same valley, M or P, and $C_{MP} = C_{PM}$, of cooperons which are not diagonal in the valleys. In the 2D case the magnetoresistance is described by[1,4]

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

where $\sigma_0 = e^2/2\pi^2\hbar$, $f_2 = \ln x + \Psi\ (1/2 + 1/x)$, and Ψ is the digamma function. The characteristic magnetic fields H_ϕ, H_v, and $H_{\gamma\xi}$ are related to the phase relaxation times τ_α, which determine the disruption of the coherence of particles: $H_\alpha = \hbar c/4eD\tau_\alpha$ ($\alpha = \phi, v, \gamma\xi$), where D is a diffusion coefficient.

The phase relaxation in (1) is governed by the inelastic scattering time τ_ϕ and by the elastic times τ_v and $\tau_{\gamma\xi}$, which corresponds to an intervalley transition. The quantity $1/\tau_{\gamma\xi}$ is, in general, a sum of two components.[4] The first stems from the asymmetry of the spectrum due to the trigonal distortion of the Fermi surface and is proportional to γ^2. The other component ($1/\ \tau_-$) depends on the term ξ , which is linear in k_z, and arises because the state in each valley is a superposition of states with angular-momentum projections $M_z = \pm 3/2$: One of the momentum directions corresponds to a predominantly positive projection, while the other direction corresponds to a predominantly negative one. An elastic scattering, even if it does not depend on the spin, alters the momentum of a particle and also the relative contributions of the different angular-momentum projections to the electron wave function. By analogy with elastic scattering, this process leads to a phase relaxation when there is a momentum-dependent splitting of the spectrum.[4] The corresponding time $1/\tau_-$ is on the order of the intervalley transition time, which is possible in tellurium only to the extent that the two projections M_z are mixed at a nonzero momentum. In the case of the 2D gas of holes at the $(10\bar{1}0)$ tellurium surface, there is no trigonal distortion of the Fermi contour, and the time $\tau_{\gamma\xi}$ is governed completely by the time τ_-.

By making a least-squares fit of expression (1) to the experimental plots of $\Delta\sigma\ (H,T)$, we found the values of the parameters in this expression under two assumptions: 1) The values of $H_{\gamma\xi}$ and H_v are different; 2) they are the same. The contribution of the classical magnetoresistance was taken into account by adding a term of the form bH^2 . The data in Fig. 1 are consistent with the conclusion that the values of $H_{\gamma\xi}$ and H_v are essentially the same, in agreement with theory. The best agreement is found with $H_{\gamma\xi} \simeq H_v \simeq 300$ Oe ($T = 1.3$–4.2 K). The value $H_\phi(1.3\ \text{K}) = 10$ Oe and its temperature dependence can be approximated by the expression $H_\phi(T) = A_\phi T^2 + H_\phi(0)$, where $A_\phi = 5$ Oe/K^2 and $H_\phi(0) = 5$ Oe (Fig. 2). The qua-

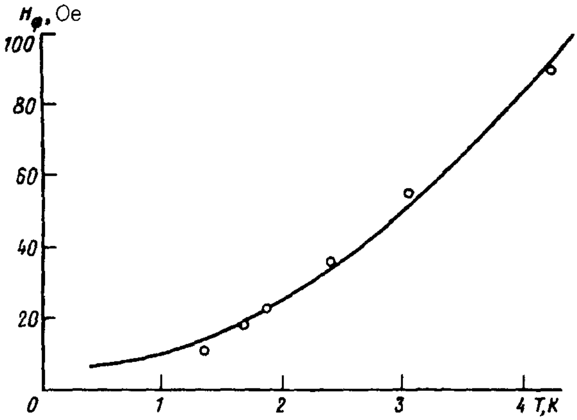

FIG. 2. Temperature dependence of H_ϕ. O—Found experimentally; curve—approximation by a function $A_\phi T^2 + H_\phi(0)$[$A_\phi = 5$ Oe/K^2, $H_\phi(0) = 5$ Oe].

dratic $H_\phi(T)$ dependence apparently indicates that an electron–electron interaction is playing an important role in the phase relaxation for this orientation.

This study of the anomalous magnetoresistance of a 2D hole gas at the tellurium $(10\bar{1}0)$ surface demonstrates the extremely important role which is played by the particular features of the band structure in the weak localization of particles.

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