Observation of quantum oscillations of the magnetoresistance of multiply connected objects with a hopping conductivity

Ya. B. Poyarkov, V. Ya. Kontarev, I. P. Krylov, and Yu. V. Sharvin
Institute of Physical Problems, Academy of Sciences of the USSR

(Submitted 12 August 1986)
Pis'ma Zh. Eksp. Teor. Fiz. **44**, No. 6, 291–293 (25 September 1986)

A study has been made of the magnetoresistance of grid structures made from oxidized disordered PbTe films. At $T = 1.12$ K, oscillations have been observed with a period corresponding to a change of approximately $hc/2e$ in the magnetic flux through each aperture of the grid. The temperature dependence of the resistance is described by Mott's law for films with a hopping conductivity and a variable hopping length.

It has recently been observed that the resistance of multiply connected samples of disordered metals oscillates as a function of the magnetic flux (Φ) in the apertures of the sample, because of the effect of the magnetic vector potential on the phase of the electron waves. The oscillation period is $\Phi_0/2 = hc/2e$ in the case of cylinders or grids.[1-3] In the case of isolated thin rings, the continuous oscillation spectrum has maxima at period values of Φ_0 and $\Phi_0/2$ (Refs. 4 and 5).

It is worthwhile to search for similar effects among conductors with a different—hopping—conductivity mechanism. Despite the pronounced localization of electrons, interference effects should, in principle, be observed even in this case. Nguen, Spivak, and Shklovskiĭ[6,7] have predicted that for grids of semiconductors the oscillation period $\Phi_0/2$ would be replaced by the period Φ_0 when the concentration of scatterers changes.

We have carried out the first observations of oscillations of the magnetoresistance of grids made of oxidized films of lead telluride. This particular material was chosen because its resistance can be varied over a wide range at liquid-helium temperatures by illumination with various doses of light, by virtue of the frozen photoconductivity.[8]

The PbTe films are synthesized by molecular vapor deposition on a glass substrate with platinum film contacts at 20 °C and at a pressure $< 10^{-5}$ Torr. Before the oxidation, the conductivity of the film, with a high concentration of donors, increases with decreasing temperature. Oxidation in air causes the conductivity to become thermally activated because of the compensation of donors. The films and the prepared samples are stored under normal atmospheric conditions.

The test sample is fabricated from a film 1600 Å thick by electron lithography. It is a grid with square cells and a structural period of 2 μm. The width of the conducting bridges of the grid does not exceed 0.5 μm. The grid has six cells along the direction of the current flow and 35 in the perpendicular direction.

The measurement circuit, including a V7-29 digital electrometer, can measure resistances up to ~ 5000 GΩ at a measuring current of about 10^{-13} A. The dark resistance of a sample at liquid-helium temperatures is immeasurably large, and we were forced to carry out a preliminary illumination of the sample in the measurements. During the first few minutes after the illumination, the resistance increases slightly, but in 10–20 min it gives way to a noise with a broad spectrum of periods, reaching the duration of the experiment itself. The amplitude of this noise varied by a factor of two or three in different experiments. In some particularly successful experiments carried out at night, the noise amplitude was $\sim 5\%$ at a time 1 h after exposure to light.

The temperature dependence of the resistance of the sample, R, can be approximated within the errors by

$$R = R_0 \exp(T_0/T)^{\nu}, \tag{1}$$

where $\nu = 0.3 \pm 0.1$, and the values of R_0 and T_0 depend on the extent of the illumination of the sample (Fig. 1). The fact that expression (1), close to Mott's law, describes the results is evidence of a hopping conductivity with a variable hopping length in the bulk of the sample.

In measurements of the magnetoresistance, we swept through the field range repeatedly in order to single out the useful signal, which was comparable to the noise. At 128 fixed values of the field, directed normal to the surface of the sample, over the interval 0–26 Oe, we accumulated and averaged the electrometer readings with the help of a computer. The geomagnetic field was cancelled within 0.1 Oe.

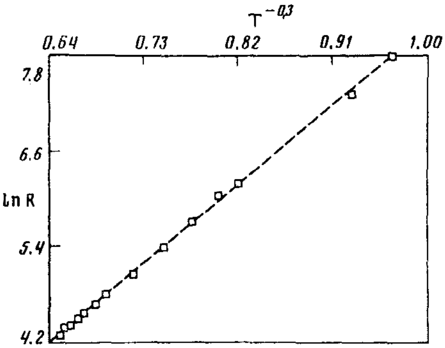

FIG. 1. Plot of $\ln R$ versus $T^{-0.3}$ for a grid-shaped PbTe sample illuminated at $T = 4.2$ K, according to measurements over the interval $1.12 \leqslant T \leqslant 4.2$ K. The value of R is expressed in gigohms. The dashed line corresponds to the values $R_0 \cong 0.06$, $T_0 \cong 3000$ K in relation (1).

The upper curve in Fig. 2 is the result of an averaging after 24 sweeps at $T = 1.12$ K. The period of the observed oscillations is $H_1 = 7 \pm 0.5$ Oe. The dashed lower curve was found in a single sweep. The oscillations in the magnetoresistance with a period of about 7 Oe are also clearly observed at 1.3 and 2 K. At $T \gg 3$ K, the oscillations are indistinguishable.

The apparent reason for the observed oscillations is a quantum interference of electron states with a period which is, according to Refs. 6 and 7, equal to the flux quantum $\Phi_0 = hc/e$ or a quantum $\Phi_0/2$.

Since the width of the bridges in our grid cannot be regarded as small, we can

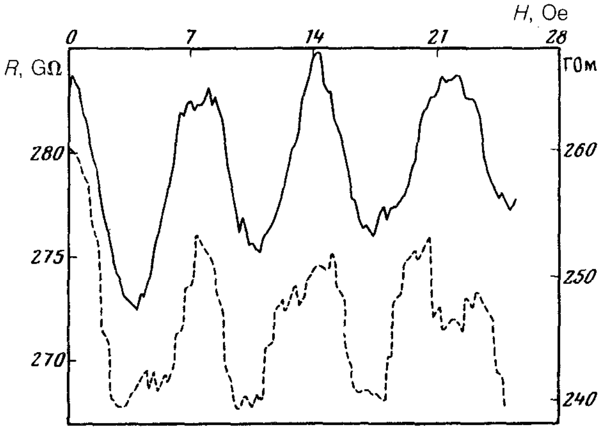

FIG. 2. Resistance of a PbTe grid sample versus the magnetic field at $T = 1.12$ K. The extent of the illumination is close to saturation at the experimental temperature. The scale at the right gives the resistances for the dashed line.

only assert that the effective area (S) of the apertures lies in the range $2^2 > S > 1.5^2$ μm^2, so we can write

$$3 \cdot 10^{-7} > H_1 S > 1.5 \cdot 10^{-7}\ \mathrm{G \cdot cm^2}\ . \tag{2}$$

The value $H_1 S = \Phi_0/2 = 2.07 \times 10^{-7}$ G·cm^2 lies in this interval. Inequality (2) also shows that the period of Φ_0 is not observed under our experimental conditions.

We wish to thank V. F. Chugunov for fabricating the grids by microlithography.

[1] B. L. Al'tshuler, A. G. Aronov, and B. Z. Spivak, Pis'ma Zh. Eksp. Teor. Fiz. **33**, 101 (1981) [JETP Lett. **33**, 94 (1981)].

[2] D. Yu. Sharvin and Yu. V. Sharvin, Pis'ma Zh. Eksp. Teor. Fiz. **34**, 285 (1981) [JETP Lett. **34**, 272 (1981)].

[3] B. Pannetier, J. Shaussy, R. Rammal, and P. Gandit, Phys. Rev. Lett. **53**, 718 (1984).

[4] Y. Gefen, Y. Imry, and M. Ya. Azbel, Phys. Rev. **52**, 129 (1984).

[5] R. A. Webb, S. Washburn, C. P. Umbach, and R. B. Laibovitz, Phys. Rev. Lett. **54**, 2696 (1985).

[6] V. L. Nguen, B. Z. Spivak, and B. I. Shklovskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **41**, 35 (1985) [JETP Lett. **41**, 42 (1985)].

[7] V. L. Nguen, B. Z. Spivak, and B. I. Shklovskiĭ, Zh. Eksp. Teor. Fiz. **89**, 1770 (1985) [Sov. Phys. JETP **62**, 1021 (1985)].

[8] I. P. Krylov and B. E. Nadgornyi, Pis'ma Zh. Eksp. Teor. Fiz. **35**, 56 (1982) [JETP Lett. **35**, 65 (1982)].

Translated by Dave Parsons