Electron localization and negative magnetoresistance in disordered PbTe films

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

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A negative magnetoresistance, $\Delta R(H) < 0$, has been observed in PbTe films in the hopping-conductivity region. The increase in the carrier density due to the frozen photoconductivity causes $\Delta R/R$ to drop to zero and changes the sign of $\Delta R(H)$.

In this letter we report a study of PbTe films with a thickness $d = 1.2 \times 10^{-5}$ cm synthesized by depositing the vapor of the telluride on a glass substrate at room temperature. From measurements of the Hall constant of a freshly deposited film we found the value $N \simeq 10^{19}$ cm^{-3} for the donor density. The impurity level in the original material was no greater than 10^{17} cm^{-3}, so that structural defects of the film or extra

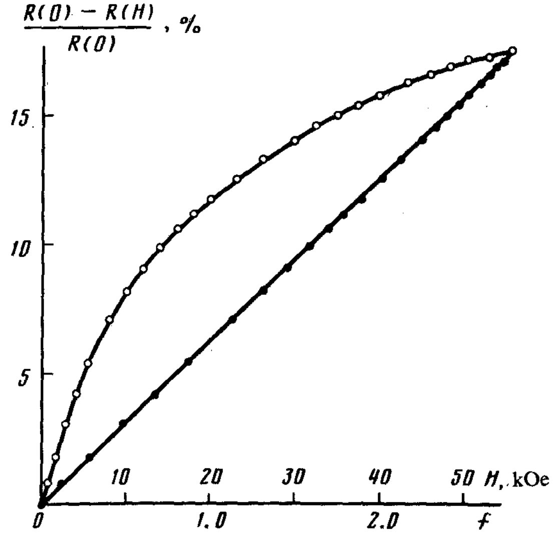

FIG. 1. Surface resistivity of the PbTe films versus the magnetic field H at $T = 1.3$ K [H‖n, $R(0) = 3.1$ mΩ]. Plotted along the abscissa axis for the filled points is the function $f = \ln(\alpha H) + \psi[(1/2) + (1/\alpha H)]$ with a coefficient $\alpha = 2.1 \times 10^{-3}$ Oe^{-1}.

Pb atoms serve as the donor centers. The conductivity of a freshly deposited film increased with decreasing temperature.

After deposition, donor compensation was arranged by oxidation in air. The oxidation gives rise to acceptors in the PbTe, reduces the free-carrier density n, and causes a transition to a thermally activated conductivity. At liquid-helium temperatures the resistance of the compensated films obeys the Mott law $R = R_0 \exp[(T_0/T)^\nu]$ with an exponent $\nu \simeq 0.3$. Here and below, R is the surface resistivity of the film. For the highest-resistance films we have $R_0 \simeq 1$ mΩ and $T_0 \simeq 100$ K.

The imposition of a magnetic field H on the compensated PbTe films reduces the resistance (Fig. 1). In this letter we report measurements of the negative magnetoresistance in a magnetic field normal to the plane of the film (**H**‖**n**). Longitudinal and transverse negative magnetoresistances of similar magnitude were observed in the case **H**⊥**n**.

A hopping conductivity is characterized by a large positive magnetoresistance.[1] As strong field may in fact cause a metal-semiconductor transition if the density n at $H = 0$ is near the critical value n_c on the metal side. Al'tshuler *et al.*[2] have suggested that a negative magnetoresistance could occur in the hopping-conductivity region if n_c decreased upon the imposition of a field. According to their arguments,[2] the behavior of the negative magnetoresistance would be described by $\Delta R/R \propto (n_c - n)^{-5/8}$; i.e., it should increase with increasing $n < n_c$ and as the threshold $n = n_c$ is approached. We made use of the frozen-photoconductivity effect[3] to change the carrier density in the PbTe films. Illumination of a film cooled to liquid-helium temperature caused its resistance to decrease; after the light was turned off, the resistance remained at a

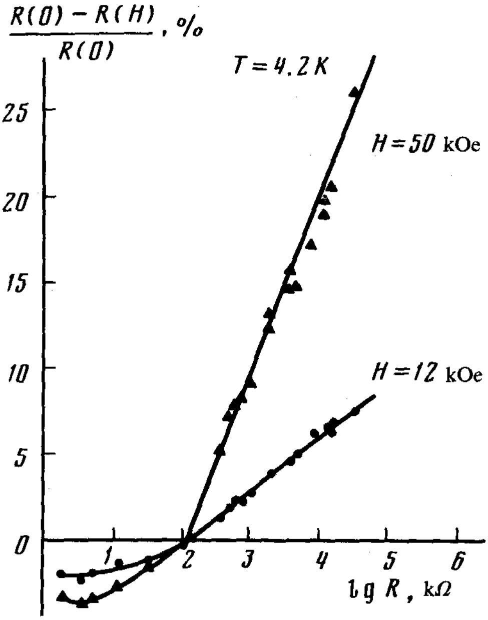

FIG. 2. The negative magnetoresistance in a fixed H versus the film resistance R at $H = 0$ ($T = 4.2$ K, $\mathbf{H}\|\mathbf{n}$).

constant level for an indefinitely long time. Figure 2 shows the negative magnetoresistance in a fixed field H as a function of the resistance R at $H = 0$. Our experimental data completely contradict the theoretical predictions of Ref. 2: $|\Delta R/R|$ decreases with increasing n, i.e., with decreasing R.

We measured the negative magnetoresistance of five films which had been oxidized for various lengths of time. All the results obtained at the same temperature lie within a few percent of the curve shown in Fig. 2. As the temperature is lowered from 4.2 to 1.3 K, the slope in the negative-magnetoresistance region increases by a factor of 1.2 in a field $H = 50$ kOe or by a factor of 2.3 at $H = 12$ kOe. The magnetoresistance changes sign at $R \simeq 100$ kΩ. The temperature dependence of R, on the other hand, remains thermally activated.

A theory has been derived for the magnetoresistance of disordered conductors in the metallic-conductivity region.[4] According to this theory, the small increment is $\Delta R/R = Rf(H)$, where the function $f(H)$ does not depend on the parameters of the sample. It can be seen from Fig. 2 that the conclusions of Ref. 4 are not directly applicable to our case. The experimental results on $\Delta R/R = Af(H)$ with an empirical coefficient A can, however, be described by an expression derived for a 2-D film without an electron-electron interaction:

$$f(H) = \ln(\alpha H) + \psi\left(\frac{1}{2} + \frac{1}{\alpha H}\right).$$

Here $\psi(x) = [\ln\Gamma(x)]'$ is the digamma function. The empirical coefficients A and α

depend on R and T. As the temperature is lowered from 4.2 to 1.3 K, the coefficient A falls off by about 10%, while we find $\alpha \propto T^{-1}$ at resistances $R \simeq 1$ mΩ. According to the theory we would have $\alpha = 4eD\tau_\varphi/\hbar c$, where D is the electron diffusion coefficient, and τ_φ is the phase relaxation time of the electrons set by inelastic collisions. Using the value $\alpha = 2.1 \times 10^{-3}$ Oe^{-1} at $T = 1.3$ K, we find the product $D\tau_\varphi = 3 \times 10^{-11}$ cm^2, which corresponds to electron diffusion over a distance $\simeq 10^{-5}$ cm before phase relaxation occurs.

In addition to the magnetoresistance, we measured the transverse Hall voltage U_H for comparatively low-resistance films ($R < 2$ mΩ). The $U_H(H)$ dependence turned out to be nonlinear. Working from the linear region, $U_H \propto H$ (in fields $H < 10$ kOe), we found the Hall constant $\mathscr{R}_H$ and the Hall angle θ_H. As the temperature is lowered from 4.2 to 1.3 K, the values of $\mathscr{R}_H$ and θ_H increase by a factor of 2–3. Down to the lowest attainable value $R \simeq 1$ kΩ, illumination of the films caused a decrease in $\mathscr{R}_H$ described approximately by $\mathscr{R}_H \propto R$, while θ_H did not change in order of magnitude. Analyzing the results with the help of the standard relations of the Drude theory, we estimated the electron mean free path to be $l \simeq 0.1$ Å and the density to be $n \simeq 5 \times 10^{19}$ cm^{-3} at $R \simeq 2$ kΩ. This value of n corresponds to a Fermi energy $\mu \simeq 1$ eV. The rms potential fluctuations $\Delta u \simeq 0.72 \times 10^{-10} N^{1/2} n^{-1/12}$ caused by fluctuations in the number of donors, $\Delta N = (N r_0^3)^{1/2}$, in regions with dimensions equal to the Debye length $r_0 = 3.2 \times 10^{-3} n^{-1/6} \simeq 10^{-5}$ cm are $\Delta u \simeq 0.01$ eV over a broad range of the density n. The condition $\mu \gg \Delta u$ thus holds in the PbTe films with $R < 10$ kΩ, and for these films we should expect a metallic rather than thermally activated conductivity. A pronounced carrier localization is apparently causing a small Hall effect in these films, as it does in other hopping-conductivity semiconductors, so that the standard relations of the Drude theory do not apply.

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