Tunneling spectroscopy of the energy spectrum of lead telluride in a quantizing magnetic field

V. N. Vinchakov, V. I. Kaĭdanov, and S. A. Rykov
Polytechnical Institute, Leningrad

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Tunneling spectroscopy in a quantizing magnetic field has been used to study the electron dispersion relation in the conduction band and in the two-dimensional surface valence subband of lead telluride.

Tunneling spectroscopy in a quantizing magnetic field has several advantages over other oscillation methods for studying the energy spectra of semiconductors. In contrast with the method based on the Shubnikov-de Haas effect, it can be used to study the energy spectrum over a broad energy interval in a single sample. There is no difficulty here in deciphering the oscillations of the interband transitions, which may arise in magnetooptic spectroscopy. Finally, there is the attractive possibility of studying the spectrum of both bulk and surface states. The method of tunneling spectroscopy in a quantizing magnetic field has been used successfully to study the energy spectra of semiconductors with an isotropic dispersion relation.[1,2] Among semiconductors with an anisotropic spectrum it has been applied to silicon[3] the lead telluride.[4] The goals of these experiments were to detect and study only two-dimensional surface bands.

In this letter we report a study of the conductivity of tunneling metal-insulator-semiconductor structures made from lead telluride in magnetic fields up to 80 kOe. The test samples are PbTe single crystals grown by the Bridgman-Stockbarger method, doped with thallium to a hole concentration $p \cong 1.2 \times 10^{19}$ cm^{-3}. Using a standard modulation technique at 4.2 K, we measured the first and second derivatives, dI/dV and D^2I/dV^2, of the I-V characteristics of p-PbTe-Al_2O_3-Pb metal-insulator-semiconductor structures with a tunneling-transparent insulating layer. These structures were fabricated on semiconductor crystals oriented in (100) planes by the technique of Ref. 1.

We studied the second derivative of the I-V characteristic as a function of the magnetic field **H** for two orientations of this field: parallel to the plane of the transition (**H**⊥**I**) and perpendicular to it (**H**‖**I**). In both cases, at bias voltages corresponding to tunneling of electrons from the metal into states of the vacant conduction band ($V > 0.3$ V), we observed oscillations due to a Landau quantization of bulk states. Figure 1 shows the positions of the minima of the oscillations for various bias voltages. These curves reflect the motion of the Landau levels in the magnetic field. The series of levels corresponding to quantization of the bulk states in a zero magnetic field is extrapolated to the bottom of the conduction band, E_c.

At bias voltages corresponding to a tunneling of electrons into bulk states near the bottom of the conduction band of the semiconductor, we studied the dependence of the oscillations on the orientation of the PbTe crystal in the magnetic field. Rotation of the crystal in the (100) plane revealed no more than two periods in the reciprocal

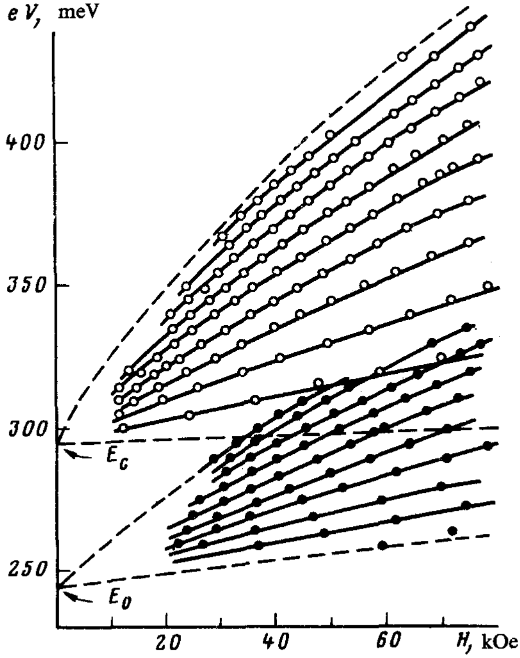

FIG. 1. Positions of the minima of d^2I/dV^2 versus the magnetic field in the case $\mathbf{H}\|\mathbf{I}$ (E_c is the edge of the conduction band, and E_0 is the bottom of the surface valence subband).

magnetic field, $\Delta(1/H)$, in the oscillation pattern.[5] A Fourier analysis identifies each period, and their behavior as a function of the crystal orientation (Fig. 2) has made it possible to determine the anisotropy coefficient of the effective masses, $K=m_{\|}/m_{\perp}=9\pm 1$.

At $\mathbf{H}\|[100]$, all of the constant-energy ellipsoids have an identical orientation with respect to the magnetic field (there is a single oscillation period).[5] For this orientation, and at various bias voltages, we determined the extremal intersections of the ellipsoids with the plane perpendicular to $\mathbf{H}$ and the cyclotron effective masses:

$$S=2\pi e/\hbar c\,\Delta(1/H)\ , \qquad (1)$$

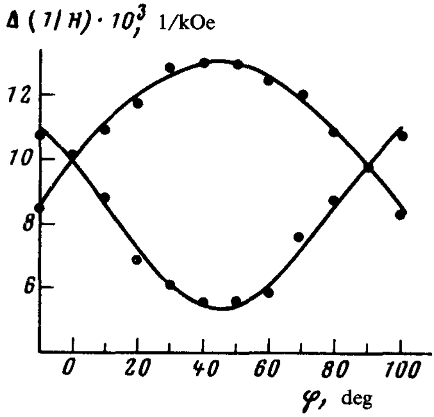

FIG. 2. Periods of the oscillations of the tunneling conductivity in the reciprocal magnetic field versus the orientation of the crystal in the magnetic field. Here $\varphi=0$ for $\mathbf{H}\|[100]$, and the rotation is in the (100) plane.

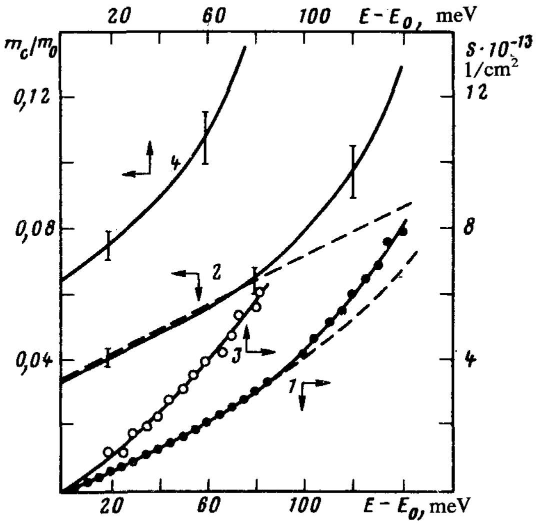

FIG. 3. Energy dependence of the extremal cross sections of the constant-energy surfaces and of the cyclotron effective masses for bulk states (curves 1 and 2) and for the surface-valence subband (curves 3 and 4) (H‖I).

$$m_c = \frac{\hbar^2}{2\pi}\frac{dS}{dE} = \frac{\hbar^2}{2\pi}\frac{dS}{d(eV)}. \qquad (2)$$

Figure 3 shows curves of $S(E-E_c)$ and $m_c(E-E_c)$, which describe the dispersion relation, along with some theoretical curves (the dashed curves) calculated from the two-band model[5] with the parameter values $m_{\perp 0} = 0.022m_0$, $E_g = 0.19$ eV, and $K = 9$. We see that up to $E - E_c \cong 0.09$ eV the two-band model gives a satisfactory description of the experimental behavior, while at higher energies the description breaks down, and more-complicated models must be used in the calculations.[6,7]

In addition to the series of levels which extrapolate to the bottom of the conduction band, in the case **H**‖**I** we see levels which extrapolate to minima of surface subbands. Figure 1 shows the Landau levels for the surface valence subband E_0. For this subband we used Eqs. (1) and (2) to calculate S (curve 3 in Fig. 3) and m_c (curve 4 in Fig. 3) as functions of $E - E_0$. The values of the mass at the edge of the subband ($\sim 0.064m_0$) agree well with the mass calculated ($0.063m_0$) from the parabolic band model.[8]

In summary, tunneling spectroscopy in a quantizating magnetic field, which has been used previously in a successful study of semiconductors with an isotropic spectrum, can also be used to study anisotropic multivalley models, in which case it provides valuable information on both bulk and surface states.

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