to H_{dc} which was set to 2054 oe, the subsidiary resonance peak. The results show that the optimum modulation frequency is about 0.8 Mc/sec for a microwave field near the threshold field, h_c. Furthermore, it is evident that H_m is quite sensitive to changes in either modulation frequency or microwave field. These results are in general agreement with the Suhl theory although a detailed comparison cannot as yet be made.

The above Suhl theory can, of course, be extended to the parallel pumped case where the microwave magnetic field is parallel to the dc field. Figure 2 shows the results obtained for this parallel pumped condition. In Fig. 2(a) an oscilloscope trace shows the subsidiary absorption as a function of H_{dc} with no modulation applied. The noisy absorption is due to the relaxation oscillations which usually accompany subsidiary resonance.[2] As the modulation field amplitude is slowly increased, the subsidiary absorption gradually becomes suppressed as shown in the succeeding traces 2(b), 2(c), and 2(d). For this microwave field ($h/h_c = 1.26$) a modulating field of 0.36 oe is required for complete suppression. The optimum modulating frequency is 0.25 Mc/sec as compared to the 0.8-Mc/sec frequency for the perpendicular pumped case of Fig. 1. At power levels of 5 db or more above threshold the disappearance of the absorption with increasing modulation amplitude takes place in a discontinuous manner and will be described in detail in a forthcoming paper. The application of these results as a tool to explore the spin-wave spectrum and to various microwave devices will also be discussed.

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OSCILLATORY MAGNETORESISTANCE IN n-TYPE PbTe

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Distinct oscillations of the transverse magnetoresistance of three oriented single crystals of n-type PbTe in dc magnetic fields have been observed. These results confirm the existence of a multivalley band structure having prolate energy ellipsoids oriented along the ⟨111⟩ crystalline axes.[1,2] It is further established that there are four ellipsoids, thus locating the energy minima at the zone edge. The temperature dependence of the oscillatory amplitudes yields a value for the cyclotron mass m_e^* and, in addition, the transverse and longitudinal effective masses are calculated. A recent note,[3] describing the behavior of the transverse magnetoresistance in pulsed fields in an n-type PbTe crystal, has given indications of oscillatory effects. However, the measurements, showing a single minimum, were not interpreted in terms of a possible model for the band structure.

The bulk of our measurements were made on a [110]-oriented sample having a carrier concentration n of $3.45\times10^{17}/\text{cm}^3$ and a Hall mobility of 1.2×10^6 cm^2/volt-sec at 1.7°K. With the current along the [110] direction, measurements as shown in Fig. 1 were obtained with magnetic fields up to 26.5 kgauss in the [001] and [1$\bar{1}$0] directions at 1.7 and 4.2°K. Measurements made on additional [110] and [100] samples having dif-

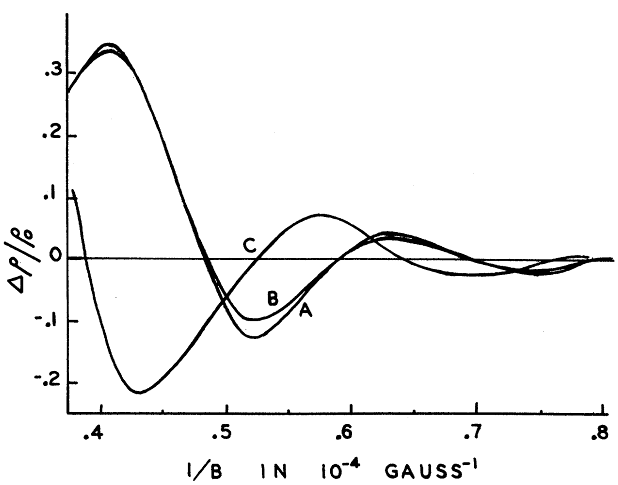

FIG. 1. Oscillatory component of the transverse magnetoresistance for current along [110]; curve A: B_{001} at 1.7°K; curve B: B_{001} at 4.2°K; curve C: $B_{1\bar{1}0}$ at 1.7°K. ρ_0 is the zero-field resistivity.

ferent carrier concentrations yielded oscillatory effects of lower amplitudes but leading to results in agreement with the data presented. Oscillatory effects in the longitudinal direction were not resolved in these samples, the amplitudes being at least an order of magnitude smaller than the transverse effects. In all cases, magnetoresistance and Hall voltage measurements were made using standard four-probe techniques. Data were taken for all combinations of current and magnetic field directions on two sides of the crystal and the results averaged. The Hall voltage and the magnetoresistance above 1 kgauss were linear functions of the magnetic field with a small oscillatory component superimposed. The oscillatory part was obtained by biasing out the linear term with a signal from a rotating-coil gaussmeter while slowly sweeping the magnetic field.

Periodic oscillations in the magnetoresistance will occur as a result of the Landau levels passing through the Fermi level E_f. In a degenerate system, which strictly applies in our case,

$$E_f = \frac{(\pi\hbar)^2}{2m_0^* m_D^*}\left(\frac{3n}{\pi}\right)^{2/3},$$

where $m_D^* = m_T^* N_v^{2/3} K^{1/3}$ is the reduced density-of-states effective mass, N_v is the number of valleys, and $K = m_L^*/m_T^*$, the mass anisotropy for a given valley. With $E_f/\hbar\omega = \alpha/B$, where $\omega = eB/m_e^*$ is the cyclotron frequency, the period, in units of $1/B$, can then be expressed as $1/\alpha$. The value of α is

$$31.4\,(n/N_v)^{2/3} f(K),$$

for B in units of 10^4 gauss and n in units of $10^{18}/\text{cm}^3$.

For a $\langle 111\rangle$ model, oscillations of a single period would be expected for B along a [100] direction because of the single effective mass associated with this direction. For this orientation the experimentally determined value of α is 4.9 ± 0.3 as obtained in Fig. 2(a). The effective-mass ratio K determined from weak-field magnetoresistance is 4.5 ± 0.5 at 300°K and decreases somewhat at lower temperatures, presumably due to an admixture of ionized impurity scattering.[2] Using this value for K, and the expression for $f(K)_{100}$ as given in Table I, eight- and four-valley models yield $\alpha = 3.3 \pm 0.1$ and 5.2 ± 0.1, respectively. Thus a four-valley ellipsoid model is established.

The treatment of transverse magnetoresistance

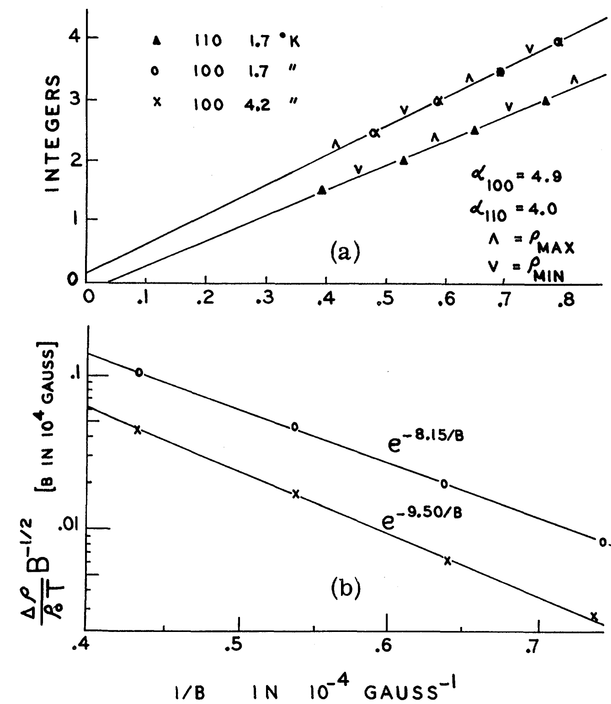

FIG. 2. (a) Nodes of the [001] and [1$\bar{1}$0] oscillations in Fig. 1 plotted at half-integer points for the determination of the periods and the phase shifts. (b) Decay of the B_{001} oscillations vs $1/B$ at 1.7 and 4.2°K for the determination of the damping factors and thus the cyclotron effective mass $(m_e^*)_{100}$.

by Adams and Holstein[4] gives the following expression for the oscillatory component for the case of at least several quantum levels and including only thermal broadening:

$$\frac{\rho_{os}}{\rho} = -C\left(\frac{1}{\hbar\omega E_f}\right)^{1/2} T \sum_{M=1}^{\infty} \frac{(-1)^M \cos(2\pi M E_f/\hbar\omega - \frac{1}{4}\pi)}{M^{1/2}\sinh(2\pi^2 MkT/\hbar\omega)},$$

where ρ is the resistivity in the classical limit

Table I. Values of m_e^* and $f(K)$ for two B directions and ellipsoids along the $\langle 111\rangle$ axes.

B	m_e^*	$f(K)$
[100]	$m_T^* K^{1/2}[3/(K+2)]^{1/2}$	$K^{1/6}[3/(K+2)]^{1/2}$
[110]	$m_T^* K^{1/2}$	$K^{1/6}$
	$m_T^* K^{1/2}[3/(2K+1)]^{1/2}$	$K^{1/6}[3/(2K+1)]^{1/2}$

and ρ_{os} is the oscillatory component. Our experimental results indicate that the damping is so severe that only the first term in the summation need be considered. This striking attenuation in the amplitudes for decreasing B can be attributed to both thermal broadening and broadening of the Fermi level due to inhomogeneities in the crystal, the latter being the dominant effect. Collision broadening should be very small because of the high mobility.

For B in the [110] direction, two periods would normally be observed. However, because of the damping terms, the component due to the high effective mass will be very small after several periods, leaving predominantly the low-effective-mass oscillations. From the data, plotted in Fig. 2(a), the ratio $\alpha_{110}/\alpha_{100}$ determines a value of K in approximate agreement with the value determined from weak-field magnetoresistance at 300°K. In the [100] case, the phase agrees with that predicted by Adams and Holstein. The phase in the [110] case is somewhat shifted from the predicted value as might be expected from a small admixture of the high-mass period.

The damping term which includes the effect of inhomogeneity and thermal broadening can be written as $\exp[-(\beta_1+\beta_2)/B]$, where $\beta_1 \simeq 200(m_e{}^*/m_D{}^*)(\Delta n/n)$ and $\beta_2 = 14.8\ m_e{}^*T$. The observed damping, $\beta_1 \simeq 7$, indicates a value for $\Delta n/n$ of about 10% which is consistent with the measured inhomogeneity.

To obtain the value of the total damping term [where the effect of inhomogeneity broadening is included in Eq. (1)], $\Delta\rho B^{-1/2}/\rho_0 T$ vs $1/B$ was plotted in Fig. 2(b). ρ in Eq. (1) was taken to be the actual resistivity at a given field, i.e., $\rho \propto \rho_0 B$; however, the actual magnetic field dependence in front of the oscillatory term has only a small effect on the determination of the damping factor. Since the difference in the slope at the two temperatures arises from the change in the value of the β_2 term, an effective mass $m_e{}^* = 0.035 \pm 0.005$ could be determined. Thus for $K = 4.5$, $m_T{}^* = 0.025 \pm 0.005$, $m_L{}^* = 0.12 \pm 0.03$, and $m_D{}^* = 0.10 \pm 0.02$. Thermoelectric measurements at $T \leq 10$°K have given $m_D{}^* = 0.08 \pm 0.03$.[2]

More complete results will be published in the future, including studies of longitudinal magnetoresistance and Hall oscillations.

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TRANSVERSE-EVEN VOLTAGE: A HIGH-FIELD GALVANOMAGNETIC EFFECT ASSOCIATED WITH OPEN ORBITS IN METALS

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The magnetoresistance, determined from the voltage measured parallel to the current, represents only one component of the even electric field, the even part of the electric field being that part which is unchanged by a reversal of the magnetic field. The other electric field components lie transverse to the current, and account, for example, for the well-known planar Hall effect. Here, we report observations in copper of such transverse voltages, and demonstrate a significant application of the transverse-even voltage in the determination of open-orbit directions. In addition to providing information about the shape of the Fermi surface, we find that these observations vividly support the concept of open orbits.[1]

When the magnetic field lies in the plane transverse to the current the planar Hall effect vanishes. However, an even voltage usually persists due to the presence of a slight longitudinal misalignment of the Hall contacts to the sample. Such voltages are of one sign because they represent reproductions of the magnetoresistance on a reduced scale, and indeed, they are not true transverse voltages. In contrast, the transverse-even voltages which we have observed in high-purity copper single crystals for high magnetic fields transverse to the current do not scale with the magnetoresistance and characteristically exhibit changes of sign.[2] This new behavior, im-