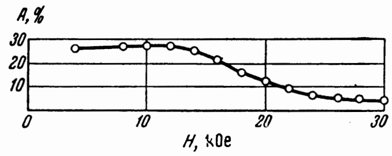

FIG. 3. Dependence of the anisotropy of the electrical resistance

$$A = \frac{(\Delta r / r)_{max} - (\Delta r / r)_{min}}{(\Delta r / r)_{max}}$$

for a sample of bismuth on the magnetic field intensity; $T = 4.2°K$, $H \perp C_3$.

pendence of $\sigma(H)$ on the magnetic field intensity may be the result of a combination of the magnetic-field variations of $n(H)$ and $\tau(H)$. On the other hand, for bismuth ($n_1 = n_2$), the behavior of the Hall constant is determined essentially by the mobilities of the carriers. If we assume that the monotonic variation of the Hall constant in fields stronger than 20 kOe is due to the variation of τ with the field, then $\tau = \alpha H^{-0.5}$. Then the linear variation of $\sigma(H)$ in strong fields is obtained if $n \sim H^{3/2}$. Such a dependence is actually cited by Azbel' and Brandt.[6] When the overlap changes, the number of electrons and holes varies in the same manner, and therefore pure bismuth remains a metal with $n_1 = n_2$, while for bismuth with impurities the difference $n_1 - n_2 = \Delta n$ remains constant and is determined uniquely by the Hall constant R.[7,8]

As is well known,[9] the minima of the resistance in the Shubnikov-De Haas effect arise when the level of the state densities passes through the chemical potential. If we assume that the last minimum on the $\Delta r/r = f(H)$ and $R(H)$ curves is due to spin splitting of the last Landau level, then we can estimate the value of the spin splitting from the experimental data. In the case of a field parallel to the binary axis (C_2) and perpendicular to the trigonal axis (C_3) the value of the spin splitting is 18% larger than the value of the orbital splitting, while for $H \perp C_2$ and $H \perp C_3$, the spin splitting coincides within 5% with the orbital splitting. The sharp change in the Hall constant and the change in the anisotropy A (Fig. 3) may possibly be due to a different, more isotropic law of electron dispersion at the bottom of the band.

The authors consider it their pleasant duty to thank Academician P. L. Kapitza for interest in the work and M. Ya. Azbel' for acquainting them with an unpublished paper and for a discussion of the results.

[1] Grenier, Reynolds, and Sybert, Phys. Rev. **132**, 1 (1963).

[2] N. B. Brandt and L. G. Lyubutina, JETP **46**, 1711 (1964), Soviet Phys. JETP **19**, 1150 (1965).

[3] E. P. Vol'skiĭ, JETP **46**, 2035 (1964), Soviet Phys. JETP **19**, 1371 (1964).

[4] Smith, Baraff, and Rowell, Phys. Rev. **135A**, 1118 (1964).

[5] M. H. Cohen and E. J. Blount, Phil. Mag. **5**, 115 (1960).

[6] M. Ya. Azbel' and N. B. Brandt, JETP, this issue, p. 1206, Soviet Phys. JETP, p. 804.

[7] Lifshitz, Azbel', and Kaganov, JETP **31**, 63 (1956), Soviet Phys. JETP **4**, 41 (1957).

[8] N. E. Alekseevskiĭ and T. I. Kostina, JETP **41**, 1722 (1961), Soviet Phys. JETP **14**, 1225 (1961).

[9] B. I. Davydov and I. Ya. Pomeranchuk, JETP **9**, 1294 (1939).

Translated by J. G. Adashko
180

QUANTUM OSCILLATION OF THE THERMAL EMF IN n-TYPE InSb

S. S. SHALYT, R. V. PARFEN'EV, and M. S. BRESLER

Institute for Semiconductors, Academy of Sciences, U.S.S.R.

Submitted to JETP editor January 28, 1965; resubmitted February 10, 1965

J. Exptl. Theoret. Phys. (U.S.S.R.) 48, 1212-1214 (April, 1965)

THE quantization of the energy spectrum of electrons in a conductor, placed in a magnetic field H, may, under certain conditions, manifest itself as the oscillatory dependence of certain transport coefficients on the field intensity. To observe this quantum effect, it is necessary to have: 1) a strong effective magnetic field: $uH/c \gg 1$; 2) sufficiently low temperature: $\kappa T \ll \hbar\Omega$; 3) a degenerate state of the electron gas: $\mu > \kappa T$ (u is the mobility, $\Omega = eH/m^*c$ is the cyclotron frequency, μ is the chemical potential, and κ is Boltzmann's constant). In the theoretical interpretation, the quantum oscillations appear as the effect of the periodic dependence of the density-of-states function on the energy.

Quantum oscillations have been observed in some metals in a number of transport processes: the magnetoresistance, the Hall effect, the thermal emf, and the thermal conductivity.[1] They have been observed also in some semicon-

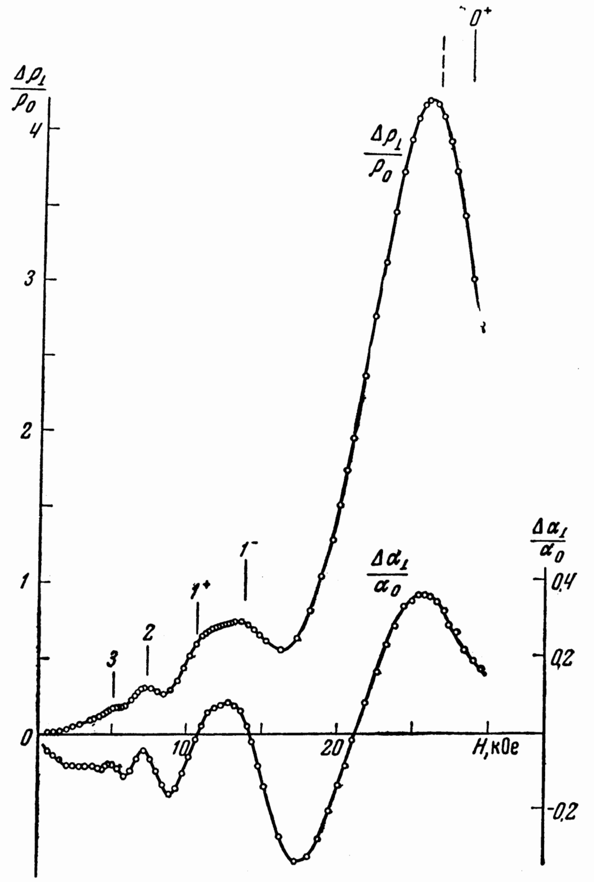

FIG. 1. Experimental curves of the dependence of the magnetoresistance ($\Delta\rho\perp/\rho_0$) and of the thermoelectric power ($\Delta\alpha\perp/\alpha_0$) on the magnetic field intensity at $T \approx 4°K$. The vertical lines indicate the values of the magnetic fields at which, according to the theory,[3,4,6] the magnetic Landau levels $N = 0^+, 1^-, 1^+, 2, 3$ intersect in turn (starting from the strong-field side) the chemical potential level $\mu(H)$ (after correction for the incomplete degeneracy). The dashed vertical line represents the value of the magnetic field which is obtained on allowing for the actual value of the Hall coefficient near the zeroth maximum.[7]

ductors in the degenerate state, the magnetoresistance and the Hall effect being involved (InSb, InAs, PbTe, Bi_2Te_3, Ge).[1,2]

In the present study, we found that at helium temperatures the thermal emf of InSb in a transverse magnetic field exhibits the same oscillatory dependence as the transverse magnetoresistance. Figure 1 compares the experimental data for these two effects, obtained in a study of a single-crystal sample of InSb ($2.7 \times 3 \times 40$ mm), having a carrier density $n(H \to 0) = 1.32 \times 10^{16}$ cm^{-3} and a mobility $u = 9 \times 10^4$ cm$^2 \cdot$ V$^{-1} \cdot$ sec^{-1} (at $T = 4.2°K$).

Figure 1 shows clearly four equal-phase maxima located at $H_{max} = 26$, 12.7, 7.2 and 5.0 kOe. The positions of these maxima are found theoretically from the condition of intersection of the chemical potential level $\mu(H)$ by the magnetic Landau levels

$$\varepsilon_{N\pm} = \hbar\Omega(N + 1/2) \pm 1/2|g|\mu_B H.$$

The theoretical formulas obtained from this condition [3,4] show that the first, relatively narrow, maximum on the strong-field side in Fig. 1 ($H_{max} = 26$ kOe), corresponds to the magnetic Landau level with the quantum number $N = 0^+$. The next maximum (in the region $H = 11-14$ kOe) is more extended on the field scale, since it represents the superposition of two partly overlapping peaks, corresponding to the spin splitting of the first ($N = 1$) Landau level. In order to increase the spin splitting of this level and thus to separate the peaks of the split maximum. we investigated additionally another sample of InSb with a higher electron density ($n = 4.3 \times 10^{16}$ cm^{-3}, $T = 1.4°K$), in which the first maximum was found to be shifted toward stronger fields ($H = 22-31$ kOe). The clear splitting pattern of the first maximum into two peaks ($H_{max,1^-} = 29$ kOe, $H_{max,1^+} = 23.5$ kOe) is shown in Fig. 2. The other, narrower, maxima in Fig. 1 represent the unsplit Landau levels $N = 2$ and $N = 3$.

The equality of phases of the maxima, in the experimental curves of $\Delta\rho_\perp/\rho_0$ and $\Delta\alpha_\perp/\alpha$, is not a trivial result since the magnetoresistance oscillations are determined, to a considerable extent, by the periodic variation of the scattering probability,[4] while the thermal emf oscillations appear in the theory without scattering, and are due to oscillations of the entropy only.[5]

In the earlier study of the present authors,[6] where the spin splitting of the first maximum was observed in the region 11–15 kOe, we assumed that the considerable broadening of the Landau levels would make it impossible to estimate the g-factor with an acceptable accuracy. In the present study, this splitting was shifted into the region of stronger fields (22–30 kOe) and appeared more clearly. However, an estimate of the g-factor by means of the formulas taken from the theory of Gurevich and Éfros [4] gave the same value as in[6]: $|g| = 34$ (instead of $|g| = 50$). In view of this result, Éfros considered the problem of the influence of the nonquadratic form of the dispersion law on the splitting in n-type InSb and came to the conclusion that allowance for this influence did not greatly improve matters in the investigated range of fields.

We are grateful to A. L. Éfros and Yu. N. Obraztsov for discussing the theoretical problems.

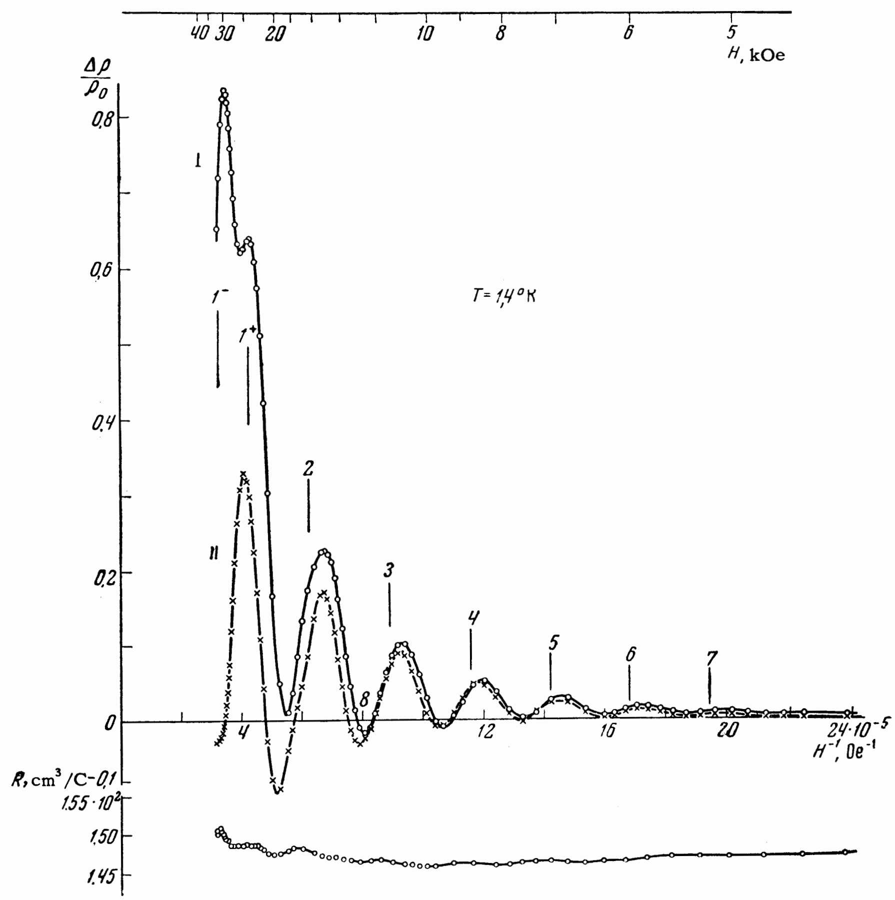

FIG. 2. Experimental curves of the dependence of the transverse ($\Delta\rho_{\perp}/\rho_0$) and longitudinal ($\Delta\rho_{\parallel}/\rho_0$) magnetoresistances of n-type InSb on the magnetic field intensity at T = 1.4°K. The lower curve shows the Hall coefficient. The vertical lines with the indices 1^-, 1^+, 2, ... , have the same meaning as in Fig. 1.

[1] A. H. Kahn and H. P. R. Frederikse, Solid State Physics 9, 257 (1959).

[2] Amirkhanov, Bashirov, and Zakiev, DAN SSSR 148, 1279 (1963), Soviet Phys. Doklady 8, 182 (1963); FTT 5, 469 (1963), Soviet Phys. Solid State 5, 340 (1963); Ellet, Cuff, and Kuglin, Bull. Am. Phys. Soc. 7, 202 (1962); K. Auch and G. Landwehr, Z. Naturforsch. 18a, 424 (1963); Bernard, Roth, Straub, and Mulhern, Jr., Phys. Rev. 135, A1386 (1964).

[3] S. S. Shalyt and A. L. Éfros, FTT 4, 1233 (1962), Soviet Phys. Solid State 4, 903 (1962).

[4] L. É. Gurevich and A. L. Éfros, JETP 43, 561 (1962), Soviet Phys. JETP 16, 402 (1963).

[5] Yu. N. Obraztsov, FTT 7, 573 (1965), Soviet Phys. Solid State 7, (in press).

[6] Bresler, Parfen'ev, and Shalyt, FTT 7, 1266 (1965), Soviet Phys. Solid State 7 (in press).

[7] Pavlov, Parfen'ev, Firsov, and Shalyt, JETP 48, 1565 (1965), Soviet Phys. JETP 21 (in press).

Translated by A. Tybulewicz

MAXIMUM IN THE MELTING CURVE OF ANTIMONY

S. M. STISHOV and N. A. TIKHOMIROVA

Crystallography Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor January 29, 1965

J. Exptl. Theoret. Phys. (U.S.S.R.) 48, 1215-1216 (April, 1965)

THE phase diagram of antimony was investigated in [1,2]. In these investigations, which did not agree fully with each other, a monotonic reduction of the melting point of antimony was found right up to pressures of 57 kbar.[2] Vereshchagin and Kabalkina [3] carried out an x-ray diffraction study of antimony at high pressures. They discovered two new crystalline modifications of antimony: Sb II - with a simple cubic structure, and Sb III - with a close-packed hexagonal structure. The pressures at which the transitions occurred at room temperature were: Sb I → Sb II - 70 kbar, Sb II → Sb III - 85 kbar.

The Sb II—Sb III transition is in agreement with