# *CONCERNING THE GALVANOMAGNETIC PROPERTIES OF BISMUTH*

N. E. ALEKSEEVSKIĬ and T. I. KOSTINA

Institute of Physics Problems, Academy of Sciences, U.S.S.R.

Submitted to JETP editor January 28, 1965

J. Exptl. Theoret. Phys. (U.S.S.R.) 48, 1209-1211 (April, 1965)

As is well known, bismuth belongs to the group of so-called poor metals, that is, metals in which the number of conduction electrons is small. The small number of conduction electrons leads to a low value of effective masses, so that the cyclotron frequency $\omega^*$ for bismuth is two or three orders of magnitude larger than the cyclotron frequency for the free electron, and the distance between the Landau levels in the magnetic field $\hbar\omega^* = \zeta$ ($\zeta$ is the chemical potential) is narrower in fields $\sim 10^4$ Oe. In several recent papers [1-4] the variation of the frequency of the quantum oscillations with the magnetic field is attributed to changes in the number of carriers (electrons $n_1$ and holes $n_2$) upon change in the magnetic field intensity H. It can be assumed that the change in the number of carriers should noticeably affect also the behavior of the monotonic part of the resistance tensor in a magnetic field.

We have investigated samples of bismuth of different purity and different crystallographic orientations. The measurements were made at temperatures 77, 20.4 and 4.2°K and in fields up to 35 kOe. Figures 1 and 2 show typical dependences of the change in the electrical resistance $\Delta r/r$ and the Hall constant R on the magnetic field intensity for one sample of bismuth ($r_{273°K}/r_{4.2°K} = 280$). The monotonic part of the variation of the resistance in the magnetic field in weak fields changes in proportion to $H^2$ for all temperatures. At temperatures 77 and 20.4°K, the quadratic dependence goes over into a linear one (the Kapitza law). For T = 4.2°K, the first quadratic dependence ($\Delta r/r = \alpha_1 H^2$), observed in small fields, goes over after a small transition region into the second quadratic dependence ($\Delta r/r = \alpha_2 H^2$, $\alpha_1 > \alpha_2$), with the second quadratic dependence observed only for sufficiently pure samples. In magnetic fields stronger than 12 kOe, the quadratic dependence is replaced by a linear one. In the same region of fields the Hall constant R increases rapidly, and in fields larger than 20 kOe, quantum oscillations are superim-

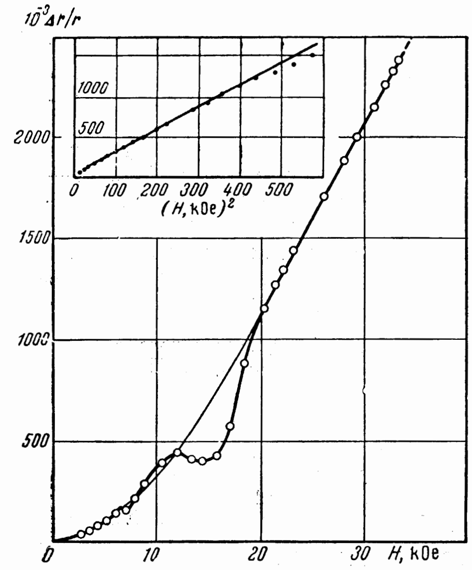


FIG. 1. Dependence of the variation of the electric resistance $\Delta r/r$ on the magnetic field intensity for a bismuth sample; T = 4.2°K, H ⊥ $C_3$, H ⊥ $C_2$.

posed on the monotonic part of R, which decreases like $H^{0.5}$. In fields larger than 14 kOe, the anisotropy of the electric resistance decreases sharply (Fig. 3). It must be noted that the magnetic fields at which such variations of $\Delta r/r = f(H)$ and of R(H) are observed, depend only on the orientation of the field relative to the crystallographic axes, and do not depend on the purity of the sample. We can attempt to explain the results by taking into account the large spin splitting in bismuth,[5] which leads to a change in the number of carriers with magnetic field.[4] Since the conductivity of the metal in the magnetic field $\sigma(H)$ depends linearly on the number of carriers n and on the relaxation time $\tau$, the observed linear de-

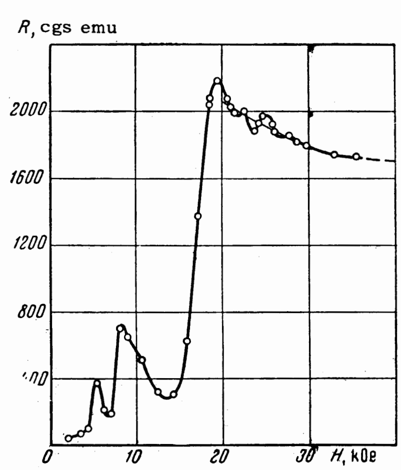


FIG. 2. Dependence of the Hall constant R on the magnetic field intensity for a bismuth sample; T = 4.2°K, H ⊥ $C_3$, H ∥ $C_2$.

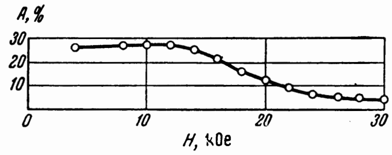


FIG. 3. Dependence of the anisotropy of the electrical resistance

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

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 $\tau$ 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, $\mu$ is the chemical potential, and $\kappa$ 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-