PECULIARITIES OF THE HALL EFFECT IN TIN IN A LARGE EFFECTIVE MAGNETIC FIELD

V. N. KACHINSKIĬ

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

Submitted to JETP editor May 3, 1962

J. Exptl. Theoret. Phys. (U.S.S.R.) **43**, 1158-1163 (October, 1962)

A large number of samples were used for an investigation of the Hall effect in tin having an open Fermi surface. The results obtained can be accounted for qualitatively on the basis of notions developed by I. M. Lifshitz et al.[1,2] In particular, the Hall effect peculiarities (predicted in these references) associated with open trajectories of isolated directions have been detected. An investigation of the temperature dependence of the Hall effect showed that for a considerable region of directions of the magnetic field, the magnitude of the Hall effect is determined by processes of a kinetic nature, despite the large values of the effective magnetic field.

IN metals with open Fermi surfaces, as shown by I. M. Lifshitz et al[1,2] the dependence of the resistance and of the Hall effect on the direction of the magnetic field relative to the crystal axes should exhibit at large effective magnetic fields certain singularities connected with the occurrence of open carrier trajectories. No such singularities of the Hall effect were observed experimentally so far, although the Hall effect in single crystals of metals at rather large effective yields has been the subject of many investigations (for example, [3,4]). The reason for it was either an insufficiently large effective field or improper choice of specimen orientation.

We have undertaken a detailed investigation of the Hall effect in white tin, which has an open Fermi surface, the shape of which has been sufficiently well investigated.[5,6] The measurements were made at 4.2°K in a 6.9 kOe field on single crystal specimens of cylindrical form, approximately 2 cm long and 1.5—3 mm in diameter, with different orientations of the axes relative to the crystallographic directions. The initial material for the preparation of the specimens was high purity tin with $\rho_{290°K}/\rho_{4.2°K} = 60{,}000$. The effective field $H \cdot \rho_{290°K}/\rho_{4.2°K}$ thus had a value $\sim 5 \times 10^8$ Oe. Four contacts were mounted on each specimen, to measure the emf in two mutually perpendicular directions in a plane normal to the specimen axes. (For a report of the procedure and the preliminary results of the investigation see [7].)

This procedure, similar to that used by Borovik[3], yielded the magnitude and direction of the electric vector of the Hall field for each direction of the magnetic field (the Hall-field vector is generally speaking not perpendicular to the direction of the magnetic field). The emf on the contacts was measured with the aid of a dc amplifier with superconducting modulator having a sensitivity 5×10^{-10} V.[8] The Hall effect was determined, as usual, as half the difference between the voltages obtained with two opposite directions of the magnetic field, i.e., as an effect that is odd with respect to the field direction (concerning the simultaneously-observed even effect see [9]). The magnetic field in all experiments was parallel to the plane perpendicular to the specimen axis. The results of measurements of the Hall effect are presented in the form of projections E_z and E_y of the Hall field vector on the z axis, which is parallel to the magnetic field, and on the y axis, which is perpendicular to it, i.e., in a coordinate system rigidly connected to the magnetic field (see [3]). The current flows in the specimen in a direction parallel to the x axis. The xyz coordinate system is a right-hand one.

Simultaneously with the Hall effect, we measured in all the specimens the resistance in the magnetic field, so as to compare the singularities of the Hall effect with the singularities of the resistance in a magnetic field, investigated by Alekseevskiĭ and Gaĭdukov[5].

Figure 1 shows diagrams of Hall-effect rotation diagrams for specimen Sn-11, the axis of which lies in the (010) plane and is inclined 27° to the [001] axis. As can be seen on the stereographic

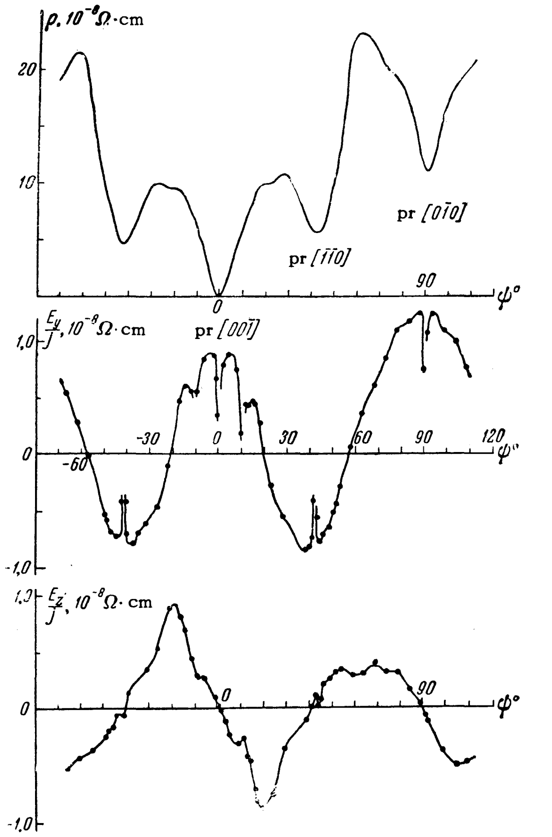

FIG. 1. Specimen Sn-11 ($\varphi = 0°$, $\theta = 20°$). Diagrams of Hall-field rotation E_x/j and E_z/j and of resistance in magnetic field $\rho = E_y/j$ (j – current density). The magnetic field intensity is H = 6.9 kOe; ψ – angle between the direction of the field and the projection of the [001] axis on the plane of rotation of the field; φ – angle between the [100] axis and the projection of the specimen axis on the (001) plane, θ – angle between specimen axis and the [001] axis.

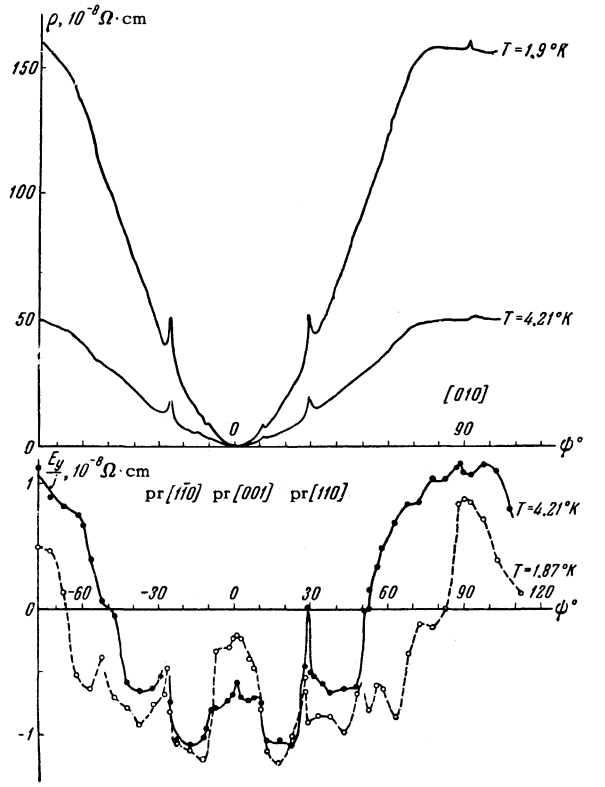

FIG. 2. Specimen Sn-17 ($\varphi = 0°$, $\theta = 60°$). Rotation diagrams of E_y/j and ρ for two values of the temperature; H = 6.9 kOe.

projection in Fig. 4, the directions of the magnetic field for this specimen do not enter at all into the two-dimensional region of the singular directions of the magnetic field, and open trajectories occur only when **H** is parallel to the projections of the [010], [110], and [100] axes. These directions correspond to narrow minima of the angular dependence of E_y —the Hall field component normal to **H**. (In addition, there exist two minima, apparently, in the directions of the projections of [150] and [1$\bar{5}$0], not accompanied by noticeable singularities in the resistance.) Such rotation diagrams are typical for all specimen orientations, in which open trajectories arise only at fixed **H** directions (see also Fig. 3a). The component of the Hall field E_z parallel to the magnetic field has no essential singularities, as is the case of all other specimens. When **H** is parallel to the projections of the symmetry axes, E_z vanishes, and the Hall field is perpendicular to the magnetic field. We shall henceforth refer only to the E_y component.

Figure 2 shows rotation diagrams for another typical case (Sn-17, the specimen axis is in the (100) plane and the angle ψ between the specimen axis and [001] is 60°). Here the directions of the magnetic field enter into the two-dimensional region of singular directions (at values of ψ between −23° and +23°). In this case the singularities of the Hall effect (minima) and of the resistance (maxima) correspond to the directions in which the density of the layer of open trajectories increases sharply. In the directions corresponding to the passage through the boundary of the two-dimensional region, no singularities were observed in the behavior of the Hall effect. Such rotation diagrams are characteristic of all specimens of this type. An exception is the specimen Sn-13 ($\varphi = 36°$, $\theta = 90°$); at an angle $\psi = 30°$ between the field **H** and the [001] axis (passage through the boundary of the two-dimensional region), the Hall effect and the resistance experience a small jump.

From the material obtained we can conclude that the Hall emf sharply decreases (and possibly reverses sign) when a thick layer of open trajectories, having a common average direction, is produced (magnetic field directions corresponding to the thick lines on the diagram of the singular directions of the field (Fig. 4b), and continuations of

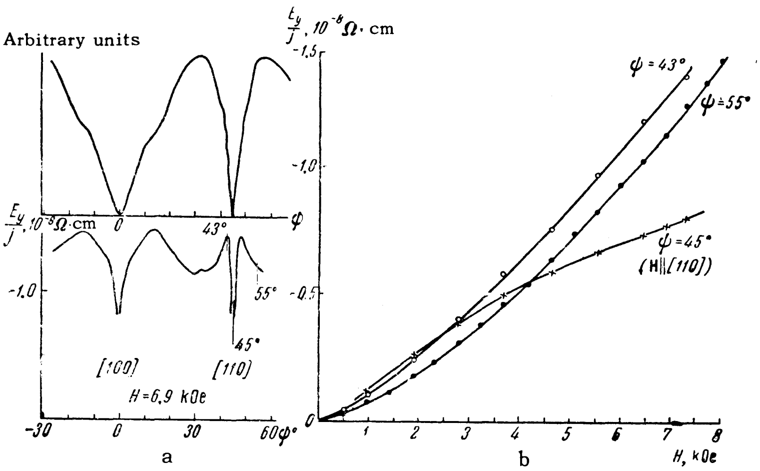

FIG. 3. Specimen Sn-7: a – rotation diagrams of E_y/j and ρ; H = 6.9 kOe, b – dependence of E_y/j on H for three directions of the magnetic field, noted on diagram a.

these lines inside the two-dimensional region of singular directions). The minima on the angular dependence of the Hall field are in many cases more distinct and sharper than the singularities of the resistance (see Fig. 1); the latter can have the form of smooth minima (Fig. 1), narrow minima (see [5]), and narrow maxima (Fig. 2). The presence of a small number of open trajectories (two-dimensional region of special field directions) does not manifest itself essentially on the behavior of the Hall effect.

It is difficult to make any statements concerning the depth of the Hall-field minima and the character of the dependence on the magnetic field in these directions, inasmuch as the narrowness of these singularities ($\sim 1-2°$) enables even an insignificant crystal imperfection to greatly distort this dependence, and even cause disappearance of the minimum. We can only note that the depth of the minima increases with increasing field. Figure 3b shows the dependences of the Hall field on the magnetic field for the specimen Sn-7 (specimen axis parallel to the fourfold [001] axis). It must be emphasized that the Hall emf depends on the magnetic field in nonlinear fashion, something characteristic of other specimens, too. The linear dependence is observed only when **H** ∥ [001] (specimen Sn-10); the Hall constant has in this case a value $(-4.8 \pm 0.2) \times 10^{-3}$ cgs emu.

Another singularity of the rotation diagrams of the Hall field is the dependence of the sign of the effect on the direction of the magnetic field (we have in mind the component E_y perpendicular to the magnetic field) (see also [3,4]). The results obtained on many specimens have shown that in large effective fields the sign of the Hall effect (for a fixed value of the field) depends only on the direction of the magnetic field relative to the crystallographic axes and is independent of the direction of the current vector. A stereographic projection showing the regions of the directions of the magnetic field corresponding to different signs, at an effective field $\sim 4.2 \times 10^8$ Oe, is shown in Fig. 4. The lines drawn on the diagram are the traces of the planes in which the magnetic field was rotated in different specimens. The filled circles on the right half of the diagram show the positions of the narrow minima of the Hall effect; for comparison, a diagram of the special directions of the magnetic field, obtained in [5] by investigating the resistance in the magnetic field, is shown in the same figure.

The fact that the hole Fermi surfaces in tin are multiply connected brings about a situation wherein carrier orbits with "electronic" direction of revolution may appear on one of these surfaces for certain directions of the magnetic field. Since the number of hole states for tin is equal to the number of electronic states, the balance of the number of carriers of different signs is thus disturbed (see [2]). Thus, when **H** ∥ [001], the outline directions of the intersections of the tubes

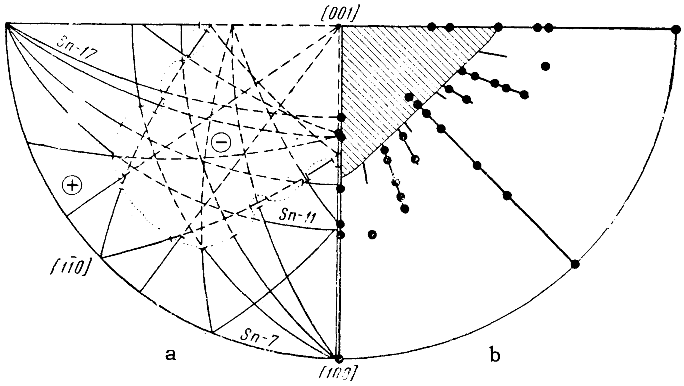

FIG. 4. a – Stereographic projection of the directions of the magnetic field corresponding to different signs of the Hall effect, b – stereographic projection of the special directions of the magnetic field for resistance (after[5]). The dots denote the directions of the field corresponding to the singularities of the Hall effect.

parallel to the [001] axis with the open hole surface of the fourth zone correspond to negative charges. Corresponding to this field direction is a Hall emf that increases linearly with the field, with negative Hall coefficient (see above; the corresponding concentration of the negative carriers is 0.35 per atom). At the same time, it is not quite clear why a rather large odd positive Hall emf arises when the directions of **H** are close to that of the (001) plane. In this case, apparently, the balance of the number of carriers is not disturbed (when there are no open trajectories), and processes of kinetic character are responsible for the occurrence of the Hall emf. This is confirmed by the temperature dependence of the Hall emf in these directions. Figure 2 shows rotation diagrams of E_y for two temperatures: 4.2 and 1.9°K. The change in the resistance in the magnetic field for such a decrease in temperature indicates almost doubling of the free path in this same field. As can be seen from the foregoing plots, a larger change in the Hall emf with temperature is observed at directions of H close to (001) (ψ from 60 to 120°). In addition, the Hall emf changes strongly in the region where thick layers of open trajectories arise ($\psi = \pm 10°$).

The author is grateful to N. A. Brilliantov and A. I. Shal'nikov for interest in the work, to Yu. P. Gaĭdukov and V. G. Peschanskiĭ for a discussion, and to S. V. Volkov for help with the experiments.

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

[2] I. M. Lifshitz and V. G. Peschanskiĭ, JETP **35**, 1251 (1958) and **38**, 188 (1960), Soviet Phys. JETP **8**, 875 (1959) and **11**, 137 (1960).

[3] E. S. Borovik, Izv. AN SSSR, ser. fiz. **19**, 429 (1955), Columbia Tech. Transl. p. 383. FMM **2**, 33 (1956).

[4] J. A. Marcus and J. Jahia, Phys. Rev. **113**, 137 (1959).

[5] Alekseevskiĭ, Gaĭdukov, Lifshitz, and Peschanskiĭ, JETP **39**, 1201 (1960), Soviet Phys. JETP **12**, 837 (1961). N. E. Alekseevskiĭ and Yu. P. Gaĭdukov, JETP **41**, 1079 (1961), Soviet Phys. JETP **14**, 770 (1962).

[6] A. V. Gold and M. G. Priestley, Phil. Mag. **5**, 1089 (1960).

[7] V. N. Kachinskiĭ, DAN SSSR **135**, 818 (1960), Soviet Phys. Doklady **5**, 1260 (1961).

[8] V. N. Kachinskiĭ, PTÉ, in press.

[9] V. N. Kachinskiĭ, JETP **41**, 665 (1961), Soviet Phys. JETP **14**, 476 (1962).

Translated by J. G. Adashko
205