SOVIET PHYSICS JETP VOLUME 22, NUMBER 4 APRIL, 1966

ANISOTROPY OF THE ELECTRICAL RESISTANCE OF INDIUM IN A MAGNETIC FIELD

Yu. P. GAĬDUKOV

Moscow State University

Submitted to JETP editor May 13, 1965

J. Exptl. Theoret, Phys. (U.S.S.R.) 49, 1049-1053 (October, 1965)

The dependence of the resistance on the crystallographic direction and the magnetic field intensity was measured for three single-crystal samples of indium whose axes were parallel to the crystal axes [001], [101], and [110]. None of these samples exhibited anisotropy of the resistance in a magnetic field. The dependences of their resistance on the magnetic field intensity for different crystallographic directions were in the form of curves, which showed saturation. The results obtained confirm that the Fermi surface of indium is not open.

OLSEN'S[1] measurements of the resistance ρ of polycrystalline indium samples in a magnetic field H showed that the curve of the dependence $\rho(H)$ exhibited saturation. This led him to suggest that the Fermi surface of indium had apparently no open sections.

The galvanomagnetic properties of indium single crystals were measured by Borovik and Volotskaya.[2] They discovered that the samples investigated had slight anisotropy of their resistance in a constant magnetic field $H = 24$ kOe. The resistance at the minima and maxima of the polar diagrams $\rho(\vartheta)$ (ϑ was the angle of rotation of the magnetic field) reached saturation as the magnetic field was increased. The results of Borovik and Volotskaya confirmed the absence of open sections in the Fermi surface of indium.

However, no final conclusion about the nature of the Fermi surface of indium (closed or open) can be drawn from these results. The point is that indium has an odd number of conduction electrons. Therefore, the electron and hole volumes cannot compensate each other in the Fermi surface of indium. If indium has an open Fermi surface, the nature of the anisotropy of its resistance in strong effective fields should be the same as, for example, that of gold:[3] narrow resistance maxima should be observed for those directions of the magnetic field which correspond to the open sections of the Fermi surface. The angle α between the current **J** and the average directions of open sections is important because[4]

$$\rho(H) = AH^2 \cos^2\alpha + B.$$

It is evident from this expression that a resistance maximum cannot appear at angles close to $\pi/2$. Moreover, the value of the coefficient α is proportional to the number of open sections along a given field direction. Therefore, if the number of open sections is small, the averaging associated with the crystal imperfections, the magnetic field inhomogeneity, etc., may strongly depress the resistance maximum.

The best conditions for the observation of singularities in the resistance anisotropy are obtained along the magnetic field directions close to the rational directions in a crystal around which appear two-dimensional regions of singular directions of the magnetic field, leading to open sections of the Fermi surface. The orientations of the axes of the four samples used by Borovik and Volotskaya [2] were not determined. This prevented them from determining the crystallographic directions for which the resistance of indium tended to saturation in a magnetic field. Therefore, we may assume that in their experiments the conditions were unfavorable for the observation of narrow resistance maxima. For example, had there been open sections in the Fermi surface of indium, parallel to the basal plane (001), the resistance in the samples whose axes were close to the [001] axis for any field direction $\mathbf{J} \perp \mathbf{H}$ should have tended to saturation as the magnetic field increased.

It should be mentioned that, according to Harrison's model,[5] open sections in the Fermi surface of indium would be most likely along the directions parallel to the (001) plane.

In view of this, it was very interesting to carry out accurate measurements of the resistance anisotropy using indium samples whose axes were parallel to certain rational directions.

SAMPLES AND MEASUREMENTS

Single-crystal samples of indium were grown by the Obreimov—Shubnikov method in glass capillaries, whose inner surfaces were coated with soot from a gas burner. The sample diameter was 1.5—2 mm, the length about 30 mm.

The orientation of the samples was determined optically with a goniometer, type GD-1. For this purpose, glass capillaries containing samples were etched at the ends in hydrofluoric acid. The unetched part of the capillary was used as a jacket protecting the sample. The ends of each sample were then etched in an aqueous solution of potassium bichromate. After the etching, the strongest reflectivity was exhibited by the crystal faces (001), $\{100\}$, and $\{111\}$. The reflections from the $\{111\}$ faces made it possible to distinguish with certainty the [001] and $\langle 100 \rangle$ axes. The accuracy of the determination of the orientation of the axes of a sample was not less than ±0.5°.

From the 30 single crystals grown, we selected three. The axes of these samples were parallel to the crystal axes [001], [101], and [110]. The samples were mounted in the usual way for galvanomagnetic measurements. The [110] indium sample had, apart from potential leads, additional leads to measure the Hall emf along the direction close to the [001] axis.

The accuracy of the alignment of the samples in a magnetic field was ±1°.

The measurements of the polar diagrams $\rho(\vartheta)$ and of the dependences $\rho(H)$ for $\mathbf{J} \perp \mathbf{H}$ were carried out in two stages: using automatic recording on a two-coordinate recorder and manually at selected points. The latter method was used because the elimination of the thermal emf, the Hall emf (whose value was comparable with the value of the useful signal), the null drift of an amplifier, (type FÉOU-18), etc., could be carried out more accurately and conveniently in measurements at selected points. Automatic recording was needed in order not to miss any singularities of the resistance which could exist over narrow ranges of the angle and magnetic field.

The measurements were carried out in fields up to 23 kOe at temperatures of 4.2 and 1.3°K.

RESULTS AND DISCUSSION

When the three samples were cooled from 300 to 4.2°K, their resistance samples decreased by a factor of 18 000. On further cooling from 4.2 to 1.3°K, the resistance of each decreased by a of three (the resistance at T = 1.3°K was determined by the extrapolation of the dependence $\rho(H)$ to zero value of H). The rotation diagrams $\rho(\vartheta)$, obtained for H = 20 kOe, are shown in Figs. 1—3 (the positions of the axes indicated near the curves were determined to within ± 5°). The same figures include the dependences $\rho(H)$ for some directions of the magnetic field.

The resistance anisotropy was practically absent in the investigated samples. The deviation from the average value did not exceed ±7%. However, for In [001] the observed anisotropy was undoubtedly due to an incorrect mounting of the potential leads, since it disagreed with the crystal symmetry. The fact that the mounting may affect indium samples can be seen in the case of In

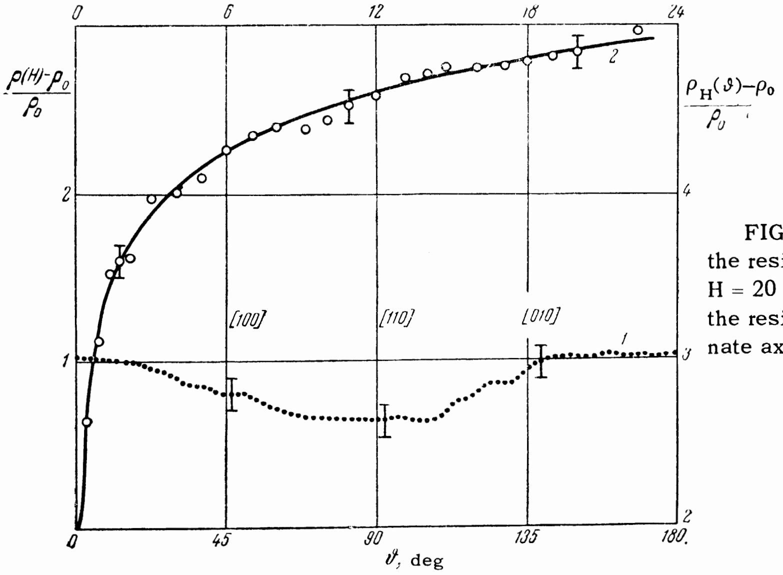

FIG. 1. Sample In [001], T = 4.2°K. Curve 1: dependence of the resistance on the angle of rotation of the magnetic field, H = 20 kOe; ordinate axis on the right. Curve 2: dependence of the resistance on the magnetic field (H, kOe), $\mathbf{H} \parallel [100]$; ordinate axis on the left.

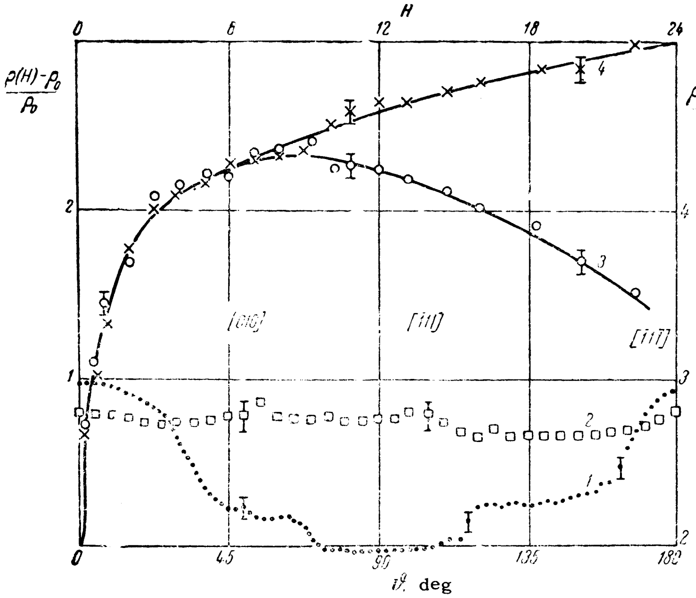

FIG. 2. Sample In [101], T = 4.2°K. Curves 1 and 2: dependence of the resistance on the angle of rotation of the magnetic field, H = 20 kOe, for different positions of the potential leads; ordinate axis on the right. Curves 3 and 4: dependence of the resistance on the magnetic field (H, kOe), at the minimum and maximum of curve 1; ordinate axis on the left.

[101]. In the initial mounting, the potential leads were soldered close to the current leads. The measurements showed a relatively strong resistance anisotropy (curve 1 in Fig. 2). Since the minimum and maximum of the resistance in the diagram $\rho(\vartheta)$ of the sample In [101] did not coincide with the rational directions in the crystal, we suspected the influence of the mounting. When the mounting was corrected, on the basis of recommendations given in the paper of Alekseevskiĭ, Brandt, and Kostina,[6] we obtained the diagram shown by curve 2 in Fig. 2.

The influence of an incorrect mounting is due to the appearance of an emf at the potential leads of the sample, which is associated with the nondiagonal terms of the symmetrical part of the resistance tensor and which distorts the true dependence $\rho(H)$ for a given field direction when $J \perp H$ accurately. This distortion is illustrated by curves 3 and 4 in Fig. 2, which were obtained from the measurements on the sample In [101] in the initial mounting.

It is possible that the $\rho(\vartheta)$ diagram of the sample In [110] is the true diagram since its symmetry agrees with the crystal symmetry, and the $\rho(H)$ curves have the "normal" form at the minimum and maximum.

It is evident from the $\rho(\vartheta)$ diagrams for the samples In [001], In [101], and In [110], obtained at selected points or by continuous recording, that there are no resistance maxima near the rational directions (within an experimental error of ±3%). The directions in the vicinity of the [001] axis were investigated particularly carefully. For this purpose, the axis of the sample In [110] was rotated by ±1, ±2, and ±3° from the position for

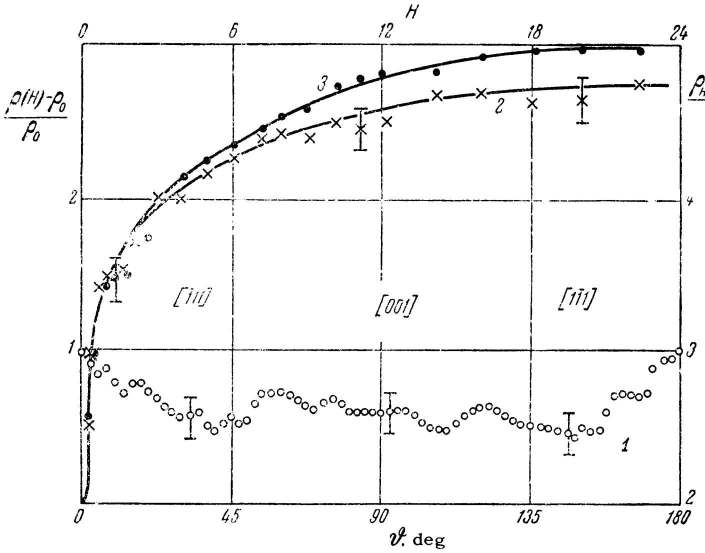

Fig. 3. Sample In [110], T = 4.2°K. Curve 1: dependence of the resistance on the angle of rotation of the magnetic field, H = 20 kOe; ordinate axis on the right. Curves 2 and 3: dependence of the resistance on the magnetic field (H, kOe) for H‖[001] and H‖[1$\bar{1}$0]; ordinate axis on the left.

which J ⊥ H. The rotation was carried out in a plane passing through the sample axis and the (001) axis. We determined the $\rho(\vartheta)$ diagram for each position. The $\rho(\vartheta)$ plots for all the positions of the sample In [110] were in the form of rectilinear segments.

Simultaneously with the $\rho(\vartheta)$ diagrams, we determined the dependence of the Hall emf on the angle ϑ for the sample In [110]. It was found that the Hall emf for any one of the positions 0, ±1, ±2, and ±3°, measured from the [001] axis, was not anisotropic within an experimental error of ±2%. The Hall emf depended linearly on the magnetic field.

As is evident from Figs. 1 and 3, the $\rho(H)$ dependence of indium single crystals tends to saturation at the value of $\Delta\rho(H)/\rho_0$ which is close to three. Cooling to 1.3°K does not affect this value.

Thus, the measurements carried out show that there are no resistance anisotropy singularities characteristic of metals with open Fermi surfaces along the magnetic field directions close to the indium crystal axes [001], ⟨100⟩, ⟨111⟩, and ⟨110⟩. Hence, with the accuracy with which the measurements were carried out, we may conclude that the Fermi surface of indium has no open sections. It is not possible to estimate quantitatively the limit above which the Fermi surface may be assumed to be closed. However, if we use the angular accuracy of the measurements amounting to ±1.5°, then according to the expression $\tan\vartheta = d/b$, the diameter d of the necks which may connect the hole Fermi surfaces in the second zone should not be greater than 0.02b, where b is the dimension of the Brillouin zone along a given direction.

In conclusion, we take this opportunity to thank V. F. Gantmakher and R. T. Mina for their interest in these measurements.

---

[1] J. L. Olsen, Helv. Phys. Acta **31**, 713 (1958).

[2] E. S. Borovik and V. G. Volotskaya, JETP **38**, 261 (1960), Soviet Phys. JETP **11**, 189 (1960); V. G. Volotskaya, JETP **45**, 49 (1963), Soviet Phys. JETP **18**, 36 (1964).

[3] Yu. P. Gaĭdukov, JETP **37**, 1281 (1959), Soviet Phys. JETP **10**, 913 (1960).

[4] I. M. Lifshitz and V. G. Peschanskiĭ, JETP **38**, 188 (1960), Soviet Phys. JETP **11**, 137 (1960).

[5] W. A. Harrison, Phys. Rev. **118**, 1190 (1960).

[6] Alekseevskiĭ, Brandt, and Kostina, JETP **34**, 1339 (1958), Soviet Phys. JETP **7**, 924 (1958).

Translated by A. Tybulewicz
136