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INVESTIGATION OF THE GALVANOMAGNETIC PROPERTIES OF Pd

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The galvanomagnetic properties were investigated of single-crystal samples of Pd whose purity was represented by $\rho(T = 300°K)/\rho(T = 4.2°K) = 1500-2100$. It was established that the Fermi surface of palladium is open. The experimental results are consistent with a Fermi surface of the "spatial network of corrugated cylinders" type, with the cylinders' axes along the fourfold axes of the reciprocal lattice. The average constant diameter of these "cylinders" is approximately $(0.25 \pm 0.03)b$, where b is the Pd reciprocal lattice period in the [100] direction: $b = 2(2\pi/a)$, $a = 3.88$ Å.

A large number of papers have already been published on the Fermi surface of non-transition metals. Although the galvanomagnetic properties of transition metals have been investigated,[1] sufficiently detailed data on the Fermi surface of these metals are not yet available. Therefore, we have undertaken a study of the galvanomagnetic properties of Pd and, on the basis of the results obtained, discuss here the possible shape of the Fermi surface of this metal.

PREPARATION OF THE SAMPLES AND THE METHOD OF MEASUREMENT

The initial material was technical-grade palladium powder which was subjected to special chemical purification. The resultant extremely pure Pd sponge, containing $< 10^{-4}$% Mg and Si, was fired in a quartz ampoule under continuous pumping conditions. The fired sample was placed in a special ampoule for fusion in a high-frequency furnace (Fig. 1).

The upper chamber of the ampoule, the broad part of which (a) contained the sample, was placed in the high-frequency circuit of the furnace in such a way that the sample was centrally disposed. Fusion was carried out both in vacuum and in inert gases. The purest samples were obtained by melting in an inert gas atmosphere. To form more perfect crystals, the molten metal was pumped, by opening a tap A, into the lower chamber of the ampoule b, which was a capillary. The Pd samples obtained in this way consisted, as a rule, of 2—3 blocks of different orientations from which single-crystal samples were cut.

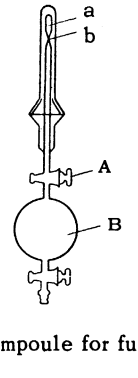

FIG. 1. Ampoule for fusion.

The crystallographic orientations of the single-crystal samples were determined by the back reflection method using type URS-70 x-ray apparatus. Samples of the required orientation were cut by electrical erosion. The samples were in the form of slabs of the following dimensions: $l = 6-8$ mm, $b = 0.8-1$ mm, $d = 0.2-0.25$ mm. Copper bars were used as current leads. As reported earlier,[2] the current density gradient at the sample ends did not affect the results of the measurements. The same copper bars were used to determine the sign of the Hall emf. Copper wire of 0.05 mm diameter was used to provide potential contacts; the distance between these contacts was 2—4 mm.

The measurements were carried out at T = 4.2°K. The angular dependences of the resistance and the Hall emf were normally investigated in fields up to 26 kOe; some samples were measured in a field H = 36 kOe. The dependences $\rho(\varphi)$ for H = const, where φ is the angle of rotation of the magnetic field, were recorded with an automatic electronic potentiometer type ÉPP-09. Some measurements were carried out in pulsed fields up to 100 kOe.[3] To determine more exactly the influence of the

Sample No.	$\frac{\rho\ (300°\ K)}{\rho\ (4{,}2°\ K)}$	Orientation*		Magnitude of anisotropy	
		θ°	ξ°	$H = 26$ kOe	$H = 34{,}5$ kOe
3	1735	6	27	1.90	3.0
5	2190	48	45	1.20	—
6	1465	26	23	1.48	—
8	1600	36	40	1.33	—
9	1480	0	0	1.85	2,5
10	1900	55	45	1.15	—
12	2030	45	22	1.34	—
13	1960	35	43	1.46	1.65
14	1930	31	45	1.45	1.77
15	1880	41	45	1.49	1.85
16	1780	28	17	1.65	—
17	1740	43	45	1,27	—
19	1615	31	0	1.40	—
20	1720	55	45	1.10	—
21	2160	47	23	1.28	—
29	1630	33	4	1.92	—
34	1580	38	9	1.69	—
35	1600	43	8	1,55	—
37	1600	64	39	1,30	—
39	1600	61	39	1.24	—
40	1600	64	39	1.30	—
51	1900	45	0	1.95	—

*θ is the polar and ξ is the azimuthal angle of the sample axes with respect to the principal axes of the crystal.

crystallographic orientation on the dependence $\rho_H(\varphi)$, the measurements were carried out with the samples at an angle to the magnetic field, the angle being varied from 0 to 15°. (The inclination of the sample to the magnetic field was achieved either by tilting the Dewar vessel directly or by attaching the sample to a movable stage, which could be rotated by means of a rod introduced through a trap.) Over 50 samples of various orientations were investigated and data for some of them are presented in the table.

EXPERIMENTAL RESULTS

The angular dependences of the sample resistance $\Delta\rho/\rho$, the most typical of which are shown in Fig. 2, were relatively simple and indicated weak resistance anisotropy (finer structure was not detected even in pulsed field measurements up to 100 kOe). The dependences of the resistance on the magnetic field are given in Figs. 3–5 for various orientations. The quadratic rise of the resistance in the magnetic field is observed over a wide range of angles, but saturation of the resistance occurs only for certain directions: for example **H** ‖ [100] and **H** ‖ [110] for **J** ‖ [101] (Fig. 2b).

For these directions of the magnetic field the plots of $\rho_H(\varphi)$ exhibit minima the depths of which (except those corresponding to **H** ‖ [100]) depend on the orientation of the current. For **J** ‖ [100], a resistance maximum is observed along the [110] direction and $\rho \propto H^2$ (Fig. 2). In order to establish more precisely whether these directions are the open ones, current plots were recorded.[4] (A current plot represents the dependence $\rho_H(\alpha)$, where α is the angle between the current and the average direction of the open cross sections of the Fermi surface.) Analysis of the current plots[4] indicated open trajectories for those directions of the magnetic field, with respect to the crystallographic axis, along which the resistance showed saturation as a function of the field.

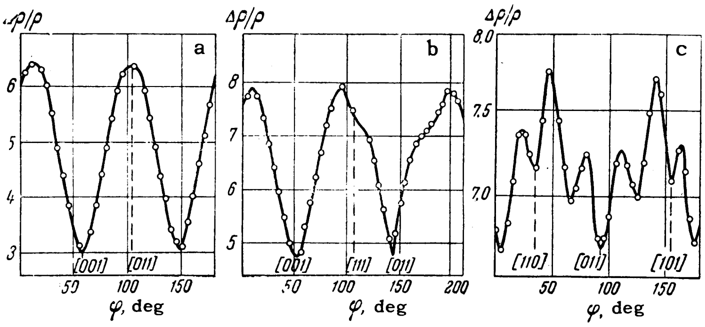

FIG. 2. Dependence of the relative change in the resistance on the angle between the magnetic field direction and the crystal axes (T = 4.2°K, H = 26 kOe): a) Pd-9; b) Pd-51; c) Pd-10.

All the directions of the magnetic field for which minima were observed in the angular dependences

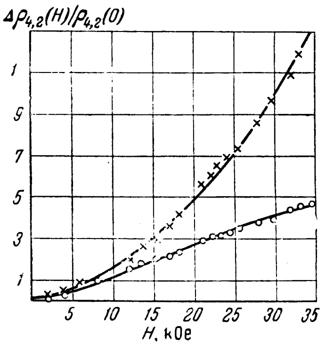

FIG. 3. Change of the resistance in a magnetic field for sample Pd-9 for various values of the angle φ: × – φ = 100°; o – φ = 55°.

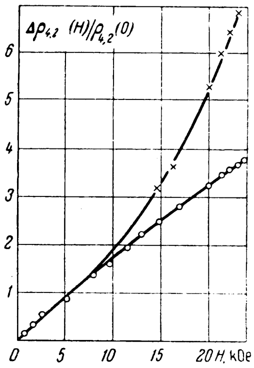

FIG. 4. Change in the resistance in a magnetic field for sample Pd-51: × – φ = 50°; o – φ = 140°.

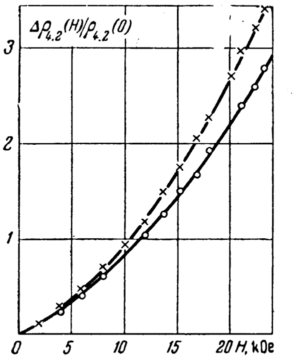

FIG. 5. Change in the resistance in a magnetic field for sample Pd-10: × – φ = 50°; o – φ = 90°.

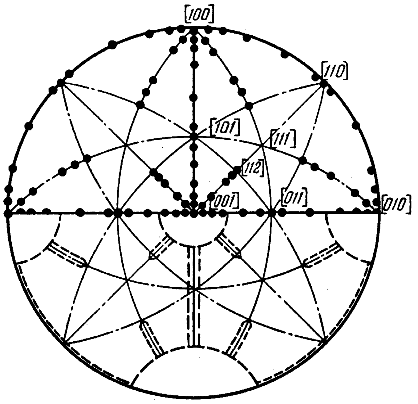

FIG. 6. Stereographic projection of the directions of the resistance minima (the upper half) and of the special magnetic field directions for the Fermi surface of palladium (the lower half). The regions around the [100] directions are two-dimensional areas representing the magnetic field directions for which open cross sections exist.

$\rho_H(\varphi)$ were plotted on a stereographic projection (Fig. 6). The resultant stereographic projection of the minima is essentially the projection of the special directions of the magnetic field for the open Fermi surface of palladium (the lower part of Fig. 6). The notation of the regions in the lower half of the stereographic projection is the same as in [6].

DISCUSSION OF RESULTS

The stereographic projection indicates that the directions along which the resistance minima appear in the angular dependences $\rho_H(\varphi)$ lie, mainly, on lines which represent the projection traces of the (100) planes. The depths of these minima, with the exception of those along and close to the [100] directions, depend on the orientation of the current. The maximum depth is obtained when the magnetic field plane is perpendicular to (100). This allows us to regard the directions along the fourfold axes as the open trajectory directions.[1]

As the magnetic field diverges from the [100] axis, the depth of the minimum decreases. In the region of $\theta = 35°$ the minimum transforms into a maximum and the maximum increases with further divergence. If we assume that the angle $\theta \approx 35°$ is the limiting angle of the existence of open trajectories, [4] we can estimate approximately the area of the two-dimensional region around the [100] direction. It is not possible to estimate the dimensions of this region in the way it was done in [5,6].

The stereographic projection of the special directions of the magnetic field corresponds to a Fermi surface of the "spatial network of corrugated cylinders" type, with the cylinder axes directed along the fourfold axes of the reciprocal lattice of Pd (palladium has a face-centered cubic lattice). Using the relationship between the limiting angle and the area of the two-dimensional region, [7] as well as the relationship between the area of this region and the diameter of the corrugated cylinders, [4] we estimated the constant average diameter of these cylinders $d_{av} \approx (0.25 \pm 0.03)b$, where b is the reciprocal lattice period in the [100] direction ($b = 2(2\pi/a)$, $a = 3.88\,\text{Å}$). Analysis of the current plots allows us to assume that in palladium, as in lead, [6] we are dealing with a compensated metal whose Fermi surface consists of two parts which are equal in volume and opposite in sign ($V_e = V_h$), but one of which is open and the other closed.

Having determined the sign of the Hall coefficient for **H** ∥ [100], we can find whether the closed surface is of the hole or electron type. For **H** ∥ [100], the compensation of the volumes is incomplete and the sign of the Hall coefficient is determined by the sign of the closed surface. The experimentally determined sign of the Hall coefficient indicates an electron surface and, therefore, the open surface of palladium represents holes. The dependence of the Hall emf on the magnetic field (for **H** ∥ [100]) is given in Fig. 7. The experimental value of the Hall coefficient allows us to estimate the minimum diameter (d_{min}) of the cylinders forming the open Fermi surface of palladium.[7] Since

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[1] The depths of the resistance minima appearing near the [100] direction along a line which represents the projection of the (101) plane depend on the angle between the [100] direction and the magnetic field direction, where **H** ∥ (101) and the magnetic field plane is perpendicular to (101).

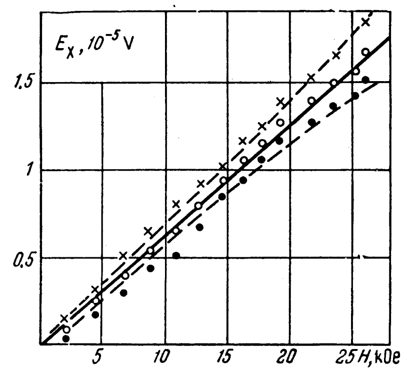

FIG. 7. Dependence of the Hall emf on the magnetic field intensity for a fixed angle φ(φ = 55°) for sample Pd-9. The dashed curves represent the Hall emf dependences for two opposite directions of the magnetic field.

$$R_{[100]} = 1 / \Delta nec,$$

where $\Delta n = 2h^{-3}b^2 d_{min}$ and $R_{[100]} = 2.32 \times 10^{-3}$ cgs emu, we find that

$$d_{min} \approx (0.21 \pm 0.03)\, b.$$

This is in good agreement with the value of d_{av} found above.

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[1] Alekseevskiĭ, Egorov, Karstens, and Kazak, JETP **43**, 731 (1962), Soviet Phys. JETP **16**, 519 (1963).

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

[3] N. E. Alekseevskiĭ and V. S. Egorov, JETP **45**, 448 (1963), Soviet Phys. JETP **18**, 309 (1964).

[4] Alekseevskiĭ, Gaĭdukov, Lifshitz, and Peschanskiĭ, JETP **39**, 1201 (1960), Soviet Phys. JETP **12**, 837 (1961).

[5] N. E. Alekseevskiĭ and Yu. P. Gaĭdukov, JETP **35**, 554 (1958), Soviet Phys. JETP **8**, 383 (1959).

[6] N. E. Alekseevskiĭ and Yu. P. Gaĭdukov, JETP **41**, 354 (1961), Soviet Phys. JETP **14**, 256 (1962).

[7] I. M. Lifshitz and V. G. Peschanskiĭ, JETP **35**, 1251 (1958), Soviet Phys. JETP **8**, 850 (1959).

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