EFFECT OF PRESSURE ON THE FERMI SURFACES OF ZINC AND CADMIUM

Yu. P. GAĬDUKOV and E. S. ITSKEVICH

Institute of Physical Problems and Institute of High Pressure Physics, Academy of Sciences, U.S.S.R.

Submitted to JETP editor March 5, 1963

J. Exptl. Theoret. Phys. (U.S.S.R.) **45**, 71-82 (August, 1963)

The anisotropy of the electrical resistance of zinc and cadmium single crystals in a magnetic field of 8700 Oe was studied under a pressure of 7000 kg/cm^2. The pressure dependence of the resistance oscillation period of zinc was investigated up to 8000 kg/cm^2 in a magnetic field along the [0001] axis at helium temperatures; a fixed hydrostatic pressure was generated in a high-pressure bomb. The magnetoresistance of cadmium does not vary under pressure, while in zinc it decreases about 20%, when the current direction lies in the basal plane of the crystal. When the current is parallel to the [0001] axis the magnetoresistance is found to decrease 35—40% in both metals. In zinc, pressure changes the deviation limit from the [0001] axis of special magnetic field direction in the $(10\bar{1}0)$ plane. The resistance oscillation period of zinc decreases from 6.3×10^{-5}/Oe at zero pressure to 2.1×10^{-5}/Oe at 8100 kg/cm^2. The data are employed to determine the change induced in the Fermi surface of zinc by hydrostatic pressure. The critical pressure at which the open cross sections in the (0001) plane of zinc disappear is estimated to be $\sim 30{,}000$ kg/cm^2.

1. INTRODUCTION

WE have begun an experimental investigation of the effect produced by high pressures on the Fermi surfaces of metals in accordance with certain ideas of I. M. Lifshitz.[1] Our first task was to develop a technique for applying high pressures at liquid helium temperatures in such a manner as to enable work in magnetic fields with single crystals of metals having a high degree of both physical and chemical purity, without producing any undesirable irreversible deformations. The existing techniques for producing high pressures at low temperatures did not yield hydrostatic pressures, in any event during the generating process.[2,3][1)] This was the principal obstacle to obtaining undistorted deformations and reproducible results for single crystals at helium temperatures (see [4], for example).

One of the present authors[5] had developed and tested experimentally a procedure which largely satisfies the requirements. A pressure bomb made of heat-treated beryllium bronze is filled with a mixture of oil and kerosene. The pressure in the working space is generated at room temperature and is fixed mechanically; the bomb is then inserted into a Dewar and cooled slowly. Pressures up to 8000 kg/cm^2 at liquid helium temperatures are obtained.

Lifshitz showed[1] that the topology of Fermi surfaces of metals can be changed by pressure. For example, we can expect that a gradually deformed open Fermi surface will become a closed surface. This transformation greatly alters the anisotropy of the electrical conductivity tensor in a magnetic field. Specifically, the resistance anisotropy changes; the magnetic-field dependence of resistance in certain directions is altered, the angular dependences of resistance in static fields losing their minima or maxima associated with the existence of open conduction electron trajectories. A reverse transformation of closed Fermi surfaces into open surfaces is also possible and can actually be expected to occur in metals at pressures of the order 10^5 kg/cm^2. We can expect to observe the deformation of the Fermi surface in the pre-transformation region. Small deformations of the Fermi surface can be detected by investigating changes in the angular sizes of ranges of magnetic field directions for which open cross sections of Fermi surfaces exist (which we call the "special" directions of the magnetic field.)

The indicated changes will be observable with the highest probability in metals exhibiting an anisotropy of compressibility. We therefore selected zinc and cadmium, which possess open

1)We are not considering low pressures smaller than the pressure of helium solidification.

Fermi surfaces, as the first objects in which we would investigate the influence of pressure on resistance anisotropy. It is known,[6,7] that the Fermi surface of zinc possesses open cross sections parallel both to the [0001] axis and to the (0001) plane. From the Harrison model of this surface,[8] which was confirmed experimentally by Joseph and Gordon,[9] it is concluded that extremely thin necks are found in the multiply-connected open surface. In [9] the minimum cross sections of the necks are $0.0043\,\text{Å}^{-2}$ in the basal plane and $0.06\,\text{Å}^{-2}$ in the [0001] direction. It can be assumed that even relatively small pressures will change these cross sections considerably. Galvanomagnetic measurements enable us to observe only the changed sizes of necks in the basal (0001) plane, since they can be obtained from the angular sizes of a two-dimensional region and the so-called "whisker" in the stereographic projection of the special magnetic field directions.[6]

The Fermi surface of cadmium, which has a ratio c/a almost identical with that of zinc, differs from the latter by having no open sections parallel to the (0001) plane.[6] According to the Harrison model the Fermi surfaces of zinc and cadmium should not differ essentially.[10] It is therefore of interest to investigate the influence of pressure on the resistance anisotropy of cadmium single crystals in magnetic fields and to compare the results obtained for zinc and cadmium.

A direct study of the influence of pressure on the dimensions of metal Fermi surfaces is possible through the investigation of various oscillating quantum effects such as the oscillation of diamagnetic susceptibility (the de Haas–van Alphen effect), the oscillation of resistance in a magnetic field (the Shubnikov–de Haas effect) etc. Since all these phenomena are of the same character, all their oscillation periods P in a magnetic field H should coincide, being determined by the extremal cross sections S_m of the Fermi surfaces:[11]

$$P = \Delta(1/H) = 2\pi e\hbar / cS_m.$$

One of the first publications in which the pressure dependence of the period of quantum oscillations in a magnetic field was noted is [12], where the oscillation period of the Hall emf was observed to increase 1.5% in bismuth subjected to a gas pressure of ~ 100 atm. In [13] galvanomagnetic effects under hydrostatic pressure were studied employing the ice technique for producing high pressures.[2,14] Here also the pressure dependences of the oscillation periods of the Hall emf and of resistance in bismuth were detected. This method was subsequently used extensively and successfully in [15] to study the influence of hydrostatic pressure on the de Haas–van Alphen effect. It was shown that of the three observed components of susceptibility oscillations in zinc the long-period component is most strongly influenced by pressure. In the [0001] direction at 4.2°K the period of this component increased from 5.2×10^{-5}/Oe at zero pressure to 7.8×10^{-5}/Oe at 1700 kg/cm^2. Thus a relatively small pressure changes some extremal cross sections of the zinc Fermi surface by a factor of almost one and one-half; we therefore expected that several times greater pressures would produce even greater changes in the sizes of these cross sections.

In the present work we investigate the Shubnikov–de Haas effect in zinc at pressures up to 8000 kg/cm^2. This effect in zinc was first observed in the [0001] direction in [16]; Renton determined the period of resistance oscillations to be 6×10^{-5}/Oe. The Shubnikov–de Haas effect has not yet been observed in cadmium.

2. SAMPLES AND MEASURING METHODS

Single crystal samples of zinc[2)] and cadmium were cut by means of electroerosion from monocrystalline blocks grown by the Obreimov-Shubnikov method. The samples, which were 15—20 mm long with 1-mm diameters, were subjected to no subsequent treatment except etching in acids; their orientation was checked with x rays.

The samples were mounted under the top cap equipped with current and potential leads, of the high-pressure vessel; the axes of the samples were parallel to the vessel axis. Before filling the working chamber with the pressurizing gas, the angular dependence of resistance $R_H(\vartheta)$ was measured in a transverse static magnetic field at 4.2°K (ϑ is the rotational angle of the magnetic field in a plane perpendicular to the sample axis). Magnetic fields up to 9 kOe were generated in the 112-mm gap of the electromagnet. The emfs from the sample were amplified with an F-116/I instrument and were registered automatically during the continuous rotation of the electromagnet.

Following heating, the working chamber was slowly filled with the gas at room temperature; after about three hours the pressure reached 10,000 kg/cm^2. During the pressure increase and decrease the resistance of the sample was monitored

2)We take this opportunity to thank B. N. Aleksandrov (Physico-technical Institute, Ukrainian Academy of Sciences) for providing us with high-purity zinc.

Table I

Sample	Orientation*, φ; θ', deg	p=0 (before compression)			p = 7000 kg/cm²			p=0 (after compression)		
		$10^4 R_{300}$, Ω	$10^7 R_{4.2}$, Ω	α	$10^4 R_{300}$, Ω	$10^7 R_{4.2}$, Ω	α	$10^4 R_{300}$, Ω	$10^7 R_{4.2}$, Ω	α
Zn-I **	5; 90	8.5	0.53	16200	8.42	0.83	10100	8.7	0.55	15800
Zn-II	25; 90	15.4	1.21	12700	14.8	1.60	9260	15.4	1.31	11800
Zn-III	30; 90	13.7	0.89	15400	13.0	1.12	11600	13.9	0.90	15500
Zn-IV	15; 50	7.9	—	—	7.3	0.53	14100	7.83	0.50	15660
Zn-V ***	[0001]	0.60	—	—	0.54	—	—	0.59	—	—
Cd-I	0; 90	4.45	0.67	6600	4.17	0.81	5120	4.47	0.60	7500
Cd-II	[0001]	2.4	0.15	16600	2.10	0.18	12000	—	—	—

*φ is the angle between the $(\bar{2}110)$ plane and the plane passing through the sample axis and the [0001] axis; θ' is the angle between the sample axis and the [0001] axis.

**In the work with the Zn-I sample hydrostatic conditions (slow compression) were not maintained completely.

***$R_{4.2}$ for Zn-V was too small to be measured.

continuously to within 0.05%. This enabled the detection of defects resulting from nonhydrostatic pressure. The resistances of our zinc and cadmium samples decreased continuously as the pressure was increased.

The bomb containing the pressurized sample was cooled for two or three hours; the cooling effect of liquid nitrogen was transmitted through gaseous helium. $R_H(\vartheta)$ was recorded under pressure after the bomb was covered with liquid helium. The processes of heating and pressure relaxation were the reverse of cooling and compression.

Following the release of the gas from the bomb, $R_H(\vartheta)$ was measured for a third time at 4.2°K. In each run (with and without pressure) the resistance was measured at 300°(R_{300}) and 4.2°($R_{4.2}$) with H = 0.

During the same runs the magnetic-field dependence of electrical resistance R(H) was measured for a fixed magnetic field direction H ∥ [0001]. R(H) was measured at 1.5° and 4.2°K using measuring currents up to 2 A in a field increasing linearly with time from 1.5 to 10 kOe. The emf from the sample was amplified with an F-116/I instrument before being registered by an automatic ÉPP-09 recorder.

The resistance oscillations of zinc in a magnetic field having [0001] orientation were observed against a background of approximately linearly increasing resistance. This hampered the clear observation of the oscillations. Therefore an emf increasing linearly with the magnetic field and compensating the linear increase of the resistance was fed simultaneously with the emf from the sample to the input of the F-116/I. The basic measurements were performed with linear compensation of the magnetoresistance of the samples. The measurements showed in the figures represent the equation

$$\Delta R(H) = R(H) - [AH + B],$$

where the constants A and B were in each instance selected for the suitable visualization of ΔR(H). The oscillation periods were determined within 5% from the resistance maxima.

The pressure was determined in each run using the calibration described in [5]. This calibration, which had been used for liquid hydrogen, is also suitable for helium temperatures because there was no pressure difference in the bomb between the temperatures of liquid hydrogen and liquid nitrogen. Pressures in the bomb were also measured with a tin pressure gauge installed adjacent to the sample and serving as a part of a current lead. The pressure was determined from the shift of the superconducting transition point of tin using the formula $dT_{cr}/dp = 4.5 \times 10^{-5}$ deg-cm²/kg. [4] The maximum discrepancy between the pressures recorded by the two different means was ~ 8%. However, since the value of dT_{cr}/dp in the given pressure region was not measured independently but was determined by extrapolation from the low pressure region, we preferred to employ the calibration described in [5]. We estimate the accuracy of the pressures to be 5—7%.

3. INFLUENCE OF PRESSURE ON THE ELECTRICAL RESISTANCE ANISOTROPY OF ZINC AND CADMIUM IN A MAGNETIC FIELD

Table I gives the states of the samples and measurements before and during compression, and following pressure relaxation (at H = 0). $R_{4.2}$ was measured with 5% accuracy. Here and below we use the ratio $\alpha = R_{300}/R_{4.2}$.

Table II

	Before compression	1st compression	After 1st compression	2nd compression	After 2nd compression	3rd compression	After 3rd compression
$10^4 R_{300}$, Ω	4.45	4.17	4.47	4.15	4.46	4.17	4.45
$10^7 R_{4,2}$, Ω	0.67	0.81	0.60	0.59	0.44	0.49	0.43
α	6600	5120	7500	6980	10100	8500	10300

It is evident that after depressurization samples retain their initial properties; this result is associated with conservation of the resistance $R_{4.2}$. Under pressure the average decrease of α is 25%. It must be noted that the increase of $R_{4.2}$ with pressure is not associated with irreversible deformation (Tables I and II).

A. Zinc. The angular dependences $R_H(\vartheta)$ at 4.2°K for samples I, II, III, and V are alike under pressure within error limits (Fig. 1). The resistances of samples I—IV in a field of 8700 Oe at 7000 kg/cm² decrease by ~ 20%. Under the same conditions the resistance of sample V, which exhibits almost no anisotropy, decreases 40%. In order to determine the influence of pressure on R(H) for a fixed value of ϑ the change of α is taken into account. A reduction of α leads to 20% decrease of the effective magnetic field (the Koehler rule). This can account for the observed reduction in the magnetic resistance of zinc under pressure.

Figure 2 shows $R_H(\vartheta)$ for sample Zn-IV with its axis forming the angle $\theta' = 50°$ with the [0001] direction. For this sample the rotation plane of the magnetic field intersects the "whisker" close to the end of the latter (Fig. 11 of [6]). The depth of the minimum in the (10$\bar{1}$0) plane is appreciably diminished under pressure and returns to its original value following the relaxation of pressure.

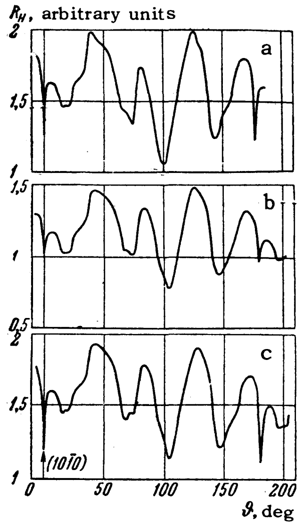

FIG. 2. Resistance of sample Zn-IV vs. rotational angle of magnetic field (H = 8700 Oe) at 4.2°K. a – at p = 0; b – at p = 7000 kg/cm²; c – at p = 0.

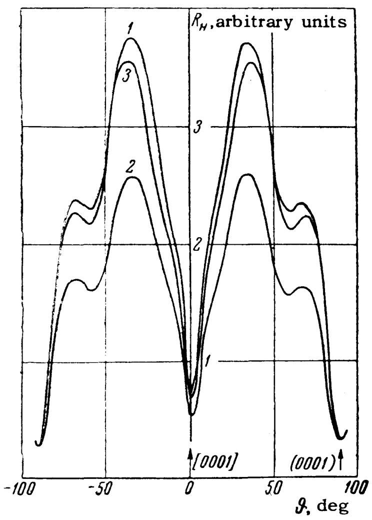

FIG. 1. Resistance of sample Zn-II vs. rotational angle of magnetic field (H = 8700 Oe) at 4.2°K. Curve 1 – p = 0; curve 2 – p = 7400 kg/cm²; curve 3 – p = 0 (after relaxing pressure).

From the measured angular dependence of resistance at zero pressure and at different angles between the sample axis in the plane $\varphi = 15°$, and the direction perpendicular to the rotational plane of the magnetic field, we derived a variation in the depth of the resistance minimum that is equivalent to the pressure effect. It was concluded from these measurements that a pressure of 7000 kg/cm² shortens the "whisker" by not less than 1°. Of course, this directly observable influence of pressure on the angular dependence of magnetoresistance in zinc single crystals must be investigated more thoroughly; we propose to do this for the angular dependences of both the whisker and the two-dimensional region of special magnetic-field directions around the [0001] direction.

B. Cadmium. In the sample Cd-I under 7000 kg/cm² there is practically no change of $R_H(\vartheta)$. However, a distinct smoothing out of the minimum is clearly observable in the direction H ∥ [0001] (Fig. 3). In sample Cd-II, $R_H(\vartheta)$ decreases about 40% for all angles ϑ.

In Cd-I following compression a considerable increase of α associated with a decrease of $R_{4.2}$ was observed. Cd-I was subjected to two additional compression cycles; Table II shows that the third cycle yielded stable values of $R_{4.2}$. This improvement of the original single crystal may possibly have resulted from the fact that a cad-

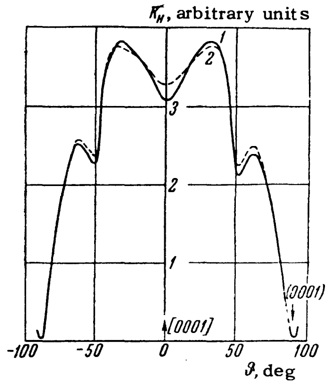

FIG. 3. Resistance of sample Cd-I vs. rotational angle of magnetic field (H = 8700 Oe) at 4.2°K. Curve 1 – p = 0; curve 2 – p = 7200 kg/cm².

mium sample was compressed very slowly under hydrostatic conditions at room temperature. These conditions can lead to the partial "curing" of lattice defects.

C. Discussion of results regarding the effect of pressure on magnetoresistance anisotropy. As a simplified model of the zinc Fermi surface in the second Brillouin zone for numerical calculations we can use the open surface shown in [6]. From the angular radius of the two-dimensional region (θ_0) and the length (θ) of "whiskers" in the stereographic projection (Fig. 11 of [6]) we can evaluate the minimum dimensions of the tube parallel to $[2\bar{1}10]$. Denoting the linear size of this tube in the [0001] direction by d_1 and in the $[\bar{1}010]$ direction by d_2, we find that

$$d_1 = 1.5\, b \operatorname{tg}\theta \operatorname{tg}\theta_0/(\operatorname{tg}\theta - \operatorname{tg}\theta_0), \quad (1)^*$$

$$d_2 = 0{,}23\, b - 1{,}5 b \operatorname{tg}\theta_0/(\operatorname{tg}\theta - \operatorname{tg}\theta_0), \quad (2)$$

where $b = 1.58\,\text{Å}^{-1}$ is the edge of the Brillouin zone in the (0001) plane. Substituting $\theta_0 = 6°$ and $\theta = 42°$ from [6], we obtain $d_1 = 0.18\,b$ and $d_2 = 0.03\,b$.

Taking into account the changed length of the "whisker" under pressure, we substitute $\theta = 41°$ in (2). Assuming that θ_0 does not vary, we obtain $d_2 = 0.022\,b$ (the corresponding change of d_1 is negligibly small). Thus at a pressure of 7000 kg/cm² the area of the considered Fermi surface cross section diminishes about 25%. In order to make this estimate more precise we must consider the possible changes in the angular sizes of the two-dimensional region. We thus anticipate that at pressures of the order 30×10^3 kg/cm² open cross sections of the zinc Fermi surface in the (0001) plane will disappear.

For cadmium the observed reduced depth of the resistance minimum for H ∥ [0001] cannot easily be associated with any specific change of the Fermi surface. We can only remark that the direction of the change is the same as for the minimum in zinc due to the "whisker"; it can therefore be assumed that the cadmium Fermi surface either has a very thin layer of open sections parallel to the (0001) plane or that these open sections can easily arise through uniaxial stretching along [0001].

*tg = tan.

4. INFLUENCE OF PRESSURE ON THE SHUBNIKOV–DE HAAS EFFECT IN ZINC

A. Determination of the anisotropy of the period of resistance oscillations. Before proceeding to investigate the zinc samples under pressure we determined the range of magnetic field directions for which the Shubnikov–de Haas effect could be observed with the employed technique. It was determined how the oscillation period depended on the field direction; for this purpose we investigated samples having different orientations. For each of five values of θ' (90, 80, 70, 65, and 60°) the value of φ was 0, 15, or 30°. For each sample $\alpha \approx 15{,}000$ was obtained.

Measurements were obtained in a 20-mm gap between the magnet poles at 4.2°K. Oscillations were observed most distinctly in a magnetic field parallel to [0001]. Figure 4 shows one of the R(H) curves obtained without employing linear compensation (the compensation usually coincided in magnitude with the dashed line). The figure shows that maxima of both large and small amplitudes are observed. We investigated the oscillations of large amplitude. For H ∥ [0001] and for any current direction in the (0001) plane the period of these oscillations is $P = (6.0 \pm 0.3) \times 10^{-5}$ Oe. When the magnetic field deviated from the [0001] direction, the contribution of the oscillating part of the resistance was sharply reduced. For the deviation $\theta = 25°$ from [0001], R(H) becomes practically smooth. The existence of resistance oscillations

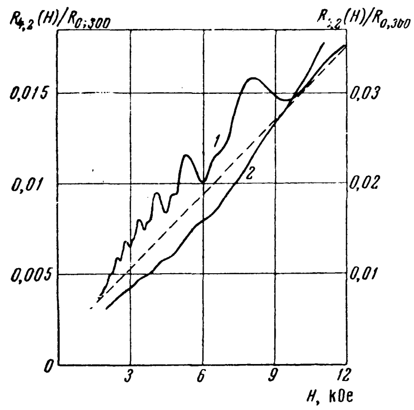

FIG. 4. Resistance vs. magnetic field at T = 4.2°K. Curve 1 – Zn sample with axis orientation $\varphi = 15°$, $\theta' = 90°$; H ∥ [0001]; ordinate scale on left. Curve 2 – Zn sample with axis orientation $\varphi = 0°$, $\theta' = 70°$; magnetic field deviated 20° from [0001] direction; ordinate scale on right.

Table III

Sample	T, °K	p, kg/cm²	Magnetic field (kOe) at resistance maxima. Parentheses enclose the ratio of maximum amplitudes after and before pressurization: 2**	3	4	5	6	7	8	Period* 10^{-5}/Oe
Zn-III	1.5	0	7.75	5.2	3.9	3.2? ***				6.3
		6000			9.5	7.5	6.25	5.35	4.8?	2.7
		0	7.8 (0.95)	5.2 (0.95)	3.9 (1)	3.1				6.4
Zn-II	1.5	0	8.15	5.5	4.15	3.35	2.75			6.0
		7100			10.0	8.0	6.6	5.7	5?	2.5
		0	8.2	5.35	4.1	3.25				6.2
Zn-I ****	1.5	0	8.15	5.3	4.0	3.2	2.7	2.3	2?	6.2
		1900	9.2	6.35	4.85	3.95	3.3			4.8
		2800		7.8	5.85	4.6	3.85	3.3	2.85?	4.4
		0	8.1 (1)	5.25 (0.95)	3.95 (1)	3.15 (1)	2.6	2.2	1.95?	6.4
Zn-Ia*****	4.2	600	7.9	5.3	4.0	3.2	2.7			6.1
		3500		8.2	6.2	5.0	4.15	3.6		3.9
		8100			9.6	8.0	6.8	6.0	5.35	2.1
		0	8.1	5.25 (0.75)	3.95 (0.7)	3.15 (0.7)	2.65			6.4
Zn-VI (φ = 15°, θ′ = 90°)	1.6	0	8.2	5.3	4.0	3.2				6.2
		1900 (ice)	8.7	5.8	4.35					5.8
		0	8.8	5.65 (0.4)	4.25 (0.3)	3.35 (0.3)				6.1

*The period was taken as the mean for differences of the reciprocal magnetic field associated with resistance maxima.

**2–8 are the serial numbers of the oscillation maximum in the coordinate 1/H; these were determined from the oscillation period.

***The sign ? indicates 10% accuracy.

****Following each run with p equal to 1900 and 2800 kg/cm² the pressure was relaxed completely.

*****Sample Zn-I was again mounted under the top cap of the bomb.

at these angles could only be established by using compensation and increasing the measuring current.

The period of oscillations decreases slightly (within the investigated limits of θ) as the magnetic field departs from the [0001] direction. Thus, for $\theta = 20°$, we have $P = (5.7 \pm 0.3) \times 10^{-5}$/Oe. (The small-amplitude resistance maxima were observable reliably only for the [0001] direction and were observed exactly halfway between the principal maxima. It can therefore be assumed that their period is either the same as the main period 6×10^{-5}/Oe or that it is one-half of the latter.)

B. Effect of pressures up to 8000 kg/cm² on the period of oscillations. The oscillating part of the magnetoresistance was measured under pressure in a 112-mm electromagnet gap. When the pole separation was increased from 20 to 112 mm the inhomogeneity of the magnetic field was enhanced, thus reducing the amplitude of the oscillations to approximately one-third. It was therefore inadvisable to devote much time to investigating the temperature and pressure dependences of the oscillation amplitude.

The influence of pressure on the oscillation period was studied for H ∥ [0001] in three zinc samples: Zn-I, Zn-II, and Zn-III (Table I). For each sample mounted within the working volume of the bomb the resistance oscillation periods were determined in the following order: at zero pressure, in a compressed state at different pressures, and following the relaxation of pressure. The results are shown in Figs. 5 and 6 and in Table III; with increasing pressure the oscillation period is seen to diminish.

Since the results of our present work differed fundamentally from those in [15], it was necessary to measure the oscillation periods in samples under hydrostatic pressure in a bomb filled with ice, where the pressure was monitored by means of a tin pressure gauge. The magnetic field in

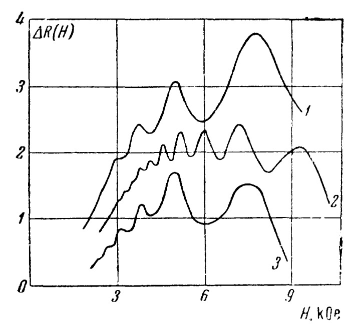

FIG. 5. Resistance oscillations in magnetic field H ∥ [0001] for sample Zn-III at 1.5°K. Curve 1 – p = 0; curve 2 – p = 7100 kg/cm²; curve 3 – p = 0 (after the relaxation of pressure). The sensitivity of the measuring circuit and measuring current were identical for all curves.

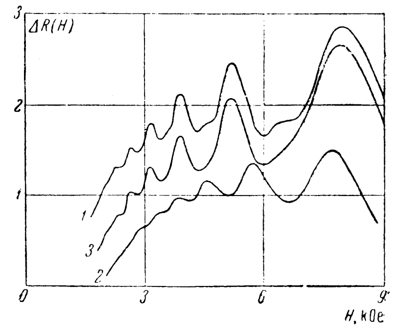

FIG. 6. Resistance oscillations in magnetic field H ∥ [0001] for sample Zn-I at 4.2°K. Curve 1 – p = 0; curve 2 – p = 2800 kg/cm²; curve 3 – p = 0 (after the relaxation of pressure). The sensitivity of the measuring circuit and measuring current were identical for all curves.

these measurements was more homogeneous, the measurements being taken in a 50-mm gap of the electromagnet. In the runs with Zn-VI the pressure was 1900 ± 200 kg/cm². The results are shown in Fig. 7 and in Table III; in this case the oscillation period was diminished as the pressure was increased.

C. Discussion of results for the Shubnikov–de Haas effect. The measured oscillations of the magnetoresistance of zinc single crystals at 8000 kg/cm² furnished additional confirmation that the described technique permits the maintenance of hydrostatic conditions during the application and relaxation of high pressures. It is known that the amplitudes of quantum oscillations are most sensitive to pressure inhomogeneities. In measurements following the relaxation of pressure in a single cycle no essential irreversible changes of the amplitudes of resistance maxima are observed. On the other hand, as is shown by the runs with the ice-filled bomb, the amplitudes of maxima following pressure relaxation are reduced to one-third of the amplitudes before applying pressure.

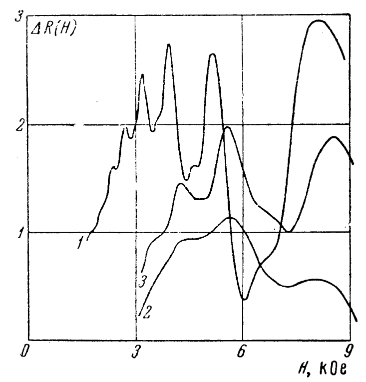

FIG. 7. Resistance oscillations in magnetic field H ∥ [0001] for sample Zn-VI at 1.6°K. Curve 1 – p = 0; curve 2 – p = 1900 kg/cm² (ice); curve 3 – p = 0 (after pressure relaxation). The sensitivity of the measuring circuit and measuring current were identical for all curves.

The magnitude and anisotropy of the resistance oscillation period of zinc single crystals in a magnetic field, which were measured experimentally without pressure, are in good qualitative agreement with the literature[9,15,17,18] for the susceptibility oscillation component of the longest period. In these experiments the oscillation period lay in the range 6×10^{-5}—6.4×10^{-5}/Oe for H ∥ [0001] and 5.5×10^{-5}—5.7×10^{-5}/Oe for $\theta = 20°$. We obtained the results 6×10^{-5} and 5.7×10^{-5}/Oe, respectively. It follows from a comparison with [18] that the resistance oscillation maxima of zinc coincide with the susceptibility oscillation minima within accuracy limits.[3)]

We therefore have every reason to believe that both in [15] and in the present work the effect of pressure on the same Fermi surface cross section of zinc was being investigated. According to the latest precise measurements,[9] these cross sections belong to an ellipsoid of rotation (the so-called needle-shaped portion of the Fermi surface) extended along the [0001] direction and are not associated with the open Fermi surface revealed by galvanomagnetic measurements.

Table III shows that the period of resistance oscillations diminishes with increasing pressure. At the maximum pressure 8100 kg/cm² the period is 2.1×10^{-5}/Oe. At 1900 kg/cm², obtained by means of ice, the period decreases by only about 6%. This is not surprising, since the tin pressure gauge was made of polycrystalline wire and indicates the mean pressure inside the bomb; in a layer of ice this pressure is evidently highly inhomogeneous.

Our result showing a diminished oscillation period disagrees with the results in [15,20,21]. As already noted, in [15] it was observed in an investigation of the influence of pressure on the de Haas–van Alphen effect that the considered oscillation period in the direction H ∥ [0001] increases considerably.

We find it difficult to account for the different behaviors of the oscillation periods under pressure in the Shubnikov–de Haas and the de Haas–van Alphen effects. It can only be stated that, just as under pressure, the reduction of c/a for zinc with decreasing temperature[22] leads to a de-

3)The hypothesis of Stark that the resistance oscillations of zinc are not of the ordinary type, but are induced by magnetic breakdown, in the case of oscillations on a needle-shaped Fermi surface does not affect their period, which is identical with the period of the de Haas–van Alphen effect.[19]

creased susceptibility oscillation period; at 61.2°K this oscillation period is 12.5×10^{-5}/Oe.[23] If we relate the change of the oscillation period to the change of c/a the results in [23] confirm our present results. It is clear, however, that to arrive at any definite conclusion in this matter we will require experiments that will investigate simultaneously the behavior of the oscillation periods under pressure in both the Shubnikov–de Haas and the de Haas–van Alphen effects.

From the decreased oscillation period under pressure we conclude that pressure increases the area of the corresponding extremal Fermi surface cross section; in [9] this minimum cross section was denoted by α. The increased area of the extremal Fermi surface cross section under pressure is shown in Fig. 8.

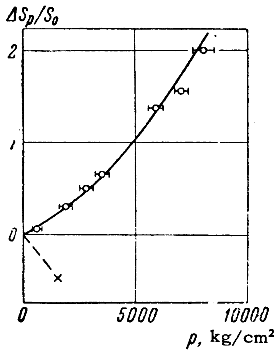

FIG. 8. Pressure dependence of minimum cross-section area of the needle-shaped portion of the zinc Fermi surface. o – present work; x – from [15].

Our results can be compared with Harrison's model of the zinc Fermi surface.[8] In this model the radius of the free electron sphere for a hexagonal-close-packed metal can be represented by

$$r = \left[\frac{\sqrt{3}\,n}{2\pi c/a}\right]^{1/3} \frac{2\pi}{a},$$

where n is the valence of the metal. Assuming that at 4.2°K we have a = 2.655 A and c/a = 1.831, [23] we find that for zinc at zero pressure r = $1.586\ \mathrm{A}^{-1}$. Using Bridgman's data,[24] and the similar data in [25] for the compressibility of zinc, we find that at 4.2°K and 8000 kg/cm², c/a = 1.816 (using a = 2.652 A). This gives r_p = $1.593\ \mathrm{A}^{-1}$. The minimum cross section in the Harrison model can be regarded approximately as an equilateral triangle. From the changes of a and r under pressure we find that at 8000 kg/cm² the sides of the given triangle increase by $0.016\ \mathrm{A}^{-1}$. From the experimentally determined area increase of this same cross section we calculate that each side of the triangle increases by $0.013\ \mathrm{A}^{-1}$, thus showing entirely satisfactory agreement. The Harrison model can therefore account for our results.

We are indebted to Academician P. L. Kapitza and to Professor L. F. Vereshchagin for enabling us to conduct these investigations and to Professor N. E. Alekseevskiĭ for his interest.

[1] I. M. Lifshitz, JETP **38**, 1569 (1960), Soviet Phys. JETP **11**, 1130 (1960).

[2] B. G. Lazarev and L. S. Kan, JETP **14**, 439 (1944).

[3] P. F. Chester and G. O. Jones, Phil. Mag. **44**, 1281 (1953).

[4] N. B. Brandt and N. I. Ginzburg, FTT **3**, 3461 (1961), Soviet Phys. Solid State **3**, 2510 (1962).

[5] E. S. Itskevich, PTÉ No. 4, 148 (1963).

[6] N. E. Alekseevskiĭ and Yu. P. Gaĭdukov, JETP **43**, 2094 (1962), Soviet Phys. JETP **16**, 1481 (1963).

[7] E. Fawcett, Phys. Rev. Letters **6**, 534 (1961).

[8] W. A. Harrison, Phys. Rev. **126**, 497 (1962).

[9] A. S. Joseph and W. L. Gordon, Phys. Rev. **126**, 489 (1962).

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

[11] I. M. Lifshitz and A. M. Kosevich, JETP **33**, 88 (1957), Soviet Phys. JETP **6**, 67 (1958).

[12] W. C. Overton and T. G. Berlincourt, Phys. Rev. **99**, 1165 (1955).

[13] Alekseevskiĭ, Brandt, and Kostina, Izv. AN SSSR **21**, 790 (1957), Columbia Tech. Transl., p. 792.

[14] B. G. Lazarev and A. S. Kan, JETP **14**, 463 (1944).

[15] Dmitrenko, Verkin, and Lazarev, JETP **35**, 328 (1958), Soviet Phys. JETP **8**, 229 (1959).

[16] Lazarev, Nakhimovich, and Parfenova, JETP **9**, 1169 (1939).

[17] C. A. Renton, Proc. of the 7th International Conference on Low Temperature Physics, Toronto, 1960 (Univ. of Toronto Press, 1960).

[18] J. S. Dhillon and D. Shoenberg, Phil. Trans. Roy. Soc. (London) **248**, 1 (1955).

[19] R. W. Stark, Phys. Rev. Letters **9**, 482 (1962).

[20] B. I. Verkin and I. M. Dmitrenko, JETP **35**, 291 (1958), Soviet Phys. JETP **8**, 200 (1959).

[21] B. I. Verkin and I. M. Dmitrenko, DAN SSSR **124**, 557 (1959), Soviet Phys. Doklady **4**, 118 (1959).

[22] E. Grüneisen and E. Goens, Z. Physik **29**, 141 (1924).

[23] T. G. Berlincourt and M. C. Steele, Phys. Rev. **95**, 1421 (1954).

[24] P. W. Bridgman, Proc. Am. Acad. Arts Sci. **77**, 187 (1949).

[25] G. A. Alers and J. R. Neighbours, J. Phys. Chem. Solids **7**, 58 (1958).

Translated by I. Emin
14