DEFORMATION OF THE BISMUTH FERMI SURFACE BY PRESSURES UP TO 8 KBAR

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The effect of hydrostatic pressure up to 8 kbar on the quantum oscillations of the electrical resistance of bismuth in a magnetic field has been studied at liquid helium temperatures. The angular dependence of the extreme cross sections of the electron and hole ellipsoids has been measured at various pressures in a sufficiently large range of angles. The variation of the extreme ellipsoid cross sections has been found to be approximately the same.

THE problem of what actually happens to the spectrum of charge carriers in bismuth upon change in the distance between the atoms can finally be resolved if the pressure dependence of all the parameters of the spectrum is measured. Here there still remains the problem of extending the pressure to such levels for which one can expect to have reached the interesting range in the phase diagram of bismuth from the viewpoint of the possible change of the spectrum of charge carriers and of transitions in the lattice. The change in the electron part of the Fermi surface of bismuth (ellipsoids) has been measured previously [1] by a direct method. By measuring the Shubnikov-de Haas effect at pressures up to 7.5 kbar, it has been possible to determine that the very small cross section of the ellipsoid decreases by about 40%. It has not been possible to measure the cross section of the hole ellipsoid at constant current. Although the data given in the same reference concerning the effect of pressure (up to 1.5 kbar) on the de Haas-van Alphen effect, cover larger cross sections and make it possible to deduce a similar decrease of the electron ellipsoid, the small value of the pressure did not allow us to take this conclusion to be a final one.

We have attempted measurements of the angular dependence of the cross sections of the electron and hole ellipsoids for bismuth at pressures up to 8 kbar with the purpose of revealing the character of the deformation under pressure and if possible the anisotropy of this deformation. The effect of hydrostatic pressure on the period of quantum oscillations of the electrical resistance was studied in the experiments, and also the surface impedance for different directions of the magnetic field relative to the crystallographic axes of the specimen.

METHOD OF MEASUREMENTS AND TREATMENT OF SAMPLE

A modulation method was employed [2] for the measurement of the quantum oscillations of the electrical resistance of bismuth in a magnetic field. A constant magnetic field produced by an electromagnet was modulated by a low frequency field by means of auxiliary coils. The amplitude of modulation did not exceed 20 Oe, the modulation frequency was 29 Hz. A constant current up to 50 mA was passed through the specimen. The voltage from the potential contacts was applied to the input of a low frequency tuned amplifier with phase detector, whose output signal was proportional to $\partial\rho/\partial H$. The signal was applied to the y coordinate of a two-coordinate plotter, on the x coordinate of which was applied the voltage from a Hall pickup, fastened to the pole of the electromagnet. A similar method of study of quantum oscillations of the electrical resistance can be used for metals and semiconductors having a sufficiently large value of the derivative $\partial\rho/\partial H$.

Samples of bismuth used in the measurements were cut by an electro-erosion method from single-crystal stock.[1)] The specimens had the shape of plates of dimension $16 \times 3 \times 1$ and $16 \times 3 \times 0.5$ mm. The trigonal axis C_3 was at an angle of 30° to the plane of rotation of the magnetic field, which in turn was perpendicular to the longitudinal axis of the specimen. The binary axis C_2 lay in this plane.[2)] The high-pressure chamber and the procedure of applying the pressure were

[1)]The authors are grateful to M. S. Khaĭkin for supplying the single crystals of bismuth.

[2)]The authors are grateful to G. P. Pushtarik for x-ray determination of the orientation of specimens.

described in [3]. The pressure in the chamber was determined by a superconducting tin manometer.

RESULTS OF MEASUREMENTS

The direction of the magnetic field parallel to the binary axis C_2 was determined from the angular dependence of the electrical resistance $\rho(\theta)$ on the direction of the magnetic field. The dependence of the electrical resistance on the magnetic field intensity was measured for different angles θ between the direction of the magnetic field and projection of the trigonal axis on the plane of rotation of the magnetic field and at various pressures (the angle θ is reckoned from the direction of the projection of C_3 on this plane).

Sample records of the oscillations of the electrical resistance and the surface impedance are shown in Figs. 1a and 1b. As is seen from the drawing, it was possible to detect no less than five maxima at all pressures for the electron ellipsoid and not less than nine for the hole. All the maxima were sufficiently sharp. This made it possible to determine the period with adequate accuracy.

The basic results of the measurements are shown in Fig. 2, where the angular dependence of the frequency of oscillation ω is shown for the electron (a) and the hole (b) ellipsoids at different pressures. For the hole ellipsoid, it was possible to follow the angular dependence of the frequency in the range of angles $\theta = 0-60°$, and for the electron, in the range $\theta = 90-15°$. The maximum deviations of the values of the measured cross sections for the hole ellipsoid from the mean curve amounted to 6–7%, and for the electron ellipsoid to 10–12%. The measured dependences of ω on P for $H \parallel C_2$ and $H \perp C_2$ are shown in Fig. 3. The results of measurement for the direction $H \parallel C_2$ are in agreement with the data given in [1].

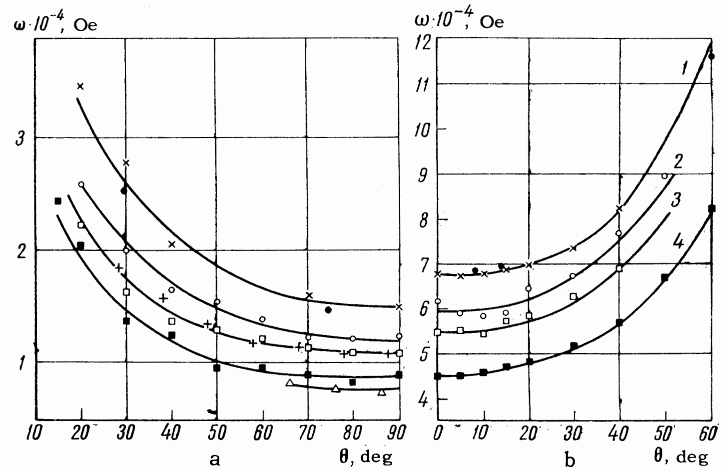

FIG. 2. Angular dependence of the frequency of oscillations of the electric resistance ω, associated with the electron (a) and hole (b) parts of the Fermi surface of bismuth. ● – sample No. 1, P = 0; × – sample No. 2; ○ – sample No. 1, P = 3 kbar; □ – sample No. 1, P = 4.5 kbar; + – sample No. 2, P = 4.3 kbar; ■ – sample No. 1, P = 7.5 kbar; △ – sample No. 2, P = 8 kbar.

We also made measurements of the oscillations of the surface impedance at a frequency of 1 MHz up to pressures of 4 kbar in the same high-pressure chamber. The results obtained agreed with the measurements of the electrical resistance.

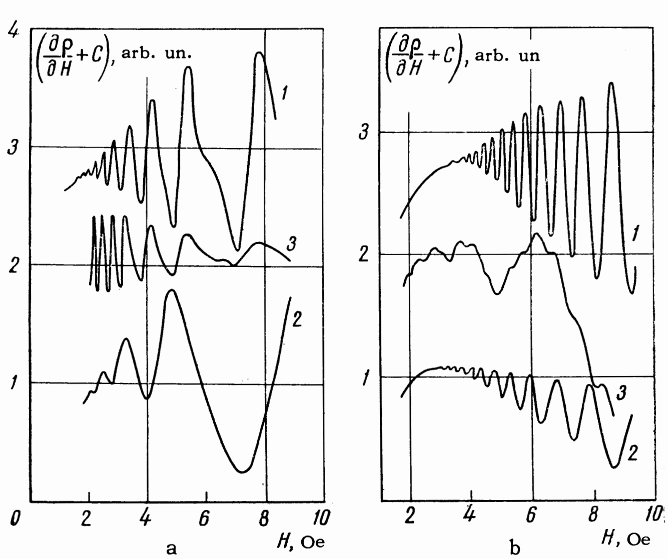

FIG. 1. Examples of recordings of the oscillations of the electrical resistance $\partial\rho/\partial H$ and the surface impedance $\partial R/\partial H$ for different pressures and directions of the magnetic field (C is an arbitrary constant). a – curve 1: $\partial\rho/\partial H$, $\theta = 90°$, P = 0; 2 – $\partial\rho/\partial H$, $\theta = 90°$, P = 7.5 kbar; 3 – $\partial R/\partial H$, $\theta = 90°$, P = 1.6 kbar; b – curve 1: $\partial\rho/\partial H$, $\theta = 0°$, P = 0; 2: $\partial\rho/\partial H$, $\theta = 0°$, P = 7.5 kbar; 3: $\partial\rho/\partial H$, $\theta = 50°$, P = 7.5 kbar.

DISCUSSION OF RESULTS

It is seen from Fig. 2 that all the measured cross sections both of the electron and of the hole

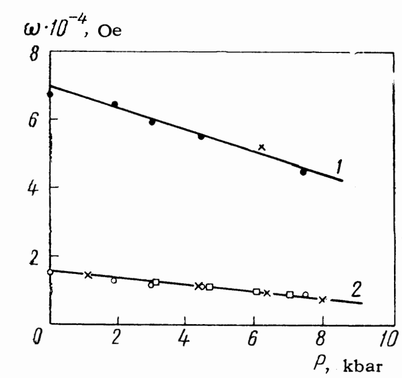

FIG. 3. Pressure dependence of the frequency of oscillation ω of the electric resistance for bismuth: curve 1 – $\theta = 0°$; 2 – $\theta = 90°$; ● – sample No. 1; × – sample No. 2, □ – data from [1].

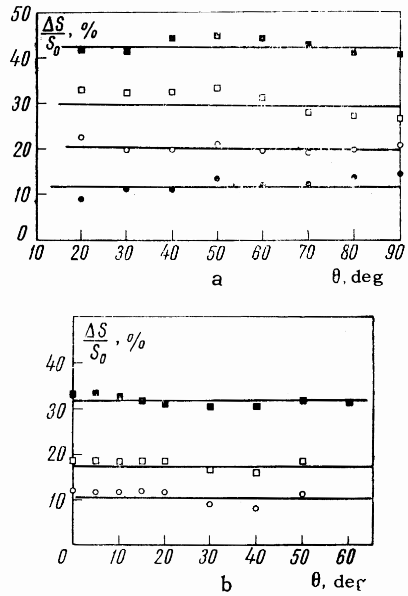

FIG. 4. Angular dependence of the relative change of the area of the extremal cross sections $\Delta S/S_0$ of the electron (a) and hole (b) parts of the Fermi surface for different pressures; ● – P = 1.9 kbar, ○ – P = 3 kbar, □ – P = 4.5 kbar, ■ – P = 7.5 kbar.

ellipsoids decrease with increasing pressure. Figure 4 shows the dependence of the relative change of the area of the Fermi surface $\Delta S/S_0 = f(\theta)$ for various pressures. The results obtained testify to the similar decrease of all the measured cross sections of the electron and hole parts of the Fermi surface.

It should be noted that at all pressures the relative decrease of the small cross sections are larger for the electron ellipsoid than for the hole ellipsoid. The differences in the changes exceed the error limits. This can be attributed either to a small increase in the anisotropy of the electron ellipsoids (the increase of the ratio a/b, where a and b are the large and small semi-axes of the ellipsoid), or to a small deformation in the sphere of the hole ellipsoid (decrease of a/b), or to both, which agrees with the prediction of Brandt.[4]

Extrapolating the dependence $\omega(P)$ shown in Fig. 3 towards higher pressures, we note that they intersect the pressure axis at different points: for 17–18 kbar for the section of the electron ellipsoid and 25—26 kbar for the hole ellipsoid. This is the result of the above-mentioned anisotropy of deformation under pressure either of the hole or of the electron ellipsoids. One can, in particular, resolve this problem by increasing the pressure. The authors propose to make these experiments in the near future.

Some regular deviations of the experimental points from the linear dependence of $\Delta S/S_0$ on θ, both for holes and for electrons and at all pressures, have no explanation. The phase of the oscillations associated with the hole and electron parts of the Fermi surface is not changed any significant amount at pressures up to 8 kbar.[1]

It must be noted that the amplitude of oscillations of the electrical resistance under pressure falls off insignificantly, whereas the value of the remaining resistance increases with increase in pressure (see the table).

P, kbar	$\alpha = \rho\,(300°\,K)/\rho\,(4{,}2°\,K)$	
	sample No. 1	sample No. 2
0	105	200
1.9	65.4	—
3	50	—
4.3	—	96
4.5	45	—
6.54	—	25.6
7.5	30.5	—

The problem of the nature of the growth of the residual resistance ρ_{res} under pressure, which was observed earlier in measurements of the electrical resistance of single crystals at liquid helium temperatures, has already been discussed in [3] and [5]. On the one hand, this growth can be due to defects caused by the well-known nonhydrostatic nature of the pressure in the bomb and their partial or complete annealing on heating to room temperature. On the other hand, the very insignificant decrease in the amplitude of the oscillations observed by us with pressure, for both electrons and holes, makes it possible to believe that for bismuth ρ_{res} increases with increase in pressure because of the change in the concentration of the current carriers.[6] Numerical comparison of the data in the table with the results of [6] shows that such a decrease in the carrier density determines essentially the observed decrease in α.

It is also interesting to observe that, in contrast with the amplitudes of oscillations of the electrical resistance, the amplitude of oscillation of the impedance at frequencies around 1 MHz is damped at a pressure of 4 kbars, although the depth of the skin layer computed from the formula $\delta = \sqrt{\rho/2\pi\omega}$ is equal to 1.7 mm, which exceeds the thickness of the specimen, and consequently its entire volume makes a contribution to the oscillation of the surface impedance. We are unable to explain this contradictory behavior of the oscillations of the electrical resistance and surface impedance.

In conclusion, the authors of the paper consider

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