CYCLOTRON RESONANCE IN TIN IN AN INCLINED MAGNETIC FIELD

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Cyclotron resonance in tin single crystals was investigated at a frequency of 9.5 GHz in a magnetic field inclined to the surface of the metal at angles of 0–90°. Resonances were observed for any field direction in the (010), (110) and (001) planes. For a given crystallographic direction of the field the effective masses for the central cross sections did not depend on the inclination of the field. The dependence of the amplitude of the three resonances on the angle of inclination of the field was determined. Resonance was observed in orbits encompassing several unit cells of the reciprocal lattice.

CYCLOTRON resonance in a magnetic field inclined with respect to the surface of a metal has been described in several recent experimental papers. When the angle of inclination is large (up to 80°), cyclotron resonance in copper, silver, and gold takes place on spherical parts of the Fermi surface (belly orbits) and the effective carrier masses measured in an inclined field differ by ≈5% from the values obtained in a parallel field.[1-3] Koch and Kip[4] have investigated cyclotron resonance in tin in a field inclined at 30, 45, and 90° to the surface; the resonance is observed only when the angle between the magnetic field and the [100] axis does not exceed 10° but not for other crystallographic directions.

The present paper reports the results of an experimental investigation of cyclotron resonance in tin in a magnetic field inclined at angles $\varphi = 0-90°$ to the metal surface. The samples were tin single crystals in the form of 12 × 1 × 1 mm parallelepipeds; they were cut by the electric-spark method from plane-parallel slabs 1 mm thick, grown, in demountable polished quartz molds from tin whose resistivity ratio was $\rho(300°K)/\rho(4.2°K) \approx 10^5$. The orientation of the crystals was checked by x-ray diffraction; the orientations of four investigated samples are listed in a table below (to within ≈30′).

The experiments were carried out at 9.5 GHz using the frequency modulation method.[5] An investigated sample was used as a resonance element of a strip resonator in which a linearly polarized electromagnetic wave was excited so that high-frequency currents flowed linearly along the surface of the sample parallel to the axis of rotation in a magnetic field. A magnetic field of 0.1–10 kOe intensity was produced by an electromagnet and modulated at a frequency of 11 cps. The dimensions of the sample were sufficiently small to ensure penetration of the modulation field into the sample. The angle of inclination of the field φ was measured with an accuracy of ≈10′ in the range $\varphi \gtrsim 20°$ and ≈2′ in the range $\varphi \lesssim 5°$. When the inclination of the field was small, the signal amplitude depended strongly on φ, which enabled us to determine the position of the plane of the sample to within 3′–5′. The temperature of the sample was usually 1.8°K.

Sample No.	Direction of normal to working surface	Plane of rotation of magnetic field
I	[110]	(1$\bar{1}$0)
II	[100]	(010)
III	12° from [001] to [100]	(010)
IV	5° from [100] to [011]	4° from (001) to (100)

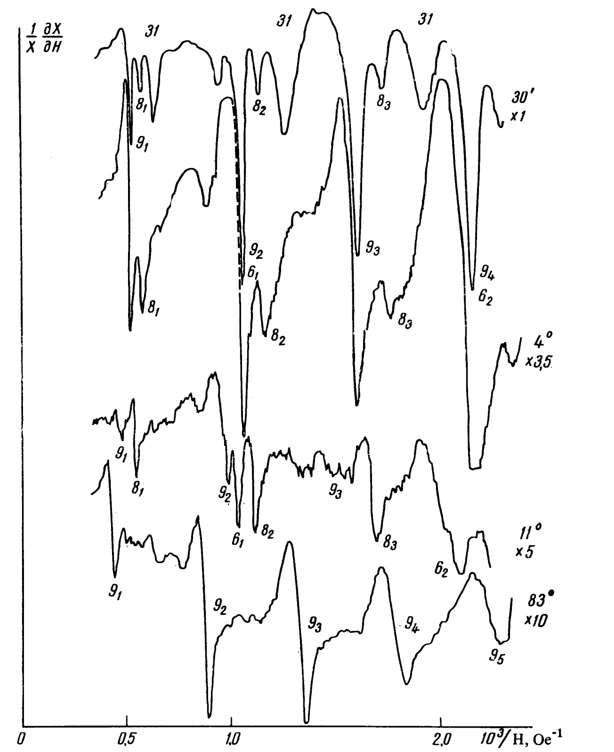

FIG. 1. Cyclotron resonance traces in a plane close to (001). Sample IV. The numbers alongside the curves on the right give the angle of inclination of the field and the amplification of the circuit. The numbers next to the peaks give the number of the resonance series (the number of the mass); the subscripts indicate the resonance order.

Resonances in central orbits. Examples of cyclotron resonances are given in Fig. 1. At large angles of inclination of the field we observe series of resonances 1, 2, 4, 6, 8, 9, 12, and 16 (the numbering of the resonances and of the effective masses is the same as in[6]). The accuracy of the measurement of the effective masses is ≈1.5%; within this limit the results of measurements in inclined and parallel fields[6] are equal.

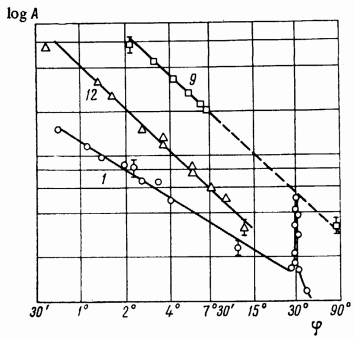

FIG. 2. Dependence of the amplitude A (in relative units) of the resonances 1 (sample I), 9 (sample IV), and 12 (sample I) on the inclination of the field (the results of measurements of the amplitude of the resonance 1 in samples II and III are in agreement with those shown above). The abscissa gives log (spin φ). The amplitude of the resonance 9 is sufficiently high for reliable measurements only in the angular ranges 0–10° and 80–90°. The vertical marks near some points indicate the probable experimental error.

The dependence of the amplitude A of the resonances 1, 9, and 12 on the field inclination is shown in Fig. 2. The accuracy of the measurement of the amplitude, estimated from the reproducibility of results in different experiments, is ≈10% (for weaker resonances measurements of this accuracy are impossible). For the resonances 9 and 12 (orbits ϵ and δ in the third zone) we have: $A \propto (\sin\varphi)^{-1\pm0.05}$. The amplitude of the resonance 1 (orbit ζ in the fourth zone) decreases more slowly when φ is increased: $A \propto (\sin\varphi)^{-0.8\pm0.2}$, and when the orbit approaches the edge of the "barrel," the resonance amplitude increases by a factor of 3 or 4.

The width of a strip which lies next to the central cross section of the Fermi surface and which represents electrons making an appreciable contribution to cyclotron resonance is governed by the permissible change in the cyclotron frequencies of these electrons: $\Delta\omega \approx \tau^{-1}$, where τ is the mean free time. When the field is inclined we must allow also for a change in the resonance frequencies due to the Doppler effect. For a Fermi surface with spherical parts the width of the strip and therefore the amplitude of the cyclotron resonance should both be proportional to $\sin^{-1}\varphi$. This conclusion is in good agreement with the measured amplitudes of the resonances 9 and 12.

The characteristic features of the dependence of the amplitude of the resonance 1 on the field inclination can be explained in a natural manner by the shape of the cross section of the "barrel" wall of the Fermi surface in the fourth zone, which can be plotted very accurately using the results of measurements of the cyclotron resonance cutoff.[7] The weaker rate of decrease of the amplitude of this resonance is due to a slight flattening of the "barrel" walls near their centers, which reduces the drift velocities of electrons near the orbit ζ. When $\varphi = 30°$ a considerable part of the orbit passes along the cylindrical part of the "barrel" neck where the drift of electrons is practically absent and therefore the resonance amplitude increases rapidly.

Thus, cyclotron resonance in the central cross sections of the Fermi surface of tin is observed along all crystallographic directions for any angle of inclination of the magnetic field and the opportunities to study this resonance are limited solely by the sensitivity of the apparatus. Koch and Kip[4] have observed cyclotron resonance only for some directions of the field because of an inhomogeneity of the magnetic modulation field which has not penetrated deeply into a relatively large sample used in their investigation.

Kaner and Blank[8] discuss "resonance in a chain of trajectories" in an inclined field. The mechanism of this resonance is associated with current surges in the interior of a metal at distances which are multiples of the extremal diameters of the electron orbits; this phenomenon results in an anomalous penetration of electromagnetic waves into the metal. The microwave energy is then absorbed and this should alter the sign of $\partial Z/\partial H$ at resonance; such a change of the line profile has not been observed in our experiments. Consequently, in spite of its weaker dependence on the inclination of the field, resonance in a chain of trajectories makes a much smaller contribution to the impedance than ordinary resonance in a central cross section, which increases the microwave reflection. It follows from Fig. 2 that when $\varphi \approx 1$, resonance in a chain of trajectories is at least an order of magnitude weaker than ordinary resonance. Unfortunately, no comparison of the magnitudes of these two effects is made in[8] which makes it difficult to select the optimum conditions for the observation of resonance in a chain of trajectories.

Resonance in orbits encompassing several reciprocal-lattice unit cells. When the field is rotated in a plane close to (001) (sample IV in table), strongly anisotropic series of peaks (Fig. 3) are observed in the angular range 0–15° near the [110] axis; the periods of these peaks correspond to effective masses of 0.8–1.2 and they vary rapidly with the field inclination. In the same angular range we can see resonances corresponding to effective masses of 3–5 which have not been investigated in detail because of the insufficient intensity of the magnetic field provided by the electromagnet. Evidently, these resonances are due to orbits in the fourth or fifth zone, encompassing several unit cells in the reciprocal lattice. If an electron moving along such an orbit crosses the skin layer at several

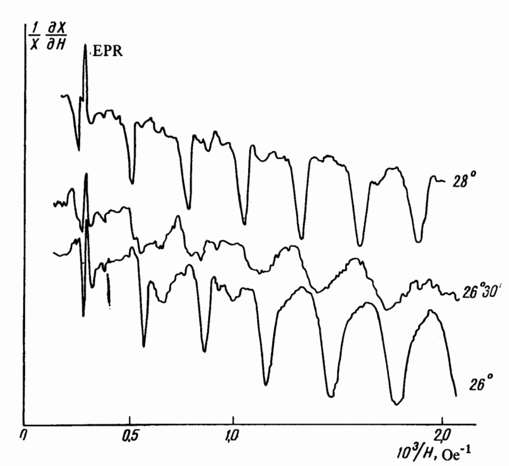

FIG. 3. Resonances in a plane close to (001) in sample IV (cf. table). The angles of inclination of the field to the plane of the sample, ∡ (**H**, [110]) = 41° − φ, are given to the right of each curve.

period of motion of the electron between consecutive passages through the skin layer. The line width of such resonance is $\Delta H/H \approx 1/n$, where n is the number of passages of the electron through the skin layer during one half of the rotation period. It is assumed that the electron returning to the skin layer from the interior is out of phase with the microwave field or it does not return to the skin layer at all. In our opinion, this case is represented by the middle curve, in Fig. 3, for which $n = 2-3$.

When the period of rotation of an electron in an orbit and the period of its motion between consecutive passages through the skin layer are both multiples of the microwave field period, the resonance line should become narrower. These conditions can be achieved by a small change of the magnetic field direction and they are represented by the upper and lower curves in Fig. 3 for which $\Delta H/H \approx 1/20$. Such a narrowing of the line indicates that an electron makes 7–10 rotations along the orbit, compared with, for example, ≈25 rotations in the ϵ orbit. This difference is obviously due to the higher probability of electron scattering during its motion near the surface, compared with its motion in the interior. If the electron trajectories were known exactly, the reported results could, in principle, be used to estimate the probability of electron scattering as a function of the distance from the surface of the metal. The available information is insufficient to make this calculation.

points in the orbit, we may observe resonance similar to the open-orbit resonance,[9,10] corresponding to the

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11