PENETRATION OF MICROWAVES THROUGH A METAL AT CYCLOTRON RESONANCE

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An investigation has been made of the selective transparency of metals to microwaves, arising as the result of cyclotron resonance cutoff, that is, as the result of the simultaneous equality of the wave frequency and the cyclotron frequency of a certain group of carriers, and the equality of their orbit diameters with the thickness of the sample. The experiments were performed with a ~0.2-mm thick bismuth single crystal cooled to ~1.5°K. The power transfer coefficient is $\sim 10^{-10}$ at a frequency of 9.4 GHz.

A number of papers have been published in recent years which have been devoted to the phenomenon of penetration of high-frequency electromagnetic waves through a metallic single crystal. The propagation of plasma waves, which is associated with the collective motion of the carriers in a metal placed in a magnetic field, has been studied in detail, and has been described, for example, in[1,2]. The present paper is devoted to the study of the penetration of high-frequency energy through a metal by means of another mechanism—the motion of definite groups of carriers in a constant magnetic field along orbits whose diameters are comparable with the thickness of the sample, that is, under conditions of observation of the cyclotron resonance cutoff[3] and other dimensional effects.

As the starting point for the study of this effect, we have used the paper of Azbel',[4] in which he predicted the penetration into the bulk of the metal of bursts (layers) of current, formed by current carriers undergoing cyclotron resonance (cyclotron frequency $\Omega = eH/m^*c = \omega$, where ω is the frequency of the electromagnetic field). The existence of the current bursts in the quasistationary case ($\Omega \gg \omega$) has been proved experimentally[5] and studied theoretically.[6] In this region of frequencies, the penetration of electromagnetic waves through metals has also been observed.[7]

An estimate of the transmission of a microwave signal of frequency $\omega = \Omega$ through a metal plate has been made in[8] under the condition of equality of the diameter d of the extremal orbit of some group of carriers with the thickness D of the plate. In experiments on electron paramagnetic resonance by the method of radioscopy of a metal by a microwave wave, weak and broad lines were observed at $\omega \approx \Omega$ and were interpreted as the phenomenon described above; they were called geometric cyclotron resonance.[9] However, in these experiments, neither of the conditions $\omega = \Omega$ and $d = D$ was ever satisfied. At the same time, it was noted in[10] that the penetration of the high-frequency energy through the metal in the region of cyclotron resonance can be attributed to excitation of plasma waves in the metal.

Thus the possibility of observation of the selective transparency of the metal to microwaves, associated with the cyclotron resonance cutoff, remained uncertain. The experiments described in this paper were carried out in an attempt to clarify the situation.

EXPERIMENT

The experiments were performed at a frequency of 9.36 GHz, specimen temperature ~1.5°K on a single crystal of bismuth, which had the shape of a disk of diameter 18 mm and thickness 182 ± 2 microns. The angle between the trigonal axis C_3 of the single crystal and the normal **N** to the surface of the specimen was ~1°. The cyclotron resonance cutoff had been observed previously in similar specimens.[11]

The magnetic field was produced by a Helmholtz system and could be rotated in the plane containing the normal to the sample. The earth's field was compensated with an accuracy to within $\sim 10^{-2}$ Oe by three sets of Helmholtz coils; a permalloy pickup served as the zero field indicator.

A traveling wave oscillator stabilized by a superconducting resonator[12] served as the source of the microwave signal; the oscillator output power was ~1 mW. Another similar oscillator was used as a heterodyne. A beat-frequency signal of

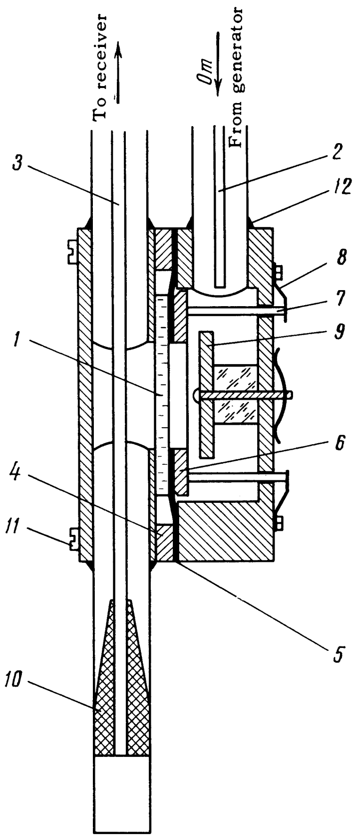

FIG. 1. Diagram of the apparatus for the observation of the transparency of a crystal. 1 – crystal specimen, 2 – input coaxial line, 3 – output coaxial line, 4 – ring gasket of thickness 250 microns, 5 – copper diaphragm of thickness 20 microns, 6 – clamping ring, 7 – polystyrene post, 8 – bronze spring, 9 – resonant strip, 10 – absorber, 11 – clamping screw, 12 – soldering with non-superconducting solder.

frequency ~30 MHz was received by a superheterodyne receiver with a 1-kHz bandwidth; it was thus possible to detect a signal $\sim 10^{-14}$W, attenuated 110 db from the power level of the oscillator. For further increase in the sensitivity of the recording circuit, modulation of the magnetic field with a frequency of 12 Hz was used, together with a narrow-band amplifier connected to the output of the receiver, with a synchronous detector and a time constant of several seconds.

The experiments were performed with the apparatus shown in Fig. 1. To increase the signal, a strip resonator is connected in the line on the transmitter side. One wall of the resonator is the sample 1. The coupling of the resonator with the input line 2 is critical; therefore, almost all the power of the transmitter is fed to the sample (the losses in the resonator are principally determined by the currents in the bismuth). On the side of the receiver, the specimen serves as the outer wall of the coaxial line 3, at the lower end of which is located an absorber 10. This can decrease the received signal, but makes the receiving line broadband.

The electrical contact of the sample with the instrument is achieved by placing the sample 1 in the cavity formed by the plane of the output line 3, a ring gasket 4, and a diaphragm 5 of annealed copper of thickness 20 microns, which is pressed against the specimen by the ring 6 through the polystyrene posts 7 by the springs 8. Such a construction makes it possible to avoid damage to the specimen during the experiment and to guarantee an attenuation of the coupling between the input and output lines 2 and 3 to the level −100 dB. This quantity changes somewhat from experiment to experiment, since parasitic currents obviously filter through the contact between the sample and the sealing planes; it is difficult to insure constancy of these contacts. These currents can be eliminated if the specimen is soldered to the window of the output line of the apparatus; however, such a procedure inevitably leads to damage of the crystal. Such an attempt was made, and it was shown that the crystal, soldered along its perimeter by Wood's metal to a tube of annealed copper with wall thickness ~20 microns, becomes unsuitable even for the study of such a gross effect as the excitation of magnetoplasma waves.[13]

RESULTS

Figure 2a shows a recording of the derivative, with respect to the field, of the signal applied to the input of the receiver. The magnetic field **H** lies in the plane of the sample close to the direction of the bisector axis C_1; $H^{(1)}_{cut}$ is the cutoff field of the extremal orbits of the electrons belonging to the ellipsoid whose major axis is parallel to **H**; $H^{(2)}_{cut}$ and $H^{(3)}_{cut}$ are the cutoff fields for the two other ellipsoids. For $\mathbf{H} \parallel C_1$, one ought to have $H^{(2)}_{cut} = H^{(3)}_{cut} = 2H^{(1)}_{cut}$. Nonfulfilment of this equality leads to an error in the orientation of the field amounting to ~5°.

The singularities of the derivative, which are located near $H^{(1)}_{cut}$, $H^{(2)}_{cut}$ and $H^{(3)}_{cut}$, are associated with the cyclotron resonance on the electrons experiencing specular reflection,[11] and with the emergence to the surface of the sample of bursts of current that arise inside the metal at cyclotron resonance.[4] For comparison, part of the recording of the derivative of the surface resistance is given in Fig. 2 for the same specimen, obtained in an experiment on the observation of the cutoff of cyclotron resonance under similar conditions. For fields $H^{(2)}_{cut}$ and $H^{(3)}_{cut}$, no singularities are seen in the record of the surface resistance; they are also seen in Fig. 2a. The dependence on the field of the absolute value of the field for which the signal is observed (Fig. 3) is identical with that for the cutoff field of electron orbits. Actually, assuming the electron ellipsoids to be cylinders in first approximation, we obtain the result that H_{cut} should change like $H_{cut} \propto \sec\vartheta$, where ϑ is the angle between the direction of the field and the axis of the cylinder. In the polar diagram of Fig. 3, this dependence is expressed by a straight line parallel to the projection of the axis of the cylinder on the plane in which the field **H** lies: the angle between the straight lines for $H_{cut}^{(1)}$ and $H_{cut}^{(2)}$ should, according to[15], be equal to 19°; the small difference is due to the fact that the plane in which the field H is rotated and the bisecting plane of the specimen are not identical.

Numerous facts show that the penetration of the microwave signal through the bismuth single crystal is actually due to the excitation of bursts of current in the metal and their emergence to the surface upon cutoff of the cyclotron resonance. We note that the observed effect cannot be explained, for example, by the excitation of plasma waves,[10] since the signal is maximum at the field H_7 of the weakest cyclotron resonance of seventh order, which lies close to the cutoff field, and is absent at the locations of the stronger resonances H_6 and H_5.

The transmission coefficient of the microwave through the sample can be estimated on the basis of data on the anomalous skin effect[16] and the relative change in the surface resistance at cyclotron resonance, which amounts to $\sim 10^{-3}$, by assuming that the additionally absorbed energy of the electromagnetic field is completely transformed into current bursts. By using the well-known formula (see[17], p. 359) for the power attenuation in the transmission of a wave through a boundary between two media in the case of normal incidence, we obtain a value $\sim(2-4) \times 10^{-4}$, whence we get, for the power transmission coefficient, $T \sim 10^{-7}$ (one need consider reflection only from a single surface, since the presence of the resonator on the transmitter side makes it possible to transfer nearly all the power fed to the resonator to the bismuth sample). The experiment gives an appreciably smaller value, $T \sim 10^{-10}$; however, this difference is not surprising if we take it into account that the wave incident on the surface of the bismuth specimen from the inside should experience total internal reflection at an angle of incidence $\gtrsim 1'$. But this angle is of the order of the possible error in parallelism of the planes of the sample or of the individual pieces.

The line shape of the transmitted signal is connected with the current distribution in the skin layer of the metal; however, the presence of a parasitic signal with unknown phase leads to its uncontrolled change. In this connection, only the line width can be an object of discussion at the present time. As is seen from Fig. 2a, the line near $H_{cut}^{(1)}$ extends from the cutoff field both in the direction of weaker and in the direction of stronger fields.

The transparency for a field smaller than $H_{cut}^{(1)}$ is connected with the cyclotron resonance for electrons experiencing specular reflection. Here the orbits of the resonating electrons on both sides of the specimen approach the surface of the metal and give a burst of current directly at the surface. In such a case, the transparency obviously takes place over the entire range of satisfaction of the condition $n\Omega = \omega$ and the line width of the signal must be the same as the line width of the cyclotron resonance m, which is also observed experimentally.

For the right side of the line, located in a field larger than $H_{cut}^{(1)}$ (Fig. 2a), the depth of the skin layer should play a decisive role, and it is natural to expect a width $\Delta H/H \sim 2\delta/D$, where δ is the skin depth. By using the ordinary value of δ for the anomalous skin effect[16] we get $2\delta/D \approx 0.008$. The measured value is $\Delta H/H \approx 0.15$, which is about 20 times the value expected, and testifies to the very slow attenuation of the amplitude of the microwave field in the depth of the metal. Penetration of the high-frequency field in the anomalous skin effect to a depth much greater than δ was observed previously in the investigation of the splitting of the resonance of the limiting point in indium, for an oblique field[18] and in the study of the size effect in indium.[19] In both researches, it was noted that the field penetrates to a depth $\sim 8\delta$. The even greater difference in our case can be connected with the fact that the phase conditions for the presence of a burst of field—that Ω be an exact multiple of ω—are satisfied for a field $H_7 = 3.87 \pm 0.03$ Oe, which is somewhat greater than the cutoff field $H_{cut}^{(1)}$, the decrease in the diameter of the orbit should lead to a decrease in the transparency, and an approach to the condition of cyclotron resonance should lead to a growth in the amplitude of the current burst, and to an increase in the transparency. It is clear that this can lead to line broadening. The described experiments have had as their first aim the investigation of the possibility of observation of the cutoff of extremal orbits by observation of the transparency of a metal to microwaves in a magnetic field. However, the observed effect, even for bismuth, is weak and the line width is very great, which makes

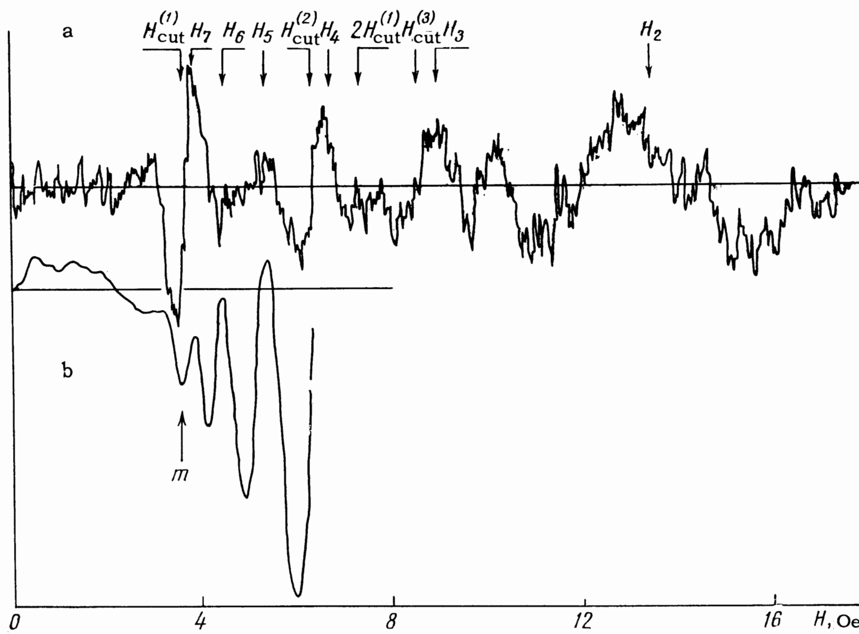

FIG. 2. Recording of the derivative with respect to the field: a – of the signal which passes through the sample and b – of the surface impedance. The direction of the field is close to the bisectrix axis. $H_{cut}^{(1)}$, $H_{cut}^{(2)}$ and $H_{cut}^{(3)}$ are the cutoff fields of electronic orbits from three ellipsoids; H_8, ..., H_1 are the computed fields of cyclotron resonances of order 2, ..., 7 for an ellipsoid whose major axis is parallel to the field; m is the cyclotron resonance on electrons experiencing mirror reflection.

masked by the strong peaks of the cyclotron resonance. For a field $H > H_{cut}^{(3)}$ peaks are seen in the recording of the derivative of the signal passing through the specimen (Fig. 2a); these peaks are possibly connected with the change in the parasitic signal because of the strong (order of 10–100%) change in the Q of the resonator at low orders of cyclotron resonance.

When the magnetic field is directed along the normal to the sample, the line shape of the signal passing through the sample does not change, which permits us to follow its relative displacement with great accuracy. Figure 3 shows the anisotropy of $H_{cut}^{(1)}$ and $H_{cut}^{(2)}$ measured in this fashion. The experimental points lie strictly along straight lines, the angle between which is equal to ~17°.

The absolute value of the power penetrating through the sample was estimated from the change in the signal at the output of the receiver (ahead of the narrow-band amplifier). Upon passage by the field of a line located at $H_{cut}^{(1)}$, the change in the signal was of the order of the noise of the receiver and amounted to 10% of the level of the parasitic signal, which corresponds to the attenuation of the radiated power of the generator by ~110 dB. The losses in the supply lines were estimated at ~10 dB. Thus the transmission coefficient of the signal through the sample amounts to $\sim 10^{-10}$.

It is interesting to note that upon increase of the field from zero to values which are greater than $\sim H_{cut}^{(3)}$, the received microwave signal falls off by about an order of magnitude, reaching the level of receiver noise ($\sim 10^{-14}$ watt), and remains unchanged upon further increase in the field to ~30 Oe. The reason for this phenomenon is not clear; it is possible that the microwave power transmission recorded in a weak field at low temperatures is associated not with parasitic currents, but with other effects, for example, with the acoustic branch of plasma waves.[14] However, these observations are not sufficiently complete to serve as the object of a detailed analysis.

DISCUSSION

The strongest signal in the record of the experiment, shown in Fig. 2a, is observed for a field in which cutoff of cyclotron resonance takes place, as shown in Fig. 2b. Calculation of the cutoff field from the thickness of the sample, on the basis of measurements[11], gives the same value of $H_{cut}^{(1)}$. For the values of $H_{cut}^{(2)}$ and $H_{cut}^{(3)}$ corresponding to the cutoff of the orbits of the electrons belonging to two other ellipsoids, signals of the same shape are

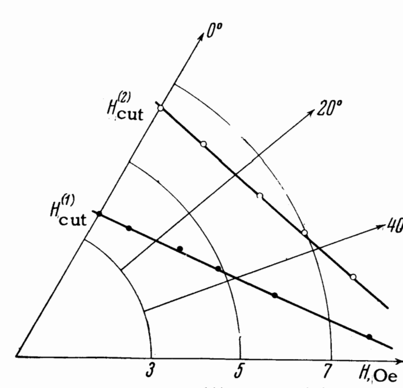

FIG. 3. Dependence of $H_{cut}^{(1)}$ and $H_{cut}^{(2)}$ on the direction of the magnetic field. The angle is calculated from the plane of the sample.

the possibility of their use in the study of the Fermi surface of bismuth rather small. Nevertheless, it can be hoped that, given some improvement of the experimental method, the study of the transparency should be an excellent instrument for investigating the distribution of field inside the metal. Thus the use of frequency variation and the employment of a signal equalizer circuit with phase shifter offer great possibilities. In such a way it is possible in principle to explain both the amplitude and phase distribution of the currents in the skin layer of a metal.

The performed experiments give a direct proof of the appearance in cyclotron resonance of bursts of microwave current and of a field inside the metal at appreciable distances from its surface, exceeding the ordinary skin depth by several orders of magnitude. The formation of current bursts is associated with the penetration of the energy of the high-frequency field inside the metal, observed in the form of a signal passing through the specimen. Thus the metallic single crystal of macroscopic thickness has a selective transparency, under definite conditions, to electromagnetic waves of microwave frequency.

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