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OSCILLATORY DEPENDENCE OF THE SURFACE IMPEDANCE OF A METAL ON A WEAK MAGNETIC FIELD

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An oscillatory dependence of the surface impedance Z of a metal on a weak magnetic field H in the microwave region was observed in Sn, In, and Cd [1]. Observation of the same effect in Sn, Al, Cu [2], and W [3] was also reported. Detailed researches were recently reported on the oscillations of Z(H) in Sn, In, and Al [4]. In this letter we explain the physical causes of this effect and report some results of its investigation in Bi, chosen because its Fermi surface has been investigated in detail [5].

The existing calculations of Z(H) pertain either to the region of cyclotron resonance [6], characterized by the inequalities $\tau \ll T$ and $r \gg \delta$ (τ - time that the electron stays in the skin layer δ; $T = 2\pi/\omega$ - period of the microwave field; r - radius of the electron orbit in the field H), or else to the relaxation region [7,8], for which $\tau \gg T$ and $r \ll \delta$. The region where oscillations of Z(H) are observed in a weak field H is determined by the relations $\tau \sim T$ and $r \gg \delta$; there are no calculations for this case. So far, only electrons moving in the skin layer δ along arcs whose centers lie deep in the metal (Fig. 1A) have been considered in searches for the causes for the oscillations. A comparison, for example, of the times τ and T or of the velocities of the electron and the wave in the skin layer for such orbits gives the correct order of magnitude of the field H at which a singularity of Z(H) is possible. Such an approach, however, does not give a convincing explanation of the origin of the oscillations [4].

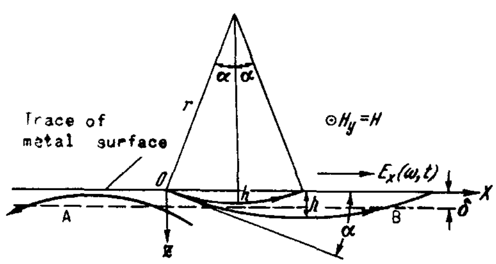

Fig. 1

The explanation of the physical causes of the oscillations of Z(H) is based on an allowance for the contributions made to the microwave current by electrons moving along arcs whose centers lie above the surface of the metal (Fig. 1B). Such electrons, moving from the point 0 on the surface of the metal, penetrate to a depth h and return after a time t_0 to the surface, from which they are scattered (or reflected). Let us examine their motion, guiding ourselves by the following principal considerations:

1. We take into account all the electrons belonging to the cylindrical Fermi surface and moving with identical velocities v_F along arcs of equal radius $r = pc/eH$ (p - radius of curvature of the Fermi surface at the point representing the electron).

2. From among the set of arcs with different center positions, we choose those for which motion along the initial sections satisfies the Landau conditions for optimal acceleration of the electrons by the microwave field. This condition calls for equality of the velocities v_e of the wave and of the electron in the OZ direction, and it defines an optimal angle $\alpha = v_e/v_F = \omega/kev_F \ll 1$.

3. At certain values of H, the time of motion of the electron along the arc, $t_0 = 2\alpha/\Omega$ ($\Omega = ev_FH/pc$), can be simply related to the period T; this should lead to repeated appearance of singularities, i.e., to oscillations of Z(H) as H is varied.

Case (1): $h > \delta$, $\tau < T$; the interaction between the electron and the microwave field occurs principally on the start end end of the orbit, the central part of which lies inside the metal. The maximum contribution of the electrons to the microwave current occurs under the condition $t_0 = nT$ or $(\alpha/\pi)\omega = n\Omega$ (which is obvious when $h \gg \delta$ and $\tau \ll T$ - this case is analogous to cyclotron resonance $\omega = n\Omega$). For the corresponding values of H_n we obtain

$$H^{-1}_{n(1)} = n\pi e v_F^2/cp\omega^2\delta = n\cdot\Delta H^{-1}; \quad (n = 1, 2, 3, \ldots)$$

where we put $k = 1/\delta$.

Thus, oscillations of z(H), periodic in A^{-1} with a period ΔH^{-1}, whould occur in this case.

Case (2): $h < \delta$; the amplitude of the microwave field is practically constant on the entire orbit. Therefore the contribution to the microwave current is maximal at $t_0 = (n + \frac{1}{2})T$ (the acceleration of the electron in a homogeneous microwave field after a time nT is equal to zero). Consequently, the singularities of Z(H) occur when

$$H^{-1}_{n(2)} = (n + \tfrac{1}{2})\Delta H^{-1} \qquad (n = 0, 1, 2, \ldots);$$

i.e., the oscillations of Z(H) have the same period as in the case (1), but shifted $\frac{1}{2}\Delta H^{-1}$. To check on this deduction, we calculated approximately the contribution ΔI of the electrons to the microwave current as a function of the field H (the arc was replaced by a parabola and attenuation was neglected):

$$\Delta I \backsim (\omega t_0)^{-1}[C(\sqrt{\omega t_0}) + iS(\sqrt{\omega t_0})],$$

where C and S are Fresnel integrals. The positions of the maxima of S as functions of H^{-1} coincide with $H^{-1}_{n(2)}$.

An estimate for ordinary metals (Sn) at $\omega = 6 \times 10^{10}$ sec^{-1} yields $H_1 = 1/\Delta H^{-1} \simeq 3$ Oe, which agrees with the experiments of [1-4]. For Bi we have $H_1 \simeq 0.3$ Oe, which also agress with experiment: the oscillations of Z(H) on Bi electrons are observed at $H \lesssim 1$ Oe (H parallel to the axis of the electronic "ellipsoid").

In the case of Bi $\delta \simeq 10^{-4}$ cm and $h_{n=1} \simeq \frac{1}{2}r\alpha^2 \simeq 2 \times 10^{-4}$ cm, so that case (1) should take place for $n \sim 5$, and a transition to case (2) may be observed when the field becomes stronger, on going to n = 1. This does actually take place: if we divide the measured values of H_n^{-1} by $\Delta H^{-1}_{n=4-5}$, then we obtain the following series: 0.5, 1.25, 2.1, 3.0, 4.0, 5.0, 6. The values of H_n^{-1} were determined from the maxima of X = ImZ(H), which should correspond to the maxima of S.

Experiments with Bi at 9.4 and 18.7 GHz yielded a relation $H_n \sim \omega^{1.5\pm0.3}$, while measurements [4] in a wider range gave $\omega^{1.52\pm0.05}$. The fact that the growth of H_n with increasing frequency is slower than expected for the anomalous skin effect ($\sim\omega^{5/3}$ for $\delta \sim \omega^{-1/3}$), may be due to the fact that when ω increases the conditions for electron motion change from case (1) to (2), as a result of which the values of H_n should decrease.

The relation $H_n(\varphi) = H_n(0)/\cos\varphi$ is satisfied both in the plane of the surface of the sample and outside this plane ($0 < \varphi \lesssim 80°$ is the angle between H and the axis of the electronic "ellipsoid," the central part of which is indistinguishable from a cylinder [5]). Oscillations of Z(H) were observed only in metals [1,4] whose Fermi surfaces have practically cylindrical tubes and the anisotropy of H_n makes it possible to relate them uniquely with these tubes.

The oscillations of Z(H) in ordinary metals [1,4] have the character of rather smooth curves, in agreement with the foregoing arguments. The oscillations in Bi have an essentially different form: the singularities of Z(H) at H_n are relatively narrower and are accompanied by suboscillations on the side of larger H. Figure 2 shows the first two groups of oscillations. The sharpening of the oscillations may be attributed to the contribution of the electrons that have experienced an m-fold specular reflection from the surface [9], but the use of the relation $mt_0 = nT$ alone does not explain the appearance of the suboscillations.

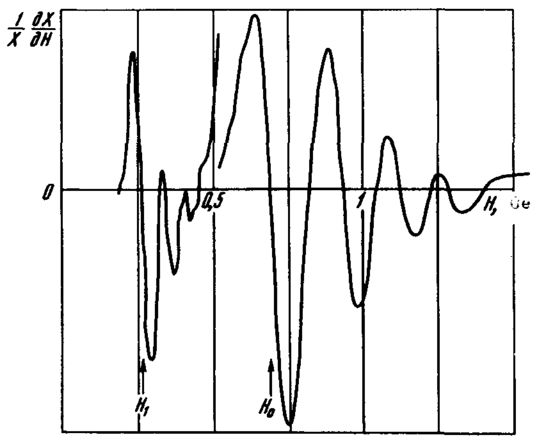

Fig. 2

As already shown, allowance for the electrons colliding with the metal surface makes it possible to explain the oscillations of Z(H) in a weak field. These electrons play an essential role in the relaxation region [7,8]. We note that their contribution can influence the observation of the cyclotron resonance of the limiting orbits, when the perimeter of the orbit approaches the mean free path. Since in this case the entire effect is due to electrons that enter the skin layer only 2 - 3 times as they move along the closed orbit, the role of the electrons moving along different incomplete orbits may become appreciable after the lapse of time intervals that are multiplets of T.

The proposed explanation of the origin of the oscillations of Z(H) in a weak field apparently solves the problem in principle, but the development of an exact theory, of course, is still a task facing us.

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CONCERNING THE METALLIC PHASE OF CARBON

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The shock compressibility of graphite in the region of its hypothetic transition [4] into the metallic phase was investigated by the reflection method [1], with the aid of measuring devices described in the paper of Al'tshuler et al. [2,3] The densities of the synthetic-graphite samples were 1.77 and 1.85 g/cm^3. Samples of Ceylon graphite were pressed to a density 2.23 g/cm^3 from finely crushed powder.

The results are plotted pressure - specific volume (P-V) coordinates. They are compared in the figure with the data of Coleburn [5], who investigated the shock compressibility of pyrolytic graphite, which has a hexagonal lattice structure, and with the results of Alder and Christian's dynamic measurements of the compressibility of graphite [4].

The latter were used by Bundy [6] to construct the phase-equilibrium diagram of carbon.

A satisfactory agreement between our present data and the results of Adler and Christian is observed up to pressures of the order of 600 kbar. A certain scatter of our experimental points in the region of pressures from 400 kbar and higher is due to the different initial density of the samples. In addition, just as in the work of Alder and Christian [4], it is noted that the registered shock-wave amplitudes, and consequently also the positions of the