Anomalous electromagnetic transparency of tungsten in low magnetic fields

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Penetration of 2 microwave electromagnetic signal through a tungsten plate under conditions of the anomalous skin effect, when the external magnetic field is missing or is small, is observed experimentally.

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It is well known that different weakly damped electromagnetic waves can propagate in sufficiently pure metals at low temperatures and in the presence of a constant magnetic field **H**.[1] At $H=0$, an electromagnetic wave incident on the surface of the metal penetrates into it only to the skin depth δ. It has recently been indicated in theoretical papers[2-4] that electromagnetic waves can propagate in the skin layer or the field can be effectively "pulled" out of it into the bulk of the metal along separate crystallographic directions, determined by the local geometry of the Fermi surface in the absence of a constant magnetic field.

The purpose of the present work is to make a direct experimental observation of the penetration of an electromagnetic microwave signal through a tungsten plate under the conditions of the anomalous skin effect. The specimen with a thickness of $d=0.95$ mm used for the measurements, was cut out of a single crystal on an electric-spark stand$^{1)}$ with a resistivity ratio $\rho_{300}/\rho_{4.2}=4\times10^4$. It was polished with abrasive powders and the polishing was completed electrochemically. A diagram of the experiment is shown in Fig. 1. A current **j** was excited with a linearly polarized microwave signal on one side of the specimen, which formed the common wall between two resonators, and a surface current was recorded in an analogous manner on the other wall. The experiment was performed in the $\mathbf{n}\|[110]$ and $\mathbf{j}\|[\bar{1}10]$ (**n** is the vector normal to the surface of the specimen) geometry. The vector of the constant magnetic field H of magnitude 0–1 kOe could be oriented in an arbitrary direction, lying in the (001) plane. The experiment was performed at frequencies of 500–600 MHz in the continuous-oscillation mode. Careful shielding of the transmitting and receiving circuits permitted decreasing the magnitude of the "leakage" signal bypassing the specimen to a level less than the sensitivity threshold of the apparatus, which was 125 dB/W. The pumping amplitude of the microwave field at the surface of the specimen did not exceed 0.5 Oe.

The following basic experimental results were obtained.

I. In the liquid helium temperature range with $H=0$, a microwave signal was always recorded on the receiving surface of the specimen.

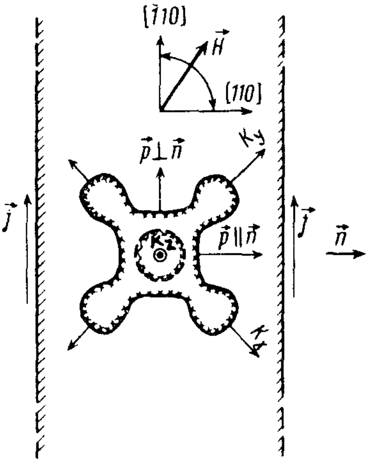

FIG. 1. Geometry of the experiment and the electronic "jack" on the Fermi surface of tungsten.

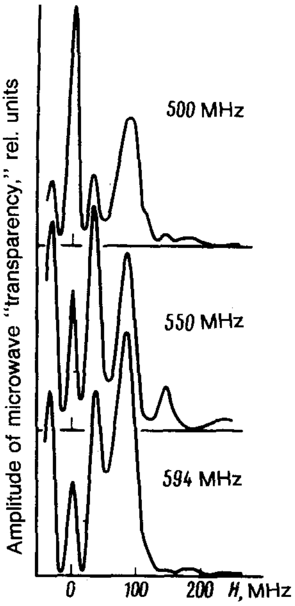

FIG. 2. Experimental traces of the amplitude of the microwave electromagnetic "transparency" of tungsten at 1.7 K.

II. The amplitude of the signal recorded with $H = 0$ increased as the temperature decreased from 4.2 to 1.7 K by a factor of 6–10 and was recorded at a level no less than 80 dB/W at 1.7 K. The estimated depth of the skin layer in this experiment was not more than 10^{-4} cm. The amplitude of the skin field at a distance $d/\delta \to \infty$, due to "active" electrons, is proportional to $(\delta/l)^2 x^{-2} e^{-x}$, where $x = d/l$, which gives $l \approx 1$ mm for the free path, $l \approx d$, $\delta \sim 10^{-4} - E_{\rm ck}^{(d)} \sim E_{\rm ck}^{(0)} (\delta/d)^2 \lesssim 10^{-6} E_{\rm ck}^{(0)}$, while for the "inactive" electrons[4] $E_{\rm ck}^{(d)} \sim E_{\rm ck}^{(0)} \delta^2/dl$ is of the same order of magnitude for $d \approx l$, which, in order to record the observed ratio, required a signal-to-noise sensitivity of the apparatus of 160 dB/W ignoring losses in transmitting the signal from the specimen to the resonator. These estimates, as well as the increase in the signal amplitude with decreasing temperature, leads us to conclude that the detected signal is not related to the detection of the skin field.

III. Application of a constant magnetic field oriented parallel to the surface of the specimen leads to oscillatory suppression of the signal (Fig. 2). The value of the "cutoff" field, $H = 145$ Oe, corresponds to a maximum cyclotron trajectory of carriers, $D_{\rm ext}$, equal to the thickness of the specimen, d. These trjaectories correspond to the escape of electrons from the region of the "jack's bump" on the Fermi surface with momentum 1.15×10^{-19} g cm/s, i.e., the specimen is electromagnetically transparent in a field $\mathbf{H} \perp \mathbf{n}$, as long as $D_{\rm ext} \gtrsim d$.

The penetration of the microwave electromagnetic field through the tungsten specimen in the [100] direction with $H = 0$ can be related to excitation of weakly damped electromagnetic waves, due to the presence of an energetic group of carriers with nearly equal momenta $\mathbf{p}_F$. For the geometry of the present experiment, identical groups of electrons moving in [100] directions do exist. It is shown in Ref. 4 that such a group of electrons with $\mathbf{p}\perp\mathbf{n}$ can have a large effect on the formation of the skin layer and can give rise to a weakly damped component of the electromagnetic field with wavelength $\lambda\sim\delta$, penetrating into the bulk of the metal. Under these conditions, the group of electrons with $\mathbf{p}\|\mathbf{n}$ can excite a long-wavelength electromagnetic mode with $\lambda\sim v_F/\omega$ ($\mathbf{v}_F$ is the Fermi velocity and ω is the frequency of the microwave signal). On the other hand, the same group of electrons in the presence of parabolic points on the Fermi surface or points where the Fermi surface flattens out can "pull" the field out of the skin layer over a distance $\sim l$.[3]

The oscillatory dependence of the microwave "transparency" of the specimen in the presence of a magnetic field can be attributed to several mechanisms of interaction of the carriers with the skin field; see, for example, Ref. 5. However, identification of trajectory or wave-type electromagnetic disturbances, just as the effect occurring at $H=0$, requires further experimental and theoretical studies. It should be noted that indirect indications of propagation of the microwave field through a metallic plate with $H=0$ were obtained in Ref. 6. However, the peculiarities of the experimental procedure used therein and, apparently, the presence of an indirect leakage signal precluded direct observation of this effect, which was possible in the present work.

We have thus demonstrated experimentally that: 1) in a pure metal, when $l\gtrsim d$, in the absence of a magnetic field microwave signals can propagate over a distance greatly exceeding the skin depth; 2) for H parallel to the surface, when $l\gtrsim d$ and $d\lesssim D_{\text{ext}}$, the electromagnetic field is efficiently transferred through the metallic plate.

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[1)] The tungsten bar was grown at the Institute of Solid State Physics of the USSR Academy of Sciences.

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