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Microwave Transparency of Thin Metal Plates in Parallel Magnetic Field

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It is a theoretical study of transparency oscillations in thin plates in magnetic field with the frequency widely ranging, including high frequencies where the "spikelike" mechanism changes to the "time-of-flight" mechanism of field penetration into the metal. The sensitivity of the oscillation amplitude to the surface state can be used to study the surface scattering of electrons.

Penetration of electromagnetic waves of high frequencies $\omega$ appreciably greater than the frequency of electron rotation $\Omega = v_{f} R$ in a magnetic field $H$ parallel to the sample surface into a metal essentially depends on the relationship between the electron time of flight through a skin layer and the electromagnetic wave period. When $\delta = \pi / (R\omega)^{1/2}$, an electron, as it moves out of the skin layer, does not feel non-stationarity of the high-frequency (h.f.) field $E(x)$ which penetrates into the sample as narrow spikes, separated by a distance equal to the skin depth $2\eta$ on the Fermi surface ($FS$) $[1]$. In plates of the thickness $\delta$ the emergence of the next spike on the face $x = \delta$ opposite to the skin layer causes anomalous transparency of the sample which oscillates with the magnetic field, known as the size effect (SE). When $\delta > 2\eta R$, the correlation between the faces $x = -\delta$ and the nearest $N$-th spike is through electrons with a non-extreme orbit diameter $2r$ equal to $\delta - 2\eta R$. If the frequency $\omega$ is a multiple of the oscillation frequency $(1/N)$ of such electrons, i.e. $\omega = n\Omega$, then the plate transparency is of resonance nature, and between its main peaks due to the SE, there should be series of resonance peaks with the intensity specified by the formula

$$E(\delta)/E(0) = \left(1, \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \ldots\right)^{1/2} \left[1 + \frac{1}{2} \left(\frac{\Omega}{\omega}\right) \frac{1}{2} \left(\frac{\Omega}{\omega}\right)^{1/2} \right]^{1/2}$$

where the probability of specular reflection $q$ for small angles of incidence on the sample surface $\phi$ may be represented as $q = \frac{1}{4} \left(1 - \phi^{2} \right)^{2}$, and the subscripts 1 and 2 indicate the faces $x = 0$ and $x = \delta$, respectively. If there are no cylindrical portions of the FS, the spike fields are formed only by a narrow fraction of electrons on the FS, and the resonance intensity is smaller by a factor of $(R/\delta)^{2}$, vs. small number of electrons responsible for the spike. If the electromagnetic wave is excited on both sides of the plate, there arise in the bulk sample two series of spikes and their resonance binding for $\omega = n\Omega$, is through electrons with non-extreme orbit diameter $2r$.

The small error between the brances in eq. (I) is due to electrons slipping along the almost specular plate faces and screen the h.f. field of an external electromagnetic wave and the field penetrating into the sample. In case of diffuse reflection of electrons the potential screening current and consequently the factor are absent. By comparing the signal amplitude for smooth and rough sample boundary, one can estimate the coefficients $g_{1}$ and $g_{2}$ and obtain reliable information on the typical height and correlation radius of the surface roughness.

For frequencies $\omega > (\pi / (R\Omega))^{1/2}$, the electron displacement $\Delta$ along the normal to the sample surface within the time $2\eta / \omega$ is much smaller than $\Delta$, i.e. the electromagnetic wave phase alternates many times within the electron time of flight through the skin layer. Against the background of the pronounced spatial dispersion characteristic of the anomalous skin effect, there clearly appears a temporal dispersion of the h.f. field distribution. While moving into the conductor in a path curved by the magnetic field, an effective electron executes nonlinear scanning of the electromagnetic wave oscillations in spatial oscillations and forms a weakly damping component of the h.f. field depending on the coordinate in a peculiar way. Differentiating with respect to the magnetic field and thus eliminating the background part of the h.f. field distribution, we obtain

$$\frac{d\delta E(x)}{dx} = H \delta E(0) / (\pi r) \exp(\Delta \delta / \delta x) \left[1 - i (\delta x / \delta x) \right]^{3/2}$$

$$\times \exp(-2i(\delta x / \delta x)^{1/2}) \cos(2\pi(\delta x / \delta x)^{1/2} / \lambda)$$

Here $\Delta$ is an extreme value of $\Delta$ as a function of the momentum projection on the magnetic field direction $p_{x}$, $\lambda^{2} = 2\eta R$ is the attenuation length, $\lambda$ is the electron mean free path, and $\Delta / \delta$ is small in the parameter $\Delta / \delta$ and, for specular reflection of electrons by the surface, it is as follows:

$$F(\Delta / \delta) = (\pi / (\Delta / \delta))^{1/2} / [\pi / 2 \exp(\pi / 3) / (1 - 1 + 1/3)]$$

$$\times \exp(-\pi / 3) / (2\Delta / \lambda)$$
where $F(x)$ is the gamma function. The solution of the problem for arbitrary electron reflection by a sample boundary shows that it is only $F(x/\delta)$ that depends on the form of the scattering indicatrix, while the expression between the braces of eq. (2) representing the h.f. field damping with the depth is unchanged.

The weakly damping component of the h.f. field brings about oscillations of the transparency of plates of a thickness $d < 2R$, called the time-of-flight effect (TPE) associated with "type I" electrons [2]. The experimentally measured derivative of the transmittance of the electromagnetic wave is specified by eq. (2) with $x = d$ and is periodic as a function of $H = \frac{1}{2}$ with the period

$$\Delta \frac{1}{\delta}(H) = \left(2\pi^2 ev^2 / (c^2 \omega^2 d)\right)^{1/2}$$

(4)

where $e$, $\omega$, $v$, $\chi$ are the electron charge, momentum, velocity in the origin point of electron orbit in the skin layer, and $c$ is the velocity of light. This effect is more convenient to observe in low magnetic fields $1 < R < 1/2d$ where the weak damping component is the only source of the oscillatory dependence of transparency on the magnetic field and its amplitude is almost invariable through a thin metal layer of the thickness $d$.

The impedance oscillations are due to the electrons colliding with the face $x = d$ and having their orbit turning point near the opposite face. The addition to the impedance $\Delta \chi$ is as follows:

$$\Delta \chi / Z = \alpha / R(\Delta_\chi / d)^{1/2} / \Delta \chi = \left(1 - (d/\Delta \chi)^{1/2}\right) \exp\left(-2(d/\Delta \chi)^{1/2}\right)$$

$$\times \left(1 - \exp\left(2(\omega T_0^2)\right)/\left(1 - q \exp\left(2(\omega T_0^2)\right)\right)\right)$$

(5)

Here the French quotes indicate integration over the FS, along the "girdle", where $x = 0$, and $Z$ is the impedance for $H = 0$.

In magnetic fields $2R < d$, the TPE is mainly due to "type 2" electrons colliding with both faces of the plate [3,4]. Selection of electrons according to the angle of departure from the surface $\phi$ distinguishes those with the orbit center in the middle of the sample characterized by the extreme time of motion from one face to the other, $T_0$. Though these electrons are markedly "inferior" to the effective ones in the anomaly parameter, they are much more "superior" in another small parameter, $\Delta \delta$. In samples with the thickness much smaller than the electron mean free path $l$, the TPE is very sensitive to the state of the plate faces, and in case of near-specular electron reflection, owing to multiple returning of electrons to the skin layer, the TPE oscillations are of resonance character and the transparency is

$$E(d)/E(0) = \left(\Delta \delta / R\right)^{1/2} \exp\left(-2(\omega T_0^2)\right) / \left(1 - q \exp\left(-2(\omega T_0^2)\right)\right)$$

(6)

In the absence of cylindrical portions of the FS, the TPE is formed by a narrow fraction of electrons and the root singularitiy for $q = 1$ and $\omega \to \infty$ belongs to the derivative of the transmittance with respect to the magnetic field, but not to the transparency. In samples with rough faces or the thickness $d = 1$, the resonance denominator in eq. (6) should be replaced by $\exp\left(2(\omega T_0^2)\right)$. The effect amplitude is maximal, when the projection of the velocity $\chi$ of an electron, which has left the surface, is of the order of magnitude of the wave phase velocity, i.e. $ni = \delta H_0/\omega v$. Within a narrow vicinity of the cut-off field $H_0$, roughly $\Delta H \approx (\delta H_0/\omega v)^2$, the TPE intensity sharply falls off, due to rapid alternation of the field as the electron flies through the skin layer.

Figures and diagrams include:

- Figure 1: The electron trajectories responsible for the time-of-flight effect.
- Diagram 2: Type 2

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