The nature of the quantum oscillations of the radio-frequency impedance of tungsten plates

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Quantum oscillations of the real and imaginary parts of the impedance of tungsten on symmetric and antisymmetric excitation of the wave in a metal plate have been investigated experimentally. The experimental angular dependence of the oscillation amplitude and an analysis of the expressions for the impedance enable their nature to be established. The quantum oscillations of the real part of the impedance on symmetric excitation are due to Shubnikov–de Haas oscillations, while the main contribution of the oscillations of the imaginary part on antisymmetric excitation comes from the de Haas–van Alphen effect.

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We have reported[1] that in an experimental study of size effects in the high-frequency impedance of thin cadmium single-crystal plates in a magnetic field perpendicular to the surface, a strong dependence of the amplitude of the quantum oscillation phenomena was found on the means of exciting the electromagnetic wave. For example, the amplitude of quantum oscillations on bilateral wave excitation symmetric with respect to the electric field was several tens of times larger than for antisymmetric excitation. From the theoretical analysis of the spin effect in compensated metals, carried out in that work, it could be stated such an effect should occur if the main contribution to the oscillations of the real part of the impedance R for symmetrical excitation comes from oscillations of the conductivity $\sigma(H)$ (the Shubnikov–de Haas effect). The dependence of oscillation amplitude on the angle between the magnetic field and the surface, observed in the experiments, confirmed such a conclusion. This fact is important since until then it was assumed[2] that in the intermediate region of electromagnetic-wave frequency, to which radio frequencies belong, oscillations of the magnetic moment of the electron system, $M(H)$ (the de Haas–van Alphen effect), should be the determining factor.

It is shown in the present work that besides the observation of Shubnikov–de Haas oscillations in the radio-frequency surface impedance, separate observation of quantum oscillations of a different nature is possible. The means for separating the oscillations is based on applying symmetric and antisymmetric excitation of the wave in thin metal plates and studying the real and imaginary parts of the surface impedance.

The expression for the surface impedance due to the skin effect and taking quantum oscillations into account, is according to Eq. (5) of Ref. 1 of the form

$$Z_s=\frac{4\pi i\omega}{c^2}\left(1-4\pi\sin^2\theta\frac{\partial M}{\partial B}\right)^{-1}\frac{1}{k_{sk}}\operatorname{ctg}\frac{k_{sk}d}{2},$$
$$Z_a=-\frac{4\pi i\omega}{c^2}\left(1-4\pi\sin^2\theta\frac{\partial M}{\partial B}\right)^{-1}\frac{1}{k_{sk}}\operatorname{tg}\frac{k_{sk}d}{2},$$

where the indices s and a refer respectively to the cases of symmetric and antisymmetric means of excitation, ω is the wave frequency, d the plate thickness, B the magnetic induction, c the velocity of light, and θ the angle between the direction of the magnetic field and the normal to the surface. k_{sk} is the skin wave vector which is a solution of the dispersion relation

$$k^2E=\frac{4\pi i\omega}{c^2}\sigma E\left(1-4\pi\sin^2\theta\frac{\partial M}{\partial B}\right)^{-1}.$$

In accordance with our previous paper, it is defined as

$$k_{sk}\approx(1+i)\gamma^{1/2}k_H\Big/\left(1-4\pi\sin^2\theta\frac{\partial M}{\partial B}\right)^{1/2},\qquad k_H=\frac{4\pi\omega Ne}{Hc}$$

N is the carrier concentration, e the electronic charge, and $\gamma=\nu/\Omega$, where ν is the frequency of collisions with a scatterer and Ω is the cyclotron frequency. We do not consider other roots of the dispersion relation, which make a small contribution to the impedance.

The possibility of separating in the impedance conductivity and magnetic-moment oscillations is shown clearly in Table I. Expressions for the real (R_s, R_a) and imaginary (X_s, X_a) parts of the impedance corresponding to symmetric and antisymmetric excitation, obtained for the condition $|k_{sk}d/2|<1$, are written out there. Calculations show that at the frequency $f=3$ MHz the equality $|k_{sk}d/2|=0.5$ is fulfilled in a magnetic field $H=60$ kOe, where the oscillations are observed. The table is divided into columns for the zeroth and the next approximation in terms of the parameter $k_{sk}d/2$, so that impedance results should show more clearly the ratio of the oscillation amplitudes.

It can be seen from the table that the main contribution to the real part of the impedance for symmetric excitation comes from conductivity oscillations, while the imaginary part for not very small angles, θ is mainly determined by magnetic-moment oscillations that enter through the differential magnetic susceptibility $\partial M/\partial B$. The feature which distinguishes oscillations of $M(H)$ in X_a and X_s from oscillations of $\sigma(H)$ in R_s is their rather strong (as $\sin^2\theta$) dependence on the angle between the propagation direction of the wave and the direction of the magnetic field.

The experimental investigation was carried out using an autodyne detector, described previously,[3] and a modulation

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TABLE I. Expressions for the real (R_s, R_a) and imaginary (X_s, X_a) parts of the impedance for the cases of symmetric and antisymmetric excitation of the wave; $A = 2\pi\omega d/c^2$, $k^2_{0sk} = (4\pi i\omega/c^2)\sigma \propto \omega/H^2$.

	Order of approximation in the parameter $\lvert k_{sk} d/2\rvert < 1$	
	zeroth	first
R_s	$A \left\lvert \frac{k_{0\,sk}d}{2} \right\rvert^{-2}$	$\frac{1}{45} A \left\lvert \frac{k_{0\,sk}d}{2} \right\rvert^{2} (1+ 8\pi \sin^2\theta \frac{\partial M}{\partial B})$
R_a	0	$\frac{1}{3} A \left\lvert \frac{k_{0\,sk}d}{2} \right\rvert^{2} (1+ 8\pi \sin^2\theta \frac{\partial M}{\partial B})$
X_s	$-\frac{1}{3} A\ (1+4\pi \sin^2\theta \frac{\partial M}{\partial B})$	$\frac{2}{945} A \left\lvert \frac{k_{0\,sk}d}{2} \right\rvert^{4} (1+12\pi \sin^2\theta \frac{\partial M}{\partial B})$
X_a	$-A\ (1+4\pi \sin^2\theta \frac{\partial M}{\partial B})$	$\frac{2}{15} A \left\lvert \frac{k_{0\,sk}d}{2} \right\rvert^{4} (1+12\pi \sin^2\theta \frac{\partial M}{\partial B})$

technique. The second derivatives of the oscillation voltage U and of the autodyne frequency f with respect to the magnetic field modulated at a frequency of 18 Hz, were recorded on a chart recording potentiometer. It was assumed in this that $d^2U/dH^2 \propto d^2R/dH^2$ and $d^2f/dH^2 \propto d^2X/dH^2$. In one case the magnetic field, produced by a superconducting solenoid, was perpendicular to the specimen surface to an accuracy of $\pm$ 1°. In the other case both coils[4] between which the specimen was placed were clamped between two supports inclined to the solenoid axis at 5–6°. The studies were made on a tungsten specimen of thickness $d = 186\,\mu$m, at a temperature 4.2 K.

The results of the experimental study of the impedance of tungsten as a function of the frequency f of the external wave, of the means of excitation, and of the angle of inclination of the magnetic field are shown in Figs. 1–4. Here, besides the quantum-oscillation effects, size effects studied for antisymmetric excitation by many authors (see, for example, Ref. 5) are shown. It is possible to draw conclusions about the ratio of the sensitivity of the measuring system for different means of excitation, or about the inclination of the magnetic field relative to the crystal axis, from the magnitude of the amplitude of the doppleron oscillations at the start of the spectrum.

The experimental results of studying the real part of the tungsten impedance for symmetric and antisymmetric excitation are shown in Fig. 1. The upper three traces show the change in the picture of oscillation effects on changing the external wave frequency for symmetric excitation. Here lowering the frequency changes the amplitudes of both of the doppleron and of the quantum oscillations. The characteristic sharp growth of the doppleron-oscillation amplitude, followed by a sharp reduction with increasing magnetic field, which are clearly seen for a frequency $f = 3$ MHz disappear already at $f = 0.6$ MHz. The quantum oscillations increase in amplitude with decreasing frequency relative to the quasiclassical size oscillations and in this region their existence expands towards the weaker magnetic fields.

Beats between two close frequencies are observed on the traces $R_s(H)$ (Fig. 1, curve 1). Such a curve arises as a result of superposition of oscillations from two extremal sections of the Fermi surface. The main period, observed in the experiments, $\Delta H^{-1} \approx 1.72 \times 10^{-7}$ Oe^{-1}, corresponds to the known extremal section ρ_1 of the hole ellipsoid which has been observed[6] (there the period was $\Delta H^{-1} \approx 1.69 \times 10^{-7}$ Oe^{-1}). It was established from the oscillation period in the interval between the nodes of the beats that other oscillations come from the section σ of the neck of the jack.

The lower two traces in Fig. 1, which were obtained for a frequency $f = 3$ MHz, demonstrate the ratio of the amplitudes of the quantum oscillations in the real part of the impedance (Joule losses) for symmetric and antisymmetric excitation. Their appearance in the losses can be observed in the case of antisymmetric excitation on ten-fold amplification. The ratio of amplitudes of the oscillations studied $A_s/A_a \sim 60$–80 in a magnetic field $H \sim 50$–60 kOe. (The temperature was chosen to be 4.2 K to avoid error due to a temperature dependence in measuring the amplitudes of the quantum oscillations.) Such a ratio of oscillation amplitudes for different means of exciting the wave in the metal plate is explained well by an analysis of the behavior of the skin fields with the increase in magnetic field. The opposite polarization of the electric fields of the skin wave on the two sides of the plate for antisymmetric excitation leads in fact to the disappearance of the high-frequency field inside the metal with increasing magnetic field and, consequently, to a reduction in Joule losses. An electric field distribution close to uniform can be realized by identical polarization of the skin fields of the wave. In this case the electron system of the whole volume effectively interacts with the penetrating wave, leading to an appreciable increase both in the Joule losses in the specimen and in the small quantum oscillation effects which appear in them.

The change in shape of the oscillations on lowering the frequency of the external wave, seen in Fig. 1, can be explained qualitatively by the considerations presented. Quantum oscillations up to the highest magnetic fields used are observed on a background of size-effect oscillations. Therefore the ratio of amplitudes of quantum and quasiclassical size-effect oscillations, which changes with decreasing frequency, leads to a change in shape of the envelope curve to the oscillation amplitude. Improvement of the uniformity in the distribution of high-frequency field with decreasing frequency also enables one to understand the broadening of the

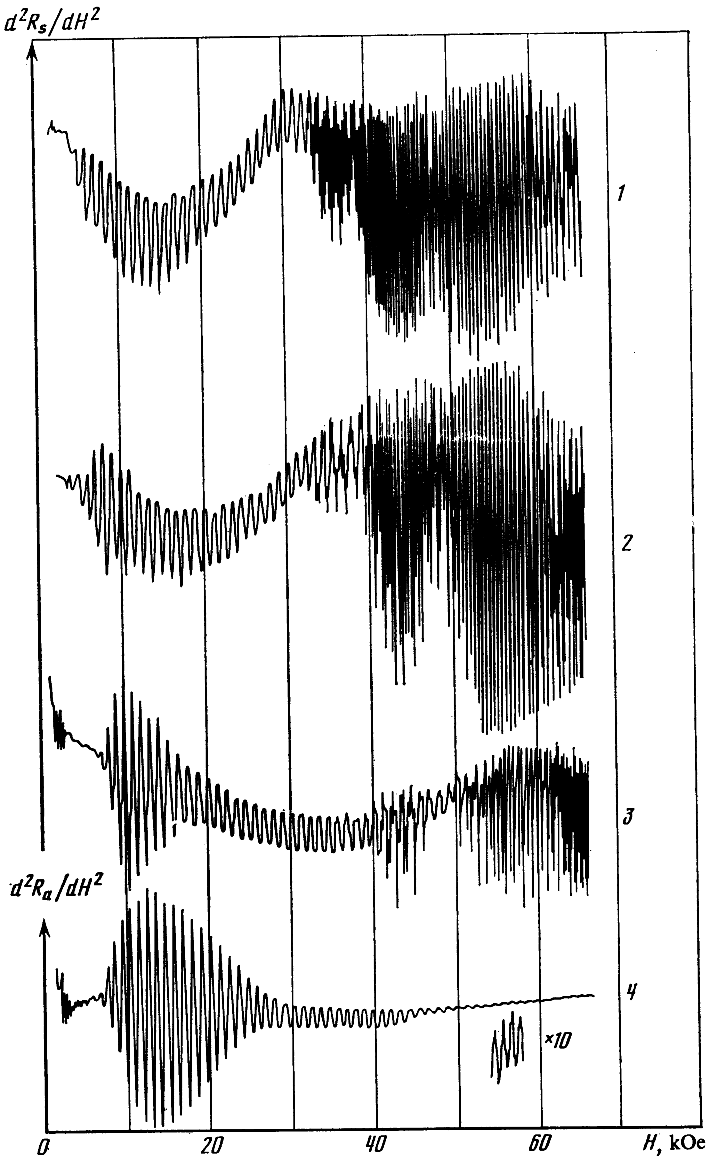

FIG. 1. Experimental traces of d^2R_s/dH^2 and d^2R_a/dH^2 for symmetric and antisymmetric excitation: 1) $f = 0.58$ MHz; 2) $f = 1$ MHz; 3,4) $f = 3$ MHz; $d = 0.186\,\mu$m; $\mathbf{H}\|C_4$, $T = 4.2$ K.

region for quantum oscillations to exist in weaker magnetic fields.

The changes in quantum oscillations of R_s and X_a observed for a magnetic field inclined at 5–6° to the normal to the specimen surface are shown in Figs. 2 and 3. From the great difference between the amplitudes of oscillations for symmetric and antisymmetric wave excitation, together with the absence of a marked angular dependence of the amplitude of the oscillations of the real part of the impedance for symmetric excitation, it can be deduced that these oscillations in tungsten, as in cadmium,[1] are connected with oscillations in conductivity.

Quantum oscillations of X_a are hardly seen in the upper trace of Fig. 3, corresponding to an angle of inclination of the magnetic field $\theta \approx 0$. (They are seen if the gain above the background is considerable.) Their amplitude grows 20–25 fold for the field inclined 5–6°. From this the observed oscillations in X_a can be connected with oscillations of the magnetic moment of the electronic system of the metal. Consideration of the magnitude of Shubnikov–de Haas oscillations in X_a, based on theoretical expressions listed in Table I, and of the experimental magnitude of the oscillations of the real part of the impedance, show that the amplitude of these oscillations in a magnetic field corresponding to a value of $|k_{sk}d/2| \approx 0.5$ is 240 times smaller than in R_s, and is comparable with the amplitude of de Haas–van Alphen oscillations for an angle of inclination $\theta = 1°$. For the magnetic field inclined at 5–6° to the normal, the magnitude of the oscillations is 20–25 times greater than the expected value for the Shubnikov–de Haas effect. This means that in the initial arrangement an error within the limits of 1° was possible for the angle of inclination of the magnetic field direction to the normal surface, and the angular dependence of the oscillations which we associated with the de Haas–van Alphen effect is in good agreement with the $\sin^2\theta$ variation.

From the analysis of the dependence of the amplitude of

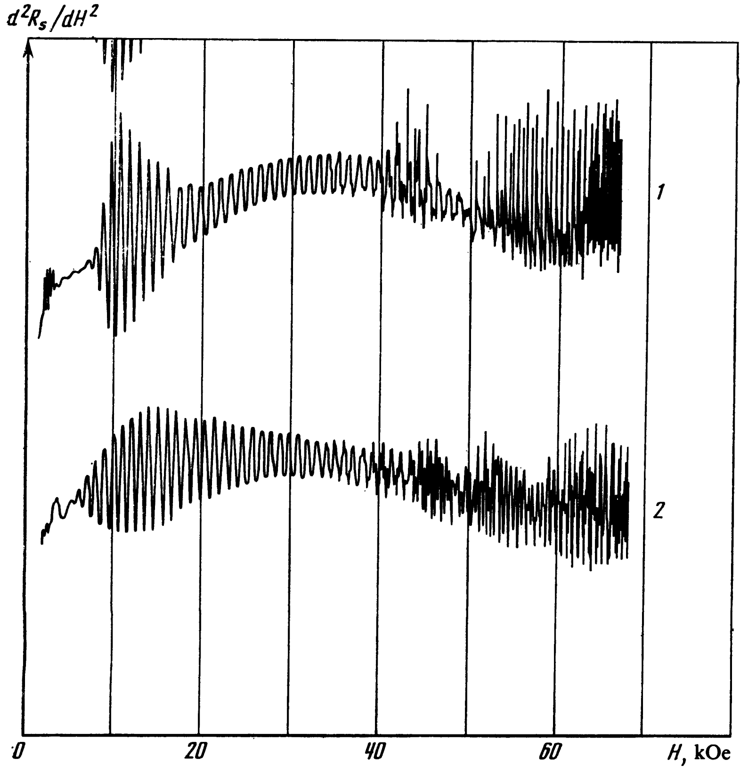

FIG. 2. Traces of oscillations of d^2R_s/dH^2 as a function of magnetic field H for the case of symmetric excitation of the wave for the angles: 1) $\theta \approx 0°$, 2) $\theta \approx 5°$; $f = 3$ MHz.

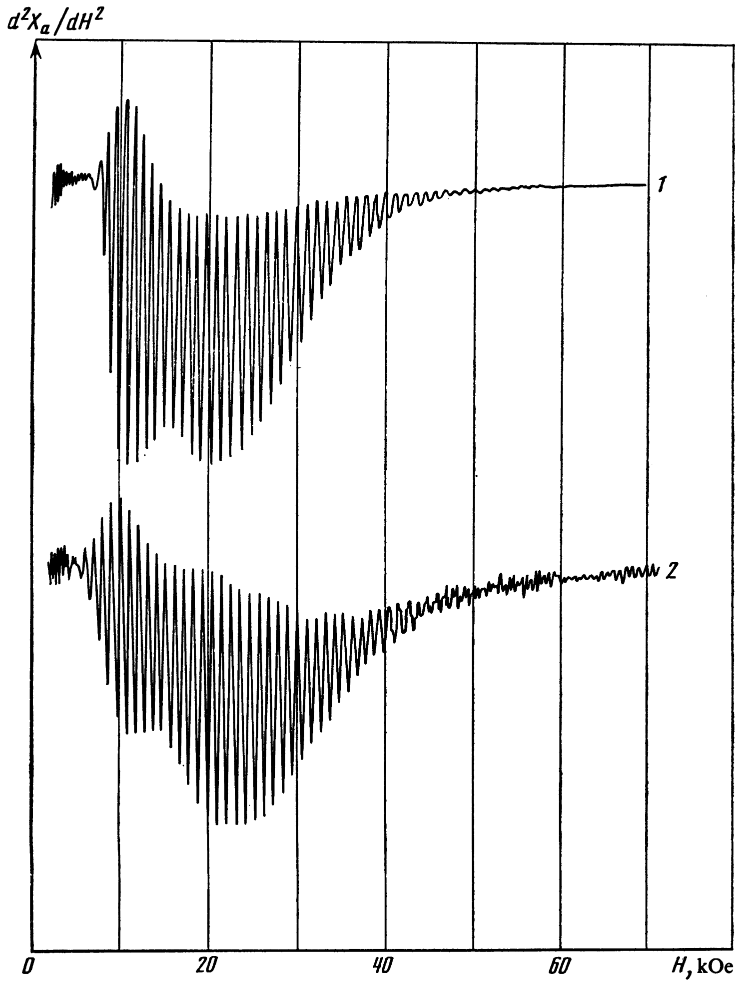

FIG. 3. Traces of oscillations of d^2X_a/dH^2 as a function of magnetic field for the case of antisymmetric excitation of the wave: 1) $\theta \approx 0$, 2) $\theta \approx 5°$; $f = 3$ MHz.

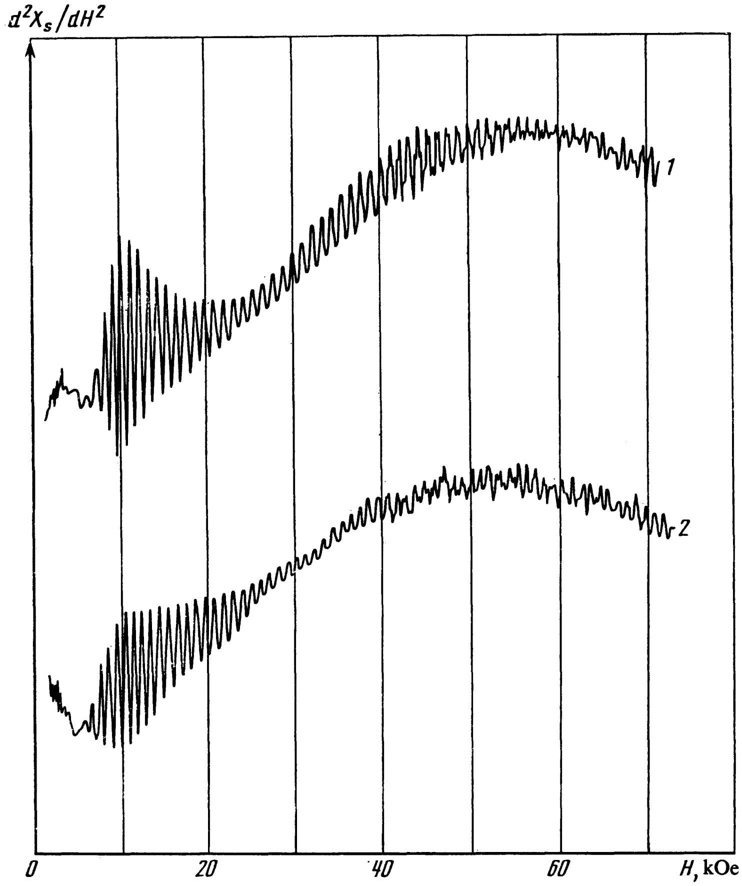

FIG. 4. Trace of oscillations of d^2X_s/dH^2 as a function of magnetic field for the case of symmetric excitation of the wave: 1) $\theta \approx 0$, 2) $\theta \approx 5°$; $f = 3$ MHz.

quantum oscillations on the angle of inclination of the magnetic field, it can be concluded that quantum oscillations of the conductivity are reponsible for the oscillations of the real part of the impedance of tungsten for symmetric excitation of the wave, while oscillations of the imaginary part for antisymmetric excitation are associated with oscillations of the magnetic moment.

We note that the study of quantum oscillations of the imaginary part of the impedance for symmetric excitation showed disagreement with the theory referred to. It follows from Table I that in this case as for antisymmetric excitation, quantum oscillations of the magnetic moment should be observed, but with one-third the amplitude. In fact, it can be concluded from the results of Fig. 4 that the oscillations observed are associated with oscillations of conductivity.

This result suggests a possible connection between the disagreement between theory and experiment in the imaginary part of the impedance for symmetric excitation for quantum oscillations and for the smooth field dependences of impedance found earlier.[4] If it is assumed, on the basis of the results on quantum oscillations, that the conductivity of the metal enters the expression for the imaginary part of the impedance for symmetric excitation, then the disagreement between theory and experiment for the smooth variation of X_s, described earlier,[4] is appreciably reduced. At the same time, no reason can be seen at present for introducing into the theory a dependence of X_a on σ in a high magnetic field.

Our experimental results and also those of Vol'skiĭ and Petrashov[7] who observed oscillations at low frequencies (~ 100 Hz) in propagation of helicons and associated these oscillations with the appearance of the de Haas–van Alphen effect, do not agree with the general calculations of Lifshitz *et al.*[2]

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