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# Investigation of the effect of surface scattering of electrons on the radio-frequency size effect in tungsten

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The radio-frequency size effect (RSE) and the magnetoresistance are experimentally investigated in a magnetic field parallel to the surface of tungsten single-crystal plates in the {110} plane, placed in a high vacuum and having different surface states: a) with adsorbed residual-gas film and b) cleaned by heating to high temperature. It is observed the surface cleaning decreases the amplitudes of the RSE lines but leaves their widths and shapes unchanged. The weakening of the RSE does not depend substantially on the positions of the orbits on the electron jack and on the hole octahedron, manifests itself weakly for the spheroid lines, and correlates with the variation of the magnetoresistance. The connection of the amplitude and width of the RSE lines with the specularity coefficient are analyzed in light of the existing theories. It is shown that the observed sensitivity of the RSE to the surface state is well described by the variation of the specularity coefficient of the grazing electrons. The changes of $p$ determined from the RSE measurement agree qualitatively with the corresponding values determined by measuring the magnetoresistance.

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## 1. INTERACTION

It is well known that the radio-frequency size effect (RSE) in a magnetic field **H** parallel to the surface of a plane-parallel metallic plate of thickness $d$ is due to two effects: the cutoff of the effective orbits (CEO) and the anomalous penetration (AP).[1] The theory of the CEO in a plate in the limiting cases of diffuse and specular scattering was developed by Kaner *et al.* in Refs. 2 and 3, respectively. The gist of the conclusions of the theory reduces to the following. At $H_0$ (where $H_0 = 2\hbar kc/ed$ is the cutoff field, $2\hbar k$ is the diameter of the electron orbit, $e$ is the charge, and $c$ is the speed of light) the electron trajectories cannot be fitted in the plate, so that in a metal with a diffuse boundary the extremal-section electrons which pass through the skin layer, become scattered by the opposite surface of the plate and lose the energy acquired from the wave. In a metal with a specular boundary, the colliding electrons return repeatedly to the skin layer at $H<H_0$, just as the volume electrons at $H>H_0$. In addition, in this case the skin layer is formed mainly by the surface electrons that glance over the surface along trajectories with centers outside the metal. The shunting of the contribution of the volume electrons into the high-frequency conductivity by the surface electrons, just as the conservation of the number of electrons participating in the formation of the skin layer at $H<H_0$, make the attenuation of the singularity of the impedance at specular reflection stronger than in the diffuse case.

The theory of the AP in a semi-infinite metal, in the limiting cases of diffuse ($|\gamma|\ll 1-p$) and specular $[|\gamma|(\delta_0/R)^{1/2}\gg 1-p]$ scatterings, and also at intermediate values of the specularity coefficient $p$

$$|\gamma|(\delta_0/R)^{1/2}\ll 1-p\ll|\gamma|\ll 1 \tag{1}$$

was developed in Refs. 1–6. Here $\gamma=(\nu-i\omega)/\Omega$, $\delta_0$ is the skin-layer depth, $\Omega$ and $\omega$ are the cyclotron and electromagnetic frequencies, respectively, $\nu$ is the collision frequency, and $R$ is the radius of the electron trajectory. In AP, the electrons form equidistant current sheets of thickness

$$\delta_\gamma=(4c^2R\Omega\gamma/3\omega\omega_0^2)^{1/3} \tag{2}$$

($\omega_0$ is the plasma frequency of the metal) at a distance that is a multiple of the diameter $2R$ from the surface. Since these bursts are formed by the volume electrons, it follows that $\delta_v$ does not depend on the character of the surface scattering. At the same time, a contribution to the formation of the main skin layer of depth $\delta_0$ is made by the volume electrons in diffuse reflection and by the surface electrons in completely specular scattering and in the intermediate case (1). Therefore $\delta_0$ depends on the specularity coefficient $p$:

$$\delta_0=\delta_v[(1-p)/\pi|\gamma|]^{1/2}. \quad (3)$$

An increase of $p$ leads to a narrowing of the main skin layer and to a corresponding decrease of the amplitudes of the field bursts.

The theory of Kaner *et al.*[2-6] was constructed for unilateral excitation of the plate, under conditions of the limiting anomalous skin layer ($|\gamma|\ll 1$). Juras[7,8] considered the more realistic case, from the experimental point of view, of bilateral excitation and $\gamma\sim 1$. By numerical computer calculations he obtained the shape of the lines of the RSE, including both the CEO and the AP at different values of $p$ and $\gamma$ and at $\omega\ll\Omega$. The influence exerted on the RSE by the dependence of the specularity coefficient on the surface-scattering angle was also considered.[9] The results obtained in Refs. 7–9 confirm qualitatively the conclusions of the theory of Kaner *et al.* that the SRE lines become weaker with increasing $p$.

Thus, numerous theoretical investigations testify to a strong sensitivity of the RSE to surface scattering. Since the influence of the specularity reduces to the onset of a contribution of glancing electrons, it follows that this sensitivity extends mainly to scattering at small angles $\varphi\sim(\delta_0/R)^{1/2}$.

We have experimentally investigated the influence of the character of the surface scattering on the RSE in a magnetic field parallel to the surface of a thin tungsten plate, for the purpose of experimentally verifying the conclusions of the theory. We used plates in the $\{110\}$ plane. It was established earlier with the aid of the static skin effect[10] and electron focusing,[11] in the case of tungsten plates in the same plane and placed in a high vacuum, that the specularity coefficient can be varied directly in the experiment by adding (or removing) films of adsorbed gases from the vacuum volume. The present investigations of the SRE line shape were investigated under similar conditions. The sample surface state was monitored, both after cleaning by high temperature heating and after sputtering an impurity film, by using the static skin effect. It was observed that the amplitude of the RSE line decreases with increasing $p$ in agreement with the conclusions of the theories. The effect of the decrease ofthe amplitude is stronger the larger the dimensions of the Fermi-surface (FS) sheets responsible for the RSE

## 2. MEASUREMENT PROCEDURE

The procedure of preparing and mounting the samples was similar to that described previously.[10-12] The tungsten samples, oriented in the $\{110\}$ plane, were cut by the electric-spark method from a single-crystal ingot with a resistivity ratio $\rho_{300\,K}/\rho_{4.2\,K}\approx 1\cdot 10^5$. The plate surface, measuring $2\times 8$ mm was mechanically ground and then electrically polished in 1% solution of NaOH until a mirror finish was produced. The thickness $d$ was monitored with a vertical optimeter with accuracy ±1 $\mu$m and ranged from 0.15 to 0.35 mm. The sections near the edge, which had a somewhat smaller thickness after the electric polishing, were removed by grinding; the samples prepared in this manner were plane parallel within not more than ±1%.

The plates were spotwelded, through tungsten suspensions of 0.2–0.3 mm in diameter, to thick (1 mm diameter) molybdenum leads in a glass ampoule of 20 mm diameter, and were additionally cleaned to remove the carbon impurity. The cleaning of the samples at an oxygen pressure $1\times 10^{-6}$ Torr and 1900 °C temperature took 10 hours. The glass ampoule with the sample were then sealed off from the vacuum installation and placed in a cryostat. The background gas pressure was $1\times 10^{-9}$ Torr and apparently dropped to $1\times 10^{-11}$ Torr after cooling to helium temperature.

To measure the magnetoresistance, clamped tungsten-wire tips of 0.1 mm diameter were mounted on the surface of the plates at distances on the order of 4–6 mm. The measurement current was made to flow along the $\langle 112\rangle$ or $\langle 111\rangle$ direction. The signal from the potential contacts was measured by a null method with an R309 potentiometer.

The crystal with the potential contacts was located inside a coil of 5–6 mm diameter, having 10–12 turns of tungsten wire of 0.2 mm diameter. The coil was welded to the two molybdenum leads and served as the $L$ part of a high-frequency tank circuit of an autodyne generator. This ensured bilateral antisymmetrical excitation.

The procedure of measuring the RSE was similar to that described in Ref. 13. In the experiments we measured the derivative of the active part of the sample impedance with respect to the magnetic field $\partial R/\partial H$. The working frequency ranged from 6 to 11 MHz, and the generation amplitude was maintained constant during the experiment.

The direction of **H** in the measurements of the magnetoresistance was perpendicular to the line of the potential contacts and to the axis of high-frequency coil. In the measurement of the RSE, the holder of the ampoule with the sample was rotated through 90° in the plane of the sample to obtain perpendicular polarization of the skin current relative to the **H** direction. The experiments were performed at different directions of $H$. A special adjusting unit made it possible to incline the ampoule with the sample and thus align with high accuracy the direction of $H$ in the plane of the sample. The orientation of the samples was determined from the symmetry of position of the SRE lines, and the parallelism of the sample surface was determined from the maximum of the amplitudes of the SRE lines.

## 3. EXPERIMENTAL RESULTS

Figures 1 and 2 show typical plots of the SRE lines for a tungsten sample with different surface states. It is known[14] that the line *e* is due to the extremal orbits on the electron spheroids, while the lines *g* and *h* are due respectively to the orbits on the waist of the electron jack and of the hole octahedron. Because of the octahedral shape of these sheets of the FS, the contribution to the RSE is made by a wide strip of orbits, close in shape to a cylinder of hexagonal cross section. For the jack, the strip is bounded by the spheroids, so that the line *g* has a smaller amplitude than *h*.

We observed in the experiments three RSE lines each in the multiple fields, and the amplitude of the lines in the doubled field was approximately one-fifth that of the first line. Therefore detailed investigations of the shape were carried out only for the principal most intense lines. It is seen from Figs. 1 and 2 that a short-duration (several seconds) heating of the sample from helium temperature to approximately 2500 °C (flash) leads to a decrease of the amplitudes of the lines *g* and *h* and has little effect on the line of the spheroids *e*. The shape and width of the lines remain practically unchanged. The magnetoresistance of the samples also decreases sharply (Fig. 3). The RSE lines in the doubled field varied in the same manner as the lines *g* and *h*.

The flash rid the sample surface of the film of residual gases adsorbed from the vacuum volume, thus increasing the specularity coefficient $p$.[10,11] If the tungsten coil is heated in the same manner after the flash, then a fraction of the gases that are released from the coil again condense on the sample and decrease $p$. This raised the amplitudes of the RSE lines *g* and *h*, as well as the magnetoresistance, to their previous values while the line *e* remained practically unchanged. Heating the apparatus to room temperature followed by cooling also contaminated the surface by a gas film and led to the same changes as heating the coil.

The effect was repeatedly reproducible in several experiments and for several samples. No substantial dependence on the temperature and on the positions of the orbits on the FS was observed. It should be noted that magnetoresistance of a plate with a film impurity decreased after several cycles of purification and sputtering, while in the case of a clean surface it remained unchanged (Fig. 3). It is probable that the first few flashes rid the sample surface of compounds of the type WO, $WO_2$, and $WO_3$. It is known that the bonds between the chemosorbed atoms and the substrate serve as additional centers of scattering on the surface of the metal.[15]

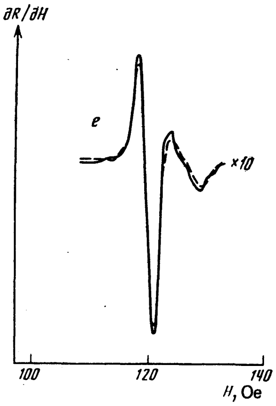


FIG. 2. RSE lines of the spheroid electrons (*e*). The conditions and symbols are the same as in Fig. 2, the gain is approximately 10 times larger than for the *h* line.

Despite the fact that the samples were prepared from one ingot of high purity, for some of them the amplitude of RSE line was comparable with the noise level. It appears that these samples were deformed during the mounting. The amplitude of the RSE lines for such samples increased nonmonotonically after the flashes, whereas the magnetoresistance decreased. Subsequent sputtering from the tungsten coil increased the magnetoresistance to the previous value and to increase further the amplitude of the RSE line. Such an uncorrelated behavior of the RSE and of the magnetoresistance is apparently due to partial annealing of the samples in the course of the flash. In fact, the amplitude

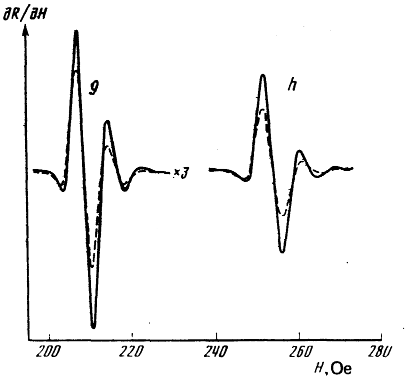


FIG. 1. Plot of the RSE lines of electrons (*g*) and holes (*h*) at different surface states. The solid curves represent the RSE lines for a sample with a dirty surface, and the dashed ones for a clean surface; $\sphericalangle(\mathbf{H}, \langle 100\rangle) = 30°$, $d = 0.27$ mm, $\omega/2\pi = 6.33$ MHz. The *g* line was recorded with a gain increased by a factor of 3.

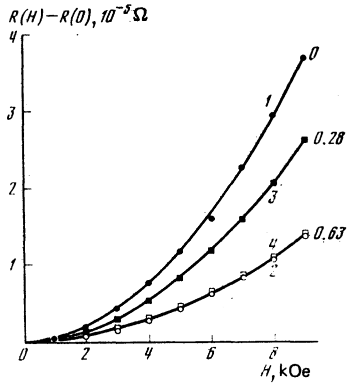


FIG. 3. Dependence of the transverse magnetoresistance on the magnetic field for the same sample as in the investigations of the RSE (Fig. 1, 2) with different surface states: 1, 3—dirty, 2, 4—clean. Curves 3 and 4 were obtained after five cycles of purification and adsorption. The numbers alongside the curves correspond to the values of $p$ calculated from the resistivity ratio.

of the RSE line is $A \sim \exp(-\pi d/l)$ (where $l$ is the electron mean free path), and in a strong field, under the conditions of static field effect, the magnetoresistance does not depend on $l$.[16] For the undeformed samples, the amplitude of the RSE lines were larger by approximately one order of magnitude than for the deformed ones, and therefore the changes of $l$ after the flash have little effect. Since this effect cannot be completely excluded, the plots of the RSE lines in Figs. 1 and 2 were drawn after five cycles of purification and adsorption of the impurity atoms.

## 4. DISCUSSION OF THE RESULTS

Since we measured in the experiments the derivative $\partial R/\partial H$ of the active part of the surface impedance

$$Z=R-iX=\frac{4\pi i\omega}{c^2}\frac{E(0)}{E'(0)}, \tag{4}$$

it follows that the amplitude of the RSE line is

$$A\sim \operatorname{Im}\frac{\partial[E(0)/E'(0)]}{\partial H}\sim \delta_v \operatorname{Im}\frac{E(0)}{E'(0)},$$

where $E(0)$ is the electric field and $E'(0)$ is the derivative of the field at the surface with respect to the distance into the interior of the metal. In our experiments only one return of the electrons to the initial skin layer was possible ($l \approx \pi d \approx 1$ mm), i.e., under the investigated conditions the RSE is due mainly to the AP. The width of the RSE lines is proportional to the duration of the flash $\delta_v$, and in accordance with (2) remained unchanged with changing character of the scattering. The amplitude of both the imaginary and of the active part of the field in the first flash is given by[6]

$$E(2R)\approx\frac{E'(0)}{(\pi^3R)^{1/2}}\frac{\delta_0^{3/2}}{\delta_v}. \tag{5}$$

Substituting this expression in (4) we can readily show that the ratio of the amplitudes of the RSE lines at specularity coefficients $p_1$ and $p_2$ is

$$A_1/A_2=[(1-p_1)/(1-p_2)]^{1/4}. \tag{6}$$

It follows from the theory of the static skin effect[17] that the transverse magnetoresistance of a plate of compensated metal, $\rho(H)$, in a strong magnetic field parallel to the surface $[d < l,\ R \ll (1-p)l]$, decreases, when the probability of the specular reflection increases from $p_1$ to $p_2$, by a factor $(1-p_1)/(1-p_2)$. Generally speaking, this ratio can be regarded only as an estimate, since $p$ depends on the scattering angle and on the wave vector of the electrons. Nevertheless, a close correlation was observed in Ref. 11 between the values of $p$ determined from the ratio $\rho_1/\rho_2$ and from the ratio of the amplitudes of the electron focusing in multiple fields. Then, assuming the surface state prior to the first flash to be completely diffused ($p=0$), it is easy to calculate the values of $p$ for the succeeding states of the surface in our case. These data are given in Fig. 3 and agree with the data of Ref. 11.

In the experiments we observed a good correlation between $A_1/A_2$ and $\rho_1/\rho_2$, in accordance with the relations presented above. Nonetheless, it is apparently impossible to use the values of $p$ determined from the magnetoresistance to check on relation (6). First, the amplitude of the flashes under conditions (1) is determined by the contribution of the grazing electrons that collide with the surface at small angles $\varphi \sim (\delta_0/R)^{1/2}$, while the magnetoresistance is determined by the large-angle scattering. In Ref. 18 it is shown that the probability of spectral reflection increases strongly with decreasing $\varphi$ in analogous experimental conditions, and accordingly the difference between the values of the probability for the pure and dirty surfaces increases. Second, expression (6) is valid under the conditions $0.75 < p < 0.95$ (1), which is not satisfied by the values of $p$ determined from the static skin effect.

The decrease of the ratio $A_1/A_2$ for the spheroid line is apparently due to several circumstances. First, the hexagonal shape of the trajectories $g$ and $h$ causes the value of $\varphi$ for grazing electrons and holes to be substantially larger than $(\delta_0/R)^{1/2}$, and accordingly decreases more rapidly than $H^{1/2}$ in weak fields. Second, the sag of the arc of the trajectory of the grazing electrons increases like $H^{-1/3}$, and these trajectories of the octahedron and of the jack are partially crowded out of the skin layer with decreasing $H$. Therefore, the main contribution for the $e$ line are made by grazing trajectories of the spheroid electrons. Finally, the value of $p$ for spheroids is larger than for the octahedron and for the jack, owing to the larger deBroglie wavelength.[19] All this can lead to an increase of $p$ for the line $e$ compared with $g$ and $h$ and accordingly to a weaker influence of the surface states.

Indeed, a comparison of the experimental curves with the theoretical ones[8] shows that $p \approx 1$ for the spheroid line. At the same time, the shape of the jack and octahedral lines corresponds to $p \approx 0.5$ for a dirty surface and $p \approx 0.75$ for a clean one. We note that the theoretical line shape according to Refs. 7–9 agrees much better with experiment than that obtained in Refs. 2–6. In fact, it is well known from the experiments that the condition $H=H_0$ corresponds to the left edge of the RSE lines (see, e.g., Refs. 20 and 21) in accordance with the data of Refs. 7–9, whereas according to Refs. 2–6 this value corresponds to the maximum of the RSE line.

It must be borne in mind that these values of $p$ must be regarded only as estimates, since the conditions of the experiments differ from the theoretical ones with respect to some parameters or others. Nonetheless, the qualitative agreement with the foregoing analysis, which manifests itself in the decrease of the amplitude of the RSE line when the probability of specular reflection is increased is obvious. For quantitative comparisons we must have, apparently, both a further improvement of the theories, and experimental investigations on metals with simple single-sheet FS.

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# Effect of surface waves on the reflection of sound by a rough surface

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The reflection of sound incident from a liquid on the rough surface of an isotropic solid is considered. For angles of incidence corresponding to total internal reflection, the reflection coefficient has a sharp minimum due to the excitation of surface waves. The minimum is deep for small (compared with the sound wavelength) and weakly sloping roughnesses. This can be due to the competition of a roughness with a small ratio of the acoustic impedances of the liquid and the solid. The location and shape of the minimum have been studied as a function of the sound frequency and the parameters of the roughness. The considered phenomenon can serve as an experimental method for study of the structure of the surface of a solid.

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## 1. INTRODUCTION

The problem of the scattering of various waves by a rough surface has been considered in a large number of researches (see, for example, Ref. 1). In one of the latest papers on this subject,[2] the reflection of sound from the rough surface of a solid body is described. Since the solid in this research was assumed to be absolutely rigid, the effect of any waves propagating in it was not taken into account. However, the problem discussed represents great practical interest,[3] in particular as one of the methods of nondestructive testing. Figure 1 (taken from the work of Rollins[3]) shows the experimental dependence of the reflection coefficient of ultrasound incident from a liquid on the surface of a solid as a function of the angle of incidence (the angle of reflection was chosen equal to the angle of incidence). In the region of total reflection, when volume sound waves cannot propagate in the solid, there exists a minimum, the location and shape of which depend on the properties of the surface.

It is natural to connect the origin of a minimum with

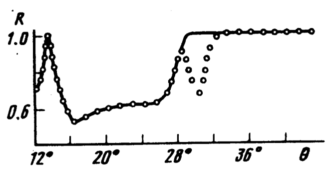


FIG. 1. Dependence of the reflection coefficient $R$ on the angle of incidence $\theta$. The curve is constructed according to Eq. (1), the points are the experimental data from Ref. 3 for a water-aluminum interface and a frequency of 5 MHz.

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