Skin effect in a metal plate and peculiarities of Gantmakher-Kaner oscillations

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An experimental and theoretical investigation is made of the behavior of the smooth and oscillating parts of the impedance of a compensated metal plate in a perpendicular magnetic field in the radio frequency range. The measurements were made on molybdenum plates with linear and circular polarizations of the exciting field. The theoretical treatment was carried out on the assumption that the carriers are diffusely reflected from the surface of the metal. It is shown that for a sufficiently large path length of the carriers, nonlocal effects have considerable influence on the peculiarities of the smooth parts of the impedance of the plate in a magnetic field. It is demonstrated that the variation of the smooth part of the impedance with magnetic field qualitatively changes the character of the Gentmakher-Kaner oscillations with linear polarization of the exciting field. The theoretical results are in good agreement with the experimental data. The rules discovered can be used to identify oscillations of the impedance and make it possible to resolve contradictions that occur in the literature in the interpretation of a number of experiments.

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INTRODUCTION

One of the most effective methods for distinguishing Gantmakher-Kaner oscillations (GKO)[1] from doppleron oscillations[2] is the application of a circularly polarized exciting field.[3] This method has been used to demonstrate the existence of dopplerons in cadmium, indium and aluminum, and copper and silver, and also to study GKO in cadmium.[4] But in the case of tungsten[5-7] and molybdenum,[7-10] this method does not permit unique interpretation of the experimental results, because the oscillations observed in different circular polarizations are very similar. Regarding the nature of the oscillations in "minus" polarization, various points of view have been expressed, none of which sufficiently convincing or permitted a choice between doppleron and GKO. The difficulty is further aggrevated by the fact that the peculiarities of GKO have not been studied with sufficient completeness. In particular, the problem remains that was posed in Ref. 11, where it was shown that in excitation by a linearly polarized field, GKO should exist only in the real part of the impedance, whereas in Ref. 1 they were observed in the imaginary part. In Ref. 11, where only specular reflection of the carriers was considered, it was hypothesized that this contradiction was due to diffuse reflection of the electrons in the experiment. The effect of the character of the reflection on excitation of a doppleron and of GKO has been considered in a number of papers.[4,12-15] But the question of the difference between GKO in the real and in the imaginary parts of the impedance and of the peculiarities of GKO in a linearly polarized field has not been investigated.

The present paper is devoted to a study of the peculiarities of GKO in the real and imaginary parts of the impedance with various polarizations of the exciting field and to explanation of the nature of the oscillations in molybdenum. It was observed that in the case of linear polarization, the amplitude of the oscillations of surface resistance caused by the Gantmakher-Kaner effect varies in a complicated way with the value of the magnetic field. The envelope of the oscillations has two maxima separated by a minimum. In the range of fields corresponding to this minimum, the amplitude of the oscillations of the reactance has a maximum. This property of GKO can be used for identification of them in those cases in which the amplitude of the GKO is comparable with the amplitude of the doppleron oscillations and the method of circular polarizations does not enable one to obtain an unambiguous answer. Application of the ideas developed to a study of the oscillations in molybdenum led to the conclusion that the oscillations in "minus" polarization are caused by the Gantmakher-Kanar effect, while the oscillations in "plus" polarization are a superposition of GKO and doppleron oscillations. This corroborates the original point of view on oscillations in molybdenum, expressed in Ref. 8.

EXPERIMENT

In the experiment, the real and imaginary parts of the surface impedance of a molybdenum plate were studied in a magnetic field $\mathbf{H} \parallel \mathbf{n} \parallel [001]$. The measurements were made with an amplitude bridge[16] and an autodyne[17] over the frequency range 0.04–2 MHz, at temperatures 2–4.2 K, in magnetic fields up to 45 kOe. Excitation of the plate was carried out with a radiofrequency field having either linear or circular polarization. Change of sign of the polarization was accomplished by commutation of the current of the superconducting solenoid used to produce the magnetic field. The inhomogeneity of the solenoid field in the central zone did not exceed $10^{-4}/\mathrm{cm}^3$. To check the circular-polarization apparatus, there was placed in the measurement coils, along with the specimen under study, a plate of aluminum, whose impedance has helicon oscillations only in "plus" polarization. The final recording of the impedance of the molybdenum was done

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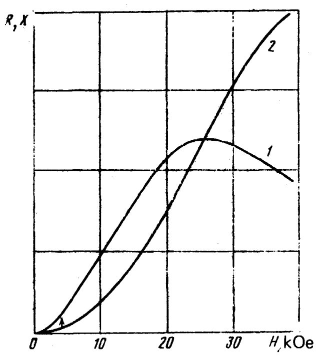

FIG. 1. Variation of surface resistance $R_{xx}(1)$ and reactance $X_{xx}(2)$ of a molybdenum plate with magnetic field. Plate thickness $d=0.826$ mm, frequency $\omega/2\pi=0.33$ MHz, $T=4.2$ K.

in the absence of the aluminum specimen used for checking.

The molybdenum plates were cut by the electroerosion method from a monocrystalline bar in such a way that the normal n to the plate coincided with the direction of the axis [001]. After the cutting, the surfaces of the specimens were ground with an abrasive with grain dimensions 5–7 μm, and then chemically polished. The resistance ratio of the molybdenum was $\rho_{300\,K}/\rho_{4.2\,K}\approx 50\,000$.

The measurement coils with the specimen under study, arranged on a rotable device, were placed in the central zone of the solenoid. The rotatable device had two degrees of freedom for orientation of the specimen in the magnetic field. For field direction H ∥ n ∥ [001] the oscillations of the impedance of the plate caused by propagation of a hole doppleron[8,9] have a maximum amplitude, near the threshold, and a maximum period.

Figure 1 shows graphs of the variations of the real (1) and imaginary (2) parts of the impedance of a molybdenum plate with magnetic field in the case of linear polarization. The relative scale along the axis of ordinates was determined from the superconductive transition of a calibration specimen made of lead, with resistance ratio $\rho_{300\,K}/\rho_{2.4\,K}\approx 90$. The error of the calibration did not exceed 10%. The arrow on the graph marks the value of the threshold field H_L for a hole doppleron. In the vicinity of the field H_L, the surface resistance and reactance vary approximately as H^2. In this range of fields, R_{xx} is considerably larger than X_{xx}. In strong fields, the resistance reaches a maximum and thereafter decreases with increase of field. The rate of change of the reactance decreases rapidly in strong fields. In the vicinity of the maximum of $R_{xx}(H)$, the values of R_{xx} and of X_{xx} become equal, and in stronger fields the reactance exceeds the resistance.

Figure 2 gives records of the derivatives $d^2R_\pm/dH^2=f(H)$. We shall not give $d^2X_\pm/dH^2$ graphs, since they are similar to the $d^2R_\pm/dH^2$ curves. In both polarizations there are observed intense oscillations of similar period, whose amplitude increases with increase of the field, reaches a maximum, and then slowly falls. Modulation of the envelopes of the curves in strong fields is caused by quantum oscillations. The principal difference between curves 1 and 2 consists in a considerably more rapid increase of the amplitude of the oscillations in plus polarization. Furthermore, in the field interval 20–40 kOe the number of oscillations in plus polarization is one larger than in minus polarization. The mean value $(\partial S/\partial k_z)_{ext}=3.17$ Å^{-1} measured in Ref. 9. The graphs presented are also similar to curves first obtained in Ref. 8. According to the interpretation in Ref. 8, the oscillations in plus polarization are caused by propagation of a doppleron and by a Gantmakher-Kanar "wave."

In linear polarization, the variation of the amplitude of oscillations of d^2R_{xx}/dH^2 and d^2X_{xx}/dH^2 has a quite different character. This is illustrated by Fig. 3. On

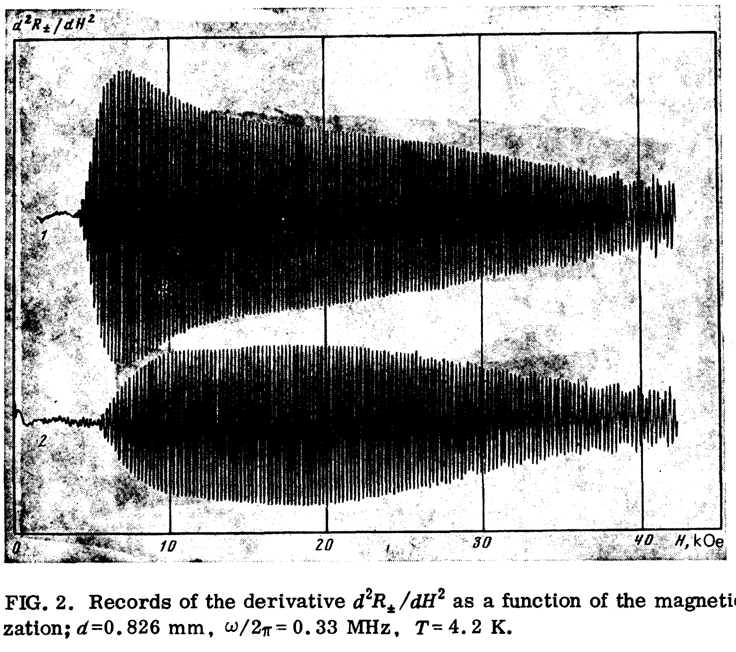

FIG. 2. Records of the derivative $d^2R_\pm/dH^2$ as a function of the magnetic field. Curve 1, "plus" polarization; 2, "minus" polarization; $d=0.826$ mm, $\omega/2\pi=0.33$ MHz, $T=4.2$ K.

both curves, the envelope of the oscillations has two maxima separated by a minimum. The minimum of the oscillations of d^2X_{xx}/dH^2 is observed comparatively close to the doppleron threshold, while the oscillations of the resistance have a minimum at a considerably stronger magnetic field, in the vicinity of which is located the second maximum of the oscillations of the reactance. On both curves there are a large number of oscillations; this makes it difficult to compare the relative positions of the extrema of the oscillations of resistance and of reactance. Examination of these curves on a scale stretched along the axis of abscissas shows that to the left of the minimum of the amplitude of d^2R_{xx}/dH^2, the oscillations of R_{xx} and X_{xx} are in phase; and to the right, in antiphase.

Measurements made at different frequencies showed that the position of the minimum of the amplitude of the oscillations of d^2R_{xx}/dH^2 with respect to magnetic field shifts in proportion to the square root of the frequency. On decrease of the plate thickness or lowering of the temperature, the position of this minimum shifts toward weaker magnetic fields. In all cases, the minimum occurs in that field range in which the value of the surface resistance is close to the value of the reactance.

THEORY

References 12, 14, and 4 treated the excitation of dopplerons and of Gantmakher-Kanar "waves" in a plate of compensated metal with various types of reflection of the electrons. It was shown that in the case of diffuse reflection, the oscillating part of the impedance of a thick plate (whose thickness d is considerably larger than the thickness $1/k_s$ of the skin layer), in the strong-magnetic-field range, is proportional to the square of the impedance of a semi-infinite metal. Since the thickness of the skin layer is proportional to H, in sufficiently strong fields $1/k_s$ becomes of the order of or larger than d, and the Fischer-Kao[18] effect occurs. It is quite natural that in this case the amplitude of the oscillations will be proportional to the square of the smooth part of the impedance of the plate. We shall demonstrate this for a model of a compensated metal[13] in which there is a group of electrons with extremal displacement u, whereas the displacements of the holes are small and their contribution to the conductivity is local.

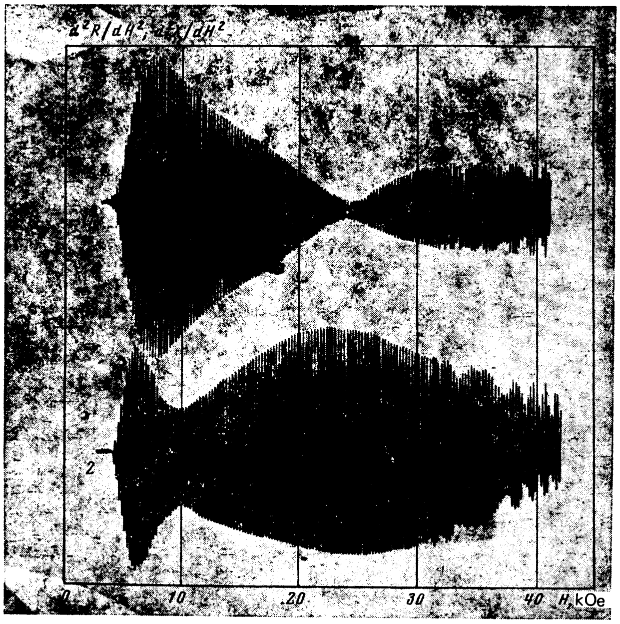

FIG. 3. Records of the derivatives d^2R_{xx}/dH^2(1) and d^2X_{xx}/dH^2 (2) with linear polarization of the field; $d=0.826$ mm, $\omega/2\pi=0.33$ MHz, $T=4.2$ K.

According to Refs. 13 and 4, in a semi-infinite metal an electric field rotating in the same direction as the electrons (minum polarization) can be represented in the form

$$E_{0-}(\zeta)=E_-(0)\{e_s(\zeta)+e_D(\zeta)-e^*_{GK}(\zeta)\}, \tag{1}$$

where $\zeta=2\pi z/u$ is a dimensionless coordinate measured along the normal to the surface, $E_-(0)$ is the electric field at the surface of the metal, and the three terms in wavy brackets describe, respectively, the field of the skin component, of the doppleron, and of the Gantmakher-Kanar "wave". The asterisk denotes the complex conjugate. The form of notation $-e_{GK^*}(\zeta)$ is due to a desire to retain the notation $e_{GK^*}(\zeta)$ for the Gantmakher-Kanar component in plus polarization.[4]

In the range of magnetic fields H that are appreciably larger than the threshold field H_L of a doppleron, the fields of the doppleron and of the Gantmakher-Kanar "wave" at the surface are small, and therefore the field of the skin component can be written in the form

$$e_s(\zeta)=\exp(iq_s\zeta), \tag{2}$$

where $q_s=k_su/2\pi$; k_s is the wave vector of the skin component.

As was noted in Ref. 13, in the strong-field range the nonlocal interaction of different components can be neglected. Therefore an expression for the field in a plate is obtained from (1) by simply changing the coefficients of the various components and adding terms that take account of the antisymmetry of the excitation:

$$E_-(\zeta)=E_-(0)\left\{\frac{e_s(\zeta)-e_s(L-\zeta)}{e_s(0)-e_s(L)}+[e_D(\zeta)-e_D(L-\zeta)]-[e^*_{GK}(\zeta)-e^*_{GK}(L-\zeta)]\right\}, \tag{3}$$

where $L=2\pi d/u$. The coefficients of $e_D(\zeta)$ and $e_{GK^*}(\zeta)$ in (3) have been taken as unity because, by virtue of the smallness mentioned above, their amplitudes are uniquely determined by the field at the surface.

The expression obtained for the impedance Z_- of the plate by use of (3) is

$$\frac{cZ_-}{8\pi q_0}=i\frac{E_-(0)}{E_-'(0)}=\left\{q_s\frac{e_s(0)+e_s(L)}{e_s(0)-e_s(L)}+q_D[e_D(0)+e_D(L)]+i[e^{*\prime}_{GK}(0)+e^{*\prime}_{GK}(L)]\right\}^{-1}, \tag{4}$$

where $q_0=\omega u/2\pi c$, $q_D=k_Du/2\pi$; k_D is the wave vector of the doppleron, and the prime denotes a derivative with respect to ζ.

Reference 13 solved exactly the problem of the field distribution and impedance of a plate of arbitrary thickness in arbitrary magnetic fields, for the parabolic-lens model. The expression from Ref. 13 for the impedance in strong fields agrees with formula (4) with $e_{GK} \equiv 0$, since in this model the Gantmakher-Kanar effect is absent.

In any other models, in strong fields $e_{GK}(0) \gg e_D(0)$. If we also take into account that $e_{GK}(L) \ll e_{GK}(0)$, we can write the expression for Z_- approximately in the form

$$Z_- = Z_0 - \frac{c}{8\pi q_0} Z_0^2 [q_D e_D(L) + i e_{GK}^{*\prime}(L)], \tag{5}$$

where

$$Z_0 = \frac{8\pi q_0}{c} \left[q_s \frac{e_s(0)+e_s(L)}{e_s(0)-e_s(L)} + i e_{GK}^{*\prime}(0) \right]^{-1}, \tag{6}$$

Z_0 is the smooth part of the impedance of the plate.

The expression for the impedance in plus polarization is obtained from (5) and (6) by omitting the doppleron term and replacing $-e_{GK^*}$ by e_{GK}. On taking into account further that the value of $e_{GK}'(0)$ is purely imaginary, we see that the expression (6) is unchanged and that the impedance Z_+ has the form

$$Z_+ = Z_0 + \frac{c}{8\pi q_0} Z_0^2 i e_{GK}'(L). \tag{7}$$

The fact that the amplitude of the oscillations is proportional to the square of the smooth part of the impedance of a plate of arbitrary thickness, for the corrugated-cylinder model, was first shown in Ref. 15, although the oscillatory parts themselves were calculated in this paper.

For a linearly polarized field, we get

$$Z_{xx} = {}^1/_2(Z_+ + Z_-) = Z_0 - \frac{c}{8\pi q_0} Z_0^2 \left[\frac{1}{2} q_D e_D(L) + \mathrm{Re}(e_{GK}(L)) \right], \tag{8}$$

where we have taken into account that differentiation of $e_{GK}(\xi)$ when $\xi \gg 1$ reduces to multiplication by i.

We shall separate the impedance Z_{xx} of the plate into a surface resistance and reactance. For the smooth part Z_0 and the oscillatory part ΔZ_{xx} we get

$$Z_0 = R_0 - iX_0, \tag{9}$$

$$\Delta R_{xx} = -\frac{c}{8\pi q_0} \left\{ (R_0^2 - X_0^2)\mathrm{Re}[e_{GK}(L)] + \mathrm{Re}\left[\frac{Z_0^2}{2} q_D e_D(L) \right] \right\}, \tag{10}$$

$$\Delta X_{xx} = \frac{c}{8\pi q_0} \left\{ -2R_0 X_0 \mathrm{Re}[e_{GK}(L)] + \mathrm{Im}\left[\frac{Z_0^2}{2} q_D e_D(L) \right] \right\}. \tag{11}$$

From (10) and (11) it is evident that the oscillations of R_{xx} and of X_{xx} due to the doppleron have the same character. In contrast, the different behavior of R_0 and of X_0 with respect to a magnetic field produces substantial differences between the GKO reactance and surface resistance. If at some value of the magnetic field R_0 and X_0 are equal, then the amplitude of the GKO surface resistance vanishes, and the oscillations of the surface resistance are caused entirely by the doppleron. Furthermore, upon passage through this value of the field the phase of the GKO in R_{xx} changes by π. If in the vicinity of this point the value of X_0 increases while R_0 drops, then the GKO amplitude in the reactance has a maximum.

In strong fields, $e_{GK}'(0)$ is determined by the relation

$$-ie_{GK}'(0) = a(H_L/H)^3, \tag{12}$$

where a is a positive number of order of magnitude unity, whose exact value depends on the type of singularity in the nonlocal conductivity (for the corrugated-cylinder model,[4] $a = 2/\pi$). As a result, (6) takes the form

$$Z_0 = \frac{8\pi q_0}{c} \left[q_s \frac{1+e^{iq_sL}}{1-e^{iq_sL}} + a\left(\frac{H_L}{H}\right)^3 \right]^{-1}, \tag{13}$$

where

$$q_s = \left[2ai \frac{u}{l_0} \left(\frac{H_L}{H}\right)^3 \right]^{1/2}, \tag{14}$$

l_0 is the mean path length of the carriers, which determines the transverse static conductivity of the compensated metal.

We shall consider the peculiarities of the Fischer-Kao[18] effect in the presence of spatial dispersion. It follows from (13) and (14) that two cases are possible. In the first case, in that magnetic-field range in which the thickness $1/k_s$ of the skin layer becomes comparable with the thickness d of the plate, the second term in square brackets in (13) is smaller than the first, and nonlocal effects play no role in Z_0. This situation is realized when the inequality

$$d \gg l_0 \tag{15}$$

is satisfied. In this case, the impedance Z_0 varies with H in the following manner. In the field range in which

$$(H_L/H)^3 \gg 2au/l_0, \tag{16}$$

Z_0 is mainly real, and R_0 is proportional to H^2, X_0 to H^3. In the field range in which

$$(H_L/H)^3 \ll u/l_0, \tag{17}$$

but

$$q_s L \gg 1, \tag{18}$$

R_0 and X_0 become equal and increase in proportion to H. At still stronger fields, where $q_s L \sim 1$, the classical Fischer-Kao[18] effect begins; that is, the surface resistance reaches a maximum and then begins to decrease, and the reactance approaches a constant value.

In the second case, opposite to (15), when the condition $q_s L \sim 1$ is satisfied within the range (16), spatial dispersion substantially affects the Fischer-Kao effect. The reactance X_0 increases in proportion to H^3 in the range $q_s L \gg 1$ and in proportion to H^4 in the range where $q_s L \ll 1$ but

$$a(H_L/H)^3 L \gg 1. \tag{19}$$

Here R_0 remains much larger than X_0 and increases as H^2 over the whole range (19). At a value of H corresponding to the condition

$$a(H_L/H)^3 L = 1, \tag{20}$$

R_0 and X_0 become equal. In the vicinity of this point, R_0 reaches a maximum and then decreases, whereas X_0 increases monotonically, approaching a constant limit.

The variation of the surface resistance R_0 and reactance X_0 with the value of H in the two cases considered is represented in Fig. 4. The dotted curves

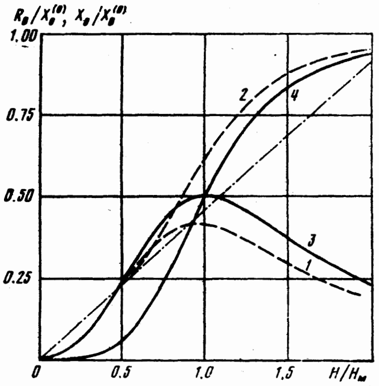

FIG. 4. Graphs of the surface resistance R_0 (Curves 1 and 3) and reactance X_0 (Curves 2 and 4) of a plate as functions of the magnetic field. $X_0^{(0)}$ is the limiting value of X_0 for $H\to\infty$. The dash-dot straight line is the graph of R and X for a semi-infinite metal.

represent the graphs of R_0 and X_0 in the case of a normal skin effect [the second term in square brackets in (13) is small in comparison with the first over the whole range of fields represented]. The solid curves correspond to the limiting case $d \ll l_0$. They have been plotted over the field range where $q_s L \ll 1$. For convenience, the magnetic-field unit has been taken as the value H_M corresponding to the position of the maximum of R_0. The values of H_M in the cases $d \gg l_0$ and $d \ll l_0$ are different and are, respectively,

$$H_M = 0.23 d [a/(l_0 u_L)]^{1/2} H_L, \tag{21}$$

$$H_M = (ad/u_L)^{1/2} H_L, \tag{22}$$

where u_L is the displacement of resonance electrons when $H = H_L$ (at $H \sim H_M$, therefore, $q_s L \sim 1$ for the dotted curves, but $q_s L \ll 1$ for the solid). The dependence of H_M on the frequency of the exciting field ω is the same in both cases: $H \propto \sqrt{\omega}$; but the temperature dependent of l_0 and consequently of temperature when $d \ll l_0$ and is inversely proportional to $\sqrt{l_0}$ when $d \gg l_0$.

We note that the solid curves of R_0 and X_0 intersect at the point $H = H_M$, whereas the dotted curves diverge in the field range $H > 0.7\, H_M$. Therefore according to (10) the amplitude of the GKO in R_{xx} for $d \gg l_0$ vanishes over a field range whose upper limit is the value $0.7\, H_M$ and whose lower limit is determined by the inequality (17). But in the case $d \ll l_0$, the amplitude of the GKO vanishes only at the point $H = H_M$.

It follows from (10) and (11) that in strong fields, where the resistance R_0 is falling while the rectance X_0 remains constant, the amplitude of the GKO in R_{xx} decreases with increase of the field more slowly than in X_{xx}. Here the product $H\Delta R_{xx}$ directly determines the dependence of the amplitude of the function $e_{GK}(L)$ on H.

Finally, we notice the difference between the GKO in the two circular polarizations. Change of phase of the factor Z_0^2 in (5) and (7) leads to the appearance of a difference between the phases of the GKO in opposite polarizations, which, with increase of H, increases to the value 2π. For different models of the Fermi surface, the value of the phase shift may differ from 2π, if the initial phase of the GKO depends on the magnetic field.[4] Thus in the case of the corrugated-cylinder model, the total phase difference of GKO in opposite polarizations reaches the value 3π. As a result, the periods of GKO in Z_+ and Z_- should differ somewhat.

DISCUSSION

If we start from the fact that Doppler-shifted cyclotron resonance in molybdenum is due to holes, then the theoretical conclusions obtained are in good agreement with the experimental results. This applies, first, to the behavior of the surface resistance R_0 and reactance X_0; second, to the presence of a minimum of the envelopes of R_{xx} at the value $H = H_M$ at which $R_0 = X_0$ and of a maximum of the envelopes of X_{xx} in the vicinity of this value of H; third, to the change of phase of the oscillations of R_{xx} by π on passage through the value H_M; fourth, to the small increase of the period of the oscillations of Z_- in molybdenum in relation to the period of Z_+. Comparison of theory with experiment enables us to draw the conclusion that the oscillations of the impedance of molybdenum in minus polarization are caused by a Gantmakher-Kanar "wave," whereas the oscillations in plus polarization represent a superposition of doppleron oscillations and GKO.

The sharp increase of the oscillations of R_+, and also of R_{xx} and X_{xx}, in fields $H > 4.15$ kOe is due to the excitation of a hole doppleron, whose amplitude reaches a maximum at a value $H \approx 6$ kOe and then drops rapidly. In this range, GKO grow with H, but according to (10) and (11) their contribution to X_{xx} is much smaller than to R_{xx}. This explains the presence of a maximum of the envelopes of X_{xx} and R_{xx} in fields $H \approx 6$ and 8 kOe and of a minimum of the envelopes of X_{xx} at a field $H \approx 10$ kOe.

All the above-enumerated properties of oscillations in linear and circular polarizations should make it possible to identify doppleron oscillations and GKO unambiguously in other cases also, when their amplitudes are commensurate.

In conclusion, we note that the character of the graphs of X_0 and R_0 in Fig. 1 and also the form of the envelopes of R_{xx} in the vicinity of its minimum indicate a noticeable influence of spatial dispersion on the Fischer-Kao effect. This is natural, because in our experiments the value of l_0 is comparable with d and the inequality (15) is not satisfied. As a result, the observed shift of the maximum of R_0 on change of temperature is smaller than in the normal skin effect. Under these conditions, it is very difficult to get information about the length of the free path of the carriers from measurements of the Fischer-Kao effect. Such an experimental situation is encountered quite often. In particular, this apparently applies to experiments[19,20] the results of which have been processed on the assumption that the skin effect was normal.

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Instabilities in the spin system of optically oriented electrons and nuclei in semiconductors

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It is shown that quadrupole splitting of the spin levels of the arsenic nuclei in $Ga_xAl_{1-x}As$ solid solutions makes possible slow rotation of the field of the dynamically polarized nuclei. These rotations are connected not with the rotation of individual nuclear spins, but with the change in the intensity of the field produced by the nuclei for which the quadrupole-interaction axes are differently oriented. It is shown that this leads, under certain conditions, to instability of the stationary states in the system of optically oriented electrons and nuclei of the semiconductor and to the onset of oscillations of the degree of polarization of the recombination radiation, with a period determined by the time of the longitudinal spin relaxation of the lattice nuclei. The results are compared with the experimenal data.

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1. INTRODUCTION

Interband absorption of circularly polarized light in a semiconductor is accompanied by spin orientation of the photoexcited electrons, which leads to dynamic polarization of the crystal-lattice nuclei. The polarized nuclei act in turn on the electron orientation via the effective magnetic field produced by the hyperfine interaction.[1] Thus, a nonlinear system of coupled electron and nuclear spins is produced. The nonlinearity of this system manifests itself, for example, in hysteresis of the dependence of the degree of polarization of the recombination radiation on the external magnetic field.[2,3] A number of studies have revealed phenomena that attest to the onset of instabilities in this system[4] and to the onset of associated self-oscillations.[3,5] These experiments were performed on $Ga_xAl_{1-x}As$ solid solutions, in which an essential role is played by the quadrupole splittings of the nuclear spin levels, due to local disturbances of the cubic symmetry.[2,3,5-8]

The quadrupole splitting in $Ga_xAl_{1-x}As$ solid solutions is particularly substantial for the arsenic nuclei, for which the cubic symmetry of the environment is violated even in the first coordination sphere if one or several gallium atoms in this sphere are replaced by aluminum atoms. This is confirmed by experiments on optically detected nuclear magnetic resonance.[3,5,6] The quadrupole interactions manifest themselves, in particular, in the strong dependence of the shape of the Hanle curve on the direction of the external magnetic

