Gantmakher–Kaner effect in strong magnetic fields

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The Gantmakher–Kaner (GK) effect is investigated theoretically for a compensated metal. A dependence of the amplitude of the GK oscillations on the polarization of an exciting rf field is predicted. This dependence is associated with the excitation of dopplerons in a plate. In the polarization in which dopplerons exist, some of the energy of the skin layer field, contained in harmonics of wavelength close to the cyclotron displacement of a resonant group of carriers, is carried away into the interior of the sample by dopplerons. This weakens the GK oscillations of this polarization compared with oscillations with the opposite polarization.

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1. Gantmakher and Kaner[1] were the first to investigate oscillations of the impedance of a metal plate associated with focusing of "ineffective" electrons in a magnetic field. This phenomenon, subsequently called the Gantmakher–Kaner (GK) effect, was considered in the range of weak fields corresponding to the extreme anomalous skin effect ($\delta \ll u/2\pi \ll l$, where δ is the skin depth, u is the maximum displacement of electrons in a cyclotron period, and l is the mean free path of carriers). These fields are characterized by the fact that the oscillation amplitude is independent of the sense of rotation of the exciting rf field. In the case of pure, particularly compensated, metals the condition for the skin effect to be anomalous in respect of the magnetic field ($\delta < u/2\pi$) is disobeyed at frequencies f of the order of megahertz even in fields H of the order of a few kilooersted. This range of fields ($\delta \sim u/2\pi$) corresponds to the doppleron excitation threshold.[2,3] It follows that the polarization in which dopplerons are excited is preferred to the opposite direction.

We shall investigate the GK effect in a compensated metal as a function of the polarization of the exciting rf field in any magnetic field. It is shown that there is a range of fields in which the amplitudes of the GK oscillations are very different for different polarizations. Outside this range the GK effect is independent of the polarization of the exciting field. Formally, the influence of the polarization on the amplitude of the GK effect is due to the fact that a doppleron pole exists in one of the polarizations (Fig. 1a) and an increase in the magnetic field causes this pole to approach the branching point of the conductivity tensor in the plane of the complex wave vector. Therefore, we can expect the excitation of dopplerons to affect the GK component.

2. We shall now carry out a quantitative analysis. We shall select the following model of the Fermi surface: we shall assume that the hole Fermi surface is a corrugated cylinder and the electron surface is a simple cylinder (this represents the local contribution of electrons to conduction). The axes of both cylinders are parallel to the magnetic field directed along the normal to the surface of a plate (z axis). The selected Fermi surface can be used to describe nonlocal effects associated with holes in metals such as tungsten or molybdenum. The nonlocal conductivity tensor for the circular polarization of the field is in this model[4]

$$\sigma_\pm(k) = \mp i\frac{Nec}{H}\left[\frac{1}{(1-\xi_\pm^2)^{1/2}} - 1 \pm i\gamma\right], \quad \xi_\pm = \frac{ku}{2\pi}(1\pm i\gamma), \tag{1}$$

where k is the wave vector of the incident waves; N is the hole density; e is the absolute electron charge; c is the velocity of light in vacuum; H is the magnetic field; $u/2\pi = (v_z/\Omega)_{ext}$; v_z is the projection of the hole velocity on the z axis; Ω is the cyclotron frequency; $\gamma = \nu/\Omega$; ν is the frequency of collisions of carriers with scatterers; the polarization with the plus index corresponds to rotation of the electromagnetic field in the same direction as the cyclotron rotation of holes. Equation (1) is derived for the case when $\omega \ll \nu \ll \Omega$, where ω is the wave frequency.

We shall calculate the contribution made to the impedance by the GK effect in the case of antisymmetric excitation of a plate and specular reflection of carriers from the plate surfaces. According to Fisher *et al.*,[3] the part of the plate impedance oscillating with the magnetic field is in this case described by

$$Z_\pm = 8i\omega\int_{-\infty}^{+\infty}\frac{e^{ikL}}{c^2k^2 - 4\pi i\omega\sigma_\pm(k)}dk, \tag{2}$$

where L is the plate thickness. The contribution to Eq. (2) associated with the GK effect is given by the integral along a cut (integration contours are shown in Fig. 1) and it is described by

$$\Delta Z_\pm = 8i\omega\int_{i\frac{2\pi}{u}\gamma}^{i\infty}\hat{P}\left(\frac{e^{ikL}}{c^2k^2 - 4\pi i\omega\sigma_\pm(k)}\right)dk, \tag{3}$$

where $\hat{p}\Phi = \Phi_2 - \Phi_1$, and Φ_f are the values of the function on different edges of the cut.

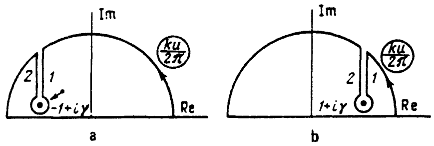

FIG. 1. Integration contours: a) for the positive polarization; b) for the negative polarization. The numbers 1 and 2 identify the opposite edges of a cut. The point in Fig. 1a is a doppleron pole and the arrow is the direction of the motion of this pole on increase of the magnetic field. The skin poles are not shown.

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Using Eq. (1), we can represent Eq. (3) in the explicit form:

$$\Delta Z_\pm = \pm i \frac{2^{3/2}}{\pi} \frac{H^2}{Nc^2 (mv_z)_{ext}} e^{\mp i 2\pi L/u} I_\pm,$$
$$I_\pm = \int_\gamma^\infty \exp\left(-\frac{2\pi L}{u} x \pm i \frac{\varphi}{2}\right) G_\pm(x)\, dx, \tag{4}$$
$$G_\pm(x) = \left(1 \mp i \frac{x-\gamma}{4}\right)^{-1} [\gamma^2 x^2 + (x-\gamma)^2]^{-1/4} \Big\{ h^2 (1 \mp i4x) + 1 \mp i2\gamma$$
$$- \frac{\exp(\pm i\varphi)}{2[1 \mp i(x-\gamma)/2][\gamma^2 x^2 + (x-\gamma)^2]^{1/2}} \mp 2h[-1 \pm i(\gamma + 2x)] \Big\}^{-1},$$
$$\varphi = \mathrm{arctg} \frac{x-\gamma}{\gamma x}, \quad h = \left(\frac{H}{H_0}\right)^3, \quad H_0^3 = \frac{4\pi\omega Nc}{e} (mv_z)^2_{ext},$$

where m is the cyclotron mass. Bearing in mind that the principal contribution to $I_\pm$ is due to the range $x \sim u/2\pi L \ll 1$, we can represent the integral $I_\pm$ in the form

$$I_\pm \approx 2^{1/2} \gamma^2 e^{-L/l} \int_0^\infty e^{-Lt/l} \frac{g^{1/2}\, dt}{[\alpha_\pm \gamma^2 g - s]^2 + \gamma^2 t^2} \{[(\gamma g^{1/2} + s)^{1/2} (\alpha_\pm \gamma^2 g - s)$$
$$- \gamma t (\gamma g^{1/2} - s)^{1/2}] \pm i [\gamma t (\gamma g^{1/2} + s)^{1/2} + (\gamma g^{1/2} - s)^{1/2} (\alpha_\pm \gamma^2 g - s)]\}, \tag{5}$$
$$\alpha_\pm = 2(h^2 \pm 2h + 1), \quad g = t^2 + \gamma^2 (1 + 2t),$$
$$s = \gamma^2 (1+t), \quad |\alpha_\pm \gamma^2 - 1| > 4\gamma.$$

It follows from the above expression for this integral that the polarization of the exciting field affects not only the sign of the imaginary part of the impedance,[4] but also the oscillation amplitude (the resultant difference is associated with the term $\alpha_\pm$). The dependence of $\alpha_\pm$ on the magnetic field h shows that the amplitudes of the GK effect in different polarizations are different in a range of fields which has upper and lower bounds. On the low-field side the difference between the amplitudes begins to appear from $h \sim 0.5$, i.e., in the range of fields which correspond to the doppleron excitation threshold ($h = 0.5$ is the collisionless doppleron threshold[5]).

The asymptotic values of the function $F = |I_+/I_-|$, representing the ratio of the amplitudes of the GK oscillations in the polarizations corresponding to the indices $\pm$, have the following form in the limit of weak and strong fields:

$$F \approx 1 - 80 (\gamma l/L)^2 h (h^2 + 1) \tag{6}$$

(weak fields: $\alpha_\pm \gamma \ll L/l \sim 1$ but $u/2\pi L \ll 1$) and

$$F \approx 1 - 4/h \tag{7}$$

(strong fields: $\alpha_\pm \gamma \gg L/l$).

Unfortunately, we were unable to calculate the function F with the precision of a few percent in the intermediate range of fields $\alpha_\pm \gamma \sim L/l$. This value was calculated on a computer for arbitrary values of h. The results of these calculations are presented in Fig. 2 where γ is regarded as a parameter (the dependence on the magnetic field is governed by the quantity $h \propto H^3$). It follows from curves 1 and 2 in Fig. 2 that the collision frequency has little effect on the minimum value $F_{\min}$. Physically, this follows from the observation that in

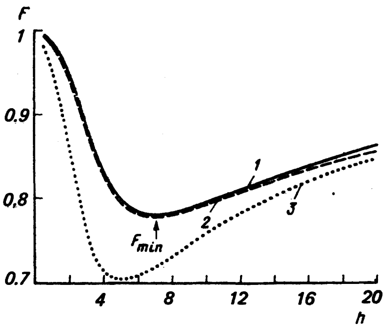

FIG. 2. Dependences of the ratio of the amplitude of the GK oscillations in the plus and minus polarizations on the magnetic field. Curve 1 corresponds to $L/l = 2$ and $\gamma = 2 \times 10^{-2}$, curve 2 to $L/l = 1$ and $\gamma = 10^{-2}$, and curve 3 to $L/l = 0.5$ and $\gamma = 10^{-2}$.

this range of fields the doppleron damping length is equal to the damping length of the GK component governed by the mean free path of the resonant carriers. Therefore, although the collision frequency does affect the absolute values of the doppleron and GK oscillation amplitudes, the relative value of F is hardly affected. A reduction in the plate thickness L reduces $F_{\min}$ and shifts toward lower values the fields h at which the minimum occurs (curve 3 in Fig. 2). This can be explained qualitatively as follows. The contribution to the GK oscillations is made by spatial harmonics whose damping length is greater than the thickness of the sample, i.e., $(k'')^{-1} \gtrsim L$. Therefore, the width of a GK line (expressed in terms of the wave vectors) is governed by the quantity $k'' \sim 1/l + 1/L$. Hence, it follows that in thinner samples the doppleron dispersion curve $k_D(H)$ penetrates the range of wave vectors contributing to the GK effect in lower fields H where the doppleron amplitude is greater. Therefore, the influence of dopplerons on the GK oscillations becomes stronger. It should be noted that a reduction in the plane thickness is limited by the condition of validity of Eq. (2): the plate should be thick compared with the skin layer, i.e., $L > \delta$. For fields near an extremum of F this condition can be started in the form $L/l > \gamma^{1/3}$.

A physical description of this effect is as follows. In the positive polarization case some of the energy of the skin layer field, contained in the harmonics of wavelength close to the cyclotron displacement of a resonant carrier group, is carried away to a distance of the order of the mean free path not only by holes in the resonant cross section of the Fermi surface (GK effect) but also by dopplerons. In the opposite polarization the field is entirely due to the GK component. This can be deduced formally as follows. Let us represent the condition for the field h corresponding to $F_{\min}$ in the form

$$\frac{L}{l\alpha_\pm \gamma} \sim \frac{1+\xi'}{u/2\pi L} \sim 1,$$

where $1 + \xi' \approx \frac{1}{2} h^2$ for $h > 4$ is the distance from the doppleron pole to the branching point[5] and $\alpha_\pm \sim 2h^2$. This means that dopplerons affect those values of the wave vectors which govern the GK effect.

We shall conclude by pointing out that the phenomenon described above is typical only of compensated metals because the term $\pm 2h$ in $\alpha_\pm$, which results in a difference between the amplitudes of the GK oscillations, appears due to the addition $\sigma_\pm^{(1)} + \sigma_\pm^{(2)}$ (the upper index of the conductivity denotes the edge along which the required function is calculated). In the case of uncompensated metals this difference vanishes and for compensated metals it is governed by the Hall conductivity of a local group of carriers.

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Investigation of the mechanism of the motion of charged dislocations in ZnSe

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The motion of electrically charged dislocations in ZnSe is investigated by measuring the dislocation currents. It is shown that the kinetics of the motion of the dislocations is determined by thermally activated surmounting of Peierls barriers, whose heights are found to be directly proportional to the linear density of the dislocation charge. A physical model that accounts for the appearance of the Peierls barriers and for a number of plastic effects is proposed.

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INTRODUCTION

There are two main reasons why it is of interest to study the regularities in the motion of dislocations in $A^{II}B^{VI}$ compounds (CdS, ZnS, ZnSe, CdSe, ZnO, ZnTe, and others). First, knowledge of the laws of motion of these dislocations may provide a key to the understanding of such phenomena observed in these compounds as the photoplastic effect (PhPE) and the electroplastic effect (EPE).[1-3] Second, as has been shown in a number of studies,[4-8] the dislocations in these compounds bear a considerable electric charge (of the order of one electron per interatomic distance), and this, it may be supposed, will lead to features of the motion of dislocations that are not observed in other materials.

Unfortunately, certain characteristics of $A^{II}B^{VI}$ compounds have prevented the use of familiar methods to study the laws of motion of dislocations in them. For example, the tendency of freshly introduced dislocations to remain fixed for times of the order of several minutes makes it impossible to use the etch pit method for recording the motion of individual dislocations. On the other hand, methods involving macroscopic deformation suffer from the disadvantage that in $A^{II}B^{VI}$ compounds the large plastic deformation that is necessarily accumulated during the course of such experiments alters the parameters describing the motion of the dislocations.

We have recently developed a method for recording plastic deformations by measuring the dislocation currents.[9] We feel that this method will make it possible to overcome the difficulties mentioned above; in addition, this method makes it possible continously to follow such an important parameter of the dislocations in $A^{II}B^{VI}$ compounds as their electric charge during the course of the deformation.

TECHNIQUE

In this study we used ZnSe single crystals with the sphalerite structure, grown from the melt and having a dark resistivity of 10^8 to 10^{13} $\Omega\cdot$cm and a dislocation-nucleus density of ~10^5 cm^{-2}. Deformation specimens measuring $6\times4\times1.5$ mm were cut from ingots with a diamond saw, were ground smooth with abrasive powders, and were polished with diamond paste. Then the specimens were etched with CrO_3 + HCl to remove the work hardened layer some 50–100 μm thick from the surfaces. Either liquid (In + Hg) or indium electrodes were fixed to the large (4×6 mm) surfaces of the specimens by ultrasonic soldering in order to record the dislocation currents. The specimens were deformed by compression along the long (6 mm) dimension. The 6×1.5 mm face was a $(1\bar{1}0)$ plane, and the (111) plane, in which the dislocations move, is perpendicular to this plane and makes an angle of 45° with the compression axis. As was previously shown,[8] with such a deform-

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