Mechanism of conduction-electron relaxation in a strong magnetic field in indium

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The decay of helicons in spherical high-purity indium single crystals with a residual conduction-electron mean free path of the order of 5 mm is studied in magnetic fields of 1–18 kOe at liquid helium temperatures. Sharp peaks are observed in the dependences of the helicon decay on the angles between the crystallographic axes and the magnetic field. The peaks appear on increase of the temperature from 1.3 to 4.2 K. A consistent explanation of the results of the investigation of the anisotropy and the laws of variation of the helicon decay with the temperature can be given only under the assumption of the existence of mutual electron-phonon drag in the indium. A model of the relaxation mechanism is presented that describes the experimental results.

1. INTRODUCTION

The relaxation of the quasimomentum of the electron-phonon system of metals with a closed Fermi surface (FS) at low temperatures can be represented, under conditions of electron-phonon scattering dominance, as the result of the diffusion of the electron over the Fermi surface and scattering processes with umklapp.[1,2] Here, as careful analysis of the kinetic equation with account of the effect of mutual electron-phonon drag shows,[3] reconciled diffusion and processes with umklapp should take place and should be mutually dependent; increase in the diffusion time should lead to a slowing of the dissipation of the quasimomentum of the electron-phonon system through umklapp processes and conversely. One of the experimental phenomena of such coordinating diffusion-umklapp mechanism of relaxation should be a temperature dependence of the anisotropy of the diagonal components of the conductivity tensor of the metals in a strong magnetic field.[3] The investigation of this anisotropy is of significant interest, since it should contain a number of features due directly to the effect of the mutual electron-phonon drag, the problem of the existence of which in metals remains open up to the present.

Preliminary results were reported in Ref. 4 of the experimental observation of the anisotropy of the diagonal components of the conductivity tensor of indium in a strong magnetic field; the character of the anisotropy changed qualitatively with the temperature in the range 1.3–4.2 K. The latter property is indicated by the fact that the observed anisotropy was determined not so much by the energy spectrum of the conduction electrons, as by the mechanism of their relaxation, i.e., essentially by the anisotropy of the transport relaxation time. Results are given below of a careful experimental investigation of the observed anisotropy. New sharp peaks in the angular dependences of the electron-phonon part of the conductivity in a strong magnetic field are reported. This allows us to suggest more confidently the existence in indium of the effect of mutual electron-phonon drag. A model of the mechanism of relaxation of the conduction electrons is set forth and accounts for the results of the experiment.

2. METHODS AND CONDITIONS OF EXPERIMENT

The method of helicon resonance was used, in which spherical single crystals of diameter 10 mm were used as samples—resonators. The use of such samples removed at least two reasons for increase in the error of measurement of the anisotropy: electrical contacts and the effect of the shape of the sample. The samples were grown in a dismountable quartz mold prepared with optical accuracy. The initial indium was produced by M. Zolotarev in the Department of Pure Materials, Institute of Solid State Physics, Academy of Sciences USSR by the method of Ref. 5. The residual free path length in the samples was 5–7 mm, which corresponds to a resistance ratio ρ (300 K)/ρ (1.3 K)$\approx$500,000–700,000. Orientation of the samples was carried out by an x-ray method with accuracy $\pm 2^0$, with subsequent improvement of the accuracy of the orientation to $\pm 0.2^0$ by the optical method of Ref. 6. The correctness of the orientation was verified in the course of experiments in situ by the changes in the frequency of the de Haas–van Alfv̆en oscillations.

The measurements were carried out at temperatures 1.3–4.2 K in magnetic fields up to 18 kG. The Q factor of the fundamental helicon resonance (1,0) was measured in transverse geometry[7] in an exciting magnetic field perpendicular to the constant field $\mathbf{H}_0$. The frequency of the excitation was of the order of 1 Hz. As estimates show, the contribution of the nonlocal mechanisms of damping[8] and scattering of the electrons at the boundaries of the sample can be neglected. Special attention was paid to prevention of acousto-helicon phenomena[9]. A signal that was in-phase with the voltage on the coil in which the sample was placed was recorded at fixed amplitude of the current in the coil. Examples of experimental records of the resonances are shown in Fig. 1.

The boundary y value problem for helicons in a sphere has been solved only for a metal with a spherical Fermi surface and isotropic relaxation time.[7] The exact solution for helicons in a sphere of a metal with an arbitrary anisotropy of the Fermi surface does not exist at the present time. However, for a metal with a closed Fermi surface of arbitrary shape, in the limit of strong magnetic fields, the Q factor of the resonance can be calculated by using the fact that in this

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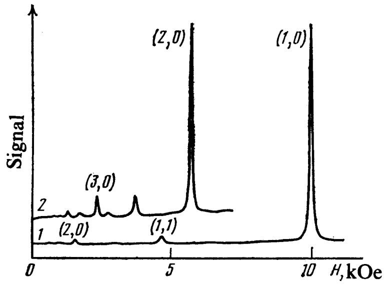

FIG. 1. Examples of experimental recordings of helicon resonances in indium single-crystal spheres of diameter 10 mm at $T = 1.3$: 1—$f = 3.3$ Hz, 2—12.3 Hz.

case the spectrum and the polarizations of currents and fields of the helicons coincide with the spectrum and polarizations in a metal with a spherical Fermi surface.[10] Therefore, the distributions of currents in a sphere in these two cases differ little from one another. One of the evidences of this is that the positions of the helicon resonances in the indium spheres are well described by the formulas from Ref. 7 for a metal with a spherical Fermi surface.

The calculation of the Q factor of the helicon resonance according to the well-known formula

$$Q=\omega\int_V (h_i h_i^*/8\pi)\,dV/\rho_{ik}\int_V j_i j_k^*\,dV \tag{1}$$

(ω, h_i, j_i are, respectively, the frequency, magnetic field and current of the helicon, ρ_{ik} is the tensor of electrical resistivity of the metal, $i,j = x,y,z$), with the use of the current distributions obtained in Ref. 7, leads to the expression

$$Q=\alpha\left(\frac{\rho_{xx}+\rho_{yy}+\beta\rho_{zz}}{4\rho_{xy}}\right)^{-1}\approx\alpha\left(\frac{\sigma_{xx}+\sigma_{yy}+\beta\sigma_{xy}^2/\sigma_{zz}}{4\sigma_{xy}}\right)^{-1}, \tag{2}$$

where the factors $\alpha\approx 0.25$, $\beta\approx 2$, with accuracy to small corrections of the order of $(\omega_c\tau)^{-2}$ do not depend on the magnetic field and on the conductivity of the metal (ω_c and τ are the cyclotron frequency and the relaxation time of the electrons). The approximate equality in (2) indicates the neglect of longitudinal-transverse components of σ_{ik} which are small in indium, as estimates show.

In our experiments, the condition of the local limit ($l<\lambda\sim 2R$ is satisfied; l, λ, R are the free path length, the wavelength and the radius of the sphere, respectively, and the Q factor of the helicon resonance (2) was determined by the static conductivity tensor, the components of which have the following structure in indium[10,11]:

$$\sigma_{yy}\simeq\sigma_{xx}\sim\int_{FS} S(p_z)\,\tau^{-1}(p_z)\,dp_z, \tag{3a}$$

$$\sigma_{zz}\sim\int_{FS}\tau(p_z)\langle v_z^2\rangle dp_z, \tag{3b}$$

$$\sigma_{yx}=-\sigma_{xy}=(n_e-n_h)\,ec/H_0. \tag{3c}$$

Here the axis $\mathbf{z}\|\mathbf{H}_0$; v_z, p_z are the components of the velocity and momentum of the electron; S is the cross section area of the Fermi surface at the plane p_z = const; n_e and n_h are the concentrations of electrons and holes, respectively.

If τ does not depend on p_z, as, for example, in isotropic scattering, it can be taken outside the integral in (3) and the expression for Q factor can be rewritten in the form

$$Q^{-1}=\frac{\Phi}{H_0}\tau^{-1}\approx 4\tau^{-1}/\overline{\omega}_c, \tag{4}$$

where τ^{-1} is the effective (transport) collision frequency (in order to emphasize this, we write it as $\tau_{\rm eff}^{-1}$), $\overline{\omega}_c$ is the characteristic cyclotron frequency; Φ is a function determined by the shape of the Fermi surface and depending only on the angle between the magnetic field $\mathbf{H}_0$ and the crystal axes. The quantity Φ can be calculated in the case of a known Fermi surface.

It follows from Eqs. (2)–(4) that all the singularities of the dependence of the Q factor of the helicon resonance on the temperature—the impurity content, the direction of the magnetic field and so on—have the same nature as the singularities of the components of the conductivity tensor.

3. EXPERIMENTAL RESULTS

Examples of experimental recordings of the helicon resonance in spherical single-crystal indium are shown in Fig. 1. Upon lowering of the temperature from 4.2 to 1.3 K, the Q factor of the helicon resonance increased by a factor of 25–30 and dominated the electron-phonon scattering over a significant portion of the investigated interval. Over the entire range of temperatures and magnetic fields, the Q factor of the resonance was no less than 10, which indicated that the condition of a strong field $\overline{\omega}_c\tau_{\rm eff}\gg 1$ was satisfied and in the analysis of the data we could use Eq. (2) for the Q factor and the approximate formulas (3) for the conductivity over the entire range of temperatures investigated.

The dependences of the value of the helicon damping $\Gamma=\frac{1}{4}Q^{-1}\approx(\omega_c\tau)^{-1}$ on the angle between the magnetic field and the crystallographic axes in the (010) and (011) planes are shown in Fig. 2.

Attention is called to the following feature of the curves: the dependences shown in Fig. 2 for each plane at different temperatures are not similar to one another; the number of extrema depends on the temperature. A significant anisotropy arises near a number of directions of the magnetic field only upon increase in the temperature. Thus, upon increase in the temperature a sharp peak appears near the [001] direction (Fig. 2a), and deep minima near the [111] direction (Fig. 2c). In the case of isotropic $\tau_{\rm eff}$, according to (4), the dependence of the quantity $\Gamma\sim\tau_{\rm eff}^{-1}/\overline{\omega}_c$ on the angle should be a universal function for the given crystallographic plane, while the corresponding curves should simply coincide with one another in the scale of Fig. 2. The experimentally observed features of the curves can be explained only by the fact that there exists an angular dependence of the anisotropy of the transport relaxation time $\tau_{\rm eff}$. In the range of magnetic fields that we studied (1–18 kG), and within the limits of error of the measurements (1–5%), the width of the line ΔH of helicon resonance did not depend on the magnetic field over the entire temperature range 1.3–4.2 K. This suggests saturation of the diagonal components of the resistivity tensor of indium in the strong magnetic field, inasmuch as $\Delta H = H_{\rm res}/Q = (\rho_{xx}+\rho_{yy}+2\rho_{zz})/R_H$, R_H is the Hall constant. Significant departures from saturation arise at

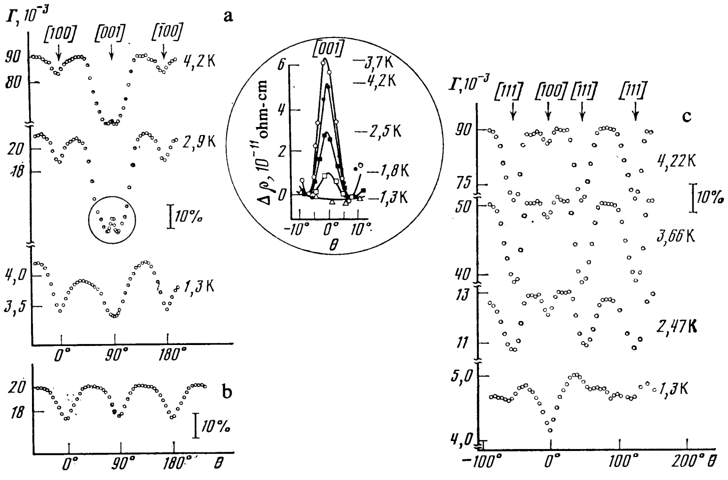

FIG. 2. Anisotropy of helicon damping in indium spheres upon rotation of the magnetic field in different crystallographic planes. a, b—plane (010), c—plane (011). The insert shows the dependence of the magnetoresistance $\Delta\rho = \Delta\Gamma R_H H_0$ on the orientation of the magnetic field near the [001] direction, R_H is the Hall constant. The anisotropy of the damping shown in Fig. 2b corresponds to a sample with the addition of impurity at $T = 1.3$.

much higher magnetic fields under the conditions of magnetic breakdown, which was observed in indium in Ref. 12.

For additional proof of the absence of a connection between the change in the anisotropy wth simple transition from very strong effective fields to very weak ones upon increase in the temperature (the change in the value of the parameter $\Gamma \approx (\overline{\omega}_c \tau_{\text{eff}})^{-1}$) recordings were made of the anisotropy for identical $\Gamma \approx (\overline{\omega}_c \tau_{\text{eff}})^{-1}$, but different dominating types of scatterers. It turns out that the anisotropy depends significantly on the type of scattering centers; compare the anisotropies of damping of helicons in the case of dominating scattering by impurities (Fig. 2b, indium with addition of an impurity) and the dominating electron-phonon scattering at the same mean value of the parameter (Fig. 2a, $T = 2.9$ K). It is also seen from Figs. 2a, b that in the case of dominating scattering by impurities, the angular dependence of the reciprocal of the Q factor changes by 500%, additional minima and maxima do not arise (see the lower curve of Fig. 2a and Fig. 2b).

The change of the reciprocal of the Q factor with temperature, i.e., in essence, the effective collision frequency τ_{eff}^{-1}, follows a power law T^n, where the exponent n depends on the direction of the magnetic field relative to the crystallographic axes and ranges from 4 to 4.5 (Fig. 3). The following correlation exists here: the exponent is larger at the minima of the anisotropy than at the maxima.

The addition of an impurity significantly lowers the Q factor of the helicon resonance; however, for example for the [100] direction, the temperature dependence does not change within the limits of accuracy of the measurement (2%) (i.e., the Matthiessen rule is satisfied). The anisotropy of the temperature-independent portion of the effective collision frequency at $T > 3.5$ K is the same, with accuracy $\approx 3\%$, in samples with impurity contents that differs by 500%.

We have observed a high sensitivity of a number of measured characteristics to the existence of even a small ($\approx 1\%$ by volume) amount of twinning layers, which easily arise both in the cutting of the samples and as a result of strains. The twinning layers led to a large distortion of the anisotropy of the Q factor of the helicon resonance and to the appearance of anisotropy of the position of the helicon resonance relative to the magnetic field and the frequency. In the absence of layers, on rotation of the magnetic field, the departures of the position of the resonance did not exceed 0.2% in the investigated indium spheres and followed the crystallographic symmetry. The appearance of layers $\approx 1\%$ by vol-

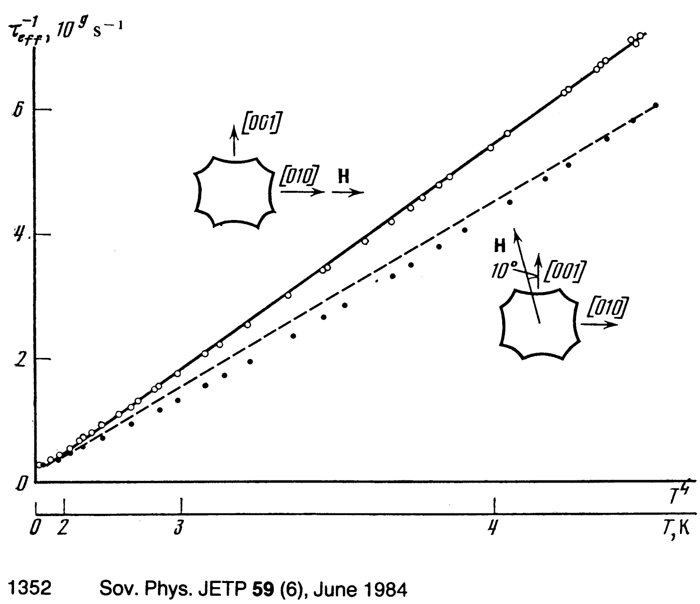

FIG. 3. Dependence of the law of variation with temperature of the transport electron-phonon collision frequency in indium on the orientation of the magnetic field in the crystal.

ume led to 2–5% anisotropy having a 180° symmetry in the position of the resonance. The effects just mentioned are obviously connected with the significant changes in the conductivity σ_{ik} in the region of twinning layers and are of interest on their own account. In the present paper, we have tried to carry out measurements on the most perfect indium single crystals.

4. DISCUSSION OF THE RESULTS

The basic features of the anisotropy of the Q factor observed under conditions of dominant scattering of conduction electrons by impurities can be connected with the anisotropy of the Fermi surface of indium without account of the anisotropy of the scattering from impurities. Analysis shows that this anisotropy (Figs. 2a, b, c, curves corresponding to $T = 1.3$K) is connected basically with the anisotropy of the longitudinal component of the conductivity σ_{zz}. The anisotropy of σ_{zz} is in turn due to the dependence on the orientation of the magnetic field of the component $\langle v_z \rangle$ of the velocity of the electron parallel to the magnetic field, averaged over the cyclotron period and p_z [see Eq. (3b)]. An anisotropy of the same nature is observed in the torsional moment of aluminum, measured in a magnetic field. The Fermi surface of aluminum is close in shape to the Fermi surface of indium.

The change in the anisotropy of the Q factor of the helicon resonance upon increase in the temperature can occur in principle as a result of the inclusion of the anisotropic electron-phonon scattering, with the probability dependent on the location of the electron on the Fermi surface. Such an anisotropy of the electron-phonon scattering exists in the whole series of metals including indium, and has been studied experimentally[14,15]. However, it has not yet been possible to explain our results consistently by formally assuming the frequency of the electron-phonon collisions τ^{-1} in Eq. (3) to be anisotropic. Substituting in (3) the frequency of collisions in the extremely anisotropic model form

$$\tau^{-1}(p_z) = \sum_i \alpha_i \delta(p_z - p_{zi}^0) + \text{const}, \qquad (5)$$

where p_{zi}^0 are the z components of the momenta of electrons with maximum probability of collisions with phonons, α_i are weighting constants, δ is the Dirac function. We then obtain

$$\sigma_{xx} + \sigma_{yy} \sim \sum_i \alpha_i S(p_{zi}^0) + \text{const}, \quad \sigma_{zz} \sim \text{const} \int_{FS} \langle v_z \rangle dp_z, \qquad (6)$$

where $S(p_{zi}^0)$ is the cross-section area of the Fermi surface perpendicular to the magnetic field and passing through the point p_{zi}^0. Thus, the extremal anisotropic scattering, taken formally into account, leads to additional angular dependences of the reciprocal of the Q factor that are entirely determined by the topology of the Fermi surface. Real scattering anisotropies[15] should lead to an angular dependence that is even smoother than (6). On the basis of the known Fermi surface of indium,[15,16] it has not been possible to explain the appearance of a sharp peak in the magnetic field near the [001] direction and several other features of the observed anisotropy in such fashion. Analysis of the case in which the sharp maxima on the Fermi surface have a time τ between successive collisions leads to similar conclusions. A more careful account of the details of the mechanism of relaxation of the conduction electrons is necessary.

Gurzhi and Kopeliovich have shown theoretically[3] that account of the effects of mutual electron-phonon drag can lead to strong anisotropy of the conductivity in a strong magnetic field, as was noted in the Introduction. Especially sharp angular dependences should appear under conditions in which the electron-phonon scattering processes with umklapp (U processes) have already "died out" and are localized in individual small regions of the Fermi surface, in "hot" points (or "dimples"). Just such a situation can be realized, as estimates show, in indium at temperatures below 4K. The necessity of resorting to the drag of localized electron-phonon U processes for the explanation of the temperature dependence of the electrical resistivity of indium in a strong magnetic field was first shown in Ref. 1.

For the explanation of the basic features of the electron-phonon part of the anisotropy of the damping of the helicons we consider the model situation shown in Fig. 4a. The model represents a sphere with six hot points, lying on mutually perpendicular lines. As a result of the U processes, the electrons "hop" between the points $A \leftrightarrow A^*$, $A' \leftrightarrow A'^*$, $B \leftrightarrow B^*$. Keeping in mind the explanation of the results for indium, which has tetragonal symmetry, we can assume the probabilities of scattering with umklapp between points of types A and B to be unequal.

According to the Gurzhi-Kopeliovich theory, the relaxation of the quasimomentum of the electron-phonon system as a result of electron-phonon scattering under the conditions of drag takes place only if some of the electrons can pass off to infinity in the expanded p space under the action of collisions with phonons. The electrons should have the possibility of moving, for example, from point A to A' (Fig. 4b) as a result of hopping between the least removed parts of the Fermi surface (U-processes) and again to A as a result of diffusion over the Fermi surface due to normal processes (N processes). The characteristic relaxation time here is composed of the diffusion time and the umklapp time (in contrast to the case in which drag is absent, all the processes are independent and the collision frequencies add). Since in a strong magnetic field the electron should diffuse from the layer of orbits through the region A^*, through the layer of orbits of width b^A (Fig. 4b) to the layer that passes through the region A then, changing the direction of the magnetic field and the value of b^A itself, we can change the diffusion time. As a result, the total relaxation time turns out to be dependent on the direction of the magnetic field. The relaxation time is minimal if the hot points, between which U processes are operating, lie in a single plane perpendicular to the magnetic field and are united by a common orbit. In this situation, diffusion is not required for relaxation of the quasimomentum of the electrons. The transverse diagonal components of the conductivity tensor σ_{xx}, σ_{yy} take on their maximum values here.

The considered model in the case of the magnetic field lying in the (100) plane is described quantitatively by the

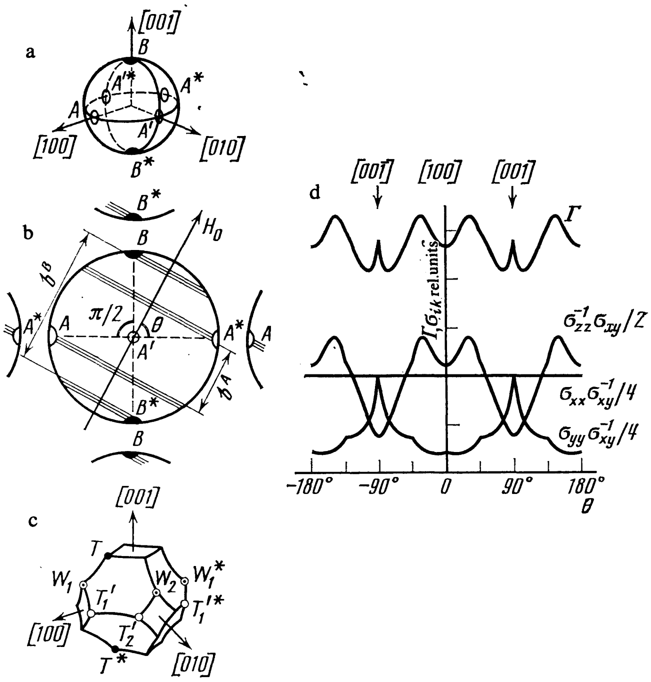

FIG. 4. Results of calculation of the anisotropy of the components of the conductivity tensor of the helicon decay: a, b—model Fermi surface and its projection; c—Fermi surface of indium in the second zone; the points T', T and W are shown. These points determine the character of the anisotropy the singularities due to the remaining points arise at these same orientations of the magnetic field; d—the anisotropy of the (010) plane for the model Fermi surface at $\alpha = R_U{}^A/R_F = 0.45$; $\beta = R_U{}^B/R_F = 2$; $\alpha' = R_U{}^{A'}/R_F = \alpha$, x is the rotation axis.

following set of linear equations, to which, according to Ref. 3, the kinetic equation is reduced:

$$J_A(R_U^A+R_D^A)+J_BR_D^B=\mathbf{u}\mathbf{g}^A+eE_z\int_{p_{zA^*}}^{p_{zA}}\frac{S(p_z)}{D}dp_z, \tag{7a}$$

$$J_AR_D^B+J_B(R_U^B+R_D^B)=\mathbf{u}\mathbf{g}^B+eE_z\int_{p_{zB^*}}^{p_{zB}}\frac{S(p_z)}{D}dp_z, \tag{7b}$$

$$J_{A'}R_U{}^{A'}=\mathbf{u}\mathbf{g}^{A'}, \tag{7c}$$

$$J_Ag_z{}^A+J_Bg_z{}^B={}^1/_2h^3neE_z, \tag{7d}$$

where J is the umklapp current through the hot point, R_U, and R_D are the respective umklapp and diffusion resistances that characterize the umklapp and diffusion processes:

$$R_U{}^{-1}\approx\frac{r_0{}^2}{v}\tau_U{}^{-1},\qquad R_U{}^A=R_U{}^{A'},$$

$$R_D^{A,B}\approx\tau_F\frac{b^{A,B}}{p_F}\frac{v}{p_F{}^2}=\frac{b^{A,B}}{p_F}R_F,$$

v and p are the characteristic Fermi velocity and momentum, τ_u^{-1} is the probability of electron scattering by phonon with umklapp, r_0 is the characteristic radius of the hot point, τ_F and R_F are respectively the diffusion time and the diffusion resistance of an electron at a distance of the order of p_F, $\mathbf{u} = \mathbf{u}_x + \mathbf{u}_c$; $\mathbf{u}_x = c\mathbf{H}_0^{-2}[\mathbf{E}\times\mathbf{H}_0]$ is the Hall drift, $\mathbf{u}_s$ is the drift along the magnetic field $\mathbf{H}_0$, $\mathbf{E}$ is the electric field of the wave, $\mathbf{H}_0$ is the constant magnetic field; D is the diffusion coefficient of the electron on the Fermi surface[2,3], $\mathbf{g}^A$, $\mathbf{g}^B$, $\mathbf{g}^{A'}$ are the changes in the momentum of the electron in the transition as a result of U processes between the points A, A^*; B, B^* and A', A'^*, respectively. The quantities J_A, J_B, $J_{A'}$ and the drift $\mathbf{u}_c$ along the magnetic field are determined from Eqs. (7). The electric current density (see Ref. 3) can be represented in the form

$$\mathbf{J}_\perp=-\frac{2c}{h^3H^2}\sum_{i=A,\,B,\,A'}[\mathbf{g}^i\mathbf{H}_0]J_i+ne\mathbf{u}_x, \tag{8}$$

$$j_z=\frac{2e}{h^3}\left[eE_z\int\frac{S^2(p_z)}{D}dp_z-\sum_{i=A,\,B,\,A'}J_i\int_{p_{zi^*}}^{p_{zi}}\frac{S(p_z)}{D}dp_z\right]+neu_c. \tag{9}$$

The first term in (8) is the dissipative current transverse to the magnetic field, the second is the nondissipative Hall current. Summation is carried out over all vectors $\mathbf{g}$ corresponding to processes with umklapp. For the (001) plane, a system of equations is easily obtained by substituting B for A' in (7)–(9). We shall assume the diffusion coefficient D to be independent of the coordinates on the Fermi surface.

The results of the calculation of the components of the conductivity tensor and the damping of the helicons on the basis of the model are shown in Fig. 4d.

The anisotropies are determined by only two parameters: $\alpha = R_U{}^A/R_F$ and $\beta = R_U{}^B/R_F$, which characterize the relations between the probabilities of U processes and the diffusion times of the electrons as a result of N processes. Increase in α and β leads to isotropization of the conductivity and helicon damping and to increase in the width of the peaks in their angular dependences. In the case of $\alpha, \beta \gg 1$ the relaxation time of the electron-phonon system is determined basically by the U processes, the probability for which does not depend on the direction of the magnetic field (the value of the magnetic field is much smaller than the field of the magnetic breakdown). Upon decrease of α and β, the peaks become steadily sharper, the value of the relative changes of the components of the conductivity and helicon damping increases, inasmuch as the contribution of diffusion between the hot points increases, the time of which, as was noted above, depends on the orientation of the magnetic field. The sign of the inequality between the parameters ($\alpha < \beta$) is uniquely determined by the position of the sharp peak in the (010) plane. Upon decrease in the parameter β relative to the value given in Fig. 4d, additional unobserved minima arise in the damping in directions of the [101] type in the (010) plane. The latter are connected with the fact that at such orientations of the field, the electrons can go off to infinity in p space without diffusion, moving, for example, in the following fashion: A→–umklapp-A *→motion along orbit→B→umklapp B *→motion along orbit→A and so on (Fig. 4b).[1)]

A picture of transport relaxation, similar to what has been given, should, in our opinion, be observed under conditions of mutual electron-phonon drag in indium. The role of points of type A can be played by points of type T' and (or) W (see Fig. 4, B). It should be emphasized that, in spite of the large total number of hot points in indium, equivalent hot points (between which U processes take place) are connected by common orbits in the same directions of the magnetic field and in the simple model considered. This essentially validates the application of such a model. From a comparison of Figs. 2a and 4d, it is seen that the character of the calculated model anisotropy, with account of the relative simplicity of the proposed model, agrees rather well with that observed experimentally in the dominant electron-phonon scattering.

The anisotropies in the (011) and (001) planes also agree qualitatively with the predictions of the Gurzhi-Kopeliovich theory. However, in this case, it is necessary to include the contribution of the topology of the Fermi surface to the anisotropy of σ_{zz}^{-1}, i.e., in essence, the anisotropy of the helicon damping at $T = 1.3$ K. The "valleys" in the angular dependences of σ_{zz}^{-1}, due to the topology of the Fermi surface, can "compensate" for several of peaks predicted by the simple model.

The temperature dependences of helicon damping are determined by the dependences of the umklapp and diffusion resistances R_U and R_F, i.e., essentially, of the reciprocals of the probability of electron-phonon scattering with umklapp and of the diffusion time. In the case of orientations of the magnetic field in which the hot points, between which the U processes take place, are joined in common orbits, the effective relaxation time is determined predominantly by the umklapp resistance R_U and in the case of the characteristic momentum of the phonons exceeding the minimum distance between the parts of the Fermi surface $\tau_{\text{eff}} \sim R_U \sim T^{-4}$ (see Ref. 3). In these directions, the helicon damping should change according to a law similar to T^4. Far from such orientations of the magnetic field, the effective relaxation time τ_{eff} is proportional to the sum of the diffusion and spin-flip resistances $\tau_{\text{eff}} \sim R_U + R_D$, here $R_D \propto T^{-5}$ (see Ref. 3). Thus, far from the direction of the magnetic field at which the hot point are united by common orbits, the helicon damping should change with temperature more rapidly than T^4. Such a picture agrees well with that observed experimentally. For a more detailed comparison of the absolute vlaues of the experimental values with the theory of the drag of the microscopic parameters of the electron-phonon system of the metal, the construction of a model is necessary that describes the Fermi surface directly in the region of the hot points.

Analysis of our data, and estimates made on the basis of known Fermi surfaces, show that the Peierls exponential in the temperature dependence of the conductivity of indium in a strong magnetic field (and helicon damping) should evidently be observed at temperatures below 1 K. For the observation, larger and purer samples are needed. In our samples, in the range of temperatures 0.3–1.3 K, the changes in the damping of the helicons did not exceed 10%, the exact determination of the law of change with temperature was made difficult, since the necessary condition of dominance of the electron-phonon scattering was not satisfied.

Interest attaches to the experimental study of the observed features of the conductivity of indium by direct methods, for example, with the help of the four-contact method, although this is a rather difficult experimental problem. Large samples and measurements of the resistivity at the level of 10^{-11}–10^{-12} ohm-cm are necessary. The relative anisotropy of the individual components of the conductivity should be much greater than the damping of the helicons (Fig. 4d).

In conclusion, the authors express their deep gratitude to V. F. Gantmakher and A. I. Kopeliovich for useful discussions, of the results of valuable remarks made during the research, to V. T. Dolgopolov for numerous discussions, and also to V. A. Gasparov for calling our attention to Ref. 15.

[1)] We take this opportunity to point out that the numerical values of the parameter $R_U{}^A/R_F$ in our paper[4] are given incorrectly.

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