Anisotropy of helicon damping in indium during localized electron-phonon *U* processes

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It is shown by using a helicon method that the transport relaxation time of conduction electrons in indium in a strong magnetic field is highly anisotropic. The results are explained at a quantitative level by means of the Gurzhi-Kopeliovich mechanism {R. N. Gurzhi and A. I. Kopeliovich, Zh. Eksp. Teor. Fiz. **67**, 2307 (1974) [Sov. Phys. JETP. **40**, 1144 (1974)]; Usp. Fiz. Nauk. **133**, 33 (1981) [Sov. Phys. Usp. **24**, 17 (1981)]}. This mechanism takes into account in detail the quasimomentum balance in the electron-phonon system.

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In metals having a closed Fermi surface the electron-phonon scattering processes involving a spin flip (*U* processes) "freeze out" as the temperature is lowered, and in a certain temperature range the *U* processes can occur only in separate, small regions on the Fermi surface. When such a localization of the *U* process occurs, the transverse electrical conductivity should be anisotropic in a strong magnetic field, and this anisotropy should be sensitive to the electron-phonon relaxation mechanism and to phonon-drag (nonequilibrium) effects.[1] In this letter we are reporting an effort to observe this anisotropy experimentally. We studied the anisotropy of the collisional damping of helicons in indium; the nature of this anisotropy should be the same as that in the transverse electrical conductivity, since the transverse components of the conductivity are primarily responsible for the damping of helicons.[2]

The helicon method makes it possible to use very pure, high-quality bulk single crystals of indium, and it eliminates at least two factors that tend to increase the error in measurements of the anisotropy: the electrical contacts and the effect of the shape of the sample. The resonator samples used in the present experiments are spherical single crystals 10 mm in diameter made from indium with a residual mean free path ~5 mm, which corresponds to a resistivity ratio[1)] $\rho(300\ \mathrm{K})/\rho(1.3) \approx 500\,000$. The samples were grown in a dismountable quartz form of optical quality.

The measurements were taken at temperatures in the range 1.3–4.2 K in magnetic fields up to 10 kOe. The helicon damping was determined from the Q factor of the (1, 0) resonance in the transverse geometry.[3] The exciting magnetic field was directed parallel to the [001] axis; the static magnetic field was rotated in the plane perpendicular to this direction. The wave frequency was ~1 Hz. Estimates show that the contribution of nonlocal damping mechanisms[4] and the scattering of electrons by the surfaces of the sample can be ignored. Particular care was taken to eliminate acoustohelicon phenomena.[5]

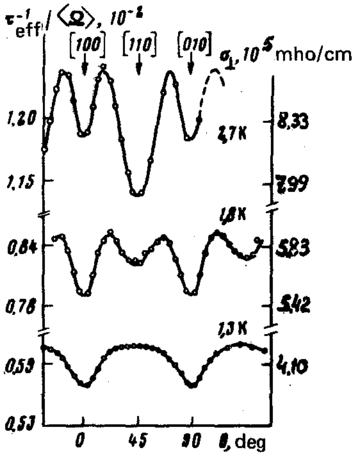

FIG. 1. Dependence of the helicon damping $\Gamma = \tau_{eff}^{-1}/\langle\Omega\rangle$ on the direction of the magnetic field in the (001) plane at various temperatures. Also shown are the values of $\sigma_\perp$. $H = 9$ kOe.

As the temperature was lowered from 4.2 to 1.3 K, the damping of the helicons fell off by a factor of 25, implying that electron-phonon scattering is predominant over a substantial part of this temperature range.

The occurrence of the helicon resonance was automatically demonstrated by the circumstance that the strong-field condition $\Omega\tau_{eff} \gg 1$ was satisfied over the entire temperature range (Ω is the cyclotron frequency, and τ_{eff} is the transport relaxation time).

Figure 1 shows some of the experimental results on the helicon damping Γ as a function of the angle between the strong external magnetic field **H** and the crystal axes. Also shown in this figure are the values of $\tau_{eff}^{-1}/\langle\Omega\rangle$ and $\sigma_\perp \approx (\sigma_{xx} + \sigma_{yy})/2$, which are related by[2]

$$\Gamma = \sigma_\perp/\sigma_{xy} = \tau_{eff}^{-1}/\langle\Omega\rangle,$$

where σ_{xy} is the Hall component of the conductivity, which was determined within ~1% from the position of the helicon resonance and which was independent of the direction of the magnetic field and the temperature; and $\langle\Omega\rangle$ is the cyclotron frequency averaged over P_z (the projection of the electron momentum on the magnetic field). Interestingly, the curves in Fig. 1 do not have the same shape; the number of extrema depends on the temperature. The only way to explain this result is to conclude that there is an angular dependence of τ_{eff} which varies with the temperature.

It thus follows from these results that the transport relaxation time of the electrons in a magnetic field in indium is anisotropic, with the electron-impurity and the electron-phonon relaxation times having different types of anisotropy.

In order to distinguish the effects resulting from the electron-phonon processes, we plotted the angular dependence of η, the relative change in the transverse conductivity with the temperature:

$$\eta = (\sigma_\perp - \sigma_\perp^\circ)/\sigma_\perp^\circ,$$

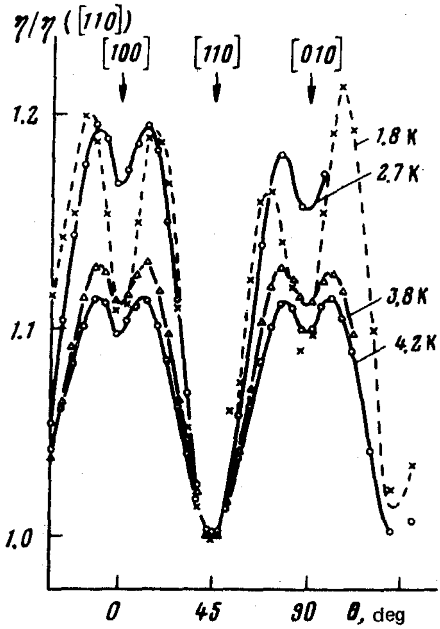

FIG. 2. Angular dependence of the relative change in the transverse electrical conductivity $\eta = (\sigma_\perp - \sigma_\perp^0)/\sigma_\perp^0$ at various temperatures, $\eta([110]) \sim T^n$. The curve for $T = 1.8$ K was recorded under the condition $\sigma_\perp^{\text{phonon}} < \sigma_\perp^0$. $n \approx 5$.

where $\sigma_\perp^0$ is the residual transverse conductivity. These results are plotted in Fig. 2.

The matched nature of the anisotropy and the fact that the anisotropy varies with the temperature cannot be explained solely on the basis of the diffusion mechanism, without appealing to U processes. Difficulties also arise in attempts to explain the results in terms of an independent parallel operation of diffusion and U processes.

Figure 3 shows the values of the anisotropy η calculated from the relaxation me-

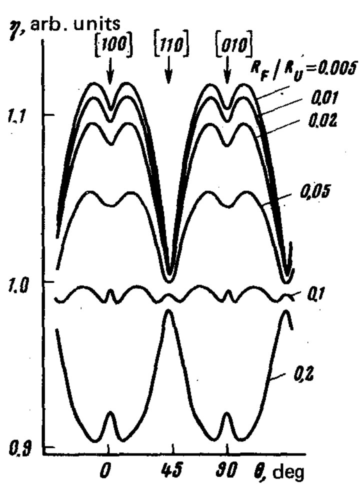

FIG. 3. Angular dependence of the relative change in the transverse conductivity, η, calculated from the Gurzhi-Kopeliovich model[1] for various ratios of the resistance to spin flip, R_U, and of the resistance to diffusion across the entire Fermi surface, R_F.

chanism proposed by Gurzhi and Kopeliovich.[1] This mechanism operates under condiitons of small-angle, electron-phonon scattering with localized U processes; the quasimomentum balance in the electron-phonon system is taken into account in detail in this mechanism. The diffusion of conduction electrons over the Fermi surface and the U processes turn out to be interrelated and to depend on the direction of the magnetic field. Under our experimental conditions, the thermal momentum of the phonons is $q = kT/\hbar s \lesssim 5 \times 10^6$ cm^{-1}; the Fermi momentum is $P_F \sim 10^8$ cm^{-1}; and the condition $q \ll P_F$–required for a description of the normal electron-phonon scattering in terms of diffusion-holds over the entire temperature range studied.

According to the recent model of Rijsenbrij *et al.*,[6] the distance between the separate parts of the Fermi surface of indium is minimal at the T points of the Brillouin zone.[6] Since the thermal momentum of the phonon, q, is clearly too small for U processes to occur at the centers of the "cups" of the Fermi surface under the conditions of the present experiments, it is logical to suggest that these processes are localized near the T points. In this case there are 24 scattering channels with spin flip: four groups each consisting of four equivalent T points. We are assuming that the resistance to spin flip, R_U, is independent of the magnitude and direction of the magnetic field.

Comparison of Figs. 2 and 3 shows that the theoretical curves with $R_F/R_U \leqslant 0.02$ give a completely satisfactory description of the anisotropy observed experimentally.

The temperature dependence of the transverse conductivity found experimentally is strongly dependent on the magnetic field direction (Fig. 2) and cannot be described for all directions by an expression of the type T^n, where n is an integer. To calculate the temperature dependence of $\sigma_\perp$ and to compare the results with experiment is a more complicated problem than the anisotropy problem, since it requires a detailed account of the topology of the Fermi surface, particularly in the region in which the U processes are localized.

In conclusion, we wish to thank E. P. Vol'skiĭ for a discussion of these results and V. F. Gantmakher for some valuable comments.

[1)]The indium was produced in the Department of Pure Materials, Institute of Solid State Physics, Academy of Sciences of the USSR.

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