Dispersion of transverse-sound velocity in gallium in strong transverse magnetic fields

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We report experimental observation of singularities in the dispersion of the velocity of transverse sound in a strong magnetic field **H**. These singularities are due to the symmetry and the connectivity of the intersections between the Fermi surface and planes perpendicular to **H**.

The elasticity equation of metals placed in a strong magnetic field ($kr_H \ll 1$, r_H is the radius of the electron orbit in the magnetic field H) perpendicular to the wave vector k of the sound was investigated in a number of studies.[1-3] In the approximation of a quadratic isotropic dispersion of the electrons, it was established that the electronic shear moduli and the dispersion $\Delta s/s$ of the transverse-sound velocity, which determines these moduli, are equal to zero under these conditions. The case of arbitrary dispersion was considered recently by Kontorovich,[3] who has shown that the dispersion of the transverse-sound velocity at $kr_H \ll 1$ and $\mathbf{k} \perp \mathbf{H}$ can reach an appreciable magnitude, so that the electronic shear moduli determined by this dispersion turn out to be comparable with the corresponding lattice moduli.

This result is explained in[3], for a pure deformation interaction of sound with electrons, described by a deformation-potential tensor $\hat{\Lambda}(\mathbf{p})$, as follows: In the approximation of isotropic electron relaxation time τ, the dispersion of the transverse-sound velocity is expressed in terms of the off-diagonal components of $\hat{\Lambda}(\mathbf{p})$ in the following manner:

$$\frac{\Delta s}{s} = \frac{(\omega\tau)^2}{2\rho s[1+(\omega\tau)^2]}[\langle \bar{\Lambda}^2_{im}\rangle + O(\Omega^{-2})], \quad i \neq m. \tag{1}$$

Here ω is the sound frequency, ρ is the metal density, Ω^{-1} is the period of revolution in the magnetic field, the angle brackets denote averaging over the Fermi surface and summation over the bands, and the bar denotes averaging over the period of revolution in the magnetic field.

The quantity $\Delta s/s$ and its variation with the magnetic field depend on whether $\bar{\Lambda}_{im}$ differs from zero or not. In the former case $\Delta s/s$ can reach large values and can saturate as $H \to \infty$. In the latter case $\Delta s/s$ is determined by the small term $O(\Omega^{-2})$ connected with the incomplete averaging, meaning by the finite character of r_H in comparison with the wavelength of the sound or the electron mean free path l, and the dispersion is given by $\Delta s/s \sim (kr_H)^2 \sim H^{-2}$ or $\Delta s/s \sim (r_H/l)^2 \sim H^{-2}$.

It was shown for the first time in[3] that $\bar{\Lambda}_{im}$ ($i \neq m$) is determined not only by the symmetry of the intersections of the Fermi surface with the planes perpendicular to **H** but also by the connectivity of these intersections. A brief summary of the results of[3] is the following: 1) for singly-connected high-symmetry sections the value of $\Delta s/s$ of the transverse sound decreases like H^{-2} in accord with[1,2]; 2) multiply-connected sections of any symmetry correspond to saturation of $\Delta s/s$ as $H \to \infty$; 3) for singly-connected low-symmetry sections, $\Delta s/s$ can either saturate or decrease like H^{-2}, depending on the mutual orientation of the sound-polarization vector **u** and of the vector **H**.

The present paper is devoted to an experimental study of the dispersion of the transverse-sound velocity in gallium, a metal in which both singly-connected and multiply-connected sections of the Fermi surface can exist[4] and where the condition $\omega\tau \gg 1$ can be attained at relatively low ultrasound frequency.[5]

The gallium samples were disks 1–2 mm thick and 11 mm in diameter, and the normal to the plane of the disk coincided within 0.2° with the [100] axis. The pickups of the linearly-polarized transverse sound were *AC*-cut quartz plates. The sound polarization vector **u** was set with accuracy 1–2° along the axis [010] or [001], thereby ensuring the condition for the existence of linearly-polarized transverse sound at $H=0$. The perpendicularity of the vectors k and H was established by means of the inclination fork effect,[6] using a special device for mechanically inclining the sample.

Figure 1 shows plots of $\Delta s/s$ of sound of varying

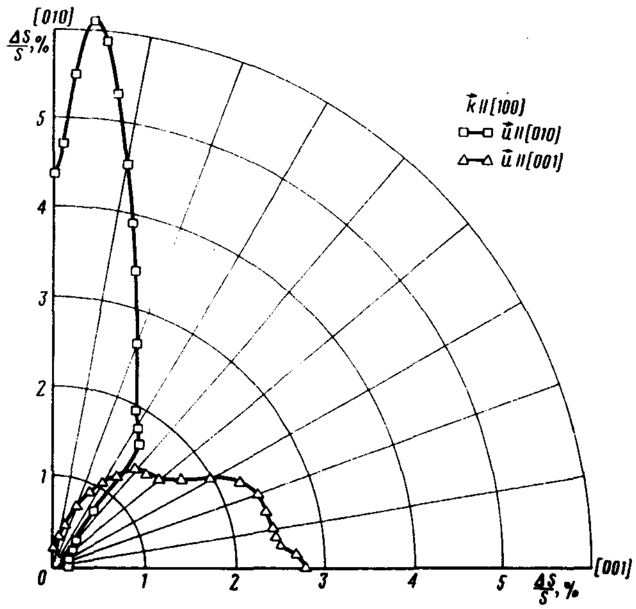

FIG. 1.

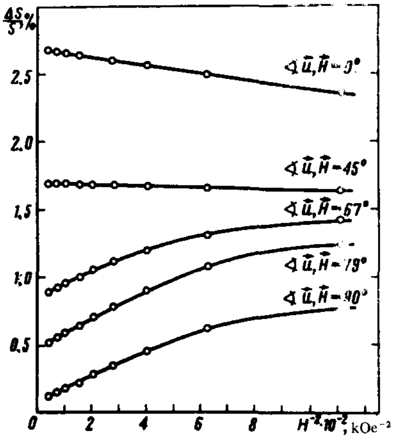

FIG. 2.

polarization against the direction of H in the (100) plane, obtained in a field $H = 15$ kOe of frequency $\omega/2\pi = 50$ MHz at a temperature $T = 1.7\,^\circ$K. Under these conditions, as shown earlier, [5] $\Delta s/s$ differs insignificantly from its limiting value as $\omega\tau \to \infty$. The maximum dispersion of the transverse-sound velocity, obtained in the experiment, did not exceed 6%, which agrees in order of magnitude with[3].

The plots of $\Delta s/s$ of transverse sound with polarization **u** || [001] against the magnetic field, at different angles between **u** and **H**, obtained under the conditions $\omega/2\pi = 50$ MHz and $T = 1.7\,^\circ$K, are shown in Fig. 2. It follows from this figure that in the case of parallel **u** and **H** the function $\Delta s/s$ consists of two parts, one saturating and the other decreasing with increasing **H**. The relation $\Delta s/s \sim H^{-2}$ is satisfied for the latter at the indicated sound frequency at $H = 4$ kOe. No decrease of $\Delta s/s$ with increasing **H** was observed for **u** || **H**.

The relation obtained by us between the decreasing part of $\Delta s/s$ and the angle between the vectors **u** and **H** was compared with the theoretical relation[3] with allowance for the symmetry of the possible singly-connected sections of the Fermi surface. At an arbitrary direction of **H** in the (100) plane, when the singly-connected sections of the Fermi surface have a single symmetry element m_x (in a coordinate system in which **x** || **k** and **L** || **H**), the theory predicts a decrease of $\Delta s/s$ with increasing **H**, proportional to $(kr_H)^2$, and a tendency of the saturating part of $\Delta s/s$, due to the singly-connected sections, to increase with increasing component **u** along the **H** direction. As seen from Fig. 2, in this case the results of the experiment are in full agreement with[3].

If **H** is directed along a principal axis, the singly-connected sections in gallium have a symmetry $2m_x m_y$ and, according to[3], they should contribute to the dispersion of the transverse-sound velocity. This contribution should vary with field like $(r_H/l)^2$ both at **u** ⊥ **H** and at **u** || **H**. In the experiment at **u** ⊥ **H**, a different dependence of the dispersion on the magnetic field was observed, of the $(kr_H)^2$ type. Such a dependence of $\Delta s/s$ on the magnetic field is due in this case, possibly, to the insufficiently exact orientation of **H** along a principal axis of the crystal or else to an angular divergence of the force lines of the magnetic field [we note that transition from the $(r_H/l)^2$ dependence to $(kr_H)^2$ occurs with **H** making with the principal axis an angle $\phi \sim (kl)^{-1}$ equal to 3′–10′ in our Ga sample at $T = 1.7\,^\circ$K]. In addition, the $(r_H/l)^2$ dependence could be masked also by the contribution made to the transverse-sound velocity by electron-phonon interaction mechanisms other than the deformation mechanism.

Unfortunately, the absence of sufficiently complete data on the electronic spectrum of gallium do not make possible a detailed comparison of the experimental results with the theory. The authors hope that investigations of the inclination fork effect in Ga, which are now under way, will make it possible to solve this problem.

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