Determination from magnetoacoustic measurements of the relaxation times of isolated groups of current carriers in a metal

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A method is proposed for determining the relaxation times of isolated groups of current carriers in a simultaneous measurement of the amplitudes of quantum oscillations of the velocity and damping of sound in a metal. The relaxation times of holes in the third ($\tau_1 = 2.5\times 10^{-10}$ sec) energy band and of electrons in the sixth ($\tau_2 = 4\times 10^{-10}$ sec) energy band of tin were determined.

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The interaction of sound waves with the conduction electrons in metals in a magnetic field can be deduced, in particular, from the quantum oscillations of the damping and velocity of sound.[1,2] The amplitudes of there quantum oscillations are generally related by Kramers-Kronig-type relations, but in the low-frequency region investigated in this paper, they are related by a simpler relation that includes the relaxation time of the corresponding group of current carriers. Simultaneous measurements of the amplitudes of the quantum oscillations of the velocity and damping of sound make it possible to propose a method for determining the relaxation times τ_i of the isolated groups of current carriers groups in a metal.[1)]

THEORY

The quantum oscillations of the sound velocity and damping in a metal can be described by the polarization operator $\mathbf{\Pi}(\omega,\mathbf{q})$, whose general expression is given in Ref. 2. The following relations can be written for the longitudinal sound propagating at right angles to the magnetic field $\mathbf{q}\perp\mathbf{H}$:

$$\omega = \omega_0(\mathbf{q}) \sqrt{1 + \Pi(\omega, \mathbf{q})},$$

$$\Pi(\omega, \mathbf{q}) = -2\zeta \frac{\Omega}{\epsilon_F} \sum_{n=0}^{N=[\epsilon_F/\Omega]} \sum_{\alpha=-\infty}^{\infty} \frac{J_\alpha^2(qR_n)}{(x_n + x_{n-\alpha})} \frac{\alpha\Omega}{(\alpha\Omega - \omega + i\nu)}, \tag{1}$$

where ζ is a dimensionless coupling constant of the electron-phonon interaction, ϵ_F is the Fermi energy, Ω is the cyclotron frequency, ω is the sound frequency, $\nu = \tau^{-1}$ is the electron collision frequency, $J_n(x)$ is the nth Bessel function, $R_n = \left[(2n+1)\frac{c}{eH}\right]^{1/2}$ is the orbit radius of the electron in the nth Landau level, and $x_n = \left[1-(n+\frac{1}{2})\frac{\Omega}{\epsilon_F}\right]^{1/2}$ is the z projection of the dimensionless electron momentum at the Fermi level. We have assumed in this discussion that the current carriers obey the isotropic dispersion law. If the arbitrary spectrum is taken into account, then we must multiply the result by a numerical coefficient of the order of unity.

In the investigated region of low frequencies $\omega\tau \ll 1$ and strong magnetic fields $qR \ll 1$, the small values of α in Eq. (1) are important. We expand the denominator in Eq. (1) in small α, after which the resulting summation over α can be calculated exactly. As a result, we obtain

$$\Pi(\omega, \mathbf{q}) = -\frac{\zeta}{4} \frac{q^2}{2m(\omega - i\nu)} \left(\frac{\Omega}{\epsilon_F}\right)^2 \sum_n \frac{n}{x_n^3}. \tag{2}$$

Using the Poisson summation formula in Eq. (2), we obtain

$$\Pi(\omega, \mathbf{q}) = \zeta \frac{q^2}{2m(\omega - i\nu)} \left\{1 - \frac{1}{2}\left(\frac{\Omega}{\epsilon_F}\right)^2 \sum_{j=1}^{\infty} \int_0^{<N} \frac{n \cos 2\pi j n}{x_n^3} dn\right\}. \tag{3}$$

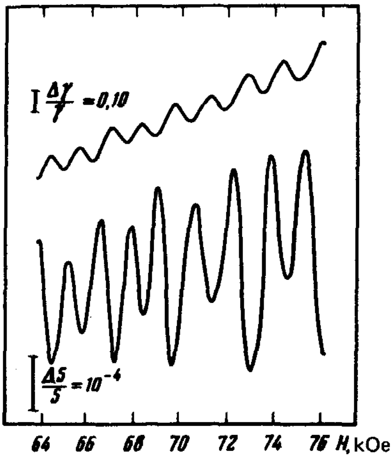

FIG. 1. Quantum oscillations of the longitudinal sound velocity and damping in a sample with **n**||[100], **H**||[001] and $T=4.2$ K.

Here, the first term corresponds to sound dispersion and damping without a magnetic field[4] and the second term describes the quantum oscillations. Equation (3) is valid when the condition $\omega\tau_D \ll 1$ is satisfied, where τ_D is the Dinglovskii relation time, which describes the width of the quantum oscillations.

A simple relation, which relates the real and the imaginary parts of $\mathbf{\Pi}(\omega,\mathbf{q})$, is derived from Eq. (3). In terms of the relative damping $\mathrm{Im}\mathbf{\Pi}_{osc} = \Delta\gamma/\gamma$ and dispersion $\mathrm{Re}\mathbf{\Pi}_{osc} = \Delta S/S$ of the sound, this relation is written as follows:

$$\left(\frac{\Delta S}{S}\right)_{osc} = -\omega\tau\left(\frac{\Delta\gamma}{\gamma}\right)_{osc} . \tag{4}$$

We note that another relation, which relates the amplitudes of the quantum oscillations of the sound velocity and damping in this low frequency region, was obtained in Ref. 5 on the basis of the Rodriguez theory.[1] This formula, however, proved to be incorrect–specifically, it gives an oscillation amplitude of the sound velocity that is larger than the damping oscillations.

EXPERIMENT

An "acoustic" measuring oscillator was assembled by us for simultaneously measuring the amplitudes of the quantum oscillations of the sound velocity and damping. The operation of this instrument is based on a contactless excitation of standing sound waves in a metal plate in a magnetic field.[6] A buildup of standing sound waves within the plate is accompanied by the appearance of resonance characteristics in the frequency dependence of the surface impedance of the metal. The frequency and amplitude of the resonance characteristics and hence the frequency and amplitude of the oscillation of the proposed instrument are determined by the sound velocity and damping in the metal. The variation of these parameters $\Delta S/S$ and $\Delta\gamma/\gamma$ was measured in the experiment. The measurement procedure is described elsewhere.[7]

The amplitudes of the quantum oscillations of the velocity and damping of longitudinal sound were measured at a frequency of 1.7 MHz in a tin single crystal in the form of a disk with a diameter of 1.8 cm and a thickness of 0.1 cm. The normal **n** to the plane of the disk coincided with the second-order symmetry axis [100], and the sample quality was characterized by the resistance ratio $\rho_{300K}/\rho_{4.2K} = 8\times 10^4$. The measurements were performed at $T = 4.2$ K in a magnetic field parallel to the plane of the disk.

Figure 1 shows the experimental traces of the quantum oscillations of the sound velocity and damping in tin for **H**||[001]. The frequencies of the observed oscillations correspond to the extremal cross sections of δ_1^1 and δ_1^2.[8] The amplitudes of the quantum oscillations of the sound velocity and damping from the δ_1^1 cross section in a field $H = 70$ kOe are, respectively, $(\Delta S/S)_{osc} = 3.7\times 10^{-4}$ and $(\Delta\gamma/\gamma)_{osc} = 0.15$. According to Eq. (4), this defines the relaxation time $\tau_1 = 2.5\times 10^{-10}$ sec in the third hole band. At **H**||[010] the oscillations from the τ_2^1 cross section had the maximum amplitude; they were equal to, $(\Delta S/S)_{osc} = 4.9\times 10^{-4}$ and $(\Delta\gamma/\gamma)_{osc} = 0.12$, respectively, in a field $H = 70$ kOe. This determines the relaxation time $\tau_2 = 4\times 10^{-10}$ sec in the sixth electron band of tin. The measurement accuracy of the quantum-oscillation amplitudes of sound velocity and damping is 10%.

[1)]The paper of Korolyuk *et al.*[3] is devoted to determination of the electron relaxation time from the nonresonance magnetoacoustic measurements. In this paper, however, the authors measured the relaxation time averaged over all groups of carriers.

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