A new type of magnetoacoustic vibration in thin metal layers

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Changeover processes of conduction electrons during their reflection by the surface of the sample may be detected in a new magnetoacoustic effect.

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Kinetic phenomena in conductors that are thin in comparison with the charge carrier mean free path ($d \ll l$) differ qualitatively from the case of a large sample due to the interaction of the electrons with the metal boundary. This interaction[1] may have the nature of both "diffusion scattering," when the quasimomenta of the electron before and after its impact with the boundary, **p** and **p**′, are weakly correlated, and also "mirror reflection" when they are related by the equations

$$\mathbf{p}' \times \mathbf{n} = \mathbf{p} \times \mathbf{n}; \ \epsilon(\mathbf{p}') = \epsilon(\mathbf{p}); \ \mathrm{sign}\, v_n(\mathbf{p}') = -\,\mathrm{sign}\, v_n(\mathbf{p}); \tag{1}$$

where **n** is the internal normal to the surface of the sample. In the first case there is a new, frequently fundamental dissipation mechanism, and in the second the classification of the electron orbits in an external magnetic field is changed significantly (see, for example, Refs. 2 and 3).

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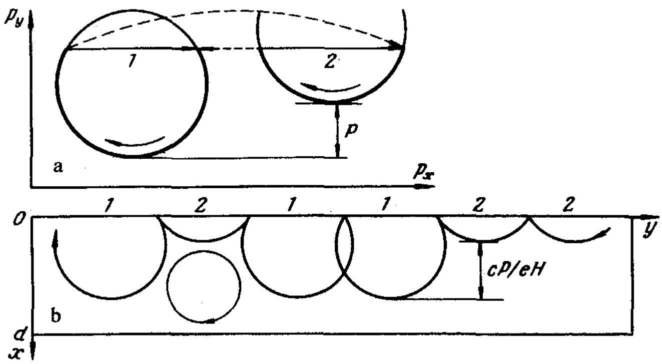

FIG. 1. a-motion of the electron in p-space: dashed lines indicate changeovers which are possible for surface reflection; b-electron trajectories in the metal layer ($H > H_2$).

The fact that even for a pure mirror reflection the relationship between **p** and **p**′ is, generally speaking, ambiguous, deserves attention: if the straight line $\mathbf{p}\times\mathbf{n} = \text{const}$ intersects the Fermi surface (FS) at several points with $v_n(\mathbf{p}) > 0$, then at the moment of impact with the boundary there may be a changeover of the electron, for example, into another FS sheet. Such "surface jumps," if their probability along the carrier free path $\nu^{-1} = l/v_F$ is not small, may appear as kinetic effects and, in particular, may change the dependence of the ultrasound absorption coefficient on the applied magnetic field.

Let the sound wave $u_x = u_{ox}\exp(ikx - i\omega t)$ propagate along the normal to the metal layer ($0 \leqslant x \leqslant d \gg k^{-1}$) such that there are two convex FS cavities compatible with parallel transport:

$$\epsilon(\mathbf{p}_1) = \epsilon(\mathbf{p}_2) = \epsilon_F;\quad \mathbf{p}_2 = \mathbf{p}_1 - 2\pi\hbar\mathbf{b}. \tag{2}$$

The vector **b** which, in particular, may simply coincide with the period of the reciprocal crystal lattice, is located in the $(\mathbf{p}_x, \mathbf{p}_y)$-plasma and makes an angle θ with the $\mathbf{p}_x$-axis.

Then, in the magnetic field $\mathbf{H} = (0,0,H)$ that is parallel to the layer, the electrons which collide with one of its boundaries move along open trajectories; the latter, due to the surface changeovers, consist of sections shifted along the normal to the layer at a distance

$$cP/eH = 2\pi\hbar b\,|\sin\theta|\,c/eH, \tag{3}$$

as shown in Fig. 1. Clearly, in the static case when $\omega \ll \nu$, the contribution of these electrons to acoustic absorption depends on the phase difference of the sound wave at a distance cP/eH, which leads to absorption oscillations with a change in H.

The calculation of this effect is not difficult if the electron distribution function f is known. The solution of the kinetic equation in the p_z, λ, t variables is

$$(f - f_0)(\dot{u}_{xx}\partial f_0/\partial\epsilon)^{-1} = \sum_{i=1}^{2} \chi(\lambda, t) \equiv \sum_{i=1}^{2} \left(A_i \mathcal{E}^{t}_{\lambda_i} + \int_{\lambda_i}^{t} dt' \Lambda_i \mathcal{E}^{t}_{t'}\right);$$
$$\mathcal{E}^{\beta}_{\alpha} \equiv \exp\left(\int_{\beta}^{\alpha} dt''(ikv + \nu)\right). \tag{4}$$

Here λ_i is the time for the last collision of the electron located at the ith FS cavity with the surface of the layer, $f_0(\epsilon)$ is the Fermi function, Λ is the difference between the deformation potential and its average value on the FS, and A_i are determined from the boundary condition which for mirror reflection has the form

$$\chi(\tau_i, \tau_i) = a\chi(0, \tau_k) + (1-a)\chi(0, \tau_i); \quad \int_{\lambda_i}^{\lambda_i+\tau_i} v_x dt \equiv \int_0^{\tau_i} v_x dt_i = 0. \tag{5}$$

Naturally, we are interested in the case where the jump probability a exceeds the probability of bulk scattering of the electron during the time between impacts with the boundary, τ_i: $1 > a \gg r/l$, where r is the Larmor radius. Moreover, A_i are independent of a and are equal to

$$A \cong \frac{1}{\nu(\tau_1+\tau_2)} \sum_{i=1}^{2} \int_0^{\tau_i} dt_i \Lambda_i \zeta_{t_i}^{\tau_i} \cong \frac{\sqrt{2\pi/ikv_0''}}{\nu(\tau_1+\tau_2)} \sum_{i=1}^{2} \Lambda_{io} \exp(-ikx_{io}), \tag{6}$$

where the functions with the index 0 are taken at the electron turning point $v_x = 0$.

The absorption coefficient for longitudinal sound may be calculated from the equation

$$\Gamma = (2k^2 eH/c\rho h^3) \mathrm{Re} \left\langle \int dp_z \sum_{i=1}^{2} \int_0^{\tau_i} dt_i \Lambda_i \chi(0, t_i) \right\rangle, \tag{7}$$

in which ρ is the density of the crystal, the angular brackets denote averaging over the thickness of the sample, and the limits of integration were picked such that the turning points in the 1 and 2 orbits, where the electron effectively interacts with the acoustic field, are concurrently placed in the layer. The oscillatory part of the absorption coefficient is

$$\Delta\Gamma_{\mathrm{osc}} \cong \Gamma_0 (l/d)\, \phi(H) \cos(kcP/eH);$$

$$\phi(H) = \begin{cases} 0, & (H < H_1); \quad H_1 \equiv cP/ed; \\ \sim H/H_1 - 1 & (0 < H - H_1 << H_1); \\ \mathrm{const} \sim 1, & (H_2 < H << kdH_2); \quad H_2 \equiv c\Delta p_y/ed. \end{cases} \tag{8}$$

Here Γ_0 is the absorption of sound in the absence of a magnetic field,[4] and Δp_y is the maximum size of the FS cross section $p_z = \mathrm{const}$. For fields $H \sim H_2$ the amplitude of the oscillations (8) is on the order of the entire absorption coefficient, and many times $(\sim\sqrt{kr}\, H_2/(H-H_2) \gg 1)$ exceeds the amplitude of the normal Pippard resonance, which is possible only for $H > H_2$.[5] Such a large value of the effect is explained by the fact that in this problem the shift of the trajectory after the jump $x_{10} - x_{20} = cP/eH$ is the same for all the electrons colliding with the layer boundary.

We shall now consider another possible case when $\mathbf{p}_x$ is some symmetrical direction in p-space along which two different FS sheets are located: $\epsilon_1(p_1)=\epsilon_F$ and $\epsilon_2(p_z)=\epsilon_F$. If $p_y=0$ is the FS plane of symmetry, the calculation differs from what has been given only by the fact that the length $x_{10}-x_{20}$ depends on p_z. This leads to the appearance of the factor $\sim 1/\sqrt{kr}$ in the oscillation amplitude of the absorption coefficient: for $H > c\,(p_{y_1}^{\max}+p_{y_2}^{\max})/ed$

$$\Delta\Gamma_{\mathrm{osc}} \sim \Gamma_0 (l/d\sqrt{kr}) \cos(kc\,|p_{y1}^{max}-p_{y2}^{max}|/eH-\pi/4). \qquad (9)$$

Thus, magnetoacoustic oscillations of large amplitude are possible in thin metallic layers due to the process of electron jump during collisions with the conductor boundary. In contrast to the known magnetoacoustic effects, their period carries information concerning the mutual positions of individual FS cavities.

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