Acousto-electric effect in bounded metal

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Abstract

Earlier, a mutual transformation of transverse sound and electromagnetic waves in metals had been investigated in details and found scientific and technical applications (see, e.g., the review [1]). Here we consider theoretically the vibrations of electric potential generated by longitudinal elastic wave in bounded metal, and compare the results with some experimental data measured in pure Ga at low temperatures.

Key words: Longitudinal elastic waves; Electric field; Metal surface

1. As it is well known [2], high-frequency ultrasound wave in metal is accompanied by macroscopic electric field due to nonequilibrium – time-dependent – distribution of charge carriers with energy spectrum modulated by elastic distortions, $\varepsilon(\mathbf{p}) \rightarrow \varepsilon(\mathbf{p}) + \Lambda_{ik}(\mathbf{p})u_{ik}(\mathbf{x},t)$. Here "high-frequency" (HF) means that sound wavelenth is comparable or shorter than electron mean free path: $2\pi s/\omega < v_F\tau$. Nevertheless, even the hyper-sound frequencies are much less than plasma frequency in a good metal. Therefore, the metal stays electrically neutral with high accuracy, and in longitudinal case we have to find an electric field $\mathbf{E}$ (or its scalar potential φ) from the neutrality condition

$$\langle\psi\rangle \equiv 2(2\pi\hbar)^{-3}\int \psi dS_F/v = 0 \tag{1}$$

and the kinetic equation

$$v_x(\psi - e\varphi)' - i\varpi\psi = -i\omega\Lambda u' \tag{2}$$

where $\mathbf{v}$ is the electron velocity on Fermi surface S_F; Λ , the xx-component of deformation potential tensor Λ_{ik} ; $\varpi \equiv \omega + i/\tau$. Substantively, the effect can only be measured on the sample surface; so we need in correct solution of the boundary problem for Eqs. (1), (2), satisfying both the mechanical boundary conditions and the same for nonequilibrium electrons distribution function ψ .

2. Let consider a semi-infinite sample, $x \geq 0$, and – in adiabatic aproachment – a given elastic field in it, with specified boundary values of displacements u_0 and distortions u_0' (here and below we omit the common temporal factor $\exp(-i\omega t)$). For the sake of simplicity we assume: a) an isotropic metal in which we may set $\Lambda \rightarrow L(3\ v_x^2/v_F^2 - 1)$ [2] and b) so-called "specular" boundary condition: $\psi(0, v_x > 0) = \psi(0, v_x < 0)$. The latter – rather acceptable for ideal metal surface [3] – enables us, after even continuation of functions $\varphi(x)$ and $u(x)$ onto $x < 0$ semi-axis, to solve the Eqs. (1), (2) directly by Fourier transform. Then the inversion yields the potential distribution in the sample as a sum of two terms quite differently depending on x :

$$e\varphi_0(x) = u'(x)L\frac{s}{v_F}\left(\frac{a}{W(a)} + \frac{3}{a} - a\right)$$

$$e\varphi_1(x) = iu_0L\frac{\omega}{v_F}\int_1^\infty \frac{4a^2}{a^2 - z^2}\frac{\exp(i\varpi xz/v_F)zdz}{\left(2z + \ln\frac{z-1}{z+1}\right)^2 + \pi^2} \tag{3}$$

$$a(\omega) \equiv \frac{v_F}{s}\frac{\omega\tau}{\omega\tau + i} \tag{4}$$

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The first term is similar to the wave of elastic distortions but the second one is a "quasi-wave" arising due to ballistic movement of free carriers. If ultrasound is excited on the border $x = 0$, the asymptotic form of φ_1 at a great distance from a border, $x \gg |v_F/\varpi|$, is

$$e\varphi_1(x) \approx -4Lu_0 \frac{\omega}{\varpi x} \ln^{-2}\left(\frac{\varpi x}{v_F}\right) \exp\left(\frac{i\varpi x}{v_F}\right) \qquad (5)$$

In collisionless limit ($\omega\tau \gg 1$) the quasi-wave part of potential damps non-exponentially and runs into the sample with near Fermi velocity; so the latter can be measured in a pulse mode in samples of thickness $d \sim v_F\tau$. We plan a special publication on the observation of sound-generated electric quasi-waves, but in present paper only surface potential of deformed metal is considered below.

3. If the sound beam comes from the projector placed on opposite facet of a thick sample, Eqs. (3) at $x = 0$ give us the surface potential that can be measured (by galvanic contact or capacitive coupling) as a voltage between the distorted "sound spot" on sample surface and its distant points, free of deformations. At fixed sound power the frequency dependence of the effect is determined by a-depending factors in (3). The asymptotic forms can be written as

$$\varphi_0(0) \approx u'(x)L\frac{s}{v_F} \cdot \frac{1}{2} \ln \frac{1+a}{1-a}$$

$$\varphi_1(0) \approx iu_0L\frac{\omega}{v_F} \cdot \frac{1}{2} \ln(1-a^2) \qquad (6)$$

in HF limit $|a| \gg 1$, and at $|a| \ll 1$ effect is very small: these factors become $\approx (4/5) \cdot a$ and $\approx -0.345 \cdot a^2$ repectively.

The measurments have been carried out on pure monocrystals of Ga, W and Al; in particular, in Ga the parameter $\omega\tau$ runned up to $\omega\tau \simeq 5$ at working frequency $\simeq 55MHz$ and minimal temperature $T \sim 1K$. Temperature dependences of amplitude and phase of the signal arises from that of electron relaxation time, τ . For Ga the $\tau(T)$ dependence is known from semi-empirical calculations [4], assuming mainly small-angle scattering: $(\omega\tau(T))^{-1} \approx 0.2 + 0.05T^2 + 0.15T^3$ (T in K). Using this result for our computation, we found a qualitatively acceptable agreement between the theoretical and experimental curves in two different directions of the wave vector $\mathbf{k}$ (see Fig. 1).

4. The specular boundary condition used above simplifies the problem vastly, but it is evidently too ideal for real metal monocrystals. To clarify the effect of electrons scattering by surface defects, we undertake the calculation in opposite case of "diffuse" reflection of carriers by the sample surfase ($\psi(0, v_x > 0) = const$). It has been carried out by Wiener–Hopf technique with asymptotic factorization of kernel. Here the problem can be solved only separately in limit cases of free and fixed sample border. The HF asimptotics are

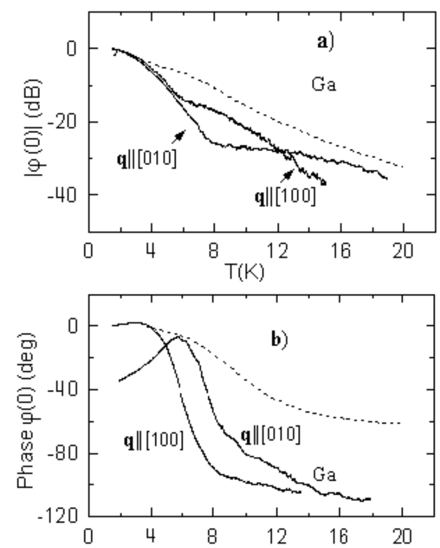

Fig. 1. The temperature dependences of amplitude (a) and phase (b) of surface electric potential generated by sound wave moving along two crystallographic directions in Ga. Dash lines - theoretical calculation by formulas (3), (4) (v/s = 200; f = 55 MHz).

$$e\varphi_{fix}(0) \approx u_0'L\frac{s}{v_F} \cdot \frac{1}{4} \ln \frac{1-a}{1+a}$$

$$e\varphi_{free}(0) \approx iu_0L\frac{\omega}{v_F} \cdot \left(\frac{1}{4}\ln(1-a^2) + 3.317 \cdot i\right) \qquad (7)$$

and at $|a| \ll 1$ one can find $\varphi_{fix} \propto 2.234 \cdot a$ and $\varphi_{free} \propto 1.991 \cdot ia^2$ – instead of formulas (6) and after them. Thus we conclude that even strong surface scattering can affect the magnitude of potential only numerically (up at low frequencies and slightly down at HF), but qualitatively it does not change the frequency and temperature dependences in the phenomenon under consideration. It can be used in comparative estimations of the constants of deformation potential in different metals and new "synthetic" metal-like compounds.

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