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Electromagnetic generation of ultrasound in metals at low temperatures

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Abstract. Excitation of longitudinal and transverse ultrasound by electromagnetic waves incident on the metal surface is the subject of the present work. This is a simple and convenient experimental technique. The reason for this approach is to overcome the primary difficulty during precise measurements of the frequency or temperature dependences of the velocity and attenuation of ultrasound in pure metals by the conventional methods where it is difficult to achieve reliable acoustic contact between the transducer and the sample. The reasons are (i) the creation of this contact unavoidably results in a deformation of a surface layer of the metal affecting the experimental results, (ii) as the temperature is varied over a broad range, the properties of the acoustic contact itself change resulting in non-reproducible experimental results.

Keywords. Electromagnetic generation; ultrasound in metals; low temperature.

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1. Physical principles

Over a wide range of frequencies, magnetic fields and temperatures, different mechanisms of contactless conversion of electromagnetic and ultrasonic waves come into play at the metal boundary. Nevertheless they can be discusssd within the framework of a single approach based on a detailed analysis of the drag on the crystal lattice exerted by the conduction electrons (Kontorovich 1970; Wallace 1971; Dobbs 1973; Vasil'ev and Gaidukov 1983).

In the normal skin-effect conditions the excitation of ultrasound by an electromagnetic wave incident on the metal surface is possible only in the presence of a constant magnetic field H_0. If this field is applied parallel to the surface of the metal and perpendicular to the direction of the alternating current, a Lorentz force directed inward into the metal acts on the electrons in the skin layer δ. This force produces a space modulation of the electric charge density and the ions of the lattice in the skin layer rearrange themselves such that within the volume of the metal the condition of local electric neutrality would be satisfied. As a result, a compression wave is excited at the surface and propagates inwards into the metal.

In a magnetic field directed normal to the surface transverse sound is excited in the metal. This is due to the fact that under the action of the electric field of the wave the momenta of the electrons and the ions in the skin layer are opposite directed and the Lorentz force deflects these particles in the same direction.

In both cases when longitudinal or transverse sound is excited the equation of forced acoustic oscillations for plane monochromatic waves propagating from the surface of the metal can be written in the form

$$\frac{\partial^2 u}{\partial t^2} - S^2\frac{\partial^2 u}{\partial z^2} = \frac{1}{\rho c}[j, H_0], \tag{1}$$

where u is the displacement vector, S the sound velocity, ρ the metal density, c the velocity of light, j the current density and H_0 the magnetic field.

Assuming that the electromagnetic field at the surface varies in proportion to $\exp i(\omega t - kz)$, we can write the expression for the density of alternating current flowing in the skin layer as

$$j(z, t) = \frac{(1+i)c}{4\pi\delta} H \exp\left[-(1+i)\frac{z}{\delta}\right]\exp(i\omega t), \tag{2}$$

where H is the amplitude of the alternating magnetic field, $\delta = c/(2\pi\omega\sigma)^{1/2}$, σ is the conductivity of the metal and ω is the circular frequency. (Direction z is normal to the surface.)

In order to find the amplitude of the excited sound we substitute the last expression into the wave equation

$$\frac{\partial^2 u}{\partial z^2} + q^2 u = \frac{H_0 H(1+i)}{4\pi\rho S^2\delta}\exp\left[-(1+i)\frac{z}{\delta}\right], \tag{3}$$

where $q = 2\pi/\lambda$ and λ is the wavelength of the sound wave. At distances greater compared to the thickness of the skin layer the solution has the form

$$|u| = \frac{H_0 H}{4\pi\rho S\omega}\frac{1}{(1+\beta^2)^{1/2}}, \tag{4}$$

where $\beta = q^2\delta^2/2$ is a parameter that takes into account through the conductivity the dependence of the amplitude of the excited ultrasound on the temperature.

As the temperature is decreased, in pure metals the mean freepath of electron (l) increases and one obtains $\delta < \lambda < l$ and one enters the regime of anomalous skin effect. In the regime of the anomalous skin-effect, excitation of transverse ultrasound in a metal is possible even in the absence of a constant magnetic field. The excitation mechanisms in weak fields and in the absence of the constant field, can be pictured in the following manner. Electrons situated in the skin layer are accelerated by the electric field of the electromagnetic excitation and by collisions transfer the excess momentum to the lattice. At the same time the ions of the lattice experience the direct action of the electric field in the skin layer. Excitation of ultrasound at the metal surface can occur if these two forces are locally unbalanced. In the absence of the constant magnetic field, this occurs when the mean free path of the carriers l exceeds the thickness of the skin layer. In this case the collision force is spatially separated from the region of the direct action of the alternating electric field, and both lead to transverse stress on the lattice.

From the point of view of the intensity of sound excited by the contactless method the most effective method is the generation of standing ultrasonic waves in plane parallel metal plates. The establishment of standing acoustic waves across the thickness of the plate is accompanied by the appearance of resonance singularities in the frequency dependence of the surface impedance of the sample.

It is easy to show that the resonance increment to the surface impedance of the plate can be written in the form (Gordon and Seidel 1971)

$$\Delta Z_{res} = \frac{2i\omega}{\rho d} \frac{H_0^2}{c^2} \sum_{m=1}^{\infty} \frac{1 - \cos m\pi}{\omega^2 - \omega_m^2 + i\gamma\omega}. \tag{5}$$

This expression was obtained on the assumption that $\delta \ll \lambda$, that is $\beta \to 0$. As the frequency, the magnetic field or the temperature varies the spatial distribution of the exciting force also varies. In the case of finite thickness of the skin layer, the expression for ΔZ_{res} can be brought to the form:

$$\Delta Z_{res} = \frac{2i\omega}{\rho d} \frac{H_0^2}{c^2} \frac{1 + i\beta}{1 + \beta^2} \sum_{m=1}^{\infty} \frac{1 - \cos m\pi}{\omega^2 - \omega_m^2 + i\gamma\omega}, \tag{6}$$

where d is the thickness of the plate, and γ is the attenuation of ultrasound.

2. Experimental

A block diagram of the experimental set-up to detect singularities in the surface impedance of metal plates is shown in figure 1. The set-up include commercial (i) RF oscillator, (ii) the sample with surrounding coils, (iii) low noise amplifier, (iv) phase detector system and (v) X–Y recorder. An example of the resonance singularity of the surface impedance of white tin plate due to excitation of the transverse sound is shown in figure 2. The field dependence of the amplitude of this resonance at $T = 4$ K is shown in figure 3. The decrease of the amplitude of the acoustic resonance in the high magnetic field region is connected with the strong dependence of the conductivity of tin on a magnetic field. At the maximum of the curve the parameter β is equal to unity. In metals where there is no dependence of the conductivity on a magnetic field, the amplitudes of the acoustic resonance singularities are proportional to the square of H_0 (Vasil'ev *et al* 1983).

The sharpness of the acoustic resonances in a metal plate can be used to create an oscillator in which frequency and amplitude of generation gives information about the velocity of sound and the attenuation in metal. Figure 4 shows field dependences of the velocity and attenuation of sound in white tin at $T = 4$ K (Vasil'ev *et al* 1980). Change of the transverse sound polarization reveals the anisotropy of the amplitudes of quantum oscillations shown in figure 5 (Vasil'ev and Nurmagambetov 1983).

The technique of contactless excitation of ultrasound in metals can be applied to semiconductors and even insulators. It is necessary to create a thin metal layer at the

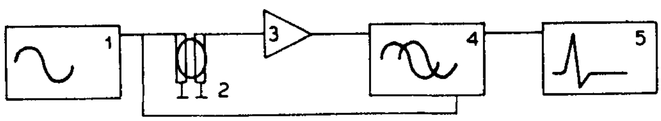

Figure 1. Experimental arrangement for observing the effect of direct generation of ultrasound in metal plates.

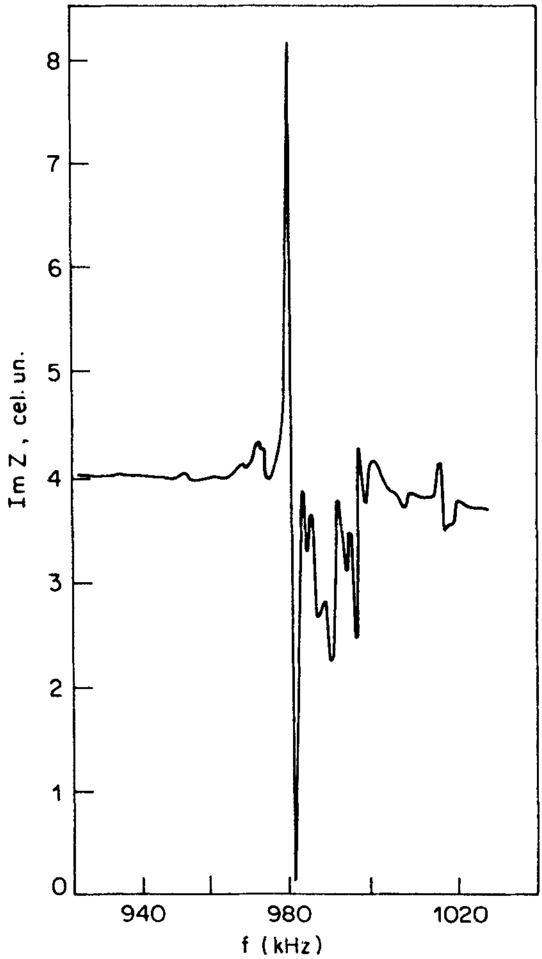

Figure 2. Resonance singularity of the surface impedance of white tin plate due to excitation of standing acoustic wave. Wave vector $q \| [100]$, polarization $p \| [010]$. $H = 70$ kOe, $T = 4$ K.

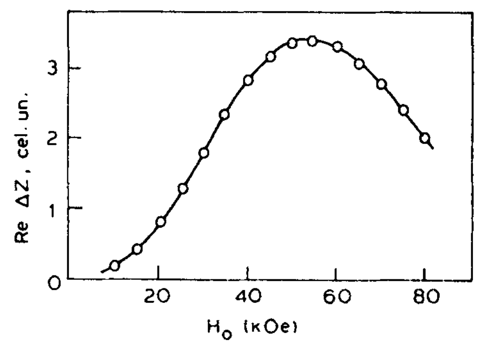

Figure 3. Field dependence of the amplitude of the acoustic resonance of the transverse ultrasound in white tin plate. $q \| [100]$, $p \| [001]$, $T = 4$ K.

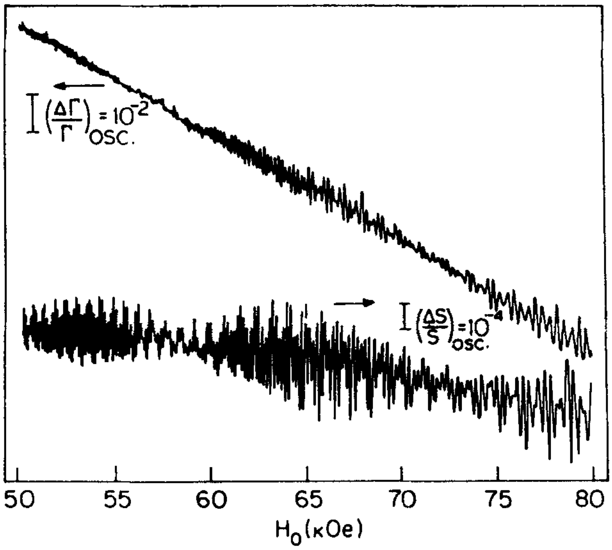

Figure 4. Field dependences of the velocity and attenuation of transverse ultrasound in white tin ($T=4$ K).

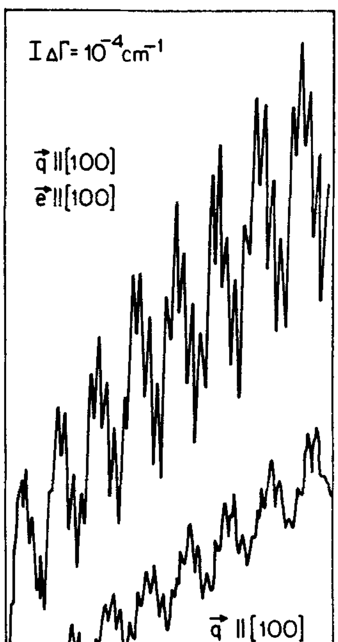

Figure 5. Quantum oscillations of the attenuation coefficient for a transverse ultrasound of different polarizations in white tin. H∥[100], $T=4$ K.

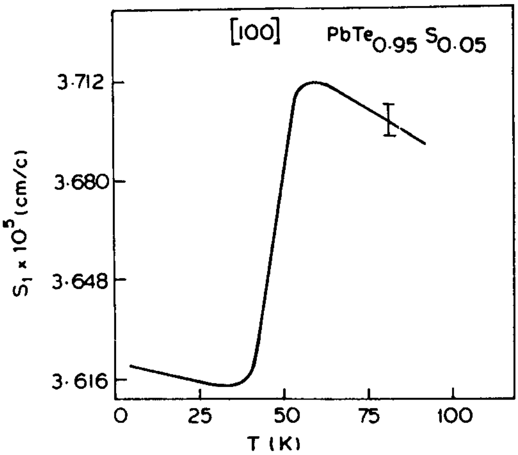

Figure 6. Temperature dependences of the velocity of longitudinal ultrasound in $PbTe_{0.95}S_{0.05}$.

surface of the sample under investigation and use one of the above mentioned methods. An example of such an investigation is shown in figure 6. By the noncontact acoustic methods anomalies were found in the velocity and attenuation of longitudinal and transverse sound due to ferroelectric transition in the semiconductor compound $PbTe_{0.95}S_{0.05}$.

We think that a further development of research in the field of electromagnetic generation of ultrasound in metals will be associated with the study of the phenomenon itself and to greater extent with its ever wider use in laboratory practice and in industrial application.

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