Electromagnetic excitation of sound in metals

A. N. Vasil'ev and Yu. P. Gaĭdukov

M. V. Lomonosov Moscow State University

Usp. Fiz. Nauk **141**, 431–467 (November 1983)

Excitation of sound oscillations in a metal by an electromagnetic wave incident on its surface is investigated. An analysis is presented of the different mechanisms of contactless conversion in the limit of local conductivity and under the conditions of the anomalous skin-effect. It is shown that in a sufficiently intense magnetic field when the cyclotron radius of the electron orbit is small compared to the wavelength of sound the principal role in the processes of conversion is played by inductive coupling. In the absence of a constant magnetic field the dynamic equilibrium between forces exerted on the lattice by the electrons and by the external field may be upset by the scattering of electrons at the metal boundary. The mechanism of excitation due to the diffuse scattering of electrons at the surface is very important in the UHF range. The special features of electromagnetic excitation of sound in semimetals, superconductors and ferromagnetic substances have been determined. The essential role of the forces exerted on the lattice by the electrons removed from the state of equilibrium is determined in semimetals by the large value, compared with normal metals, of the ratio of the deformation potential tensor to the Fermi energy. The technique of contactless excitation of sound is of interest as one of the methods of acoustic NMR and can be used to study different kinds of coupling of collective excitations in metals with sound waves. This refers both to the study of geometric and cyclotron resonances in the case of electromagnetic excitation of sound, and also to the problem of studying the helicon-phonon and the doppleron-phonon resonances and the coupling with collective modes in ferromagnetic substances.

PACS numbers: 43.35.Rw, 72.55. + s

CONTENTS

1. INTRODUCTION

Excitation of sound oscillations in a metal by an electromagnetic wave incident on its surface is at present the subject of intense experimental and theoretical study. Investigation of the processes of electromagnetic excitation (EME) represents an independent and rapidly developing direction of solid state physics. Work in this direction enables us to achieve a deeper understanding of electron-phonon interactions in metals, while EME as a method is used widely in carrying out various acoustic investigations.

In contrast to the traditionally used technique of exciting ultrasound in metals by using piezoelectric or magnetostrictive transducers the method of electromagnetic excitation does not require establishing direct acoustic contact with the sample. In addition to the fact that making such a contact presents definite difficulties at superlow or high temperatures and at frequencies in the UHF range it is highly undesirable in working with perfect single crystals of metals. The method of contactless excitation of sound has no fundamental limitations on frequency or temperature and in certain cases enables one to carry out measurements that are in accessible to other methods.

Electromagnetic excitation of sound at the boundary of a metal is associated with forces acting on the crystal lattice. This phenomenon combines the characteristic features of magnetoacoustic effects and electromagnetic interactions.

 0038-5670/83/110952-22$01.80

Propagation of sound waves in a metal is accompanied by the appearance of an electromagnetic field as a result of the fact that the electron subsystem is brought away from equilibrium. In its turn the perturbation of the electrons by an external electromagnetic field leads to the appearance of elastic stresses in the metal. Together with the direct action of the electric field on the ions of the lattice an essential role in the EME processes is played by forces exerted on the lattice by the electrons brought out of equilibrium.

Over a wide range of frequencies, magnetic fields and temperatures different mechanisms of contactless conversion of electromagnetic and sound waves come into play at the metal boundary. Nevertheless they can be discussed within the framework of a single approach based on a detailed analysis of the drag on the crystal lattice exerted by the conduction electrons.[1,2] The complete system of equations describing the problem includes the Maxwell equations, the kinetic equation for the electron distribution function, the equations of elasticity with the forces exerted on the lattice by the electrons taken into account, and the boundary conditions at the metal surface. In the dynamical equations of the theory of elasticity the interaction of the electrons with the lattice is described by additional volume forces. In the general case the equation of forced sound oscillations can be written in the form

$$\rho \frac{\partial^2 \xi_i}{\partial t^2} = \frac{\partial \sigma_{ik}}{\partial x_k} + \mathbf{F}_i, \qquad (1)$$

where the exciting force is

$$\mathbf{F}_i = \frac{1}{c}\,[\mathbf{j},\ \mathbf{H}_0]_i - \frac{m}{e}\frac{\partial j_i^{\text{эл}}}{\partial t} - \frac{\partial}{\partial x_k}\langle \Lambda_{ik}\chi\rangle; \qquad (2)$$

here $j = j - en\,\partial\xi/\partial t$ is the total current, $\Lambda_{ik} = \lambda_{ik} - \langle\lambda_{ik}\rangle/\langle 1\rangle$ is the renormalized tensor of the deformation potential of the electrons in the metal, χ is the nonequilibrium increment to the electron distribution function. The first term in $\mathbf{F}_i$ represents the momentum transferred to the electrons and the lattice from the external field per unit time (taking into account the overall electrical neutrality of the system), and the remaining terms describe the momentum carried away by the electrons; $(m/e)\partial\mathbf{j}/\partial t$ is the change in the momentum of the electrons situated in the given volume element. The deformation force $-\partial/\partial x_k\langle\Lambda_{ik}\chi\rangle$, introduced into the equations of the theory of elasticity by Silin,[3] and also the current **j** have the nature of an electron current. In actual fact Λ_{ik} contains only that part of the force which is due to the deviation from local equilibrium. The equilibrium part is included in the renormalization of the stress tensor σ_{ik}. The tensor of the deformation potential combines two physically different mechanisms of forces exerted by the electrons on the lattice.[4,5] The term $-(\partial/\partial x_k)\langle\Lambda_{ik}\chi\rangle$ describes both the momentum carried away by the free motion of the electrons into other volume elements, and the momentum transferred to the lattice when work is done in deforming it.

The role played by the different components of the force $\mathbf{F}_i$ in the processes of EME of sound depends on the external parameters of the problem: the frequency, the temperature, the magnetic field and on the kinetic characteristics of the metal and the structure of its Fermi surface. At low frequencies in a sufficiently strong magnetic field when the cyclotron radius of the electron orbit is small compared to the wavelength of sound the principal role in the interaction of the electrons with sound is played by the inductive mechanism.[6] Therefore in the expression (2) one can retain only the Lorentz force, and neglect the deformation force. Excitation of sound in metals by the Lorentz force has been investigated in detail by Kontorovich *et al.*[7,8] This mechanism of EME is one of the more promising ones from the point of view of practical application. As one of the first attempts to utilize the contactless method one can cite the experimental work of Randall, Rose and Zener[9] who studied interval friction in alloys. As shown in Fig. 1 the sample being investigated was placed between the poles of a permanent magnet. The exciting and receiving inductive coils placed at the ends of the sample were connected respectively to a generator and a receiver of electromagnetic oscillations. The excitation of longitudinal sound waves in the sample occurred as a result of the Lorentz interaction between the current induced in the skin layer of the metal with the nonaxial component of the constant magnetic field. The inverse process, i.e., the generation of electromagnetic waves by sound, provided the possibility of recording acoustic oscillations. The same phenomenon was observed in the experiments of Aksenov, Vikin and Vladimirskiĭ[10] on the study of nuclear magnetic resonance with the sound oscillations being excited directly in the wire of which the coil of the NMR-spectrometer was made.

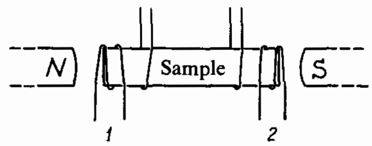

FIG. 1. Block diagram of the experiment on the excitation of longitudinal sound in a metal.[9] The sample was suspended by silk threads at the nodes of the acoustic oscillations. 1,2 are the exciting and receiving coils.

The excitation of transverse sound by an electromagnetic wave in the absence of a constant magnetic field was investigated for the first time by Kaganov and Fiks[11,12] and Kaganov, Fiks and Shikina.[13] In the absence of the field H_0 in a homogeneous metal dynamic equilibrium is observed between forces exerted on the lattice by the electrons and the external field. In an inhomogeneous metal the equilibrium can be disturbed. This occurs under the conditions of the anomalous skin-effect and on scattering of electrons at the metal boundary. In the case of reflections from the boundary a part of the momentum of the conduction electrons is transferred to the lattice, as a result of this an additional δ-like force appears at the boundary. We know that in the case of specular reflection from the boundary the force is zero. The mechanism of excitation due to diffuse scattering of electrons at the surface becomes important at frequencies in the UHF range.

The equations of the theory of elasticity,[1] as applied to the problem of EME of sound in semimetals, were utilized in the articles by Kravchenko,[14] Babkin, Dolgopolov and Kravchenko[15] and Babkin and Kravchenko.[16] The significant role played by the deformation interaction in semimetals is determined by the large, compared with normal metals, value of the ratio $\lambda_{ik}/\varepsilon_F$.

In a number of theoretical papers[17–23] the calculation of the forces exerted on the lattice by the electrons taken out of equilibrium was carried out "from first principles" without introducing the tensor of the deformation potential. In the case of a consistent carrying out of the calculations for metals with an arbitrary dispersion law both these approaches give results in agreement with each other.

The results of investigations of contactless excitation of sound in metals carried out prior to 1972 have been reported in the reviews by Wallace[24] and Dobbs.[25] The work carried out up to the present has significantly extended the realm of phenomena realized in the case of electromagnetic excitation of sound. The regularities governing EME have been established in the local limit $l/\delta \ll 1$ (δ is the thickness of the skin layer, l is the mean free path of the carriers) and in the regime of the anomalous skin-effect. The main features of the excitation of ultrasound in the UHF range have been determined and the mechanisms of conversion in superconductors, semimetals and ferromagnetic substances have been established.

The authors of the present review have as their aim to present the principal results of experimental and theoretical work in this field, carried out up to the present, and also to note a number of problems requiring further investigation.

2. ELECTROMAGNETIC EXCITATION OF SOUND IN METALS IN THE LOCAL LIMIT

In the local limit the excitation of sound by an electromagnetic wave incident on the metal surface is possible only in the presence of a constant magnetic field H_0. In spite of the fact that the technique of contactless excitation has been utilized for a comparatively long time for the study of different physical parameters of metals, the experimental investigation of the phenomenon itself began in 1966–1967 in the work of Gantmakher and Dolgopolov on bismuth[26,27] and of Larsen and Saermark on aluminum.[28,29] Experiments on bismuth are discussed below in analyzing EME in semimetals. In the work of Larsen and Saermark a sharp increase in the amplitude of quantum oscillations of the surface impedance of single crystal aluminum disks was observed at frequencies corresponding to the establishment of standing waves across its thickness. The phenomenon was observed in a strong magnetic field at helium temperatures and, although in the experiment the condition of equality of the phase velocities of the two types of waves was not fulfilled, it was interpreted by the authors as the result of the helicon-phonon interaction. Nevertheless this erroneous assumption was fated to play a positive role in the early stages of investigation of EME in metals—many investigations were directed, in particular, towards proving the inadequacy of this assertion. In the experiments of Houck *et al.*[30] and Betjemann *et al.*[31] it was shown that excitation of sound by an electromagnetic wave occurs over a wide range of frequencies and of magnetic fields and depends only weakly on the temperature in the range from 4.2 to 300 K. Generation of sound was observed both in compensated metals and in uncompensated ones, including the situation when the propagation of helicons is impossible due to doppler-shifted cyclotron resonance. In Ref. 31 it was also noted that excitation of transverse sound occurs in a geometry when the constant magnetic field is perpendicular to the surface of the metal and coincides in direction with the propagation of sound $\mathbf{q}_t \parallel \mathbf{H}_0$. Excitation of longitudinal sound was observed in a magnetic field parallel to the surface of the metal with $\mathbf{q}_l \perp \mathbf{H}_0$.

In its general outline the theory of the conversion of electromagnetic and sound oscillations at the boundary of a conducting medium is presented in Refs. 7, 8 and as applied to plane parallel plates in Ref. 14. The theory of EME in the limit of $l/\delta \ll 1$ was also developed in papers of Refs. 17, 18, 32–35 and is described in detail in the reviews of Refs. 24, 25.

If a constant magnetic field is applied parallel to the surface of the metal and perpendicular to the direction of the alternating current $\mathbf{j}$ 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 rearrange themselves in such a way that within the volume of the metal the condition of local electric neutrality would be satisfied. As a result of this 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 connected with the fact that under the action of the electric field of the wave the electrons and the ions of the lattice in the skin layer acquire oppositely directed momenta and Lorentz force deflects these particles in the same direction. Moreover the electrons colliding with the lattice transfer to it an additional momentum along the metal surface.

When the waves are propagated along a symmetry axis of the third (or higher) order longitudinal and transverse acoustic oscillations are separated, and the velocities of both transverse waves coincide. 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

$$\frac{\partial^2\xi}{\partial t^2} - S^2\frac{\partial^2\xi}{\partial z^2} = \frac{1}{\rho c}[\mathbf{j}, \mathbf{H}_0], \tag{3}$$

where ξ is the displacement vector, S is the sound velocity, ρ is the metal density, and c is the velocity of light.

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

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

where H is the amplitude of the alternating magnetic field, $\delta = c/\sqrt{2\pi\omega\sigma}$, σ is the conductivity of the metal and ω is the frequency.

In order to find the amplitude of the excited sound we substitute expression (4) into the wave equation

$$\frac{\partial^2\xi}{\partial z^2} + q^2\xi = -\frac{H_0H(1+i)}{4\pi\rho S^2\delta}\exp\left[-(1+i)\frac{z}{\delta}\right], \tag{5}$$

where $q = 2\pi/\lambda$, λ is the wavelength of the sound wave. At distances great compared to the thickness of the skin layer the solution has the form[24]

$$|\xi| = \frac{H_0 H}{4\pi\rho S\omega}\frac{1}{\sqrt{1+\beta^2}}, \tag{6}$$

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 sound on the temperature.

The efficiency of contactless conversion of electromagnetic and sound energy can be defined as the ratio of the flux of acoustic energy $\rho S\omega^2\xi^2/2$ to the average value of the Poynting vector of the electromagnetic wave at the surface of the metal $\omega\delta H^2/16\pi$. According to (6) the efficiency of conversion η is equal to

$$\eta = \frac{H_0^2}{2\pi\rho S\omega\delta}\frac{1}{(1+\beta^2)}. \tag{7}$$

Estimates[25] show that in aluminum at room temperature at a frequency of 10 MHz in a field of 10 kOe the efficiency of conversion η is approximately 10^{-4}, i.e., from one watt of electromagnetic energy absorbed by the metal approximately 100 microwatts goes into sound excitation. For comparison we note that the efficiency of conversion of a quartz transducer is approximately 10^{-2}.

From the point of view of the intensity of sound excited by the contactless method the most effective is generation of standing sound waves in plane parallel metal plates. In this case the sample under investigation is placed in an inductor coil which in turn is a part of an oscillatory circuit or is connected to a bridge circuit. In this case the electromagnetic field on opposite sides of the plate satisfies the conditions of antisymmetric excitation.

Let us consider the excitation of standing sound waves in a plane parallel plate. In the case of a thin skin layer the spatial distribution of the exciting force is given in the first approximation by a δ-function:

$$F(z) = -\frac{H_0 H}{4\pi}[\delta(z) - \delta(z-d)], \tag{8}$$

where d is the plate thickness. With the boundary condition corresponding to a free metal surface,

$$\left.\frac{d\xi}{dz}\right|_{z=0,\,d} = 0, \tag{9}$$

the wave equation for an isotropic medium or for a case when the direction of propagation coincides with one of the principal crystallographic axes takes on the form

$$\frac{\partial^2\xi}{\partial z^2} + \left(\frac{i\omega\gamma}{S^2} + \frac{\omega^2}{S^2}\right)\xi = \frac{H_0 H}{4\pi\rho S^2}[\delta(z) - \delta(z-d)], \tag{10}$$

where γ is the damping coefficient for sound. The solution of the wave equation (10) can be written in the form

$$\xi(z) = \frac{H_0 H}{2\pi\rho d}\sum_{m=1}^{\infty}\frac{(1-\cos m\pi)\cos(\omega_m z/S)}{\omega^2 - \omega_m^2 + i\gamma\omega}, \tag{11}$$

where $\omega_m = m\pi S/d$, m is an integer.

The establishment of standing sound 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. In order to estimate the amplitude of these singularities we calculate the amplitude of the electromagnetic wave radiated from the surface of the metal. The increment in the electric field due to the propagation of sound in the metal is given by the expression

$$\Delta \mathbf{E} = \frac{1}{c}\left[\frac{\partial\xi}{\partial t}, \mathbf{H}_0\right]. \tag{12}$$

In particular, there is on the surface of the metal an alternating electric field the amplitude of which is proportional to the velocity of displacement of the ions of the lattice on the surface and to the constant magnetic field. Since the tangential component of the electric field is continuous across the boundary of the two media an electromagnetic wave is radiated from the surface of the metal, the electric vector of which is determined by expression (12). The radiated wave alters the reflectivity of the metal and consequently its surface impedance.

In the general case the electric field acting on the surface of the metal can be represented as the sum of the electric field in the absence of the sound wave E_0 and a resonance increment associated with the excitation of sound. In this case the surface impedance is given by

$$Z = \frac{E_0 + \Delta E_{\rm res}}{I_0} = Z_0 + \Delta Z_{\rm res}, \tag{13}$$

where I_0 is the current in the skin layer. Taking into account expression (11) the resonance increment to the surface impedance of the plate can be written in the form

$$\Delta Z_{\rm res} = \frac{2i\omega}{\rho d}\frac{H_0^2}{c^2}\sum_{m=1}^{\infty}\frac{1-\cos m\pi}{\omega^2 - \omega_m^2 + i\gamma\omega}. \tag{14}$$

Expression (14) is obtained on the assumption that $\beta \to 0$. As the frequency, the magnetic field or the temperature is varied the spatial distribution of the exciting force also varies. In the case of finite thickness of the skin layer the expression for $\Delta Z_{\rm res}$ can be brought to the form

$$\Delta Z_{\rm res} = \frac{2i\omega}{\rho d}\frac{H_0^2}{c^2}\frac{1+i\beta}{1+\beta^2}\sum_{m=1}^{\infty}\frac{1-\cos m\pi}{\omega^2 - \omega_m^2 + i\gamma\omega}. \tag{15}$$

From this expression in particular it follows that the resonance increment to the surface impedance is a mixture of absorption and dispersion signals and that

$$\left.\frac{\operatorname{Im}\Delta Z_{\rm res}}{\operatorname{Re}\Delta Z_{\rm res}}\right|_{\omega=\omega_m} = \beta.$$

The results of the classical theory of the EME of sound in metals presented above were subjected to exhaustive experimental verification. A block diagram of one of the most frequently utilized methods of contactless excitation is shown in Fig. 2. The exciting coil is placed near the surface of a sample situated in a constant magnetic field. A piezoelec-

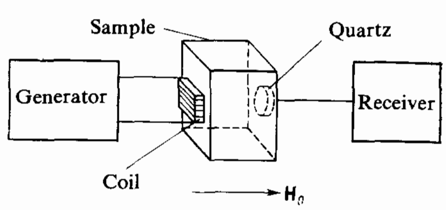

FIG. 2. Method of investigating EME at frequencies in the megahertz range.

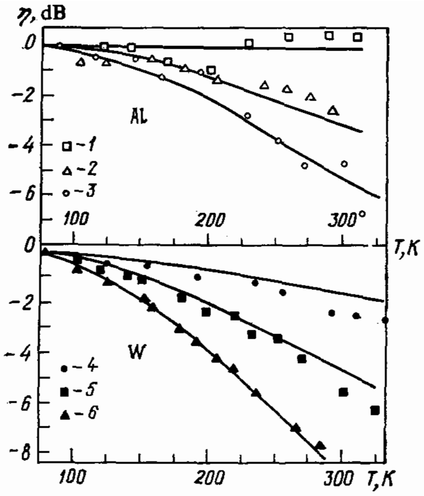

FIG. 3. Temperature dependences of the efficiency of EME of transverse sound in aluminum (1, 2, 3–10; 51.2; 70.5 MHz) and in tungsten (4, 5, 6–12.9; 24.2; 36.8 MHz[36]). The theoretical curves are shown by solid lines.

tric transducer is attached to the opposite surface. The measurements are usually made in a pulsed regime and it is also possible to use a second coil instead of a transducer as a detector of the sound oscillations in the metal. Excitation of sound by this method was produced in different metals in the frequency range up to 500 MHz and in magnetic fields up to 150 kOe. Confirmation was obtained of the dependence (6) of the amplitude of the excited sound on the magnetic field, density and the velocity of sound in the metal. Measurements of the amplitude of the excited sound as a function of frequency and temperature have been made by Gaerttner *et al.*[36] These data are shown in Fig. 3 and demonstrate sufficiently good agreement with the above theory. The technique of contactless excitation was used to generate circularily polarized sound waves[37] and were utilized by Gaerttner and Maxfield[38] in an experiment on the excitation of longitudinal sound in liquid metals. For a liquid that wets the walls of the vessel the boundary condition for the fixed surface $\xi|_{z=0} = 0$ influences significantly the efficiency of conversion of electromagnetic and sound energy, in this case $\eta_{\text{fix}} = \eta_{\text{free}}$.

A study of the resonance singularities of the surface impedance of metallic plates associated with the establishment of standing sound waves across their thickness has also been widely used for investigating the EME. Fig. 4 shows records of $\operatorname{Re}\Delta Z_{\text{res}}$ and $\operatorname{Im}\Delta Z_{\text{res}}$, observed by Lyall and Cochran[39,40] in plates of gallium. The experimental records agree well with the dependences calculated according to equation (15).

In Refs. 41–43 it was shown in investigations of surface impedance of single crystals of tin that a sharp increase in the amplitude of the quantum oscillations of the surface impedance at the resonance frequencies observed by Larsen and Saermark[28,29] is due primarily to the quantum oscillations of the velocity of sound[1)]. The experimental records are shown

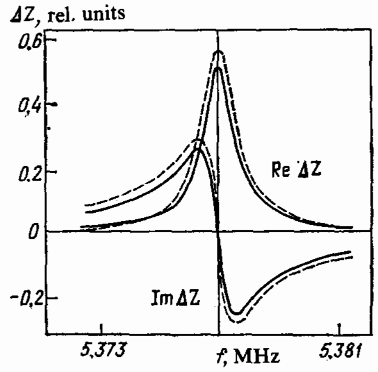

FIG. 4. The real $\operatorname{Re}\Delta Z$ and the imaginary $\operatorname{Im}\Delta Z$ parts of the resonance increment to the surface impedance of a gallium plate.[39] The broken lines show dependences calculated in accordance with formula (15).

in Fig. 5. For the absorption and dispersion signals described by Lorentz lines in the case of the velocity oscillations the amplitude of the oscillations $\partial \operatorname{Re}\Delta Z/\partial H_0$ at the resonance frequency is minimal, while $\partial \operatorname{Im}\Delta Z/\partial H_0$ is maximal, and this was observed experimentally. A study of the quantum oscillation of the velocity and damping of sound by the contactless method was continued in Refs. 44–47. In particular in Ref. 47 an autogenerator is described for the investigation of the damping and the dispersion of sound in metals. In this apparatus the excitation and the reception of acoustic oscillations in the plate is effected by two coils surrounding the sample. The transmission characteristic of such a system in a magnetic field has resonance singularities at frequencies corresponding to the excitation of standing sound waves in the plate. This enables one to construct an autogenerator operating at resonance frequencies. In the absence of a magnetic

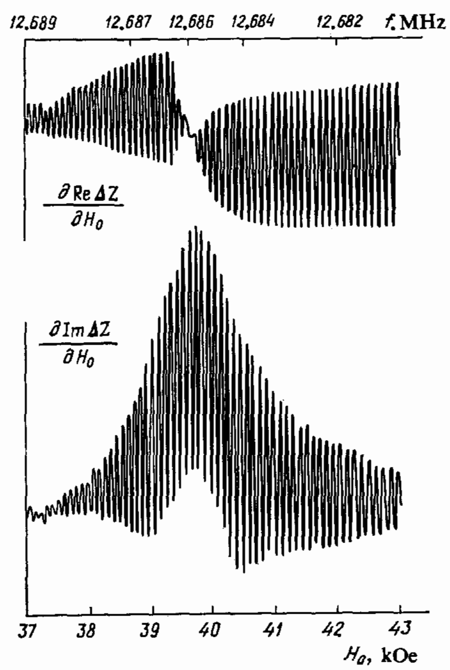

FIG. 5. Dependences of the amplitude of quantum oscillations $\partial \operatorname{Re}\Delta Z/\partial H_0$ and $\partial \operatorname{Im}\Delta Z/\partial H_0$ of the magnetic field at the frequency of acoustic resonance in a tin plate.[43]

[1)]A detailed analysis of the effect of the magnetic field on the velocity of propagation of sound waves in metals has been carried out by Rodriquez.[137,138]

field the coupling coefficient between the coils is chosen below the threshold for self-excitation of the generator. When a magnetic field is introduced the coupling between the coils due to the conversion of electromagnetic and acoustic waves in the metal is increased, and this leads to generation at the frequency of the acoustic resonance of the sample. The frequency of generation is determined by the velocity of the sound wave in the metal, the amplitude of the generation brings information on the damping of the sound and on the efficiency of conversion of electromagnetic and acoustic waves at the surface.

Already at the earliest stages of its use in experimental practice the phenomenon of EME found wide application in the field of nondestructive testing of materials. In Refs. 48–50 different variants of the measuring devices were proposed designed primarily for quality control of surface finish and of discovering volume defects of industrial manufactured items.

3. ELECTROMAGNETIC EXCITATION OF TRANSVERSE SOUND UNDER CONDITIONS OF ANOMALOUS SKIN-EFFECT

As the temperature is decreased conditions in pure metals can be realized corresponding to the two inequalities $l/\delta > 1$, $\delta < \lambda$ being satisfied. In the regime of the anomalous skin-effect excitation of transverse sound in a metal is possible in the absence of a constant magnetic field. The mechanism of EME in weak fields and in the absence of the field H_0 can be represented in the following manner.[11] Electrons situated in the skin layer are accelerated by the electric field of the electromagnetic wave and by collisions transfer the excess momentum to the lattice. Moreover, the ions of the lattice experience the direct action of the electric field in the skin layer. Excitation of sound at the surface of the metal can occur if these two forces are locally unbalanced. In the absence of the field H_0 this occurs when the mean free path of the carriers 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 stress on the lattice due to a displacement. In the isotropic case transverse sound excited in the absence of a constant magnetic field is polarized along the vector of the electric field in the skin layer. When the field H_0 is introduced the "magnetic" component of transverse sound ξ_H polarized along the vector of the alternating magnetic field at the surface is also excited under the action of the Lorentz force in addition to the "electric" component ξ_E.

One of the first experiments on the excitation of transverse sound under conditions of the anomalous skin-effect was that of Gaerttner, Maxfield and Wallace[51] using single crystals of tungsten and aluminum. In the absence of the field H_0 excitation of the electric component of the sound wave was observed. Subsequent to this Thomas, Turner and Hsu[52,53] carried out experiments on the EME of transverse sound in potassium. In weak fields $\omega_c/qv_F < 1$ (ω_c is the cyclotron frequency, v_F is the Fermi velocity of the carriers) the amplitudes of both the electric and the magnetic components of the excited sound depended on the magnetic field nonlinearly. These dependences are shown in Fig. 6. The amplitude of the magnetic component ξ_H increased with increasing H_0, but in weak fields significant deviations from a linear dependence were observed. The amplitude of the electric component ξ_E decreased with increasing magnetic field.

A qualitative analysis of the experimentally observed dependences was made by Turner, Thomas and Hsu[53] within the framework of the free electron model. Following this paper, in order to describe the EME of sound under the conditions of anomalous skin-effect, we write the Maxwell equations for circularly polarized components of the electromagnetic field at the surface of the metal. In the Fourier representation they have the form

$$j_\pm \pm \frac{ic}{4\pi^2} H_\pm = i\beta\sigma_0 E_\pm, \qquad (16)$$

where the current is $j_\pm = j_x \pm ij_y$. Each of the components of the current $j_\pm$ is the sum of the electronic $j_{e\pm}$ and ionic $j_{i\pm}$ components. Utilizing the kinetic equation the expression for the current density can be brought to the form

$$j_\pm = ine\omega\xi_\pm + \sigma_\pm \left(E_\pm - \frac{m}{\tau e}\frac{\partial \xi_\pm}{\partial t}\right); \qquad (17)$$

here $\sigma_\pm = \sigma_{xx} \mp i\sigma_{xy}$ are the circular components of the conductivity tensor of a metal in a magnetic field. Equations (16), (17) enable us to derive the relation between the amplitude of the displacement of the ions and the electromagnetic field at the surface:

$$E_\pm = \frac{ine\omega}{\sigma_0}\frac{\sigma_\pm - \sigma_0}{\sigma_\pm - i\beta\sigma_0}\xi_\pm \mp \frac{ic}{4\pi^2}\frac{H_\pm}{\sigma_\pm - i\beta\sigma_0}. \qquad (18)$$

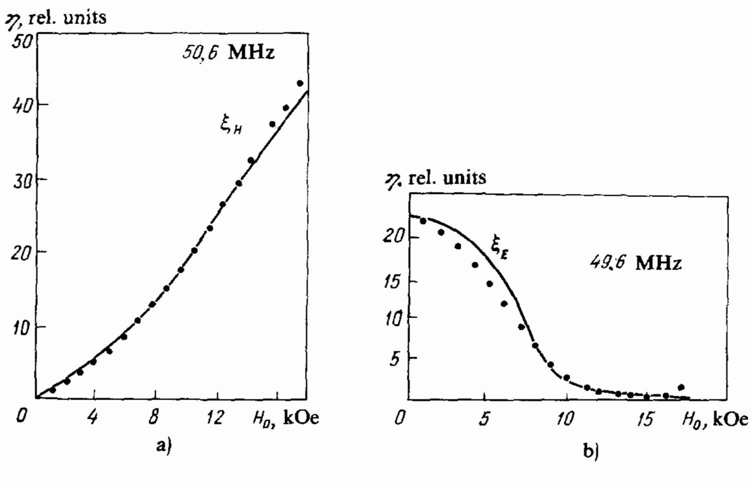

FIG. 6. Field dependences of the efficiency of excitation of magnetic ξ_H (a) and electrical ξ_E (b) components of transverse sound in potassium.[53]

The expression for the forced sound oscillations in the case of an isotropic medium can be written in the form

$$M\frac{\partial^2\xi_\pm}{\partial t^2}=$$
$$MS^2\frac{\partial^2\xi_\pm}{\partial z^2}+ZeE_\pm\mp\frac{Ze}{c}iH_0\frac{\partial\xi_\pm}{\partial t}-\frac{Zm}{ne\tau}\left(j_e+ne\frac{\partial\xi_\pm}{\partial t}\right), \quad (19)$$

where M, Ze are the mass and the charge of the ion, m, n are the mass and the concentration of the charge carriers, τ is the relaxation time. The third term on the right hand side of the wave equation represents the Lorentz force acting on the ions. The last term is due to the collisions of the electrons with the moving ions of the lattice. A Fourier transformation of equation (19) taking into account the boundary conditions corresponding to the free surface of the metal enables us to obtain the relation

$$\left[q^2S^2-\omega^2\left(1\pm\frac{\omega_c}{\omega}+A_\pm\right)\right]\xi_\pm=\frac{\omega}{\pi i}B_\pm, \quad (20)$$

where the following notations have been introduced

$$A_\pm=\frac{Zmi}{M\tau\omega}\frac{(1-i\beta)(1-\sigma_0/\sigma_\pm)}{1-i\beta\sigma_0/\sigma_\pm}, \quad (21)$$

$$B_\pm=\mp\frac{Zec}{4\pi M\sigma_0\omega}\frac{1-\sigma_0/\sigma_\pm}{1-i\beta\sigma_0/\sigma_\pm}H_\pm. \quad (22)$$

At distances great compared with the thickness of the skin layer the inverse Fourier transformation of equation (20) yields the solution of the problem:

$$\xi_\pm=\frac{B_\pm}{S}\exp\left[-\frac{i\omega z}{S}\left(1\pm\frac{\omega_c}{2\omega}+\frac{A_\pm}{2}\right)\right]. \quad (23)$$

In the case of a thin skin layer when terms containing the parameter β can be neglected (23) reduces to

$$\xi_\pm=\mp\frac{cZe}{4\pi M\sigma_0\omega S}\left(1-\frac{\sigma_0}{\sigma_\pm}\right)H_\pm. \quad (24)$$

Going over to linearly polarized sound we represent (24) in the form

$$\xi_\pm\sim(\mp a-ib)H_\pm, \quad (25)$$

where a and b are the real and the imaginary parts of the expression $(1-\sigma_0/\sigma_\pm)$. The magnetic component of the sound being excited is $\xi_H\sim bH$, while the electric component is $\xi_E\sim aH$.

Thus, within the framework of the free electron model the real and the imaginary parts of $[1-(\sigma_0/\sigma_\pm)]$ determine the displacement of the lattice respectively along the vectors of the alternating electric and magnetic fields at the surface. In the local limit $\sigma_0/\sigma_\pm=1\mp i\omega_c\tau$ the magnetic component of the displacement ξ_H reduces to the form (6) obtained earlier.

While the experimental data of Refs. 52, 53 demonstrated qualitative agreement with the above model the precision measurements of Wallace *et al.*[54] demonstrated significant quantitative differences between theory and experiment. These investigations were also carried out on a single crystal of potassium at helium temperatures. Experimental data and a calculation using the free electron model are shown in Fig. 7. In strong magnetic fields $\omega_c/qv_F>1$ the amplitude of the magnetic component ξ_H increases linearly with increasing H_0, asymptotically approaching the calculated dependence. In weak fields the experimentally measured dependence lies significantly below the theoretical one, and near the Kjeldaas threshold $\omega_c/qv_F=1$ the amplitude of the magnetic component even decreases with increasing H_0. Such a dependence cannot be explained within the framework of the above model. The field dependence of the electric component ξ_E qualitatively is the same as the theoretical one, however the experimentally measured amplitude of ξ_E at $H_0=0$ exceeds the calculated value by approximately a factor of seven.

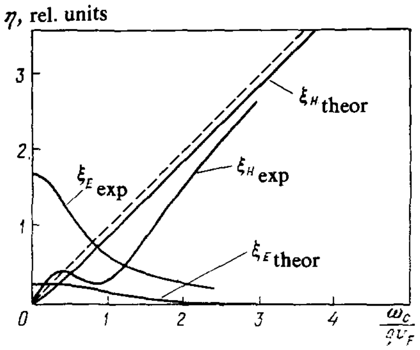

FIG. 7. Field dependences of the efficiency of excitation of different components of transverse sound in potassium at $T=4.2$ K.[54] Theoretical dependences of $\xi_{H_{theor}}$ and $\xi_{E_{theor}}$ were calculated for $ql=1.9$. The broken line is an extrapolation of the linear dependence of ξ_H in strong fields.

Additional proof of a significant deviation from the free electron model was obtained in the paper by Chimenti *et al.*[55] Measurements were made on potassium with both the excitation and the detection of sound carried out with the aid of spiral coils situated near the surface of the sample. The experimental geometry utilized did not permit carrying out separate measurements of the electric and magnetic components of the sound being excited. The reason for this is the totally symmetric nature of the process of generation and detection of sound. The quantity being measured in such an experimental arrangement—the voltage on the receiving coil—is proportional to the sum of the squares of the two components $u\sim\omega^2(|\xi_E|^2+|\xi_H|^2)$. The experimentally measured dependence on the magnetic field of the amplitude of the sound being excited is shown in Fig. 8. The shaded region represents the boundaries of the theoretically possible dependences according to the free electron model. The experiment is not described by the free electron model for any val-

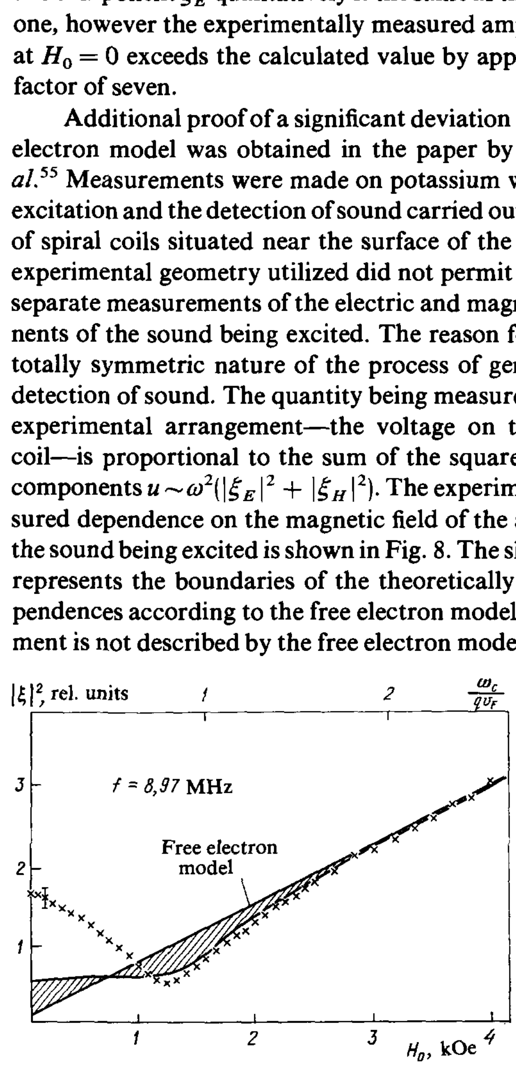

FIG. 8. Dependence of the amplitude of the sound being excited $|\xi|^2=|\xi_H|^2+|\xi_E|^2$ on the magnetic field in potassium.[55] The shaded region represents the boundaries of applicability of the free electron model.

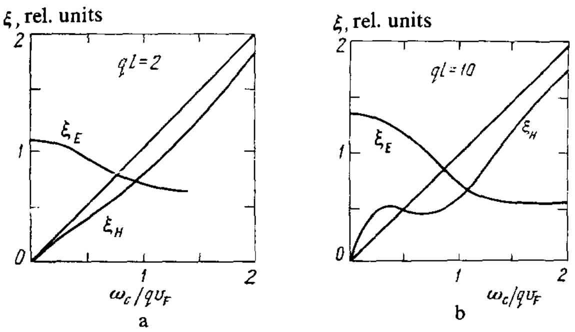

FIG. 9. Calculated dependences of the amplitude of the displacements ξ_H and ξ_E on the magnetic field[57] for $ql = 2$ and $ql = 10$.

ues of the adjustable parameter ql. Considerable deviations from the theory were also observed in experiments on aluminum.[56]

A number of theoretical investigations[57–62] have been devoted to the analysis of the experimentally observed deviations from the free electron model. A common feature of all of them is the introduction of additional mechanisms determining the nonmonotonic field dependence of the amplitude of the transverse sound in weak fields.

Kaner and Fal'ko[57] solved the problem of the generation of sound in alkali metals taking into account the deformation interaction between the conduction electrons and the ions of the lattice. The deformation force leads to stresses which are the more effective the greater is the inhomogeneity of the electromagnetic field in the metal. The solutions of the problem obtained for different values of the parameter ql can be conveniently represented in graphical form. Fig. 9 shows the calculated dependences of the amplitudes ξ_H and ξ_E on the magnetic field for $ql = 2$ (Fig. 9a) and $ql = 10$ (Fig. 9b). For $ql = 2$ the function ξ_H (H_0) deviates noticeably from a straight line near the Kjeldaas threshold and approaches a straight line in strong fields. The experimental data of Refs. 52, 53 agree well with this calculated curve. As the parameter ql increases the value of the deformation force increases, and together with it the amplitude of the magnetic component ξ_H in weak fields also increases. The competition between the deformation and inductive mechanisms of EME determines the nonmonotonic dependence of ξ_H on the magnetic field. Calculation for $ql = 10$ yields good agreement with the data of Refs. 54, 55. However, it should be noted that the estimate of the parameter of nonlocality in the experiment is considerably lower $ql \approx 1.9$. As far as the field dependences of the amplitude of the electric component ξ_E of the sound being excited are concerned, qualitatively the calculations agree with experiment. Kaner and Fal'ko[57] made a suggestion that the observed discrepancies can be due to an additional force arising as a result of diffuse scattering of electrons at the metal surface. Although qualitatively taking diffusion scattering at the boundary into account does lead to the appearance of a minimum in the field dependence of the amplitude of the sound being excited, quantitative agreement with experiment is not obtained. Thus, in Refs. 62, 135 it was shown that under the conditions of the experiment of Chimenti *et al.*[55] (the frequency was 9 MHz, the mean free path of the carriers was 1.4×10^{-2} cm) the calculations for purely specular and purely diffuse scattering at the boundary differ by not more than 40%.

A renormalization of the efficiency of the inductive mechanism of excitation in metals with an arbitrary dispersion law was discussed by Banik and Overhauser.[59] In the absence of collisions the conduction electrons are not completely dragged by the lattice. If the lattice undergoes periodic motion with the velocity $\partial\xi/\partial t$, then in the case of an isotropic spectrum the carriers acquire an additional velocity

$$\Delta\mathbf{v} = \left(1 - \frac{m}{m^*}\right)\frac{\partial\xi}{\partial t}, \tag{26}$$

where m^* is the effective mass of the electron. The inductive force in this case has the form

$$\frac{1}{c}\left(1 - \frac{m}{m^*}\right)\left[\frac{\partial\xi}{\partial t},\ \mathbf{H}_0\right]. \tag{27}$$

Taking the renormalization of the inductive interaction into account the expressions for the electric and magnetic components of the sound being excited can be written thus:[59]

$$\xi_E = \frac{cH}{4\pi\omega\rho S}\,\frac{m}{m^*}\,\frac{(3\pi^2 n)^{1/3}\,\hbar\omega}{Seql}\left|\frac{\mathrm{Re}\,G}{|G|^2} - 1\right|, \tag{28}$$

$$\xi_H = \frac{cH}{4\pi\omega\rho S}\left|\frac{m}{m^*}\,\frac{(3\pi^2 n)^{1/3}\,\hbar\omega}{Seql}\,\frac{\mathrm{Im}\,G}{|G|^2} - \frac{H_0}{c}\left(\frac{m}{m^*} - 1\right)\right|, \tag{29}$$

where $G(q)$ is the function introduced by Kjeldaas[63] to describe the nonlocal electrical conductivity of the metal $\mathbf{j}_e = \sigma_0 G(q)\,\mathbf{E}$.

A comparison of the above expressions with results of the free electron model (23), (24) shows that the amplitude of the electric component ξ_E contains an additional fact of m/m^*. The expression for ξ_H also contains this factor and, moreover, includes the Lorentz term with the coefficient $[(m/m^*) - 1]$. This term either increases or diminishes the amplitude of ξ_H in weak fields depending on whether the ratio m/m^* is less than or greater than unity. A calculation of the effect of the renormalization of the Lorentz mechanism on the amplitude $|\xi| = \sqrt{|\xi_E|^2 + |\xi_H|^2}$ of the sound being excited in potassium for different values of the parameter m/m^* is shown in Fig. 10. The best agreement with experiment[55] is given by the dependence with $m/m^* = 2$. However, this value deviates strongly from the experimentally determined value of the effective mass in potassium $m/m^* = 0.83$.[2)]

Summarizing the foregoing results we should note that for the spherically closed Fermi surface of potassium the theory does not give an adequate description of the experimentally observed dependences. At the same time, taking into account the effective mass tensor in describing the EME in aluminum in the regime of the anomalous skin-effect[60,61] made it possible to obtain a sufficiently good agreement with experiment.

[2)]Kaner and Fal'ko[136] have pointed out the equivalence of the approaches of Refs. 57, 59 in the free electron approximation.

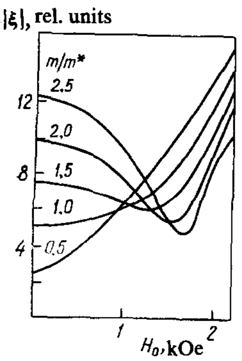

FIG. 10. Calculation of the effect of renormalization of the Lorentz mechanism on the amplitude $|\xi|$ of the sound being excited in potassium.[59] The calculation is made for $ql = 10$ at frequency of $f = 10$ MHz.

4. GEOMETRIC AND CYCLOTRON RESONANCES IN THE CASE OF ELECTROMAGNETIC EXCITATION OF SOUND IN METALS

Until now we have been considering the excitation of transverse sound in a magnetic field parallel to the direction of propagation of the wave. Excitation of transverse sound in a perpendicular magnetic field $\mathbf{H}_0 \perp \mathbf{q}$, was first observed in the experiment of Gaerttner and Maxfield[64] on a single crystal of silver. In this geometry in the regime $ql \gg 1$ oscillations of the efficiency of conversion were observed to be periodic in terms of the parameter $1/\lambda H_0$: In this experiment there were also simultaneously observed oscillations of the coefficient of sound absorption with the same period, with the phases of the oscillations of η and γ being slightly different. The experimental data are shown in Fig. 11. The oscillations were observed most distinctly in a magnetic field perpendicular to the direction of the electric field in the skin layer and corresponded to the geometrical resonance of Bömmel-Pippard for the electrons of one of the extremal sections of the Fermi surface of silver. A rise in the temperature of the crystal led to a rapid disappearance of oscillations, however the monotonic component of the efficiency of conversion varied slowly. This is related to the fact that the number of magnetoacoustic oscillations is in the first approximation proportional to l in the regime $ql \gg 1$, while the monotonic component depends comparatively weakly on the mean free path

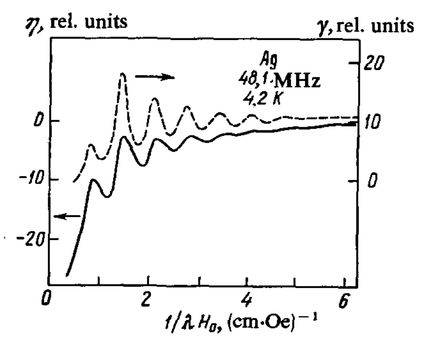

FIG. 11. Oscillations of the efficiency of EME of transverse sound in silver in a magnetic field perpendicular to the direction of propagation of the wave. The broken line shows oscillations of the coefficient of sound absorption.[64]

when the condition $ql > 1$ is satisfied. Gaerttner and Maxfield[64] made the suggestion that the oscillations of the efficiency of conversion are due to the interference of forces acting on the lattice in the skin layer and in the current sheets associated with the anomalous penetration of the field to distances that are integral multiples of the cyclotron diameter of the carriers in the magnetic field.

A qualitative analysis of the observed phenomenon was given by Babkin and Kravchenko.[66] They noted that under the conditions of the experiment of Ref. 64 the oscillations of the amplitude of the sound being excited are determined by the electrons of the extremal section of the Fermi surface perpendicular to the field H_0 that are gliding parallel to the surface of the sample. The solution of the problem reduces to the calculation of the distribution of the electric field in the metal taking into account the anomalous penetration and to the solution of the wave equation in which the exciting force is a functional of the electric field. In the case of a convex Fermi surface and of short sound waves $qR_c \gg 1$ the amplitude of the sound being excited in geometry $\mathbf{H}_0 \perp \mathbf{E} \| \mathbf{x}$ is determined by the expression[66]

$$\xi_x = -\frac{ieE}{\rho S\omega h^3}\left[\int \frac{dS_F}{v}\frac{v_x\lambda_{xz}}{v_z} + \overline{\omega_c\tau}\,\frac{2\lambda^0_{xz}\cdot p^0_x}{v_0}\sqrt{\frac{2\pi}{|qD''_0|}}\cos\left(qD_0-\frac{\pi}{4}\right)\right]; \tag{30}$$

here the direction of propagation of the sound coincides with the z axis, D_0 is the extremal diameter of the electron orbit corresponding to the section of the Fermi surface normal to H_0, the subscript 0 denotes the point of intersection of the orbit $\varepsilon(p) = \varepsilon_F, p_y = p_{y\,\mathrm{extr}}$ with the belt $v_z = 0$, $D'' = d^2D/dp_y^2$, the bar over $\omega_c\tau$ corresponds to averaging over the orbit.

The first term in (30) describes the contribution of all the electrons on the Fermi surface to the effect of generation. The second term describes the oscillations periodic in $1/\lambda H_0$, corresponding to the establishment on the diameter of the orbit of an integral number of half wavelengths of sound, i.e., to geometric resonance. The oscillations of the amplitude of the sound being excited are proportional to the value of the tensor of the deformation potential λ_{xz} at the point of the Fermi surface corresponding to the intersection of plane $p_x = p_{x\,\mathrm{extr}}$ with the belt $v_z = 0$. This provides the possibility to determine from the experimental data on the EME of sound the value of $\lambda_{ik}(p)$ on the Fermi surface.

The problem of the conversion of an electromagnetic wave into a sound wave in the geometry $\mathbf{q}, \perp \mathbf{H}$ taking into account the nature of the scattering of the electrons at the metal boundary was solved by Fal'ko.[67] In the case of purely diffuse scattering at the boundary the oscillating part $\tilde{\xi}_x$ is equal to

$$\tilde{\xi}_x \sim A_1 \frac{\cos(qD_0+\Delta)}{\sqrt{qD_0}}. \tag{31}$$

In the case of specular reflection we have

$$\tilde{\xi}_x \sim A_2 \frac{\cos(qD_0+\Delta)}{qD_0}; \tag{32}$$

A_1, A_2 are the amplitudes taking into account the value of the alternating electric field and the parameters of the metal being investigated. The exact form of A_1, A_2 is given in Ref. 67. The period and the phase Δ of the oscillations do not depend on the nature of the scattering of the electrons at the surface. The amplitude of the oscillations in the case of specular scattering is smaller by a factor of $\sqrt{qD_0} \gg 1$ than the amplitude of the oscillations in the case of diffuse scattering. The phase shift is associated with the fact that the oscillations of the conductivity which determine the anomalous penetration of the field into the sample and the oscillation of the coefficient of absorption of sound under the conditions of geometric resonance are shifted with respect to one another by $\pi/2$.

The problem of the conversion of electromagnetic and sound waves under the conditions of cyclotron resonance has been discussed by Fal'ko and Yampol'skiĭ.[68] They showed that the nature of the surface scattering of the carriers significantly affects the dependence of the amplitude of the sound being excited on the magnetic field. In the case of specular reflection the amplitude in the main approximation depends on the magnetic field monotonically. In the case of diffuse reflection the amplitude of the sound passes through a maximum in the region of intersection of sound and transverse cyclotron waves. In both cases cyclotron and geometric resonance should be observed with a small amplitude. It is shown in Ref. 68 that under the conditions of cyclotron resonance the main role in the processes of conversion is played by the deformation coupling. The induction force is small compared with it according to the parameter $qR_c \gg 1$. Experiments on contactless excitation of sound in metals under the conditions of cyclotron resonance have not been carried out up to the present time.

5. ELECTROMAGNETIC EXCITATION OF SOUND IN SEMIMETALS

The study of contactless excitation of sound in semimetals was started practically simultaneously[26,27] with the first experiments on EME in normal metals. In the papers of Gantmakher and Dolgopolov[69], of Dobbs *et al.*[70] of Hsu and Thomas[71] using bismuth and Dolgopolov[72] using antimony it was noted that the distinctive characteristic of EME in semimetals is strong temperature dependence of the efficiency of conversion in weak fields $\omega_c/qv_F < 1$. Thus, in experiments on single crystals of bismuth placed in a magnetic field $h_0 < 100$ Oe, a lowering of the temperature from room temperature down to 4.2 K led to an increase of η by two orders of magnitude.[69] In a magnetic field parallel to the surface of the metal both longitudinal and transverse sound was excited.

The temperature dependence of the amplitude of acoustic resonance in a plane parallel plate of antimony is shown in Fig. 12. At liquid helium temperatures the efficiency of conversion became saturated. The experiment was carried out in the regime of a skin layer thin compared to the wavelength of sound. We note that under these conditions the efficiency of the Lorentz mechanism of conversion is practically independent of temperature.

As the magnetic field was increased a nonmonotonic dependence of the efficiency of excitation on H_0 was observed. In bismuth samples of different quality the maximum of the efficiency was obtained in the range of values of the field of 50—500 Oe. The maximum of the efficiency was shifted toward stronger fields with increasing frequency and increasing sound velocity $H_0^{\max} \sim S\sqrt{\omega}$.

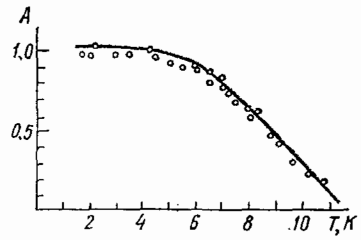

FIG. 12. Temperature dependence of the amplitude of acoustic resonance in a plate of antimony.[72] $H_0 = 1.2$ kOe, $f = 2.8$ MHz.

The dependence on the velocity was determined from experiments on the excitation of longitudinal and transverse sound of different polarization. The experimental data of Ref. 70 are shown in Fig. 13.

A detailed analysis of the EME processes in semimetals was carried out by Babkin *et al.*[15], by Babkin and Kravchenko[16] and Gilinskiĭ *et al.*[73] The field dependences of the efficiency of conversion of electromagnetic and acoustic waves in bismuth were discussed by Quinn[22] and Zil'berman and Pavlovich.[76] Lee *et al.*[23] developed the theory of contactless excitation of electric ξ_E and magnetic ξ_H components of transverse sound in semimetals under conditions of anomalous skin-effect.

The singularities of EME in semimetals are determined by the specific properties of their electron spectrum. The Fermi surface of semimetals consists of electron and hole valleys the distances between which in **p**-space considerably exceed their dimensions. At low temperatures the equilibrium distribution of carriers in each valley is established during times considerably shorter than the time for the establishment of equilibrium between valleys. When an electromagnetic wave is incident on the surface of a semimetal the equilibrium distribution of carriers in the system—both within each valley and also between valleys—is disturbed.[74,75] This means that if electrical neutrality of the whole system is to be preserved the concentrations of elec-

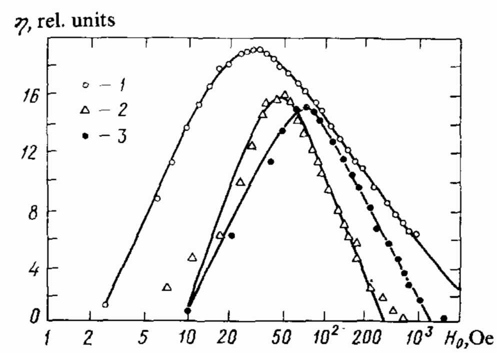

FIG. 13. Field dependences of the efficiency of EME of transverse sound in bismuth.[70] $T = 4.2$ K. 1—$f = 10.9$ MHz, $H_0^{\max} = 30$ Oe; 2–31.8 MHz, 47 Oe; 3—49.3 MHz, 71 Oe.

trons belonging to individual valleys may be changed. This type of nonequilibrium specific for semimetals associated with the establishment of gradients of concentrations of carriers leads to the appearance of volume forces deforming the lattice. In ordinary metals with a singly connected Fermi surface the deformation force is determined only by the part of λ_{ik} which depends on $\mathbf{p}$. This permits one, in particular, to utilize the renormalized tensor of the deformation potential Λ_{ik}. The specific characteristics of semimetals consist of the fact that due to the appearance of the concentration gradients the principal contribution to F^D is made by the parts of λ_{ik} which do not depend on $\mathbf{p}$. The essential role of the deformation potential in semimetals is determined by the large value of the ratio $\lambda_{ik}/\varepsilon_F$. We shall in future discuss only that part of the deformation force which is the determining one for semimetals $F^D = \Sigma_i \hat{\lambda}^i \nabla n^i$, where i is the number of the valley.

In order to estimate the effectiveness of the deformation mechanism of the EME of sound it is necessary to determine the values of the concentration gradients in each valley. In an electric field parallel to the surface of the semimetal currents of carriers belonging to different valleys arise along the normal to the surface. At the same time the total current along the normal is zero. The appearance of such currents in the absence of the field H_0 is due to the anisotropy of the conductivity in different valleys, and in the presence of a magnetic field it is due to the drift of the carriers in crossed electric and magnetic fields. If the intervalley transitions on the surface are sufficiently rare one can assume that a redistribution of the particles between the valleys does not occur. Under these conditions the absence of a total flux of particles across the boundary of the semimetal is equivalent to vanishing on the surface of normal currents of electrons in each individual valley. This means that a redistribution of particles between valleys at the surface differs from the volume redistribution and, as a result of the appearance of concentration gradients, diffusion currents arise which compensate drift. The undeformed lattice is thermodynamically in a nonequilibrium state with respect to the altered spatial electron distribution, and as a result of this elastic stresses appear in it. Elastic stresses in the sound wave vary with the frequency of the external field. We note the qualitative feature of the effect of generation produced by the deformation force in semimetals. As the temperature increases the relaxation processes begin to include shortwave phonons which can significantly reduce the time of intervalley relaxation and to bring it closer to the relaxation time within a valley. Intensive intervalley transitions equalize the concentration gradients and in this case the effectiveness of the deformation mechanism is diminished. This, in particular, is responsible for the strong temperature dependence of the efficiency of conversion in semimetals.

In a magnetic field the principal contribution to currents directed along the normal to the surface is made by the drift of the carriers in crossed fields. Therefore in analysing EME it is possible to neglect the anisotropy of the conductivity in different valleys and to restrict oneself to the model of a semimetal with one electron and one hole Fermi-spheres, situated far from each other in the Brillouin zone.

Let us consider the case of the normal skin-effect when the thickness of the skin layer is significantly greater than the radii of the Larmor orbits. In order to determine the efficiency of the deformation mechanism of excitation it is necessary to solve the Maxwell equations and the diffusion equations simultaneously. This problem has been solved in the paper by Babkin and Kravchenko[77], who showed that the electromagnetic wave incident on the surface of a semimetal excites in it two waves damped over different distances:

$$E(z, t) = (E_1 e^{k_1 z} + E_2 e^{k_2 z}) e^{-i\omega t}. \tag{33}$$

For $k_{1,2}$ the following expressions have been obtained

$$k_1^2 = L^{-2} - i\delta_0^{-2}, \quad k_2^2 = \delta^{-2}(i + L^2\delta_0^{-2})^{-1}, \tag{34}$$

where the diffusion length L is given by

$$L^2 = \frac{\sigma_e \sigma_h}{(\sigma_e + \sigma_h)} \frac{\tau_R}{e^2 \partial n/\partial\varepsilon}; \tag{35}$$

here $\delta^{-2} = 2\pi\omega c^{-2}(\sigma_e + \sigma_h)$, $\delta_0^{-2} = 2\pi\omega c^{-2}(\sigma_e^0 + \sigma_h^0)$, $\partial n/\partial\varepsilon$ is the density of the states at the Fermi level, τ_R is the intervalley relaxation time. The diffusion currents damped out at a depth L affect the nature of the distribution of currents and fields in the sample.[78] For a skin-effect which is normal in the ordinary sense, but with the condition $l \ll \delta_0 \ll L$ being satisfied, a characteristic anomaly occurs which is due to the presence of two waves with different dispersion laws; the additional wave penetrating to the depth $\sim L$ can be referred to as a "concentration" wave. This specific anomaly also leads to the dependence of the efficiency of EME in semimetals on the rate of surface recombination.

The change in the concentration of carriers associated with the decaying waves in a metal is determined by the expression[77]

$$n_e - n_0 = n_h - n_0 = (n_1 e^{k_1 z} + n_2 e^{k_2 z}) e^{-i\omega t}. \tag{36}$$

In the case when the flux of particles recombining on the surface $\Phi_p = S_p[n(0) - n_0]$ (where S_p is the rate of recombination at the boundary) is small compared to the diffusion flux $\Phi_{diff} = D[\partial(n - n_0)/\partial z]$ (where $D \approx (\frac{1}{3})\tau v_F^2/\omega_c^2\tau^2$) the scattering at the boundary does not lead to intervalley transitions. The nonequilibrium concentration in this case can be written in the form

$$n_{1,2} = \frac{k_{1,2} e E_{1,2}}{(k_{1,2}^2 - L^{-2})} \frac{\partial n}{\partial\varepsilon} [(\omega_{ce}\tau_e)^{-1} + (\omega_{ch}\tau_h)^{-1}], \tag{37}$$

where

$$E_{1,2} = E(0) \frac{(L^{-2} - k_1^2)(L^{-2} - k_2^2)}{(L^{-2} - k_{2,1}^2)(k_2^2 - k_1^2)}; \tag{38}$$

τ_e, τ_h are the relaxation times, ω_{ce}, ω_{ch} are the cyclotron frequencies for the electrons and holes respectively.

The change in the concentration of carriers in the valleys leads to the appearance of volume forces which deform the lattice:

$$F^D = (\hat{\lambda}_e - \hat{\lambda}_h) \nabla n. \tag{39}$$

The solution of the equation for the forced sound oscillations with the exciting force (39) can be written in the form

$$\xi = i\,\frac{(\lambda_e-\lambda_h)_{l,\,t}}{\rho S^2}\,q\left(\frac{n_1}{k_1^2+q^2}+\frac{n_2}{k_2^2+q^2}\right). \tag{40}$$

The efficiency of the deformation mechanism of conversion is determined by the expression[72]

$$\eta = 8\pi\,\frac{S}{c}\,\frac{e^2\delta_0^4 y^6\,(\lambda_e-\lambda_h)^2\,(\partial n/\partial\varepsilon)^2}{\rho c^2}\,K, \tag{41}$$

where

$$K = \left|\frac{k_2}{k_1}\right|^2 |k_2^2+q^2|^{-2}\,[(\omega_{ce}\tau_e)^{-1}+(\omega_{ch}\tau_h)^{-1}]^{-2}. \tag{42}$$

Since $|k_1| \gg |k_2| \gtrsim q[|k_2|/|k_2|/|k_1| \lesssim (\omega_c\tau)]^{-1}]$ and the ratio $|n_2/n_1| = |k_2/k_1|$ excitation of sound takes place primarily at the expense of the wave k_2 which is damped slowly as the wave progresses into the metal.

In the range of magnetic fields where $|k_2| \gg q$, the coefficient of conversion is proportional to H_0^2. In the magnetic field $H_0^{\max}$ determined from the condition $q\delta = 1\eta$ attains a maximum value, and in fields greater than $H_0^{\max}$, $\eta \sim H_0^{-2}$. The temperature dependence of the efficiency of transformation is determined by the variation of the intravalley τ and the intervalley τ_R relaxation times. For $H_0 < H_{0R}$ $\eta \sim \tau_R$, while for $H_0 > H_{0R}$ $\eta \sim \tau_R\tau^{-2}$.

As has been shown in Refs. 72, 77, in the opposite limiting case when the diffusion flux of particles Φ_{diff} is small compared to the flux of particles recombining at the surface Φ_p, the expression for the efficiency of the deformation mechanism of conversion can be brought to the form

$$\eta = 8\pi\,\frac{S}{c}\,\frac{e^2q^6\,(\lambda_e-\lambda_h)^2\,(\partial n/\partial\varepsilon)^2\,L^4\delta^4}{\rho c^2\,|i+q^2\delta^2|^2}\,(\omega_{ce}\tau_e+\omega_{ch}\tau_h)^2. \tag{43}$$

The conversion coefficient, as before, for $q\delta \ll 1$, is proportional to the square of the magnetic field $\eta = CH_0^2$, while the maximum of η with respect to the field is attained at $q\delta \sim 1$. However, the coefficient C is greater than the corresponding quantity in (41) by a factor of $(\delta L/\delta_0^2)^2$. The temperature dependence of η in this case is determined by the value of $(\tau\tau_R)^2$ for $H_0 < H_0^{\max}$ and τ_R^2 for $H_0 > H_0^{\max}$.

The theoretical analysis of the field dependences of the efficiency of conversion of electromagnetic and sound waves in bismuth carried out by Zil'berman and Pavlovich,[76] showed that in the general case the maximum efficiency of conversion is attained when the wavelength of the sound wave becomes of the order of the dimensions of the spatial inhomogeneity $q\delta \sim 1$ or $qL \sim 1$. This means that, in principle, two maxima of η can be observed as each of these conditions is satisfied.[3)]

In the experiments of Refs. 69, 70, 81 it was shown that the giant quantum oscillations of the sound absorption coefficient[82] observed on single crystals of bismuth were accompanied by quantum oscillations of the efficiency of conversion with half the period. Analysis of quantum effects involved in EME of sound in semimetals was carried out by Kravchenko.[78,83] Magnetic quantization exerts a characteristic influence on the normal skin-effect in semimetals. In addition to the usual manifestation of the Landau quantization in the surface impedance through the oscillation of magnetic permeability and conductivity in the case of semimetals an essential role is played by effects associated with the change of concentration of carriers in the quantizing field. If the magnetic induction is spatially inhomogeneous the equilibrium concentrations of electrons and holes is determined by the value of $\mathbf{B}$ at the same point $n_0^e = n_0^h = n(B)$. Such a situation occurs under the conditions of normal skin-effect when the alternating induction in the electromagnetic wave $\mathbf{B}(z,t)$ has a component along the direction of the constant induction $\mathbf{B}_0$ created by the external field H_0. Theory shows,[83] that the efficiency of conversion in the quantum case differs from the classical case by the factor

$$\left[1+\left(\frac{B_0}{\omega\tau_R n_0}\,\frac{\partial n}{\partial B}\right)^2\right].$$

The second term describes the increments which vary as a function of B_0^{-1} with a period which is half the period of the de Haas–van Alfen oscillations. The quantum effects become more prominent as the parameter $\omega\tau_R$ decreases and the magnetic field H_0 increases.

The phenomenon of the doubling of the frequency of the quantum oscillations of the transformation efficiency in bismuth is shown in Fig. 14. We note that the relative magnitude of the effect in the oscillations of η exceeded by an order of magnitude the effect in the oscillations of the damping γ.[81] The alternating rise and fall of the maxima of the quantum oscillations is discussed in Ref. 83.

From other papers devoted to the investigation of the special feature of the deformation mechanism of EME we note the work of Kontorovich and Sapogova,[84] in which it is shown that in strong magnetic fields for $\mathbf{q}\cdot\mathbf{H}_0 = 0$ the increase with frequency of the efficiency of conversion for $ql \gg 1$ continues right up to $\omega\tau \sim 1$.

Fal'ko[85] investigated the EME in semimetals in an inclined magnetic field. He showed that when the magnetic field deviated from the direction $\mathbf{q}\cdot\mathbf{H}_0 = 0$ by a small angle φ_{cr} the amplitude of the sound being excited increases sharply. This phenomenon is analogous to the "deviation effect" observed in experiments investigating the absorption coefficient and the velocity of sound in bismuth in a magnetic field.[86,87] The angle φ_{cr} is determined from the condition

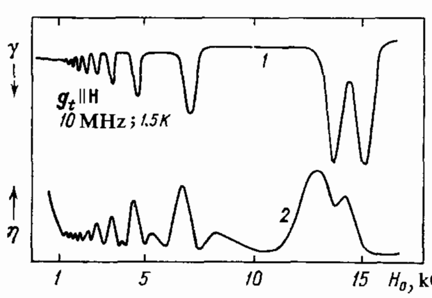

FIG. 14. Giant quantum oscillations of the coefficient of sound absorption in bismuth (1) and the oscillations of the efficiency of EME (2).[81] The scale is different for the dependences 1 and 2.

[3)]The maximum in the field dependences of the amplitude of the sound being excited was observed also in normal metals under the action of the Lorentz excitation mechanism. In Ref. 79 in the course of studying the surface conductivity of tin in a strong magnetic field the existence of a maximum in the efficiency of conversion at $q\delta \sim 1$[80] was utilized for the direct determination of the thickness of the skin layer in a metal.

$\sin\varphi_{erp} = S/\overline{v_F^{max}}$, where v_F^{max} is the maximum velocity of the electrons from the neighborhood of the elliptic reference point on the Fermi surface. The bar over v_F^{max} denotes averaging over the period of rotation of electrons in the field $\mathbf{H}_0$.

Babkin and Kravchenko[88] investigated the problem of the excitation of acoustic plasmons in bismuth. Two mechanisms for the coupling of electromagnetic and acoustic plasma waves resulting from the anisotropy of the electron spectrum and the drift of the carriers in the magnetic field of the wave are discussed.

Experimental confirmation of effects predicted in Refs. 84, 85, 88 has not been obtained to date. Such measurements would be of interest because in them characteristic features of magnetoacoustic resonances and electromagnetic effects would be simultaneously realized.

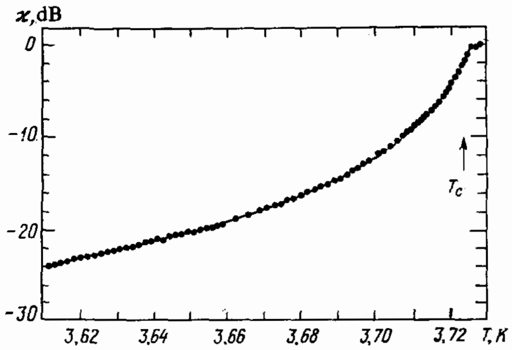

FIG. 16. Temperature dependence of the normalized efficiency of conversion $\varkappa$ in tin in the superconducting state.[90] The theoretical curve joining the experimental points is obtained using a single adjustable parameter $\delta/\lambda_L(0) = 15.74 \pm 0.24$.

6. ELECTROMAGNETIC EXCITATION OF SOUND IN SUPERCONDUCTORS

In this section we discuss the results of investigations of EME in superconductors at frequencies in the MHz range. The transition of a metal into the superconducting state significantly lowers the efficiency of contactless transformation. In the experiment of Bidgood *et al.*[89] the temperature dependence of the efficiency of EME in a single crystal of tin was investigated. Measurements were carried out over a wide range of values of ql in the absence of a constant magnetic field. As the temperature decreased the efficiency of conversion increased becoming saturated in the region of residual resistance. At the temperature of the superconducting transition a sharp decrease in the signal detected by the coil was observed. The result of the measurements is shown in Fig. 15a. Excitation of sound in this experiment was produced by a quartz transducer, and a highly sensitive coil, the construction of which is shown in Fig. 15b, was used as a detector. Such an experimental arrangement is determined first of all by the fact that in utilizing a coil as a generator the alternating magnetic field produced by it can significantly change the efficiency of conversion near T_c.

As has been mentioned above in the nonlocal limit at frequencies when the wavelength of the sound wave is much larger than the thickness of the skin layer $q\delta \ll 1$ the principal mechanism of conversion is the coupling of the electric field in the skin layer with the ions of the lattice. As the transition is made into the superconducting state the depth of penetration of the electromagnetic field into the metal sharply diminishes and this results in the rapid decrease of the signal below T_c. Detailed measurements of the efficiency of contactless conversion below the temperature of the superconducting transition were made in Refs. 90, 91. In the normal state the magnitude of η_n below 4.2 K did not depend on the temperature and in tin amounted to approximately -120 dB. In the superconducting state measurements were made of the normalized efficiency $\varkappa = \eta_S/\eta_n$ whose temperature dependence is given in Fig. 16. A calculation of the efficiency of EME in the region of the transition into the superconducting state carried out by Thomas *et al.*[90] enables us to write the expression for the normalized efficiency $\varkappa$:

$$\varkappa = \frac{1+q^4\delta^4}{[q^2\delta^2+(\sigma_{2S}/\sigma_n)]^2+(\sigma_{1S}/\sigma_n)^2}, \tag{44}$$

where the complex conductivity of the superconductors is $\sigma_S(q,\omega) = \sigma_{1S} + i\sigma_{2S}$, and σ_n is the conductivity of the metal in the normal state. For $|\Delta T| \ll T_c$ the expressions for σ_{1S}/σ_n and σ_{2S}/σ_n can be written in the form[92]

$$\frac{\sigma_{1S}}{\sigma_n} = 1 + \frac{1}{2}\frac{E_S}{kT}\ln\left(\frac{8E_S}{e\hbar\omega}\right) - 0{,}852\left(\frac{E_S}{kT}\right)^2, \tag{45}$$

$$\frac{\sigma_{2S}}{\sigma_n} \approx \frac{2\delta^2}{\lambda_L^2(0)}\frac{\Delta T}{T_c}, \tag{46}$$

where E_S is the energy gap of the superconductor which depends on the temperature, $\lambda_L(0)$ is the London penetration depth at $T = 0$. The theoretical dependence shown in Fig. 16 is obtained using only a single adjustable parameter $\delta/\lambda_L(0)$. The measurements carried out in Ref. 90 have thus made it possible to propose a new method of determining the penetration depth in London superconductors. The best agreement with experimental data was achieved for $\lambda_L(0)$

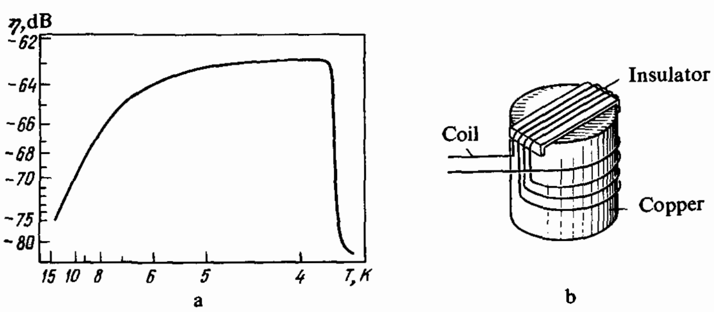

FIG. 15. a) Temperature dependence of the efficiency of excitation of transverse sound in tin at a frequency of 16 MHz in the absence of a magnetic field;[89] b) construction of the receiving coil.

$= 253 \pm 25$ A, which is in good agreement with the data available in the literature.[93]

In superconductors of the second kind EME of transverse longitudinal sound was studied by Vienneau and Maxfield.[94] In this work they also measured the normalized efficiency of conversion with both the field and temperature dependence of $\varkappa$ being determined primarily by the change in the thickness of the skin layer as a function of the magnetic field and temperature. Measurements were made on alloys of Pb-In and Nb-Mo. The quality of these alloys at helium temperatures corresponded to conditions of local conductivity. The EME of sound in them is associated with the Lorentz mechanism of conversion. In the frequency range of 3–90 MHz used in this experiment the thickness of the skin layer in alloys in the normal state exceeds the wavelength of sound. In this case taking into account the spatial distribution of the exciting force [the factor $(1+\beta^2)^{-1/2}$] in expression (6) exerts a significant effect on the efficiency of EME. With the transition into the mixed state the thickness of the skin layer decreases from the value of $\delta \sim 100$ μm for $H_0 > H_{0c}$ to the London penetration depth $\lambda_L(0) \sim 1$ μm for $H_0 = 0$. This leads to a corresponding change in the correction factor $(1+\beta^2)^{-1/2}$.

The field dependences of the normalized efficiency of conversion $\varkappa$ in the alloy Pb-In are given in Fig. 17. The maximum of $\varkappa$ was attained in a certain field $H_0 < H_{0c2}$, and $\varkappa$ approached zero as $H_0 \to 0$. The above experimental data imply that the EME in superconductors at low frequencies is described satisfactorily by the theory of contactless conversion under conditions both of local and of nonlocal conductivity.

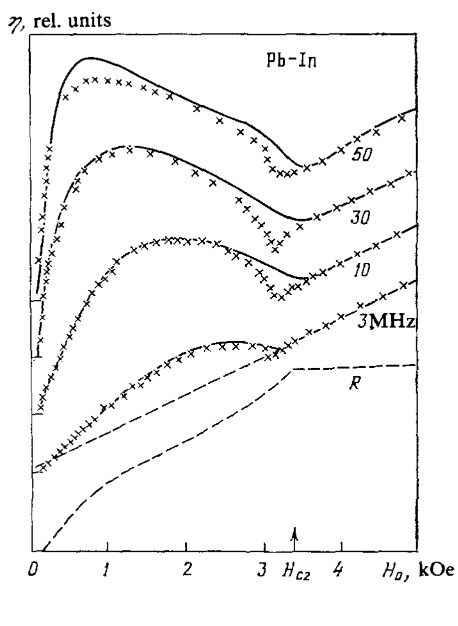

FIG. 17. Field dependences of the normalized efficiency of EME of transverse sound in the alloy Pb_{85}–In_{15} for $T = 4.2$ K.[94] The zeros for each curve are displaced along the vertical axis. The broken line R represents the field dependence of the real part of the surface impedance for $f = 10$ MHz.

7. CONVERSION OF ELECTROMAGNETIC AND SOUND WAVES IN THE UHF RANGE

The discussion up to this point of the processes of conversion of electromagnetic and sound waves at the surface of a metal was restricted to the region of relatively low frequencies for which the thickness of the skin layer in a metal is much smaller than the wavelength of sound. As the frequency of the electromagnetic radiation is increased the thickness of the skin layer diminishes in proportion to $\omega^{-1/2}$. At the same time the wavelength of sound is $\lambda \sim \omega^{-1}$. At frequencies in the UHF range ($f \gtrsim 1$ GHz) the wavelength of sound becomes small compared to the thickness of the skin layer and the efficiency of the volume mechanisms of conversion discussed above falls off sharply. Under these conditions the nature of scattering of the electrons at the metal boundary becomes important.[11] In the case of diffuse scattering a so-called "surface" force appears which becomes the determining one in the UHF range. The role of the surface force in processes of conversion was first demonstrated by Abeles[95] in an experiment using indium films. A block diagram of the experiment is shown in Fig. 18a. A film of approximately 0.25 μm thickness was laid down on a polished end of a germanium rod after which the film-covered surface was pressed tightly against an opening at the bottom of a microwave resonator. The measurements were carried out in a pulsed regime at a frequency of 9.3 GHz. Subsequent to the exciting pulse several echo signals were observed with delayed times corresponding to the time of passage of transverse sound down to the lower end of the germanium rod and back. The quantity measured in the experiment—the ratio of the amplitude of the first echo signal to the amplitude of the exciting pulse—characterized two processes occurring consecutively: the conversion of the electromagnetic wave into a sound wave and then the inverse process, i.e., the radiation of electromagnetic waves when the sound waves impinged on the surface of the metal. This quantity is proportional to the square of the efficiency of conversion η^2. The dependence of η^2 on the temperature is shown in Fig. 18b. We note that just as at low frequencies a decrease in the temperature below the point of superconducting transition leads to a rapid dimunition of the efficiency of conversion.

The experimental investigation of EME of transverse sound in metals in the UHF range was continued in the work of Weisbarth[96] and Zemel *et al.*[97–102] Improvement of the

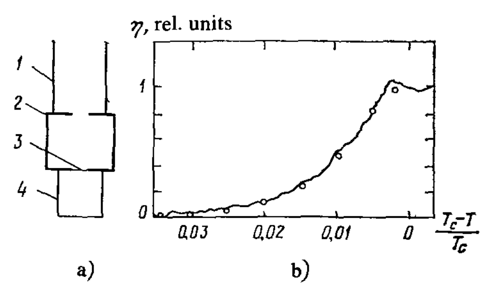

FIG. 18. a) Block diagram of the apparatus (1—wave guide; 2—UHF resonator; 3—indium film; 4—germanium rod); b) dependence of the efficiency of conversion on the reduced temperature[95] [the points on the graph correspond to calculations according to formula (52)].

method proposed by Abeles made it possible to extend significantly the temperature range of measurements with the investigation of the conversion processes being carried out in metals both in the superconducting and in the normal state.

The physical picture of excitation of acoustic oscillations in metals in the region of $l/\delta > 1$ can be presented in the following manner.[102,103] Let us consider a thin film $d < l$, when one can neglect scattering in the volume of metal. In this case the transverse momentum acquired by an electron in the skin layer is determined by the expression

$$\mathbf{P}_t = -\frac{e\mathbf{E}\delta e^{-i\omega t}}{v_F}. \tag{47}$$

The number of electrons colliding per unit time with a unit area of each surface is equal to $n_0 v_F/2$. In the case of diffuse reflection from the boundary the momentum acquired by the electrons is transferred to the lattice. The work done by the electric field on the electrons in the skin layer is transformed into the energy of sound oscillations:

$$\rho\xi\omega S = -\frac{1}{2} eE\delta n_0 e^{-i\omega t}. \tag{48}$$

Using the expression for the flux of acoustic energy in the form $W = \rho\xi^2\omega^2 S/2$ and taking into the account the relation $E = H\omega\delta/c$, we obtain the expression for the efficiency of contactless conversion:

$$\eta = \frac{AW}{P} = GAH^2e^2n_0^2\omega^2\delta^4 \frac{1}{8PZ_S c^2}, \tag{49}$$

where A is the area of the film, P is the intensity of the microwave radiation, Z_S is the acoustic impedance of the metal. Taking into account the fact that the electrons collide with the surface at different angles and, moreover, may be scattered within the volume of the metal results in the appearance of an additional factor:

$$G = \left| \frac{n}{n_0}(1+\cos qd) - 2\frac{1}{\delta^2}\left(1 - \frac{q\delta \sin qd}{\sin (d/\delta)}\right)(\delta^{-2} - q^2)^{-1} \right|^2. \tag{50}$$

Thus, the electron contribution to the efficiency of conversion is proportional to the fourth power of the thickness of the skin layer. Below the temperature of the superconducting transition the thickness of the skin layer in the metal asymptotically approaches the London penetration depth. A decrease in the number of normal electrons n as the film goes over into the superconducting state is taken into account by the introduction of the factor n/n_0.

The dependence of η^2 on the temperature in the range $0.4T_c - T_c$, obtained using a film of indium,[97] is shown in Fig. 19. The theoretical curves N and A shown in the diagram were calculated taking into account the temperature dependence of thickness of the skin layer in a superconductor[99] in the regime of the normal N and anomalous A skin effect. The experimental data agree best if all with the theoretical dependence A calculated on the assumption $n/n_0 = 1$. As the temperature is raised the experimental points deviate somewhat from the curve A, and this is apparently connected with the decrease in the mean free path of the carriers and the gradual transition to the regime of the normal skin effect. According to the two-fluid model the number of normal electrons below T_c is determined by the relation $n/n_0 = (T/T_c)^4$. Taking this factor into account leads, however, to considerable deviations from the experimental data (dotted curve in Fig. 19). Zemel[102] suggested that in the experiment destruction of Cooper pairs on scattering at the boundary of the film was being observed. This is in agreement with direct experiments on the absorption of microwave radiation in superconductors.[104]

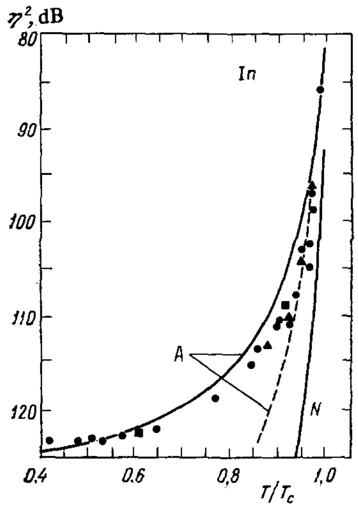

FIG. 19. Temperature dependence of the efficiency of EME in superconducting indium.[97] The theoretical curves A and N correspond to calculations in the limit of anomalous and normal skin-effect. The solid curves were computed on the assumption $n/n_0 = 1$. The broken curve was computed on the basis of the two-fluid model taking into account the temperature dependence of n/n_0.

A quantitative estimate of the contribution of the volume mechanisms of conversion in London superconductors was obtained by Zemel and Goldstein.[99] In the whole range of temperature measurements the contribution of the volume conversion is lower by 17–20 dB than the efficiency of the surface mechanism. Golub[105,106] showed that for Pippard superconductors the volume forces make a considerable contribution to the efficiency of conversion, while the role of the surface force diminishes.

In Ref. 99 the influence of the thickness of the film on the efficiency of contactless excitation was also investigated. The measurements were made on gold films of different thicknesses, and the experimental data are presented in Fig. 20. The dependence of η^2 on the thickness of the film is due,

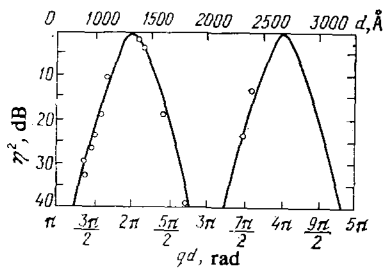

FIG. 20. Dependence of the efficiency of EME of transverse sound in gold on the thickness of the film.[99] Solid curves represent calculations of the efficiency as a function of the parameter qd ($q = 4.7 \cdot 10^5$ cm^{-1}). Along the top are shown absolute values of the film thicknesses.

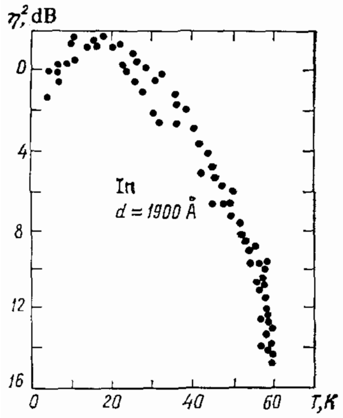

FIG. 21. Temperature dependence of the efficiency of EME in indium in the normal state.[101] The calibration was carried out in terms of the magnitude of η at $T = 4.2$ K.

primarily, to the interference of the forces on its surfaces. Just as in the case of low frequencies, the efficiency of EME is a maximum when the film thickness is equal to an integral number of sound waves.

Investigations of the processes of conversion of electromagnetic and acoustic waves in normal metals in the UHF range are represented, first of all, by the experimental work of Goldstein *et al.*[100,101] In these papers the temperature dependences of the efficiency of EME in films of indium, tin and gold were studied in the range from 4.2 to 100 K. The results of the measurements on indium are shown in Fig. 21. In the neighborhood of 15 K a maximum of the efficiency is observed, while with a further increase of temperature there is a rapid decrease in the value of η^2.

A detailed analysis of the frequency and temperature dependences of the efficiency of conversion was carried out by Zemel[102] and by Ivanovski and Kagasnov.[107,108] The basic parameter, which significantly depends on the temperature, is the mean free path of the carriers. In discussing the variation of η with temperature it is necessary to take into account the relationships between the mean free path l, the thickness of the skin layer δ and the film thickness d.

For films whose thickness satisfies the relation $qd = 2\pi n$, in the limit of a large mean free path $l/\delta > 1$ the expression for the efficiency of conversion (49) reduces to the form

$$\eta = \frac{Ae^2E^2n_0^2}{2PZ_S}\left|\operatorname{tg}\frac{d}{\delta}\right|^2\delta^2\left(1-\frac{1}{1-q^2\delta^2}\right)^2. \qquad (51)$$

This expression is valid at low temperatures. Under the conditions of the anomalous skin effect a small fraction of electrons moves parallel to the surface and is at all times situated in the skin layer. The majority of the carriers spend only a short time in the skin layer and only during that time obtain additional energy from the field. Therefore the conversion determined by the volume interaction tends to a constant value as the mean free path increases. In this case the role of the effective mean free path is played by the thickness of the skin layer. The influence of the surface mechanism of conversion decreases as l increases, since in this case the number of collisions with the surface diminishes, while the energy obtained from the field remains the same. The last assertion is valid when the mean free path does not exceed the thickness of the film. Thus, the existence of a maximum of the temperature dependence of the efficiency of conversion is determined by the temperature variation of the surface mechanism of conversion. In accordance with estimates of Ref. 107 the surface mechanism of conversion is effective at frequencies $f \gg 10^8$–10^9 Hz. At lower frequencies there should be no maximum in the efficiency, however, the corresponding experimental data have not been obtained up to now.

As the temperature is raised the mean free path of the carriers is diminished and the conditions of the anomalous skin effect are no longer satisfied. In the limiting case of the normal skin effect $l/\delta \ll 1$, $d/\delta \ll 1$ the expression for the efficiency of conversion can be written in the form

$$\eta = \frac{Ae^2E^2n_0^2}{2PZ_S}\left[l\left[1-\exp\left(\frac{d}{l}\right)\right]\frac{q^2l^2}{1+q^2l^2}\right]^2. \qquad (52)$$

For $d/l < 1$ and $ql > 1$ η diminishes proportionally to l^2 as the mean free path decreases. This is associated with a decrease in the surface force. An even greater falling off in the efficiency with a further increase in δ and with a transition to the regime $ql < 1$ (the highest temperatures in Fig. 21) is due to the fact that the region of unbalanced action of the field on the ions of the lattice—within a distance δ from the surface—becomes small compared with the wavelength of sound. In this case the surface force is compensated locally by the direct action of the electric field of the wave on the ions of the lattice.

The efficiency of conversion of electromagnetic and acoustic energy in metal films at low temperatures is quite high and comparable with the efficiency of the traditionally utilized transducers in the UHF range. Thus, in the experimental of Zemel and Goldstein[98] the value of η at 4.2 K amounted to approximately $5\cdot10^{-5}$. This opens up the possibility of using thin metal films as electromechanical transducers in the UHF range.[109]

8. ELECTROMAGNETIC EXCITATION OF SOUND IN FERROMAGNETIC SUBSTANCES

In the case of contactless excitation of sound in ferromagnetic substances the conversion process is modified by additional mechanisms characteristic of magnetic materials. First of all there is the magnetostrictive interaction. In a magnetic field H_0, which does not produce saturation, excitation of acoustic oscillations is produced by the action of the radio-frequency field on the total magnetization $\mathbf{M}$. In this case the force acting on the lattice arises as a result of a magnetoelastic coupling of the magnetization with the lattice. Moreover, over a wide range of variation of the magnetic field and the temperature one should take into account the excitation mechanisms characteristic of normal metals.

Among all the ferromagnetic materials investigated until the present time nickel in a certain sense is a unique object as a result of the high value of magnetostriction and low crystalline anisotropy. The EME of transverse and longitudinal sound in nickel has been investigated over a wide range

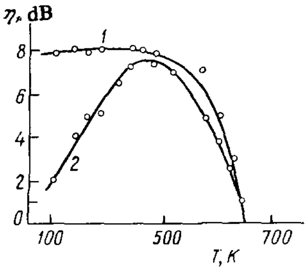

FIG. 22. Temperature dependences of the efficiency of EME in nickel in a magnetic field.[110] H_0 (kOe) = 6 (1) and 2 (2).

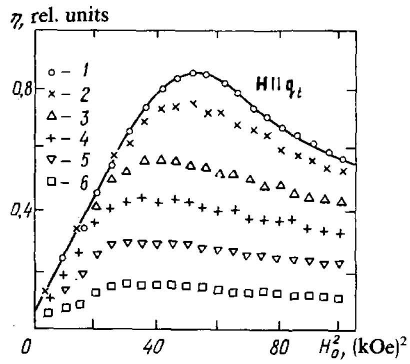

FIG. 23. Field dependences of the efficiency of EME in nickel for different orientations of H_0 with respect to the direction of propagation of sound q_t.[113] The solid curve joins the experimental points for $H_0 \| q_t$.[113] 1—0°; 2—15°; 3—30°; 4—45°; 5—60°; 6—75°.

of magnetic fields and temperatures in the work of Gitis[110], Drobot'ko and Naberezhnykh[111,112] and of other authors.[113,116] In magnetic fields higher than the field of magnetic saturation of the sample the conversion of electromagnetic and sound waves at helium temperatures is determined practically entirely by the Lorentz excitation mechanism.[112] In a nonsaturating magnetic field the principal mechanisms responsible for the exciting of sound is the magnetoelastic coupling.[110,113] This conclusion follows from an analysis of the temperature and field dependences of the intensity of the sound being excited. In particular, when nickel is heated above the Curie temperature (630 K) a decrease is the efficiency of conversion by more than 40 dB was observed. Temperature dependences of the efficiency of conversion obtained for different values of the magnetizing field are shown in Fig. 22. In a magnetic field close to the saturating field (curve 1) the efficiency of conversion decreased monotonically as the temperature was raised. The rapid falling off of η begins in the neighborhold of 460 K. In a weaker field (curve 2) at the same temperature a maximum of efficiency is observed, the absolute value of which decreases as the magnetizing field is increased. The maximum of η at 460 K is determined by the fact that at this temperature the magnetic anisotropy constant of nickel tends to zero[117] and the motion of the domain walls and of the magnetization vector is sharply intensified. As the sample is magnetized to saturation the domain structure disappears and a maximum in the temperature dependence of η is practically not observed.

The field dependences of the efficiency of conversion in nickel also exhibit nonmonotonic variation. For different orientations of the field $\mathbf{H}_0$ with respect to the direction of propagation of transverse sound these dependences are shown in Fig. 23. The efficiency of conversion increased proportionally to H_0^2 up to ~3 kOe, and in fields above 5 kOe a decrease in η with increasing magnetic field was observed. A maximum in the field dependences of η was observed both in single crystals and in polycrystalline samples of nickel.[113] On heating above the Curie temperature the efficiency of EME was described satisfactorily by the Lorentz mechanism of conversion (some deviations were observed in Ref. 114).

Experimental study of processes of magnetoelastic excitation of sound in different magnetic materials was carried out by Gorodetsky *et al.*[118] Special features of the efficiency of contactless excitation were observed near the spin-reorientation transition in $ErFeO_3$, the ferromagnetic resonance in Fe_3O_4 and in the neighborhood of the magnetic phase transition in terbium. The data that were obtained were explained at least qualitatively within the framework of the magnetoelastic mechanism of conversion.[4)]

Calculations of the efficiency of EME in ferromagnetic materials were carried out in Refs. 113, 119. The mode of Ref. 113 based on the theoretical analysis of Gorodetskty *et al.*[118] and Le Craw and Comstock[120] gives quite a good description of the experimental data on nickel. According to these papers the magnetoelastic coupling in ferromagnetic materials in fields below the threshold of saturation exerts a much greater effect on the lattice than the Lorentz force. The amplitude of the transverse or longitudinal sound excited in each specific case depends on the mutual orientation of the vectors of magnetization, constant and alternating magnetic fields with respect to the crystallographic axes of the sample and on the magnitude of the magnetoelastic coefficients C_{me}. In the general case of excitation of transverse sound the stress acting on the lattice due to the displacement can be represented in the form

$$\sigma = \frac{C_{me} H M_S \cos(\varphi_0 - \varphi) \cos 2(\varphi_0 - \varphi)}{H_0 M_S \cos(\varphi_0 - \varphi) + \alpha}, \qquad (53)$$

where M_S is the saturation magnetization, φ_0 and φ are respectively the angles between the direction of the magnetic field H_0 and the axis of easy magnetization and the magnetization vector $M, \alpha = \partial^2 E_k / \partial \varphi^2$, where E_k is the energy of crystalline anisotropy of the ferromagnetic substance.

The principal mechanisms of EME of sound in ferromagnetic materials can be represented in the following manner. Rotation of domains in the external field leads to linear and volume magnetrostriction. The radio-frequency magnetic field modulates the static stresses, as a result of which the amplitude of the sound being excited contains a term proportional to the dynamic magnetostriction (derivative with respect to the field on the static magnetostriction). The linear magnetostriction is responsible primarily for the exci-

[4)]Preliminary measurements[113] showed that the efficiency of conversion measured at room temperature in cobalt and in iron is described satisfactorily by the Lorentz excitation mechanism.

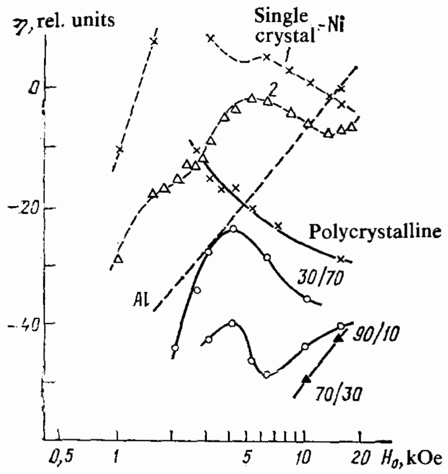

FIG. 24. Field dependences of the efficiency of EME in single crystals, in polycrystalline nickel samples and in Ni–Fe alloys.[114] $T \approx 300$ K, $f = 3$–6 MHz. An aluminum sample (broken line curve) was used to calibrate the apparatus. Curves 1 and 2 correspond to different orientations of the constant and the radio-frequency magnetic fields with respect to the crystallographic axes of nickel.

citation of transverse sound, while the volume magnetostriction produces excitation both of transverse and of longitudinal sound.

The different mechanisms responsible for contactless excitation of sound in ferromagnetic materials can be separated out as has been done in the experimental work of Pacher and Maxfield.[114] In this work alloys of nickel and iron were investigated over a wide range of temperatures. The alloys in this case were chosen so that the widest possible range of variation of the value of magnetostriction and of the magnetic anisotropy constant would be realized.

The experimental results obtained for single crystals of nickel and for polycrystalline nickel and in Ni-Fe alloys are shown in Fig. 24. We note at once a result that until now has never been really explained: in a saturating magnetic field the efficiency of excitation of sound in polycrystalline nickel turned out to be lower by 18 dB than would follow from the Lorentz excitation mechanism. Calibration of the results obtained was carried out by means of a comparison with the results of measurements for aluminum the efficiency of excitation of sound in which has been taken as a standard.

The alloy 30% Ni–70% Fe (by weight) exhibits strong volume magnetostriction up to several kilo-oersted and a low linear magnetostriction in weak fields. The efficiency of EME in this alloy attains a maximum in the region of 4 kOe and is equal to the efficiency of the Lorentz mechanism in aluminum in the same field.

The alloy 90% Ni—10% Fe was chosen because at room temperature its magnetic anisotropy constant is the same as in nickel and, moreover, the values of the saturation magnetization in both are practically the same. Nevertheless the efficiency of excitation of transverse sound in this alloy is considerably lower than in polycrystalline nickel. This result indicates that in addition to the magnetic anisotropy of the metal, some other factors exert an important influence on the efficiency of EME in ferromagnetic substances.

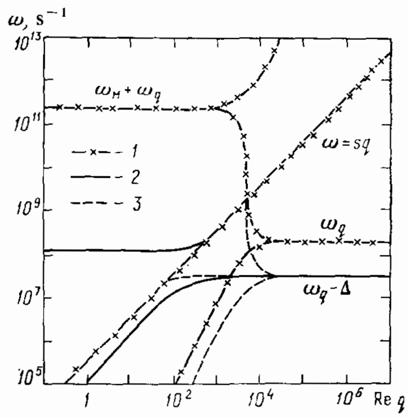

FIG. 25. Calculation of the dispersion relations for the coupled system of electromagnetic, spin and sound waves in nickel at room temperature.[116] Only the right-circularly polarized waves are shown. 1—dispersion relations for $\Delta = 0$; 2—spin-phonon coupling; 3—coupling of electromagnetic and spin waves.

This conclusion is confirmed also by measurements on the alloys 70% Ni–30% Fe and 81% Ni–19% Fe. In the first of these the energy of crystalline anisotropy is very small as result of which one might have expected a high efficiency of conversion. In the alloy 81% Ni–19% Fe, where the linear magnetostriction is small the excitation of sound is not observed at all right up to 15 kOe. At 15 kOe the efficiency of the Lorentz mechanism of excitation should be comparable with η for nickel above the Curie temperature. However, the efficiency of EME of sound in the saturation region for the alloys indicated above is considerably lower. The experimental data presented above indicate that the theory of contactless excitation of sound in ferromagnetic materials requires further development. Ferromagnetic acoustic resonance in the case of EME of sound in ferromagnetic substances has been studied by Povey *et al.*[115,116] The response of the ferromagnetic material to a radio-frequency magnetic field was investigated taking into account the coupling of electromagnetic, spin and acoustic waves.[5)] The results of a calculation of dispersion relations for a coupled system of sound, spin and electromagnetic waves are shown in Fig. 25. The calculation of Ref. 116 was carried out for a single crystal of nickel in a magnetic field perpendicular to the surface and exceeding the saturation field. The dependences shown in the diagram correspond to right-circularly polarized waves. The following parameters of the coupled system were used: $\omega_q = 2\cdot 10^8\ s^{-1}$ is the frequency of spin waves in the absence of coupling, $\Delta = 1.7\cdot 10^8\ s^{-1}$ is the characteristic frequency of the magnetoelastic coupling, $S_t = 3.5\cdot 10^5$ cm/s is the velocity of transverse sound, $\delta^2 = 10^4/\omega$ cm^2 is the square of the thickness of the skin layer, $\omega_M = 4\pi\gamma' M_s = 1.2\cdot 10^{11}\ s^{-1}$, γ' is the magnetomechanical ratio.

As is shown in Fig. 25, the metal becomes transparent in the absence of relaxation of spin waves for a radio-frequency magnetic field at the frequency $\omega_+ = \omega_q + \omega_M$. This is due to the conversion of the electromagnetic and spin waves at

[5)]A general investigation of the processes of coupling of collective excitations in ferromagnetic substances has been carried out by Akhiezer, Bar'yakhtar and Peletminskiĭ[121] and by Blank and Kaganov.[122]

the surface. The spin wave in this case represents free precession of magnetization with an infinite wavelength. The condition for ferromagnetic resonance is modified by the magnetoelastic coupling and assumes the form $\omega = \omega_q - \Delta$. In this frequency range acoustic, spin and electromagnetic waves are strongly coupled. The radio-frequency magnetic field at the surface excites a spin wave, which in turn, excites sound by means of the magnetoelastic coupling. The calculated value of the efficiency of conversion η in this case amounts to approximately 10%.

Analysis of papers devoted to EME in ferromagnetic materials enables one to draw the conclusion that two principal mechanisms of generation occur. The first of them is the Lorentz excitation mechanism modified by magnetization currents. The second is the magnetoelastic coupling which, in principle, can be intensified by ferromagnetic resonance. Calculation of Ref. 115 shows that in nickel the magnetoelastic coupling at the frequency of ferromagnetic resonance is much more effective than the Lorentz excitation mechanism. In strong fields the Lorentz mechanism dominates. In magnetic insulator the Lorentz force is absent and the mechanism of magnetoelastic excitation must become the main one.

9. ACOUSTIC NUCLEAR MAGNETIC RESONANCE IN THE CASE OF CONTACTLESS EXCITATION OF SOUND IN METALS

In the observation of nuclear magnetic resonance (NMR) in conducting media it is usually assumed that only the spins of nuclei situated within the confines of the skin layer of thickness δ take part in the resonance absorption of the energy of the electromagnetic field. In order to increase the amplitude of the observed signals metallic powders are used, the grain dimension of which is $d < \delta$. The NMR signal in this case is averaged over all the crystallographic directions and this, in particular, does not permit an investigation of the anisotropy of the Knight shift in single crystals of metals. The contactless excitation of sound in metals makes it possible to overcome this difficulty to some extent. Acoustic NMR (ANMR) is one of the subfields of radio-frequency spectroscopy and consists of selective absorption of energy of sound waves by a nuclear spin system under the condition that the phonon frequency corresponds to the separation between the magnetic energy levels. The nature of the spin-phonon interaction i.e., of the mechanism facilitating the transfer of acoustic energy to the system of nuclear spins is the same as in the phenomenon of spin-lattice relaxation. The oscillations of the ions create at each point of the sample an alternating electromagnetic field, and the nuclear spins interact with the magnetic component of this field. The experimentally observed signal in this case is the total absorption signal from nuclei in the skin layer and in the bulk of the sample.

The problem of acoustic NMR is solved by methods analogous to those used earlier in discussion of EME in metals. For circularly polarized waves the magnetization of the nuclear spin system is given by the expression

$$M_\pm = \chi_\pm H_\pm, \tag{54}$$

where the nuclear susceptibility $\chi_\pm$ is equal to

$$\chi_\pm = \frac{\pm i\alpha M_0 T_N}{1 + i\omega T_N \pm i\alpha H_0 T_N}; \tag{55}$$

here α is the gyromagnetic ratio of the nuclei, M_0 is the saturation nuclear magnetization in the direction of the constant magnetic field, T_N is the transverse nuclear relaxation time. The expression for $\chi_\pm$ is a solution of the Bloch equation for nuclear magnetization.

The theory of ANMR in the case of contactless excitation of sound in metallic plates has been developed by Quinn.[123] In the case when the nonelectronic mechanisms of damping of sound in a metal predominate, and this is what occurs at low temperatures, the expression for the resonance increment to the surface impedance of the plate can be written in the form

$$(\Delta Z)_{\rm res} = \frac{16\pi}{d}\frac{\omega_c\Omega_c}{\omega_p^2}\tilde{\tau}\left[1 - \frac{\omega_c\Omega_c c^2}{S_t^2\omega_p^2}\omega\tilde{\tau}\left(\nu_{2\pm} + \frac{c^2\omega}{S_t^2\omega_p^2\tau}\right)\right], \tag{56}$$

where ω_p is the plasma frequency of the carriers, Ω_c is the ion cyclotron frequency, $\tilde{\tau}$ is a parameter characterizing the nonelectronic damping of sound (at low temperatures $\tilde{\tau} = 10^{-4} - 10^{-3}$ s). The presence of $\nu_{2\pm}$, the imaginary part of $-4\pi\chi_\pm$, determines the acoustic contribution to the nuclear magnetic resonance signal.

We can compare the contribution to the NMR signal associated with the excitation of sound with the ordinary NMR signal from nuclei situated in the skin layer. According to Ref. 123, the "amplification coefficient" is equal to

$$\frac{\Delta Z_{\rm res}^{\rm NMR}}{Z_0^{\rm NMR}} \approx 2^{5/2}\frac{\delta}{d}\frac{\omega\tau}{(1+\omega_c^2\tau^2)^{1/2}}\left(\frac{C\omega_c}{S_t\omega_p}\Omega_c\tilde{\tau}\right)^2. \tag{57}$$

For a potassium plate of 0.1 cm thickness in a magnetic field of 30 kOe the amplification of the NMR signal amounts to approximately 10^2.

In the general case, in addition to the magnetic dipole mechanism of sound absorption by the nuclear spin system described above, it is necessary to take into account also other mechanisms: electric quadrupole interaction and the modulation of the dipole-dipole interactions.[124] The result of taking into account these interactions for different spin-phonon coupling constants G can be represented in the form of a graph. In Fig. 26 three mechanisms have been arbitrarily

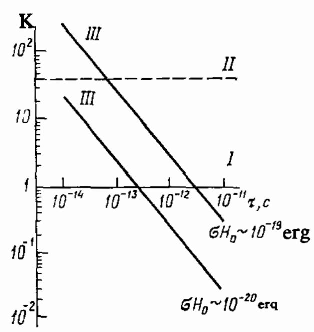

Fig. 26. Calculation of the efficiency of different mechanisms of coupling of a nuclear spin-system with a sound wave.[124] I—contribution of the electromagnetic absorption in the skin layer without taking into account the generation of sound; II—magnetic dipole coupling mechanism; III—contribution due to the additional mechanisms of sound absorption different from the magnetic dipole coupling.

singled out: I is the usually considered contribution of the electromagnetic absorption in the skin layer without taking into account the generation of sound; II is the contribution discussed by Quinn resulting from the mechanism of magnetic dipole absorption of the sound being excited in the sample; III is the contribution resulting from additional mechanisms of sound absorption which are different from the magnetic dipole interaction. The relative contribution to the NMR signal of the mechanisms indicated above depends in an essential manner on the mean free path of the carriers in the metal.

The calculation carried out by Solovarov,[124] shows that at low temperatures taking the generation of sound in the metal into account is necessary in observing NMR and, moreover, that the contribution to the NMR signal made by mechanisms of sound absorption other than the magnetic dipole mechanism may be significant.

The convenience of the contactless method of excitation consists of the fact that in an experiment the standard NMR technique is utilized, with the only additional condition being that the samples being investigated have to be plane parallel.

10. CONCLUSIONS

Evaluating the trends in the development of research in EME of sound in metals we may note that by the present time a sufficiently good understanding has been achieved of the mechanisms of the conversion of electromagnetic and sound waves in normal metals, and in semimetals over a wide range of frequencies, magnetic fields and temperatures. The existing discrepancies between experiment and theory in the case of excitation of transverse sound in the nonlocal limit are basically quantitative in nature. The EME of sound has found wide application as a method of investigating different acoustic phenomena in metals.[46,89,125,126]

In the field of research on processes of conversion of electromagnetic and sound waves in normal metals and in superconductors in the UHF range a considerable theoretical base has been created for the development of further research. We also note that already by the present time these problems have acquired important practical significance. Thus, in analyzing the work of the Stanford superconducting radio-frequency linear accelerator it was found that the main cause of the finite, temperature-independent residual resistance of the superconductor is the generation of transverse acoustic phonons. According to the BCS theory[127] the surface impedance of a superconductor tends to zero as the temperature approaches absolute zero. However, experimental data indicate that as the temperature is reduced the surface impedance approaches a certain value different from zero. After subtracting out different external causes (of the type of a frozen-in magnetic flux, etc.) the lower limit of the value of the surface impedance in the UHF range is determined by the generation of sound on the surface of the superconductor. A number of experimental and theoretical papers[128–134] has been devoted to the study of this problem from the point of view of practical applications.

In our view a further study of the contactless excitation of sound in ferromagnetic materials is a promising direction of research. Apparently this field is in the stage of initial accumulation of experimental data. The EME technique is very convenient for the study of different kinds of coupling of collective excitations in metals with sound waves. This includes both the study of geometric and cyclotron resonance in the case of contactless excitation of sound, and also the problem of studying helicon-phonon and doppleron-phonon resonances and the coupling with the collective modes in ferromagnetic substances. The EME of sound in metals is of interest also as one of the methods of acoustic NMR not requiring any considerable complication of experimental technique.

Apparently on the whole one can assert that a further development of research in the field of electromagnetic excitation of sound in metals will be associated both with the study of the phenomenon itself and also with its ever wider use in laboratory practice and in practical applications.

In conclusion the authors express their deep gratitude to V. T. Dolgopolov, M. I. Kaganov, V. M. Kontorovich, and V. Ya. Kravchenko for valuable discussions of the problem and for a number of useful comments made by them in the course of preparation of the manuscript for publication.

1. V. M. Kontorovich, Zh. Eksp. Teor. Fiz. **45**, 1638 (1963) [Sov. Phys. JETP **18**, 1125 (1964)].
2. V. M. Kontorovich, Zh. Eksp. Teor. Fiz. **59**, 2116 (1970) [Sov. Phys. JETP **32**, 1146 (1971)].
3. V. P. Silin, Zh. Eksp. Teor. Fiz. **38**, 977 (1960) [Sov. Phys. JETP **11**, 703 (1960)].
4. V. L. Gurevich, I. G. Lang, and S. T. Pavlov, Zh. Eksp. Teor. Fiz. **59**, 1679 (1970) [Sov. Phys. JETP **32**, 914 (1971)].
5. V. M. Kontorovich, Zh. Eksp. Teor. Fiz. **61**, 1181 (1971) [Sov. Phys. JETP **34**, 630 (1973)].
6. V. G. Skobov and É. A. Kaner, Zh. Eksp. Teor. Fiz. **46**, 273 (1964) [Sov. Phys. JETP **19**, 189 (1964)].
7. V. M. Kontorovich and A. M. Glutsyuk, Zh. Eksp. Teor. Fiz. **41**, 1195 (1961) [Sov. Phys. JETP **14**, 852 (1962)].
8. V. M. Kontorovich and N. A. Tishchenko, Izv. Vyssh. Uchebn. Zaved. Radiofiz. **6**, 24 (1963).
9. R. H. Randall, F. C. Rose and C. Zener, Phys. Rev. **56**, 343 (1939).
10. S. I. Aksenov, B. A. Vikin, and K. V. Vladimirskiĭ, Zh. Eksp. Teor. Fiz. **28**, 762 (1955) [Sov. Phys. JETP **1**, 609 (1955)].
11. M. I. Kaganov and V. B. Fiks, Fiz. Met. Metalloved. **19**, 489 (1965).
12. M. I. Kaganov and V. B. Fiks, Zh. Eksp. Teor. Fiz **62**, 1461 (1972) [Sov. Phys. JETP **35**, 767 (1972)].
13. M. I. Kaganov, V. B. Fiks and N. I. Shikina, Fiz. Met. Metalloved. **26**, 11 (1968).
14. V. Ya. Kravchenko, Zh. Eksp. Teor. Fiz. **54**, 1494 (1968) [Sov. Phys. JETP **27**, 801 (1968)].
15. G. I. Babkin, V. T. Dolgopolov and V. Ya. Kravchenko, Pis'ma Zh. Eksp. Teor. Fiz. **13**, 563 (1971) [JETP Lett. **13**, 402 (1971)].
16. G. I. Babkin and V. Ya. Kravchenko, Zh. Eksp. Teor. Fiz. **61**, 2084 (1971) [Sov. Phys. JETP **34**, 1111 (1972)].
17. J. J. Quinn, Phys. Lett. **A25**, 522 (1967).
18. H. L. Grubin, IEEE Trans. Sonics Ultrason. **SU-16**, 27 (1969).
19. D. J. Meredith, R. J. Watts-Tobin and E. R. Dobbs, J. Acoust. Soc. Am. **45**, 1393 (1969).
20. R. C. Alig, Phys. Rev. **178**, 1050 (1968).
21. P. D. Southgate, J. Appl. Phys. **40**, 22 (1969).
22. J. J. Quinn, Phys. Rev. Lett. **24**, 817 (1970).
23. K. C. Lee, A. M. deGraaf, D. Hsu and R. L. Thomas, Phys. Rev. **B8**, 460 (1973).
24. W. D. Wallace, Int. J. Nondestr. Test **2**, 309 (1971).
25. E. R. Dobbs, In: Physical Acoustics, Principles and Methods (Ed. by W. P. Mason) Academic Press, New York, **10**, 127 (1973).
26. V. F. Gantmakher and V. T. Dolgopolov, In: Materialy X Mezhdunarod-noi konferentsii po fizike nizkikh temperatur (Proc. X Intern. Conf. on Low Temp. Phys.) Moscow, **3**, 133 (1966).
27. V. F. Gantmakher and V. T. Dolgopolov, Pis'ma Zh. Eksp. Teor. Fiz. **5**,

17 (1967) [JETP Lett. 5, 12 (1967)].
[28]P. K. Larsen and K. Saermark, Phys. Lett. A24, 374 (1967).
[29]K. Saermark and P. K. Larsen, Phys. Lett. A24, 668 (1967).
[30]J. R. Houck, H. V. Bohm, B. W. Maxfield and J. W. Wilkins, Phys. Rev. Lett. 19, 224 (1967).
[31]A. G. Betjeman, H. V. Bohm, D. J. Meredith and E. R. Dobbs, Phys. Lett. A25, 753 (1967).
[32]R. Turner, K. R. Lyall and J. F. Cochran, Can. J. Phys. 47, 2293 (1969).
[33]E. R. Dobbs, J. Phys. Chem. Solids 31, 1657 (1970).
[34]R. A. Gordon and G. Seidel, J. Phys. Chem. Solids 34, 1587 (1973).
[35]R. A. Gordon and G. Seidel, Phys. Lett. A35, 102 (1971).
[36]M. R. Gaerttner, W. D. Wallace and B. W. Maxfield, Phys. Rev. 184, 702 (1969).
[37]R. L. Thomas, G. Turner and H. V. Bohm, Phys. Rev. Lett. 20, 207 (1968).
[38]M. R. Gaerttner and B. W. Maxfield, Phys. Rev. Lett. 26, 119 (1971).
[39]K. R. Lyall and J. F. Cochran, Phys. Lett. A29, 626 (1969).
[40]K. R. Lyall and J. F. Cochran, Can. J. Phys. 49, 1075 (1971).
[41]Yu. P. Gaĭdukov and A. P. Perov, Pis'ma Zh. Eksp. Teor. Fiz. 8, 666 (1968) [JETP Lett. 8, 412 (1968)].
[42]Yu. P. Gaĭdukov and A. P. Perov, Akust. Zh. 17, 314 (1971) [Sov. Phys. Acoust. 17, 266 (1971)].
[43]Yu. P. Gaĭdukov, A. P. Perov and I. F. Voloshin, Pis'ma Zh. Eksp. Teor. Fiz. 9, 585 (1969) [JETP Lett. 9, 356 (1969)].
[44]Yu. P. Gaĭdukov, A. N. Vasil'ev and A. G. Lyubimov, Fiz. Nizk. Temp. 5, 1318 (1979) [Sov. J. Low Temp. Phys. 5, 623 (1979)].
[45]A. Ya. Blank. A. N. Vasil'ev and Yu. P. Gaĭdukov, Pis'ma Zh. Eksp. Teor. Fiz. 32, 526 (1980) [JETP Lett. 32, 505 (1980)].
[46]A. N. Vasil'ev and Yu. P. Gaĭdukov, Zh. Eksp. Teor. Fiz. 81, 2234 (1981) [Sov. Phys. JETP 54, 1186 (1981)].
[47]A. N. Vasil'ev, Yu. P. Gaĭdukov and A. P. Perov, Prib. Tekh. Eksp. No. 6, 176 (1980).
[48]J. Herbertz, Ultrasonics No. 10, 239 (1967).
[49]W. D. Wallace, J. R. Houck, R. Bowers, B. W. Maxfield and M. R. Gaerttner, Rev. Sci. Instr. 39, 1863 (1968).
[50]E. R. Dobbs and J. D. Llewellyn, Int. J. Nondestr. Test. 2, 49 (1971).
[51]M. R. Gaerttner, B. W. Maxfield and W. D. Wallace, Bull. Am. Phys. Soc. 14, 64 (1969).
[52]R. L. Thomas, G. Turner and D. Hsu, Phys. Lett. A30, 316 (1969).
[53]G. Turner, R. L. Rhomas and D. Hsu, Phys. Rev. B3, 3097 (1971).
[54]W. D. Wallace, M. R. Gaerttner and B. W. Maxfield, Phys. Rev. Lett. 27, 995 (1971).
[55]D. E. Chimenti, C. A. Kukkonen and B. W. Maxfield, Phys. Rev. B10, 3228 (1974).
[56]D. E. Chimenti, Phys. Rev. B13, 4245 (1976).
[57]É. A. Kaner and V. L. Fal'ko, Zh. Eksp. Teor. Fiz. 64, 1016 (1973) [Sov. Phys. JETP 37, 516 (1973)].
[58]G. I. Babkin and V. Ya. Kravchenko, Zh. Eksp. Teor. Fiz. 67, 1006 (1974) [Sov. Phys. JETP 40, 498 (1974)].
[59]N. C. Banik and A. W. Overhauser, Phys. Rev. B16, 3379 (1977).
[60]N. C. Banik and A. W. Overhauser, Phys. Rev. B17, 4505 (1978).
[61]N. C. Banik and A. W. Overhauser, Phys. Rev. B18, 3838 (1978).
[62]L. R. Ram Mohan, S. Kartheuser and S. Rodriquez, Phys. Rev. B20, 3233 (1979).
[63]T. Kjeldaas Jr., Phys. Rev. 113, 1473 (1959).
[64]M. R. Gaerttner and B. W. Maxfield, Phys. Rev. Lett. 29, 654 (1972).
[65]É. A. Kaner and B. F. Gantmakher, Usp. Fiz. Nauk 94, 193 (1968) [Sov. Phys. Usp. 11, 81 (1968)].
[66]G. I. Babkin and V. Ya. Kravchenko, Pis'ma Zh. Eksp. Teor. Fiz. 17, 174 (1973) [JETP Lett. 17, 124 (1973)].
[67]V. L. Fal'ko, Zh. Eksp. Teor. Fiz. 65, 2369 (1973) [Sov. Phys. JETP 38, 1184 (1974)].
[68]V. L. Fal'ko and V. A. Yampol'skiĭ, Fiz. Nizk. Temp. 3, 477 (1977) [Sov. J. Low Temp. Phys. 3, 231 (1977)].
[69]V. F. Gantmakher and V. T. Dolgopolov, Zh. Eksp. Teor. Fiz. 57, 132 (1969) [Sov. Phys. JETP 30, 78 (1970)].
[70]E. R. Dobbs, R. L. Thomas and D. Hsu, Phys. Lett. A30, 338 (1969).
[71]D. Hsu and R. L. Thoma, Phys. Rev. B5, 4668 (1972).
[72]V. T. Dolgopolov, Zh. Eksp. Teor. Fiz. 61, 1545 (1971) [Sov. Phys. JETP 34, 823 (1972)].
[73]I. A. Gilinskiĭ, M. B. Sultanov and Yu. V. Lëvin, Zh. Eksp. Teor. Fiz. 66, 225 (1974) [Sov. Phys. JETP 39, 106 (1974)].
[74]É. I. Rashba, Zh. Eksp. Teor. Fiz. 48, 1427 (1965) [Sov. Phys. JETP 21, 954 (1965)].
[75]V. Ya. Kravchenko and É. I. Rashba, Zh. Eksp. Teor. Fiz. 56, 1713 (1969) [Sov. Phys. JETP 29, 918 (1969)].
[76]P. E. Zil'berman and V. V. Pavlovich, Fiz. Tverd. Tela (Leningrad) 14, 598 (1972) [Sov. Phys. Solid State 14, 504 (1972)].
[77]G. I. Babkin and V. Ya. Kravchenko, Zh. Eksp. Teor. Fiz. 60, 695 (1971) [Sov. Phys. JETP 33, 378 (1971)].
[78]V. Ya. Kravchenko, Author's abstract doctoral dissertation, Institute of Solid-State Physics, Academy of Sciences of the USSR, Chernogolovka, 1972.
[79]Yu. P. Gaĭdukov and A. P. Perov, Pis'ma Zh. Eksp. Teor. Fiz. 13, 307 (1971) [JETP Lett. 13, 219 (1971)].
[80]H. Fisher and Y. H. Kao, Solid State Commun. 7, 275 (1969).
[81]E. R. Dobbs, J. Phys. Chem. Solids 31, 1657 (1970).
[82]V. L. Gurevich, V. G. Skobov and Yu. A Firsov, Zh. Eksp. Teor. Fiz. 40, 786 (1961) [Sov. Phys. JETP 13, 552 (1961)].
[83]V. Ya. Kravchenko, Zh. Eksp. Teor. Fiz. 62, 377 (1972) [Sov. Phys. JETP 35, 202 (1972)].
[84]V. M. Kontorovich and N. A. Sapogova, In: Materialy XVII Vsesoyuznogo soveshchaniya po fizike nizkikh temperatur (Proceedings of the XVII All-Union Conference on Low Temperature Physics) Donetsk, 1972, p. 163.
[85]V. L. Fal'ko, Fiz. Nizk. Temp. 1, 260 (1975) [Sov. J. Low Temp. Phys. 1, 127 (1975)].
[86]A. P. Korolyuk, M. A. Obolenskiĭ and V. L. Fal'ko, Zh. Eksp. Teor. Fiz. 59, 377 (1970) [Sov. Phys. JETP 32, 205 (1971)].
[87]A. P. Korolyuk, M. A. Obolenskiĭ and V. L. Fal'ko, Zh. Eksp. Teor. Fiz. 60, 269 (1971) [Sov. Phys. JETP 33, 148 (1971)].
[88]G. I. Babkin and V. Ya. Kravchenko, Fiz. Tverd. Tela (Leningrad) 19, 229 (1977) [Sov. Phys. Solid State 19, 131 (1977)].
[89]R. H. Bidgood, M. J. Lea and E. R. Dobbs, J. Phys. (Paris) F7, 1791 (1977).
[90]R. L. Thomas, M. J. Lea, E. Sendezera, and E. R. Dobbs, J. Phys. (Paris) F5, L21 (1975).
[91]R. L. Thomas, M. J. Lea, E. J. Sendezera, E. R. Dobbs, K. C. Lee and A. M. de Graaf, Phys. Rev. B14, 4889 (1976).
[92]J. R. Cullen and R. A. Ferrell, Phys. Rev. 146, 282 (1966).
[93]J. M. Pierce and H. A. Hogg, J. Appl. Phys. 44, 1342 (1973).
[94]L. A. Vienneau and B. W. Maxfield, Phys. Rev. B11, 4339 (1975).
[95]B. Abeles, Phys. Rev. Lett. 19, 1181 (1967).
[96]G. S. Weisbarth, Phys. Lett. A27, 230 (1968).
[97]Y. Goldstein and A. Zemel, Phys. Rev. Lett. 28, 147 (1972).
[98]A. Zemel and Y. Goldstein, Phys. Rev. B7, 191 (1973).
[99]A. Zemel and Y. Goldstein, Phys. Rev. B9, 1499 (1974).
[100]Y. Goldstein, S. Barzilai and A. Zemel, Phys. Rev. Lett. 32, 463 (1974).
[101]Y. Goldstein, S. Barzilai and A. Zemel, Phys. Rev. B10, 5010 (1974).
[102]A. Zemel, In: Ultrasonic Symposium, Proc. IEEE, 1974, p. 519.
[103]G. I. Ivanovski, M. I. Kaganov and V. B. Fiks, Fiz. Tverd. Tela (Leningrad) 15, 1441 (1973) [Sov. Phys. Solid State 15, 972 (1973)].
[104]B. Abeles and Y. Goldstein, Prov. LT-XI, 1968, v. 2, p. 965.
[105]A. A. Golub, Fiz. Tverd. Tela (Leningrad) 15, 1468 (1973) [Sov. Phys. Solid State 15, 988 (1973)].
[106]A. A. Golub, Zh. Eksp. Teor. Fiz. 69, 1007 (1975) [Sov. Phys. JETP 42, 512 (1975)].
[107]G. I. Ivanovski and M. I. Kaganov, Vestn. Mosk. Univ. Fiz. Astron. (USSR) 16, No. 3, 308 (1975).
[108]G. I. Ivanovski and M. I. Kaganov, Fiz. Tverd. Tela (Leningrad) 18, 2704 (1976) [Sov. Phys. Solid State 18, 1576 (1976)].
[109]D. E. Chimenti and B. W. Maxfield, J. Appl. Phys. 46, 4073 (1975).
[110]M. B. Gitis, Fiz. Tverd. Tela (Leningrad) 14, 3563 (1972) [Sov. Phys. Solid State 14, 2992 (1973)].
[111]V. F. Drobol'ko and V. P. Naberezhnykh, Fiz. Nizk, Temp. 2, 872 (1976) [Sov. J. Low Temp. Phys. 2, 428 (1976)].
[112]V. F. Drobol'ko and V. P. Naberezhnykh, Fiz. Nizk. Temp. 6, 72 (1980) [Sov. J. Low Temp. Phys. 6, 35 (1980)].
[113]M. Hanabusa, T. Kushida and J. C. Murphy, J. Appl. Phys. 44, 5106 (1973).
[114]E. E. Pacher and B. W. Maxfield, In: Ultrasonics Symposium: Proceedings, Milwaukee, Wisc. 1973, p. 526.
[115]M. J. W. Povey, E. R. Dobbs and D. J. Meredith, J. Phys. (Paris) F3, L234, (1973).
[116]M. J. W. Povey and E. R. Dobbs, In: 5th Intern. Conf. on Internal Friction and Ultrasonic Attenuation in Crystalline Solids, New York; Heidelberg, 1975, v. 1, p. 168.
[117]G. I. Aubert, J. Appl. Phys. 39, 504 (1968).
[118]G. Gorodetsky, B. Luthi, T. J. Moran and M. E. Mullen, J. Appl. Phys. 42, 1234 (1972).
[119]R. B. Thompson and G. A. Alers, Bull. Am. Phys. Soc. Ser. II 19, 370 (1974).
[120]R. C. LeCraw and R. L. Comstock, cited in collected papers of Ref. 25, V, 3B, p. 130, 1966.

[121]A. I. Akhiezer, V. G. Bar'yakhtar and S. V. Peletminskiĭ, Zh. Eksp. Teor. Fiz. **35**, 228 (1958) [Sov. Phys. JETP **8**, 157 (1959)].
[122]A. Ya. Blank and M. I. Kaganov, Usp. Fiz. Nauk **92**, 583 (1967) [Sov. Phys. Usp. **10**, 536 (1968)].
[123]J. J. Quinn, J. Phys. Chem. Solids **31**, 1701 (1970).
[124]N. K. Solovarov, Zh. Eksp. Teor. Fiz. **69**, 274 (1975) [Sov. Phys. JETP **42**, 141 (1975)].
[125]L. R. Testardi and J. H. Condon, Phys. Rev. **B1**, 3928 (1970).
[126]N. K. Batra, R. L. Thomas, K. C. Lee and A. M. de Graaf, Phys. Ref. **B8**, 5473 (1973).
[127]J. Bardeen, L. M. Cooper and J. R. Schieffer, Phys. Rev. **108**, 1175 (1957).
[128]J. P. Turneaure and I. Weissman, J. Appl. Phys. **39**, 4417 (1968).
[129]J. Halbritter, Phys. Lett. **A42**, 82 (1971).
[130]C. Passow, Phys. Rev. Lett. **28**, 427 (1972).
[131]J. Halbritter, Phys. Lett. **A49**, 379 (1974).
[132]E. P. Kartheuser and S. Rodriguez, Appl. Phys. Lett. **24**, 338 (1974).
[133]E. P. Kartheuser and S. Rodriquez, J. Appl. Phys. **47**, 700 (1976).
[134]E. P. Kartheuser and S. Rodriquez, J. Appl. Phys. **47**, 3651 (1976).
[135]G. Feydev, E. Kartheuser, L. R. Ram Mohan and S. Rodriquez, Phys. Rev. **B25**, 7141 (1982).
[136]E. A. Kaner and V. L. Falko, Solid State Commun. **35**, 353 (1980).
[137]S. Rodriquez, Phys. Rev. **130**, 1778 (1963).
[138]S. Rodriquez, Phys. Rev. **132**, 535 (1963).

Translated by G. M. Volkoff