Nonlinear electromagnetic generation of longitudinal ultrasound in zinc

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Nonlinear electromagnetic generation of longitudinal ultrasound in Zn under the conditions of normal and anomalous skin effects was investigated. It was found that the temperature dependence of the generation efficiency can be described taking into account three qualitatively different mechanisms of conversion—induction, thermoelastic, and deformation. Under the conditions of the experiment the efficiency of the induction mechanism was virtually independent of the temperature. The efficiency of the thermoelastic mechanism decreased and that of the deformation mechanism increased with decreasing temperature. Quantitative agreement between the experimental data and the computational results is obtained only under the assumption that a parameter which has the dimension of mass and describes the electron-phonon interaction (the "deformation" mass $\tilde{m}$) is 4.3 ± 0.7 times greater than the free-electron mass m.

INTRODUCTION

The mechanisms of linear transformation, which are responsible for the generation of ultrasound in metals at the frequency of an electromagnetic wave incident on the surface of the metal, are a standard subject of investigation in electromagnetic-acoustic conversion (EMAC) problems.[1–6] While significantly less efficient that piezoelectric and magneteostrictional transducers, EMAC nonetheless is of interest both for studying the acoustic properties of conductors and for determining the coupling parameters between the electronic, ionic, and spin subsystems.

The induction force[7–10] and the deformation force[11–18] have been studied in greatest detail as sources of linear transformation of waves. The induction force is manifested only in the presence of a constant magnetic field $\mathbf{H}_0$ and reduces to ponderomotive interaction of $\mathbf{H}_0$ with alternating current induced by an electromagnetic wave in the skin layer δ of the metal. This force is proportional to the intensities of constant and alternating magnetic fields and imparts an additional momentum to the electrons, which in turn transfer it to the lattice in collisions. The deformation force also operates in the absence of a constant magnetic field, but this force can be observed only under the conditions of the anomalous skin effect, when the electron mean-free path length l is longer than the penetration depth δ_A of an electromagnetic field in the metal. The amplitude of the lattice vibrations induced by the deformation force is proportional to the electron-phonon interaction constant, corresponding to the component of the deformation-potential tensor $\Lambda_{ik}(\mathbf{p})$. Experimental investigations of linear generation of transverse ultrasound in potassium single crystals[12,13] and aluminum single crystals[14] by the deformation force have shown that quantitative agreement between the experimental data and the computational results can be achieved by writing the tensor Λ_{ik} in the form $\tilde{m}v_i v_k$ (see Ref. 19) and by assuming that the electron-phonon interaction mass (the deformation mass $\tilde{m}$) is several times greater than the free-electron mass m. Nonuniform temperature oscillations, due to the thermoelectric effect,[20] as well as the inertial force (Stewart-Tolman force[21]) can serve as a source of linear EMAC.

In the last few years the focus of investigations of electromagnetic excitation of ultrasound has shifted to the study of subtle nonlinear conversion mechanisms. The induction mechanism for generating longitudinal ultrasound at twice the frequency of the incident electromagnetic wave has also been studied before. Thus it was shown in Refs. 22 and 23 that under conditions of the normal skin effect ($l \ll \delta$) the amplitude of the excited ultrasound is proportional to the squared intensity of the alternating magnetic field $\mathbf{H}$ and inversely proportional to the velocity of ultrasound, the density of the metal, and the frequency. The part of the induction force acting of the lattice that is quadratic in the amplitude of the wave incident on the metal is directed into the bulk of the metal. This results in excitation of compression waves, propagating along the normal to the surface (see below) in the metal. The efficiency of the induction mechanism of conversion is highest when the wavelength λ of the excited ultrasound is significantly longer than the depth of the skin layer.

The deformation mechanism of nonlinear conversion has been less studied. In Ref. 24 it was shown for a tungsten single crystal that generation of longitudinal ultrasound is observed under the conditions of the anomalous skin effect and is efficiently suppressed by an external magnetic field, but measurements over a wide temperature range, which would have made it possible to identify the mechanism of transformation, were not performed.

The theoretical analysis of the deformation mechanism of EMAC encompasses both weak nonlinearity (Ref. 25) and strong nonlinearity (Refs. 26 and 27). These two cases differ by the degree to which the alternating magnetic field affects the dynamics of electrons in the skin layer and they predict different asymptotic behavior of the amplitude of the excited ultrasound as a function of the amplitude of the incident wave and the electron mean free path in the metal. The deformation force is strongly related to the nonlocal character of the electronic conductivity in metals at low temperatures. It is manifested when the electromagnetic field does not act directly on ions in the skin layer where the electrons transfer momentum to the lattice. The efficiency of this conversion mechanism is highest when $\delta \ll \lambda \ll l$.

Apart from the induction and deformation forces, longitudinal ultrasound at twice the frequency of the incident

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electromagnetic wave can also be generated by other source of nonlinearity. The most important such source is the force arising due to the appearance of thermoelastic stresses in the Joule-heated skin layer.[28]

In this paper we investigate nonlinear generation of longitudinal ultrasound in zinc single crystals in the temperature interval covering the range of existence of normal and anomalous skin effects in zinc.

METHOD OF MEASUREMENT AND RESULTS

The measurements were performed in the interval 4–40 K on single-crystal plane-parallel plates of zinc with transverse dimensions of about 1×1 cm^2 and thickness 0.4 cm. The plates were prepared by cleaving along the hexagonal plane from a massive block. Thus the normals to the surfaces of the plates coincided with the six-fold symmetry axis [0001]. Since the specimens were prepared by cleaving along cleavage planes, it can be assumed that the properties of the surface layers are very nearly the same as the bulk properties.

In order to determine the magnitude and temperature dependence of the electron mean free path l in Zn [$\rho l = 1.8\cdot 10^{-11}$ $\Omega\cdot$cm^2 (Ref. 29)] we measured the dc resistivity ρ on a specially prepared crystal of the same quality as the specimens being studied. The ratio of the resistivities at room temperature and the temperature of liquid helium was equal to 10^4. These data were used to calculate the temperature dependence of the penetration depth of an electromagnetic field in Zn under conditions of the normal and anomalous skin effects.

A longitudinal piezoelectric transducer was glued to one of the working surfaces of the specimens and a flat spiral induction coil as positioned at the other surface at a distance $d = 0.02$ cm from it. In order to prevent the parasitic generation of ultrasonic waves owing to leakage of the second harmonic of the driving signal to the piezoelectric transducer the receiving channel of the apparatus was carefully shielded and, as shown in Fig. 1, the specimen was placed in a metal box and the gap between the walls of the box and the specimen was sealed off with indium. The temperature distribution along the specimen was checked with CuFe–Cu thermocouples. For a driving signal of maximum strength the difference of the temperatures on the opposite surfaces of the specimen was equal to 1–2 K.

The sinusoidal driving signal was produced by a G3-41 generator whose frequency could be continuously adjusted. The ac current generated by the driving signal in the inductance coil reached 1 A, which corresponded to an alternating magnetic field with intensity ~ 35 Oe at the surface of the crystal.[1)] The measurements were performed in three frequency bands of the driving signal near 3, 5, and 9.5 MHz. The ultrasound was detected with the help of lithium niobate transducers, whose resonance frequencies corresponded to the doubled frequency of the driving signal, i.e., 6, 10, and 19 MHz. The signal from the piezoelectric transducer was fed into an SK4-59 spectrum analyzer.

The measurements consisted of the following. At a fixed temperature the frequency of the driving oscillator was scanned in an interval Δf corresponding to the transmission band $2\Delta f$ of the piezoelectric transducer. The amplitude-frequency characteristic of the specimen was recorded on the screen of the spectrum analyzer in the storage mode; the characteristic is shown schematically in Fig. 2. Several resonances of standing elastic waves on the thickness of the plate (resonances of the Fabry–Perot type) fit into the transmission band of the piezoelectric transducer. The figure of merit of these resonances was equal to 10–100. The measurements were performed in both the manual and automatic modes using a computer. The amplitudes A of the acoustic resonances in the specimen are proportional to the amplitude U of the excitation and inversely proportional to the attenuation Γ of the ultrasonic waves. In order to determine the temperature dependence of the attenuation we performed independent measurements of Γ using a piezoelectric transducer for both generation and detection of ultrasound.

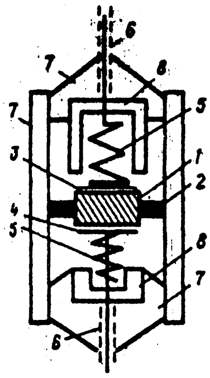

FIG. 1. Layout of the measuring chamber: 1) specimen, 2) indium screen, 3) piezoelectric transducer, 4) spiral induction coil, 5) springs, 6) coaxial cables, 7) box, 8) insulator.

In order to establish the fact that all these results are determined by the properties of the single crystal and not by instrumental effects, for example, the properties of adhesive which provided the acoustic contact between the piezoelectric transducer and the specimen, the experiments described below were repeated using as the specimen a duraluminum plate. All measured quantities in these test experiments were independent of the temperature in the interval $T = 4$–40 K.

Generation of longitudinal ultrasound was observed in the entire temperature interval investigated. The results of measurements of $A(T)$ and $1/\Gamma(T)$ at 9.5 MHz are presented in Fig. 3. At high temperatures the dependence $A(T)$ is

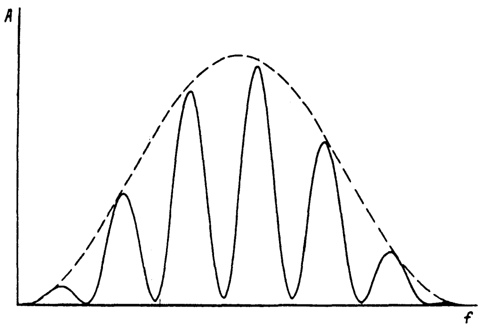

FIG. 2. Amplitude-frequency characteristics of a composite resonator consisting of a piezoelectric transducer and the specimen. The dashed line is the amplitude-frequency characteristic of the piezoelectric transducer itself.

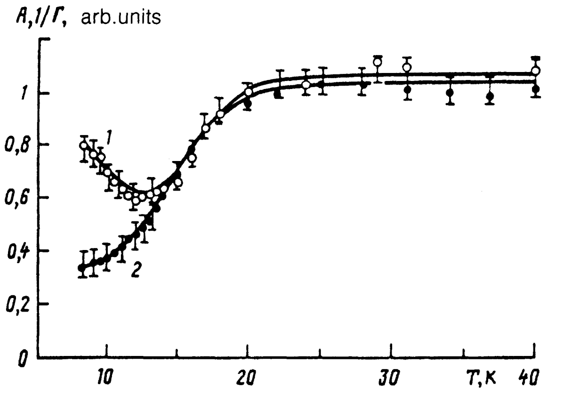

FIG. 3. Temperature dependences of the amplitude A of the acoustic resonance in the specimen (curve 1) and the inverse attenuation $1/\Gamma$ (curve 2) at an ultrasonic frequency of 19 MHz. The curves are normalized to the values of A and $1/\Gamma$ at high temperatures.

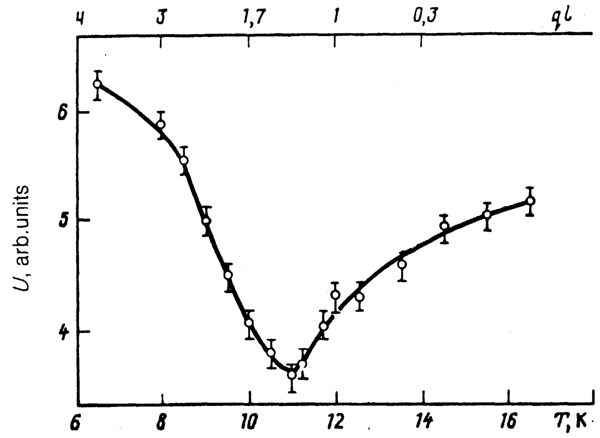

FIG. 5. Temperature dependence of the amplitude U of ultrasound generated in Zn by the nonlinear mechanism at the frequency of the electromagnetic wave 5 MHz. The intensity of the rf magnetic field is equal to 35 Oe.

completely determined by the behavior of $1/\Gamma(T)$ and discrepancies between these curves are observed only at low temperatures, $T \leqslant 14$ K. The functions $A(T)$ and $1/\Gamma(T)$ obtained at other frequencies are also analogous. Dividing point-by-point the curves $A(T)$ and $1/\Gamma(T)$ it is possible to reconstruct the temperature behavior of the amplitude $U(T)$ of the excited ultrasound. It is virtually constant in the temperature interval $T = 20$–40 K and, as shown in Figs. 4–6, varies nonmonotonically at lower temperatures.

In addition to investigating the temperature dependence of the amplitude of the generated ultrasound, we also measured the dependence of the amplitude the intensity of the rf magnetic field H. We found that at the signal frequencies 3 and 9.5 MHz at the temperature of liquid helium this dependence is quadratic.

THEORY

Let a plane electromagnetic wave with frequency ω be incident on the boundary of the metallic half-space $z > 0$. The complete system of equations, describing the generation of longitudinal ultrasound at the frequency 2ω, includes Maxwell's equations, the kinetic equation for the nonequilibrium correction to the electron distribution function, and the equations of heat conduction and elasticity:

$$\text{rot rot}\,\mathbf{E} = -\frac{4\pi}{c^2}\frac{\partial \mathbf{j}}{\partial t}, \quad \mathbf{j} = -e\langle \mathbf{v}\chi \rangle, \tag{1}$$

$$\left(\frac{\partial}{\partial t} + \mathbf{v}\nabla + \frac{e}{c}[\mathbf{vH}]\frac{\partial}{\partial \mathbf{p}} + \nu\right)\chi = -e\mathbf{vE}, \tag{2}$$

$$C\frac{\partial \theta}{\partial t} - \varkappa\frac{d^2\theta}{dz^2} = Q, \tag{3}$$

$$\frac{d^2U}{dz^2} + q^2U = -\frac{1}{\rho_m S^2}F. \tag{4}$$

Here $\mathbf{E}(z,t)$ is the electric field of the wave, c is the velocity of light, e and $\mathbf{v}$ are the electron charge and velocity, $\chi\partial f_0/\partial\varepsilon$ is the nonequilibrium correction to the electron distribution function $f_0(\varepsilon)$, ν is the collision frequency, C is the heat

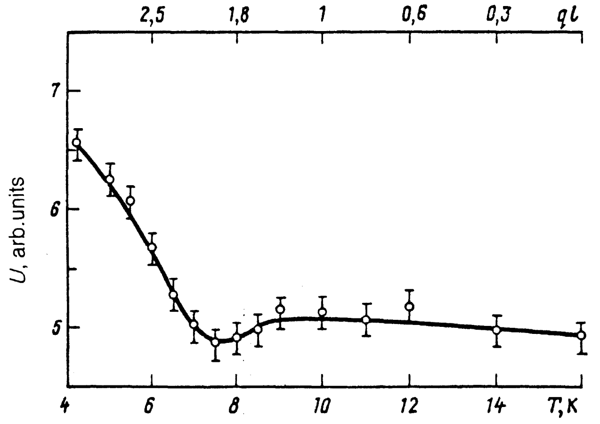

FIG. 4. Temperature dependence of the amplitude U of nonlinear generation of longitudinal ultrasound in Zn at the frequency of the electromagnetic wave 3 MHz. The intensity of the rf magnetic field is equal to 10 Oe. The amplitude of the nonlinear generation by induction is chosen as the unit of measurement along the ordinate axis. The dimensionless parameter ql, where $\mathbf{q}$ is the wave vector of ultrasound and l is the electron mean free path length, is plotted along the abscissa axis at the top.

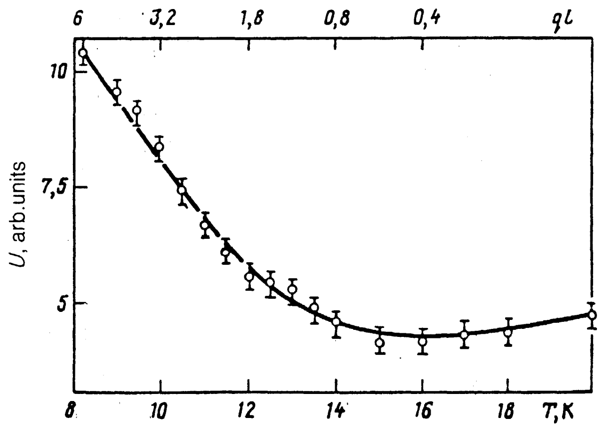

FIG. 6. Temperature dependence of the amplitude U of nonlinear generation of longitudinal ultrasound in Zn at the frequency of the electromagnetic wave 9.5 MHz. The intensity of the rf magnetic field is equal to 35 Oe.

capacity, $\varkappa$ is the thermal conductivity, θ is the oscillating correction to the temperature, Q is the power density of the heat source, U is the displacement, S is the velocity of longitudinal ultrasound, $q = 2\omega/S$ is the wave vector of the ultrasonic wave at the frequency 2ω, ρ_m is the density of the metal, and the angle brackets denote integration over the Fermi surface.

The temperature θ is a thermodynamically equilibrium characteristic of the state of the body. For this reason, a temperature oscillating with frequency $2\omega[\theta \sim \exp \times(-i\,2\omega t)]$ can be employed if $2\omega \ll \nu$. It is important to note that in this case the condition $|k_T l| \ll 1$, where the thermal wave number $k_T = (2i\omega C/\varkappa)^{1/2}$, is satisfied automatically. Indeed, in order of magnitude $\varkappa \approx Clv$ (v is the average velocity of the carriers) and $|k_T l| = (2\omega Cl^2/Clv)^{1/2} \approx (2\omega/\nu)^{1/2}$, where $\nu = v/l$. There is no anomalous skin effect in the presence of heat propagation!

The weakness of the coupling between the electromagnetic and elastic subsystems, which is characteristic for problems of electromagnetic excitation of ultrasound, makes it possible to study different mechanisms of EMAC independently of one another. Accordingly, the density of the force F acting on an element of volume of the metal can be represented as a sum of three terms: and induction term

$$F^{\rm IND} = jH/2c, \tag{5}$$

a deformation term

$$F^{\rm DEF} = -\langle \Lambda_{ik} d\chi_2/dz \rangle \tag{6}$$

where χ_2 is the quadratic part of χ and $\Lambda_{ik}(\mathbf{p})$, as we have mentioned above, is the deformation-potential tensor, and a thermoelastic part

$$F^{\rm TE} = -\alpha K d\theta/dz. \tag{7}$$

Here α is the volumetric expansion coefficient and K is the bulk modulus.

The boundary conditions for Maxwell's equations are continuity of the tangential components of the electric and magnetic fields and the boundary condition for the kinetic equation is Fuchs' phenomenological condition[30] for scattering of electrons by a surface. The boundary condition for the equation of elasticity has the form[27]

$$\partial U/\partial z|_{z=0} = (1/\rho_m S^2)\langle \Lambda_{ik}\chi \rangle.$$

That $\partial U/\partial z|_{z=0}$ is different from zero is a consequence of the nonspecular nature of the scattering of electrons by the surface of the crystal. The boundary condition for the heat-conduction equation is described below.

The theory of the induction and deformation mechanisms for nonlinear generation of longitudinal ultrasound is developed in Refs. 22–27. Here we only summarize the results for the case $q\delta \ll 1$, corresponding to the conditions of the experiment in the regime of both normal and anomalous skin effects. The amplitude of ultrasonic waves excited by the Lorentz force (5) is determined by the expression

$$|U^{\rm IND}| = \lambda \frac{H^2}{32\pi^2 \rho_m S^2} = \frac{\lambda \xi}{4\pi}, \tag{8}$$

where λ is the wavelength of the excited ultrasound and ξ is the ratio of the energy density of the alternating magnetic field $H^2/8\pi$ to the elastic modulus $\rho_m S^2$. Under the conditions of the experiment $|U^{\rm IND}|$ is virtually independent of the temperature; this makes it possible to use this quantity as a scale factor when representing the temperature dependence of the amplitude of ultrasound excited by other conversion mechanisms. The absolute quantity $|U^{\rm IND}|$, calculated from the formula (8) at the frequency of the electromagnetic wave 9.5 MHz in a field of 35 Oe was equal to $6\cdot 10^{-14}$ cm.

Under the conditions of the normal spin effect the deformation mechanism of EMAC is inefficient, while under the conditions of the anomalous skin effect with fully developed electrodynamic nonlinearity, characterized by the parameter

$$b = (Hel^2/8cp_F\delta)^{1/2} \sim 1, \quad \delta = \delta_A[1-\exp(-1/b)]^{1/2}, \tag{9}$$

where p_F is the Fermi momentum and δ_A is the penetration depth of the electromagnetic field in the metal under the conditions of the anomalous skin effect, the amplitude of the ultrasound excited by the deformation force (6) is described by the interpolation formula of Ref. 26, valid for an arbitrary nonlinearity to within a constant factor[2)]

$$|U^{\rm DEF}| = \frac{\lambda\xi}{6\pi^4}\frac{\tilde{m}}{m}(ql)^2 \ln\frac{1}{q\delta_A}\left[1-\exp\left(-\frac{1}{b}\right)\right]^2. \tag{10}$$

With the exception of the deformation-induced mass $\tilde{m}$, all parameters necessary for calculating $|U^{\rm DEF}|$ from the formula can be obtained from independent measurements. Because this formula contains the nonlinearity parameter the dependence of $|U^{\rm DEF}|$ on H must deviate from quadratic as the alternating field increases.

We now study the thermoelastic mechanism for nonlinear generation of ultrasound under conditions of the normal and anomalous skin effects. In the case of the normal skin effect the source of thermoelastic stresses is the time-dependent part of the Joule heating

$$Q = -\mathrm{Re}\frac{i\omega H^2}{8\pi}\exp[2i(kz-\omega t)], \tag{11}$$

where $k = (4\pi i\omega/c^2\rho)^{1/2}$ is the electrodynamic wave number, and the boundary condition reduces to the requirement that there be no heat flux through the surface:

$$\varkappa \frac{d\theta(z)}{dz}\bigg|_{z=0} = 0. \tag{12}$$

In this case the expression for the oscillating correction to the temperature can be written in the form

$$\theta(z) = \mathrm{Re}\frac{i\omega H^2}{8\pi\varkappa}\,\frac{\exp(2ikz)-(2k/k_T)\exp(ik_T z)}{k_T^2-4k^2}. \tag{13}$$

Substituting this expression into the formulas (7) and (4) makes it possible to calculate the amplitude of the longitudinal ultrasound excited in the metal by thermoelastic stresses under the conditions of the normal skin effect:

$$|U^{\rm TE}| = \lambda\frac{\alpha H^2}{32\pi^2 C}\frac{k_T}{k_T+2k} = \frac{\lambda\xi}{4\pi}\frac{\alpha K}{C}\frac{k_T}{k_T+2k}. \tag{14}$$

In deriving the expression (14) we employed the condition $q \ll |k_T|, |k|$, which is valid under the conditions of the experiment in the case of the normal skin effect. We note that under the condition $k \ll k_T$, which is valid at high temperatures, the ratio of the amplitudes of the thermoelastic and Lorentz generation of ultrasound is equal to $\alpha K/C = \gamma$, the Grüneisen parameter.

Under the conditions of the anomalous skin effect heat is released in the specimen in a layer of thickness $\sim\delta_A \ll l$. In the macroscopic approach the heat source in this case cannot be regarded as being distributed. A rigorous approach in this case is as follows: In the formula (3) we must set $Q=0$ and the heat flux through the boundary must be taken as the boundary condition:

$$\varkappa \frac{d\theta(z)}{dz}\bigg|_{z=0} = \mathrm{Re}\int_0^\infty E(z)j(z)\,dz. \qquad (15)$$

Using the expressions[31] for the field and current distributions in the case $l \gg \delta_A$, we can write the wave part of the solution of the heat-conduction equation in the form

$$\theta(z,t) = \mathrm{Re}\frac{i\omega\delta_A H^2}{4\pi^2\varkappa k_T} I \exp[i(k_T z - 2\omega t)], \qquad (16)$$

where

$$I = \int_0^\infty \frac{x\,dx}{(x^3-1)^2} \approx -0{,}2 + i\cdot 0{,}35. \qquad (17)$$

Correspondingly, the amplitude of longitudinal ultrasound excited in the metal by thermoelastic stresses under anomalous skin effect conditions is equal to

$$|U^{\mathrm{TE}}| = \frac{\lambda\xi}{4\pi^2}\gamma q\delta_A G\left(\frac{|k_T|}{q}\right), \qquad (18)$$

$$G(x) = \frac{x^3}{1+x^4}[(a_1+a_2x^2)^2 + (a_1x^2 - a_2)^2]^{1/2},$$

$$a_1 \approx 0{,}24, \quad a_2 \approx 0{,}067. \qquad (19)$$

DISCUSSION

When comparing the experimental data with the theory we must take into account the fact that in the formulas (8), (10), (14), and (18) the magnitudes of the amplitudes of nonlinear generation are given, i.e., quantities which would be observed in an experiment with each mechanism operating separately. Figure 7 shows the computed dependence of $|U|$ on T for three conversion mechanisms at the frequency 9.5 MHz of the electromagnetic wave: induction mechanism [curve 1, formula (8)], deformation mechanism [curve 2, formula (10)], and thermoelastic mechanism [curve 3, formulas (14), (18), and (19)]. The value of $|U^{\mathrm{IND}}|$ is taken as the unit of measurement along the vertical axis. It is obvious that at high temperatures the thermoelastic force plays the determining role in conversion processes. As the temperature decreases $|U^{\mathrm{TE}}|$ decreases; this is determined by the temperature dependence of the electrodynamic $|k|^{-1}$ and thermal $|k_T|^{-1}$ penetration depths. Under the conditions of the anomalous skin effect $|U^{\mathrm{TE}}|$ is negligibly small. The displacements owing to the thermoelastic stresses were estimated using data on the coefficient of cubical expansion, the thermal conductivity, and the heat capacity of zinc.[32-34] Generation of ultrasound by the deformation force is observed only at low temperatures under the conditions of the anomalous skin effect (at temperatures $T \leqslant 15$ K).

According to our estimates, the nonlinearity parameter calculated for $H = 35$ Oe is equal to $b \sim 1$, for which $|U^{\mathrm{DEF}}|$ should deviate significantly from a quadratic function of the intensity H of the rf magnetic field. The absence of such a deviation in the experiment could be connected, in our opinion, with the fact that the quasistationary electromagnetic field generated by the spiral induction coil is nonuniform in the plane of the plate and its effective value can be less than the computed value.

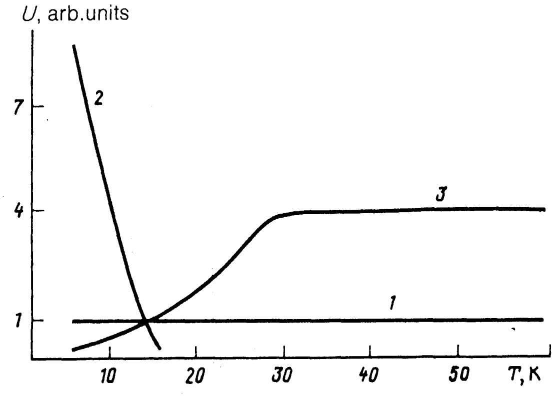

FIG. 7. Computed temperature dependence of the amplitudes U of nonlinear generation of longitudinal ultrasound in Zn at the frequency of the electromagnetic wave 9.5 MHz in an alternating magnetic field of 35 Oe by induction (curve 1), deformation (curve 2), and thermoelastic (Fig. 3) conversion mechanisms.

Moreover, it should be noted that in the analysis performed here the appreciable temperature gradient in the specimen was neglected. As mentioned above, the temperature difference between the opposite sides of the plate reached 1–2 K, i.e., the temperature gradient in the metal is equal to 2.5–5 K/cm.

In plotting the experimental data in Figs. 4–6 we chose the amplitude of ultrasound excited by the induction force at the corresponding frequency as the unit scale along the ordinate axis. In the temperature interval shown in these figures the experimental dependences $U(T)$ are nonomonotonic. At all frequencies studied, as the temperature decreases the amplitude of the generated ultrasonic waves decreases, passes through a minimum, and once again increases. As the frequency increases the position of the minimum shifts into the region of higher temperatures, and the increase in the amplitude of the generated ultrasound becomes even more pronounced at low temperatures. It remains unclear, however, why the minimum in the dependence $U(T)$ is more pronounced at the intermediate frequency of 5 MHz than at the frequencies 3 and 9.5 MHz.

The experimentally observed dependences qualitatively agree with the theory. The amplitude of the ultrasound decreases with decreasing temperature because the thermoelastic mechanism, whose efficiency in this temperature interval decreases, is not operating. The increase in the amplitude of the generated ultrasound as the temperature further decreases can be explained, in our opinion, only by the manifestation of the deformation mechanism of EMAC.

Analysis of the expression for the amplitude of ultrasound excited by the deformation force (10) shows that the contribution of this mechanism increases as a function of the parameter ql, plotted on the upper abscissa axis in Figs. 4–6. As the frequency increases this mechanism of EMAC comes into play at increasing higher temperatures. At the same time, the temperature dependence of the amplitude of thermoelastically generated ultrasound (14) does not depend on the frequency. This explains the displacement of the minimum in the dependence $U(T)$ with increasing frequency. In accordance with Eq. (10), we have $|U^{\rm DEF}| \sim l^2$, which is in good agreement with the experimental data. If the simplest ideas about the structure of the deformation tensor are employed (see above), then the numerical comparison of the results of theory and experiment can be made by varying the only unknown parameter in the problem—the deformation mass $\tilde{m}$. Satisfactory agreement is obtained for a value of m that is 4.3 ± 0.7 times greater than the free-electron mass $\tilde{m}$. As we have already mentioned, an analogous situation also occurs in the analysis of the linear deformation mechanism of EMAC in potassium (Refs. 12 and 13) and aluminum (Ref. 14).

Thus our investigations of electromagnetic excitation of ultrasonic waves in both the linear and nonlinear conversion regimes under conditions of the anomalous skin effect demonstrate that the deformation mass is systematically greater than the free-electron mass.

In conclusion we thank V. I. Khizhnom for stimulating remarks regarding methodology and M. A. Gulyanskii, N. M. Makarov, and V. A. Yanpol'skii for useful discussions.

[1)] See, however, below.

[2)] The more accurate form of this formula is based on a private communication from Makarov and Yanpol'skiĭ.

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