CONCLUSION

The results of our investigation show that thermoelectric phenomena are a powerful means of investigating kinetic processes in a metal. The magnitude and the temperature dependence of the phonon dragging make it possible to obtain information on phonon scattering by lattice distortions. The electronic part of the thermoelectric power can be connected with the electron scattering by impurities and serve by the same token as a method for investigating distortions of the crystal field by a given impurity. It is obvious that success in this direction will be determined by further experimental and theoretical analysis of these phenomena in metals.

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Phenomenological theory of three-pulse electroacoustic echo in powders

B. D. Laĭkhtman

A. F. Ioffe Physico-technical Institute, USSR Academy of Sciences

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The amplitude and duration of an echo pulse are calculated as functions of the amplitude and frequency of the external field, of the duration of the field pulses, and of the interval between them.

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The recently observed three-pulse electroacoustic echo in powders[1,2] has demonstrated that the investigated substances preserve a prolonged memory of the electric and mechanical actions to which they are subjected. The most interesting in this connection is the question of the mechanism of the memory. Also important is another question of whether the most general properties of the memory, inherent in practically any mechanism, are capable of explaining the main features of the electroacoustic echo, such as the dependence of the amplitude and duration of its pulse on the amplitude and frequency of the fields applied in the three pulses that produce the echo, the duration of these pulses, and the interval between them. The purpose of this paper is to answer the second question.

It should be noted first of all that the memorization takes place apparently in individual grains and not in the powder as a whole. Indeed, the dependence of the echo amplitude on the field frequency in the third pulse has a resonant character with a maximum at the field frequency of the first two pulses and with a width equal to the reciprocal pulse duration.[1] This fact indicates that the memorization is connected with processes occurring in those powder grains whose mechanical-oscillation frequencies are at resonance with the frequency of the external field. Since the experiments were performed under acoustic resonance conditions and the frequency of the external field was much larger than the reciprocal pulse duration, such grains are separated by distances much greater than their dimensions and exert practically no influence on one another.[3] Each resonating grain remembers the phase difference of its own oscillations excited by the first and second pulses of the field. The third field pulse excites, among others, oscillations whose initial phase is equal to the remembered phase difference, and the phase evolution in time goes in a direction opposite to the direction of the evolution after the first pulse. Then, after a time equal to the interval between the first and the second pulses, the phases of the oscillations of all the excited grains become equal, the combined dipole moment increases sharply, and it is this which is recorded as the echo signal.

The vanishing of the echo when the powder is stirred after the second pulse[1] can be attributed to the fact that the dipole moment connected with the resonant oscillations of the individual grains have definite directions relative to the external field. When the powder is stirred, the conditions for the excitation of the resonant oscillations by the third pulse become worse and the combined dipole moment decreases. It is these two factors which cause the vanishing of the echo signal.

For a phenomenological description of the memory we can introduce an additional parameter η that characterizes the deviation of the crystal from the thermodynamic-equilibrium state. Only an order-of-magnitude calculation is carried out here, so that the tensor structure of the parameter η plays no role. At small deviations of η from its equilibrium value ($\eta = 0$) the free energy per unit volume of the crystal can be expanded in powers of η. In this expansion it is necessary to include both the terms that depend only on η and the terms that ensure the connection between the parameter and the strain.1) Thus, the η-dependent part of the free energy per unit volume can be written in the form

$$F_\eta = {}^1/_2 a\eta^2 + {}^1/_2 b(\nabla\eta)^2 + \Lambda_{ik}u_{ik}\eta + \Lambda_{iklm}u_{ik}u_{lm}\eta, \tag{1}$$

where u_{ik} is the strain tensor. The equation for the relaxation of the parameter η is of the form

$$g\partial\eta/\partial t = -\delta F/\delta\eta. \tag{2}$$

As is evidenced by the experimental data, the lifetime of the nonequilibrium state produced under the influence of the external-field pulses greatly exceeds the damping power of the mechanical oscillations of the powder grains. This means that during the entire lifetime of the oscillations we can neglect the first two terms of (1). The nonequilibrium state that remembers the phase difference of the oscillations produced in the resonant grains under the influence of the first and second pulses of the external field is described by the distribution resulting from the time-independent part of the product $u_{ik}u_{lm}$ in the last term of (1). The same term describes the onset of the mechanical oscillations of the resonant grains after the third field pulse.2) Equation (2) and the elasticity-theory equations are solved in the same manner as in[3,4]. The final expression for the current produced after the third pulse and describing the echo signal is (the relaxation of the echo between the second and third pulses is not taken into account here)

$$I \sim n(\omega)\frac{Rp}{\Gamma}\left(\frac{Q}{\omega}\right)^3 T e^{-\Gamma T}\mathscr{E}_{10}^{*}\mathscr{E}_{20}\mathscr{E}_{30} f_3(t-T-T_1)e^{-i\omega t} + \text{c. c.}, \tag{3}$$

where p and Q are coefficients describing the piezoeffect of one grain[3];

$$R = (\rho g)^{-1}\int [\Lambda_{iklm}u_{ik}^{\alpha\lambda}u_{lm}^{\alpha\lambda}]^2 d^3x,$$

ρ is the crystal density; $u_{ik}^{\alpha\lambda}$ is the strain describing the natural oscillations of one grain[3] (the integration is over the volume of the grain); Γ is the damping coefficient of the mechanical oscillations of the grain; $n(\omega)$ is the distribution function of the resonant frequencies of the powder grains; ω is the frequency of the external field; $\mathscr{E}_{10}$, $\mathscr{E}_{20}$, and $\mathscr{E}_{30}$ are the amplitudes of the external field in the first, second, and third pulses; T is the interval between the first and second pulses, and T_1 is the interval between the first and third pulses. The shape of the echo pulse is described by the function (assuming rectangular field pulses)

$$f_3(t) = \int e^{-i\Omega t}\sin\frac{\Omega\tau_1}{2}\sin\frac{\Omega\tau_2}{2}\sin\frac{\Omega\tau_3}{2}\frac{d\Omega}{\Omega^3}, \tag{4}$$

where τ_1, τ_2, and τ_3 are the durations of the first, second, and third pulses. Terms of order τ/T were discarded in (3). The expression for the integral (4) is quite cumbersome and will not be presented here; only the main properties will be described. First, $f_3(t) = 0$ if $|t| > (\tau_1 + \tau_2 + \tau_3)/2$, so that the echo pulse duration is equal to the sum of the durations of the external-field pulses. The shape of the pulse is determined by the relations between τ_1, τ_2, and τ_3. Let $\tau_\alpha > \tau_\beta > \tau_\gamma$. Then the function $f_3(t)$ has at $\tau_\alpha < \tau_\beta + \tau_\gamma$ a single maximum for $t = 0$, with

$$f_3(0) = \frac{\pi}{16}(2\tau_1\tau_2 + 2\tau_2\tau_3 + 2\tau_3\tau_1 - \tau_1^2 - \tau_2^2 - \tau_3^2). \tag{5}$$

Second, at $\tau_\alpha > \tau_\beta + \tau_\gamma$ the function $f_3(t)$ assumes a maximum value in the entire interval $|t| < \tau_\alpha - (\tau_\beta + \tau_\gamma)$, and in this interval

$$f_3(t) = \frac{\pi}{4}\tau_\beta\tau_\gamma. \tag{6}$$

The dependence of the echo amplitude on the frequency is determined by the frequency dependence of the coefficients in (3). Recognizing that p does not depend on the frequency, $Q \sim \omega^{-1}$, [3] and $R \sim \omega^4$, then in the simplest case $\Gamma T \ll 1$ the frequency dependence is determined by the relation $I \sim n(\omega)/\Gamma(\omega)\omega^2$.

A quantitative comparison of the theory with the presently available experimental data can be carried out only for the duration of the echo pulse and for the dependence of its amplitude on the field amplitudes in the first three pulses. For these quantities, formulas (3) and (4) account fully for the experimental data.[1] Qualitatively, the existence of a memory describes without difficulty the cumulative enhancement of the three-pulse echo[2] as a result of the addition of the values of η which remember successive pairs of field pulses. It appears that the saturation of the cumulative enhancement is due to effects that are nonlinear in η and are not taken into account here.

It should be noted that the memory effect makes a contribution also in the two-pulse echo.[5,6] This contribution is due to the fact that the phase difference of the grain oscillations, which occurs after the second field pulse, is duplicated by oscillations which have also been produced after the second field pulse and take part in the recording. The corresponding part of the current is given by

$$I \sim n(\omega)\frac{Rp}{\Gamma^2}\left(\frac{Q}{\omega}\right)^3 (e^{-\Gamma T/2}-e^{-3\Gamma T/2}-\Gamma T e^{-3\Gamma T/2}) \times \mathscr{E}_{10}^{*}\mathscr{E}_{20}^{2} f_2(t-2T)\, e^{-i\omega t} + \text{c. c.}, \tag{7}$$

where the shape of the pulse takes the same form as when echo is produced with participation of nonlinear effects of elasticity theory[4]:

$$f_2(t) = \int e^{-i\Omega t} \sin\frac{\Omega\tau_1}{2} \sin^2\frac{\Omega\tau_2}{2} \frac{d\Omega}{\Omega^3}. \tag{8}$$

Two memory mechanisms capable of explaining the physical meaning of the parameter η have been proposed so far. The first is redistribution of the electrons in the traps under the influence of the constant inhomogeneous electric field, as proposed by Shiren and co-workers to explain the three-pulse echo in CdS crystals.[7] The insensitivity of the echo signal to ionization of air in an ampoule with powder[1] may be due to the fact that the redistribution of the electrons occurs in the entire volume of the grain, whereas the ionized air influences only the surface electrons. The second memory mechanism may be redistribution of the defects in the grain under the influence of the inhomogeneous strain field.[1]

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1)The connection with the strain turns out to be more important than the connection with the electric field, for the same reasons that nonlinear effects of elasticity theory are more important than the electric nonlinearities in the two-pulse echo.[4]

2)It must be borne in mind that $\Lambda_{ik}u_{ik}\eta$, together with the nonlinear effects of elasticity theory, also ensures memory. This mechanism does not alter the subsequent estimates and is therefore disregarded for simplicity.

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