Temperature dependence of the ultrasonic attenuation in indium

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(Submitted 12 July 1985)
Pis'ma Zh. Eksp. Teor. Fiz. **42**, No. 5, 197–200 (10 September 1985)

A contactless method has been used to study the temperature dependence of the attenuation of transverse ultrasound in indium. There is a clearly defined minimum in the attenuation near the Debye temperature. At high temperatures the attenuation falls off slowly with increasing temperature.

This study was stimulated by a contradiction in the existing models for the attenuation of ultrasound in metals. The classical analysis of the propagation of ultrasonic waves[1] shows that the attenuation Γ, determined by the combined effects of the thermal-conductivity and viscosity mechanisms, is inversely proportional to the fifth power of the temperature at $T \ll T_D$, where T_D is the Debye temperature, while it is proportional to the temperature at $T \gg T_D$. This result was derived for an arbitrary propagation direction of ultrasound in a metal. In metal single crystals, the waves break up into longitudinal and transverse waves as ultrasound propagates along acoustic axes. A calculation of the temperature dependence of the attenuation of ultrasound propagating along a high-symmetry direction[2] shows that the asymptotic behavior found for $\Gamma(T)$ in Ref. 1 remains valid over the entire temperature range only for longitudinal ultrasound. The exclusion of the thermal-conductivity mechanism in the propagation of transverse ultrasound makes the attenuation independent of the temperature at $T \gg T_D$. The attenuation in the region $T \sim T_D$ was not calculated in Refs. 1 and 2, however; according to the existing models, the low-temperature and high-temperature asymptotic expressions should join near T_D.

In the present study we use a contactless method to study the attenuation of transverse ultrasound in indium near T_D and at high temperatures. The reason for this experimental approach is that the primary difficulty in precise measurements of the temperature dependence of the attenuation in a pure metal by the conventional methods is the achieving of reliable acoustic contact between the transducer and the sample. In the first place, the creation of this contact unavoidably results in a deformation of a surface layer of the metal, and this deformation will affect the experimental results. Second, as the temperature is varied over a broad range, the properties of the acoustic contact itself will change, with the frequent consequence that the experimental results are not reproducible.

In order to carry out measurements over a broad temperature range, it is necessary to choose a metal with a relatively low Debye temperature and a high melting point. However, these temperatures are correlated with each other, so that it is not possible, strictly speaking, to carry out measurements in single crystals at $T \gg T_D$. One of the most suitable systems for such experiments is indium. Its Debye temperature is[3] 129 K, and its melting point is 430 K. The present measurements use a high-purity indium single crystal in the form of a disk 2 cm in diameter and 0.2 cm thick. The ultrasound propagation direction $\mathbf{q}_t$ coincides with the normal to the plane of the disk, which deviates 3.5 ° from a [001] fourfold symmetry axis. The contactless method for exciting ultrasound in a metal is outlined in Ref. 4. In the present experiments we detect the resonant structural features in the surface impedance of the plate as ultrasonic standing waves are created in the bulk of the plate.

According to the theory of electromagnetic excitation of ultrasound, the increments in the surface impedance of a plate at the resonant frequencies ω_n can be written

$$\Delta Z = \frac{2i\omega}{\rho d}\,\frac{H^2}{c^2}\,\frac{1-i\beta}{1+\beta^2}\sum_{n=1}^{\infty}\frac{1-\cos\pi n}{\omega^2-\omega_n^2-i\Gamma\omega S}\,, \tag{1}$$

where ω is the frequency, H is the static magnetic field, ρ is the density, d is the thickness of the plate, and c is the velocity of light. Here $\beta=\omega c^2/4\pi\sigma S^2$, where σ is the conductivity of the metal, and S is the velocity of the ultrasound. In the presence of a field H, the ultrasonic attenuation $\Gamma=\Gamma+\Delta\Gamma$ contains a term $\Delta\Gamma$ given by[5]

$$\Delta\Gamma = \omega\,\frac{H^2\beta}{8\pi\rho S^3\,(1+\beta^2)}\,. \tag{2}$$

We see that at $\beta \ll 1$ the term $\Delta\Gamma$ is proportional to ω^2 and is independent of the frequency at $\beta \gg 1$.

It follows from (1) that the amplitudes of acoustic resonances in a plate are proportional to the square of the static magnetic field and inversely proportional to the ultrasonic attenuation. Through the parameter β, the amplitudes of the acoustic resonances also depend on the conductivity of the metal. In the present experiment, this factor is taken into account through the use of data on the temperature dependence of the conductivity of indium.[6]

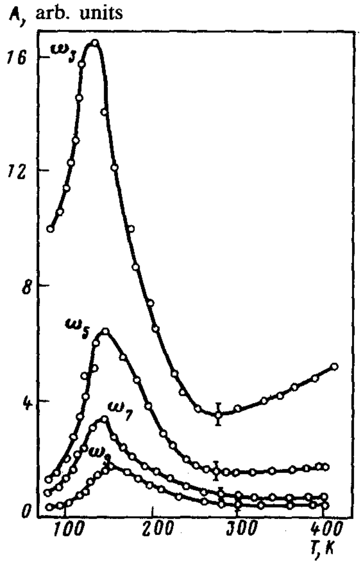

FIG. 1. Temperature dependence of the heights of the acoustic resonances of transverse ultrasound in an indium plate. $\mathbf{q}_t \parallel [001]$, $H=25$ kOe.

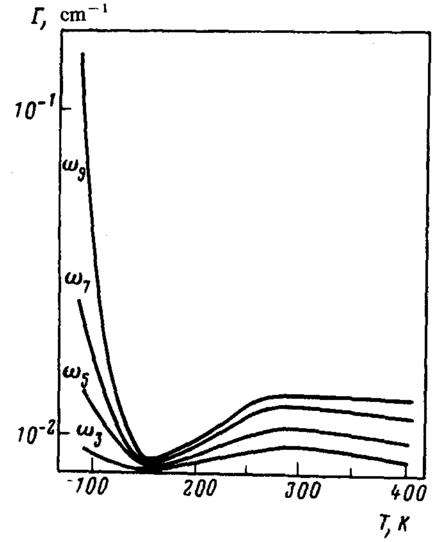

FIG. 2. Temperature dependence of the attenuation of transverse ultrasound in indium. At $T = 300$ K, $\omega_3 = 4.36\times10^6$ s^{-1}, $\omega_5 = 7.27\times10^6$ s^{-1}, $\omega_7 = 1.02\times10^7$ s^{-1}, and $\omega_9 = 1.31\times10^7$ s^{-1}.

The temperature dependence of the resonant structural features caused in the surface impedance of the plate by the excitation of the transverse ultrasound is measured at the first four harmonics ($n = 3,5,7,9$) of the fundamental frequency $\omega_1 = \pi S(T)/d$ over the temperature interval 80–420 K. Figure 1 shows the temperature dependence in a field $H = 25$ kOe. The heights of all the acoustic resonances go through a maximum near T_D; at high temperatures, the resonances at ω_3 and ω_5 increase monotonically, while those at ω_7 and ω_9 decrease monotonically, with the temperature.

The ultrasonic attenuation is calculated from the measured heights of the acoustic resonances and the temperature dependence as represented by β. From the results found in this manner we subtract the field increment. The quantity $\Delta\Gamma$ does not vary in a monotonic way with the temperature: It is small at $\beta \ll 1$ and $\beta \gg 1$ and goes through a maximum at $\beta = 1$. The maximum of $\Delta\Gamma$ is reached experimentally only at the frequencies ω_7 and ω_9. Figure 2 shows curves of $\Gamma(T)$. The values of Γ are normalized independently on the basis of half-widths of the resonant lines at $T = 80$ K.

The attenuation increases roughly quadratically with the frequency over the entire temperature interval studied. As the temperature is raised from 80 K to the Debye temperature, the attenuation decreases sharply, reaching a minimum near T_D. As the temperature is raised further, the attenuation starts to increase again; it goes through a maximum and then falls off slowly with increasing temperature. It is difficult to make a direct comparison with the asymptotic behavior in Refs. 1 and 2 since the limit $T \gg T_D$ was not reached; however, the absence of an increase in the attenuation of transverse ultrasound at high temperatures seems to us to be evidence in favor of the model of Ref. 2.

We wish to thank V. F. Gantmakher for furnishing the sample and M. I. Kaganov for useful discussions.

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Translated by Dave Parsons