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ACOUSTICAL INVESTIGATIONS OF ULTRASONIC PROPAGATION PARAMETERS IN FIVE CUBIC CRYSTALS

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Ultrasonic attenuation studies have been made on Pb, Pt, Cr, Mo and W using their available second- and third-order elastic moduli (SOEM and TOEM) data at room temperature. Results obtained reveal the fact that the phonon viscosity mechanism is the dominating factor of attenuation over the other types of losses. Hence, phonon viscosity which is the controlling factor of Akhieser's loss is also discussed in the present paper in terms of the dislocation drag coefficients (screw and edge).

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1. Introduction

Study of acoustic wave attenuation and the velocity in various insulating crystals have been made recently [1–3]. As we move ahead from insulating crystals, conducting crystals are also of great importance. In conducting crystals, which are rich in free electrons, the thermo-elastic attenuation may also make some valuable contribution to the total ultrasonic attenuation at room temperature. Because of this peculiar behaviour we are interested in evaluating the attenuation due to the phonon viscosity mechanism as well as the thermoelastic mechanism for metallic crystals Pb, Pt, Cr, Mo and W.

2. Theory

The principal cause of attenuation for the perfect, nonferroelectric and nonferromagnetic crystals are due to the phonon viscosity, the thermoelastic relaxation and electron–phonon interaction. However at room temperature there remain only two types of losses what is due to phonon viscosity and thermoelastic relaxation. The loss due to electron–phonon interaction is only appreciable below 80 K and hence it could be ignored safely at room temperature. Akhieser [4] has assumed that the equilibrium distribution of thermal

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phonons in a crystal can be disturbed by the propagation of an acoustic phonon and the re-establishment of the equilibrium is the relaxational phenomenon. Mason [5] has given the following relation

$$\alpha_l = \frac{E_0(\frac{1}{3} D_l)\omega^2\tau_l}{2PV_l^3(1+\omega^2\tau_l^2)}, \tag{1}$$

which becomes, under the condition $\omega\tau_l \ll 1$

$$\alpha_l = \frac{E_0 \dfrac{D_l}{3} \omega^2\tau_l}{2V_l^3 P}, \tag{2}$$

where α_l is the attenuation for the longitudinal wave, E_0 is the internal energy density, D_l is a non-linearity constant which is obtained with the help of SOEM and TOEM data [6, 7, 8] using the relation

$$D_l = 9\langle r_i^{j2}\rangle - \frac{3C_v T\langle r_i^j\rangle^2}{E_0}. \tag{3}$$

Here $\langle r_i^j\rangle$ and $\langle r_i^{j2}\rangle$ are the average Grüneisen constants. Similar expressions could be obtained for shear waves replacing D_l, τ_l and V_l by D_s, τ_s and V_s. τ_l and τ_s are the relaxation times for longitudinal and shear waves and are related by

$$\tau_s = \tau_{th} = \tfrac{1}{2}\tau_l = \frac{3K}{C_v V^2}, \tag{4}$$

where K is the thermal conductivity and C_v is the specific heat per unit volume. The thermo-elastic attenuation which is caused by the thermal conduction between the compressed and rarefied parts of the medium due to acoustic wave propagation, and is given by

$$\alpha_{th} = \frac{\omega^2\langle r_i^j\rangle^2 KT}{2\varrho V_l^5}. \tag{5}$$

The phonon–phonon collisions can produce an appreciable effect on the motion of linear imperfections in a lattice through the phenomenon of drag. Thermal losses due to such a motion can be computed by multiplying the following drag coefficients by the square of the dislocation velocity.

$$B_{screw} = 0.071\eta,$$

$$B_{edge} = \frac{\eta}{(1-\sigma)^2}\, 0.053 - \frac{0.0079}{(1-\sigma)^2}\left(\frac{\mu}{K}\right)^2 \chi,$$

where

$$\chi = \eta_l - \tfrac{4}{3}\eta_s, \quad K = \tfrac{1}{3}(C_{11}+2C_{12}), \quad \mu = \tfrac{1}{3}(C_{11}-C_{12}+C_{44}),$$

η, σ and K are the shear modulus, Poisson ratio and bulk modulus respectively. C_{11}, C_{12} and C_{44} are the second order elastic moduli for the cubic metals.

3. *Results and discussion*

Some of the results obtained from the available data [6, 7, 8] of SOEM and TOEM for Pb, Pt, Cr, Mo and W and other required thermodynamical data [9], are given in Table I. The average Grüneisen constants $\langle r_i^j \rangle$, average square Grüneisen constant $\langle r_i^{j2} \rangle$ and non-linearity constant D have been evaluated for the longitudinal and shear acoustic wave propagating along the $\langle 100 \rangle$, $\langle 110 \rangle$ and $\langle 111 \rangle$ directions, shear waves polarised along the $\langle 100 \rangle$ and $\langle 110 \rangle$ directions, and are listed in Table II.

TABLE I

Primary physical constants calculated for Pb, Pt, Cr Mo and W

Metals	V_l 10^5 cm/sec	V_s 10^5 cm/sec	E_0 10 erg/cm^3	C_v 10^7 erg/cm^3 K	τ_{th} 10^{-12} sec
Pb	2.65	1.89	3.31	1.35	0.35
Pt	3.93	1.75	7.02	2.70	0.27
Cr	6.98	3.27	5.41	3.04	1.82
Mo	6.71	4.18	4.26	2.38	0.23
W	5.09	3.20	4.62	2.44	3.37

TABLE II

Grüneisen number and non linearity constanst for Pb, Pt, Cr, Mo and W

Direction	Metal	$\langle r_i^j \rangle$	$\langle r_i^j \rangle$ Long	$\langle r_i^j \rangle$ Shear	D Long	D Shear
$\langle 100 \rangle$	Pb	1.45	5.16	1.11	38.78	9.99
	Pt	1.09	3.08	0.85	23.61	7.65
	Cr	0.32	0.35	0.05	2.56	0.40
	Mo	0.72	0.86	0.04	5.11	0.37
	W	0.69	0.65	0.07	3.58	0.68
$\langle 110 \rangle$	Pb	1.48	3.80	15.93	26.33	143.52
	Pt	1.10	2.31	8.65	16.67	77.88
	Cr	0.30	0.22	0.97	1.49	8.71
	Mo	0.81	0.80	0.56	3.90	5.03
	W	0.68	0.58	0.46	3.10	4.18
$\langle 111 \rangle$	Pb	1.49	3.64		24.39	
	Pt	1.14	4.55		36.64	
	Cr	0.29	0.22		1.56	
	Mo	0.87	0.78		3.76	
	W	0.67	0.59		3.21	

TABLE III

Attenuation of acoustic waves and the drag coefficient for screw and edge dislocation in five cubic metals at room temperature

Direction	Metal	$(\alpha/f^2)_{Akh}$ 10^{-18} dB s² cm⁻¹ Long	$(\alpha/f^2)_{Akh}$ Shear	$(\alpha/f^2)_{th}$ 10^{-18} dB s² cm⁻¹	B_{screw} M. P Long	B_{screw} M. P Shear	B_{edge} M. P Long	B_{edge} M. P Shear
⟨100⟩	Pb	1.82	1.70	0.49	2.144	0.27	3.32	0.51
	Pt	0.39	0.73	0.03	2.26	0.37	3.02	0.63
	Cr	1.21	0.91	0.19	4.84	0.33	6.87	0.85
	Mo	0.18	0.03	0.02	1.18	0.44	1.64	0.75
	W	2.49	0.96	0.26	18.16	1.11	25.12	2.56
⟨110⟩	Pb	1.65	2.81	0.50	1.455	3.96		
	Pt	0.27	7.44	0.03	1.60	3.73		
	Cr	0.69	19.63	0.018	2.98	7.11		
	Mo	0.14	0.37	0.01	10.71	4.28		
	W	2.16	5.87	0.12	16.31	7.08		
⟨111⟩	Pb	1.52		0.52				
	Pt	0.60		0.02				
	Cr	0.72		0.02				
	Mo	0.14		0.01				
	W	2.23		0,12				

Table III lists the ultrasonic attenuation suffered by longitudinal and shear acoustic waves propagating along the above given directions with drag coefficients for screw and edge dislocations. The (α/f^2) values along the two directions are equal in the present case too [10, 11], and from the Table III, it is clear that more than 90% of the total attenuation is caused by a phonon-viscosity mechanism which reveals the fact that the maximum amount of the absorbed acoustic energy is either transformed to thermal energy or is used up in equalising the temperature difference among the various phonon branches. The D_l/D_s ratio along the ⟨100⟩ direction for both the crystals is greater than 3 which proves that the rate of conversion of acoustic energy into thermal energy is greater for the case of longitudinal wave propagation. The evaluated values of attenuation and drag coefficients are of the same order as that of the other conduction crystals [10, 11, 12]. Though Barrett and Holland [13] have criticised the Mason–Bateman approach of evaluating the ultrasonic attenuation which has been used here. According to them, strain waves modulate the frequency and energy density of thermal phonons. This modulation creates a variation in the instantaneous population of a mode from its equilibrium value. Their next objection is that the present approach involves $C(i)$ rather than $E(i)$. Both the $C(i)$ and $E(i)$ are Debye function of θ_0/T and differ by a numerical factor only. However it is also established that these two effects do not cause an appreciable effect on the value of ultrasonic attenuation when $\omega\tau \ll 1$.

Recently Nava et al. [14] considering the anisotropic elastic continuum model approximation has given an expression for attenuation in terms of the ultrasonic Grüneisen parameter (UGP), but due to a lack of various thermal, elastic and acoustic data, it is preferred to calculate U.G.P. by knowing the experimental value of attenuation.

Hence considering the complexities and unknown factors involved in other approaches and the failure of objections made by Barrett and Holland to the Mason–Bateman theory, one can doubtlessly confirm the validity of the latter approach particularly under the present physical conditions.

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