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Dissipation of Acoustic Waves in Barium Monochalcogenides

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1. Introduction

The term *acoustic* refers to a periodic pressure wave. The term includes waves in the audio frequency range as well as those above audio frequency range (ultrasonic and hypersonic) and below the audio frequency range. Acoustic waves are characterized by their speed and absorption. Acoustic absorption is a measure of the energy removed from the acoustic waves by conversion to heat as the wave propagates through a given thickness of material; it has unit dB/cm (or Np/cm). Absorption is a material property, in contrast to attenuation, which includes energy loss due to scattering and reflection as well as and depends upon sample size and experimental configuration.

The elastic and inelastic properties of solids are suitable for the study of acoustic dissipation which account for the direct conversion of acoustic energy into thermal energy. In measurement of the attenuation of acoustic waves in solids using pulse echo method, the attenuation is usually found to be greater than the absorption due to intrinsic dissipation. Acoustic energy is removed from the propagating acoustic wave, but is not immediately converted into heat.

The most important cause of the attenuation is the scattering of acoustics wave from imperfections. In terms of phonon description of acoustic waves, this is a two-phonon process, in which incoming and outgoing phonons have different wave vectors. The perturbation at the scattering centre may be due to a mass difference of an impurity atom from the normal mass or to a change in interatomic forces.

In polycrystalline solids, sound is scattered from the boundaries between the microcrystal grains. The grain boundaries act as scattering centers due to the discontinuity of the elastic constants, and the amount of loss depends on the grain size and on the wavelength of the acoustic wave. When the wavelength of the acoustic wave is small compared to the grain size, the loss is independent of frequency and inversely proportional to the mean grain diameter. When the wavelength is large compared to the grain size, the loss is proportional to the fourth power of the frequency (Rayleigh scattering) and to the third power of grain diameter.

Another source of nondissipative loss is diffraction of acoustic field from the transducer. This is an important loss mechanism in megahertz frequency range, but at higher frequencies it is negligible. At higher frequencies, a loss mechanism occurs due to lack of flatness and parallelism of the end faces of the specimen. At higher frequencies (10 GHz), the wavelength of the sound in a solid is of the order of optical wavelength in visible range and hence, the surface of the specimen should be polished with optical quality.

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Various causes can be attributed to the dissipation of acoustic waves propagating in different types of solids. These causes depend primarily on the physical conditions of the material under investigation. Having control over the physical conditions of the material, one cause can be studied eliminating others. Most of the energy from the propagating acoustic wave through the medium is absorbed and converted into heat. Following causes may be attributed to the attenuation of the acoustic wave propagating through a solid;

(a) Electron-phonon interaction, (b) Phonon-phonon interaction, (c) Lattice imperfection, (d) Thermoelastic loss (e) Ferromagnetic and Ferroelectric losses and (f) NMR and Thermal relaxation etc.. In non conducting non-ferromagnetic solids at 50 K and above, phonon-phonon interaction is the principal cause of acoustical dissipation.

Among the wide band gap II-IV semiconductors, the barium chalcogenides [BaX, X=S, Se, Te] are interesting in connection with optoelectronic applications in blue light wavelength regime. The Barium Chalcogenides form very important closed shell ionic systems crystallized in the NaCl (B1) type and CsCl (B2) type structures at ambient conditions. Alkaline earth chalcogenides are currently under intense investigations driven by their applications in light emitting diodes (LEDs) and laser diodes (LDs). It is expected that these compounds may provide new II-IV candidates for the fabrication of various electrical and optical devices [Charifi et al. (2005) and Bouhemadou et al. (2006)].

Experimental as well as theoretical work on different aspects of these compounds has been reported in the recent past [Charifi et al. (2005), Bouhemadou et al. (2006), Hassan and Akbarzadeh (2006) and Cervantes et al (1998)]. However, results on temperature dependent acoustical behaviour of these chalcogenides viz. acoustical dissipation due to phonon-phonon interaction, thermoelastic loss, dislocation damping, Gruneisen parameter, non-linearity parameters and thermal relaxation time etc, which are very important parameters necessary to explain the microstructure and other related physical properties of these chalcogenides have not been studied. Recently, we studied in detail [Singh and Singh 2010] acoustical behaviour of these compounds starting from second and third order elastic constants (obtained at different temperatures), which were used to evaluate Gruneisen parameters and non-linearity parameters along different crystallographic directions viz. $\langle 100 \rangle$, $\langle 110 \rangle$ and $\langle 111 \rangle$ for longitudinal and shear modes in the temperature range 50K-500 K. Taking electrostatic and Born repulsive potentials and utilizing some parameters viz. nearest neighbour distance, hardness parameter and specific heat as a function of Debye temperature; acoustical dissipation coefficients were obtained at different temperatures.

2. Absorption of acoustic waves by thermal phonons

The anharmonic interactions among phonons in a solid are responsible for attenuation of ultrasonic waves, and are particularly important in insulators where absorption due to free electrons is absent. Also, when a longitudinal wave propagates in a crystalline solid, compression and rarefaction is produced and heat is transmitted from compressed part to rarefied parts and dissipation of acoustic waves occurs. Dislocation damping due to screw and edge dislocations also produces appreciable loss in solids.

2.1 Phonon-phonon interaction

In perfect, insulating, non-ferromagnetic and non-ferroelectric substances, dissipation of acoustical energy occurs mainly due to phonon-phonon (p-p) interaction and thermoelastic

loss. Akhiezer (1939) was first to propose the phonon-viscosity mechanism for acoustical dissipation, but he did not include the finite value of relaxation time for thermal equilibrium process. Bommel and Dransfeld (1960) later took this work considering the relaxation time to be finite. They obtained results comparable to the experimental results. Further, Woodruff and Ehrenreich (1960) used the Boltzmann equation method to evaluate the steady state distribution of thermal phonons and acoustical attenuation. They considered the N (normal) and U (Umklapp) processes. But due to insufficient information regarding parameter ' γ ', used, Mason (1965) used Gruneisen constant (γ_i^j), which is related to second and third order elastic constants and this approach is found to be very useful for the estimation of ultrasonic attenuation in various crystals.

At room temperature and in a wide temperature region also, thermal phonon relaxation time, τ_{th} , varies from 10^{-10} sec to 10^{-12} sec from metallic to dielectric crystals. As temperature increases, τ_{th} decreases. Hence, condition $\omega\tau_{th} \ll 1$ holds good and at the same time the individual phonon loses its significance and idea of the phonon gas having macroscopic parameter is described. In the Akhiezer regime ($\omega\tau \ll 1$), a sound wave passing through a solid can be attenuated by two processes. First, if the wave is longitudinal, periodic contractions and dilations in the solid induce a temperature wave via thermal expansion. Energy is dissipated by heat conduction between regions of different temperatures. This is called thermoelastic loss. Second, dissipation occurs as the gas of thermal phonons tries to reach an equilibrium characterized by a local (sound wave induced) strain. This is internal friction mechanism.

The physical basis for obtaining attenuation coefficient is that the elastic constants contributed by thermal phonons relax [Bommel and Dransfeld (1960), Pippard (1955) and Mason (1955)]. The phonon contribution to the unrelaxed elastic constants is evaluated by taking into consideration the change in energy of the thermal phonons due to applied instantaneous strain. The frequency of each mode ν_i is changed by $\frac{\partial \nu_i}{\nu_i} = -\gamma_i^j S_j$, where γ_i^j

is generalised Gruneisen parameter & S_j is instantaneous strain. It is assumed that all the phonons of a given direction of propagation and polarization have equal change in frequency. Then phonons of i th branch and j th mode suffer a change in temperature $\frac{\Delta T_i}{T_0} = -\gamma_i^j S_j$ (T is the temperature). A relaxed elastic constant is obtained after there is phonon-phonon coupling among various branches and ΔT_i relax to a common temperature change, ΔT given by $\frac{\Delta T}{T} = -\langle \gamma_i^j \rangle S_j$; where $\langle \gamma_i^j \rangle$ is the average value of γ_i^j .

The sudden application of acoustical pressure to a body at temperature T causes different temperature increments for different phonon modes, which relax back to new equilibrium at a temperature $T + \Delta T$ through the phonon-phonon collision. This temperature difference lags behind the periodic stress and causes a relaxational absorption.

The relation between the attenuation and ΔC_e (change in the elastic constant due to non-equilibrium temperature separation of the phonon modes by the applied strain) is given as:

$$\alpha = \Delta C_e \omega^2 \tau_{th} / 2dV^3(1 + \omega^2 \tau_{th}^2) \quad (1)$$

Where α is attenuation in dB/cm, d is density, ω is angular frequency of the ultrasonic wave and V is the velocity of the wave.

When the strain S_j is applied to the crystal, there is change in mode frequency given by:

$$\omega_i = \omega_{i0} (1 - \sum_{j=1} \gamma_i^j S_j) \quad (2)$$

ω_{i0} is frequency of the mode in the standard state. By measurements of SOEC and TOEC, it could be predicted that γ_i^j do not vary much. When the above expression is differentiated, one obtains:

$$\gamma_i^j = (\partial \omega_i / \partial S_j) / \omega_{i0} \quad (3)$$

γ_i^j is known as Gruneisen number. A general formula for γ_i^j has been given by Brugger in terms of tensor notation:

$$-\gamma_i^j = -\gamma_i^{jk} = U_i U_j + N_p N_q (C_{jkpq} + U_r U_s C_{jkpqrs}) / 2C_e \quad (4)$$

Where jk are the two index symbols for strain S_j . N_p and N_q are the direction cosines for the propagation direction and C_e is the required elastic constant determined by the type of the wave and the direction of propagation. U_j and U_k are the direction cosines for the particle displacements. C_{jkpq} and C_{jkpqrs} are the second and third order elastic constants in tensor notations. Now a suddenly applied strain neither changes the number of modes nor their entropy. Mason considered thermal energy of the modes under Debye's approximation,

$$U_{th} = 3\hbar \sum_i (N_i / \omega_{gi}^2) \int_0^{\omega_{gi}} (\omega^2 / (\exp(\hbar\omega / kT) - 1)) d\omega \quad (5)$$

on differentiation of the sum of the elastic energy plus the total thermal energy of all modes, one obtains:

$$T_j = \partial U_{th} / \partial S_j \quad (6)$$

$$= C_{ij}^S S_j + 3\hbar (\partial / \partial S_j) (\sum_i (N_i / \omega_{gi}^3) \int_0^{\omega_{gi}} (\omega^3 / (\exp(\hbar\omega / kT) - 1)) d\omega$$

and finally one gets:

$$T_j = C_{ij}^S + 3 \sum_i E_i (\gamma_i^j)^2 S_j + 3 \sum_i E_i \gamma_i^j \quad (7)$$

where T_j is the stress associated with the strain S_j , C_{ij} is the corresponding elastic constants resulting from no entropy exchange between any of the modes and γ_i^j is the Gruneisen number. E_i is the thermal energy associated with each direction and each mode. The above expression, shows that elastic constant changes by

$$\Delta C_e = 3 \sum_i E_i (\gamma_i^j)^2 \quad (8)$$

This development is valid for shear modes for which the average rise in temperature is zero. For longitudinal modes, the increase in modulus resulting from the difference between the adiabatic and isothermal conditions is to be supported and it is given by:

$$\Delta C_e = (3 \sum_i E_i \langle \gamma_i^j \rangle) - \gamma^2 CT \quad (9)$$

Replacing the value of ΔC_e , one gets:

$$\alpha = ED\omega^2 \tau_{th} / 6dV^3 (1 + \omega^2 \tau_{th}^2) \quad (10)$$

for

$$\omega \tau_{th} \ll 1, \quad \alpha = ED\omega^2 \tau_{th} / 6dV^3 \quad (11)$$

Equation (1) reduces to

$$(\alpha / f^2)_l = 2\pi^2 E_0 (D_l / 3) \tau_l / dV_l^3 \quad (12)$$

and

$$(\alpha / f^2)_s = 2\pi^2 E_0 (D_s / 3) \tau_s / dV_s^3 \quad (13)$$

for longitudinal and shear waves, respectively.

$$\text{where } D = 9 \langle (\gamma_i^j)^2 \rangle - (3CT \langle (\gamma_i^j)^2 \rangle / E) \quad (14)$$

Here D is the non-linearity constant. Mason and co-workers (1964) have obtained a number of tables in terms of second and third order elastic constants to calculate $\langle (\gamma_i^j)^2 \rangle$ and $\langle (\gamma_i^j)^2 \rangle$ for different directions of propagation and polarization. Gruneisen numbers along different directions of propagation viz. $\langle 100 \rangle$, $\langle 110 \rangle$ and $\langle 111 \rangle$ can be obtained using Mason (1965) approach.

Thermal relaxation time, τ (subscripts l and s for longitudinal and shear waves) is given as,

$$\tau = \tau_s = \frac{\tau_l}{2} = \frac{3K}{C_v \langle V \rangle^2} \quad (15)$$

Where K is thermal conductivity, C_v is specific heat per unit volume and $\langle V \rangle$ is Debye average velocity given by

$$\frac{3}{(\langle V \rangle)^3} = \frac{1}{V_L^3} + \frac{2}{V_S^3} \quad (16)$$

The Debye temperature is given by [Jasiukiewicz & Karpus (2003)],

$$\Theta_D = \hbar \langle V \rangle q_d / K_B \quad (17)$$

K_B is Boltzmann constant and

$q_d = (6\pi^2 N_a)^{1/3}$ where N_a is atom concentration

According to Mason and Batemann [1964], SOEC and TOEC are related by Gruneisen parameter γ_i^j and hence by non-linearity parameter, D . $\langle (\gamma_i^j)^2 \rangle$ and $\langle \gamma_i^j \rangle^2$ are square average & average square Gruneisen parameters, V is sound wave velocity (V_l) for longitudinal wave and (V_s) for shear wave and d is density.

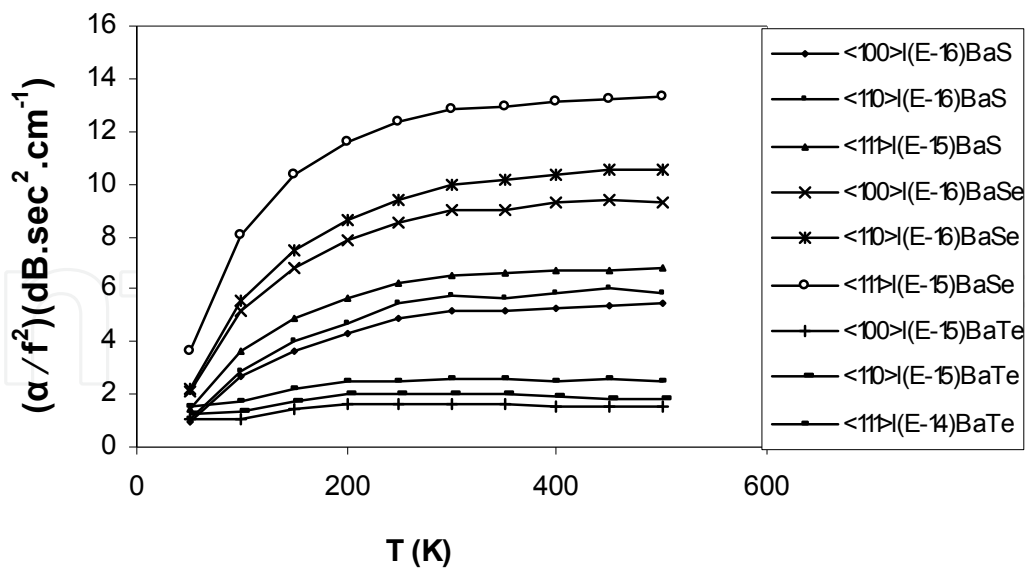


Fig. 1. Temperature variation of $(\alpha/f^2)_l$ along different directions.

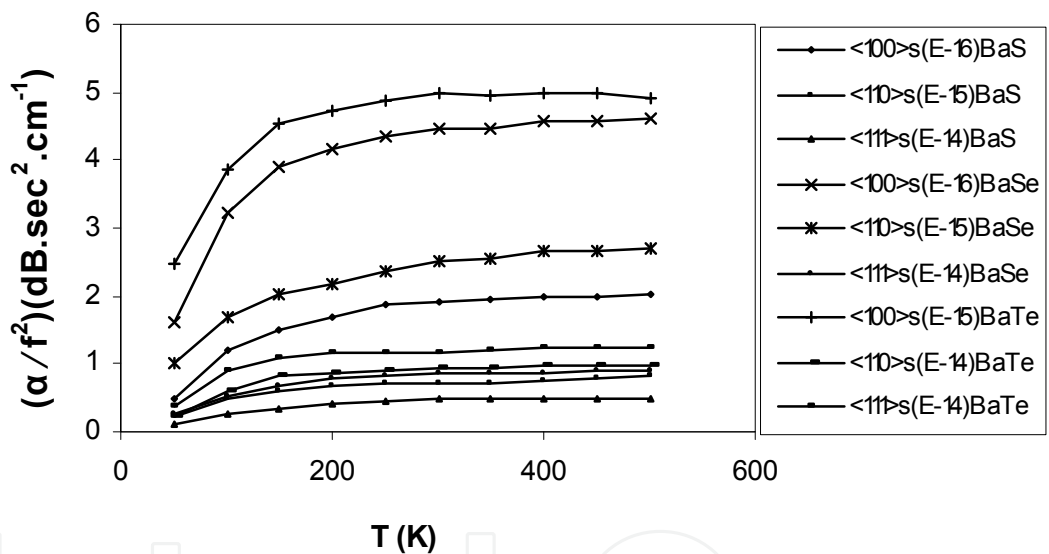


Fig. 2. Temperature variation of $(\alpha/f^2)_s$ along different direction directions.

The ultrasonic attenuation due to phonon-phonon interaction for longitudinal, $(\alpha/f^2)_l$ and shear waves, $(\alpha/f^2)_s$ are evaluated using equations (12) and (13), respectively. Typical attenuation versus temperature curves ($(\alpha/f^2)_l$ and $(\alpha/f^2)_s$ vs Temperature) along [100], [110] and [111] directions of propagation are shown in Figs. (1-2) , and it can be seen that the temperature dependence divides into two regions. Region 1, (upto Debye temperature of respective solids, which has been shown in Table 1) attenuation coefficient varies rapidly and in Region II, attenuation coefficient becomes temperature independent. To understand the physical processes involved, it is helpful to consider region I and II separately. When $\omega\tau_{th} < 1$ (Region 2), where ω is the acoustic frequency and τ_{th} is the mean lifetime of thermal phonons, the phonon mean free path is short compared to the acoustic wavelength and phonons see a very gradual spatial gradient of the acoustic strain. In the opposite extreme ($\omega\tau_{th} > 1$), the phonon mean free path is long compared to the acoustic

wavelength, and the acoustic wave is best thought of as a beam of coherent phonons which are on an actual footing with the thermal phonons. The mode of interaction is then by phonon-phonon interaction.

Compound	Θ_D (K)	$\langle V \rangle$ (10^5cm/sec)	M (Mol. Weight)
BaS	200	4.18	169.39
BaSe	170	2.61	216.28
BaTe	143	2.39	264.92

Table 1. Debye temperature (Θ_D) and average Debye velocity ($\langle V \rangle$) at 300 K

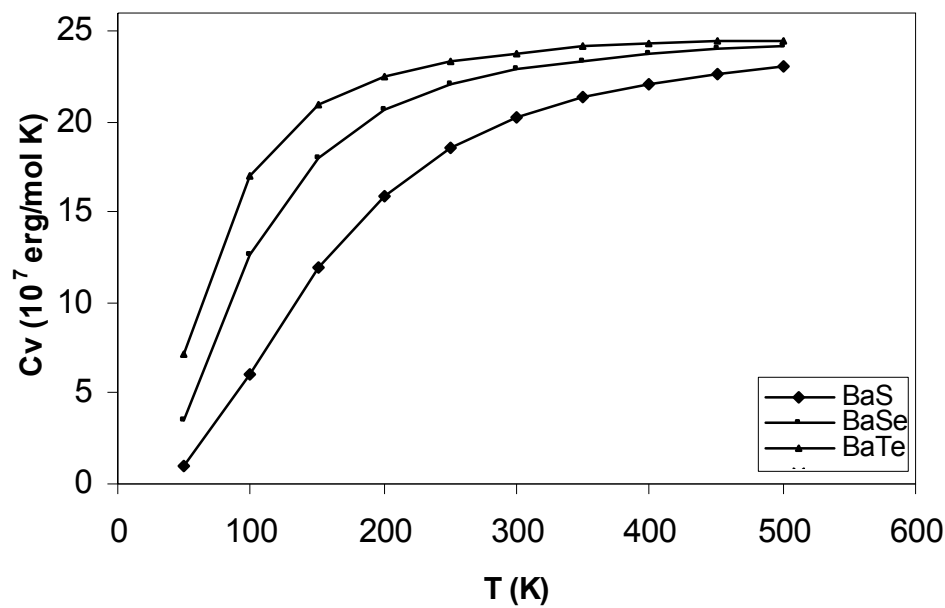


Fig. 3. Temperature variation of specific heat (C_v)

The attenuation due to phonon-phonon interaction for longitudinal and shear waves $(\alpha/f^2)_l$, $(\alpha/f^2)_s$ increases up to Θ_D and then becomes constant. When $(\Theta_D/T) \geq 1$, $(\alpha/f^2)_l$ and $(\alpha/f^2)_s$ increase and for values of temperatures satisfying $(\Theta_D/T) < 1$, attenuation becomes nearly constant, because $(\alpha/f^2)_l$ or $(\alpha/f^2)_s$ due to p-p interaction is mainly affected by the specific heat, C_v (since (α/f^2) due to phonon-phonon interaction is related to C_v , (through the relaxation time). For $(\Theta_D/T) \geq 1$, C_v increases and becomes nearly constant for the values satisfying $(\Theta_D/T) < 1$, (Fig. 3).

The value (α/f^2) at a given temperature is minimum for BaS and maximum for BaTe. The value of (α/f^2) depends upon Debye temperature (Θ_D). The Debye temperature is maximum for BaS and minimum for BaTe, (Table 1). Thus greater the Θ_D value, smaller is the attenuation. The value of Θ_D depends on the Debye average velocity $\langle V \rangle$ and inverse of cube root of molecular weight i.e. $M^{-1/3}$ through $(N/V)^{1/3}$ where N is the Avogadro number and V ($V = M/d$, M= mol. wt. and d= density) is volume. $\langle V \rangle$ is maximum for BaS and minimum for BaTe, therefore larger is the $\langle V \rangle$, smaller will be attenuation. The attenuation increases in these chalcogenide series with increasing the Molecular weight. The Θ_D and $\langle V \rangle$ are SOEM dependent. Thus the increase in the value of $(\alpha/f^2)_l$, $(\alpha/f^2)_s$ and $(\alpha/f^2)_{th}$ from BaS to BaTe is mainly influenced by SOEM values and Molecular weight.

2.2 Thermoelastic loss

In an isotropic polycrystalline solid, strain varies according to applied stress from one grain to another (Lucke, 1956). The substance is isotropic due to random orientation of grains. The individual grain may be anisotropic. The propagation of longitudinal wave creates compression and rarefactions throughout the crystal. The rarified regions are cooler than compressed regions and hence there is a flow of heat between the two regions and the direction of flow of this energy will be reversed after every half cycle. Since there is a relaxational phenomenon, there is a loss of energy. Attenuation due to this effect is given by (Mason, 1965)

$$\alpha = 2\pi^2 f^2 K (C_{nn}^{\sigma} - C_{nn}^{\theta}) / dV^3 C_V C_{nn} \quad (17)$$

where C_{nn}^{σ} and C_{nn}^{θ} are adiabatic and isothermal elastic constants, K is thermal conductivity and C_V is specific heat per unit mass. The difference between C_{nn}^{σ} and C_{nn}^{θ} may be obtained with the help of SOEC and TOEC. This loss does not make any appreciable contribution to the total ultrasonic attenuation in case of dielectric and semiconducting crystals due to low value of thermal conductivity. In case of metals thermal conduction arises due to electronic and lattice contribution so it is large enough to cause appreciable contribution to the total ultrasonic attenuation. For shear wave propagation no compression or rarefaction occurs hence no thermoelastic loss. Propagation of sound wave through crystal produces compression and rarefactions as a result heat are transmitted from compressed region (at higher temperature) to rarefied region (at lower temperature) and hence thermoelastic loss occurs, which is given by.

$$\alpha_{th} = \frac{4\pi^2 f^2 \langle \gamma_i^j \rangle^2 KT}{2dV_L^5} \quad (18)$$

Ultrasonic attenuation due to this effect has also been evaluated in case of barium monochalcogenides and is given in Fig. 4..

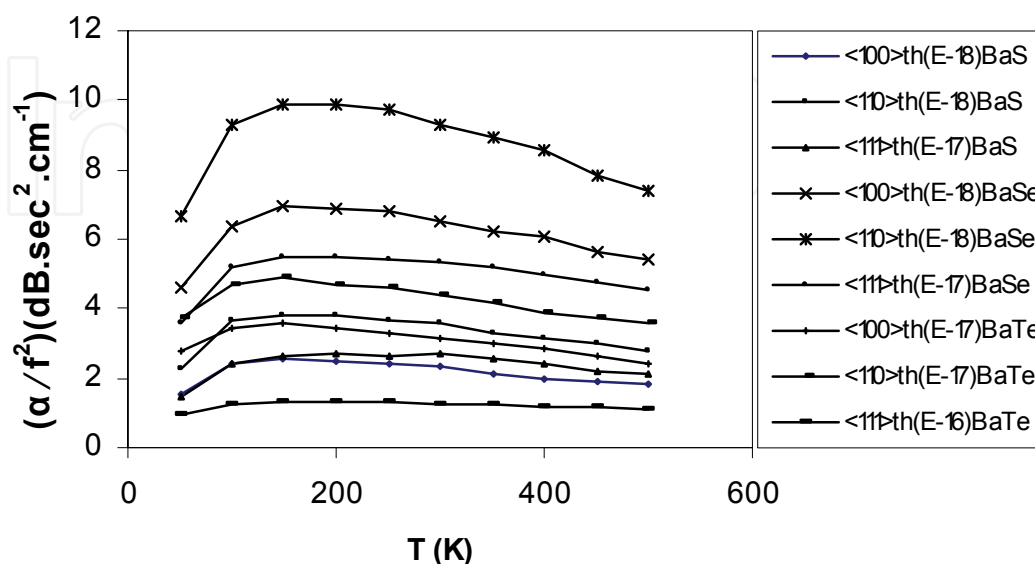


Fig. 4. Temperature variation of $(\alpha/f^2)_{th}$ along different direction

$(\alpha/f^2)_{th}$ is directly proportional to rate of heat transfer from compressed regions to rarefied regions. In the low temperature range, 50-200 K, heat is transferred at faster rate from compressional regions to the rarefied regions resulting larger rate of thermoelastic loss. The rate of increase of thermoelastic loss is small beyond 200 K.

2.3 Phonon processes and drag on dislocations

A dislocation is a linear imperfection in a crystal. In edge dislocation, near the dislocation line, the crystal is severely strained. In a screw dislocation, Burger vectors are parallel to the dislocation line. In general, a dislocation is composed of mixtures of screw and edge dislocations. Another process for which thermal losses due to p-p interaction can produce an appreciable effect is the drag on dislocations as they are moved through a lattice. Leibfried et al. (1954) discussed the mechanism of scattering of phonons by moving dislocations and the results show that the resulting differential produces a drag force which is proportional to the velocity of the dislocation. Mason (1965) proposed a theory to explain the mechanism involved in the drag produced on a dislocation by phonon-viscosity. This was evaluated on the basis of the effect caused by the change in dimensions of phonon modes and their subsequent equilibrium through a thermal relaxation process.

Dislocation damping due to screw and edge dislocations also produces appreciable loss due to phonon-phonon interaction. The loss due to this mechanism can be obtained by multiplying dislocation viscosities by square of dislocation velocity. Dislocation damping due to screw and edge dislocations is given by equations (21) and (22).

The Phonon-viscosity, which is analogous to shear-viscosity in liquids damps the motion of both type (screw and edge) dislocations and has the value

$$\eta = EDk / C < V >^2 = ED\tau_{th} / 3 \quad (19)$$

These phonon-viscosities are presented in the form of drag coefficients for the motion of screw and edge type of dislocations. Here the Cortell's (Cortell, 1963) condition $a_0 = 3b / 4$ is valid, where a_0 the dislocation core radius and 'b' is the Brugger's vector. B_{screw} and B_{edge} are given by

$$B = b^2 / 8\pi a^2 \quad (20)$$

substituting $a_0 = 3b / 4$ the above equation reduces to,

$$B_{screw} = 0.071\eta \quad (21)$$

and

$$B_{edge} = (0.0532\eta + 0.0079(\mu / K)^2 \chi / (1 - \sigma)^2 \quad (22)$$

where σ , μ , K and χ are Poisson's ratio, shear modulus, bulk modulus and compressional viscosity respectively. These values can be calculated using the relations

$$\mu = (C_{11} - C_{12} + C_{44}) / 3, \quad K = (C_{11} + 2C_{12}) / 3, \\ \text{and } \chi = (4 / 3\eta_l - \eta_s) \quad (23)$$

Compound	B _{screw}		B _{edge}	
	Long.	Shear	Long.	Shear
BaS	0.23	0.10	0.45	0.55
BaSe	0.29	0.17	0.60	0.79
BaTe	0.47	1.30	1.07	3.22

Table 2. Phonon viscosity due to screw and edge dislocation at 300K longitudinal (in cp) and shear (in mp.) waves.

Debye average velocity and Debye temperature have been calculated using equations (16) and (17) and are presented in Table 2.

Square average Gruneisen numbers $\langle \gamma_i^2 \rangle_l$ and $\langle \gamma_i^2 \rangle_{s^*}$ and average square Gruneisen parameter $\langle \gamma_i \rangle_l^2$ and $\langle \gamma_i \rangle_{s^*}^2$ for longitudinal and shear waves, nonlinearity coupling constants D_l , D_s , D_{s^*} and their ratios D_l/D_s , and D_l/D_{s^*} along different directions of propagation are given in Table 3. Results are as expected [Mason (1967), Kor and Singh (1993)].

Compound	Direction	$\langle \gamma_i^2 \rangle_l$	$\langle \gamma_i \rangle_l^2$	$\langle \gamma_i \rangle_s^2$	$\langle \gamma_i \rangle_{s^*}^2$	D_l	D_s	D_{s^*}	D_l/D_s	D_l/D_{s^*}
BaS	100	0.94	0.17	0.04	--	7.82	0.37	--	20.81	--
	110	1.06	0.26	0.15	1.93	8.63	1.43	17.37	6.03	0.49
BaSe	100	0.90	0.24	0.04	--	7.27	0.43	--	16.79	--
	110	1.04	0.36	0.22	1.80	8.04	1.98	16.28	4.06	0.49
BaTe	100	1.68	1.28	0.30	--	10.63	2.73	--	3.88	--
	110	2.14	1.75	4.49	1.33	12.93	40.46	12.00	0.31	1.00

Table 3. Square Average and average square Gruneisen number for longitudinal $\langle \gamma_i^2 \rangle_l$, $\langle \gamma_i \rangle_l^2$ and shear $\langle \gamma_i \rangle_s^2$, $\langle \gamma_i \rangle_{s^*}^2$ Waves, nonlinearity coupling constants D_l , D_s and nonlinearity coupling constants ratios D_l/D_s , D_l/D_{s^*} at 300K
 l for longitudinal wave
 s for shear wave, polarized along [001]
 s^* for shear wave, polarized along $[\bar{1}10]$

Viscous drag due to screw (B_{screw}) and edge dislocations have been obtained (B_{edge}) using equation (21) and (22), as given in Table 2.

The phonon mean free path due to phonon-phonon collision is a rapidly changing function of temperature at low temperatures. Fig. 4 shows the τ_{th} vs T plot for barium monochalcogenides.. Thermal relaxation time is evaluated using equation (6). Temperature variation of thermal relaxation time is shown in Fig. 4 which shows exponential decay according to relation $\tau = \tau_0 \exp (- t/T)$, where τ_0 and t are constants.

From the values of thermal relaxation time, it can be seen that the condition $\omega \tau_{th} \ll 1$ is satisfied even at GHz range acoustic wave frequency.

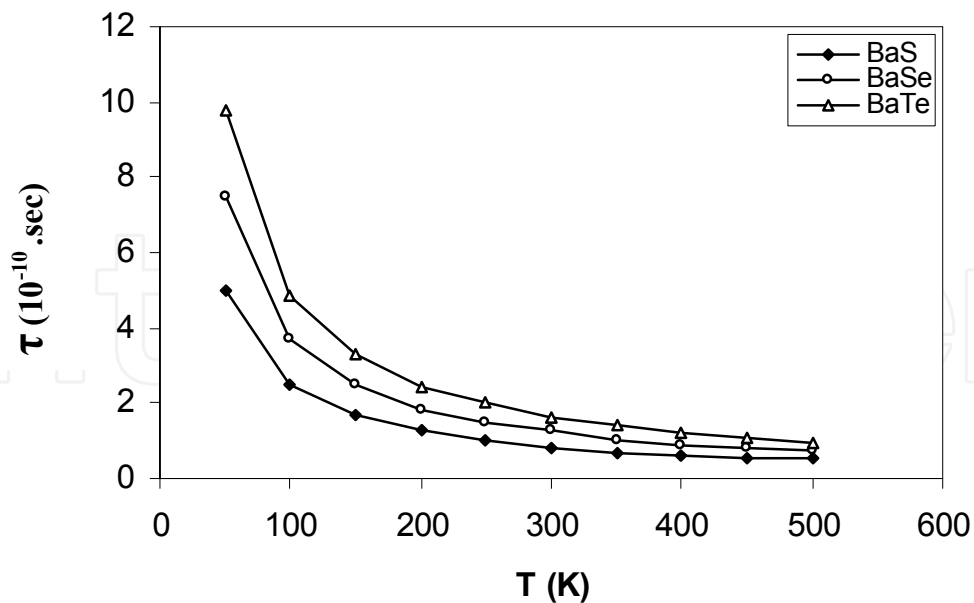


Fig. 4. Temperature variation of thermal relaxation time (τ).

3. Conclusions

Acoustical dissipation and related parameters have been evaluated over a wide temperature range using simple approach and starting from second and third order elastic constants. These values of second and third order elastic constants have been used to obtain acoustical Gruneisen parameters and non-linearity coupling constants. Utilizing values of non-linearity coupling constants, ultrasonic attenuation due to phonon-phonon interaction, thermoelastic loss and dislocation damping due to screw and edge dislocations have been obtained over a wide temperature range. In the present approach, Grunesen parameters have been evaluated for longitudinal and shear modes by considering only finite number of modes (39 modes for longitudinal wave while 18 modes for shear waves). However, a more rigorous approach is needed, in which all possible phonon modes can be incorporated.

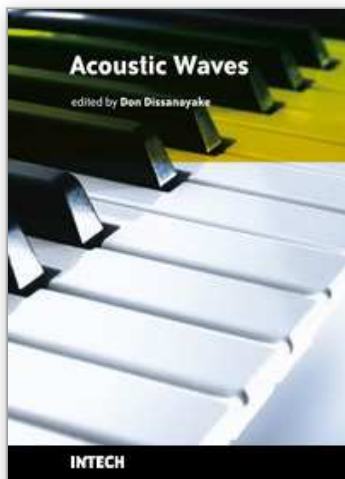
4. Acknowledgements

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SAW devices are widely used in multitude of device concepts mainly in MEMS and communication electronics. As such, SAW based micro sensors, actuators and communication electronic devices are well known applications of SAW technology. For example, SAW based passive micro sensors are capable of measuring physical properties such as temperature, pressure, variation in chemical properties, and SAW based communication devices perform a range of signal processing functions, such as delay lines, filters, resonators, pulse compressors, and convolvers. In recent decades, SAW based low-powered actuators and microfluidic devices have significantly added a new dimension to SAW technology. This book consists of 20 exciting chapters composed by researchers and engineers active in the field of SAW technology, biomedical and other related engineering disciplines. The topics range from basic SAW theory, materials and phenomena to advanced applications such as sensors actuators, and communication systems. As such, in addition to theoretical analysis and numerical modelling such as Finite Element Modelling (FEM) and Finite Difference Methods (FDM) of SAW devices, SAW based actuators and micro motors, and SAW based micro sensors are some of the exciting applications presented in this book. This collection of up-to-date information and research outcomes on SAW technology will be of great interest, not only to all those working in SAW based technology, but also to many more who stand to benefit from an insight into the rich opportunities that this technology has to offer, especially to develop advanced, low-powered biomedical implants and passive communication devices.

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