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High Frequency Acoustic Attenuation of Longitudinal and Shear Waves in Germanium at Different Temperatures

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Abstract: ***Perfectly elastic solids are those, where Hooke's law is obeyed to perfection. In such elastic solids, even a small amplitude wave can propagate with undiminished amplitude and intensity. But, most of the real solids show a deviation from perfectly elastic behaviour, and they exhibit "unharmonicity", due to existence of zero point energy. As harmonic approximations are not valid for real solids, a stress wave in the form of high frequency acoustic wave, travelling through it gets attenuated. In present work, making use of second, third and higher order elastic constants, some aspects of elastic and acoustic properties of semiconductor germanium are studied. Assuming a temperature dependant lattice parameter and non-linearity parameter D_L, D_S, the acoustic wave attenuation 'A' is calculated for longitudinal waves and shear waves of frequency 300 MHz and 406 MHz . The losses leading to attenuation are attributed to phonon-phonon interactions within the solid. Attenuation of high frequency waves is found to be temperature and frequency dependant. Theoretically calculated values of D_L, D_S and attenuation 'A' are compared with experimental values obtained by W.P.Mason.***

Keywords: Acoustic wave attenuation, Longitudinal waves, Shear waves, Elastic constants.

1. Introduction

The elastic properties of solids are as important to basic research as they are to technology. The powerful theory of elasticity comes to help when the elementary theory fails to give adequate information about stress distribution. In the harmonic oscillator theory, there is a considerable difference between theoretical and experimental data. When Hooke's law is perfectly obeyed for solids, then any wave will progress without attenuation through the solids. Since harmonic approximations are not valid for real solids, stress waves are attenuated even in absence of any dissipating mechanisms[1]. Attenuation is thus a direct consequence of 'unharmonicity' in solids[2]. Thus the failure of harmonic oscillator theory to explain the experimental results about attenuation of waves, led various workers to modify it. Gruneisen and Mason were perhaps the first to make allowance for 'unharmonicity' by assuming a temperature dependant parameter and non-linearity parameter in calculating the acoustic wave attenuation[3-5]. Attenuation of high frequency ultrasonic waves in semiconductor silicon has been investigated[15]. In the present work the attenuation of longitudinal waves and shear waves of frequency 300MHz and 406MHz are calculated using the above concept. The theoretically calculated values of non-linearity parameter D_L, D_s and attenuation A are compared with the experimental values obtained by W. P. Mason.

2. Theory

When longitudinal waves propagate through solids, then, attenuation of the waves is caused due to thermoelastic effect. In this case alternate regions of compression and rarefaction are set up in the solid, which differ in temperature. The temperature gradient thus created, gives rise to the heat energy flow, resulting in energy dissipation in solids, and hence leads to attenuation of the longitudinal waves as well as shear waves. The attenuation for longitudinal waves in this case is given as in ref[3], by

$$\alpha = \frac{1}{2V_L}\frac{\Delta m}{m_0}\left[\frac{\omega^2\tau}{1+\omega^2\tau^2}\right] \text{ Np/Cm} \qquad (1)$$

where m_0 is the unrelaxed modulus of elasticity of the solid, Δm is the increment in modulus of elasticity, ω is the angular frequency, τ is the relaxation time given by $\tau = \psi / \rho C_v V_L^2$, ψ, ρ and C_v are the thermal conductivity, density and specific heat capacity of solid . V_L is the velocity of propagation of the longitudinal wave through the solid, which is given by ref[6]

$$V_L = [\frac{m_0}{\rho}]^{\frac{1}{2}} \qquad (2)$$

From eq (1) and (2)

$$\alpha = \frac{1}{2\rho V_L^3}\,\Delta m\left[\frac{\omega^2\tau}{1+\omega^2\tau^2}\right] \text{ Np/Cm} \qquad (3)$$

The increment in modulus of elasticity is given as

$$\Delta m = 3\sum_i E_0(\gamma_i^1)^2 - \gamma_{av}^2 C_v T \qquad (4)$$

Where E_0 is the average thermal energy, γ_i^1 and γ_{av} are the values of the Gruneisen constant, and the average value of Gruneisen constant for longitudinal waves along the [100] axis.

Using eq (4) in eq(3), the attenuation of longitudinal waves in solid is

$$\alpha = \frac{1}{2\rho V_L^3} \times [3\sum_i E_0(\gamma_i^1)^2 - \gamma_{av}^2 C_v T] \times \left[\frac{\omega^2\tau}{1+\omega^2\tau^2}\right] \text{ Np/Cm} \qquad (5)$$

$$\text{or } \alpha = \frac{E_0\left(\frac{D}{3}\right)}{2\rho V_L^{\,3}}\left[\frac{\omega^2\tau}{1+\omega^2\tau^2}\right] \text{ Np/Cm} \qquad (6)$$

where D = $\frac{3}{E_0}$ [$3\sum_i E_0(\gamma_i^1)^2 - \gamma_{av}^2 C_v T$] is the non-linearity parameter for the propagating longitudinal waves. If n_i is the statistical frequency of the Gruneisen constant of longitudinal waves along [100] axis , and then non-linearity parameter D is expressed as in ref [15]

$$D_L = 3\left[\frac{3\sum_i(\gamma_i^1)^2 n_i}{\sum_i n_i} - \frac{\gamma_{av}^{\,2} C_v T}{E_0}\right] \qquad (7)$$

Finally the attenuation of the longitudinal waves in terms of dB/Cm is obtained as in ref[15]
Attenuation = A = 8.686 x α dB / Cm (8)

For pure shear wave propagation through solids, the average value of Gruneisen constant γ_{av} for shear waves along the [100] axis is zero. Hence the non-linearity parameter D for shear wave propagation can be obtained by replacing γ_i^1 by γ_i^5 Gruneisen constant for shear waves, γ_{av} by zero in in eq (7).Therefore the non-linearity parameter D for shear wave is given by

$$D_S = 3\left[\frac{3\sum_i(\gamma_i^5)^2 n_i}{\sum_i n_i}\right] \qquad (9)$$

Further replacing longitudinal velocity V_L by shear velocity V_S in eq (6) , α can be found and hence using eq (8) , attenuation 'A' for shear waves can be calculated.

3. Parameters Used for Calculations for Semiconductor Germanium

Table .1 gives the various parameters for semiconductor material germanium like density ρ, the average thermal energy E_0, specific heat capacity at constant volume C_v , second order elastic constant C_{11} , the longitudinal wave velocity V_L ,the shear velocity V_S ,the average Gruneisen constant γ_{av} , $\sum_i(\gamma_i^5)^2 n_i$ for shear waves and $\sum_i(\gamma_i^1)^2 n_i$ for the longitudinal waves along [100] axis, for various temperature.

Table 1

Temperature ^0K	Density ρ gm/cm^3	$E_0 * 10^7$ ergs	$C_v * 10^7$ ergs/gm. ^0k	V_S*10^5 cm/s	V_L*10^5 cm/s	γ_{av} Ref[3]	$\sum_i(\gamma_i^1)^2 n_i$ Ref[3]	$\sum_i(\gamma_i^5)^2 n_i$ Ref[3]
73	5.335	14.80	0.65	3.576	4.959	0.830	24.68	2.52
113	5.333	51.82	1.11	3.572	4.954	0.779	32.92	3.15
153	5.331	101.5	1.38	3.568	4.947	0.760	31.43	3.20
193	5.328	160.1	1.52	3.563	4.942	o.754	31.14	3.36
233	5.323	223.1	1.61	3.558	4.935	0.748	30.56	3.38
293	5.320	322.8	1.68	3.551	4.920	0.746	29.34	3.99

4. Result and Discussion

Table 2

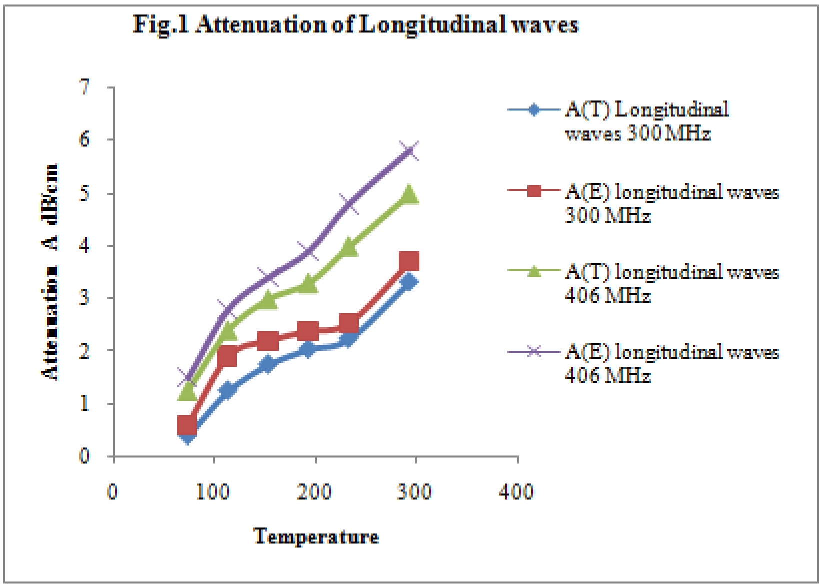
Temperature ^0K	longitudinal waves of frequency 300MHz				longitudinal waves of frequency 406 MHz			
	D_L (T)	D_L (E)	A (T) dB/cm	A(E)dB/cm Ref[3]	D_L (T)	D_L (E)	A (T) dB/cm	A(E)dB/cm Ref[3]
73	3.21	3.91	0.4	0.6	3.19	3.35	1.25	1.5
113	4.22	4.46	1.25	1.9	4.32	4.46	2.4	2.8
153	4.69	4.96	1.75	2.2	4.69	4.86	2.99	3.4
193	5.04	5.10	2.04	2.38	5.14	5.10	3.3	3.9
233	5.25	5.58	2.24	2.54	5.35	5.68	4	4.8
293	5.28	5.67	3.32	3.7	5.58	5.87	5	5.8

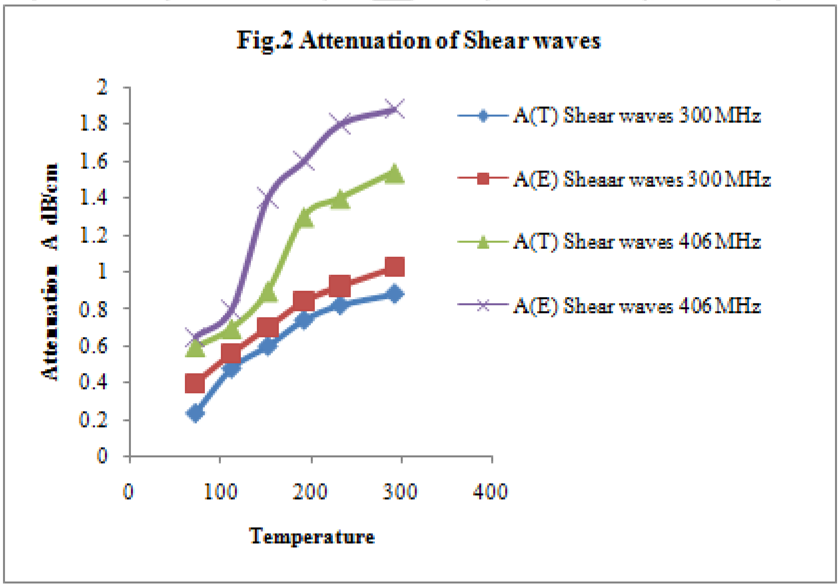
Table 3

Temperature ^0K	Shear waves of frequency 300MHz				Shear waves of frequency 406 MHz			
	D_s (T)	D_s (E)	A (T) dB/cm	A(E)dB/cm Ref[3]	D_s (T)	D_s (E)	A (T) dB/cm	A(E)dB/cm Ref[3]
73	3.24	3.94	0.24	0.4	3.26	3.36	0.6	0.65
113	4.23	4.56	0.48	0.56	4.34	4.48	0.7	0.8
153	4.69	4.96	0.6	0.7	4.69	4.86	0.9	1.4
193	5.08	5.16	0.74	0.84	5.24	5.14	1.3	1.6
233	5.30	5.62	0.82	0.92	5.35	5.68	1.4	1.8
293	5.34	5.67	0.88	1.02	5.58	5.87	1.54	1.88

(T) ---- Theoretically calculated values of non-linearity parameter D_L, D_S and attenuation A (E) ---- Experimentally obtained values of D_L, D_S and attenuation A by W.P.Mason Ref [3].

Using the parameters in table.1, the calculated values of non-linearity parameter D_L and the attenuation A in semiconductor germanium ,for longitudinal waves at 300 MHz and 406 MHz ,along [100] axis, as well as the experimentally obtained values of D_L and A by W.P.Mason are given in table.2.Similarly D_S and attenuation A for shear waves along [100] axis are given in table .3.





The table .2.and table.3 give an account of the non –linearity parameter D and the attenuation A in semiconductor germanium,for the longitudinal waves and shear waves of frequency 300 MHz and 406 MHz, respectively along the [100] axis. A good agreement is observed between the theoretically calculated values of D_L ,D_S and A using the temperature dependant second order elastic constants, with those experimentally obtained by W.P.Mason. The variation of attenuation A with temperature for longitudinal waves is shown in fig.1. while for shear waves it is shown in fig.2.

The non-linearity parameter D_L goes on increasing with the temperature, for the longitudinal waves in germanium, which may be due to decrease in value of the average Gruneisen constant γ_{av}. The value of D_S for shear waves also show a increase with the temperature. The losses leading to attenuation in semiconductor germanium are attributed to phonon-phonon interaction and the thermoelastic losses due to thermal conduction between the compressed and expanded part of the medium, owing to longitudinal and shear acoustic wave propagation. From the graph it is evident that the attenuation of acoustic waves in semiconductor germanium is strongly temperature dependant and it goes on increasing with the temperature, both in case of longitudinal and shear waves. Also for the longitudinal and shear waves, it is seen that the frequency of acoustic waves influences the attenuation of waves. The waves of larger frequency suffer large attenuation as compared to low frequency waves. From the calculations it is evident that the magnitude of attenuation A for longitudinal waves is greater than that for the shear waves.

Hence for same frequency and temperature the longitudinal waves are more attenuated as compared to the shear waves.

5. Conclusions

The semiconductor germanium, is a good material for attenuation of the longitudinal as well as shear acoustic waves propagating through it. For same frequency and temperature the longitudinal waves are more attenuated as compared to the shear waves. The knowledge of second order and higher order elastic constants for a material can be used for calculating the non-linearity parameter and acoustic wave attenuation in it.

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