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Non-Destructive Studies in Hexagonal Nanocrystalline ZnO and BeO Semiconductors

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Abstract: ***In the current work we, investigate the elastic, mechanical, thermal and also the ultrasonic properties of nanocrystalline ZnO and BeO semiconductors at room temperature. These semiconductors have hexagonal structure and exhibit semiconducting nature. Theoretically we found that BeO has mechanical properties superior to those of ZnO. The elastic properties (second-and third order elastic coefficients) have been evaluated using Lennard-Jones potential. The elastic property of BeO is improved than those of ZnO, since ZnO have lower values of elastic coefficients. The ultrasonic properties like ultrasonic attenuation & sound velocity in these semiconductors have been studied in different directions at room temperature. We calculated the ultrasonic velocity in different directions and came to conclusion that these semiconductors are anisotropic.***

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Keywords: Semiconductor materials; Elastic properties; Thermal conductivity; Ultrasonic properties

1. Introduction

Zinc oxide (ZnO) typically exists in the form of a white powder that is almost insoluble in water. The powder is extensively used as an additive in a large variety of substances and goods, such as plastics, ceramics, glass, cement, rubber, grease, pigments, creams, glue, varnishes, colors, meals, batteries, ferrites, and flame retardants. Although it exists as the mineral zincite in the Earth's crust, most of the ZnO used in industry is synthesized synthetically. Scientists have been inspired to examine the potential for employing II-VI compounds semiconductors in commercial applications by their distinctive and interesting features. Zirconium oxide (ZnO) is a transparent, semiconducting, piezoelectric, and dielectric oxide [1–5]. Beryllium oxide (BeO), a component of the group of alkaline-earth oxides, is the only one to crystallise in the hexagonal wurtzite structure rather than the rock-salt structure. It is an oxide with white crystals. It is noteworthy because, in addition to being an electrical insulator, it has a thermal conductivity that is higher than that of any other non-metal, with the exception of diamond, and even surpasses that of some metals. It is used as a refractory because of its high melting point. Natural occurrences of it include the mineral bromellite. Glucina or glucinium oxide was historical terms for beryllium oxide. [6].

Furthermore, BeO is not one of the hardest substances known, but it is also harder compared to other alkaline-earth oxides. These intriguing physical characteristics are connected to the distinctive BeO interatomic bonding phenomenon. [7]. Among oxides, BeO is remarkable because it combines good thermal and electrical insulator with significant thermal conductivity. Moreover, it resists rusting. Applications that take use of beryllium oxide powder's unique features are the only ones that can employ it due to the substance's extreme toxicity when inhaled and the high expense of the raw material. Because of its superior thermal conductivity and strong electrical resistance, it is most frequently utilised as an electronic substrates, acting as a powerful heat sink. Since BeO is transparent to microwaves, the material may be used as windows, radomes and antennas in microwave communication systems and microwave ovens. Since the material is transparent to x-rays, it can be used as an x-ray window, particularly for severe operating conditions. It can also be used in high-power laser tubes [8].

Carlotti et al. [9] have used surface Brillouim scattering to determine the elastic constants of a transparent ZnO film in the micron range of thickness. Size -dependent thermal conductivity of zinc oxide nanobelts have characterized by Kulkarni et al. [10]. Structural and thermodynamic properties of hexagonal BeO at high pressure and temperature have been studied by Song et al. [11]. The thermal conductivity of BeO single crystal has been measured by Slack et al. [12].

The estimation of the ultrasonic attenuation (UT) is accomplished using non-destructive ultrasonic methods to investigate the physical properties of the semiconductor materials. The physical characteristic of ultrasonic attenuation, which is intimately associated to various physical quantities similar to thermal conductivity, specific heat, thermal energy density, and higher order elastic coefficients, is significant for evaluating a semiconductor material. The estimated ultrasonic parameters and associated thermo-physical characteristics are discussed for the characterization of the various semiconductor materials. The resulting information is compared to other hexagonally structured semiconductor materials for analysis. In order to characterize the selected semiconductor materials, the estimated ultrasonic parameters are presented along with relevant thermo-physical properties. Comparing the collected information to other semiconductor compounds with hexagonal structures is accomplished for analysis.

2. Theory

We divide the theory into two parts,

2.1 Second-and third order Elastic constants

The higher order elastic constants have a very significant influence in determining the attenuation in the semiconductor. The semiconductor^s higher order elastic constants are crucial information for evaluating the mechanical and dynamical characteristics of the substance. Higher order elastic coefficients have been calculated using the interaction potential model technique. The second and third order strain derivative of elastic energy density has been used to produce the formulations of higher order elastic coefficients. The second (C_{IJ}) and third (C_{IJK}) order elastic constants of material are defined by following expressions.

$$C_{IJ} = \frac{\partial^2 U}{\partial e_I \partial e_J}; \qquad I \text{ or } J = 1,......6 \qquad [1]$$

$$C_{IJK} = \frac{\partial^3 U}{\partial e_I \partial e_J \partial e_K}; I \text{ or } J \text{ or } K = 1,......6 \qquad [2]$$

Where, U is elastic energy density, $e_I = e_{ij}$ (i or j = x, y, z, I=1, …6) is component of strain tensor. Eqs (1) and (2) lead to six second and ten third order elastic constants (SOEC and TOEC) for the hcp semiconductor compounds [13, 14].

$$\left.\begin{aligned} C_{11} &= 24.1\, p^4 C' & C_{12} &= 5.918\, p^4 C' \\ C_{13} &= 1.925\, p^6 C' & C_{33} &= 3.464\, p^8 C' \\ C_{44} &= 2.309 p^4 C' & C_{66} &= 9.851\, p^4 C' \end{aligned}\right\} \qquad [3a]$$

$$\left.\begin{aligned} C_{111} &= 126.9 p^2 B + 8.853 p^4 C' & C_{112} &= 19.168 p^2 B - 1.61 p^4 C' \\ C_{113} &= 1.924 p^4 B + 1.155 p^6 C' & C_{123} &= 1.617 p^4 B - 1.155 p^6 C' \\ C_{133} &= 3.695 p^6 B & C_{155} &= 1.539 p^4 B \\ C_{144} &= 2.309 p^4 B & C_{344} &= 3.464 p^6 B \\ C_{222} &= 101.039 p^2 B + 9.007 p^4 C' & C_{333} &= 5.196 p^8 B \end{aligned}\right\} \qquad [3b]$$

2.2 Ultrasonic attenuation and allied Parameters

Thermoelastic relaxation mechanisms and phonon-phonon interaction, also known as Akhieser loss, are the main reasons of ultrasonic attenuation in solids at room temperature. The following expression represents the ultrasonic attenuation coefficient $(A)_{Akh}$ caused by thermoelastic relaxation and phonon-phonon interaction. [14,15].

$$(A/f^2)_{Akh} = 4\pi^2 \left(3E_0 < (\gamma_i^j)^2 > - < \gamma_i^j >^2 C_V T\right) \tau / 2\rho V^3 \quad [4]$$

$$(A)/f^2)_{Th} = 4\pi^2 < \gamma_i^j >^2 kT / 2\rho V_L^5 \qquad [5]$$

where, f: frequency of the ultrasonic wave; Vs: ultrasonic velocity for shear wave; V_L: longitudinal ultrasonic velocity; E_0: thermal energy density; γ_i^j: Grüneisen number (i, j are the mode and direction of propagation).

The Grüneisen number for hcp semiconductor compound along <001> orientation or $\theta = 0^0$ is a direct consequence of second and third order elastic constants. $D = 3\left(3E_0 < (\gamma_i^j)^2 > - < \gamma_i^j >^2 C_V T\right)/E_0$ is known as acoustic coupling constant, which is the measure of acoustic energy converted to thermal energy. When the ultrasonic wave propagates through nanocrystalline semiconductor material, the equilibrium of phonon distribution is disturbed. The time for re-establishment of equilibrium of the thermal phonon distribution is called thermal relaxation time (τ) and is given by following expression:

$$\tau = \tau_S = \tau_L / 2 = 3k / C_V V_D^2 \qquad [6]$$

Here τ_L and τ_S are the thermal relaxation time for longitudinal and shear wave. k and C_V are the thermal conductivity and specific heat per unit volume of the material respectively. The Debye average velocity (V_D) is well related to longitudinal (V_L) and shear wave (V_{S1}, V_{S2}) velocities. The expressions for ultrasonic velocities are given in our previous papers [16, 17]:

$$V_D = \left[\frac{1}{3}\left(\frac{1}{V_L^3} + \frac{1}{V_{s1}^3} + \frac{1}{V_{s2}^3}\right)\right]^{-1/3} \qquad [7]$$

The mathematical formulation of UA (ultrasonic attenuation) is described as[16]:

$$\alpha_{long} = \frac{2\pi^2 f^2}{\rho V_l^3}\left(\frac{4}{3}\eta_e + \chi\right) \qquad [8]$$

$$\alpha_{shear} - \frac{2\pi^2 f^2}{\rho V_S^3}\eta_e \qquad [9]$$

Ultrasonic attenuation offers crucial micro-structural properties of the semiconductors by evaluating the ultrasonic wave's absorption in the medium. The following equation gives the ultrasonic attenuation coefficient $(\alpha)_{Akh}$ resultant from the phonon-phonon interaction process [17, 18].

$$(\alpha/f^2)_{Akh} = \frac{4\pi^2 \tau E_0 \left(\frac{D}{3}\right)}{2\rho V^3} \qquad [10]$$

The thermal relaxation (τ) time, is as follows:

$$\tau = \frac{3k}{C_V V_D^2} = \tau_S = \tau_L / 2 \qquad [11]$$

Here τ_L and τ_S are the thermal relaxation time for the longitudinal wave (V_L) and shear wave (V_S) respectively, the thermal conductivity is represented as ‘k’. The $(\alpha/f^2)_{Th}$

(thermoelastic loss) is evaluated through the subsequent equation [19]:

$$(\alpha/f^2)_{Th} = 4\pi^2 < \gamma_i^j >^2 \frac{kT}{2\rho V_L^5} \qquad [12]$$

The total ultrasonic attenuation $(\alpha/f^2)_{Total}$ is indicated through the following equation as [20]:

$$(\alpha/f^2)_{Total} = (\alpha/f^2)_{Th} + (\alpha/f^2)_L + (\alpha/f^2)_S \qquad [13]$$

Wherever $(\alpha/f^2)_{Th}$ is the thermoelastic loss, $(\alpha/f^2)_L$ and $(\alpha/f^2)_S$ are respectively the ultrasonic attenuation coefficients for the longitudinal wave (V_L) and shear wave (V_S).

3. Results and Discussion

3.1 Higher order elastic constants

The unit cell parameters 'a' (basal plane parameter) and 'p' (axial ratio) for ZnO and BeO are 3.25Å, 2.719Å and 1.602, 1.624 [21, 11]. The value of m and n for chosen materials are 6 and 7. The values of b_0 are $2.2\text{x}10^{-64}$ erg cm^7 and $8.3\text{x}10^{-64}$ erg.cm^7 for ZnO and BeO respectively. The SOEC and TOEC have been calculated for these semiconductors compound using Eq. (3) and are presented in Table 1.

Table 1: SOEC and TOEC (in GPa) of ZnO and BeO semiconductor at room temperature.

SOEC→ Alloys↓	C_{11}	C_{12}	C_{13}	C_{33}	C_{44}	C_{66}
ZnO(Present)	220.26	54.09	45.15	208.53	54.16	86.38
ZnO [9]	206±4	--	108±10	211±4	44.3±1	44.6±1
ZnO[17]	207	--	101	209	46.1	44.5
ZnO [18]	207	117.7	106.1	209.5	44.8	--
BeO(Present)	488.0	119.8	102.8	487.9	123.3	191.4
BeO[19]	461.0	126.5	88.5	491.6	147.4	167.0
BeO[20]	470.0	168.0	119.0	494.0	153.0	152.0
BeO[21]	460.0	125.0	82.0	490.0	145.0	167.0

TOEC→ Alloys↓	C_{111}	C_{112}	C_{113}	C_{123}	C_{133}	C_{344}	C_{144}	C_{155}	C_{222}	C_{333}
ZnO	-3591	-569	-116	-147	-704	-660	-171	-114	-2842	-2542
BeO	-7958	-1261	-263	-335	-1648	-1545	-390	-260	-6296	-6112

The elastic constants of the semiconductor material are important, since they are related to hardness and therefore of interest in applications where mechanical strength and durability are important. Also, the second order elastic constants are used for the determination of the ultrasonic attenuation and related parameters. It is obvious from Table 1 that, there is good agreement between the present and reported theoretical/experimental second order elastic constants [9, 17-21]. Thus our theoretical approach for the calculation of second order elastic constants for hexagonal structured semiconductor at room temperature is well justified. However, third order elastic constants are not compared due to lack of data in the literature but the negative third order elastic constants are justified in the literature [13-15, 22-24]. Hence applied theory for the evaluation of higher order elastic constants at room temperature is justified. The elastic constants of BeO is approximately double that of ZnO. The elastic constants results show that the crystals are elastically stable, since stability conditions $C_{44}>0$, $C_{11}>0$ and $C_{11}>C_{12}$ are satisfied. This shows thermally softening behaviour of chosen semiconductor.

The bulk modulus (B) for these materials can be calculated with the formula $B= 2(C_{11}+ C_{12}+ 2C_{13} + C_{33}/2)/9$. The evaluated B for ZnO and BeO using the presently calculated SOEC at 300K is 104GPa and 234 GPa. The B for polycrystalline ZnO is 142.2 GPa [16] and B for BeO is 240 GPa [19], 244 GPa [20], 222 GPa [21] and 210 GPa (experimental) under ambient pressure [25]. A comparison of bulk moduli shows justification for the calculated higher-order elastic constants.

3.2 Ultrasonic velocity and allied parameters

The density and thermal conductivity at room temperature have been taken from the literature [10, 12]. The value of C_V and E_0 are evaluated using tables of physical constants and Debye temperature. The quantities k and calculated acoustic coupling constants (D_L & D_S) are presented in Table 2.

Table 2: Density (ρ: in 10^3 kg m^{-3}), specific heat per unit volume (C_V: in $10^6 Jm^{-3}K^{-1}$), thermal energy density (E_0: in $10^8 Jm^{-3}$), thermal conductivity (k: in $Wm^{-1}K^{-1}$) and acoustic coupling constant (D_L, D_S) of ZnO and BeO.

	ρ	C_V	E_0	k	D_L	D_S
ZnO	5.61	1.545	2.734	60	55.927	1.163
BeO	3.01	1.638	1.822	370	53.341	1.117

The calculated orientation dependent ultrasonic wave velocities and Debye average velocities at 300 K are shown in Figs 1–4. Figs 1–3 show that the velocities V_L and V_{S1} have minima and maxima respectively at 45° with the unique axis of the crystal while V_{S2} increases with the angle from the unique axis. The combined effect of SOEC and density is reason for abnormal behaviour of angle dependent velocities.

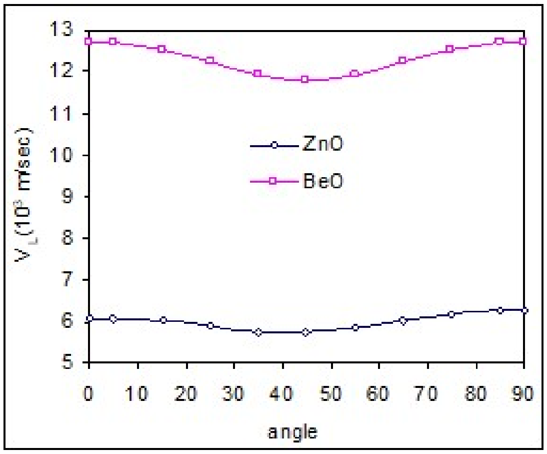

Figure 1: V_L vs angle with Z axis of semiconductor

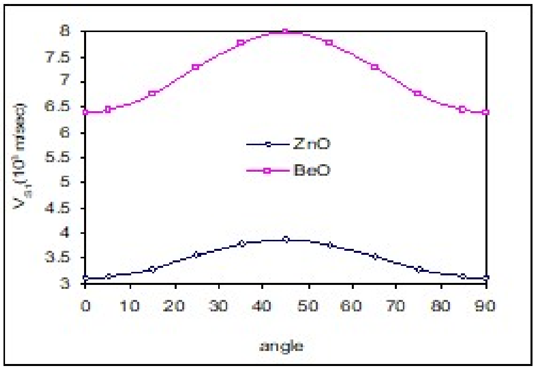

Figure 2: V_{S1} vs angle with unique axis of semiconductor

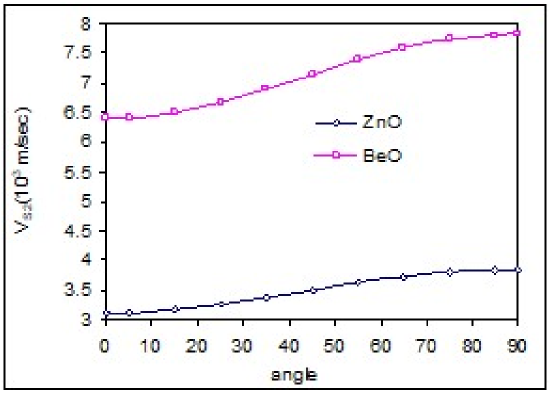

Figure 3: V_{S2} vs angle with unique axis of semiconductor

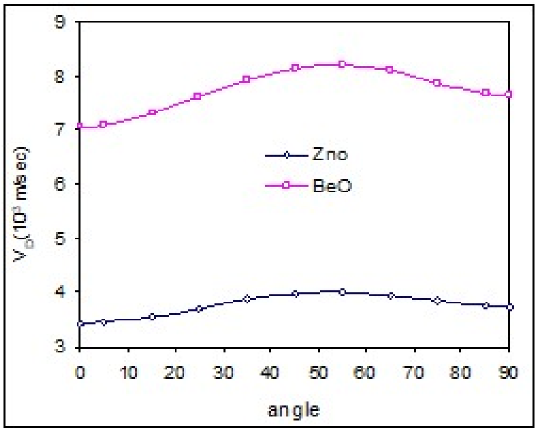

Figure 4: V_D vs angle with unique axis of semiconductor

The nature of the angle dependent velocity curves in the present work is found similar to that for heavy rare-earth metals, laves-phase compounds and other hexagonal wurtzite structured materials (GaN, AlN, InN) [13-15, 22-24]. These semiconductors such as ZnS, ZnSe, SiC, GaN and ZnO have shown similar properties with their crystal structure. The sound velocities for longitudinal and shear mode of ZnO are 6098 m/s and 3108 m/s in present calculation while 6035±50 m/s and 2790± 30m/s was measured by Carlotti et al.[9]. Hence values of velocities are in good agreement with experimental values. Thus the angle dependencies of the velocities in these semiconductor materials are justified. The ultrasonic velocities in BeO are double that in ZnO due to values of elastic constants.

V_D of these semiconductor compounds are increasing with the angle and have maxima at 55° at 300 K (Fig. 4). Since V_D is calculated using V_L, V_{S1} and V_{S2} [13-15], therefore the angle variation of V_D is influenced by the constituent ultrasonic velocities. The maximum V_D at 55° is due to a significant increase in longitudinal and pure shear (V_{S2}) wave velocities and a decrease in quasi-shear (V_{S1}) wave velocity. Thus it can be concluded that when a sound wave travels at 55° with the unique axis of these semiconductors then the average sound wave velocity is maximum.

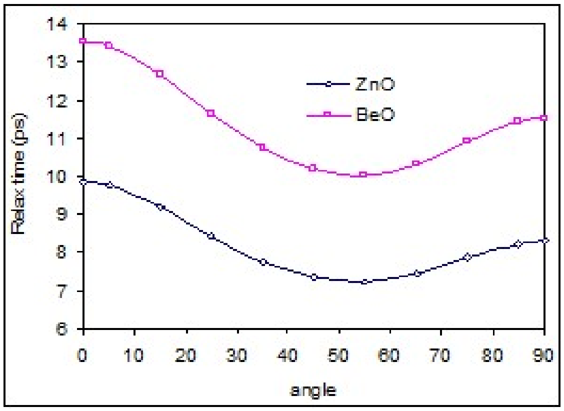

Figure 5: Relaxation time vs angle with unique axis of semiconductor

The calculated thermal relaxation time is visualised in Fig. 5. The angle dependent thermal relaxation time curves follow the reciprocal nature of V_D as $\tau \propto 3K / C_V V_D^2$. τ has maximum value 9.85 ps and 13.52 ps for the wave propagation along unique axis ($\theta = 0^0$) of ZnO and BeO respectively. The minimum values of τ for ZnO and BeO are found to be7.24 ps and 10.04 ps respectively along $\theta = 55^0$. This implies that τ for these are mainly affected by the thermal conductivity. The τ for semiconductor materials is the order of ps [24]. Hence the calculated τ justifies the hcp structure of chosen semiconductor compounds at room temperature. The minimum τ for wave propagation along $\theta = 55^0$ implies that the re-establishment time for the equilibrium distribution of thermal phonons will be minimum for propagation of wave along this direction.

The Debye temperature of ZnO and BeO is 452K and 1123K, which is similar to 420K and 1280K determined by Kulkarni et al. [10] and Slack et al. [12] respectively. BeO has a low average atomic mass and a high Debye temperature (1123K). Thus BeO has a higher thermal conductivity compared to other oxides. Debye (average) sound velocity is useful for the evaluation of Debye temperature [26] and the Debye temperature is well related to C_V and E_o [27]. The V_D for ZnO and BeO is 3.44×10^3 m/s and 7.08×10^3 m/s respectively, which has a similar trend as the Debye temperature. Thus the present average sound velocity directly correlates with the Debye temperature, specific heat and thermal energy density of theses semiconductor materials.

3.3 Ultrasonic attenuation

In the evaluation of ultrasonic attenuation, it is supposed that wave is propagating along the unique axis (001 direction) of these semiconductor materials. The attenuation coefficient over frequency square $(A/f^2)_{Akh}$ for longitudinal $(A/f^2)_L$ and shear wave $(A/f^2)_S$ are calculated using Eq. (4) under the condition $\omega\tau \ll 1$ at room temperature. The thermoelastic loss over frequency square $(A/f^2)_{Th}$ is calculated with the Eq. (5).[28]. The values of $(A/f^2)_L$, $(A/f^2)_S$, $(A/f^2)_{Th}$ and total attenuation $(A/f^2)_{Total}$ are presented in Table 3.

Table 3: Ultrasonic attenuation coefficient (in 10^{-17} Nps^2m^{-1}) of ZnO and BeO

	ZnO	BeO
$(A/f^2)_{Th}$	0.36	0.11
$(A/f^2)_L$	311.47	55.58
$(A/f^2)s$	24.46	4.58
$(A/f^2)_{Total}$	336.29	60.27

Table 3 indicates that the thermoelastic loss is very small in comparison to Akhieser loss and ultrasonic attenuation for longitudinal wave $(A/f^2)_L$ is greater than that of shear wave $(A/f^2)_S$. This reveals that ultrasonic attenuation due to p-p interaction along longitudinal wave is governing factor for total attenuation ($(A/f^2)_{Total} = (A/f^2)_{Th} + (A/f^2)_L + (A/f^2)_S$). The total attenuation is mainly affected by thermal conductivity. Thus it may predicted that at 300K the material BeO behaves as its purest form and is more ductile as evinced by minimum attenuation while ZnO is least ductile. Therefore impurity will be least in the material BeO at room temperature.

Since $A \propto V^{-3}$ and velocity is the largest for BeO , thus the attenuation A should be smallest and material should be most ductile. The minimum ultrasonic attenuation for BeO justifies its quite stable hcp structure . The total attenuation of these semiconductors are much larger than third group nitrides (AlN: 4.441×10^{-17} Nps^2m^{-1}; GaN: 14.930×10^{-17} Nps^2m^{-1} and InN: 20.539×10^{-17} Nps^2m^{-1}) due to their large thermal conductivity and acoustic coupling constants [17, 24]. This implies that the interaction between acoustical phonon and quanta of lattice vibration for these semiconductors are large in comparison to third group nitrides.

4. Conclusions

On the basis of above analysis, we conclude the following:

- Our theory of higher order elastic coefficients is acceptable for the hexagonal structured semiconductors.
- The order of thermal relaxation time for these semiconductor materials is found in picoseconds, which justifies their hcp structure at 300K. The re-establishment time for the equilibrium distribution of thermal phonons will be minimum for the wave propagation along $\theta = 55^{0,}$ on account of "τ" being smallest along this direction.
- The acoustic coupling constant of these semiconductors for longitudinal wave are found to be five times larger than GaN /AlN /InN. Hence the conversion of acoustic energy into thermal energy will be large for these materials. This shows general suitability of chosen semiconductor.
- The ultrasonic attenuation caused by phonon-phonon interaction mechanism is predominant over total attenuation, the thermal conductivity been governing factor.
- The mechanical properties of BeO are better than those of ZnO, because ZnO has low elastic constants and ultrasonic velocities.

Thus obtained results in the present work can be used for further investigations, general and industrial applications. Our theoretical approach is valid for ultrasonic characterization of these nanocrystalline semiconductor materials at room temperature. The ultrasonic behavior in ZnO and BeO as discussed above shows important microstructural characteristic features, which are well connected to thermoelectric properties of the nanocrystalline semiconductor materials. These results, together with other well-known physical properties, may expand future prospects for the application and study of these nanocrystalline semiconductor materials.

References

[1] W. L. Hughes, Synthesis and characterization of ZnO for piezoelectric applications, PhD thesis, School of Materials Science & Engineering, Georgia Institute of Technology (USA. 2006).

[2] U. Özgür, Y. I. Alivov, C. Liu, A. Teke, M. A. Reshchikov, S. Doğan, V. Avrutin, S. J. Cho, H. Morkoçd, J. Appl. Phys. 98 (2005) 041301.

[3] C. Jin, Growth and characterization of ZnO and ZnO-based Alloys-$Mg_xZn_{1-x}O$ and MnxZn1-xO PhD thesis, North Carolina State University, Raleigh. (2003).

[4] G. Ferblantier, F. Mailly, R. Al Asmar, A. Foucaran, F. P. Delannoy, Sensor and Actuators A122 (2005) 184.

[5] H. S. Bae, Seongil Im, Thin Solid Film s 469-470 (2004) 75-79.

[6] R. M. Hazen, L. W. Finger, J. Appl. Phys. 59 (1986) 3728.

[7] K. B. Josi, R. Jain, R. K. Pandya, B. L. Ahuja, B. K. Sharma, Radiation Phys. and Chem. 51 (1998) 519.

[8] C. Oligschleger, R. O. Jones, S. M. Reimann, H. R. Schober, Phys. Rev. B 53 (1996) 6165.

[9] G. Carlotti, D. Fioretto, G. Socino, E. Verona, J. Phys: Condens Matter 7 (1995) 9147.

[10] A. J. Kulkarni, M. Zhou, App. Phys. Lett. 88 (2006) 141921.

[11] H. F. Song, H. F. Liu, E. Tian, J. Phys: Condens Matter 19 (2007) 456209.

[12] G. A. Slack, S. B. Austerman, J. Appl. Phys. 42 (1971) 4713.

[13] Panday, D.K.and Yadav, R. R. *Applied Acoustics.,* 2009,vol. 70, No 3, P. 412-415.

[14] Panday, D.K.,and Yadav, R.R. *Materials Letters.,* Vol. 59, No 5, 2005, P 564-569.

[15] Verma, S. K., Panday, D.K. and Yadav, R.R. *Physica B: Condensed Matter,* vol. 407, No 18, 15 , 2012, Pp. 3731-3735.

[16] Balla, V. Singh, D., Pandey, D. K., Yadav, C. P. International Journal of Thermophysics (2020), p.41:46 .

[17] Yadav, C. P., and Pandey, D.K. *Ultrasonics.,* 2019,Vol. 96, P. 181-184.

[18] Singh, D. and Panday, D.K. Pramana. J. Physics., Vol. 72, No. 2 2009, pp. 389–398

[19] Khan, A. Yadav, C. P., Pandey, D.K., Singh, D., and Singh, D., *J. PURE APPL. ULTRASON.*, 2019, VOL. 41, NO. 1.

[20] Dhawan, P. K., Wan, M., Verma, S .K, Pandey, D .K, and Yadav R.R. *JOURNAL OF APPLIED PHYSICS*, 2015, vol.117, 074307.

[21] S. J. Pearton, D. P. Norton, K. Ip, Y. W. Heo, T. Steinerb, Superlattice and Microstructures 34 (2003) 29.

[22] Landolt-Bornstein, Numerical Data and Function Relationship in Science and Technology, Group III Vol. 11, Bellin Springer 1979.

[23] D. Singh, Y. P. Varshni, Phys. Rev. B 25 (1982) 7376.

[24] C. F. Cline, H. L. Dunegan, G. W. Henderson, J. Appl. Phys. 38 (1967) 1944.

[25] G. G. Bentle, J. Am. Ceram. Soc. 49 (1996) 125.

[26] N. N. Siroto, A. M. Kuzmina, N. S. Orlovo, Dokl. Akad. Nauk SSSR 314 (1990) 856.

[27] Singh, S. P., Singh, G., Verma, A. K., Jaiswal, A. K., Yadav,R. R., *Metals and Materials International* 2021, vol.27 p.2541–2549.

[28] Yadav, C. P., Pandey, D. K., and Singh, D. *Indian J Phys.,* 2021,vol.**93,** p.1147.