Original Paper

Elastic moduli of ternary tellurite glasses at room temperature

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Longitudinal and shear ultrasonic velocities in the ternary tellurite glasses have been measured at room temperature with different percentages of the third component. The ternary tellurite glasses have the form (composition in mol%): 70 TeO_2 - $(30-x)$ V_2O_5 - xA_nO_m, where A_nO_m is CeO_2 or ZnO, and $x = 3, 5, 7, 10$ mol%. The elastic properties, longitudinal, shear, bulk and Young's modulus, have been calculated together with Poisson's ratio and Debye temperature. A qualitative analysis has been carried out after calculating the ring diameter of the glass network.

Quantitatively, the estimated bulk modulus and Poisson's ratio of the ternary $TeO_2-V_2O_5-CeO_2$ system have been calculated, using the bond compression model and according to the cation-anion bond of each oxide present in the glass, in order to analyze the room-temperature elastic moduli data.

Information about the structure of the glass can be deduced after calculating the number of network bonds per unit volume, the average stretching force constant, the average ring size and the mean cross link density.

Elastische Moduln ternärer Telluritgläser bei Raumtemperatur

An ternären Telluritgläsern der Zusammensetzung (in Mol-%) 70 TeO_2 - $(30-x)$ V_2O_5 - xA_nO_m (mit A_nO_m für CeO_2 oder ZnO und $x = 3, 5, 7$ sowie 10 Mol-%) wurde bei Raumtemperatur die longitudinale und transversale Ultraschallgeschwindigkeit gemessen. Berechnet wurden die elastischen Eigenschaften, und zwar der Longitudinal-Modul, der Schermodul, der Kompressionsmodul und der E-Modul sowie die Poisson-Zahl und die Debye-Temperatur. Nach Berechnung des Ringdurchmessers des Glasnetzwerkes wurden die Ergebnisse qualitativ diskutiert.

Quantitativ wurden der Kompressionsmodul und die Poisson-Zahl mit Hilfe des Bindungs-Kompressions-Modells und unter Berücksichtigung der Kationen-Anionen-Bindung aller im Glas vorhandenen Oxide berechnet, um die Elastizitätsmoduli bei Raumtemperatur zu ermitteln.

Aus der Berechnung der Anzahl der Netzwerk-Bindungen pro Volumeneinheit, der mittleren Dehnungskonstante, der durchschnittlichen Ringgröße und der mittleren Vernetzungs-Dichte können Hinweise zur Struktur der Gläser abgeleitet werden.

1. Introduction

The tricomponent tellurite glasses $TeO_2-V_2O_5-A_nO_m$, where $A_nO_m = CeO_2$ or ZnO, have been known as a semiconductors and show the memory switching phenomena [1 to 4]. Because elastic properties are very informative about the structure of solids and are directly related to the interatomic potential, it is very important to measure and analyze the elastic moduli of these advanced materials. Recently (1997 and 1998), we have measured the elastic properties of $TeO_2-V_2O_5$ glasses [5] and the radiation effect on the ultrasonic attenuation with the values of the internal friction of $TeO_2-V_2O_5-Ag_2O$ glasses [6]. Previously we have measured the elastic properties and Debye temperature of pure, binary, ternary and quaternary transition metal

and rare-earth tellurite glasses [7 to 10]. Also the present report will carry on the quantitative analysis of the elastic moduli.

2. Experimental work

The ternary 70 TeO_2 · $(30-x)$ V_2O_5 · $xCeO_2$ and 70 TeO_2 · $(30-x)$ V_2O_5 · $xZnO$ glasses were prepared by mixing together specified weights of tellurium oxide (99.99 %, Aldrish) and vanadium pentaoxide (99.9 %, Aldrish) with cerium oxide (99.99 %, Aldrish) for the first series, and ZnO (99.95 %, Aldrish) for the second series in a closed silica crucible. The x percentages were 3, 5, 7 and 10 mol% for each CeO_2 and ZnO. In order to reduce tendency to volatilization, the mixture was kept at 400 °C for a period of one hour for cerium glasses and half an hour for zinc glasses. The crucible was then transferred to the melting muffle furnace (NEY

Table 1. Composition, melting temperature, annealing temperature and color of the tricomponent tellurite glasses

sample no.	chemical formula	melting temperature and melting time	annealing temperature in °C	color
Ce-1	70 TeO$_2$ · 27 V$_2$O$_5$ · 3 CeO$_2$	750°C, 1/2 h	300	black
Ce-2	70 TeO$_2$ · 25 V$_2$O$_5$ · 5 CeO$_2$	780°C, 1/2 h	300	black
Ce-3	70 TeO$_2$ · 23 V$_2$O$_5$ · 7 CeO$_2$	810°C, 1/2 h	300	black
Ce-4	70 TeO$_2$ · 20 V$_2$O$_5$ · 10 CeO$_2$	850°C, 1/2 h	300	black
Zn-1	70 TeO$_2$ · 27 V$_2$O$_5$ · 3 ZnO	700°C, 20 min	250	brown
Zn-2	70 TeO$_2$ · 25 V$_2$O$_5$ · 5 ZnO	720°C, 20 min	250	brown
Zn-3	70 TeO$_2$ · 23 V$_2$O$_5$ · 7 ZnO	750°C, 20 min	250	brown
Zn-4	70 TeO$_2$ · 20 V$_2$O$_5$ · 10 ZnO	780°C, 20 min	250	brown

2-525 S II) with a temperature in the range of 750 to 850°C depending on the sample composition for half an hour for the cerium glasses. This course for zinc glasses was 20 min at a temperature in the range 700 to 780°C depending on the sample composition. The homogeneity of the samples was achieved by stirring with an alumina rod. The melt for each composition was then cast into a clean steel mold at room temperature. The cerium and the zinc glasses were annealed at respectively 300 and 250°C for one hour. The annealing furnace (R.ST 08/214) was then switched off and allowed to cool to room temperature. This casting procedure served to release thermal stresses and to minimize cracking of glass. The glass rods so produced are of dimensions greater than 1 cm^3. The two opposite faces were ground roughly approximately parallel on a lapping machine with 600 grade SiC powder. The glass was polished with 0.3 μm alumina powder using a precision polishing machine. Opposite faces were finished optically flat and parallel with a high mirror-like surface. Out of the scope of this paper, the glass transformation temperature T_g of the produced glasses was measured by using DTA-Shimadzu series 30 (with a heating rate 10 K/min), in order to anneal the glass samples at temperatures below T_g. T_g was found in the range 320 to 350°C for the end members of both glass series. As both the preparation and annealing furnaces had capacities greatly exceeding the volume of the crucible, the temperature gradients across the glass at any time during melting and annealing were negligible, so the glass was homogeneous. Table 1 shows the chemical formula, the melting point, annealing temperature and, color for all compositions belonging to both series. Examination of the different glasses was carried out by X-ray spectroscopy. The densities of the glasses were measured at room temperature (308 K) by the standard displacement method, using toluene as immersion liquid.

The plus-echo technique has been used to determine the ultrasonic velocities at room temperature. The ultrasonic wave velocities v (in cm/s) were calculated according to the relation:

$$v = 2\,x/t \tag{1}$$

where x is the sample thickness in cm, and t the time between two successive echoes. The geometric dimensions of the samples were around 1 cm in all directions.

The experimental errors in both velocity and density measurements were collected to give $\pm 1\%$ in the elastic moduli.

3. Results and discussion

Ternary 70 TeO$_2$ = $(30-x)$ V$_2$O$_5$ = xA$_n$O$_m$ glasses, where A$_n$O$_m$ = CeO$_2$ or ZnO, with different concentrations of A$_n$O$_m$ from 3 up to 10 mol% are achieved. After studying all x-ray diffraction patterns for all annealed samples no significant or sharp peaks, i.e. characteristics of the crystalline structure, were found, so all produced samples are in the amorphous state.

3.1 Density and molar volume results

Table 2 shows the variation of both density and molar volume for all glasses as a function of the modifiers. The molar volume of all glasses has been calculated by using the following equation:

$$V = M_g/\varrho_g \tag{2}$$

where M_g and ϱ_g are the glass molecular weight and density, respectively. The results show that the density increased from 6.09 to 6.76 g/cm^3 with increasing CeO$_2$ content (3 to 10 mol%) and also increased with an increase in ZnO (3 to 10 mol%) from 5.08 to 5.26 g/cm^3. The observed increase in density with increasing CeO$_2$ and ZnO contents may be attributed to the substitution of vanadium atoms, with atomic weight of 50.94, for cerium and zinc atoms, with atomic weights of 140 and 65.4, respectively. Densities of the tricomponent tellurite glasses are higher than the density of the binary 70 TeO$_2$ · 30 V$_2$O$_5$ glasses where ϱ = 4.6 g/cm^3 [5]. The change in molar volume V of the present ternary glasses is due to the change in the structure caused by the decrease of interatomic spacing inside the glass network resulting in a more compact and dense glass. The molar volume of these systems decreases from 27.3 to 24.3 cm^3 and from 32.2 to 29.7 cm^3 when modified with CeO$_2$ and ZnO, respectively, as represented in table 2. From this volume, one may understand that V as the volume of the corresponding structural unit with its surrounding space decreases by introducing the transition metal and rare earth oxides.

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Table 2. Ultrasonic velocities, elastic moduli, Poisson's ratio and Debye temperature of cerium and zinc tellurovanadate glasses at room temperature

A_nO_m in mol%	ϱ in g/cm^3	V in cm^3	v_l in m/s	v_s in m/s	L in GPa	G in GPa	K in GPa	E in GPa	σ	Θ_D in K
3 CeO$_2$	6.0882	27.3	3460	1429	72.9	12.7	56	35.7	0.395	218
5 CeO$_2$	6.1327	28	3525	1469	76	13.2	58.6	36.9	0.394	219
7 CeO$_2$	6.5384	26.2	3619	1508	85.6	14.9	65.8	41.5	0.393	228
10 CeO$_2$	6.7610	24.5	3760	1567	95.6	16.6	73.5	46.3	0.391	240
3 ZnO	5.0769	32.2	4129	1721	86.6	15.04	66.5	42	0.390	246
5 ZnO	5.1169	31.5	3962	1652	80.3	13.96	61.7	39	0.392	235
7 ZnO	5.1919	30.7	3280	1367	55.9	9.7	42.9	27.06	0.393	195
10 ZnO	5.2585	29.7	2641	1100	36.7	6.36	28.2	17.74	0.395	156

3.2 Room temperature ultrasonic velocities results

The longitudinal and shear ultrasonic velocities in four cerium and four zinc tellurovanadate glasses with compositions in mol% 3, 5, 7 and 10 for each modifier are given in table 2. It can be seen that in the $TeO_2-V_2O_5-CeO_2$ system, both longitudinal and shear ultrasonic velocities increase from 3460 to 3760 m/s and from 1442 to 1567 m/s, respectively, as the cerium oxide content increases and both velocities follow the same trend. The continuous increase in the ultrasonic velocity with the increase of the CeO$_2$ content is the result of increasing the rigidity of the glass system. Consequently, cerium atoms enter the glass network with coordination number 8, i.e. an octahedral form. Octahedral groups are more rigid compared to tetrahedral groups of vanadate. In the light of the above discussion, the increase in the ultrasonic velocity with the increase in the mol% of CeO$_2$ suggests that the fraction of octahedral groups increase at the expense of the tetrahedral groups. On the other hand, both longitudinal and shear ultrasonic velocity decreases from 4129 to 2641 m/s and from 1721 to 1100 m/s, respectively, as the zinc oxide content increases.

3.3 Elastic moduli, Poisson's ratio and Debye temperature

Table 2 collects the elastic properties of the different cerium or zinc tellurovanadate glasses such as, the longitudinal modulus L, the shear modulus G, the bulk modulus K, the Young's modulus E, and Poisson's ratio σ. These various quantities were calculated using the following equations:

$$L = \varrho v_l^2 \tag{3}$$

$$G = \varrho v_s^2 \tag{4}$$

$$K = L - (4/3)G \tag{5}$$

$$E = 2(1 + \sigma)G \tag{6}$$

$$\sigma = (L - 2G)/(2(L - G)) \tag{7}$$

where ϱ is the density, and v_l and v_s are the measured longitudinal and shear ultrasonic velocities, respectively, and the quantities are in GPa. Elastic moduli increased for higher percentage of CeO$_2$ in the glass series 70 TeO$_2 - (30-x)$ V$_2$O$_5 - x$CeO$_2$, while the elastic moduli decreased for the second ternary tellurovanadate glass series 70 TeO$_2 - (30-x)$ V$_2$O$_5 - x$ZnO. Debye temperature (Θ_D) was obtained from the measured ultrasonic velocities v_l and v_s by the expression:

$$\Theta_D = (h/k)\{9N/(4\pi\,V)\}^{1/3}\,v_m \tag{8}$$

with

$$v_m = \left\{\frac{(1/v_l^3) + (2/v_s^3)}{3}\right\}^{-1/3} \tag{9}$$

where h is the Planck's constant, k the Boltzmann's constant, and N the number of vibrating atoms per unit volume. If the Debye model is to represent all the vibrational modes (acoustic and optical), then N is equal to $(p\,N_A)$. p is the number of atoms in the chemical formula and N_A is Avogadro's number.

Table 2 collects the values of all the elastic moduli of the present tricomponent tellurite glasses and also, Poisson's ratio and Debye temperature for each glass. The qualitative interpretation for the bulk modulus data will be discussed and then by explanation of the other moduli G, L, E follows automatically. According to the bond compression model [11], the structure consisting of a three-dimensional network of bonds (A = cation, O = oxygen atom) and can be expressed in the form as in Equation (10).

$$K = \text{constant } F_b/(l)^n \tag{10}$$

where F_b is the A$-$O bond bending force constant, which to a first approximation may be taken as proportional to the bond stretching force constant F, and l is the diameter of the atomic rings. The explanation for l is as follows: $l = $ (number of A$-$O bonds in ring $\times$ length of A$-$O bond)/π. The model was adapted in principle to mixed oxide glasses [12], and it was concluded that the model can be very useful qualitatively if one assumes that with gradual changes in glass compositions. The crosslink density (n_c^1) (defined as the number of bridging bonds per cation, minus two) tends to increase, then atomic ring sizes tend to decrease. In this case the bulk modulus K will increase according to equation (10).

Table 3. Variation of the network ring diameter (l) for every glass composition

A_nO_m in mol%	l in nm
3 CeO$_2$	0.444
5 CeO$_2$	0.436
7 CeO$_2$	0.421
10 CeO$_2$	0.405
3 ZnO	0.426
5 ZnO	0.433
7 ZnO	0.475
10 ZnO	0.527

Table 3 collects the calculated values of the ring diameter of both glass series. In the first case (3 to 10 mol% CeO$_2$) the bulk modulus increases from 56 to 73.5 GPa as V=O bonds are replaced by V−O−Ce. The increase in bulk modulus is due to the gradual increases in crosslink density of the glass structure, this is attributed to all the added cerium being in the form of octahedral Ce−O$_8$ groups. This would tend to cause the network ring sizes l to decrease from 0.444 to 0.405 nm with increasing cerium oxide content and, consequently, the bulk modulus tends to increase. On the other hand, as ZnO entered the glass network as a third composition, the bulk modulus decreased from 66.5 to 28.2 GPa. In this composition we believe the Zn^{2+} ions reside in the glass interstitial as network modifier. These broken network bonds are replaced by ionic bonds between interstitial modifying Zn^{2+} ions and the oxygen atoms of the network. This alteration in structure is accompanied by a change in the ring sizes. It seems that glasses with large atomic ring sizes (l from 0.427 to 0.530 nm) will cause the decrease in bulk modulus.

In ternary glasses both the degree of cross-linking and the relative proportions of different types of bonds may be changed with composition. It is clear that both types of mechanism will be present, i.e. to summarize, we propose to interpret our glass elastic data on the model of [12]:
a) the data decrease with increasing crosslink density (for constant ratio of bond-bending to stretching force constant),
b) they decrease with increasing ratio of bond-bending to stretching force constant F_b/F (at constant cross link density).

The first mechanism was found to be most favorable for our results. The variation of Poisson's ratio with composition ought to be exactly the reverse of the bulk modulus variations described earlier, i.e., σ would decrease as the ratio of increase of cross link density with CeO$_2$ content increases. Then in the second group, σ must increase with decreasing of cross link density as ZnO increases (table 2). It can be seen that when CeO$_2$ concentration increases in the glass network, the Debye temperature increases from 218 to 240 K. This implies an increase in the rigidity of the glass network, which continues as long as the molar volume decreases and

the mean ultrasonic velocity increases from 1131 to 1229 m/s. On the other hand, as ZnO increases, the Debye temperature decreases from 246 to 156 K, which implies a decrease in the rigidity of the glass network, accompanied by a corresponding fall in all other parameters. These values are close to the previous values for $(100-x)$ TeO$_2$−xV$_2$O$_5$ [5].

4. Theoretical analysis of elastic moduli and Poisson's ratio

To understand and analyze the experimental values of the elastic moduli obtained, it is very important to state the model of calculating the bulk modulus K_{bc} of polycomponent oxide glasses according to the bond compression model [12 to 15]:

$$K_{bc} = \sum_n (n_b \, r^2 \, F'/9) \qquad (11)$$

where n designates different types of network bonds, n_b is the number of network bonds per unit volume, F' the first order stretching force constant, and r the cation-anion bond length. The bond length has been adopted from the crystal structure and F has been calculated according to the relation $F = 17/r^3$ [11]. The number of network bonds per unit volume n_b has been calculated according to the percentage of each oxide in the glass as in equation (12), and n_f is the number of formula units per unit volume and is equal to the density of state per mass of one formula unit

$$n_b = n_f \, N_A \, \varrho_g/M_g \qquad (12)$$

where ϱ_g and M_g are the density and the molecular weight of the glass, respectively. The data of the present oxides TeO$_2$, V$_2$O$_5$, and CeO$_2$ or ZnO are given in table 4.

Table 5 shows the bulk modulus K_{bc}, the number of network per unit volume n_b, the average stretching force constant of each glass F' together with the measured bulk modulus K_e of the present tricomponent tellurite glasses doped with CeO$_2$ and ZnO contents, respectively. The total values of the calculated bulk modulus are higher than those of binary vanadium tellurite glasses [5]. The previous result can be explained as the increase in the number of network bonds per unit volume from $1.0 \cdot 10^{32}$ to $1.8 \cdot 10^{32}$ m^{-3}, and from $8.06 \cdot 10^{31}$ to $8.80 \cdot 10^{31}$ m^{-3}, when CeO$_2$ and ZnO were modified, respectively. On the other hand, the average stretching force constant reduces from 234 to 216 N/m and from 239 to 233 N/m for each series. It has been concluded [17] that if K_e is less than K_{bc} (for these materials), compression proceeds via a mechanism requiring much less energy than is required for pure compression of network bonds. When the ratio of (K_{bc}/K_e) is close to one, it means that an interaction between neighboring bonds is neglected in the model as in the case of CeO$_2$ contents. On the other hand, the ratio of (K_{bc}/K_e) > 1 could indicate a relatively open three-dimensional network, with

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Table 4. Coordination number, cation-anion bond length and the first order stretching force constant of the oxides TeO_2, V_2O_5, CeO_2, ZnO

	coordination number	cation-anion bond length r in nm	first order stretching force constant F' in N/m	reference
TeO_2	4	0.199	216	[16; pp. 461]
V_2O_5	5	0.18	291	[16; pp. 470]
CeO_2	8	0.241	121	[16; pp. 582]
ZnO	6	0.215	171	[16; pp. 462]

Table 5. Bond compression bulk modulus, K_{bc}, of the ternary tellurite glasses

A_nO_m in mol%	K_{bc} in GPa	K_e in GPa	K_{bc}/K_e	F in N/m	$n_b \cdot 10^{31}$ in m^{-3}
3 CeO_2	98.4	56	1.76	233.9	10
5 CeO_2	94.4	58.6	1.61	228.5	9.7
7 CeO_2	99.3	65.8	1.51	223.5	16.1
10 CeO_2	104.2	73.5	1.42	215.8	18.4
3 ZnO	82.5	66.5	1.24	239.3	8.06
5 ZnO	82.7	61.7	1.34	237.4	8.19
7 ZnO	83.2	42.9	1.94	235.5	7.14
10 ZnO	83.2	28.2	2.95	232.6	8.8

ring size tending to increase with increasing of (K_{bc}/K_e). Alternatively a high value of (K_{bc}/K_e) could imply the existence of layer or chain network as in the case of ZnO series.

Poisson's ratio will be calculated by using equation (13) [11]

$$\sigma_{th} = 0.28 \, (n^l_c)^{-0.25} \qquad (13)$$

where σ_{th} is the theoretical Poisson's ratio, and (n^l_c) is the number of cross links per glass formula, and is equal to

$$(n^l_c) \equiv (1/\eta)\{\Sigma(n_c \, N_c)\} \qquad (14)$$

where n_c is the number of cross links per cation and is equal to the number of bonds minus two. N_c is the number of cations per glass formula unit and η is the total number of cations per glass formula unit,

$$\eta = \Sigma N_c. \qquad (15)$$

Table 6 collects the values of the calculated Poisson's ratio for both glass series. The calculated Poisson's ratio decreases from 0.222 to 0.219 with the increase of CeO_2

Table 6. Total number of cations per glass formula unit, number of average cross links per glass formula and calculated Poisson's ratio of the ternary tellurite glasses

A_nO_m in mol%	η	n^l_c	σ_{th}
3 CeO_2	1.27	2.53	0.222
5 CeO_2	1.25	2.56	0.221
7 CeO_2	1.23	2.59	0.221
10 CeO_2	1.20	2.66	0.219
3 ZnO	1.27	2.48	0.223
5 ZnO	1.25	2.48	0.223
7 ZnO	1.23	2.48	0.223
10 ZnO	1.20	2.49	0.223

Table 7. Theoretical elastic moduli of tricomponent tellurite glasses

A_nO_m in mol%	G_{th} in GPa	L_{th} in GPa	E_{th} in GPa
3 CeO_2	67.12	187.6	164.04
5 CeO_2	64.69	180.4	158.00
7 CeO_2	68.06	189.8	166.20
10 CeO_2	72.08	200.1	175.70
3 ZnO	56.10	157.1	137.22
5 ZnO	56.15	157.3	137.34
7 ZnO	56.47	158.3	138.13
10 ZnO	56.47	158.2	138.13

concentration in the $CeO_2-V_2O_5-TeO_2$ glasses. This decrease is due to the increase of the mean crosslink density from 2.53 to 2.66 as the CeO_2 content increases. On the other hand, Poisson's ratio is nearly constant for the second series of tellurite glasses while ZnO increases.

After calculating both K_{bc} and σ_{th}, it is very easy to calculate the rest of the elastic moduli as follows:

$$G_{th} = 1.5 \, K_{th} \, \{(1 - 2\sigma_{th})/(1 + \sigma_{th})\}, \qquad (16)$$

$$L_{th} \equiv K_{th} + 1.33 \, G_{th}, \qquad (17)$$

$$E_{th} \equiv 2 \, G_{th} \, (1 + \sigma_{th}). \qquad (18)$$

Table 7 collects the calculated values of shear, longitudinal, Young's moduli for the present tricomponent tellurite glasses. It is clear that all the calculated elastic moduli (G_{th}, L_{th}, E_{th}) show the same behavior as K_{bc}.

5. Conclusions

The ultrasonic velocity measurements of the tricomponent tellurite glass system reveal the following facts:

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a) The variation of sound velocity (both longitudinal and transverse) with composition indicates an increasing and decreasing linear variation with the third component CeO_2 and ZnO, respectively.

b) The results for the elastic moduli (longitudinal, shear, bulk, Young's), and for Debye temperature and Poisson's ratio indicate an opposite behavior for both series. The trend in the values of the elastic moduli and both Debye temperature and Poisson's ratio indicate that there occurs a tightening in the bonding of the network by increasing third component where A_nO_m = CeO_2 or ZnO. Information about the structure of these noncrystalline solids have been deduced after calculating the number of network bonds per unit volume, the values of the average stretching force constant, the average ring diameter and the mean cross link density.

6. List of symbols

E = experimental Young's modulus in GPa
E_{th} = calculated Young's modulus in GPa
F = stretching force constant in N/m
F_b = cation-anion bond bending force constant in N/m
G = experimental shear modulus in GPa
G_{th} = calculated shear modulus in GPa
h = Planck's constant ($6.6 \cdot 10^{-34}$ J $\cdot$ s)
K = experimental bulk modulus in GPa
K_{bc} = bulk modulus according to the bond compression model in GPa
K_{th} = calculated bulk modulus in GPa
k = Boltzmann's constant ($1.38 \cdot 10^{-23}$ JK^{-1})
L = experimental longitudinal modulus in GPa
L_{th} = calculated longitudinal modulus in GPa
l = diameter of the atomic rings in nm
M_g = glass molecular weight
N = number of vibrating atoms per unit volume in cm^{-3}
N_A = Avogadro's number ($6.022 \cdot 10^{23}$ mol^{-1})
N_c = number of cations per glass formula unit
n_b = number of network per unit volume
n_c = number of cross links per cation
n^1_c = number of cross links per glass formula
n_f = number of formula units per unit volume
p = number of atoms in chemical formula
r = cation-anion bond length
T_g = glass transformation temperature in °C
V = molar volume in cm^3
υ = ultrasonic wave velocity in m/s
υ_l = longitudinal ultrasonic wave velocity in m/s
υ_m = mean ultrasonic wave velocity in m/s
υ_s = shear ultrasonic wave velocity in m/s
η = total number of cations per glass formula unit
Θ_D = Debye temperature in K
ϱ_g = glass density in g/cm^3

σ = experimental Poisson's ratio
σ_{th} = calculated Poisson's ratio

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