Thermal expansion and structural properties of some $(\text{PbO})_x(\text{ZnO})_{35-x}(\text{TeO}_2)_{65}$ glasses

Jiri Schwarz¹ · Helena Ticha¹Received: 22 July 2020 / Accepted: 8 March 2021 / Published online: 20 March 2021
© The Author(s) 2021

Abstract

The glasses $(\text{PbO})_x(\text{ZnO})_{35-x}(\text{TeO}_2)_{65}$ with $0 < x < 25$ were prepared by conventional melting method. The substitution of ZnO by PbO leads to a decrease in the glass transition temperature (T_g) from 338 to 280 °C and an increase in the linear coefficient of thermal expansion (α) from 15.8 to 19.2 ppm K⁻¹. A correlation between α and T_g has been confirmed by the Lindemann rule. The two prediction methods of the coefficient of thermal expansion (α) were compared with experimental values: the simple additivity model and the Mackenzie method. From Raman spectra, it is evident that the substitution of ZnO by PbO leads mainly to the conversion of TeO_4 structural units to TeO_3 structural units. This conversion leads to network depolymerization.

Keywords Tellurite glasses · Thermomechanical analysis · Coefficient of thermal expansion · Raman spectroscopy

1 Introduction

Glasses based on TeO_2 are of interest from the materials promising for development in telecommunication applications. Those have a wide glass-forming region, a wide spectral region of optical transmittance, a high refractive index, a relatively low temperature of preparation, and the ability to host rare earth elements [1–4]. For a recent review related to TeO_2 based glasses, see Ref. [5]. In recent years, some attention was given to the preparation and study of the glasses of PbO–ZnO– TeO_2 system modified by rare earth elements, see e.g. [1, 6], and also to the study of optical properties and structural arrangement in various glasses PbO–ZnO– TeO_2 system, see e.g. [7–10]. Despite some reservations to PbO due to its potential risk for an environment in several cases its application in glasses preparation gives still some benefits. For instance: (1) The addition of lead oxide to glass raises its refractive index and lowers its working temperature and viscosity. PbO based glasses have also acceptable corrosion properties

and low processing temperatures. Even if a higher temperature of preparation is necessary, no darkening/coloration is observed while in Bi_2O_3 glasses if melted close or above 1000 °C a darkening is observed due to termoreduction of Bi_2O_3 entities [11].

(2) One advantage of PbO based glasses is also a possibility to omit alkaline oxides which, due to a possible motion of alkaline ions in the electrical field, leads to instability of electrical properties of those glasses [12].

(3) Certain PbO based oxide glasses containing rare earth elements are promising materials in the field of optoelectronic devices, solid-state lasers, and light-emitting diodes, see e.g. [13–15].

From a recycling point of view, lead-containing waste glass can be used to produce anti-radiation materials or it can be decomposed into individual substances/elements that can be reused to produce new materials [16].

In Ref. [10] we examined the role of substitution of ZnO by PbO on the glass transition temperature (T_g), the optical band gap (E_g), and the structural arrangement inferred

✉ Jiri Schwarz, jiri.schwarz@upce.cz | ¹Department of General and Inorganic Chemistry, Faculty of Chemical Technology, University of Pardubice, Studentska 573, 532 10 Pardubice, Czech Republic.

from the Raman spectroscopy. It was found that substitution of ZnO by PbO leads to a decrease in the T_g and E_g values, the density of Pb–O–Te linkages increases at the expense of the density of Te–O–Te linkages and, the formation of $[\text{TeO}_3]^{2-}$ units proceeds at the expense of $[\text{Te}_3\text{O}_8]^{4-}$ units.

Since there are several indications that PbO–ZnO–TeO₂ glasses have various interesting properties, we mentioned above, promising for potential application, this paper is devoted to the study of selected glasses from the system $(\text{PbO})_x(\text{ZnO})_{35-x}(\text{TeO}_2)_{65}$ which complement the glasses studied in Ref. [10]. The main aim of this work is determination of the coefficient of the thermal expansion (α_{TMA}) and the structural arrangement inferred from the Raman spectroscopy results.

2 Materials and methods

The studied materials $(\text{PbO})_x(\text{ZnO})_{35-x}(\text{TeO}_2)_{65}$, where $x=0; 5; 10; 15; 20$ and 25 mol%, were prepared in batches of 20 g from oxides PbO, ZnO, and TeO₂ (purity > 99.9%; SIGMA-ALDRICH) in Pt crucible with a Pt lid. The stoichiometric amounts of oxides were mixed and inserted into a preheated electrical furnace at a temperature (T) 600 °C. The temperature was increased in the following step to melting temperature $T \approx 650\text{--}750$ °C (depending on the chemical composition of the mixture). The obtained melts were homogenized for approximately 30 min. and after was poured onto a polished nickel plate preheated at 200 °C and then was cooled down to ambient temperature. The obtained glasses were annealed for one hour at a temperature close to their glass transition temperature (T_g). The glasses prepared were clear, slightly yellow with a shiny surface and the absence of XRD patterns confirmed the glassy nature of the samples prepared. The density (ρ) of the glasses was determined using the Archimedeian method and distilled water was used as the referent liquid. The molar volume (V_m) was calculated according to the relation: $V_m = \bar{M}/\rho$, where $\bar{M}$ is the average molar weight of the glass. The values of ρ and V_m were determined with a relative error $\pm 0.5\%$. The values of the dilatometric glass-transition temperature (T_g), the dilatometric deformation temperature (T_d), and the coefficient of thermal expansion (α_{TMA}) were estimated employing a thermo-mechanical analysis of the samples. The cubes of glasses $5 \times 5 \times 5$ mm were heated at a heating rate of 5 K min^{-1} under 10 N force loading (TMA CX04 equipment, R.M.I. Pardubice, Czech Republic). The values of T_g were determined with relative error $\pm 0.5\%$, T_d and α_{TMA} values were determined with relative error $\pm 1.5\%$.

Raman spectra were measured at room temperature on the natural shiny surface of the bulk samples with a

Horiba–Jobin Yvon LaBRam HR Spectrometer. The spectra were recorded in back-scattering geometry under excitation with Nd–YAG laser radiation (532 nm) at a power of 10 mW taking 10 scans with an exposition time of 2 s. The spectra were reduced using the Shuker–Gammon relation [17] and their intensities were normalized. Reduced and normalized spectra were decomposed using LabSpec 5 software (Horiba Jobin Yvon).

3 Analysis

3.1 Coefficient of the thermal expansion (α)

In the relevant literature, the methods proposed for the prediction of α values were derived especially for silicate glasses, see e.g. [18–24]. We have used two methods for the studied tellurite glasses:

1. The simple additivity model, see e.g. [24] which is a linear combination (LC) of the α values of oxides forming the glass. The coefficient of the thermal expansion of glass is given by the relation:

$$\alpha_{\text{LC}} = \sum_{i=1}^n \varphi_i \alpha_i, \quad (1)$$

where φ_i is the volume fraction and α_i is the value of the thermal expansion of the i -th oxide of a glass. The values of α_i for relevant oxides are tabulated in Table 1.

2. Mackenzie method (M) was developed by Mackenzie, Makishima and Yaman, see e.g. [25]. This method relates the values of α to several properties like the packing density of mass particles present and their bond strengths. In the method of Mackenzie, Makishima, and Yaman, the expression for the coefficient of the thermal expansion of a glass (α_M) is given by the relation [25, 26]:

$$\alpha_M = \frac{\rho [11.2(V_t^2 - 0.4) \sum (r_M/r_O) f_{B,i}] [\sum c_{p,i} f_i]}{(3V_t^2 \sum k e_{v,i} \sum M_{r,i} f_i) \cdot 10^2}, \quad (2)$$

where ρ is the experimental density; V_t is packing density; r_M is ionic radius of metal; r_O is ionic radius of oxygen (1.35×10^{-10} m); $f_{B,i}$ is fraction of the number of bonds in i -th oxide; $c_{p,i}$ is specific heat; f_i is molar fraction of oxide; k is constant (23.9); $e_{v,i}$ is dissociation energy related to 1 mol; M_r is relative molecular mass.

Packing density V_t is function of V_m^c :

$$V_t = \frac{1}{V_m^c} \sum f_i V_i, \quad (3)$$

Table 1 The values of properties of ZnO, PbO and TeO₂ used for calculation of expansion coefficient of glasses studied

Property	PbO	Ref	ZnO	Ref	TeO ₂	Ref
M (g·mol ⁻¹)	223.19	*	81.39	*	159.6	*
ρ (g·cm ⁻³)	9.53	*	5.61	*	5.67	*
V_m (cm ³ ·mol ⁻¹)	23.4	*	14.5	*	28.1	*
r_M (m)	1.18E-10	[26]	7.45E-11	[26]	8.4E-11	[27]
r_M/r_O	0.874	[26]	0.552	[26]	0.622	[26]
e_v (10 ⁻³ J m ⁻³)	17.6	[26]	40.46	[26]	54	[26]
V_i (cm ³ mol ⁻¹)	10.4	[26]	7.3	[26]	13.9	[26]
c_p (J·mol ⁻¹ K ⁻¹)	45.8	[28]	40.3	[28]	64.0	[29]
V_t	0.442		0.500		0.494	
y_i	6	[26]	6	[26]	6	[26]
α_i (ppm K ⁻¹)	16.0	[30]	5.0	[30]	18.5	[30]

*Safety data sheet of compound

and V_m^c is calculated:

$$V_m^c = \sum f_i V_{mi} \quad (4)$$

where V_i is the factor of the spatial packing of the relevant oxide and V_{mi} is the molar volume of the i -th oxide of the glass. The fraction of bonds in i -th oxide $f_{B,i}$ is done:

$$f_{B,i} = f_i(m_M) \frac{y_i}{B_t} \quad (5)$$

where m_M is the number of cations in oxide (M_mO_n); y_i is coordination number of element M (in i -th oxide), B_t is the total number of metal–oxygen bonds in a concrete glass

$$B_t = \sum (f_i(m_M) y_i).$$

For a calculation of the linear coefficient of the thermal expansion by LC and M-methods, we used the literature parameters [26–30] summarized in Table 1.

4 Results and discussion

4.1 Density and molar volume

Table 2 shows the experimental values of density (ρ) and molar volume (V_m) for the investigated (PbO)_x(ZnO)_{35-x}(TeO₂)₆₅ glasses. With increasing content of PbO, the density increases from 5.64 g cm⁻³ up to 6.58 g cm⁻³ and the molar volume increases from 23.44 cm³ mol⁻¹ up to 25.48 cm³ mol⁻¹. It is a rather expected result, because in the glasses investigated the lighter ZnO with smaller ionic radius ($M_r(\text{ZnO}) = 81.39$, $r(\text{Zn}^{2+}) = 0.745 \text{ \AA}$) is replaced by heavier PbO ($M_r(\text{PbO}) = 223.19$, $r(\text{Pb}^{2+}) = 1.18 \text{ \AA}$), see Table 1. A quite small increase in V_m may be associated with the fact that at a lower PbO content, Pb could mainly be incorporated into the empty space of a glass network and hence it behaves rather as a network modifier. The Zn²⁺ ions usually connect the chain ends, hence the ZnO substitution with PbO, up to about $x = 25$ mol%, where PbO acts mainly as a network modifier [31], leads to a further network depolymerization and to a decrease in the T_g and T_d values as

Table 2 Experimental and calculated values of density and molar volume of studied glasses

Chem.frac-tion PbO/ ZnO	ρ (g·cm ⁻³)	V_m (cm ³ ·mol ⁻¹)	ρ^c (g·cm ⁻³)	V_m^c (cm ³ ·mol ⁻¹)	$RD(\rho)$ (%)	$RD(V_m)$ (%)
0/35	5.64	23.44	5.66	23.36	0.35	-0.34
5/30	5.85	23.79	5.84	23.85	-0.17	0.25
10/25	6.04	24.25	6.02	24.31	-0.33	0.25
15/20	6.22	24.66	6.19	24.78	-0.48	0.49
20/15	6.41	25.07	6.36	25.25	-0.78	0.72
25/10	6.58	25.48	6.52	25.72	-0.91	0.94

$RD = (\text{calculated} - \text{experimental}) / \text{experimental}$

RD relative deviation between theoretical and experimental values

evident from Table 3. The calculated values of density ($\rho^c = \bar{M}/V_m^c$) and molar volume [V_m^c ; Eq. (4)] are shown in Table 2. The values of $RD(V_m)$ and $RD(\rho)$, are smaller than 1%, although they rise with an increase in PbO content, see Table 2.

4.2 The glass transition temperature and coefficient of thermal expansion

The values of the glass transition temperature (T_g), the deformation temperature (T_d), and the linear coefficient of thermal expansion (α_{TMA} ; for the temperature range of 100–200 °C) are collected in Table 3. As evident with the increasing content of PbO replacing ZnO, the values of T_g and T_d decrease and the values of α_{TMA} simultaneously increase. The calculated values of α_M and α_{LC} differ from the experimental values α_{TMA} in the range of –14.58 to +11.39%, while the average relative deviation of the Mackenzie method is +5% and the method of linear combination is –11%.

It is obvious that for investigated glasses the prediction methods used are the limiting ones, as documented in Fig. 1. We suppose that at a low concentration of PbO up to 5–10 mol%, this one is modifier only and in the concentration region 5–20 mol% PbO acts in both its roles, i.e. modifying and network forming [10].

A correlation between the linear coefficient of thermal expansion and the glass-transition temperature was explained e.g. in Ref. [32] with the help of the Lindemann rule. There are also some indications that both the linear coefficient of the thermal expansion and the glass-transition temperature can be correlated with the cohesive energy of a network, see e.g. Refs. [33, 34], respectively. For simplicity, as a measure of the cohesive energy of our glasses network, we use the average single bond strength (B) of the glass, see e.g. Ref. [35]. Here $B = \sum x_i B_i$ where x_i is the molar fraction of the i -th oxide participating in the glass network formation and B_i is

Fig. 1 Compositional dependence of the experimental (α_{TMA}) and calculated (α_{LC} , α_M) values of the thermal expansion coefficient

the average single bond energy of the i -th oxide. Using the values $B_{Pb-O} = 101 \text{ kJ mol}^{-1}$, $B_{Zn-O} = 151 \text{ kJ mol}^{-1}$ and $B_{TeO_2} = 285 \text{ kJ mol}^{-1}$, see Ref. [35], we calculated $B(x)$ the values of our glasses and the dependence of α_{TMA} and T_g versus B is shown in Fig. 2. It is evident that there exists a good correspondence between both the linear coefficient of the thermal expansion, the glass-transition temperature, and the average single bond strength of the glasses $(PbO)_x(ZnO)_{35-x}(TeO_2)_{65}$.

4.3 Raman spectra

The Raman spectra of the glasses studied are shown in Figs. 3 and 4 is shown and the typical decomposed spectrum of $(PbO)_{15}(ZnO)_{20}(TeO_2)_{65}$ glass. The compositional dependence of the relative band intensity (rbi) for the studied glasses is shown in Fig. 5. The bands assignment is summarized in Table 4.

In Fig. 5 is shown compositional dependence of the relative band intensity (rbi) for studied glasses.

Table 3 The values of glass transition and deformation temperature and the experimental and calculated values of linear coefficient of thermal expansion for investigated glasses

Chem.frac- tion PbO/ ZnO	T_g (°C)	T_d (°C)	α_{TMA} (ppm.K ⁻¹)	α_{LC} (ppm.K ⁻¹)	α_M (ppm.K ⁻¹)	$RD(\alpha_{LC})$ (%)	$RD(\alpha_M)$ (%)
0/35	338	362	15.8	14.7	17.6	–6.96	11.39
5/30	326	352	16.3	15.1	17.9	–7.36	9.82
10/25	314	340	17.2	15.4	18.2	–10.47	5.81
15/20	301	318	18.0	15.8	18.5	–12.22	2.78
20/15	292	318	18.8	16.1	18.9	–14.36	0.53
25/10	280	287	19.2	16.4	19.2	–14.58	0.00

$RD = (\text{calculated} - \text{experimental}) / \text{experimental}$

RD relative deviation between theoretical and experimental values

Fig. 2 Dependence of the glass transition temperature (T_g ; relative error $\pm 0.5\%$) and linear coefficient of the thermal expansion (α_{TMA} ; relative error $\pm 1.5\%$) on the average single bond strength. For better clarity, the experimental values of α_{TMA} are multiplied by 10

Fig. 4 Deconvoluted Raman spectra of $(PbO)_{15}(ZnO)_{20}(TeO_2)_{65}$ glass

Fig. 3 Reduced and intensity normalized Raman spectra of $(PbO)_x(ZnO)_{35-x}(TeO_2)_{65}$ glasses

It is evident that rbi at 786 cm^{-1} decreases while rbi at 738 cm^{-1} increases. The changes in rbi are inverse and seem to be correlated since $rbi_{786} + rbi_{738}$ varies in a narrow region from 57.6 ($x=0$) to 60.9 ($x=25$). Hence, the

Fig. 5 Relative band intensities (rbi) versus molar fraction of PbO. The relative band intensity is the ratio of integrated intensity of each individual band, obtained by Raman spectra deconvolution, divided by the sum of integrated intensity of individual bands

substitution of ZnO by PbO similarly as in the other TeO_2 glasses [9] leads to a conversion of TeO_4 and or TeO_{3+1} units (trigonal bipyramids—tbp) to TeO_3 units (trigonal pyramids—tp). Contrary to changes in rbi_{786} and rbi_{738} , the changes in the other Raman band intensities are quite subtle. The rbi at 670 cm^{-1} increases while the rbi at 618 cm^{-1} ,

Table 4 Assignment of fitted bands in Raman spectra of $(\text{PbO})_x(\text{ZnO})_{35-x}(\text{TeO}_2)_{65}$ glasses [31, 36–40]

Peak	ν/cm^{-1}	Assignments
A	786	Te–O [−] stretching in TeO_{3+1} and TeO_4 units
B	738	Te–O [−] stretching in TeO_3 and namely in TeO_{3+1} units
C	670	Te–O–Te asymmetric stretching between TeO_4 units with connection via oxygen in axial position (Te–O _{ax})
D	618	Te–O–Te asymmetric stretching between TeO_4 units with connection via oxygen in equatorial position (Te–O _{eq})
E	468	Te–O–Te symmetric bending vibrations in vertex sharing polyhedra and Te–O–Te chains
F	409	The total symmetric combinations of Te–O–Te motion, Te–O–Te symmetric bending vibrations in vertex sharing polyhedral and asymmetric Te–O–Te bending due to nonequivalent Te–O bonds
G	335	Pyramids of TeO_3 with NBO, bending motion of oxygen in Pb–O–Te bridge
H	112	Vibration of heavy metal atoms (Pb^{2+})

468 cm^{-1} and 409 cm^{-1} , respectively, slightly decreases with an increase in PbO content. The increase in rbi_{670} could mean that despite the $\text{tpb} \rightarrow \text{tp}$ conversion, the density of Te–O_{ax} connection in all probability increases at the expense of Te–O_{eq} connections since the changes in these rbi are inverse and it is valid: $rbi_{670} + rbi_{618} = 27.3 \pm 0.7$. One cannot exclude, however, that the changes in rbi_{670} and rbi_{618} reflect an ordering around the Te–O_{ax} connection compensated by a disordering around Te–O_{eq} connections. A decrease in rbi_{468} and rbi_{409} means a decrease in the Te–O–Te connection, resulting in some network depolymerization. Both $\text{tpb} \rightarrow \text{tp}$ conversion and a decrease in Te–O–Te connections leads in fact to a decrease in network rigidity which is manifested by a decrease in the glass transition temperature and by an increase in the thermal expansion of the glasses considered, see Table 3. The quite small increase in rbi_{335} and rbi_{112} with an increase in PbO content is of interest. We assume that the Raman band at around 335 cm^{-1} and its rbi increase mainly reflects the formation of some Te–O–Pb linkages. The Raman band at around 112 cm^{-1} has in all probability a dual origin. Usually, in Pb containing oxide glasses the Raman response at around 100 cm^{-1} is attributed to the vibration of Pb atoms respectively to the vibration of Pb^{2+} ion, see e.g. [39, 40]. This band was observed, however, for our glass where $x=0$ ($(\text{ZnO})_{35}(\text{TeO}_2)_{65}$). Jaba et al. [41] found similar rbi in $(\text{ZnO})_{30}(\text{TeO}_2)_{70}$ glasses and it is tentatively attributed to a symmetric stretching vibration of Te–O. It should be noted that Raman activity at around 112 cm^{-1} could in all probability also be attributed to the librational modes of TeO_4 units [42]. The exact assignment of this Raman band in the studied glasses needs further study. An increase in rbi_{112} with an increase in PbO content and simultaneous decrease in ZnO content indicates, however, that this Raman band for $x > 0$ can also be attributed to the vibration activity of Pb atoms. The results obtained are in harmony with our recent results [10] except for the compositional trend in rbi_{600} . In both recently studied glasses $(\text{PbO})_x(\text{ZnO})_{30-x}(\text{TeO}_2)_{70}$ and $(\text{PbO})_x(\text{ZnO})_{40-x}(\text{TeO}_2)_{60}$ the

rbi_{600} slightly increases with an increase in PbO content. We do not currently have a reasonable explanation for this discrepancy.

5 Conclusions

The thermal expansion coefficient (α) and structure of $(\text{PbO})_x(\text{ZnO})_{35-x}(\text{TeO}_2)_{65}$ ($0 \leq x \leq 25$) glass system were studied. The possibility prediction of α was studied using two methods: the simple additivity model and the Mackenzie method. The increasing content of PbO leads to an increase in α and a decrease in the glass-transition temperature. A correlation between these through the cohesive energy of a network was verified. The Raman spectra show on depolymerization of the TeO_2 glass network with increasing concentration of PbO, which primarily acts mainly as a glass modifier in the concentrations used.

Acknowledgements The authors acknowledge the financial support from the Faculty of Chemical Technology of University of Pardubice, Czech Republic and The Czech Science Foundation project No. 19-11814S.

Funding This study was funded by Faculty of Chemical Technology of University of Pardubice and by Czech Republic and The Czech Science Foundation project No. 19-11814S.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended

use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Damak K, Yousef ES, Al-Shihri AS, Seo HJ, Ruessel C, Maalej R (2014) Quantifying Raman and emission gain coefficients of Ho^{3+} doped TeO_2 center dot ZnO center dot PbO center dot PbF_2 center dot Na_2O (TZPPN) tellurite glass. *Solid State Sci* 28:74–80. <https://doi.org/10.1016/j.solidstatesciences.2013.12.012>
- Damak K, Yousef ES, Ruessel C, Maalej R (2014) White light generation from Dy^{3+} doped tellurite glass. *J Quant Spectrosc Radiat Transf* 134:55–63. <https://doi.org/10.1016/j.jqsrt.2013.10.013>
- El-Damrawi G (2000) Transport behavior of PbO – PbF_2 – TeO_2 glasses. *Physica Status Solidi A Appl Res* 177:385–392. [https://doi.org/10.1002/\(sici\)1521-396x\(200002\)177:2%3c385::aid-ppssa385%3e3.3.co;2-2](https://doi.org/10.1002/(sici)1521-396x(200002)177:2%3c385::aid-ppssa385%3e3.3.co;2-2)
- Prezas PR, Graca MPF, Soares MJ, Kumar JS (2015) Optical and structural properties of $(70-x-y)\text{TeO}_2$ – 20WO_3 – $10\text{Y}_2\text{O}_3$ – $x\text{Er}_2\text{O}_3$ – $y\text{Yb}_2\text{O}_3$ glasses. *Appl Surf Sci* 336:28–33. <https://doi.org/10.1016/j.apsusc.2014.08.166>
- El-Mallawany R (2018) Tellurite glass smart materials. Springer International Publishing AG, Cham
- Ramamoorthy RK, Bhatnagar AK, Rocca F, Dalba G, Mattarelli M, Montagna M (2014) Er^{3+} local structure and its optical properties in ZnO – PbO tellurite glasses. *J Non-Cryst Solids* 383:153–156. <https://doi.org/10.1016/j.jnoncrysol.2013.04.066>
- Ramamoorthy RK, Bhatnagar AK (2015) Effect of ZnO and PbO / ZnO on structural and thermal properties of tellurite glasses. *J Alloys Compd* 623:49–54. <https://doi.org/10.1016/j.jallcom.2014.10.061>
- Ticha H, Schwarz J, Tichy L (2017) On the structural arrangement and optical band gap $(\text{PbO})_x(\text{ZnO})_{10}(\text{TeO}_2)_{90-x}$ glasses. *J Non-Cryst Solids* 459:63–67. <https://doi.org/10.1016/j.jnoncrysol.2017.01.012>
- Alazoumi SH, Aziz AA, El-Mallawany R, Aliyu US, Kamari HM, Zaid MHM, Matori KA, Ushah A (2018) Optical properties of zinc lead tellurite glasses. *Results Phys* 9:1371–1376. <https://doi.org/10.1016/j.rinp.2018.04.041>
- Ticha H, Schwarz J, Tichy L (2019) Raman spectra and optical band gap in some PbO – ZnO – TeO_2 glasses. *Mater Chem Phys* 237:121834. <https://doi.org/10.1016/j.matchemphys.2019.121834>
- Sanz O, Haro-Poniatowski E, Gonzalo J, Fernandez Navarro JM (2006) Influence of the melting conditions of heavy metal oxide glasses containing bismuth oxide on their optical absorption. *J Non-Cryst Solids* 352:761–768. <https://doi.org/10.1016/j.jnoncrysol.2006.02.002>
- Sharif A (2019) Harsh environment electronics: interconnect materials and performance assessment. Wiley-VCH, Weinheim
- Pisarska J, Kos A, Sołtys M, Górny A, Pietrasik E, Pisarski WA (2018) Spectroscopy and energy transfer in $\text{Tb}^{3+}/\text{Sm}^{3+}$ co-doped lead borate glasses. *J Lumin* 195:87–95. <https://doi.org/10.1016/j.jlumin.2017.11.020>
- Zur L, Kos A, Górny A, Sołtys M, Pietrasik E, Pisarska J, Goryczka T, Pisarski WA (2018) Influence of acceptor concentration on crystallization behavior and luminescence properties of lead borate glasses co-doped with Dy^{3+} and Tb^{3+} ions. *J Alloys Compd* 749:561–566. <https://doi.org/10.1016/j.jallcom.2018.03.282>
- Rani PR, Venkateswarlu M, Mahamuda S, Swapna K, Deopa N, Rao AS, Prakash GV (2019) Structural, absorption and photoluminescence studies of Sm^{3+} ions doped barium lead alumino fluoro borate glasses for optoelectronic device applications. *Mater Res Bull* 110:159–168. <https://doi.org/10.1016/j.materresbull.2018.10.033>
- Xing M, Fu Z, Wang Y, Wang J, Zhang Z (2017) Lead recovery and high silica glass powder synthesis from waste CRTfunnel glasses through carbon thermal reduction enhanced glassphase separation process. *J Hazard Mater* 322:479–487. <https://doi.org/10.1016/j.jhazmat.2016.10.012>
- Shuker R, Gammon RW (1970) Raman-scattering selection-rule breaking and the density of states in amorphous materials. *Phys Rev Lett* 25:222–235. <https://doi.org/10.1103/PhysRevLett.25.222>
- Priven AI (2003) Calculation of the structural linear expansion coefficient from the chemical composition of glasses in the $\text{R}_2\text{O}(\text{RO})$ – Al_2O_3 – B_2O_3 ($\text{R} = \text{Li}, \text{Na}, \text{Ca}, \text{and Ba}$) system. *Glass Phys Chem* 29:60–68. <https://doi.org/10.1023/A:1022361826966>
- Priven AI, Mazurin OV (2003) Comparison of methods used for the calculation of density, refractive index and thermal expansion of oxide glasses. *Glass Technol* 44:156–166
- Gan FS (1974) New computation system on inorganic physical-properties of oxidized glass. *Sci Sin* 17:533–551
- Appen AA (1970) The chemistry of glass. *Izd. Chimia, Leningrad* (In Russia)
- Novopashin AA, Seregin NN (1979) Calculation of the thermal expansion coefficient of silicate glasses according to their structure–energy characteristics. *Soviet J Glass Phys Chem* 5:389–395
- Gilard P, Dubrul L (1937) Calculation of physical properties of glass: III. Index of refraction. *J Soc Glass Technol* 21:476–488
- Winkelmann A, Schott O (1894) Ueber thermische widerstand-coefficienten verschiedener gläser in ihrer abhängigkeit von der chemischen zusammensetzung. *Annalen der Phyc* 51:730–746
- Makishima A, Mackenzie JD (1976) Calculation of thermal expansion coefficient of glasses. *J Non-Cryst Solids* 22:305–313. [https://doi.org/10.1016/0022-3093\(76\)90061-2](https://doi.org/10.1016/0022-3093(76)90061-2)
- Volf MB (1988) Mathematical approach to glass. Elsevier, Amsterdam
- El-Mallawany RAH (2002) Tellurite glasses handbook: physical properties and data. CRC PRESS, London
- Cox JD, Wagman DD, Medvedev VA (1984) Codata key values for thermodynamics. Hemisphere Publishing Corp, New York
- Glushko VP (1972) Thermal constants of substances: a handbook. VINITI, Moscow
- Gan FS (1963) New system of calculation of some physical properties of silicate glasses. *Sci Sin* 12:1365–1391
- Silva MAP, Messaddeq Y, Riberio SJL, Poulain M, Villain F, Briois V (2001) Structural studies on TeO_2 – PbO glasses. *J Phys Chem Solids* 62:1055–1060. [https://doi.org/10.1016/S0022-3697\(00\)00278-X](https://doi.org/10.1016/S0022-3697(00)00278-X)
- Kato H, Chen HS, Inoue A (2008) Relation between thermal expansion coefficient and glass transition temperature in metallic glasses. *Scr Mater* 58:1106–1109. <https://doi.org/10.1016/j.scriptamat.2008.02.006>
- Tsuru Y, Shinzato Y, Saito Y, Shimazu M, Shiono M, Morinaga M (2010) Estimation of linear expansion coefficient from cohesive energy obtained by ab-initio calculation of metals and ceramics. *J Ceram Soc Jpn* 118:241–245. <https://doi.org/10.2109/jcersj2.118.241>
- Tichy L, Ticha H (1995) Covalent bond approach to the glass-transition temperature of chalcogenide glasses. *J Non-Cryst Solids* 189:141–146. [https://doi.org/10.1016/0022-3093\(95\)00202-2](https://doi.org/10.1016/0022-3093(95)00202-2)
- Dimitrov V, Komatsu T (2010) An Interpretation of optical properties of oxides and oxide glasses in terms of the average

- electronic ion polarizability and average single bond strength. *J Univ Chem Technol Metall* 45:219–250
36. Baki SO, Tan LS, Kan CS, Kamari HM, Noor ASM, Mahdi MA (2013) Structural and optical properties of Er^{3+} – Yb^{3+} codoped multi-composition TeO_2 – ZnO – PbO – TiO_2 – Na_2O glass. *J Non-Cryst Solids* 362:156–161. <https://doi.org/10.1016/j.jnoncrysol.2012.11.042>
37. Sekiya T, Mochida N, Ohtsuka A (1994) Raman spectra of Mo-TeO_2 (M=Mg, Sr, Ba and Zn) Glasses. *J Non-Cryst Solids* 168:106–114. [https://doi.org/10.1016/0022-3093\(94\)90125-2](https://doi.org/10.1016/0022-3093(94)90125-2)
38. McCoy JS, Andrew BJ, Lipton S, Windisch CHF Jr, Watson NM, Olszta MJ, Rodriguez CP (2013) Structure and chemistry in halide lead–tellurite glasses. *J Phys Chem C* 117:3456–3466. <https://doi.org/10.1021/jp310820t>
39. Miller E, Nassau K, Lyons KB, Lines ME (1988) The intensity of Raman-scattering in glasses containing heavy-metal oxides. *J Non-Cryst Solids* 99:289–307. [https://doi.org/10.1016/0022-3093\(88\)90438-3](https://doi.org/10.1016/0022-3093(88)90438-3)
40. Duverger C, Bouazaoui M, Turrell S (1997) Raman spectroscopic investigations of the effect of the doping metal on the structure of binary tellurium-oxide glasses. *J Non-Cryst Solids* 220:169–177. [https://doi.org/10.1016/s0022-3093\(97\)00317-7](https://doi.org/10.1016/s0022-3093(97)00317-7)
41. Jaba N, Mermet A, Duval E, Champagnon B (2005) Raman spectroscopy studies of Er^{3+} -doped zinc tellurite glasses. *J Non-Cryst Solids* 351:833–837. <https://doi.org/10.1016/j.jnoncrysol.2005.02.003>
42. Cerriotti M, Pietrucci F, Bernasconi M (2006) Ab initio study of the vibrational properties of crystalline TeO_2 : α , β , and γ phases. *Phys Rev B* 73:104304. <https://doi.org/10.1103/PhysRevB.73.104304>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.