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Study of thermal properties of glass system 77% B_2O_3–23% PbO doped with ZnO in the temperature range 300 to 700 K

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The thermal properties: specific heat capacity (C_p), thermal conductivity (λ), and thermal diffusivity (a) of the glass system 77% B_2O_3–23% PbO doped with ZnO, were measured in the temperature range 300 to 700 K. It was found that electronic conduction has no significant contribution to the thermal conductivity. The main mechanism of heat transfer is therefore due to both phonons and photons. A discussion of the results is made in view of various theoretical aspects.

1. Introduction

Due to the many technical applications of glass, in recent years a great deal of work has been devoted to measure its thermal properties. On the other hand, these properties have received much less attention especially at temperatures higher than 300 K. In studying the thermal conductivity in such material, different mechanisms of heat transfer may exist according to whether the thermal conduction is electronic, by phonons or photons. There may be one or more mechanism which contributes to the total thermal conductivity.

The aim of this work is to measure the thermal conductivity (λ), thermal diffusivity (a) and specific heat capacity (C_p) of the glass system 77% B_2O_3–23% PbO doped with ZnO (0, 1, 2, 3, 4 wt %) in the temperature range 300 to 700 K. Also to investigate the results in view of the theoretical aspects of heat transfer.

2. Experimental details

The glass system B_2O_3–PbO was doped with ZnO at different weight ratios of 1, 2, 3 and 4 wt %. Samples were prepared from high purity reagent grade chemicals. B_2O_3, PbO and ZnO powders were well mixed together and thoroughly shaken, then they were melted in a silica crucible in a muffle electric furnace at 850° C. Then melt was left for about 1 h at 850° C and periodically shaken, then rapidly quenched in air on a steel plate. The glass sample produced had composition of 77% B_2O_3–23% PbO. This sample was crushed in a mortar and then 1, 2, 3 and 4 wt % quantities of ZnO were added. This was thoroughly mixed and melted in a silica crucible at 950° C. The melt was left for 2 h at 950° C, periodically shaken and then rapidly crushed on a steel plate at 200° C. It was then left for 24 h in the 200° C furnace to release mechanical stress from the glass samples.

The glass system obtained was cut into circular discs of diameter 0.02 m and thickness 0.003 m. The optimum diameter to thickness ratio was achieved, so as to make negligible the value of heat losses by radiation from the sample sides [1].

For the simultaneous determination of thermal properties (C_p, a, and λ), a plane temperature wave method was used [2, 3]. The experimental errors in these measurements did not exceed 3% for specific heat capacity and thermal diffusivity, and were from 3 to 6% for thermal conductivity.

3. Results and discussion

3.1. Specific heat capacity C_p

Fig. 1 shows the effect of temperature on specific heat capacity (C_p) of the glass system 77% B_2O_3–23% PbO doped with different concentrations of ZnO. It was found that C_p increases with increasing amounts of ZnO in the glass system. Also it is clear from Fig. 2 that the value of C_p is higher for the glass samples with no zinc oxide. These data indicate the formation of BO_3 and BO_4 groups and non-bridging oxygen in the form of tetraborate and diborate groups [4]. This means that the addition of zinc oxide increases the formation of the tetrahedral BO_4 group. The increase of C_p with temperature may be explained in terms of anharmonicity of lattice vibration.

3.2. Thermal conductivity

Fig. 3 shows the variation of thermal conductivity with temperature. It can be seen that the value of thermal conductivity increases as the zinc oxide concentration increases. Also it was observed that the thermal conductivity value (λ) for the glass sample having 0 wt % ZnO was very low compared with the other samples. Consequently, lead borate glasses with no ZnO are typical thermal insulators.

The d.c. electrical conductivity, σ, for the most

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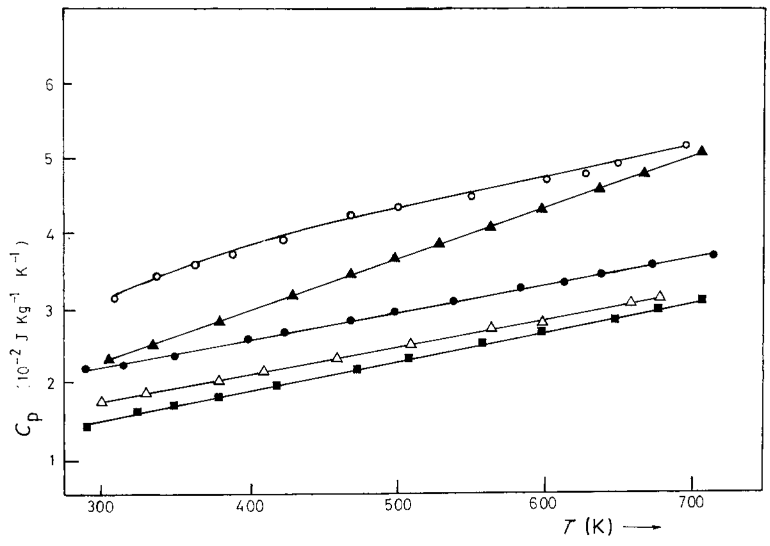

Figure 1 The variation of specific heat capacity with temperature for the glass system 77% B_2O_3–23% PbO doped with ZnO at 0 (■), 1 (△), 2 (●), 3 (▲) and 4 (○) wt %.

conductive system, 77% B_2O_3–23% PbO doped with 4 wt % ZnO, was measured. It was found to be of the order of $10^{-4}\,\mathrm{ohm^{-1}\,m^{-1}}$ at 400 K and of the order of $10^{-12}\,\mathrm{ohm^{-1}\,m^{-1}}$ at 490 K. The electronic part of thermal conductivity was calculated using the Wiedmann–Franz law [5],

$$\lambda_e = L_0 \sigma T$$

where λ_e is the electronic part of thermal conductivity, L_0 is the Lorenz number and T is the absolute temperature.

The calculated value was found to be of the order of $10^{-22}\,\mathrm{Wm^{-1}\,K^{-1}}$, which is very small compared with the total thermal conductivity. This means that the electronic contribution to thermal conductivity for the lead borate samples doped with ZnO (at 0, 1, 2, 3 and 4 wt %) in the measured temperature range is negligible.

There are two other mechanisms affecting the behaviour of thermal conductivity in this system of glasses. The first mechanism is the phonon contribution which decreases as the $1/T$ law [6]. The second mechanism is the radiative contribution which is called the photon thermal conductivity; this is considerable for the non-opaque glass sample as it depends upon the refractive index and the absorption coefficient [7]. The radiative part, λ_{phot}, is related to the optical properties of the sample by the formula

$$\lambda_{\mathrm{phot}} = \frac{16}{3} \frac{\sigma_0 n^2 T^3}{\alpha}$$

where σ_0 is the Stefan–Boltzman constant, n is the refractive index and α is the absorption coefficient. From this relation, $\lambda_{\mathrm{photon}}$ increases as T^3.

From Fig. 3 it was observed that the total thermal conductivity increases with temperature. From our point of view this increment is due to the photon part of thermal conductivity. Due to the absence of optical properties of this glass system, it is difficult to calculate λ_{phot} separately. However, we can conclude that the main mechanism of heat transfer in this glass system is attributed to both phonons and photons. So

$$\lambda_{\mathrm{total}} = \lambda_{\mathrm{phonon}} + \lambda_{\mathrm{photon}}$$

3.3. Thermal diffusivity, *a*

Fig. 4 shows the variation of thermal diffusivity with temperature for this glass system. Thermal diffusivity is related to C_p and λ by the relation $a = \lambda/\varrho C_p$, where ϱ is the density of the investigated samples. It is seen that thermal diffusivity (a) decreases as the temperature increases.

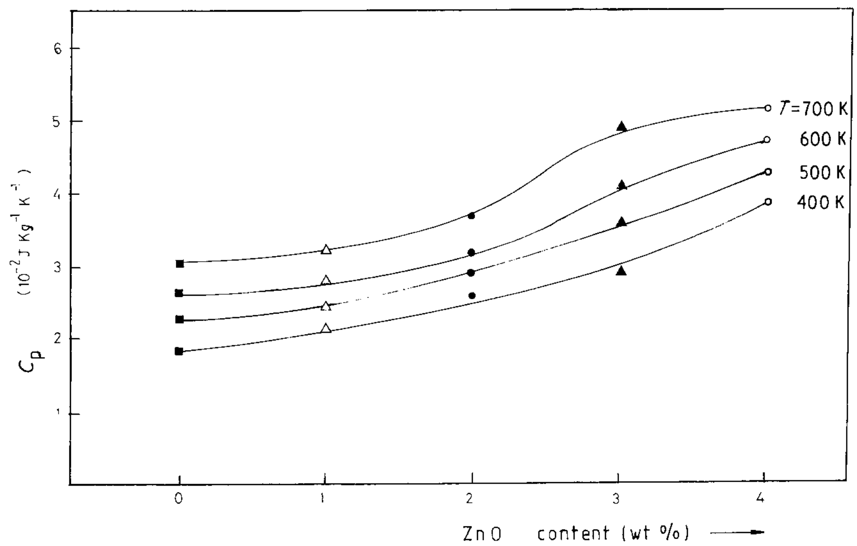

Figure 2 The variation of specific heat capacity with the percentage of ZnO. 0 (■), 1 (△), 2 (●), 3 (▲) and 4 (○) wt %.

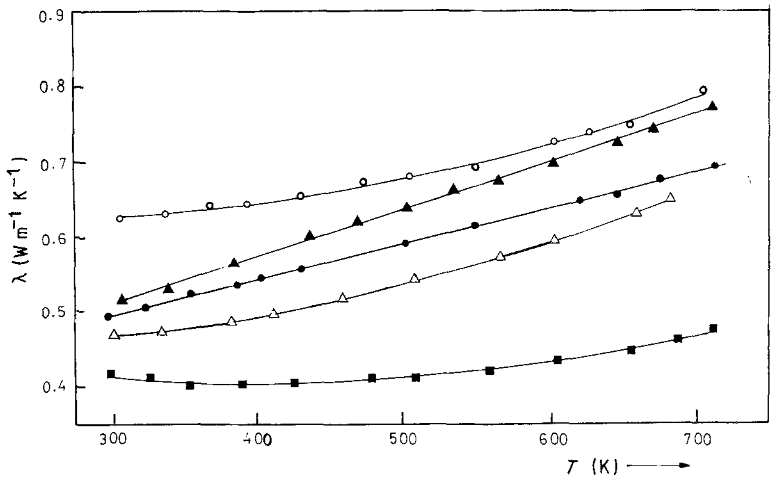

Figure 3 The variation of thermal conductivity for the system 77% B_2O_3–23% PbO doped with ZnO. 0 (■), 1 (△), 2 (●), 3 (▲) and 4 (○) wt %.

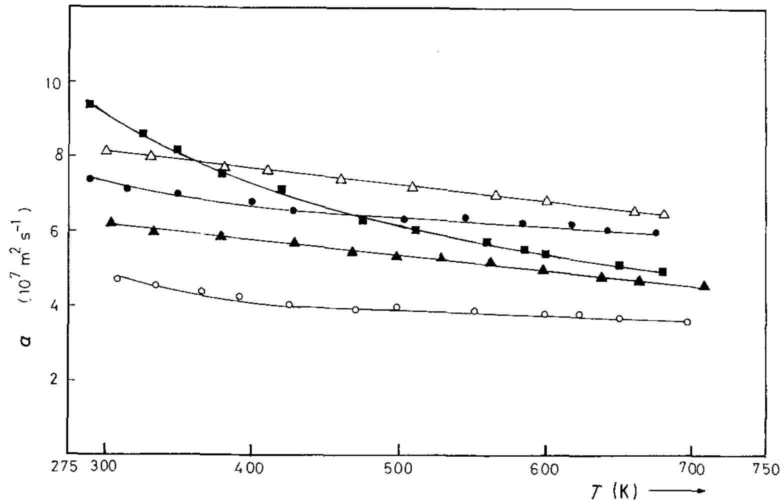

Figure 4 The variation of thermal diffusivity of glass system 77% B_2O_3–23% PbO doped with ZnO. 0 (■), 1 (△), 2 (●), 3 (▲) and 4 (○) wt %.

4. Conclusion

It was found that in such materials as the 77% B_2O_3–23% PbO system, the electronic part of thermal conductivity does not contribute to the total thermal conductivity in the temperature range of 300 to 700 K. The photon part of thermal conductivity has a considerable value which cannot be ignored, although the main contribution is due to phonons. Results of measuring the specific heat capacity and thermal diffusivity coefficients showed that the investigated materials are typical insulators, and there are no transitions of any kind in this range of temperatures.

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