Preparing the transparent Gadolinium Silicoborate glass for radiation shielding material

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Abstract. Research on radiation shielding material is ongoing to overcome the problem of radiation effect. The gamma and x-ray have a high effect of radiation, and they are used in hospital and industry. It is necessary to pay attention for the reason of safety, especially for people who work in radiation area. The glass as shielding material has an advantage because of its transparent. Silicoborate glasses have a mechanical strength, that can be used as radiation shielding material (x-ray and gamma-ray), which are formed from a heavy-oxide materials. For preparation the glass in this study, we used the melt quenching method at 1200 °C with the base materials are SiO₂, B₂O₃, Gd₂O₃ and Alkali Oxide (Na₂O, K₂O, Li₂O, Al₂O₃). The samples of glass are characterized in terms of transparency, density, molar volume, mass attenuation coefficients and effective atomic number. The glass systems can be expressed by (45-x)B₂O₃:10SiO₂:40Li₂O:5Al₂O₃:xGd₂O₃ where x = 0, 5, 10, 15, which were high transparency in the visible region. The transmission is almost 90 % for x = 10. The mass density, the molar volume, the mass attenuation coefficient, and the effective atomic number are increase with increasing the amount of Gd₂O₃ in the silicoborate glasses.

1. Introduction

Effective atomic number (Z_{eff}) is the important parameter for determining physical properties as a result of interaction between radiation with matter for various alloys [1,2] GaAs and InP crystal [3]. The cross section as a result of interaction depends on the element of composite materials but not described the summation of element in composite for all energy range. The Z_{eff} can be calculated from mass attenuation coefficient of materials and useful parameter for radiation shielding properties [4]. Radiation (x-ray/gamma-ray) shielding is an ongoing research to overcome the problem of radiation effect, which is up to now has been extensively investigated. The interaction of energetic radiation x-ray/gamma-ray and neutron with matter is essential in radiation technologies, medical, nuclear engineering, agriculture, space technology, industries, and other application [5].

Silicoborate glasses have a mechanical strength when applied as radiation shielding material (x-ray and gamma ray) since is formed from a heavy-oxide materials. The heavy-oxide materials have a high
molecular weight and also high effective atomic number. Thus, it is promising radiation shielding materials due to the effective atomic number high and strong absorption of radiation.

2. Methodology

The experiments will carry out by melt quenching method at high temperature for prepare and fabrication silicoborate glass. The base materials are SiO$_2$, B$_2$O$_3$, Gd$_2$O$_3$ and Alkali Oxide (Na$_2$O, K$_2$O, Li$_2$O, Al$_2$O$_3$), have high-grade purity. The quantities of material were weighed by using an electronic balance with accuracy 0.0001 g. Gadolinium silicoborate glass with different compositions were melted in an electrical furnace at temperature 1200 °C. Then the melted glass was poured in mold and annealed at 500 °C. Several percentage of Gd$_2$O$_3$ with different alkali oxides have been carried out to obtain transparent glasses, as can be seen in table 1.

The densities of prepared glasses were measured by Archimedes principle using water (H$_2$O) as the immersion liquid, which measure the mass of glass in the air ($M_a$) and the mass of glass in water ($M_w$). Density of glass sample can be obtained by using the following formula

$$\rho = \frac{M_a}{M_w} \times \rho_f \times \left( \frac{\rho_f M_a - \rho_w M_w}{\rho_w M_a} \right),$$

where $\rho_f$ is the density of fluid (water). The volume molar was calculated by using the data of density $\rho$ and molar mass M. The UV-3600 Shimadzu Spectrometer is used to measure the transmittance of glass sample at the wavelength 300-800 nm. Theoretical calculations of mass attenuation coefficients and effective atomic numbers were using XCOM programs [6].

| No. | Sample | B$_2$O$_3$ | SiO$_2$ | K$_2$O | Na$_2$O | Li$_2$O | Al$_2$O$_3$ | Gd$_2$O$_3$ | Visible |
|-----|--------|------------|---------|--------|--------|--------|------------|------------|---------|
| 1   | SK0    | 65         | 10      | 25     | -      | -      | -          | -          | Transparent |
| 2   | SK5    | 60         | 10      | 25     | -      | -      | -          | 5          | Transparent |
| 3   | SK10   | 55         | 10      | 25     | -      | -      | -          | 10         | Milky |
| 4   | SN0    | 65         | 10      | -      | 25     | -      | -          | -          | Transparent |
| 5   | SN5    | 60         | 10      | -      | 25     | -      | -          | 5          | Transparent |
| 6   | SN10   | 55         | 10      | -      | 25     | -      | -          | 10         | Milky |
| 7   | SL300  | 55         | 10      | -      | -      | 30     | 5          | -          | Transparent |
| 8   | SL305  | 50         | 10      | -      | -      | 30     | 5          | 5          | Transparent |
| 9   | SL310  | 45         | 10      | -      | -      | 30     | 5          | 10         | Transparent |
| 10  | SL315  | 40         | 10      | -      | -      | 30     | 5          | 15         | Milky |
| 11  | SL400  | 45         | 10      | -      | -      | 40     | 5          | 0          | Transparent |
| 12  | SL405  | 40         | 10      | -      | -      | 40     | 5          | 5          | Transparent |
| 13  | SL410  | 35         | 10      | -      | -      | 40     | 5          | 10         | Transparent |
| 14  | SL415  | 30         | 10      | -      | -      | 40     | 5          | 15         | Transparent |
| 15  | SL420  | 25         | 10      | -      | -      | 40     | 5          | 20         | Milky |

Several variation of Gd$_2$O$_3$ with different alkali oxides have been carried out to obtain transparent glass. For glass systems (65-x)B$_2$O$_3$:10SiO$_2$:25K$_2$O:xGd$_2$O$_3$ and (65-x)B$_2$O$_3$:10SiO$_2$:25Na$_2$O:xGd$_2$O$_3$, the transparent glass can be shown for x up to 5 % mole at melting temperature of 1200 C. The glass systems (55-x)B$_2$O$_3$:10SiO$_2$:30Li$_2$O:5Al$_2$O$_3$:xGd$_2$O$_3$ where x = 0, 5, 10. And for the glass systems (45-x)B$_2$O$_3$:10SiO$_2$:40Li$_2$O:5Al$_2$O$_3$:xGd$_2$O$_3$ where x = 0, 5, 10, 15. The percentage of Gd$_2$O$_3$ in this glass matrix is higher than others.

3. Results and discussion

Several glass systems have been carried out to obtain transparent gadolinium silicoborate glass. The choice of alkali oxide influences the amount of Gd$_2$O$_3$ mole percentage to produce transparent glass. The glass systems (65-x)B$_2$O$_3$:10SiO$_2$:25K$_2$O:xGd$_2$O$_3$ and (65-x)B$_2$O$_3$:10SiO$_2$:25Na$_2$O:xGd$_2$O$_3$ are transparent only for x = 5 % mole. The glass systems (55-x)B$_2$O$_3$:10SiO$_2$:30Li$_2$O:5Al$_2$O$_3$:xGd$_2$O$_3$ where x = 0, 5, 10. And for glass systems (45-x)B$_2$O$_3$:10SiO$_2$:40Li$_2$O:5Al$_2$O$_3$:xGd$_2$O$_3$ where x = 0, 5, 10, 15. Li$_2$O and Al$_2$O$_3$ in a glass system gave better results on glass transparency than other alkali oxides (Na$_2$O or K$_2$O), because the percentage of Gd$_2$O$_3$ reaches 15 % mole. Increasing the percentage
of Gd$_2$O$_3$ in the glass matrix will increase density, molar volume, mass attenuation coefficient and effective atomic number of the glass.

The densities of prepared glasses were measured by Archimedes principle using water (H$_2$O) as the immersion liquid. Density of glass sample can be obtained by using the following formula $\rho = \rho_f \{M_a/(M_a-M_f)\}$, where $\rho_f$ is density of fluid (water). The molar volume was calculated by using the data of density $\rho$ and molar mass $M$. Measurements were made on a glass system (65-x)B$_2$O$_3$:10SiO$_2$:25K$_2$O:xGd$_2$O$_3$ and (45-x)B$_2$O$_3$:10SiO$_2$:40Li$_2$O:5Al$_2$O$_3$:xGd$_2$O$_3$.

Table 2 Density and molar volume of gadolinium silicoborate glass

| No | Sample | Gd$_2$O$_3$ (%) | Density (g/cm$^3$) | Molar volume (cm$^3$/mol) |
|----|--------|----------------|-------------------|--------------------------|
| 1  | SK0    | 0              | 2.277             | 32.848                   |
| 2  | SK5    | 5              | 2.665             | 33.567                   |
| 3  | SK10   | 10             | 2.893             | 35.985                   |
| 4  | SL400  | 0              | 2.390             | 22.754                   |
| 5  | SL405  | 5              | 2.725             | 25.333                   |
| 6  | SL410  | 10             | 2.908             | 28.766                   |
| 7  | SL415  | 15             | 3.103             | 31.686                   |

Gd$_2$O$_3$ has high molecular weight. It influences density and molar volume of glass. As can be seen on table 2, density and molar volume increase if percentage of Gd$_2$O$_3$ increases in the glass system. Both for the glass system (65-x)B$_2$O$_3$:10SiO$_2$:25K$_2$O:xGd$_2$O$_3$ & (45-x)B$_2$O$_3$:10SiO$_2$:40Li$_2$O:5Al$_2$O$_3$:xGd$_2$O$_3$

In order to investigate the optical properties of glass, the transmittance was measured as a function of wavelength in range of 300-800 nm. The transmittance of these glasses (sample SL400, SL405, SL410, SL415) is compared with commercial glass window and x-ray shielding. All the glasses showed high transmittance in visible region. The transmittance is almost 90% for glass (45-x)B$_2$O$_3$:10SiO$_2$:40Li$_2$O:5Al$_2$O$_3$:xGd$_2$O$_3$ where x = 10.

![Figure 1. Transmission (%) of glass](image1.jpg)

![Figure 2. Glass pictures (Gd$_2$O$_3$: 0%, 5%, 10%, 15%)](image2.jpg)

The mass attenuation coefficient and effective atomic number are important parameter as radiation shielding material. It is expected that the presence of Gd$_2$O$_3$ in a glass system will increase mass attenuation coefficient and effective atomic number. The calculations are carried out theoretically based on data chemical compounds of glass systems. Theoretical calculations of mass attenuation coefficient and effective atomic number have been carried out for the sample SL400, SL405, SL410, SL415. The results can be seen in the following picture (figure 3 and figure 4).

The mass attenuation coefficient and effective atomic number increased when the Gd$_2$O$_3$ concentration increasing, as can be seen in figure 3 and figure 4, respectively. It is indicated that the photon interaction probability increases with increasing the concentration of Gd$_2$O$_3$ in alloy.
Figure 3. Mass attenuation coefficient  

Figure 4. Effective atomic number

The figure 3 and figure 4 showed that the mass attenuation coefficient and effective atomic number increased when the Gd$_2$O$_3$ concentration increasing, at the lower photon energy. It means the photon interaction probability increases with higher concentration. On the other hand, the mass attenuation coefficient and the effective atomic number decreased with the increase of photon energy. The same result was reported for the glass system BaO-ZnO-B$_2$O$_3$[7].

These result, therefore, indicated that the Gadolinium Silicoborate glass system of (45-x)B$_2$O$_3$:10SiO$_2$:40Li$_2$O:5Al$_2$O$_3$:xGd$_2$O$_3$ (where x = 0, 5, 10, 15) have high potential as shielding materials. It was prepared by melting quenching method at lower temperature (1200 C) compare another glass system at 1400 C [7].

4. Conclusion

The melt quenching technique is used to prepare the gadolinium silicoborate glass by several glass systems using alkali oxide. The glass system (45-x)B$_2$O$_3$:10SiO$_2$:40Li$_2$O:5Al$_2$O$_3$:xGd$_2$O$_3$ where x = 0, 5, 10, 15, have a high transparency in the visible region. The transmission is almost 90 % for x = 10. The mass density and molar volume are increase as the percentage of Gd$_2$O$_3$ increases in the glass system. The mass attenuation coefficient and effective atomic number also increase as Gd$_2$O$_3$ increases. This glass system is high potential material for radiation shielding application.

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