Thermoluminescence energy response of germanium doped calcium borate glasses using theoretical calculation

T. N. H. TENGKU KAMARUL BAHRI[a*], H. WAGIRAN[a], A. R. EL-SERSY[b], S. HASHIM[a], R. HUSSIN[a]
[a]*Department of Physics, Faculty of Science, Universiti Teknologi Malaysia, 81310, UTM Johor Bahru, Malaysia*
[b]*Department of Ionizing Radiation, National Institute for Standards (NIS)Tersa Street, El Haram, Giza, 12211 Egypt.*

This is a theoretical study about the energy response of germanium doped calcium borate glass subjected to photon irradiation in the energy range of 20 keV to 20 MeV. It has been observed that germanium doped calcium borate glass has higher TL response at incidence photon energies below 150 keV. However, the relative TL response decrease as the incident photon energy increases and the relative responses are almost constant in the energy range 150 keV to 10 MeV. The result of this study will be helpful in order to get information on the energy response of germanium doped calcium borate glass to photon irradiation as this material can be used as radiation dosimeter.

(Received April 07, 2014; accepted June 24, 2015)

Keywords: Energy response, Germanium doped, Calcium borate glass, Thermoluminescence, Theoretical

1. Introduction

An important step in the production of a thermoluminescence (TL) is the specification of thermoluminescence characteristics as a candidate for TL dosimetry. The TL energy response is one of the most important characteristics of TL material that can be used for any dosimetric applications in the field of photon radiation. The energy response is a measure of energy absorbed in TL material used in comparison to the energy absorbed in a material taken as a reference (i.e., air or tissue), when irradiated at the same exposure. In general, air is used as a reference material in dosimetry. Hence, from the information of energy response, filter selection or any other correction method for the TL material can be done. In addition, it is beneficial to select a particular TL material for any special application [1-6].

Among the inorganic materials that have been studied for dosimetric use, an important place belongs to borate compounds. Borates are extensive been studied because of its easy preparation, low cost and high sensitivity compared to other TL materials [7]. These borate compounds show an effective atomic number close to that of human tissue (Z_{eff} = 7.42). This fact makes some borates become the suitable materials to be considered as environmental and medical dosimeter [8]. To date, many investigations on thermoluminescence characteristics of borate compounds had been done but most of them are focused on lithium borate. The thermoluminescence studies of lithium borate compounds are of attention due to their easy handling process, near tissue equivalent absorption coefficient (Z_{eff} =7.3) and low cost. J. H. Schulman et al. [9] were the first started the TL studies of lithium borate compounds in 1965 and then, various detailed on TL studies of alkali and alkaline earth tetra borates were continued up to present times especially on magnesium and lithium borate compounds [10].

Therefore, the present study is intended to introduce new material based on borate glasses combine with other materials such as calcium and doped with germanium that can improve the properties of recent TL detectors. In this study, due to very low hygroscopic nature of borate, good chemical stability can be performed by adding calcium. The good stability is important because the presence of water can reduce TL efficiency related to non- radiative relaxations during thermal simulation [8]. Meanwhile, for germanium, it has deep electron traps which will make this material stable for months or years [11]. In order to determine photon energy response of the dosimeters, it is essential to know the mass energy absorption coefficient. In this work, the mass energy absorption coefficient as a function of photon energy of germanium doped calcium borate glass are calculated and compared to the results of undoped calcium borate glass and bone.

2. Materials and methods

The mass energy absorption coefficient of a mixture or compound $\left(\frac{\mu_{en}}{\rho}\right)_m$ can be obtained based on mixture rule by applying Equation 1.

$$\left(\frac{\mu_{en}}{\rho}\right)_m = \sum_i \left(\frac{\mu_{en}}{\rho}\right) w_i \qquad (1)$$

where $\left(\frac{\mu_{en}}{\rho}\right)_i$ and W_i are the mass energy absorption coefficient and the weight fraction of the element; boron (B), oxygen (O), calcium (Ca) and germanium (Ge), respectively. The weight fraction of the element present in undoped and germanium doped calcium borate glass is given in Table 1. Meanwhile, the mass energy absorption coefficients of the elements are taken from Tables of X-Ray Mass Attenuation Coefficients and Mass Energy Absorption Coefficients provided by J. H. Hubbell and S. M. Seltzer [12].

Table 1. Chemical composition of undoped and germanium doped calcium borate.

Weight fraction of the element				
Material	Boron (B)	Oxygen (O)	Calcium (Ca)	Germanium (Ge)
Undoped calcium borate	0.217400	0.568193	0.214407	0.000000
Germanium doped calcium borate (at GeO_2 = 0.1 mol %)	0.217400	0.568214	0.213693	0.000694

Photon energy response, S_E (E) is defined by S.W. McKeever and R. Chen as in Equation 2 [13]:

$$S_E(E)=\frac{\left(\frac{\mu_{en}}{\rho}\right)_m}{\left(\frac{\mu_{en}}{\rho}\right)_{ref}} \quad (2)$$

where $\left(\frac{\mu_{en}}{\rho}\right)_m$ refers to the mass energy absorption coefficient of the material whereas $\left(\frac{\mu_{en}}{\rho}\right)_{ref}$ is the mass energy absorption coefficient of reference medium or material. In this work, air is used as a reference medium because the ratio of absorbed dose to exposure for air is constant [14].
Relative energy response $(RER)_E$ definition is applied for photon energy response in practical used. The relative energy response is normalized to the average photon energy from a source of Cobalt-60 (1.25 MeV) as given in Equation 3.

$$(RER)_E=\frac{S_E(E)}{S_E(1.25MeV)} \quad (3)$$

3. Results and discussion

The mass energy absorption coefficient for germanium doped calcium borate glass as a function of photon energy is given in Fig. 1. From the previous study [15], it has been proved that the effective atomic number of calcium borate glass is closed to bone (Z_{eff} =14). Therefore, the mass energy absorption coefficients of bone taken from ICRU Report 44 were used for comparison [16]. Bone composes of the following main elements (weight fraction): (H: 3.4), carbon (C: 15.5), nitrogen (N: 4.2), oxygen (O: 43.5), sodium (Na: 0.1), magnesium (Mg: 0.2), phosphorus (P: 10.3), sulphur (S: 0.3) and calcium (Ca: 22.5) [16].

The mass energy absorption coefficient of undoped and germanium doped calcium borate glasses decrease rapidly as the photon energy increase up to 200 keV (Fig. 1). The results are in good agreement with the mass energy absorption coefficient of bone. The decrease in the mass energy absorption coefficient is due to the dominant of the photoelectric effect in photon interaction process at lower energy region. In this process, the cross section varies directly to target material with atomic number, Z^{4-5} and inversely proportional to incident photon energy, $E^{3.5}$. Therefore, this process is dominant for high atomic number of material and low incident photon energy. This is a concurrence with the fact that bone has the highest effective atomic number (Z_{eff} =14), followed by germanium doped calcium borate glass (Z_{eff} =13.03) and calcium borate glass (Z_{eff} =13).

In the energy range of 200 keV to 600 keV, the mass energy absorption coefficient of undoped and germanium doped calcium borate glasses are almost constant and when the energy is higher than 600 keV to 20 MeV the mass energy absorption coefficients decrease slowly. It may be because the cross section of Compton scattering varies linearly with atomic number of the materials and decrease as the incident photon energy increases. The dominant process of this process is in the intermediate energy region (200 keV to 20 MeV). These results indicate that the chemical composition of the materials gives less significant influence in the intermediate energy region.

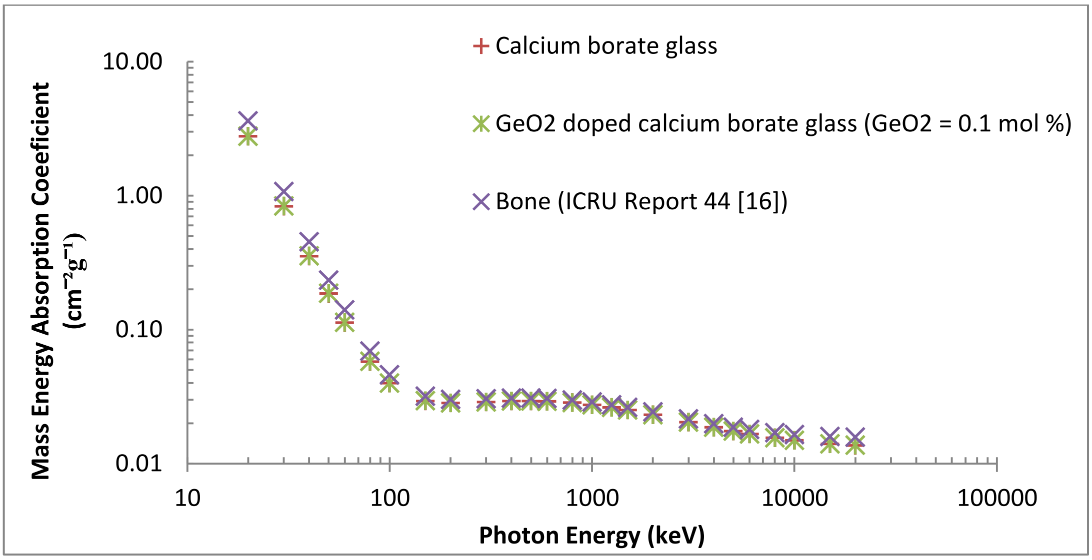

Fig. 1. Comparison of mass energy absorption coefficients of undoped, germanium doped calcium borate glass (GeO_2 = 0.1 mol %) and bone.

Fig. 2 shows the relative energy response (normalised to 1.25 MeV) of undoped and germanium doped calcium borate glass and bone. The dashed line in the figure is the acceptable response range that can satisfy the dosimeter performance criteria [17]. The results of calculated relative energy response indicate that bone, undoped and germanium doped calcium borate glasses have over response at low energy up to 150 keV. In the energy range 150 keV to 10 MeV, the responses are constant and started to increase at energy beyond 10 MeV. However, at energy below 100 keV, various filter need to be added to reduce the over response of the energy dependence. This result is quite similar with the common used TL materials such as $CaSO_4$ and CaF_2, which showed poor energy dependence.

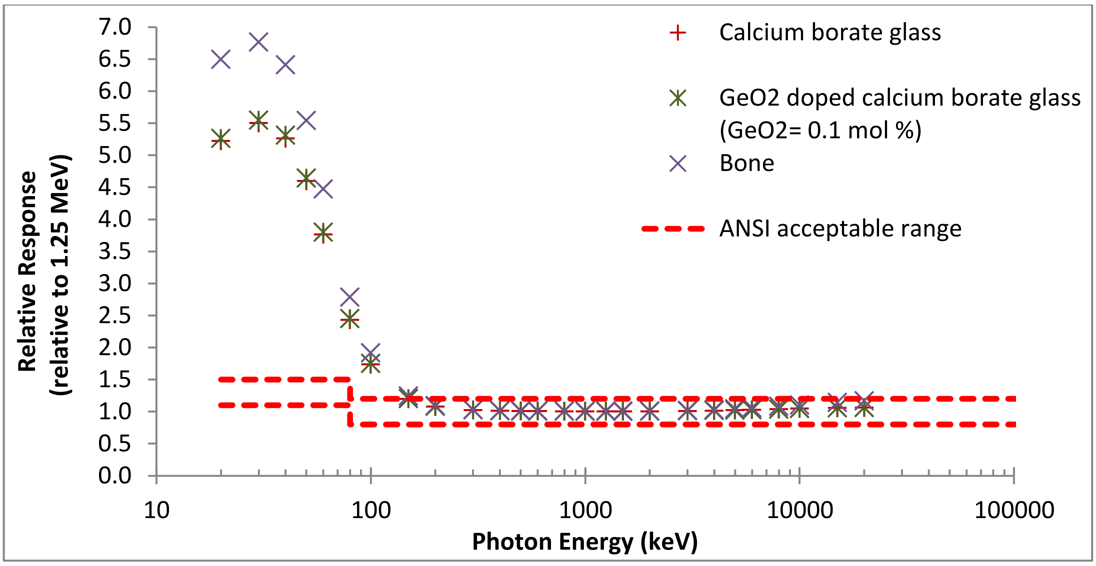

Fig. 2. Relative energy response (relative to 1.25 MeV) of calcium borate glass, germanium doped calcium borate glass (GeO_2 0.1 mol %) and bone

Fig. 3 shows the photon energy response of calcium borate glass at different germanium concentrations. It is found that the relative response of the glass increase with GeO_2 concentration especially at lower energy range up to 150 keV. The photoelectric effect is the dominant photon interaction process for high- Z materials, However, in the energy range 150 keV to 10 MeV, the relative responses are almost constant. The Compton scattering contribution can be seen in the intermediate part of the energy region 150 keV to 10 MeV. Therefore, the glasses have almost constant response in this energy region. This shows the weak dependence of atomic number values on the incident photon energy in the intermediate energy region.

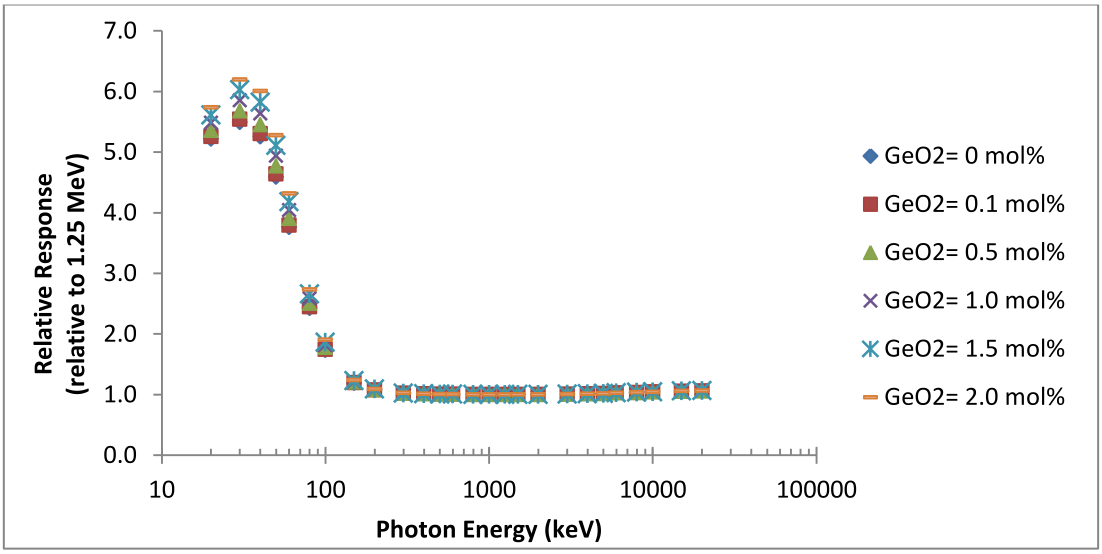

Fig. 3. Photon energy response of different germanium concentration doped calcium borate glass (GeO_2 = 0.0 – 2.0 mol %).

4. Conclusion

A limited response in the energy range 150 keV to 10 MeV has been observed for germanium doped calcium borate glass. The study shows that a significant increase in TL response occurred at lower energy region below 150 keV when the germanium concentration was increased.

Acknowledgments

The authors would like to thanks the Ministry of Higher Education (MOHE) and Universiti Teknologi Malaysia for providing the research grant (GUP: 07H71) and facilities.

References

[1] I. Hossain, H. Wagiran, H. Asni, Optoelectron. Adv. Mater - Rapid Commun., **6**(1-2), 162 (2012).
[2] O. Gurler, H. Oz, S. Yalcin, O. Gundogdu, Appl. Radiat. Isot., **67**(1), 201 (2009).
[3] J. H. Hubbell, Int. J. Appl. Radiat. Isot., **33**, 1269 (1982).
[4] S. D. Davis, C. K. Ross, P. N. Mobit, L. Van der Zwan, W. J.Chase, K. R. Shortt, Radiat. Prot. Dosim., **106**, 33 (2003).
[5] M. A. Saeed, N. A. Fauzia, I. Hossain, A. T. Ramli, B. A. Tahir, Chin. Phys. Lett., **29**(7), 078701 (2012).
[6] M.A. Saeed, I. Hossain, N. Hida, H. Wagiran, Rad. Phys. Chem., **91**, 98 (2013).
[7] L. H. Jiang, Y. L. Zhang, C. Y. Li, J. Q. Hao, Q. Su, J. Alloy. Comp., **482**(1-2), 313 (2009).
[8] S. Rojas, K. Yukimitu, A. S. S. de Camargo, L. A. O. Nunes, A. C. Hernandes, J. Non-Cryst. Solids, **352**, 3608 (2006).
[9] J. H. Schulman, R. D. Kirk, E.J. West, Luminescence Dosimetry, Proc. Int. Conf. Lumin. Dosim., **1967**, 113(1965).
[10] T. Depci, G. Ozbayoglu, A. Yilmaz, A. N. Yazici, Nucl. Instrum. Meth. Phys. Res. B, **266**(5), 755 (2008).
[11] N. H. Yaakob, H. Wagiran, M. I Hossain, A. T. Ramli, D. Bradley, S. Hashim, H. Ali., J. Nucl. Sci. Technol., **48**, 1115 (2011).
[12] J. H. Hubbell, S. M. Seltzer, Tables of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients. National Institute of Standards and Technology, Gaithersburg, Maryland, 1995.
[13] S.W. McKeever, R. Chen, Theory of Thermoluminescence and Related Phenomena. World Scientific, Singapore, 1997.
[14] H. Wagiran, I. Hossain, H. Asni and A.T. Ramli, J. Eng. Thermophys., **21**(1), 2 (2012).
[15] T. N. H. Tengku Kamarul Bahri, H. Wagiran, R. Hussin, I. Hossain, T. Kadni, Rad. Phys. Chem., **102**, 103 (2014).
[16] K.E. Goldstone, Clin. Radiol., **41**(3), 220 (1989).
[17] ANSI N545-1975, Performance, Testing, and Procedural Specification for Thermoluminescence Dosimetry (Environmental Applications). American National Standards Institute, New York, 1975.

*Corresponding author: tnhidayah2@gmail.com