THERMOLUMINESCENCE PROPERTIES OF STRONTIUM-COPPER CO-DOPING LITHIUM-BORATE GLASS FOR IONIZING RADIATION APPLICATION

HAYDER KHUDHAIR OBAYES

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Physics)

Faculty of Science
Universiti Teknologi Malaysia

APRIL 2017

الحمد الله رب العالمين

Special dedication to:

To my beloved parents

Father. KHUDHAIR OBEYES KHUDHAIR and great Mother.

AZHAR HAMED MOUSA

Whose love, kindness, patience and prayer have brought me this far

For their love, understanding and support through my endeavours

To my siblings

(ENAS, ORAS & HASSANEEN)

Whose presence fills my life with joy and success

For their endless encouragement, laughs and cares,

Never forget to dedicate my full appreciation for my beloved country that is dear to my heart in every step forward in my life

(Iraq)

ACKNOWLEDGEMENT

All praises be to Allah, first and foremost, the most Gracious, the Merciful. Peace and blessing of Allah be upon His noble and last messenger, Muhammad (S. A. W.). There is no God worthy of worship except Allah and Muhammad is his servant, prophet and Messenger. I am grateful to Allah who gave me the courage and strength to complete this research in due time.

I would like to express my sincere gratitude to my supervisors **Prof. Dr. ROSLI BIN HUSSIN, Prof. Dr. Husin Bin Wagiran and Dr Muhammad Saeed Alam** for their support, guidance and constructive critics in the course of fulfilling this gigantic task.

I am indebted to the management and entire staff of Universiti Teknologi Malaysia, more especially the academic and non-academic staff of Physics Department. I also have the obligation to thank the entire staff of Malaysian Nuclear Agency, Faculty of Nuclear Science, Universiti Kabangsan Malaysia (UKM) and National Cancer Institute Malaysia for given me opportunity to use their facilities throughout the research activity.

Sincere regards to all my colleagues in the Department of Physics for their guidance, assistance, technical and non-technical support during this research

I am grateful to my beloved parents for their support all along, my brothers and sisters for their guidance and encouragement.

ABSTRACT

Thermoluminescent dosimetry (TLD) has become a reliable and promising method used in ionizing radiation-dose measurements nowadays. There are wide range of TLD materials in use and among them the glassy matrix structure represents a potentially attractive system due to the outstanding properties such as good thermal stability, human tissue equivalent properties, relatively low cost, easily shaped and good ability to host luminescent activators in elevated concentrations. Many efforts have been devoted to develop tissue equivalent suitable glassy scintillator materials for ionizing radiation measurements. The aim of the present studies was to determine the influences of dopant ($SrCO_3$) and co-dopant (Cu_2O, Mg_2O, Na_2O, P_2O_2) on lithium-borate (LB) glasses upon their physical, structure, thermal and TLD properties. Six series of glass compositions xLi$_2$CO$_3$–(100-x)H$_3$BO$_3$, 15Li$_2$CO$_3$–(85–y)H$_3$BO$_3$–ySrCO$_3$,15Li$_2$CO$_3$–(83–z)H$_3$BO$_3$–2SrCO$_3$–zCu$_2$O, 15Li$_2$CO$_3$–(83–u)H$_3$BO$_3$–2SrCO$_3$–uMg$_2$O, 15Li$_2$CO$_3$–(83–v)H$_3$BO$_3$–2SrCO$_3$–vNa$_2$O and 15Li$_2$CO$_3$–(83–w)H$_3$BO$_3$–2SrCO$_3$–wP$_2$O$_2$ with varying concentrations of x, y, z, u, v, w (in mol%) were synthesized using melt quenching technique. The amorphous phase, structure, composition, morphologies, thermal and physical properties of synthesized glass samples were characterized using X-ray diffraction (XRD), Fourier transform infrared (FTIR), Energy-dispersive X-ray (EDX) spectroscopy, Field emission scanning electron microscope (FESEM) and Differential thermal analysis (DTA) respectively. The TLD properties were measured in terms of thermoluminescence (TL) response, sensitivity, linearity, fading, reusability, minimum detectable dose, and Z-effective. These synthesized glass systems were exposed to various types of ionizing radiations such as Co-60 gamma ray, 6 and 10 MeV electrons, 6 and 10 MV X-ray photons. The XRD patterns confirmed the true amorphous state of all prepared glass samples. The FTIR results show that the structure of the glass samples is that of LB glass. The dopant ($SrCO_3$) and co-dopant (Cu_2O) in LB glass were not changing the main feature of the structure. The EDX analyses of samples show that the composition of the glasses is that of LB, its doped and co-doped. The FESEM results show homogeneous morphology. The DTA shows that the prepared glass samples are physically and thermally stable. Samples doped with 2.0 mol% of $SrCO_3$ and 0.01 mol% of Cu_2O concentration showed the highest TL efficiency. Furthermore, the co-doped glasses exhibited very significant TL properties such as linear dose response, good reusability, low minimum detectable dose and high sensitivity. The samples also showed good dose linearity characteristic and TL sensitivity in the dose range of 0.5-4.0 Gy when irradiated with 10 MeV electrons. The achieved effective atomic number of glass samples was found to be 9.69 and 11.08 for LB doped with 2.0 mol% of $SrCO_3$ and co-doped with 0.01 mol% of Cu_2O, respectively. The relative energy response of both doped and co-doped samples have been calculated theoretically and the results obtained are in good agreement with the experimental ones. In conclusion, the studied glass samples were found to have excellent properties required in TLD applications.

ABSTRAK

Dosimetri pendarcahaya terma (TLD) telah menjadi satu kaedah boleh percaya dan berpotensi dalam pengukuran dos sinaran mengion kini. Terdapat pelbagai jenis bahan TLD telah digunakan dan antaranya struktur matriks berkaca, merupakan satu sistem berpotensi yang menarik berdasarkan cirinya yang menonjol seperti kestabilan terma yang baik, sifat kesetaraan tisu manusia, kos yang agak rendah, mudah dibentuk, kemampuan yang baik untuk menjadi hos pengaktif pendarcahaya pada kepekatan tinggi. Banyak usaha ditumpukan untuk membangunkan bahan pengerdip berkaca yang sesuai serta setara tisu untuk pengukuran sinaran mengion. Tujuan kajian ini adalah untuk menentukan pengaruh dopan ($SrCO_3$) dan kodopan (Cu_2O, Mg_2O, P_2O_5, Na_2O) ke atas kaca litium-borat (LB) terhadap sifat fizikal, struktur, terma, dan TLD. Enam siri komposisi kaca $x Li_2CO_3$–(100-x)H_3BO_3, $15Li_2CO_3$–(85–y)H_3BO_3–$y SrCO_3$, $15Li_2CO_3$–(83–z)H_3BO_3–$2SrCO_3$–$z Cu_2O$, $15Li_2CO_3$–(83–u)H_3BO_3–$2SrCO_3$–$u Mg_2O$, $15Li_2CO_3$–(83–v)H_3BO_3–$2SrCO_3$–$v Na_2O$, dan $15Li_2CO_3$–(83–w)H_3BO_3–$2SrCO_3$–$w P_2O_2$ dengan kepekatan x, y, z, u, v, w (dalam mol%) yang berbeza telah disintesis menggunakan teknik pelindapan cair. Fasa amorfus, struktur, komposisi, morfologi, sifat terma dan fizikal sampel kaca tersintesis telah dicirikan masing-masing menggunakan pembelauan sinar-X (XRD), inframerah transformasi Fourier (FTIR), spektroskopi serakan tenaga sinar X (EDX), mikroskop elektron imbasan pancaran medan (FESEM), dan analisis terma pembeza (DTA). Sifat TLD diukur dari segi tindak balas pendarcahaya terma (TL), kepekaan, kelinearan, kelunturan, kebolehgunaan semula, dos pengesanan minimum, dan Z-efektif. Sistem kaca tersintesis ini didedahkan kepada pelbagai jenis sinaran mengion seperti sinar gama Co-60, elektron bertenaga 6 dan 10 MeV, dan foton sinar X bertenaga 6 dan 10 MV. Pola XRD mengesahkan fasa amorfus sebenar semua sampel kaca yang disediakan. Keputusan FTIR menunjukkan struktur utama sampel kaca ialah kaca LB. Dopan ($SrCO_3$) dan kodopan (Cu_2O) dalam kaca litium borat tidak mengubah sifat utama struktur. Analisis EDX terhadap sampel menunjukkan komposisi sampel ialah komposisi LB, dopan dan kodopan. Keputusan FESEM menunjukkan morfologi yang homogen. DTA menunjukkan sampel kaca disediakan adalah stabil dari segi fizikal dan terma. Sampel didop dengan kepekatan 2.0 mol% $SrCO_3$ dan 0.01 mol% Cu_2O menunjukkan kecekapan TL paling tinggi. Tambahan pula, kaca dikodopkan menunjukkan sifat TL yang ketara seperti tindak balas dos yang linear, kebolehgunaan semula yang baik, dos pengesanan minimum yang rendah dan sensitiviti yang tinggi. Sampel juga menunjukkan ciri kelinearan dos dan kepekaan dos yang baik dalam julat dos 0.5-4.0 Gy apabila disinarkan dengan elektron bertenaga 10 MeV. Nombor atom berkesan sampelkaca yang diperolehi ialah 9.69 dan 11.08 masing-masing bagi LB yang didopkan dengan 2.0% $SrCO_3$ dan dikodopkan dengan 0.01 mol% Cu_2O. Respon tenaga relatif bagi kedua-dua kaca LB terdop dan terkodop dikira secara teori dan hasil yang diperoleh bersesuaian dengan hasil eksperimen yang dijalankan. Kesimpulannya, sampel kaca yang dikaji didapati mempunyai ciri terbaik yang diperlukan dalam aplikasi TLD.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

CB	-	Conduction band
BI	-	Band gap
VB	-	Valence band
DTA	-	differential thermal analysis
EDX	-	Energy dispersive X-ray
ICRU	-	International commoission of radiation unite
ERD	-	Environmental radiation dosimetry
ECC	-	Elemental correction coefficient
FESEM	-	Field emotion scan electron microscopy
LET	-	Low liner energy transfer
FTIR	-	Fourier transform infrared
ICRP	-	international commission on radiological protection
KE	-	Kinetic energy
LINAC	-	Linear accelerator
MeV	-	Million electron volts
MLC	-	Multi leaf collimator
MU	-	Monitor unit
MV	-	Megavolt
NBO	-	Non bridging oxygen
PMT	-	Photomultiplier Tube
PRD	-	personal radiation dosimetry
RD	-	Radiation dosimetry
RF	-	Radio frequency
TL	-	Thermoluminescence
TLD	-	Thermoluminescence dosimetry

TTP	-	Time temperature profile
XRD	-	X-Ray diffraction
TD	-	Threshold dose
TMAC	-	Total mass attennation coefficient
GFA	-	Glass forming ability
KBR	-	Potassium bromide
CT	-	Computed tomography
MNCI	-	Malaysian national cancer institute
LLD	-	Lowest level of detection

LIST OF SYMBOLS

σ_B	-	Standard deviation
$(RER)_E$	-	Relative Energy Response
^{60}Co	-	Cobalt-60
Cu_2O	-	Copper(I) Oxide
D	-	Absorbed Dose
$D\ (t)$	-	Radiation dose at time
D_0	-	Minimum detectable dose
E_g	-	Energy band gap
F	-	Calibration factor of TL system
F	-	Field Strength
$f\,(D)$	-	Linearity index
H_3BO_3	-	Boric Acid
Li_2CO_3	-	Lithium Carbonate
m	-	Mass
MgO	-	Magnesium Oxide
Mi	-	average molecular weight
M_T	-	Total molecular weight
n	-	Refractive index
N_A	-	Avogadro’s number
Na_2O	-	Sodium Oxide
P_2O_2	-	Phosphorus
r_i(Å)	-	inter-nuclear distance
R_m	-	Molar refraction
r_p(Å)	-	Polaron radius
$S_E\ (E)$	-	Photon energy response

$SrCO_3$	-	Strontium Carbonate
CC, R^2	-	Correlation coefficient
t	-	Time
V_M	-	Molar volume
Vm	-	molar volume
W_i	-	Weight fraction of element
x	-	Mole fraction
Z	-	Atomic number
Z_{eff}	-	Effective atomic number
P	-	Density
Tc	-	Glass crystallization temperature
Tg	-	Glass transition temperature
Tm	-	Glass melting temperature
Trg	-	Glass forming ability
Hr	-	Hruby parameter

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Study Background

In radiation safety related health physics, the term so called radiation dosimetry (RD) refers to the determination of the radiation dosage that is received by any matter including tissue upon exposing it to direct or indirect ionizing radiation. It indeed measures and evaluates directly or indirectly the amount of exposure in terms of equivalent or absorbed effective dose or some other quantities related to ionization radiation. The dosimetric dose range of interest depends on the source and nature of radiation. The specification provided by International Commission of Radiation Units (ICRU) are for personal dosimetry it ranges from 0.01 - 1.0 mSv, for X-ray diagnosis the range is 0.1 - 100 mGy and for radiotherapy it varies between 1 - 5 Gy [1].

Radiation monitoring devices are the only way to detect and measure the presence of radiation, which cannot be detected by sensor. In the environmental and medical dosimetry, different types of radiation detectors are used for quantifying the radiation dose. However, a single detector cannot measure all kinds of radiation or useful in all situations. The most popular dosimeters used for detecting ionization radiation include ionizing chamber, film, luminescent and semiconductor materials. Other devices that are also used for this purpose are diamond dosimeter, plastic dosimeter, gel dosimeter etc.

Borate glass system is an interesting and potential material in radiation dosimetry. This glass system was first used for precious metal working and later in ceramic industries. It is well known that Boron and its compounds find extensive applications from glass to fibers, flame-retardants to nuclear applications and several others. Present developments in the area of radiation dosimetry for the protection from radiation exposure allowed the researchers to exploit borate glass as a novel thermoluminescence (TL) material, which is greatly potential for ionizing radiation dose measurement. Borate glasses are chemically stable compounds and can easily be doped with impurities such as rare earths, transition and alkaline metals. Such doped materials exhibit high sensitivity, linearity and good fading properties suitable for dose measurement [2]. In this regard, lithium borate (LB) is one of the appropriate materials for radiation dosimetry, particularly for clinical and radiation therapeutic application. It is because, the effective atomic number ($Z_{eff} = 7.3$) of LB system is nearly equivalent to human tissue and easy to handle.

The LB based TL detectors are first commercially developed in 2001 [3]. The dosimetric properties of these materials ($Li_2B_4O_7$: Cu, In, Ag and $Li_2B_4O_7$: Cu) in the sintered pellet form are widely studied to determine their potential as tissue equivalent TLDs. These materials revealed glow curves with prominent dosimetric peaks and higher TL sensitivity. Furetta [4] examined the dosimetric properties of LB systems based TLDs. The annealing procedure of $Li_2B_4O_7$: Cu system is thoroughly examined. In addition, the TL sensitivity, glow-curve shape, minimum detectable dose, photon dose response, relative photon energy response, fading, reproducibility and precision of dose measurements of such material is inspected. Numerous natural and synthetic borates are exploited for diverse industrial applications. Generally, natural borates are cleaned from their impurities in processing plants and further treated to more qualified end products including anhydrous borax, anhydrous and hydrous boric acid, borax penta- and deca-hydrate, as well as sodium per-borate in re-crystallization process.

Inconsistency of borate chemistry [5], allows researchers to synthesize numerous borate structures usable in high technology areas. Despite all these several shortfall in terms of efficiency, stability and accuracy remain utter challenges to overcome.

The choice of dosimetric materials critically depend on their several essential characteristics such as the good sensitivity and linearity between dose and TL response, low fading rate, inexpensive to manufacture, good stability through multiple readout cycles and a near-tissue equivalent of effective atomic number (Z_{eff}). The later one is very important because materials with higher or lower Z_{eff} than human tissue may misjudge the contributions of high energy photons leading to radiation damage. The search for the best material in terms of these characteristics added further impetus to the discovery and testing of a number of various novel glass compounds.

Radiation dose measuring instruments are essential for any environment having existing ionizing radiation. Apart from the specific properties possessed by TL materials for a particular application, some other basic and general conditions must fulfill. These include isolated glow curve around 200 °C (180 – 250 °C), Z_{eff} near to the human tissue, high signal per unit of dose, low fading characteristics, good linear dose response, easy annealing procedure, stability to chemical and environmental effects, non-toxicity, abundance and cheap composite materials. To date, a promising TL phosphor fulfilling all of the above mentioned characteristics is far from being achieved. Although several TL materials are developed and some reached the commercial level but they suffer from many disadvantages. Continuous efforts are made to either develop a new phosphor with an enhanced TL characteristics for improving the already existing TL material. This is achieved by modifying the host with other elements, changing or varying the doping element or co-doping the phosphor with new impurities.

Complex TL materials processing and lack of reusability has discouraged the use of film in radiation dosimetry [6]. Studies on lithium flouride (LiF) by Harshaw Company revealed a very small TL sensitivity of this material due to the removal of unknown impurities during the processing procedure of the crystal. Titanium was found to be one of these impurities and was incorporated in this mateial to fabricate a phosphor having enhanced TL response. LiF is now considered as the standard TL phosphor known as 'TLD-100'. However, LiF phosphor has the disadvantage of complex annealing procedure and supra-linearity trend after the first 10 Gy dose [7, 8].

Over the years, several techniques are developed to prepare glassy TL host. Melt quenching technique is a promising method for preparing high quality glass easily and economically. This method is based on the melting process and subsequent rapid quenching of a metal oxide, where the viscosity is increased very quickly to a high value without forming the crystalline phase. Upon increasing the temperature in dark some minerals emit a transient glow called TL. It is this TL process that is exploited in radiation dosimetry. Denial *et al.* used these TL phenomena and measured the amount of radiation exposure on LiF. They acknowledged that this material is the most suitable phosphor for assessing the ionizing radiation exposure [9]. Currently, borate glass system owing to their lower fabrication cost, high sensitivity and easy availability received focused industrial attention for developing TL products.

Inspired by these notable attributes of LB phosphor, this work intends to develop a new Sr doped LB glass dosimeter for the precise measurement of ionizing radiation dosage. The TL properties of strontium (Sr) doped lithium borate glass and co-doped with copper (Cu), phosphorous (P), sodium (Na) and magnesium (Mg) are thoroughly examined. This is achieved by synthesizing a series of LB glasses via melt quenching method. The composition of co-doped LB: Sr, M (where M: Cu, P, Na and Mg) glass system are optimized and the prepared glasses are characterized to determine the effects of Sr contents on their structural and TL properties. Attempts are made to determine a relationship between co-dopants concentration and TL response of the synthesized TLD. Experimental results are analyzed, interpreted and compared with other findings.

1.2 Problem Statement

Commercially available TLD-100 has some problem such as complex annealing procedure and supra-linearity trend at 10 Gy dose of exposure. Literature showed that the dosimetric properties of lithium borate system with Sr /Cu co-doping are not widely studied. Furthermore, the hygroscopic nature of lithium borate based glass system as well as the quenching effect, less sensitivity and fading behavior of the doping materials contributed to the setback of earlier developed phosphor. Thus, as a possible solution to the existing limitations the modification of strontium doped lithium borate system with copper co-doping is proposed.

1.3 Objectives of the Study

The main goal is to determine the fundamental TLD properties of Sr-Cu, Sr-Mg, Sr-Na and Sr-P co-doped Lithium borate glass system. Based on the problem statement the following objectives are set:

1) To evaluate the effects of Sr doping and Cu co-doping on the structure, chemical composition, thermal, morphological, TL and physical properties of Lithium borate glass systems.

2) To determine the influence for annealing temperature, annealing time and heating rate on the TL intensity of synthesized co-doped Lithium borate glass systems as proposed TLD.

3) To optimize the concentration of the Sr dopant and Cu, P, Na and Mg co-dopants in the Lithium borate glass best in TL intensity.

4) To determine the influence of TL properties of the Sr-Cu co-doped of Lithium borate glass system subjected to different types of irradiations (photons, electrons and cobalt-60 gamma) useful for TLD.

1.4 Scope of the Study

A new LB glass system doped with Sr and co-doped with Cu, P, Na and Mg are synthesized via melt-quenching method to evaluate their TL performance. These glasses are subjected to various photons, electrons and cobalt-60 gamma irradiations. The amorphous nature of all the un-doped, doped and co-doped glass are confirmed by X-ray diffraction (XRD) analysis. Glass morphology is analyzed using field emission scanning electron microscope (FESEM), where the fractional percentage of the composite elements is determined for effective atomic number of the proposed TLD. Thermal properties in terms of glass stability, transition temperatures and Hruby parameter are determined using differential thermal analyzer (DTA). The identification of elemental traces is performed using energy dispersive X-ray (EDX) measurement. The weight fraction obtained via EDX is further used for the calculation of effective atomic number. The effect of the modifier and the co-dopant concentration variation on the structure (bonding vibrations) of the proposed dosimeters is investigated by Fourier transform infrared (FTIR) spectroscopy. Physical properties including glass density, molar volume, ion concentration, polaron radius, inter-nuclear separation and field strength are calculated.

The TL measurements involves the determination of the dosimetric properties of Sr doped LB glass system co-doped with Cu, P, Na and Mg. The optimum concentration for doping and co-doping is evaluated in terms of TL response of this glass system. These optimum glass compositions are further selected to evaluate their dosimetric properties. The best combination of TL set up (annealing procedure, time in the rang 15-60 minutes and Annealing temperature in the range 100-400 ^{o}C, heating rate in the range 1-7 ^{o}C/s) are determined using the optimized Sr doped and Cu co-doped glass sample that give higher response compared to other compositions. These TL parameters remained constant throughout all TL characterization. The TL properties such as glow curve, dose response, sensitivity, fading, minimum detection dose, reproducibility, relative energy response, bleaching, accuracy of dose performance are evaluated under the exposure of various irradiations. The kinetic parameters including the activation energy and frequency factor are estimated using peak shape method and initial rise method for understanding of TL phenomenon. This method is shown to better justify the trap nature of the present glass system.

1.5 Significance of the Study

The proposed new materials can be used as good TLD system for clinical, personal and environmental dose monitoring applications. The performance of these TLD materials would ensure the dose delivered to the patients and workers more accurately in order to improve the level of safety in line with the guidance by the International Commission on Radiological Protection (ICRP).

The current study is expected to promote a better understanding on:

1) New material properties with optimize composition for accurate dose measurement leading to human safety.

2) Influence of co-doping and strontium on the TL properties of newly proposed glass system will be understood.
3) New glass composition may have commercial potential.
4) Fundamental understanding of the TL response.
5) Easy glass preparation, simple composition and low cost material would help large scale industrial production.
6) Accurate and efficient dose measurement using dosimeter based on this new composition.

1.6 Thesis Organization

This thesis is organized into seven chapters. Chapter 1 highlights the background of the study and the research gap to justify the need of this research. It includes the hypothesis and research question, research objectives, scope and significance of the study.

Chapter 2 provides a critical literature review relevant to this study. The general concept of luminescence and TL in particular as well as the theories and models associated with TL are emphasized. The dosimetric properties of TL phosphor are also discussed.

Chapter 3 describes the detail methodology and procedures in terms of instrumentation and analysis that are needed to fulfill the proposed objectives. It encloses the identification of material, glass sample preparation and description of sample characterizations.

Chapter 4 provides the results of various characterizations on thermal, physical, morphological and structural properties towards the fulfillment of the proposed objectives.

Chapter 5 presents the experimental results and analysis. The evaluation of TL properties, discussion, interpretation and comparisons. The results obtained from the characterization, temperature time profile settings and optimization of dopants and co-dopants are discussed in depth**.**

Chapter 6 depicts the main dosimetric properties of the proposed TLDs and their analysis in terms of various mechanisms.

Chapter 7 concludes the thesis with further information of this research in terms of recommendations for future work.

REFERENCES

1. Units, I.C.o.R. *Fundamental Quantities and Units for Ionizing Radiation*. Vol. 60. 1998: International Commission on Radiation.
2. Garrett, D. E. *Borates: Handbook of Deposits, Processing, Properties and Use*. 1998: Academic Press.
3. Prokic, M. Lithium Borate Solid TL Detectors. *Radiation Measurements*, 2001. 33(4): p. 393-396.
4. Furetta, C., et al. Dosimetric Characteristics of Tissue Equivalent Thermoluminescent Solid TL Detectors Based on Lithium Borate. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 2001. 456(3): p. 411-417.
5. Yu, Z.-T., et al. Synthesis and X-ray Crystal Structures of Two New Alkaline-Earth Metal Borates: $SrBO_2(OH)$ and $Ba_3B_6O_9(OH)_6$. *Journal of the Chemical Society, Dalton Transactions*, 2002(9): p. 2031-2035.
6. Ahmed, S. N. *Physics and Engineering of Radiation Detection*. 2007: Academic Press.
7. Lakshmanan, A. A New High Sensitive CaSO4: Dy Thermostimulated Luminescence Phosphor. *Physica Status Solidi (a)*, 2001. 186(1): p. 153-166.
8. Lee, J., et al. Role of Dopants in LiF TLD Materials. *Radiation Measurements*, 2008. 43(2): p. 303-308.
9. McKinlay, A. F. *Thermoluminescence Dosimetry*. 1981.
10. Balogun, F., Ogundare, F. and Fasasi, M. TL Response of Sodalime Glass at High Doses. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 2003. 505(1): p. 407-410.

11. Correcher, V., Garcia-Guinea, J. and Rivera, T. Thermoluminescence Sensitivity of Daily-Use Materials. *Radiation Effects & Defects in Solids*, 2009. 164(4): p. 232-239.

12. Depci, T., et al. *The Thermoluminescent Properties of Lithium Triborate (LiB_3O_5) Activated by Aluminium.* Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 2008. 266(5): p. 755-762.

13. Engin, B., Aydaş, C. and Demirtaş, H. Study of the Thermoluminescence Dosimetric Properties of Window Glass. *Radiation Effects & Defects in Solids: Incorporating Plasma Science & Plasma Technology*, 2010. 165(1): p. 54-64.

14. Natarajan, V., et al. Photoluminescence, Thermally Stimulated Luminescence and Electron Paramagnetic Resonance of Europium-ion Doped Strontium Pyrophosphate. *Materials Research Bulletin*, 2004. 39(13): p. 2065-2075.

15. Raghavaiah, B., et al. Thermoluminescence Studies on $PbO–2O_3–2O_3$ Glasses Doped with Iron Ions. *Optical Materials*, 2007. 29(5): p. 566-572.

16. Santos, C., et al. Thermoluminescence of Aluminophosphate Glasses in the Metaphosphate Composition. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 2006. 246(2): p. 374-378.

17. Rojas, S., et al. Undoped and Calcium Doped Borate Glass System for Thermoluminescent Dosimeter. *Journal of Non-Crystalline Solids*, 2006. 352(32): p. 3608-3612.

18. Liu, L., et al. Thermoluminescence Characteristics of SrB6O10:Tb. *Journal of Rare Earths*, 2006. 24(3): p. 276-280.

19. Kim, D.-N., et al. Thermal and Electrical Properties of $BaO–B_2O_3–ZnO$ Glasses. *Journal of Non-Crystalline Solids*, 2002. 306(1): p. 70-75.

20. Le Bourhis, E. Glass: Mechanics and Technology. 2008: John Wiley & Sons.

21. Zachariasen, W. H. The Atomic Arrangement in Glass. *Journal of the American Chemical Society*, 1932. 54(10): p. 3841-3851.

22. Elkholy, M. Thermoluminescence of $B_2O_3–Li_2O$ Glass System Doped with MgO. *Journal of Luminescence*, 2010. 130(10): p. 1880-1892.

23. Debenedetti, P. G. and Stillinger, F. H. Supercooled Liquids and the Glass Transition. *Nature*, 2001. 410(6825): p. 259-267.

24. Pradhan, A., Thermoluminescence Dosimetry and Its Applications. *Radiation Protection Dosimetry*, 1981. 1(3): p. 153-167.

25. El-Faramawy, N., et al., The Dosimetric Properties of In-House Prepared Copper Doped Lithium Borate Examined using the TL-technique. *Radiation Physics and Chemistry*, 2000. 58(1): p. 9-13.

26. Keszler, D. A. Synthesis, Crystal Chemistry and Optical Properties of Metal Borates. *Current Opinion in Solid State and Materials Science*, 1999. 4(2): p. 155-162.

27. Moryc, U. and Ptak, W. Infrared Spectra of β-BaB_2O_4 and LiB_3O_5: New Nonlinear Optical Materials. *Journal of Molecular Structure*, 1999. 511: p. 241-249.

28. Zachariasen, W. The Crystal Structure of Lithium Metaborate. *Acta Crystallographica*, 1964. 17(6): p. 749-751.

29. König, H. and Hoppe, R. Über Borati der Alkalimetalle. II. Zur Kenntnis von LiB3O5 [1]. Zeitschrift für Anorganische und Allgemeine Chemie, 1978. 439(1): p. 71-79.

30. Krogh-Moe, J. The Crystal Structure of Lithium Diborate, Li_2O. $2B_2O_3$. *Acta Crystallographica*, 1962. 15(3): p. 190-193.

31. Ogorodnikov, I., et al., Thermally Stimulated Luminescence and Lattice Defects in Crystals of Alkali Metal Borate LiB_3O_5(LBO). *Radiation Measurements*, 2001. 33(5): p. 577-581.

32. Iwai, M., et al. Crystal Growth and Optical Characterization of Rare-Earth (Re) Calcium Oxyborate $ReCa_4O(BO_3)_3$ (Re= Y or Gd) as New Nonlinear Optical Material. *Japanese Journal of Applied Physics*, 1997. 36(3A): p. L276.

33. Yang, Z., et al. Photon Cascade Luminescence of Gd^{3+} in $GdBaB_9O_{16}$. *Journal of Alloys and Compounds*, 2000. 308(1): p. 94-97.

34. He, M., et al. The Ternary System Li_2O–Al_2O_3–B_2O_3: Compounds and Phase Relations. *Journal of Solid State Chemistry*, 2002. 165(1): p. 187-192.

35. Dewey Jr, C., et al. Frequency Doubling in $KB_5O_8 \cdot 4H_2O$ and $NH_4B_5O_8 \cdot 4H_2O$ to 217.3 nm. *Applied Physics Letters*, 1975. 26(12): p. 714-716.

36. Chuangtian, C., et al. Lithium Borate, Laser Systems. 1989, Google Patents.

37. Wu, Y., et al. CsB_3O_5: A New Nonlinear Optical Crystal. *Applied Physics Letters*, 1993. 62(21): p. 2614-2615.

38. Chen, C.-T. *Linear System Theory and Design*. 1995: Oxford University Press, Inc.
39. Vij, D. *Luminescence of Solids*, 1998. Plenum Press: New York.
40. Ghose, D., Hippler, R. and Vij, D. *Luminescence of Solids*. 1998, Plenum Press, New York USA.
41. Furetta, C. *Handbook of Thermoluminescence*. 2003: World Scientific.
42. Wiedemann, E. Florescence and Phosporesence. *Annual Physical Chemistry*, 1888. 34: p. 446-463.
43. Selli, N. T. and Tunali, A. Using of Photoluminescent Tile for Evacuation of the Buildings During Electrical Failure.
44. Claude, F. *Luminescence—Encyclopedia of Inorganic Chemistry*. 1984, New York: Academic Press.
45. McKeever, S. W. *Thermoluminescence of Solids*. Vol. 3. 1988: Cambridge University Press.
46. McKeever, S. *Thermoluminesce of Solids*. Cambridge Solid State Science Series (Cambridge University Press, 1985), 1985.
47. Bos, A. Theory of Thermoluminescence. *Radiation Measurements*, 2006. 41: p. S45-S56.
48. Horowitz, Y. S. Thermoluminescence and Thermoluminescent Dosimetry, v.1. 1984.
49. Alaei, P. Introduction to Health Physics. *Medical Physics*, 2008. 35(12): p. 5959-5959.
50. Yaakob, N. H., et al. Thermoluminescence Response of Ge-and Al-doped Optical Fibers Subjected to Low-dose Electron Irradiation. *Journal Of Nuclear Science and Technology*, 2011. 48(7): p. 1115-1117.
51. Chen, R. and Horowitz, Y. *Thermoluminescence and Thermoluminescent Dosimetry*. 1984, Edited by: Horowitz, YS.
52. McKeever, S., Lewandowski, A. and Markey, B. A New Look at Thermoluminescence Kinetics. *Radiation Protection Dosimetry*, 1993. 47(1-4): p. 9-16.
53. Ha, V. T. T., et al. Preparation and Characteristics of LiF: Mg, Cu, Na, Si Thermoluminescent Material. *Journal of Science, Mathematics-Physics*, 2007. 23: p. 225-231.

54. Bilski, P. Lithium Fluoride: from LiF: Mg, Ti to LiF: Mg, Cu, P. Radiation Protection Dosimetry, 2002. 100(1-4): p. 199-205.

55. Kim, J., et al. The Glow Curve Structure for the LiF: Mg, Cu, Na, Si TL Detector with Dopants Concentrations and Sintering Temperatures. *Radiation Measurements*, 2004. 38(4): p. 435-438.

56. Kim, H.-J., et al. Thermoluminescence Dosimetric Properties of LiF (Mg, Cu, Na, Si). *J. Korean Phys. Soc*, 1989. 22: p. 415-420.

57. Tang, K., et al. On the Roles of Dopants in LiF: Mg, Cu, Si Thermoluminescent Material. *Radiation Protection Dosimetry*, 2013. 155(2): p. 141-145.

58. Azorin, J. Preparation Methods of Thermoluminescent Materials for Dosimetric Applications: An Overview. *Applied Radiation and Isotopes*, 2014. 83: p. 187-191.

59. Azorín, J., et al. Preparation and Thermoluminescence Properties of Aluminium Oxide Doped with Europium. *Radiation Protection Dosimetry*, 2002. 100(1-4): p. 277-279.

60. Santiago, M., et al. Radioluminescence of Rare-Earth Doped Aluminum Oxide. *Applied Radiation and Isotopes*, 2012. 71: p. 15-17.

61. Schulman, J., Kirk, R. and West, E. *Use of Lithium Borate for Thermoluminescence Dosimetry*. 1967, Naval Research Lab., Washington, DC.

62. Manam, J. and Sharma, S. Evaluation of Trapping Parameters of Thermally Stimulated Luminescence Glow Curves in Cu-doped $Li_2B_4O_7$ Phosphor. *Radiation Physics and Chemistry*, 2005. 72(4): p. 423-427.

63. Santiago, M., et al., Thermoluminescence of sodium Borate Compounds Containing Copper. *Journal of Materials Science Letters*, 1998. 17(15): p. 1293-1296.

64. Manam, J. and Sharma, S. Thermally Stimulated Luminescence Studies of Undoped and Doped $K_2B_4O_7$ Compounds. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 2004. 217(2): p. 314-320.

65. Rojas, S., K. Yukimitu and A. C. Hernandes. Dosimetric Properties of UV Irradiated Calcium Co-Doped Borate Glass–Ceramic. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 2008. 266(4): p. 653-657.

66. Tekin, E., et al. Thermoluminescence Studies of Thermally Treated CaB_4O_7:Dy. *Radiation Measurements*, 2010. 45(7): p. 764-767.
67. Santiago, M., et al. Thermoluminescence of Strontium Tetraborate. *Physica Status Solidi (a)*, 1998. 167(1): p. 233-236.
68. Santiago, M., et al. Thermo-and Radioluminescence of Undoped and Dy-doped Strontium Borates Prepared by Sol-Gel Method. *Radiation Measurements*, 2011. 46(12): p. 1488-1491.
69. Li, J., et al. Thermally Stimulated Luminescence Studies for Dysprosium Doped Strontium Tetraborate. *Radiation Measurements*, 2005. 39(2): p. 229-233.
70. Prokic, M. MgB_4O_7: Mn as a New TL Dosemeter. *Radiation Protection Dosimetry*, 1993. 47(1-4): p. 191-193.
71. Furetta, C., et al. Dosimetric Characterisation of a New Production of MgB_4O_7:Dy, Na Thermoluminescent Material. *Applied Radiation and Isotopes, 2000*. 52(2): p. 243-250.
72. Santiago, M., et al. Thermoluminescence of SrB_4O_7:Dy. *Physica Status Solidi (a)*, 2001. 185(2): p. 285-289.
73. Shani, G. *Radiation Dosimetry Instrumentation and Methods*. 2000: CRC Press.
74. Schauer, D. B., A. Sayeg. J. Handbook of Radioactivity Analysis. Second Edition ed. 2003, Great Britan: Academic Press.
75. Kortov, V. Materials for Thermoluminescent Dosimetry: Current Status and Future Trends. *Radiation Measurements*, 2007. 42(4): p. 576-581.
76. Garlick, G. and Gibson, A. The Electron Trap Mechanism of Luminescence in Sulphide and Silicate Phosphors. *Proceedings of the Physical Society*, 1948. 60(6): p. 574.
77. Rawat, N., et al. Use of Initial Rise Method to Analyze a General-Order Kinetic Thermoluminescence Glow Curve. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 2009. 267(20): p. 3475-3479.
78. Chen, R., Glow Curves With General Order Kinetics. *Journal of the Electrochemical Society*, 1969. 116(9): p. 1254-1257.

79. Balarin, M. Direct Evaluation of Activation Energy from Half-Width of Glow Peaks and a Special Nomogram. *Physica Status Solidi (a)*, 1975. 31(2): p. K111-K114.

80. Balarin, M. Half-Width and Asymmetry of Glow Peaks and Their Consistent Analytical Representation. *Journal of Thermal Analysis*, 1979. 17(2): p. 319-332.

81. Jones, D. The Calculation of Effective Atomic Number, Z. *The British Journal of Radiology*, 1979. 52(616): p. 330-331.

82. Prokic, M. Dosimetric Properties of $Li_2B_4O_7$:Cu, Ag, P Solid TL Detectors. 2002.

83. Pekpak, E., Yilmaz, A. and Ozbayoglu, G. An Overview on Preparation and TL Characterization of Lithium Borates for Dosimetric Use. *The Open Mineral Processing Journal*, 2010. 3(1).

84. Chen, R. and McKeever, S. W. *Theory of Thermoluminescence and Related Phenomena*. Vol. 200. 1997: World Scientific.

85. Mahesh, K., Weng, P.-s. and Furetta, C. *Thermoluminescence in Solids and its Applications*. 1989.

86. Hunda, B., et al. Effect of Melt Composition on the Luminescent Properties of Czochralski-Grown $Li_2B_4O_7$ Single Crystals. *Inorganic Materials*, 2005. 41(9): p. 990-994.

87. Kayhan, M. Effect of Synthesis and Doping Methods on Thermoluminescence Glow Curves of Manganese Doped Lithium Tetraborate. 2009, MS Thesis, Middle East Technical University, Turkey.

88. Furetta, C., et al. Thermoluminescent (TL) Properties of the Perovskite KMgF 3 Activated by Ce and Er Impurities. *Applied Radiation and Isotopes*, 2001. 55(4): p. 533-542.

89. Alajerami, Y. S. M., et al. Dosimetric Characteristics of a LKB: Cu, Mg solid Thermoluminescence Detector. *Chinese Physics Letters*, 2013. 30(1): p. 017801.

90. Randall, J. and Wilkins, M. Phosphorescence and Electron Traps. I. The study of Trap Distributions. in *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*. 1945. The Royal Society.

91. Takenaga, M., Yamamoto, O. and Yamashita, T. Preparation and Characteristics of $Li_2B_4O_7$: Cu phosphor. *Nuclear Instruments and Methods*, 1980. 175(1): p. 77-78.

92. Lakshmanan, A., Bhatt, R. and Supe, S. Mechanism of Nonlinearity in the Response Characteristics of Thermoluminescent Dosimeters. *Journal of Physics D: Applied Physics*, 1981. 14(9): p. 1683.

93. Manam, J. and Sharma, S. Thermally Stimulated Luminescence Studies of Undoped and Doped CaB_4O_7 Compounds. *Semiconductor Physics Quantum Electronics and Optoelectronics*, 2003. 6(4): p. 465-470.

94. Pekpak, E., Yilmaz, A. and Özbayoglu, G. An Overview on Preparation and TL Characterization of Lithium Borates for Dosimetric Use. *Open Mineral Processing Journal*, 2010. 3(1): p. 14-24.

95. Xiong, Z. Y., et al. Thermoluminescence Spectra of Lithium Tetraborate Single Crystal. in *Advanced Materials Research*. 2011. Trans Tech Publ.

96. Özdemir, Z., Özbayoğlu, G. and Yilmaz, A. Investigation of Thermoluminescence Properties of Metal Oxide Doped Lithium Triborate. *Journal of Materials Science*, 2007. 42(20): p. 8501-8508.

97. Takenaga, M., Yamamoto, O. and Yamashita, T. A New Phosphor $Li_2B_4O_7$:Cu for TLD. *Health Physics*, 1983. 44(4): p. 387-393.

98. Lorrain, S., et al. A Study of New Preparations of Radiothermoluminescent Lithium Borates with Various Activators. *Radiation Protection Dosimetry*, 1986. 17(1-4): p. 385-392.

99. Puppalwar, S., et al. Luminescence Characteristics of Li_2NaBF_6:Cu Phosphor. Nuclear Instruments and Methods in *Physics Research Section B: Beam Interactions with Materials and Atoms*, 2012. 274: p. 167-171.

100. Manam, J. and Sharma, S. Thermally Stimulated Luminescence Studies of BaB_4O_7 Compound. *Journal of Materials Science*, 2004. 39(20): p. 6203-6208.

101. Sanchez, G., et al. ESR-Thermoluminescence Correlation Studies of sodium and Lithium Diborate Compounds. *Journal of Physics: Condensed Matter*, 1989. 1(12): p. 2235.

102. El-Faramawy, N. A., et al. The Dosimetric Properties of In-house Prepared Copper Doped Lithium Borate Examined using the TL-technique. *Radiation Physics and Chemistry*, 2000. 58(1): p. 9-13.

103. Manam, J. and Sharma, S. Evaluation of Trapping Parameters of Thermally Stimulated Luminescence Glow Curves in Cu-doped $Li_2B_4O_7$ Phosphor. *Radiation Physics and Chemistry*, 2005. 72(4): p. 423-427.

104. Proki_, M. Dosimetric Characteristics of $Li_2B_4O_7$:Cu, Ag, P solid TL Detectors. *Radiation Protection Dosimetry*, 2002. 100(1-4): p. 265-268.

105. Tiwari, B. and Sabharwal. S. Investigations on the Solidification Behavior of $Li_2B_4O_7$. *Journal of Crystal Growth*, 2004. 273(1): p. 167-171.

106. Wall, B., et al. The Suitability of Different Preparations of Thermoluminescent Lithium Borate for Medical Dosimetry. *Physics in Medicine and Biology*, 1982. 27(8): p. 1023.

107. Pekpak, E., Yılmaz, A. and Özbayoğlu, G. The Effect of Synthesis and Doping Procedures on Thermoluminescent Response of Lithium Tetraborate. *Journal of Alloys and Compounds*, 2011. 509(5): p. 2466-2472.

108. Necmeddin Yazici, A., et al. Thermoluminescent Properties of $Sr_2P_2O_7$ Doped with Copper and Some Rare Earth Elements. *Journal of Luminescence*, 2010. 130(10): p. 1744-1749.

109. Mishra, G., et al. Thermoluminescence and Mechanoluminescence of Gamma-ray-irradiated SrB_4O_7:Dy Phosphors. *Micro & Nano Letters, IET*, 2011. 6(12): p. 978-981.

110. Gopal Reddy, C. and Narasimha Reddy, K. Pre-and Post-Irradiation Deformation Effects on the Thermoluminescence of KCl: Y Crystals. *Solid State Communications*, 1994. 92(3): p. 245-247.

111. Ilkay, L., Ozbayoglu, G. and Yilmaz, A. Synthesis. Characterizations and Investigation of Thermoluminescence Properties of Strontium Pyrophosphate Doped with Metals. *Radiation Physics and Chemistry*, 2014.

112. Meijerink, A., van Heek, M. M. E. and Blasse, G. Luminescence of Ag+ in Crystalline and Glassy SrB_4O_7. *Journal of Physics and Chemistry of Solids*, 1993. 54(8): p. 901-906.

113. Boutinaud, P. and Bill, H. Optical Centers Related to Silver in Ag^+ -doped Strontium Fluoride Crystals. *Journal of Physics and Chemistry of Solids*, 1996. 57(1): p. 55-64.

114. Verwey, J., Coronado, J. and Blasse, G. The Luminescence of Cu (I) in Strontium Tetraborate. *Journal of Solid State Chemistry*, 1991. 92(2): p. 531-536.

115. Blasse, G., Dirksen, G. J. and Meijerink, A. The Luminescence of Ytterbium(II) in Strontium Tetraborate. *Chemical Physics Letters*, 1990. 167(1–2): p. 41-44.

116. Meijerink, A., Jetten, H. and Blasse, G. Luminescence and Energy Transfer in Lead-Activated Strontium Haloborate (Sr, Pb)2B5O9X (X = Cl, Br). *Journal of Solid State Chemistry*, 1988. 76(1): p. 115-123.

117. Stefani, R., et al. Photoluminescent Behavior of SrB_4O_7:RE^{2+}(RE= Sm and Eu) Prepared by Pechini, Combustion and Ceramic Methods. *Journal of Solid State Chemistry*, 2006. 179(4): p. 1086-1092.

118. Sakirzanovas, S., et al. Concentration Influence on Temperature-Dependent Luminescence Properties of Samarium Substituted Strontium Tetraborate. *Journal of Luminescence*, 2012. 132(1): p. 141-146.

119. Lacam, A. and Chateau, C. High-Pressure Measurements at Moderate Temperatures in a Diamond Anvil Cell with a New Optical Sensor: SrB_4O_7:Sm^{2+}. *Journal of Applied Physics*, 1989. 66(1): p. 366-372.

120. Schipper, W. J., Meijerink, A. and Blasse, G. The Luminescence of Tm^{2+} in Strontium Tetraborate. *Journal of Luminescence*, 1994. 62(2): p. 55-59.

121. Seshagiri, T. K., et al. Spectroscopic and Luminescence Studies of thulium Doped Strontium Borate Glass. *Journal of Non-Crystalline Solids*, 2010. 356(20–22): p. 1032-1036.

122. Yavetskiy, R. P., et al. Radiation Defects in SrB_4O_7:Eu^{2+} crystals. *Journal of Alloys and Compounds*, 2007. 441(1–2): p. 202-205.

123. Su, Q., et al. Preparation of Divalent Rare Earth Ions in Air by Aliovalent Substitution and Spectroscopic Properties of Ln^{2+}. *Journal of Alloys and Compounds*, 2002. 344(1–2): p. 132-136.

124. Stefani, R., et al. Photoluminescent behavior of SrB_4O_7:RE^{2+} (RE=Sm and Eu) Prepared by Pechini, Combustion and Ceramic Methods. *Journal of Solid State Chemistry*, 2006. 179(4): p. 1086-1092.

125. Tanner, P. A., et al. Luminescence of Uranium-Doped Strontium Tetraborate (SrB4O7). *Journal of Physics and Chemistry of Solids*, 1997. 58(7): p. 1143-1146.

126. Mohapatra, M., et al., Investigation of Uranium Luminescence in SrB_4O_7 Matrix by Time Resolved Photoluminescence, Thermally Stimulated

Luminescence and Electron Spin Resonance Spectroscopy. *Journal of Alloys and Compounds*, 2014. 611(0): p. 74-81.

127. Bajaj, N. and Omanwar, S. Thermo Luminescence Study of SrB_4O_7: Cu Phosphor Prepared by Combustion Synthesis. in *International Journal of Modern Physics: Conference Series*. 2013. World Scientific.

128. Jiang, L., et al. Thermoluminescence Properties of Ce^{3+}-doped $LiSr_4(BO_3)_3$ Phosphor. *Materials Letters*, 2007. 61(29): p. 5107-5109.

129. Wu, L., et al. Structure Determination and Relative Properties of Novel Cubic Borates MM'4 (BO3) 3 (M= Li, M'= Sr; M= Na, M'= Sr, Ba). *Inorganic Chemistry*, 2005. 44(18): p. 6409-6414.

130. Lan, Z., Chengyu, L. and Qiang. S. Long Lasting Phosphorescence in Eu^{2+} and Ce^{3+} Co-Doped Strontium Borate Glasses. *Journal of Rare Earths*, 2006. 24(1): p. 196-198.

131. HUANG, Y., et al. Optical Properties of Eu^{2+}-doped Strontium Borate Glasses Containing F and Li^+ ions. *Journal of Rare Earths*, 2008. 26(4): p. 490-494.

132. Jiang, L., et al. Synthesis, Photoluminescence, Thermoluminescence and Dosimetry Properties of Novel Phosphor $KSr_4(BO_3)_3$:Ce. *Journal of Alloys and Compounds*, 2009. 482(1): p. 313-316.

133. Jiang, L. H., et al. Thermoluminescence Studies of $LiSrBO_3:RE^{3+}$ (RE=Dy, Tb, Tm and Ce). *Applied Radiation and Isotopes*, 2010. 68(1): p. 196-200.

134. Jiang, L., et al., Thermoluminescence Characteristics of $NaSr_4(BO_3)_3:Ce^{3+}$ Under β-ray Irradiation. *Journal of Rare Earths*, 2009. 27(2): p. 320-322.

135. Takenaga, M., Yamamoto, O. and Yamashita, T. Preparation and Characteristics of $Li_2B_4O_7$:Cu phosphor. *Nuclear Instruments and Methods*, 1980. 175(1): p. 77-78.

136. Jiang, L., et al. Thermoluminescence Studies of $LiSrBO_3:RE^{3+}$ (RE= Dy, Tb, Tm and Ce). *Applied Radiation and Isotopes*, 2010. 68(1): p. 196-200.

137. Liu, L., et al. Thermoluminescence Characteristics of SrB_6O_{10}:Tb. *Journal of Rare Earths*, 2006. 24(3): p. 276-280.

138. Li, J., et al. Thermally Stimulated Luminescence Studies for Dysprosium Doped Strontium Tetraborate. *Radiation Measurements*, 2005. 39(2): p. 229-233.

139. Manam, J. and Sharma,

S. K. Evaluation of Trapping Parameters of Thermally Stimulated Luminescence Glow Curves in Cu-doped $Li_2B_4O_7$ Phosphor. *Radiation Physics and Chemistry*, 2005. 72(4): p. 423-427.

140. Rawat, N., et al. TL and OSL Studies on Lithium Borate Single Crystals Doped with Cu and Ag. *Journal of Luminescence*, 2012. 132(8): p. 1969-1975.

141. Kelemen, A., et al. Thermoluminescence Characterization of Newly Developed Cu-doped Lithium Tetraborate Materials. *Radiation Physics and Chemistry*, 2012. 81(9): p. 1533-1535.

142. Hashim, S., et al. Dosimetric Characteristics of LKB:Cu,P Solid TL Detector. *Radiation Physics and Chemistry*, 2014.

143. Chopra, V., et al. TL Dosimetry of Nanocrystalline Li2B4O7:Cu Exposed to 150;MeV proton, 40;MeV and 90;MeV Electron Beam. *Radiation Physics and Chemistry*, 2014. 102(0): p. 5-10.

144. Chen, R. and McKeever, S. W. S. Characterization of Nonlinearities in the Dose Dependence of Thermoluminescence. *Radiation Measurements*, 1994. 23(4): p. 667-673.

145. McKeever, S. W., Moscovitch, M. and Townsend, P. D. Thermoluminescence Dosimetry Materials: Properties and Uses. 1995: Nuclear Technology Pub.

146. Podgorsak, E. Radiation Oncology Physics. A Handbook for Teachers and Students/EB Podgorsak.–Vienna: International Atomic Energy Agency, 2005. 657.

147. Tiwari, B. et al. Thermoluminescence Studies on Cu-doped $Li_2B_4O_7$ Single Crystals. *Journal of Luminescence*, 2010. 130(11): p. 2076-2083.

148. Furetta, C. Handbook of Thermoluminescence World Scientific Library, UK, (2010).

149. Oberhofer, M. and Scharmann, A. Applied Thermoluminescence Dosimetry. 1981: Adam Hilger Ltd.

150. McKeever, S. W. Optically Stimulated Luminescence Dosimetry. Nuclear Instruments and Methods in *Physics Research Section B: Beam Interactions with Materials and Atoms*, 2001. 184(1): p. 29-54.

151. Ege, A. T., et al. Determination of Thermoluminescence Kinetic Parameters of Li2B4O7: Cu, Ag, P. *Radiation Measurements*, 2007. 42(8): p. 1280-1284.

152. Driscoll, C., et al., The Thermoluminescence Properties of Lithium Borate Dosemeters. *Radiation Protection Dosimetry*, 1983. 6(1-4): p. 305-308.

153. Haack, K. and Majborn, B. Reactor Gamma Heat Measurements with Calorimeters and Thermoluminescence Dosimeters. *Nuclear Instruments and Methods*, 1973. 111(2): p. 283-286.

154. Pradhan, A., Bhatt, R. and Supe, S. Ultraviolet Dosimetry and Thermoluminescence Process in $Li_2B_4O_7$:Cu TLD Phosphor. *The International Journal of Applied Radiation and Isotopes*, 1983. 34(6): p. 941-943.

155. Martini, M., Paravisi, S. and Liguori, C. A New High Sensitivity Spectrometer for 3-D Thermoluminescence Analysis. *Radiation Protection Dosimetry*, 1996. 66(1-4): p. 447-450.

156. Gundurao, T., Sarwade, J. and Moharil, S. Correlated ESR, PL and TL Studies on Copper Activated Thermoluminescence Dosimetry Phosphors. *Radiation Effects and Defects in Solids*, 1996. 138(1-2): p. 177-184.

157. Kutomi, Y., Tomita, A. and Takeuchi, N. Thermally Stimulated Exoelectron Emission and Thermoluminescence in $Li_2B_4O_7$ Crystallized Glasses. *Physica Status Solidi (a)*, 1986. 97(2): p. K169-K172.

158. Ekdal, E., et al. Thermoluminescence Characteristics of $Li_2B_4O_7$ Single Crystal Dosimeters Doped with Mn. *Radiation Physics and Chemistry*, 2014. 96(0): p. 201-204.

159. McKeever, S. W., Moscovitch, M. and Townsend, P. D. Thermoluminescence Dosimetry Materials: Properties and Uses. 1995.

160. Darus, M. M. and Sahar, M. R. The Effect of Solution pH on P_2O_5-cullet-CaO Glass. 2000.

161. Sunitha, D. V., et al. Study on Low Temperature Solution Combustion Synthesized Sr_2SiO_4:Dy^{3+} Nano Phosphor for White LED. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 2014. 127(0): p. 381-387.

162. McKinlay, A. Thermoluminescence Dosimetry (Medical Physics Handbooks 5). 1981: Adam Hilger.

163. Chen, R. and Kirsh, Y. The Analysis of Thermally Stimulated Processes. 2013: Elsevier.

164. Bos, A. High Sensitivity Thermoluminescence Dosimetry. Nuclear Instruments and Methods in *Physics Research Section B: Beam Interactions with Materials and Atoms*, 2001. 184(1): p. 3-28.

165. Driscoll, C., et al. Annealing Procedures for Commonly used Radiothermoluminescent Materials. *Radiation Protection Dosimetry,* 1986. 14(1): p. 17-32.

166. Burgkhardt, B. and Piesch, E. Reproducibility of TLD Systems-A Comprehensive Analysis of Experimental Results. *Nuclear Instruments and Methods*, 1980. 175(1): p. 159-161.

167. da Rosa, L. A. R., Regulla, D. F. and Fill, U. A. Reproducibility Study of TLD-100 Micro-Cubes At Radiotherapy Dose Level. *Applied Radiation and Isotopes*, 1999. 50(3): p. 573-577.

168. Furetta, C. and Weng, P.-S. Operational Thermoluminescence Dosimetry. 1998: World Scientific.

169. Ferreira, C. C., et al. Total Mass Attenuation Coefficient Evaluation of Ten Materials Commonly used to Simulate Human Tissue. in *Journal of Physics: Conference Series*. 2010. IOP Publishing.

170. Jackson, D. F. and Hawkes, D. J. X-ray Attenuation Coefficients of Elements and Mixtures. Physics Reports, 1981. 70(3): p. 169-233.

171. Gerward, L., et al. X-ray Absorption in Matter. *Reengineering XCOM. Radiation Physics and Chemistry*, 2001. 60(1): p. 23-24.

172. Gowda, S., et al. Photon Mass Attenuation Coefficients, Effective Atomic Numbers and Electron Densities of Some Thermoluminescent Dosimetric Compounds. *Pramana*, 2004. 63(3): p. 529-541.

173. Ege, A. T., et al. Effect of Heating Rate on Kinetic Parameters of β-Irradiated $Li_2B_4O_7$:Cu, Ag, P in TSL Measurements. Measurement Science and Technology, 2007. 18(3): p. 889.

174. Jackson, D. F. and Hawkes. D. X-ray Attenuation Coefficients of Elements and Mixtures. *Physics Reports*, 1981. 70(3): p. 169-233.

175. Mayneord, W. On a Law of Growth of Jensen's Rat Sarcoma. *The American Journal of Cancer*, 1932. 16(4): p. 841-846.

176. McKeever, S. *Thermoluminescence of Solids*, 1985. Cambridge University, Cambridge.

177. Tengku Kamarul Bahri, T., et al. Thermoluminescence Properties of CaO–B_2O_3 Glass System Doped with GeO_2. *Radiation Physics and Chemistry*, 2014. 102: p. 103-107.

178. Prokić, M. Development of Highly Sensitive CaSO4 : Dy/Tm and MgB_4O_7:Dy/Tm Sintered Thermoluminescent Dosimeters. *Nuclear Instruments and Methods*, 1980. 175(1): p. 83-86.

179. Abdel-Baki, M., et al. Factors Affecting Optical Dispersion in Borate Glass Systems. *Journal of Physics and Chemistry of Solids*, 2007. 68(8): p. 1457-1470.

180. AnChiu, C., Xian, W. and Moss, C. F. Flying in Silence: Echolocating Bats Cease Vocalizing to Avoid Sonar Jamming. *Proceedings of the National Academy of Sciences of the United States of America*, 2008. 105(35): p. 13116-13121.

181. Shelby, J. E. and Ruller, J. Properties and Structure of Lithium Germanate Glasses. *Physics and Chemistry of Glasses*, 1987. 28(6): p. 262-268.

182. Ahmed, M., Hogarth, C. and Khan, M. A Study of the Electrical and Optical Properties of the GeO_2-TeO_2 Glass System. *Journal of Materials Science*, 1984. 19(12): p. 4040-4044.

183. Pickett, S., Carriedo, S. and Wang, C. Determining the Signal-to-Noise Ratio and Optimal Photomultiplier Gain Setting in the GenePix 4000B. 2001, Axon Instruments, Inc.

184. Obayes, H. K., et al. A New Strontium/Copper Co-doped Lithium Borate Glass Composition with Improved Dosimetric Features. *Journal of Luminescence*, 2016. 176: p. 202-211.

185. Obayes, H. K., et al. Strontium Ions Concentration Dependent Modifications on Structural and Optical Features of $Li_4Sr(BO_3)_3$ Glass. *Journal of Molecular Structure*, 2016. 1111: p. 132-141.

186. Saidu, A., et al. Structural Properties of Zinc Lithium Borate Glass. *Optics and Spectroscopy*, 2014. 117(3): p. 396-400.

187. Murugan, G. S. and Varma, K. Lithium Borate–Strontium Bismuth Tantalate Glass Nanocomposite: A Novel Material for Nonlinear Optic and Ferroelectric Applications. *Journal of Materials Chemistry*, 2002. 12(5): p. 1426-1436.

188. Obayes, H. K., et al. Structural and Optical Properties of Strontium/Copper Co-doped Lithium Borate Glass System. *Materials & Design*, 2016. 94: p. 121-131.

189. Pal Singh, G., et al. Investigation of Structural, Physical and Optical Properties of CeO_2–Bi_2O_3–B_2O_3 Glasses. *Physica B: Condensed Matter*, 2012. 407(21): p. 4168-4172.

190. Singh, G. P., et al. Density and FTIR Studies of Multiple Transition Metal Doped Borate Glass. *Materials Physics and Mechanics*, 2012. 14: p. 31-36.

191. Pal Singh, G. and Singh, D. Spectroscopic Study of ZnO doped CeO_2–PbO–B_2O_3 Glasses. *Physica B: Condensed Matter*, 2011. 406(18): p. 3402-3405.

192. Pal Singh, G. and Singh, D. Modification in Structural and Optical Properties of CeO_2 doped BaO–B_2O_3 Glasses. *Journal of Molecular Structure*, 2012. 1012: p. 137-140.

193. Pisarski, W. A., Pisarska, J. and Ryba-Romanowski, W. Structural Role of Rare Earth Ions in Lead Borate Glasses Evidenced by Infrared Spectroscopy: $BO_3 \leftrightarrow BO_4$ Conversion. *Journal of Molecular Structure*, 2005. 744: p. 515-520.

194. Singh, G. P., et al. Modification in Structural and Optical Properties of ZnO, CeO_2 Doped Al_2O_3–PbO–B_2O_3 Glasses. *Physica B: Condensed Matter*, 2012. 407(8): p. 1250-1255.

195. Juline, C., et al., Infrared Studies of the Structure of Borate Glass. Mater. Sci. Eng., B, 1989. 3: p. 307-312.

196. Gaafar, M., et al. Elastic Properties and Structural Studies on Some Zinc-Borate Glasses Derived from Ultrasonic, FT-IR and X-ray Techniques. *Journal of Alloys and Compounds*, 2009. 475(1): p. 535-542.

197. Singh, D., et al. Optical and Structural Properties of Li_2O–Al_2O_3–B_2O_3 Glasses Before and After γ-irradiation Effects. *Journal of Applied Physics*, 2008. 104(10): p. 103515-103515-5.

198. Gandhi, Y., et al. Influence of WO3 on Some Physical Properties of MO–$_2O_3$–B $_2O_3$(M= Ca, Pb and Zn) Glass System. *Journal of Alloys and Compounds*, 2009. 485(1): p. 876-886.

199. Sharma, G., et al. Effects of Gamma Irradiation on Optical and Structural Properties of PbO–Bi_2O_3–B_2O_3 Glasses. *Radiation Physics and Chemistry*, 2006. 75(9): p. 959-966.

200. Husung, R. D. and Doremus, R. H. The Infrared Transmission Spectra of Four Silicate Glasses Before and After Exposure to Water. *Journal of Materials Research*, 1990. 5(10): p. 2209-2217.

201. Dunken, H. and Doremus, R. H. Short Time Reactions of a Na_2O-CaO-SiO_2 Glass with Water and Salt Solutions. J*ournal of Non-Crystalline Solids*, 1987. 92(1): p. 61-72.

202. Dimitrov, V. and Komatsu, T. An Interpretation of Optical Properties of Oxides and Oxide Glasses in Terms of the Electronic Ion Polarizability and Average Single Bond Strength. *J. Univ. Chem. Technol. Metall*, 2010. 45(3): p. 219-250.

203. Awang, F. N. M. R. S. S. K. G. R. J. A. M. R. D. A., Spectral Investigation of Sm^{3+}/Yb^{3+}co-doped Sodium Tellurite Glass. *Chinese Optics Letters* (2013). 11(6): p. 61605.

204. Obayes, H. K., et al. Strontium Ion Concentration Effects on Structural and Spectral Properties of $Li_4Sr(BO_3)_3$ Glass. *Journal of Non-Crystalline Solids*, 2015. 427: p. 83-90.

205. El-Alaily, N. and Mohamed, R. Effect of Irradiation on Some Optical Properties and Density of Lithium Borate Glass. *Materials Science and Engineering: B*, 2003. 98(3): p. 193-203.

206. Elfayoumi, M., et al. Spectroscopic Studies of Sm^{3+} and Eu^{3+} Co-doped Lithium Borate Glass. *Journal of Alloys and Compounds*, 2010. 492(1): p. 712-716.

207. Gedam, R. S. and Ramteke, D. D. Electrical and Optical Properties of Lithium Borate Glasses Doped with Nd_2O_3. *Journal of Rare Earths*, 2012. 30(8): p. 785-789.

208. Alajerami, Y. S. M., et al. Optical Properties of Lithium Magnesium Borate Glasses Doped with Dy^{3+} and Sm^{3+} Ions. *Physica B: Condensed Matter*, 2012. 407(13): p. 2398-2403.

209. Pal Singh, G. and Singh, D. P. Effect of WO_3 on Structural and Optical Properties of CeO_2–PbO–B_2O_3 Glasses. *Physica B: Condensed Matter*, 2011. 406(3): p. 640-644.

210. Singh, G. P. and Singh, D. Spectroscopic Study of ZnO Doped CeO_2–PbO–B_2O_3 Glasses. *Physica B: Condensed Matter*, 2011. 406(18): p. 3402-3405.

211. Dimitrov, V. and Komatsu, T. Classification of Simple Oxides: A Polarizability Approach. *Journal of Solid State Chemistry*, 2002. 163(1): p. 100-112.

212. Duffy, J. Chemical Bonding in the Oxides of the Elements: A New Appraisal. *Journal of Solid State Chemistry*, 1986. 62(2): p. 145-157.

213. Dimitrov, V. and Sakka, S. Electronic Oxide Polarizability and Optical Basicity of Simple Oxides. *I. Journal of Applied Physics*, 1996. 79(3): p. 1736-1740.

214. Obayes, H. K., et al. Thermoluminescence Properties of Lithium Borate Glass Subjected To 60-CO Gamma Ray. *Jurnal Teknologi*, 2015. 76(13).

215. Lim, T. Y., et al. Thermoluminescence Response of Dysprosium Doped Strontium Tetraborate Glasses Subjected to Electron Irradiations. *Applied Radiation and Isotopes*, 2015. 102: p. 10-14.

216. Saidu, A., et al. Thermoluminescence Characteristics of Zinc Lithium Borate Glass Activated with Cu^+ ($ZnO–Li_2O–B_2O_3$: Cu^+) for Radiation Dosimetry. *Journal of Radioanalytical and Nuclear Chemistry*, 2014: p. 1-6.

217. Obayes, H. K., et al. Thermoluminescence Response of Nanoparticles Gold Doped Lithium Borate Glass Subjected To Photon Irradiation. *Jurnal Teknologi*, 2015. 77(1).

218. Jiang, L., et al. Thermoluminescence Properties of Ce^{3+}- Doped $LiSr_4(BO_3)_3$ Phosphor. *Materials Letters*, 2007. 61(29): p. 5107-5109.

219. Alajarami, Y., Thermoluminescence and Optical Characteristics of Lithium Potassium Borate Glass for Radiation Therapy Dose Measurement. 2014.

220. Aboud, H., Fundamental Properties of Cu-Doped and Co-doped SnO2 of Lithium Potassium Borate Glass Exposed to Photn Below 4 Gy. (2013).

221. Xiong, Z., Zhang, C. and Tang, Q. Thermoluminescence characteristics of $Li_2B_4O_7$:Cu, Ag, P. *Chinese Science Bulletin*, 2007. 52(13): p. 1776-1779.

222. Tugay, H., et al. The Thermoluminescent Properties of Natural Calcium Fluoride for Radiation Dosimetry. Nuclear Instruments and Methods in *Physics Research Section B: Beam Interactions with Materials and Atoms*, 2009. 267(23): p. 3640-3651.

223. Haydar Aboud, H. A., et al. Photoluminescence and Thermoluminescence Properties of SnO2 Nanoparticles Embedded in Li_2O-K_2O-B_2O_3 with Cu-Doping (Chinese Title: Photoluminescence and Thermoluminescence Properties of SnO_2 Nanoparticles Embedded in Li_2O-K_2O-B_2O_3 with Cu-Doping). *Chinese Optics Letters*, 2013. 11(9): p. 1603.

224. Alajarami, Y. Thermoluminescence and Optical Characteristics of Lithium Potassium Borate Glass for Radiation Therapy Dose Measurement., in *Physics*. 2014, Universiti Technologi Malaysia.

225. Refaei, A., Wagiran, H. and Saeed, M. Thermoluminescence Properties of Optical Fibers Doped with RE^{+3} (RE= Sm, Nd) Ions Subjected to X-Ray Irradiation. in *Applied Mechanics and Materials*. 2014. Trans Tech Publ.

226. Cameron, J. R., Suntharalingam, N. and Kenney, G. N. Thermoluminescent Dosimetry. 1968.

227. Azorín, J. Determination of Thermoluminescence Parameters from Glow Curves—I. A Review. *International Journal of Radiation Applications and Instrumentation. Part D. Nuclear Tracks and Radiation Measurements*, 1986. 11(3): p. 159-166.

228. Mhareb, M., et al. Thermoluminescence Properties of Lithium Magnesium Borate Glasses System Doped with Dysprosium Oxide. *Luminescence*, 2015.

229. Hubbell, J. H. and Seltzer, S. M. Tables of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients. 1996. National Institute of Standards and Technology http://physics. nist. gov/PhysRefData/XrayMassCoef, 2003.