Thermoluminescence study and evaluation of trapping parameters of samarium doped barium silicate phosphor

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**ARTICLE**

**ABSTRACT**

We report the detailed analysis of thermoluminescence (TL) glow curves and the evaluation of kinetic parameters of Sm\(^{2+}\)-incorporated BaSi\(_2\)O\(_5\). The effect of various heating rates on TL kinetics and glow peak temperatures of Sm\(^{2+}\)-doped BaSi\(_2\)O\(_5\) phosphors exposed to beta particle irradiation at room temperature are investigated. The glow curve of the phosphor exposed to \(\beta\)-irradiation consists of two main peaks with maxima at about 91°C and 193°C and exhibits good linearity between 1 and 10 Gy. The activation energies and frequency factors of trap centers involved in the TL emission were calculated from the TL glow curve of the sample by means of variable heating rate (VHR), repeated initial rise (RIR), and computerized glow-curve deconvolution (CGCD). Analysis of the main dosimetric peak techniques indicate that activation energies (\(E\)) and pre-exponential factor (\(s\)) vary between 0.93 and 1.72 eV, \(10^{10}\) and \(10^{13}\) s\(^{-1}\). It is found that the temperature of the glow peaks shifts toward the higher temperatures and the TL intensity smoothly decreases as the heating rate increases. The behavior of the TL intensities and glow peak temperatures as a function of the heating rate are discussed with regards to thermal quenching.

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1. Introduction

There are many factors in choosing an ideal and useful dosimetric material for luminescence studies. As one of the most significant compounds, silicates are extensively used as the matrix of inorganic phosphors due to their advantages such as easy synthesis, good thermal quenching, high chemical stability, and ideal excitation and emission wavelengths [1,2]. Especially, alkaline-earth silicates are appropriate compounds as radiation detectors due to their water resistance and chemical stability, and exceptional storage luminescence properties have been exploited for dosimetry [3–6]. The barium silicate compound comprises different compositions as a host material with the various ratios of BaO and SiO\(_2\), namely Ba\(_2\)SiO\(_4\), Ba\(_3\)SiO\(_5\), Ba\(_3\)Si\(_2\)O\(_7\), Ba\(_2\)Si\(_2\)O\(_7\), and Ba\(_2\)Si\(_2\)O\(_7\) [7]. Among them, BaSi\(_2\)O\(_5\) has attracted much attention by aiming a potential in luminescence investigations especially, Eu-doped BaSi\(_2\)O\(_5\) phosphors [2,6,8–10] are stated to be a potential candidate for white light-emitting diodes, field emission displays, and TL dosimetry. Doping may either cause the formation of new defect centers or recovering of existing levels within the bandgap for a defective host which changes both the optical and electronic features of the materials. Therefore, it is of great importance by choosing both the dopant and its concentration for the preparation of luminescence materials. Nakauchi et al. [6] reported that Eu\(^{2+}\)-doped BaSi\(_2\)O\(_5\) presented linear thermoluminescence (TL) dose–response between 0.01 and 1000 mGy where the material could be used in imaging plates. Recently, Abdel-Hameed et al. [11] presented the photoluminescence properties of newly produced Gd\(^{3+}\) and Mn\(^{2+}\) co-doped BaSi\(_2\)O\(_5\) yellow phosphor and reported that the phosphor is potential for practical application and optical devices. As an activator, the Sm\(^{3+}\) ion is regarded as one of the most popular and efficient doping ions among the different rare-earth ions since the compounds doped with Sm\(^{3+}\) ions present a narrow line emission profile and a long lifetime [12]. Besides, the trivalent samarium has potential applications in high-density optical storage, solid-state lightening, temperature sensors, color displays, etc. [13]. It is also reported that Sm\(^{3+}\) acts as an electron trap and may be simultaneously recombination and luminescent centers [14].

While there may seem to be limited novelty in work on materials that are used in commercial applications, there is an ongoing need to identify factors that can be exploited. The current article offers new data on luminescence ceramic materials (LCM). The example of rare-earth-doped BaSi\(_2\)O\(_5\) shows specific properties
that can be employed in the glaze and glass industries. They also have relevance for improvements in solar cell production. It is worth noting that it is hard to find and extract barium silicate in nature as a mineral. Furthermore, Sm-doped phosphors have potential as orange phosphor for practical application and optical devices. The glass industry has existed for millennia and progress and innovation thus appear slow, but the small steps highlighted here do constitute innovation and are of commercial relevance.

In the current study, we focused on BaSi$_2$O$_5$ phosphor doped with Sm$^{3+}$ ions synthesized via gel combustion method at various concentrations to investigate its TL characteristics and to search whether we obtain a promising material for TL dosimetry. A detailed investigation of produced TL glow curves using different optical filters and dopant concentrations was done. The influence of TL dosimetric behaviors, namely dose–response, heating rate, and repeatability on the TL glow curve of the phosphor, was reported. Moreover, the order of kinetics ($b$), trap depth ($E$) and frequency factor ($s$) has been systematically conducted using various heating rates (VHR), repeated initial rise (RIR) with $T_{\text{m}}-T_{\text{stop}}$ analysis, and computerized glow-curve deconvolution (CGCD) methods. The effect of thermal quenching causing a shift of the TL glow peaks toward the high-temperature regions by the changing heating rate was discussed in detail and the required parameters were calculated.

2. Materials and methods

BaSi$_2$O$_5$ (naturally known as sanbornite) nanomaterials incorporated with lanthanide ions were prepared by the gel combustion method. High-purity barium carbonate (BaCO$_3$, Sigma-Aldrich ≥99.0%) and silicon dioxide (Merck, fumed, ≥99.0%) were used in the study. In the preparation of the samples, 1 mol of BaCO$_3$ is put in a quartz beaker and then is dissolved by adding 1 M HNO$_3$ on it. After adding 20 mL of ultrapure water, 2 mol of SiO$_2$ is added to the fumed beaker. The beaker is covered, and it is mixed well for 10 min at 80°C. Then 25 mol of glycerine and 25 mol of citric acid are added as reducing fuel. Following this, they are covered by a watch glass at the same temperature and stirred with a magnetic stirrer for 1 h. At the end of the period, the beaker is opened, and excess water is removed at the same temperature until the gel becomes a consistency. The colorless, viscous, and consistent gel is placed in the microwave oven in the fume cupboard and a combustion reaction is performed. To complete the combustion reaction of the ceramic materials obtained and to remove the organic residues, the samples are annealed at 1180°C for 2 h after the synthesis. Following this, the oven is closed and cooled in its natural state. One day later, the samples taken from the ash oven are washed once with pH 3.2 acetic acid solution and twice with purified water, respectively, and nanomaterials filtered are then dried in an oven at 110°C. Samples are placed in a desiccator to cool which prevents the samples from gathering moisture while they cool. For the synthesis of Sm$^{3+}$-doped ceramic samples, these same experimental steps were implemented by adding nitrate salts of samarium in the appropriate molar ratio to the solution. High purity of Smelment (Sm (NO$_3$)$_3$, Merck >99.9%) is used and doping was made with different ratios (0.005; 0.01; 0.02; 0.03 and 0.07) of Sm (NO$_3$)$_3$, Merck >99.9%). Obtained BaSi$_2$O$_5$ phosphors with various mol% concentrations of Sm (III) nitrate were ground into the powder. Then, pellet-formed samples were prepared with a radius of 8 mm, ~1 mm of thickness and ~30 mg of weight for each required concentration for further measurements.

TL measurements have been conducted utilizing Lexasyg Smart TL/OSL reader system equipped with an internal $^{90}$Sr/$^{90}$Y beta source having 0.10 GBq dose rate at room temperature (RT) which emits 1.95 GBq beta radiation. Each TL signal and corresponding background signal were recorded then analyzed by subtracting the background signal from RT to 450°C with 2°C$^{-1}$ heating rate except the heating rate experiment. IRSL-TL 565-nm filter (Schott-BG 39-Glass 3 mm; AHF-BrightLine HC 575/25-Interference 5 mm; FWHM 31.1 nm) was selected in front of the photomultiplier tube and used for each TL measurements.

3. Results and discussions

3.1. XRD analysis

Phase purities of powder phosphors synthesized via a gel combustion method were investigated through XRD patterns of the non-doped (BaSi$_2$O$_5$) host and the samples incorporated with different Sm$^{3+}$ concentrations. Figure 1 represents the respective XRD patterns of BaSi$_2$O$_5$:xDy$^{3+}$ and BaSi$_2$O$_5$:xSm$^{3+}$ phosphors ($x = 0.005, 0.01, 0.02, 0.03, 0.07$), and standard pattern of Ba$_2$SiO$_5$ (JCPDS Card no. 98-001-5486). Note that dominant Miller indices of diffraction planes are only shown in Figure 1. The Ba$_2$SiO$_5$ exhibits two different crystal structures, namely high-temperature monoclinic structure and low-temperature orthorhombic structure. Nevertheless, the temperature studied here was selected to be 1180°C.

Taking into account the effective ionic radii of cations depending on different coordination numbers (CN), the effective ionic radii of Sm$^{3+}$ (CN6 = 0.96 Å, CN7 = 1.02 Å) is the closest to that of Ba$^{2+}$ ions (CN6 = 1.35 Å, CN7 = 1.38 Å). The introduction of Sm$^{3+}$ ions actually did not lead to any change in the crystal lattice but changes the lattice parameters due to dissimilar ionic radius between dopants and the
substituted for Ba$^{2+}$ ions, which may cause to generate the lattice strain too. There are still some traces although many attempts, including variation of sintering temperature, different fuel combination and time have been made, but these impurities do not influence the TL emission spectrum. When $x = 0.02$, an orthorhombic structure is formed completely with lattice parameters $a$ (Å) = 13.53, $b$ (Å) = 7.69 and $c$ (Å) = 4.63, $Z = 4$ and $V = 481.73$ Å$^3$, as shown in Figure 2. The lattice parameters $a$, $b$ or $c$ are linearly increasing with increasing $x$, which meets Vegar's law, implying that Ba$^{2+}$ is substituted by Sm$^{3+}$.

3.2. TL intensity dependence on the concentration of Sm

To identify the phosphor concentration with the maximum TL yield, optimization was performed by changing the dopant concentrations in BaSi$_2$O$_5$ host material. As an example, Figure 3a shows the results taken with the IRLS-TL 565-nm filter of samples doped with different concentrations of Sm. Both the low (91°C) and the high-temperature peaks (193°C) are perfectly observed in the sample doped with 3 mol% Sm. The graph of the change of the normalized area concerning all dopant concentrations is shown in Figure 3b. It is apparent from the data that with increasing Sm$^{3+}$ doping amount from 0.005 to 0.03, the number of luminescence centers is increased, and the maximum TL area enhances and, then reaches the highest value at $x = 0.03$. Nevertheless, any further increase of $x$ beyond the optimal concentration leads to a gradually decline in the maximum TL area due to the concentration quenching which destroys trap levels. For the TL study, 3 mol% Sm amounts were observed as the optimum concentration. For this reason, this concentration amount has been considered at all subsequent calculations and so BaSi$_2$O$_5$:0.03Sm$^{3+}$ has been used throughout the study.

3.3. Dose–response

The dose–response behavior of BaSi$_2$O$_5$:0.03Sm$^{3+}$ was also studied. In the experiment carried out to study the effect of dose dependence of the whole TL glow curve,
the chosen Sm-doped phosphor sample was exposed to β-ray source between 0.1 and 10 Gy. Figure 4a presents overall TL glow curves of BaSi₂O₅:0.03Sm³⁺ phosphor for various β doses. Overall TL glow curve consisted of 2 TL peaks centered at 91°C and 193°C, respectively. Figure 4a obviously indicates that the TL emission intensity ascends with the rising β dose up to 10 Gy for both the low (91°C) and the high-temperature peaks (193°C). In the literature, there are some studies on why the intensity of the TL glow peaks was enhanced with β-ray doses [15–17]. It was speculated that filling more and more traps with increasing dose amount causes an increase in the TL intensity. In the TL experiment, the trapped charge carriers with the heating were released and further recombined with their counterparts at the recombination centers (a trap and/or deep level) gave rise to the increase in TL intensity. Additionally, no shift in each TL glow peak positions (within the limits of experimental errors) was observed when the β dose was increased. Therefore, we suggest that the obtained glow curve in our study obey the first-order kinetics for two visible peak maxima. Furthermore, for the material to be used for different practical applications linear dose pattern needs to be obtained. For this purpose, in order to observe the dose behavior of the studied phosphor (i.e. BaSi₂O₅:0.03Sm³⁺), a graph of the total TL glow-curve area versus the irradiation dose is plotted on a log-log scale and the slope giving the value of b is then calculated. According to the obtained b value, it is decided whether the dose dependency is linear (b = 1), sublinear (b < 1) or superlinear (b > 1). Figure 4b also shows the linear response behavior of the BaSi₂O₅:0.03Sm³⁺ taking into account the total TL glow curve [18,19]. It is apparent from Figure 4b that there is a perfect linear relationship between 1 and 10 Gy with correlation coefficients squared (R²) 0.9997 for BaSi₂O₅:0.03Sm³⁺. Our findings show that the slope of the fitted line was approximately 1 which suggests that BaSi₂O₅:0.03Sm³⁺ phosphor depicts linear behavior.

3.4. Repeatability

Repeatability is one of the most important characteristics and another very useful property when considering practical applications of the phosphor samples [20]. Conventionally, the TL glow intensity of the compound scrutinized is expected to remain constant throughout the repetitions when it comes to dosimetric purposes. In order to study the repeatability of the phosphor sample at 5 Gy dose, BaSi₂O₅:0.03Sm³⁺ sample was used. The test was conducted for 10 consecutive cycles including thermal annealing, irradiation and reading with the same conditions for each annealing cycle. The TL glow curves were recorded from RT to 450°C with a constant
heating rate of 2 °C s⁻¹. Figure 4c illustrates the results after 10 repeated cycles. As can be seen from Figure 4d, the sample exhibited high repeatability at a standard deviation of 2.29%, which was acceptable for dosimetric applications according to Furetta’s work [21]. Therefore, we speculate that BaSi₂O₅:0.03Sm³⁺ phosphor may be a promising candidate for the usage in various dosimetric applications.

### 3.5. Evaluation of thermoluminescence kinetic parameters

#### 3.5.1. Effect of heating rate on the thermoluminescence

A considerable amount of literature presents various techniques for determining the trap parameters from the glow curves depending on TL kinetics. One of the
most common methods among these is the one obtained by repeating the experiment under the same conditions but using different heating rates during measurements of the TL glow peaks. In a typical TL experiment, the TL glow curves tend to shift toward the higher temperature regions as the heating rate increases [22,23]. Figure 5a shows the TL glow curves of BaSi2O5:0.035Sm3+ obtained by various heating rates (VHR method). At the heating rates of $\beta = 0.5^\circ \text{C s}^{-1}$, the TL glow curve of BaSi2O5:0.035Sm3+ consisted of two peaks with a maximum at around 72°C and 171°C. As expected, it is clearly seen that the TL glow curves of the sample smoothly shifted toward higher temperatures. There may be two plausible explanations for the observed pattern, namely (i) thermal quenching and (ii) temperature effects (the so-called distributed lag effect) [24]. (i) The luminescence efficiency may vary with the temperature and this may influence the TL results. Therefore, it is necessary to evaluate the area under the glow curve to see if there is a thermal quenching effect in the studied sample. Thermal quenching is out of the question if the area under the glow curve does remain constant with increasing the heating rate but in our case, as shown in Figure 5b the glow-curve area strongly decreases with increasing the heating rate. This finding indicates that thermal quenching phenomenon is dominant in the sample. Therefore, thermal quenching effects on the measured TL glow curve should be considered and the parameters of thermal quenching should be calculated.

As expressed previously mentioned, thermal quenching phenomenon distorts TL experimental glow curves. In addition to TL intensity, this phenomenon also affects the maximum intensity of the peak positions, which plays an important role in determining the basic kinetic parameters. Therefore, the temperature lag effect arising during TL readout took into consideration before computing thermal quenching parameters. Generally, the equation to be used for the evaluation of the thermal quenching parameters of W and C from the measured TL data which are widely used in the literature is as follows [25]:

$$\frac{A}{I_{QUE}} - 1 = C \exp\left(\frac{-W}{kT_m}\right)$$

where $A$ indicates the peak integral of the unquenched glow peak. Plotting $\ln(A/I_{QUE} - 1)$ against $1/kT_m$ yields a straight line with a slope of $-W$ and intercept $\ln(C)$, where $C$ can be calculated. The acquired plots are presented in Figure 5(c-d). The quenching parameters for peak (I) and peak (II) obtained from Figure 5(c-d) are
$W = 0.07 \text{ eV}$ and $C = 1.64 \times 10^3 \text{ s}^{-1}$ and $W = 0.2 \text{ eV}$ and $C = 2.99 \times 10^3 \text{ s}^{-1}$, respectively.

(ii) The light is emitted when a sample is heated. The temperature of the sample and the heating component are normally expected to be equal. However, there are several cases in the TL experiments that really show this is not the case. Temperature gradient and non-ideal contact can be given as an example. The temperature lag effect occurs during the thermoluminescence readout. The degree of the thermal contact between the heating element and sample plays an important role in determining the trapping parameters of the glow peak. Therefore, temperature lag effect

Figure 5. (a) TL glow curves, excited by the $^{90}\text{Sr}^{90}\text{Y} \beta$ source of $\text{BaSi}_2\text{O}_5:0.03\text{Sm}^{3+}$ at different heating rates. (b) The behavior of the glow peak area as a function of the heating rate. (c) Plots for quenching parameters evaluation for peak (I) and peak (II). (d) Plot of $T_m$ versus $\beta$ (heating rate) to evaluate $E$ with Booth-Bohun-Parfianovitch method for uncorrected and temperature lag corrected data. $ln(T_m^2/\beta)$ versus $1/kT_m$ plot for the measured data and the corrected data due to the temperature lag of $\text{BaSi}_2\text{O}_5:0.03\text{Sm}^{3+}$ for (e) peak (I) and (f) peak (II).
cannot be ignored in the calculations of kinetic parameters.

Booth–Bohun–Parfianovitch (BBP) suggested a method to assess the activation energy using the following equation [26–28]:

$$E = k \frac{T_{m1} T_{m2}}{T_{m1} - T_{m2}} \ln \left( \frac{T_{m1}}{T_{m2}} \right)^2$$

The glow peak temperature $T_{m}$, and the temperature of the lower portion of the glow curve $T_{m1}$ can be obtained by the usage of two linear heating rates of $\beta_1$ and $\beta_2$. A formalism to correct for temperature lag was suggested by Kitis and Tuyn [29] given by the expression

$$T_{m} = T_{m1} - c \ln \left( \frac{\beta_1}{\beta_2} \right)$$

where, $T_{m1}$ and $T_{m2}$ are the peak maximum temperatures obtained with the rate of heating $\beta_1$ and $\beta_2$, respectively, and $c$ is a constant. The value of the $c$ can be obtained by selecting the lowest two heating rates used during the experiment, i.e. 0.5 and 0.75°C C s$^{-1}$.

BBP method has been utilized to determine the measured (uncorrected) values of two TL glow peaks at 91°C and 193°C, from 2°C s$^{-1}$, of BaSi$_2$O$_5$:0.03Sm$^{3+}$ sample. However, observed maximum peak temperatures do not show real values and those should be corrected considering the temperature lag effect. Figure 5(e, f) presents how $T_{m}$ with or without temperature lag effect changes depending on the heating rate. Determined activation energy values for two main glow signals for different heating rates that the correction is taking into account and not are presented in Table 1.

Furthermore, the conventional VHR method to estimate the kinetic parameters has been also used. The calculation of kinetic parameters was evaluated using the variable heating rate technique which depends on the peak position of $T_{m}$ and heating rate [25]. As it is well known from the theory, plotting $ln(T_{m}^2/\beta)$ versus $1/kT_m$ exhibits a linear pattern with slope $E$ and an intercept $ln(E/sk)$. VHR method has been performed in order to analyze the TL kinetics of two main glow peaks (uncorrected) of BaSi$_2$O$_5$:0.03Sm$^{3+}$ and compared with the ones calculated after temperature lag corrections. Figure 5g illustrates a comparison of the maximum temperatures of two peaks before and after lag correction. From the data in Figure 5(e-g), although the behavior of the maximum temperatures of two peaks corresponding measured data (uncorrected) exhibits a straight line, a better straight line was generated after the temperature lag correction. In Table 2, activation energy ($E$) and frequency factor ($s$) values calculated in the present work are summarized for two peaks.

The data obtained using the VHR technique reveal that the observed trap parameters are significantly affected due to the effect of temperature lag occurred between the thermocouple and the measured sample. This difference is caused by non-ideal thermal contact between the heater element and the sample. $T_{m}$ is a strong function of the depth of the trap center (activation energy) $E$ and frequency factor $s$ for a given heating rate. Accordingly, to get rid of the temperature lag as much as possible, the lowest possible heating rate should be preferred, otherwise, temperature lag effect will be inevitable.

Additionally, it is revealed that when thermal quenching is present the trap depth calculated using the VHR method significantly overestimated as seen in Table 2 compared to the other methods [25]. However, corrected $s$ values were found in the range of $10^{25}$–$10^{35}$ s$^{-1}$. Such high values may not represent the real physical values and therefore, they should be evaluated correctly since it may point to the effect of overlapping peaks. The following subsections will present the possible locations and parameters of the overlapped TL peaks.

### 3.5.2. Repeated initial rise (RIR) method

Garlick et al. proposed an analysis of TL glow peaks using the initial rise method for the first time [30]. In this method, $I(T) \propto \exp(-E/kT)$ expresses the initial rise region of a TL curve peak. A key indicator in this method is that the number of trapped electrons in the low-temperature interval of the TL glow peak is considered to have remained almost unchanged. This assumption is only valid for the temperatures up to a

| $\beta$ (K s$^{-1}$) | Peak I | Peak II | Peak I | Peak II |
|---------------------|--------|--------|--------|--------|
| 1                   | 0.73   | 0.73   | 1.36   | 1.36   |
| 2                   | 0.72   | 0.75   | 1.56   | 1.39   |
| 3                   | 0.77   | 0.86   | 1.40   | 1.53   |
| 4                   | 0.76   | 0.87   | 1.37   | 1.54   |
| 5                   | 0.74   | 0.88   | 1.44   | 1.55   |
| 6                   | 0.60   | 0.78   | 1.40   | 1.43   |
| 7                   | 0.61   | 0.79   | 1.25   | 1.43   |
| 8                   | 0.62   | 0.79   | 1.10   | 1.44   |
| 9                   | 0.56   | 0.79   | 1.11   | 1.44   |
| 10                  | 0.51   | 0.80   | 0.97   | 1.45   |
| Averages            | 0.66 ± 0.03 | 0.80 ± 0.02 | 1.30 ± 0.06 | 1.46 ± 0.02 |

| $E$ (eV) | Peak I | Peak II |
|----------|--------|--------|
| $s$ (s$^{-1}$) |
| 1.18 ± 0.06 | 1.70 ± 0.02 |
| 2.14 ± 0.17 | 3.02 ± 0.02 |

| $E$ (eV) | Peak I | Peak II |
|----------|--------|--------|
| $s$ (s$^{-1}$) |
| 2.88 × 10$^{18}$ | 7.82 × 10$^{25}$ |
| 5.43 × 10$^{25}$ | 4.62 × 10$^{25}$ |
critical temperature which is assigned to the TL intensity not bigger than 10\% of the maximum TL intensity [31]. BaSi$_2$O$_5$:0.03Sm$^{3+}$ was heated at a constant rate of 2°C s$^{-1}$ from 50°C at the intervals of 5°C from 50°C to 360°C. The TL experiment has been performed for each interval and the studied sample was quickly cooled down to RT with Lexsyg Smart TL/OSL reader system’s nitrogen gas cooling phase. This protocol including processing steps such as irradiation, heating, cooling, and again heating was carried out up to the final temperature of 360°C as shown in Figure 6a. By using the Arrhenius plot, i.e. In (I) against 1/T straight line of slopes gave us activation energy or trap depth. Figure 6b depicts the result of the calculated activation energies as a function of $T_{\text{stop}}$, $E - T_{\text{stop}}$ or $E - T_{\text{stop}}$ plot may represent two different behaviors as the “staircase” structure or “continuous line” of slope around 1.0 for the overlapping peaks. As seen from the figure, five TL traps were seen at around 90°C, 135°C, 180°C, 300°C, and 365°C and activation energy values

![Figure 6](image_url)

**Figure 6.** (a) TL glow curves obtained by RIR method of BaSi$_2$O$_5$:0.03Sm$^{3+}$ phosphor. (b) A plot of $T_m$ against $T_{\text{stop}}$ obtained for BaSi$_2$O$_5$:0.03Sm$^{3+}$. 
corresponding to these traps were estimated to be $1.03 \pm 0.06$, $0.96 \pm 0.07$, $1.30 \pm 0.11$, $0.40 \pm 0.09$, and $1.68 \pm 0.15$ eV. Each value shows the average of the values over the plateau and error values to the respective standard deviation. Activation energies corresponding to these plateaus indicate the presence of shallow and deep traps within the band gap of the BaSi$_2$O$_5$:0.03Sm$^{3+}$ phosphor sample. It is worth noting that the RIR method does not always give reliable information about the values of activation energy depending on the ratio of the glow curve affected by thermal quenching [32]. However, it is known that the activation energy, heating rate, and frequency factor are the main components of the position and shape of the TL peaks. The peak at the higher temperature with low activation energy can be observed through the low-frequency factor when the heating rate is constant during the thermal treatment [33–35]

3.5.3. Computerized glow-curve deconvolution (CGCD)

The $T_m$-$T_{stop}$ experiments mentioned in the above section only give us further information about the number of peaks and their possible positions, but it is not easy to determine the kinetic parameters (i.e. activation energy $- E$ (eV), frequency factor $- s$ (s$^{-1}$) and order of kinetics $- b$) without fully separating the peaks seen in Figure 7. Hence, it is necessary to decompose overlapping peaks in the glow curves using software such as CGCD. During this study, thermoluminescence glow-curve deconvolution (tgcd): An R-package developed by Peng J et al. was used [36]. The TL glow curves of BaSi$_2$O$_5$:0.03Sm$^{3+}$ irradiated with $\beta$-rays were deconvoluted and theoretically stimulated by tgcd: An R package software. Note that general order approximation (GOK) and one trap one recombination model [37] were used in this analysis. The glow curves analyzed using tgcd: An R package for the phosphor sample measuring with a heating rate of 2 Cs$^{-1}$ are depicted in Figure 7, where both the experimental points and fitted glow peaks are presented. Detailed kinetic parameters are also tabulated in Table 3. After decomposing the TL glow peaks, the Figure of Merit (FOM) value was determined to be 1.346% which indicates that the goodness-of-fit measure is quite sufficient to determine the results because the FOM values greater than 5% implies significant errors in the fitted values. Figure 7 indicates that the TL glow curve of BaSi$_2$O$_5$:0.03Sm$^{3+}$ is the superposition of at least five separated TL glow peaks with $T_m$ values of 92°C, 137°C, 190°C, 299°C, and 387°C in the temperature range between RT and 450°C. The range of the activation energies for five localized energy levels in the forbidden energy is 0.39–1.72 eV. In general, lower temperature TL peaks form more shallow traps (for lower values of $E$) and higher temperature TL peaks are caused by deep traps (for higher $E$). Chen’s peak shape method [38] indicated that the calculated symmetry factor ($\mu$) of a specific TL peak gives information about the order of kinetics. If $\mu$ is equal to 0.42 and 0.52, the TL peak follows the first- and second-order kinetics, respectively. When $\mu$ is between the range of 0.42–0.52; then, it follows the general order kinetics. According to Table 3, all deconvolved TL peaks have the properties of the general order kinetics. The number of the peaks separated by the CGCD method and the activation energy values given in Table 3 are in good agreement with the values obtained by the RIR method. Therefore, we assume that the retrapping of the charge carriers onto the shallower trap level of five

![Figure 7](image-url)

**Figure 7.** Theoretically deconvoluted glow curves obtained by computerized glow-curve deconvolution (CGCD) method using tgcd: an R Package software.
overlapped traps occurs due to the localized process in the synthesized material. When considering the possible origin of the trapping centers, some defects in the strontium aluminate − F centers (oxygen vacancies occupied by two electrons or \( V_0^{2+} \)), \( F^+ \) centers (oxygen vacancies occupied by one electron or \( V_0^{1+} \) or), their aggregates such as \( F_2 \) centers (two associated oxygen vacancies occupied by four electrons), and the \( F_2^+ \) centers (two associated oxygen vacancies occupied by three electrons) could be available in the strontium aluminate. Also, the vacancies of the two other main lattice constituents \( V_{Sr} \) and \( V_{Al} \) can be involved in the charge-trapping mechanism. Furthermore, there are other possibilities, like interstitial or substitutional ions, that can either be trapping centers themselves or attract other defects for charge compensation. For example if an Sm\(^{3+}\) would replace a Ba\(^{2+}\) ion, there would be 1+ charge incompatibility. This would either act as an electron trap or these defects could cooperate 2 Sm\(^{3+}\) ions could need three sites of Ba\(^{3+}\) ions. The possibility to trap an electron would also be dependent on the reduction and oxidation potential of the ion, as well as on the trapped electron energy level position in the host.

### 4. Conclusions

In this work, Sm-doped \( BaSi_2O_5 \) phosphors have been prepared using a gel combustion method. The TL experiments indicate that the TL glow curves of \( BaSi_2O_5:0.03Sm^{3+} \) were composed of two peaks centered at 91°C and 193°C with a heating rate of 2°C s\(^{-1}\) after 5 Gy β-irradiation. The collected TL data of \( BaSi_2O_5:0.03Sm^{3+} \) sample after being exposed to beta irradiation starting show a linear behavior from 1 to 10 Gy of dose−response. Using traditional calculation methods such as RIR and Booth–Bohun–Parfianovitch, the trapping parameters for \( BaSi_2O_5:0.03Sm^{3+} \) have been determined and compared with glow-curve data collected using tcgc: An R Package software. Without preheating, CGCD and \( T_{av}-T_{stop} \) analyses indicated that the experimental glow curves of \( BaSi_2O_5:0.03Sm^{3+} \) consist of at least five overlapping peaks within the TL glow curve, possibly forming a continuum of closely located energy states. The activation energies (\( E \)) and frequency factors (\( s \)) involved in the TL emission for the CGCD method were found to be between 0.93 and 1.72 eV and \( 10^{10−13} \) s\(^{-1}\), respectively. We observed thermal quenching in the analysis of the activation energy values using the RIR method and the values of C and W for the best fit values of the quenching parameters were calculated. Therefore, the results present that the synthesized phosphor may be used as a promising material in the mid-dose range for nonperishable TL applications in fractional environmental and retrospective dosimetry.

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