Thermoluminescence characteristics of different phase transitions from nanocrystalline alumina

N. Y. Abdou · Mohamed Sabry · Nabil El-Faramawy

Abstract
Nanocrystalline boehmite material was synthesized using the hydrothermal method. Different annealing temperatures have been used to transform boehmite into different alumina phases to study the effect of different phase transitions on the thermoluminescence properties of alumina. XRD analysis was carried out to investigate the crystal structure of the different alumina phases. The thermoluminescence glow curves for different alumina phases showed different structures; however, the sensitivity was almost constant for all the phase transitions of alumina over the applied dose ranging from 0.55 to 330 Gy.

Keywords Thermoluminescence · Boehmite · Alumina · Phase transitions

Introduction
Thermoluminescence (TL) dosimetry is considered one of the most used techniques for studying the interaction of radiation with the matter for various applications [1]. Although numerous natural materials [2–6] are employed in thermoluminescence dosimetry, developing and synthesizing novel materials remains an ongoing research topic [7–9].

There is a great demand for nanomaterials in all applications, especially in luminescence applications, because of their advantages in optical and electronic properties [10–12].

Aluminium oxide (Al₂O₃), particularly on the nanoscale, is a ceramic material utilized in various applications. It can be used as a catalyst supporting manufacturing electronic equipment, as a biological material substitute, or as a radiation dosimeter [13–16].

Nano alumina can be a good candidate for luminescence materials because of some intrinsic defects in the crystal-lattice, such as OH, non-bridging oxygen hole centers, V-type centers and oxygen vacancies. Such defects are responsible for trapping and storing charge carriers under irradiation exposure and for electron–hole recombination at thermal stimulation [17].

Several synthesis processes and precursors have been used to synthesize nano alumina, with boehmite (AlOOH) as one of the most popular applications. There are more than fifteen transition phases of alumina, such as χ, κ, γ, δ, η, and θ, as well as the most stable α-Al₂O₃ phase produced after heat treatment of alumina by high temperature [13, 18, 19]. The transformation from one phase of alumina to another until it reaches α-Al₂O₃ phase requires a reconstruction of the crystal structure of alumina [20, 21].

Any change in the chemical and crystal structure, particle size, shape, and morphology of luminescence material may change the thermoluminescence characteristics of this material, which would cause an error in the estimation of the radiation dose [1, 22, 23]. Previous research showed that a modification could occur in the glow curve structures due to phase transitions. For example, Sahare et al. investigated the TL response of various phases of K₂Ca₂(SO₄)₃·Cu. According to their findings, variations in the TL glow curve structures may be attributed to changes in the phase transition of the nanophosphor materials [22]. Furthermore, Rani and Sahare discovered that the structures of the TL glow curves changed due to the phase transition of aluminium oxide when annealed at selected temperatures [13].

As a result, further advanced studies are required to determine the change in thermoluminescence characteristics of alumina caused by heat treatment at selected temperatures. The current work studied the thermoluminescence properties...
of some transition alumina obtained from the thermal treatment of nanocrystalline boehmite at selected temperatures.

**Materials and methods**

**Preparation**

The boehmite was synthesized as follows: Amounts of 0.05 mol of AlCl$_3$·6H$_2$O and 0.1 mol of CO(NH$_2$)$_2$ were dissolved in distilled water, then placed on a magnetic stirring for 0.5 h to dissolve completely. After that, the solution was autoclaved for 3 h at 453 K. The resulting white precipitate was rinsed many times in distilled water before being heated in an oven at 353 K for 20 h [10].

For the transfer of the boehmite powder to different alumina phases, the boehmite powder was annealed at various temperatures (773 K—973 K—1273 K—1473 K—1673 K) for 3 h, then cooled to room temperature. The expected phase transitions of alumina were obtained after annealing the boehmite at selected annealing temperatures (Fig. 1).

**Characterization**

The different phase transition of Al$_2$O$_3$ was determined using X-ray diffraction (Shimadzu XD-DI Diffractometer) powder diffractometry (Cu K$_{α1}$ radiation) operated at a voltage of 40 kV and intensity of 30 mA.

The crystallite sizes were calculated using Scherer’s equation Eq. 1 [24, 25].

$$\text{crystallite size} = \frac{k\lambda}{\beta \cos \theta}$$  (1)

where $k$ is the average crystallite’s shape factor (predictable shape factor is 0.9), “$\lambda$” is the wavelength (1.54056 Å for CuKα), “$\beta$” is the full width at half maximum (FWHM) in radians, and “$\theta$” is the peak position in radians.

The TL-glow curves for distinct Al$_2$O$_3$ phases were recorded using a Lexsyg Smart TL/OSL luminescence reader in the Nuclear Radiation Measurements Lab, Department of Physics, Faculty of Science, Ain Shams University. Lex Studio 2.0 operating software runs on a personal computer linked to the reader. The reader is additionally linked to a nitrogen source for cooling purposes. The reader has $^{90}$Sr/$^{90}$Y beta source with a maximum energy of 2.2 MeV and a dose rate of 110 mGy/s. Samples from different alumina phases were irradiated with different doses from 0.55 to 330 Gy from $\beta$-particles to study the dose-response range for different alumina phases.

**Thermoluminescence glow curve analysis**

**$T_m$-$T_{stop}$ method**

The $T_m$-$T_{stop}$ method was utilized to determine the number and locations of the overlapped peaks in the glow curves of different alumina phases [26–29].

Samples from alumina phases were annealed at 673 K for 30 min before being irradiated with 55 Gy from a $\beta$-source. After that, they were heated to a temperature of $T_{stop}$ (328 K) and then cooled down to room temperature. Then, the samples corresponding to each alumina phase were heated at 623 K. TL-glow curves were obtained. The previous process is repeated numerous times with the same dose and the same samples were heated to a slightly higher $T_{stop}$ each time, in steps of 5 K throughout $T_{stop} = 328–618$ K. For each reading cycle, the first maximum intensity recorded in the second turn of each reading cycle was recorded as $T_m$. At the end of all reading cycles, different $T_{stop}$ and $T_m$ temperatures were obtained and plotted as $T_m$ versus $T_{stop}$.
Glow curve deconvolution (CGCD)

After determining the number of the glow peaks composing the glow curves of the different phases of Al₂O₃ experimentally using the Tm-Tstop technique, the computerized glow curve deconvolution method (CGCD) [30] was used to resolve the glow curves into the glow peaks all at once and determine the kinetic parameters. The MATLAB software employed to analyze the glow curves is based on the Nelder-Mead non-linear optimization method and employs the general order kinetics deconvolution equation given by

\[ I(T) = I_m \exp \left( \frac{E}{kT} \left( \frac{T - T_m}{T_m} \right) \right) \times \left[ 1 + \frac{E(b - 1)(F(T, E) - F(T_m, E))}{kT^2 b \exp \left( \frac{-E}{kT_m} \right)} \right]^{\frac{1}{b - 1}} \]  

(2)

where \( I_m \) is the maximum intensity, and \( k \) is the Boltzmann constant.

The functions \( F(T, E) \) and \( F(T_m, E) \) are defined as

\[ F(T, E) = T \exp \left( \frac{-E}{kT} \right) + \frac{E}{k} \left( Ei \left( \frac{-E}{kT} \right) \right) \]  

(3)

where \( Ei(-x) \) is the exponential integral function, \( x > 0 \) [31].

The frequency factor (S) can be found exploiting the condition at the maximum intensity and is given by

\[ S = \left( \frac{E\beta}{kT_m^2} \right) \frac{1}{1 + (b - 1) \left( \frac{2kT_m}{E} \right)} \exp \left( \frac{E}{kT_m} \right) \]  

(4)

where \( \beta \) is the heating rate. The lifetime of each trap can be determined employing the equation given by

\[ \tau = s^{-1} \exp \left( \frac{E}{kT} \right) \]  

(5)

where \( T \) is the storage temperature (about 300 K).

Results and discussion

X-ray diffraction (XRD) results

The XRD analysis for the boehmite and obtained alumina phases after annealing of the boehmite at selected annealing temperatures are shown in Fig. 2. The results confirmed the complete transformation of the annealed samples at temperatures 1473 K and 1673 K into α-alumina. The crystallite size

| Table 1 XRD parameters for different alumina phase |
|---------------------------------|-------|------|--------|-----------------|
| Alumina phase | peak no | 2θ   | d (Å)  | FWHM (θ) | Crystalline size (nm) |
| Boehmite | 26 | 14.54 | 6.09 | 0.23 | 50.2 |
| | 55 | 28.29 | 3.16 | 0.25 |
| | 83 | 38.45 | 2.34 | 0.27 |
| At 773 K | 27 | 14.56 | 6.08 | 0.23 | 32.7 |
| | 55 | 28.28 | 3.15 | 0.25 |
| | 83 | 38.44 | 3.34 | 0.29 |
| At 973 K | 9 | 16.76 | 5.29 | 0.69 | 10.6 |
| | 7 | 13.95 | 6.35 | 0.69 |
| | 52 | 66.98 | 1.40 | 1.09 |
| At 1273 K | 99 | 67.24 | 1.39 | 0.57 | 23.1 |
| | 60 | 42.6 | 2.12 | 0.32 |
| | 49 | 34.78 | 2.58 | 0.32 |
| At 1473 K | 9 | 25.65 | 0.89 | 0.24 | 34.8 |
| | 55 | 35.23 | 0.89 | 0.24 |
| | 83 | 37.86 | 0.91 | 0.24 |
| At 1673 K | 6 | 43.58 | 2.07 | 0.26 | 32.23 |
| | 9 | 57.72 | 1.6 | 0.3 |
| | 3 | 35.38 | 2.57 | 0.25 |
sizes were calculated using Eq. 1, and the result showed that the crystallite size for all alumina phases was nanosized. The variation in the phase transition of alumina at selected annealing temperatures and crystallite sizes is clearly shown (Table 1).

It can be observed from Table 1 that as the annealing temperature increases, the particle size decreases and then increases again with an increase in the annealing temperature because the gaps between the chains and the crystal defects are gradually reduced and finally disappeared, resulting in complete crystallization of α-alumina, these results agree with those result obtained by Rani and Sahare [13] and Takayuki Tsukada et al. [20]

![Fig. 3 The characteristic glow curve of boehmite sample annealed at a 773 K b 973 K c 1273 K d 1473 K and e 1673 K after exposed with 330 Gy from β-particle](image)
Fig. 4  $T_m - T_{\text{stop}}$ results for boehmite sample annealed at: a 773 K b 973 K c 1273 K d 1473 K and e 1673 K
Thermoluminescence glow curve structure

The glow curve structure is one of the most important properties that should be studied to identify the change caused by annealing the alumina samples at selected temperatures. Thus, samples from various prepared alumina phases were irradiated at 330 Gy from β-particle, then the relationship between TL-intensities and temperatures were represented graphically (Fig. 3).

The glow curves of the prepared alumina samples have almost the same shape as they contain two main glow peaks, but the location of these peaks and the area under each curve is different from one type to another (Fig. 3). The positions of the two main peaks were at 408 K and 539 K for Al₂O₃ annealed at 773 K; 396 K and 518 K for Al₂O₃ annealed at 973 K; 390 K and 500 K for Al₂O₃ annealed at 1273 K and 1473 K; and 454 K, and 583 K for Al₂O₃ annealed at 1473 K and 1673 K.

In addition, the area under the glow curves of the annealed alumina samples at different temperatures increased gradually with the increase of the annealing temperature for the annealed samples at temperatures (773 K—973 K—1273 K). After that, as the annealing temperature increased more than 1273 K, the area under the glow curves decreased. The increased annealing temperature from 773 up to 1273 K may help to improve defect and ion diffusion and eliminate intrinsic tensile stresses in the crystalline lattice. Hence, the area under glow curves increases. Then, by increasing the annealing temperature more than 1273 K, the electron traps and recombination centers may be damaged or increase the competition, leading to a decrease

| Table 2 | The calculated trapping parameters of the investigated alumina phases using CGCD at dose 330 Gy |
|---------|-----------------------------------------------|
|          | Alumina phase | Peak No | Tm (k)  | E (ev)     | S (s⁻¹) 10¹⁰ | b        | τ (y)             |
| At 773 K | Peak 1        | 388.75±0.9  | 0.73±0.027 | 0.092±0.007 | 1.8±0.002  | 6.66×10⁻⁵ |
|          | Peak 2        | 419.72±0.6  | 0.78±0.022 | 0.058±0.037 | 1.1±0.009  | 5.82×10⁻⁴ |
|          | Peak 3        | 448.06±1.4  | 0.89±0.002 | 0.255±0.005 | 1.2±0.019  | 1.08×10⁻² |
|          | Peak 4        | 485.86±0.6  | 0.94±0.020 | 0.145±0.028 | 1.3±0.057  | 1.5×10⁻¹  |
|          | Peak 5        | 528.86±1.2  | 1.04±0.003 | 0.191±0.028 | 1.4±0.039  | 5.92      |
|          | Peak 6        | 563.67±3.0  | 1.16±0.005 | 0.480±0.016 | 1.5±0.002  | 203.87    |
|          | Peak 7        | 612.21±0.3  | 1.28±0.004 | 0.594±0.036 | 1.6±0.015  | 1.42×10⁴  |
| At 973 K | Peak 1        | 382.11±1.3  | 0.73±0.027 | 0.375±0.018 | 1.9±0.014  | 6.53×10⁻⁵ |
|          | Peak 2        | 410.43±0.2  | 0.78±0.022 | 0.202±0.082 | 1.1±0.016  | 4.67×10⁻⁴ |
|          | Peak 3        | 438.64±1.6  | 0.89±0.002 | 0.062±0.018 | 1.2±0.002  | 2.81×10⁻³ |
|          | Peak 4        | 473.69±3.0  | 0.94±0.020 | 2.910±0.166 | 1.3±0.011  | 2.99×10⁻¹ |
|          | Peak 5        | 512.26±2.6  | 1.04±0.003 | 3.040±1.650 | 1.4±0.001  | 8.20      |
|          | Peak 6        | 551.40±4.2  | 1.16±0.005 | 3.040±1.190 | 1.5±0.023  | 279.16    |
|          | Peak 7        | 602.11±0.9  | 1.28±0.004 | 1.280±3.310 | 1.6±0.007  | 1.19×10⁴  |
| At 1273 K| Peak 1        | 374.64±0.6  | 0.87±0.005 | 16.60±3.500 | 1.4±0.001  | 7.3×10⁻⁵  |
|          | Peak 2        | 403.44±0.9  | 0.90±0.005 | 5.570±1.170 | 1.3±0.036  | 7.53×10⁻⁴ |
|          | Peak 3        | 434.31±0.6  | 1.05±0.010 | 52.90±16.20 | 1.0±0.001  | 2.79×10⁻² |
|          | Peak 4        | 456.89±0.1  | 1.16±0.001 | 177.0±4.250 | 1.0±0.008  | 4.55×10⁻¹ |
|          | Peak 5        | 474.59±1.0  | 1.20±0.003 | 181.0±25.00 | 1.5±0.001  | 2.86      |
|          | Peak 6        | 498.16±1.4  | 1.24±0.003 | 91.80±2.510 | 1.2±0.003  | 21.29     |
|          | Peak 7        | 525.34±2.2  | 1.27±0.024 | 42.30±27.30 | 1.9±0.062  | 156.38    |
|          | Peak 8        | 545.50±5.2  | 1.29±0.017 | 20.30±2.090 | 1.6±0.016  | 747.31    |
|          | Peak 9        | 589.96±3.5  | 1.37±0.001 | 10.00±1.460 | 1.9±0.010  | 2.71×10⁴  |
| At 1473 K| Peak 1        | 378.13±3.5  | 0.83±0.042 | 4.320±3.940 | 1.1±0.041  | 5.73×10⁻⁵ |
|          | Peak 2        | 450.96±72   | 0.98±0.001 | 2.860±0.639 | 1.1±0.017  | 3.81×10⁻² |
|          | Peak 3        | 467.65±13   | 1.08±0.031 | 10.80±0.070 | 1.7±0.323  | 3.54×10⁻¹ |
|          | Peak 4        | 587.09±0.2  | 1.21±0.049 | 0.619±0.542 | 1.4±0.070  | 1.12×10³  |
| At 1673 K| Peak 1        | 373.06±3.8  | 0.79±0.046 | 2.090±2.050 | 1.1±0.018  | 2.78×10⁻⁵ |
|          | Peak 2        | 453.93±2.6  | 0.97±0.015 | 1.560±0.835 | 1.1±0.005  | 3.48×10⁻² |
|          | Peak 3        | 455.73±0.9  | 1.14±0.032 | 164.0±116.0 | 1.7±0.088  | 3.39×10⁻¹ |
|          | Peak 4        | 583.34±2.6  | 1.27±0.052 | 2.920±2.870 | 1.5±0.028  | 2.68×10³  |
Fig. 5  Deconvolution analysis of the thermoluminescence glow curve of boehmite sample annealed at: a 773 K, b 973 K, c 1273 K, d 1473 K and e 1673 K after exposed with 330 Gy from β-particle
in the area under the curves as previously observed in other works [32].

**Thermoluminescence glow curve analysis**

The glow curve is a superposition of the glow peaks, which corresponds to the de-localized states between the valence and conduction bands. To resolve the glow curve to its composing peaks and find the associated kinetic parameters, the \( T_m - T_{\text{stop}} \) method was employed (Fig. 4).

The relation between \( T_m \) and \( T_{\text{stop}} \) appeared like a staircase structure, and the number and location of the plateau regions represent the number and locations of the glow peaks that make up the glow curve (Fig. 4). Therefore, the glow curves for \( \text{Al}_2\text{O}_3 \) annealed at 773 K and 973 K have seven expected peaks, while \( \text{Al}_2\text{O}_3 \) annealed at 1273 K has nine expected peaks and \( \text{Al}_2\text{O}_3 \) annealed at 1473 K and 1673 K have four expected peaks. The position of each expected glow peaks for different alumina phases is given (Table 2).

Based on the expected number of glow peaks determined by \( T_m \) and \( T_{\text{stop}} \) computerized glow curve deconvolution (CGCD) technique was used to resolve the glow curves into the glow peaks all at once and determine the kinetic parameters (Fig. 5).

It is clearly shown in Fig. 5 that the annealing of the alumina at selected annealing temperature causes a change in the glow curve structure, which may be attributed to the re-arrange of the available electronic energy levels. This change may be due to the phase transformation or a change in the size of the particles occurs with the change in the annealing temperatures [25]. The kinetic parameters are calculated using the CGCD method (Table 2). The quality of the fitting was tested by the Figure Of Merit (FOM) criteria [33], and the FOM value is less than 2% which indicates the goodness of the fitting.

**Dose-response**

It is important to find the relationship between the light emitted from any material after irradiation and the applied doses. This relationship generally involves a linear function that allows this material to be used to determine an unknown irradiation dose.

The \( \text{Al}_2\text{O}_3 \) samples were irradiated at various \( \beta \)-doses ranging from 0.55 to 330 Gy for this analysis. The relationship between the irradiation doses and the given TL-intensities per mass of the investigated samples are obviously revealed (Fig. 6).

The changes in the glow curves according to the different applied doses for the investigated \( \text{Al}_2\text{O}_3 \) samples are shown in Fig. 7a–e. These figures show that increasing irradiated dose increased the area under the glow curves without changing the position of the peaks.

The TL—intensity is thought to occur as follows:

\[ F \rightarrow F^+ + e^- \text{ Irradiation process.} \]
\[ F^+ + e^- \rightarrow F^* \text{ Stimulation process.} \]
\[ F^* \rightarrow F + hv \text{ Heating process.} \]

After absorbing high-energy radiation, the F center loses an electron and becomes the \( F^+ \) center. The recombination of the electron with the \( F^+ \) center creates an exciting F center (\( F^* \)), and by thermal stimulation, that decays into its ground state (3P transition to 3S) with photon emission. So, the \( \beta \)-dose increases, the number of exciting \( F^* \) centre increases which an increase in the photons produced with the thermal stimulation. Thus, the area under the glow curves increases with the increase in the radiation dose [32, 34, 35].

A way to quantify the linearity of a material is the linearity index \( F(D) \) [31], given by the following formula.

\[
 f(D) = \frac{f(D)/D}{f(D_1)/D_1} \tag{7}
\]

where \( f(D) \) and \( f(D_1) \) are the TL responses at doses "D" and "\( D_1 \)". \( D_1 \) is the normalization dose in the linear region. The linearity index is 1 within the linear range, > 1 within the supra-linear range, and < 1 within the sub-linear range. It was found that all the \( \text{Al}_2\text{O}_3 \) samples annealed at 773 K, 973 K, 1273 K, 1473 K, and 1673 K exhibited a linear dose—response in the range from 0.55 Gy up to 330 Gy (Fig. 6).

The characteristic glow curve of \( \text{Al}_2\text{O}_3 \) (a) at 773 K, (b) at 973 K, (c) at 1273 K, (d) at 1473 K and (e) at 1673 K after being exposed to different \( \beta \)-doses is presented (Fig. 7).
all alumina phases the shape and position of the glow peaks do not change after exposure to different β-doses (Fig. 7). However, the area under all glow curves of studied alumina phases increases with increasing β-doses.

The linearity index as a function of the applied dose is shown (Fig. 8). Observing (Fig. 8) confirmed the linear dose-response behaviour as the linearity index values for all the phases were close to 1. The linearity behaviour of the samples under consideration is summarized (Table 3).
Sensitivity

Sensitivity is defined as the TL response per unit dose per unit mass of the dosimeter. To investigate this property for the different phases of Al₂O₃, the samples were irradiated at different doses of beta particles from 0.55 up to 330 Gy. The sensitivity was calculated at each dose. The sensitivity behaviour as a function of the applied dose for the investigated samples is revealed (Fig. 9). The sensitivity was almost constant for all the phases of Al₂O₃ over the applied dose ranging from 0.55 to 330 Gy (Fig. 9).

Conclusions

In the present work, the nanocrystalline boehmite was synthesized and annealed to selected temperatures (773 K—973 K—1273 K—1473 K—1673 K) to transform boehmite into different alumina phases. The XRD results confirmed the complete transformation of the annealed alumina samples at temperatures 1473 K and 1673 into α-alumina. The thermoluminescence glow curves for the five alumina phases showed different structures indicating the effect of the annealing temperature on the trap distribution in the material under investigation. The investigated samples showed a long-range linear dose-response, almost constant sensitivity as a function of the applied dose and long lifetimes indicating signal stability. This makes the samples good candidates for dosimetric applications, especially the samples annealed at temperatures 1473 K and 1673 K due to the formation of the α-Al₂O₃ phase which is the most stable phase of Al₂O₃.

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Table 3 The Linear and sub-linear region for different phase of Al₂O₃ respectively

| Phase of Al₂O₃ (K) | Linear range (Gy) | Equation         |
|-------------------|-------------------|------------------|
| 773               | 0.55 up to 330    | Y = 0.95 X + 2.47 |
| 973               | 0.55 up to 330    | Y = 0.91 X + 2.00 |
| 1273              | 0.55 up to 330    | Y = 0.99 X + 5.03 |
| 1473              | 0.55 up to 330    | Y = 1.0 X + 2.94  |
| 1673              | 0.55 up to 330    | Y = 1.0 X + 2.99  |

Fig. 8 The linearity index of the investigated Al₂O₃ samples as a function of the applied doses from β-particle (0.55 up to 330 Gy)

Fig. 9 The sensitivity for different phases of Al₂O₃, after exposure to different doses from β-particle
Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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References

1. Azorin J (2014) Preparation methods of thermoluminescent materials for dosimetric applications: an overview. Appl Radiat Isot 83:187–191

2. Sabry M, Alazab HA, Gad A, El-Faramawy N (2021) Thermoluminescence properties of natural Egyptian calcite. J Lumin 238:118273

3. El-Faramawy N, Alazab HA, Gad A, Sabry M (2022) Study of the thermoluminescence kinetic parameters of a β-irradiated natural calcite. Radiat Phys Chem 190:109793

4. Farouk S, El-Azab H, Gad A, El-Nashar H, El-Faramawy N (2020) Investigation of thermoluminescence glow curves in quartz extracted from the Central Eastern Desert. Egypt Lumin 35:586–593

5. Ademola JA (2014) Luminescence characteristics of feldspar from Nigeria. Nat Sci 2014

6. Aloraini D (2020) Sensitization of natural rhyolite rock using high gamma doses for thermoluminescence dosimetry. Luminescence 35:1043–1047

7. Alazab HA, Abdou N, Saudi H, Abd-Allah W (2021) Thermoluminescence properties of bioglass for radiation dosimetry. Silicon. https://doi.org/10.1007/s12633-021-01364-1

8. Kadam A, Mishra GC, Dhoble S (2021) Thermoluminescence study and evaluation of trapping parameters CaTiO3: RE (RE=Eu3+, Dy3+) phosphor for TLD applications. J Mol Struct 1225:129129

9. Khandaker MU, Nawi SNM, Bradley DA, Lam SE, Sani SFA, Suleiman A (2021) Studies of thermoluminescence kinetic parameters of polymer pencil lead graphite under photon exposures. Appl Radiat Isot 174:109757

10. Ahmed M, Salah A, Ashour A, Hafez H, El-Faramawy N (2018) Dosimetric properties of Cr doped Al2O3 nanophosphors. J Lumin 196:449–454

11. Abdou N, Farag M, Abd-Allah W (2020) Thermoluminescent properties of nano-magnesium phosphate ceramic for radiation dosimetry. Eur Phys J Plus 135:317

12. Murty BS, Shankar P, Raj B, Rath B, Murday J (2013) Textbook of nanoscience and nanotechnology. Springer Science and Business Media.

13. Rani G, Sahare P (2013) Effect of phase transitions on thermoluminescence characteristics of nanocrystalline alumina. Nucl Instrum Methods Phys Res Sect B 311:71–77

14. Panias D, Krestou A (2007) Effect of synthesis parameters on precipitation of nanocrystalline boehmite from aluminate solutions. Powder Technol 175:163–173

15. Kaya C, Butler E (2002) Plastic forming and microstructural development of α-alumina ceramics from highly compacted green bodies using extrusion. J Eur Ceram Soc 22:1917–1926

16. Trinkler L, Bezrini B, Jakimovic u, Grabis J, Steins I (2011) Peculiarities of photoluminescence of Al2O3 bulk and nanosize powders at low temperatures. Opt Mater 33:817–822

17. Kortov V, Pustovarov V, Zvonarev S, Shtang T (2016) Luminescence and radiation-induced color centers in anion-defective alumina crystals after high-dose irradiation. Radiat Meas 90:90–93

18. Bowen P, Carry C, Luxembourgn D, Hofmann H (2005) Colloidal processing and sintering of nanosized transition aluminas. Powder Technol 157:100–107

19. Wei S, Zhang L, Ben Y, Zhou T, Li Z, Yang H, Selim FA, Wong C, Chen H (2017) High dispersibility of α-Al2O3 powders from coprecipitation method by step-by-step horizontal ball-milling. J Mater Sci: Mater Electron 28:16254–16261

20. Tsukata T, Segawa H, Yasumori A, Okada K (1999) Crystallinity of boehmite and its effect on the phase transition temperature of alumina. J Mater Chem 9:549–553

21. Sathyaaseelan B, Baskaran I, Sivakumar K (2013) Phase transition behavior of nanocrystalline Al2O3 powders. Soft Nanosci Lett 2013

22. Sahare P, Bakare J, Dhole S, Kumar P (2012) Effect of phase transition and particle size on thermoluminescence characteristics of nanocrystalline K2Ca2(SO4)3: Cu+ phosphor. Radiat Meas 47:1083–1091

23. Sahare P, Bakare J, Dhole S, Ingale N, Rupasov A (2010) Synthesis and luminescence properties of nanocrystalline LiF: Mg, Cu, P phosphor. J Lumin 130:258–265

24. Cullity BD (1956) Elements of X-ray diffraction. Addison-Wesley Publishing

25. Rani G, Sahare PD (2015) Effect of temperature on structural and optical properties of boehmite nanostructure. Int J Appl Ceram Technol 12:124–132

26. McKeever SW (1988) Thermoluminescence of solids, vol 3. Cambridge University Press

27. Farouk S, Gad A, Al-Azab H, El-Nashar H, El-Faramawy N (2021) Thermoluminescence response and its kinetic analysis of a natural milky quartz associated with tin-tungsten-fluorite mineralization. Radiat Phys Chem 181:109333

28. Gavhane KH, Bhoraskar VN, Dhole SD, Dahiwale SS (2020) Tm-Tstop analysis and dosimetric properties of Ce doped BaB4O7 phosphor. J Alloy Compd 817:152805

29. Uzun E (2021) Analysis of alpha-alumina by variable dose and Tm-Tstop methods and simulations of the whole process. Luminescence 36:1402–1411

30. El-Kinawy M, El-Nashar HF, El-Faramawy N (2019) New designed software to deconvolute the thermoluminescence glow-curves. SN Appl Sci 1:1–7

31. Erdelyi A, Magnus W, Oberhettinger F, Tricomi FG (1954) Tables of integral transforms, vol 2. McGraw-Hill Book Company, Incorporated

32. Tatumi SH, Ventieri A, Bitencourt JFS, Gonçalves KA, Mittani M (2021) Novel applications, pp 177–196

33. Balian HG, Eddy NW (1977) Figure-of-merit (FOM), an improved criterion over the normalized chi-squared test for assessing
goodness-of-fit of gamma-ray spectral peaks. Nucl Inst Methods 145:389–395
34. Kortov V, Mil’man I, Nikiforov S, Pelenev V (2003) Mechanism of F-center luminescence in anion-defective aluminum oxide single crystals. Phys Solid State 45:1260–1266
35. Yu ZQ, Li C, Zhang N (2002) Size dependence of the luminescence spectra of nanocrystal alumina. J Lumin 99:29–34

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