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BLEACHING BY BLUE STIMULATION AND X-RAY IRRADIATION RESPONSE OF $\text{Al}_2\text{O}_3\text{:C}$ TL GLOW PEAKS SEPARATED BY DECONVOLUTION

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Abstract

In this study, we separated the TL glow peak of the $\text{Al}_2\text{O}_3\text{:C}$ sample and investigated the blue light-stimulated bleaching and radiation dose response of each isolated TL glow peak. Prior to these studies, the measured TL glow peaks were corrected for thermal quenching using the pulsed light-stimulated luminescence (POSL) technique based on the Mott-Seitz model. The resulting quenching parameters were $W = 1.10 \pm 0.02$ (eV) and $\nu = 2.54 \pm 1.21 \times 10^{14}$ (s^{-1}). The T_m - T_{stop} method was used to obtain information on the number of overlapping peaks in the TL signal corrected for thermal quenching, and the computerized glow curve deconvolution (CGCD) method with applied general order kinetics was employed to obtain the TL kinetic parameters. The glow curves exhibited at least three component glow peaks ($197 \pm 3^\circ\text{C}$, $227 \pm 2^\circ\text{C}$, and $318 \pm 2^\circ\text{C}$, denoted as C1, C2, and C3, respectively). In all isolated peaks, the bleaching effect by blue light stimulation exhibited two different exponential decay patterns, including a fast initial bleaching rate followed by a slower bleaching rate, which could be explained by the competition between optical stimulation and phototransfer. In the dose response study, peaks C1 and C2 showed a sublinear dose response, while peak C3 exhibited a supralinear response.

Keywords

$\text{Al}_2\text{O}_3\text{:C}$, thermal quenching, computerized glow curve deconvolution (CGCD) method, kinetic parameters, bleaching, radiation dose response

1. Introduction

$\text{Al}_2\text{O}_3\text{:C}$, which has high sensitivity to ionizing radiation, has attracted considerable attention as a material for TLD to measure environmental radiation doses (e.g., very low radiation doses). However, the application of $\text{Al}_2\text{O}_3\text{:C}$ to TLD has a major drawback, namely that the TL (thermoluminescence) glow curve of this material shows a strong

heating rate dependence. Akselrod *et al.* (1998) investigated this effect using OSL (optically stimulated luminescence), TL and TSC (thermally stimulated conductivity), and found that the F-center luminescence lifetime results were in entire agreement with the classical Mott–Setz temperature dependence. The activation energy (W) and frequency factor (ν), which are thermal quenching parameters, were found to be independent of the trap filling degree, sample type, and heating or cooling rate. Based on these experimental results, it was concluded that the variation in luminescence efficiency ($\eta(T)$) according to heating rates was due to the thermal quenching phenomenon of F-

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centered luminescence. Dallas *et al.* (2008) also discussed the thermal quenching of $\text{Al}_2\text{O}_3\text{:C}$ and proposed an alternative method to evaluate the luminescence efficiency using the “deconvolution method” based on curve fitting of experimental glow curve.

Recently, the interest in this phosphor was intensified when it was considered as a sensitive and practical material for OSL dosimetry due to its excellent OSL properties and capability of avoiding thermal quenching (Botter-Jensen *et al.*, 2003). This phosphor shows linearity of light output up to 7 orders of magnitude of radiation dose without fading information due to its deep trap properties and excellent environmental stability. Yukihiro and McKeever (2006) studied the UV emission at 335 nm (F^+ center) in the OSL of $\text{Al}_2\text{O}_3\text{:C}$ using POSL measurements, and presented OSL characteristics in this band, which include dose behaviour, time dependence after irradiation, and response of the OSL signal to the type of radiation. They discovered that the UV emission band exhibited a different dependence on ionization density compared to that observed in the F-center emission (360–480 nm), and that its intensity increased over time after irradiation. Later, Biswas *et al.* (2013) discussed the effect of blue (470 nm) illumination on the dosimetric TL peak in $\text{Al}_2\text{O}_3\text{:C}$ for blue and UV emissions. They reported that the major dosimetric trap of $\text{Al}_2\text{O}_3\text{:C}$ consists of multiple individual traps or trap distributions, and similar behaviour was observed in both blue and UV emissions.

The process of detecting OSL requires removing the scattered stimulating light from the photomultiplier tube and detecting the luminescence using appropriate optical filters in front of the photomultiplier tube. The main emission peak of $\text{Al}_2\text{O}_3\text{:C}$ at about 180°C is a broad band centred at 420 nm, which is related to the F-centers emission band (Akselrod and Kortov, 1990). With regard to the dependence of sensitivity on the stimulating wavelength, the intensity of the stimulated luminescence increases with decreasing wavelength (Whitley and McKeever, 2000). Therefore, for efficient detection of OSL in $\text{Al}_2\text{O}_3\text{:C}$, the stimulating wavelength should be as close as optical filter properties permit to the luminescence wavelength. Considerable research has been made on the measurement of OSL in $\text{Al}_2\text{O}_3\text{:C}$, mainly based on stimulation with green light, where it is easy to separate the luminescence and the stimulating light (Botter-Jensen *et al.*, 1996). Alternatively, Blue stimulation combined with appropriate optical filters has the advantage of a higher initial yield of OSL intensity and faster readout time compared to green stimulation, so it can be used for OSL measurement of $\text{Al}_2\text{O}_3\text{:C}$ (Umisedo *et al.*, 2010).

In this study, TL signal of the $\text{Al}_2\text{O}_3\text{:C}$ sample was corrected for the thermal quenching effect using the POSL technique based on the Mott-Seitz model proposed by Akselrod *et al.* (1998). Then, the TL signal corrected for the thermal quenching effect was separated using the computerized glow curve deconvolution (CGCD) method. Finally, the bleaching to blue light and the response to

radiation dose for each separated TL glow curve were investigated.

2. Sample and equipment

The sample used in this study was $\text{Al}_2\text{O}_3\text{:C}$ powder with ultrahigh sensitivity to radiation and particle size of 53–63 μm supplied by Landauer, Inc. (USA). All TL measurements were performed at a heating rate of 5°Cs^{-1} in a temperature range of 20–450°C, except for the thermal quenching experiment, under nitrogen atmosphere using an automated Risø TL/OSL system (model TL/OSL-DA-15) installed in the Central Laboratory of Kangwon National University. Luminescence detection was achieved by an EMI 9235QA photomultiplier tube using a Hoya U340 filter peaking at 280–380 nm. The bleaching experiment was conducted using blue light emitting diodes ($\lambda = \sim 470$ nm) with a power density of 28 mWcm^{-2} at the sample position provided by the Risø TL/OSL system.

POSL measurements for thermal quenching correction were performed using the KNU POSL measurement system installed at Kangwon National University (Choi *et al.*, 2014). In the POSL system, a pair of 470 nm blue high-power LEDs (LXHL-PB02) were used as the optical stimulation source, combined with a 3-mm-thick Schott GG420 long-pass filter and a VIS liquid light guide (VIS-LLG, Newport #77631). POSL was detected at wavelengths from 255–405 nm (full width at half maximum) using a multichannel scaler (ORTEC MCS-PCI) and a photomultiplier tube (PMT) (Bialkali EMI 9235QB) equipped with a 7.5-mm thick U340 bandpass filter. A mini X-ray generator (Varian VF-50J; 50 W max. at 50 kV and 1 mA) delivering about 0.8 Gys^{-1} was installed for sample irradiation.

3. Experimental

3.1. Recovery of the thermally quenched glow curve

Heating rate (β) is one of the important parameters that affect the TL glow curve during TL measurement. In the absence of thermal quenching, the TL glow curve shifts toward higher temperatures as the heating rate increases, whereas the area under the normalized TL signal (TL/β) versus temperature curve should remain constant regardless of the heating rate. However, in many luminescent materials, a decrease in luminescence intensity at high temperatures is observed due to the phenomenon of thermal quenching. Therefore, the area (total number of emitted photons) is expected to decrease as the heating rate increases. In other words, the area under the normalized TL/β versus temperature curve will decrease as the heating rate increases (Pagonis *et al.*, 2013). Meanwhile, Bos *et al.* (2010) reported an exact opposite case, known as the abnormal heating rate effect, in the dosimetric material $\text{YPO}_4\text{:Ce}^{3+}, \text{Sm}^{3+}$, which is a phenomenon in which the area under the normalized TL/β versus temperature curve increases as the heating rate increases.

In this study, TL glow curves were measured at six different heating rates of 0.1, 0.5, 1.0, 2.0, 5.0, and 8.0 °C s⁻¹ in a nitrogen atmosphere after X-ray irradiation of 0.4 Gy. As can be seen in Fig. 1, the peak area of the normalized TL/β versus temperature plot decreases as the heating rate increases, confirming that the thermal quenching phenomenon occurred (see Fig. 3b and Table 1 for details). In order to correct the thermal quenching effect, we employed the correction method using POSL proposed by Akselrod *et al.* (1998). The correction for thermal quenching is based on the determination of thermal quenching efficiency. If the phonon-assisted transition is negligible, the lifetime ($\tau(T)$) is given as

$$\tau(T) = \frac{\tau_0}{1 + \tau_0 \nu \exp(-\frac{W}{kT})} \quad (1)$$

Here, $\tau(T)$ is the lifetime for the temperature-dependent excited state, τ_0 is the radiative lifetime, W is the activation energy, k is the Boltzmann constant, T is the temperature, and ν is the frequency coefficient. Then, the luminescence efficiency ($\eta(T)$) can be obtained as follows

$$\eta(T) = \frac{1}{1 + \tau_0 \nu \exp(-\frac{W}{kT})} \quad (2)$$

To obtain the parameters W and ν , we measured τ as a function of temperature, and fitted the resulting data to Eq. 1. Lifetime represents the time required for electrons trapped by irradiation to be released through optical stimulation and subsequently recombine with holes at recombination centers, resulting in the emission of light. However, the lifetime is governed by the relaxation time associated with a transition at the luminescence center rather than by the time required for electron release from a trap or electron transport through the conduction band from the trap to a

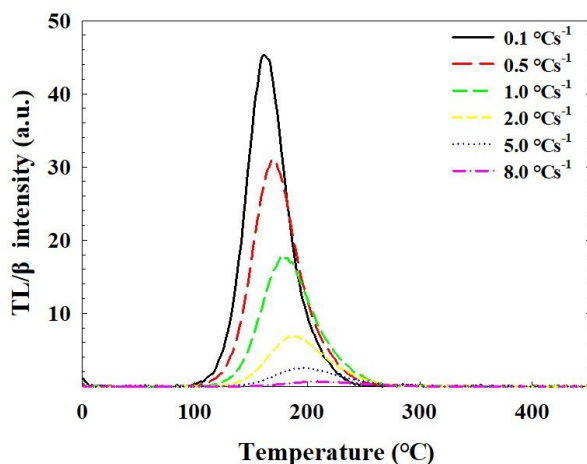


Fig. 1. TL signal (TL/β) versus temperature curves of Al₂O₃:C measured in a temperature range of 20–450 °C using various heating rates in a nitrogen atmosphere after 0.4 Gy of X-ray irradiation. The intensities of TL peaks measured at heating rates of 0.1 and 0.5 °C s⁻¹ are the results obtained by multiplying the actual measured peak intensities by 0.3 and 0.5, respectively.

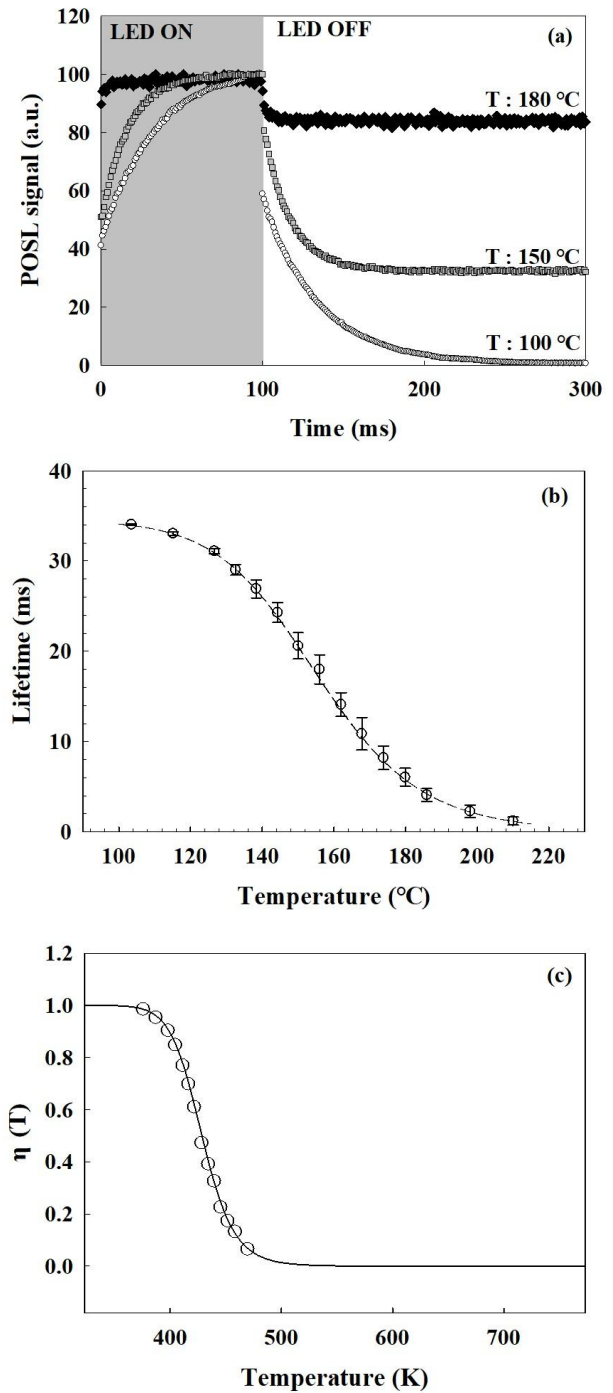


Fig. 2. (a) POSL signals and (b) Lifetimes at different measurement temperatures. (c) Luminescence efficiency as a function of temperature. The samples were optically stimulated under the following pulse conditions: pulse width 100 ms, dynamic range 500 ms, and dwell time 1 ms for 100 sweeps.

recombination center. Therefore, in typical TR-OSL, where the duration of the stimulating light pulse is very short, the depletion of trapped electrons during pulse stimulation is negligible, and the effects of re-trapping in

shallow traps can be ignored. The lifetime can be calculated by fitting the TR-OSL decay curve with $I(t) = \sum C_k \exp(t/\tau_k) + B$, where $I(t)$ is the TR-OSL signal at time t , C_k is the amplitude of the exponential component with lifetime τ_k , τ_k is the lifetime, and B is the background signal. The lifetimes were measured at 10°C intervals from 100°C to 210°C after 0.4 Gy of X-ray irradiation. Two components of the lifetime were evaluated: 34 ms (fast component) and 200 ms (slow component). Of the two lifetime components, the fast component is associated with F center luminescence, whereas the slow component is due to phosphorescence in shallow traps (Markey *et al.*, 1994). Fast lifetime component was used for thermal quenching correction. Examples of the POSL and lifetimes obtained at various temperatures are shown in Fig. 2a and 2b, respectively. The samples were optically stimulated under following optimal pulse conditions, i.e., pulse width of 100 ms , dynamic range (pulse duration) of 500 ms , and dwell time of 1 ms for 100 sweeps. The stability of the pulse conditions of the equipment used in this study was confirmed in Choi *et al.* (2014). Fig. 2a shows an example of POSL spectra composed of the build-up of luminescence during stimulation and decaying luminescence following the end of the stimulation light pulse. The increase in the intensity of POSL and background after stimulation as the measurement temperature increases can be

explained by the increase in thermal assistance to optical stimulation as the measurement temperature increases (Chithambo *et al.*, 2016). Fig. 2b shows that the lifetime decreases with increasing temperature, from 34 ms at 100°C to 2 ms at 210°C . Nonlinear regression analysis on the data using Eq. 1 gave the values of $W = 1.10 \pm 0.02\text{ (eV)}$ and $\nu = 2.54 \pm 1.21 \times 10^{14}\text{ (s}^{-1}\text{)}$. Using these values, the luminescence efficiency ($\eta(T)$) was calculated using Eq. 2 (Fig. 2c), which was used for thermal quenching correction. Fig. 3a shows the glow curves after correction for different heating rates using this method. It is interesting that the second peak, which was barely visible before thermal quenching correction, appeared clearly after thermal quenching correction. To verify that the correction was successful, the areas of the glow curves measured at various heating rates before and after correction were compared. As can be seen in Fig. 3b, the integrated glow curve areas at different heating rates after correction are similar, confirming successful correction. The ratios shown in Fig. 3b were normalized to the sum of the area after subtracting the background signal from the TL glow curve measured at a heating rate of 0.1°Cs^{-1} in a temperature range of $20\text{--}450^\circ\text{C}$ (Dogan *et al.*, 2017). Table 1 represents the relative ratios calculated by this method. The sample-to-sample variation in luminescence intensity was normalized using the TL peak area measured with an X-ray dose of 0.2 Gy after

Table 1. Relative ratios of the integrated TL glow curve areas in a temperature range of $20\text{--}450^\circ\text{C}$ according to various heating rates before and after thermal quenching correction. These ratios were normalized by the sum of the glow curve area measured at a heating rate of 0.1°Cs^{-1} .

	Heating rate ($^\circ\text{Cs}^{-1}$)					
	0.1	0.5	1.0	2.0	5.0	8.0
Uncorrected	1.00 ± 0.05	0.68 ± 0.03	0.61 ± 0.03	0.47 ± 0.02	0.41 ± 0.02	0.35 ± 0.02
Corrected	1.00 ± 0.05	0.99 ± 0.06	1.01 ± 0.06	1.00 ± 0.05	0.98 ± 0.07	0.99 ± 0.06

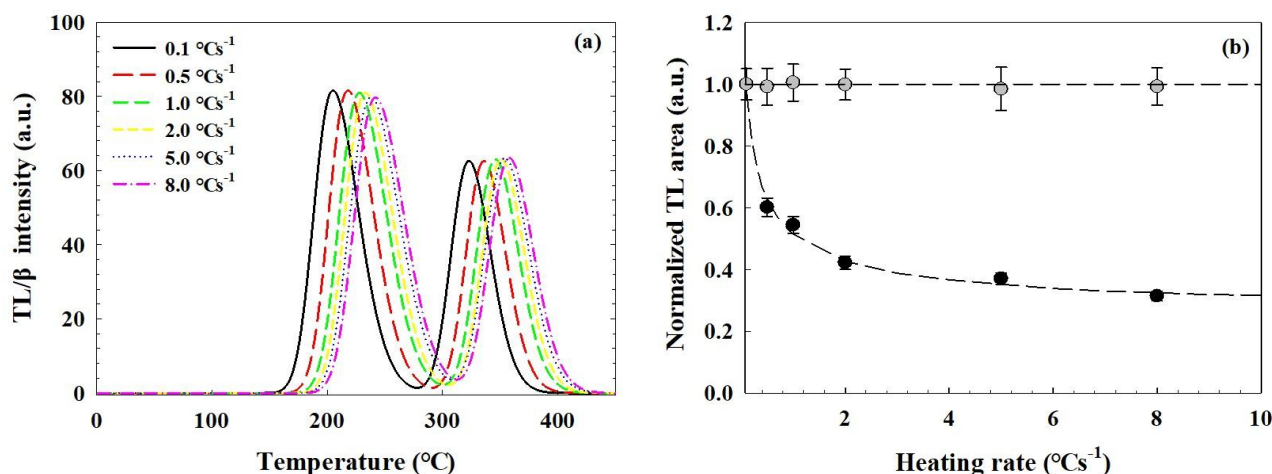


Fig. 3. (a) TL signal (TL/β) versus temperature curves at various heating rates after thermal quenching correction. (b) Integrated areas of TL glow curves before and after thermal quenching correction. The integrated areas of glow curves measured at different heating rates after the correction are similar, confirming the correction is successful. The second peak, which was barely visible before thermal quenching correction, appeared clearly after thermal quenching correction. The ratios were normalized by the sum of the areas after subtracting the background signals from the luminescence curves measured at a heating rate of 0.1°Cs^{-1} .

the first TL measurement. Three aliquots were used for each measurement, and the error bars represent the scatter of the measurements.

3.2. Peak separation

TL glow curves are usually composed of multiple overlapping peaks, which can be easily separated using the CGCD method (Kim and Hong, 2015). However, when analysing complex glow curves using the CGCD method, information on the number of glow peaks in the glow curve is required, because the results obtained using this method are highly dependent on the input parameters used in the deconvolution program. In this study, the number of glow peaks in the TL glow curves was determined using the T_m - T_{stop} method (McKeever, 1980). After irradiating the sample with 0.4 Gy of X-ray at 20°C, the sample was heated to a temperature defined as T_{stop} and then cooled to 20°C. The sample was then reheated to 350°C and the remaining TL glow curves were recorded. This process was repeated several times at different T_{stop} values with 5°C intervals under the same heat treatment/irradiation conditions. This process confirmed the presence of three plateau regions, suggesting that the TL glow curve consists of at least three glow peaks (Fig. 4).

Based on this information, the kinetic parameters of individual peaks were analysed using the CGCD method with nonlinear fitting of glow peaks according to general order kinetics (Akselrod et al., 1998; Chithambo et al., 2014). General order kinetics was approximated by the formula (Kitis et al., 1998):

$$I(T) = I_m b \frac{b}{b-1} \exp\left(\frac{E}{kT} \frac{T-T_m}{T_m}\right) \left[(b-1)(1 - \Delta) \frac{T^2}{T_m^2} \exp\left(\frac{E}{kT} \frac{T-T_m}{T_m}\right) + Z_m \right]^{-\frac{b}{b-1}} \quad (3)$$

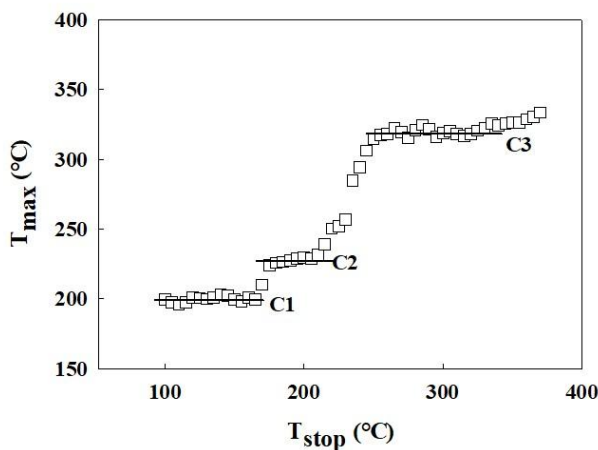


Fig. 4. Plot showing the first maximum temperature (T_m) of the remaining TL glow peaks for each temperature T_{stop} according to the T_m - T_{stop} procedure. The presence of three plateau regions suggests that the TL glow curve consists of at least three glow peaks.

Here, $\Delta = 2kT/E$, $\Delta_m = 2kT_m/E$, $Z_m = 1 + (b-1)\Delta_m$, I is the glow peak intensity, E is the activation energy, k is the Boltzmann constant, T is the absolute temperature, and b is the kinetic order. In this method, the activation energy, peak temperature, and order of the kinetics were independently optimized through iterative calculations. The computer program used for this analysis was designed using Mathematica software (version 8.0). The frequency factors corresponding to the values were evaluated using the formula:

$$s = \frac{\beta E}{kT_m^2 Z_m} \exp\left(\frac{E}{kT_m}\right), \quad (4)$$

where $\beta (= \frac{dT}{dt})$ is the heating rate, and other kinetic parameters are as previously described. Fig. 5a shows the separated peaks in the TL glow curve, and as can be seen in Fig. 5a, the TL glow curve was separated into three glow peaks at $197 \pm 3^\circ\text{C}$, $227 \pm 2^\circ\text{C}$, and $318 \pm 2^\circ\text{C}$, which are named as C1, C2, and C3, respectively. The resulting trap parameters corresponding to each separated peak are displayed in Table 2. Fig. 5b shows the residuals between the experimental TL data and the sum of the separated peaks. The goodness-of-fit of the measured glow curves was tested using the figure of merit (FOM) proposed by Balian and Eddy (1977).

$$\text{FOM} = \frac{\sum |y_i - f_i|}{\sum f_i} \times 100 (\%), \quad (5)$$

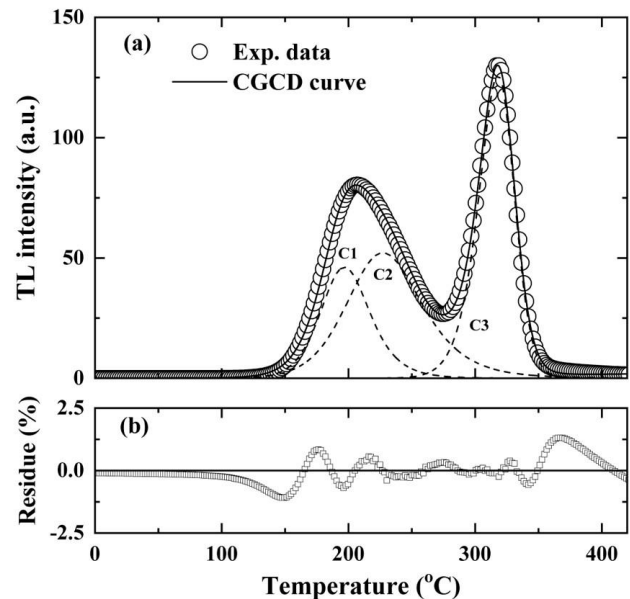


Fig. 5. (a) Glow curve obtained through experiment and peaks separated from the glow curve using the CGCD method, (b) Residue of the fitted curve. TL measurements were performed in a nitrogen atmosphere at a heating rate of 5°C s^{-1} in a temperature range of 20–450°C after X-ray irradiation of 0.4 Gy.

Table 2. Glow peak trapping parameters, heating rates and radiation responses of $\text{Al}_2\text{O}_3\text{:C}$ TL peaks separated using CGCD method.

TL Component	Peak temperature T_m (°C)	E (eV)	b	s (s^{-1})	Heating rate ($^{\circ}\text{Cs}^{-1}$)	Radiation response	Reference
C ₁	197 ± 3	1.39 ± 0.4	2.00 ± 0.05	$3.14 \pm 0.27 \times 10^{14}$	5	saturating	Dallas <i>et al.</i> (2008)
C ₂	227 ± 2	1.01 ± 0.12	2.00 ± 0.20	$3.62 \pm 0.19 \times 10^9$		saturating	
C ₃	318 ± 2	2.57 ± 0.23	1.41 ± 0.19	$3.15 \pm 0.31 \times 10^{21}$		supralinear	
	193	1.47	1.2	5.70×10^{14}	0.5		
	239	1.32	2.0	1.12×10^{11}			
	311	2.55	1.3	8.50×10^{19}			

where Y_i is the measured value and f_i is the fitted value of TL intensity at that temperature. The FOM value is less than 3.3%, indicating a good fit.

3.3. Bleaching of the separated peaks

The time dependence of bleaching was investigated by comparing the TL glow curves measured before and after blue stimulation. The procedure was started by measuring the TL glow curves of the sample after irradiation with an X-ray dose of 0.4 Gy, followed by blue stimulation for various bleaching times of 0, 5, 20, 100, 250, and 600 s. An example of the glow curve after bleaching is shown in Fig. 6a. These bleached glow curves were then separated using the CGCD method mentioned earlier, and the measured luminescence intensities were normalized using the same method described in Section 3.1. Fig. 6b shows the bleaching of peaks C1, C2, and C3. Three aliquots were used in each measurement, and the error bars represent the scatter of measurements.

3.4 X-ray irradiation response of the separated peaks

The response of each isolated TL glow peak to radiation dose was investigated using growth curves. The multiple-aliquot additive dose method was used to construct the growth curves (Aitken, 1985). The sequence adopted was as follows. After measuring the background, X-ray doses ranging from about 0.1 Gy to 5 Gy were applied to different groups of three aliquots each, and the TL was measured. Then, a second monitor dose was applied to each aliquot and the measured TL signal was used for normalization. Using the glow curves obtained in this way, the peaks were separated using the CGCD method described above. Growth curves showing the luminescence intensity versus the radiation dose were constructed using the integrated TL signals of the isolated peaks C1, C2, and C3. An example of the addition dose growth curve is shown in Fig. 7, and the error bars displayed in Fig. 7 indicate the scatter of the measurements.

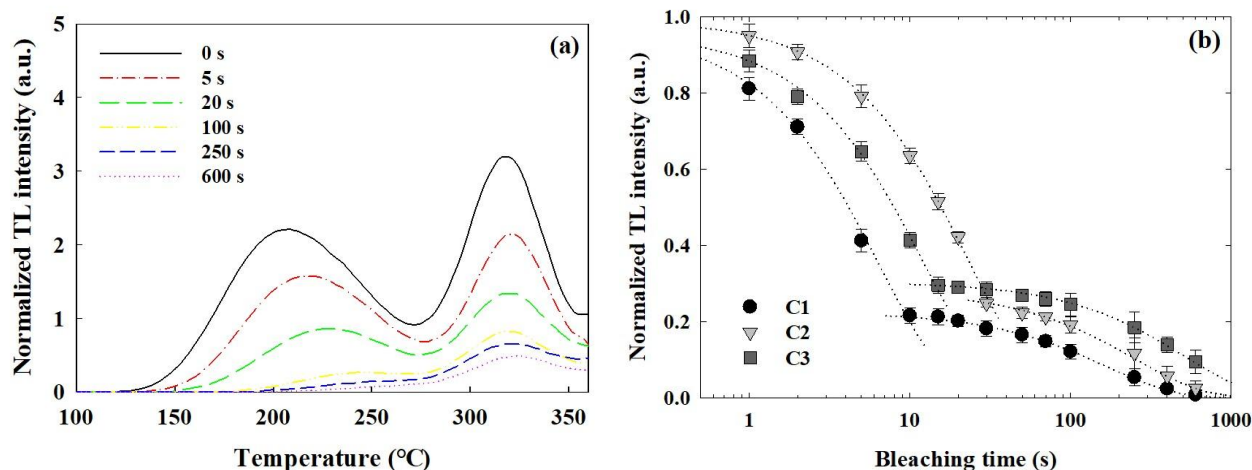


Fig. 6. (a) Selected glow curves after various bleaching times. (b) Normalized TL intensities for bleaching of peaks C1, C2, and C3. All data were displayed on a linear-logarithmic scale, showing a pattern of rapid initial bleaching followed by gradual bleaching. The lines were fitted $f_1(t)=0.96 \exp(-0.16 t) + 0.21 \exp(-0.003 t)$ for peak C1, $f_2(t)=0.99 \exp(-0.04 t) + 0.02 \exp(-0.002 t)$ for peak C2 and $f_3(t)=0.96 \exp(-0.08 t) + 0.30 \exp(-0.002 t)$.

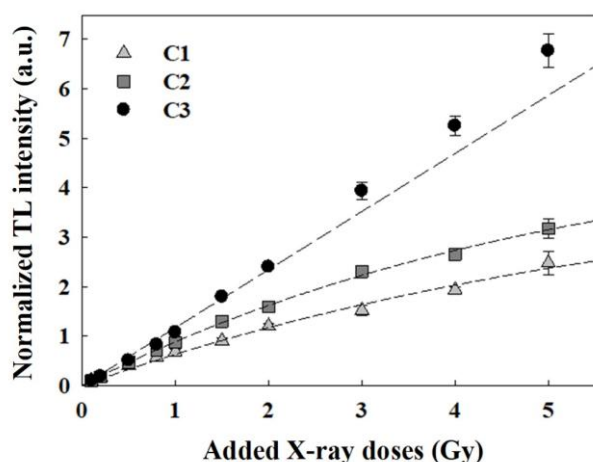


Fig. 7. Normalized TL intensities of peaks C1, C2, and C3 measured after irradiation with increased beta doses. Peaks C1 and C2 showed sublinear dose responses, whereas peak C3 exhibited a supralinear response.

4. Results and discussion

By using the POSL method to correct the thermal quenching effect, the quenching parameters of $W = 1.10 \pm 0.02$ (eV) and $\nu = 2.54 \pm 1.21 \times 10^{14}$ (s⁻¹) were obtained, which are in excellent agreement with the values reported by Akselrod *et al.* (1998). Using these values, the glow curves were successfully reconstructed. The trapping parameters are an important factors in the research field of luminescence dosimetry. In this study, at a heating rate of 5°Cs⁻¹, the activation energies, kinetic orders and frequency factors were obtained as 1.39 ± 0.04 (eV), 2.00 ± 0.05 , $3.14 \pm 0.27 \times 10^{14}$ (s⁻¹) for peak C1, 1.01 ± 0.12 (eV), 2.00 ± 0.20 , $3.62 \pm 0.19 \times 10^9$ (s⁻¹) for peak C2 and 2.57 ± 0.23 (eV), 1.41 ± 0.19 , $3.15 \pm 0.31 \times 10^{21}$ (s⁻¹) for peak C3, respectively. Dallas *et al.* (2008) introduced a thermal quenching correction process for Al₂O₃:C samples exhibiting three different forms of the glow curves (narrow, wide, and double glow curves) and presented glow peak trapping parameters derived through deconvolution. Analysis of the sample exhibiting a wide glow curve form revealed three peaks components at maximum peak temperatures of 193°C, 239°C and 311°C, respectively. In addition, the activation energy, kinetic order, and frequency factor values corresponding to each peak temperature were calculated to be 1.47 (eV), 1.2, 5.7×10^{14} (s⁻¹); 1.32 (eV), 2, 1.12×10^{11} (s⁻¹) and 2.55 (eV), 1.3, 8.5×10^{19} (s⁻¹), respectively (Table 2). As can be seen in Table 2, when comparing our trapping parameters obtained from this study with their results, some showed similar values, while others showed different values. These discrepancies can be attributed to the peak temperature differences of approximately 5–10°C and the

temperature lag effects that may occur in the high heating rates (Topaksu and Yazici, 2007). Zahedifar (2012) also studied the glow peak kinetics and found that the glow curve of Al₂O₃:C consists of three component glow peaks, which is consistent with our results.

In the bleaching investigation, there is a rapid initial bleaching in all peaks, which continued at a slower rate during the 600 s of light exposure. The bleaching rates of peaks C1, C2 and C3, which are expressed in terms of the residual TL signal versus the light exposure time, exhibit two different exponential decays expressed in the form of $f(t) = \sum_{i=1}^2 a_i e^{-\lambda_i t}$, where a_i and λ_i are a constant and decay constant, respectively. The decay constants of $\lambda_1 = 0.16$ s⁻¹ and $\lambda_2 = 0.003$ s⁻¹ for peak C1, $\lambda_1 = 0.04$ s⁻¹ and $\lambda_2 = 0.002$ s⁻¹ for peak C2 and $\lambda_1 = 0.08$ s⁻¹ and $\lambda_2 = 0.002$ s⁻¹ for peak C3 were evaluated. One possible explanation for the appearance of two decay components could be competition between two different processes: optical stimulation and phototransfer. In the early stage of bleaching, optical stimulation dominates, causing the signal to decay more quickly. However, after a few seconds of bleaching, the electron concentration in the optically active traps decreases significantly. At this stage, the phototransfer process becomes more dominant than optical stimulation, resulting in a slower signal decay (Bulur *et al.*, 1999; Chithambo *et al.*, 2017). The bleaching rates and errors were evaluated individually using a least-squares fit on linear/log-scale plots. The maximum residual TL signals of each peak were different after bleaching. After 600 s of bleaching, the TL intensities of peaks C1, C2, and C3 decreased to about 4%, 6%, and 9% of their initial values, respectively.

In the X-ray dose response study, peaks C1 and C2 showed sublinear dose responses, whereas peak C3 exhibited a supralinear response (Table 2), as shown in Fig. 7.

5. Conclusions

In this study, using the T_m - T_{stop} method it was found that the TL glow curve of Al₂O₃:C after X-ray irradiation exhibited at least three glow peaks in temperature ranges of 20–350° C. The glow peaks separated using the CGCD method after thermal quenching correction were well described by the general order kinetics model. Examining the bleaching effect caused by blue light stimulation on the separated peaks, it can be seen that the bleaching rate exhibits two different exponential decays, which can be explained by the competition between optical stimulation and phototransfer. These decay peaks included gradual bleaching after rapid initial bleaching, and after bleaching for 600 s, the TL intensities of peaks C1, C2 and C3 decreased to approximately 4%, 6% and 9% of the initial values, respectively. In the X-ray dose response study, peaks C1 and C2 showed sublinear dose responses, whereas peak C3 exhibited a supralinear response.

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