Journal of Luminescence 275 (2024) 120807

Contents lists available at ScienceDirect

Journal of Luminescence

journal homepage: www.elsevier.com/locate/jlumin

Full Length Article

$SrAl_2O_4$: Ce: Synthesis and dosimetric characteristics of a new highly sensitive TL phosphor for dosimetry

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ARTICLE INFO

Keywords:
Strontium aluminate
Dosimetry
Thermoluminescence
Solid-state synthesis

ABSTRACT

Strontium aluminate ($SrAl_2O_4$) doped with different Ce concentrations was synthesized by the solid-state reaction method to find the best thermoluminescent response. The crystal structure of the material has been analyzed by Rietveld refinement of X-ray diffraction (XRD) results. The effects of different dopant concentrations and thermal annealing regimes on TL sensitivity and the optimum conditions for producing dosimeters with superior sensitivity to commercial dosimeters were investigated. It has been shown that the maximum TL sensitivity is obtained at a concentration of 0.3 mol% Ce and a heat treatment at 1000 °C for 2 h. The TL glow curve of Ce-doped strontium aluminate ($SrAl_2O_4$) pellets shows three TL peaks at 90, 150, and 250 °C. The dosimetric characteristics of the new material examined in this work are linear response in the dose range with applications in personal and environmental dosimetry; TL sensitivity; minimum detection dose; reproducibility; energy dependence; and TL signal fading. Based on the results obtained, the synthesized material is a dosimeter with a sensitivity 2.44 times higher than the commercial dosimeter TLD-100 (LiF:Ti,Mg).

1. Introduction

Optical and thermal stimulations on materials exposed to radiation produce light, which is proportional to the radiation dose. Therefore, there is much research on new luminescent materials that can be used in dosimetry [1].

Dosimetry estimates the absorbed amount of radiation using one or more detectors. An ideal detector should have a signal that is linearly proportional to the absorbed dose of radiation for a given radiation field [2].

Among the various materials investigated, strontium aluminate doped with rare earths has been investigated for its interesting physical properties and applications in photonics, luminescence radiation detectors, and luminescence pigments [3–9]. In addition, this material is relatively inexpensive and easy to obtain by synthesis techniques such as combustion [10,11], solid-state reaction [12,13], hydrothermal [14], and sol-gel [15], which makes it an attractive option to be used in practical applications such as radiation dosimetry by thermoluminescence (TL).

Mothudi et al. [16] showed that the red-light emission in Eu- and Dy-doped strontium aluminate is due to the substitution of the Eu^{3+} ion in place of the strontium atom. On the other hand, the Dy^{3+} ion acts as a hole capture center [16]. Similarly, Pardhi et al. [17] synthesized Eu and Dy doped strontium aluminate and revealed the nature and behavior of traps upon irradiation with UV and γ radiation, showing the presence of a peak at 92 °C with UV radiation and a peak at 73 °C with γ radiation. Furthermore, Pardhi et al. [17] observed that the TL intensity of both TL peaks increases with UV irradiation time up to 15 min.

Zúñiga-Rivera et al. [18] synthesized and analyzed the TL response of two groups of strontium aluminate samples produced by the combustion method, the first group doped with Eu and Dy, and the second group doped with Eu and Nd. Both samples showed two overlapping TL peaks at low temperatures around 70 and 100 °C, and 60 and 130 °C, respectively.

Recently, Canaza-Mamani et al. [19] synthesized pure strontium aluminate by the solid-state reaction method to investigate its TL properties. The TL glow curve of this material presented three peaks at 135, 260, and 350 °C. In addition, these authors identified the defect

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https://doi.org/10.1016/j.jlumin.2024.120807
Received 29 April 2024; Received in revised form 29 June 2024; Accepted 19 July 2024
Available online 19 July 2024

centers responsible for the emission of the TL peaks using the electron paramagnetic resonance technique.

As we can see, studies of the effect of rare earth doping on strontium aluminate crystals have been carried out by several researchers. However, within these studies, we did not find systematic studies of the effect of Ce doping on the thermoluminescence properties of strontium aluminate synthesized by the solid-state reaction method. Therefore, the purpose of this work is to produce dosimeters in the form of Ce-doped strontium aluminate pellets and to investigate their TL properties when irradiated with γ and β rays. In addition, study the dosimetric characteristics of this material for its use in radiation dosimetry.

2. Material and methods

Ce-doped strontium aluminate ($SrAl_2O_4$: Ce) was obtained by the solid-state reaction synthesis technique, using strontium carbonate ($SrCO_3$ - 98 %) and aluminum oxide (Al_2O_3 - 98 %) as precursors and cerium oxide (CeO_2 - 99.9 %) as dopant. In addition, less than 8 mol% of boric acid (H_3BO_3) was added as a flux [20]. The stoichiometric quantities of the precursors, the dopant, and the boric acid were homogenized in an alumina ball mill for 4 h, then the mixture was placed in an alumina crucible and then placed in a furnace at 1200 °C for 2 h in a simple air atmosphere, after which it was slowly cooled to room temperature by turning off the furnace.

The X-ray diffraction (XRD) pattern of the material synthesized with different concentrations of Ce was recorded in the 2θ range from 10° to 70° using a Rigaku Model Miniflex 6000 X-ray diffractometer with Cu-Kα radiation (λ = 1.5406 Å), speed of 2.0°/min, and steps of 0.005°.

To perform thermoluminescence measurements and dosimetric characterization of strontium aluminate, 5 groups of pellets of 6 mm diameter, 1 mm thickness, and 50 mg mass were produced by pressing the fine powder of the synthesized material in a circular stainless-steel mold at 11 tons for 5 min and sintered at temperatures of 800, 900, 1000, 1100, and 1200 for 2 h in a simple air atmosphere, respectively. Fig. 1 shows the whole synthesis process, the stainless-steel mold, and the strontium aluminate pellets produced.

TL measurements were performed with a Harshaw TL reader, model 3500, with a heating temperature of up to 400 °C, a linear heating rate of 4 °C/s, and continuous nitrogen flow. TL emission curves were measured immediately after irradiation, except for fading measurements.

Four sources were used for the irradiation of the pellets: (1) a ^{60}Co γ source from Picker, model Gammatron with a dose rate of 9.93 mGy/min at a distance of 10 cm from the source; (2) a ^{90}Sr β source with a dose rate of 60 mGy/s; this source is incorporated inside the Lexsyg TL/OSL reader; (3) a Philips MG 450 X-ray source with a maximum voltage of 200 kV; and (4) an ultraviolet (UV) light source with a 75 W XENON ORIEL UV lamp, model 6237, at a distance of 14 cm from the UV source.

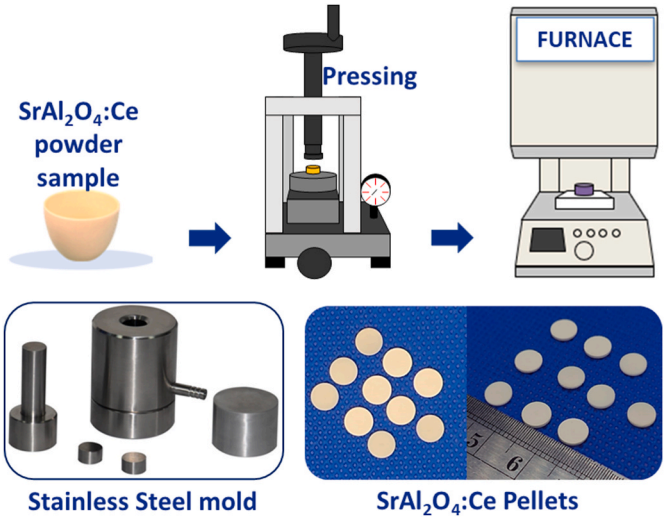

Fig. 1. (Top) Experimental methodology for obtaining $SrAl_2O_4$: Ce pellets. (Bottom) The stainless-steel mold used for pressing the sample and pictures of the $SrAl_2O_4$: Ce phosphor pellets sintered at high temperatures.

3. Results and discussion

3.1. Structural characterization by X-ray diffraction (XRD)

In Fig. 2(a), we present the X-ray diffractograms of strontium aluminate phosphor for different Ce doping concentrations (0.1, 0.2, 0.3, 0.4, and 0.5 mol%). The presence of sharp and intense peaks at the same position indicates good crystallinity and no interference of the dopant on the crystalline structure in the concentration range analyzed. A preliminary analysis of the position of the XRD peaks of the synthesized material shows the presence of strontium aluminate ($SrAl_2O_4$) in its monoclinic phase, which agrees with the crystallographic record COD-2002284 (COD - Crystallography open database). However, other low-intensity peaks corresponding to other secondary phases are observed in lower percentages. Fig. 2(b) illustrates the behavior of the main peak position of $SrAl_2O_4$ for different Ce dopant concentrations; the triangles indicate that the center of the main peak shifts slightly toward higher angles as the Ce dopant concentration increases. The slight shift of the main peak to higher angles (see Fig. 2(b)) is possibly due to lattice distortion induced by cerium ions by substituting some of the strontium ions in strontium aluminate. A similar result was observed by Velayutham et al. [21] in Ce-doped $Sr_{0.5}Ba_{0.5}Nb_2O_6$ ceramics synthesized by the solid-state reaction method.

To study the effect of heat treatment and dopant concentration on the crystal lattice parameters and verify the formation of secondary crystalline phases in the synthesized samples, the XRD data were analyzed by Rietveld refinement.

Table 1 presents the refinement parameters, crystalline parameters, and percentage of the crystalline phases (monoclinic, hexagonal, and

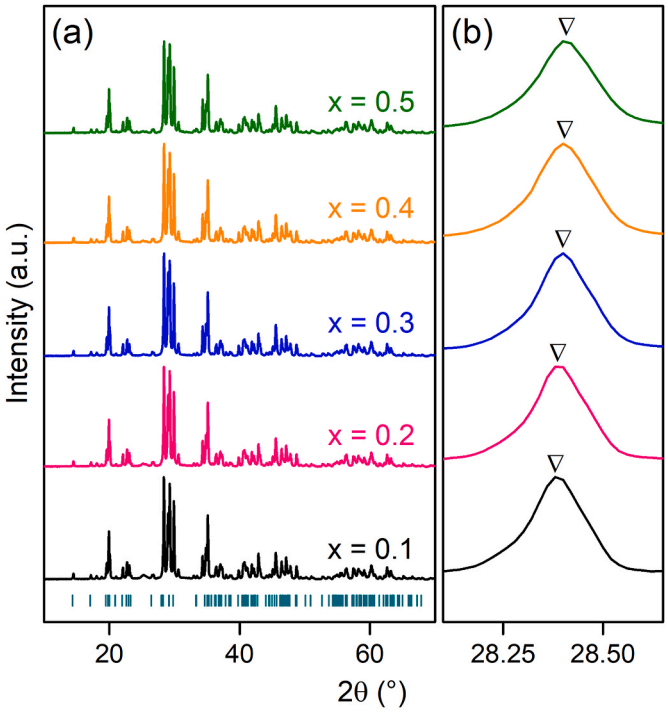

Fig. 2. (a) XRD patterns of the crystal $SrAl_2O_4$ doped with different concentrations of Ce together with the standard spectrum (shown as green vertical lines). (b) Slight shift of diffraction main peak after doping with Ce.

Table 1
Rietveld refinement parameters and lattice parameters of strontium aluminate samples doped with different Ce concentrations.

Ce Concentration (mol%)	Phase Percentage (%)		Refinement parameters			Lattice parameters				Volume
			R_p	R_{wp}	χ^2	a (Å)	b (Å)	c (Å)	α, γ, β (°)	(Å^3)
0.1	Monoclinic	84.3	7.9151	11.7780	6.98	5.1572	8.8194	8.4419	90, 90, 93.40	383.31
	Hexagonal	12.2				9.0430	9.0436	8.3835	90, 120, 90	593.76
	Trigonal	3.5				6.1919	6.1911	10.4131	90, 120, 90	345.67
0.2	Monoclinic	85.7	7.9098	11.0081	6.11	5.1576	8.8211	8.4437	90, 90, 93.40	383.51
	Hexagonal	11.0				9.0443	9.0446	8.3854	90, 120, 90	594.07
	Trigonal	3.4				6.3943	6.3949	10.297	90, 120, 90	364.70
0.3	Monoclinic	76.5	7.4714	10.4939	5.49	5.1577	8.8199	8.4432	90, 90, 93.31	383.40
	Hexagonal	19.8				9.0431	9.0433	8.3863	90, 120, 90	593.96
	Trigonal	3.6				6.2271	6.2277	10.4065	90, 120, 90	349.53
0.4	Monoclinic	75.9	8.8113	11.7983	6.74	5.1579	8.8210	8.4428	90, 90, 93.39	382.43
	Hexagonal	12.3				9.0443	9.0441	8.3858	90, 120, 90	594.03
	Trigonal	11.8				6.2521	6.2528	10.3931	90, 120, 90	351.91

trigonal) of $SrAl_2O_4$ doped with different Ce concentrations obtained by the Rietveld refinement method from the experimental XRD data. Despite the formation of strontium aluminate in its monoclinic phase, there is a high concentration of secondary phases for all Ce concentrations. It is known that annealing at high temperatures after the synthesis of the material allows for an improvement in the percentage of a single crystalline phase [15,22,23]. Therefore, strontium aluminate samples were heat treated at 800, 900, 1000, and 1100 °C for 2 h.

Fig. 3 shows the Rietveld refinement of the XRD data for strontium aluminate phosphor doped with 0.3 % Ce after heat treatment at 1000 °C for 2 h. The refinement analysis shows a significant improvement in the percentage of the monoclinic phase relative to the sample without heat treatment, being 95.5 % of the monoclinic phase, 5.5 % of the trigonal phase, and 0.4 % of the hexagonal phase.

Table 2 presents the Rietveld refinement parameters and lattice parameters of the three crystalline phases found in the samples of $SrAl_2O_4$ doped with 0.3 mol% Ce for different heat treatments (800, 900, 1000, and 1100 °C for 2 h). From this table, we can observe that the heat treatment alters the percentage of crystalline phases, being a heat treatment at 1000 °C the most suitable to obtain strontium aluminate in its monoclinic phase. Therefore, for further studies, the $SrAl_2O_4$ sample doped with 0.3 mol% Ce with heat treatment at 1000 °C for 2 h after synthesis was used.

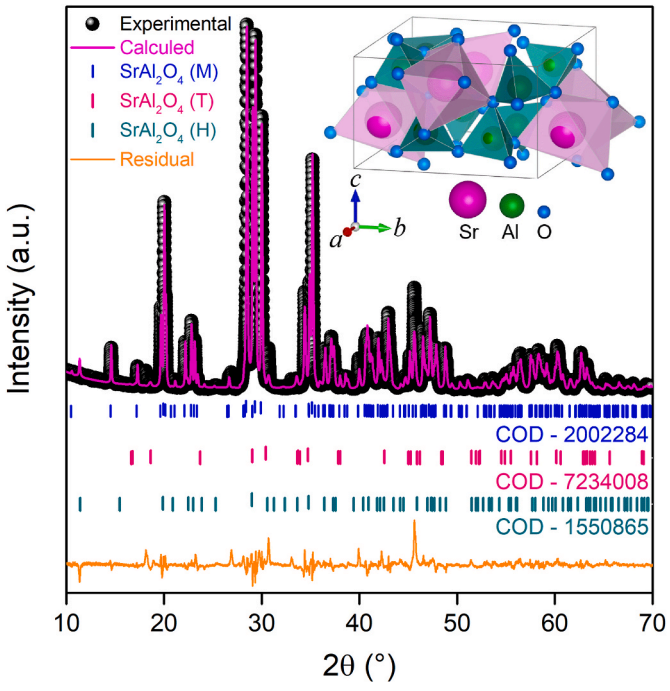

Fig. 3. XRD patterns of $SrAl_2O_4$. Experimental (black spheres), calculated (pink solid line), residual (orange solid line), and the blue, red, and green verticals indicate the Bragg positions of $SrAl_2O_4$ for the monoclinic (M), tetragonal (T), and hexagonal (H) phases, respectively. The monoclinic crystal structure of $SrAl_2O_4$ is shown in the inset of the figure.

3.2. Thermoluminescence (TL)

3.2.1. TL glow curve

The characteristics of the TL glow curve of a material depend to a large extent on the luminescent defect centers generated during the synthesis process. These centers may be due to impurities (dopants) introduced into the material's structure [24,25]. Therefore, we initially studied the effect of the dopant concentration on the TL emission curve, looking for the most suitable dopant concentration to produce a material highly sensitive to ionizing radiation.

Fig. 4 shows the TL glow curves of $SrAl_2O_4$ pellets for different Ce concentrations obtained by the sintering process at 1000 °C. From this result, we can observe the presence of two slightly overlapping main peaks centered at 150 and 250 °C, and a satellite peak around 90 °C superimposed on the first main peak. In the inset of Fig. 4, we can observe that the intensity of the peak at 250 °C varies with Ce concentration. The sample doped with 0.3 mol% Ce presents the best sensitivity in its TL response. On the other hand, the peak position at 250 °C presents a slight shift for lower temperatures. Due to the position of the peak at 250 °C and the low overlap with other peaks, this peak is ideal for use in radiation dosimetry. Therefore, for the following studies, a sample doped with 0.3 % Ce was used.

For the study of the dosimetric characteristics of $SrAl_2O_4$: Ce, pellets were produced by pressing the powdered sample using a stainless-steel mold, and then sintered at high temperatures. For this purpose, a systematic study of the effect of sintering temperature (800, 900, 1000, 1100, and 1200 °C for 2 h) on the response was initially carried out. The glow curves for different sintering temperatures are shown in Fig. 5. In the inset of Fig. 5, we observe that the TL intensity of the peak at 250 °C increases rapidly with sintering temperatures up to 1000 °C. For a temperature of 1100 °C, there is a slight increase, followed by a rapid decay for a temperature of 1200 °C. This result is in agreement with the X-ray diffraction results: for a temperature of 1100 °C, the concentration of the monoclinic phase of strontium aluminate decreases. In addition, the increase in TL intensity is possibly due to the crystallinity enhancement of strontium aluminate in its monoclinic phase, which occurs up to a temperature of 1000 °C. Therefore, the phosphor sample $SrAl_2O_4$ doped with 0.3 mol% Ce was selected to produce sintered pellets at a temperature of 1000 °C for 2 h for further analysis.

Fig. 6 shows the TL glow curves of $SrAl_2O_4$: Ce pellets measured for different γ radiation doses between 1 and 1000 mGy. The TL glow curve shows two intense peaks at 150 and 250 °C, slightly overlapping each other. A satellite peak at 90 °C superimposed with the 150 °C peak and

Table 2
Rietveld refinement parameters, lattice parameters, and percentage of crystalline phases of $SrAl_2O_4$:Ce samples annealed at different temperatures.

Heat treatment (°C)	Phase Percentage (%)		Refinement parameters			Lattice parameters				Volume
			R_p	R_{wp}	χ^2	a (Å)	b (Å)	c (Å)	α, γ, β (°)	(Å^3)
800	Monoclinic	77.6	7.8872	10.9461	5.97	5.1575	8.8201	8.4428	90, 90, 93.39	383.39
	Hexagonal	19.1				9.0436	9.0436	8.3859	90, 120, 90	593.96
	Trigonal	3.30				6.3765	6.3765	10.3129	90, 120, 90	363.14
900	Monoclinic	72.6	9.1805	13.6067	9.10	5.1566	8.8207	8.4417	90, 90, 93.39	383.30
	Hexagonal	21.7				9.0421	9.0421	8.3866	90, 120, 90	593.82
	Trigonal	6.50				6.3749	6.3749	10.3120	90, 120, 90	362.92
1000	Monoclinic	95.5	8.2062	12.1942	7.23	5.1565	8.8203	8.4425	90, 90, 93.39	383.31
	Hexagonal	0.40				9.0422	9.0422	8.3882	90, 120, 90	593.95
	Trigonal	5.5				6.2218	6.2217	10.4162	90, 120, 90	349.20
1100	Monoclinic	87.80	9.0347	12.4522	8.01	5.1583	5.1583	5.1583	90, 90, 93.39	383.55
	Hexagonal	7.90				9.0463	9.0463	9.0463	90, 120, 90	594.01
	Trigonal	4.40				6.3784	6.3784	6.3784	90, 120, 90	363.04

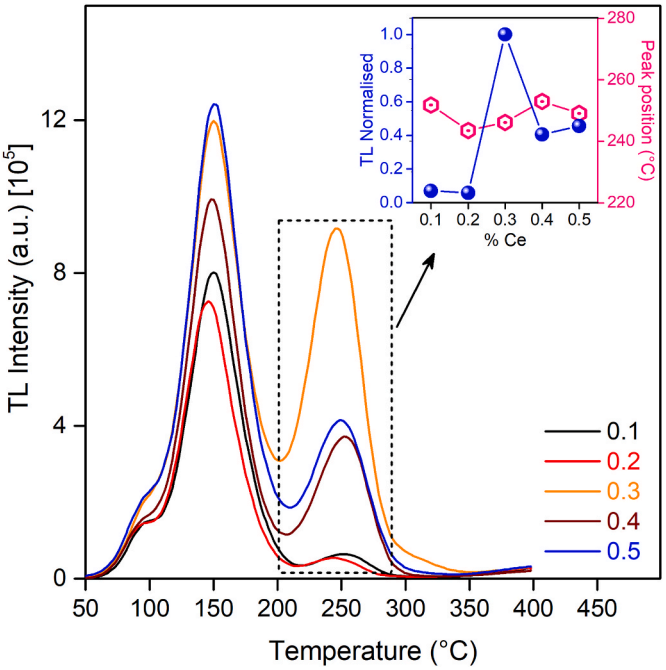

Fig. 4. TL glow curves of $SrAl_2O_4$: Ce pellets for different percentages of Ce irradiated with a γ dose of 50 mGy. The inset shows the intensity (open black circle) and position of the TL peak (pink spheres) in the region of 190 and 290 °C with increasing Ce concentration.

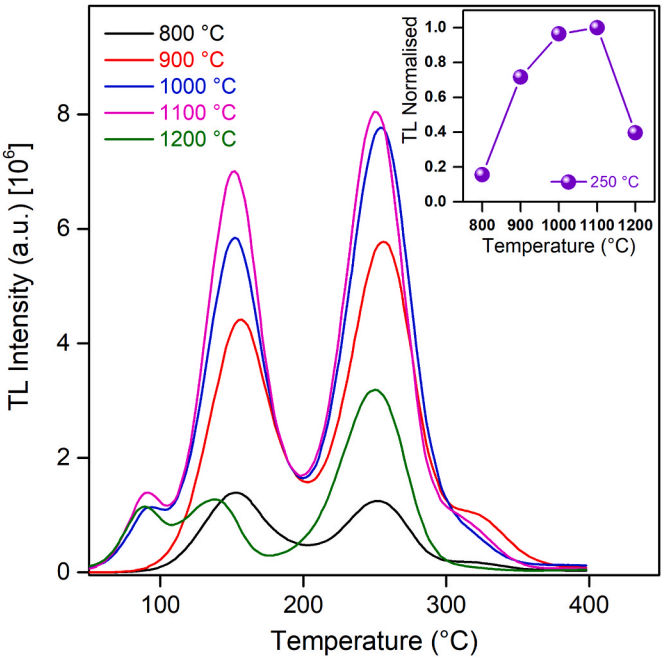

Fig. 5. TL glow curve of $SrAl_2O_4$: Ce pellets sintered at different temperatures and irradiated with a dose of 1 Gy. In the inset of the figure, the TL intensities of the TL peak at 250 °C are shown as a function of sintering temperature.

another satellite peak at 310 °C superimposed with the 250 °C peak is also observed. The TL peak at 90 °C is unstable at room temperature and decays completely in less than 1 h. The position of the peaks at 150 and 250 °C remains unchanged with the γ radiation dose, which is indicative that both peaks obey first-order kinetics.

In addition, the TL glow curves of $SrAl_2O_4$: Ce with γ (0.5 Gy), β (0.5 Gy), and UV (20 s irradiation) irradiation were measured and are shown in Fig. 7. The position of the TL peaks at 150 and 250 °C does not change with γ and β irradiation. This result shows that $SrAl_2O_4$: Ce can be effective for performing dosimetry with both types of radiation using the same TL peaks. On the other hand, when the sample is irradiated with UV rays, both TL peaks present a shift of 10 °C for high temperatures. Also, we observed that the TL intensity varies with the type of radiation; the response with γ radiation is two times more intense than the response with β radiation.

3.3. Dosimetric characterization

3.3.1. Linearity

It is important to investigate the linearity of TL response with irradiation dose to establish the dose range in which the material can be used as a TL dosimeter. A linear TL dose response is a desirable property of dosimetric materials, as it provides the simplest possible calibration of a TL dosimeter.

Chouby et al. [26] investigated the TL response of Eu and Dy doped $SrAl_2O_4$ irradiated with γ radiation in the range of 50 Gy to 2 kGy, observing a linear behavior. However, these doses are too high for personal and environmental dosimetry purposes. On the other hand, Canaza-Mamani et al. [19] observed a linear behavior of the TL response in undoped strontium aluminate for γ radiation doses in the order of kGy.

In this work, the linearity study was performed by analyzing the behavior of the TL peak intensity as a function of dose (also called the calibration curve) with logarithmic axes and decades of equal dimensions. In this way, we can graphically observe whether the curve behaves linearly (slope = 45°), supralinearly (>45°), or sublinearly

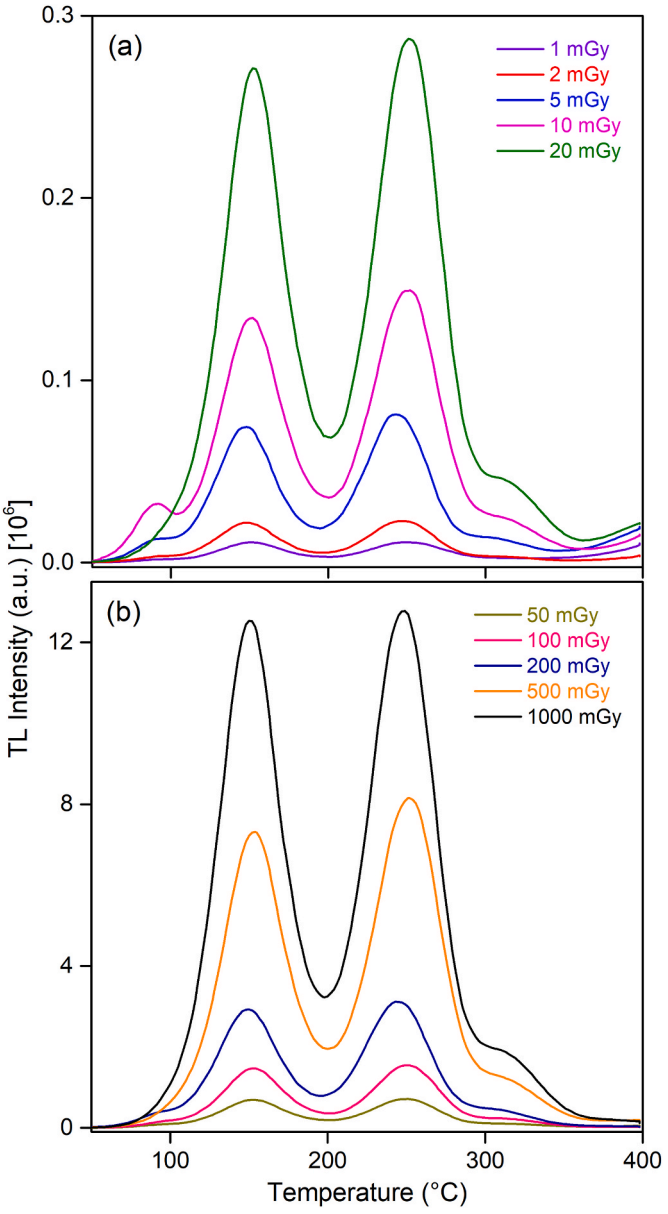

Fig. 6. TL glow curves of $SrAl_2O_4$: Ce measured for different doses of γ radiation.

(<45°). Fig. 8 shows the TL intensity behavior of the peaks at 150 and 250 °C as a function of γ radiation dose. It is observed that the intensity of the two peaks presents a linear behavior in the analyzed dose range, making this material ideal for applications in dosimetry.

3.3.2. Sensitivity

To analyze the TL sensitivity of $SrAl_2O_4$ pellets, undoped and doped with 0.3 mol% Ce, we compared their TL response with that of the commercial dosimeter TLD-100 (LiF:Ti,Mg), purchased from Harshaw Bicron. For this purpose, $SrAl_2O_4$ pellets and the TLD-100 dosimeter were irradiated with the same γ irradiation dose of 1 Gy, and then the TL glow curve was recorded. For comparison purposes, the intensity of both materials was normalized to mass. In Fig. 9, we can observe that $SrAl_2O_4$; Ce pellets present TL peaks 2.44 times more intense than the dosimetric peak of TLD-100. Moreover, $SrAl_2O_4$: Ce pellets present two slightly overlapping simple peaks compared to the complex glow curve of TLD-100.

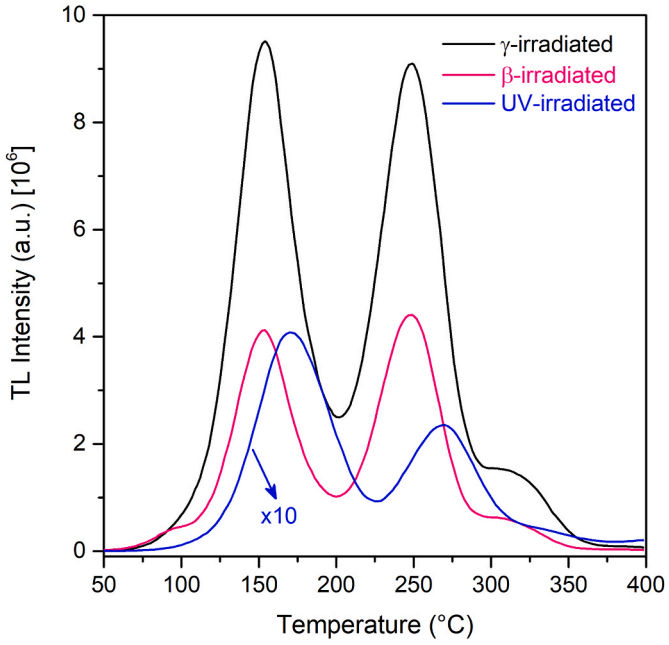

Fig. 7. TL glow curves of $SrAl_2O_4$: Ce irradiated with γ, β, and UV. The irradiation doses for γ and β rays were 0.5 Gy and 20 s irradiation for UV rays.

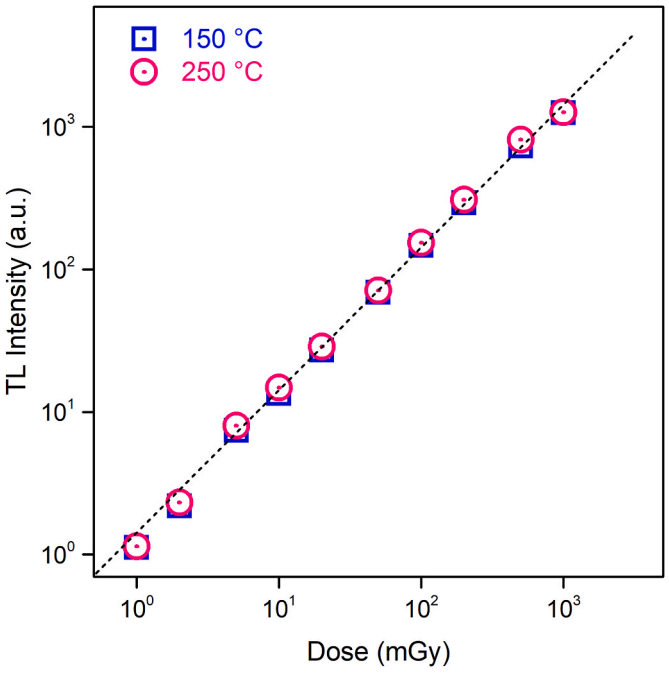

Fig. 8. The graph depicts the relationship between TL intensity and radiation dosage (γ) for the TL peaks at 150 and 250 °C. The dashed lines (black) in the graph represent linearity.

3.3.3. Reproducibility

A promising luminescent material to be used in TL dosimetry must keep the TL signal intensity constant after several cycles of irradiation and TL readings. For this reason, $SrAl_2O_4$: Ce pellets were subjected to several annealing-irradiation-reading cycles. The procedure for each cycle consists of (i) annealing at 500 °C for 30 min; (ii) irradiation with 1 Gy of γ radiation dose; and finally, (iii) TL reading in the temperature range of 50 – 400 °C. This procedure was carried out for 10 cycles on the same set of pellets. The results indicated that, after the reproducibility procedure, the sensitivity of both TL peaks at 150 and 250 °C presents

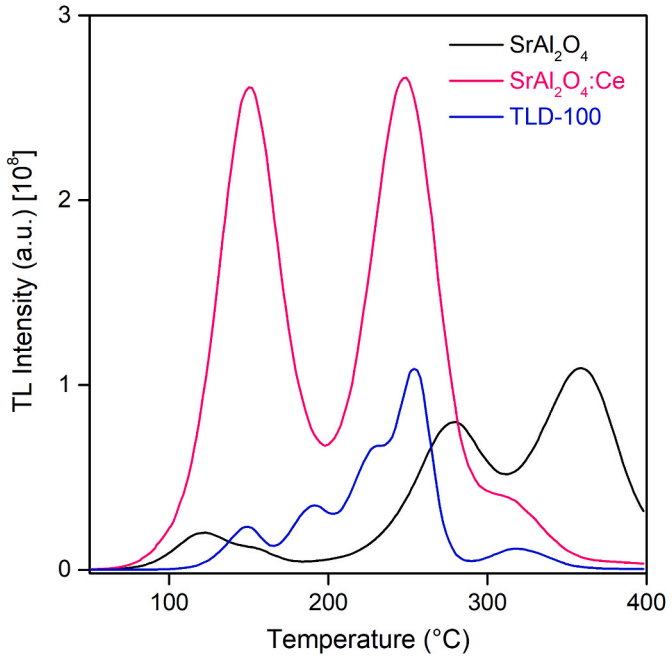

Fig. 9. Comparison of the TL sensitivity of pure and doped $SrAl_2O_4$ pellets with the TLD-100 dosimeter irradiated with a γ dose of 1 Gy. The TL intensity is normalized to the mass of each dosimeter.

good reproducibility with a deviation in the order of 5 % relative to the mean intensity for 10 cycles, as shown in Fig. 10.

3.3.4. Fading study

The fading of a TL material is the loss of its TL intensity during the storage period after irradiation. The most commonly used commercial TL dosimeters in dosimetry, such as the TLD-100, are characterized by low fading.

To study the fading of the $SrAl_2O_4$: Ce pellets produced in this work, a group of these pellets were irradiated with a dose of 1 Gy of γ rays. These irradiated pellets were stored at room temperature and in the dark, and TL readings were taken after different storage time intervals. Fig. 11 shows the intensity behavior of both TL peaks at 150 and 250 °C as a function of storage time. The inset of Fig. 11 shows the TL glow curves for some storage times. It can be seen from the figure that the TL peak at 150 presents a 30 % fading of the TL signal in the first 14 days. On the other hand, the TL peak at 250 °C shows a 6.5 % fading of the TL signal after 4 days of storage, and for time above 4 days, the signal remains unchanged (see inset of Fig. 11). Therefore, the TL peak at 250 °C is the most stable and suitable for applications in radiation dosimetry. However, it is recommended to perform the TL reading after storing the $SrAl_2O_4$: Ce pellets at room temperature for at least 4 days after irradiation.

3.3.5. Minimum detectable dose (MDD)

The sensitivity of the dosimetric material and the TL light detection system (TL reading equipment) are two factors that determine the minimum detection dose of a dosimetric material. According to Harvey et al. [27,28], this value is defined as the interpolation on the dose axis corresponding to 3 times the value of the standard deviation ($(3\sigma_{TL})$) of TL measurements of non-irradiated samples (TL background signal). A standard deviation (σ_{TL}) was obtained from 20 readings of the TL background signal of the non-irradiated sample using the Harshaw 3500 reader.

Fig. 12 shows the method used to determine the MMD value of $SrAl_2O_4$: Ce phosphor. The estimated MMD value obtained in Fig. 12 is approximately 1.7 μGy. Therefore, it was demonstrated that the TL intensities of $SrAl_2O_4$: Ce phosphor are suitable for dose detection in the interval mGy to Gy.

3.3.6. Energy dependence

To study the energy dependence in their TL response of Ce-doped $SrAl_2O_4$ pellets, 4 groups of 5 pellets were exposed to X-rays with a dose of 4.245 mGy at different energies between 40 and 110 keV. Fig. 13 (a) shows that both TL glow peaks of $SrAl_2O_4$ pellets possess low energy dependence for energies between 40 and 72 keV, and for energies above 72 keV, they exhibit strong energy dependence. Moreover, the result in

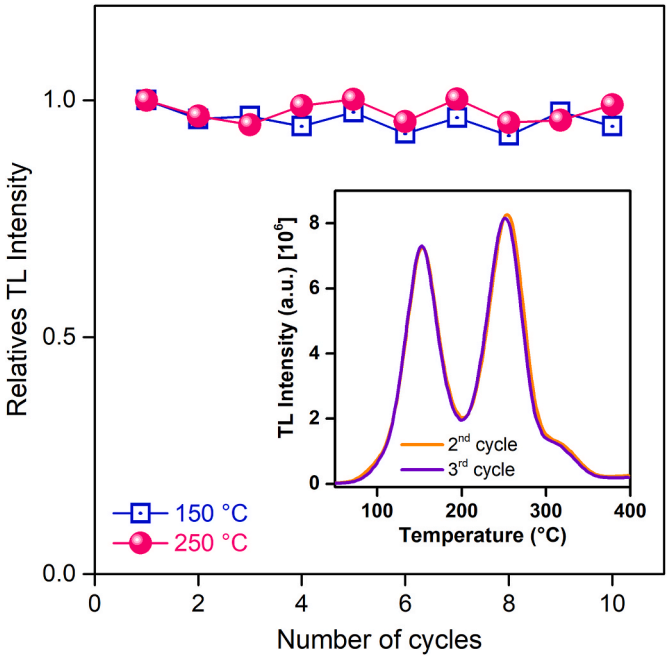

Fig. 10. Reproducibility of TL intensity of $SrAl_2O_4$: Ce pellets after 10 repeated annealing-irradiation-TL reading cycles. The inset of the figure shows the TL glow curve for the second and third readout cycles.

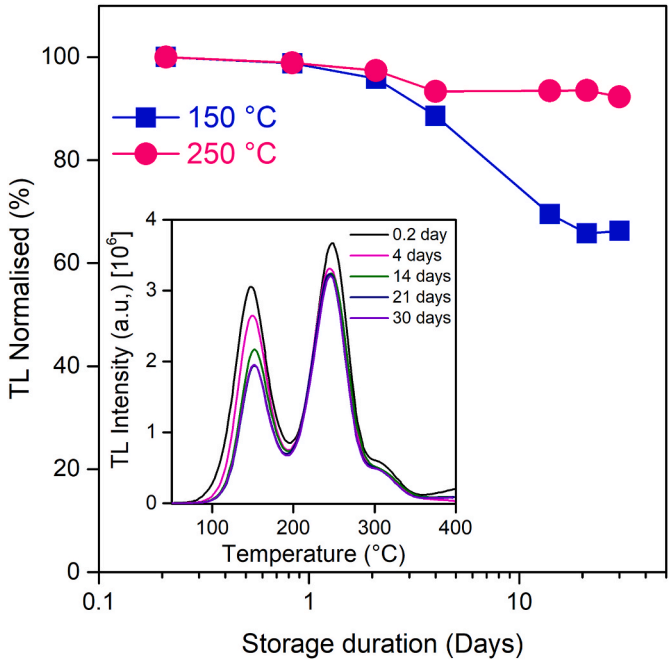

Fig. 11. Fading of the dosimetric peak intensity at 250 °C as a function of storage time. The pellets were stored in a dark room at room temperature.

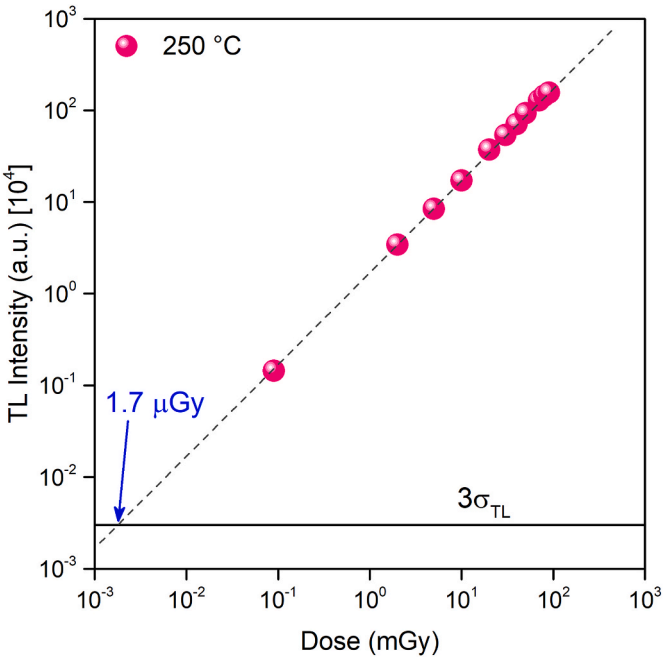

Fig. 12. Dosimetric TL peak intensity at 250 °C as a function of γ radiation dose for the range 0.1–100 mGy and determination of the minimum detectable dose (MDD). The dashed black line is the fit from experimental results using a linear equation.

Fig. 13(a) shows that $SrAl_2O_4$ pellets have a maximum TL response for photon energies of 64 keV (see inset of Fig. 13(a)). Fig. 13(b) shows that the position of the maximum temperature of both peaks is invariant with X-ray photon energy.

4. Conclusions

Ce-doped strontium aluminate synthesized by the solid-state reaction method is found to be a TLD material with high sensitivity for the detection of γ, β, and UV radiation. $SrAl_2O_4$ phosphor doped with 0.3 mol% Ce and annealed at a temperature of 1000 °C shows the highest sensitivity in its TL response. The structure of the glow curve of the pellets sintered at 1000 °C for 2 h shows two main peaks at 150 and 250 °C. The dosimetric peak around 250 °C shows low fading, good stability, and repeatability in its TL response after several measurement cycles, with sensitivity 2.44 times higher than the commercial dosimeters used (TLD-100), and a linear behavior to the irradiation dose in the dose range from 1 to 1000 mGy. The smallest minimum dose that can be detected with this material is 1.7 μGy of ^{60}Co γ-rays. The phosphor's easy synthesis method also makes it very cost-effective for large-scale production with applications in radiation dosimetry.

CRediT authorship contribution statement

José G. Valencia-López: Methodology, Investigation, Formal analysis, Data curation. **Nilo F. Cano:** Writing – original draft, Validation, Supervision, Project administration, Investigation, Formal analysis, Conceptualization. **Betzabeth J. Lopez-Flores:** Data curation, Investigation, Methodology. **Jorge S. Ayala-Arenas:** Methodology, Investigation, Formal analysis. **Betzabel N. Silva-Carrera:** Methodology, Investigation, Formal analysis. **Jessica Mosqueira-Yauri:** Visualization, Validation, Resources, Investigation, Formal analysis, Conceptualization.

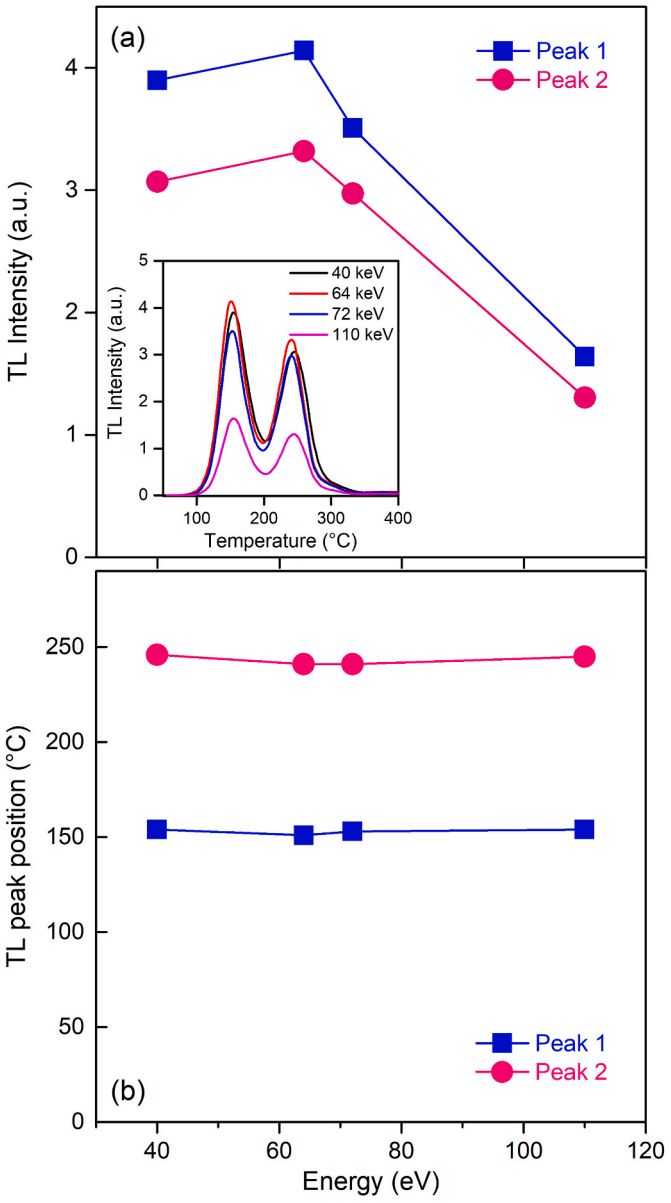

Fig. 13. (a) TL intensity response of $SrAl_2O_3$: Ce pellets as a function of X-ray energy, and in the inset figure, the TL glow curve of pellets exposed to different X-ray energies. (b) Variation of peak temperature position as a function of X-ray energy.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work was supported by PROCIENCIA-CONCYTEC, Peru, in the framework of the call E041-2022-1 (Process number N°501078121–2022 PROCIENCIA).

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