Research Article

Investigation of Stereometric and Fractal Patterns of Spin-Coated LuMnO_3 Thin Films

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In this paper, we have performed qualitative and quantitative analysis of LuMnO_3 thin films surfaces, deposited by spin coating over $\text{Pt}(111)/\text{TiO}_2/\text{SiO}_2/\text{Si}$ substrates, to evaluate their spatial patterns as a function of the film's sintering temperature. Atomic force microscopy was employed to obtain topographic maps that were extensively analyzed via image processing techniques and mathematical tools. 3D (three-dimensional) topographical images revealed that films sintered at 650°C and 750°C presented the formation of smoother surfaces, while the film sintered at 850°C displayed a rougher surface with a root mean square roughness of ~ 2.5 nm. On the other direction, the height distribution of the surface for all films has similar asymmetries and shape, although the film sintered using the highest temperature showed the lower density of rough peaks and a sharper peak shape. The advanced fractal parameters revealed that the film sintered at 850°C is dominated by low spatial frequencies, showing less spatial complexity, higher microtexture homogeneity, and uniform height distribution. These results suggest that the combination of stereometric and fractal parameters can be especially useful for identification of unique topographic spatial patterns in LuMnO_3 thin films, helping in their implementation in technological applications, such as photovoltaic solar cells and information magnetic data storage and spintronic devices.

1. Introduction

Multiferroic oxide systems of the RMnO_3 type (R =rare earth or transition metal ion) are materials that exhibit singular properties of ferromagnetism and ferroelectricity in a single phase, enabling wide applications in several areas. In this regard, they are considered as promising materials for

photovoltaic applications to the information magnetic data storage industry, transducers, magnetic field sensors, many high-technology devices such as random-access memories, and spintronic devices because of their interesting magnetoelectric coupling property [1–4].

Some of the H-RMnO_3 type rare earth (R) manganites with a perovskite structure are part of the multiferroic oxide

system, and they have represented an important research area for solid-state and materials chemists and applied physicists for last decades, where “H” characterizes a hexagonal structure with space group P63cm [5–7]. The hexagonal structure with crystallographic group (P63cm) is built up of MnO_5 trigonal bipyramids, and in the basal (ab) plane, the pyramids are linked at the base corners to construct a triangular lattice. The rare-earth ions are located between these MnO_5 layers and they are linked with the oxygen atoms [8].

H- LuMnO_3 -type multiferroic oxides have been extensively investigated because they exhibit both magnetoelectric [9–11] and magnetoelastic effects [12]. Therefore, this system is an interesting material for application in ferroelectric photovoltaic devices [13]. Currently, a lot of research studies have been focused on the various forms of these materials, such as powders, nanostructures, bulk, and thin films [11, 14–17]. The development of multiferroic thin film deposition technologies, which allows the deposition of strain formed structure, was an important step to tune the functionalities of material, providing an additional degree of freedom in new materials [3, 18].

Several experimental and theoretical studies about the structural and magnetic properties of LuMnO_3 in the ferroelectric phase have been reported in the literature [10, 11, 19], although there are still some important questions that remain unanswered, for example, the origin of the grain size effects on the correlation between the magnetizations and structures. Furthermore, reports using the atomic force microscopy (AFM) technique for studies associated with the surface of thin LuMnO_3 films are rare and somehow an important tool to evaluate physical properties of surfaces for technological application.

In recent years, morphological studies have been explored because AFM technique is strongly sensible and accurate. It is important to mention that multiferroic materials contribute to the development of new scientific methods [20]. In addition, topographical maps obtained by AFM allow us to access several parameters, such as stereometric [21–23], fractal [24–27], multifractal [28–30], and power spectrum density (PSD) [23, 31, 32], which are very useful for characterization of surfaces at micro- or nanoscale. For this reason, exploring the nanoscale morphology of LuMnO_3 thin films can provide reliable answers about the effect of sintering temperature on the formation of its topography. This can reveal how the spatial patterns of its surface, such as roughness, peak density, shape of peaks, texture quality, uniformity of height distribution, and heterogeneity of topographic texture distribution are affected when there is coalescence of grains on the surface.

Using a simple chemical method, we have synthesized LuMnO_3 in films' precursor solutions that were spin coated in Pt(111)/ TiO_2 / SiO_2 /Si substrates. Our goal was evaluating the nanoscale patterns of the films using a combination of stereometric and advanced fractal parameters that, at the present moment, has not been reported yet. We have used several mathematical and analytical methods for obtaining the results. Specifically, we have explored the tools provided by MountainsMap commercial software to make an

extensive image processing work. Moreover, we have used different algorithms for fractal parameters that are not provided by commercial software.

2. Materials and Methods

2.1. Materials and Samples' Preparation. To produce a LuMnO_3 precursor solution, lutetium (III) nitrate hydrate 99.99% pure (supplied by Aldrich), was previously dissolved, at 50°C, in glacial acetic acid ($\text{CH}_3\text{CO}_2\text{H}$) and nitric acid (HNO_3), with a 2:1 molar ratio mixture, during 24 h. Afterwards, manganese (II) acetate tetrahydrate ($(\text{CH}_3\text{COO})_2 \text{Mn} \cdot x\text{H}_2\text{O}$), 99.99% pure (supplied by Merck), was added stoichiometrically to the lutetium precursor solution. The resulting solution was stabilized, with pure 2-methoxyethanol, in a solvent (2:1:6) molar ratio ($\text{CH}_3\text{CO}_2\text{H}/\text{HNO}_3/\text{CH}_2\text{OCH}_2\text{CH}_2\text{OH}$) during 24 hours, achieving a 0.2 molar concentration [33]. The LuMnO_3 precursor solutions were deposited onto metallized Pt (111) (150 nm)/Ti (70 nm)/ SiO_2 (500 nm)/Si (1 mm) substrates supplied by the SVM company with a 144 cm² area by using a Laurell WS-400-6NPP instrument. Thus, the solution dropped into the substrate was spin coated at 3000 rpm during 60 s and the resulting green layer was dried at 80°C in a hot plate for 1 min and presintering at 400°C in a tubular furnace for 10 minutes. This process was repeated 8 times to obtain presintering thin films with thicknesses of approximately 260 nm [11]. Afterwards, the presintering films were sintered at 650°C, 750°C, and 850°C during 1 h and labeled as $\text{LuMnO}650$, $\text{LuMnO}750$, and $\text{LuMnO}850$, respectively.

2.2. Analysis of the Samples. The films morphology was analyzed by using an atomic force microscope (Veeco Multimode NanoScope IVa) working on the tapping mode, with a scan rate of 1.0 Hz, scanning areas of $2.5 \times 2.5 \mu\text{m}^2$, and resolution of 256×256 pixels. Images were collected in air, at room temperature ($296 \pm 1\text{K}$) and $60 \pm 1\%$ relative humidity, using a silicon cantilever (model RTESP-300 from Bruker, with a 40 N/m spring constant). The complete analysis of the LuMnO_3 thin films morphology was based on the evaluation of the stereometric parameters in accordance with the ISO 25178-2: 2012 standard. These parameters have their physical meaning well-described in [23, 34–37] and in our analysis have been obtained by the MountainsMap® 8.0 commercial software [38]. In summary, we computed and evaluated several parameters, explicitly: height, feature, spatial, functional, hybrid, volume, and core Sk. Additionally, qualitative renderings, such as contour lines, furrows, and texture directions, obtained by Fourier transforms on the height function were computed for surface microtexture evaluation of the films.

Furthermore, we have determined advanced fractal parameters to study surface microtexture. Fractal dimension (FD) was computed using the counting box method described by Mandelbrot and Wheeler [39], while fractal lacunarity (FL) was computed using a model described by Salcedo et al. [40]. From the lacunarity curve, we estimated

the lacunarity coefficient (β) using equation (1), for obtaining data about surface texture homogeneity [41]:

$$L(r) = \alpha \cdot r^\beta, \quad (1)$$

where $L(r)$ is lacunarity, α is a constant, and r is the box size.

The average power spectrum density (PSD) of fractal regions of the spectra was calculated using linearized graphs obtained according to the mathematical theory explained by Jacobs et al. [42]. From the linearized graph, we have estimated the Hurst coefficients of all spectra using equation (2) according to Jacobs et al. [42], where γ is the slope of the linearized curve that was obtained using the WsxM[®] 5.0 software [43]:

$$H_c = \frac{\gamma - 2}{2}. \quad (2)$$

Fractal succolarity (FS) was calculated using the model described by Melo and Conci [44], where, from equation (3), the calculated values were obtained for all thin films:

$$FS(T(k), \text{dir}) = \frac{\sum_{k=1}^n P_0(T(k)) \cdot P(T(k), p_c)}{\sum_{k=1}^n PR(T(k), p_c)}, \quad (3)$$

where dir is the liquid entry direction, $P_0(T(k))$ is the occupation percentage, $T(k)$ are boxes of equal size $T(n)$, PR is occupation pressure, and p_c is centroid position (x, y).

Surface entropy (E) was obtained from the information theory description using Shannon Entropy equation [45] (equation (4)), where p_{ij} is assigned to be the probability that a height matrix term h_{ij} promotes a complete uniformity of height distribution:

$$E^{(2)} = - \sum_{i=1}^N \sum_{j=1}^N p_{ij} \cdot \log p_{ij}. \quad (4)$$

The obtained value was centralized and normalized according to equation (5) to give us a normalized value of E [46]:

$$E = \frac{E^{(2)} - E_{\min}^{(2)}}{E_{\max}^{(2)} - E_{\min}^{(2)}}, \quad (5)$$

where the factors $E_{\min}^{(2)}$ and $E_{\max}^{(2)}$ are calculated from Shannon entropy equation [45, 47] that is based on information theory and give us a normalized measure of E . FS and E were obtained using algorithms programmed in RStudio[®] Version 1.3.1093 software [48], while FL using FORTRAN 77 [41]. All advanced fractal parameters were computed from AFM topographical matrix extracted by WSXM software. The computational routines were programmed in R language (For FS and E) and Fortran 77 (for FL).

To compute experiments precision, we have used variance analysis (ANOVA) and Tukey test with a p value of 0.05, for all thin films were taken four measures in random regions along the surface.

3. Results and Discussion

3.1. Surface Nanoscale Morphology Analysis. The nanoscale morphology of LuMnO₃ thin films sintered at 650, 750, and 850°C is shown in Figure 1. As can be seen, the two lowest sintering temperatures (LuMnO650 and LuMnO750) promoted the formation of smoother surfaces, while the highest temperature provided a rougher surface. In Figure 1(e), it is possible to observe the great contours on more mountainous regions, which refers to the grains' contour as can be better observed in Figure S1 (supplementary material), which presents the images of Figure 1 in 2D. This behavior is due to the great reorganization of the crystal, which may be associated with the grain growth, discordance movement, and isotropy of the surface microtexture, which occurred due to the greater coalescence of the grains.

The morphology evaluated is similar to that found on other works previously published, where the effect of the sintering temperature was studied, and it was confirmed that only after 850°C there was the complete formation of pure polycrystalline phase of LuMnO₃ [11]. This system is also assigned to have a hexagonal phase or single crystal structure, as reported by other authors in [19, 49]. In fact, the height parameters shown in Table 1 confirm our qualitative observation, as LuMnO850 presented the highest topographic roughness, which was computed for both average roughness (S_a) (~1.8 nm) and the root mean square roughness (S_q) (~2.5 nm). Additionally, the topographic pattern is similar for maximum peak height (S_p), maximum pit height (S_v), and maximum height (S_z), showing that there is a persistence of topographic patterns in LuMnO850 significantly different from LuMnO650 and LuMnO750.

The relative frequencies of the topographic heights shown in Figures 1(b), 1(d), and 1(f) reveal that the height distribution of the films surface has similar asymmetries and shape. In other words, although the distributions are not Gaussian, as $S_{ku} \neq 3$ and $S_{sk} \neq 0$, all topographic patterns have an inclination to right (S_{sk} with + signal) and leptokurtic distribution ($S_{ku} > 3$) (Table 1) [50, 51]. The S-shape red curve observed in all relative height histograms is Abbott-Firestone curve [52] that exposes a widely smooth line for all surfaces, as a result of the similar asymmetry and distribution shape for topographical heights. This indicates that, for recurrent depths, a progressive increase in the content of the material covered in relation to the evaluated area occurs, which was observed for all surfaces without statistically significant difference ($p > 0.05$).

3.2. Advanced Stereometric Evaluation. The relationship between topographic patterns and the microtexture of the films was evaluated using stereometric parameters [34] more specifically, as shown in Table 2. In this table, the functional parameters of the topographic patterns suggest that the LuMnO850 microtexture is strongly different from LuMnO650 and LuMnO750. Specifically, a greater inverse areal material ratio (S_{mc}) is observed for LuMnO850, which is not observed in any other film. This behavior is also noted

FIGURE 1: 3D AFM topographical maps and histogram of relative heights of LuMnO₃ thin films of (a, b) LuMnO₆₅₀, (c, d) LuMnO₆₅₀, and (e, f) LuMnO₈₅₀.

for peak extreme height (S_{xp}). Furthermore, the core thickness and volume parameters, whose definitions are shown in Figure S2 (supplementary material) [35], confirm that the roughness distribution is responsible for forming a microtexture with more intense patterns, as observed for LuMnO₈₅₀. In this regard, LuMnO₈₅₀ has the largest core

roughness depth (S_k), reduced peak height (S_{pk}), and reduced valley depth (S_{vk}) (Table 2). In addition, the average value of peak material portion (S_{mr1}) and valley material portion (S_{mr2}) do not fluctuate ($p > 0.05$), showing that the percentage of material that represents the peak patterns related to S_{pk} and S_{vk} remains stable. Similarly, all volume

TABLE 1: Height surface parameters of LuMnO₃ thin films, according to ISO 25178-2:2012.

Parameter	Unit	LuMnO650	LuMnO750	LuMnO850
<i>Height</i>				
Sq	(nm)	0.30 ± 0.03	0.61 ± 0.35	2.48 ± 0.53
Ssk*	(—)	0.33 ± 0.15	0.39 ± 0.43	0.22 ± 0.08
Sku*	(—)	3.60 ± 0.31	4.24 ± 1.37	3.17 ± 0.45
Sp	(nm)	1.38 ± 0.21	2.78 ± 1.86	8.23 ± 0.82
Sv	(nm)	1.18 ± 0.16	2.62 ± 0.95	9.09 ± 1.94
Sz	(nm)	2.56 ± 0.18	5.40 ± 2.80	17.27 ± 2.32
Sa	(nm)	0.24 ± 0.02	0.45 ± 0.22	1.81 ± 0.43

* denotes samples without significant difference, ANOVA One-Way and Tukey Test ($p > 0.05$).

TABLE 2: Stereometric parameters of the LuMnO₃ thin films, in accordance with ISO 25178-2:2012.

Parameter	Unit	LuMnO650	LuMnO750	LuMnO850
<i>Functional</i>				
Smc	(nm)	0.39 ± 0.04	0.70 ± 0.32	3.04 ± 0.80
Sxp	(nm)	0.54 ± 0.05	1.10 ± 0.59	4.23 ± 0.57
Sk	(nm)	0.72 ± 0.07	1.23 ± 0.40	6.00 ± 1.69
Spk	(nm)	0.39 ± 0.05	0.98 ± 0.86	2.58 ± 0.20
SVk	(nm)	0.27 ± 0.04	0.60 ± 0.40	2.00 ± 0.30
Smr1*	(%)	12.43 ± 0.85	11.87 ± 2.13	12.88 ± 0.68
Smr2*	(%)	90.57 ± 0.88	88.70 ± 3.53	90.55 ± 2.62
Vmp	($\mu\text{m}^3/\mu\text{m}^2$)	$1.9e^{-05} \pm 2.8e^{-06}$	$5.1e^{-05} \pm 4.8e^{-05}$	$1.2e^{-04} \pm 8.6e^{-06}$
Vmc	($\mu\text{m}^3/\mu\text{m}^2$)	$2.6e^{-04} \pm 2.8e^{-05}$	$4.7e^{-04} \pm 2.0e^{-04}$	$2.0e^{-03} \pm 5.3e^{-04}$
Vvc	($\mu\text{m}^3/\mu\text{m}^2$)	$3.8e^{-04} \pm 4.0e^{-05}$	$6.8e^{-04} \pm 3.2e^{-04}$	$2.9e^{-03} \pm 7.9e^{-04}$
Vvv	($\mu\text{m}^3/\mu\text{m}^2$)	$3.1e^{-05} \pm 3.3e^{-06}$	$6.8e^{-05} \pm 4.3e^{-05}$	$2.3e^{-04} \pm 2.7e^{-05}$
<i>Feature</i>				
Spd	($1/\mu\text{m}^2$)	122.04 ± 12.04	53.56 ± 29.05	10.73 ± 2.78
Spc	($1/\mu\text{m}^2$)	2.82 ± 0.08	3.73 ± 0.76	7.56 ± 0.16
<i>Hybrid</i>				
Sdq	(—)	0.01 ± 0.00	0.02 ± 0.00	0.05 ± 0.01
Sdr	(%)	0.01 ± 0.00	0.02 ± 0.00	0.14 ± 2.78

* denotes samples without significant difference, ANOVA One-Way and Tukey Test ($p > 0.05$).

parameters of core surface associated to peak or valley material show that LuMnO850 have more intense patterns. In fact, this is recorded by the dale void volume (Vvv), core void volume (Vvc), peak material volume (Vmp), and core material volume (Vmc) (Table 2). These results confirm the qualitative observation made in Figure 1(e)), suggesting that a greater thickness and volume of material are observed in the formed topography.

The feature parameters reveal that LuMnO850 shows a lower density of rough peaks and a more pointed peak shape, as it presents lower peak density (Spd) ($\sim 10 \mu\text{m}^{-2}$) and higher arithmetic mean peak curvature (Spc) ($\sim 7.6 \mu\text{m}^{-2}$), respectively. In addition, the hybrid parameters indicate that LuMnO850 presents the least flat surface because the root mean square gradient (Sdq) (0.053) is greater than in any other films. This physical property is confirmed by the measure of developed interfacial area ratio (Sdr), where LuMnO850 shows the lowest average value ($\sim 0.14\%$).

3.3. Microtexture Analysis. As an important qualitative observation tool available in MountainsMap and widely used for the evaluation of surface microtextures of thin films or other systems [25, 53–57], the renderings of the surface

microtexture shown in Figure 2 reveal contour lines and furrows belonging to each analyzed sample. As seen in Figure 2(e) (contour lines), the grain appears to have a rice-like shape, which can also be seen in Figure S1, while the smoother morphology of LuMnO650 and LuMnO750 reveal grain clusters' minors who have not coalesced. Observing the color scales exhibited in the renderings of Figures 2(a), 2(c), and 2(e), it is possible to observe that LuMnO650 and LuMnO750 present less intense roughness distributions than LuMnO850, which confirms the observation carried out during the analysis of the 3D morphology images of the films (Figure 1). The furrows that surround the grains in LuMnO850 exhibit valleys with greater depths, which is confirmed by the quantitative parameter's Maximum depth furrow (~ 6 nm) and mean depth furrow (~ 2 nm) (Table 3).

The specific texture parameters shown in Table 3 suggest that there is no difference in the surface texture of the analyzed films. In fact, texture isotropy (TI), autocorrelation length (Sal), texture-aspect ratio (Str), and all texture directions, explicitly, first, second, and third directions do not show statistically significant difference. Interestingly, the polar graph of Figure 3 shows that the texture distribution of the films has different shapes. Naturally, these stereometric parameters are obtained from Fourier transforms using

FIGURE 2: Qualitative renderings of contour lines and furrows systems of the surface microtexture of (a, b) LuMnO650, (c, d) LuMnO750, and (e, f) LuMnO850.

always the same height distribution function [37]. As the topographic heights exhibited a similar behavior (leptokurtic) (Table 1), it is reasonable that these parameters do not fluctuate. Moreover, it is also observed that the topographic asymmetries are similar, as S_{sk} also do not fluctuate, as shown in Table 1, which shows that distributions' profile has similar characteristics, although their roughness have different behaviors. For this reason, the characterization of different spatial patterns of the surface microtexture was made using fractal parameters that consider specific

mathematical equations based on models recently described by other authors [25, 41].

3.4. Fractal Characterization. To understand better the effect of the sintering temperature on the formation of topographic spatial patterns of the films, we computed advanced fractal parameters. Figure 4 shows the lacunarity distribution and the power spectrum density (PSD) of the analyzed samples. Figures 4(a)–4(c) show that the films exhibit a

TABLE 3: Surface microtexture parameters of LuMnO₃ thin films, according to ISO 25178-2:2012.

Parameter	Unit	LuMnO650	LuMnO750	LuMnO850
<i>Furrows</i>				
Maximum depth	(nm)	0.83 ± 0.07	1.34 ± 0.34	6.05 ± 0.11
Mean depth	(nm)	0.35 ± 0.02	0.55 ± 0.15	2.15 ± 0.19
<i>Texture</i>				
TI*	(%)	56.48 ± 9.39	56.50 ± 12.54	56.92 ± 5.68
Sal*	(μm)	0.19 ± 0.02	0.23 ± 0.04	0.21 ± 0.03
Str*	(—)	0.56 ± 0.09	0.56 ± 0.12	0.57 ± 0.06
First direction*	(°)	128.39 ± 23.41	135.00 ± 0.01	107.26 ± 18.79
Second direction*	(°)	134.99 ± 13.09	105.88 ± 27.50	83.89 ± 41.92
Third direction*	(°)	96.62 ± 41.71	76.77 ± 44.95	121.50 ± 22.70

* denotes samples without significant difference, ANOVA One-Way and Tukey Test ($p > 0.05$).

FIGURE 3: Polar representation of texture directions of surface microtexture of (a) LuMnO650, (b) LuMnO750, and (c) LuMnO850.

strong fractal pattern, as the lacunarity has persistently decreased when the box size has increased. Figures 4(d)–4(f) reveal that the films present extensive self-affine behavior because power spectra found in the fractal region display well-adjusted fits ($R^2 > 0.95$). The computed parameters reveal that spatial complexity of the films decrease from LuMnO650 to LuMnO850 because fractal dimension (FD) consistently decrease with the film sintering temperature (LuMnO650 > LuMnO750 > LuMnO850), showing that the surface microtexture changed when sintering temperature increases, as result of increasing in the topographic roughness.

This pattern affected the signal quality of the dominant spatial frequencies because LuMnO850 exhibited a higher Hurst coefficient ($H_C \sim 0.9$), explicitly, being dominated by low spatial frequencies, while LuMnO650 registered a lower H_C value (~ 0.1) (Table) being dominated by high dominant spatial frequencies. The PSD is a very useful tool for

differentiating surfaces on a micro- or manometric scale and that has been extensively used in the analysis of different films [23, 31, 32, 58]. Based on the PSD, we observed that high sintering temperatures form LuMnO₃ surfaces with lower spatial frequencies. We attribute this fact to a more rugged height distribution, probably due to the increase in the particle size as effect of increasing the sintering temperature.

A major contribution of the effect of sintering temperature on the surface microtexture of the films is relative to their surface heterogeneity. The reorganization of the crystal for high sintering temperature promotes a most homogeneous microtexture, as LuMnO850 shows the lowest value of the lacunarity coefficient (β) ($6.97e-08$) (Table 4), while the films sintered at lowest temperatures (650°C and 750°C) exhibit similar and more heterogeneous textures. This takes place because although these samples show smoother surfaces, the distribution of gaps along the surface does not

FIGURE 4: Surface lacunarity and PSD of (a-b) LuMnO650, (c-d) LuMnO750, and (d-e) LuMnO850, respectively.

TABLE 4: Fractal and parameters' advanced fractal of LuMnO₃ thin films.

Parameter	Unit	LuMnO650	LuMnO750	LuMnO850
FD	(—)	2.391 ± 0.011	2.331 ± 0.062	2.264 ± 0.020
H_C	(—)	0.113 ± 0.016	0.273 ± 0.027	0.863 ± 0.013
$ \beta $	(—)	$5.33e^{-06} \pm 3.34e^{-06}$	$2.06e^{-06} \pm 1.40e^{-06}$	$6.97e^{-08} \pm 4.84e^{-08}$
FS*	(—)	0.522 ± 0.002	0.512 ± 0.013	0.510 ± 0.027
E^*	(—)	0.973 ± 0.004	0.952 ± 0.046	0.977 ± 0.014

* denotes samples without significant difference, ANOVA One-Way and Tukey Test ($p > 0.05$).

show a coherent organization, which is not observed for LuMnO850. Despite this, all films show similar surface percolation since fractal succolarity (FS) does not show a statistically significant difference ($p > 0.05$) (Table 4). This means that the surface porosity does not change when the sintering temperature increases, although the gaps are organized more evenly along the surface. Furthermore, all films also showed strong uniformity of height distribution because their surface entropy was similar ($E \sim 1$) [41], also without a statistically significant difference ($p > 0.05$). This particular result reveals that the microtextures have height distributions with almost no discontinuity points that can promote material failures [46]. Specifically, some physical properties, such as wear, adhesion, and microfriction, can be measured uniformly across the surface, as the height distribution is a real response of the cantilever vibration in function of the analyzed topography [59], which we naturally attribute to a uniform process of films' deposition via the spin-coating method. Thus, it is observed that advanced fractal parameters reveal unique aspects of the films' microtexture that could not be observed by traditional analysis.

4. Conclusion

The spatial patterns of LuMnO₃ thin films were studied from topographic maps obtained by atomic force microscopy. The morphology of sintered films with lower temperatures was smoother, while the higher temperature promoted a rougher surface, which was confirmed by the topographic parameters of height. Advanced stereometric parameters revealed that the roughness distribution of films sintered at lower temperatures was uniquely different from the film sintered at 850°C, where the peak shape was more sharp and the distribution of roughness was less dense, which influenced the thickness and volume of material present in the core of the surfaces. Qualitative renderings of the material's microtexture confirmed the observed morphological differences, although specific texture parameters computed by Fourier transforms on the height function have suggested that the microtextures of the films were assigned to be similar. Nevertheless, the spatial patterns proved to be different because the advanced fractal parameters revealed that the film sintered at 850°C presents less spatial complexity and that it is dominated by low dominant spatial frequencies. This higher sintering temperature coalesced the grains so that their microtexture became more homogeneous. Moreover, because of the uniform deposition process, the surface porosity and topographic uniformity of the films did

not fluctuate when sintering temperature has increased. Therefore, our results showed that a combination of stereometric and fractal parameters can be especially useful for controlling the process of fabrication of thin films based on rare-earth-based perovskites oxides.

Data Availability

The data presented in this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Supplementary Materials

Figure S1. Graphical study of volume parameters (left) and Sk parameters (right) based on the Abbott curve calculated for the samples: (a) LuMnO650, (b) LuMnO750, and (c) LuMnO850. Figure S2. 2D AFM topographic maps of (a) LuMnO650, (b) LuMnO750, and (c) LuMnO850. (Supplementary Materials)

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