

Surface Roughness and Fractal Analysis of TiO₂ Thin Films by DC Sputtering [†]

Helena Cristina Vasconcelos ^{1,2,*} , Telmo Eleutério ¹ and Maria Meirelles ^{1,3} 

¹ Faculty of Science and Technology, University of the Azores, Ponta Delgada, S. Miguel, 9500-321 Azores, Portugal; telmo.mf.eleuterio@uac.pt (T.E.); maria.gf.meirelles@uac.pt (M.M.)

² Laboratory of Instrumentation, Biomedical Engineering and Radiation Physics (LIBPhys, UNL), Department of Physics, NOVA School of Science and Technology, 2829-516 Caparica, Portugal

³ Research Institute of Marine Sciences, University of the Azores (OKEANOS), Horta, Faial, 9901-862 Azores, Portugal

* Correspondence: helena.cs.vasconcelos@uac.pt

[†] Presented at the 4th Coatings and Interfaces Online Conference, 21–23 May 2025; Available online: <https://sciforum.net/event/CIC2025>.

Abstract

This study examines the effect of oxygen concentration and sputtering power on the surface morphology of TiO₂ thin films deposited by DC reactive magnetron sputtering. Surface roughness parameters were obtained using MountainsMap[®] software(10.2) from SEM images, while fractal dimensions and texture descriptors were extracted via Python-based image processing. Fractal dimension was calculated using the box-counting method applied to binarized images with multiple threshold levels, and texture analysis employed Gray-Level Co-occurrence Matrix (GLCM) statistics to capture local anisotropies and spatial heterogeneity. Four samples were analyzed, previously prepared with oxygen concentrations of 50% and 75%, and sputtering powers of 500 W and 1000 W. The results have shown that films deposited at higher oxygen levels and sputtering powers exhibited increased roughness, higher fractal dimensions, and stronger GLCM contrast, indicating more complex and heterogeneous surface structures. Conversely, films produced at lower oxygen and power settings showed smoother, more isotropic surfaces with lower complexity. This integrated analysis framework links deposition parameters with morphological characteristics, enhancing the understanding of surface evolution and enabling better control of TiO₂ thin film properties.

Keywords: surface roughness; fractal analysis; TiO₂ thin films; reactive magnetron sputtering; Gray-Level Co-occurrence Matrix (GLCM); morphological complexity; thin film characterization; image processing



Academic Editor: Qi Hua Fan

Published: 4 August 2025

Citation: Vasconcelos, H.C.; Eleutério, T.; Meirelles, M. Surface Roughness and Fractal Analysis of TiO₂ Thin Films by DC Sputtering. *Eng. Proc.* **2025**, *105*, 2. <https://doi.org/10.3390/engproc2025105002>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The morphological characteristics of thin film surfaces are of critical importance in determining the performance of advanced functional materials, particularly in optoelectronic, photocatalytic, and sensing applications. In reactive magnetron sputtering processes, the interaction of plasma species with the substrate under varying power densities and gas compositions often results in kinetically driven, non-equilibrium growth conditions that produce surfaces with complex topographies.

Conventional roughness parameters, such as the arithmetic average roughness (Ra), root mean square roughness (Rq), maximum peak-to-valley height (Rz), and total height (Rt), have been widely used to evaluate surface quality [1,2].

In our previous work [1], we reported the structural and compositional properties of these TiO₂ films, including XRD results. The present study builds upon that dataset by applying advanced image analysis methods to examine surface complexity in greater detail.

However, these parameters are inherently scale-dependent and insufficient for characterizing the hierarchical and irregular features that often emerge during film growth at the nanoscale [2].

While these metrics provide valuable information, they do not fully capture the multiscale and often anisotropic morphology exhibited by sputtered thin films. Previous studies, including our own work [1], focused primarily on such conventional roughness parameters obtained via commercial metrology software (MountainsMap®). However, this leaves a gap in the literature regarding a more integrated characterization that includes fractal and statistical texture descriptors.

To overcome these limitations, this study aims to provide a more complete morphological characterization of TiO₂ films under varying deposition conditions by combining roughness, fractal geometry, and GLCM-based texture analysis. Fractal geometry offers an alternative framework for capturing the scale-invariant and hierarchical aspects of surface morphology. The concept of the fractal dimension (Df), particularly as estimated by the box-counting method, enables quantification of surface complexity and spatial filling behavior across multiple length scales [3,4]. However, Df estimation is sensitive to image resolution and sampling strategies [5], requiring careful control of binarization thresholds and segmentation parameters. For sputtered or vapor-deposited films, surface profiles often exhibit self-affine behavior rather than strict self-similarity, meaning the surface roughness scales differently in vertical and lateral directions, a feature well-captured by fractal analysis [6]. Notably, the fractal dimension of a surface lies in the range $2 < Df < 3$ and increases with morphological irregularity, grain clustering, or shadowing effects, all of which are directly influenced by sputtering power and gas composition [7]. Complementing global fractal analysis, statistical texture descriptors derived from the Gray-Level Co-occurrence Matrix (GLCM) provide a local-scale measure of surface heterogeneity and anisotropy. Features such as contrast, correlation, energy, and homogeneity extracted from SEM-derived grayscale images allow for a second-order statistical description of gray-level spatial distributions, revealing structural anisotropies and periodicities not captured by scalar roughness metrics [8]. Importantly, these features are sensitive to the deposition conditions and have been linked to changes in nucleation density and growth dynamics. In recent years, integrated approaches combining fractal metrics and GLCM-based texture descriptors have been advocated to yield a more complete understanding of thin film surface evolution [9,10]. Such dual analysis not only bridges local and global morphological features but also enhances the interpretability of structure–property relationships, particularly in cases where roughness metrics alone may obscure underlying complexity [5].

In this study, we investigate the surface morphology of TiO₂ thin films deposited via DC reactive magnetron sputtering using varying sputtering powers and O₂/Ar gas ratios. SEM images were used to extract roughness parameters, fractal dimensions, and GLCM texture descriptors, providing a comprehensive framework for linking deposition parameters to morphological complexity.

2. Methodology

The TiO₂ thin films analyzed in this study were previously deposited by DC reactive magnetron sputtering onto natural vegetal fiber substrates, specifically ginger lily (*Hedychium gardnerianum*) fibers, as described in our earlier work [1]. The base pressure was maintained below 2×10^{-6} mbar, using a titanium target (99.995%) and an O₂/Ar gas mixture with oxygen flow ratios of 50% and 75%. Sputtering power was set to either

500 W or 1000 W, with a deposition time of 30 min. The present work does not involve new depositions; instead, it reanalyzes the exact same set of samples and SEM images previously acquired in [1], focusing now on advanced morphological descriptors such as fractal dimension and GLCM texture analysis.

The study was structured according to a 2×2 factorial design, combining 2 sputtering powers and 2 oxygen concentrations. This resulted in 4 TiO₂ samples, each representing a unique set of deposition conditions. Although limited in number, this experimental design allows for a systematic exploration of the independent and combined effects of power and oxygen ratio on surface morphology.

The structural characterization of these films (phase identification via XRD) was previously reported in [1]. Additional FTIR and XPS data on the same set of samples are available in [11], confirming TiO₂ phase formation and chemical bonding. The current study focuses exclusively on morphological complexity based on SEM image analysis using the same samples, employing newly applied fractal and texture-based methods.

Building on this previously acquired dataset, the surface morphology of the TiO₂ thin films was analyzed using a combination of conventional roughness parameters, fractal dimension estimation, and texture analysis based on SEM images. Figure 1 illustrates the workflow of the process and analysis procedures applied in this study.

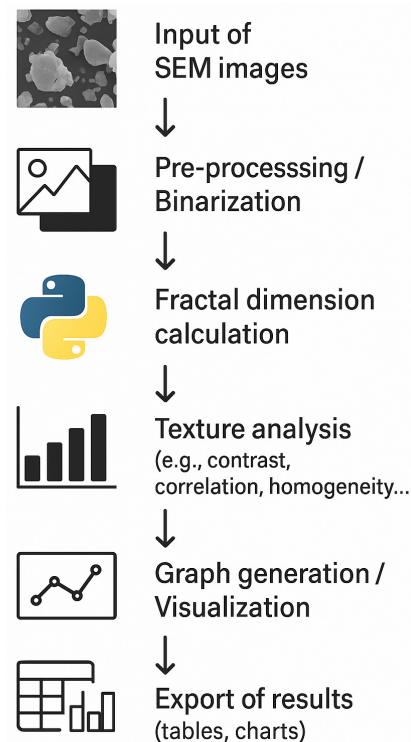


Figure 1. Flowchart illustrating this process.

2.1. Surface Roughness Parameters

Roughness parameters (Ra, Rq, Rz, Rt) were extracted from SEM images of our previous work, using MountainsMap[®] software [1]. These parameters offer a baseline characterization of the films' surface quality but are limited in capturing hierarchical and anisotropic features.

It is important to note that the roughness values reported here are based on single SEM image measurements for each sample and do not reflect statistical variation or measurement uncertainty. As such, descriptors such as "High", "Moderate", or "Low" are used qualitatively to compare surface trends across deposition conditions. No error bars or standard deviations are provided. Future studies will address this limitation by incorporating

multiple measurements per sample or complementary techniques such as atomic force microscopy (AFM) for more robust statistical analysis.

2.2. Fractal Dimension Estimation and Texture Analysis

To quantitatively characterize the surface structure of the SEM images, two complementary methods were applied: Gray-Level Co-occurrence Matrix (GLCM) texture analysis and fractal dimension (Df) analysis, both performed using Python (v3.10.0) with the scikit-image, OpenCV, and numpy libraries. Prior to analysis, SEM images were pre-processed through normalization of grayscale intensity values to the full 8-bit range (0–255). This step reduces variability due to acquisition conditions and ensures reproducibility and consistency in subsequent texture and fractal measurements. For the GLCM texture analysis, each image was first binarized, then analyzed using co-occurrence matrices computed at distances 1 and 2 pixels, across four directions: 0° , 45° , 90° , and 135° , resulting in eight configurations (1@ 0° , 1@ 45° , 1@ 90° , 1@ 135° , 2@ 0° , 2@ 45° , 2@ 90° , 2@ 135°). These directions were chosen to capture anisotropic patterns and ensure orientation sensitivity. The use of distance 1 allows detection of fine texture features and local variations, while distance 2 provides information on broader, coarser structures, together offering a multiscale texture representation. The selection of distances 1 and 2 balances sensitivity to local detail and robustness against noise, following established practices in texture analysis [8]. From each GLCM, standard texture descriptors such as contrast, correlation, energy, and homogeneity were extracted. In parallel, fractal dimension analysis was performed using the box-counting method. To assess the influence of segmentation level on fractal complexity, five binarization thresholds were applied: $T = 0.50, 0.60, 0.70, 0.75$, and 0.80 . Such threshold-dependent analysis is critical for avoiding artifacts due to single-scale segmentation, as emphasized in studies of sampling length influence on Df stability [5]. This approach enables evaluation of the stability of the fractal dimension (Df) across different structural definitions—from more inclusive to more restrictive—ensuring that the measured complexity is not an artifact of a single threshold setting and ensuring the consistency of fractal behavior across different segmentation levels [5].

Although SEM-based analysis does not capture vertical topography as directly as atomic force microscopy (AFM), it offers a reliable and reproducible basis for fractal and texture analysis when images are acquired under consistent conditions. Future work will consider AFM characterization to complement and validate the 2D-based findings.

3. Results and Discussion

3.1. Surface Roughness Parameters

The surface roughness of TiO_2 thin films varied significantly with sputtering power and oxygen concentration in the gas mixture, as detailed in a prior study [1]. Increasing oxygen from 50% to 75% consistently raised roughness metrics (R_q , R_a , R_z) at both power levels, indicating that a more reactive environment enhances morphological complexity. At 500 W, R_q rose from 5.009 nm to 77.80 nm, and R_a from 68.10 nm to 393.7 nm. This suggests that excess oxygen promotes cluster formation by reducing adatom mobility or altering energy dissipation. At 1000 W, the trend intensified due to increased ion bombardment and sputtered species energy, reflected in R_z increasing from 279.0 nm (500 W/75% O_2) to 1741 nm (1000 W/75% O_2), indicating pronounced vertical growth and columnar or mound-like structures due to shadowing and reduced surface diffusion. R_{sk} shifted from 0.2396 to -0.2808 at 500 W as oxygen increased, marking a transition from peak- to valley-dominated topographies, possibly linked to densification. Figure 2 visually summarizes these effects, illustrating how oxygen and power jointly influence film topography.

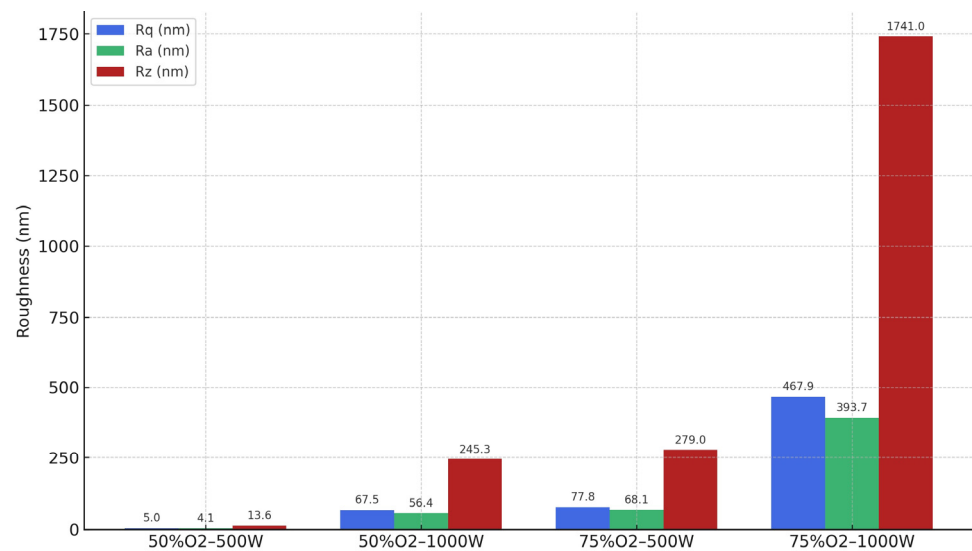


Figure 2. Surface roughness parameters (ISO 21920) [12]—Rq (root mean square), Ra (arithmetic mean), and Rz (maximum peak-to-valley height)—of TiO₂ thin films deposited by DC reactive sputtering at 500 W and 1000 W with 50% and 75% oxygen concentrations.

3.2. Dimension (Df) Analysis

To investigate the scale-dependent complexity of TiO₂ surface morphology, a fractal dimension (Df) analysis was performed using binarized SEM images from samples Im1, Im2, Im3, and Im4. This method enables a quantitative assessment of structural richness across multiple observational scales, reflecting the degree of self-similarity and hierarchical organization of the surface. The progressive thresholding offers a multiscale visual representation, demonstrating how threshold selection influences the perceived morphology and setting the stage for the quantitative Df analysis. Figure 3 shows sample Im1, deposited using 50% oxygen and 1000 W. The SEM image in panel (a) reveals a porous and heterogeneous morphology composed of irregular microstructures and elongated features predominantly aligned along the horizontal axis. This grayscale image served as the basis for fractal segmentation. Panels (b) through (f) display binarized versions of the original image obtained using increasing threshold values ($T = 0.50, 0.60, 0.70, 0.75$, and 0.80), illustrating how structural features evolve with segmentation selectivity. At $T = 0.50$, segmentation is highly inclusive, preserving both fine and broad surface features, resulting in a dense, highly connected binary texture with strong black-and-white contrast. At $T = 0.60$, less prominent details are filtered out, enhancing the visibility of dominant elongated ridges and clarifying large-scale organization while maintaining structural complexity. At $T = 0.70$, significant simplification occurs as finer porosity and noise are largely removed, revealing a clearer dominance of horizontal formations and suggesting hierarchical organization where key features exist independently of small-scale roughness. At $T = 0.75$ and 0.80 , the segmentation becomes increasingly selective, retaining only the most prominent and persistent structures: mainly interconnected ridges and larger surface channels. These likely correspond to energetically or kinetically favored growth pathways formed under the applied deposition conditions. This progressive filtering illustrates the scale-dependent nature of surface complexity: lower thresholds reveal a broad range of fine and coarse features, while higher thresholds emphasize the dominant structural backbone. The recurrence of specific morphological elements across thresholds suggests a self-similar, fractal-like organization, a pattern that becomes evident as additional samples are examined.

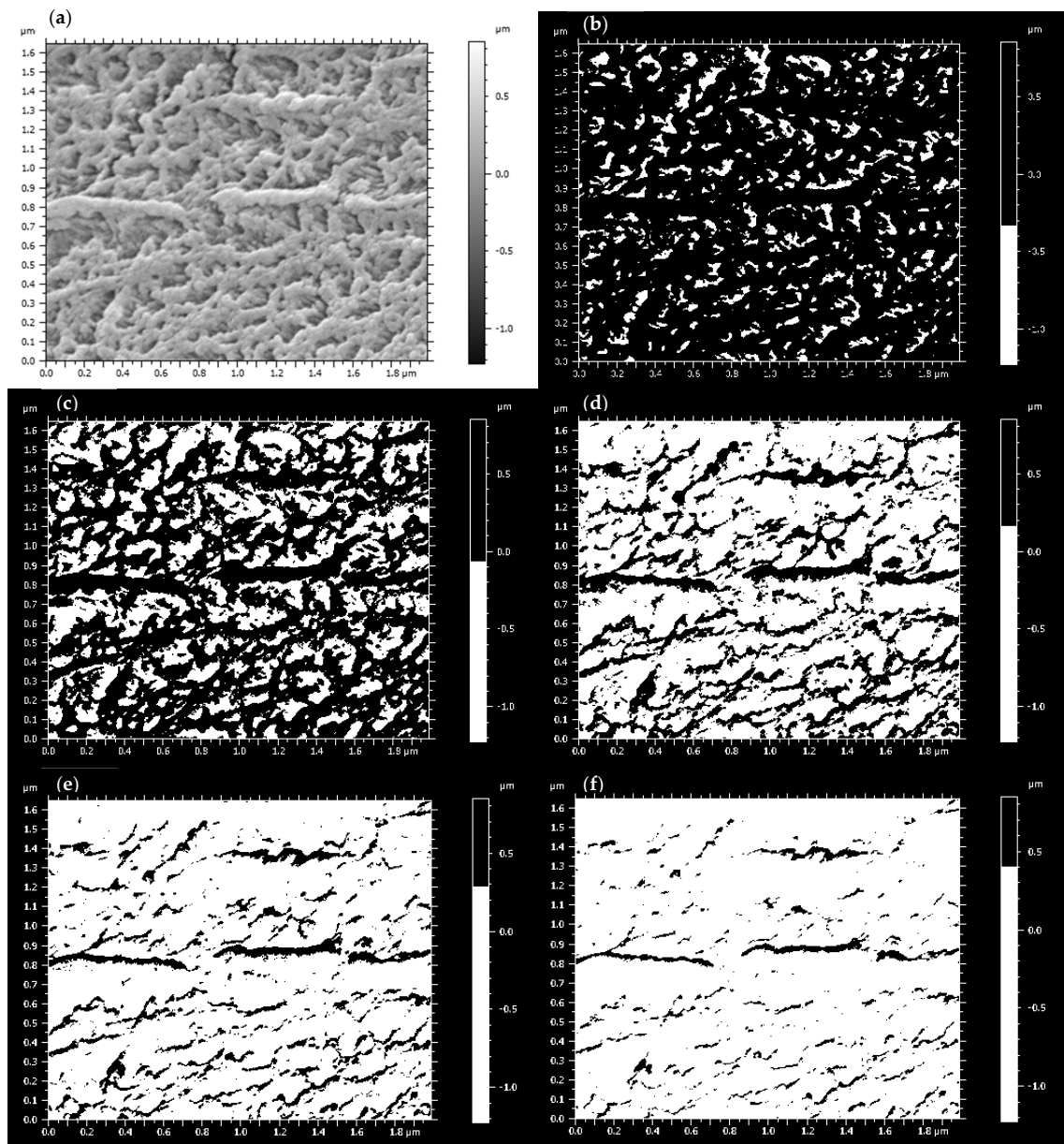


Figure 3. SEM image and binarized maps of sample Im1 at different binarization thresholds: (a) original grayscale image; (b–f) binarized images at $T = 0.50, 0.60, 0.70, 0.75$, and 0.80 , respectively.

Sample Im2, obtained by DC reactive sputtering with 75% oxygen and 500 W of power, is presented in Figure 4. The grayscale SEM image in panel (a) reveals a compact, granular morphology with rounded nodular features. The surface is densely packed, showing subtle topographical variations without any dominant directional alignment. This micrograph forms the basis for the fractal segmentation analysis shown in panels (b) through (f). Panels (b–f) present binarized versions of the original SEM image, corresponding to progressively higher threshold values ($T = 0.50, 0.60, 0.70, 0.75$, and 0.80). This sequence illustrates how morphological features are incrementally filtered as segmentation becomes more selective. At $T = 0.50$ (panel b), segmentation is highly inclusive, capturing both fine granular structures and broader topographical zones in a dense binary pattern. Although this preserves much of the surface's inherent texture, the excess of detail can obscure dominant structural patterns. At $T = 0.60$ (panel c), minor surface features begin to disappear, emphasizing more prominent nodular clusters and simplifying background textures. At $T = 0.70$ (panel d), only the most pronounced protrusions remain, revealing an intermediate

level of structural organization with smaller-scale features largely removed and no evident directional bias. At $T = 0.75$ and 0.80 (panels e and f), segmentation becomes highly selective, retaining only the largest and most persistent morphological elements, likely associated with kinetically favored growth regions. These coarser patterns suggest a hierarchical surface structure rather than a continuous network. Altogether, this threshold progression highlights the scale-dependent nature of surface complexity: lower thresholds capture a wide range of micro- and macro-features, while higher thresholds isolate the morphological backbone. The recurrence of specific features across multiple thresholds supports the notion of a self-similar, fractal-like organization, forming the foundation for the quantitative analysis of the fractal dimension (D_f) that follows.

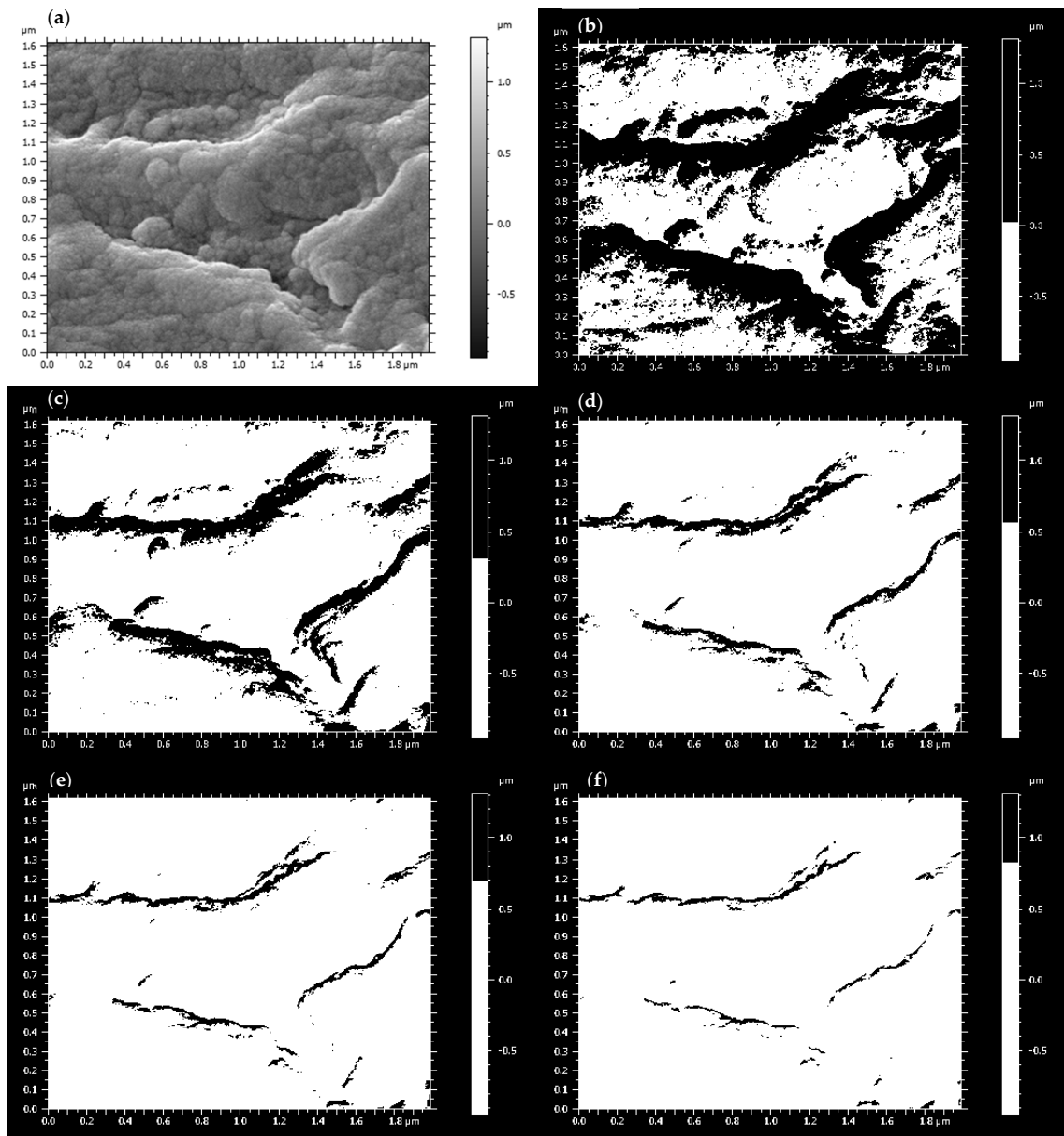


Figure 4. SEM image and binarized maps of sample Im2 at different binarization thresholds: (a) original grayscale image; (b–f) binarized images at $T = 0.50, 0.60, 0.70, 0.75$, and 0.80 , respectively.

Sample Im3, obtained by DC reactive sputtering with 75% oxygen and 1000 W of power, is presented in Figure 5. Panel (a) presents the grayscale SEM image revealing a layered, terraced morphology dominated by smooth, horizontally aligned ridges. Unlike

the more porous or granular textures in other samples, Im3 exhibits relatively low surface roughness with an anisotropic, orderly growth pattern.

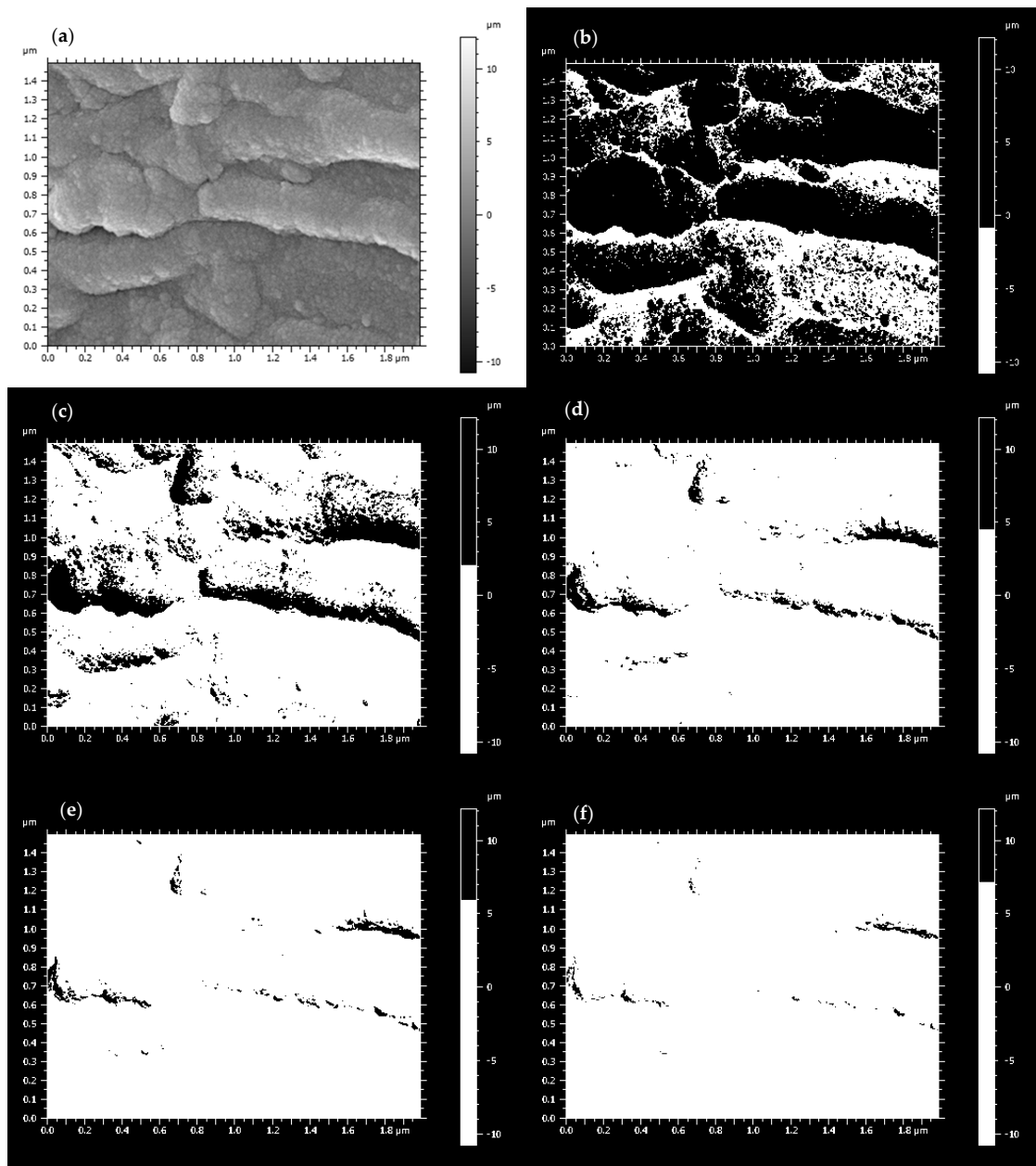


Figure 5. SEM image and binarized maps of sample Im3 at different binarization thresholds: (a) original grayscale image; (b–f) binarized images at $T = 0.50$, 0.60 , 0.70 , 0.75 , and 0.80 , respectively.

Panels (b–f) display binarized versions of the image at increasing thresholds $T = 0.50$, 0.60 , 0.70 , 0.75 , and 0.80 , respectively, showing progressive filtering of morphological features. At $T = 0.50$ (panel b), a wide range of surface details is preserved, capturing both fine textures and dominant ridges, though fine-scale features are less prominent than in irregular samples. At $T = 0.60$ (panel c), minor features fade, highlighting the anisotropic horizontal ridges. At $T = 0.70$ (panel d), most noise and minor textures disappear, revealing the intermediate-scale ridges. Finally, at $T = 0.75$ and 0.80 (panels e and f), only the most prominent ridges remain, representing the core morphological framework likely shaped by the kinetic growth conditions.

This threshold sequence underscores Im3's reduced surface complexity compared to more porous films, yet indicates a scale-dependent, self-similar structure with persistent layered ridges. These observations underpin the forthcoming fractal dimension (D_f) analysis that will quantify the surface's hierarchical organization.

Sample Im4, obtained by DC reactive sputtering with 50% oxygen and 500 W of power, is presented in Figure 6. The grayscale SEM image (panel a) shows a smooth, relatively featureless surface with a few rounded nodular features, indicating lower topographical complexity compared to other samples and suggesting a more uniform growth with limited surface texturing.

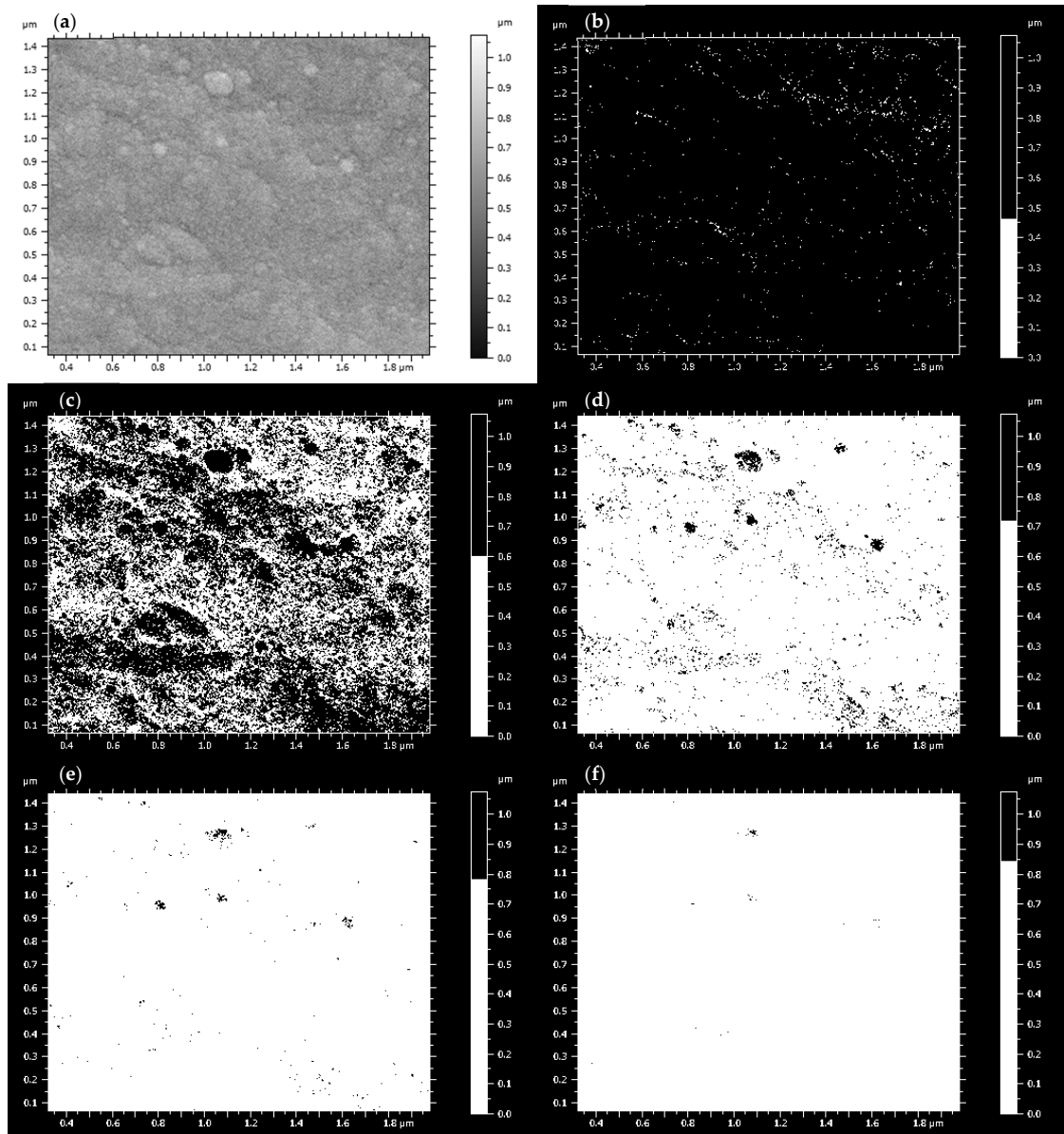


Figure 6. SEM image and binarized maps of sample Im4 at different binarization thresholds: (a) original grayscale image; (b–f) binarized images at $T = 0.50, 0.60, 0.70, 0.75,$ and 0.80 , respectively.

Binarized images at increasing thresholds ($T = 0.50, 0.60, 0.70, 0.75, 0.80$ in panels b–f) reveal the progressive filtering of surface features. At $T = 0.50$, only sparse, subtle structures appear, consistent with a surface lacking significant micro- or nanoscale variation. Increasing to $T = 0.60$, more texture emerges as fine-grained speckling and nodules become distinguishable, though the pattern remains diffuse and without strong directional order.

At $T = 0.70$, most minor textures are filtered out, leaving mainly larger nodules and elevated features, showing limited hierarchical organization. At the highest thresholds ($T = 0.75$ and 0.80), segmentation is highly selective, isolating only prominent protrusions while the majority of the surface appears uniform, indicating a non-fractal, non-hierarchical morphology dominated by few localized elements.

This threshold progression confirms that Im4 has the lowest structural complexity among the studied films, with limited self-similarity and an absence of interconnected or branching features, consistent with growth under low-energy, low-oxygen conditions producing a simple, compact surface topology.

Fractal analysis was performed on binarized versions of the SEM images using the box-counting method. The fractal dimension (Df) values provide a measure of morphological complexity and surface irregularity, where higher values typically indicate more intricate, space-filling structures, while lower Df values reflect smoother or simpler morphologies. Figure 7 presents the variation in Df as a function of threshold (T) for all analyzed SEM images (Im1 to Im4), each corresponding to distinct deposition conditions. The estimated Df values ranged from approximately 1.35 to 1.85, showing a clear trend of increasing Df with higher oxygen concentration and greater sputtering power. This progression reflects the growing morphological complexity and spatial richness of the surface as the deposition environment becomes more energetic and oxidizing. This behavior aligns with theoretical models of sputtered thin film growth, where shadowing and reduced adatom diffusion under energetic conditions promote hierarchical structuring [7]. The highest Df (~ 1.85) was recorded for the sample deposited at 1000 W/75% O_2 (Im3), which also corresponds to the sample that exhibited the highest roughness values in earlier topographic analysis (e.g., R_q and R_z). These values are consistent with previous reports on sputtered TiO_2 films, where increased surface complexity under high-energy conditions has been associated with elevated Df values and directional growth patterns [4]. This supports the interpretation that fractal dimension captures the multiscale, hierarchical nature of surface features, going beyond what is revealed by conventional roughness parameters that measure only vertical deviations.

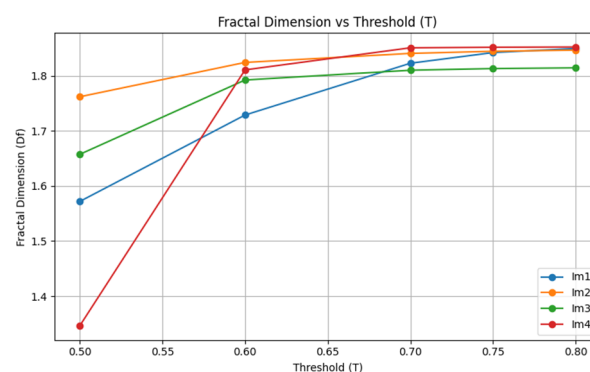


Figure 7. Fractal dimension (Df) as a function of threshold (T) for binarized SEM images of TiO_2 films deposited under varying sputtering conditions: Im1 (50% O_2 , 1000 W), Im2 (75% O_2 , 500 W), Im3 (75% O_2 , 1000 W), and Im4 (50% O_2 , 500 W). Df was estimated using the box-counting method.

Conversely, the lowest Df (~ 1.35) was observed in the film deposited at 1000 W/25% O_2 (Im4), particularly evident at the lowest threshold ($T = 0.50$). This indicates a more compact and uniform surface topology, likely related to metallic-rich deposition conditions, which typically favor denser film growth due to enhanced surface diffusion and reduced oxidation during formation. The variation in Df with threshold levels also provides valuable insight: at lower thresholds ($T = 0.50$ – 0.60), the differences between samples are more pronounced, while at higher thresholds ($T \geq 0.70$), Df tends to converge. This suggests that the finer, lower-intensity features contribute most to the differentiation in complexity,

whereas larger-scale structures appear more similar across samples when binarized at higher intensity cutoffs.

Altogether, these results confirm the value of fractal dimension as a complementary morphological descriptor, capturing aspects of surface organization that are not accessible through standard roughness parameters, and providing a quantitative framework to assess structural richness as a function of deposition conditions.

3.3. GLCM Texture Analysis

To complement morphological and roughness analyses, surface texture was characterized using Gray-Level Co-occurrence Matrix (GLCM) descriptors computed from grayscale SEM images of the TiO_2 thin films. This second-order statistical method quantifies surface regularity, heterogeneity, and anisotropy by analyzing the frequency of pixel intensity pairs at defined spatial relationships. Key descriptors—contrast, correlation, dissimilarity, energy, and homogeneity—were calculated across four directions (0° , 45° , 90° , 135°) and two-pixel distances ($d = 1$, $d = 2$), enabling a multiscale, orientation-sensitive assessment. Lower distances capture fine local features, while higher distances reflect broader structural patterns. The angular variation helps detect anisotropic growth behaviors linked to specific deposition conditions. This is consistent with established applications of GLCM in image analysis, where pixel pair statistics are used to detect directional textures and second-order spatial patterns [8].

For sample Im1 (50% oxygen and 1000 W), the SEM image reveals a heterogeneous and porous morphology with irregular microstructures predominantly aligned along the horizontal axis. This directional anisotropy is clearly reflected in the GLCM texture descriptors shown in Figure 8. Notably, contrast and dissimilarity values increase significantly at angles of 90° and 135° , indicating greater variation in gray levels along vertical and diagonal directions, which statistically confirms the horizontal elongation of surface features.

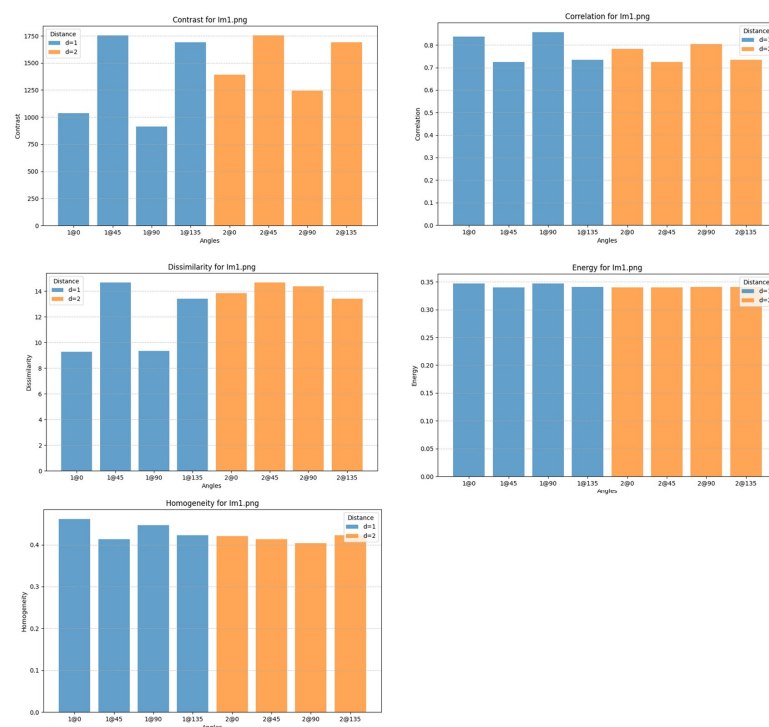


Figure 8. GLCM texture descriptors for sample Im1 (50% O_2 , 1000 W) as a function of threshold (T) at pixel distances $d = 1$ and $d = 2$, analyzed for four angular directions (0° , 45° , 90° , and 135°): contrast, correlation, dissimilarity, energy, and homogeneity.

This anisotropic texture likely results from the interplay of intermediate oxygen concentration and high sputtering power. At 1000 W, increased kinetic energy of sputtered species enhances surface diffusion, directional re-emission, and shadowing effects, promoting elongated ridges and interconnected porous pathways aligned preferentially in the horizontal direction. Meanwhile, the 50% oxygen content provides sufficient reactivity for oxide formation without over-saturating the surface, supporting structured yet non-uniform growth and thus complex anisotropic patterns.

Comparing pixel distances $d = 1$ and $d = 2$, the texture parameters reveal scale-dependent surface organization. Contrast and dissimilarity generally increase with distance, particularly at 90° , reflecting longer-range gray-level transitions consistent with spacing between major surface features. Concurrently, correlation decreases with distance, indicating less predictable pixel intensity relationships at broader scales, signifying a complex texture without regular periodicity. Energy remains low across all directions, suggesting the absence of strong uniform patterns, while homogeneity decreases at $d = 2$, especially at 90° , confirming disruption of smoothness over larger spatial extents.

These GLCM results quantitatively support the SEM observations, revealing a surface with pronounced anisotropy and multiscale complexity shaped by the reactive sputtering conditions applied during deposition.

The GLCM texture analysis results for sample Im2 (75% oxygen, 500 W) are presented in Figure 9. Compared to Im1, the increased oxygen partial pressure creates a more oxidizing plasma environment, favoring complete oxidation and the formation of stoichiometric TiO_2 phases. Simultaneously, the lower sputtering power reduces the kinetic energy of sputtered species, limiting surface diffusion and adatom mobility. Together, these factors promote a more compact and homogeneous morphology with reduced surface roughness and less structural anisotropy, which is clearly reflected in the GLCM descriptors. At pixel distance $d = 1$, contrast and dissimilarity are low across all directions, indicating reduced gray-level variation and a more uniform fine-scale texture consistent with limited directional growth instabilities. However, at $d = 2$, these parameters increase notably, especially at 90° and 135° , indicating that longer-range brightness variations exist, corresponding to broader topographical features such as columnar formations or grain boundaries. This highlights a multiscale organization: smooth at the local scale but retaining intermediate-range complexity. Correlation values are high at $d = 1$ and remain relatively high at $d = 2$, reflecting strong gray-level relationships and uniform texture across scales. Energy and homogeneity are consistently high and show minimal angular variation, confirming a regular, repeated surface pattern with minimal discontinuities.

Importantly, the angular dependence is less pronounced than in Im1, indicating a more isotropic surface texture. The reduced kinetic energy at 500 W limits directional surface diffusion, favoring randomized nucleation and finer-grained, symmetric growth.

In summary, the GLCM analysis shows that Im2 possesses a uniform, isotropic texture with low local heterogeneity and moderate mesoscale complexity. This texture arises from the combined effects of high oxygen flow and moderate sputtering power, resulting in a smoother, less complex surface than Im1, but retaining some residual structural variation at intermediate scales.

The GLCM texture analysis for sample Im3 (75% oxygen and 1000 W) is shown in Figure 10. This combination creates a strongly oxidizing plasma and high kinetic energy species, promoting compact, dense films with pronounced microstructural features and enhanced crystallinity. Contrast and dissimilarity values are intermediate to high, especially at $d = 2$ and angles 45° and 135° , indicating mesoscale structural variations like preferential orientation domains or vertically aligned grain boundaries. At $d = 1$, contrast is lower, reflecting finer-scale uniformity typical of columnar growth.

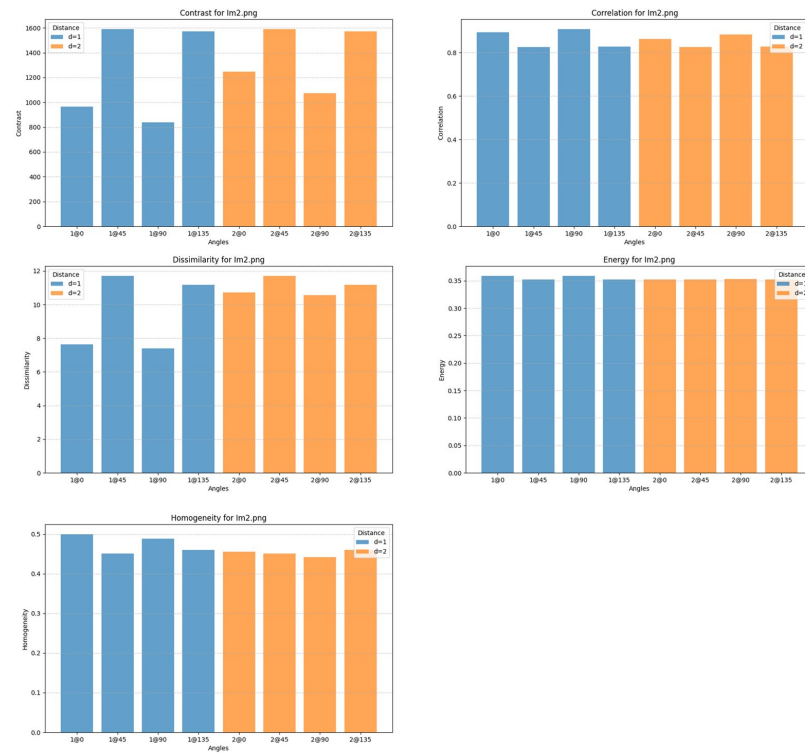


Figure 9. GLCM texture descriptors for sample Im2 (75% O₂, 500 W) as a function of threshold (T) at pixel distances d = 1 and d = 2, analyzed for four angular directions (0°, 45°, 90°, and 135°): contrast, correlation, dissimilarity, energy, and homogeneity.

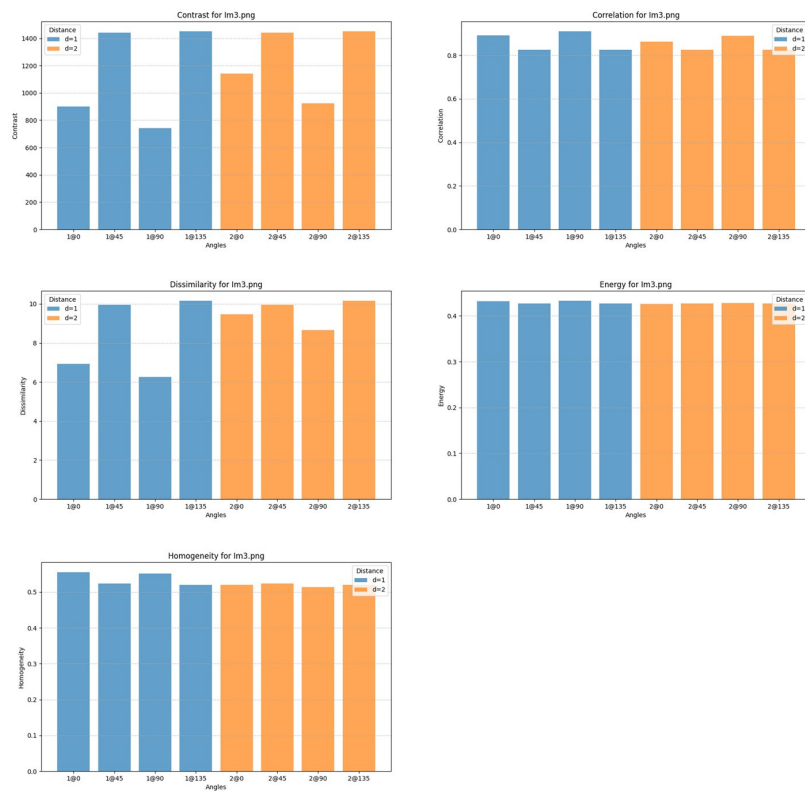


Figure 10. GLCM texture descriptors for sample Im3 (75% O₂, 1000 W) as a function of threshold (T) at pixel distances d = 1 and d = 2, analyzed for four angular directions (0°, 45°, 90°, and 135°): contrast, correlation, dissimilarity, energy, and homogeneity.

Correlation remains high at both distances, slightly higher at $d = 1$, indicating strong local pixel intensity relationships and stable microstructure. A small decrease at $d = 2$ along 135° hints at subtle anisotropy linked to columnar texture from shadowing or adatom migration. Energy and homogeneity are consistently high and nearly angle-independent, confirming uniform, compact films with fine structural order and minimal abrupt intensity changes. Angular variations show anisotropy with higher contrast and dissimilarity at 45° and 135° at $d = 2$, likely due to column tilting or shadowing effects, emphasizing the need for multi-distance GLCM to capture hierarchical textures. Compared to Im2, which shows isotropic and smooth surfaces due to lower power, Im3's high power leads to vertical growth and internal complexity, despite similar oxygen levels.

In summary, Im3 exhibits a dense, directionally textured film with high correlation, homogeneity, and mesoscale contrast along oblique angles, reflecting the interplay of strong oxidation and elevated adatom mobility. This results in uniform local texture with mesoscale anisotropies, highlighting the impact of energetic, oxygen-rich sputtering on surface morphology and potential functional properties.

The GLCM texture analysis for sample Im4 (50% O_2 , 500 W), shown in Figure 11, reflects the effects of a moderately oxidizing plasma combined with low sputtering energy. These conditions limit adatom mobility and reactivity, favoring the formation of granular, isotropic morphologies with reduced densification and minimal crystallographic alignment. Contrast and dissimilarity are moderate at $d = 1$ but increase noticeably at $d = 2$ —especially at 45° and 135° —revealing mesoscale structural variation likely associated with grain coalescence or weak preferential domains. The lower values at short distances point to greater uniformity in local gray-level transitions, while broader pixel separations reveal more complex organization. Correlation remains high across directions and distances, confirming strong local intensity relationships and a repetitive, though non-directional, texture. A slight drop in correlation at $d = 2$ suggests minor long-range disorder, likely due to random grain nucleation and limited surface diffusion. Energy is relatively stable across parameters, indicating reasonable gray-level uniformity, though less marked than in more ordered films. Homogeneity is moderately high and angularly consistent, supporting the presence of a compact but slightly disordered surface.

Im4 displays a locally ordered, isotropic texture without significant anisotropy or hierarchical structure. Compared to Im3 (75% O_2 , 1000 W), which showed directionally textured and denser films due to enhanced mobility, Im4 highlights the impact of lower sputtering power—at constant oxidation—on promoting smoother, more homogeneous surface morphologies in TiO_2 thin films.

The GLCM analysis reveals a clear dependence of surface texture on sputtering power and oxygen concentration. Films deposited at higher power (1000 W)—Im1 (50% O_2) and Im3 (75% O_2)—exhibit increased contrast and dissimilarity, particularly at longer pixel distances, reflecting enhanced gray-level variability and the presence of mesoscale structural features, such as elongated grains or columnar domains. These effects are further modulated by oxygen content: while Im1 shows strong anisotropy with horizontally aligned features, Im3 presents a more compact but directionally textured morphology, likely due to combined high reactivity and surface mobility.

Conversely, low-power depositions (500 W)—Im2 and Im4—yield smoother, more isotropic textures. Im2 (75% O_2) displays high correlation and homogeneity, and low contrast, consistent with a uniform, fine-grained surface, stemming from complete oxidation and limited adatom mobility. Im4 (50% O_2), while also relatively isotropic, exhibits slightly higher contrast and lower energy at $d = 2$, suggesting moderate mesoscale disorder, possibly due to granular coalescence in a less reactive environment.

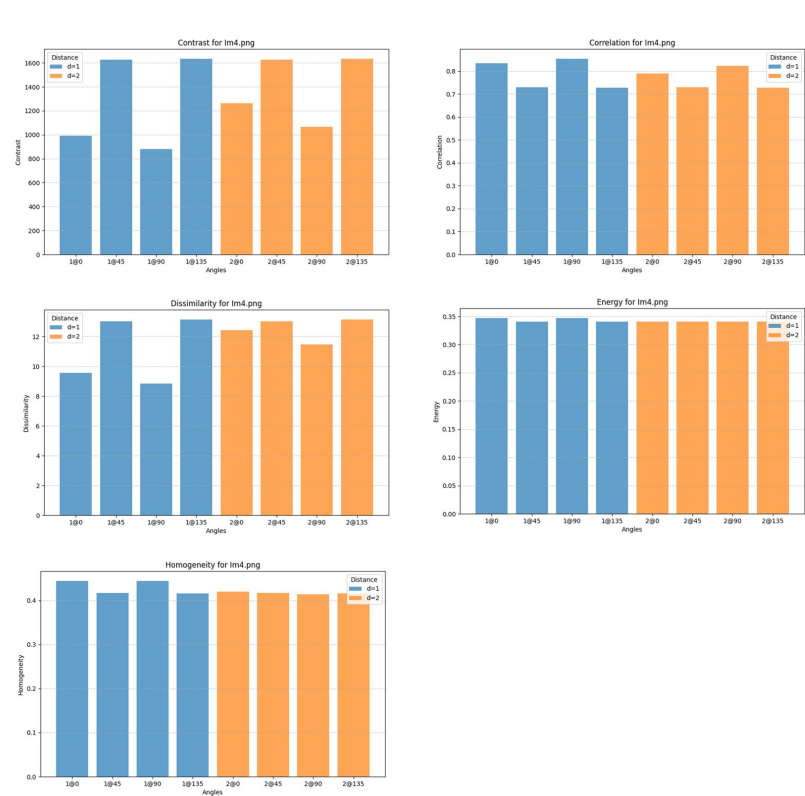


Figure 11. GLCM texture descriptors for sample Im4 (50% O₂, 500 W) as a function of threshold (T) at pixel distances d = 1 and d = 2, analyzed for four angular directions (0°, 45°, 90°, and 135°): contrast, correlation, dissimilarity, energy, and homogeneity.

Overall, the results demonstrate that sputtering power primarily governs surface roughness and textural complexity, while oxygen concentration modulates the degree of oxidation and crystallinity. The GLCM descriptors effectively capture these multiscale morphological variations, offering a robust statistical approach for correlating deposition conditions with film texture—key for tailoring functional properties in TiO₂ thin films. As highlighted in recent reviews, combining GLCM descriptors with fractal analysis provides a robust dual approach for capturing both local anisotropy and global complexity [5].

3.4. Comparative Summary of Morphological and Textural Features

To consolidate the findings from surface roughness measurements, fractal dimension analysis, and GLCM-based texture characterization, Table 1 presents a comparative synthesis of the four TiO₂ thin film samples. This overview highlights the influence of sputtering power and oxygen concentration on surface morphology and textural organization.

Table 1. Deposition parameters and morphological characteristics of TiO₂ thin film samples.

Sample	Power (W)	O ₂ (%)	Ra (nm)	Rz (nm)	Df	GLCM Contrast	GLCM Correlation	GLCM Dissimilarity	GLCM Energy	GLCM Homogeneity	Morphology Summary
Im1	1000	50	High	High	* Mod.	High	* Mod.	High	Low	* Mod.	Porous, anisotropic, horizontal microstructures
Im2	500	75	* Mod.	* Mod.	Low	Low (d = 1)/ * Mod. (d = 2)	High	Low (d = 1)/ * Mod. (d = 2)	High	High	Compact, isotropic, homogeneous surface
Im3	1000	75	High	High	High	* Mod./High (d = 2)	High	* Mod./High (d = 2)	High	High	Dense, textured, columnar, anisotropic
Im4	500	50	Low	Low	Low	* Mod. (d = 1)/High (d = 2)	High	* Mod. (d = 2)	* Mod.	* Mod.	Granular, isotropic, low anisotropy texture

* Mod. means moderate.

The comparison reveals consistent trends: higher sputtering power tends to increase surface complexity, as reflected by higher roughness parameters (R_a , R_z) and fractal dimension (D_f), while also promoting textural anisotropy. Elevated oxygen content contributes to more complete oxidation, denser structures, and vertical growth features.

The trends observed in both fractal dimension and GLCM descriptors can be explained by key thin film growth mechanisms inherent to sputtering processes. At higher sputtering powers, the increased energy of the incident species enhances adatom surface mobility, leading to competitive growth and the development of preferential orientations or columnar structures. These structures contribute to anisotropy and greater spatial variability, which are reflected in higher fractal dimensions (D_f) and elevated GLCM contrast and dissimilarity values. Additionally, shadowing effects—particularly under low diffusion conditions—favor vertical growth and ridge formation, reinforcing hierarchical complexity and directionality at the mesoscale.

In contrast, at lower power and oxygen levels, reduced energy input results in limited adatom rearrangement and more isotropic nucleation, yielding smoother, compact morphologies with fewer high-frequency features. These surfaces exhibit lower D_f values and more homogeneous GLCM profiles. Grain boundary density and coalescence patterns, modulated by oxygen reactivity, also influence surface roughness and local gray-level transitions. Thus, the fractal and texture metrics used in this work provide a quantitative means to interpret the morphological signatures of the underlying physical growth mechanisms.

These effects are quantitatively supported by the five GLCM descriptors—contrast, correlation, dissimilarity, energy, and homogeneity—which reveal multiscale surface properties. For instance, higher contrast and dissimilarity values are associated with more heterogeneous and hierarchically structured surfaces, while higher energy and homogeneity indicate uniformity and repetition in pixel intensity patterns. Correlation provides insight into the predictability and order of local gray-level transitions.

The summarized parameters in Table 1 offer an integrated perspective on how deposition conditions govern the evolution of surface features, from microstructural order to mesoscale texture, thus informing the optimization of functional thin films grown by reactive sputtering.

4. Conclusions

This study presented an integrated morphological characterization of TiO_2 thin films deposited via DC reactive magnetron sputtering under varying oxygen concentrations and sputtering powers. By combining classical roughness parameters, fractal dimension (D_f) analysis, and GLCM texture descriptors, we constructed a multiscale and multidimensional framework to analyze surface complexity.

The results show that both increasing sputtering power and oxygen content lead to higher roughness (R_a , R_q , R_z) and fractal dimension, indicating greater surface irregularity and structural richness. These parameters also correlate with higher GLCM contrast and lower homogeneity, particularly in samples deposited at 1000 W with 75% O_2 . Films grown under low-power and low-oxygen conditions exhibit smoother and more isotropic surfaces with lower D_f values and more uniform GLCM profiles.

Fractal analysis, especially when performed across multiple binarization thresholds, proved effective in identifying hierarchical organization and self-similar features, revealing patterns beyond the reach of traditional roughness metrics. GLCM texture descriptors further clarified local anisotropies and spatial ordering, linking deposition dynamics to statistical gray-level variation.

This combined approach enhances the understanding of how deposition parameters influence surface morphology, offering a refined methodology for the structural assessment of thin films with complex topographies.

Author Contributions: Conceptualization, H.C.V.; methodology, H.C.V. and M.M.; software, T.E.; validation, M.M. and T.E.; formal analysis, H.C.V.; investigation, H.C.V.; data curation, T.E.; writing—original draft preparation, H.C.V.; writing—review and editing, H.C.V.; visualization, M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data are presented in the paper; no external data are available.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Eleutério, T.; Sério, S.; Vasconcelos, H.C. Growth of Nanostructured TiO₂ Thin Films onto Lignocellulosic Fibers through Reactive DC Magnetron Sputtering: A XRD and SEM Study. *Coatings* **2023**, *13*, 922. [CrossRef]
2. Sayles, R.S.; Thomas, T.R. The spatial representation of surface roughness by means of the structure function: A practical alternative to correlation. *Wear* **1977**, *42*, 263–276. [CrossRef]
3. Liebovitch, L.S.; Toth, T. A fast algorithm to determine fractal dimensions by box counting. *Phys. Lett. A* **1989**, *141*, 386–390. [CrossRef]
4. Stojadinović, S.; Rožić, L.; Grbić, B.; Radić, N.; Dostanić, J.; Stojadinović, S.; Vasilčić, R. Morphology and Fractal Dimension of TiO₂ Thin Films. *Maced. J. Chem. Chem. Eng.* **2013**, *32*, 309–317. [CrossRef]
5. Zuo, X.; Tang, X.; Zhou, Y. Influence of sampling length on estimated fractal dimension of surface profile. *Chaos Solitons Fractals* **2020**, *135*, 109755. [CrossRef]
6. Zhou, W.; Cao, Y.; Zhao, H.; Li, Z.; Feng, P.; Feng, F. Fractal Analysis on Surface Topography of Thin Films: A Review. *Fractal Fract.* **2022**, *6*, 135. [CrossRef]
7. Mwema, F.M.; Akinlabi, E.T.; Oladijo, O.P. *Sputtered Thin Films: Theory and Fractal Descriptions*; CRC Press: Boca Raton, FL, USA, 2021.
8. MathWorks. Texture Analysis Using the Gray-Level Co-Occurrence Matrix (GLCM). MathWorks Documentation. Available online: https://www.mathworks.com/help/images/texture-analysis-using-the-gray-level-co-occurrence-matrix-glcm.html?utm_source=chatgpt.com (accessed on 1 April 2025).
9. Singh, G.; Yadav, R.P.; Bhasker, H.P.; Kumar, M.; Rajput, P.; Rao, P.N.; Rai, S.K.; Singh, M.K. Investigation of fractal feature of multiferroic BiFeO₃ thin films deposited on different substrates. *Mater. Res. Express* **2018**, *5*, 126405. [CrossRef]
10. Ghosh, K.; Pandey, R. Fractal assessment of thin films deposited by random and ballistic deposition models. *AIP Conf. Proc.* **2020**, *2265*, 030316.
11. Eleutério, T.; Sério, S.; Teodoro, O.M.N.D.; Bundaleski, N.; Vasconcelos, H.C. XPS and FTIR Studies of DC Reactive Magnetron Sputtered TiO₂ Thin Films on Natural Based-Cellulose Fibers. *Coatings* **2020**, *10*, 287. [CrossRef]
12. ISO 21920; Surface roughness—Terms, definitions and parameters. International Organization for Standardization: Geneva, Switzerland, 2020.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.