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Enhanced Electrical Properties of Graphite-Doped Titanium Dioxide Thin Films via Sol-Gel Method

K.L. Foo[1*], S.J. Tan[2,3], C.Y. Heah[2,3] and Y.M. Liew[3,4]

[1]Institute of Nano Electronic Engineering (INEE), Universiti Malaysia Perlis (UniMAP), 01000 Kangar, Perlis, Malaysia.
[2]Faculty of Mechanical Engineering & Technology, Universiti Malaysia Perlis (UniMAP), Level 1, Block S2, Campus UniCITI Nature, Sungai Chuchuh, 02100 Padang Besar, Perlis, Malaysia.
[3]Center of Excellence Geopolymer and Green Technology (CEGeoGTech). School of Material Engineering, Universiti Malaysia Perlis (UniMAP), 77 Pejabat Pos Besar, 01000, Kangar, Perlis Malaysia.
[4]School of Materials Engineering, Kompleks Pusat Pengajian Jejawi 2, Universiti Malaysia Perlis (UniMAP), Taman Muhibbah, 02600 Jejawi, Arau, Perlis, Malaysia.

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ABSTRACT

Graphite-doped titanium dioxide (Gr-TiO_2) thin films were synthesized via the sol-gel method to enhance the electrical properties of TiO_2 for advanced electronic and biosensor applications. The study focuses on optimizing the drying temperatures and graphite doping levels to achieve improved film crystallinity, morphology, and conductivity. Thin films were deposited using spin-coating and analyzed through scanning electron microscopy (SEM), high-power microscopy (HPM), and current-voltage (I-V) measurements. Results indicate that increasing drying temperature enhances grain coalescence and reduces porosity, leading to improved electrical conductivity. Graphite doping effectively narrows the bandgap and introduces additional charge carriers. These findings demonstrate the potential of Gr-TiO_2 thin films for applications in photovoltaics, sensors, and other optoelectronic devices.

Keywords: Graphite-doped TiO_2, Sol-gel method, Electrical conductivity, Thin films, Optical properties.

1. INTRODUCTION

Titanium dioxide (TiO_2) is a wide bandgap semiconductor material [1] that has attracted considerable attention due to its excellent optical, electrical, and mechanical properties. It is widely used in various applications, including photocatalysis [2], solar cells [3], gas sensors [4], and environmental protection [5] due to its high stability, non-toxicity [6], and photocatalytic activity. However, one of the primary limitations of TiO_2 is its low electrical conductivity, which restricts its effectiveness in electronic and optoelectronic devices, such as photovoltaics [7] and sensors. To overcome this limitation, doping TiO_2 with various materials has been proposed as a method to enhance its electrical properties and broaden its application potential.

Graphite, a highly conductive form of carbon [8], has been increasingly explored as a dopant to improve the densification and the properties of TiO_2 [9]. Graphite doping can modify the electronic structure of TiO_2 by introducing additional charge carriers and reducing its bandgap, which enhances its performance in energy-related applications. Graphite-doped TiO_2 (Gr-TiO_2) thin films have shown promising results in terms of improved conductivity, light absorption, and overall device performance.

*Corresponding author: klfoo@unimap.edu.my

The sol-gel method [10] is a cost-effective and versatile technique for synthesizing TiO_2 thin films, which offers control over the material's structure and properties. This method involves the hydrolysis and condensation of titanium precursors, resulting in the formation of a gel that can be converted into a thin film. By incorporating graphite into the sol-gel solution, it is possible to achieve uniform doping and enhance the electrical conductivity of the TiO_2 films.

In this study, we explore the synthesis of Gr-TiO_2 thin films using the sol-gel method and investigate the impact of graphite doping on the structural, optical, and electrical properties of TiO_2. The films were characterized using scanning electron microscopy (SEM), high-power optical microscopy (HPM), and current-voltage (I-V) measurements to evaluate their structure, morphology, and conductivity. The results demonstrate the significant influence of graphite doping on improving the electrical conductivity and light absorption properties of TiO_2, making Gr-TiO_2 thin films a promising candidate for a range of applications in photovoltaics, sensors, and optoelectronic devices.

2. MATERIAL AND METHODS

In this section, we outline the key steps involved in the synthesis and characterization of Gr-TiO_2 thin films. The process includes the preparation of the TiO_2 sol, doping with graphite, deposition onto substrates, and subsequent drying. Characterization techniques such as SEM, HPM, and I-V measurements were used to evaluate the structural, morphology, and conductivity properties of the films.

2.1 Synthesis of Gr-TiO_2 Thin Films

The Gr-TiO_2 thin films were synthesized using a sol-gel method due to their simplicity and cost-effectiveness. Titanium (IV) isopropoxide (TTIP) was used as the titanium precursor, while ethanol and glacial acetic acid acted as the solvent and stabilizer, respectively.

The synthesis process involved mixing TTIP (10 mL) with ethanol (90 mL) under constant stirring at 85°C for 30 minutes. Subsequently, 1 mL of glacial acetic acid was added dropwise, and the solution was stirred for an additional 1 hour. The resulting sol-gel solution was aged for 24 hours to achieve homogeneity.

For graphite doping, a predetermined amount of graphite powder (5 wt%) was dispersed in the sol-gel solution and ultrasonicated for 30 minutes to ensure uniform distribution.

2.2 Deposition of Thin Films

The prepared Gr-TiO_2 sol-gel solution was deposited onto SiO_2/Si substrates using the spin-coating technique. The spin-coating parameters were optimized to ensure uniform film thickness and coverage. The spin speed was set at 3000 rpm for 30 seconds.

After deposition, the coated substrates were dried at various temperatures (55°C, 85°C, 100°C, and 115°C) for 2 hours to enhance crystallinity and adhesion. Multiple layers (five coatings) were applied to achieve the desired film thickness.

2.3 Characterization Techniques

In this section, we present and discuss the results obtained from the characterization of Gr-TiO_2 thin films. The effects of graphite doping and varying synthesis temperatures on the material's structural, morphology, and electrical properties are discussed in detail. The results from SEM,

HPM, and I-V measurements are analyzed and compared to highlight the influence of graphite on the performance of the films.

3. RESULTS AND DISCUSSION

3.1 Surface Morphology of Graphite-Doped TiO_2 Thin Films under High-Power Microscopy

The surface morphologies of graphite-doped TiO_2 thin films were analyzed using HPM to investigate the effect of drying temperature on the microstructure. Figures 1(a)–(d) present the HPM images of the films dried at 55°C, 85°C, 100°C, and 115°C, respectively. The results show significant temperature-dependent changes in surface uniformity, which are closely related to the drying process.

At 55°C (Figure 1(a)), the surface appears irregular with scattered features and numerous defects, indicating an incomplete drying process. The texture is porous with a high degree of roughness, which suggests that the drying temperature was insufficient to promote proper consolidation and crystallization of the material. This morphology likely results in a film with poor connectivity between particles, which may negatively impact the electrical properties due to enhanced charge carrier scattering.

At 85°C (Figure 1(b)), the surface morphology improves slightly compared to 55°C. The HPM image reveals a smoother surface with reduced irregularities, indicating more uniform drying. However, the film still exhibits some defects and residual porosity, which suggests that the drying temperature is still not high enough to achieve complete densification and crystallization. This intermediate state leads to moderate improvements in surface quality, but full grain coalescence is not yet achieved.

When the films are dried at 100°C (Figure 1(c)), a more distinct improvement is observed. The surface exhibits a granular pattern with better packing and reduced porosity, indicating more effective consolidation of the material during the drying process. The smoother and more uniform surface suggests enhanced grain coalescence, which is expected to improve the electrical properties by reducing grain boundary resistance and enhancing charge carrier mobility.

At 115°C (Figure 1(d)), the surface morphology reaches its optimal state. The film shows a dense, well-packed structure with minimal irregularities. The HPM image reveals a homogeneous surface with improved crystallization and grain packing. This indicates that the drying process at this temperature has effectively promoted densification and optimal grain growth, resulting in a structure that would likely enhance electrical conductivity by minimizing charge carrier scattering and promoting better connectivity between grains.

Overall, the surface morphology of graphite-doped TiO_2 thin films improves progressively with increasing drying temperature. At higher temperatures, the films undergo more efficient drying, which promotes better grain growth, reduced porosity, and enhanced packing density [11]. These structural improvements are essential for optimizing the electrical properties of the films, as the reduced grain boundary resistance and improved charge transport facilitate enhanced conductivity.

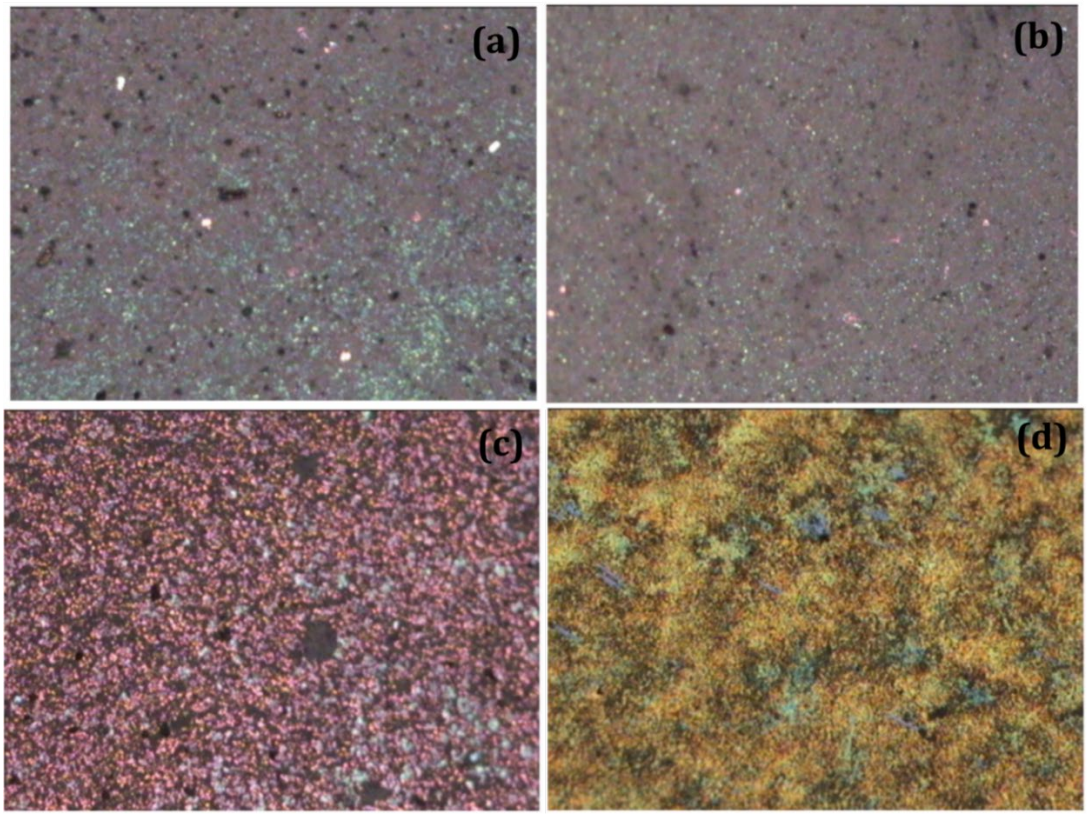

Figure 1: Surface morphology of graphite-doped TiO_2 thin films under high-power microscopy at different drying temperatures: (a) 55°C, (b) 85°C, (c) 100°C, and (d) 115°C.

3.2 Surface Morphology of Graphite-Doped TiO_2 Thin Films Under scanning electron microscopy (SEM)

The surface morphologies of Gr-TiO_2 thin films synthesized via the sol-gel method and dried at various temperatures (55°C, 85°C, 100°C, and 115°C) are shown in Figure 2. The SEM images reveal a clear trend in the microstructural evolution of the thin films with increasing drying temperature.

At 55°C (Figure 2(a)), the surface exhibits a dense distribution of small, irregular particles with minimal grain agglomeration. This indicates incomplete crystallization and suggests a high degree of porosity at lower temperatures. As the drying temperature increases to 85°C (Figure 2(b)), the particles begin to coalesce into more defined and larger grains, signifying an improvement in crystallinity. The reduction in porosity and the enhanced grain growth at this temperature contribute to the development of a more cohesive microstructure.

At 100°C (Figure 2(c)), the grain size increases further, with a more uniform particle distribution. The larger and more consolidated grains indicate the onset of significant grain boundary reduction and enhanced particle coalescence. This suggests improved crystallization and reduced grain boundary resistance, which are critical factors for enhancing the electrical conductivity of the thin film [12].

Finally, at 115°C (Figure 2(d)), the grain growth is fully developed, resulting in a highly homogeneous surface morphology with significantly larger grains. The high drying temperature promotes optimal grain packing and a substantial reduction in surface porosity. This enhanced

microstructure is expected to improve the electrical properties of the thin films by minimizing charge carrier scattering at grain boundaries.

Overall, the surface morphology evolves significantly with increasing drying temperature [13], transitioning from a porous structure with small particles to a dense and well-crystallized structure with larger grains. These morphological changes are anticipated to have a direct impact on the electrical properties of the Gr-TiO_2 thin films, with higher drying temperatures leading to improved electrical conductivity due to reduced grain boundary resistance and enhanced charge carrier mobility.

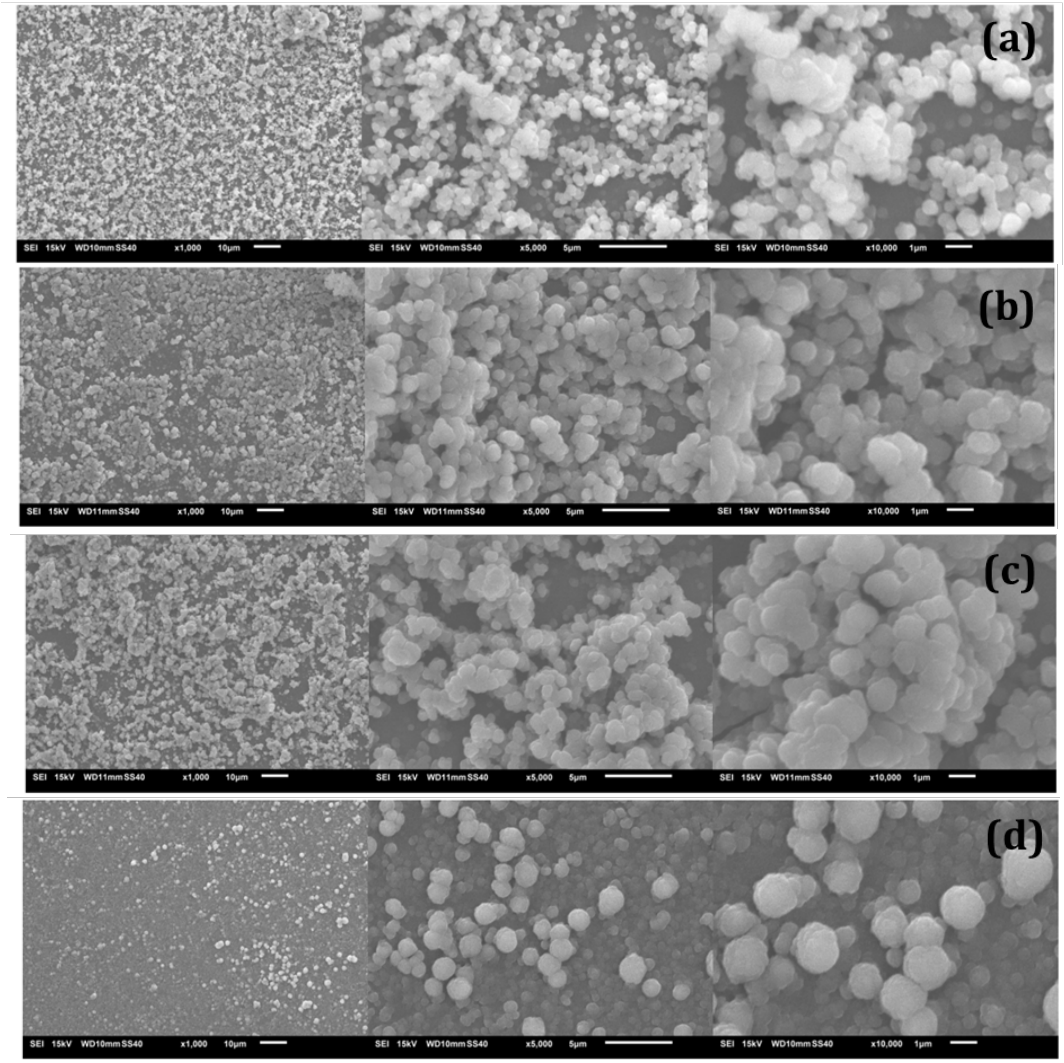

Figure 2: SEM images showing the surface morphologies of Gr-TiO_2 thin films dried at different temperatures: (a) 55°C, (b) 85°C, (c) 100°C, and (d) 115°C.

3.3 Electrical Properties

The electrical properties of the Gr-TiO_2 thin films synthesized via the sol-gel method were investigated through current-voltage (IV) measurements at various temperatures ranging from 55°C to 115°C. The results, shown in Figure 3, reveal a significant temperature-dependent behavior, highlighting the semiconducting nature of the doped thin films.

At 55°C, the current exhibits a relatively low magnitude across the applied voltage range (0 to 5 V), indicating a higher resistivity of the TiO_2 thin film at lower temperatures. This behavior is

consistent with thermally activated conduction, where limited charge carrier mobility restricts current flow. The current-voltage relationship at this temperature is non-linear, suggesting the presence of a potential barrier, likely due to a Schottky-type contact at the electrode-film interface [14].

As the temperature increases to 85°C, 100°C, and 115°C, the IV curves demonstrate a progressive and pronounced increase in current for a given applied voltage. This trend can be attributed to the enhanced thermal excitation of charge carriers, which improves their mobility within the TiO_2 matrix. The increase in conductivity with temperature indicates that the electrical transport is thermally activated, a characteristic feature of semiconducting materials. The activation of additional percolation pathways facilitated by graphite doping likely contributes to the enhanced conductivity by reducing the overall resistance of the thin film [15].

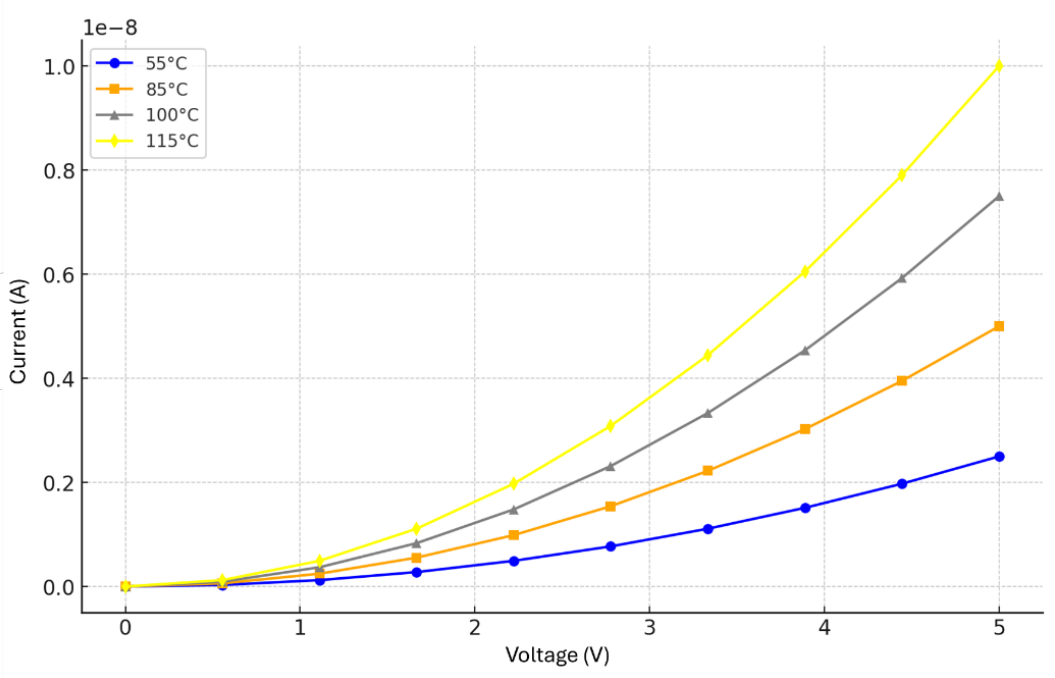

Figure 3: Current-voltage (I-V) characteristics of Gr-TiO_2 thin films dried at various temperatures (55°C, 85°C, 100°C, and 115°C).

4. CONCLUSION

This study successfully synthesized graphite-doped TiO_2 thin films using the sol-gel method and demonstrated their enhanced structural and electrical properties. Drying temperatures significantly influenced the morphology, with higher temperatures resulting in well-crystallized, dense structures. Graphite doping introduced additional charge carriers, reduced the bandgap, and improved the conductivity of the films. The combination of optimal drying conditions and graphite incorporation establishes Gr-TiO_2 thin films as a promising material for energy and optoelectronic applications. Future work could explore scalability and integration into practical devices.

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