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Influence of Oblique Angle Deposition on the Structural, Optical, and Photocatalytic Performance of TiO_2 Thin Films

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ABSTRACT

In the present study, TiO_2 thin films were deposited on glass substrates using thermal evaporation technique at oblique angles of 40˚, 60˚, 70˚, and 80˚ to study the influences of deposition angles on the structural, optical, and photocatalytic properties of the deposited films. FESEM and AFM studies showed increasing deposition angle results in a porous and rough surface morphology. This is attributed to shadowing effects and limited adatom diffusion. The optical transmittance and absorption spectra were recorded using a UV–Vis spectrophotometer, indicating that films deposited at higher oblique angles exhibited enhanced light transmission and modified absorption behavior. The photocatalytic activity of the TiO_2 thin films was evaluated through methylene orange degradation under UV irradiation. The degradation efficiency was followed in time steps of 30, 60, 90, and 120 min. The results showed that the sample deposited at 60˚ exhibits the maximum photocatalytic activity. This is regarded as an enhancement due to its optimized surface roughness and increased surface area, improving photon absorption and charge carrier separation.

1. Introduction

Titanium dioxide (TiO_2) is a commonly studied semiconductor oxide that naturally occurs in three crystalline forms: anatase, rutile, and brookite. Among these, the anatase phase has the highest photocatalytic efficiency because of its better charge carrier mobility and lower recombination rate of electron-hole pairs generated by light [1]. TiO_2 has excellent physical and chemical properties, such as high refractive index, strong stability against chemicals and mechanical stress, non-toxicity, and great optical transparency. Because of these qualities, it is used in various technologies, including wastewater treatment, photovoltaic devices [2], photoelectrochemical devices [3], photocatalytic coatings, and sensors. With a band gap energy of about 3.2 eV, TiO_2 shows strong photoactivity under ultraviolet light. Photons with energy equal to or greater than the band gap excite electrons from the valence band to the conduction band, creating electron-hole pairs that drive redox reactions on the surface. Many methods for synthesis and thin-film deposition have been used to create TiO_2 layers with specific properties [4]. These methods include sol-gel processing [5], hydrothermal growth [6], and electron beam evaporation [7]. However, the physical structure, porosity, and surface appearance of TiO_2 films can change significantly based on the deposition technique and conditions. This variation directly affects their optical and photocatalytic behavior. The overall photocatalytic efficiency of TiO_2 systems depends not only on their intrinsic band gap but also on the recombination rate of charge carriers, the density of active surface sites, and the specific surface area available for redox reactions [8, 9]. When exposed to light, the created electrons and holes move toward the surface,

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where they interact with adsorbed species like oxygen and water, leading to the formation of reactive oxygen species that break down organic contaminants [10]. Among the different film deposition techniques, Oblique angle deposition (OAD) has become an effective way to create nanostructured thin films with adjustable porosity and column-like shapes. This technique takes advantage of the geometric effect of vapor hitting the substrate at an angle. When combined with self-shadowing and limited movement of atoms on the surface, this results in the formation of low-density, anisotropic nanocolumns and helical structures [11]. The resulting nanostructured surfaces provide a larger surface area, more light scattering, and better access to reactive sites [12], all of which are beneficial for photocatalytic applications [13]. Thus, the OAD technique offers a strong method to optimize both the shape and functional performance of TiO_2 thin films without needing doping or complicated post-processing treatments. In 2022, Abhishek Kumar Pandey and colleagues deposited Titanium dioxide on ITO glasses utilizing the GLAD sputtering technique at deposition angles of 0, 17, 25, and 30 degrees [14]. At the deposition angles of 0, 17, and 25 degrees, the energy gap measured 3.52 electron volts, while at an angle of 30°, the energy gap of 3.68 electron volts was recorded.

In this study, Titanium dioxide thin films were created using the oblique angle thermal evaporation method. The effects of different deposition angles on their structural, optical, and photocatalytic properties were carefully examined. The optical properties were assessed through UV-Vis absorption and transmission spectroscopy, while surface morphology was analyzed using field-emission scanning electron microscopy (FESEM). Additionally, the photocatalytic activity of the films was tested by observing the breakdown of methylene orange ($C_{14}H_{14}N_3NaO_3S$) under ultraviolet light. This research aims to provide a better understanding of how oblique deposition geometry can be used to adjust the nanoscale structure and improve the performance of TiO_2 thin films for photocatalytic and optoelectronic uses.

2. Experimental Details

Titanium dioxide (TiO_2) thin films were deposited on glass substrates using a high-vacuum coating unit, the VACUUM COATING NIT MODEL 15F6 from HIND HIGH VAC, made in India, through the thermal evaporation technique. The depositions were performed at room temperature without external substrate heating. The deposition was carried out at angles of 40°, 60°, 70°, and 80° to see how the change in deposition angle can affect the films' properties. Before deposition, the glass substrates were cleaned to ensure good film adhesion and surface quality. They were first sonicated in a soap and water solution for 10 minutes, then rinsed with absolute ethanol and acetone, and finally dried in air. High-purity TiO_2 powder (99.99%) was placed in a molybdenum crucible connected to copper electrodes. When current passed through the crucible, the powder heated up and evaporated. During deposition, the chamber pressure was lowered to about 3×10^{-3} mbar using a rotary pump and then down to 3×10^{-5} mbar with a turbomolecular pump. The distance between the source and the substrate was kept at 20 cm, and the deposition rate was about 2.5 nm/s, which was monitored by a quartz crystal thickness gauge. The final film thickness was around 113 nm. After deposition, the optical properties of the TiO_2 films were measured using a UV–Vis spectrophotometer in the range of 200–1100 nm, focusing on both transmission and absorption. To test photocatalytic activity, methylene orange (MO) was used as the model dye pollutant We dissolved 0.0015 g/mol of methylene orange in 100 ml of deionized water (15 ppm). A 50 W xenon lamp emitting a broad continuous spectrum in the UV–visible region (approximately 300–800 nm) was employed as the light source for photocatalytic degradation experiments. The distance between the light source and the photocatalyst suspension was kept at 10 cm.

Before UV irradiation, the samples were placed in the MO solution and stirred in the dark for 30 minutes to reach adsorption and desorption equilibrium. Then, the films were exposed to UV light while the solution was continuously stirred for 120 minutes. The absorbance of the solution was recorded every 30 minutes using a UV–Vis spectrophotometer (Optizen POP, Korea). The surface shape of the TiO_2 thin films was examined using field-emission scanning electron microscopy (FESEM), while atomic force microscopy (AFM) was used to study the surface roughness and topography of the prepared specimens.

3. Results and Discussion

3.1. Morphological Properties

The morphology of the surface changes significantly with deposition angles, as recorded by fielde mission SEM images of the TiO_2 thin films deposited at 40˚, 60˚, 70˚, and 80˚, as shown in Figures 1 A-D. At a deposition angle of 40˚, the film has a relatively compact structure with less aggregation of grains and a rather smooth surface. When this angle is extended to 60˚, a higher and more uniform distribution of nanograins is created, with reduced spacing among particles. For a deposition angle of 70˚, the surface nanostructuring is more striking, with larger domains and island-like features, which are indicative of increased atomic shadowing and directional growth. Greater roughness and surface area were observed for this sample. In contrast, the film deposited at 80˚ exhibits more porous morphology with finer grains scattered over a few larger-sized agglomerates. The considerable shadowing effect at this deposition angle restricts lateral coalescence, therefore yielding a less compact morphology. A clear trend with respect to grain size, aggregation, and surface coverage is thus discerned from these observations for increasing deposition angle.

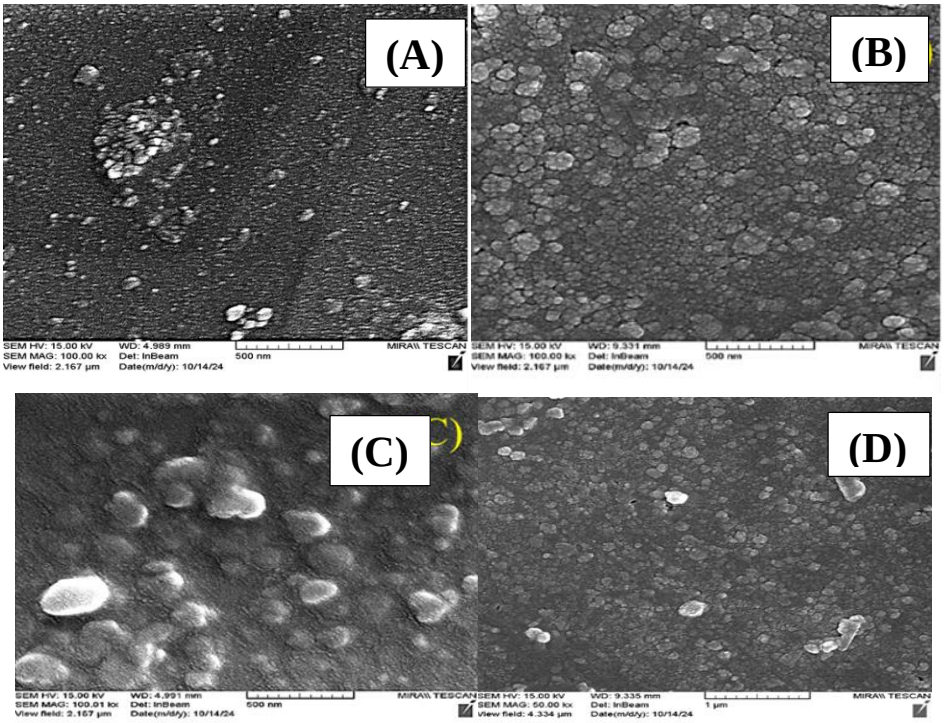

Fig. 1. FESEM images of TiO_2 films deposited at various angles: A) 40 °, B) 60 °, C) 70 °, and D) 80 °.

The AFM investigation indicates slight fluctuations in the surface roughness of the TiO_2 thin films based on the oblique deposition angle. The RMS roughness exhibits a small rise from 0.724 nm at 40° to 0.855 nm at 60°, indicating a gradual alteration of the surface morphology with the elevation of the deposition angle. At 70°, a slight reduction in roughness to 0.801 nm is noted, potentially linked to partial structural stability or localized surface reorganization. The film formed at 80° demonstrates the greatest RMS roughness (1.022 nm), signifying increased height variations and extended surface characteristics**.** Despite the absolute variations in RMS roughness being limited, the discerned trend aligns with the gradual evolution of surface texturing caused by shadowing effects at elevated oblique angles. It is important to acknowledge that AFM offers localized surface information, and the development of columnar structures is predominantly facilitated by supplementary morphological analysis.

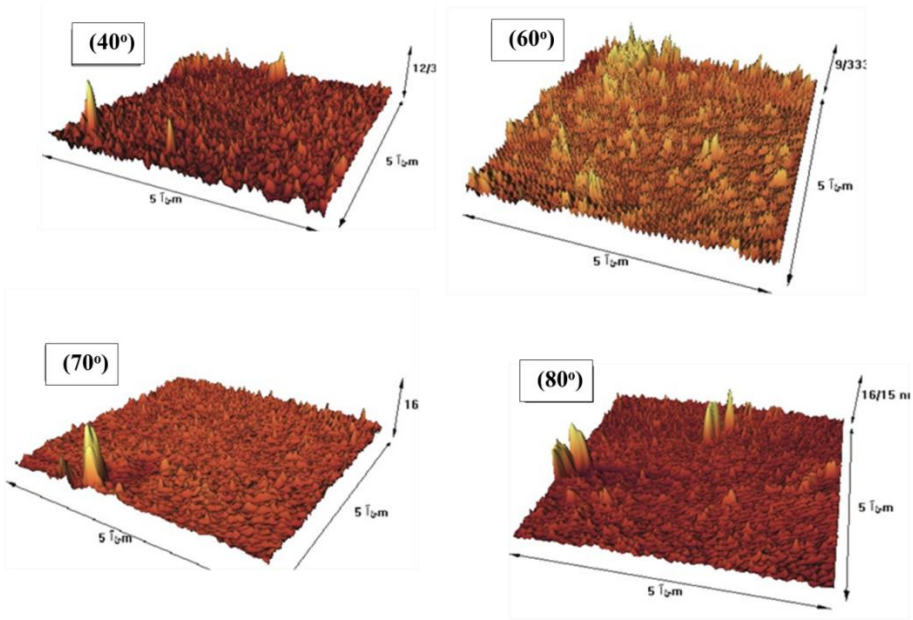

Fig. 2. AFM images of all specimens.

3.2. Optical Properties

The optical transmittance spectra of TiO_2 thin films deposited at angles of 40˚, 60˚, 70˚, and 80˚ show a significant increase in transmission within the UV-visible range. This is followed by a broad plateau that extends into the near-infrared region. For all samples, the transmittance quickly rises above 350-380 nm and levels off between 75-85% in the visible spectrum. The film deposited at 40° has the highest overall transmittance, indicating a denser and less light-scattering surface. The 60° film has slightly less transparency but maintains a smooth spectral profile. As the deposition angle goes up to 70˚ and 80˚, a gradual decrease in transmittance is observed. This is likely due to increased surface roughness and more light being trapped because of shadowing effects.

These results show that the angle of oblique deposition significantly influences the optical properties of TiO_2 films by affecting their density, morphology, and scattering characteristics. The strong transmittance across all samples, over 70%, also suggests good optical quality, making them suitable for photocatalytic and optoelectronic applications [12]. Figure 3 demonstrates the transmission spectra of TiO_2 films deposited at various angles.

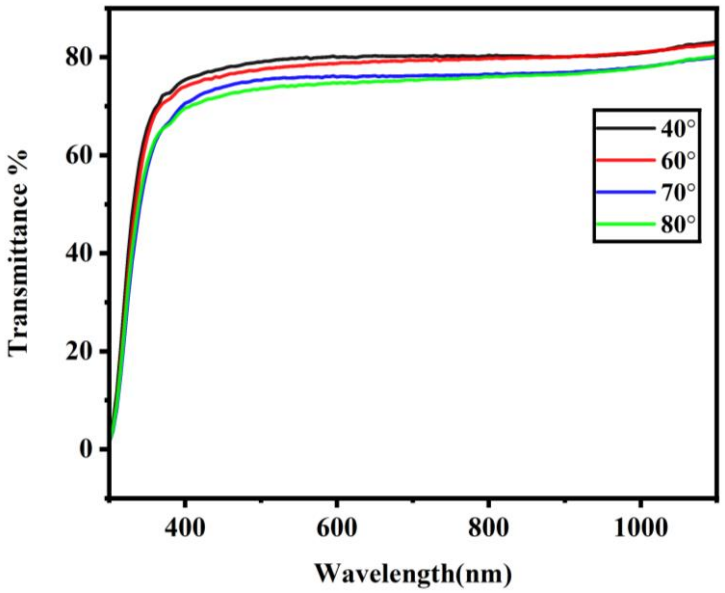

Fig. 3. Transmission spectra of TiO_2 films deposited at various angles.

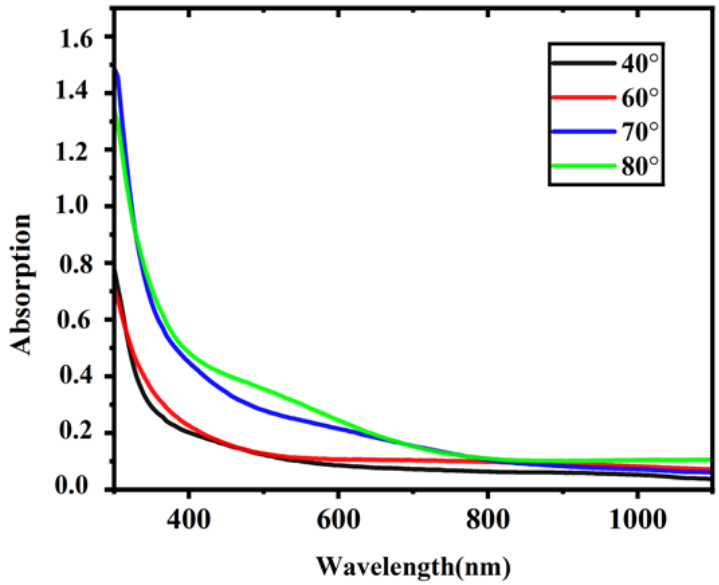

Fig. 4. Absorption of TiO_2 films deposited at various angles.

The Titanium dioxide thin film absorption spectra show consistent patterns of increased absorption as the wavelength decreases (for all deposition angles tested) and decreased levels of absorption for wavelengths greater than 400nm. Overall, the Titanium dioxide thin film samples deposited at the steepest angles (that is, 70 and 80 degrees) exhibit the highest levels of light-harvesting and absorption properties in the UV region (i.e., <~400 nm). Higher than average UV absorption levels are likely due to the enhanced surface area and scattering effects associated with higher deposition angles as opposed to those of lower deposition angles (i.e., 40 and 60 degrees). Furthermore, the lack of significant transitions in the visible and near infrared (greater than 600 nm) ranges is consistent with the inherent wide bandgap property of TiO_2. Therefore, we can conclude that the angle of deposition for Titanium dioxide thin films is an important variable for regulating the optical properties of the resulting films; specifically, the use of steeper angles to deposit Titanium dioxide thin films leads to greater overall UV absorption characteristics than those of Titanium dioxide thin films deposited at less steep angles. Figure 4 shows the absorption of TiO_2 films deposited at various angles.

The assessment of the energy gap in the samples is conducted using the Tauc method, which is predicated on the absorption coefficient of incoming photons [15], as expressed in the following equation.

$$\alpha h\nu = A(h\nu - E_g)^n \quad (1)$$

Where hν is the energy of the incident photon, E_g is the sample energy gap, and α is a constant which is independent of the photon energy. The factor n depends on the nature of the semiconductor band gap; for direct band gap semiconductors, it is 1/2. Figure 5 shows the band gap energy of the TiO_2 thin films prepared at different deposition angles.

From the Tauc plots derived from UV–Vis absorption spectra, the Eg values of the TiO_2 thin films deposited at various oblique angles were estimated. The corresponding band gaps for the films deposited at 40˚, 60˚, 70˚, and 80˚ were determined to be 2.76 eV, 2.80 eV, 2.83 eV, and 2.90 eV, respectively. These values are listed in Table 1 along with values from previous reports. One can notice that among all the films deposited at different angles, the film deposited at 80° shows the widest band gap. Oblique Angle Deposition (OAD) facilitates the development of columnar and porous TiO_2 nanostructures, attributed to significant shadowing effects and restricted surface diffusion of adatoms. The growth modes enhance the density of structural defects and undercoordinated atoms, resulting in the formation of localized trap states within the band gap. The existence of mid-gap states facilitates extra sub-bandgap optical transitions, leading to a red shift in the absorption edge and a decrease in the effective optical band gap, as typically seen in glancing angle deposited oxide films. Recent studies indicate that the morphology and defect states resulting from oblique angle growth significantly affect the optical absorption characteristics in TiO_2 and similar materials [14]. At low to moderate deposition angles, defect states and partially ordered domains indicate a restricted level of crystallinity, along with structural imperfections and oxygen vacancies that modify the density of states near the band edges. With an increase in the deposition angle to 60˚ and 70˚, a gradual narrowing of the band gap is noted. This trend aligns with enhanced crystallinity and improved long-range structural order, which facilitate stronger orbital overlap and increased electronic delocalization, as evidenced by defect-mediated localized optical transitions in TiO_2 [16]. The observed red shift of the absorption edge indicates improved charge transport and increased light absorption in the UV–visible spectrum. Further increasing the deposition angle to 80° may result in stabilization or a slight increase in the optical band gap. At elevated angles, shadowing effects prevail, leading to the formation of highly porous and loosely packed columnar structures. The diminished film density and impaired intergrain coupling may restrict charge delocalization, resulting in elevated energy optical transitions. Furthermore, increased surface roughness and porosity can lead to light scattering effects that modify the apparent band gap energy, in agreement with findings in complex oblique angle systems [17]. The variation in the optical band gap with deposition angle indicates a balance among factors such as crystallinity, defect density, film density, and grain connectivity. Moderate oblique angles (approximately 60°–70°) produce a structurally balanced film, which integrates sufficient porosity for improved light absorption and adequate structural order for effective charge transport. This combination accounts for the reduced effective band gap and the improved photocatalytic performance noted for films deposited at these angles, consistent with recent studies that associate morphology-driven defect engineering with functional enhancements in OAD/GLAD thin films [18]. The optical band gap values obtained for obliquely deposited TiO_2 thin films are noticeably lower than those typically reported for bulk or normally deposited undoped TiO_2. It is important to note that these values represent optical band gaps derived from UV–Vis absorption measurements rather than intrinsic electronic band gaps of crystalline TiO_2. During oblique angle deposition, the growth proceeds under non-equilibrium conditions accompanied by pronounced shadowing effects, leading to porous and tilted columnar microstructures with a high degree of structural disorder. Such disorder promotes the formation of defect-related localized electronic states, particularly oxygen-vacancy–associated states, which introduce sub-bandgap absorption and broaden the Urbach tail. As a result, the optical absorption edge gradually shifts toward lower photon energies, yielding reduced optical band gap values when analyzed using the Tauc method. Therefore, the

observed reduction in optical band gap is attributed primarily to disorder- and defect induced optical effects rather than to changes in crystalline phase or chemical composition. Similar behavior has been reported for TiO_2 thin films prepared by oblique or glancing angle deposition, where enhanced porosity and defect density strongly influence the optical response.

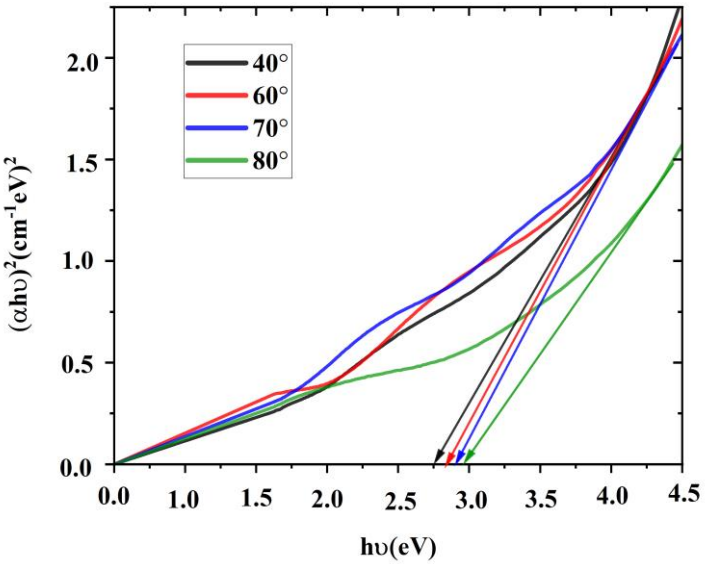

Fig. 5. Energy gap of thin TiO_2 films with deposition angles of 40°, 60°, 70°, and 80°.

Table 1. Comparison of the calculated band gap values with the reported values.

sample	Band GAP (eV)	References
TiO_2 Thin film	3.37-3.50	[18]
TiO_2 GLAD	3.52-3.68	[14]
TiO_2 OLAD	2.76-2.90	This Work

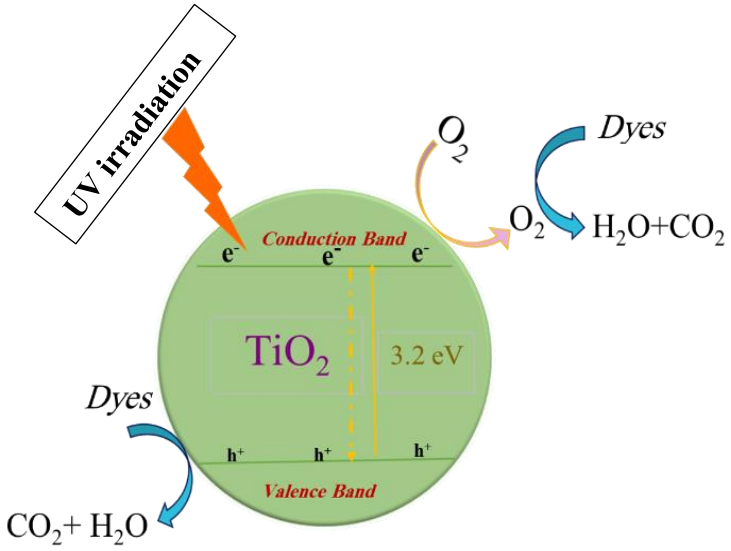

Fig. 6. The diagrammatic illustration of the photocatalytic process involving Titanium dioxide.

3.3. Photocatalytic Activity

Fig. 6 illustrates the basic mechanism of photocatalysis in TiO_2. When the film is exposed to UV light with photon energy equal to or greater than its band gap, electrons move from the valence band to the conduction band. This process leaves behind positively charged holes. The charge carriers then travel to the film's surface, where they take part in redox reactions that create reactive species like hydroxyl radicals (•OH) and superoxide ions (O_2^-•). These species break down organic dye molecules into smaller, harmless compounds like CO_2 and H_2O. For clarity, T0 is the initial concentration of MO measured at zero time before UV irradiation and without the TiO_2 thin film (blank condition). Figure 7 (A to D) displays the UV–Vis absorption spectra of the MO solution during different UV exposure times (0, 30, 60, 90, and 120 min.) in the presence of TiO_2 thin films deposited at 40˚, 60˚, 70˚, and 80˚. In every case, the intensity of the main absorption peak for MO gradually decreases over time, confirming that the TiO_2 thin films effectively catalyze the photodegradation process. However, the rates of degradation vary considerably depending on the deposition angle, highlighting the important role of film structure and morphology in photocatalytic efficiency. Figure 8A shows the relative concentration of MO (C/C_0) over irradiation time. The data reveal a steady decline in C/C_0 for all samples. The film deposited at 60˚ exhibits the fastest degradation rate, followed closely by the one deposited at 70˚. In contrast, the films deposited at 40˚ and 80˚ show slower degradation rates. The photocatalytic reactions were evaluated using a pseudo-first-order kinetic model given by:

$$kt = -\ln(C/C_0) \quad (2)$$

Here, k represents the apparent rate constant. The linear plots of $-\ln(C/C_0)$ versus irradiation time in Figure 8B indicate that all samples follow first-order kinetics, which is typical for heterogeneous photocatalytic systems. The highest k value for the 60° film suggests that this deposition angle creates the best surface features for efficient charge separation and dye adsorption. The improved photocatalytic activity at intermediate deposition angles, particularly at 60°, stems from a combination of structural and optical factors. FESEM and AFM analyses show that the films deposited at 60˚ has a well-developed nanostructured surface with moderate roughness and even grain distribution. This morphology provides a larger active surface area, facilitating better photon penetration and dye molecule adsorption. Additionally, optical analysis indicates that the band gap slightly decreases with increasing deposition angle up to 70˚, enhancing photon absorption in the UV range and promoting the generation of electron-hole pairs. Interestingly, although the 70˚ film has a slightly smaller band gap and higher surface roughness, its photocatalytic activity is marginally less than that of the 60˚ sample. This can be attributed to excessive porosity and a higher chance of charge carrier recombination at steeper angles, where columnar structures become more dispersed due to significant self-shadowing effects. On the other hand, the 40° film is relatively dense and smooth, leading to a smaller surface area and fewer active sites, while the 80˚ sample suffers from discontinuities and uneven coverage, which hinder effective charge transport. Overall, the findings reveal that photocatalytic activity in TiO_2 thin films is influenced by a delicate balance of surface morphology, optical absorption, and charge-carrier dynamics rather than by a single structural factor. The 60˚ deposition angle strikes an optimal balance among these elements, resulting in efficient generation and use of reactive species. Thus, adjusting the oblique deposition angle proves to be a straightforward yet effective method to improve the photocatalytic performance.

A noticeable contradiction arises when comparing the optical absorption behavior and the photocatalytic performance of the TiO_2 thin films deposited at different oblique angles. According to the optical absorption results, the films deposited at higher oblique angles (70˚ and 80˚) exhibit enhanced UV light absorption, which is attributed to their increased surface porosity, higher surface area, and stronger light scattering effects. Such characteristics are generally expected to promote photocatalytic efficiency due to improved photon harvesting. However, the photocatalytic degradation experiments reveal that the maximum photocatalytic activity is achieved by the film deposited at an intermediate angle of 60°, rather than by the films deposited at steeper angles. This observation indicates that higher UV absorption does not necessarily translate into superior photocatalytic performance. This discrepancy suggests that, although films deposited at larger oblique angles possess enhanced optical absorption, excessive porosity and structural discontinuity at very high angles may adversely affect charge carrier transport and increase electron–hole recombination rates. In contrast, the TiO_2 thin film deposited at 60° likely exhibits an optimal balance between surface roughness, effective surface area, structural connectivity, and charge carrier separation efficiency, leading to superior photocatalytic activity despite its comparatively lower UV absorption. Therefore, these findings demonstrate that optical absorption alone is not a sufficient parameter for predicting photocatalytic performance, and that the deposition angle plays a critical role in determining the interplay between morphological, optical, and electronic properties of TiO_2 thin films.

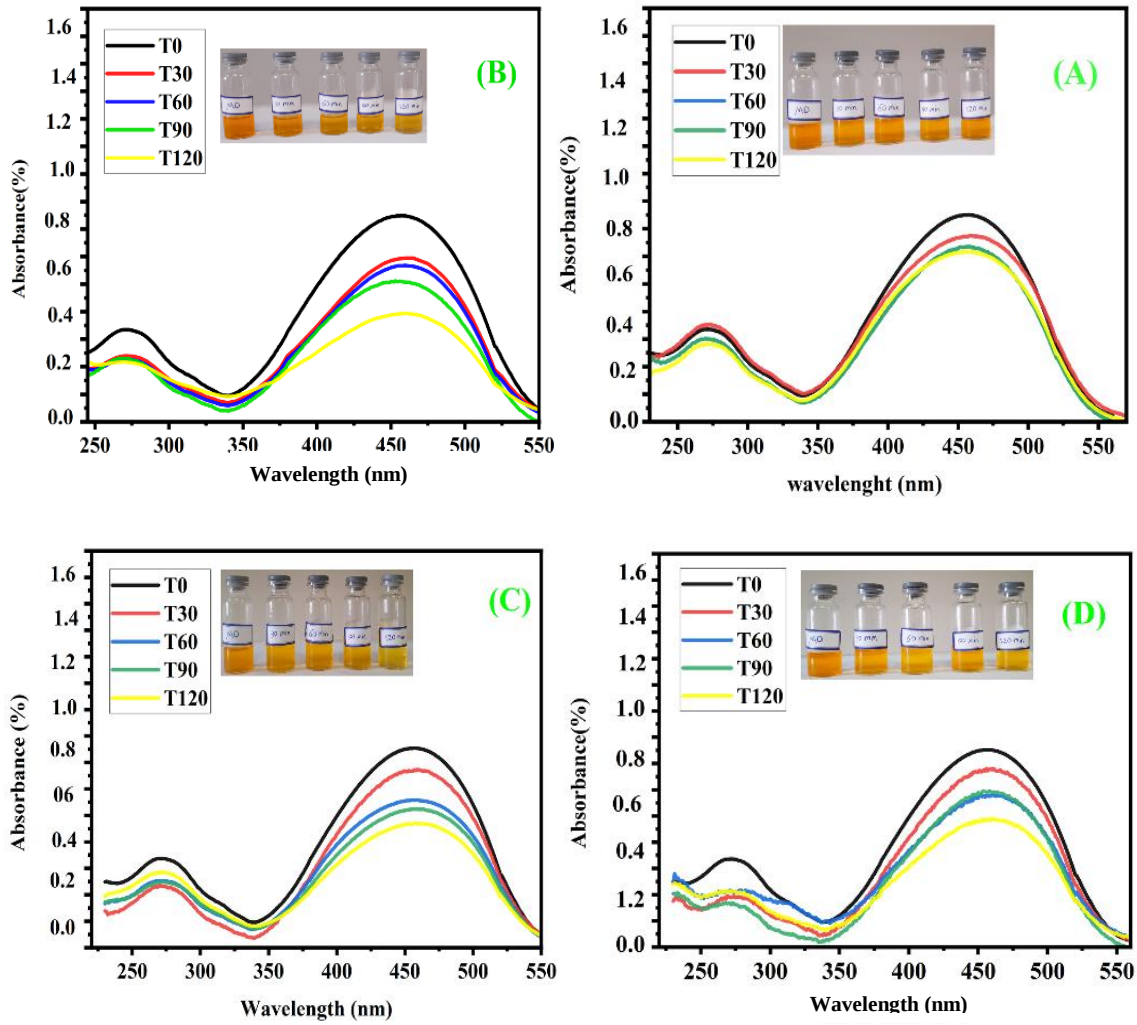

Fig. 7. The UV-Vis absorption spectrum illustrating the photodegradation of methylene orange during different UV exposure times (0, 30, 60, 90, and 120 min.) using TiO_2 thin films deposited at various angles: A) 40˚, B) 60˚, C) 70˚, and D) 80˚.

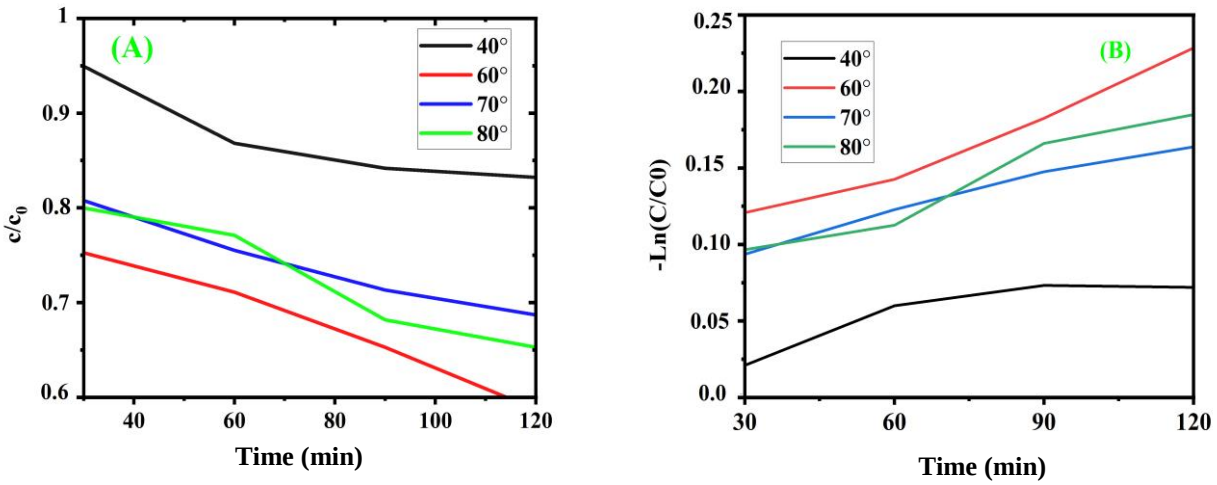

Fig. 8. (A) The degradation of methylene orange of all samples when exposed to UV light at different exposure times (0, 30, 60, 90, and 120 min.). (B) Plot of -Ln(C / C_0) against irradiation time.

4. Conclusions

This study shows that the angle at which TiO_2 thin films are deposited, using oblique angle deposition technique, has a significant effect on their structure, how they look, and how well they work as photocatalysts. When one changes the angle at which the film is deposited, shadowing changes its shape and degree of porosity. This changes how well the film works as a photocatalyst and how well it absorbs light. The results demonstrated that the films deposited at 60° showed superior performance compared to the other samples. The porous structure was better because it let photons in more easily, made more active sites, and helped separate charges. On the other hand, low deposition angles made thick films that didn't let light through very well. In contrast, excessively high deposition angles led to reduced charge transport due to the deterioration of the film microstructure. These results show that changing the angle of deposition, especially between 60˚ and 70˚, is a simple and effective way to make TiO_2 thin films more photoactive without having to add anything to them or make changes after they are deposited.

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Conflicts of 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.

Authors Contribution Statement

All authors contributed equally to this work.

References

[1]Tulli, F., Morales, J.M., Salas, E.E., Moran Vieyra, F.E. and Borsarelli, C.D., 2021. Photocatalytic efficiency tuning by the surface roughness of TiO_2 coatings on glass prepared by the doctor blade method. *Journal of Photochemistry and Photobiology*, 97, pp.22-31.

[2]Kirk, C.H., Wang, P., Chong, C.Y.D., Zhao, Q., Sun, J. and Wang, J., 2024. TiO_2 photocatalytic ceramic membranes for water and wastewater treatment: Technical readiness and pathway ahead. *Journal of Materials Science*, 183, pp.152-164.

[3]Salmaniannezhad, H., Salmaniannezhad, H., Zarei Moghadam, R., Khani, M., Ardani, M. and Shokri, B., 2023. Design and fabrication of multi-layers antireflection coating consisting of MgF_2 and SiO_2. *Progress in Physics and Applied Materials*, 3, pp.141-146.

[4]Yousefzadeh, S., Rostam Jadidoleslam, N. and Moharrami, K., 2026. Hydrothermally Synthesized TiO_2 Nanostructures on Ti foil for Visible Light Assisted Photocatalytic Degradation of Tetracycline. *Progress in Physics and Applied Materials*, 6, pp.15-25.

[5]O'Byrne, M., Kerzabi, B., Abbarchi, M., Lifschitz, A., Zamora, T., Malgras, V., Gourdin, A., Modaresialam, M., Grosso, D. and Putero, M., 2024. Investigation of the anatase-to-rutile transition for TiO_2 sol-gel coatings with refractive index up to 2.7. *Thin Solid Films*, 790, p.140193.

[6]Adedokun, O., Obaseki, O.S., Yam, F.K., Ooi, M.D.J., Adedokun, O.M. and Jubu, P.R., 2024. Influence of growth temperature on structural, optical, morphological and photoelectrochemical characteristics of vertically aligned hydrothermally synthesized TiO_2 nanorods. *Physica B: Condensed Matter*, 688, p.416155.

[7]Lee, S.H., Na, K.H., Kim, J.Y., Yoon, H.S., Han, H. and Choi, W.Y., 2024. Fabrication and characterization of electrospun Cu-doped TiO_2 nanofibers and enhancement of photocatalytic performance depending on Cu content and electron beam irradiation. *Polymers*, 16, p.694.

[8]Wang, Y.H., Rahman, K.H., Wu, C.C. and Chen, K.C., 2020. A review on the pathways of the improved structural characteristics and photocatalytic performance of titanium dioxide (TiO_2) thin films fabricated by the magnetron-sputtering technique. *Catalysts*, 10, p.598.

[9]Lan, N.T.K., Duoc, N.T., Duy, N.N., Van Chung, C., Du, B.D. and Hien, N.Q., 2020. Synthesis of Ag nano/TiO_2 by electron beam irradiation for photo-degradation of rhodamine B compound in water. *Vietnam Journal of Chemistry*, 58, pp.398-403.

[10]Villamayor, A., Pomone, T., Perero, S., Ferraris, M., Barrio, V.L., G-Berasategui, E. and Kelly, P., 2023. Development of photocatalytic nanostructured TiO_2 and NiO/TiO_2 coatings by DC magnetron sputtering for photocatalytic applications. *Ceramics International*, 49, pp.19309-19317.

[11]Hawkeye, M.M., Taschuk, M.T. and Brett, M.J., 2014. Introduction: Glancing angle deposition technology. In: *Glancing Angle Deposition of Thin Films*.

[12]Quang, D.D., Nguyen, T.N., Nguyen, D.T., Hai, T.N.D., Vu, T.H., Le, T.T., Vu, T.M. and Le, V.V., 2025. Fabrication and characterization of pulsed electron beam deposited TiO_2 thin films with glancing angle deposition techniques for biosensing application. *Vietnam Journal of Science and Technology*, 63, pp.285-296.

[13]Yasuda, Y., Kitahara, N. and Hoshi, Y., 2013. Glancing Angle Sputter Deposition of Titanium Dioxide Films for Photocatalytic Applications. *ECS Transactions*, 50, pp.25-35.

[14]Pandey, A.K., Tiwari, A.K. and Paliwal, H., 2022. Enhancement of mechanical, thermal and optical properties of TiO_2 thin films using glancing angle deposition technique. *Optical Materials*, 134, p.113054.

[15]Bensouici, F., Bououdina, M., Dakhel, A.A., Tala-Ighil, R., Tounane, M., Iratni, A., Souier, T., Liu, S. and Cai, W., 2017. Optical, structural and photocatalysis properties of Cu-doped TiO_2 thin films. *Applied Surface Science*, 395, pp.110-116.

[16]Zarei Moghadam, R., Omrany, A.H., Taherkhani, M. and Shokrian, F., 2021. Fabrication of multi-layer antireflection coating consisting of ZnS and MgF_2. *Progress in Physics and Applied Materials*, 1, pp.7-13.

[17]Naas, L.A., Bouaouina, B., Bensouici, F., Mokeddem, K. and Abaidia, S.E., 2024. Effect of TiN thin films deposited by oblique angle sputter deposition on sol-gel coated TiO_2 layers for photocatalytic applications. *Thin Solid Films*, 793, p.140275.

[18]Kang, M., Kim, S.W. and Park, H.Y., 2018. Optical properties of TiO_2 thin films with crystal structure. *Journal of Physics and Chemistry of Solids*, 123, pp.266-270.