

# Substrate Dependency of Nucleation Mechanism in the formation of TiO<sub>2</sub> Thin Films by Sol-gel Spin-Coating Method

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## Abstract:

Titanium dioxide (TiO<sub>2</sub>) thin films were deposited on glass (Corning 7059) and p-type silicon substrates using the sol-gel spin coating technique. The sol-gel solution was prepared by mixing hydrochloric acid (HCl) and deionized water (DIW) in a 1:1 ratio, along with titanium isopropoxide (TIP) and absolute ethyl alcohol (AEA) in a 1:7 ratio. The films were deposited at a fixed spin speed of 1000 rpm with varying deposition times (5, 10, 15, 20, 25 and 30 sec). The deposited films were characterized using Raman spectroscopy, X-ray diffraction (XRD) and ellipsometry, while microscopic imaging was used to analyze surface morphology. Raman spectra confirmed the crystalline nature of the TiO<sub>2</sub> films, with the rutile phase exhibiting a peak at approximately 819 nm. XRD results indicated that the maximum [ $\delta$ ] was estimated to be 10.5 nm on glass and 15.13 nm on silicon, as observed. The refractive index (n) of TiO<sub>2</sub> films on silicon was consistently higher than that on glass across different deposition times. Additionally, the dielectric constant (k) of TiO<sub>2</sub> films on glass indicated better insulating properties compared to those on silicon. Thickness measurements revealed that TiO<sub>2</sub> films on silicon were smoother than those on glass across varying deposition times. Roughness analysis showed that the surface roughness (Ra) of TiO<sub>2</sub> films on glass decreased with increasing deposition time, whereas the roughness of TiO<sub>2</sub> films on silicon fluctuated.

**Keywords — sol-gel; titanium dioxide, thin film and material structure.**

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## I. INTRODUCTION

Titanium dioxide (TiO<sub>2</sub>) thin films are promising nanomaterials for solar power applications due to their unique properties, including low cost, non-toxicity, good stability, and excellent optical and electrical characteristics [1]. TiO<sub>2</sub> is particularly suitable for thin-film applications, where its properties contribute to enhancing the quality of materials used in solar energy panels. The optical properties of TiO<sub>2</sub> will be examined to assess whether these thin films are a suitable choice for

solar applications. TiO<sub>2</sub> is one of the most attractive materials in nanotechnology because of its many intriguing properties. TiO<sub>2</sub> thin films have gained significant interest in various applications, including optical devices, sensors, refractory coatings, wear and corrosion-resistant coatings, and solar cells. TiO<sub>2</sub> is a promising oxide material with excellent electrical and optical properties, as well as a high transmittance of visible light, which is vital for solar energy applications [2-4]. Several factors influence the performance of TiO<sub>2</sub> in these applications, such as particle size, crystallinity,

electrical properties, optical behavior, and morphology [5-7]. Various methods are available for producing TiO<sub>2</sub> thin films, including the sol-gel technique [8], hydrothermal method [9], chemical vapor deposition [10-11], and direct oxidation [12-13]. Among these, the sol-gel spin coating technique is particularly versatile due to its ability to produce unique metastable structures at low reaction temperatures and its excellent chemical homogeneity. The sol-gel process involves the use of titanium tetraisopropoxide, which undergoes high hydrolysis and polycondensation rates, forming condensed particles when combined with water. Modifying the alkoxides with different chemical agents is crucial in the sol-gel process, as it allows the creation of new molecular precursors, resulting in films with varied properties. The sol-gel technique has become a promising method for producing nano-sized TiO<sub>2</sub> thin films because of its simplicity, cost-effectiveness, and potential for large-scale production. Low processing temperatures are desirable for many technological applications because they prevent damage to substrates and minimize harmful interactions between the film and substrate. However, sol-gel processing typically requires temperatures exceeding 400°C for crystallization and the removal of organics. The strong reactivity of alkoxides with water can lead to uncontrolled precipitation, limiting the use of the sol-gel technique. This issue can be mitigated by using chelating agents, such as acetic acid, to control the reactivity. Both amorphous and polycrystalline forms of TiO<sub>2</sub> can be easily produced using the sol-gel method. Many studies have shown that process parameters such as withdrawal rate, sol concentration, and the number of coating layers significantly influence the structural, optical, and electrical properties of TiO<sub>2</sub> thin films. To optimize the properties of TiO<sub>2</sub> films, improving their crystallinity is essential. However, as-deposited TiO<sub>2</sub> films are often amorphous when substrates are not heated during the spin coating process, which is commonly done in industrial settings. Thus, annealing is necessary after deposition to improve crystallinity and achieve optimal properties for applications like photocatalysis, dye-sensitized solar cells, and

photo-induced hydrophilicity. Heat treatment during annealing can affect the film's structure, altering its properties and chemical composition. Thin film coatings are also used to enhance the energy efficiency and color of glass and as reflective mirror coatings. As single-layer thin films become more commonly used in various devices, there is increasing demand for multilayer films that combine the properties of different materials. Multilayer films offer excellent optical and electrical properties, such as high refractive index, large band gap, and high transmittance in the visible region, making them ideal for use in applications like computer disks, optical filters, and solar cells.

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In this study, TiO<sub>2</sub> thin films were prepared on glass and silicon substrates using the sol-gel spin coating method, with the spin coating time as a variable. The films were then annealed at 400°C for 1 hour to optimize their crystallinity. Properties of these films were studied by Raman Scattering, X-ray diffraction (XRD), Ellipsometry and surface roughness measurements.

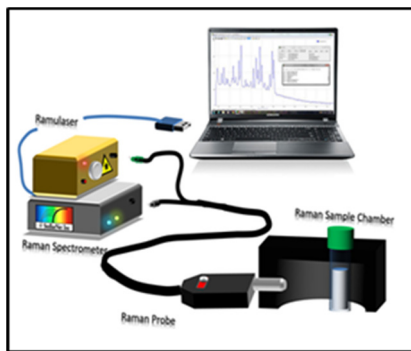
## II. MATERIALS AND METHODS

The deposition of TiO<sub>2</sub> thin film using the sol-gel method follows a series of sequential steps, as detailed below: Step 1: Preparation of Acid-Water Solution: Prepare an acid-water solution by mixing 1 ml of Hydrochloric Acid (HCl) and 1 ml of Deionized Water (DIW) in a 1:1 ratio (e.g., 0.5 ml HCl + 0.5 ml DI water). Add HCl gradually to DI water while stirring to prevent excessive heat generation. Step 2: Preparation of Solvent Solution: Mix Titanium Isopropoxide (TIP) and Absolute Ethyl Alcohol (AEA) in a 1:7 ratio (TIP:AEA). Stir the mixture for a few minutes at room temperature until a homogeneous solution is achieved. Step 3: Mixing Acid-Water Solution with Solvent Solution: Slowly add the pre-prepared acid-water solution to the TIP-AEA solvent solution while stirring continuously. Use a magnetic stirrer to vigorously stir the mixture for 2 hours at room temperature, ensuring the formation of a stable TiO<sub>2</sub> sol-gel. Step 4: Substrate Preparation and Cleaning: Cut silicon and glass substrates into 5 × 8 mm dimensions using a diamond cutter. Clean the substrates by sequentially immersing them in acetone, ethanol, and DI water for 15 minutes each in an ultrasonic cleaner. After cleaning, dry the substrates using nitrogen gas or allow them to air dry. Step 5: Thin Film Deposition: Apply 0.1 ml of the prepared TiO<sub>2</sub> sol-gel onto the cleaned substrates using a liquid dispenser (Fig.1). Use a spin coater to deposit the thin film at a fixed speed of 1000 RPM for varying deposition times (5, 10, 15, 20, 25, and 30 seconds).

Step 6: Annealing: After spin coating, anneal the thin films on a hot plate at 400°C for 2 hours to enhance crystallinity. The annealing process should be conducted in air to optimize the crystalline phase formation [14].



(a)



(b)



(c)

Fig.1 (a) Spin coater with back pressure liquid dispenser, (b) Quasar-TEC-X2-785nm Raman spectrometer and (c) FS-RT300 Automated-Mapping multi-wavelength ellipsometer system used in this experiment.

Table I Sol-gel Parameters

Parameters	Ratio	Quantity
HCl:DI H <sub>2</sub> O	one:one	2mL
TIP:AEA	one:seven	8mL
Sol-gel stirring	70°C	1hr
Substrates	Nil	Si & Glass
Substrates cleaning	15 min	Acetone, Ethanol & DI water

Table II Deposition Parameters

Parameters	Ratio	Quantity
Spincoater rpm	Nil	1000
Spun-Sol-Gel	Nil	0.1mL
Annealing Tem.	Nil	400°C
Growth time (sec)	Nil	5,10,15,20,25&30

### III. RESULTS AND DISCUSSION

Fig. 2 shows the Raman spectra of TiO<sub>2</sub> thin films deposited at different deposition times were analyzed using a portable Quasar-TEC-X2-785nm Raman spectrometer. Raman spectroscopy utilizes laser light to probe molecular vibrations within a compound's bonds. It reveals a peak at ≈819 nm, indicating the presence of rutile structural phase on both, glass and silicon substrates. The as-deposited TiO<sub>2</sub> films exhibit a broad rutile Raman peak at 819 nm on glass substrates and a sharp rutile peak at 819 nm on silicon substrates observed.

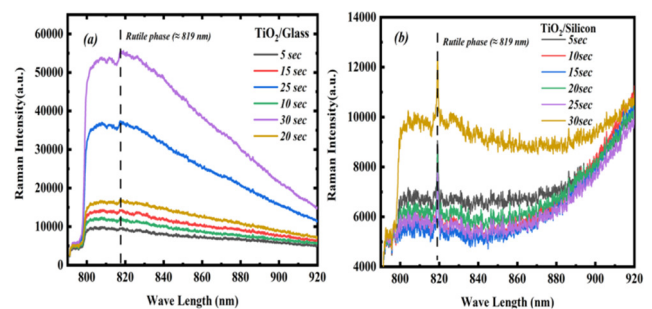


Fig. 2 Raman spectra of TiO<sub>2</sub> thin film as a function of deposition time on glass and silicon substrates, respectively.

Fig.3 the fitted peak intensities of the Raman spectra are shown as a function of deposition time.



Peak intensity represents the transition probability of TiO<sub>2</sub> thin films. Films deposited on silicon exhibit relatively stable properties across different spin deposition times, whereas those on glass show significant variations. For films deposited on glass substrates, the Raman intensity steadily decreases with increasing deposition time. On silicon substrates, the Raman intensity peaks at approximately 819 nm slightly increases with increasing deposition time observed. The rutile structural phase is identified on both substrates by referencing the dotted lines in Fig. 2.

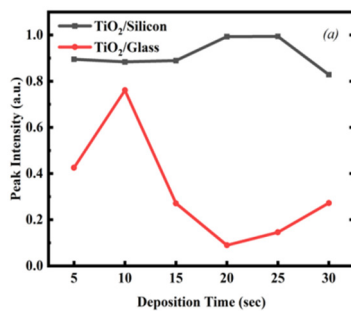


Fig. 3 Fitted peak intensities of Raman spectra of TiO<sub>2</sub> thin film with various deposition times on glass and silicon substrates.

Fig. 4 shows the peak position of TiO<sub>2</sub> thin films on glass and silicon substrates as a function of different deposition time. TiO<sub>2</sub> thin films on silicon exhibit relatively consistent peak positions, whereas those on glass show significant variations with changing spin deposition time. The peak position of TiO<sub>2</sub> in Raman spectra provides critical insights into its structural properties, phase composition, and interaction with the substrate. The impact of the peak position on silicon and glass substrates can be analyzed as follows: TiO<sub>2</sub> primarily exists in anatase, rutile, and brookite phases, with rutile being the most thermodynamically stable at high temperatures. The Raman peak at 819 nm corresponds to the rutile phase, indicating that the deposited TiO<sub>2</sub> films on both glass and silicon substrates predominantly exhibit this crystalline structure. The peak position and shape of the Raman spectra can be affected by substrate-induced

strain, crystallinity, and film thickness. On glass substrates, a broader peak at 819 nm suggests lower crystallinity or smaller grain sizes, possibly due to weaker substrate-film interactions. On silicon substrates, a sharper peak at 819 nm indicates improved crystallinity, likely due to better lattice matching or heat dissipation effects. Longer deposition times generally lead to increased crystallinity, resulting in sharper and more intense peaks. The Raman intensity increases with deposition time for on silicon substrates, confirming improved structural ordering over time. Any deviation in the peak position (e.g., a shift from 819 nm) could indicate stress, defects, or changes in phase composition<sup>[20]</sup>. The interaction of TiO<sub>2</sub> with different substrates affects its bandgap and electronic properties, influencing applications in photocatalysis, optoelectronics, and sensors.

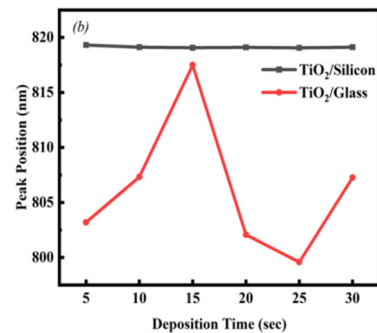


Fig. 4 Peak position of Raman spectra at different deposition time on glass and silicon substrates.

Fig. 5 shows the Full width half maximum (FWHM) of Raman spectra of TiO<sub>2</sub> thin film as a function of deposition time on glass and silicon substrates. FWHM provides information about crystallite size. TiO<sub>2</sub> thin films on glass show no clear correlation with deposition time, while films on silicon substrates exhibit only minor variations. This suggests that the crystallinity of TiO<sub>2</sub> films on glass remains relatively unchanged regardless of deposition time. In contrast, on silicon substrates, the minor variations in FWHM indicate slight changes in crystal quality or strain, but overall, the structural properties remain relatively stable.

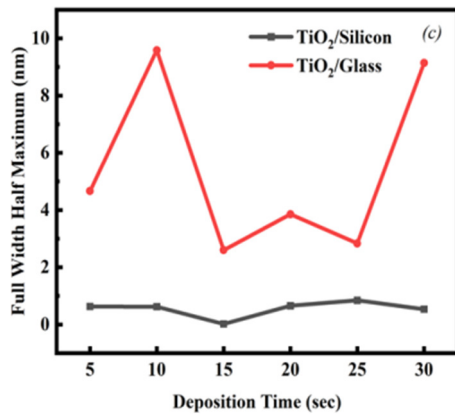


Fig. 5 Full Width at Half Maximum of TiO<sub>2</sub> thin films on glass and silicon substrates at various deposition times.

Fig. 6 shows the peak area of Raman spectra of TiO<sub>2</sub> films as a function of deposition time on glass and silicon substrates. TiO<sub>2</sub> thin films on glass substrates show significant area fluctuations with increasing deposition time and for silicon substrate, exhibits no significant variation of area with increasing deposition time. The Raman peak area is proportional to the amount of Raman-active material present and reflects the crystallinity of the film. A larger peak area suggests a higher concentration of the specific phase (rutile in this case) and improved crystallinity. On glass substrates, variations in peak area with deposition time indicate possible amorphous content or mixed-phase regions. On silicon substrates, the peak area remains more stable, suggesting better film-substrate interaction and consistent crystal growth.

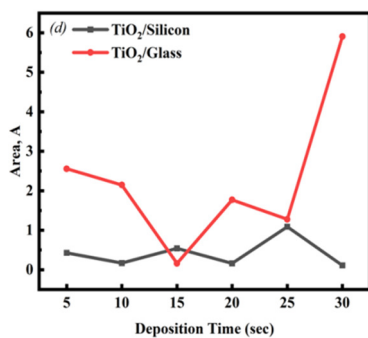


Fig. 6 Peak Area of Raman spectra on glass and silicon substrates as a function of deposition time.

Fig. 7 shows the surface roughness measurement of TiO<sub>2</sub> thin film on Silicon and glass substrates at

different deposition time. Roughness measurements were conducted using the Mitutoyo roughness measurement device to compare the smoothness of the substrates. As shown in the graph Fig. 7, the Ra value for TiO<sub>2</sub> thin films on glass decreases with increasing deposition time. For silicon substrates, the Ra value generally decreases but fluctuates noticeably at a deposition time of 20 seconds. Roughness values for both substrates were also recorded before thin film deposition as indicated in the graph.

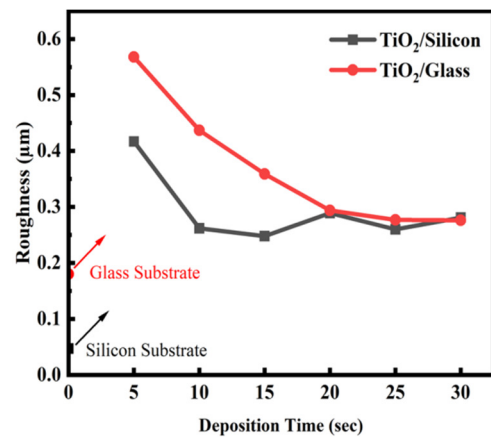


Fig. 7 shows the surface roughness of TiO<sub>2</sub> thin films as a function of deposition time on glass and silicon substrates.

Higher surface roughness is often associated with increased grain size and potential voids in the film, affecting the crystallinity. On silicon substrates, TiO<sub>2</sub> films tend to exhibit lower surface roughness, which promotes better crystallinity and a more uniform structure. On glass substrates, rougher surfaces may indicate non-uniform grain growth, leading to lower crystallinity and potential amorphous regions.

Fig. 8 presents the Ellipsometry analysis of TiO<sub>2</sub> thin films deposited on silicon and glass substrates, illustrating the results as a function of deposition time. Ellipsometry was employed to determine the thickness and optical properties of the fabricated thin films. TiO<sub>2</sub> films on silicon substrates exhibit a more consistent thinning behavior over time compared to those on glass. The refractive index for both substrates initially shows elevated values,

followed by a decrease and subsequent increase, with the glass substrate displaying greater variability than silicon. Meanwhile, the dielectric constant on silicon undergoes significant fluctuations, occasionally approaching zero, whereas on glass, it remains relatively stable.

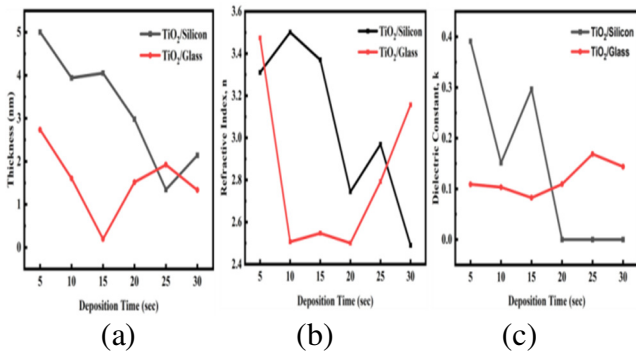


Fig. 8 shows (a) Thickness, (b) Refractive index and (c) dielectric constant of TiO<sub>2</sub> thin film on glass and silicon substrates as a function of deposition time

The nucleation of TiO<sub>2</sub> thin films on glass and silicon substrates significantly influences their thickness, refractive index, and dielectric constant due to differences in surface energy, roughness, and chemical interactions. Nucleation on silicon substrates tends to be more uniform due to silicon's smoother surface and better lattice matching with TiO<sub>2</sub>, leading to more consistent film growth. As a result, thickness increases steadily over time. Glass surfaces are generally more amorphous and less reactive, causing irregular nucleation sites and a less uniform growth rate. This can result in greater variation in thickness across the substrate. Uniform nucleation facilitates a denser film structure on silicon, contributing to a higher and more stable refractive index. However, during initial nucleation, the refractive index may fluctuate until a continuous layer forms. However on glass, the irregular nucleation can cause porosity and less dense films, leading to greater variability in the refractive index. The refractive index may initially rise due to island growth before stabilizing. Consistent nucleation leads to fewer defects and a more uniform dielectric response on silicon. However, initial fluctuations may occur as the film transitions from discrete

islands to a continuous layer. On glass substrates, irregular nucleation can introduce voids and defects, causing the dielectric constant to be lower and more stable compared to silicon but less responsive to electric fields. In summary, nucleation on silicon substrates tends to promote more uniform thickness, higher and more stable refractive indices, and a more variable dielectric constant initially. On glass, nucleation leads to greater variability in thickness and refractive index but a more stable, albeit lower, dielectric constant.

Fig. 9 shows microscopic images of TiO<sub>2</sub> thin films under two different conditions on silicon and glass substrates, as a function of deposition time. The analysis of these images was employed to examine the morphology of the samples at different spin deposition times. The results reveal a trend of enhanced crystallinity and improved homogeneity as the deposition time increases.

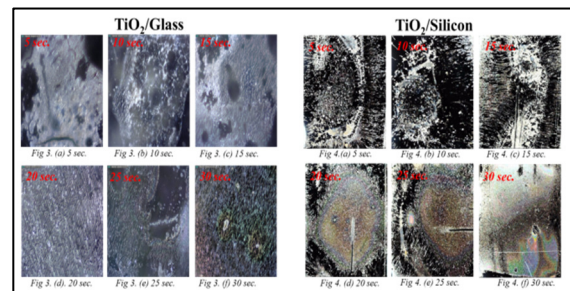


Fig. 9 shows microscopic images of the surface morphology of TiO<sub>2</sub> thin films on glass and silicon substrates, as a function of deposition time.

Fig. 10 shows the X-ray diffraction (XRD) of TiO<sub>2</sub> on silicon and glass substrates as a function of deposition time. The structural properties were investigated using an XRD instrument Bruker D8 Advance diffractometer (Bruker, Germany) with Cu K $\alpha$  ( $\lambda \sim 1.54 \text{ \AA}$ ) radiation in  $2\theta \sim 20^\circ - 70^\circ$ , scan rate 0.2 and 0.0484 step size. The average crystallite size,  $[\delta]$ , was estimated from the Full width half maximum ( $\beta$ ) of the XRD spectra using Scherrer's formula as follows:

$$[\delta] = \frac{k\lambda}{\beta \cos\theta} \quad (1)$$

where  $\kappa$  is a constant, the shape factor value is 0.9,  $\lambda$  represents the wavelength of X-ray (1.54 Å),  $\beta$  is the full width at half maximum (FWHM), and  $\theta$  is the Bragg angle of the diffraction peak, respectively<sup>[13]</sup>. The XRD results indicated that the maximum  $[\delta]$  was estimated to be 10.5 nm on glass and 15.13 nm on silicon, as observed. These values are typically related to the crystallite size determined using the Scherrer equation, where  $[\delta]$  refers to the average size of crystallites in the thin films. The differences in values between the substrates (glass and silicon) suggest variations in the crystallinity or microstructure of the TiO<sub>2</sub> films, potentially influenced by factors like nucleation behavior and film growth conditions.

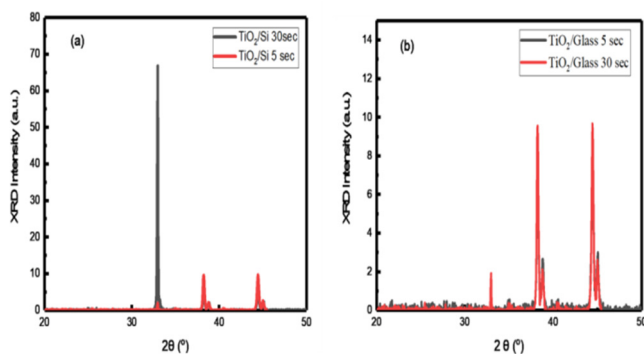


Fig. 10 X-Ray Diffraction analysis confirms the presence of TiO<sub>2</sub> phase at Bragg angles of  $2\theta = 33^\circ$  on both, silicon and glass substrates.

The impact of using silicon and glass substrates for TiO<sub>2</sub> thin films can be analyzed based on several key factors, including film adhesion, crystallinity, optical properties, and surface morphology: 1. Adhesion and surface Interaction on silicon substrate: TiO<sub>2</sub> films tend to exhibit strong adhesion due to the compatibility of silicon's surface energy and the chemical interaction between TiO<sub>2</sub> and native SiO<sub>2</sub>. However, on glass substrate, adhesion can be weaker compared to silicon, as glass is more inert and lacks a native oxide layer to bond with TiO<sub>2</sub> effectively. 2. Crystallinity and phase formation on silicon substrate: The presence of a crystalline silicon substrate can influence the phase of TiO<sub>2</sub>, potentially promoting the formation of

anatase or rutile phases depending on annealing conditions. On the other hand, glass substrate, being amorphous, glass does not provide a template for crystallization, which can lead to more disordered TiO<sub>2</sub> structures unless high-temperature annealing is applied. 3. Optical Properties, silicon substrate: Due to silicon's high refractive index and absorption properties, TiO<sub>2</sub> films may exhibit different optical interference patterns, affecting transparency and reflectivity. TiO<sub>2</sub> on glass substrate is more commonly used for optical applications due to its high transparency, making it ideal for coatings in photocatalysis and photovoltaics. 4. Raman spectra and structural stability on silicon substrate, Raman spectra typically show more stable peak intensities, indicating a more uniform film formation across different deposition times. Glass substrate, variations in Raman peak intensities suggest non-uniform film formation, possibly due to differences in adhesion and surface energy. Nucleation of TiO<sub>2</sub> thin films on silicon and glass substrates significantly differs due to variations in surface properties such as surface energy, roughness, and chemical composition<sup>[15]</sup>. These factors influence the nucleation rate, film uniformity, and crystalline phase formation. Nucleation on Silicon Substrate shows stronger nucleation and uniform Growth because silicon (Si) naturally forms a thin layer of native SiO<sub>2</sub> when exposed to air, which interacts well with the TiO<sub>2</sub> sol-gel precursor. The oxide layer provides nucleation sites, promoting strong adhesion and uniform grain growth. The nucleation density is higher, leading to a smoother and more continuous film formation. If the deposition and annealing temperatures are optimized, epitaxial or preferentially oriented growth of TiO<sub>2</sub> phases (anatase or rutile) may occur<sup>[16]</sup>. Silicon's crystalline nature can provide a template effect, influencing the orientation of TiO<sub>2</sub> grains. Due to better chemical interaction with TiO<sub>2</sub> precursors, the wetting angle is lower, which results in faster nucleation compared to glass. Nucleation on glass



substrate exhibits slower and more random nucleation because glass is amorphous and chemically inert, meaning it does not provide active nucleation sites. Nucleation tends to occur randomly, leading to lower nucleation density and larger grain sizes. TiO<sub>2</sub> precursors may experience delayed wetting, which can cause variations in film thickness and homogeneity [17]. Depending on the glass type, the surface roughness may vary, impacting how nucleation starts. Uneven nucleation can lead to island growth, resulting in non-uniform film formation and variations in Raman peak intensities [18]. Due to poor interaction with TiO<sub>2</sub>, higher annealing temperatures are often required to induce crystallization. Glass substrates favor the formation of the anatase phase at lower temperatures but may require higher temperatures (>500°C) to form rutile due to weaker substrate influence [19].

#### IV. CONCLUSION

Titanium dioxide thin films have been successfully deposited by the sol-gel process. Based on the roughness results, greater deposition time produces a smoother surface on both substrates. Raman Spectroscopy reveals a peak at  $\approx 819$  nm, indicating the presence of rutile structural phase on both, glass and silicon, substrates. XRD results indicate that the maximum  $[\delta]$  is 10.5 nm on glass and 15.13 nm on silicon at a deposition time of 30 seconds. TiO<sub>2</sub> thin films tend to thin out more consistently with increasing spin deposition time on silicon compared to those on glass. Ellipsometry analysis showed that while the deposition time increased, the refractive index decreased for TiO<sub>2</sub> thin films on silicon but on glass the opposite. Dielectric constant shows decreasing fluctuations in thin films on silicon; but on glass, a more stable trend with smaller differences can be observed. Raman curve fitting data analysis of thin films on silicon displayed almost identical peak positions with varying deposition times, and very similar relationship with values of peak intensity, FWHM, and area; glass reflects the opposite, fluctuating

throughout. Results indicate that silicon substrate provides better adhesion and stability, making it suitable for electronic and sensor applications, while glass offers high transparency, making it ideal for optical coatings and photocatalytic applications.

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#### REFERENCES

- [1]. Castillo N., Olguin, D., Conde A., Gallaro., Jimenez .S.-Sandoval “Structural and morphological properties of TiO<sub>2</sub> thin films prepared by spray pyrolysis”, *Revista Mexicana De Fisica* 50(4)382, 2004.
- [2]. Q. Fan, B. McQuillin, A.K. Ray, M.L. Turner and A.B. Seddon, *J. Phys., D, Appl. Phys.* 33 2683 (2000).
- [3]. T. Sasaki, Y. Ebina, M. Watanabe and G. Decher, *Chem. Commun.* 2163 (2000).
- [4]. D. H. Kim, J. S. Yang, K. W. Lee, S. D. Bu, D.W. Kim and T.W. Noh, *J. Appl. Phys.* 93 6125 (2003).
- [5]. Mahshid S., Askari M., Ghamsari M. S., Afshar N., LAHUTI S., “Mixed-phase TiO<sub>2</sub> nanoparticles preparation using sol-gel method *Journal of Alloys and Compounds*” 47,58-589, 2009.
- [6]. Wang C.C. and Ying J.Y. “Sol-gel synthesis and hydrothermal processing of Anatase and rutile Titania nanocrystal” *Chem. Mater* 11, 3113-3120, 1999.
- [7]. H. and T. Liu, W. Yang, T. Ma, Cao, J. Tao, J. Zhang and T. Hu Synthesis and Characterization of titania prepared by using a photo assisted sol-gel method. *Langmuir*, 19, 3001-3005, 2003.
- [8]. Wang C.C. and Ying J.Y. “Sol-gel synthesis and hydrothermal processing of Anatase and rutile Titania nanocrystal” *Chem. Mater* 11, 3113-3120, 1999.
- [9]. H. and T. Liu, W. Yang, T. Ma, Cao, J. Tao, J. Zhang and T. Hu Synthesis and Characterization of titania prepared by

using a photo assisted sol-gel method. Langmour, 19,3001-3005, 2003.

[10]. Bischof B. L. and Anderson M. A. . “Peptization Process in the Sol-Gel Preparation of Porous Anatase TiO<sub>2</sub>”. Chem. Mater., 7, 1772-1778, 1995.

[11]. Jinghuan Zhang, Xin Xiao, Junmin Nan. “Hydrothermalhydrolysis synthesis and photocatalytic properties of nano-TiO<sub>2</sub> with an adjustable crystalline structure”. Journal of Hazardous Materials 176,617–622, 2010.

[12]. Dongjin Byun, Yongki Jin, Bumjoon Kim, Joong Kee Lee, Dalkeun Park “Photocatalytic TiO<sub>2</sub> deposition by chemical vapor deposition”. Journal of Hazardous Materials, 73,199-206, 2000.

[13]. Cullity B. D., Elements of X-Ray Diffraction, Adison-Wesley 1978.

[14]. Moniruzzaman Syed, Tierney Crosby, Marcus Frierson, Miara Hurd, Jamil Muhammad, Brianna Taylor, Taj Thompson, Madihazaman Syeda, Jolaikha Sultana and Md Farhan Azim”Structural and Electronic Impact on Various Substrates of TiO<sub>2</sub> Thin Film Using Sol-Gel Spin Coating Method” Journal of Materials Science Research; Vol. 13, No. 2; 2024.

[15]. Balachandran K., Venckatesh R., Rajeshwari Sivaraj, “Synthesis of NanoTiO<sub>2</sub>-SiO<sub>2</sub> composite using sol-gel method : Effect of size, surface morphology and thermal stability”, IJEST, 2 (8), pp.3695-3700, 2010.

[16]. C. Sanchez, J. Livage, M. Henry and F. Babonneau, J. Non-Cryst. Solids 100 65-76 (1988).

[17]. S.M Tracey, S.N.B Hodgson, A.K. Ray and Z. Ghassemlooy, J. Muter. Process. Technol. 7, 86-94 (1998).

[18]. U. Selvaraj, A.V Prasadaraao, S. Komarneni and R. Roy, J. Am. Ceram. Soc.,75, 1167-1170 (1992).

[19]. Moniruzzaman Syed, Jurnee Gibson, DeAnthony, White, Danisha Watson, Yahia Hamada, Muhtadyuzzaman Syed and Temer S. Ahmadi, Effects of Annealing Temperature on Anatase-Rutile TiO<sub>2</sub> Multilayer Thin Films prepared by Sol-Gel Spin Coating Method, “International Journal of Scientific Research and Engineering Development”Volume 2 Issue 6, Nov- Dec 2019

[20]. C. Guillard, H. Lachheb and A. Houas, J. Photochem. Photobiol. 158, 27-36 (2003).