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Comparative Investigation of Optical and Electrical Properties of Pure and Ag/Sn Doped TiO_2 Thin Films Synthesized via Sol–Gel Dip Coating Technique

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Abstract: a) Background: Optoelectronic and energy applications make extensive use of TiO_2 thin films. Their characteristics are heavily influenced by doping effects, flaws, and structure. Sol-gel dip coating makes it possible to fabricate thin films in a controlled and economical manner. Band structure and electrical transport characteristics are drastically altered by doping.

b) Objective: The optical and electrical characteristics of doped TiO_2 films are examined in this work. Ag and Sn doped systems were compared. Relationships between structure and properties were determined for both doped systems.

c) Methods: Precursor solutions were made using the sol-gel technique under carefully regulated hydrolysis conditions. Dip coating used controlled withdrawal speed and repeated cycles to deposit films. Defect-free, homogeneous film formation was guaranteed by intermediate drying. Organic residues were eliminated and crystallinity was enhanced by annealing at 450°C. Electrical, UV-Vis, SEM, and XRD measurements were carried out in a methodical manner.

d) Results: In every thin-film sample, anatase phase development was verified. Ag doping used a grain boundary pinning method to decrease crystallite size. Lattice strain and defect concentration were greatly boosted by Sn doping. Following doping, optical absorption increased with visible region shift. The band gap dropped to lower values from about 3.2 eV. The samples with the largest band gap reduction were Sn-doped films. Increased charge carrier density led to an increase in electrical conductivity. When compared to Ag-doped films, Sn-doped films showed greater conductivity.

e) Comparison with Literature: The observed anatase phase is consistent with sol-gel TiO_2 systems that have been reported. Ag-induced grain refinement is consistent with previously described boundary pinning mechanisms. Defect and lattice distortion models are consistent with Sn-induced strain. Defect-state and band tailing theories are consistent with band gap narrowing. The reported oxygen vacancy transport pathways are consistent with electrical trends.

f) Conclusion: TiO_2 films' optical and electrical characteristics are efficiently tuned by doping. Ag doping uses plasmonic interactions to improve optical absorption. Electrical conductivity is enhanced by Sn doping through defect generation mechanisms. The applicability for optoelectronic and energy device applications is confirmed by the results.

Keywords: *TiO_2 thin films, Sol–gel method, Dip coating, Ag doping, Sn doping, Optical properties, Electrical conductivity, Band gap engineering*

1. Introduction

1.1 Overview of TiO_2 as Functional Semiconductor

TiO_2 is a well-researched semiconductor with outstanding functional characteristics. It has excellent resistance to environmental deterioration and great chemical stability. Anatase, rutile, and brookite crystal phases are the three polymorphs. The anatase phase is the most photo-catalytically and optically efficient of them. Because of the favourable electrical structure, this phase exhibits increased surface activity. TiO_2's band gap is located in the UV area at about 3.2 eV. Under typical environmental lighting circumstances, this restricts the absorption of visible light. Grain size, defect states, and crystallinity all have a significant impact on optical response. Both surface exposure and functional performance are improved by thin film geometry. Coatings, sensors, and energy applications all make extensive use of TiO_2 films. Their tuneable optical and electrical properties give them their versatility. Strong UV absorption behaviour of TiO_2 coatings was observed in earlier research (Evtushenko et al., 2015).

1.2 Sol–Gel Technique for Thin Film Fabrication

The sol-gel method allows for controlled synthesis at comparatively low temperatures. Metal alkoxide precursors undergo hydrolysis and condensation. Metal-oxygen linkages progressively polymerize to form networks. Film homogeneity and coating stability are efficiently regulated by solution viscosity. Aging greatly increases structural uniformity and gel connection. Drying starts the densification of gel networks and eliminates

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solvents. Amorphous gel is transformed into crystalline oxide thin layers by annealing. Grain growth characteristics and phase development are influenced by temperature treatment. At the molecular level, uniform dopant inclusion is possible with the sol-gel technique. This method works well for large-area coatings and is reasonably priced. Brinker and Scherer (1990) described the fundamentals of sol-gel chemistry. Hench and West (1990) also identified parts of fundamental processing.

1.3 Dip Coating Deposition Method

A common method for applying consistent thin coatings is dip coating. The substrate is submerged in the precursor solution and removed at a regulated rate. The thickness and surface shape of deposited films are determined by the withdrawal speed. Surface coverage is continually improved and thickness is increased through repeated coating cycles. Internal tensions are decreased and film cracking is avoided through intermittent drying. Annealing increases the films' crystallinity and adhesion strength. For industrial applications, dip coating guarantees scalability and reproducibility. Large substrates can be coated with it with little equipment complexity. Electrical conductivity and optical transparency are strongly influenced by film thickness. For dependable optical and electronic device performance, uniform films are necessary. Recently, dip coating methods were refined for the production of thin films (Bulut & Köel, 2024).

1.4 Importance of Doping in TiO_2 Thin Films

Doping adds new defect states and alters the electrical structure. These defect levels affect the behaviour of charge transport and are located within the band gap. Charge carrier recombination can be considerably decreased by dopants. This enhances TiO_2 materials' photocatalytic and optoelectronic capabilities. The absorption shift toward the visible light range is made possible by band gap tuning.

Defect density, lattice strain, and crystallite size are all impacted by doping. Increased carrier concentration in the lattice leads to an increase in electrical conductivity. In doped TiO_2 systems, oxygen vacancies are crucial. Effective homogenous distribution of dopant ions is made possible by the sol-gel process. Both optical absorption and electrical transport qualities are improved by controlled doping. Kamarulzaman et al. (2015) talked about band gap engineering principles. Chen et al. (2018) revealed dopant incorporation mechanisms.

1.5 Role of Silver (Ag) Doping in TiO_2 Films

In TiO_2 thin films, plasmonic phenomena are introduced by silver doping. The effectiveness of light absorption is greatly increased by localized surface plasmon resonance. Strong electromagnetic fields are produced when Ag nanoparticles interact with incident light. Under visible light, this enhances photocatalytic activity and optical responsiveness. In the TiO_2 lattice, Ag atoms have a tendency to separate at grain boundaries. Grain growth is constrained during the annealing process by this border pinning action. Defect density rises and crystallite size falls as a result. Increased defect density lowers recombination losses and enhances charge separation. Grain distribution patterns and surface shape are also altered by Ag doping. By means of carrier trapping mechanisms, it enhances electrical conductivity. Cheng et al. (2008) described mechanisms of plasmonic amplification. In Ag-doped oxide systems, grain refinement effects were documented (Grine et al., 2022).

1.6 Role of Tin (Sn) Doping in TiO_2 Films

Substitutional defects are introduced into the TiO_2 crystal lattice by tin doping. Because of their compatibility with similar ionic radii, Sn ions take the place of Ti ions. Lattice strain and structural distortion are greatly increased by this swap. Sn doping efficiently improves defect concentration and raises microstrain. The development of oxygen vacancies increases with fault density. These openings enhance electrical conductivity and serve as donors. Band structure and optical absorption characteristics are significantly impacted by Sn doping. Through electronic transitions mediated by defects, it narrows the band gap. When compared to Ag-doped films, Sn-doped films frequently show greater lattice distortion. This leads to smaller crystallites and wider XRD peaks. Bayan et al. (2021) demonstrated Sn doping effects in TiO_2 systems. Ke et al. (2011) discussed the impact of defect chemistry.

1.7 Structure–Property Relationship in Doped TiO_2 Films

The optical and electrical behaviour of films is directly influenced by their structural characteristics. Band gap is influenced by crystallite size via quantum confinement effects. Smaller grains improve the availability of reaction sites and increase surface area. Defect states are introduced and the electronic band structure is altered by lattice strain. Defect concentration within a crystalline lattice is represented by dislocation density. Higher flaws result in better carrier transmission and absorption. Scattering and optical transmission characteristics are influenced by surface shape. The entire substrate surface has uniform electrical pathways thanks to uniform films. Near the band edge area, tail absorption is influenced by defect states. Carrier mobility and defect-assisted transport pathways are essential for electrical conductivity. The total performance of TiO_2 thin films is determined by a combination of structural characteristics.

1.8 Key Factors Influencing TiO_2 Thin Film Properties

Table 1: Key Parameters Affecting Structural, Optical, and Electrical Properties

Parameter	Influence on Properties	Supporting Reference
Crystallite size	Affects band gap and optical absorption	Serpone et al., 1995
Lattice strain	Introduces defect states and band modification	Bayan et al., 2021
Dopant type	Controls optical and electrical tuning	Kamarulzaman et al., 2015
Annealing temperature	Influences crystallinity and phase formation	Hanaor et al., 2012
Film thickness	Determines optical transmission and conductivity	Xu et al., 2011

Important factors affecting the characteristics of TiO_2 thin films are shown in Figure 1. Band gap and optical absorption behaviour are influenced by crystallite size (Serpone et al., 1995). Quantum confinement effects are greatly enhanced by particle size reduction. Defect states are introduced into the crystal structure by lattice strain. These flaws successfully alter the electrical band structure (Bayan et al., 2021). Increased strain produces localized energy levels and disorganization.

Optical and electrical property tuning is significantly controlled by dopant type. Through plasmonic interactions, Ag doping improves optical absorption (Kamarulzaman et al., 2015). Defect density and carrier concentration are greatly increased by Sn doping. Phase transformation behaviour and crystallinity are influenced by annealing temperature. Crystal growth and structural ordering are enhanced by higher temperatures (Hanaor et al., 2012). Additionally, it lowers faults under ideal processing circumstances. Both optical transmission and electrical conductivity response are influenced by film thickness.

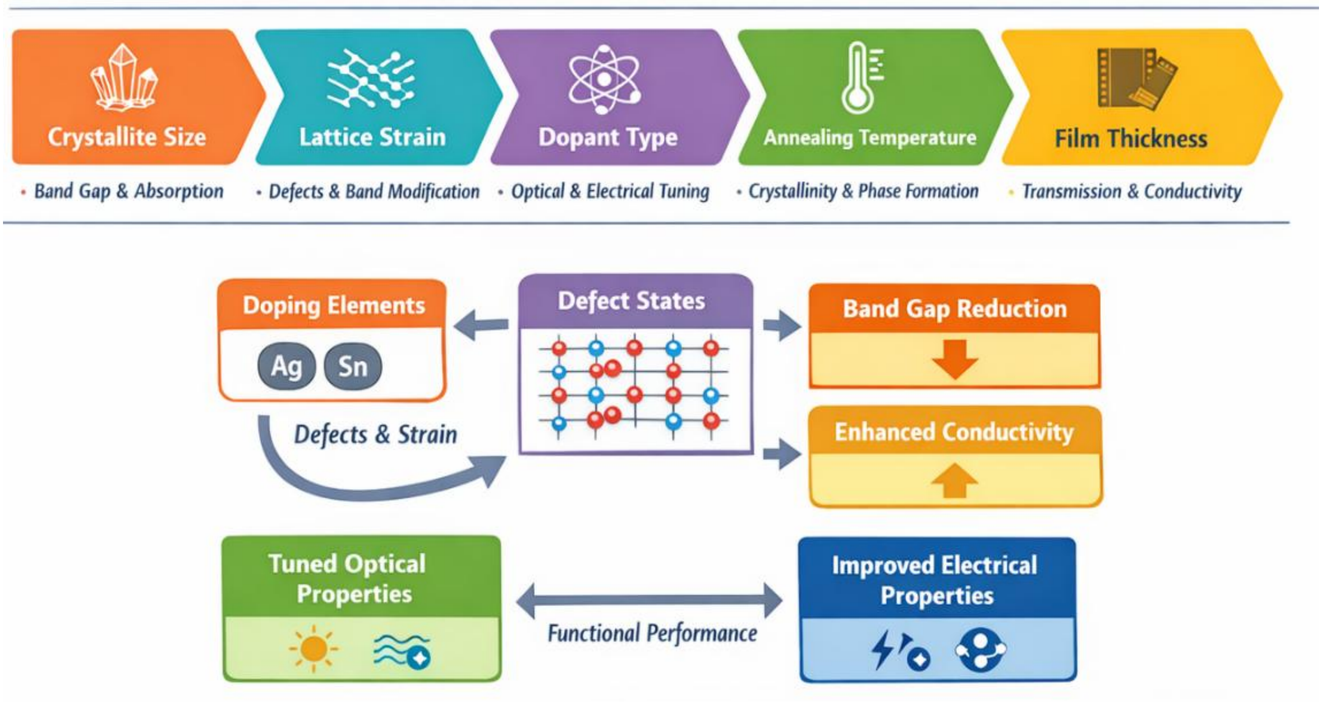


Figure 1: Structure–Property Relationship in Doped TiO_2 Thin Films
(Serpone et al., 1995; Xu et al., 2011; Hanaor et al., 2012; Kamarulzaman et al., 2015; Bayan et al., 2021)

According to Xu et al. (2011), thicker coatings improve electrical conduction channels but decrease transmission. Doping-induced defect development in the TiO_2 lattice is also depicted in the graphic. These flaws increase the effectiveness of light absorption and decrease the band gap. Electrical conductivity is greatly improved by increased carrier density. Strong interaction between structure and characteristics is generally shown in Figure 1. TiO_2 can be optimized for optoelectronic applications by controlled processing.

1.10 Research Gap and Justification

The majority of research focuses on individual dopant systems. There is still little comparison between Ag and Sn doping. There are few findings that link optical band gap decrease to structural strain. In doped TiO_2 films, electrical properties are frequently less investigated. The link between comprehensive structure, optics, and electricity is still not well documented. For a better understanding, rigorous comparative research is therefore necessary. Most studies focus on single dopant systems independently. Comparative analysis between Ag and Sn doping remains limited. Few reports correlate structural strain with optical band gap reduction. Electrical properties are often less explored in doped TiO_2 films. Comprehensive structure–optical–electrical relationship is still underreported. Therefore, systematic comparative investigation is required for better understanding.

1.11 Aim of the Present Study

In this work, pure, Ag, and Sn doped TiO_2 films are examined. For the creation of thin films, the sol-gel dip coating method is employed. X-ray diffraction techniques are used to investigate structural qualities. Scanning electron microscopy analysis is used to look at surface morphology. UV-visible spectroscopy measurements are used to assess optical characteristics. Conductivity and transport analysis are used to study electrical properties. A methodical comparison of Ag and Sn doping is carried out. For functional applications, correlations between structure and properties are developed.

2. Literature Review

2.1 Sol–Gel Processing of Oxide Thin Films

Hydrolysis and condensation reactions are efficiently controlled by sol-gel technology. It creates uniform oxide networks with regulated microstructure development. Metal alkoxides gradually polymerize to produce stable oxide frameworks. Aging greatly increases structural homogeneity and gel connection. Drying starts the densification of gel networks and eliminates solvents. Crystalline oxide thin films are produced by annealing amorphous gels. Processing factors have a significant impact on defect concentration and crystallinity. Uniform dopant inclusion at the molecular level is made possible by sol-gel techniques. For large-area coatings, this method is still affordable and scalable. Hench and West (1990) reported basic sol-gel ideas. Ciriminna et al. (2013) reviewed advanced sol-gel applications.

2.2 Dip Coating and Thin Film Deposition Control

Dip coating successfully guarantees consistent layer deposition and repeatable thickness. Film thickness and shape are directly controlled by substrate pullout speed. Several coating cycles progressively improve surface coverage and thickness. Interlayer drying lessens internal tension and stops the development of film cracks. Annealing increases the crystallinity and stickiness of deposited coatings. The optical and electrical properties of a film are greatly influenced by its thickness. Stable optical transmission and electrical conduction behaviour are guaranteed by uniform coating. Because dip coating is easy to use and inexpensive to fabricate, it is frequently used. The effectiveness of dip coating for oxide thin films has increased recently (Bulut & Köel, 2024).

2.3 Optical Properties of TiO_2 Thin Films

Strong UV absorption properties are displayed by TiO_2 thin films. Particle size, flaws, and crystallinity all affect the optical band gap. When compared to other phases, the anatase phase exhibits greater optical activity. The absorption edge and optical transition behaviour are affected by defect states. Defect-induced energy level creation results in band gap narrowing. Film shape and thickness have a significant impact on optical characteristics. Band gap determination is a common use of UV-Vis spectroscopy. Optical band gap values can be reliably estimated using the Tauc method. Evtushenko et al. (2015) reported on the optical characteristics of TiO_2 films. Kamarulzaman et al. (2015) talked about band gap engineering principles.

2.4 Effect of Ag Doping on TiO_2 Thin Films

Ag doping greatly increases optical absorption by introducing plasmonic phenomena. The effectiveness of visible light harvesting is increased by localized surface plasmon resonance. Strong electromagnetic fields are produced when Ag nanoparticles interact with incident light. This improves TiO_2 films' photocatalytic and optoelectronic capabilities. Ag doping uses a boundary pinning method to limit grain development. Surface area and defect density are efficiently increased by smaller crystallites. Defects greatly lower recombination losses and enhance charge separation. Systems doped with silver exhibit better trends in optical and electrical performance. Cheng et al. reported mechanisms for plasmonic enhancement (2008). Grine et al. (2022) observed grain refining behaviour.

2.5 Effect of Sn Doping on TiO_2 Thin Films

Lattice deformation and a marked rise in defect concentration are caused by Sn doping. Due to their compatibility with similar ionic radii, Sn ions replace Ti sites. Lattice strain and structural disorder are successfully introduced by this substitution. Increased defect density and the creation of oxygen vacancies are caused by higher strain. By acting like donors, oxygen vacancies improve electrical conductivity. Through defect-mediated transitions, Sn doping affects the optical band gap. It improves absorption of visible light and reduces the band gap. Compared to Ag-doped films, Sn-doped films frequently exhibit greater strain. The effects of Sn doping were documented by Bayan et al. (2021). Ke et al. (2011) discussed the behaviour of oxygen vacancies.

2.6 Comparative Doping and Research Gap

Rarely have Ag and Sn doping been compared together in earlier research. The majority of studies concentrate on individual dopant systems. There are few studies that link optical band gap decrease to structural strain. Comparative doping investigations continue to focus less on electrical properties. There is still a lack of thorough reporting on structure-property interactions. Comparative dopant analysis is necessary, according to recent studies (Chowdhury et al., 2025). This study successfully fills that gap in comparative research.

Table 2: Summary of Literature Trends

Aspect	Reported Trend	Reference
Sol–gel processing	Controlled network formation	Hench & West, 1990
Dip coating	Thickness control via withdrawal speed	Bulut & Günel, 2024
Optical properties	Band gap depends on defects	Evtushenko et al., 2015
Ag doping	Plasmonic enhancement	Cheng et al., 2008a
Sn doping	Lattice strain and defect formation	Bayan et al., 2021
Recent studies	Comparative doping importance	Chowdhury et al., 2025

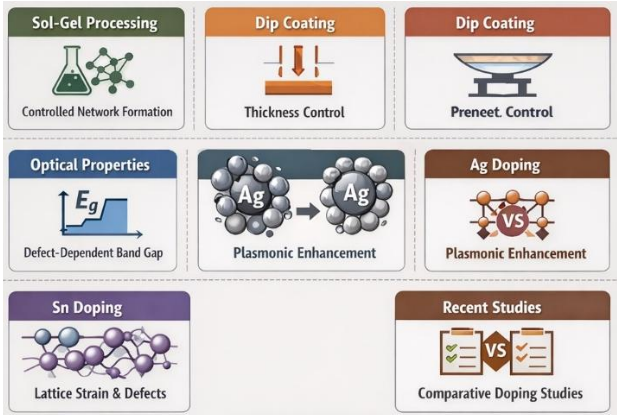


Figure 2: Summary of Literature trends (Hench & West, 1990; Cheng et al., 2008a; Evtushenko et al., 2015; Bayan et al., 2021; Bulut & Günel, 2024; Chowdhury et al., 2025)

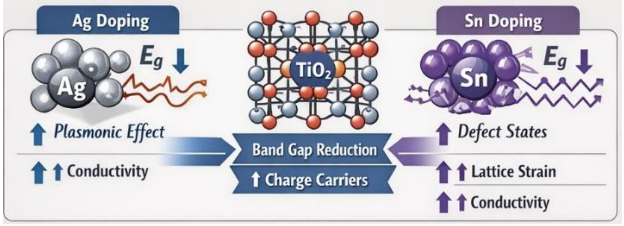


Figure 3: Literature-based mechanism of Ag and Sn doping effects in TiO_2 thin films, (Cheng et al., 2008a; Bayan et al., 2021; Kamarulzaman et al., 2015; Ke et al., 2011).

3. Materials and Methods

3.1 Precursor Materials and Chemicals

The raw material for the Ti precursor was titanium isopropoxide. For sol-gel hydrolysis operations, it has excellent reactivity. As a solvent, ethanol regulated the wetting and viscosity characteristics. During the dip coating deposition procedure, it guaranteed even spreading. Acetic acid efficiently regulated the rate of the hydrolysis reaction and stabilized sol. This guaranteed uniform sol formation and stopped precipitation from happening too quickly. Ag dopant ions were supplied in the precursor solution by silver nitrate. For substitutional doping, tin chloride was used as a precursor for Sn dopants. Every chemical utilized met analytical grade purity requirements. Cleaning and preparation processes involved the use of deionized water. Hydrolysis and condensation processes are followed by sol-gel precursor chemistry (Hench & West, 1990).

3.2 The Cleaning and Substrate Preparation Process

Glass substrates were chosen because of their flat surfaces and transparency. Ethanol and deionized water were used in succession to clean the substrates. Organic pollutants were successfully eliminated from substrate surfaces by ultrasonic cleaning. Improved adhesion qualities and homogeneous coating were guaranteed by clean surfaces. Hot air was used for drying in order to eliminate any remaining moisture. Film homogeneity and performance qualities are greatly impacted by proper cleaning. The quality of thin film deposition is greatly influenced by surface preparation. Studies on thin film manufacturing reported standard cleaning procedures (Bulut & Köel, 2024).

3.3 The Doping and Sol Preparation Procedure

Controlled mixing under constant magnetic stirring was required for the synthesis of the sol. Under stirring, the titanium precursor was gradually dissolved in the ethanol solvent. Dropwise additions of acetic acid were used to efficiently regulate the rate of hydrolysis. To achieve homogeneity, the mixture was agitated for several hours. To ensure a uniform distribution throughout the solution, dopants were added gradually. Dopants of Ag and Sn were added independently for analysis in comparative research.

Ions were uniformly incorporated into the TiO_2 network thanks to controlled doping. Sol's homogeneous gel formation and structural stability were enhanced by aging. High-quality thin film deposition requires homogenous sol formation. Previous investigations have addressed sol-gel doping mechanisms (Ciriminna et al., 2013).

3.4 Dip Coating for Thin Film Deposition

Controlled immersion and extraction speeds were used for dip coating. To create a homogeneous coating, substrates were submerged in a sol solution. In order to regulate film thickness, withdrawal speed was kept constant. The thickness and homogeneity rose steadily after several coating cycles. Intermediate drying was done after each coating cycle. Drying enhanced the film's adherence to the substrate surface and eliminated the solvent. Consistent optical and electrical characteristics were guaranteed by uniform deposition. For the production of thin films, dip coating offers scalability and reproducibility. Withdrawal speed and solution viscosity have a significant impact on film thickness. Recent thin-film experiments supported the dip coating approach (Bulut & Köel, 2024).

3.5 Annealing and Drying Process

Following each coating cycle, films were dried under carefully monitored circumstances. Drying guaranteed the films' structural stability and stopped them from cracking. For crystallization, final annealing was done at 450°C. Annealing successfully transformed amorphous films into crystalline TiO_2 phases. Grain growth and phase change were strongly impacted by temperature. Grain size gradually increased at higher temperatures, while crystallinity was enhanced. Additionally, organic residues were entirely eliminated from the film structure through annealing. Electrical conductivity and optical qualities were greatly enhanced by heat treatment. TiO_2 studies addressed the impact of thermal processing (Hanaor et al., 2012).

3.6 Methods of Characterization

Film phase identification and crystalline structure were examined using XRD. Peak broadening was used to calculate lattice strain and crystallite size. SEM efficiently investigated grain dispersion patterns and surface morphology. It offered details on surface roughness and film homogeneity. Absorption and optical band gap values were found using UV-Vis spectroscopy. The band gap was estimated using the tauc plot approach. Conductivity and charge transport characteristics were assessed by electrical tests. These measurements demonstrated how doping affects electrical behaviour. A comprehensive understanding of the structure-property relationship was obtained by combined characterisation. Thin film research frequently employs characterization techniques (Kamarulzaman et al., 2015).

Table 3: Materials and Process Parameters Used

Parameter	Description	Purpose
Titanium isopropoxide	Precursor material	TiO_2 formation
Ethanol	Solvent	Controls viscosity
Acetic acid	Stabilizer	Controls hydrolysis
Silver nitrate	Dopant	Enhances optical properties
Tin chloride	Dopant	Improves electrical properties
Annealing temperature	450°C	Crystallization

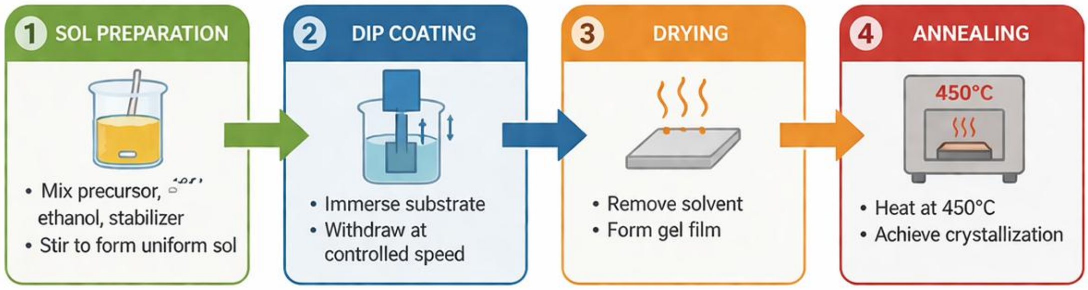
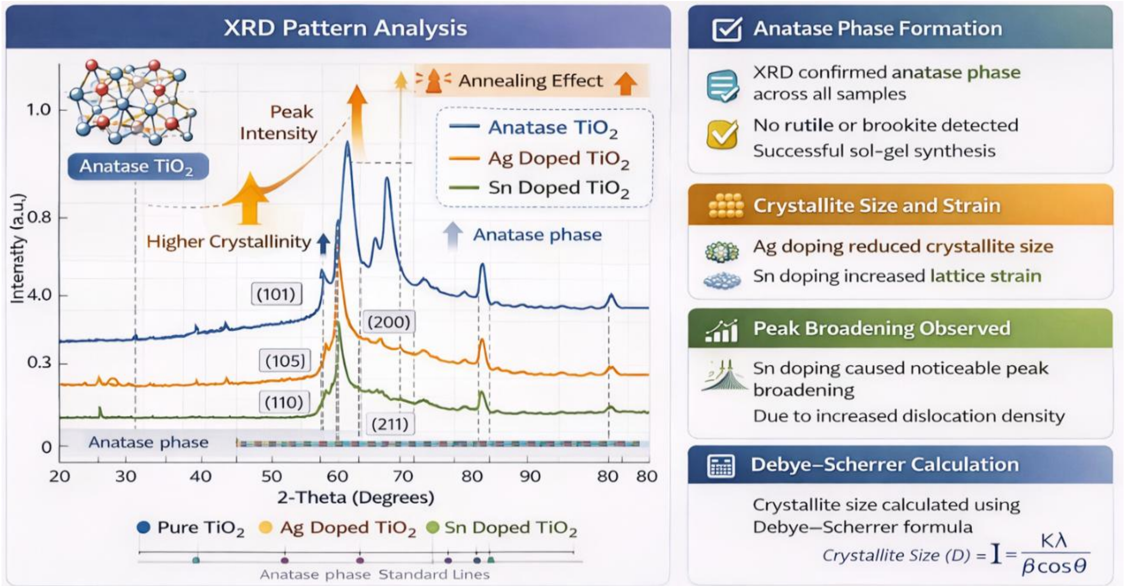


Figure 4: Sol–Gel Dip Coating Process Flow Diagram



Anatase Phase Formation

XRD confirmed anatase phase across all samples

No rutile or brookite detected

Successful sol-gel synthesis

Crystallite Size and Strain

Ag doping reduced crystallite size

Sn doping increased lattice strain

Peak Broadening Observed

Sn doping caused noticeable peak broadening

Due to increased dislocation density

Debye–Scherrer Calculation

Crystallite size calculated using Debye–Scherrer formula

$$\text{Crystallite Size } (D) = \mathrm{I} = \frac{K\lambda}{\beta\cos\theta}$$

Figure 5: Phase identification and crystallinity analysis of doped TiO_2 thin films

4. Results

4.1 Structural Analysis

4.1.1 Phase Identification and Crystallinity

Anatase phase development was verified by XRD signals in every synthetic sample. Standard anatase TiO_2 planes were correlated with characteristic diffraction peaks. Diffraction patterns showed neither brookite nor rutile peaks. This shows that phase control during the sol-gel synthesis process was successful. After annealing, peak intensity rose, suggesting higher levels of crystallinity. The Debye-Scherrer equation approach was used to determine the crystallite size. Because of the grain boundary pinning effect, Ag doping decreased crystallite size. Peak broadening effects were evident due to increased lattice strain caused by Sn doping. Dopant inclusion into the crystal lattice led to an increase in dislocation density. This suggests a much larger concentration of defects inside the lattice structure. Changes in structure have a significant impact on the behaviour of optical and electrical characteristics. In doped TiO_2 systems, similar findings were documented (Hanaor et al., 2012).

4.2 Morphological Analysis

4.2.1 Surface Morphology and Grain Distribution

SEM pictures revealed thin film surfaces that were consistent and free of cracks. The granular morphology of pure TiO_2 films was dense and compact. Undoped samples showed a comparatively greater grain size distribution. The grains in Ag-doped films were more evenly spaced and finer. Grain growth was inhibited, which led to grain refining. Films doped with Sn exhibited mild clustering and aggregation. This suggests a higher density of defects and the existence of lattice deformation. Light scattering and absorption properties are strongly influenced by surface shape. Electrical conduction channels across the film surface are improved by uniform shape. Strong correlations exist between structural and optical qualities and morphological traits. The results of SEM analysis are consistent with patterns in thin film morphology that have been published (Grine et al., 2022).

4.3 Optical Characteristics

4.3.1 Analysis of UV-Visible Absorption

Strong absorption in the ultraviolet region was clearly seen in the UV-Vis spectra. The intrinsic band gap transition of TiO_2 is shown by the absorption peak. Following dopant inclusion, the absorption edge moved toward the visible region. Red shift denotes a substantial narrowing of the optical band gap energy. Because of the effects of plasmonic interactions, Ag doping increased absorption. Through defect-induced electronic transitions, Sn doping enhanced absorption. Tail states close to the conduction band area were produced by higher defect densities. In doped TiO_2 thin films, optical absorbance was increased. These modifications improve appropriateness for applications involving optoelectronic devices. The behaviour of optical absorption is consistent with earlier research (Evtushenko et al., 2015).

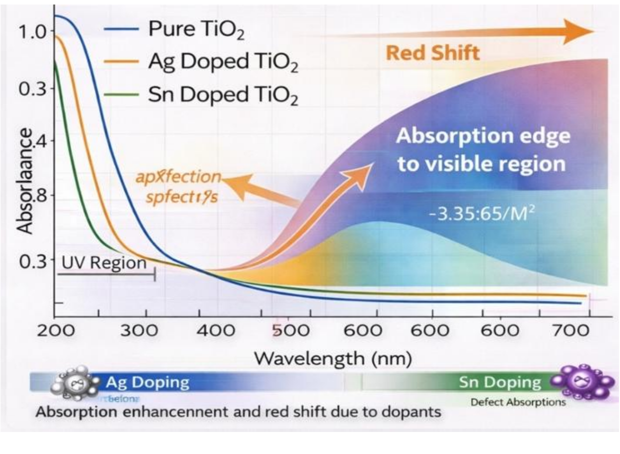


Figure 6: Uv-Vis Absorption Analysis of Doped TiO_2 Films

4.3.2 Tauc Plot Assessment of Band Gap

The Tauc plot method was used to calculate the optical band gap. The band gap of pure TiO_2 films was around 3.2 eV. Band gap reduction values were slightly reduced in Ag-doped films. The samples with the largest band gap reduction were Sn-doped films. Defect level formation inside the band structure caused the band gap to narrow. Defect states and quantum confinement have a significant impact on band gap fluctuation. The efficiency of absorbing visible light is greatly increased by a smaller band gap. Advanced optoelectronic applications require band gap tuning. These findings align with research on band gap engineering (Kamarulzaman et al., 2015).

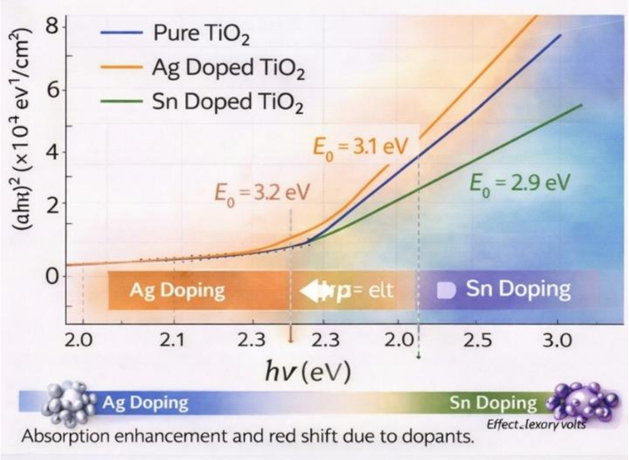


Figure 7: Tauc Plot for Band Gap estimation of Doped TiO_2 Films

4.4 Electrical Properties

4.4.1 Analysis of Electrical Conductivity

In doped TiO_2 thin films, electrical conductivity dramatically enhanced. Because of the large band gap, pure TiO_2 films had reduced conductivity. Ag doping enhanced carrier mobility via transport processes mediated by defects. Ag dopants improved electron transport behaviour by introducing shallow energy levels. By increasing the concentration of oxygen vacancies, Sn doping improved conductivity. Charge carrier density was increased by oxygen vacancies acting as donors. Electrical conduction channels were enhanced by higher carrier densities. When compared to Ag-doped films, Sn-doped films showed greater conductivity. Defect density and lattice distortion have a significant impact on electrical characteristics. Enhancement of conductivity facilitates possible use in electronic devices. Doped oxide films showed comparable conductivity patterns (Ke et al., 2011).

Table 4: Summary of Optical and Electrical Properties

Sample	Band Gap (eV)	Absorption Shift	Conductivity Trend
Pure TiO_2	~3.2	UV region	Low
Ag doped TiO_2	~3.0–3.1	Slight red shift	Moderate
Sn doped TiO_2	~2.8–3.0	Strong red shift	High

Figure 8: Electrical Conductivity Variation with Doping Concentration

5. Discussion

5.1 Structure–Property Relationship

5.1.1 Lattice Effects and Dopant Incorporation

The effective inclusion of dopants in the TiO_2 lattice is confirmed by structural data. Ag and Sn ions were successfully incorporated into the crystalline structure. Ag doping uses a boundary pinning method to limit grain development. This greatly increases surface activity and decreases crystallite size. Strong strain effects and lattice distortion are introduced by Sn doping. Lattice mismatch and structural disorder are increased by substitutional Sn ions. Increased strain causes more defect states in the crystal lattice. These flaws have a substantial impact on electrical and optical characteristics. Doped TiO_2 systems were found to exhibit similar structural behaviour (Hanaor et al., 2012).

5.2 Optical Properties

5.2.1 Comparison of Literature and Band Gap Variation

Defect state generation is responsible for the lowering of the optical band gap. Within the prohibited band gap, dopants introduce localized energy levels (Kamarulzaman et al., 2015). These levels efficiently enable electronic transitions at lower energies. Sub-bandgap absorption and visible light response are made possible by tail states (Evtushenko et al., 2015). The samples with the largest band gap reduction were Sn-doped films. Higher lattice distortion and defect density are to blame (Bayan et al., 2021). Plasmonic effects caused a moderate narrowing of the band gap in Ag-doped films. Optical absorption is greatly increased by localized surface plasmon resonance (Grine et al., 2022)

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Table 6: Comparison of Optical Band Gap with Literature

Material System	Band Gap (eV) (Present Study)	Literature Value (eV)	Reference
Pure TiO_2	~3.2	3.2–3.3	Kamarulzaman et al., 2015
Ag–TiO_2	~3.0–3.1	2.9–3.1	Grine et al., 2022
Sn–TiO_2	~2.8–3.0	2.7–3.0	Bayan et al., 2021

5.2.2 Optical Trends

The observed band gap values closely correspond to trends documented in the literature. Compared to Ag-doped films, Sn-doped films exhibit a greater band gap reduction. Higher defect density and lattice distortion effects are to blame for this. Ag doping uses a plasmonic interaction method to improve optical absorption. Photon absorption efficiency is increased by localized surface plasmon resonance (Grine et al., 2022). Through defect-mediated transitions, Sn doping improves absorption (Bayan et al., 2021). In the vicinity of the band edge, a higher defect density raises the absorption coefficient. Photocatalysis and solar device applications are supported by optical improvement. These results are consistent with earlier optical research (Evtushenko et al., 2015).

5.3 Electrical Properties

5.3.1 Mechanism of Conductivity Enhancement

Increased charge carrier density improves electrical conductivity. Doping increases the concentration of free electrons by introducing donor levels (Ke et al., 2011). Improved electrical transport behaviour is facilitated by oxygen vacancies. According to Ke et al. (2011), these vacancies serve as shallow donors that facilitate electron conduction paths. Ag doping uses a defect-assisted transport method to increase carrier mobility. Due to vacancy formation, Sn doping dramatically raises carrier density (Bayan et al., 2021).

Table 7: Comparison of Electrical Conductivity with Literature

Material System	Conductivity Trend (Present Study)	Reported Behaviour	Reference
Pure TiO_2	Low conductivity	Low	Ke et al., 2011
Ag–TiO_2	Moderate increase	Improved mobility	Grine et al., 2022
Sn–TiO_2	High increase	High carrier density	Bayan et al., 2021

5.3.2 Electrical Trends

Compared to Ag-doped films, Sn-doped films showed greater conductivity. This is because Sn doping has a higher concentration of oxygen vacancies. Charge carrier density is greatly increased by higher vacancy concentration (Ke et al., 2011). Plasmonic effects cause a moderate improvement in Ag-doped films. Hopping across defect states is how electrons are transported (Grine et al., 2022). Because of the enhanced scattering effects, excess flaws may decrease mobility. For balanced conductivity performance, the ideal doping concentration is required. Electrical behaviour is consistent with oxide thin-film trends (Ke et al., 2011).

5.4 Combined Electrical and Optical Performance

Optical and structural modifications taken together greatly improve functional performance. Surface area and active sites are increased when crystallite size is reduced (Hanaor et al., 2012). Defect states improve optical absorption and alter band structure. Light absorption and carrier production efficiency are enhanced by band gap narrowing (Evtushenko et al., 2015). Electrical conduction channels are improved by increased carrier density (Ke et al., 2011). Plasmonic enhancement is the main way that Ag doping enhances optical responsiveness (Grine et al., 2022). By creating vacancies, Sn doping improves electrical conductivity (Bayan et al., 2021). Doped TiO_2 is appropriate for optoelectronic applications due to combined effects. These consist of photocatalytic systems, solar cells, and sensors.

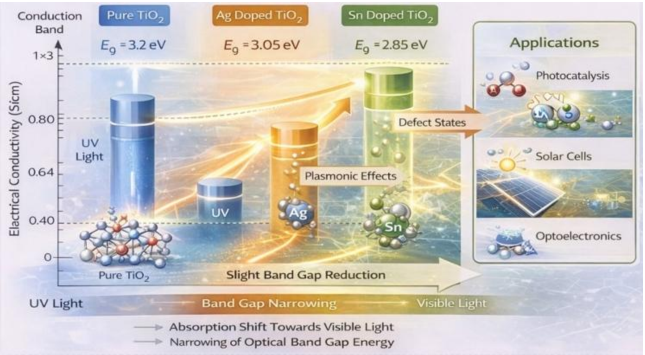

Figure 9: Comparative band gap variation from pure to doped TiO_2

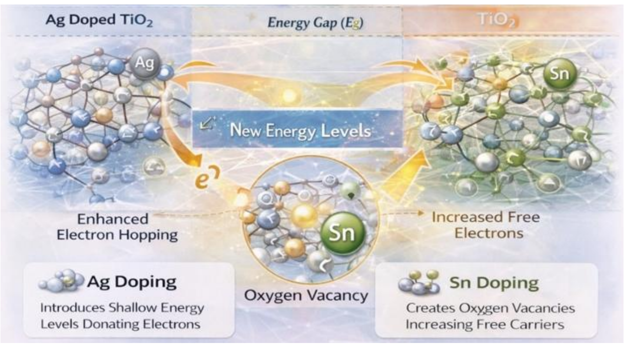

Figure 10: Electrical conduction mechanism showing role of oxygen vacancies

6. Limitations

6.1 Measurement and Experimental Restrictions

6.1.1 Limitations on Electrical Characterization

Electrical measurements were restricted to simple conductivity analysis. The current study did not thoroughly examine advanced transport systems. There was no direct experimental evaluation of carrier concentration or mobility. For a thorough transport investigation, no measurements of the Hall effect were made. These considerably restrict our comprehension of the dynamics of intrinsic charge transport. Without sophisticated methods, electrical conduction mechanisms are still only partially understood. Previous oxide thin film experiments reported similar limits (Ke et al., 2011).

6.1.2 Limitations on Optical Characterization

Only UV-visible absorption analysis was used for optical characterization. Studies using photoluminescence were not carried out to assess defect states. There was no experimental investigation of charge carrier recombination dynamics. Without additional spectroscopic confirmation, absorption edge shifts were interpreted. This limits our ability to fully comprehend optical transition mechanisms. Deeper understanding of band structure may be possible with the use of advanced optical techniques. Previous optical research emphasized these limitations (Evtushenko et al., 2015).

6.2 Limitations on Materials and Processing

6.2.1 Optimization of Dopant Concentration

In the current work, dopant concentration optimization was not thoroughly investigated. For comparative analysis, only a small range of doping levels were examined. The ideal level of focus for optimum performance is still unclear. Recombination centers brought about by excessive doping might drastically lower performance. Optical and electrical qualities must be balanced by controlled optimization. In doped TiO_2 systems, similar findings were documented (Kamarulzaman et al., 2015).

6.2.2 Morphological and Structural Limitations

The study did not thoroughly examine the impacts of film thickness change. The impacts of porosity and surface roughness were not quantitatively examined. Without thorough microscopic measurement, grain boundary effects were interpreted. These elements have a major impact on electrical transport and optical absorption. To fully comprehend structure-property, more research is necessary.

Table 8: Summary of Limitations and Their Impact

Limitation Area	Description	Impact on Study
Electrical analysis	Only conductivity measured	Limited transport understanding
Optical analysis	No PL or advanced spectroscopy	Incomplete defect analysis
Dopant optimization	Limited concentration range	Suboptimal performance
Structural analysis	Limited quantitative morphology	Partial structure-property correlation

Figure 11: Limitations in Optical and Electrical Characterization

7. Future Scope

7.1 Advanced Characterization of Optics

Photoluminescence should be used in future research to analyze defect states. Carrier recombination kinetics can be vividly seen by time-resolved spectroscopy. Accurate optical constants and thickness measurements can be obtained by ellipsometry. Advanced spectroscopic methods can be used to improve band structure analysis. These techniques improve our knowledge of optical transitions in doped systems.

7.2 Advanced Electrical Analysis

It is necessary to incorporate advanced electrical characterisation, such as the Hall effect. Carrier mobility and carrier concentration values are obtained by Hall measurements. Charge transport processes can be efficiently analyzed using impedance spectroscopy. Studies of temperature-dependent conductivity can provide insight into the behaviour of activation energy. These methods offer a more thorough understanding of electrical transport systems. In oxide semiconductor research, advanced techniques were advised (Ke et al., 2011).

7.3 Multi-Doping Techniques and Material Optimization

For improved properties, multi-dopant systems should be investigated in future research. Co-doping can concurrently enhance electrical and optical performance in a synergistic way. More systematic research should be done on dopant concentration optimization. Both surface area and functional efficiency can be increased through nanostructuring. These methods can greatly enhance the performance characteristics of the device. The benefits of multi-doping techniques are highlighted in recent research (Chowdhury et al., 2025).

7.4 Research Focused on Applications

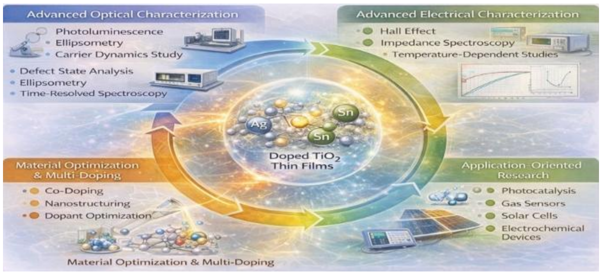

Figure 12: Future Research Directions for Doped TiO_2 Thin Films

Applications for photocatalysis and sensors can be thoroughly studied. For environmental monitoring applications, gas sensing properties can be assessed. Band gap manufactured films can be used to investigate solar energy applications. Enhanced surface activity and conductivity are advantageous for electrochemical sensors. Optimizing both optical and electrical qualities is necessary for these applications.

8. Conclusion

TiO_2 thin films were effectively generated via sol-gel dip coating. Structural analysis methods were used to confirm the formation of the anatase phase. Ag doping greatly enhanced optical responsiveness and polished grains. Plasmonic effects efficiently improved surface interactions and light absorption. Electrical conductivity and lattice strain were greatly enhanced by Sn doping. Charge carrier density and transport behaviour were improved by oxygen vacancies. Improved visible light absorption characteristics were made possible via band gap reduction. By using a doping technique, optical and electrical characteristics were successfully adjusted. The combined findings show that it is appropriate for sophisticated optoelectronic applications. These results are consistent with earlier research on doped TiO_2 systems (Kamarulzaman et al., 2015).

9. Novelty of Work

Ag and Sn doped TiO_2 films are compared. Optical and electrical properties are evaluated simultaneously. For both dopants, the structure-property link is methodically examined. Defect development methods are associated with optical and electrical characteristics. Deeper understanding of dopant-specific effects can be gained by comparative study. Studies in the literature currently in publication hardly ever provide such a comprehensive analysis.

10. Significance of Study

The study offers information for creating effective optoelectronic materials. The development of better photocatalytic and sensing devices is supported by the results. Improved visible light absorption efficiency is made possible by band gap engineering. Applications in electronic and sensing devices are supported by increased conductivity. Doped TiO_2 films exhibit promise for use in environmental and energy applications. Research on functional oxide semiconductors is advanced by the findings. These results are consistent with contemporary approaches to material design (Chowdhury et al., 2025).

Table 9: Practical Implications of Optical and Electrical Improvements

Property Improvement	Impact	Application Area
Band gap reduction	Visible light absorption	Solar cells
Increased conductivity	Faster charge transport	Sensors
Defect engineering	Enhanced reactivity	Photocatalysis
Grain refinement	Increased surface area	Energy devices

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Conflict of Interest

The authors declare no conflict of interest.

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Ethical Approval and Patient Consent

Not applicable for this materials-based experimental study.

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