

Electrical Performance Enhancement of CVD-Grown Undoped Tin Oxide (SnO₂) Thin Films through Substrate Temperature Variation

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Received: 16-04-2026, Received in Revised form: 05-06-2026, Accepted: 17-06-2026, Published: 30-06-2026

Abstract

Undoped tin oxide (SnO₂) thin films deposited by chemical vapor deposition (CVD) were investigated at substrate temperatures from 310 °C to 400 °C. Four-point probe measurements revealed a significant reduction in resistivity from 1840 Ωcm at 310 °C to 3.13×10⁻⁴ Ωcm at 390 °C, while the sheet resistance decreased from 9.2×10⁷ to 15.68 Ω/square. The optimal electrical performance at 390 °C with conductivity (σ) of 3.19×10³ (Ωcm)⁻¹ surpasses many reported values for undoped SnO₂, and this value approaches industrially relevant transparent conducting oxide standards. The conductivity enhancement is attributed to increased carrier concentration and mobility due to improved crystallinity and oxygen vacancy formation at high substrate temperatures. Hence, the results revealed that substrate temperature is an important parameter for modifying the electrical performance of undoped SnO₂ thin films suitable for transparent electrode applications in photovoltaics and flat-panel displays.

Keywords: SnO₂, Electrical Resistivity, Conductivity, Sheet resistance, Chemical Vapor Deposition

Introduction

Tin oxide (SnO₂) is an n-type semiconductor with a wide bandgap whose intrinsic conductivity arises from non-stoichiometry, specifically oxygen vacancies and tin interstitials that act as electron donors. It is widely employed as a transparent conducting oxide in various electronic and optoelectronic devices [1][2]. Transparent conducting oxides (TCOs) form the cornerstone of modern optoelectronics, enabling devices ranging from solar cells and light-emitting diodes to touch screens and smart windows [3][4]. Among TCOs, tin dioxide (SnO₂) is unique for its exceptional thermal and chemical stability, mechanical hardness, low cost, and non-toxicity compared with indium tin oxide (ITO) [5][6]. However, undoped SnO₂ typically has lower conductivity than ITO; therefore, it requires optimization of deposition parameters, particularly substrate temperature, to achieve competitive performance. Tin oxide electrical conductivity stems from defect concentrations, such as oxygen vacancies and tin interstitials, which act as electron donors. Substrate temperature strongly affects defect concentrations, grain size and electrical transport properties during deposition [7].

The electrical conductivity σ of a semiconductor is governed by:

$$\sigma = ne\mu \quad (1)$$

with n as the concentration of free electrons (cm⁻³), e as the elementary charge (1.602×10⁻¹⁹ C) and μ as the electron mobility (cm²/Vs). For SnO₂, maximizing both n and μ is essential for high-performance TCO applications, which typically require σ > 10³ S cm⁻¹, corresponding to ρ < 10⁻³ Ωcm [8]. In evaluating the electrical properties of conductive thin films, sheet resistance (R_{sh}) is an indispensable index. It is obtained by the four-probe

technique and accounts for the resistance of a square layer area. The four-point probe method used here provides accurate resistivity measurements without contact-resistance effects [9]. The relation between R_{sh} and the resistivity (ρ) is calculated with equation (2) with knowledge of the thickness (t) of the film as:

$$R_{sh} = \rho/t \quad (2)$$

For a given resistivity, sheet resistance is inversely proportional to the film thickness t.

Substrate temperature influences multiple interrelated phenomena in thin films during deposition. These include precursor decomposition kinetics, where higher temperatures increase the thermal decomposition of SnCl₄; crystallite growth promoted by enhanced mobility (surface diffusion of adatoms); oxygen incorporation and stoichiometry; grain boundary formation; and dopant activation (in doped films) [2][7]. Understanding these relationships is essential for rational film design. However, few studies have examined the electrical properties of undoped SnO₂ across a wide temperature range using CVD, with most literature focusing on doped SnO₂ thin films (F-doped or Sb-doped) or alternative deposition methods (spray pyrolysis and sol-gel) [10][11]. Previous studies have shown resistivity decreases with increasing deposition temperature due to enhanced crystallinity and carrier concentration [12][13]. However, excessive temperature can reduce conductivity through precursor re-evaporation or stoichiometric changes [14]. This study quantifies the relationship between substrate temperature and key electrical parameters like resistivity, sheet resistance and conductivity to optimize undoped SnO₂ deposited by CVD for transparent electrode applications in photovoltaics and flat-panel displays.

Materials and Methods

Film Synthesis

Undoped SnO₂ films were deposited on glass substrates via CVD using SnCl₄ precursor. The following temperatures were employed in performing the film deposition: 310 °C, 330 °C, 350 °C, 370 °C, 390 °C and 400 °C.

Substrate Preparation:

Soda-lime glass substrates of dimensions 25 mm × 25 mm × 1 mm were cleaned consecutively with:

- Detergent solution with ultrasonic agitation (15 min, 40 °C)
- Deionized water rinsing (5 cycles)
- Acetone ultrasonic bath (10 min)
- Isopropanol ultrasonic bath (10 min)
- And finally, expose to a hand dryer for a few minutes to dry properly.

Deposition Parameters:

- Precursor: Tin(IV) chloride (SnCl₄), serving as both precursor and solvent.
- Carrier gas: Oxygen
- Pressure: 1.5 bar (absolute)
- Substrate temperatures of 310 °C, 330 °C, 350 °C, 370 °C, 390 °C and 400 °C
- Deposition time: 6 minutes (constant)
- Cooling: Natural convection to 50 °C before removal

Deposition Process

The substrates were placed in the reactor susceptor and were heated to the target temperatures, then oxygen was passed through the bubbler containing the precursor at 1.5 bar pressure. Hydrochloric acid (HCl) and water (H₂O) vapor were exhausted from the reactor. The samples were allowed to cool, tested with a digital multimeter and finally stored in dried Petri dishes.

Electrical Characterization

The electrical measurements were carried out on the deposited films using a four-point probe system equipped with a linear probe head (probe spacing: 1.0 mm). Measurements were taken at five different positions on each sample, and the mean value was reported. The probe current was maintained at 1.0 mA to avoid heating effects. The sheet Resistance of the undoped SnO₂ films at various deposition temperatures was calculated using equation (2).

Thickness Measurement

The film thicknesses were measured using the stylus profilometer (TENCOR P-10 Profilometer) with a stylus radius of 2.5 µm and an applied force of 3.0 mg. Measurements were taken at three different locations for each film, and the mean thickness was determined. Films deposited at different substrate temperatures showed a consistent thickness of 0.2±0.01 µm.

Results and Discussion

The deposited films with different substrate temperatures were found to have a thickness of 0.2±0.01 µm as measured using stylus profilometry. This uniformity validates that the deposition rate was constant under the employed conditions. This allowed the direct evaluation of electrical properties as a function of substrate temperature without thickness variations.

The electrical properties of the deposited SnO₂ thin films are reflected in the resistivity, sheet resistance and conductivity of the samples at different deposition temperatures. Table 1 shows the electrical parameters of the synthesized undoped SnO₂ at various substrate temperatures.

Table 1: Electrical parameters of undoped SnO₂ thin films at various substrate temperatures

Temperature °C	Resistivity (Ωcm)	Sheet Resistance (Ω/square)	Conductivity (Ωcm) ⁻¹
310	1840	92000000	0.000543
330	2.8415	142075	0.351927
350	2.8415	142075	0.351927
370	0.007486	374.3	133.5827
390	0.000313	15.65	3194.888
400	0.004236	211.8	236.0718

Figure 1 shows the variation of resistivity in undoped SnO₂ thin films with substrate temperature.

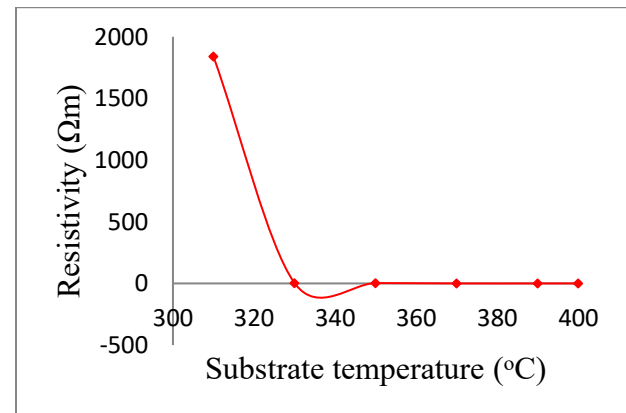


Figure 1: Variation of resistivity of undoped SnO₂ thin films with substrate temperature

From the graph, it was observed that as substrate temperature increased up to 390 °C, resistivity decreased exponentially [13][15]. Resistivity decreased from 1840 Ω·cm at 310 °C to 3.13×10⁻⁴ Ω·cm at 390 °C, a reduction of approximately seven orders of magnitude. This improvement is attributed to increased oxygen vacancy concentration at higher temperatures, which acts as a donor; improved crystallinity and grain growth; reduced grain-boundary scattering; and enhanced carrier mobility due to defect annealing [5][16]. The sheet resistance (R_{sh}) of films deposited on a glass substrate showed a similar

decreasing trend, from $9.2 \times 10^7 \Omega/\text{square}$ at 310°C to $15.65 \Omega/\text{square}$ at 390°C . The corresponding decrease in sheet resistance is consistent with the resistivity reduction, supporting the dominant effect of substrate temperature on charge-transport properties [13][14]. At lower temperatures (310°C to 350°C), the films exhibit high resistivity due to poor crystallinity, small grain size and limited oxygen vacancy formation. The high sheet resistance indicates considerable grain boundary scattering, which impedes charge transport [17]. The relatively constant resistivity between 330°C and 350°C suggests a threshold temperature for significant structural formation. In contrast, from 350°C to 390°C , resistivity dropped rapidly from $0.175 \Omega \cdot \text{cm}$ to $3.13 \times 10^{-4} \Omega \cdot \text{cm}$, indicating enhanced crystallinity and defect formation. The improvement at 390°C suggests optimal conditions for simultaneous grain growth and defect incorporation. Figure 2 shows the variation of conductivity in undoped SnO_2 thin films with substrate temperature.

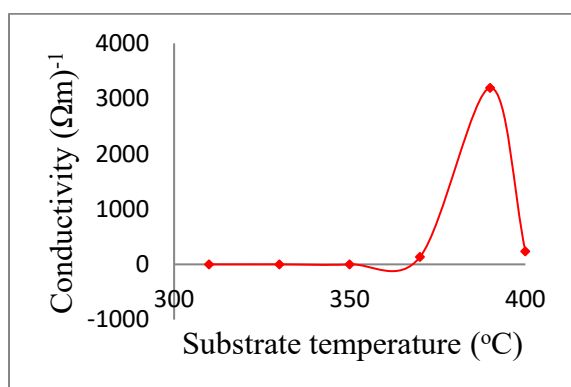


Figure 2: Variation of conductivity with substrate temperature of undoped SnO_2 thin films

The conductivity of the synthesized SnO_2 thin films increases from $5.43 \times 10^{-4} (\Omega\text{cm})^{-1}$ at 310°C to $3.19 \times 10^3 (\Omega\text{cm})^{-1}$ at 390°C representing an improvement of over six orders of magnitude. The optimal conductivity at 390°C ($3.19 \times 10^3 (\Omega\text{cm})^{-1}$) achieved in this study is one of the highest reported for undoped SnO_2 thin films, and it compares favorably with reported values for doped SnO_2 thin films from other deposition methods and approaches the performance of doped TCO material. This optimal substrate temperature of 390°C represents a balance between defect formation and structural ordering [10][11]. At substrate temperatures above 390°C , conductivity decreases drastically to $236 (\Omega\text{cm})^{-1}$ at 400°C as observed in Figure 2. This degradation is attributed to re-evaporation of oxygen vacancies or tin species at excessive temperatures, stoichiometric changes that reduce carrier concentration, and possible phase segregation or surface roughening [14].

Comparison with Literatures

Table 2 compares the electrical properties of undoped SnO_2 thin films obtained in this study with previously reported values.

Table 2: Comparison of electrical properties obtained in the study with previously reported values for undoped SnO_2 thin films

Deposition	Substrate Temperature (°C)	Resistivity (Ωcm)	Conductivity (Ωcm) ⁻¹	Reference
CVD	390	3.13×10^{-4}	3.19×10^3	This work
Spray Pyrolysis	400	6.5×10^{-3}	1.54×10^2	Saji et al. [13]
Spray Pyrolysis	450	1.2×10^{-2}	83.3	Elangovan et al. [12]
Sol-Gel	500	3.5×10^{-2}	28.6	Sanon et al. [14]
APC VD	475	8.0×10^{-4}	1.25×10^3	Karsloglu et al. [15]

Conclusion

Substrate temperature significantly influenced the electrical properties of CVD-grown undoped SnO_2 thin films. The resistivity was found to have decreased exponentially from $1840 \Omega\text{cm}$ at 310°C to $3.13 \times 10^{-4} \Omega\text{cm}$ at 390°C , with a corresponding increase in the films' conductivity from 5.43×10^{-4} to $3.19 \times 10^3 (\Omega\text{cm})^{-1}$. Films deposited at 390°C exhibit optimal electrical performance, which makes them most suitable for transparent electrode applications in photovoltaics and flat-panel displays. The observed conductivity enhancement is attributed to increased oxygen vacancy concentration, improved crystallinity and reduced grain-boundary scattering at elevated substrate temperatures. The degradation in film performance at 400°C is associated with re-evaporation effects and stoichiometric changes.

These findings provide a roadmap for tuning SnO_2 electrical properties through CVD-grown deposition-temperature control and show that undoped SnO_2 can achieve performance levels comparable to doped TCO materials. This offers a cost-effective and non-toxic alternative for optoelectronic applications.

Acknowledgments

The authors thank their loved ones for their encouragement and support throughout this work.

Competing Interests

None.

Authors' Contribution

Conceptualization and methodology, A. Obunegbe and K.O. Ojo; formal analysis, investigation, resources, data curation, A. Obunegbe; writing - original draft preparation, A. Obunegbe; writing - review and editing,

A. Obunegbe. All authors have read and agreed to the published version of the manuscript.

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