Synthesis, Development and Electrical Characterization of TiO_2 Thin Films by Sol Gel and Spin Coating Method

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Abstract

This study focuses on the synthesis and characterization of titanium dioxide (TiO_2) thin films using the sol-gel method. TiO_2, known for its exceptional photocatalytic and electrical properties, has gained significant attention in various applications, including photovoltaics, sensors, and optoelectronic devices. The sol-gel approach offers a versatile and cost-effective technique for fabricating high-quality thin films with controlled thickness and uniformity. The TiO_2 thin films were deposited onto substrates using a precursor solution, followed by a thermal annealing process to achieve crystallization. The electrical properties of the films were systematically investigated by using static electrical system. Electrical characterizations, including resistivity, TCR and activation energy revealed the potential applications of the TiO_2 films in electronic devices. This research work demonstrates the feasibility of using the sol-gel method to develop TiO_2 thin films with desirable electrical characteristics, paving the way for their integration into advanced electronic and optoelectronic systems.

Keywords: Titanium dioxide, crystallization, synthesis, sol-gel, electrical properties.

Introduction:

Metal oxide semiconductors, such as titanium dioxide (TiO_2), zinc oxide (ZnO), and tin oxide (SnO_2), have become increasingly important in materials science and various technological domains due to their unique electronic, optical, and chemical properties [1, 2]. These thin films are essential in the development of a wide range of applications, including transparent conductive oxides (TCOs) for touchscreens and displays, gas sensors, photocatalysts, and photovoltaic devices. The demand for these materials is driven by their high stability, cost-effectiveness, and the ability to fine-tune their properties through doping, surface modification, and phase control. In addition, metal oxide semiconductors are critical for the development of next-generation electronic devices, such as thin-film transistors, memristors, and flexible electronics, where their high mobility, wide bandgap, and tunable electrical characteristics are advantageous [2-5]. In the field of renewable energy, these materials are pivotal in enhancing the efficiency of solar cells and catalyzing water splitting for hydrogen production. The versatility and performance of metal oxide semiconductor thin films make them indispensable in both existing technologies and emerging fields such as nanotechnology and environmental remediation, where advanced materials with tailored properties are increasingly required [6, 7].

Titanium dioxide is a widely studied material due to its exceptional properties, including high refractive index, chemical stability, and strong photocatalytic activity. These characteristics make TiO_2 a versatile candidate for applications in areas such as photovoltaics, sensors, photocatalysis, and protective coatings [8, 9]. The sol-gel method is one of the most effective techniques for synthesizing TiO_2 thin films, offering advantages like simplicity, cost-effectiveness, and the ability to produce films with controlled composition and microstructure. This process involves the hydrolysis and condensation of metal alkoxides to form a colloidal suspension or gel, which is subsequently deposited onto a substrate and annealed to produce the final thin film [10, 11]. The resulting TiO_2 thin films exhibit varying phases, primarily anatase and rutile, which significantly influence their optical and electrical properties. Titanium dioxide thin films are widely recognized for their excellent optical and photocatalytic properties, making them suitable for diverse applications, including self-cleaning surfaces, gas sensing, and photocatalysis for environmental remediation [12, 13]. The objective of this study is to explore the synthesis of TiO_2 thin films using the sol-gel method, followed by a comprehensive analysis of their electrical properties. By optimizing the synthesis parameters, this research aims to develop high-performance TiO_2 thin films suitable for integration into advanced electronic and optoelectronic devices [13, 14].

2. Materials and methods

The sol-gel and spin coating methods was adopted for development of TiO_2 thin films. All the AR grade chemicals were used without any further purification. Titanium isopropoxide (TTIP, Ti [OCH $(CH_3)_2]_4$) was used as the titanium precursor. Acetic acid glacial (CH_3COOH) was used as the catalyst supplied. Ethanol with purity 99.99 % and de-ionized water were used as the solvents [15, 16]. The synthesis and development of TiO_2 films process is illustrated in Fig. 1.

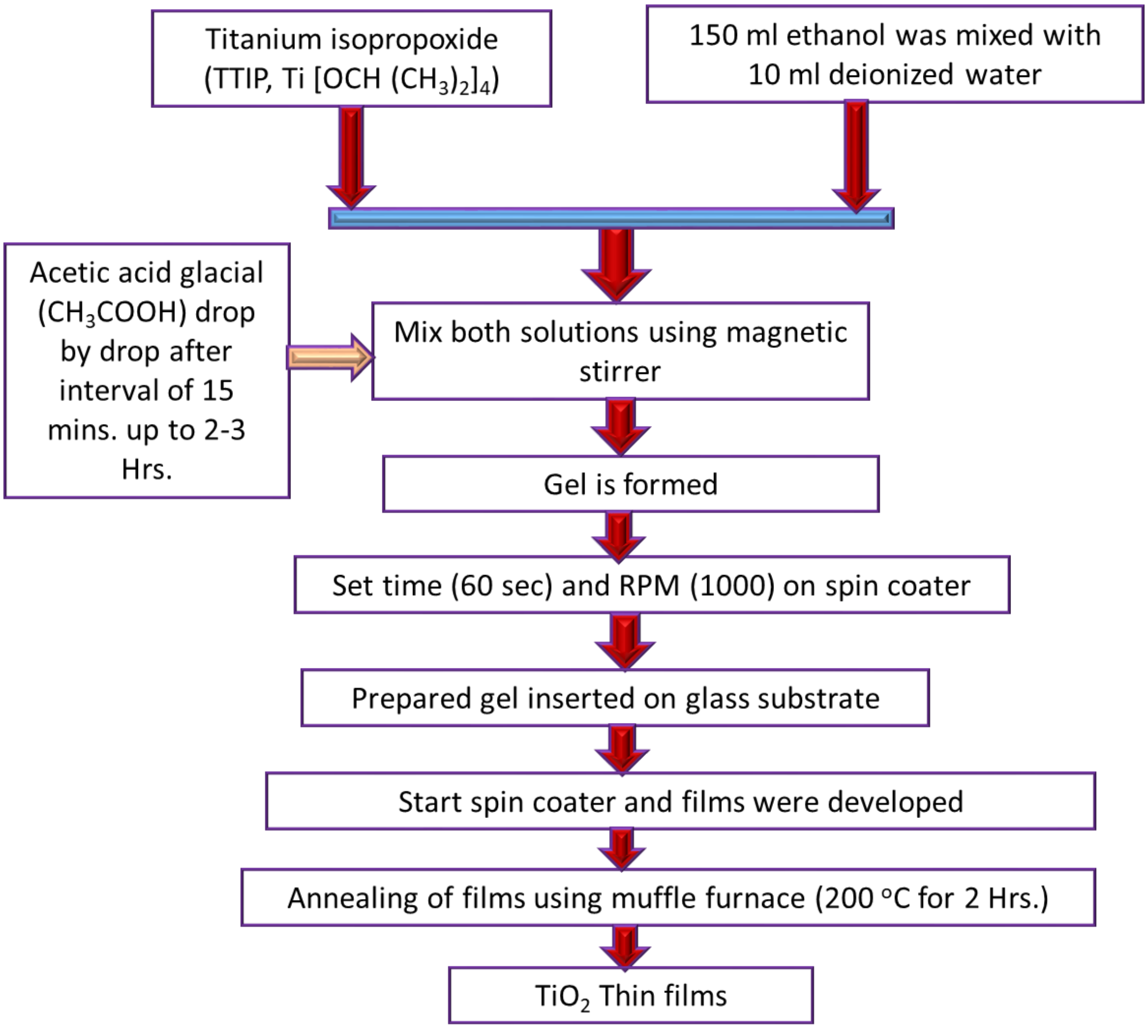

Figure 1: Synthesis and preparation of TiO_2 films process

The electrical characterizations of developed TiO_2 thin films were investigated by using the half-bridge method. The arrangement is shown in Fig. 2. The developed system consists of an electrical coil for heating phenomena. This coil is connected to a dimmer stat for controlling the voltage of the coil, and according to that, the temperature in the dome or glass chamber (25 liters and ~ 12" diameter) is controlled. A +30 VDC power supply was used for biasing the films. We used the digital thermocouple to measure or display the ambient temperature across the film. The reference resistance of 10 mega ohms was used in the circuit. The digital multimeter was used to measure voltage across the film. After measuring the voltage, it is converted into resistance by using Equation 1. At the interval of 10 °C temperature, voltage across the reference resistance was noted [17-19].

$$R\ sample = R\ ref\ [((Vsupply)/(V\ ref))-1] \qquad \text{(Eq. 1)}$$

Where, R sample – sample or film resistance,

Vsupply – Applied voltage, and

Vref – Voltage across external resistor R_L.

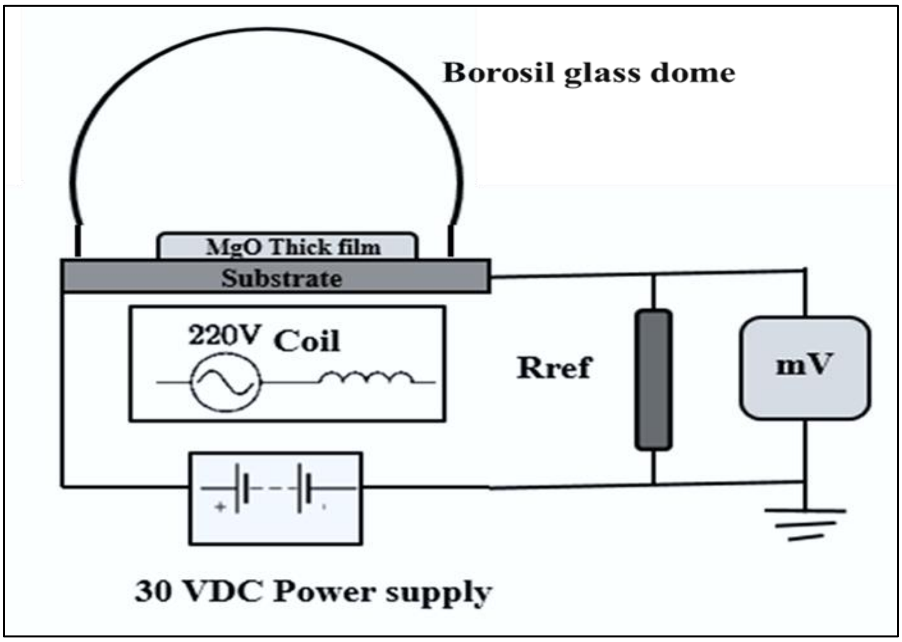

Figure 2: Static electrical system

Equation 2 was used to determine resistivity of prepared films.

$$\rho = \left(\frac{R \times b \times t}{l}\right) \Omega - m \qquad \text{(Eq. 2)}$$

Where, ρ = Resistivity of prepared film, R = resistance at normal temperature, b = breadth of film, t = thickness of the film, L = length of the film.

$$TCR = \frac{1}{R_o}\left(\frac{\Delta R}{\Delta T}\right) /^{O} C \qquad \text{(Eq. 3)}$$

Where, ΔR = change in resistance between temperature T_1 and T_2, ΔT = temperature difference between T_1 and T_2 and R_o = room temperature resistance of the film.

Eq. 4 is used to calculated activation energy of developed films.

$$\Delta E = Ae^{-Ea/kBT} \quad \text{eV} \qquad \text{(Eq. 4)}$$

Where, ΔE = Activation energy, T = Temperature in Kelvin and A = Arrhenius prefactor.

3. Result and discussion

Resistivity is a fundamental electrical property that measures a material's ability to resist the flow of electric current. It is defined as the resistance offered by a material of unit length and unit cross-sectional area and is typically expressed in ohm-meters (Ω·m). The resistivity of a material is influenced by factors such as its composition, structure, temperature, and the presence of impurities [19, 21]. In the context of metal oxide semiconductor thin films, resistivity is a critical parameter that directly affects the performance of electronic and optoelectronic devices. The ability to precisely control the resistivity of TiO_2 thin films is therefore essential for their effective integration into a wide range of advanced technologies, from energy storage and conversion to environmental sensing and beyond. The resistance versus temperature plot for TiO_2 thin films typically shows how the electrical resistance of the material changes with temperature [20, 21]. Fig. 3 reveals the resistance versus temperature plot for TiO_2 thin films.

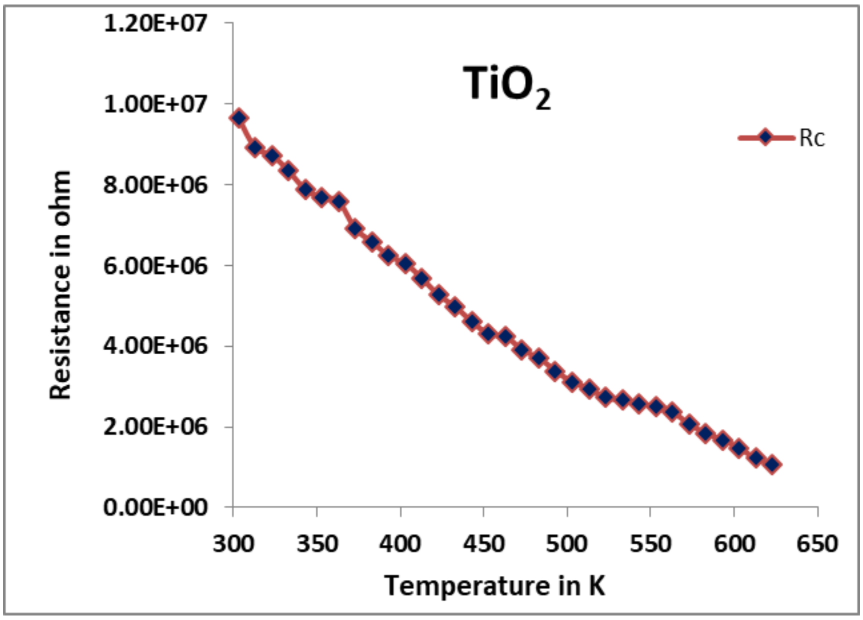

Figure 3: Resistance versus temperature plot for TiO_2 thin films

Form Fig. 3 it is observed that, resistance typically decreases as the temperature increases. This is because the thermal energy at higher temperatures excites more charge carriers (electrons and holes), reducing resistance. The decreases the magnitude of resistance as the temperature increases attributed semiconducting nature of films [18, 19]. At low temperatures, the resistance of TiO_2 thin films is recorded high due to the limited thermal excitation of charge carriers. As temperature increases, the resistance decreases, showing semiconducting behavior. The resistivity of TiO_2 thin films was found to be 3.7×10^6 Ω.m [21, 22]. The study of resistance as a function of temperature not only provides insights into the fundamental properties of TiO_2 thin films but also guides the design and optimization of devices for specific high-performance applications.

The Temperature Coefficient of Resistance (TCR) is a parameter that quantifies how the electrical resistance of a material changes with temperature. It is typically expressed in parts per million per degree Celsius (ppm/°C) or as a percentage change in resistance per degree Celsius. A positive TCR indicates that resistance increases with rising temperature, while a negative TCR means resistance decreases as temperature increases [23, 24]. The TCR of a material is crucial for applications where temperature-induced changes in resistance need to be controlled or exploited. TCR is a key factor in determining their suitability for various applications. Due to its semiconducting nature, TiO_2 films exhibits a negative TCR as shown in Table 1, where the resistance decreases as temperature increases, which is characteristic of intrinsic semiconductors. This property makes TiO_2 thin films highly valuable in temperature sensors and thermal imaging devices [24, 25]. In gas sensing applications, TCR could be enhance sensitivity, as gas adsorption alter the film's conductivity in a temperature-dependent manner.

Activation energy is the minimum energy required for charge carriers (such as electrons or holes) to move and contribute to electrical conduction in a material [19]. The activation energy of TiO_2 thin films plays a critical role in determining their electrical properties and, consequently, their suitability for various applications. In gas sensors, for example, a lower activation energy at higher temperatures enhance the sensor's response by increasing the number of charge carriers that participate in conduction when exposed to a target gas. In photocatalytic applications, the activation energy affects the efficiency of charge carrier generation and separation, which is crucial for processes like water splitting and pollutant degradation [18, 19]. For electronic devices such as resistive switching memories (memristors), the activation energy influences the switching behavior and stability of the device, especially under varying temperature conditions. Additionally, in photovoltaic devices, optimizing the activation energy through doping or controlled processing improve charge carrier mobility and reduce recombination losses, thereby enhancing the overall efficiency of the device [22, 23]. By understanding and controlling the activation energy in different temperature regions, researchers tailor the performance of TiO_2 thin films to meet the specific requirements of a wide range of advanced technologies [24, 25]. An Arrhenius plot is a graphical representation used to determine the activation energy of a material [26, 27]. It is constructed by plotting the natural logarithm of the electrical conductivity (or the reciprocal of resistance) against the reciprocal of the temperature (1/T) as shown in Fig. 4. The estimated values of activation energy of TiO_2 thin films at higher temperature region (HTR) and lower temperature region (LTR) are tabulated in Table 1.

Table 1: Electrical outcomes of TiO_2 thin films

Thickness (nm)	Resistivity (Ω.m)	TCR (/°C)	Activation energy (eV)	
			HTR	LTR
78.65	3.7×10^{6}	-0.00281	0.1628	0.0488

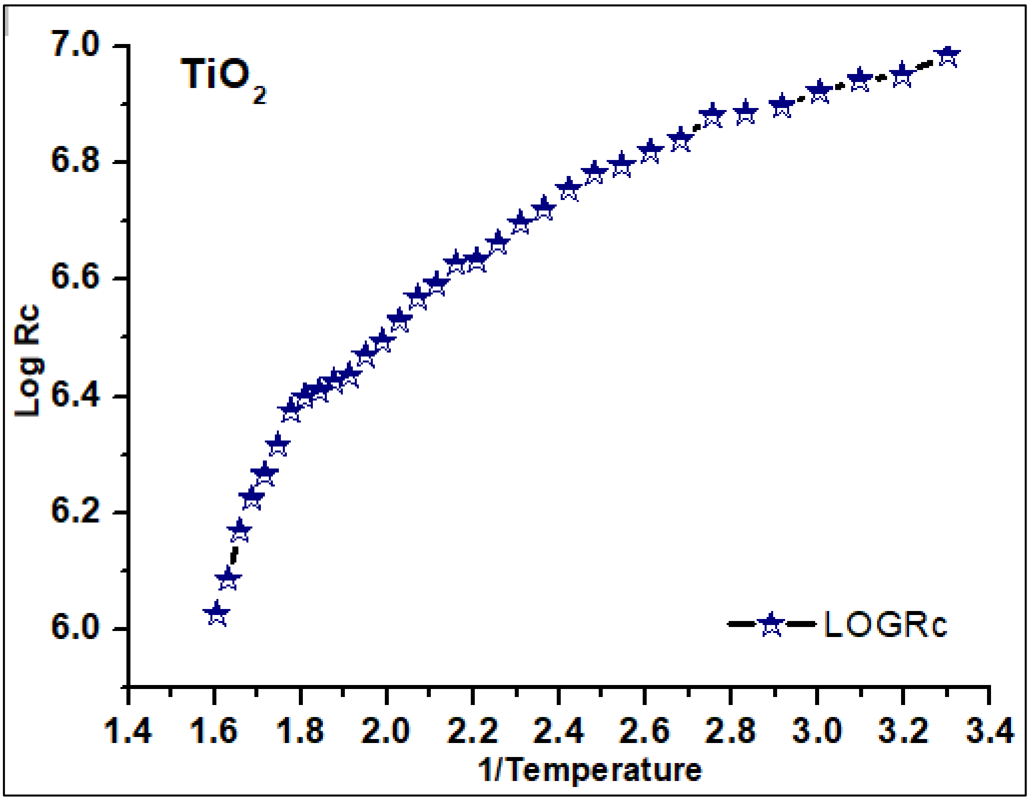

Figure 4: Arrhenius plot for TiO_2 thin films

Conclusions and Future Scope:

TiO_2 thin films developed on glass substrate by sol gel and spin coating methods. The thickness of films was found to be in nanometer range by mass difference method. The electrical parameters such as resistivity, TCR and activation energy of TiO_2 thin films were investigated using half bridge method and static electric system. The resistance versus temperature behavior of TiO_2 thin films demonstrates the material's semiconducting properties, where resistance decreases with increasing temperature due to enhanced thermal excitation of charge carriers. This temperature-dependent resistivity is crucial for various applications, such as in gas sensors, where the resistance changes in response to temperature fluctuations or gas adsorption, enabling sensitive detection mechanisms. The study has shown that TiO_2 thin films exhibit a typical semiconducting behavior with temperature-dependent resistivity, and their activation energy provides valuable insights into conduction mechanisms. These films have shown potential in applications ranging from transparent conductive layers to gas sensors and photocatalysts, highlighting their versatility and utility in advanced technologies. Future research should focus on exploring and optimizing additional processing parameters to further enhance the performance of TiO_2 thin films. Investigating the effects of different dopants and co-doping strategies could provide insights into tailoring electrical and optical properties for targeted applications. Additionally, advancing the understanding of the relationship between film microstructure and electrical behavior will be crucial for developing high-performance devices. Exploring scalable fabrication techniques and integrating TiO_2 thin films into flexible and wearable electronics represents a promising avenue for future research.

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Conflicts of Interest:

The author declare no conflict of interest.

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