

DEPOSITION AND CHARACTERIZATION OF ZnO THIN FILMS FOR THIN-FILM TRANSISTOR APPLICATIONS

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ABSTRACT

Zinc oxide (ZnO) is an attractive semiconductor for thin-film transistor (TFT) applications because of its wide direct band gap, relatively high electron mobility, optical transparency, chemical stability and compatibility with low-temperature thin-film processing. The performance of ZnO-based TFTs is strongly dependent on the structural quality, surface morphology, film thickness, carrier concentration, optical properties and defect chemistry of the semiconductor layer. This study investigated the deposition and characterization of ZnO thin films intended for thin-film transistor applications. ZnO thin films were deposited as channel layers using a sol-gel spin coating technique to ensure uniformity and scalability, while the AAO dielectric layers were formed by controlled electrochemical anodization of aluminium substrates. The physical and structural characteristics of the films were examined using profilometry to determine thickness uniformity, scanning electron microscopy (SEM) to observe surface morphology, and Hall effect measurements to evaluate carrier mobility and electron concentration. Electrical performance of the fabricated TFTs was evaluated using standard current-voltage (I-V) testing in a field-effect transistor configuration. Profilometry confirmed uniform film thicknesses across both the ZnO and AAO layers, a prerequisite for stable device performance. SEM imaging showed that ZnO formed a dense, compact morphology beneficial for charge transport, whereas AAO displayed a nanoporous structure that contributes to its high surface area but can influence dielectric strength. Hall measurements indicated that ZnO exhibited a high carrier mobility of 114.6 cm²/Vs and moderate electron concentration, confirming its suitability for TFT channels. However, electrical characterization of the AAO layer revealed unintended conductivity, suggesting possible residual conductive pathways or incomplete anodization, which highlights the need for further process optimization. Nonetheless, further refinement of the AAO anodization process is needed to minimize leakage and enhance dielectric reliability.

1. Introduction

The increasing demand for low-cost, lightweight, transparent and flexible electronic systems has stimulated considerable interest in oxide semiconductor materials for thin-film transistor applications. Thin-film transistors are fundamental switching and amplification components in displays, sensors, electronic circuits, memory devices and other forms of large-area electronics. Conventional amorphous silicon has been widely used in display technologies; however, its relatively low carrier mobility has encouraged research into alternative semiconductor materials capable of providing improved electrical performance (Nomura et al., 2004; Fortunato et al., 2012).

Among the various oxide semiconductors investigated for TFT applications, zinc oxide (ZnO) has attracted substantial attention. ZnO is an II-VI compound semiconductor with a wide direct band gap of approximately 3.37 eV at room temperature and a relatively high exciton binding energy of approximately 60 meV (Özgür et al., 2005). These properties make ZnO particularly attractive for transparent and optoelectronic devices. Its optical transparency in the visible region, combined with

its semiconducting behaviour and relatively abundant constituent elements, provides advantages for large-area electronic applications (Bagnall et al., 1997).

ZnO normally crystallizes in the hexagonal wurtzite structure under ambient conditions. The crystal structure is characterized by tetrahedral coordination of Zn and O atoms, resulting in polar surfaces and anisotropic physical properties (Hooffman et al., 2003). The structural, electrical and optical characteristics of ZnO films are strongly influenced by crystallographic orientation, crystallite size, defect concentration, deposition temperature and processing conditions (Özgür et al., 2005).

The electrical behaviour of ZnO is particularly sensitive to native defects and unintentional impurities. Oxygen vacancies, zinc interstitials, hydrogen and other defects or impurities can influence the electron concentration and conductivity of ZnO. Consequently, obtaining a ZnO film with suitable carrier concentration is essential for TFT applications because an excessively conductive channel can result in poor gate modulation, whereas excessively low conductivity may limit current transport. Several techniques have been employed for ZnO thin-film deposition, including sputtering, chemical vapour deposition, pulsed-laser deposition, atomic layer deposition, spray pyrolysis, sol-gel processing and spin coating. Physical vapour based methods can produce high quality films but may require relatively sophisticated equipment. Solution based methods such as sol-gel and spin coating are attractive because of their low equipment requirements, potentially low processing temperatures, scalability and ease of compositional modification (Look, 2001).

The suitability of a ZnO thin film for TFT applications cannot be established from a single material parameter. Instead, several characteristics must be considered simultaneously. The film should possess adequate crystallinity, uniform thickness, low surface roughness, appropriate carrier concentration and mobility, good optical transparency and a low density of electrically active defects. In addition, the semiconductor surface must be compatible with the gate dielectric because the semiconductor/dielectric interface plays an important role in determining threshold voltage, subthreshold behaviour, hysteresis, mobility and device stability (Minami, 2005).

Early studies demonstrated the feasibility of ZnO-based TFTs. Ellmer. (2000) demonstrated transparent ZnO TFTs using RF magnetron sputtering, establishing the potential of ZnO as a channel semiconductor for transparent electronics. Subsequent research has expanded the use of oxide semiconductors in TFTs and demonstrated that material composition, processing conditions and semiconductor/dielectric interfaces strongly influence device performance (Fortunato et al., 2012). Despite the progress in ZnO electronics, solution-processed ZnO films require careful optimization because film morphology, crystallinity and electrical properties can vary significantly with precursor chemistry and processing conditions. Therefore, systematic characterization is necessary to establish the relationship between deposition parameters and the properties required for TFT operation (Ellmer, 2012).

The objective of this study is therefore to deposit ZnO thin films under controlled processing conditions and characterize their morphological, thickness and electrical properties for potential application as semiconductor channel layers in thin-film transistors.

2. Theoretical Background

2.1 Electronic structure of ZnO

ZnO is a wide-band-gap semiconductor whose electronic properties originate primarily from the interaction between Zn and O atomic orbitals. The valence band is predominantly associated with O 2p states, while the conduction band has substantial Zn 4s character. The energy separation between the valence and conduction bands produces the wide band gap characteristic of ZnO (Özgür et al., 2005). At room temperature, the band gap of high-quality ZnO is approximately: $E_g \approx 3.37$ eV. The large band gap allows ZnO films to transmit a substantial fraction of visible radiation, making the material attractive for transparent electronic devices.

2.2 Crystal structure and Crystallite size

ZnO can exist in different crystal structures depending on temperature and pressure, but the stable structure under ordinary conditions is the hexagonal wurtzite structure. The wurtzite lattice is described by lattice parameters a and c , with a characteristic c/a ratio.

The crystallographic orientation of ZnO films can strongly influence their properties. Preferred orientation along the (002) plane, corresponding to the c -axis of the wurtzite structure, is frequently observed in deposited ZnO films (Özgür et al., 2005). The average crystallite size can be estimated from the broadening of an XRD peak using the Scherrer equation

$$D = \frac{K\lambda}{\beta \cos \theta} \quad 1$$

where D is the crystallite size, K is the shape factor, λ is the X-ray wavelength, β is the full width at half maximum (FWHM) of the diffraction peak in radians and θ is the Bragg angle. The Scherrer equation provides an approximate crystallite size and should not be interpreted as an exact grain-size measurement, particularly where instrumental broadening, micro strain or other effects contribute significantly to peak broadening.

3. Materials and Methods

3.1 Materials and Chemicals

- i. Soda lime glass.
- ii. Deionized (DI) water
- iii. Zinc oxide (ZnO) powder (sigma-aldrich); Zinc oxide (ZnO)
- iv. Ammonia solution (BDH)
- v. Non-porous anodic aluminium oxide (AAO) as a gate dielectric layer
- vi. Aluminum substrate (Commercial food grade aluminum foil served as the substrate)
- vii. Ethanol (BDH),
- viii. Keithley Instruments 2400 series source meters Current and voltage were measured at their output from the manufactured films.
- ix. Elcocarb (Conductive graphite/carbon paste from solaronix)
- x. After deposition, the samples were stored in a Petri dish.
- xi. Forceps was utilized to always hold the samples to prevent the introduction of any contaminants that may have resulted from touching the samples with bare hands.
- xii. Acetone (Riedel-de Haen) for cleaning the samples.
- xiii. Heating plate: during the fabrication operations, the samples were heated to varying temperatures using annealing equipment.
- xiv. Timer: The annealing operations, as well as the spin coating and spin-drying of the samples, were all meticulously timed using a timer.
- xv. M-800 desktop centrifuge. Some of the active layers in the films were spin-coated using a laboratory centrifuge machine, namely, an M-800 desktop centrifuge.
- xvi. Boric acid (BDH)
- xvii. Commercial food grade aluminium foil

3.2 Method

Preparation of Anodized Aluminum Oxide (AAO) Layer

The following steps were taken:

Cleaning of the Aluminum Substrate: The aluminium substrate was cleaned using acetone, and ethanol under ultrasonication for 15 minutes each. This was done to remove any impurities or contaminants from the surface. The substrate was then rinsed with deionized water and air dried

Electropolishing: To achieve a smooth surface, electropolishing was performed in a solution consisting of 90% phosphoric acid (H_3PO_4) and 10% distilled water at a temperature range of 50°C. A voltage of 20V was applied for 10 minutes to effectively remove surface impurities and produce a smooth, finish. The substrate was then rinsed thoroughly with deionized water.

Anodization: The aluminium substrate was immersed in a 2% (w/v) boric acid (H_3BO_3) electrolyte solution at a controlled temperature (20°C) to form a non-porous aluminium oxide layer. A constant DC voltage (30V) was applied for 60 minutes to ensure uniform anodization. The boric acid solution was stirred gently to maintain uniformity and prevent the formation of localized oxide layers.



Figure 1: Commercial food grade aluminium foil served as the substrate



Figure 2: Anodized versus un-anodized aluminium foil (shiny)

Rinsing and Drying: After anodization, the substrate was rinsed with DI water and dried to prevent any water spots or damage to the AAO layer.

Heat Treatment: Finally, the AAO layer was heat-treated at $300^\circ\text{C}/60\text{min}$ to improve its dielectric properties and stability.

Preparation anodized aluminium blanks: The prepared anodized aluminium samples were subsequently cut into 13mm by 25mm sized blanks and stuck unto 15mm by 25mm soda lime glass substrates which acts as support.

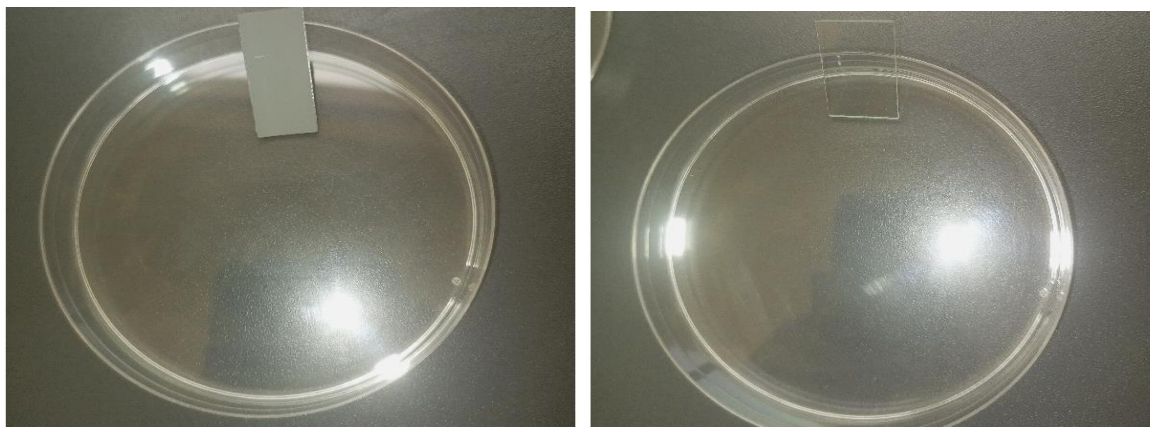


Figure 3a: Anodized alumina blank, Figure 3b: Cut soda lime glass (used as support)

Preparation of Zinc oxide (ZnO) Precursor Solution

The zinc-ammonia complex was prepared by dissolving ZnO powder in a 30% aqueous ammonia solution. The ZnO powder was gradually added to the ammonia solution while stirring continuously for 60 min to ensure optimal dissolution of the ZnO powder.

Before use, the solution was filtered using a whatman (# 1) filter paper to remove any undissolved particles. Finally, the concentration of the zinc-ammonia complex was adjusted to 0.1M for film deposition.

Spin Coating of ZnO Thin Film: The filtered ZnO precursor solution was dispensed onto the anodized aluminum oxide surface. The solution was then spin-coated at a speed of 3000 rpm for 30seconds.

A pre-baking step was performed by heating the coated film at 200°C for 10minutes to remove any residual solvents. To achieve the desired film thickness, the spin-coating cycle was typically repeated 5 times.

Annealing: The ZnO film was annealed at 300°C for 3 hours, to enhance crystallization. This step was critical for improving the electrical properties of the ZnO channel layer.

Deposition of Source and Drain Electrodes: Conductive graphite paste (Elcocarb (solaronix) was then applied by doctor blading technique. (the active area is defined by the vinyl mask) The paste was allowed to dry at 100°C and cured at 300°C/60min to enhance conductivity.

The source and drain electrodes were then patterned using a 10W laser source mounted on a modified 3d printer.

3.3 Characterization Techniques

Thickness Measurement

A profilometer (Dektak 150 from Veeco instrument TMC U.S.A) was used in determining the profilometry (thickness) of the samples.

Morphological Characterization (SEM) of the Samples

A scanning electronic microscope (Zeiss ULTRA 55 SEM) was used to observe the surface morphology of samples.

Electrical characterization

The electrical properties of the samples films were obtained using the Hall Effect measurement system (HMS-3000, Ecopia).

4. Results

Table 1: Results of thickness measurement of the samples

Sample	Reference height (Å)	Film/reference height difference (Å)	Thickness (nm)	Thickness (µm)
ZnO	-82.5	13,081.4	1,308.14	1.308
AAO	9,381.6	154,144.1	15,414.41	15.41441

Results of the Morphological Characterization (SEM) of the Samples

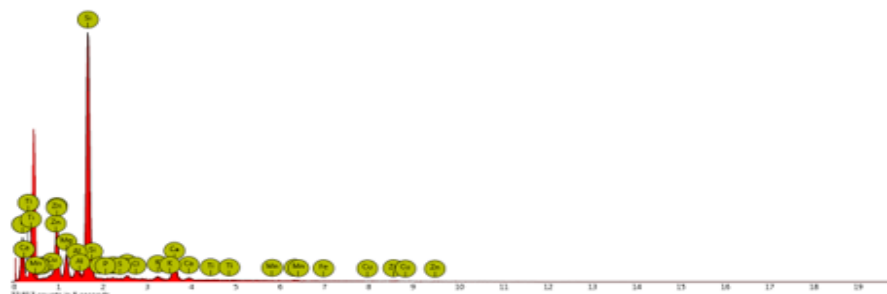
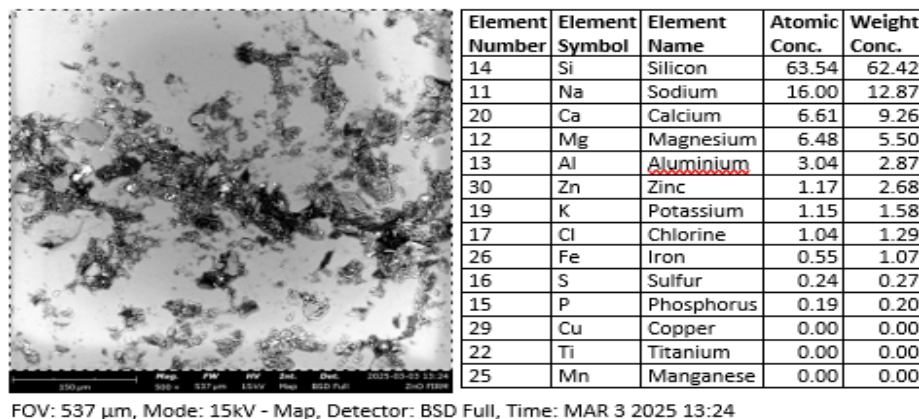


Figure 4: SEM Result for sample ZnO film with elemental composition

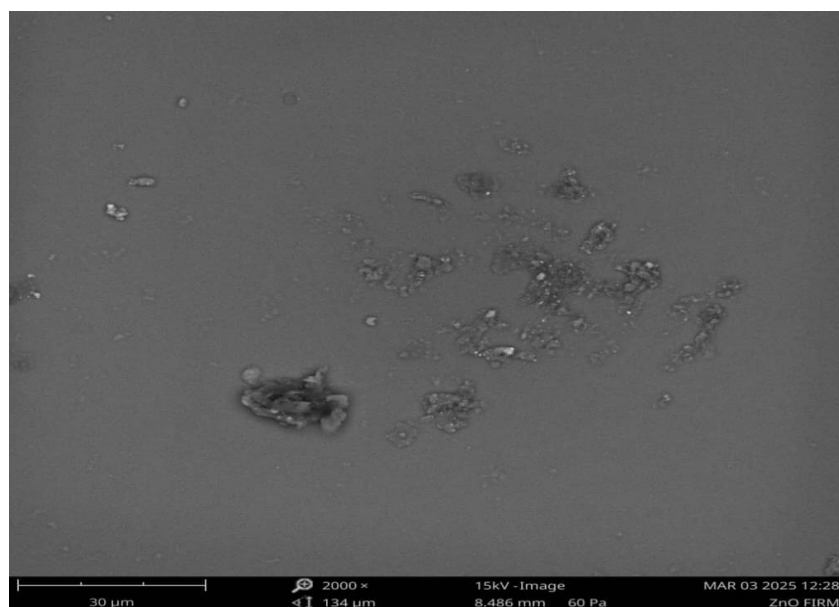


Figure 5: SEM Result for sample ZnO film at 2000x magnification

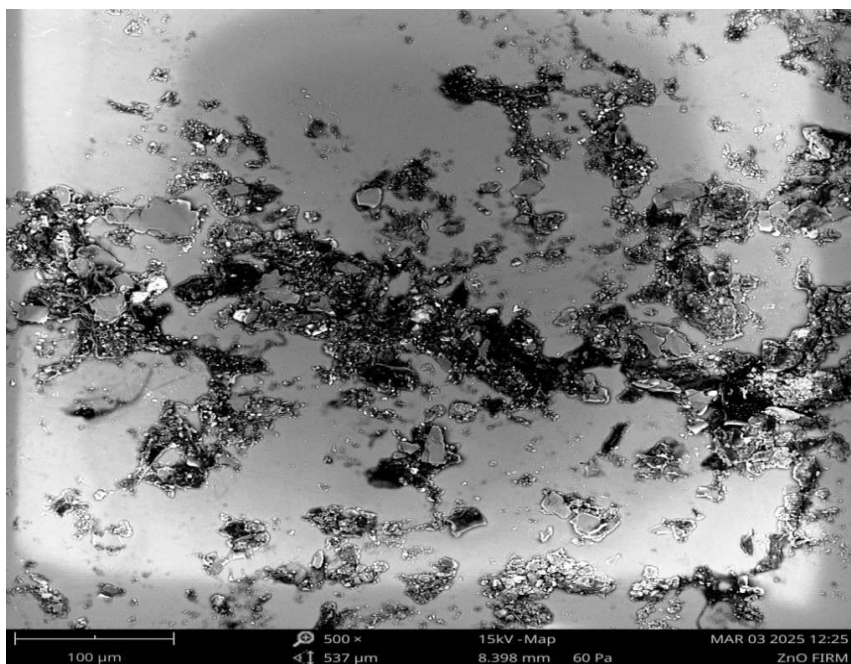


Figure 6: SEM Result for sample ZnO film at 500x magnification

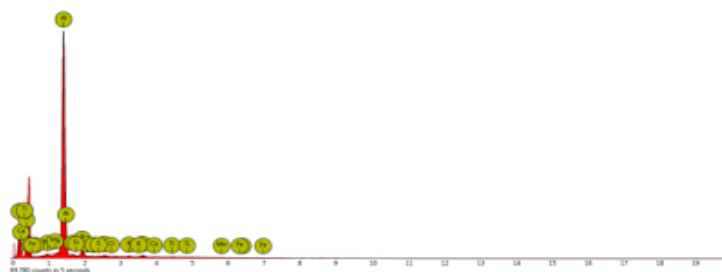
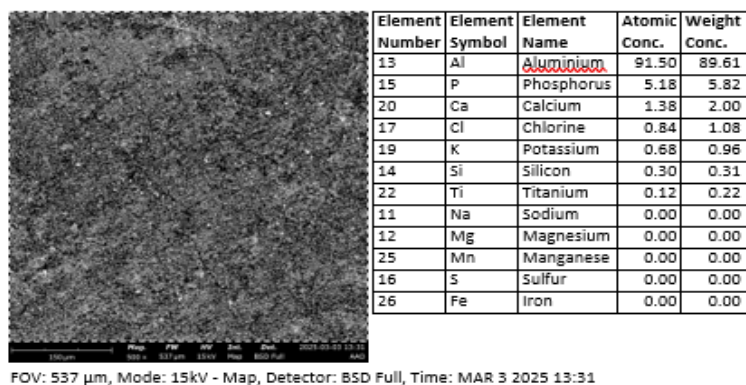


Figure 7: SEM Result for sample AAO with elemental composition

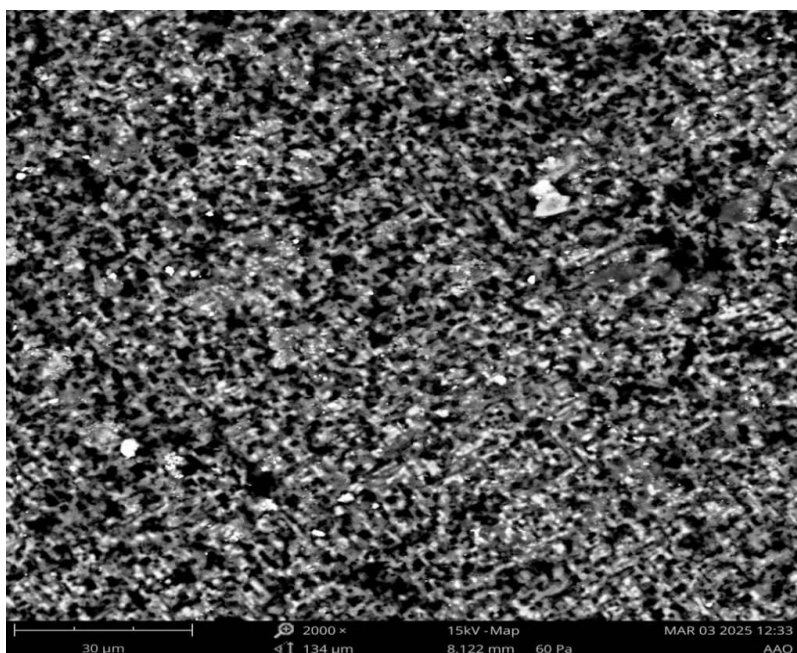


Figure 8: SEM Result for sample AAO at 2000x magnification

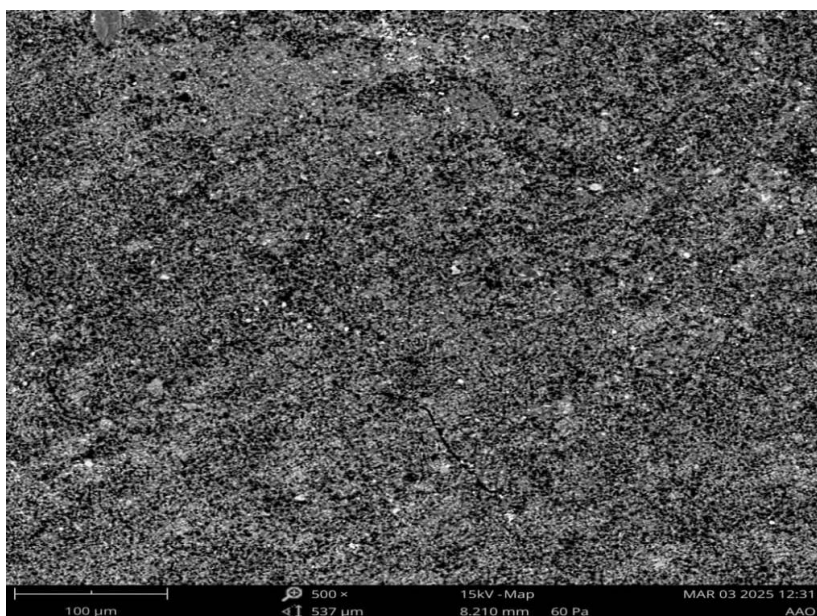


Figure 9: SEM Result for sample AAO at 500x magnification

Results of the Electrical Characterization

Table 2: Result of the hall effect measurement of sample Anodized aluminium oxide (AAO)

SAMPLE: Anodized Aluminium Oxide (AAO)	
Bulk concentration (/cm³)	-1.851E+12
Mobility (cm²/V_s)	1.146E+2
Sheet Resistance (Ω)	2.943E+8
Resistivity (Ωcm)	2.943E+4
Conductivity (1/ Ωcm)	3.398E-5
Sheet concentration(cm²)	-1.851E+8

Table 3: Result of the hall effect measurement of sample ZnO

SAMPLE: Zinc Oxide (ZnO)	
Bulk concentration (/cm³)	-8.155E+17
Mobility (cm²/V_s)	1.98E+3
Sheet Resistance (Ω)	4.260E+0
Resistivity (Ωcm)	6.390E-3
Conductivity (1/ Ωcm)	1.565E+2
Sheet concentration	-1.223E+15

5. Discussion

5.1 Discussion of the Profilometry (sample thickness) results.

The profilometry results (Table 1) confirmed that the deposited ZnO thin films and anodized aluminium oxide layers exhibit relatively uniform thicknesses. Profilometry analysis of the ZnO thin film revealed a profile-derived thickness of approximately 13,081.4 Å, corresponding to 1,308.1 nm (1.308 μm). The profilometer trace initially exhibited a relatively stable baseline associated with the uncoated/reference region, after which a substantial increase in surface height was observed over the coated region. The difference between the mean height of the reference region and that of the ZnO coated region was used to estimate the film thickness. The measured thickness indicates that the deposition process produced a micrometre-scale ZnO layer. However, the profile exhibited considerable height fluctuations within the coated region, indicating appreciable surface non-uniformity/roughness. The profilometric analysis of the anodized aluminium oxide sample revealed an average step height of 154,144.1 Å, corresponding to 15,414.41 nm or 15.41441 μm. The thickness was obtained from the vertical difference between the reference surface at 513.1 μm, having a measured height of 9,381.6 Å, and the measurement surface at 1999.8 μm, having a height of 163,525.7 Å. Thus, the anodized aluminium oxide layer exhibited a thickness of approximately 15.41 μm. The result therefore indicates the formation of a micrometre-scale AAO layer, rather than an ultrathin nanometre-scale oxide film. Uniform film thickness is critical for ensuring consistent electrostatic control across the TFT channel, minimizing threshold voltage shifts, and promoting homogeneous switching behaviour. The observed consistent layer thickness suggested that the deposition techniques employed were effective and reliable for thin film fabrication.

5.2 Discussion of the Morphological Characterization (SEM) of the Samples

The surface morphology of the deposited ZnO film and AAO substrate was investigated using scanning electron microscopy (SEM) at magnifications of 500× and 2000×. The SEM micrographs show distinct differences in the surface morphology of the two samples. The ZnO film exhibited an irregular and heterogeneous morphology characterized by particulate features and pronounced agglomeration. Particles appeared to coalesce into larger clusters at higher magnification, indicating non-uniform growth and aggregation during film formation. This morphology suggests that the deposited ZnO layer possesses appreciable surface roughness and structural non-uniformity.

The AAO sample, on the other hand, had a morphology that was relatively continuous and finely textured. The surface appeared densely covered with fine structural features at 500 magnification, whereas the 2000 magnification image revealed a more clearly defined granular/textured surface. The comparatively uniform morphology of the AAO may provide a more consistent dielectric surface for subsequent semiconductor deposition.

The EDS analysis also revealed significant differences in the composition of the elements. The ZnO-film spectrum contained Si as the dominant detected element (63.54 at. %), while Zn accounted for 1.17 at. %. The relatively low Zn concentration suggests that the EDS analysis sampled a significant contribution from the underlying substrate, particularly because the ZnO layer is a thin film. Other elements including Na, Ca, Mg, Al, K, Cl, Fe, S, P and Cu were also detected. For the AAO sample, Al was the dominant element with 91.50 at. %, followed by P (5.18 at. %) and Ca (1.38 at. %).

The aluminum-based AAO material is evident from the high Al concentration. Overall, the SEM/EDS results confirm the presence of Zn-containing material on the substrate and demonstrate that the AAO possesses a distinctly different, finely textured morphology. Because the morphology and composition of the semiconductor/dielectric interface have the potential to influence charge transport and device performance, the observed surface characteristics are crucial for the creation of ZnO/AAO TFT structures.

5.3 Discussion Results of the Electrical Characterization

The Hall-effect measurement for the AAO sample gave a bulk carrier concentration of $-1.851 \times 10^{12} \text{ cm}^{-3}$, mobility of approximately $1.146 \times 10^2 \text{ cm}^2/\text{Vs}$, sheet resistance of $2.943 \times 10^8 \Omega$, resistivity of $2.943 \times 10^4 \Omega \text{ cm}$, and conductivity of $3.398 \times 10^{-5} \Omega^{-1} \text{ cm}^{-1}$. The measured sheet concentration was $-1.851 \times 10^8 \text{ cm}^{-2}$. The relatively high resistivity and very low conductivity indicate that the AAO sample behaves predominantly as a highly resistive or insulating material. This is consistent with the expected electrical role of anodized aluminium oxide as a dielectric layer. In a thin-film transistor structure, such a layer can therefore serve as the gate dielectric, providing electrical insulation between the gate electrode and the semiconductor channel. The negative sign associated with the Hall carrier concentration indicates the carrier polarity reported by the Hall measurement. In Hall measurements, a negative Hall coefficient/concentration conventionally corresponds to electron-type conduction. The Hall-effect measurement of the ZnO sample produced a bulk carrier concentration of $-8.155 \times 10^{17} \text{ cm}^{-3}$, mobility of approximately $1.98 \times 10^3 \text{ cm}^2/\text{Vs}$, sheet resistance of 4.260Ω , resistivity of $6.390 \times 10^{-3} \Omega \text{ cm}$, conductivity of $1.565 \times 10^2 \Omega^{-1} \text{ cm}^{-1}$, and sheet carrier concentration of $-1.223 \times 10^{15} \text{ cm}^{-2}$. The negative carrier concentration indicates that the measured ZnO exhibits electron-dominated (n-type) conduction. This observation is consistent with the commonly observed n-type electrical behaviour of ZnO. The relatively high carrier concentration demonstrates that a substantial population of mobile charge carriers is available for electrical transport.

The ZnO resistivity of $6.390 \times 10^{-3} \Omega \text{ cm}$ is considerably lower than that of AAO ($2.943 \times 10^4 \Omega \text{ cm}$). Consequently, ZnO has a much greater electrical conductivity. The reported conductivity of $156.5 \Omega^{-1} \text{ cm}^{-1}$ confirms that the ZnO layer is substantially more electrically conductive than the AAO layer. Overall, the electrical characterization demonstrates a strong electrical contrast between AAO and ZnO. AAO exhibits very high sheet resistance and resistivity together with very low conductivity, supporting its proposed role as an insulating gate-dielectric material. ZnO, on the other hand, exhibits a much higher carrier concentration, low resistivity, low sheet resistance and high conductivity, indicating effective electron transport and n-type semiconductor behaviour. These characteristics are fundamentally important for the proposed ZnO/AAO thin-film transistor architecture, in which AAO provides gate insulation while ZnO serves as the electrically active semiconductor channel.

CONCLUSION

In order to determine whether ZnO thin films are suitable for use in thin-film transistor (TFT) applications, this study examined their deposition and characterization. The deposited ZnO film and anodized aluminium oxide (AAO) layer were characterized in terms of thickness, surface morphology, elemental composition, and electrical properties. The profilometry results confirmed the formation of a micrometre-scale ZnO layer with a thickness of approximately $1,308.1 \text{ nm}$ ($1.308 \mu\text{m}$), while the AAO layer exhibited a thickness of approximately $15.41 \mu\text{m}$. Although the measured thicknesses indicate successful deposition and formation of the respective layers, the fluctuations observed across the ZnO profile suggest some degree of surface non-uniformity that may require further optimization for improved device performance.

The ZnO film's surface morphology was found to be irregular and heterogeneous, with visible agglomeration and particulate characteristics, according to SEM analysis. This morphology indicates non-uniform growth and appreciable surface roughness. The AAO surface, on the other hand, had

a more consistent, finely textured, and granular morphology, suggesting that it could be used for semiconductor deposition. The EDS results further demonstrated distinct elemental compositions, with Zn-containing material detected on the ZnO-coated sample and Al dominating the AAO sample. During the analysis, the contribution of the underlying substrate was attributed to the relatively low Zn concentration detected by EDS. This highlights the significance of taking into account substrate effects and film thickness in elemental characterization. The ZnO semiconductor layer and the AAO dielectric layer were clearly distinguished during the electrical characterization. AAO was found to have a high sheet resistance of $2.943 \times 10^8 \Omega\text{cm}$, a high resistivity of $2.943 \times 10^4 \Omega\text{cm}$, a very low conductivity of $3.398 \times 10^{-5} \Omega^{-1}\text{cm}^{-1}$, and a high resistivity of $2.943 \times 10^8 \Omega$, confirming its highly resistive nature and supporting its intended use as an insulating gate-dielectric layer. In comparison, ZnO exhibited a resistivity of $6.390 \times 10^{-3} \Omega\text{cm}$, conductivity of $1.565 \times 10^2 \Omega^{-1}\text{cm}^{-1}$, and sheet resistance of 4.260Ω , indicating substantially greater electrical conduction. The negative Hall carrier concentration of $-8.155 \times 10^{17} \text{cm}^{-3}$ further indicates electron-dominated, n-type conduction in the measured ZnO sample.

The results demonstrated that the fabricated materials possess complementary characteristics required for a ZnO/AAO TFT architecture, with ZnO providing the electrically active semiconductor layer and AAO providing electrical isolation as the gate dielectric. The study therefore establishes the feasibility of the deposited ZnO and AAO layers for TFT-related applications. However, the observed ZnO surface agglomeration and profile fluctuations indicate that further optimization of the deposition conditions may be necessary to improve surface uniformity and interface quality. Such optimization, together with subsequent fabrication and electrical testing of complete TFT devices, would be important for establishing the practical switching, current-voltage, and gate-control performance of the ZnO/AAO structure.

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