

Fabrication and Electrical Characterization of ZnO Thin-Film Transistors Using Anodized Aluminum Oxide as Gate Dielectric

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Abstract

This study reports the deposition and characterization of zinc oxide (ZnO) thin films and the fabrication of a ZnO thin-film transistor (TFT) employing anodized aluminium oxide (AAO) as the gate dielectric. Profilometric analysis revealed a ZnO film thickness of 1,308.14 nm and an AAO dielectric thickness of 15,414.41 nm. The optical properties of the ZnO film were investigated using absorbance, transmittance, reflectance and direct optical band-gap measurements. The film exhibited stronger absorption in the short-wavelength region and increasing optical transmission toward longer wavelengths, indicating the characteristic wide-band-gap optical response of ZnO. The direct optical band gap was determined to be 3.20 eV. Electrical characterization of the fabricated ZnO/AAO TFT demonstrated clear gate-voltage-dependent drain-current modulation, consistent with n-channel ZnO TFT operation. The threshold voltage was approximately 6.20 V, while the maximum drain current reached 2.864 mA. An off-state current of 17.37 μ A resulted in an on/off current ratio of approximately 164.84. The maximum transconductance was 3.002 mS, and the subthreshold swing was approximately 206 mV/decade. The extracted field-effect mobility was 4.15 cm²/Vs, indicating measurable charge transport and effective gate modulation in the ZnO channel. The results demonstrate that the ZnO/AAO structure possesses the essential optical and electrical characteristics required for thin-film transistor applications. Further optimization of ZnO microstructure, defect concentration, dielectric/interface quality and deposition conditions could improve carrier transport and switching characteristics.

Keyword: Zinc oxide; thin-film transistor; anodized aluminium oxide; gate dielectric; field-effect transistor; electrical characterization; oxide semiconductor.

1. Introduction

Thin-film transistors are fundamental components of modern electronic systems and are widely employed as switching and driving elements in displays, sensors, memory systems and other large-area electronic circuits. Conventional TFT technologies have predominantly relied on amorphous silicon and organic semiconductors. However, oxide semiconductors have attracted considerable research attention because they can combine relatively high carrier mobility with optical transparency, good uniformity and potentially low-temperature processing (Fortunato et al., 2012; Kamiya et al., 2010).

Among oxide semiconductors, zinc oxide (ZnO) is particularly interesting because it possesses a direct wide band gap of approximately 3.37 eV at room temperature and a relatively large exciton binding energy of about 60 meV (Özgür et al., 2005). These properties make ZnO useful in transparent electronics, optoelectronics, ultraviolet photodetection and transistor applications. The electrical characteristics of ZnO can also be modified through deposition conditions, defects and intentional doping, providing flexibility for device engineering.

The development of oxide TFTs has been accelerated by the demonstration of high-performance amorphous oxide semiconductor devices. In particular, transparent amorphous oxide semiconductors have shown that oxide materials can provide substantially improved electron transport compared with conventional amorphous silicon while maintaining optical transparency (Nomura et al., 2004; Fortunato et al., 2012). ZnO-based TFTs similarly offer opportunities for transparent and flexible electronics.

The performance of a TFT is determined not only by the semiconductor but also by the gate dielectric and the semiconductor and dielectric interface. The gate dielectric controls the gate capacitance, accumulation of carriers in the semiconductor channel, threshold voltage, leakage current and subthreshold characteristics. Consequently, selection and engineering of the dielectric layer are essential for obtaining reproducible transistor operation.

Anodized aluminium oxide is a potentially useful dielectric for TFT applications. Aluminium can be electrochemically converted into aluminium oxide through anodization, producing an insulating oxide layer whose thickness can be controlled through anodization conditions. Aluminium anodization is relatively simple and can be performed at low cost compared with several conventional dielectric deposition techniques. The resulting aluminium oxide layer can also provide a substantial dielectric capacitance when sufficiently thin.

The objective of this study was to fabricate ZnO thin-film transistors employing anodized aluminium oxide as the gate dielectric and to investigate their electrical characteristics. Particular attention was given to the output and transfer characteristics, threshold voltage, field-effect mobility, on/off current ratio and subthreshold behaviour. The study also considers the influence of the ZnO/AAO interface and processing conditions on transistor operation.

1.1 Basic Structure of a Thin Film Transistor

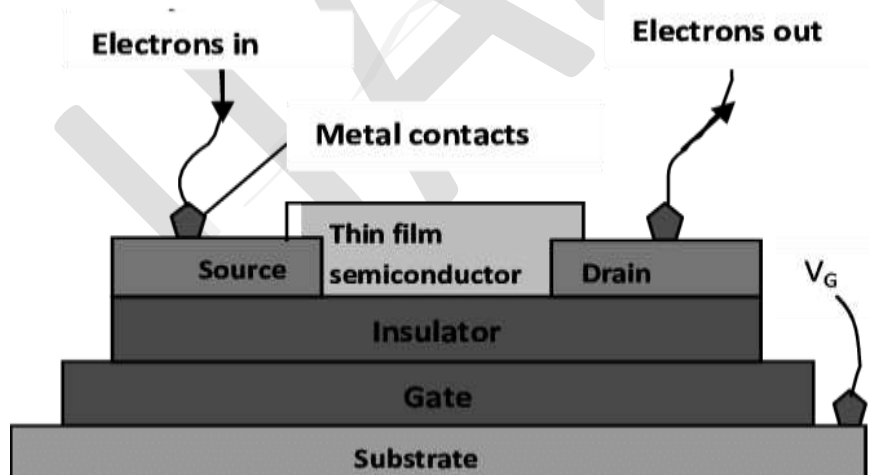


Figure 1: Basic Structure of a Thin Film Transistor (Source; Sharma et al., 2014)

According to Sharma et al. (2014), one kind of field-effect transistor called a thin-film transistor (TFT) uses a thin layer of semiconductor material placed over an insulating substrate. Figure 1.1 below shows the three primary components of a TFT's basic structure: the source, the drain, and the gate (Lu et al., 2018). To function as a switching device, the TFT relies on these components. The semiconductor sheet facilitates the flow of charge carriers between the source and drain, as stated by Kuo (2013). The gate dielectric is a thin insulating layer that

separates the gate from the semiconductor video. An electric field is generated by applying a voltage to the gate, which in turn controls the passage of charge carriers between the source and drain and changes the conductivity of the semiconductor film (Lin, 2022). Amorphous silicon, polycrystalline silicon, or indium-doped zinc oxide (IZO) are common components of semiconductor films (Sharma et al., 2014). It is important to consider the desired electrical performance, transparency, substrate and gate dielectric material compatibility, and other TFT attributes while choosing a semiconductor material. To avoid electrical insulation and charge leakage between the gate and semiconductor layer, the gate dielectric is typically composed of high-k dielectrics such as silicon nitride or silicon dioxide (Lu et al., 2018). For optimal power transmission, the gate electrode is usually composed of a highly conductive material like copper or aluminium. Tiny Field Transistors (TFTs) have multiple uses, such as in flat-panel displays, image sensors, and RFID tags (Lin et al., 2018). For many applications, getting the performance you want depends on optimizing TFT deposition processes and choosing the right materials. To enhance TFTs' electrical and optical characteristics and broaden their use, high-mobility semiconductors like IZO and low-temperature deposition techniques are crucial.

2. Materials and Methods

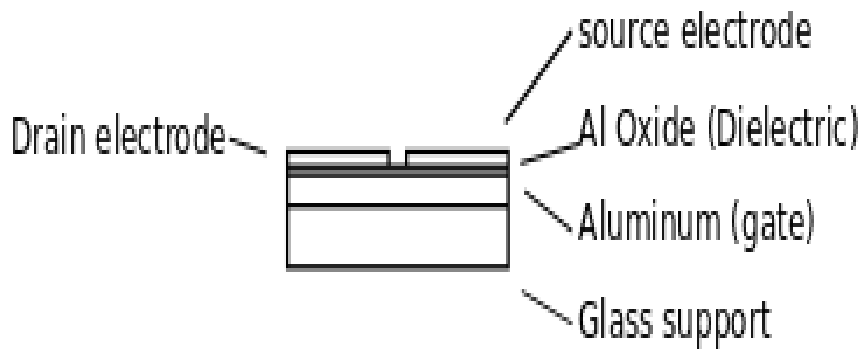
2.1 Materials and Chemicals

- 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

2.2 Method

Fabrication Methods

Based on the discussion in Li et al. (2020), this work adopted and used a monolithic approach for this study's design and fabrication. This means that all the layers were deposited on a single aluminium substrate supported by a soda lime glass.



**Figure 2: Deposited TFT Structure (Channel length = 0.5mm, Channel width = 6mm)
Fabrication of Source and Drain Electrodes**

Source and drain electrodes were deposited on the ZnO layer using the selected electrode deposition process. The electrodes defined the transistor channel. The channel length (L) and channel width (W) were determined from the device geometry.

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 $50^\circ C$. 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 ($20^\circ C$) 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 3: 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°C/60min to improve its dielectric properties and stability.

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



Figure 4a: Anodized alumina blank, Figure 4b: 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.

2.3 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.

Optical Characterization

The ultraviolet–visible (UV–Vis) transmittance properties of ZnO sample were measured using Shimadzu UV-2550 spectrometer in 300–1100 nm wavelength range. The spectrophotometer was used to determine absorbance, and the following equations were used to calculate additional optical parameters, such as transmittance, reflectance, refractive index, absorption coefficient, extinction coefficient, and energy band gap.

The transmittance (T) of the cells was evaluated using Equation (1)

$$T = 10^{-A} \quad 1$$

Reflectance was obtained using equation (2).

$$R = 1 - (A + T) \quad 2$$

The refractive index of the cells was calculated using Equation (3).

$$\eta = \frac{(1 + \sqrt{R})}{(1 - \sqrt{R})} \quad 3$$

The absorption coefficient was calculated from absorbance spectra using Equation (4). Where d is the thickness and is measured in micrometers (μm), and A is the absorbance.

$$\alpha = \frac{2.303A}{d} \quad 4$$

The extinction coefficient was obtained using Equation (5)

$$K = \frac{\alpha\lambda}{4\pi} \quad 5$$

Optical conductivity was estimated using Equation (6).

$$\sigma_o = \frac{\alpha\eta c}{4\pi} \quad 6$$

Where c is the speed of light.

The energy band gap was estimated using Tauc's model given in Equation (7)

$$(\alpha h\nu)^n = \beta(h\nu - E_g) \quad 7$$

In this equation, α is the absorption coefficient, h is the Planck constant, ν is the frequency of the incident photon, E_g is the energy of the band gap, and β is a constant. Band gaps for direct transitions have a n factor of 1, whereas those for indirect transitions have a n factor of two.

Electrical characterization

Electrical characterization was performed using a suitable source-measurement system. The drain current was measured as a function of drain voltage for different gate voltages to obtain the output characteristics. The transfer characteristics were obtained by measuring (ID) as a function of (VG) at a fixed drain voltage.

3. Results

Profilometry (thickness) graph of the samples

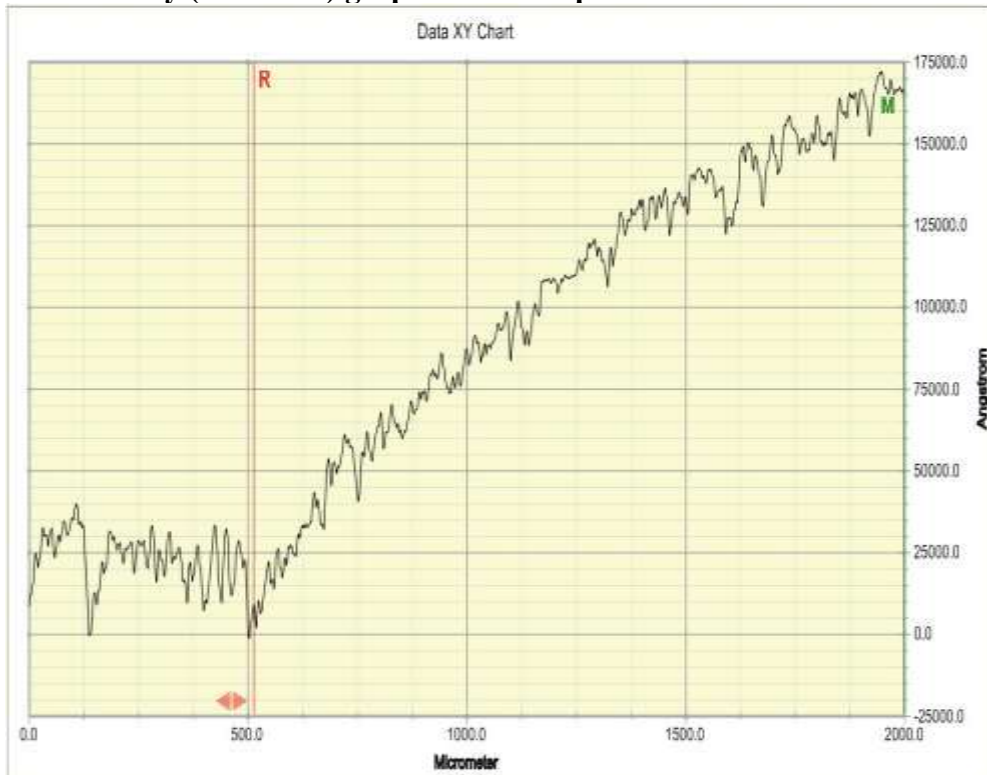


Figure 5: profilometry (thickness) graph of Anodized Aluminium Oxide sample

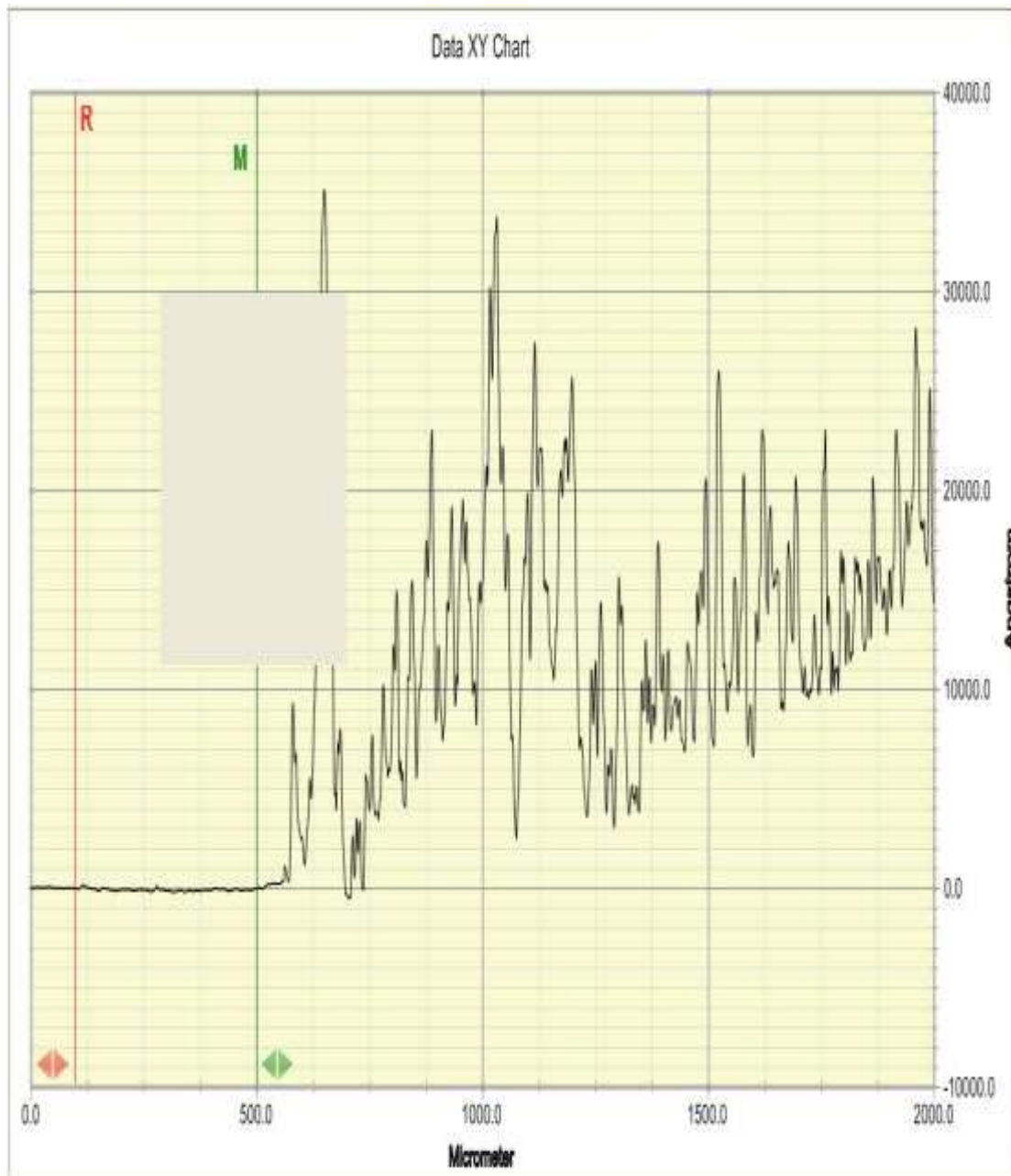


Figure 6: profilometry (thickness) graph of Zinc Oxide Thin Film Transistor sample

Table 1: Results of thickness measurement of the samples

Sample	Reference height (Å)	Film/reference difference (Å)	height 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 Optical Characterization

Figures 7 – 10 are the graphical representation of the absorbance, reflectance, transmittance, and optical band gap of the zinc oxide sample.

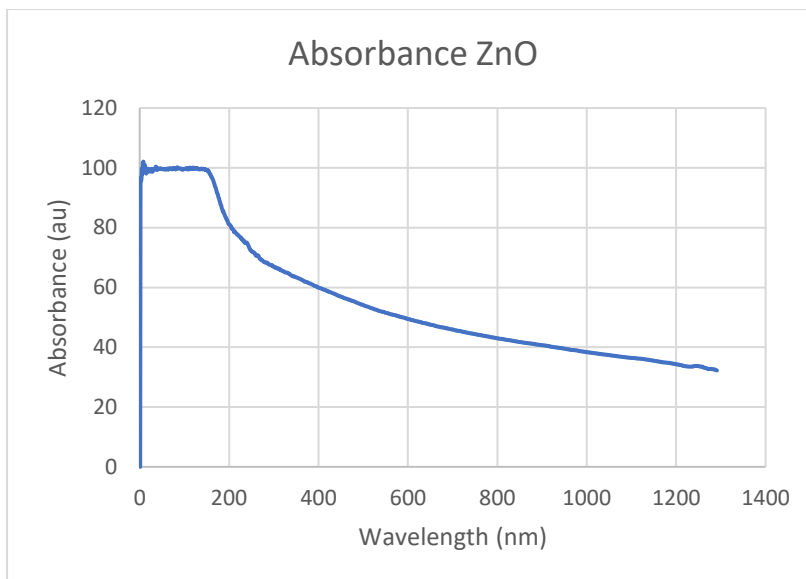


Figure 7: Uv-vis- Absorbance spectra of the zinc oxide sample



Figure 8: Uv-vis- Transmittance spectra of the zinc oxide sample

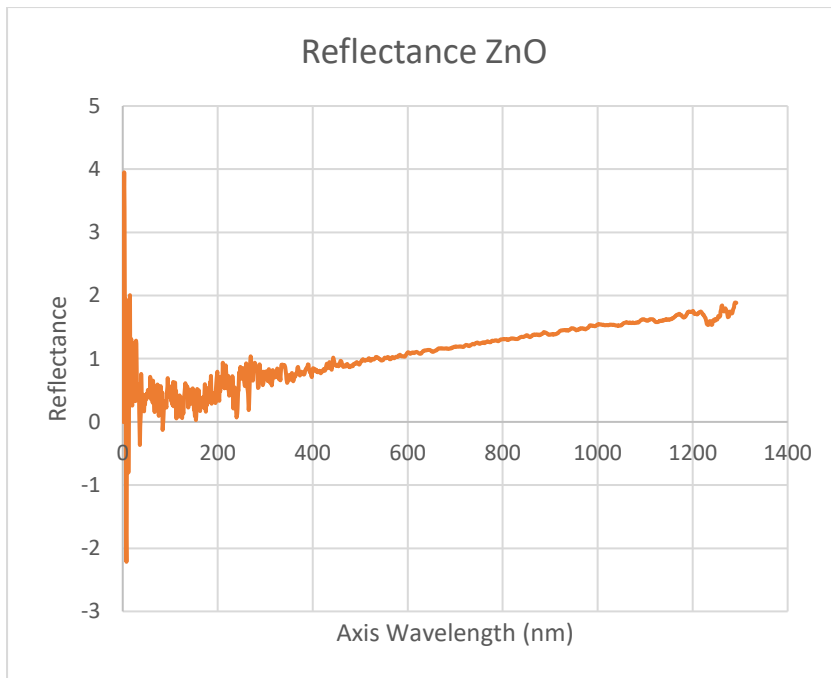


Figure 9: Uv-vis- Reflectance spectra of the zinc oxide sample

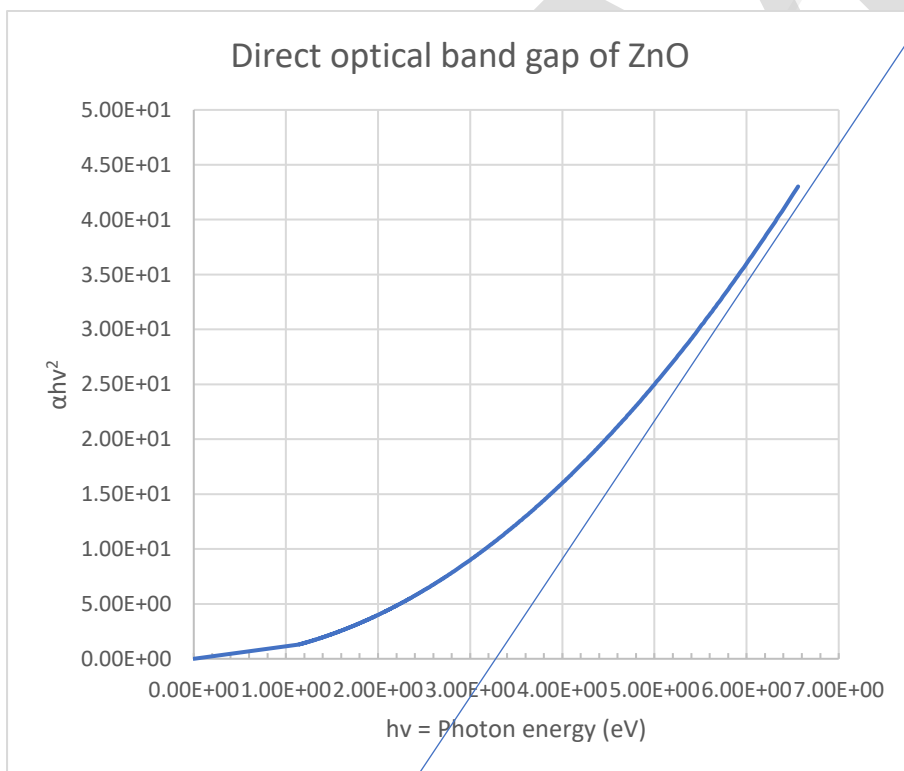


Figure 10: Uv-vis- Direct optical band gap spectra of the zinc oxide sample

Results of the transfer characteristics of the ZnO thin film transistor

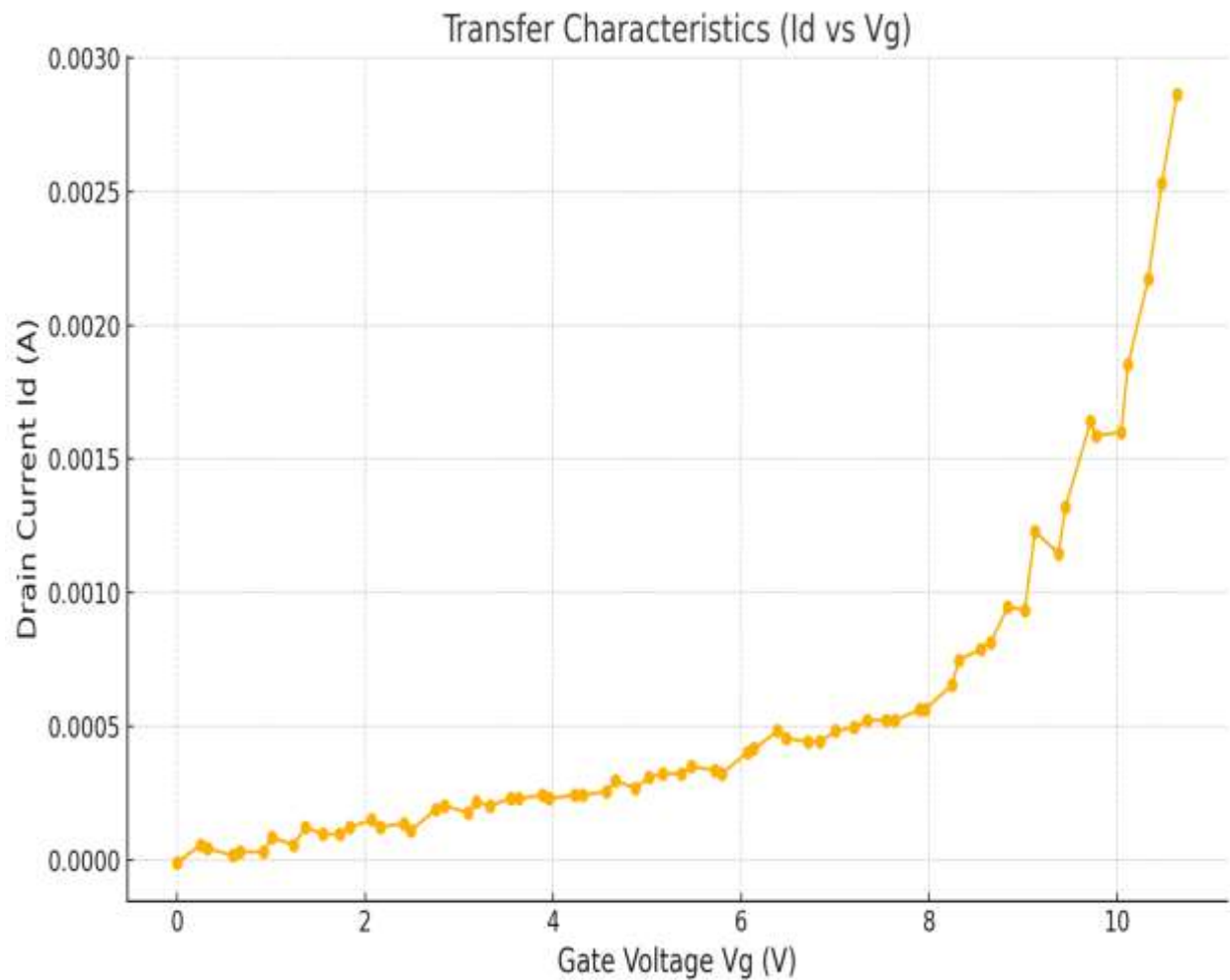


Figure 11: Transfer characteristics of the ZnO TFT

Table 2: ZnO TFT Principal parameters

No.	Parameter	Recalculated / retained value
1	Threshold voltage, V_T	≈ 6.20 V
2	Field-effect mobility, μ_{FE}	≈ 4.15 cm ² /Vs
3	On/off current ratio	≈ 164.84
4	Maximum transconductance, g_m	≈ 3.002 mS
5	Subthreshold swing, SS	≈ 206 mV/decade
6	On-state drain current, I_{on}	2.864 mA
7	Off-state drain current, I_{off}	17.37 μ A

4. Discussion

4.1 Discussion on the Profilometric Thickness of the ZnO and Anodized Aluminium Oxide Films

The profilometry measurements establish a substantial difference between the thicknesses of the ZnO semiconductor layer and the anodized aluminium oxide (AAO) dielectric layer. The ZnO film was reported to have a thickness of 1,308.14 nm (1.308 μ m), whereas the AAO layer had a thickness of 15,414.41 nm (15.414 μ m). Thus, the anodized oxide layer was

approximately 11.8 times thicker than the ZnO layer. This difference is important because the ZnO layer provides the semiconducting channel, while the AAO layer determines the electrostatic coupling between the gate electrode and the channel.

The profilometric traces in Figures 5 and 6 also reveal different surface profiles. The ZnO trace shows considerable height fluctuations after the transition from the reference region to the film region, suggesting appreciable surface topography or thickness non-uniformity across the scanned region. Such variations may originate from grain formation, deposition non-uniformity, agglomeration, or substrate roughness. In a TFT, these morphological variations can affect carrier transport because local variations in film thickness and surface structure can modify percolation pathways, interface-state density and the electrical resistance between the source and drain. The positive threshold voltage subsequently observed in the device is qualitatively compatible with this relatively weak electrostatic coupling, although dielectric thickness alone cannot be identified as its cause.

4.2 Discussion on the Optical Characterization of the ZnO Film

The optical characterization comprised the absorbance, transmittance, reflectance and direct optical-band-gap spectra of the ZnO film. Taken together, these measurements provide information about photon absorption, optical transparency and the energetic separation between the valence and conduction bands of the deposited ZnO.

4.2.1 Absorbance Spectrum

Figure 7 shows the absorbance spectrum of the ZnO film. The spectrum indicates stronger absorption toward the short-wavelength region and decreasing absorption as wavelength increases. This behaviour is characteristic of a wide-band-gap semiconductor such as ZnO because photons with energies equal to or greater than the band gap can efficiently promote electrons from the valence band into the conduction band. As the photon energy falls below the fundamental absorption edge, this interband absorption mechanism becomes progressively less effective. The observation therefore supports the formation of an optically active ZnO semiconductor film. Strong ultraviolet absorption combined with reduced absorption at longer wavelengths is one of the desirable characteristics of ZnO for transparent and optoelectronic devices.

4.2.2 Transmittance Spectrum

The transmittance spectrum presented in Figure 8 complements the absorbance behaviour. The general increase in transmission toward longer wavelengths indicates that the ZnO layer becomes progressively more transparent when the incident photon energy falls below the strong interband-absorption region. This inverse relationship between absorbance and transmittance is internally consistent with the expected optical response of ZnO.

The measured transparency is particularly relevant to TFT applications. Because ZnO combines semiconducting behaviour with optical transparency, it is attractive for transparent electronics, display backplanes, ultraviolet sensors and other devices in which electrical functionality must coexist with optical transmission.

4.2.3 Reflectance Spectrum

Figure 9 presents the reflectance spectrum. Reflectance remains relatively small compared with the overall optical response and generally increases toward longer wavelengths. Low reflectance is advantageous because it indicates that much of the radiation that is not absorbed can pass through the material rather than being reflected at the surface.

The fluctuations seen in the short-wavelength portion of the spectrum may originate from surface roughness, thin-film interference, instrument baseline effects or variations in the optical

constants close to the fundamental absorption edge. Surface morphology is particularly relevant because the profilometry measurements already indicate appreciable height variation in the ZnO film.

4.3 Discussion on the Direct Optical Band Gap of ZnO

The direct optical band-gap analysis in Figure 10 was presented as a plot of $(\alpha h\nu)^2$ against photon energy $h\nu$, which corresponds to the conventional Tauc treatment for an allowed direct electronic transition. The approximately linear high-energy portion of such a plot is extrapolated and the photon-energy intercept is interpreted as the direct optical band gap.

The optical gap is crucial for the present TFT because it confirms that the deposited material retains the wide-band-gap electronic structure responsible for both semiconductor behaviour and transparency at visible wavelengths. From the displayed extrapolation, the intercept shows the direct band gap of ZnO as 3.20 eV.

4.4 Discussion on the Electrical Properties (Transfer Characteristics) of the ZnO/AAO Thin-Film Transistor

The most important evidence that the fabricated structure functions as a field-effect device is the transfer characteristics in Figures 11. The drain current increases systematically with increasing positive gate voltage, with a particularly rapid rise at higher gate biases. This positive gate-voltage dependence is consistent with n-channel ZnO TFT behaviour, in which increasing positive gate bias produces electron accumulation near the ZnO/AAO interface and increases source-to-drain conduction. The linear-scale transfer curve shows relatively gradual current modulation at low and intermediate gate voltages, followed by a much stronger increase above approximately 8 V. The drain current eventually reaches the milliamperage range. This response confirms that the gate electrode is capable of electrostatically modulating conduction in the ZnO layer despite the relatively thick AAO dielectric. The positive threshold voltage of approximately 6.20 V indicates enhancement-type operation, meaning that a sufficiently positive gate voltage is required before strong channel conduction develops. A positive threshold voltage can arise from several interacting factors, including relatively weak gate capacitance, charge trapping at the ZnO/AAO interface, fixed dielectric charge, semiconductor carrier concentration and channel thickness. Because the present ZnO layer is comparatively thick, a considerable gate-induced charge may be required before the entire conducting pathway is effectively controlled. The current does not fall by several orders of magnitude before turn-on; instead, appreciable conduction remains at low gate voltage. Consequently, although the device demonstrates definite field-effect modulation, its present switching behaviour is characterized more by gate-controlled conductivity modulation than by an exceptionally sharp OFF-to-ON transition.

4.5 Discussion on the On/Off Current Ratio and Off-State Conduction

The measured on-state drain current was 2.864 mA, whereas the reported off-state current was 17.37 μ A, yielding an on/off ratio of approximately 164.84. The internal consistency of these values is good because their ratio reproduces the reported on/off current ratio.

The milliamperage-scale on-current demonstrates that the ZnO layer can support significant electron transport in the accumulated state. The more important limitation is therefore not the on-state conductivity but the comparatively high off-state current. An I_{on}/I_{off} ratio of approximately 1.65×10^2 indicates that the device cannot completely suppress conduction when the gate is below threshold. The relatively high I_{off} could arise from residual free carriers within the thick ZnO layer, defect-assisted transport, incomplete channel depletion, parasitic source drain conduction, dielectric leakage or interface-related conduction.

4.6 Subthreshold Swing

The calculated subthreshold swing of approximately 206 mV/decade describes the amount of gate-voltage change required to produce a tenfold change in drain current within the subthreshold region. Lower values represent stronger electrostatic gate control and fewer electrically active trap states.

A value of 206 mV/decade is noteworthy because it indicates appreciable gate control despite the substantial AAO thickness. It is also comparable in magnitude with reported oxide-semiconductor devices; for example, an Al₂O₃/ZnO structure employing an approximately 5.6-nm ZnO layer exhibited a subthreshold swing of about 194 mV/decade. Another optimized ZnO/Al₂O₃ TFTs have reached approximately 120 mV/decade.

4.7 Transconductance

The maximum transconductance (gm), was determined to be approximately 3.002 mS. Transconductance measures the sensitivity of drain current to gate voltage and therefore directly quantifies the effectiveness of gate control over channel conduction. The milliSiemens-scale value is consistent with the strong increase in drain current observed in the high-VG region of Figure 11. The occurrence of maximum transconductance at the higher gate-voltage region is also consistent with progressive formation of an electron-rich conduction channel. Once the gate voltage substantially exceeds threshold, additional gate-induced charge contributes directly to increased channel conductivity. Thus, the transconductance result reinforces the conclusion from the transfer curve that the ZnO/AAO structure exhibits genuine field-effect modulation.

4.8 Field-Effect Mobility

The obtained mobility of 4.15 cm²/Vs indicates that the deposited ZnO film provides measurable field-effect charge transport and effective gate modulation of the channel. The magnitude is within a practically useful range for ZnO-based thin-film transistor devices, particularly where ZnO is employed as an oxide semiconductor for relatively low-cost electronic and sensing applications.

The measured mobility is influenced by several factors, including the crystallinity and microstructure of the ZnO film, grain boundaries, defects and oxygen-related states, surface roughness, carrier concentration, semiconductor/dielectric interface quality, and contact resistance. In particular, defects and interface trap states can scatter charge carriers and reduce the effective mobility extracted from the transfer characteristics. The relatively thick anodized Al₂O₃ dielectric layer also results in a comparatively low gate capacitance, meaning that a relatively large gate voltage is required to induce significant channel charge. The value of 4.15 cm²/Vs therefore provides a useful experimental indication of the charge-transport performance of the fabricated ZnO TFT. The field-effect mobility result demonstrates that the fabricated ZnO thin-film transistor exhibits effective gate-controlled carrier transport, confirming the suitability of the ZnO/Al₂O₃ structure for TFT operation. Further improvement in mobility could potentially be achieved through optimization of ZnO deposition conditions, reduction of structural defects, improvement of film crystallinity, control of oxygen-related defects, and optimization of the ZnO/Al₂O₃ interface.

Conclusion

In conclusion, the deposition and characterization results demonstrated the successful formation of a ZnO semiconductor layer and an anodized aluminium oxide dielectric structure suitable for thin-film transistor applications. Profilometric analysis showed that the ZnO film had a thickness of 1,308.14 nm, while the AAO dielectric layer was 15,414.41 nm thick. The considerable thickness of the dielectric layer provides an important consideration for the

electrostatic coupling between the gate and ZnO channel. The observed variations in the ZnO surface profile also indicate the presence of film-thickness or surface-topography non-uniformity, which may influence carrier transport and the electrical characteristics of the device. The optical characterization confirmed the expected optical response of ZnO. The film exhibited stronger absorption at shorter wavelengths and increasing transmission toward longer wavelengths, while the reflectance remained relatively low. The direct optical band gap was determined to be 3.20 eV, confirming the wide-band-gap nature of the deposited ZnO and supporting its potential for transparent and optoelectronic applications. The electrical transfer characteristics confirmed field-effect operation of the ZnO/AAO TFT. The drain current increased with increasing positive gate voltage, demonstrating n-channel behaviour and gate-induced electron accumulation in the ZnO channel. A threshold voltage of approximately 6.20 V was obtained, indicating enhancement-type operation. The device produced a maximum on-state drain current of 2.864 mA and an off-state current of 17.37 μ A, giving an on/off current ratio of approximately 164.84. These results demonstrate appreciable gate-controlled conductivity, although the relatively high off-state current indicates that complete suppression of channel conduction remains a limitation of the present device. The extracted subthreshold swing of approximately 206 mV/decade and maximum transconductance of 3.002 mS further confirm effective gate modulation of the ZnO channel. The field-effect mobility of 4.15 cm^2/Vs indicates measurable carrier transport in the deposited ZnO film and demonstrates the functional potential of the ZnO/ Al_2O_3 TFT structure. Overall, the results establish that the fabricated ZnO/AAO TFT exhibits the essential optical and electrical characteristics required for oxide-semiconductor transistor operation. Nevertheless, the relatively thick AAO dielectric, surface non-uniformity, residual off-state conduction and the influence of defects and interface states represent areas for further improvement. Optimization of ZnO deposition conditions, film crystallinity, defect concentration, surface morphology and the ZnO/AAO interface is expected to enhance carrier mobility, reduce off-state conduction and improve the switching performance of the device.

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