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Mobility and threshold voltages comparison of zinc nitride-based thin-film transistor fabricated on Si and glass

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Abstract
The present work reports the fabrication and characterization of high mobility thin-film transistors, where zinc nitride is used as the active layer (~100 nm thick). For the TFT, the active layer was deposited at room temperature on different substrates (Si-p type and glass) by RF magnetron sputtering method and annealed at 350 °C post-fabrication and HfO2 was used as the gate insulation layer (~50 nm thick). The obtained value of field-effect mobility was greater than 5 cm²Vs⁻¹, with optical bandgap ~3.07 eV. The two MIS (metal insulator semiconductor) structures were analyzed using I–V and C–V measurements. It is demonstrated that Zinc Nitride is a potential candidate to be used as an active layer in TFT fabrication. The threshold voltages of the device built on Si and glass substrates were obtained as 0.8 volts and 2.6 volts respectively.

1. Introduction
Currently, many semiconductors materials such as silicon, germanium, gallium arsenide, etc are being used as an active layer in a thin-film transistor (TFT), with SiO2 or HfO2 as a dielectric material for gate insulation.

TFT is a field-effect transistor (FET) with its basic characteristics and physical structure same as that of metal-oxide field-effect transistor (MOSFET) with some important differences. TFTs show important applications viz. integrated displays, photovoltaic, sensing devices, and integrated logic devices [1–4]. The optical band gap of Zn3N2 was identified as a direct band-gap and its value varied from 2.2 eV to 3.5 eV [5–9].

Zinc nitride (Zn3N2) is a group of II–V compound semiconductors used in electronics and optoelectronics applications owing to its many attractive features such as wide direct bandgap, high refractive index, low cost, and ecological friendliness. The electrical properties of Zn3N2 have been extensively studied. Its resistivity is reported to be in the range of 10⁻³ to 10⁻¹ Ωcm depending on the method of fabrication and substrate, carrier mobility ~10⁻¹–100 cm²V⁻¹s⁻¹ and Hall measurements report it to be n-type [10–14]. Metallic contacts with Al, Au, and Ag show good ohmic behavior.

This work is focused on the deposition of zinc nitride (Zn3N2) as an active layer through nitridation of Zn using RF plasma sputtering technique on glass and Si substrate and its structural, microstructure, and electrical characterization.

2. Experiment
TFT was deposited on the p-type Si (111, ρ < 0.01 Ω cm) wafer and glass substrate simultaneously, which was cut into a correct dimension. RCA (Radio Corporation of America) and piranha method were used for cleaning the Si and glass substrate respectively and Al metal contacts were deposited using thermal vapor deposition thereafter to be used as gate contact for the bottom gate TFT. The next layer was of HfO2 of approximately 50 nm thickness as a gate insulator, deposited by RF sputtering [15, 16]. The next layer was HfO2 of 50 nm thickness as a gate insulator, which was deposited by RF sputtering, annealed at 600 °C for 1 h to improve its crystalline properties, for which the sputtering machine present substrate heating setup [17].

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And then Zn₃N₂ was used as an active layer semiconductor with a thickness of about 100 nm. The active layer is characterized by reactive conditions with zinc (99.9% purity) 2-inch diameter target with RF sputtering and N₂ as reactive gas (flow rate 10 sccm) while Ar as carrier gas (flow rate in 10 sccm). The radio frequency power of sputtering used for GK was 100 watt where the base and deposition pressures were $5 \times 10^{-6}$ mbar and $3 \times 10^{-3}$ mbar, respectively.

Similarly, after the deposition of Zn₃N₂, it was annealed at 350 °C for 30 min to improve crystallinity.

The drain and source contacts were fabricated with gold (Au) by dc sputtering through masking, while Al metal was used to make the gate contact, as shown in figure 1. While back surface contact fabrication was done in the case of the Si substrate (p-type) while the upper surface contact fabrication was used for the glass substrate, the electron beam vapor deposition technique was used for the deposition of the Al layer contact.

Crystallinity and thickness of the films were studied using grazing angle ($0.25^\circ$) XRD with x-ray reflectivity (XRR) using XPert Pro of PAN-alytical (Cu Kα1) system. AFM Bruker multi-mode 8 was used to investigate the roughness and surface morphology.

Field emission scanning electron microscopy (Nova Nano-FESEM 450) was used to study thin-films surface morphology with EDS giving the chemical analysis. UV–vis spectroscopy was done by Perkin Elmer’s LAMBDA-750 UV–Vis-NIR spectrophotometer. The electrical characteristics were measured by the Semiconductor Devices Analyzer of Agilent B1500A Technologies.

The deposition parameters as shown in the above table (1) were kept the same for both thin films (Zn₃N₂ and HfO₂) so that their physical properties could be compared on the same basis.

### 3. Result and discussion

Figures 2(a) and (b) shows the XRD pattern of multilayer thin films of deposit HfO₂–Zn₃N₂ on Si and glass substrate at room temperature. The XRD pattern is clearly showing peaks at $2\theta = 28.30^\circ$ (111) and $31.70^\circ$ (111) associated with HfO₂ and at $34.27^\circ$ (321), $36.72^\circ$ (400), and $52.92^\circ$ (440) associated with Zn₃N₂ as confirmed by JCPDF card number 00-006-0318 (HfO₂) and 00-035-0762 (Zn₃N₂).

The XRD diffraction spectrum shows a polycrystalline structure of HfO₂ and Zn₃N₂ [18, 19]. In one of the XRD spectrums of both multi-layer spectrums which deposit on the Si substrate, the crystalline peak of Si can be

![Figure 1. TFT device structure on Si and glass substrates.](image-url)
seen which shows the difference in the multi-layer structure of deposit TFT on both substrates. The film shows a lower number of peaks on the glass substrate, indicating that the crystalline structure of the deposit thin-film on the Si substrate develops more sharply than the glass substrate, mainly due to the Si surface of the glass surface. And the other major reason, where on one hand the glass is amorphous while Si crystalline on the other, the crystalline nature of Si causes the thin-film deposited on it to be more crystalline.

The thickness of the thin-films was determined using the XRR technique shown in figure (3), which is capable of studying the effect of density on the optical properties of thin-films as well as changes in the refractive index of the film.

With the XRR technique, the thickness of the Zn$_3$N$_2$ and HfO$_2$ layers were measured as different signal layer thin films that were obtained at ∼108 nm and ∼61 nm, respectively [20, 21]. The roughness and density of the films were also calculated from the XRR shown in table (2).

The surface morphology and topology of Zn$_3$N$_2$ and HfO$_2$ films were characterized by AFM and FESEM. The experiment was done in contact mode AFM. The average surface roughness using AFM was obtained as ∼23 nm and ∼12 nm for Zn$_3$N$_2$ and HfO$_2$ thin films respectively.

Here the roughness of Zn$_3$N$_2$ is higher than the roughness of HfO$_2$ because the thickness of Zn$_3$N$_2$ is twice that of HfO$_2$ and we know that as the thickness of thin-film increases, the roughness of thin-film also increases shown in figure (4) [22].

FESEM with the EDX spectrum in figures (5) and (6) show the surface morphology with the EDAX spectrum of the two films (Zn$_3$N$_2$ and HfO$_2$) separately.
EDAX confirms the presence of the constituent elements. The micrographs reveal uniform films and corroborated by the low roughness values known through AFM.

The optical band gap was calculated using the Tauc-plot shown in the inset of figures 7(a) and (b). The obtained direct band gap is 3.07 eV, falling in the range reported in the literature [23].

Hall effect measurement of Zn$_3$N$_2$ thin-film confirmed that it is an n-type semiconductor for which Hall mobility value $\mu_H = 2.34$ (cm$^2$Vs$^{-1}$) and charge carrier concentration value $n_e = 2.3 \times 10^{20}$ (cm$^{-3}$) were obtained, confirming that our TFT is n-channel Works simultaneously in enhancement mode.

Figures 8(a) and (b) give the C–V curves of the two substrates, the AC signal had a frequency 1 MHz with an amplitude 100 mV. For the Si substrate, the typical behavior of an MIS (metal insulator semiconductor) is seen. Considering that the AC signal had a relatively high frequency, the electrons did not get time to respond and the device did not enter the strong inversion region of operation. The value of capacitance per unit area was calculated from the graph.
Figure 6. FESEM image with EDX spectrum of HfO$_2$ thin film.

Figure 7. (a) UV-Vis spectrum and (b) Tauc plot of Zn$_3$N$_2$ thin film.

Figure 8. (a) CV curve of the MIS structures on Si Substrate and (b) CV curve of the MIS structures on Glass Substrate.
Since the diameter of the drain and source gold ohmic contact was 1 mm, the area of MIS capacitor was about 0.00785 cm², the values of MIS capacitance obtained from the CV graph were about 5.28 nF and 4.49 nF for Si and glass-based MIS structure, respectively. After this, the capacitance per unit area values was obtained 0.672 μF cm⁻² and 0.571 μF cm⁻² respectively.

The slight difference in gate capacitance is due to this as you can see in figure 1. In the case of Si substrate the gate is made as a back contact while in the glass substrate case the gate is made as a surface contact, here silicon the case of the substrate, the voltage provided to the gate crosses the two different surfaces Al metal, Si substrate and reaches the gate whereas, in contrast to the voltage provided to the gate in the case of the glass substrate, it is not so, so the gate A slight increase in capacitance may be due to the Schottky-diode effect (between Al metal and p-type silicon).

Figures 9(a) and (b) shows the comparison of the transfer characteristics Zn₃N₂ (thickness ~100 nm) based TFT with HfO₂ (thickness ~50 nm) gate dielectric for different substrates Si and Glass. Higher on current, higher on/off current ratio, and better sub-threshold region are seen. And figures 9(a) and (b) shows the output characteristics (V₅, I₅) of the Zn₃N₂ TFT with 500 μm channel length and width is 2000 μm, where drain current (I₅) is plotted as a function of the drain to source voltage (V₅) for gate voltage (V₃) ranging from 0 to 5 voltages, and the output characteristics clearly show a saturation region, the current crowding effect in both TFT at a low value of V₅, is appreciated shown in figures 10(a) and (b). In the above output characteristics TFT is working in enhancement-mode where drain voltage V₅ = 0 is the limit at which TFT can switch from enhancement-mode to depletion-mode, due to this thin switching boundary some microampere current in TFT flow may occur. The transverse characteristics at a constant drain voltage (V₅ = 5 V) are shown in figure (9).

This shows that long channel devices are also affected by high contact resistance. The overall results show the Zn₃N₂ films deposited at room temperature as a potential candidate as high mobility semiconductor for flexible TFTs.
crowding, degradation of the transconductance, or impact ionization, among others, etc. Between different interfaces which are also responsible for generating many electric parameters. Such as current the result of high contact resistance between different layers and collective tuning of different Fermi levels electric dynamics of the MOSFET. This mobility difference arises due to different contact resistances which are

\[ g_m = \left( \frac{\mu_{FE} C_{ox} W}{L} \right) (V_g - V_T) \]  

(1)

Where \( \mu_{FE} \) is the electron field-effect mobility and \( C_{ox} \) is the gate capacitance per unit area of gate insulator from C–V characteristics figures 7(a) and (b), the channel width (W) and length (L) are 2000 \( \mu \)m and 500 \( \mu \)m respectively and \( V_T \) is the threshold voltage. Since the structure of this TFT is the bottom gate structure, it is less likely to have a frings effect due to the lower sheet resistance affect in it compared to the top gate structure. This is why fabrication of nano-thin MOSFET type, bottom gate structure type is done.

Figures 9(a) and (b) show the normalized transfer characteristics of Zn3N2 based TFT’s on different substrates Si and Glass.

The electron field-effect mobility and threshold voltage were extracted from the square root of \( I_{ds} \) versus \( V_{gs} \) using equation (2) of the saturation regime. The transverse characteristics shown in figure 8 were used to calculate field-effect mobility, for which taking the dots at 10 different fixed points on the graph and deriving its corresponding coordinate values (\( V_g, I_d \)), using equation (2), the average The field-effect mobility was calculated, shown in table 3.

\[ I_{ds} = \mu_{FET} C_{ox} \left( \frac{W}{2L} \right) (V_{gs} - V_T)^2 \]  

(2)

The values expected for threshold voltages \( V_T \) have been extracted by the fitting tangent to the (\( V_g \) versus \( I_d \)) curves shown in figure 9 and calculated 0.8 volts and 2.6 volts respectively for Si and Glass substrate TFT.

TFTs that have been formed into devices on various substrates (Si and glass) also influence the field-effect electric dynamics of the MOSFET. This mobility difference arises due to different contact resistances which are the result of high contact resistance between different layers and collective tuning of different Fermi levels between different interfaces which are also responsible for generating many electric parameters. Such as current crowding, degradation of the transconductance, or impact ionization, among others, etc.

The transverse characteristics at a constant drain voltage (\( V_d = 5 \) V) are shown in figure 9. The sub-threshold swing is characterized by the transverse characteristics in the current-voltage curves of a MOSFET, which is calculated by the inverse of the slope of the curve between \( \log I_d \) versus \( V_g \). This is mainly in the sub-threshold region, the drain current behavior is controlled by the gate terminal which is similar to the exponentially decreasing current of a forward-biased diode.

\[ S = \left[ \frac{\partial \log(I_d)}{\partial V_g} \right]^{-1} \]  

(3)

The drain current ON-OFF ratio of the device is calculated from equation (4).

\[ \frac{I_{ON}}{I_{OFF}} = \frac{C_d \mu_{FET} (V_g - V_T)^2}{\sigma d V_0} \]  

(4)

Where \( \sigma \) and \( d \) is the conductivity and thickness of the semiconductor layer of the TFTs, respectively.

Both devices have different contact resistance, mainly due to different substrates. The aluminum metal coating is used for making gate ohmic contact where the back contact coating method is used for other Si substrates while the direct coating method is used for another and glass substrate as shown in figure (9), this is also a major reason for the difference in threshold voltage of both devices.

The high contact resistance masks the real value of field-effect mobility and reduces the on-current. Also published reports indicate that contact resistance may affect the sub-threshold region [24–26].

On the other hand, the value extracted for field-effect mobility greater than 5 cm\(^2\) Vs\(^{-1}\) is better than those reported 0.2 cm\(^2\) Vs\(^{-1}\) [27–29] although different mobility values reported in the literature are a function of different annealing temperatures.

| Table 3. Parameters obtained for TFT on Si and glass substrates. |
| S. no. | Parameter | TFT devise on Si substrate | TFT devise on a glass substrate |
|-------|-----------|---------------------------|---------------------------------|
| 1     | Mobility, \( \mu_{FET} \) (cm\(^2\)/Vs) | 5.859                      | 0.158                           |
| 2     | The threshold voltage, \( V_T \) (Volt) | 0.8                        | 2.6                             |
| 3     | Drain current ON/OFF ratio | 10\(^4\)                 | 10\(^3\)                        |
| 4     | Sub-threshold swing, S (V/dec) | 0.5472                    | 0.7385                          |
4. Conclusion

TFTs based on Zn$_3$N$_2$ film (∼100 nm) as an active layer and HfO$_2$ (∼50 nm) as insulator were fabricated using two different substrates (Si and glass) and characterized. The better electrical characteristics for the TFT on Si correspond to a higher transconductance in the device. Also, TFT on Si shows better threshold voltage ($V_{th}$) and mobility as compared to that of TFT on the glass substrate, due to better metallic contact provided by Si substrate. The output characteristics indicate that the long channel device is also affected by the high contact resistance, therefore the real field-effect mobility maybe even higher.

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Disclosure of potential conflicts of interest

The above-mentioned work is my Ph.D. work, my Ph.D. is self-financing, in it, the entire expenditure on experimentation and characterization is done by me, there is no contribution from any financial institution.

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References

[1] Ben-Sasson A, Chen Z, Facchetti A and Tessler N 2012 Solution-processed ambipolar vertical organic field-effect transistor Appl. Phys. Lett. 100 263306–1–4
[2] Domínguez M, Flores F, Luna A, Martínez J, Luna-Lopez J, Alcantara S, Rosales P, Reyes C and Orduña K 2015 Impact of active layer thickness in thin-film transistors based on zinc oxide by ultrasonic spray pyrolysis Solid-State Electron. 109 33–6
[3] Reyes P, Ku C, Duan Z, Lu Y, Solanki A and Lee K 2011 ZnO thin film transistor immunosensor with high sensitivity and selectivity Appl. Phys. Lett. 98 173702–1–3
[4] McFarlane I, Lazzari J and El-Naggar M 2015 Field effect transistors based on semiconductivemicrobiologically synthesized chalcopyridenano fibers Actuators Mater. 13 364–73
[5] Partin D E, Williams D J and O’Keeffe M 1997 J. Sol. State Chem. 132 56
[6] Futsuhara M, Yoshioka K and Takai O 1998 Thin Solid Films 322 274
[7] Simi S et al 2011 Appl. Surf. Sci. 257 9269
[8] Ayoushi R et al 2010 Phys. Status Solidi C 7 2294
[9] Banerjee S, Ferrari S, Chatteigner D and Gibaud A 2004 R v characterization of ultra-thin films using specular x-ray reflectivity q T S F 5 23–8
[10] T’Uzemen S, Kavak H and Esen R 2007 Chin. Phys. Lett. 24 3477 11
[11] Wang D et al 2004 Phys. Condens. Matter 16 4635
[12] Jiang N et al 2012 J. Phys. D: Appl. Phys. 45 135101
[13] García-Núñez C et al 2012 Thin Solid Films 520 1924
[14] Jiang N, Georgiev D G, Wen T and Jayatissa A H 2012 Thin Solid Films 520 1698
[15] Jayatissa A H, Wen T and Gautam M 2012 J. Phys. D: Appl. Phys. 45 045402
[16] Y C, Lim R and Bad J M 2009 J. Appl. Phys. 106 074512
[17] He G, Fang Q and Zhang I D 2006 Mater. Sci. Semicon. Proc. 9 870
[18] Jiang N, Georgiev D G, Wen T and Jayatissa A H 2012 Thin Solid Films 520 1698 Powder Diffraction File compiled by the joint committee on Powder Diffraction, Card no. 10-0256
[19] Jayatissa A H, Wen T and Gautam M 2012 J. Phys. D 45 045402 Powder Diffraction File compiled by the Joint Committee on Powder Diffraction, Card No. 4-0831
[20] Jiménez F 2011 BP X-ray R v T F(Northeastern University)
[21] Solookinejad G, Rozatian A S H and Habibi M H 2011 ZnO characterization by x-ray reflectivity q T S F 5 6 109
[22] Tauc J, Grigorovic R and Vancu A 1966 Phys. Status Solidi 15 627 Vance
[23] Valletta A, Fortunato G, Mariucci L, Barquinha P, Martins R and Fortunato E 2014 Contact effects in amorphous InGaZnO thin-film transistors J. Disp. Technol. 10 956–61
[24] Domínguez M, Rosales P, Torres A, Flores F, Luna J, Alcantara S and Moreno M 2016 Impact of planarized gate electrode in bottom-gate thin-film transistors Rev. Mex. Fis. 62 223–8
[25] Domínguez M, Alcantara S and Soto S 2016 Physically-based simulation of zinc oxide thin-film transistors: contact resistance contribution on the density of states Solid-State Electron. 120 41–6
[26] Aperatis E, Kambila K V and Modreanu M 2009 Properties of n-type ZnN thin films as a channel for transparent thin-film transistors Thin Solid Films 518 1036–9
[27] Khoshman J et al 2012 Thin Solid Films 520 7230
[28] Riad A S, Mahmoud S A and Ibrahim A A 2001 Physica B 296 319