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# Flexible Zinc Nitride Thin-film Transistors using Spin-on Glass as gate insulator

Miguel A. Dominguez, Jose Luis Pau and Andres Redondo-Cubero

**Abstract**—In this work, Zinc Nitride ( $\text{Zn}_3\text{N}_2$ ) based flexible thin film transistors (TFTs) are presented. The zinc nitride thin film is deposited by magnetron radio-frequency sputtering at room temperature, while spin-on glass and aluminum were used as gate insulator and source/drain electrode, respectively. Polyethylene terephthalate is used as flexible substrate. The flexible  $\text{Zn}_3\text{N}_2$  TFTs were characterized while bent to 5 mm tensile radius. The flexible TFTs exhibit an electron mobility of  $3.8 \text{ cm}^2/\text{Vs}$  and an on/off current ratio close to  $10^5$  after several cycles of bending and being exposed to air ambient for 30 days.

**Index Terms**— Flexible devices, thin-film transistors, zinc nitride, spin-on glass.

## I. Introduction

FLEXIBLE electronics is an attractive research field due to the large number of possible novel applications, such as flexible displays, sensors, medical patches or e-paper. The recent development in this technology falls in the development of flexible thin-film transistors (TFTs) as basic building block, where the research for high carrier mobility materials obtained at very low temperature is the main explored field [1-4]. Zinc nitride ( $\text{Zn}_3\text{N}_2$ ) has been recently investigated to enable high mobility TFTs, since Hall mobilities values close to  $100 \text{ cm}^2/\text{Vs}$  have been reported at low deposition temperatures [4-6]. This makes  $\text{Zn}_3\text{N}_2$  a promising candidate to replace silicon, as the mature technology in TFTs, and other alternative materials such as organics and metal-oxide based semiconductors. Lately, some research has provided physical insight into  $\text{Zn}_3\text{N}_2$  films to be studied as active layers in flexible TFTs [6-8]. As far as the authors know, there is no published works on flexible  $\text{Zn}_3\text{N}_2$  TFTs.

On the other hand, along with the high mobility active layer, the gate insulator also plays an important and significative role in the development of this technology. The gate insulator determines the charge density and leakage current mainly. Therefore, a poor-quality gate insulator may reduce the carrier mobility, degrade the transconductance of the TFT and affect the on/off drain current [9, 10]. Previous reports [11-13], indicate the possibility of use spin-on glass (SOG) as gate insulator in flexible TFTs. This gate insulator obtained at  $200^\circ\text{C}$  by spin-coating exhibits dielectric properties very similar to thermally grown silicon dioxide  $\text{SiO}_2$ . Moreover, the use of SOG may reduce the roughness of the substrates used in flexible TFTs, in order to avoid the degradation of the carrier mobility in the channel of the TFTs [14].

In this work,  $\text{Zn}_3\text{N}_2$  based flexible thin film transistors (TFTs) are presented. The zinc nitride thin film is deposited by radio-frequency magnetron sputtering at room temperature. To avoid oxidation of the  $\text{Zn}_3\text{N}_2$  film, a zinc oxide ( $\text{ZnO}$ ) film is used as passivation film. As gate insulator, LSF-SOG was deposited at  $200^\circ\text{C}$ . While aluminum, as source/drain electrode, was deposited by DC magnetron sputtering at room temperature. Polyethylene terephthalate (PET) is used as flexible substrate. The flexible  $\text{Zn}_3\text{N}_2$  TFTs were characterized while bent to 5 mm tensile radius and exposed to air ambient for several days. To the best of our knowledge, this is the first flexible TFT based on  $\text{Zn}_3\text{N}_2$  films.

## II. EXPERIMENT

The flexible  $\text{Zn}_3\text{N}_2$  TFTs were fabricated as follows: the flexible substrates were indium tin oxide (ITO) coated PET substrates commercially available (Sigma-Aldrich). The SOG was spin-coated at 3000 rpm for 30 s and cured at  $200^\circ\text{C}$  for 1.5 h. The SOG precursor solution was prepared from a solution of LSF47-SOG (33%) in 66% LSFD1 diluent (Filmtronics Inc. PA, USA). The thickness of the LSF-SOG film was 85 nm. After that, a 100 nm-thick Al film was plasma sputtered at room temperature and patterned as source/drain electrodes. The working pressure was  $10^{-2}$  mbar with a radio frequency power of 250 W. Finally, a 20 nm-thick  $\text{Zn}_3\text{N}_2$  film was plasma sputtered at room temperature followed by the deposition of a 20 nm-thick  $\text{ZnO}$  film as passivation layer. The plasma discharge was induced between a 4-in. circular Zn target (99.995% purity) and the substrate, using 30 sccm flux of Nitrogen gas (99.999%) with a radio frequency power of 100 W. The working pressure was  $10^{-2}$  mbar. The  $\text{ZnO}$  thin film was also sputtered at

room temperature from the same Zn target using a 50 sccm (99.999% pure) O<sub>2</sub> gas flow and a radio frequency power of 250 W. The magnetron sputtering system used was the ALCATEL A450 model. Figure 1 shows the schematic structure used for the inverted coplanar flexible Zn<sub>3</sub>N<sub>2</sub> TFTs. The electrical characteristics were measured using a Keithley-4200 Semiconductor Characterization System, under dark conditions, air ambient and room temperature.

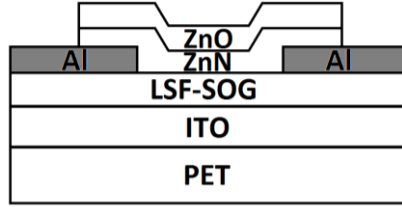


Fig. 1. Schematic cross section of the flexible Zn<sub>3</sub>N<sub>2</sub> TFTs (not to scale).

### III. RESULTS AND DISCUSSION

Figure 2 shows the transfer characteristics of the inverted coplanar Zn<sub>3</sub>N<sub>2</sub> based TFTs at voltages corresponding to linear (V<sub>ds</sub> = 0.5 V) and saturation (V<sub>ds</sub> = 10 V) regimes. The flexible Zn<sub>3</sub>N<sub>2</sub> TFTs work at enhancement mode (normally off), in other words, the drain current I<sub>ds</sub> increases with the gate voltage V<sub>gs</sub>. It can be seen that the flat band voltage (also known as turn-on voltage) is close to V<sub>gs</sub> = 0 V and the subthreshold region is similar at both regimes, which indicates a high-quality LSF-SOG/Zn<sub>3</sub>N<sub>2</sub> interface (insulator-semiconductor interface). The devices exhibit an on/off-current ratio close to 10<sup>5</sup> and a gate leakage current <1×10<sup>-8</sup> A.

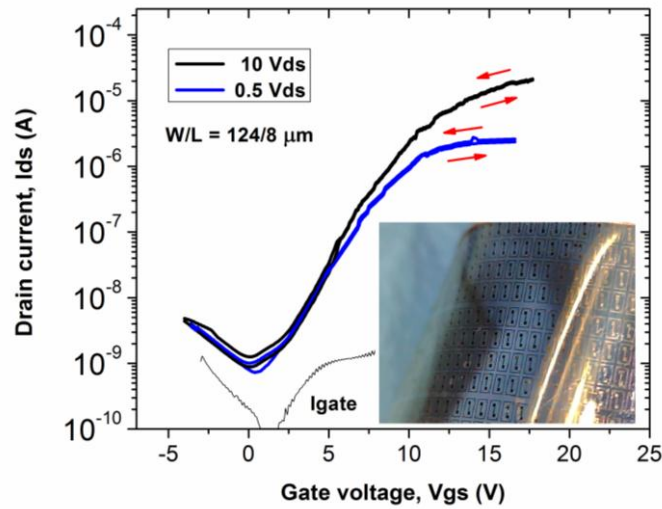


Fig. 2. Transfer characteristics of the flexible Zn<sub>3</sub>N<sub>2</sub> TFTs at linear and saturation regimes. Inset shows a photograph of the fabricated devices. The flat band voltage (turn-on) is close to V<sub>gs</sub> = 0 V and the subthreshold region is similar at both regimes, which indicates a high-quality LSF-SOG/Zn<sub>3</sub>N<sub>2</sub> interface (insulator-semiconductor interface).

The electron field-effect mobility was extracted using the equation (1) of the TFTs in the saturation regime (V<sub>ds</sub>=10 V) [15].

$$I_{ds} = \mu_{FE} \cdot C_{ox} (W/2L) (V_{gs} - V_T)^2 \quad (1)$$

Where  $\mu_{FE}$  is the field-effect mobility,  $C_{ox}$  is the capacitance per unit area of the gate insulator ( $4 \times 10^{-8}$  F/cm<sup>2</sup>), W and L are the channel width and length, respectively, and  $V_T$  is the threshold voltage. The extracted field-effect mobility was 3.8 cm<sup>2</sup>/Vs. Figure 3 shows the output characteristics of the flexible Zn<sub>3</sub>N<sub>2</sub> TFTs. The flexible devices clearly exhibit linear and saturation regimes, while the drain current is modulated with gate voltage.

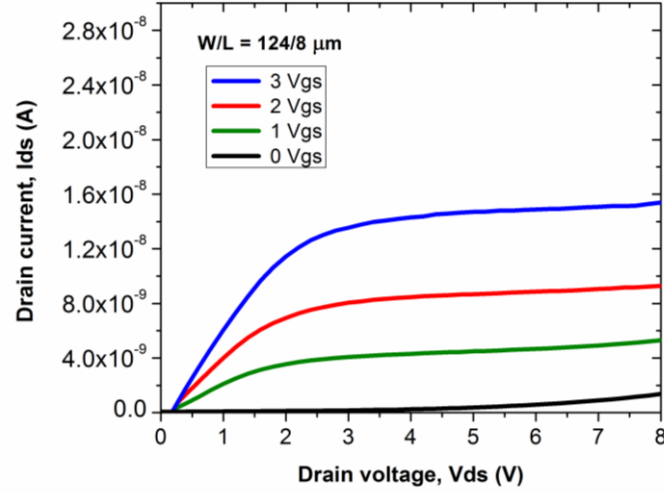
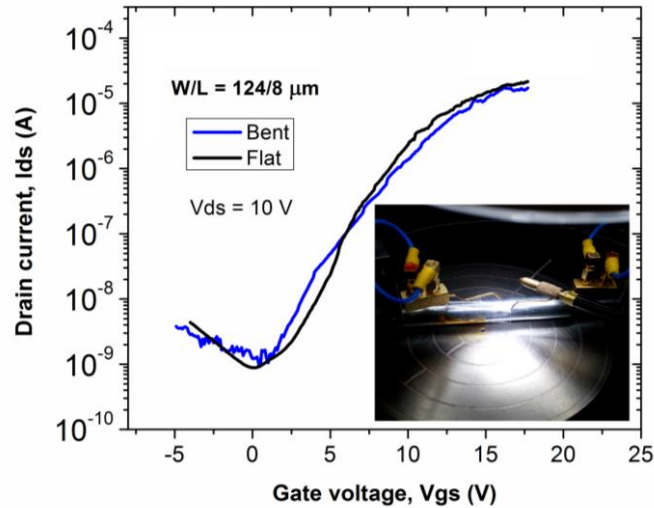


Fig. 3. Output characteristics of the flexible  $\text{Zn}_3\text{N}_2$  TFTs. The flexible devices clearly exhibit linear and saturation regimes, while the drain current is modulated with gate voltage.

The obtained results are similar to those reported by other groups on rigid substrates [16, 17]. In [16], electron mobilities from 0.02 to 4  $\text{cm}^2/\text{Vs}$  were reported for  $\text{Zn}_3\text{N}_2$  TFTs with thermal annealing from 300 °C to 400 °C. In [17], the electron mobility reported was close to 10  $\text{cm}^2/\text{Vs}$  for zinc oxynitride TFTs deposited at 50 °C and annealed at 350 °C. Moreover, the electron mobility extracted in the flexible  $\text{Zn}_3\text{N}_2$  TFTs is similar to that reported in oxide-based flexible TFTs [18, 19] and better than pentacene flexible TFTs [20]. Also, the results obtained are better than those reported in our previous  $\text{Zn}_3\text{N}_2$  TFTs on silicon wafers [8]. The improvement in the electrical characteristics is due to a different fabrication of the source/drain contacts to improve the metal-insulator interface. It is well-known that the electron mobility is sensitive to the roughness of the insulator-semiconductor interface. In our flexible TFTs, although the PET substrate presents higher roughness than a silicon wafer, the use of LSF-SOG smooth the surface to avoid degradation of the electron mobility due to scattering processes [14].

In order to evaluate the flexibility of our devices, the flexible  $\text{Zn}_3\text{N}_2$  TFTs were attached on a metal rod of 5 mm radius to compare the electrical performance during mechanical strain. The bent to a tensile radius of 5 mm is equivalent to a mechanical strain of  $\sim 0.5\%$  [21]. Figure 4a shows the transfer characteristics in saturation regime during flexible TFTs bending. The inset shows the configuration of the bending test.



a)

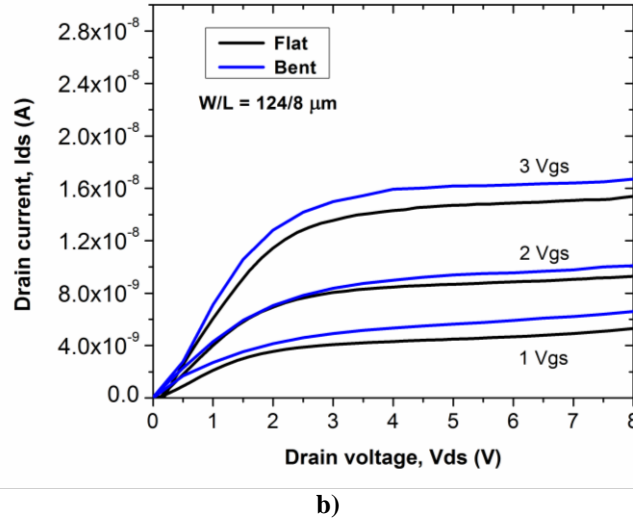
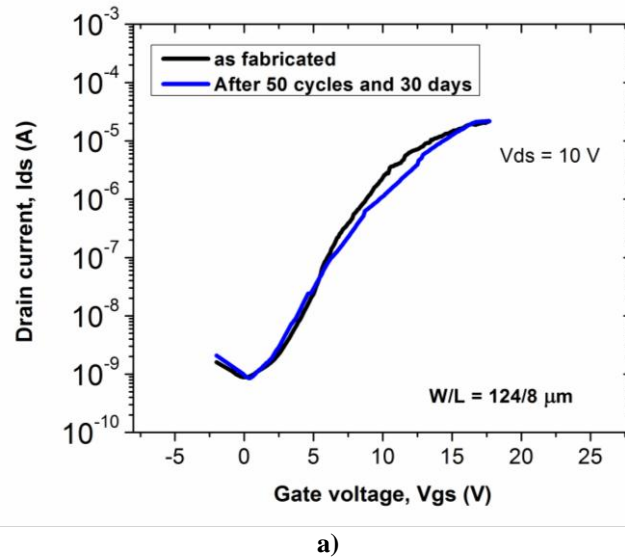


Fig. 4. Electrical characteristics of the flexible  $\text{Zn}_3\text{N}_2$  TFTs during mechanical strain. a) Transfer characteristics. Inset shows the configuration of the bending test. b) Output characteristics. The flat band voltage is close to  $V_{gs} = 0$  V, also, the values of on- and off-currents are very similar, indicating that the main interfaces of the device (insulator-semiconductor and metal-semiconductor) remain unaffected by the mechanical strain.

The devices exhibit electrical characteristics very similar with and without bending. The flat band voltage is also close to  $V_{gs} = 0$  V, and the values of on- and off-currents are very similar. This indicates that the main interfaces of the device (insulator-semiconductor and metal-semiconductor) remain unaffected by the mechanical strain. This can be corroborated by the output characteristics during device bending shown in figure 4b. The  $\text{Zn}_3\text{N}_2$  TFTs clearly show linear and saturation regimes with and without bending. Moreover, the family curves are very similar. From the above measurements, it is clear that the mechanical strain applied does not affect the electrical performance of the flexible  $\text{Zn}_3\text{N}_2$  TFTs. This is consistent for at least 8 measured TFTs. It is important to note the electrical characteristics exhibit the same performance after removing the tensile strain. Figure 5 shows the electrical characteristics of the flexible TFTs after 50 cycles of mechanical strain and 30 days of being exposed to the air ambient. The repeated mechanical strain does not deteriorate the electrical performance of the flexible  $\text{Zn}_3\text{N}_2$  TFTs. Moreover, after 30 days of being exposed to air ambient, the flexible TFTs exhibit transfer and output characteristics very similar compared to the initial measurement. Previous reports indicate an oxidation of the  $\text{Zn}_3\text{N}_2$  films under air ambient [6]. However, the passivation of the  $\text{Zn}_3\text{N}_2$  film with ZnO results in highly stable devices. On the other hand, the LSF-SOG film shows good mechanical stability during the bending test, this can be concluded since the TFTs do not exhibit a deterioration of field-effect mobility or change in the on/off-current ratio.

The above results demonstrate the large potential of  $\text{Zn}_3\text{N}_2$  films deposited at room temperature and solution-processed LSF-SOG insulator films for the fabrication of stable flexible TFTs.



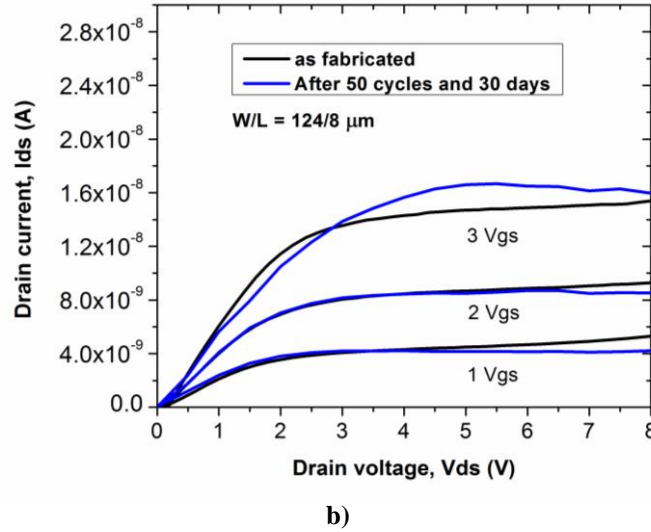


Fig. 5. Electrical characteristics of the flexible  $\text{Zn}_3\text{N}_2$  TFTs after 50 cycles of mechanical strain and 30 days of being exposed to the air ambient. a) Transfer characteristics. b) Output characteristics. The flexible TFTs exhibit transfer and output characteristics very similar compared to the initial measurement. This performance is proof of the good stability of the  $\text{Zn}_3\text{N}_2$  and LSF-SOG films.

#### IV. CONCLUSIONS

In this work, the feasibility of use  $\text{Zn}_3\text{N}_2$  films deposited at room temperature and solution-processed LSF-SOG insulator films for manufacturing flexible TFTs is presented. The devices exhibit an on/off-current ratio close to  $10^5$ , a flat band voltage close to  $V_{gs} = 0$  V and a field-effect mobility of  $3.8 \text{ cm}^2/\text{Vs}$ , after several cycles of bending and being exposed to air ambient for 30 days. This performance is a proof of the good mechanical stability of the  $\text{Zn}_3\text{N}_2$  and LSF-SOG films. Also, the passivation of the  $\text{Zn}_3\text{N}_2$  film with ZnO results in highly stable devices.

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