

# Low-Frequency Noise in InGaZnO Thin-Film Transistors with Al<sub>2</sub>O<sub>3</sub> Gate Dielectric

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**Abstract**— We present a study of the low frequency noise (LFN) behavior of amorphous indium gallium zinc oxide (a-IGZO) thin film transistors (TFTs) fabricated with Al<sub>2</sub>O<sub>3</sub> as gate dielectric. The LFN follows a 1/f-spectrum and can be described using the carrier number fluctuation theory with correlated mobility fluctuations, with a calculated trap density ( $N_T$ ) of  $4.1 \times 10^{11} \text{ cm}^{-2} \text{ eV}^{-1}$  and a scattering coefficient ( $\alpha_{sc}$ ) of  $1.5 \times 10^5 \text{ Vs/C}$ . For low drain currents, the LFN originates from fluctuations in the flat band voltage, whereas in linear regime the noise is dominated by mobility fluctuations. The extracted Hooge's parameter ( $\alpha_H$ ) is  $\sim 1.1 \times 10^{-3}$  for devices with Al<sub>2</sub>O<sub>3</sub> as gate dielectric, the lowest ever reported for a-IGZO TFTs using a high-k dielectric without any interfacial dielectric.

**Keywords**—Thin-film transistor, a-IGZO, Low-frequency Noise, Al<sub>2</sub>O<sub>3</sub>, Hooge's parameter

## I. INTRODUCTION

Metal oxide semiconductor thin-film transistors (TFTs), in particular amorphous indium gallium zinc oxide (a-IGZO) TFTs, have attracted interest for display and flexible electronics applications due to their low deposition temperatures, large area uniformity and good electrical characteristics, such as high electron mobility ( $\sim 10 \text{ cm}^2/\text{Vs}$ ) and low subthreshold swing [1]. Low frequency noise (LFN) can be used as a characterization technique to study defects in amorphous semiconductor and the quality of the semiconductor and gate dielectric interface. Additionally, for analog circuit applications, noise is an important issue to be considered as it sets the lower limit of the signal amplitude in the system. The use of high-k dielectrics as the gate dielectric has the potential to improve device performance by reducing the operational voltages and power consumption, but usually comes with a degradation in noise performance [2]–[6].

As previously reported in [3] and [6], the use of Al<sub>2</sub>O<sub>3</sub> as gate dielectric had a detrimental effect on the noise of the TFTs. It was concluded that the high LFN was due to an increase of the electron-phonon scattering originating from the remote phonon modes in the high-k dielectric. To overcome this problem and obtain devices with low noise while using high-k dielectrics, SiO<sub>2</sub> or SiN<sub>x</sub> have been employed as an interfacial dielectric in between the semiconductor and the high-k dielectric, which can improve the interface quality or suppress the remote phonon scattering from the high-k dielectric [3], [4], [7]. However, this comes with an increase in the number of fabrication steps.

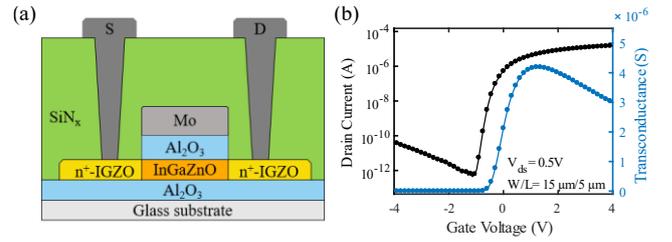


Fig. 1 (a) Schematic cross-section of the fabricated top-gate self-aligned (SA) a-IGZO TFTs with Al<sub>2</sub>O<sub>3</sub> gate dielectric, (b) Transfer characteristics,  $I_{DS} - V_{GS}$  curve, in linear regime ( $V_{DS} = 0.1 \text{ V}$ ) for  $W = 15 \text{ } \mu\text{m}$  and  $L = 5 \text{ } \mu\text{m}$ .

In this work, we characterize the LFN of a-IGZO TFTs with Al<sub>2</sub>O<sub>3</sub> as gate dielectric, without any additional interfacial dielectric layer. The origin of the LFN is investigated and the carrier number fluctuation theory with correlated mobility fluctuations ( $\Delta n - \Delta \mu$ ) is employed to describe the measurements.

## II. EXPERIMENTAL

Top-gate Self-Aligned (SA) a-InGaZnO TFTs with Al<sub>2</sub>O<sub>3</sub> gate dielectric were fabricated following a process flow similar to the one reported in [8]. A schematic cross-section of fabricated TFTs is presented in Fig. 1 (a). Briefly, fabrication started with an Al<sub>2</sub>O<sub>3</sub> buffer layer deposited by atomic layer deposition (ALD) on a glass substrate. As the active layer, 12 nm of a-InGaZnO was deposited by DC sputtering and the device's active area was defined by wet etching. 20 nm thick Al<sub>2</sub>O<sub>3</sub> was deposited by low temperature ALD as gate dielectric, followed by the sputtering of Mo/TiN as gate metals. The gate metal and gate dielectric were patterned using dry and wet etching, respectively. 150 °C, a SiN interlayer was deposited by plasma enhanced chemical vapor deposition (PECVD). A metal stack of sputtered Ti/Al/Ti was patterned by lift-off and used as source/drain contacts. A final annealing at 250 °C for 1 hour under N<sub>2</sub> ambient was performed. Low-frequency noise measurements were carried out using a dedicated LFN setup (Keysight's E4727A) at room temperature. The LFN was measured in saturation for low drain currents and linear regime of operation, with  $V_{DS}$  set to 0.5 V and the overdrive voltage swept between 0 V and 4.5 V.

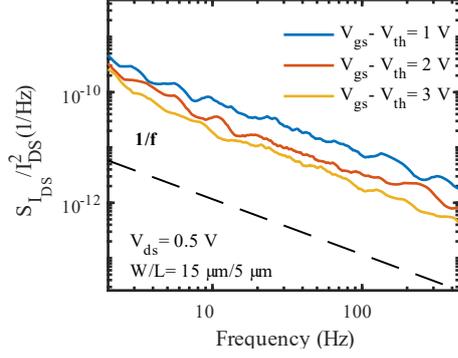


Fig. 2. Normalized drain current noise power spectral density ( $S_{ID}/I_{DS}^2$ ) of a TFT biased in the linear regime for different  $V_{gs}-V_{th}$ .

### III. RESULTS AND DISCUSSION

Fig. 1 (b) shows the transfer characteristics ( $I_{DS}$  vs.  $V_{GS}$ ) and transconductance ( $g_m$ ) of a fabricated a-IGZO TFT with 15  $\mu\text{m}$  and 5  $\mu\text{m}$  channel width ( $W$ ) and length ( $L$ ) respectively, measured in linear regime of operation,  $V_{DS} = 0.5$  V. Normally, for IGZO TFTs,  $g_m$  increases steadily. In this case however, the transconductance reaches a maximum, indicating the presence of contact resistance.

The correct extraction of the threshold voltage ( $V_{th}$ ) is a critical step to assess the origin of the noise but presents special difficulties for metal-oxide thin-film transistors since  $V_{th}$  is not clearly defined and a standardized methodology for extracting it does not exist. In the past, this ambiguity has led to opposite interpretations of the origin of the LFN when analyzing data of the same devices, as different models could be applied depending on how the threshold voltage was initially calculated [9], [10]. In this paper,  $V_{th}$  was calculated using the  $I_d^2/g_m$  method described in [11], as it takes into account the mobility power-law parameter present in IGZO TFTs and it is insensitive to the presence of contact resistance, present in our TFTs.  $V_{th}$  was then found to be 0.17 V.

The normalized drain current noise power spectral density (PSD) ( $S_{ID}/I_{DS}^2$ ) of the  $\text{Al}_2\text{O}_3$  TFT, biased in the linear regime, is presented in Fig. 2 for different  $V_{gs}-V_{th}$ .  $S_{ID}/I_{DS}^2$  decreases for increasing gate voltages and the LFN follows the expected  $1/f^\gamma$  noise spectrum, with  $\gamma = 0.9-1.1$  in the frequency range of 1 Hz to 500 Hz for all biases.

Two main theories have been used to explain the origin of the LFN in transistors: the carrier mobility fluctuations model ( $\Delta\mu$ ), in which the noise arises from carrier-phonon scattering in the semiconductor, and the carrier number fluctuations model ( $\Delta n$ ), in which the noise is caused by the flat band voltage fluctuations, usually associated with carrier trapping and detrapping in the gate dielectric close to the channel-interface [12].

For the carrier mobility fluctuation theory, the following empirical formula for the normalized drain current PSD is suggested

$$\frac{S_{ID}}{I_{DS}^2} = \frac{\alpha_H}{fN} \quad (1)$$

where  $f$  is the frequency,  $N$  is the total number of carriers involved in the conduction, and  $\alpha_H$ , known as the Hooge's

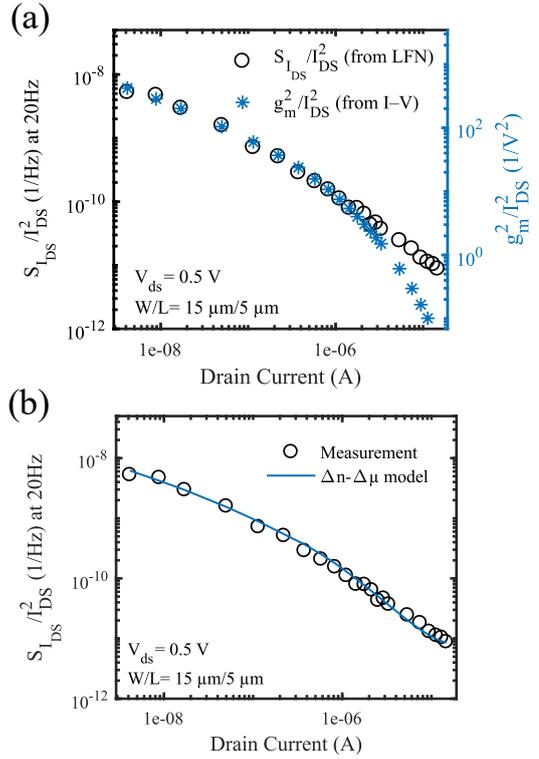


Fig. 3 (a) Normalized drain current noise power spectral density ( $S_{ID}/I_{DS}^2$ ) vs. drain current at a frequency of 20 Hz and  $(g_m/I_{DS})^2$  against drain current. The good match between the two graphs for low drain currents indicates that the  $1/f$  noise follows the carrier number fluctuation theory for the TFT biased in saturation regime. (b) Same data as before, ( $S_{ID}/I_{DS}^2$ ) vs. drain current, and fitting using the carrier number fluctuation theory with correlated mobility fluctuations,  $S_{VFB} = 1.45 \times 10^{-11} \text{ V}^2/\text{Hz}$ ,  $N_t = 4.1 \times 10^{11} \text{ cm}^{-2} \text{ eV}^{-1}$  and  $\alpha_{sc} = 1.5 \times 10^5 \text{ Vs/C}$ .

parameter, is a technology constant and it is used as a quality indicator of the device [13].

In the carrier number fluctuation theory, the normalized drain current PSD is defined as

$$\frac{S_{ID}}{I_{DS}^2} = \frac{g_m^2}{I_{DS}^2} S_{VFB} \quad (2)$$

where  $g_m$  is the transconductance, and  $S_{VFB}$  is the flat band voltage spectral density associated with fluctuations of the interface charge [14] and is defined as

$$S_{VFB} = \frac{q^2 kT}{C_{ox}^2 W L f} N_t \quad (3)$$

where  $q$  is the electron charge,  $C_{ox}$  is the gate insulator capacitance per unit area,  $k$  is the Boltzmann's constant,  $T$  is the temperature, and  $N_t$  is the density of traps near the channel/dielectric interface.

A way of assessing the origin of the low-frequency noise and distinguishing between the different theories, is by evaluating the dependence of  $S_{ID}/I_{DS}^2$  on  $I_{DS}$  and comparing it to  $(g_m/I_{DS})^2$ , as shown in Fig. 3 (a). In the carrier number fluctuations model, both quantities are proportional, with  $S_{VFB}$  as the proportionality constant, as stated in eq. (2). From Fig. 3 it is observed that the normalized current PSD is in good agreement with the  $\Delta n$  theory for low drain currents. Deviation between the PSD and  $(g_m/I_{DS})^2$  starts occurring at a drain current of about 1  $\mu\text{A}$ , which also corresponds to the bias condition for which the transistor transitions from saturation to linear regime ( $V_{gs}-V_{th} = V_{ds}$ ). From Fig. 3 (a),  $S_{VFB}$  can be calculated as  $S_{ID}/g_m^2$  for values in which both

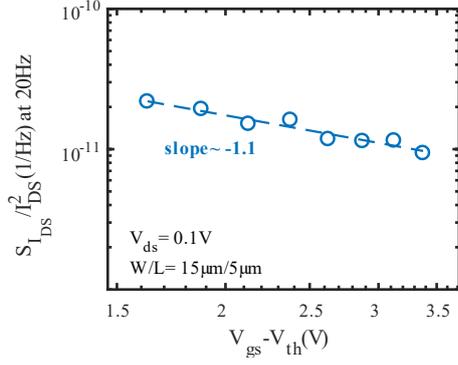


Fig. 5 Normalized drain current noise power spectral density against overdrive voltage ( $S_{IDS} / I_{DS}^2$  versus  $V_{gs} - V_{th}$ ) at a frequency of 20 Hz for a TFT biased in the linear regime. The extracted slope,  $m \approx -1.12$ , indicates that the  $1/f$  noise follows the carrier number fluctuation theory with correlated mobility fluctuations.

graphs overlap,  $S_{VFB}$  is then found to be  $1.45 \times 10^{-11} \text{ V}^2/\text{Hz}$ . Applying (3) allows extracting the trap density,  $N_t = 4.1 \times 10^{-11} \text{ cm}^{-2} \text{ eV}^{-1}$ .

For higher currents, the measured noise deviates from the  $S_{IDS} / I_{DS}^2$  calculated employing the  $\Delta n$  model. This deviation can be accounted for by refining the employed model and incorporating into the calculations the mobility fluctuations created by the trapping and detrapping of carriers. The carrier number fluctuation theory with correlated mobility fluctuations ( $\Delta n - \Delta \mu$ ) considers these, for which the normalized drain current PDS is defined as

$$\frac{S_{IDS}}{I_{DS}^2} = \left(1 \pm \alpha_{sc} \mu_{eff} C_{ox} \frac{I_{DS}}{g_m}\right)^2 \frac{g_m^2}{I_{DS}^2} S_{VFB} \quad (4)$$

where  $\mu_{eff}$  is the effective mobility and its sign depends of the nature of the traps: negative for acceptor-like traps or positive for donor-like traps, and  $\alpha_{sc}$  is the Coulomb scattering coefficient [13]. Fig. 3 (b) shows the fitting of (4) to the measurements previously presented, with  $S_{VFB}$  having the same value as before and  $\alpha_{sc} = 1.5 \times 10^5 \text{ Vs/C}$ . By incorporating the correlated mobility fluctuations, it is possible to model the LFN of the IGZO TFTs both in saturation with low drain currents and in linear regime of operation.

Another way of assessing the dominant noise mechanism is by studying the dependence of  $S_{IDS} / I_{DS}^2$  on the gate overdrive voltage at a fixed frequency, since both  $\Delta \mu$  and  $\Delta n$  models propose a different power law dependence [12], [15]. The slope of  $S_{IDS} / I_{DS}^2$  against overdrive voltage on logarithmic scale would have a value of -1 according to the  $\Delta \mu$  model and -2 in the  $\Delta n$  model, for devices biased in linear regime and for  $V_{ds} \ll (V_{gs} - V_{th})$ . A slope between -1 and -2, is an indication of the  $\Delta n - \Delta \mu$  model. As mentioned before, the correct extraction of the threshold voltage is very important to assess the origin of the noise. A small error in the calculated  $V_{th}$  can lead to a considerable change in the slope, since the x-axis is in logarithmic scale.

Fig. 5 shows  $S_{IDS} / I_{DS}^2$  against overdrive voltage and illustrates a power law dependence on  $(V_{gs} - V_{th})^m$ , with  $m \approx -1.12$  for TFTs with  $\text{Al}_2\text{O}_3$  gate dielectric. The fitting range to calculate  $m$  was selected for  $V_{gs} - V_{th} > 1.5 \text{ V}$ , in order to avoid an incorrect extraction of the slope by minimizing the effect of  $V_{ds}$  or small errors in the employed  $V_{th}$ . The extracted slope is between -1 and -2, in accordance

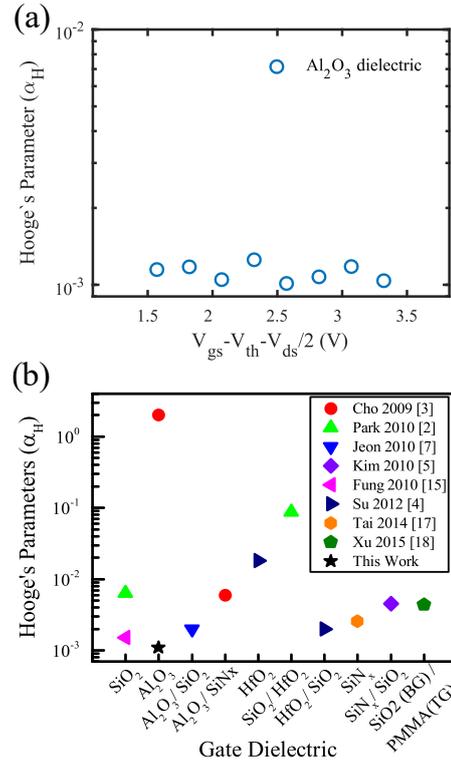


Fig. 4 (a) Extracted Hooe's parameter as a function of  $V_{gs} - V_{th} - V_{ds}/2$  for a-IGZO TFTs with a 20 nm  $\text{Al}_2\text{O}_3$  gate dielectric. (b) Reported Hooe's parameter for a-IGZO TFTs with various gate dielectrics. For devices with a bilayer of gate dielectrics, the dielectric in contact with the channel is mentioned in second place. For the last device, BG and TG correspond to back-gate and top-gate respectively.

with the  $\Delta n - \Delta \mu$  model, corroborating the results obtained earlier.

Additionally, a value of  $m$  near -1 is in close agreement with the mobility fluctuation model, a theory that proposes that the main noise contribution stems from carrier-phonon scattering in the bulk [13]. This dependence of  $S_{IDS} / I_{DS}^2$  on gate bias suggests that the mobility fluctuations in the semiconductor is the dominant noise source of the LFN in our TFTs with  $\text{Al}_2\text{O}_3$ , when biased in the linear regime.

The Hooe's parameter offers a convenient way of assessing the quality of the channel and channel/dielectric interface, as well as the noise performance of the fabricated TFTs, independently of the device's geometrical factors. The lower its value, the higher the noise performance of the device. From (1), the Hooe's parameter can be calculated as

$$\alpha_H = \frac{I_{DS}^2}{S_{IDS}} fN, \quad (5)$$

where the total number of carriers in linear regime is given by

$$N = \frac{1}{q} C_{ox} WL \left( V_{gs} - V_{th} - \frac{V_{ds}}{2} \right) \quad (6)$$

Substituting (5) in (6) one obtains

$$\alpha_H = \frac{I_{DS}^2}{S_{IDS}} \frac{f C_{ox} LW}{q} \left( V_{gs} - V_{th} - \frac{V_{ds}}{2} \right) \quad (7)$$

Figure Fig. 4 (a) shows the extracted Hooe's parameter, which is approximately  $1.1 \times 10^{-3}$ , against  $V_{gs} - V_{th} - V_{ds}/2$  for the studied TFT with aluminum oxide. This value is comparable to the lowest reported in the literature for IGZO

TFTs, as shown in Fig. 4 (b), and is 3 orders of magnitude lower than the ones previously reported for TFTs with Al<sub>2</sub>O<sub>3</sub> gate dielectric [3]. One reason that could explain the discrepancy between our results and values previously reported, is found in [13], where it is suggested that the LFN of the IGZO TFTs with aluminum oxide gate dielectric reported in [3], follows the  $\Delta n$  model instead of the  $\Delta \mu$  model. Additionally, the value reported here is the lowest ever presented for an a-IGZO TFT, using only a high-k gate dielectric without the use of an interfacial layer. Moreover, it is comparable to the value reported in [16], where IZO TFTs with anodized Al<sub>2</sub>O<sub>3</sub> as gate dielectric were characterized.

#### IV. CONCLUSION

In this work, we presented the characterization of the LFN of IGZO TFTs with low-temperature ALD Al<sub>2</sub>O<sub>3</sub> as gate dielectric. The LFN follows the carrier number fluctuation theory with correlated mobility fluctuations, with a calculated trap density of  $4.1 \times 10^{11} \text{ cm}^{-2} \text{ eV}^{-1}$  and a scattering coefficient ( $\alpha_{sc}$ ) of  $1.5 \times 10^5 \text{ Vs/C}$ . For low drain currents, the LFN primarily originates from the fluctuations in the flat band voltage, while for operation in the linear regime the noise is dominated by the mobility fluctuations. The reported Hooge's parameter is approximately  $\sim 1.1 \times 10^{-3}$  and is the lowest ever reported for an a-IGZO TFT, using only a high-k gate dielectric without the use of an interfacial layer. This result demonstrates that Al<sub>2</sub>O<sub>3</sub> as gate dielectric does not necessarily cause a detrimental effect in the LFN of a-IGZO TFTs and shows that it can be used as dielectric for low noise thin-film transistors, contrary to what was previously reported [3].

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