High Performance Dual-gate Dual-layer Amorphous Oxide Semiconductors TFTs on PI Foil for Display Application

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Abstract

We present dual-gate (DG) dual-layer (a-ITZO and a-IGZO) amorphous oxide TFTs integrated on polyimide (PI) foil. The fabricated TFTs show an apparent dual-gate field-effect mobility (μ_{FE}) of $45.0 \text{ cm}^2/(\text{V}\cdot\text{s})$, sub-threshold slope (SS^{-1}) of 0.40 V/decade and I_{ON}/I_{OFF} ratio of $>10^8$. The DG dual-layer TFT based ring-oscillators exhibit faster oscillation frequencies (f_{osc}) compared to DG a-IGZO TFT based ring-oscillators. These TFTs are paving the way to faster scan drivers and higher resolution displays. It is also verified that with DG dual-layer TFTs, the current variation can be reduced when applying an off-panel compensation method to the asymmetric channel.

Keywords: Metal-oxide semiconductors; TFT; flexible displays

1. Introduction

Amorphous oxide semiconductors (AOS) such as Indium-Gallium-Zinc-Oxide (IGZO), Silicon-Indium-Zinc-Oxide (SIZO), Hafnium-Indium-Zinc-Oxide (HIZO) and Zinc-Oxide (ZO) based thin-film transistors (TFTs) have shown desirable electrical properties, such as μ_{FE} over $10.0 \text{ cm}^2/\text{Vs}$, high I_{ON}/I_{OFF} ratio and SS^{-1} below 0.30 V/decade and are thus potential candidates for device applications such as backplanes in active matrix displays (AMLCDs and AMOLEDs), large area imagers, and thin film circuits [1-6]. Particularly, the amorphous IGZO TFTs are already in volume manufacturing in flat-panel-display industry for AMLCD and AMOLED display backplanes. However, further improvement of TFT performance in terms of μ_{FE} and SS^{-1} is required for higher resolution (8k4k) display backplanes, the Gate-In-Panel (GIP) circuits in those display backplanes, low power circuit applications and FEOL/BEOL devices in CMOS.

Few integration approaches have been made to achieve these high performance TFTs. In the first approach, several high mobility oxide materials such as Zinc-Tin-Oxide (ZTO), Tin-Gallium-Zinc-Oxide (TGZO), Indium-Gallium-Oxide (IGO), Indium-Zinc-Tin-Oxide (ITZO), Aluminum-Zinc-Indium-Tin-Oxide (AZITO), Indium-Zinc-Oxide (IZO), In-rich Indium-Gallium-Zinc-Oxide (IGZO) and Zinc-Oxynitride (ZnON) have been reported with higher μ_{FE} over $20.0 \text{ cm}^2/(\text{V}\cdot\text{s})$ while maintaining high I_{ON}/I_{OFF} ratio and steeper SS^{-1} [2-5]. In the second approach, by combining two material systems such as IZO and IGZO, ITO and IGZO, IZO and ITZO, different

compositions of HIZO and many more, high performance TFTs with μ_{FE} over $30.0 \text{ cm}^2/(\text{V}\cdot\text{s})$ are reported [6-7]. Furthermore, in the third approach, the active semiconductor channel control

Figure 1. Cross-sectional image of DG dual-layer TFTs.

by dual-gate (DG) is reported with an apparent μ_{FE} over $20.0 \text{ cm}^2/(\text{V}\cdot\text{s})$, steeper SS^{-1} and high I_{ON}/I_{OFF} ratio.

In this study, we have combined the advantages of dual-layer and DG control to enhance the performance of the amorphous oxide based TFTs without changing the integration flow of a-IGZO layer based TFTs [7-10]. The dual-layer (a-ITZO and a-IGZO) channel under DG control resulted in an apparent DG μ_{FE} of over $45.0 \text{ cm}^2/(\text{V}\cdot\text{s})$, SS^{-1} of 0.40 V/decade and I_{ON}/I_{OFF} ratio of $> 10^8$. In order to investigate the speed of scan/line drivers, high performance ring oscillators are realized with the proposed DG dual-layer based TFTs and compared to ring-oscillators integrated using DG a-IGZO TFTs. In addition, it is observed that the asymmetric semiconductor channel does not impose any problems with current compensation methods for AMOLED and AMLED panels.

2. TFT Fabrication

In the first step, a barrier film was deposited on PI foil. Subsequently, a buffer layer of PECVD SiO_2 is deposited on the a $15\text{-}\mu\text{m}$ thick spin-on polyimide substrate. On the top of the buffer layer, a bottom gate-metal (MoCr) is deposited and patterned. This is followed by deposition of the back gate dielectric (SiO_2). After the gate-dielectric deposition, the semiconductor layer (dual-layer or a-IGZO) is deposited and patterned. These semiconductor layers are deposited using direct-current (DC) sputtering from ceramic targets of a-IGZO (1:1:1) and a-ITZO (In(44%)/Sn(12%)/Zn(44%)/Al(1%)). In the next steps, the front gate-dielectric layer (PECVD SiO_2) and the

front gate-metal layer have been deposited. This is followed by the front gate-stack (Mo metal and SiO₂ dielectric) patterning using a dry etch process. Post gate-stack patterning, an ICP CVD SiNx layer is deposited as an interlayer dielectric, followed by opening of the contact vias using a dry-etch process. Next, the source/drain (S/D) metal (Ti/Al/Ti) is integrated using lift-off process. Finally, the TFTs are annealed at 165°C in N₂ environment for 3 hours. The electrical characteristics of the TFTs were measured using a parameter analyzer (Agilent 4156).

3. Result and Discussion

A schematic cross-section view of the DG dual-layer TFTs are shown in Fig. 1. In the self-aligned (SA) TFT configuration, the sheet resistivity (R_{SHEET}) of the spacing region (SP) between gate and S/D is responsible for limiting the transconductance and hence the μ_{FE} of the TFTs [13-20]. An R_{SHEET} of < 1.0 k $\Omega/\square$ is required for the SP region in order to maintain a channel resistance (R_{CHANNEL}) higher than contact resistance (R_{CONTACT}). The SP region is doped during the SiNx interlayer deposition due to hydrogen diffusion (impact of SiH₄/N₂ plasma) into AOS layers [18-20]. Since the R_{SHEET} is inversely proportional to thickness of the AOS layer, a thicker AOS layer is needed to reduce the R_{SHEET} . However, a thicker AOS layer reduces the R_{CHANNEL} as well, making it difficult to deplete the channel for V_{GS} value close to zero volts. An integration change, such as an increase in thermal budget or an increase in O₂ content while AOS deposition is then needed to avoid any change in the R_{CHANNEL} [18, 20]. These changes may lead to other changes in the overall TFT integration. Therefore, in this work, we suggest a dual-layer approach to reduce the R_{SHEET} of SP region while maintaining a large enough R_{CHANNEL} .

Figure 2. Comparison of the transistor resistance as a function of channel length ' L ' for different TFTs with SiNx interlayer. The contact resistances are obtained from the extrapolation to a zero-channel length.

To represent the impact of doping, another important parameter is the contact resistance (R_{CONTACT}). R_{SHEET} and R_{CONTACT} are extracted using transfer length method (TLM) method. The TLM structure contains nine resistive structures with fixed channel width ($W = 250 \mu\text{m}$) and varying channel length ($L = 10 - 100 \mu\text{m}$) values. From the width normalized contact resistance ' $R_{\text{CONTACT}} \cdot W$ ' versus channel length ' L ' plot as shown in Fig. 2, the R_{SHEET} and R_{CONTACT} parameters are extracted. The results of this work are also compared with earlier published work on a-IGZO and a-ITZO layers based TFTs. It is observed that a

comparable value of R_{SHEET} equal to 1.10 k $\Omega/\square$ is measured for both a-IGZO and dual-layer stack and it is close to earlier published work with a-IGZO layer [19, 20]. However, the ' R_{SHEET} ' is much lower compared to the a-ITZO layer based

Figure 3. (a) Transfer ($V_{\text{GS}}-I_{\text{DS}}$) and (b) output ($V_{\text{DS}}-I_{\text{DS}}$) characteristics of TFTs on PI foil.

Table 1. Characteristics different TFT types.

TFT Stack	Parameters			Ref.
	μ_{FE} (cm ² /V.s)	V_{ON} (V)	SS^{-1} (V/dec)	
SA a-IGZO TFTs	12.0	-1.0	0.50	17
DG a-IGZO TFTs	20.0	0	0.28	19
SA a-ITZO TFTs	27.0	-1.5	0.40	20
DG a-IGZO TFTs	20.0	0	0.28	This Work
DG dual-layer TFTs	45.0	-1.0	0.40	

TFT (5.0 k $\Omega/\square$), where the difference could be due to the thin (8 nm) a-ITZO layer [20]. Furthermore, comparable ' $R_{\text{CONTACT}} \cdot W$ ' (extracted by extrapolating the lines to the zero-channel length) values of 52.0 $\Omega \cdot \text{mm}$ and 57.0 $\Omega \cdot \text{mm}$ are obtained for a-IGZO and dual-layer based stacks, respectively.

Fig. 3(a) shows typical transfer characteristics of the DG dual-layer and DG a-IGZO TFTs while applying 10V V_{DS} . Figures of merit of these TFTs and a comparison to earlier published work

is also summarized in Table 1. A trend in the μ_{FE} improvement around different AOS based TFTs can be observed. In direct comparison to DG a-IGZO TFTs, the DG dual-layer TFTs exhibit about two times larger apparent DG μ_{FE} of $45.0 \text{ cm}^2/(\text{V}\cdot\text{s})$, slightly negative V_{ON} (V_{TH}) and comparable SS^{-1} . Furthermore, output characteristics are shown in Fig. 3(b), displaying the expected larger on-currents of the DG dual-layer TFTs compared to DG a-IGZO TFTs for similar value of V_{GS} . Other characteristics such as clear pinch-off voltage and saturation at a low V_{DS} voltage are comparable among these TFTs.

Figure 4. V_{TH} shift as function of stress time under $\pm 1 \text{ MV/cm}$ in dark at room temperature.

The bias stress shift behavior as a function of the stress time is also studied for these DG dual-layer TFTs. Under dark conditions and at room temperature, 12 TFTs ($W = 15 \text{ }\mu\text{m}$, $L = 5 \text{ }\mu\text{m}$, and $SP = 10 \text{ }\mu\text{m}$) were stressed, 6 TFTs in the positive direction and 6 TFTs in the negative direction at a field strength of $+1 \text{ MV/cm}$ ($V_{GS} = +10 \text{ V}$ and $V_{DS} = 0 \text{ V}$) and -1 MV/cm ($V_{GS} = -10 \text{ V}$ and $V_{DS} = 0 \text{ V}$), respectively for a period of 10^4 seconds. It can be seen from Fig. 4 that a V_{TH} change of less than 0.5 V is observed for positive gate bias and less than -1.5 V for negative gate bias. These time-dependent V_{TH} shift values are comparable to earlier published work on a similar type of TFT architecture [17, 19].

4. Applicability for displays

The higher mobility of the DG dual-layer TFTs may result in numerous advantages for display applications, in terms of brightness and/or resolution. Higher brightness displays can be achieved by replacing the semiconductor to the dual-layer, even without changing the pixel layout and driving voltages, due to the increased current. On the other hand, as the DG dual-layer TFTs yield larger currents, the driving voltage and supply voltage of the panel can be reduced, leading to a lower power consumption for the same brightness values. In terms of pixel scaling for AR/VR applications, a smaller footprint of the TFT will maintain the same electrical characteristics of the standard TFT, enabling higher pixel densities.

The higher mobility TFT integration flow will also be beneficial for integrated scan drivers, as a higher mobility semiconductor enables a stronger drive current for the same footprint, faster operating scan drivers to drive larger panels and optimize the scan driver for low power operation. This has been proven by realizing 19-stage ring oscillators based on the DG dual-layer TFTs and comparing it to DG a-IGZO TFTs [21]. The schematic of the Pseudo-CMOS inverter topology processed with different DG TFTs can be seen in Fig. 5 (a). Fig. 5 (b) depicts the measured oscillation frequency (f_{osc}) with respect to supply voltage (V_{DD}). Note that the stage delay (t_d) of an inverter is calculated as $t_d = 1 / (2 \times 19 \times f_{osc})$. The V_{BIAS} of this topology

has been kept at double V_{DD} . As seen from the graph (Fig. 5 (b)), the ring-oscillators based on DG dual-layer TFTs result faster frequencies compared to DG a-IGZO TFTs. Furthermore, Fig. 5(c) plots the ratio between the different oscillation frequencies. It can be concluded that the f_{osc} ratio between ring-oscillators based on DG dual-layer and ring-oscillators based on DG a-IGZO TFTs is excessively larger for lower values of V_{DD} . However, when V_{DD} value is increased, the f_{osc} ratio is reduced. For lower values of V_{DD} (where V_{TH} dominates), due to lower V_{TH} and higher apparent μ_{FE} (Fig. 3(a)), the f_{osc} ratio of DG dual-layer TFTs based ring oscillators is excessively higher than DG a-IGZO TFTs based ring oscillators. However, when V_{DD} value is increased, the value of V_{TH} is being relatively less dominant and therefore the f_{osc} ratio converges on a fixed value i.e. equal to apparent μ_{FE} ratio.

Figure 5. (a) Pseudo-CMOS inverter topology, (b) oscillation frequency with respect to V_{DD} and (c) oscillation frequency ratio comparison with respect to V_{DD} .

Figure 6. Measurement of current for different front-gate voltages of 21 TFTs (a) with a fixed back-gate voltage of 2 V , (b) with the compensated back-gate voltage.

Another possible application of this DG dual-layer TFTs is the possibility to compensate for the TFT variations present in an AMOLED panel. Since the channel of this TFT comprises two layers of different semiconducting materials, the symmetry between the front-gate and the back-gate is reduced, adding a possible obstacle for previously reported calibration methods. To study the possibility for compensation with these DG dual-layer TFTs, additional measurements have been performed, mimicking the compensation scheme proposed in [22].

Fig. 6 (a) shows the current measurements of 21 TFTs for different front-gate (data) voltages, with a fixed back-gate (calibration) voltage of 2 V , corresponding to the current for the

different pixels before calibration according to this method. After this measurement, the back-gate voltage is varied for a fixed front-gate voltage of -3.0 V, and the back-gate voltage that corresponds to a current of 137 nA is extracted in the calibration cycle. Lastly, the current for different front-gate voltages, with the compensated back-gate voltage is measured and presented in Fig. 6 (b). From these measurements, the variation of the current at a certain front-gate (data) voltage can be calculated and it is observed that the variability can be reduced by a factor 48 with the calibration method. Before compensation, the current variation at a data voltage of -3.0 V is 144 %, whereas after calibration the current variation at this data voltage is reduced to only 3.0 %. Therefore, we can conclude that the asymmetric TFT channel does not cause any problems for the calibration. Hence, the DG dual-layer TFT is highly suitable for display applications.

5. Conclusion

We have investigated the fabrication of high-performance DG dual-layer TFTs. The TFTs exhibit apparent DG μ_{FE} of 45.0 $\text{cm}^2/(\text{V}\cdot\text{s})$, SS^{-1} of 0.40 V/dec and I_{ON}/I_{OFF} ratio of $> 10^8$. In addition, we have evaluated a path for improved scan drivers, by demonstrating the DG dual-layer TFTs in 19-stage ring-oscillators, resulting in larger oscillation frequencies compared to DG a-IGZO TFTs. Finally, we have been able to investigate the current compensation method for AMOLED panels, to strongly reduce the present variability of TFTs in pixels.

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