Low-Voltage-Driven Flexible InGaZnO Thin-Film Transistor With Small Subthreshold Swing

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***Abstract*—A flexible thin-film transistor (TFT) was made by integrating a high-κ HfLaO gate dielectric and an amorphous-InGaZnO (a-IGZO) active layer on a polyimide substrate. This flexible HfLaO/a-IGZO TFT exhibits a low threshold voltage of 0.1 V, a small subthreshold swing of 0.18 V/dec, a high maximum saturation mobility of 22.1 $\mathrm{cm}^2/\mathrm{V}\cdot\mathrm{s}$, and an acceptable ON/OFF current ratio of 2×10^5. The low threshold voltage and small subthreshold swing allow the device to operate at 1.5 V for low-power applications, which should enable significant future progress in energy efficiency.**

***Index Terms*—Flexible thin-film transistors (TFTs), HfLaO, high-κ, InGaZnO (IGZO).**

I. INTRODUCTION

DUE TO their advantages of being conformable, lightweight, and nonfragile, flexible electronic devices are being considered for a variety of applications such as RFIDs, flexible displays, wearable electronics, e-textiles, artificial skin/muscles, etc. [1], [2]. The main challenge of flexible electronics is to find appropriate materials and fabrication methods to circumvent the inherent barrier of the low glass-transition temperature (T_g) for flexible substrates. Organic small molecules and polymers are flexible, but devices based on organic materials are subjected to challenges resulting from their difficult packaging and short lifetimes. Conventional hydrogenated amorphous-silicon thin-film transistors (TFTs) can be fabricated on plastic substrates by lowering the deposition temperature of the PECVD to below 200 °C. However, low-temperature-deposited Si becomes much less stable under bias stress, and its low mobility still limits its applications [3]. Although high-performance low-temperature polysilicon TFTs with flexible substrates can be made by transfer techniques, the complexity and the poor yield of the process have apparently hindered further progress [4] and [5]. Recently, nanocrystalline-silicon (nc-Si) TFTs have shown both high mobility $(> 10^2\ \mathrm{cm}^2/\mathrm{V}\cdot\mathrm{s})$ and good device stability, but the enhancement of the growth rate for nc-Si still requires further research [6]. Nomura *et al.* developed a new method for the fabrication of TFTs by presenting the first InGaZnO (IGZO) TFTs on an yttria-stabilized zirconia substrate [7] and subsequently demonstrated the production of amorphous-IGZO (a-IGZO) TFTs on a PET substrate [8]. A-IGZO can be deposited using low thermal-budget processes and exhibits levels of mobility that can be orders of magnitude higher than that of a-Si [9]–[16]. This unique feature makes it the most promising semiconductor candidate involved in flexible electronics. Recently, flexible a-IGZO TFT arrays have been implemented in the backplane of e-paper [11] and active-matrix organic light-emitting diode [12] displays. Other ingenious TFTs with a-IGZO channels fabricated on a variety of flexible substrates have also been widely investigated [11]–[16]. However, the majority of reported flexible IGZO TFTs require high operation voltages, which is a major concern in portable or battery-powered devices. To reduce the operation voltage of TFTs, a gate oxide material with a high dielectric constant is urgently needed. Among various high-κ dielectrics, HfLaO not only possesses a high dielectric constant but also exhibits superior properties such as good thermal stability, wideband offset to the conduction band, less Fermi-level pinning, and low charge trapping density when compared with other binary oxides [17], [18]. In this letter, we report a flexible a-IGZO TFT on a polyimide (PI) substrate using HfLaO high-κ gate dielectric. This device displays a low threshold voltage (V_T) of 0.1 V, a small subthreshold swing (SS) of 0.18 V/dec, a high saturation mobility (μ_{sat}) of 22.1 $\mathrm{cm}^2/\mathrm{V}\cdot\mathrm{s}$, an acceptable ON/OFF current ratio $(I_{\mathrm{on}}/I_{\mathrm{off}})$ of 2×10^5, and a low operation voltage of 1.5 V.

II. EXPERIMENTAL DETAILS

Fig. 1 shows a schematic cross-sectional view of the HfLaO/a-IGZO TFTs fabricated on the PI substrate. Bottom-gate top-contact IGZO TFTs were fabricated on a 125-μm-thick PI substrate (Kapton HPP-ST, Dupont) through a four-shadow-mask process flow. To handle the flexibility of the substrate during device fabrication and reduce the surface roughness, the PI substrate was attached to a blanket wafer and dehydrated in vacuum at 200 °C, followed by a 100-nm-thick SiO_2 deposition by an electron-beam evaporator as a buffer layer. Then, 50-nm-thick TaN gate electrodes were deposited by reactive sputtering and were patterned. Before the high-κ deposition, a NH_3^+ plasma treatment was applied to improve the TaN/high-κ

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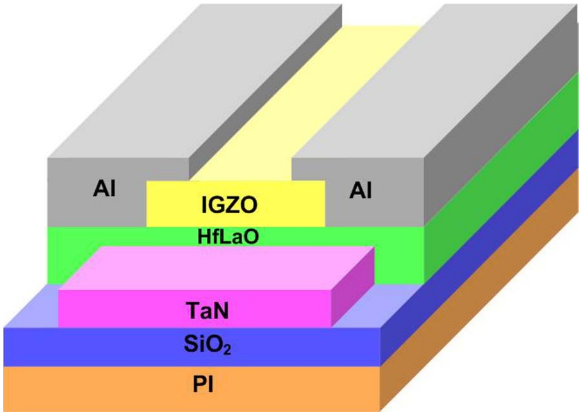

Fig. 1. Schematic cross-sectional view of a flexible IGZO TFT with an inverted staggered bottom-gate structure.

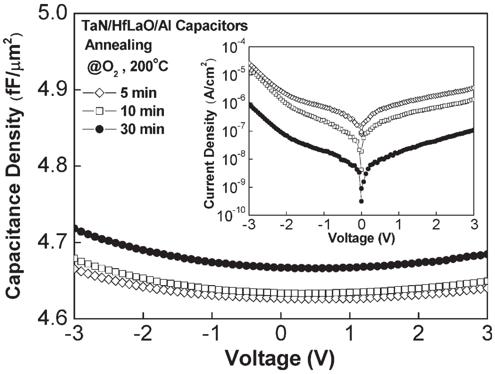

Fig. 2. C–V (inset: J–V) characteristics of TaN/HfLaO/Al capacitors fabricated on the PI substrate with different annealing conditions.

interface. This treatment was used to effectively reduce the gate leakage of dynamic random access memory capacitors [19]. Then, 40-nm HfLaO was deposited by electron-beam evaporation at room temperature. To enhance the gate oxide quality, a furnace annealing in O_2 at 200 °C for 30 min was applied [20]. The a-IGZO active layer was deposited by radio-frequency sputtering from a three-inch IGZO target $(\mathrm{In_2O_3} : \mathrm{Ga_2O_3} : \mathrm{ZnO} = 1 : 1 : 1)$ in a 5% O_2/Ar ambient without substrate heating. Finally, 300 nm of Al source and drain contact electrodes was formed using a thermal evaporator, followed by sintering at 200 °C to reduce the contact resistance. The channel dimensions of the TFTs are $500 \times 50\ \mu\mathrm{m}^2$. Prior to IGZO TFT fabrication, metal–insulator–metal capacitors were made on the same PI substrate to investigate the dielectric constant of the gate dielectric. The devices were characterized using an HP4156C semiconductor parameter analyzer and an HP4284A precision LCR meter.

III. RESULTS AND DISCUSSION

Fig. 2 and its inset show the C–V and J–V characteristics of TaN/HfLaO/Al capacitors on the PI substrate under different annealing conditions. It reveals that the sample after 30-min annealing shows the lowest leakage current density of 3×10^{-8} A/cm^2 at 1.5 V, along with the highest capacitance density of 4.6 fF/μm^2, due to dielectric densification and defect reduction. Samples with prolonged thermal annealing show no further improvement in either the leakage current or capacitance. This capacitance density gives an equivalent oxide thickness of 7.5 nm and a high κ-value of $\sim$21 for the HfLaO dielectric.

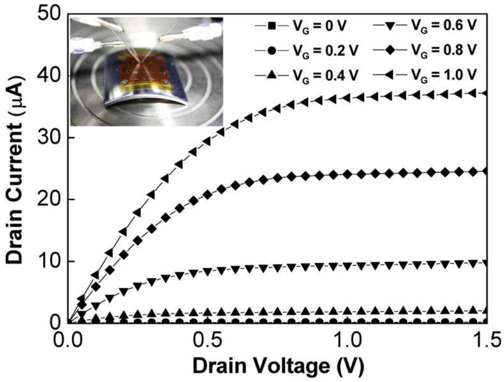

Fig. 3. Output characteristics of a representative flexible HfLaO/a-IGZO TFT. A photograph of real devices on the PI substrate is shown in the inset.

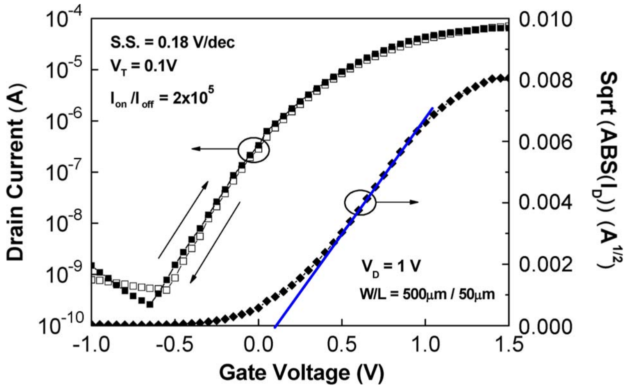

Fig. 4. Transfer characteristics of a representative flexible HfLaO/a-IGZO TFT.

The I_D–V_D characteristics of the flexible high-κ HfLaO/a-IGZO TFT are shown in Fig. 3. An enhancement-mode behavior with good saturation characteristics was observed under a low operation voltage of 1.5 V, which is a promising index for the energy efficiency in applications such as battery-powered devices. Fig. 4 shows the I_D–V_G and $I_D^{1/2}$–V_G characteristics of a representative flexible TFT device for a V_D of 1 V. Using $\mu_{\mathrm{sat}} = (2I_D/C_{\mathrm{ox}})(L/W)/(V_G - V_T)^2$, the μ_{sat} calculated from the saturation regime of the $I_D^{1/2}$–V_G plot was 22.1 cm^2/V $\cdot$ s. Moreover, a low V_T of 0.1 V and an acceptable $I_{\mathrm{on}}/I_{\mathrm{off}}$ of 2×10^5 were also acquired. Note that the prepared TFT shows fast switching at an SS of 0.18 V/dec and a negligible hysteresis of 20 mV, suggesting that the HfLaO quality is good, even though it was processed at low temperature. In addition, no obvious electrical degradation was observed from the prepared TFT when measured under a bending curvature of 0.2 cm^{-1}. Further investigation into the electrical stability relative to bending stress and the durability after a long-term bending cycle is in progress.

In Table I, we compare some important device parameters of flexible a-IGZO TFTs with different dielectrics on various

TABLE I
COMPARISON OF IGZO TFTs WITH DIFFERENT GATE DIELECTRICS ON VARIOUS FLEXIBLE SUBSTRATES

Gate dielectrics	Dielectric constant	Substrate	Operation voltage (V)	V_T (V)	SS (V/dec)	μ_{sat} (cm^2/Vs)	I_{on}/I_{off}
HfLaO 40nm [This work]	**21**	**PI**	**1.5**	**0.1**	**0.18**	**22.1**	**2×10^5**
SiON 300nm [11]	-	PEN	40	5.8	-	5.1	$>10^6$
SiN_x 150nm [12]	-	PI	30	0.9	0.25	15.1	5×10^8
$MgO_{0.3}BST_{0.7}$ 300nm [13]	18	PET	10	2.2	0.42	21.34	8.27×10^6
SiN_x 80nm [14]	8	PET	6	1.25	0.35	12.1	$>10^5$
Y_2O_3 130nm [15]	14	PET	6	1.4	0.2	3.9	1.7×10^6
Cellulose 75μm [16]	-	Cellulose	20	1.9	0.8	34	2.9×10^4

substrates. The performance of the present flexible HfLaO/a-IGZO TFT is comparable with that of devices using gate dielectrics such as SiON, SiN_x, $\mathrm{MgO}_{0.3}\mathrm{BST}_{0.7}$, $\mathrm{Y_2O_3}$, and cellulose paper. Furthermore, because of high capacitance density, the gate dielectric substantially reduces the device operating voltage to 1.5 V. Therefore, it is expected that the high-κ HfLaO gate dielectric will enable low power consumption and mechanical flexibility for future display electronics.

IV. CONCLUSION

We have succeeded in fabricating HfLaO/a-IGZO TFTs on a PI substrate. These devices feature a low V_T of 0.1 V, a small SS of 0.18 V/dec, a high μ_{sat} of 22.1 $\mathrm{cm}^2/\mathrm{V}\cdot\mathrm{s}$, and a good $I_{\mathrm{on}}/I_{\mathrm{off}}$ of 2×10^5. The integration of high-κ HfLaO dielectrics into IGZO TFTs attained the aim of reducing the driving voltage. This result permits device operation at 1.5 V, and these devices show great potential for applications in next-generation flexible displays.

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