Characteristics of HfO_2/Poly-Si Interfacial Layer on CMOS LTPS-TFTs With HfO_2 Gate Dielectric and O_2 Plasma Surface Treatment

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***Abstract*—In this paper, high-performance complementary-metal–oxide–semiconductor low-temperature polycrystalline-silicon thin-film transistors (CMOS LTPS-TFTs) with HfO_2 gate dielectric are fabricated on one wafer for the first time. Low threshold voltage and excellent subthreshold swing can be achieved simultaneously for N- and P-channel LTPS-TFTs without hydrogenation. In addition, the impacts of the HfO_2/poly-Si interfacial layer on N- and P-channel LTPS-TFTs are also specified. In order to enhance the characteristics of HfO_2 LTPS-TFT further, oxygen plasma surface treatment is employed to improve the interface quality and passivate the defects of channel grain boundaries, thus increasing the carrier mobility and reducing the phonon scattering. The CMOS LTPS-TFTs with HfO_2 gate dielectric and oxygen plasma treatment would be suitable for the application of system-on-panel.**

***Index Terms*—High-κ, low-temperature polycrystalline-silicon thin-film transistors (LTPS-TFTs), oxygen plasma, system-on-panel (SOP), 3-D integration.**

I. Introduction

HIGH-PERFORMANCE low-temperature polycrystalline-silicon thin-film transistors (LTPS-TFTs) have been widely investigated for the application of 3-D device integration on very large scale integration technology and the driving integrated circuits on glass panel [1]–[4]. In order to achieve high-performance characteristics of LTPS-TFTs with low threshold voltage $|V_{\mathrm{TH}}|$, high field-effect mobility μ_{FE}, and low subthreshold swing (S.S.), hydrogen-related plasma treatment is usually used to passivate the defects of poly-Si channel film and SiO_2/poly-Si interface [5]–[8]. Unfortunately, the introduction of hydrogen would result to the reliability issue of LTPS-TFTs [8]–[11]. The employment of high-κ materials as the gate dielectric of LTPS-TFTs has been proposed to be an effective way to improve the electrical characteristics of LTPS-TFTs without any defect passivation methods [12]–[15]. For the application of system-on-panel (SOP) and 3-D circuit integration, complementary-metal–oxide–semiconductor (CMOS) LTPS-TFTs should be studied simultaneously. However, the fabrication of N- and P-channel LTPS-TFTs with high-κ gate dielectric on one wafer has not been reported. In this paper, the N- and P-channel LTPS-TFTs with HfO_2 gate dielectric are demonstrated simultaneously for the first time. In addition, the growth of a SiO_2-like interfacial layer (IL) at the high-κ/poly-Si interface is generally observed while the high-κ materials are deposited on the poly-Si surface [12]–[14]. In this paper, the impacts of the HfO_2/poly-Si IL on the electrical characteristics of HfO_2 CMOS LTPS-TFT are specified and compared with conventional SiO_2 CMOS LTPS-TFTs.

In addition to the employment of high-κ gate dielectric, the oxygen plasma treatment has been proposed to improve the electrical characteristics of TFTs [16]–[20]. The improvements of TFTs after oxygen plasma posttreatment are due to the defect passivation of grain boundaries in the poly-Si channel film [16], [17] and the good quality of the oxide grown by oxidizing the poly-Si surface by oxygen plasma pretreatment [18]–[20]. In this paper, the oxygen plasma is used to study the impacts of the HfO_2/poly-Si IL on CMOS LTPS-TFTs with HfO_2 gate dielectric.

II. Experimental Procedure

The fabrication of devices started by depositing a 50-nm undoped amorphous-Si (α-Si) layer at 550 °C in a low-pressure chemical vapor deposition system on Si wafers capped with a 500-nm thermal oxide layer. Then, the 50-nm α-Si layer was recrystallized by the solid-phase crystallization process at 600 °C for 24 h in a N_2 ambient. Furthermore, a 500-nm plasma-enhanced chemical vapor deposition oxide (PECVD-SiO_2) was deposited at 300 °C for device isolation. The device active region was formed by patterning and etching the isolation oxide. As shown in Fig. 1(a), the source and drain (S/D) region in the active device region was implanted with phosphorus (15 keV at 5×10^{15} cm^{-2}) and boron (10 keV at 5×10^{15} cm^{-2}) for N- and P-channel LTPS-TFTs, respectively. The S/D region was activated at 600 °C for 24-h annealing in a N_2 ambient. Then, oxygen plasma surface treatment was performed for 0, 5, and 15 min at 300 °C with a power density of 1.6 mW/cm^2 in O_2 gas, as shown in Fig. 1(b). The flow rate was 100 sccm at pressure of 67 Pa. A 50-nm HfO_2 with effective oxide thickness of approximately 10.8 nm was deposited by electron-beam evaporation system at room temperature. In addition, a 49.3-nm PECVD SiO_2 was deposited at 300 °C as the gate dielectric of conventional CMOS LTPS-TFTs, which are used to compare

Manuscript received April 17, 2008; revised August 18, 2008. Current version published November 26, 2008. This work was supported by National Science Council, Taiwan, under Contract NSC-97-2221-E-009-152-MY3. The review of this paper was arranged by Editor H. S. Momose.

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Digital Object Identifier 10.1109/TED.2008.2006543

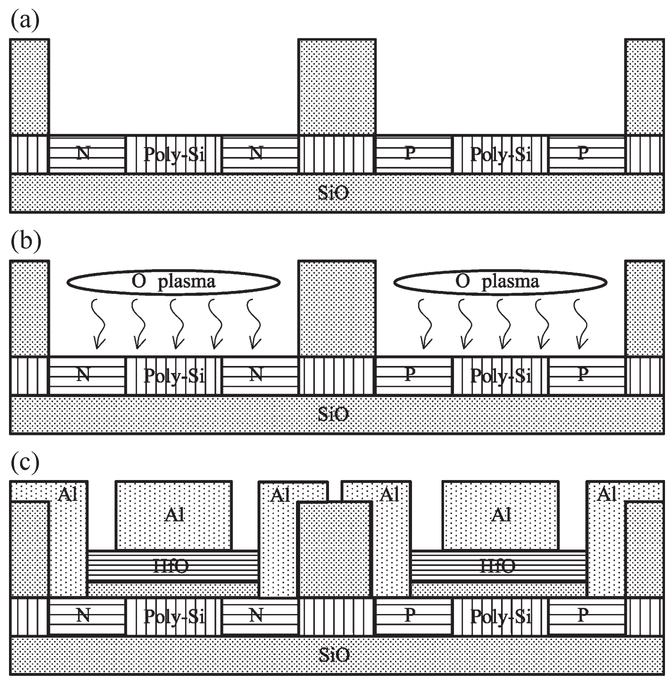

Fig. 1. Cross-sectional view of CMOS LTPS-TFTs with HfO_2 gate dielectric and oxygen plasma surface treatment.

with CMOS LTPS-TFTs with HfO_2 gate dielectric. After the patterning of S/D contact holes, aluminum was deposited by thermal evaporation system as the gate electrode and S/D contact pad. Finally, the TFT devices were completed by the contact pad definition, as shown in Fig. 1(c). Devices with gate length (L) and width (W) of 10 and 100 μm are measured, respectively. The threshold voltage $|V_{\mathrm{TH}}|$ is defined as the gate voltage at which the drain current reaches 10 nA $\times\, W/L$ and $|V_D| = 0.1$ V. The field-effect mobility (μ_{FE}) is extracted from the maximum transconductance (G_m)

III. Results and Discussion

Fig. 2 shows the transfer characteristics (I_D–V_G and field-effect mobility μ_{FE}) of CMOS HfO_2 LTPS-TFTs without oxygen plasma surface treatment. Some important parameters of CMOS HfO_2 LTPS-TFTs without oxygen plasma surface treatment and of conventional CMOS LTPS-TFTs with SiO_2 gate dielectric are also listed in Table I. The threshold voltage $|V_{\mathrm{TH}}|$ and S.S. are reduced significantly while the SiO_2 gate dielectric is replaced by HfO_2. Larger gate capacitance density, which is achieved by replacing the SiO_2 gate dielectric by HfO_2 due to the higher relative dielectric constant of HfO_2, can attract more carriers with a smaller gate voltage to turn on the LTPS-TFTs. In addition, CMOS LTPS-TFTs with HfO_2 gate dielectric have higher electron and hole field-effect mobility μ_{FE} than CMOS LTPS-TFTs with SiO_2 gate dielectric. It indicates that the native growth of a SiO_2-like IL between the HfO_2 and poly-Si has better interface quality than the deposited-SiO_2/poly-Si interface [12]–[15]. Because the poly-Si channel film has a rough Si surface and lots of dangling bonds and strain bonds on the surface of the poly-Si channel film, the native growth of the SiO_2-like IL of the HfO_2 LTPS-TFT can terminate these defects and lead to better performance of LTPS-TFT.

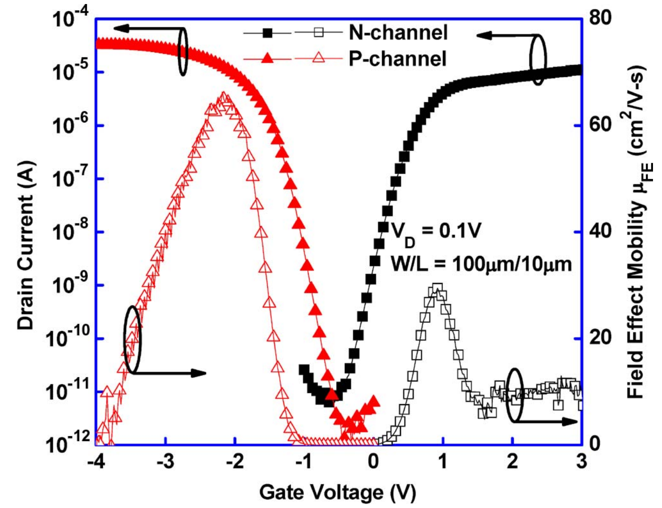

Fig. 2. Transfer characteristics (I_D–V_G and field-effect mobility μ_{FE}) of CMOS HfO_2 LTPS-TFTs without oxygen plasma surface treatment.

TABLE I
Important Parameters of CMOS HfO_2 LTPS-TFTs Without Oxygen Plasma Surface Treatment and of Conventional CMOS LTPS-TFTs With SiO_2 Gate Dielectric

Type	Gate Oxide	V_{TH} (V)	S.S. (V/dec.)	G_m (µS)	EOT (nm)	μ_{FE} (cm^2/V-s)	$I_{D(sat)}$ (mA)
N-channel	SiO_2	6.8	1.41	1.08	49.3	15.43	0.024
	HfO_2	0.34	0.198	9.2	10.8	28.75	0.226
P-channel	SiO_2	-13.3	1.60	0.82	49.3	11.71	0.014
	HfO_2	-1.22	0.144	21.2	10.8	66.25	0.718

For the characteristics of CMOS LTPS-TFTs with HfO_2 gate dielectric, as shown in Table I and Fig. 2, the hole field-effect mobility μ_{FE} is higher by about 130.4% than the electron field-effect mobility μ_{FE}, which is different from the conventional CMOS LTPS-TFTs with SiO_2 gate dielectric wherein the hole field-effect mobility μ_{FE} is lower by about 24.1% than the electron field-effect mobility μ_{FE}. It means that the IL of the HfO_2/IL/poly-Si interface has different characteristics from that of the deposited-SiO_2/poly-Si interface. It is well known that the field-effect carrier mobility μ_{FE} is dominated by the trap states near the band-tail region [7]. A higher hole field-effect mobility μ_{FE} than the electron field-effect mobility μ_{FE} for HfO_2 LTPS-TFTs indicates that there are less tail trap states near the valence band than there are near the conduction band. It implies that the native growth of the SiO_2-like IL of the HfO_2/poly-Si interface can terminate the tail trap state density near both the conduction band and the valence band, and more trap density is terminated near the valence band than near the conduction band. Fig. 3 shows the output characteristics (the I_D–V_D curve) of CMOS LTPS-TFTs with HfO_2 gate dielectric. A significantly higher driving current of the P-channel HfO_2 LTPS-TFT than the N-channel HfO_2 LTPS-TFT is obtained, which consists with the behavior of field-effect mobility μ_{FE} of HfO_2 LTPS-TFTs. It indicates that the P-channel LTPS-TFT is more suitable for the driving device of display pixel than the N-channel LTPS-TFT if a HfO_2 material is used as the gate dielectric of the LTPS-TFT.

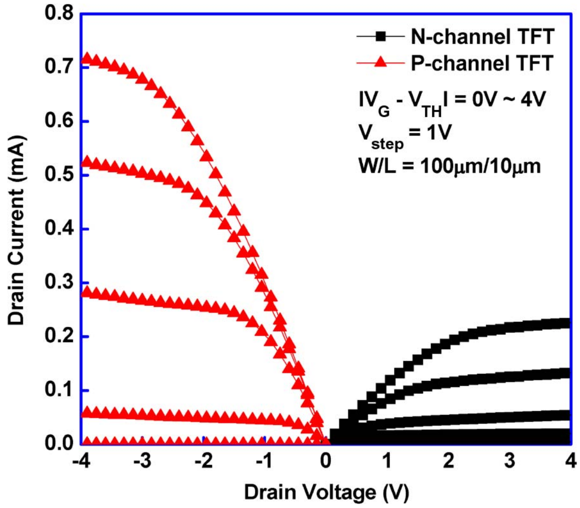

Fig. 3. Output characteristics (I_D–V_G curve) of CMOS LTPS-TFTs with HfO_2 gate dielectric.

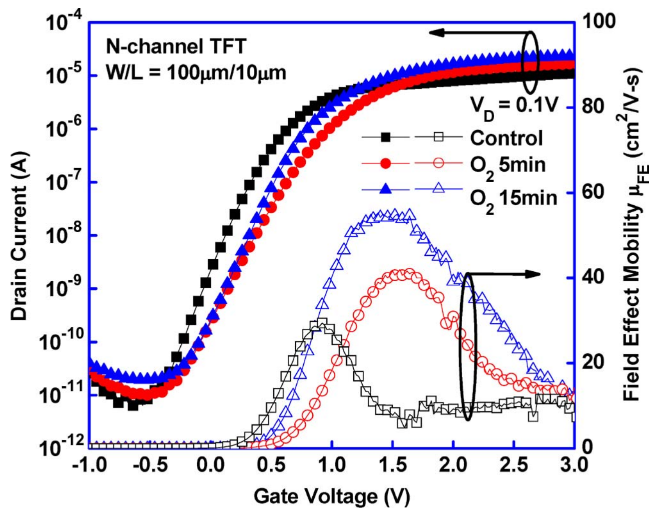

Fig. 4. Transfer characteristics (I_D–V_G and field-effect mobility μ_{FE}) of the N-channel HfO_2 LTPS-TFT with and without oxygen plasma surface treatment.

In addition to the intrinsic characteristics of LTPS-TFTs with HfO_2 gate dielectric, oxygen plasma surface treatment is employed to study the impacts of the oxidized IL of HfO_2/poly-Si interface by oxygen plasma on the CMOS LTPS-TFT with HfO_2 gate dielectric. Figs. 4 and 5 show the transfer characteristics (I_D–V_G and field-effect mobility μ_{FE}) of N- and P-channel HfO_2 LTPS-TFTs, respectively, with and without oxygen plasma surface treatment. Some important parameters of CMOS HfO_2 LTPS-TFTs with and without oxygen plasma surface treatment are also listed in Table II. The electron field-effect mobility μ_{FE} is enhanced with the increase of oxygen plasma time, which indicates that the tail trap states near the conduction band of the HfO_2/poly-Si interface are passivated to enhance the electron field-effect mobility μ_{FE} by about 46.0% and 92.4% for 5- and 15-min oxygen plasma times, respectively. However, the hole field-effect mobility μ_{FE} is reduced while oxygen plasma treatment is performed for 5 min, which indicates that the tail trap states near the valence band of the HfO_2/poly-Si interface are generated after oxygen plasma surface treatment. In oxygen plasma treatment performed for

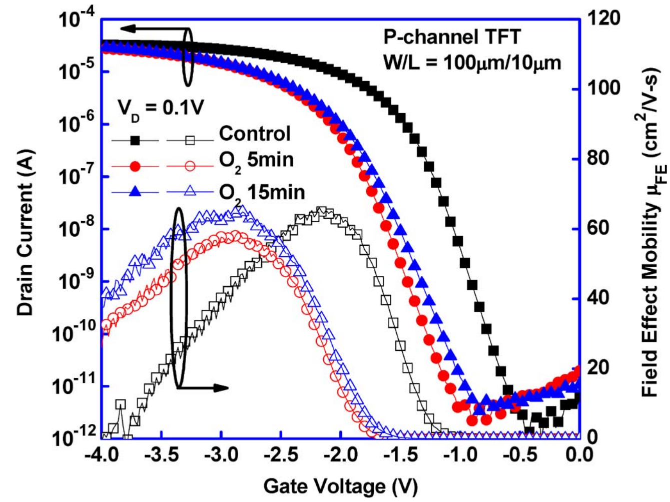

Fig. 5. Transfer characteristics (I_D–V_G and field-effect mobility μ_{FE}) of the P-channel HfO_2 LTPS-TFT with and without oxygen plasma surface treatment.

TABLE II
IMPORTANT PARAMETERS OF CMOS HfO_2 LTPS-TFTS WITH AND WITHOUT OXYGEN PLASMA SURFACE TREATMENT

Type	Gate Oxide	Treatment	V_{TH} (V)	S.S. (V/dec.)	G_m (μS)	EOT (nm)	μ_{FE} (cm^2/V-s)	$I_{D(sat)}$ (mA)
N-channel	HfO_2	Control	0.34	0.198	9.2	10.8	28.75	0.226
		O_2 5min	0.62	0.225	12.8	11.3	41.97	0.453
		O_2 15min	0.52	0.202	15.1	12.6	55.31	0.689
P-channel	HfO_2	Control	-1.22	0.144	21.2	10.8	66.25	0.718
		O_2 5min	-1.8	0.165	18	11.3	59.02	0.727
		O_2 15min	-1.72	0.178	17.7	12.6	64.84	0.854

15 min, the hole field-effect mobility μ_{FE} is higher than that in 5-min oxygen plasma treatment. It indicates the different effects of oxygen plasma surface treatment. While oxygen plasma surface treatment is initially performed for a short time, the oxygen diffused slowly and reacted with poly-Si to form a Si–O-rich IL of the HfO_2/SiO_2/poly-Si interface [18]–[20]. While oxygen plasma treatment is performed for a long time, the oxygen atom can diffuse into the poly-Si channel to passivate the defects of grain boundaries [16], [17]. Therefore, the impact of oxygen plasma surface treatment could be deduced that the effect of IL growth is dominant for the first 5-min oxygen plasma step. It results in the elimination of the tail trap states of the HfO_2/poly-Si interface near the conduction band and the generation of the tail trap states of the HfO_2/poly-Si interface near the valence band to enhance the electron field-effect mobility μ_{FE} and reduce the hole field-effect mobility μ_{FE}. After a long time of oxygen plasma treatment, the defect passivation of poly-Si channel is dominant, resulting in both electron and hole field-effect mobility μ_{FE} simultaneous enhancement.

Figs. 6 and 7 show the I_D–V_D curve of N- and P-channel HfO_2 LTPS-TFTs with and without oxygen plasma surface treatment. From Fig. 7, the drain current at $|V_D| = 4$ V of the P-channel HfO_2 LTPS-TFT with 5-min oxygen plasma surface treatment is lower than that of the HfO_2 LTPS-TFT without oxygen plasma surface treatment at $|V_G - V_{\mathrm{TH}}| \leq 3$ V. However, the drain current at $|V_D| = 4$ V of the P-channel HfO_2 LTPS-TFT with 5-min oxygen plasma surface treatment is higher than that of the HfO_2 LTPS-TFT without oxygen plasma surface treatment at $|V_G - V_{\mathrm{TH}}| \geq 4$ V, even if the hole

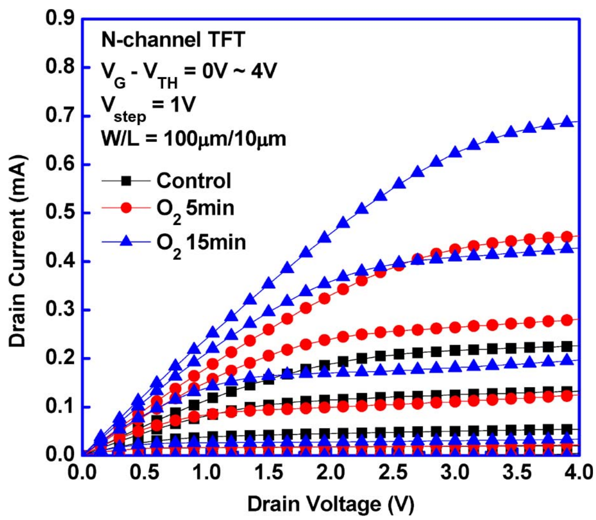

Fig. 6. I_D–V_G curve of the N-channel HfO_2 LTPS-TFT with and without oxygen plasma surface treatment.

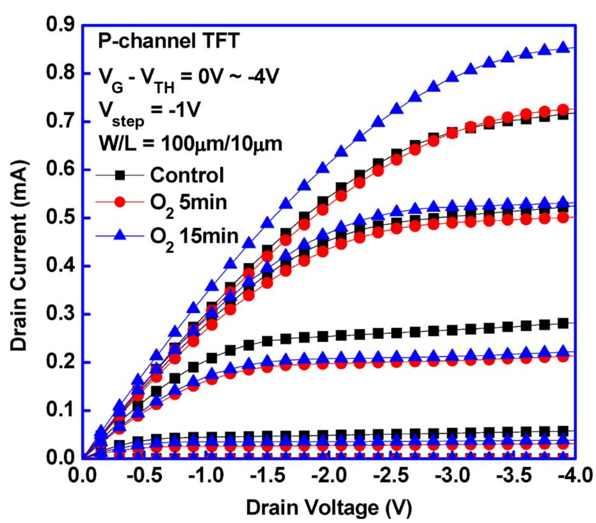

Fig. 7. I_D–V_G curve of the P-channel HfO_2 LTPS-TFT with and without oxygen plasma surface treatment.

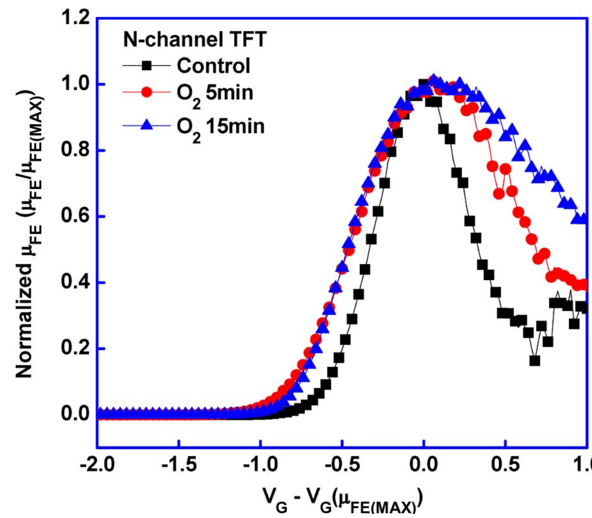

Fig. 8. Normalized field-effect mobility μ_{FE} of the N-channel HfO_2 LTPS-TFT.

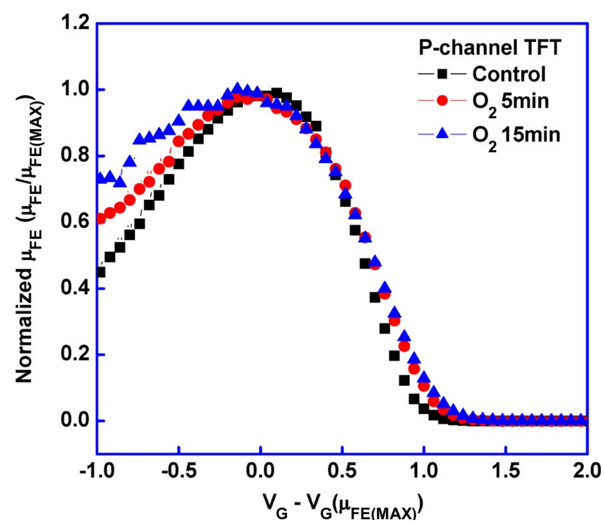

Fig. 9. Normalized field-effect mobility of the P-channel HfO_2 LTPS-TFT.

field-effect mobility μ_{EF} of the P-channel HfO_2 LTPS-TFT with 5-min oxygen plasma surface treatment is lower than that of the HfO_2 LTPS-TFT without oxygen plasma surface treatment. The same trend could be observed for the P-channel HfO_2 LTPS-TFT with 15-min oxygen plasma surface treatment, in which the drain current at $|V_D| = 4$ V of the P-channel HfO_2 LTPS-TFT with 15-min oxygen plasma surface treatment is lower than that of HfO_2 LTPS-TFT without oxygen plasma surface treatment at $|V_G - V_{\mathrm{TH}}| \leq 2$ V and higher than that at $|V_G - V_{\mathrm{TH}}| \geq 3$ V. We define the saturation current $I_{D(\mathrm{sat})}$ as the drain current at $|V_G - V_{\mathrm{TH}}| = |V_D| = 4$ V, as shown in Table II. The P-channel LTPS-TFT with oxygen plasma treatment shows a lower drain current at small $|V_G|$ and a higher drain current at large $|V_G|$, as shown in Fig. 7. Figs. 8 and 9 show the normalized field-effect mobilities μ_{EF}'s of N- and P-channel HfO_2 LTPS-TFTs, respectively. It is noted that the field-effect mobility μ_{EF} reduction is improved after the oxygen plasma treatment at high $|V_G|$. As described earlier, the oxygen plasma can passivate the defect trap states of the poly-Si channel film and improve the interface quality of the HfO_2/poly-Si interface, resulting in the reduction of phonon scattering. Therefore, the drain current of the P-channel LTPS-TFT with oxygen plasma treatment is lower at small $|V_G|$ due to lower μ_{EF} and higher at large $|V_G|$ due to the improvement of phonon scattering.

IV. Conclusion

CMOS LTPS-TFTs with HfO_2 gate dielectric are demonstrated for the first time. The effects of HfO_2/poly-Si IL on the electrical characteristics of CMOS LTPS-TFTs are also specified. In addition, the impacts of oxygen plasma surface treatment on CMOS LTPS-TFTs with HfO_2 gate dielectric are investigated. Not only the change of IL characteristics but also the defect passivation of poly-Si channel film are observed. In conclusion, oxygen plasma surface treatment can improve the driving current of CMOS LTPS-TFTs with HfO_2 gate dielectric due to the passivation of interface trap states and grain boundaries of the poly-Si channel film. The combination of HfO_2 gate dielectric and oxygen plasma surface treatment would be very suitable for the application of 3-D circuit integration and SOP.

ACKNOWLEDGMENT

The authors would like to thank the process support from National Nano Device Laboratories and the Nano Facility Center, National Chiao Tung University, Hsinchu, Taiwan.

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