High Mobility Bilayer Metal–Oxide Thin Film Transistors Using Titanium-Doped InGaZnO

Hsiao-Hsuan Hsu, Chun-Yen Chang, Chun-Hu Cheng, Shan-Haw Chiou, and Chiung-Hui Huang

***Abstract*— We report a high performance indium-gallium-zinc oxide (IGZO)/IGZO:Ti bilayer metal–oxide thin-film transistor (TFT) with a low drive voltage of <2 V. Compared with conventional IGZO TFTs, the novel bilayer metal–oxide TFTs through IGZO thickness modulation can reach the lowest off current of 1.6 × 10^{-11} A, smallest sub-threshold swing of 73 mV/decade, and highest mobility of 63 cm^2/Vs, which may create the potential application for high resolution display.**

***Index Terms*— TiO_2, indium–gallium–zinc oxide (IGZO), thin-film transistor (TFT), mobility, gettering.**

I. INTRODUCTION

INDIUM-gallium-zinc oxide (IGZO) thin-film transistor (TFT) devices have drawn much attention due to large driving current and low thermal budget. The highly integrated capability at low temperature is especially required for driving high-resolution organic light-emitting-diode (OLED) [1], [2]. Although the high-κ dielectrics were demonstrated for low-temperature TFT fabrication [3]–[9], some critical issues still cannot be overcome including large operating voltage, poor sub-threshold swing and low device mobility that are all critical for high-resolution display application. The low-mobility channel would limit circuitry operating frequencies and corresponding display response time [10] in OLED display.

To address these issues, we fabricated a high performance amorphous metal-oxide TFT using bilayer structure of IGZO/IGZO:Ti. The top IGZO with Titanium (Ti) doping can act as mobility booster to enhance device mobility and also greatly improve transistor switching characteristics. The good transistor characteristics of lowest drive voltage (V_G–V_T) of <2V, smallest sub-threshold swing (*SS*) of 73 mV/decade and highest field effect mobility (μ_{FE}) of 63 cm^2/Vs can be achieved in this novel TFTs with thickness modulation.

II. EXPERIMENTS

The TFT device with bottom gate structure was fabricated on the 200-nm-thick insulating SiO_2 grown on RCA-clean Si substrate. A 35-nm-thick TaN was first deposited by sputtering and patterning as a bottom gate electrode. Subsequently, a 56-nm-thick HfO_2 gate dielectric with large conduction band offset [11] in contact with IGZO was deposited and followed by a 400 °C N_2 annealing. Then the IGZO film with different thickness range from 10~20 nm and 5-nm-thick IGZO:Ti film were deposited under an argon ambient with 30% O_2 mixing and a chamber pressure of 7.6 mTorr at a dc power of 70W. After that, the films stack was annealed at 300 °C in N_2 ambient. The IGZO:Ti film was deposited co-sputtered by IGZO and Ti targets. The IGZO:Ti films was also examined by X-ray photoelectron spectroscopy (XPS). The cation ratio for In/Ga/Zn/Ti was 24/18/12/46. After depositing gate stacks, 280-nm-thick Al was thermally evaporated onto active region to form source and drain contact. The single-layer IGZO TFT was also fabricated with the same process for performance comparison. The bilayer metal-oxide TFTs with channel size of 540 μm × 40 μm were measured using a HP4284A precision LCR meter and a HP4156C semiconductor parameter analyzer.

III. RESULTS AND DISCUSSION

Fig. 1 shows the schematic plot and TEM picture of high-κ HfO_2 TFT using bilayer metal-oxide of IGZO/IGZO:Ti. Here, the IGZO and IGZO:Ti channel layers were examined by X-ray diffraction (XRD), where the diffractograms exhibits amorphous phase. The measured capacitance density in HfO_2 capacitor is 0.27 μF/cm^2 at 100 kHz, which gives an acceptable κ value of 17. The high-κ dielectric can lower capacitance equivalent thickness (CET) and operating voltage.

For performance comparison, a single-layer 15-nm-thick IGZO TFT as control sample was also fabricated. The 20-30 TFT devices located near wafer center were measured for each split condition to confirm the device performance and experimental results.

In Fig. 1(b) and Fig. 1(c), the output I_d–V_d and transfer I_d–V_g characteristics measured in control IGZO TFT shows an on/off ratio of 6 × 10^5, threshold voltage (V_T) of 1.15V, large *SS* of 171 mV/decade and low μ_{FE} of 5.1 cm^2/Vs. The low μ_{FE} and small driving current cannot meet the requirement of active matrix organic light-emitting diode (AMOLED) display, even with low drive voltage (V_G–V_T) of <2.5V. Fig 2(a) and 2(b) are the I_d–V_d and I_d–V_g characteristics of IGZO/IGZO:Ti bilayer metal-oxide TFTs, respectively. Compared to the control single-layer IGZO TFT, the IGZO/IGZO:Ti bilayer metal-oxide TFT shows the on-current (I_{on}) of 1.6 × 10^{-4} A that is

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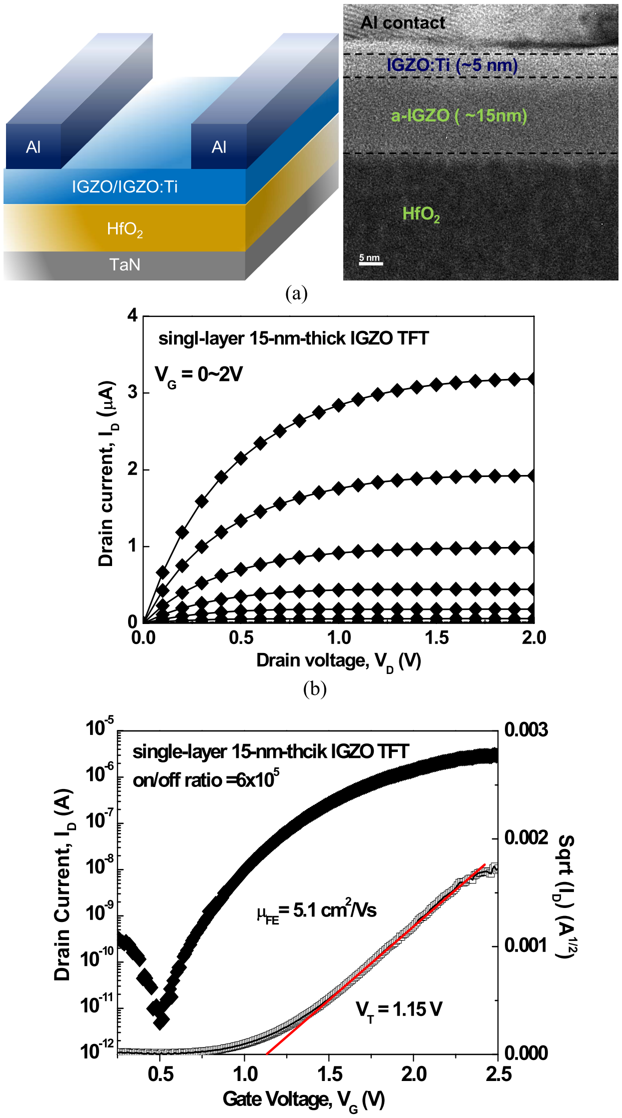
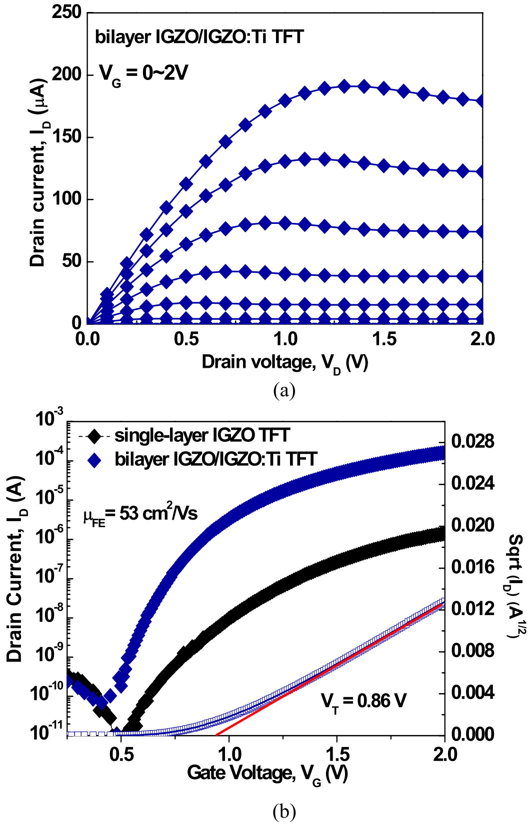


(a)

(b)

(c)

Fig. 1. (a) Schematic structure and TEM picture of IGZO/IGZO:Ti bilayer metal-oxide TFT device. (b) I_d–V_d and (c) I_d–V_g characteristics of control IGZO TFT device.



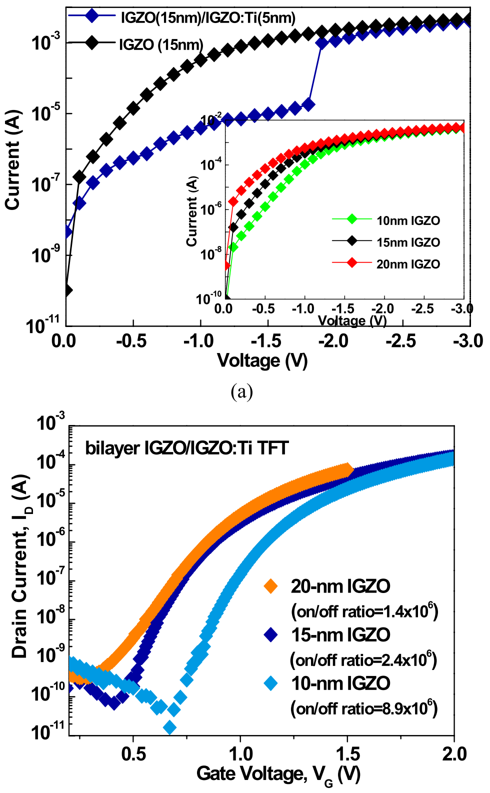
(a)

(b)

Fig. 2. (a) $I_d - V_d$ and (b) I_d–V_g characteristics of IGZO/IGZO:Ti bilayer metal-oxide TFT devices and control single-layer IGZO TFT. The square root of drain current as a function of gate voltage for threshold voltage extraction by linear extrapolation.

100× higher than IGZO TFT. The small SS of 73 mV/decade and V_T of 0.86V are also extracted from I_d–V_g curve, which are lower than 171 mV/decade and 1.15V of control IGZO TFT, respectively. Such small gate swing is supported by a lower drive voltage below 2 V. More importantly, the obtained μ_{FE} of 53 cm^2/Vs is 10× higher than control IGZO TFT, which is beneficial to drive a high current OLED device. The improved V_T and SS are attributed to the modification of interface barrier height near source/drain sides due to the passivation of IGZO:Ti, but the effective carrier injection may not contribute such high mobility enhancement. The smaller V_T of 0.86V is also measured. The excellent performance is attributed to the capping effect of thin IGZO:Ti layer. The Ti atom with higher bond enthalpy of Ti-O (672 kJ/mol) [12] is preferred to getter oxygen atom [13] and creates oxygen vacancies in bottom IGZO layer. The channel carrier is mainly dominated by oxygen vacancy in IGZO channel, as seen in the following equation: $InGaZn\text{-}O_x + V^{2+}_{InGaZn-Ox} + 2e^- \rightarrow InGaZn\text{-}O_x^*$ [14]–[16]. Here, the $V^{2+}_{InGaZn-Ox}$ represents the oxygen vacancies in IGZO channel that are responsible for carrier concentration.

Furthermore, the top IGZO:Ti layer not only acts as a gettering layer, but also a passivation layer to improve gate leakage. From the comparison of channel leakage in Fig. 3(a), the bilayer IGZO/IGZO:Ti shows a lower leakage than control IGZO. The low channel leakage at low electric field is favorable to reach a low off current (I_{off}) and high I_{on}/I_{off} ratio. It is worth to note that the channel leakage becomes large at a thicker IGZO channel (inset) that may influence gate control capability. Fig. 3(b) shows I_d–V_g characteristics of IGZO/IGZO:Ti bilayer metal-oxide TFT with different channel thickness of bottom IGZO. The bilayer metal-oxide device further achieves 20× lower I_{off} of 1.6×10^{-11}. A with reducing IGZO thickness from 20 nm to 10 nm. The thicker IGZO channel may contain more oxygen vacancies or defects that result in higher I_{off} (lower V_T) and poor SS [17]. Additionally, a much higher μ_{FE} of 63 cm^2/Vs is simultaneously obtained at this scaled channel thickness, which will be greatly helpful for scaling transistor size and improving pixel aperture ratio of high-resolution display. The use of top IGZO:Ti layer and bottom IGZO thickness scaling can provide better gate control capability to maximize charge accumulation under gate biasing and reach high electron mobility. Thus, the top IGZO:Ti capping layer plays a role



(a)

(b)

Fig. 3. (a) I–V curve of IGZO and IGZO/IGZO:Ti channel layers. (b) I_d–V_g characteristics of IGZO/IGZO:Ti bilayer metal-oxide TFT devices with different thicknesses of bottom IGZO layer.

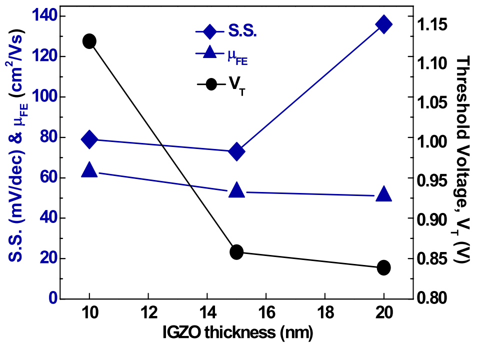


Fig. 4. Field-effect mobility sub-threshold swing and threshold voltage as a function of IGZO thickness for IGZO/IGZO:Ti bilayer metal-oxide TFT devices.

of mobility booster to improve not only μ_{FE} but also SS and I_{off}.

The I_d–V_g characteristics as a function of IGZO thickness are summarized in Fig. 4. Compared to conventional IGZO TFT with large SS and low μ_{FE}, the bilayer metal-oxide TFT with optimized thickness modulation features the best performance of lowest drive voltage of <2V, smallest SS of 73 mV/decade, and highest μ_{FE} of 63 cm^2/Vs. For a thicker IGZO case (20 nm), the correspondingly smaller driving current at $V_G = 1.5$V can be ascribed to large off current and poor gate control capability that lead to a slight mobility degradation. Fortunately, the appropriate IGZO thickness scaling can improve these issues.

IV. CONCLUSION

By integrating a bilayer metal-oxide structure, a high mobility IGZO TFT with low drive voltage was demonstrated. The good device integrity of lowest drive voltage of <2 V, smallest SS of 73 mV/decade and highest μ_{FE} of 63 cm^2/Vs can be achieved in bilayer metal-oxide TFT through IGZO thickness modulation.

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