Orders-of-magnitude enhancement in conductivity tuning in InGaZnO thin-film transistors via SiN\textsubscript{x} passivation and dual-gate modulation

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ABSTRACT
The mobility of pristine amorphous indium gallium zinc oxide (α-IGZO) thin-film transistors (TFTs) is insufficient to meet the requirement of the future ultra-high-definition displays. Reported herein is the fabrication of hydrogenated long-channel IGZO TFTs exhibiting a transconductance and an on/off ratio that are orders of magnitude superior to those of the regular devices. The gate bias stability of the treated IGZO TFTs was greatly enhanced, with the threshold voltage shifting by less than 1 V after 1 h stress. Experimentally, the hydrogenation of the active layer was achieved via the deposition of a SiN\textsubscript{x}/SiO\textsubscript{x} bilayer on top of the IGZO via plasma-enhanced chemical vapor deposition followed by post-annealing under optimized conditions. The elemental depth profiles indicated that this enhanced performance originated from the hydrogen doping of the IGZO film. Furthermore, a dual-gate structure was fabricated to alleviate the deterioration of the subthreshold properties induced by the excess hydrogen doping.

1. Introduction
Considerable attention has been paid of late to amorphous-metal-oxide-(AOS)-based thin-film transistors (TFTs), especially those based on amorphous indium gallium zinc oxide (a-IGZO) owing to its advantages of high mobility (~ 10 cm\textsuperscript{2} V\textsuperscript{−1} s\textsuperscript{−1}), high transparency, and amenability to room-temperature fabrication [1]. To fulfill the requirements of ultra-high-definition display technologies (e.g. 4 K/8 K), however, the mobility of the active layer should be greater than 30 cm\textsuperscript{2} V\textsuperscript{−1} s\textsuperscript{−1} [2,3], which makes a-IGZO less competitive than polysilicon. The previous studies on the conductivity tuning of AOS have primarily focused on partial doping with low-dimensional materials (e.g. carbon nanotube [4], nanowire [5,6]), although this strategy is not currently suitable for the manufacture of large-area devices. Another approach for enhancing the conductivity of AOS is the introduction of hydrogen, which is usually achieved via gas control film deposition [7], device annealing under a high-pressure H\textsubscript{2} atmosphere [8], hydrogen plasma treatment [9], ultraviolet light exposure [10], etc. These methods, however, either metallize the oxide semiconductor [7,10,11] or slightly affect the conductivity [7–9].

Described in this work is the fabrication of hydrogen-doped long-channel IGZO TFTs (hereinafter referred to as 'IGZO:H') with greatly improved transfer performance via the simple plasma-enhanced chemical vapor deposition (PECVD) technique. The experiment results suggest that the enhanced conductivity tuning and stability can be attributed to a combination of the moderate hydrogen diffusion from the SiN\textsubscript{x} passivation layer towards the IGZO layer and the formation of stable ionic configurations [12] during the thermal annealing. The elemental depth profiles confirm the presence of H in the treated IGZO films, but the incorporation of hydrogen simultaneously creates excess free electrons, resulting in the negative shifting of the transfer curves and the degradation of the subthreshold properties [8–10]. To overcome this issue, an additional gate (Mo) was deposited on the top of the passivation layer, enabling the dual-gate modulation of the channel carriers and reducing the subthreshold swing from the pristine value of 2.6–1.2 V/dec while the top gate was set to −4 V. Consequently, hydrogen-doped IGZO TFTs exhibiting an on-current 30 times higher than that of the regular IGZO TFTs alongside suppressed degradation of the subthreshold properties were obtained.
2. Experiments

In this study, three types of IGZO TFTs were fabricated, and the cross-sectional views of their structures are shown in Figure 1. To construct regular IGZO TFTs (Figure 1(a)), n-type heavily doped Si and 105-nm-thick thermally grown silicon oxide were used as the bottom gate and gate insulator, respectively. A 70-nm-thick IGZO layer was deposited via radio frequency sputtering and was defined using wet etching. The source/drain electrodes were deposited via direct current (DC) sputtering and were patterned via photolithography. To fabricate IGZO:H TFTs (Figure 1(b)), a passivation bilayer made up of 350-nm-thick silicon oxide and 100-nm-thick silicon nitride was first grown via PECVD on top of the regular IGZO TFTs. The deposition source gases for SiO$_x$ were SiH$_4$ and NO$_2$, and those for SiN$_x$ were SiH$_4$ and NH$_3$. Next, reactive ion etching (RIE) was utilized to develop contact holes for electrical measurements. To realize the dual-gate structure (Figure 1(c)), a 100-nm-thick Mo layer (serving as the top gate) was deposited via DC sputtering, and was defined with wet etching. Finally, all three types of IGZO TFTs were post-annealed at 350°C under a N$_2$ atmosphere for 1 h.

The channel width (400 μm) and length (200 μm) were the same for all the TFTs. For electrical characterization, the samples were measured using a semiconductor analyzer (Agilent B1500A) at ambient temperature, in the dark. For component analysis, secondary ion mass spectroscopy (SIMS) was used to investigate the elemental depth profiles of the IGZO and IGZO:H films. Owing to the passivation layers on top of the IGZO:H film, RIE was applied to etch SiN$_x$/SiO$_x$ prior to the SIMS measurements.

For the calculations, the subthreshold swing was extracted with the equation $SS = d \log(I_D)/dV_G$. The threshold voltage $V_{TH}$ was extracted as the x-axis intercept of the linear-fitted $I_D$–$V_G$ curve (linear regime) or the $I_D^{1/2}$–$V_G$ curve (saturation regime).

3. Results and discussion

3.1. Device characterization

The transfer curves for the three types of TFTs are presented in Figure 1(d–f). During the scanning, the bottom gate voltage $V_{BG}$ was swept from $-20$ to $20$ V with 0.25 V steps while the drain voltage $V_{DS}$ was set to 0.1 V (linear regime) and 10 V (saturation regime). In general, the conductivity-tuning ability of the IGZO:H TFTs was greatly improved compared to the regular IGZO devices. The on-current for the regular IGZO TFT was measured as 37.6 μA, with $V_{DS}$ at 10 V and $V_{GS}$ at 20 V. By contrast, when IGZO is encapsulated with a SiN$_x$/SiO$_x$ layer, the drain current increased to 3.9 mA under the same bias conditions. The two-orders-of-magnitude increases in the current and improved conductivity-tuning ability are probably attributable to the hydrogen diffusion from the SiN$_x$ layer towards the IGZO film during the post-annealing process. In addition, the PECVD-grown SiN$_x$ capping layer is commonly used in the hydrogenation of poly-Si [13,14]. The previous studies suggest that hydrogen doping is capable of healing subgap defect states and introducing shallow donor states to IGZO [12,15].
Hence, hydrogenated IGZO exhibits a higher electron density and a better conductivity-tuning ability compared to the regular IGZO film.

In contrast to the previous studies, where hydrogen doping usually led to transfer performance without off-state [7,8], the presented IGZO:H TFTs exhibit a good on/off ratio (10^8) without increasing the off-current. Compared to the regular IGZO TFTs, the treated device exhibited negative shifting of the transfer curve and severe deterioration in the subthreshold regime (increased SS value), as shown in Figure 1(b). To counter this effect, a 100-nm-thick Mo layer was deposited on top of the passivation layer via DC sputtering, and was defined using the same photomask as applied for the IGZO layer to form a top gate. For this dual-gate TFT, the top-gate voltage \( V_{TG} \) was fixed at a constant value during the measurement of the transfer characteristics. Interestingly, when \( V_{TG} \) was set to \(-4\) V, the turn-on voltage \( V_{ON} \) shifted from the pristine value of \(-14.5 \) to \(-3.5\) V (Figure 1(b)). This result indicates that a negative \( V_{TG} \) bias can suppress the excess free carriers originally induced by the hydrogen impurities. As for the threshold voltage, \( V_{TH} \) underwent a positive shift from \(-2.5\) V (single-gate mode) to \(1.9\) V when \( V_{TG} \) was set to \(-4\) V.

As seen in Figure 1(f), the on-state current of the dual-gate TFT remained at 3.2 mA, with \( V_{GS} \) at 20 V and \( V_{DS} \) at 10 V. Accordingly, the transconductance \( g_m \) was extracted with \( g_m = (\partial I_D/\partial V_G) \) and was plotted in Figure 1(g). The results show that the treated TFT exhibited a conductance two orders of magnitude higher than that of the regular IGZO TFT. Furthermore, the dual-gate IGZO:H TFT presented superior performance compared to the single-gate device as the peak \( g_m \) value was higher and the turn-on voltage was closer to zero. This might be related to the absence of excess carriers, which was used to be suppressed by \( V_{TG} \). With the increase of \( V_{BG} \), these carriers could be released into the channel again and could contribute to the channel transport [16,17]. The gradual decay of the transconductance in the high \( V_{BG} \) regime is probably related to the interface scattering of carriers [18,19].

### 3.2. Effect of top-gate tuning

The influence of the top gate on the performance of the IGZO:H TFTs was further investigated by applying various \( V_{TG} \) bias values (\(-4, 0, \) and \(4\) V). As shown in Figure 2(a–b), the subthreshold properties are greatly improved with decreasing \( V_{TG} \), while the on-current remained at 31 \( \mu \)A in the linear regime.

When \( V_{DS} \) was set to 10 V, the turn-on voltage \( V_{ON} \) was extracted as \(-12 \) and \(-3.5\) V for the \( V_{TG} \) values of 4 and \(-4\) V, respectively. These results indicate that a higher \( V_{TG} \) (negative) bias provides improved suppression of excess electrons. Three important parameters (transconductance with \( V_{BG} = 5 \) V, on/off ratio, and \( V_{ON} \)) are compared in Figure 2(c). In general, the transconductance greatly increased with hydrogen doping, and the \( V_{ON} \) shifted towards 0 V upon setting a negative \( V_{TG} \).

### 3.3. Effect of the encapsulation layer

The enhanced conductivity and drain current are strongly related to the encapsulation layer and annealing process. For the regular IGZO TFT, the \( I_{ON} \) at \( V_{GS} = 15 \) V in the saturation regime (\( V_{DS} = 10 \) V) was initially measured as 19.3 \( \mu \)A. Next, the same device was encapsulated with SiN_{x}/SiO_{x} bilayers and was characterized for the transfer curves without annealing (Figure 3(b)). The extracted \( I_{ON} \) increased to 226.7 \( \mu \)A, which is higher than that of the pristine IGZO TFT but considerably lower than the 2.5 mA value observed for the IGZO:H TFT (Figure 1(e)). This result indicates that simple encapsulation with SiN_{x}/SiO_{x} is insufficient to realize hydrogenation, and that thermal annealing is vital for achieving orders-of-magnitude performance enhancement. It should also be noted that the subthreshold properties of this device were severely deteriorated owing to the ion bombardment of the backchannel during the PECVD. To elucidate the effect of the encapsulation, the above SiN_{x} film was further etched, and the sample was subjected to annealing at 350°C in a N\textsubscript{2} atmosphere for 1 h (Figure 3(f)). Interestingly, the transfer curves recovered to those of the regular IGZO TFT, with a small shift in \( V_{TH} \). The measured \( I_{ON} \) for the saturation regime was 28.2 \( \mu \)A, and the \( V_{ON} \) was \(-1\) V. The above results indicate that annealing solely with SiO_{x} has a mild effect on the conductivity whereas post-annealing with a SiN_{x} layer is critical for high performance. It is thus suggested that the SiN_{x} layer probably acts as a source of hydrogen doping, which diffuses H into the IGZO film during the subsequent thermal annealing.

Note that there have been several previous studies of the SiN_{x} capping of IGZO films [11,20,21]. In contrast to the achievement of a high on/off ratio observed in this work, the previous literatures all reported that the IGZO films exhibited conducting behavior when a SiN_{x} layer was directly deposited on top of the IGZO films. The metallization of IGZO was attributed to the excessive hydrogen doping from the SiN_{x}:H film [11,20]. In this study, the realization of operational TFTs was strongly dependent on the deposition conditions for the SiN_{x} layer and the subsequent annealing. For instance, the PECVD-grown SiN_{x} films that were too thick (300 nm) or the PECVD temperatures that were too high (300°C) led to
excessive hydrogen doping, as reported in the previous studies. IGZO also exhibited conducting behavior when the annealing temperature was as high as 450°C.

### 3.4. Effect of bias stressing

To evaluate the reliability, the pristine IGZO and treated IGZO:H TFTs were tested under positive and negative gate bias stress (PGBS/NGBS) for 1 h, and were characterized through time. The shifts of the transfer curves as a function of the stress time are presented in Figure 4. In contrast to the pristine IGZO TFT, the IGZO:H device presented greatly improved stability under PGBS ($V_{GS} = 20$ V). For instance, the shift of the threshold voltage $\Delta V_{TH}$ after 1 h stress was limited to 0.5 V for the IGZO:H TFT, whereas this value was up to 8.3 V for the IGZO TFT. The $I_{ON}$ at $V_{DS} = V_{GS} = 20$ V decreased from 35.1 $\mu$A ($0$ s) to 4.5 $\mu$A ($3600$ s) for the regular IGZO TFT, whereas the $I_{ON}$ of the IGZO:H TFT remained constant at 3.5 mA throughout the duration.

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**Figure 2.** Transfer characteristics of the dual-gate IGZO:H TFT under various top gate biases with (a) $V_{DS} = 0.1$ V and (b) $V_{DS} = 10$ V. (C) Comparison of the extracted parameters, namely transconductance with $V_{BG} = 5$ V, on/off ratio, and $V_{ON}$.

**Figure 3.** Cross-sectional schematic diagrams of the a-IGZO TFT after (a) annealing, (b) capping with a SiN$_x$/SiO$_x$ passivation layer, and (c) annealing with a SiN$_x$ layer etched. (d), (e), and (f) show the corresponding transfer characteristics.
Figure 4. Gate bias stressing test for the (a,b) IGZO and (c,d) IGZO:H TFTs with $V_{GS}$ values of 20 V (PGBS) and $-20$ V (NGBS), respectively.

Figure 5. Measured SIMS elemental profiles for (a) regular IGZO and (b) IGZO:H films.

of the experiment. This enhanced stability was ascribed to the encapsulation layer and the incorporated hydrogens, which might heal the intrinsic oxygen vacancy [22]. When the TFTs were tested under NGBS, both the IGZO and IGZO:H TFTs exhibited good threshold voltage stability, as seen in Figure 4(b,d). For the IGZO TFT, the $\Delta V_{TH}$ after 1 h was about 1.0 V, and the $I_{ON}$ decreased to 86% of its original value. For the IGZO:H TFT, the transfer curve underwent a negative shift with a $\Delta V_{TH}$ of $-0.6$ V, and the $I_{ON}$ increased slightly from 3.7 mA (0 s) to 3.8 mA (3600 s). The subthreshold properties of the IGZO:H TFT deteriorated with the occurrence of a hump during the NGBS tests, as can be seen in Figure 4(d). The $V_{ON}$ shifted from $-4.5$ to $-8.5$ V after 1 h stress, and the $SS$ was degraded from the pristine value of 1.1 to 1.6 V/dec. This might be related to the shallow donor states in the subgap. During the NGBS test of the pristine IGZO TFTs, the energy levels bend upwards, and the quasi-Fermi level could be located below the levels of donor-like states. Consequently, these states tend to be unoccupied, become positively charged, and release electrons to the conduction levels, resulting in larger conductance in NGBS [23]. Also, it could be attributed to the trapped positive charges in the dielectric interface [24]. By comparing the results in regular devices, the latter effect should be minor and the former effect could be more dominant.

3.5. Elemental profiles

To further understand the mechanisms, SIMS was applied to investigate the elemental distribution (shown in Figure 5). The sputtering time for the IGZO:H film was shorter than that for the regular IGZO film, which can be explained by over-etching of the IGZO:H film during the RIE process of the capping layer. The indium signal for the regular film was about $10^5$ counts, whereas for IGZO:H film are about $5 \times 10^4$ counts. The hydrogen signals for the regular and treated films were approximately 30 and 100 counts, respectively. Using In elemental signals as the reference, the treated IGZO:H film contained a greater amount of hydrogen impurities than the regular film. This result confirms the authors’ proposal that hydrogen doping was responsible for the improvement of the conductivity-tuning ability of a-IGZO.
4. Conclusion

To summarize, orders-of-magnitude enhancement in the conductivity tuning of long-channel amorphous indium gallium zinc oxide (a-IGZO) thin-film transistors (TFTs) with hydrogen doping via simple capping with a plasma-enhanced chemical vapor deposition-(PECVD)-grown SiN\textsubscript{x} layer and annealing under optimized conditions was demonstrated. The results indicate that hydrogen diffuses from the SiN\textsubscript{x} film towards the IGZO film during the post-annealing process. Moreover, to mitigate the degradation of the subthreshold properties resulting from the excess carriers, a dual-gate structure was applied to adjust the turn-on and threshold voltage. The results presented herein may be beneficial for high-performance oxide electronics.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The authors gratefully acknowledge the financial support from the Natural Science Foundation of China [grant number 61774174], the Guangdong Provincial Department of Science and Technology [grant number 2015B090924001], and the Guangdong Natural Science Funds [grant number 2018A030313400].

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