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Fluorination-mitigated high-current degradation of amorphous InGaZnO thin-film transistors

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Abstract: As growing applications demand higher driving currents of oxide semiconductor thin-film transistors (TFTs), severe instabilities and even hard breakdown under high-current stress (HCS) become critical challenges. In this work, the triggering voltage of HCS-induced self-heating (SH) degradation is defined in the output characteristics of amorphous indium-gallium-zinc oxide (a-IGZO) TFTs, and used to quantitatively evaluate the thermal generation process of channel donor defects. The fluorinated a-IGZO (a-IGZO:F) was adopted to effectively retard the triggering of the self-heating (SH) effect, and was supposed to originate from the less population of initial deep-state defects and a slower rate of thermal defect transition in a-IGZO:F. The proposed scheme noticeably enhances the high-current applications of oxide TFTs.

Key words: amorphous indium-gallium-zinc oxide (a-IGZO); thin-film transistors (TFTs); current stress; self-heating (SH); fluorination

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1. Introduction

Amorphous oxide semiconductor (AOS) thin-film transistors (TFTs) have been intensively investigated to replace their silicon counterparts in large-area flexible displays[1], owing to their relatively high mobility, promising on/off ratio, and low fabrication temperature[2]. However, compared to incumbent silicon low-temperature TFTs, AOS TFTs suffer inadequate long-term stabilities under environmental, temperature, illumination and gate bias stresses[3, 4]. Besides the superior switching characteristics, the high-current driving capability of AOS TFTs is increasingly demanded by advanced applications, such as the gate driver on the array (GOA), electroluminescence, and micro-LED displays[5–7]. So far, the AOS TFTs under high current stresses (HCSs) have encountered complicated severe degradation behaviors, such as threshold voltage (V_{th}) shift[8], abnormal hump[9, 10], subthreshold swing (*SS*) deterioration[11], and even hard breakdown[12].

The self-heating (SH) effect is considered to be the main cause of HCS degradations, since the HCS-induced Joule heat can easily elevate the temperature of the AOS channel with poor thermal conductivity[13]. The underlying mechanism is often ascribed to SH-induced external and internal defects, such as hydrogen and oxygen vacancies[9, 14]. To suppress the SH degradations, the device architectures have been adjusted to enhance the heat dissipation[15, 16]. Besides, SH degradations were also found to be mitigated on the low-defect channel by modifying the oxygen content of AOSs[17–19].

In this study, the HCS-induced deterioration process of amorphous indium-gallium-zinc oxide (a-IGZO) TFTs were investigated in detail by defining an SH triggering voltage in the output curves. As an effective defect suppressor in AOSs, the fluorine was reported to efficiently enhance the bias stress stabilities of AOS TFTs[20, 21], and further found to effectively mitigate the triggering and evolution of the SH process under HCSs.

2. Experimental details

As shown in Fig. 1, the self-aligned top-gate (SATG) a-IGZO TFT was fabricated on the glass substrates. Firstly, a 40-nm-thick active layer was sputtered using an a-IGZO target with the molar ratio of In_2O_3 : Ga_2O_3 : ZnO = 1 : 1 : 2. After the a-IGZO active islands were patterned using the dilute hydrochloric acid, the gate insulation (GI) of 100-nm-thick silicon oxide (SiO_2) was grown at 300 °C by the plasma-enhanced chemical vapor deposition (PECVD), followed by the sputtered molybdenum (Mo) as the gate electrode. After the continuous etching of the Mo/SiO_2 gate stack, the highly conductive source/drain (S/D) of n^+ a-IGZO regions was formed by the argon (Ar) plasma treatment. A 200-nm-thick silicon nitride (SiN_x) passivation layer was subsequently deposited at 150 °C in PECVD, and then the contact holes were opened using reactive ion etching (RIE). Finally, the S/D electrodes were formed with Mo. The fluorination effect was investigated by comparatively immersing the as-deposited a-IGZO in the tetrafluoromethane (CF_4) plasma in the 300 °C PECVD reactor to form the fluorine-doped a-IGZO (a-IGZO:F). A relatively large width-to-length ratio (*W*/*L*) of 100/14 μm was chosen to achieve a high drain current. The electrical characteristics were measured at room temperature using an Agilent B1500A semiconductor analyzer.

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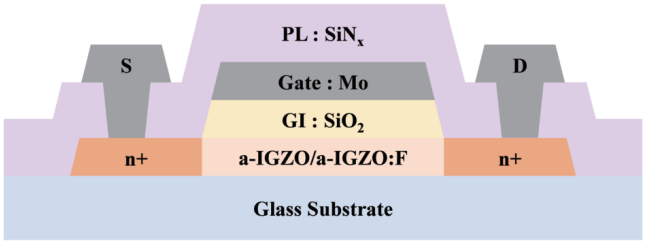

Fig. 1. (Color online) Schematic cross-section of the fabricated SATG a-IGZO TFTs.

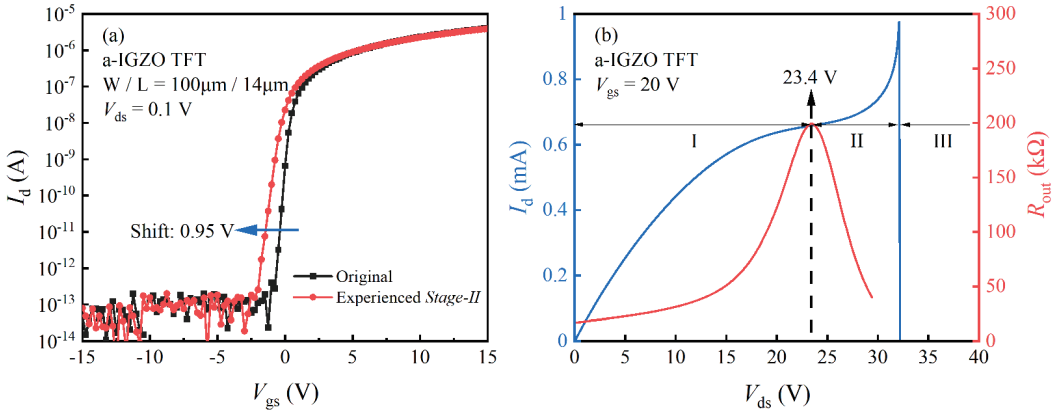

Fig. 2. (Color online) (a) Transfer curves measured at V_{ds} = 0.1 V from original a-IGZO TFT and a-IGZO TFT experienced output curve sweeping to *Stage-Ⅱ*. (b) Output characteristic and output resistance curves of the a-IGZO TFT at V_{gs} = 20 V. Three stages are divided and labeled with Ⅰ, Ⅱ and Ⅲ, respectively.

3. Results and discussion

As shown in Fig. 2(a), the drain current (I_d) versus gate voltage (V_{gs}) transfer curve of the a-IGZO TFT was measured at a drain voltage (V_{ds}) of 0.1 V, exhibiting the relatively high performance, such as field-effect mobility (μ_{FE}) of 15.5 cm^2/(V·s), on/off current ratio of 6.6 × 10^7, threshold voltage (V_{th}) of −0.2 V, and *SS* of 180 mV/dec. The HCS degradations were readily observed in the I_d–V_{ds} output curve measured at a high V_{gs} of 20 V, as illustrated in Fig. 2(b). In the relatively small V_{ds} range (*Stage-Ⅰ*), the I_d unsurprisingly exhibits the linear and then gradual saturation dependences on V_{ds}. However, the relatively high saturation current seems to instantly trigger a dramatic I_d uprising (*Stage-Ⅱ*), and abruptly leads to the severe current collapse at a large V_{ds} of 32.3 V, corresponding to the hard breakdown of a-IGZO TFT (*Stage-Ⅲ*).

Compared to the distinct transition between *Stage-Ⅱ* degradation and *Stage-Ⅲ* breakdown, it is hard to identify the triggering point of HCS degradation (*Stage-Ⅱ*) in the output curve. The output resistance (R_{out}) versus V_{ds} was further introduced in Fig. 2(b), revealing the opposite V_{ds} dependences of R_{out} between *Stages* Ⅰ and Ⅱ. In the saturation region of *Stage-Ⅰ*, the carrier concentration decreases near the drain side with the increasing V_{ds} due to the pinch-off effect, corresponding to an increasing R_{out}. In contrast, the R_{out} abnormally decreases with the increasing V_{ds} in *Stage-Ⅱ*, suggesting the appearance of an additional predominant mechanism, which is most plausible the HCS degradation. Such an inflection point of the R_{out}–V_{ds} curve can thus be used to precisely define the triggering voltage (V_{tr}) of HCS degradation.

To investigate the mechanism of the suddenly decreased R_{out} in *Stage-Ⅱ*, the V_{ds} sweeping during the output curve measurement was aborted at a V_{ds} of 32 V, corresponding to *Stage-Ⅱ*. The transfer curve of such *Stage-Ⅱ* TFT was measured again for comparison with the original a-IGZO transistor. As compared in Fig. 2(a), the *Stage-Ⅱ* a-IGZO TFT exhibits a negative V_{th} shift of 0.95 V, suggesting an increased channel carrier concentration and thus agreeing well with the reduced R_{out}. Such HCS-induced negative V_{th} shift together with the final breakdown is consistent with the previously reported SH degradation behavior under HCSs[12]. Moreover, the power of *Stage-Ⅱ* exceeds 15 mW, higher than the required SH-activated power[8]. Such SH-induced channel carriers are often ascribed to the heat-driven external dopants (e.g., hydrogen) from the doped S/D[9, 15] or the thermal induction of shallow-donor defects from deep states (e.g., oxygen vacancy V_O)[10, 22]. Considering the n$^+$ a-IGZO S/D in this work is formed by Ar plasma rather than doped with external donors, the SH effect in *Stage-Ⅱ* most plausibly turns the deep-state Vo into the shallow-donor Vo in the a-IGZO chan-

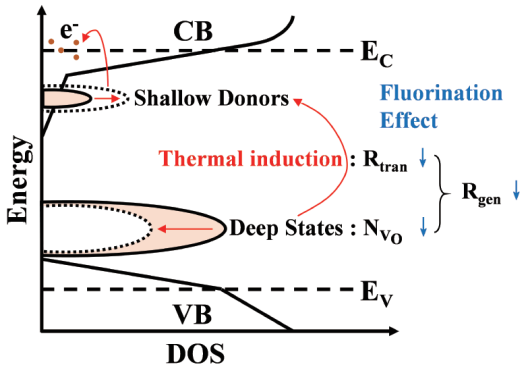

Fig. 3. (Color online) The mechanism of SH-induced defect transition, illustrated in the density of states (DOS) in a-IGZO.

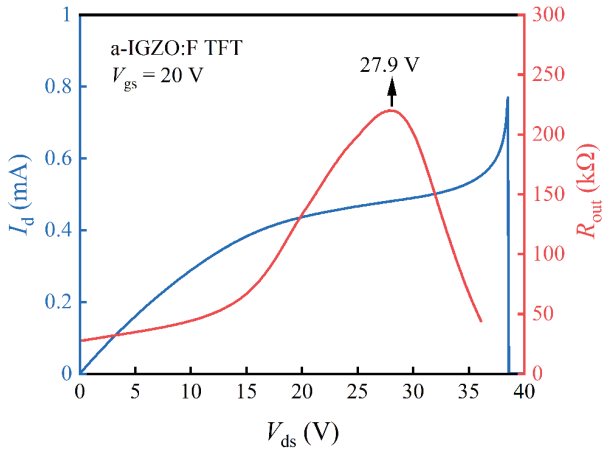

Fig. 4. (Color online) Output characteristic and output resistance curves of a-IGZO:F TFT at V_{gs} = 20 V.

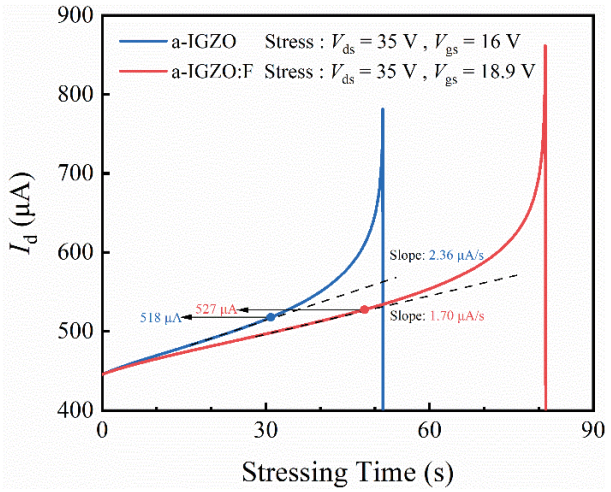

Fig. 5. (Color online) The evolution of I_d of a-IGZO and a-IGZO:F TFTs under SH stresses of the same initial power.

nel[10, 14], as illustrated in Fig. 3. Such a more defective channel is also consistent with the deteriorated *SS* in Fig. 2(a). The defined V_{tr} roughly corresponds to the SH effect elevating the channel temperature to the activation temperature of such state transition.

Since the SH-induced donors are turned from deep-state defects, it should be feasible to suppress the HCS degradation by passivating the native defect states, especially the deep-state Vo. Considering the Vo-suppressing effect of fluorine in a-IGZO, the HCS instability of a-IGZO:F TFT was quantitatively evaluated using the V_{tr}. As extracted from the R_{out}–V_{ds} curve in Fig. 4, the V_{tr} is significantly increased from 23.4 to 27.9 V by the plasma fluorination. This verifies the suppressing effect of fluorine on the initial total density of deep-state Vo (N_{Vo}), as illustrated in Fig. 3. The corresponding HCS breakdown voltage is also considerably improved from 32.3 to 38.6 V, proving the effectiveness of channel fluorination on enhancing the high-current stability of AOS TFTs.

As shown in both Fig. 2(b) and Fig. 4, the SH-induced donor generation rate (R_{gen}) in *Stage-Ⅱ* has apparently been continuously accelerated to speedily bring out the final breakdown. This could be ascribed to the higher V_{ds}-elevated SH power but may also be partially contributed by the accumulated V_{ds}-sweeping time. The fluorination effect on the state transition speed needs a more rigorous characterization method. Therefore, the time evolution of I_d is characterized under constant V_{ds} and V_{gs}. As listed in Fig. 5, V_{ds} is fixed at 35 V, while the V_{gs} values are precisely adjusted to obtain identical I_{ds} and power. Even under the constant bias stress, the I_d gradually encounters the linear increasing, fast rising and abrupt collapse, similar to the HCS degradation processes of output characteristics in Figs. 2 and 4.

In the initial stage of Fig. 5, the clearly linear slope of I_d-time curve seems to suggest a relatively low channel temperature, corresponding to a roughly constant HCS-activated R_{gen}. The linear slopes are 2.36 μA/s and 1.70 μA/s respectively for a-IGZO and a-IGZO:F TFTs, suggesting that the fluorination noticeably reduces the R_{gen} by 28%. Such noticeably slower R_{gen} could be ascribed to either the less N_{Vo} or a slower SH-induced transition rate of N_{Vo} (R_{tran}). However, as analyzed using the X-ray photoelectron spectroscopic (XPS), the Vo content of thermally oxidized a-IGZO can be further reduced by roughly 10% using the additional fluorination treatment[23–26]. Therefore, the noticeably slower R_{gen} in a-IGZO:F TFTs may not be fully explained by the fluorination-suppressed N_{Vo}. The R_{tran} of the SH a-IGZO channel is plausibly also noticeably reduced by the fluorination treatment, similar with the effect of fluorine on restraining hydrogen dopants to form shallow donors[26, 27]. As illustrated in Fig. 3, the fluorine-mitigated R_{tran} and N_{Vo} together contribute to the significant retardation of HCS degradation in Figs. 4 and 5.

Although the linear R_{gen} in the first stage of HCS degradation is different in a-IGZO and a-IGZO:F TFTs, the gradually accumulated Joule heat would eventually heat up channels to enough high temperatures to activate the utmost I_d uprush, most plausibly corresponding to the positive feedback between the channel temperature rising and the SH power increasing[22]. As further revealed in Fig. 5, such slope transition occurs at almost the same I_d of around 520 μA for both kinds of TFTs, thus corresponding to the same SH power of about 18 mW. This hints that a-IGZO and a-IGZO:F TFTs have a similar thermal dissipation efficiency, possibly since the AOS thermal conductivity mainly depends on the cationic composition and crystallinity[28] rather than anion dopants, such as fluorine. Instead, the fluorination effectively enhances the HCS stability of AOS TFTs by efficiently suppressing the initial defect state density of AOS and considerably mitigating the thermal induction rate of shallow donor states.

4. Conclusion

The complicated degradation behaviors of a-IGZO TFTs under the high-current stress were systematically investigated using the output and transfer characteristics. As extracted from the output resistance curve, a triggering voltage is proposed to evaluate the self-heating effect-activated induction of shallow-donor defects from the deep-state defects. The fluorine-doped channel was further adopted to effectively elevate the triggering voltage of self-heating degradation and thus significantly suppress the high-current stress degradations, including the final breakdown voltage. The underlying mechanism was investigated by characterizing the time evolution of the drain current under the high-current stress. While the thermal dissipation efficiencies of a-IGZO and a-IGZO:F TFTs are roughly the same, both the ini-

tial deep-state defects and the thermal induction rate of shallow donors are noticeably mitigated by the fluorination, contributing to the promising high-current stability.

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