Effects of Indium Composition Ratio on Electrical Stability of Top-gate Self-aligned Coplanar IGZO TFTs under Self-heating Stress Conditions

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Abstract—We demonstrated that the indium composition ratio in the channel layer significantly affects the electrical stability of top-gate self-aligned (TG SA) coplanar structure indium-gallium-zinc oxide (IGZO) thin-film transistors (TFTs) under self-heating stress (SHS) conditions. The transfer curves of the In-poor IGZO TFT continuously shifted in the positive direction with extended stress time, without a significant change in the subthreshold swing (SS) and field-effect mobility (μ_{FE}) values during SHS application. In contrast, the transfer curve of the In-rich IGZO TFT shifted in the negative direction until the SHS time reaches 1200 s, after which it shifted in the positive direction with extended stress time. Besides, SS and μ_{FE} values continuously increased as the SHS time increased in the In-rich IGZO TFTs. The unusual behavior of the TG SA coplanar In-rich IGZO TFT during SHS is mainly attributed to the more pronounced diffusion of hydrogen (H) atoms from the n⁺-IGZO source/drain extension region to the IGZO channel region in the In-rich IGZO than in the In-poor IGZO. The H atoms diffused into the IGZO channel layer act as either shallow donors or deep acceptors, depending on their concentration and environmental conditions, thus causing the abnormal behavior of IGZO TFTs during SHS.

I. INTRODUCTION

Presently, indium-gallium-zinc oxide (IGZO) thin-film transistors (TFTs) are extensively utilized as the backplane in organic light-emitting diode (OLED) displays [1, 2]. The widespread adoption of IGZO TFTs can be attributed to their numerous merits, including reasonable field-effect mobilities (μ_{FE}s), good large-area uniformity, low process temperature, and a high current on-off ratio [3-6]. In OLED displays, IGZO TFTs are primarily employed for implementing pixel and gate driver on array (GOA) circuits [7]. Particularly for GOA circuit applications, it is crucial for IGZO TFTs to exhibit high μ_{FE} and excellent electrical stability under self-heating stress (SHS) conditions, as these features play a vital role in the development of narrow bezel OLED displays [8]. To enhance the electron mobility in IGZO, an increase in the indium composition is necessary, given that In 5s orbitals have a large spatial spread and significant overlap, providing an efficient electron path [9].

In this study, we investigated the impact of the In composition ratio in IGZO on electrical stabilities under SHS in top-gate self-aligned (TG SA) coplanar IGZO TFTs. TG SA coplanar IGZO TFTs are widely employed as the backplane in recent OLED displays due to their small parasitic capacitance and excellent channel length scalability [10, 11]. Therefore, the findings from this study are anticipated to contribute to expanding the utility of IGZO TFTs in OLED displays.

II. RESULTS AND DISCUSSION

Fig. 1(a) illustrates a schematic cross-section of the fabricated TG SA coplanar IGZO TFT. The fabrication process for the TG SA coplanar IGZO TFT is detailed as follows: Initially, Al layer was deposited and patterned to create the back gate electrode (acting as a light shield) on a glass substrate. Subsequently, a SiO_x layer was produced using plasma-enhanced chemical vapor deposition (PECVD) as a buffer layer. IGZO layer was then deposited via radio-frequency magnetron sputtering to serve as the channel layer, with the In composition ratio in IGZO adjusted by varying the In content in the IGZO target. Following this, a SiO_x gate insulator was deposited via PECVD, followed by the deposition of a metal (Mo) as the gate electrode. After the deposition and patterning of the Mo gate electrode and SiO_x gate insulator, a SiO_x and SiN_x layer were deposited as an interlayer dielectric (ILD) using PECVD and patterned to create via holes. The source and drain electrodes of Al were deposited and patterned on the n^+-IGZO source/drain extension regions, where hydrogen diffused from the PECVD-deposited ILD serves as electron donors in IGZO, forming the source/drain extension regions [12]. Finally, for achieving stable and uniform electrical performance, the devices underwent thermal annealing at 340 °C. Fig. 1(b) depicts the representative semilogarithmic scale plots of transfer characteristics for In-poor and In-rich IGZO TFTs, where In-poor and In-rich IGZO TFTs imply the IGZO TFTs with low and high In composition ratio within IGZO, respectively. Here, V_{GS}, V_{DS}, and I_D represent the gate-to-source voltage, drain-to-source voltage, and drain current, respectively. The TFTs have a width (W)-to-length (L) ratio of 3 μm/5 μm, and measurements were conducted at $V_{DS} = 0.1$ V using an Agilent 4156C parameter analyzer
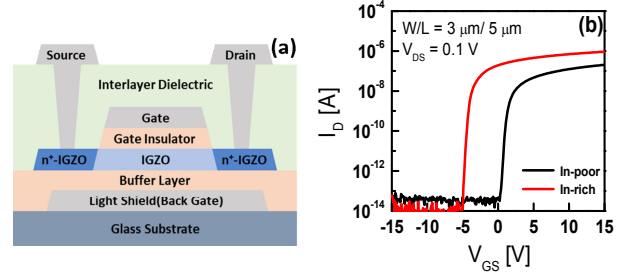

Fig. 1. (a) Schematic diagram of the fabricated TG SA coplanar IGZO TFTs; (b) Representative semilogarithmic scale plots of transfer characteristics for In-poor and In-rich IGZO TFTs.
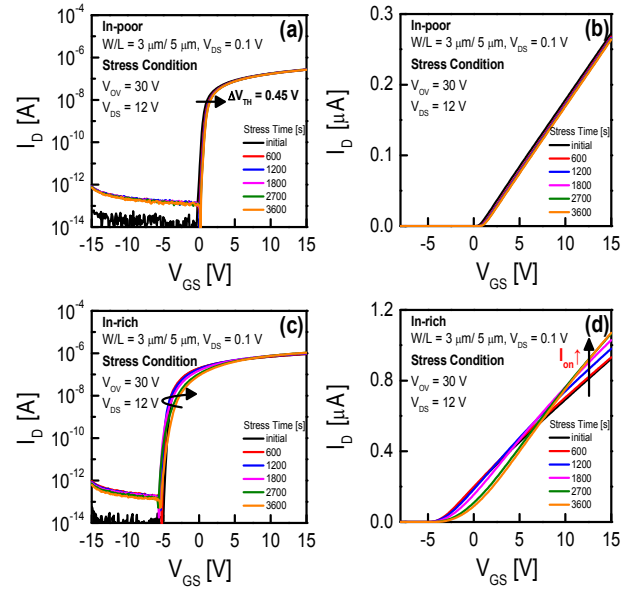

Fig. 2. Time dependence of (a) semilogarithmic; (b) linear scale transfer curves measured at $V_{DS} = 0.1$ V under SHS from In-poor TG SA coplanar IGZO TFTs. Time dependence of (c) semilogarithmic and (d) linear scale transfer curves measured at $V_{DS} = 0.1$ V under SHS from In-rich TG SA coplanar IGZO TFTs.

in air. Throughout the measurements, both the source and back gate electrodes were grounded. Fig. 1(b) shows that the In-rich IGZO TFT exhibits significantly lower threshold voltage (V_{TH}) compared to the In-poor IGZO TFT. These features are consistent with the results of previous studies [13] and are attributed to the high density of oxygen vacancies (V_Os) originating from the weak In–O bond, which can be more easily broken than Zn-O and Ga-O bonds [14]. Fig. 2(a) and (b) show the time dependence of semilogarithmic and linear scale transfer curves measured at $V_{DS} = 0.1$ V under SHS from In-poor TG SA coplanar IGZO TFTs.
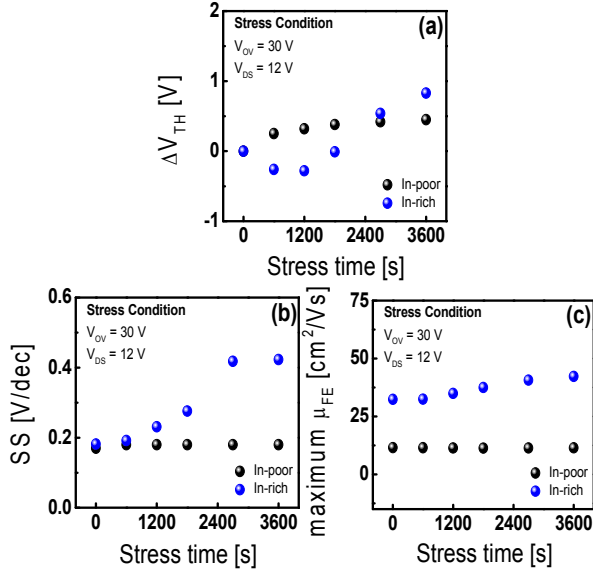
Fig. 2(c) and (d) show the corresponding curves for In-

Fig. 3. Time-dependence of (a) ΔV_{TH}; (b) SS; (c) maximum μ_{FE} values extracted from both In-poor and In-rich IGZO TFTs under SHS.

Fig. 4. Transfer curves measured at $V_{DS} = 0.1$ V and 15.1 V from the In-poor TG SA coplanar IGZO TFT: (a) before; (b) after an application of SHS for 3600 s. Transfer curves measured at $V_{DS} = 0.1$ V and 15.1 V from the In-rich TG SA coplanar IGZO TFT; (c) before; (d) after an application of SHS for 3600 s.

rich TG SA coplanar IGZO TFTs. The SHS condition used in this experiment was V_{OV} (= V_{GS} - V_{TH}) of 30 V and V_{DS} of 12 V at room temperature in a dark environment. Fig. 3(a)-(c) depict the threshold voltage shift (ΔV_{TH}), subthreshold swing (SS), and maximum μ_{FE} values extracted from both In-poor and In-rich TG SA coplanar IGZO TFTs after every SHS time. In Fig. 3, V_{TH} was determined as the V_{GS} value that results in $I_D = W/L \times 10$ nA and SS was obtained at I_D in the range of $10^{-12} - 10^{-11}$ A according to the equation:

$$SS = (\mathrm{d}(\log I_D)/\mathrm{d}V_{GS})^{-1} \qquad (1)$$

μ_{FE} values were calculated in the linear operating region as follows

$$\mu_{FE} = (\mathrm{d}I_D/\mathrm{d}V_{GS}) \times (L/WC_i V_{DS}) \qquad (2)$$

where, C_i is the gate dielectric capacitance per unit area. From Fig. 2 and 3, it is clearly observed that the time-dependent changes in the measured transfer curves under SHS for In-poor and In-rich IGZO TFTs exhibit distinct patterns. In the In-poor IGZO TFT, the V_{TH} shows a weak monotonic increase with increasing SHS time. In contrast, in the In-rich IGZO TFT, the V_{TH} decreases until the stress time reaches 1200 s, after which it sharply increases. Furthermore, in the In-poor IGZO TFT, the SS
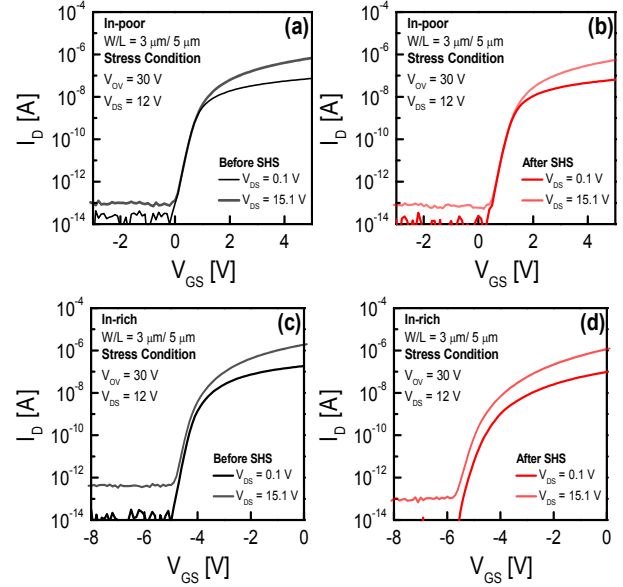
and maximum μ_{FE} values remain nearly constant regardless of the SHS time. On the other hand, in the In-rich IGZO TFT, the SS and maximum μ_{FE} values show a continuous increase with an increase in the SHS time. The results from Fig. 2 and 3 demonstrate that the In content within the IGZO film in TG SA coplanar IGZO TFTs significantly influences the electrical reliability of the TFTs under SHS.

To unveil the physical mechanisms responsible for the phenomena observed in Fig. 2 and 3, we initially compared the transfer curves measured at $V_{DS} = 0.1$ V and $V_{DS} = 15.1$ V for both In-poor and In-rich TG SA coplanar IGZO TFTs after applying SHS for different durations. Fig. 4(a) and (b) compare the transfer curves measured at $V_{DS} = 0.1$ V and 15.1 V from the In-poor TG SA coplanar 3600 s, respectively. The comparison reveals that the V_{TH} extracted from both transfer curves exhibits nearly the same value before and after SHS applications. In contrast, the comparison of the transfer curves measured at $V_{DS} = 0.1$ V and 15.1 V from the In-rich TG SA coplanar IGZO TFT before and after SHS for 3600 s (Fig. 4(c) and (d)) demonstrates a significant increase in the difference of V_{TH} extracted from the two transfer curves after the application of SHS. Generally,
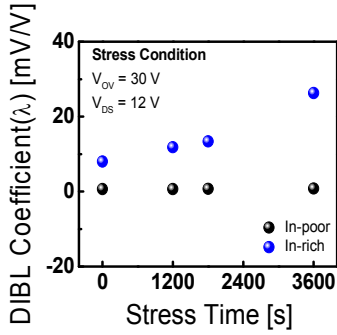
Fig. 5. Comparison of DIBL coefficients (λ) extracted from In-poor and In-rich TG SA coplanar IGZO TFTs at different SHS time points.

Fig. 6. Schematics diagrams depicting the diffusion of H atoms from the n$^+$-IGZO source/drain extension region to the IGZO channel region in (a) In-poor; (b) In-rich TG SA coplanar IGZO TFTs.

the decrease in V_{TH} with increasing V_{DS} in n-channel field-effect transistors (FETs) has been attributed to the drain-induced barrier lowering (DIBL) phenomenon, which becomes more pronounced as the channel length of the FET decreases [15]. Fig. 5 compares the DIBL coefficient (λ) over SHS time for TG SA coplanar IGZO TFTs, where λ is calculated according to the equation [16]:

$$\lambda = -(V_{TH}(V_{DS}=15.1V)-V_{TH}(V_{DS}=0.1V))/(15.1V-0.1V) \tag{3}$$

Fig. 4 and 5 indicate that, with the same gate length (L), the effective channel length (L_{eff}) of the In-rich TG SA coplanar IGZO TFT is shorter than that of the In-poor TG SA coplanar IGZO TFT. Furthermore, the L_{eff} of the In-rich TG SA coplanar IGZO TFT continues to decrease with SHS, while the In-poor TG SA coplanar IGZO TFT maintains a relatively constant L_{eff} during SHS.

This phenomenon is possibly attributed to the more pronounced diffusion of hydrogen (H) atoms from the n$^+$-IGZO source/drain extension region to the IGZO channel region in the In-rich TG SA coplanar IGZO TFT especially under SHS. It occurs because the concentration of V_O, which provides a diffusion path for H dopants in IGZO [17], is higher in In-rich IGZO than in In-poor IGZO due to a larger number of weak In–O bonds [14]. When V_O and H coexist in a single cell, H atom can be trapped in V_O (H_O^+) in IGZO and H_O^+ acts as a shallow donor [18]. Therefore, the more readily diffused H atoms to the IGZO channel region in the In-rich TG SA coplanar IGZO TFT reduce the L_{eff} of the TFT. Furthermore, they increase the concentration of
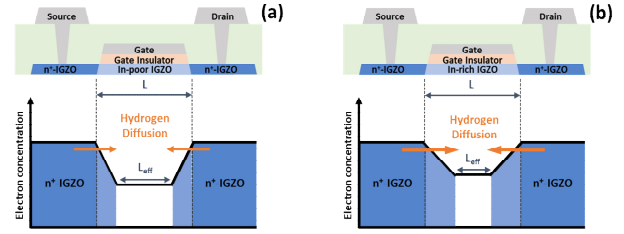
electrons within the IGZO channel, thereby lowering the V_{TH}. These phenomena become more prominent under the application of SHS, possibly attributed to the increased temperature within the TFT. Fig. 6(a) and (b) are schematic diagrams depicting the diffusion of H atoms from the n$^+$-IGZO source/drain extension region to the IGZO channel region in In-poor and In-rich TG SA coplanar IGZO TFTs, respectively. These diagrams illustrate the significant changes in electron concentration and L_{eff} resulting from SHS-induced H diffusion in the In-rich TG SA coplanar IGZO TFTs. The phenomenon of the V_{TH} increase with prolonged SHS time in the In-rich TG SA coplanar IGZO TFT is possibly attributed to the conversion of shallow H defect (H_O^+) to the acceptor-like deep defect states. When H_O^+ defect states in IGZO are occupied by electrons for prolonged time under SHS, they can be easily transformed to the acceptor-like subgap states near the valence band maximum originating from the metal-hydrogen (M-H) bonds [19, 20], which consume the free electrons in IGZO, leading to a positive ΔV_{TH} in the resulting TFTs.

The continuous increase of SS under SHS in In-rich TG SA coplanar IGZO TFT also can be mainly attributed to the increase in the concentration of shallow subgap states originating from H_O^+ defects within the IGZO channel layer. In addition, the more active thermal state transition of deep V_O into shallow V_O^{2+} due to higher concentration of V_O in the In-rich IGZO can be another reason for the SHS-induced continuous increase in SS in In-rich TG SA coplanar IGZO TFTs [21, 22]. Fig. 7 depicts the schematic diagram illustrating the charge state transition of defects within the IGZO channel in the In-high TG SA coplanar IGZO TFT under prolonged SHS exposure.

Fig. 7. Schematic diagram illustrating the charge state transition of defects within the IGZO channel in the In-high TG SA coplanar IGZO TFT under prolonged SHS exposure: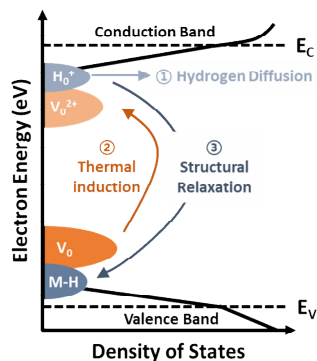 ① Creation of H_O^+ defects; ② Charge state transition from V_O to V_O^{2+}; ③ Structural transformation of shallow donor states originating from H_O^+ defects to the deep acceptor states originating from M-H bonds.

The increase in the maximum μ_{FE} value after an application of SHS in the In-rich TG SA coplanar IGZO TFT is plausibly ascribed to both the enhanced electron percolation conduction due to the increase in channel electron concentration [9] and the phenomenon where the μ_{FE} value calculated through Eq. (2) exhibits larger values than the actual values when L_{eff} is significantly smaller than L [23].

IV. CONCLUSIONS

In this study, we investigated the impact of the In composition ratio in IGZO on electrical stabilities under SHS (V_{OV} = 30 V and V_{DS} = 12 V) in TG SA coplanar IGZO TFTs. In the TG SA coplanar In-poor IGZO TFTs, the V_{TH} shows a weak monotonic increase with increasing SHS application time. In contrast, the V_{TH} decreases until the stress time reaches 1200 s, after which it sharply increases in the TG SA coplanar In-rich IGZO TFTs. Besides, while the SS and maximum μ_{FE} values remain nearly constant regardless of the SHS time in the TG SA coplanar In-poor IGZO TFTs, they display a continuous increase with the extended SHS time in the In-rich TG SA coplanar IGZO TFTs. From the experimental results, the abnormal behavior of the TG SA coplanar In-rich IGZO TFT under SHS is possibly attributed to the pronounced diffusion of H atoms from the n^+-IGZO source/drain extension region to the IGZO channel region, where the concentration of V_O is higher

in the In-rich IGZO and provides a facile diffusion path for H dopants in IGZO. The H atoms diffused into the IGZO acts as shallow donors or deep acceptors depending on its concentration and environmental conditions, leading to various operational characteristic changes in the TG SA coplanar In-rich IGZO TFTs over time under SHS.

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