

Article

The Role of Germanium Incorporation in Enhancing the Stability of Indium Zinc Oxide Thin-Film Transistors Under Water Vapor Exposure and Thermal Stress

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Abstract

This work demonstrates the potential of indium germanium zinc oxide (InGeZnO) as a promising oxide semiconductor offering an improved trade-off between mobility and stability under water exposure and thermal stress. The effect of Ge incorporation in enhancing the stability of indium zinc oxide (InZnO) thin-film transistors (TFTs) is systematically investigated through negative bias stress (NBS) and negative bias temperature stress (NBTS) measurements after different durations of deionized-water immersion. The results show that InGeZnO exhibits smaller threshold voltage (V_{TH}) shift magnitudes and reduced sub-threshold swing (SS) degradation after prolonged immersion, as well as an attenuated difference between the SS changes induced by NBS and NBTS, compared with InZnO. These electrical trends suggest that water exposure disrupts the metal–oxygen (M–O) coordination structure and increases oxygen vacancies in the exposed back channel, whereas Ge–O bonding stabilizes the M–O network and limits the evolution of these defects under gate bias and thermal stress. X-ray photoelectron spectroscopy (XPS) analysis provides further support for the proposed mechanism. Collectively, the results position Ge doping as a promising strategy for balancing high mobility with robust stability against water vapor exposure and thermal stress in oxide TFTs.

Keywords: thin-film transistors; indium germanium zinc oxide; negative bias stress; field-effect mobility; electrical stability



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1. Introduction

High-performance thin film transistors (TFTs) are essential switching devices in active matrix displays to enable high resolution and frame rate operation. Metal oxide (MO) TFTs, which benefit from relatively high field-effect mobility (μ_{FE}) and good process compatibility, have been widely regarded as promising candidates for next-generation display driving technologies [1–4] and capacitorless memory applications [5]. In particular, indium gallium zinc oxide (InGaZnO) has been extensively adopted in practical applications owing to its mature material system and established fabrication processes [6,7]. However, its field-effect mobility (μ_{FE}) typically remains around 10 to 15 cm² V^{−1} s^{−1} [8–10], which limits the performance margin for displays with higher frame rates and pixel densities. Meanwhile, other MO TFTs with higher mobility, such as InZnO [11–13] and IZTO [14–16], often exhibit greater electrical instability, reflecting the trade-off between mobility and reliability [17,18].

In this regard, Ge incorporation into InZnO has attracted increasing attention [19–22]. The high dissociation energy of Ge–O bonds stabilizes the local coordination structure [22–25], increasing the formation energy of oxygen vacancies (V_O), thereby improving electrical stability. In addition, Ge doping has been reported to reduce carrier localization, which is commonly attributed to the more delocalized nature of Ge 4s orbitals near the conduction band edge [24], maintaining relatively high μ_{FE} at low dopant concentrations. Consequently, indium germanium zinc oxide (InGeZnO) has been considered a promising channel material for achieving stable TFTs with high μ_{FE} .

Nevertheless, the reliability of InGeZnO TFTs under different stress conditions remains to be further clarified. Extensive reliability investigations have been reported under illumination [26,27], thermal stress [28–31], and electrical bias stress [32–35]. Previous studies have mitigated moisture-related instability through channel densification and back-channel passivation [15,36–39]. However, studies concerning the effects of direct water exposure on the reliability of Ge-containing oxide TFTs are still limited. In this work, the stability of InGeZnO TFTs following prolonged water exposure is systematically investigated, with InZnO serving as the reference. To minimize interference from other ambient species, both types of TFTs were directly immersed in deionized water at room temperature (RT) for various durations up to 8 h. After each immersion period, NBS and NBTS measurements were performed under the same negative gate bias at RT and 55 °C, respectively, to quantify the accelerating effect of elevated temperature on the evolution of water-induced defects in the back channel. The resulting degradation was assessed using the V_{TH} shift magnitude and SS change. As the immersion duration increased from 0 to 8 h, the differences between NBS and NBTS in these two parameters increased by only 0.15 V and 148.03 mV/dec, respectively, for InGeZnO, whereas the corresponding increases for InZnO were 0.64 V and 360.69 mV/dec. These results demonstrate the improved resistance of InGeZnO to water-related degradation under NBS and its further enhancement under thermal stress. Furthermore, a degradation mechanism was proposed and supported by X-ray photoelectron spectroscopy (XPS) analysis: water immersion disrupts M–O coordination in the back channel and induces oxygen-related defects; Ge–O bonds enhance structural stability owing to their high bond dissociation energy, reducing the reactivity of oxygen-deficient regions toward water and suppressing further defect formation and electrical activation under subsequent electrical and thermal stresses.

2. Experimental Section

Bottom-gate, top-contact InZnO and InGeZnO TFTs were fabricated on p-type Si substrates with a 90 nm thick thermally grown SiO_2 layer. A 20 nm Mo gate electrode was first deposited by electron-beam evaporation and patterned. A 10 nm HfO_2 gate dielectric was then deposited by atomic layer deposition at 300 °C. Subsequently, the InZnO and InGeZnO active layers were prepared by magnetron sputtering at room temperature under a working pressure of 3 mTorr. The InZnO layers were deposited by radio-frequency sputtering at 80 W under Ar and O_2 flow rates of 28 and 2 sccm, respectively. For the InGeZnO channel, ultrathin Ge layers were periodically inserted into the InZnO deposition sequence by direct-current sputtering at 10 W under an Ar flow rate of 20.5 sccm. The sputtering duration of each Ge insertion was fixed at 8 s, producing an InZnO/Ge/InZnO/Ge/InZnO stacked structure, as illustrated in Figure 1. For comparison, the InZnO channel was fabricated under the same deposition conditions without Ge insertion. The total channel thickness was approximately 13 nm. Afterwards, a 20 nm thick Mo layer was deposited by magnetron sputtering and patterned through a lift-off process to form the source/drain electrodes. Finally, all fabricated devices were annealed in ambient air at 250 °C for 30 min.

Electrical characterization was performed on TFTs with a channel width of 80 μm and channel lengths of 30, 20, and 10 μm ($W/L = 80/30, 80/20, \text{ and } 80/10 \mu\text{m}/\mu\text{m}$). To account for differences in channel dimensions, the drain current was normalized as $I_{\text{DS,nom}} = I_{\text{DS}}L/W$, and all drain current values presented in the subsequent figures and discussion refer to $I_{\text{DS,nom}}$. Transfer characteristics were measured in ambient air by sweeping V_{GS} from -3 to 3 V at $V_{\text{DS}} = 0.1$ V. The V_{TH} was extracted using the constant-current method and defined as the gate voltage at which $I_{\text{DS,nom}}$ reached 10 nA. The SS was calculated from $\text{SS} = dV_{\text{GS}}/d\log_{10}(I_{\text{DS}})$, with its average over the I_{DS} range from 10^{-10} to 10^{-8} A reported. The μ_{FE} was calculated in the linear region using $\mu_{\text{FE}} = g_m L / (WC_{\text{ox}} V_{\text{DS}})$, where $g_m = dI_{\text{DS}}/dV_{\text{GS}}$ and C_{ox} is the gate dielectric capacitance per unit area. The maximum μ_{FE} within the measured V_{GS} range was reported. NBS and NBTS measurements were conducted at $V_{\text{GS}} = -4$ V for 1000 s at RT and 55 $^{\circ}\text{C}$, respectively, unless stated otherwise. Each reported data point represents the mean $\pm$ standard deviation obtained from 10 TFTs measured under the corresponding test condition.

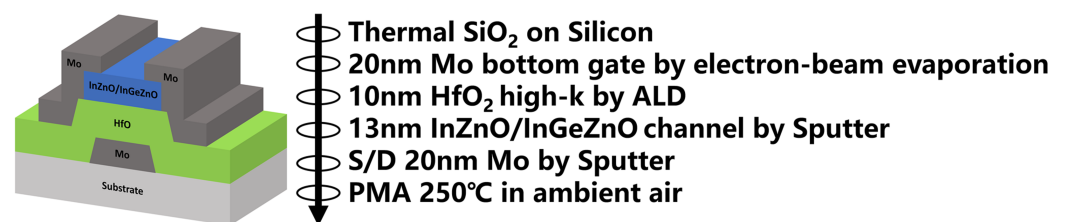


Figure 1. The schematic diagram of the TFT device and the detailed process flow.

3. Results and Discussion

Figure 2 illustrates the transfer characteristics of InZnO [Figure 2a] and InGeZnO [Figure 2b] TFTs in the initial state, after NBS and NBTS, prior to water immersion. Table 1 summarizes the mean initial parameters obtained from multiple devices, showing that InGeZnO exhibits a more positive V_{TH} (-0.53 versus -1.01 V) and a smaller SS (111.44 versus 145.90 mV/dec) without sacrificing μ_{FE} (41.35 versus 40.63 $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$). The observed differences in V_{TH} and SS are attributed to Ge–O bonding, which enhances lattice stability and raises the formation energy of V_{O} [22–25]. Meanwhile, Ge incorporation enhances the spatial overlap of In 5s orbitals, increasing conduction-band dispersion and lowering the conduction-band minimum (CBM), thereby reducing the donor activation energy. The increased dispersion enables InGeZnO to maintain a μ_{FE} comparable to that of InZnO, while the lower activation energy allows a larger fraction of the remaining donor-derived electrons to be activated into the conduction band despite the reduced concentration of V_{O} donors [17,24,40]. Furthermore, comparison of the pre-immersion stress responses reveals better stability in InGeZnO than in InZnO under both NBS and NBTS. Driven by the negative gate electric field, ionized V_{O} migrate toward the gate–insulator interface, and the resulting interfacial accumulation promotes charge trapping, leading to the negative V_{TH} shift and SS degradation. Elevated temperature further promotes the ionization of deep-level V_{O} defects in the back channel and increases the electron concentration, resulting in more severe electrical degradation under NBTS.

Figure 3 presents the transfer characteristics of InZnO [Figure 3a] and InGeZnO [Figure 3b] TFTs after different durations of deionized-water immersion. The curves exhibit an overall negative shift and increased off-current with increasing immersion time, indicating an increase in the channel electron concentration. Notably, the switching characteristics of InZnO deteriorate markedly by 8 h, suggesting appreciable modification of the channel. Figure 3c,d show no evident increase in gate leakage for either TFT after 8 h of immersion, suggesting that gate-stack degradation is unlikely to dominate the observed transfer-characteristic changes. In order to comprehensively evaluate the effects

of water exposure and elevated temperature on the channel, InZnO and InGeZnO TFTs were examined under NBS and NBTS after different durations of immersion. The V_{TH} shift magnitudes (ΔV_{TH}) and SS changes (ΔSS) extracted from the transfer characteristics measured before and after stress are summarized in Figure 4a for InZnO and Figure 4b for InGeZnO. The extracted data indicate that both ΔV_{TH} and ΔSS generally increase with immersion duration under NBS; more importantly, NBTS produces substantially larger values of both quantities. To quantify the additional electrical degradation associated with elevated temperature, D_V and D_{SS} are defined as the differences between the NBTS- and NBS-induced ΔV_{TH} and ΔSS values, respectively, at the same immersion duration t_b :

$$D_V(t_b) = |\Delta V_{TH,NBTS}(t_b)| - |\Delta V_{TH,NBS}(t_b)| \quad (1)$$

$$D_{SS}(t_b) = \Delta SS_{NBTS}(t_b) - \Delta SS_{NBS}(t_b) \quad (2)$$

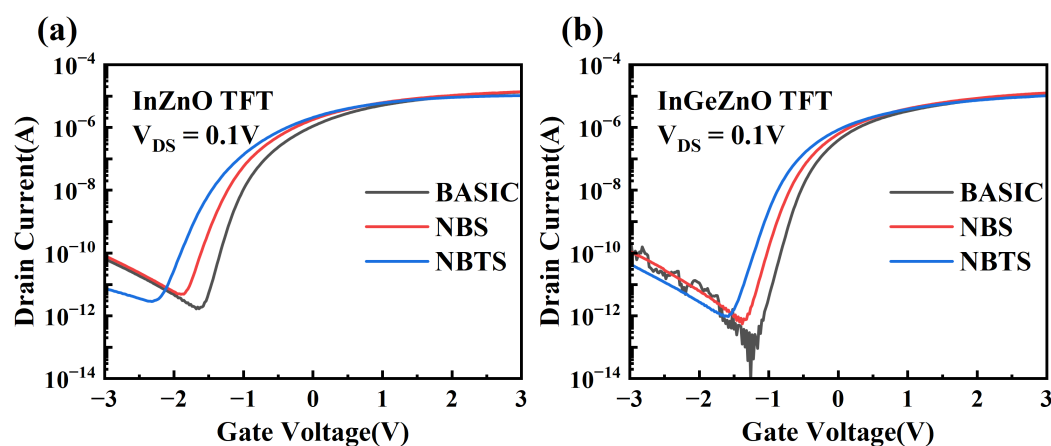


Figure 2. Transfer curves of (a) InZnO and (b) InGeZnO TFTs in the initial state and after NBS and NBTS measured at $V_{DS} = 0.1$ V.

Table 1. Initial electrical parameters of the InZnO and InGeZnO TFTs. Values are presented as the mean $\pm$ standard deviation obtained from 10 devices for each condition ($n = 10$).

Sample	V_{TH} (V)	SS (mV/dec)	μ_{FE} ($\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$)	I_{on}/I_{off}
InZnO	-1.01 ± 0.15	145.90 ± 28.63	40.63 ± 4.66	$(4.29 \pm 1.41) \times 10^6$
InGeZnO	-0.53 ± 0.06	111.44 ± 15.37	41.35 ± 1.57	$(6.05 \pm 1.22) \times 10^7$

As summarized in Table 2, from 0 to 8 h, D_V and D_{SS} in InZnO increase from 0.20 to 0.64 V and from 41.06 to 360.69 mV/dec, whereas the corresponding values in InGeZnO change from 0.17 to 0.15 V and from 26.90 to 148.03 mV/dec. Previous studies on the effects of water on oxide TFTs have mainly explained V_{TH} shifts in terms of surface adsorption: adsorbed water molecules can induce an additional electron accumulation layer at the channel surface, thereby increasing the electron concentration and resulting in a negative V_{TH} shift [40–42]. The increased shift observed in this work is consistent with this model. However, it mainly accounts for the change in carrier concentration caused by water adsorption and does not fully explain the pronounced increase in D_{SS} after immersion relative to the 0 h baseline. It is therefore reasonable to speculate that water exposure also perturbs the local M–O coordination environment and increases the electrical activity of defects in the channel, with Ge incorporation suppressing such changes.

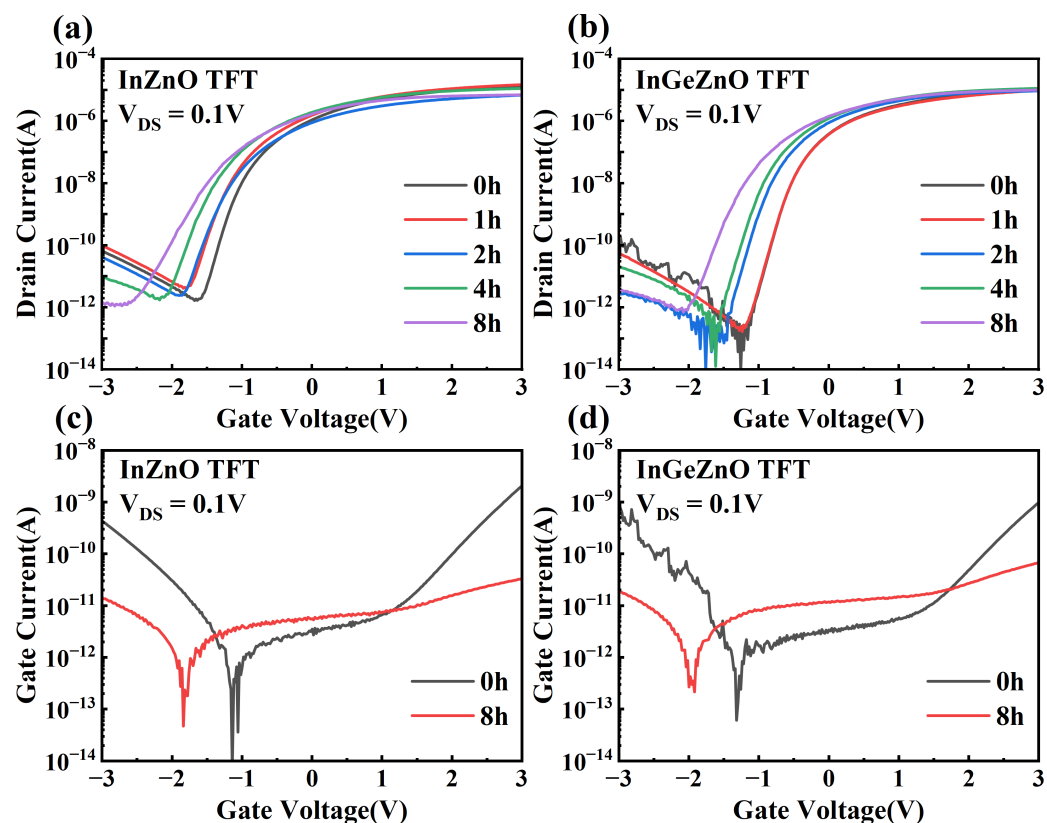


Figure 3. Transfer characteristics of (a) InZnO and (b) InGeZnO TFTs before and after immersion in deionized water for 1, 2, 4, and 8 h; gate leakage current characteristics of (c) InZnO and (d) InGeZnO TFTs before and after 8 h of immersion.

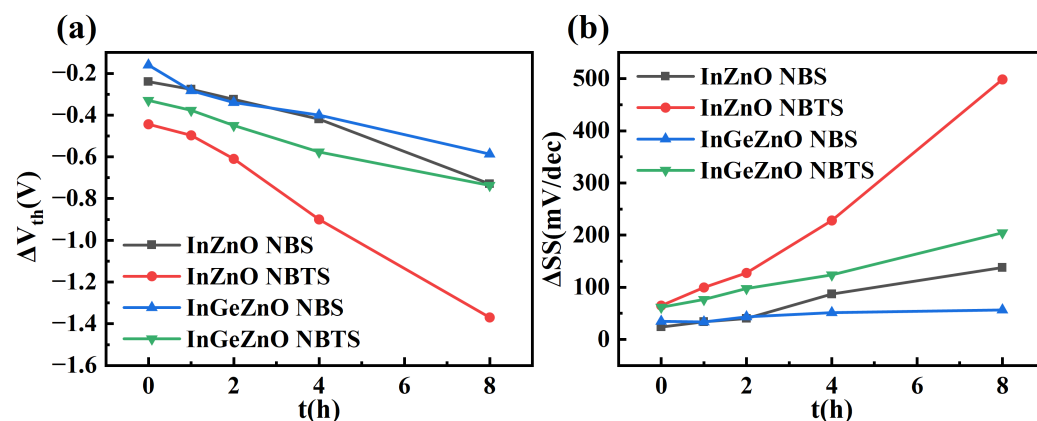


Figure 4. Dependence of (a) ΔV_{TH} and (b) ΔSS on the duration of immersion in deionized water for InZnO and InGeZnO TFTs subjected to NBS and NBTS.

Table 2. Thermal contributions to the V_{TH} shift (D_V) and SS degradation (D_{SS}) in InZnO and InGeZnO TFTs before and after 1, 2, 4, and 8 h of immersion in deionized water.

Immersion Time (h)	D_V , InZnO (V)	D_V , InGeZnO (V)	D_{SS} , InZnO (mV dec ⁻¹)	D_{SS} , InGeZnO (mV dec ⁻¹)
0	0.20	0.17	41.06	26.90
1	0.22	0.10	65.70	43.30
2	0.28	0.11	87.34	54.50
4	0.48	0.18	141.23	72.45
8	0.64	0.15	360.69	148.03

In terms of material properties, XPS was employed to investigate the influence of water exposure on the chemical states of InZnO and InGeZnO films. Generally, the O 1s spectra can be deconvoluted into three subpeaks with binding energy centered at 529.7 ± 0.1 eV (peak 1), 531.1 ± 0.1 eV (peak 2), and 531.9 ± 0.1 eV (peak 3), respectively, representing metal-bonding oxygens, oxygen associated with oxygen vacancies (V_O), and chemisorbed oxygens [43–45]. Figure 5a–c show the InZnO O 1s and InGeZnO O 1s and Ge 3d spectra before immersion, whereas Figure 5d–f show the corresponding spectra after 8 h of immersion in deionized water. Relative to the initial state, the composition of peak 1 decreases by 18.41 percentage points in InZnO, compared with 15.75 percentage points in InGeZnO; a more pronounced contrast is observed for peak 2, with its composition increasing by 15.05 percentage points in InZnO but by only 8.12 percentage points in InGeZnO. The changes observed in InZnO are consistent with the selective etching mechanism previously proposed for IGZO after deionized water immersion [40]. According to this mechanism, water preferentially reacts with Ga and Zn sites near V_O , disrupting the M–O network and increasing the relative fractions of In and V_O at the exposed surface. By contrast, Figure 5c,f show only limited redistribution among the fitted Ge 3d components, with the average Ge oxidation state remaining nearly unchanged after immersion. Together with the smaller O 1s changes in InGeZnO, this result suggests that Ge-related local coordination is largely preserved during water immersion, consistent with the stabilizing role of Ge–O bonding in the local M–O network.

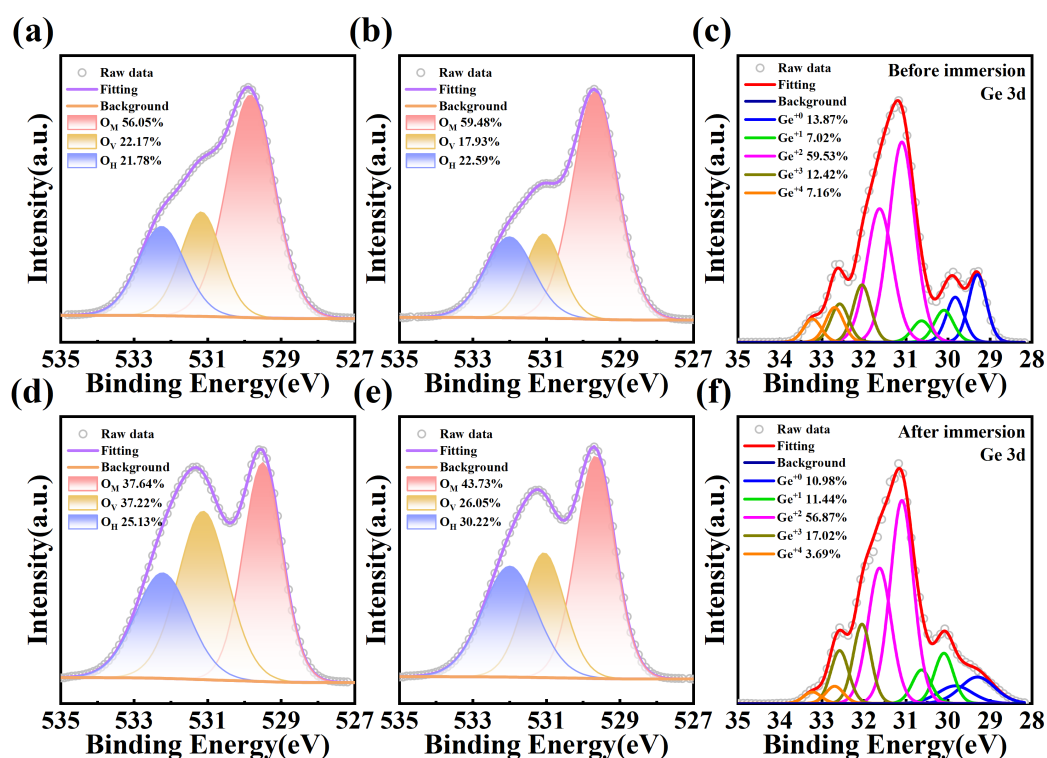


Figure 5. O 1s XPS spectra of the InZnO and InGeZnO films and Ge 3d XPS spectra of the InGeZnO film measured before immersion (a–c) and after 8 h of immersion in deionized water (d–f): (a,d) InZnO O 1s; (b,e) InGeZnO O 1s; and (c,f) InGeZnO Ge 3d.

Based on the combined XPS and electrical results, a mechanism is proposed, as schematically illustrated in Figure 6. The process can be divided into two stages: water immersion and subsequent bias stress. During immersion, oxygen-deficient regions at the exposed back-channel surface are particularly vulnerable to water, which may preferentially disrupt nearby Zn–O bonds [40]. The preferential loss of Zn species further weakens the surrounding M–O network, resulting in In enrichment and an increased concentration

of V_O at the exposed surface, as supported by the pronounced decrease in peak 1 and the marked increase in peak 2 observed in the O 1s spectra of InZnO after immersion. Under the gate electric field, defects in the back channel exert a greater influence on device characteristics. Thermal stress may further accelerate structural rearrangement, promoting the formation and electrical activation of V_O . This process can be well reflected in a marked increase in channel conductivity and more pronounced SS degradation in InZnO. By contrast, Ge incorporation markedly suppresses this degradation process. The high bond dissociation energy of Ge–O bonds strengthens the structure and reduces the reactivity of oxygen-deficient regions. This greater resistance curbs further structural degradation and limits the generation of additional V_O . XPS analysis clearly demonstrates the effect, with peak 2 showing a smaller difference in InGeZnO after immersion. This stabilization also persists under NBTS, restricting the generation and electrical activation of donor-like defects and trap states. As a result, thermal stress produces less additional degradation in InGeZnO, leading to smaller negative V_{TH} shifts and milder SS degradation.

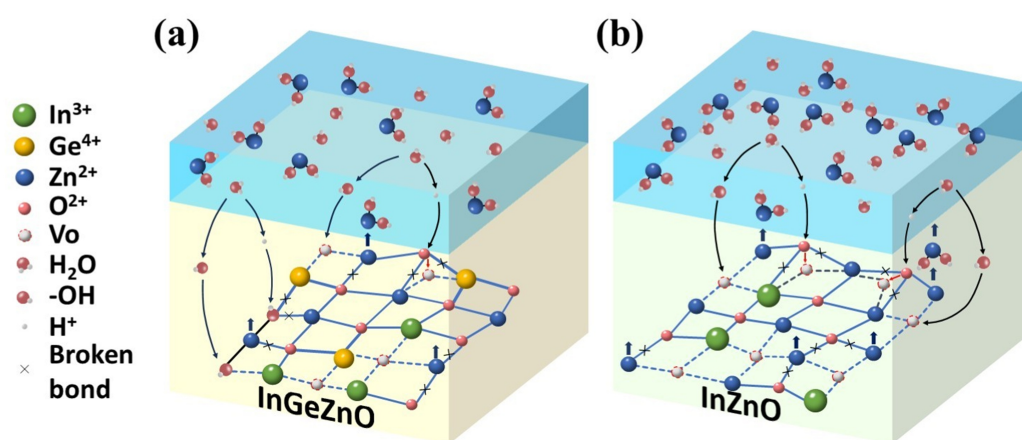


Figure 6. Schematic diagrams of the proposed degradation mechanism at the exposed back channel of (a) InGeZnO and (b) InZnO during water exposure.

4. Conclusions

In this study, Ge incorporation was investigated as a material strategy to improve the stability of InZnO TFTs under water exposure and thermal stress. The resulting InGeZnO TFTs maintained a μ_{FE} of $41.35 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and an initial V_{TH} of -0.53 V with enhanced stability. After 8 h of deionized water immersion, the NBTS-induced V_{TH} shift magnitude and SS increase are limited to 0.74 V and 204.33 mV/dec , respectively. Utilizing NBS and NBTS measurements together with O 1s and Ge 3d XPS analyses, we elucidated the mechanism of back-channel degradation induced by water exposure and further promoted by thermal stress. The results further demonstrate the role of Ge–O bonding in stabilizing the M–O network and effectively suppressing this degradation. Therefore, InGeZnO TFTs may be promising candidates for next-generation displays designed to operate in extreme environments with high temperature and humidity.

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