

Evaluation of the high mobility and stability of InGaZnO/InSnZnO bilayer thin-film transistors via quantitative defect analysis

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ABSTRACT

This study presents bilayer (BL) InGaZnO (IGZO)/InSnZnO (ITZO) thin-film transistors (TFTs) with different ITZO layer thicknesses. A BL-TFT with an optimized thickness of 5 nm for ITZO and 35 nm for IGZO demonstrated high mobility (μ_{FE}) of ~ 36 cm²/Vs, less negative threshold voltage (V_{th}) as well as minimal V_{th} shifts of 1.15 V and -0.25 V under positive-bias stress (PBS) and negative-bias stress (NBS), respectively. Such performance improvements were unattainable when layers were used independently. Photoinduced Current Transient Spectroscopy (PICTS) was employed to determine the defects inside the bandgap quantitatively. The PICTS analysis showed that integrating ITZO and IGZO in a single device leads to an optimal number of shallow donor defects that are neither too high nor too low, thus achieving high μ_{FE} and less negative V_{th} values simultaneously. Furthermore, the remarkable stability of the 5 nm ITZO/35 nm IGZO BL-TFT under both NBS and PBS was attributed to its lower defect concentrations measured at 4.1×10^{18} #/cm³ below the Fermi level and 9.0×10^{16} #/cm³ above the Fermi level. In contrast, reduced NBS and PBS stabilities of single-layer ITZO and IGZO TFTs were associated with their elevated defect densities at 6.7×10^{18} #/cm³ below the Fermi level and 3.9×10^{17} #/cm³ above the Fermi level. This quantitative defect analysis is crucial for understanding the performance and stability degradation of oxide semiconductors, ultimately aiding in addressing these challenges.

1. Introduction

The benefits of amorphous oxide semiconductors (AOSs) were identified in the early 2000s. Since then, AOSs have become crucial to modern semiconductor technology [1,2]. They have replaced traditional silicon-based semiconductors as channel materials for thin film transistors (TFTs) in display backplanes owing to their greater transmittance to visible light, lower leakage current, and higher mobility. Notably, the manipulation of AOS's chemical state, including its composition and bonding arrangement through precise process control, allows for the fine-tuning of material and device features [3–5]. Thus, researchers have expanded applications of AOS beyond traditional display backplane TFTs to include sensors [6,7], memory devices [8], and neuromorphic devices [9], among others. As AOS applications expand and display technology advances, traditional devices have begun to show functional constraints. One of the primary issues of AOSs is the need to balance mobility and stability [10]. For example, indium-gallium-zinc-oxide

(IGZO), the most often used AOS, has great negative bias stress (NBS) stability [10,11]. However, its applicability is limited due to its relatively low mobility [10,12–15]. Conversely, indium-tin-zinc-oxide (ITZO) suffers from inferior NBS stability, although it has good mobility [10,13,16–19]. Furthermore, achieving high mobility (μ_{FE}) and less negative threshold voltage (V_{th}) simultaneously is challenging [10,20].

The scientific community is fully aware of the trade-off between mobility and stability. Thus, numerous solutions have been proposed. One effective strategy is to use bi-layered (BL) devices because BL devices exhibit various properties according to their structure, material composition, and arrangement that allow for the fabrication of optimal devices by combining the strengths of multiple materials. For instance, Park et al. [21] have increased device performance by augmenting the electron density of IGZO with an InZnO layer, and Liu et al. [22] have achieved high-mobility TFTs by fabricating BL-TFTs using In₂O₃ and InZnO AOSs. Even though prior research studies have succeeded in

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improving performance using a BL-TFT architecture, the role of defect states in the performance and bias stress stability enhancement of BL-TFTs has not yet been systematically investigated. Therefore, it is necessary to quantitatively determine the defect densities and their corresponding energy levels to provide a more viable approach for the assessment of BL-TFTs and effect of specific defects on their performance.

In this study, we systematically evaluate defects in BL-TFTs using photoinduced current transient spectroscopy (PICTS) and spectroscopic ellipsometry (SE) to gain insight into the performance and bias stability enhancement of IGZO/ITZO BL-TFTs. Research objectives are: 1) To fabricate a bottom-gate TFT featuring a BL active-channel structure for improved mobility and stability as illustrated in Figs. 1(a, b). This structure will consist of a high electron mobility AOS layer (ITZO) and an NBS-stable AOS layer (IGZO) with varying thicknesses of the ITZO layer. The fabrication process will utilize sputtering techniques to achieve desired layer configurations; 2) to evaluate electrical parameters such as mobility and gate bias stress stability using a semiconductor analyzer; 3) to analyze defect states qualitatively through SE and

quantitatively via PICTS as depicted in Fig. 1(c); and 4) to investigate underlying reasons for the observed improvements in mobility and bias stability of BL-TFTs, focusing on the roles of defect states in these enhancements. A BL-TFT with an optimized thickness of 5 nm for ITZO and 35 nm for IGZO demonstrated high mobility (μ_{FE}) of $\sim 36 \text{ cm}^2/\text{Vs}$, less negative threshold voltage (V_{th}) as well as minimal V_{th} shifts of 1.15 V and -0.25 V under PBS and NBS, respectively. Such performance enhancements were not observed when the layers were used individually. Compared to the previously reported BL-TFTs, our study is unique in the following major aspects: (i) quantitative defect analysis was performed using PICTS which revealed that the main reason for the simultaneous achievement of both high μ_{FE} and less negative V_{th} in BL-TFTs, when compared to their individual counterparts, was due to the optimal number of shallow donor defects ($\sim 0.1 \text{ eV}$) that are neither too high nor too low in the BL-TFTs. (ii) Information on defects like their energy level was extracted from the PICTS data and a novel interpretation of defects in relation to bias stress stability was introduced by examining the probabilistic distribution of defects around the Fermi level using the Fermi-Dirac statistics. This interpretation revealed that the exceptional

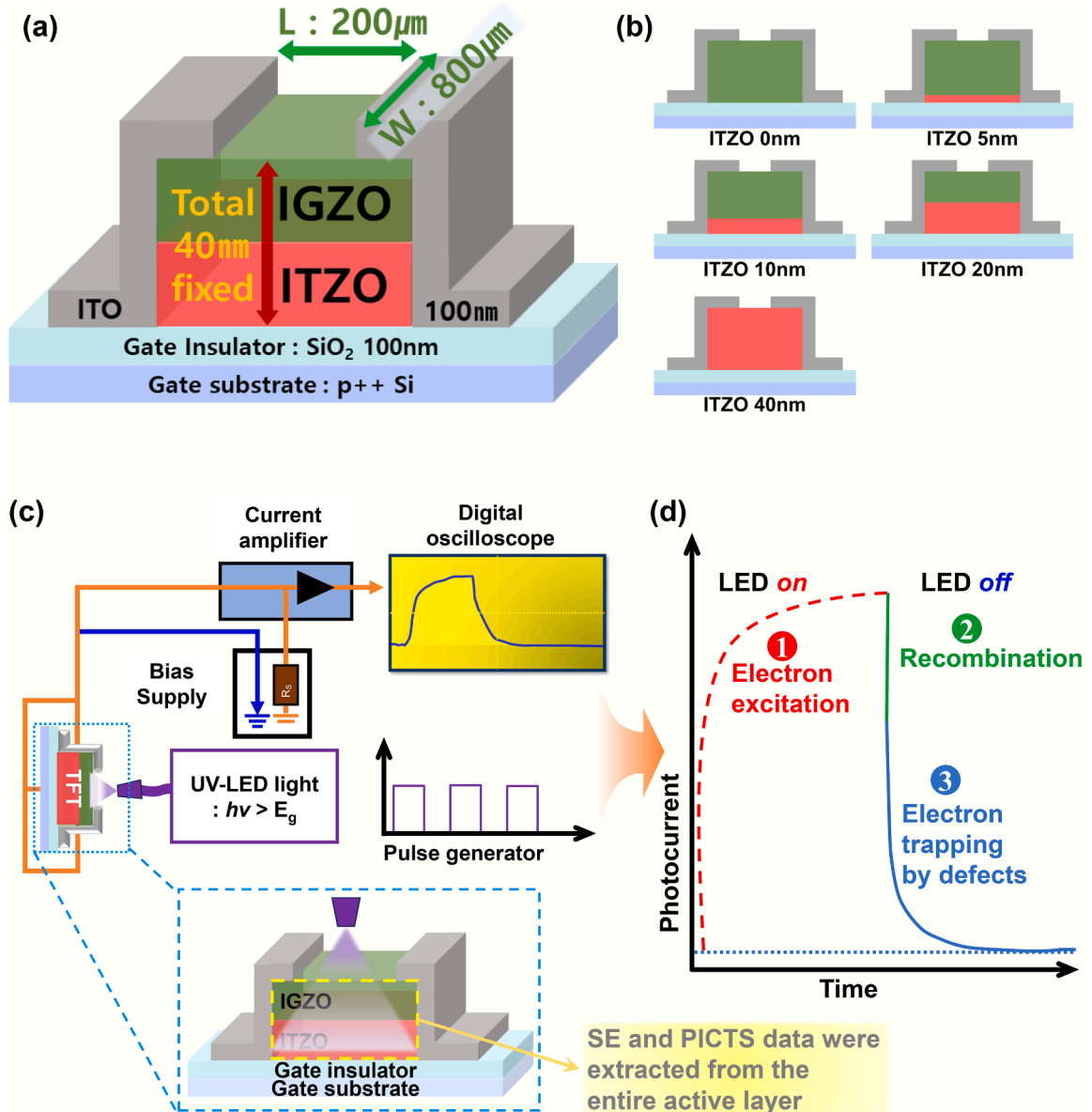


Fig. 1. IGZO/ITZO BL-TFTs fabrication and defect analysis. (a) Schematic illustration of bottom gate BL-TFT architecture. (b) Investigated thickness variations in IGZO/ITZO BL-TFTs. (c) Experimental setup of PICTS for quantitative defect investigation in BL-TFTs.

stability of the ITZO/IGZO BL-TFTs under NBS and PBS can be linked to their lower defect densities both below and above the Fermi level, respectively. Conversely, the diminished NBS and PBS stabilities of the single-layer ITZO and IGZO TFTs were correlated with their higher defect densities below and above the Fermi level, respectively. These findings highlight the significance of not only pinpointing individual defect states but also comprehending their energy levels and distribution in relation to the Fermi level to understand the electrical performance and reliability of TFTs. Therefore, we believe that the insights provided by this study will be beneficial for the AOS TFTs field and semiconductor devices in a wider context.

2. Experimental

2.1. Fabrication of IGZO/ITZO BL-TFTs

A bottom-gate top-contact BL-TFT produced in this work is schematically depicted in Fig. 1(a). The gate electrode was made of a highly p^{++} -doped Si substrate (P-type (Boron): $1.17 \times 10^{20} \sim 2.01 \times 10^{19}$ atoms/cm³). The gate insulator was 100 nm thick SiO₂. The active region, the most important aspect of this investigation, was made up of sandwiched IGZO and ITZO layers. The ITZO layer, known for its fast electron mobility, was adjacent to the gate insulator, while the IGZO layer with relatively excellent bias stability was on the far side. According to previous studies on single-channel ITZO and IGZO devices, both perform optimally at a thickness of around 40 nm [16,18,23–30]. For example, a too-thick channel layer can negatively impact threshold voltage due to the semi-insulating nature of AOS materials, leading to increased carrier scattering and reduced gate control [31]. On the other hand, a too-thin channel layer can suffer from surface roughness effects, which degrades mobility by disrupting the conduction path [31,32]. Additionally, maintaining a certain minimum thickness helps to suppress the influence of interface defects and facilitates bulk-like transport behavior [33]. Therefore, the total thickness of the active layer was fixed at 40 nm. Five devices with ITZO thicknesses of 0 nm, 5 nm, 10 nm, 20 nm, and 40 nm were manufactured (Fig. 1(b)). The ITZO (In₂O₃:SnO₂:ZnO = 2:4:2 at %) layer was deposited using an RF-magnetron sputter with Ar/O₂ ratio of 13/7.3 sccm. The power was 100 W, and the working pressure was 3 mTorr. The IGZO (In₂O₃:Ga₂O₃:ZnO = 1:1:2 at %) layer was deposited via RF-magnetron sputtering using Ar/O₂ ratio of 20/0.1 sccm. The power and working pressure were set at 150 W and 5 mTorr, respectively. To eliminate a potential interfacial issue during active layer fabrication, both layers were deposited in a single high vacuum chamber without vacuum breakdown. Source and drain electrodes were made of a 100 nm thick indium tin oxide (ITO). The ITO (In₂O₃:SnO₂ = 9:1 wt %) electrode was deposited using a DC-magnetron sputter in an Ar environment (20 sccm). The power and working pressure were 50 W and 5 mTorr, respectively. A shadow mask technique was used to pattern the source and drain electrodes with a channel width and length ratio of 800:200 μm. Finally, the devices were post-annealed in a tube furnace at 400 °C for 30 min. This step removes impurities and energetically unstable state atoms, thus improving film density, stoichiometry stability, and device performance.

2.2. Electrical characteristics of IGZO/ITZO BL-TFTs

Electrical properties of produced BL-TFTs were measured using a semiconductor-parameter analyzer (4200a-SCS, Keithley). The drain current (I_D) was measured using a gate voltage (V_G) sweep from −40 V to 40 V and a drain voltage (V_D) of 10 V. The field-effect mobility (μ_{FE}) of each device was determined using the following equation [34]: $\mu_{FE} = \frac{L}{WC_{OX}V_D g_{m,max}}$, where $g_{m,max}$ was the maximum transconductance ($\frac{\partial I_D}{\partial V_G}$), C_{OX} was the capacitance per unit area of the gate insulator, V_D was the drain voltage, and W and L were channel width and length, respectively. The device's threshold voltage (V_{th}) was approximated at the point

where the gate voltage was equal to the value given by the following equation: $I_D = W/L \times 1$ nA, where I_D was the drain current.

2.3. Defect analysis of IGZO/ITZO BL-TFTs

Spectroscopic ellipsometry was conducted using an RC2 (J.A. Woollam) instrument for thin film samples produced without the inclusion of ITO electrodes while maintaining the same BL structure. SE measurements were executed with a rotating analyzer system across a wavelength range of 193 nm to 1690 nm, employing incidence angles of 65°, 70°, and 75°. X-ray photoelectron spectroscopy (XPS) analysis was conducted utilizing a Versaprobe II system (ULVAC-PHI). The measurement was carried out with a pass energy set at 23.50 eV, employing a monochromatic Al-Kα ($h\nu = 1486.6$ eV) X-ray source with operating settings of 100 μm, 25 W, and 15 kV.

Quantitative defect analysis using PICTS was carried out following the procedure published elsewhere [35–37]. The experimental setup of PICTS is illustrated in Fig. 1(c). The IGZO/ITZO active layer was periodically irradiated with UV-LEDs (280 nm, 1 mW) with energy higher than the bandgap energy (E_g) for ~10 s using a pulse generator. To measure photo responses occurring only in the active BL IGZO/ITZO layer, the size of the UV-LED light was adjusted to a circular shape with a diameter of 5 mm and uniformly incident across the entire BL active layer. Operational principles underlying PICTS-based defect analysis can be summarized as follows (Fig. 1(d)): (1) Initially, when the LED pulse illuminates the IGZO/ITZO active BL of the device, electrons are excited from the valence band to the conduction band. This transition leads to a localized enhancement in conductivity, which is attributed to processes of generation and recombination of charge carriers; (2) upon the cessation of the LED pulse, there is an immediate reduction in photocurrent, which occurs as a result of rapid recombination of generated carriers. This swift decline reflects the dynamic nature of the charge carrier behavior in response to removal of the excitation source; (3) following this initial rapid decrease, a more gradual decline in photocurrent is observed. This slower decay is primarily due to a protracted discharge of carriers that have become trapped within defect states. The decay constant of de-trapped carriers can be derived from this photocurrent signal using the Laplace transform algorithm and the MATLAB software [16,35]. After obtaining the time constant at various temperatures, the concentration of defects along with their corresponding activation energies can be calculated according to procedures and equations outlined previously [35]. In this study, the temperature was controlled using liquid nitrogen and a peltier element, and photocurrents were recorded at 0.2 ms intervals for 10,000 s over a temperature range of 100 - 370 K.

3. Results and discussion

3.1. IV characteristics of BL-TFTs

Fig. 2(a) shows transfer characteristics of BL-TFTs with varied thicknesses of the ITZO layer. IGZO-only TFT (0 nm ITZO thickness) had a low μ_{FE} of 15.54 cm²/Vs. In contrast, ITZO-only TFT (40 nm ITZO thickness) demonstrated a high μ_{FE} of 43.44 cm²/Vs. When these two layers were combined, the mobility of IGZO/ITZO BL-TFTs was nearly doubled compared to the mobility of a single IGZO device (0 nm ITZO) with a minimum difference in values, which was around 36 cm²/Vs (Table 1). In a bottom-gate top-contact TFT architecture (Fig. 1(a)), the channel region is adjacent to the gate insulator. As a result, the large improvement in BL-TFT mobility could be mainly attributed to the ITZO layer. It was also noticed that these BL-TFTs had slightly lower mobility than the ITZO-only TFT (ITZO 40 nm). This could be possibly attributed to a change in electron energy barrier at the interface with the ITO electrode material. To validate this, valence band offsets (the difference between the Fermi level and the valence band maximum (VBM)) and bandgaps of ITO, ITZO, and IGZO were measured using XPS and SE,

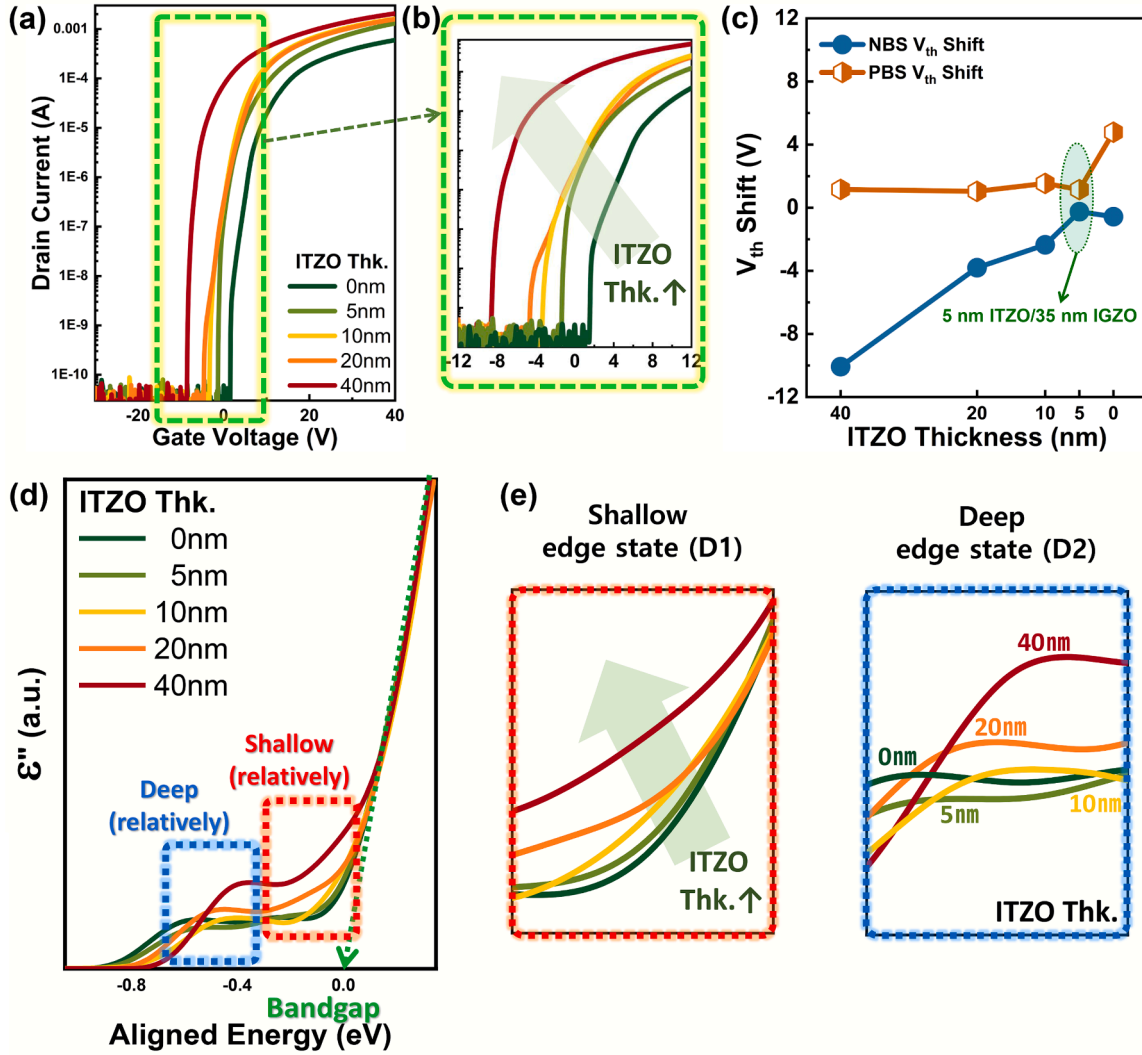


Fig. 2. (a, b) Transfer curves of IGZO/ITZO BL-TFTs. (c) NBS and PBS V_{th} shifts as a function of ITZO thickness. SE test results: (d) the imaginary part of the permittivity (ϵ'') spectra of BL-TFTs and (e) the magnification of band edge states (D1, D2) below the conduction band.

Table 1
ITZO thickness dependence of μ_{FE} and V_{th} .

ITZO thickness	0 nm	5 nm	10 nm	20 nm	40 nm
V_{th} (V)	2.70	-1.04	-2.63	-3.13	-8.23
μ_{FE} (cm^2/Vs)	15.54	36.00	36.37	36.97	43.44

respectively. As shown in **Fig. S1**, valence band offsets (ΔE_{vb}) of ITO, ITZO, and IGZO were 3.75, 2.95, and 2.99 eV, respectively. SE revealed that bandgaps (E_g) of ITO, ITZO, and IGZO were 3.67, 2.95, and 3.08 eV, respectively. Resulting electron energy barriers were then calculated as $(E_g - \Delta E_{vb})^{channel} - (E_g - \Delta E_{vb})^{electrode}$ [38]. The electron energy barrier was 0.11 eV at the ITZO-ITO interface and 0.17 eV at the IGZO-ITO interface. Therefore, the high resistance at the IGZO-ITO interface caused by electrons' relatively higher energy barriers accounted for the slightly decreased mobility found in the BL-TFTs compared to ITZO-only devices. The elevated resistance and high electron energy barrier observed at the IGZO-ITO interface is believed to be attributed to the reduced number of free carriers, resulting from a lower shallow donor-level defects in IGZO relative to ITZO, as elaborated in the subsequent section.

The IGZO-only TFT had a positive V_{th} of 2.70 V. However, the ITZO-only TFT had a negative V_{th} of -8.23 V. The high negative V_{th} in the

single ITZO TFT could be ascribed to its excessive carrier concentration. Interestingly, the V_{th} of the IGZO/ITZO BL-TFTs demonstrated a considerable positive shift when compared to the ITZO-only layer (**Table 1**). TFTs with high mobility and more positive V_{th} simultaneously are highly desirable. In the IGZO/ITZO BL-TFTs, the high-carrier ITZO channel improved device mobility, while the low-carrier IGZO layer lowered device V_{th} . Specifically, the 5 nm ITZO/35 nm IGZO BL-TFTs had a V_{th} near to zero while maintaining good mobility. **Fig. 2(b)** depicts an enlarged subthreshold zone that appears to move to the left as the thickness of the ITZO increases, indicating a negative shift in V_{th} . This effect is often linked to an increase in carrier concentration as the ITZO thickness increases [37,39]. The I_D in the turn-on state, which varies for each device, also shows differences in mobility [40]. Some devices exhibit a shoulder-shaped bend in the subthreshold region, indicating that defect states can affect device properties. Electrical parameters obtained from the transfer curve were summarized in **Table 1**. As can be seen, a decrease in ITZO layer thickness can lead to a decrease in device mobility and an increase in V_{th} . In particular, the mobility of the device with 0 nm ITZO (IGZO-only TFT) was much lower than that of the other devices.

The improved mobility in the ITZO/IGZO BL-TFTs is believed to be associated with the intrinsic high mobility ITZO, which is attributed to its lower effective electron mass of $0.26m_e$ [41], in contrast to IGZO's

effective mass of $0.34m_e$ [42]. In addition to their low electron effective mass, the increased mobility of ITZO/IGZO BL-TFTs was thought to be due to their high shallow donor defects, as discussed in Section 3.2.

The gate bias stress stability of BL-TFTs was evaluated to determine their long-term operational reliability. The change of V_{th} was recorded by applying 20 V and -20 V to the gate electrode for 2 h under positive gate bias stress (PBS) and NBS, respectively. Results are presented in Figs. S2(a, b). Generally, V_{th} was negatively and positively shifted under NBS and PBS, respectively. The positive shift in PBS was stable around 1 V in all BL-TFTs except for ITZO 0 nm (IGZO-only TFT), while the negative shift in NBS tended to increase with increasing ITZO thickness, with the ITZO 5 nm/IGZO 35 nm BL-TFT having the least V_{th} shift (Fig. 2 (c)). Thus, similar to the results obtained in the transfer characteristics, the device with ITZO 5 nm/IGZO 35 nm had the best PBS and NBS stability simultaneously.

3.2. Analysis and correlation of defects with BL-TFTs' performance

Qualitative defect analysis was performed using SE [43] to understand the underlying reason for the improved electrical performance and bias stability of the ITZO/IGZO BL-TFTs. Fig. 2(d) depicts each TFT's imaginary part of the permittivity (ϵ''), with an aligned bandgap to allow comparison of conduction band edge defect states. The spectra clearly revealed two unique states: D1, which is relatively close to the conduction band minimum (CBM), and D2, which is far from the CBM [44]. Hence, D1 states are found to correlate with carrier concentration, which in turn influences both the μ_{FE} and V_{th} . As shown in Fig. 2(e), the D1 state increased as the thickness of the ITZO layer increased, consistent with the μ_{FE} and V_{th} trend observed in transfer characteristics of the TFTs (see Table 1). Conversely, the D2 states are associated with bias stability, particularly NBS stability, as their location is relatively far from the CBM [35]. The D2 state increased in the following order: 40 nm > 20 nm > 10 nm > 0 nm > 5 nm, which corresponded to the magnitude of the negative V_{th} shift under NBS.

Defect analysis with SE cannot offer quantitative data on defects such as defect density and their corresponding energy levels. Additionally, SE has a narrow detection range (< 0.8 eV from the CBM) (see Fig. 2(d)). Hence, the correlation between defects and performance of the BL-TFTs cannot be fully and accurately demonstrated. To address this constraint, we examined defect states inside the bandgap precisely and quantitatively using PICTS as described in Section 2.3. As shown in Table S1 and

Fig. 3(a-e) PICTS analysis provided precise quantitative results of the defect density and their corresponding activation energies of the TFTs up to ~1.5 eV from the CBM. Notably, defect states at ~0.1 eV, identified as shallow donor levels [45,46], exhibited an increasing trend in the following sequence: 40 nm ($260.5 \times 10^{16} \text{ \#/cm}^3$) > 20 nm ($220.5 \times 10^{16} \text{ \#/cm}^3$) > 10 nm ($220.2 \times 10^{16} \text{ \#/cm}^3$) > 5 nm ($200.5 \times 10^{16} \text{ \#/cm}^3$) > 0 nm ($120.1 \times 10^{16} \text{ \#/cm}^3$). This pattern was consistent with the trends observed in the μ_{FE} and V_{th} curves, as illustrated in Fig. 4(a, b). Electrons trapped in the shallow donor levels could be easily de-trapped and transported to the conduction band by thermal energy at room temperature [47,48]. Thus, shallow donor defects function as charge carriers, thereby affecting both the μ_{FE} and V_{th} . A schematic representation illustrating the influence of shallow donor defects on the μ_{FE} and V_{th} is shown in Fig. 4(c). The single ITZO TFT with high shallow donor level densities demonstrates an abundance of charge carriers, resulting in both high μ_{FE} and more negative V_{th} . While a high μ_{FE} is advantageous, a significantly negative V_{th} is generally considered undesirable due to potential reliability issues. In contrast, the single IGZO TFT is characterized by a limited number of shallow donor-level defects, leading to a scarcity of free carriers, which results in low μ_{FE} and positive V_{th} . By integrating ITZO and IGZO into a single device, an optimal density of shallow donor defects is achieved, producing an optimum number of free carriers that are neither excessively high nor too low. This modulation of shallow donor defect density endows the BL-TFT devices with the ability to exhibit both high μ_{FE} and less negative V_{th} characteristics simultaneously, a feat that cannot be accomplished when the TFTs are utilized separately.

The PBS and NBS mechanism of AOS TFTs in the presence of defects can be explained as follows [49,50]. Under no bias, defects with energy levels above the E_F remain unoccupied, while those below the E_F are filled in accordance with Fermi-Dirac statistics. When PBS is applied, the energy band of the AOS channel adjacent to the gate dielectric experiences a downward bend, positioning the E_F near the CBM. This alteration leads to the previously unfilled defect states dropping below the E_F , where they subsequently capture electrons. Consequently, the V_{th} experiences a positive shift due to a deficiency in charge carriers. Conversely, under NBS conditions, the energy band of the AOS channel near the gate dielectric bends upward, bringing the E_F closer to the VBM. In this scenario, the filled defect states rise above the E_F , facilitating the release of free electrons, which results in a negative shift of the V_{th} during NBS. Hence, there exists a correlation between PBS stability and

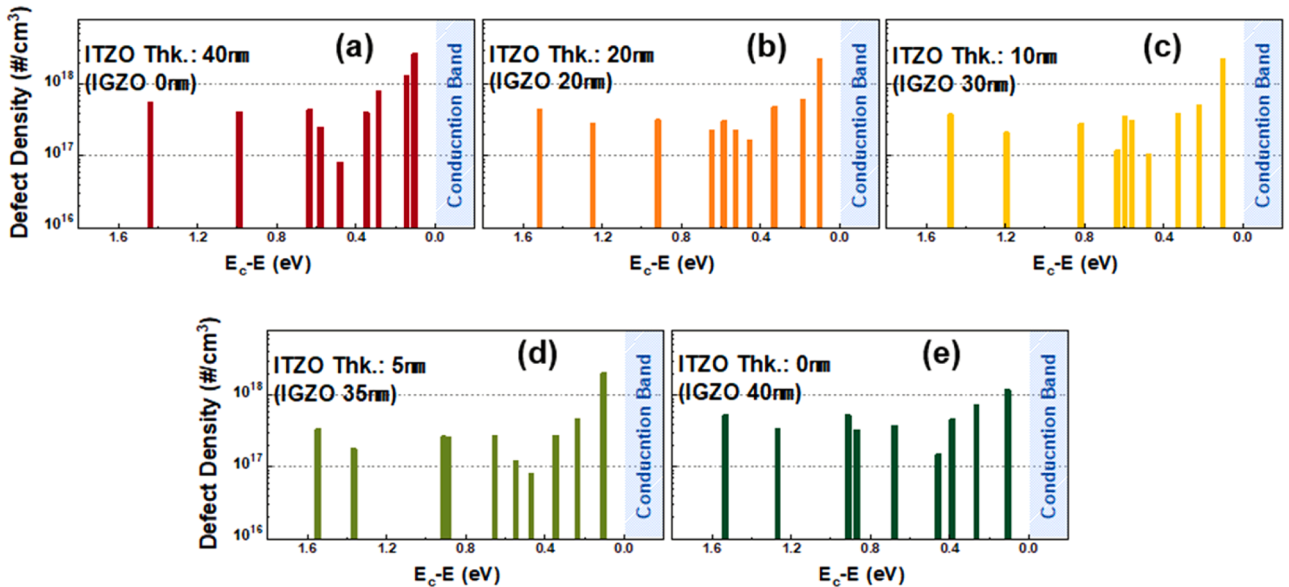


Fig. 3. Plots of the defect density with their corresponding activation energy levels ($E_a = E_c - E$) obtained using PICTS. (a) 40 nm ITZO/0 nm IGZO, (b) 20 nm ITZO/20 nm IGZO, (c) 10 nm ITZO/30 nm IGZO, (d) 5 nm ITZO/35 nm IGZO, and (e) 0 nm ITZO/40 nm IGZO BL-TFTs.

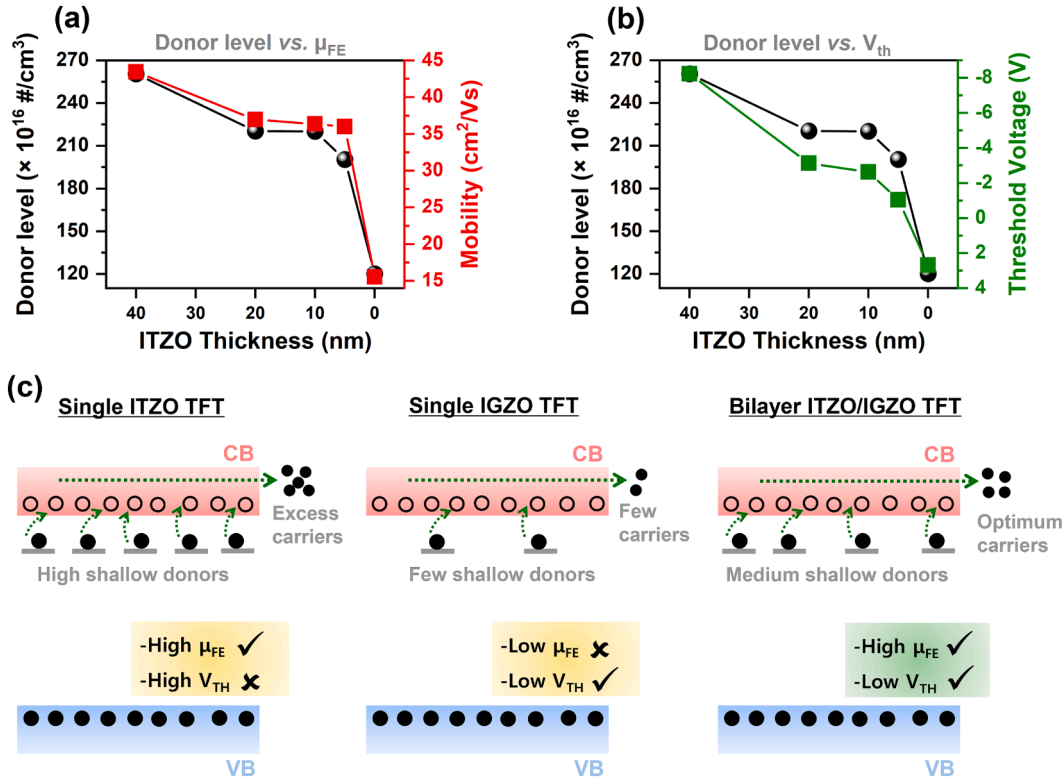


Fig. 4. Correlation of shallow donor defects with (a) μ_{FE} and (b) V_{th} of the TFTs. (c) Schematic representation illustrating the influence of shallow donor defects on the μ_{FE} and V_{th} . VB, valence band; CB, conduction band.

defects above the E_F and NBS stability and defects below the E_F . Yang et al. [51] established a statistical and quantitative framework that elucidates the relationship between defect formation energies, charge states, and the position of the E_F level. Their findings showed that defect states situated above the E_F act as acceptors (negatively charged), while those found below the E_F function as donors (positively charged). Similarly, Klein et al. [52] introduced a conceptual framework for understanding how defect charge states change depending on the E_F and predicted the electrical activity of defects and their role in charge compensation. Specifically, it defines that donors are neutral (occupied by electrons) when $E_F > E_D$ and become positively charged (unoccupied) when $E_F < E_D$; conversely, acceptors are neutral when $E_F < E_A$ and become negatively charged when $E_F > E_A$. In another study, it was confirmed that the alignment between the E_F of the semiconductor and the defect energy levels in the AOS layer directly affects the stability of transistors [53]. When E_F lies within the AOS's defect band, charge trapping occurs frequently, causing instability (e.g., hysteresis and V_{th} drift). Conversely, when E_F is positioned outside the defect band—either above or below—those traps are energetically inaccessible, leading to enhanced stability. These studies show that quantitatively assessing defects in AOS devices and examining their locations in relation to the E_F is crucial for understanding their effects on device reliability and performance. Therefore, we extracted functional data related to the defects, including defect density and defect energy level, and analyzed their distribution in relation to the E_F . While the defect data obtained from PICTS are district values (Fig. S3(a)), it is essential to recognize that, in practice, these defects are distributed stochastically, as illustrated in Fig. S3(b). In particular, the temperature-dependent electron distribution is generally known to follow the Fermi-Dirac probability distribution. In this context, certain defects, particularly those with activation energies close to the CBM, are likely to play a role in regions above the E_F . Hence, the probabilistic distribution of the defect states around the E_F was determined using the Fermi-Dirac equation:

$$f(E) = \frac{1}{1 + e^{(E_a - E_F)/k_B T}} \quad (1)$$

where E_a was the activation energy level based on the valence band maximum at 0 eV, E_F was the Fermi level energy level, k_B was the Boltzmann constant (8.62×10^{-5}), and T was the absolute temperature. By using a room temperature of 300 K and substituting the E_a from Table S1 and E_F of TFTs, defects above and below the E_F for each TFT device were determined. The E_F of single IGZO and single ITZO were obtained using SE and XPS (Fig. S1), and the values were 0.09 and 0.03 eV, respectively (Fig. 5(a)). The measurement of E_F for BL-TFTs was found to be impractical because of a restricted probing depth (< 5 nm) of XPS. Nonetheless, given the device architecture, the actual channel region in all BL devices is limited to the ITZO layer that is next to the gate insulator [34,54]. Thus, the E_F of ITZO can sufficiently represent the E_F of the BL-TFTs. The distribution of defects situated above and below the E_F for each activation energy, as determined by the Fermi-Dirac equation is provided in Tables S2 and Table S3, respectively. From the results, the defect states that play a role above the E_F are those with an energy level that is close to the CMB (specifically the first and second defect states). In contrast, the remaining defects exhibited minimal influence above the E_F , and they were all located below the E_F . The probability distribution of the first defect state at (~ 0.1 eV) for the single ITZO TFT and single IGZO TFT is schematically displayed in Figs. S3(c) and S3(d), respectively. For the IGZO-only TFT, 32 % of the defects were above E_F and 68 % were below it. Conversely, just 6 % of the defects in the ITZO-only TFT were found above the E_F , while 94 % were found below it. Additionally, the sum of all defects located both below and above the E_F is summarized in Table 2 and illustrated in Fig. 5(b, c).

As can be observed, the pattern of defect densities above and below the E_F was precisely correlated with PBS and NBS stability of the TFTs, respectively. Moreover, it was observed that the 5 nm ITZO/35 nm IGZO BL-TFT had low defects above and below the E_F simultaneously, explaining its best PBS and NBS stability among the other TFTs. Energy

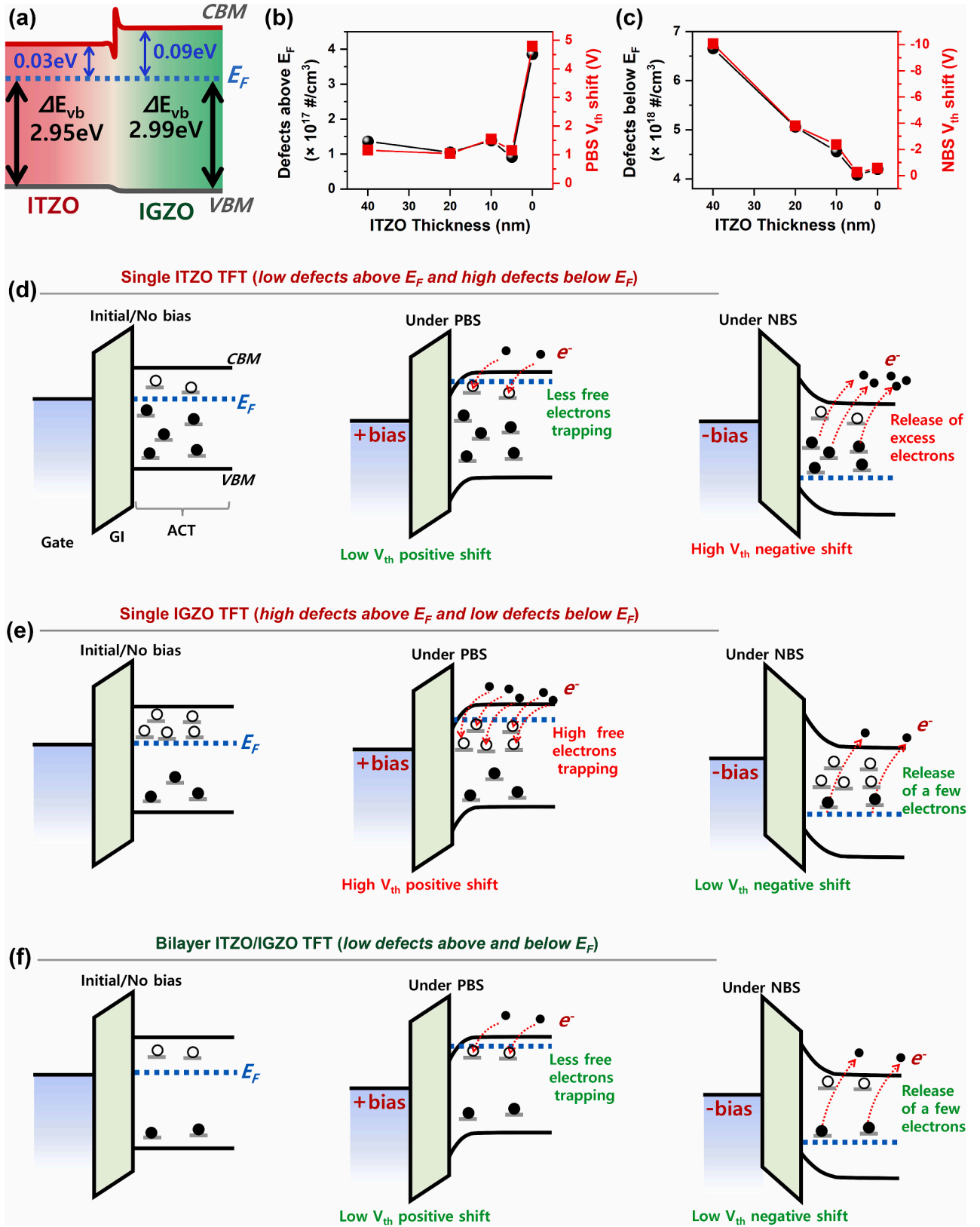


Fig. 5. (a) ITZO/IGZO BL-TFT band alignment, with E_F of ITZO and IGZO determined as ΔE_{vb} (from XPS) – E_g (from SE). Correlation of (b) PBS with defects above the E_F and (c) NBS with defects below E_F . Energy band diagrams illustrate the plausible PBS and NBS mechanisms of (d) single ITZO, (e) single IGZO, and (f) ITZO/IGZO BL-TFTs. VBM, valence band minimum; CBM, conduction band minimum; GI, gate insulator; active layer, ACT.

Table 2Probabilistic distribution of the defects below and above the E_F .

ITZO thickness (nm)	Defects above E_F ($\#/\text{cm}^3$)	Defects below E_F ($\#/\text{cm}^3$)
0	3.86×10^{17}	4.20×10^{18}
5	0.92×10^{17}	4.08×10^{18}
10	1.4×10^{17}	4.56×10^{18}
20	1.1×10^{17}	5.06×10^{18}
40	1.4×10^{17}	6.66×10^{18}

band diagrams that depict the plausible PBS and NBS mechanisms of the TFTs are provided in Fig. 5(d-f). The single ITZO TFT exhibits a low density of defects above the E_F and a high density below it, which accounts for its remarkable PBS performance and relatively poor NBS stability, in that order (Fig. 5(d)). Conversely, the IGZO-only TFT demonstrates a high defect density above the E_F and a low density below it, leading to its deteriorated PBS stability and excellent NBS stability, respectively (Fig. 5(e)). The BL-TFTs that integrate both ITZO and IGZO (particularly the device with a 5 nm ITZO layer and a 35 nm IGZO layer) showed a low defect density both below and above E_F , resulting in superior stability under both PBS and NBS (Fig. 5(f)). These findings underscore the importance of not only identifying individual defect states but also understanding their distribution relative to the E_F for improving their electrical performance and stability.

4. Conclusions

In conclusion, this study presented bilayer (BL) thin-film transistors (TFTs) composed of IGZO and ITZO, with variations in the thickness of the ITZO layer. The BL-TFT optimized with a thickness of 5 nm ITZO and 35 nm IGZO demonstrated remarkable characteristics, including a high mobility, a less negative threshold voltage, and an exceptional stability under both NBS and PBS. These favorable properties could not be achieved when the layers were employed separately, emphasizing the bilayer structure's synergistic impact. A detailed quantitative defect analysis was performed using photoinduced transient spectroscopy. Integrating ITZO and IGZO into a single device resulted in an optimum number of shallow donor defects that are neither excessively high nor too low, thereby achieving both high μ_{FE} and less negative V_{th} characteristics simultaneously. Furthermore, the outstanding stability of the 5 nm ITZO/35 nm IGZO BL-TFT under both PBS and NBS was attributed to its lower defect densities above and below the Fermi level, respectively. In contrast, diminished NBS and PBS stabilities observed in single-layer ITZO and IGZO TFTs were linked to their elevated defect densities below and above the Fermi level, in that order. Findings from this study are expected to contribute significantly to the advancement of semiconductor devices in various application fields.

CRediT authorship contribution statement

Teklebrahan Gebrekrstos Weldemhret: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Dong-Joon Yi:** Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kwangsik Jeong:** Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Kwun-Bum Chung:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.surfin.2025.106870.

Data availability

Data will be made available on request.

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