

Front channel carrier confinement enabled by interface-engineered gradient InZnO TFTs via PEALD

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ABSTRACT

Achieving both high mobility and bias stress stability remains challenging for oxide semiconductor thin-film transistors (oxide TFTs) owing to the intrinsic trade-off associated with oxygen vacancy-related carrier generation. To overcome this limitation, this work demonstrates a plasma enhanced atomic layer deposition (PEALD) processed three-layer gradient InZnO (IZO) channel (In:Zn=2:1/3:1/5:1, each 5 nm) with engineered interfacial band alignment. XPS, UPS, SE, and TCAD analyses reveal that the compositional gradient systematically modulates the oxygen vacancy distribution and electronic structure of the stacked IZO layers. The resulting interfacial band alignment and simulated electron concentration profiles indicate the formation of a dominant conduction path near the front channel region, resulting in enhanced interface-controlled carrier transport. Furthermore, Debye length (L_D) analysis shows that the effective conduction depth is limited to the front channel region, whereas excessive channel thickness contributes to defect-related bulk conduction and degrades device performance. The effectiveness of the proposed interface-engineered gradient structure was demonstrated through comparative analyses of single composition IZO films and gradient channel TFTs. The optimized gradient channel TFT exhibited a high field-effect mobility exceeding $54 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, a threshold voltage (V_{th}) of 0 V, an ultra-low subthreshold swing (S.S) of 0.079 V dec^{-1} , and improved positive bias temperature stress (PBTs) stability compared to single layer IZO TFTs. These findings highlight the importance of interface engineering and carrier distribution control in high-performance oxide semiconductor TFTs.

1. Introduction

In recent years, oxide semiconductor thin-film transistors (oxide TFTs) have attracted considerable attention owing to their low leakage current, low subthreshold swing (S.S) values, and relatively low processing temperatures (typically below 400°C) [1]. Their excellent electronic properties render extensive usability of oxide TFTs in display technologies, additionally, their incorporation has been increasingly considered in the design of emerging memory and three-dimensional (3D) integrated electronic devices [2]. Furthermore, with an increased demand for high-performance integrated devices, oxide TFTs are expected to play a crucial role in next-generation electronic and advanced display technologies. However, their application to next-generation memory devices, including dynamic random-access memory (DRAM) and NAND flash memory, requires improvements to carrier mobility and device stability [3]. Such enhancements are particularly important for

next-generation semiconductor architectures, which has been extensively scaled down to achieve higher performance.

Several studies have focused on increasing the field-effect mobility while achieving precise control and realizing thin sizes, particularly for integration into 3D device architectures [4,5]. A wide range of high-mobility oxide semiconductor systems has been investigated, including InO_x -based oxide semiconductors, such as InZnO (IZO), InSnZnO (ITZO), and InGaZnO (IGZO) [6–9]. Among them, IZO has exhibited considerable potential because of its simple lattice structure, and its conduction mechanism is mainly governed by In 5s orbitals, resulting in relatively high mobility [10]. These characteristics make IZO a promising material for the development and optimization of advanced electronic devices.

The conduction mechanism in oxide TFTs is closely associated with oxygen vacancy states (V_O), and the concentration of oxygen vacancies in oxide semiconductors can be effectively modulated by precisely

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controlling the cation ratio [11–14]. For example, In-rich oxide semiconductors inherently exhibit a higher density of oxygen vacancies owing to their relatively weak In–O bond strength and the large spatial extension of the In 5s orbital, which reduces the oxygen vacancy formation energy [15]. At moderate concentrations, oxygen vacancies act as shallow donor states, thereby enhancing the carrier concentration and leading to improved field-effect mobility [16]. However, the formation of excessive oxygen vacancies introduces localized trap states, leading to a negative shift in the threshold voltage (V_{th}) and degraded device performance [17]. Therefore, further research is needed to achieve both high mobility and near-zero V_{th} through the intrinsic control of the oxygen vacancy concentration.

Atomic layer deposition (ALD), which enables highly controlled atomic-scale film growth, is suitable for implementing such strategies [18,19]. Unlike conventional methods such as physical vapor deposition (PVD) or sputtering, ALD, particularly plasma enhanced atomic layer deposition (PEALD) offers excellent step coverage and precise control of the film thickness and chemical composition owing to its self-limiting surface reactions and precise interface formation capability [20]. PEALD employs high-density plasma to activate the surface chemistry, leading to efficient ligand impurity removal, precise thickness control, and low temperatures. These advantages enable ALD to facilitate the fabrication of high-mobility TFTs with high film densities and low defect concentrations [21]. For the fabrication of multilayer channel structures, such as dual channel and gradient channel TFTs, PEALD offers significant advantages over conventional sputtering [22]. PEALD enables atomic layer level control of both composition and thickness, allowing systematic engineering of the oxygen vacancy distribution and electronic band structure throughout the channel depth. Such precise control is particularly advantageous for interface engineering because the electronic structure, band alignment, and carrier distribution can be intentionally modulated at each heterointerface [23].

In multilayer channel TFTs, the front and back channels play distinct roles in determining the electrical characteristics of the device [24]. As the gate electric field decays with increasing distance from the gate dielectric, the electron density correspondingly decreases. Consequently, the front channel, which is located closer to the gate dielectric, plays a key role in determining the field-effect mobility [25]. In contrast, V_{th} is dominated by the effective carrier concentration and integrated charge density of the entire channel. Consequently, the back channel plays a key role in regulating the carrier density (N_e) and V_O , thereby suppressing excessive carrier accumulation [26]. However, few studies have examined in detail the origin and mechanisms of the heterostructure and gradient channel layers, as the effective conduction region and dominant transport behavior vary with the gate bias. In addition, depth-resolved electrical characterization of the channel remains experimentally challenging.

This study proposes a novel three-layer gradient IZO channel architecture deposited by PEALD. The proposed architecture consists of a front channel layer with an In:Zn ratio of 5:1 (5:1 IZO), middle channel layer with an In:Zn ratio of 3:1 (3:1 IZO), and back channel layer with an In:Zn ratio of 2:1 (2:1 IZO), all of which are sequentially stacked from top to bottom. Unlike conventional dual channel architectures consisting of a mobility layer and a stability layer separated by a single heterointerface, the proposed three-layer gradient channel was designed to establish a gradual transition in carrier concentration and electronic band structure through multiple engineered heterointerfaces [27]. This design allows the advantages of each IZO layer to be strategically positioned within the channel, promoting carrier transport in the front channel region while maintaining carrier density control in the back channel region. Accordingly, the proposed channel functions as an interface-engineered gradient structure, where the vertical distribution of oxygen vacancies and the resulting interfacial band alignment induce carrier confinement in the front channel region and enhanced electrical performance [28,29]. To examine the influence of engineered heterointerfaces on carrier transport, the gradient channel was designed while

maintaining the same overall cation composition as a single layer 3:1 IZO channel. Furthermore, Debye length (L_D) analysis combined with capacitance–voltage (C–V) measurements is employed to identify the effective conduction depth and evaluate the influence of gate-field screening on carrier transport within the gradient channel. The results demonstrate that the engineered heterointerfaces localize the dominant conduction path within the front channel region while regulating carrier density in the back channel region. These findings provide insight into the relationship between vertical cation distribution, interfacial electronic structure, and carrier transport behavior in oxide semiconductor TFTs.

2. Experimental details

2.1. Thin film deposition

IZO single layer thin-films (2:1, 3:1, and 5:1 IZO) and gradient IZO films were deposited via PEALD using [3-(dimethylamino)propyl] dimethylindium (DADI) as the indium precursor and diethylzinc (DEZ) as the zinc precursor at a deposition temperature of 200°C. During the deposition process, oxygen plasma was used as the oxygen source with a radio-frequency (RF) plasma power of 100 W. The PEALD process consisted of the following sequence: [precursor dosing – Ar purge – reactant exposure – Ar purge]. In_2O_3 was deposited using the sequence [DADI (1 s) – purge (10 s) – O_2 (1 s) – oxygen plasma (2 s) – purge (10 s)], and the ZnO sequence was [DEZ (0.1 s) – purge (10 s) – O_2 (1 s) – oxygen plasma (2 s) – purge (10 s)]. The supercycle of the IZO thin-film deposition consisted of [$\text{In}_2\text{O}_3 \times n$ cycles – ZnO $\times 1$ cycle], where $n = 2, 3$, and 5, corresponding to 2:1, 3:1, and 5:1 IZO, respectively. Gradient IZO thin-films with identical thicknesses were deposited by stacking 2:1, 3:1, and 5:1 IZO layers.

2.2. Thin film characterization

The chemical compositions and V_O value of the IZO films were analyzed using X-ray photoelectron spectroscopy (XPS, Nexa G2, Thermo Fisher Scientific Inc.). XPS measurements were performed using a monochromatic Al K α radiation source (1486.6 eV). Prior to data acquisition, the sample surfaces were sputtered using Ar $^+$ ion bombardment at 8 keV for 10 s to remove the native surface oxide layer. Ultraviolet photoelectron spectroscopy (UPS) was performed using the same analytical instrument to investigate the electronic structures of the films. A He I ultraviolet source (21.2 eV) with an applied bias of –5 eV was employed, and Ar $^+$ ion sputtering conditions identical to those used for XPS were applied prior to UPS measurements. The thicknesses and optical bandgap values of the thin films were measured using spectroscopic ellipsometry (SE, M2000D, J. A. Woollam Co.). The crystal phases of the thin-films were characterized using X-ray diffraction (XRD, Ultima IV, Rigaku Co.).

2.3. Device fabrication and evaluation

Top-gate bottom-contact (TGBC) single layer IZO and gradient channel TFTs were fabricated on glass substrates coated with a 150 nm-thick InSnO (ITO) layer, which functioned as both the source and drain electrodes. A 15 nm-thick IZO active layer was deposited via PEALD using DADI and DEZ as indium and zinc precursors, respectively. The channel width (W) and length (L) of the active layer were both 20 μm . A 10 nm-thick Al_2O_3 protective layer (PL) was deposited by PEALD to prevent photoresist contamination and chemical etchant damage from active layers, thereby suppressing the negative shift of V_{th} . A 20 nm-thick Al_2O_3 layer was deposited as the gate insulator (GI) by performing PEALD at 200 °C using trimethylaluminum (TMA) as the aluminum precursor. Finally, an 80 nm-thick Mo layer was deposited via direct current (DC) sputtering to form the gate electrode. Each layer in the TFT fabrication process was patterned using photolithography and wet

etching after the deposition. After fabrication, the single layer IZO TFTs and the gradient IZO channel TFTs were annealed at 290°C for 2 h for the device optimization under the same conditions.

The electrical characteristics of the fabricated devices were evaluated using a semiconductor parameter analyzer (HP4156A) at room temperature under dark conditions. The transfer curves were measured by sweeping the gate voltage (V_G) from -5 to 5 V while setting the drain voltage (V_D) at 0.1 and 4 V. The S.S was calculated from the transfer curves using $S.S = dV_G / d\log I_D$ in the subthreshold region, where I_D denotes the drain current. The field-effect mobility was extracted from the maximum transconductance ($g_{m,max}$) at a V_D of 0.1 V using $\mu_{FE} = (L / WC_i V_D) g_m$, where C_i is the GI capacitance per unit area [30]. V_{th} was defined using the constant-current method as the value of V_G at which I_D reached 10 nA. Positive bias temperature stress (PBTs) stability tests were performed at 60°C for 3600 s under a gate electric field of 1 MV cm^{-1} . Negative bias illumination stress (NBIS) stability tests were performed under a gate electric field of -1 MV cm^{-1} with light illumination.

3. Results and discussions

Fig. 1a illustrates the schematic structure of the gradient IZO channel TFTs, and Fig. 1b,c show the corresponding 15 nm gradient layer configurations composed of 2:1, 3:1, and 5:1 IZO. The IZO PEALD supercycles for the 2:1, 3:1, and 5:1 composition comprised 16, 14, and 10 cycles, respectively, resulting in an overall gradient channel of 3:1 IZO (124:30 in the total cation cycles). A channel with 5:1 IZO at the front channel and 2:1 IZO at the back channel is defined as the gradient forward structure, while the reversed configuration is defined as the gradient backward structure. The gradient forward TFT was designed to achieve high device performance, whereas the gradient backward TFT was configured to examine the distinct roles of the front and back channels arising from the electric field concentration [17]. The representative transfer curves of the gradient channel devices are shown in Fig. 2, and the extracted electrical parameters are listed in Table 1. In the gradient forward TFT, the In-rich 5:1 IZO layer functions as the front channel of 54.48 $cm^2 V^{-1} s^{-1}$, and negligible hysteresis of 0.1 V. This small hysteresis suggests that the V_O concentration was effectively optimized to provide high carrier mobility while minimizing charge-trapping effects [31]. In this structure, the In-rich 5:1 IZO layer was intentionally positioned near the gate insulator to enhance electron transport, while the Zn-rich back channel was employed to suppress excessive V_O formation. In contrast, the gradient backward TFT, with a Zn-rich 2:1 IZO front channel and an In-rich 5:1 IZO back channel, exhibited degraded performance, and was characterized by a higher S.S value of 0.124 V dec^{-1} , a V_{th} of -0.2 V, a relatively lower mobility of 38.21 $cm^2 V^{-1} s^{-1}$, and larger hysteresis of 0.5 V, which not improve even after additional thermal annealing, as shown in Fig. S1. In the backward structure, the In-rich 5:1 IZO layer positioned at the back channel induced excessive back channel conduction, resulting in deteriorated electrical characteristics. These results indicate that the front and back

gradient layers successfully contributed to the modulation of the electrical parameters, demonstrating that the electrical performance can be effectively improved through the gradient channel structure. Fig. 3a,b and Fig. 3c,d respectively present the PBTs and NBIS stability results of the gradient channel TFTs. Under PBTs, ionized oxygen vacancies (V_O^+ or $V_O^{\bullet}$) can capture free electrons, and it is widely regarded as the primary mechanism governing PBTs-induced instability [32]. Generally, PBTs stability can be improved by incorporating carrier suppressors, such as Ga, or passivating species, such as H.

[33,34]. As IZO which is deposited via PEALD does not utilize these stabilization strategies, fabricated devices typically exhibit moderate stability. Under NBIS, the oxygen vacancies are photoionized by light illumination, generating V_O^{2+} and free electrons, which induce a negative threshold voltage shift and instability [35]. Nevertheless, all devices show excellent NBIS stability due to the TGBC structure, which effectively shields the channel from incident light. Compared to the gradient forward TFT, the gradient backward TFT exhibited poorer PBTs and NBIS stability owing to the pronounced hump behavior originating from the In-rich 5:1 IZO back channel with a high concentration of V_O -related defects [36]. Since NBIS is applied under simultaneous negative gate bias and light illumination, the instability is closely associated with photo-induced defect generation involving oxygen vacancies [37]. Consequently, the In-rich back channel induces the formation of additional photo-induced defects, leading to more severe hump behavior and degraded electrical characteristics. These results indicate that the back channel plays a dominant role in determining the stability of the gradient channel TFTs. Therefore, these results demonstrate that the spatial distribution and compositional arrangement of the channel are critical factors that determine the mobility and stability of the oxide TFTs.

To investigate the electrical transport mechanisms in the gradient channel, comprehensive chemical, structural, electrical, and optical analyses were performed on 2:1, 3:1, and 5:1 IZO single layer thin-films. Table 2 lists the chemical compositions of the films with varying In:Zn ratios based on the XPS analysis results. As the In ALD cycle ratio increased, the measured In:Zn atomic ratio increased from 0.44:1 to 0.87:1, confirming that the supercycle design effectively modulates the film composition. Fig. 4 shows the O 1s core-level spectra of IZO thin-films with different cation ratios.

The O 1s spectra were deconvoluted into three different subpeaks centered at 529.9, 531.1, and 532.2 eV, corresponding to lattice metal-oxygen bonding (M-O), V_O -related states, and hydroxyl-related species (M-OH), respectively [12,13]. The relative contributions of each bonding state were calculated from the integrated areas of the corresponding core-level spectra, and the peak-fitting parameters are listed in Table S1. As the In:Zn ratio increased, the relative contribution of the V_O -related states increased from 29% for the 2:1 IZO film to 37% for the 5:1 IZO film, accompanied by a gradual reduction in the M-OH component. This trend indicates that increasing the In content promotes the formation of V_O in the IZO films. Previous studies have reported that

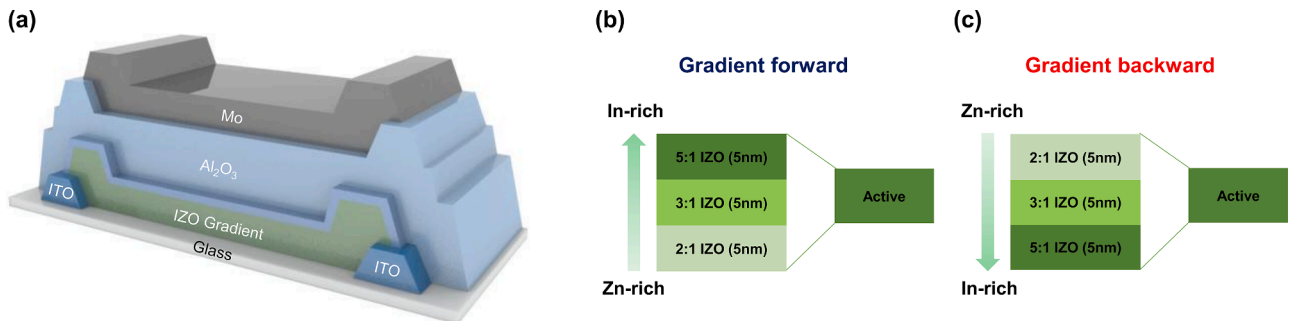


Fig. 1. Device schematic diagram of (a) the TGBC oxide TFT with an IZO gradient channel, and the corresponding (b) gradient forward and (c) gradient backward configuration, consisting of 2:1, 3:1, 5:1 IZO.

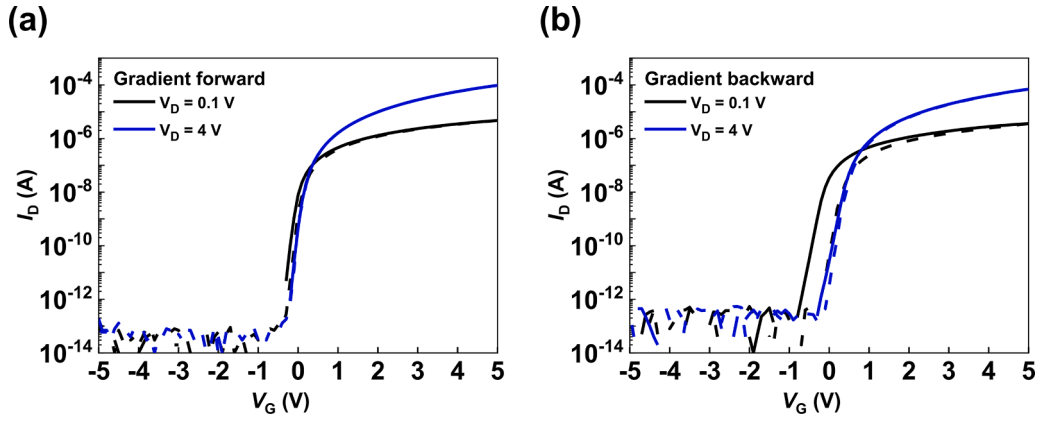


Fig. 2. Transfer curves of oxide TFTs annealed at 290°C: (a) gradient forward and (b) gradient backward channel.

Table 1

The average and standard deviation values of electrical parameters for gradient forward and gradient backward IZO channel TFTs obtained from 10 devices.

Device	Gradient forward	Gradient Backward
S.S [V dec ⁻¹]	0.079 (±0.005)	0.124 (±0.013)
V _{th} [V]	0 (±0.0)	-0.2 (±0.0)
μ _{FE} [cm ² V ⁻¹ s ⁻¹]	54.48 (±0.57)	38.21 (±0.87)
Hysteresis [V]	0.1 (±0.00)	0.5 (±0.03)

In-rich oxide semiconductors exhibit a lower V_O formation energy and a higher tendency to generate donor-related defects, resulting in an increased concentration of V_O associated states [38]. Furthermore, the relatively weak In–O bond strength facilitates oxygen release, making the formation of V_O energetically more favorable as the In content increases. Consequently, the V_O content increases with increasing In concentration, which is consistent with the poorer stability observed in the gradient backward TFT [39]. These findings demonstrate that the defect characteristics of IZO films can be effectively modulated through compositional engineering and play a critical role in determining the electrical transport behavior of gradient channel TFTs.

UPS and SE analyses were performed to investigate the electronic structure of the IZO thin-films and to determine the energy band diagram of the gradient channel, as illustrated in Fig. 5. Fig. 5a,b present the valence band region and secondary electron cutoff values obtained from the UPS measurements. The Fermi level position relative to the valence band maximum (E_F – E_V) and the work function (Φ) were determined based on these results. The extracted E_F – E_V values were nearly identical for all compositions (~2.90 eV), indicating similar valence band alignment among the films. In contrast, the work function gradually increased from 4.00 eV (2:1 IZO) to 4.04 eV (5:1 IZO) with increasing In content, indicating composition dependent modulation of the electronic structure. The optical bandgap (E_g^{opt}) values, shown in Fig. 5c, were extracted from Tauc plots by performing linear

extrapolation of the (αhν)² versus hν curves to the energy axis. The E_g^{opt} value decreased from 3.07 eV (2:1 IZO) to 2.99 eV (5:1 IZO) as the In ratio increased. This reduction in E_g^{opt} is consistent with the narrower bandgap of In₂O₃ (~2.8 eV) compared with ZnO (~3.3 eV), indicating that incorporating a greater amount of In shifts the electronic structure toward In₂O₃-like characteristics [40]. As the In ratio increases, the conduction band becomes increasingly dominated by the spatially extended In 5s orbitals, resulting in a downward shift of the conduction band minimum (CBM) [41]. Furthermore, the increased concentration of V_O-related donor states in the In-rich IZO films introduces defect states near the conduction band edge [42]. Consequently, the effective optical bandgap gradually decreases with increasing In concentration.

Based on these measured values, the energy band diagram before contact is as shown in Fig. S2. Upon contact with the individual layers, Fermi level alignment occurs, leading to slight band bending and the formation of conduction band offsets at the interfaces, as shown in Fig. 5d,e. The carrier transport behavior of the gradient channel TFTs can be understood from the energy band alignment. The extracted band structure indicates that the 5:1 IZO layer exhibits the lowest CBM among the composition layers, whereas the 2:1 IZO layer exhibits the highest CBM. Therefore, the 5:1 IZO layer acts as an electron rich transport layer, while the 2:1 IZO layer provides low amount of carrier and improved electrical stability. Meanwhile, the intermediate 3:1 IZO layer smoothly connects the electronic structures of the 5:1 and 2:1 IZO layers, enabling gradual band bending rather than abrupt band discontinuities at the interfaces. The resulting band alignment and conduction band

Table 2

Cation atomic compositions of PEALD-grown 2:1, 3:1, 5:1 IZO thin films.

In: Zn ratio	Indium [%]	Zinc [%]	Oxygen [%]	In:Zn at% ratio
2:1	14.0	31.9	54.1	0.44: 1
3:1	16.7	28.4	54.9	0.59: 1
5:1	20.7	23.7	55.6	0.87: 1

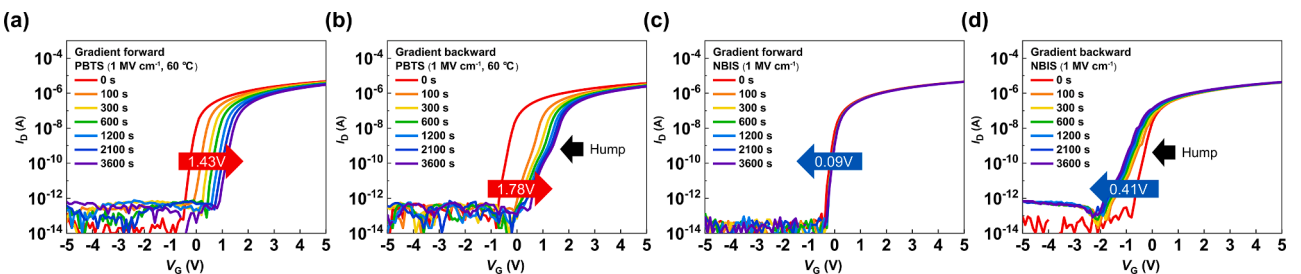


Fig. 3. PBTs stability results of (a) gradient forward and (b) gradient backward IZO channel TFTs and NBIS stability results of (c) gradient forward and (d) gradient backward IZO channel TFTs.

IZO XPS O 1s

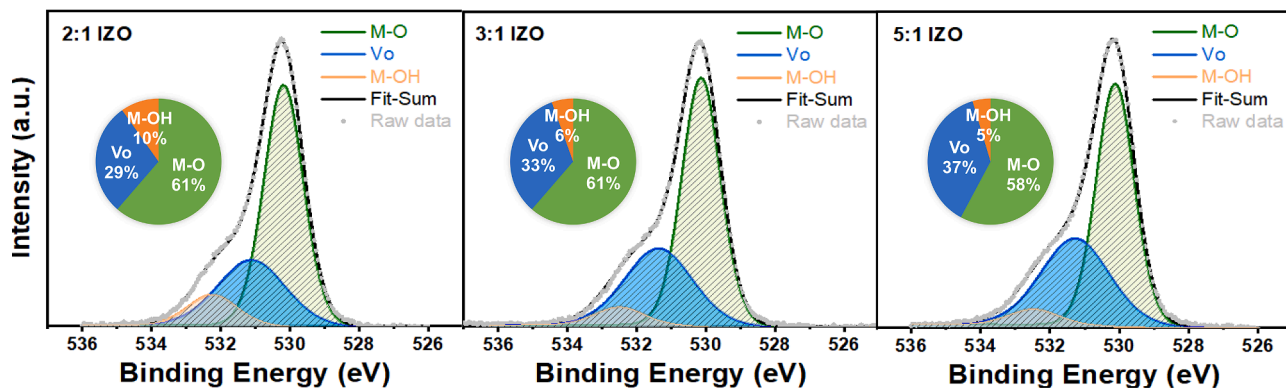


Fig. 4. XPS O 1s spectra of 2:1, 3:1, 5:1 IZO thin films, deconvoluted into three peaks corresponding to M-O, oxygen vacancy (V_o), M-OH components.

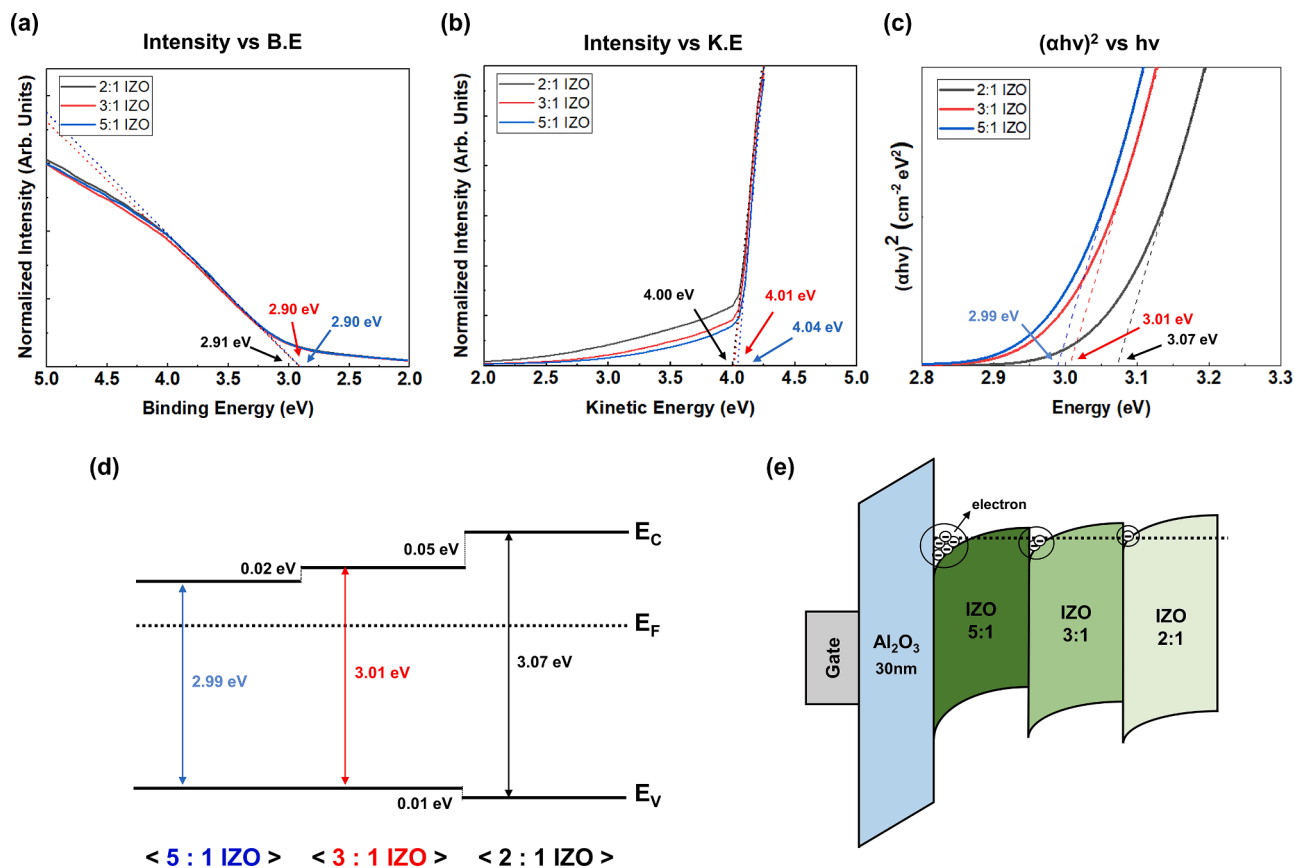


Fig. 5. (a) Fermi level position relative to the valence band maximum ($E_F - E_{vbm}$), (b) work function, and (c) Optical bandgap ($E_{g, opt}^0$) tauc plot of single 2:1, 3:1, 5:1 IZO thin films. (d) Schematic energy band diagram with Fermi level alignment. (e) Proposed energy band diagram of the gradient IZO TFT with front-channel-dominated carrier transport induced by vertical band alignment.

offsets at equilibrium promote electron accumulation near the front channel region and facilitate the formation of a dominant conduction path, contributing to the enhanced electrical performance of gradient channel TFT devices [43].

To examine whether the gradient structure induced any phase changes, XRD analysis was performed, as shown in Fig. S3 [44]. The XRD patterns exhibited no distinct diffraction peaks, confirming that all films retained amorphous structures. These results indicate that the introduction of the gradient channel structure does not induce crystallization of the IZO thin-films, and the enhanced electrical characteristics cannot be attributed to the crystallinity of the IZO films.

Single layer IZO TFTs with different cation compositions were fabricated to evaluate their intrinsic electrical characteristics. The transfer characteristics are shown in Fig. 6, and the corresponding electrical parameters are listed in Table 3. The 2:1 IZO TFT exhibited a relatively low field-effect mobility of $22.89 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and a positive V_{th} of.

0.3 V, with a PBTS-induced shift of 1.44 V, this indicates relatively stable but limited carrier transport. The 3:1 IZO TFT showed a moderate mobility of $36.15 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, a near-zero V_{th} , and a larger PBTS shift of 1.76 V, accompanied by a hysteresis of 0.3 V. These results indicate the intrinsic trade-off between carrier transport performance and stability.

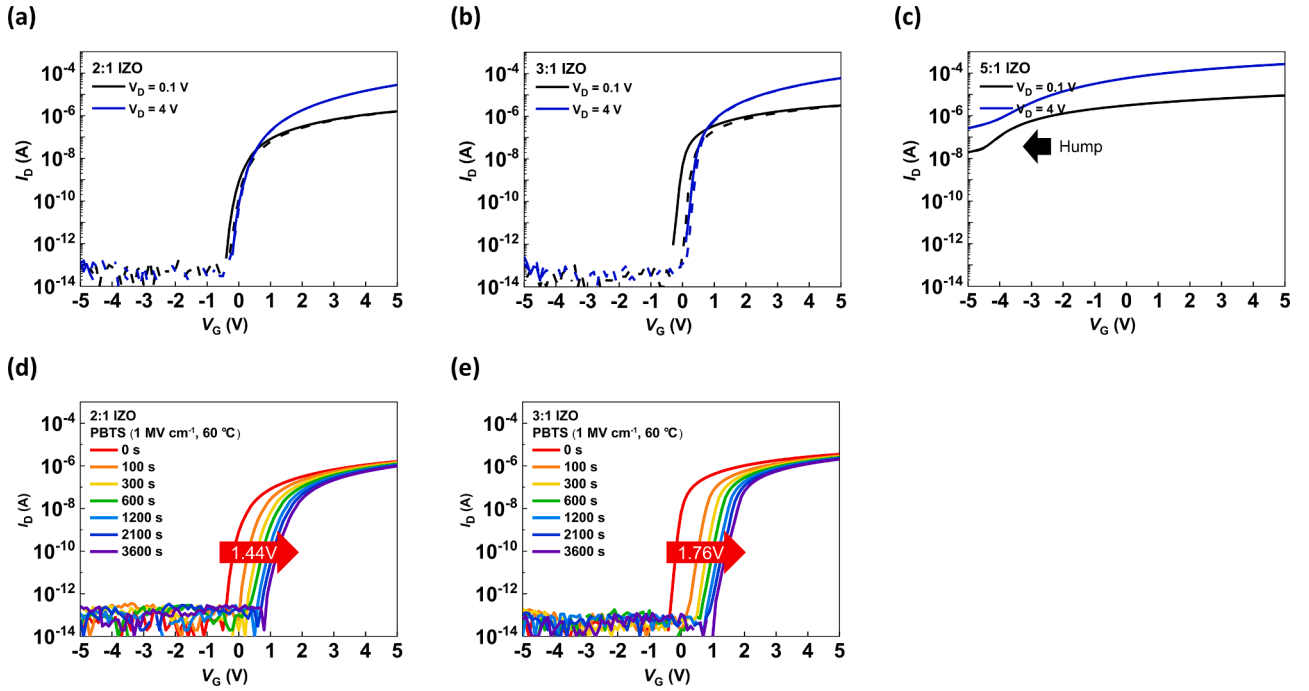


Fig. 6. Transfer curves of oxide TFTs annealed at 290°C: (a) 2:1 IZO, (b) 3:1 IZO, and (c) 5:1 IZO. PBTS results of oxide TFTs annealed at 290°C: (d) 2:1 IZO, and (e) 3:1 IZO.

Table 3

The average and standard deviation values of electrical parameters for the single layer IZO TFTs obtained from 10 devices at 290°C.

Device	2:1 IZO	3:1 IZO	5:1 IZO
S.S [V dec ⁻¹]	0.104 (±0.007)	0.065 (±0.007)	
V _{th} [V]	0.3 (±0.0)	0.0 (±0.0)	conductive
μ _{FE} [cm ² V ⁻¹ s ⁻¹]	22.89 (±0.47)	36.15 (±1.18)	
Hysteresis [V]	0.1 (±0.05)	0.3 (±0.03)	

Conversely, the 5:1 IZO TFT exhibited highly conductive and hump behavior with a large drain current, but it did not exhibit proper switching characteristics owing to an excessive carrier concentration. These composition dependent electrical characteristics were further supported by the XPS analysis results. The In-rich composition enhanced carrier transport with higher mobility, while simultaneously causing a negative shift in the threshold voltage and degraded PBTS stability due to the increased formation of V_O [45]. These results reveal that each single composition layer exhibits distinct electrical advantages and limitations: the In-rich layer provides enhanced carrier transport, whereas the Zn-rich layer offers improved V_{th} control and suppresses excessive conduction. Consequently, the gradient channel structure simultaneously achieved high mobility and an improved switching stability without degrading other key electrical parameters, demonstrating the effectiveness of compositional band engineering.

Furthermore, TCAD simulations based on the experimentally extracted energy band parameters (summarized in Table S2) revealed that the gradient channel exhibits a higher electron concentration on front channel compared with the 3:1 IZO, as shown in Fig. S4 [46]. The engineered band alignment promotes electron accumulation toward the front channel region, resulting in a dominant conduction path within the 5:1 IZO layer. In contrast, the electron concentration becomes more broadly distributed throughout the channel in the single layer structure. These results indicate that the enhanced electrical performance originates from the engineered vertical cation distribution and interfacial band alignment, which effectively localize carrier transport within the front channel region while maintaining carrier density control in the

back channel region.

In conventional single layer oxide TFTs, increasing the channel layer thickness generally enhances the field-effect mobility owing to the increased contribution of V_O related carriers [47]. From the perspective of percolation conduction mechanism, thicker oxide channels facilitate the formation of energetically favorable conduction paths, thereby improving carrier transport efficiency and enhancing mobility [47]. To determine the optimal channel thickness and effective conduction depth, gradient channel TFTs with thicknesses of 5, 15, 30, and 45 nm were evaluated, as shown in.

Fig. 7. As the channel layer thickness increased from 5 to 45 nm, the V_{th} gradually shifted toward more negative values. Mobility increased significantly from 5 to 15 nm, reaching a maximum value at 15 nm, and then gradually decreased with a further increase in thickness. The relatively low S.S observed in thinner channels can be attributed to stronger control of the gate field, whereas thicker channels promote increased bulk conduction and trap participation, resulting in degraded switching characteristics [48,49]. In addition, the PBTS stability improved with increasing thickness owing to the intrinsic characteristics of the oxide semiconductor and oxygen vacancies, as shown in Fig. S5 [50]. These results indicate that an optimal thickness exists in the gradient channel structure, where carrier transport is enhanced while maintaining an acceptable switching behavior. However, further increasing the channel thickness enhances trap-assisted bulk conduction and increases the contribution of defect-related transport pathways, thereby degrading the device performance.

To investigate the origin of this thickness-dependent electrical behavior and identify the effective conduction region within the gradient channel, C–V analysis was performed to extract the ionized donor concentration (N_d) and L_D. An effective approach for estimating the conduction depth is to evaluate the L_D [51]. The entire L_D of the oxide semiconductor channel can be expressed as follows:

$$L_D = \sqrt{\frac{\epsilon_{IZO}\epsilon_0 k_B T}{q^2 N_d}} \quad (1)$$

where ϵ_{IZO} is the dielectric constant of the IZO. As the high-frequency C–

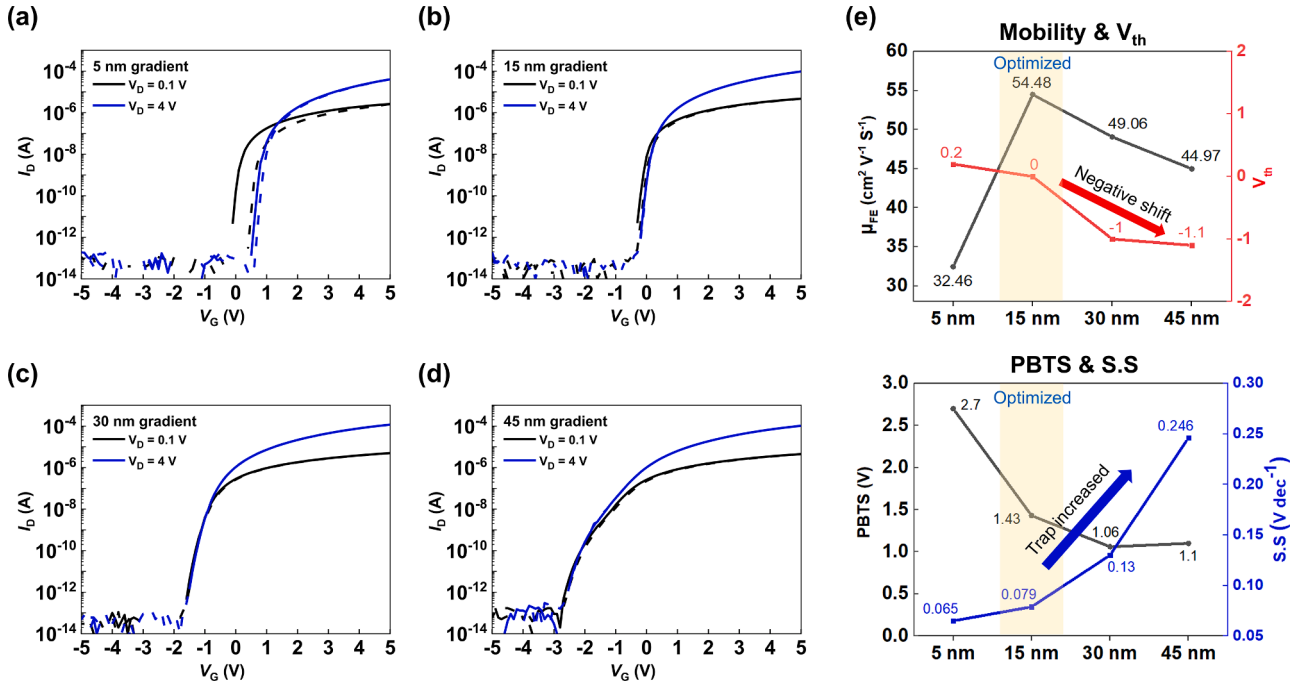


Fig. 7. Transfer characteristics of gradient IZO TFTs with channel thickness of (a) 5 nm, (b) 15 nm, (c) 30 nm, and (d) 45 nm. (e) Summary of thickness dependent electrical properties of the gradient IZO TFTs.

V characteristics are predominantly governed by the Debye screening length, the L_D value of the gradient channel was extracted from the high-frequency C-V curves to estimate the effective conduction depth [47, 52]. To ensure the reliability of the capacitance data and determine the appropriate frequency, the dissipation factor (D) was evaluated at different frequencies, as shown in Fig. S6. Of the tested frequencies, 100 kHz exhibited a low D value with reduced noise and minimal frequency dispersion. Also, 100 kHz is sufficiently high to suppress slow trap-related responses while still allowing the response of free electrons and shallow donor states [53]. Therefore, the C-V measurements were conducted at 100 kHz.

To calculate the effective L_D of the gradient channel, N_d was extracted from the minimum slope of the linear region in the $(1/C^2)$ - V

plot, expressed as follows [54]:

$$N_d = \frac{2}{q\epsilon_{IZO}} \left(\frac{d}{dV_g} \left(\frac{1}{C} \right)^2 \right)^{-1} \quad (2)$$

The C-V characteristics and extracted N_d and L_D values are presented in Fig. 8 and listed in Table 4. For the 5 nm gradient channel, the calculated L_D was approximately 5.1 nm, which is comparable to the total channel thickness, indicating that the entire channel is effectively controlled by the gate electric field. For the 15 nm gradient channel, L_D was 5 nm, which corresponds to the thickness of the upper 5:1 front channel layer. This indicates that the gate electric field is primarily confined within the top 5:1 region, implying that this high mobility layer is a primary contributor to the main conduction path under a gate bias.

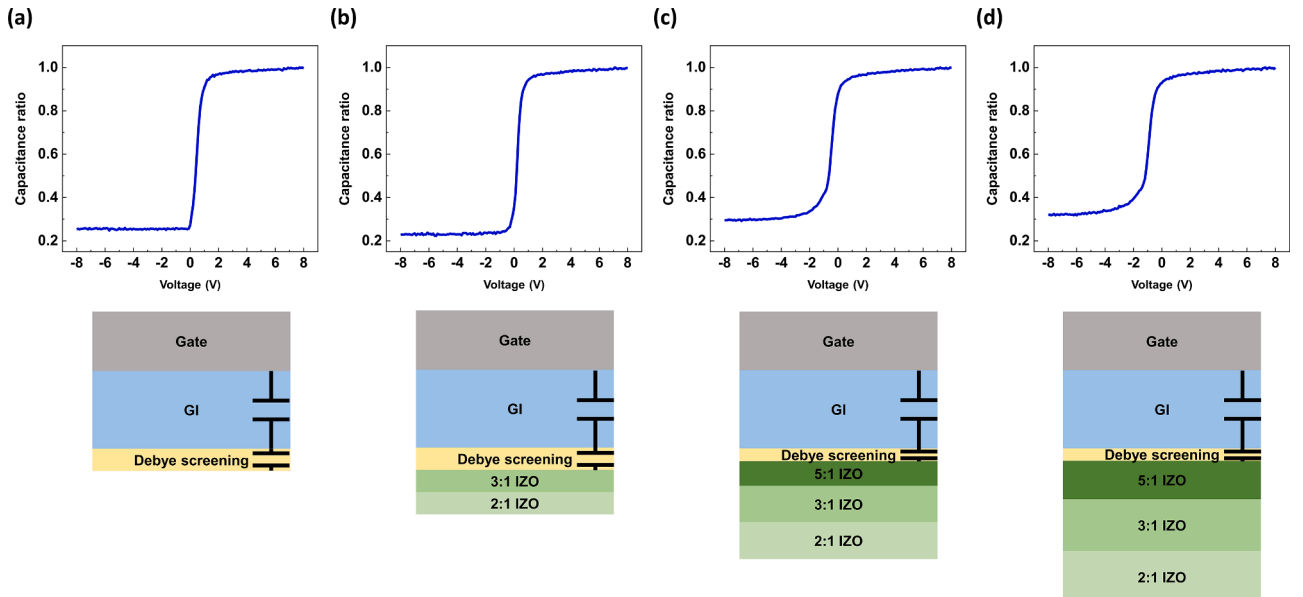


Fig. 8. C-V characteristics and capacitance model of gradient IZO TFTs with different channel thickness: (a) 5nm, (b) 15nm, (c) 30nm, and (d) 45nm.

Table 4

Thickness dependent donor concentration (N_D) and Debye length (L_D) extracted from C–V analysis.

T_{ch}	5 nm	15 nm	30nm	45nm
N_D	4.2×10^{17}	4.4×10^{17}	1.3×10^{18}	1.2×10^{18}
L_D	5.1 nm	5.0 nm	2.9 nm	3.0nm

In contrast, the 30 and 45 nm gradient channels exhibited smaller L_D values, which were attributed to the increased N_D . When the channel thickness exceeds the L_D , a residual 5:1 channel region can be observed beyond the effective electric field penetration depth. This excess 5:1 IZO region is weakly influenced by the gate electric field and contributes to defect related bulk conduction rather than confined main transport, leading to the overall degraded electrical characteristics [55,56]. Among the devices with different channel thickness values, the 15 nm gradient channel TFT exhibited the best overall electrical performance. The extracted L_D was 5 nm thick, which is comparable to the thickness of the front In-rich 5:1 IZO front layer, indicating that this region effectively contributed to the main carrier transport path while suppressing trap-related conduction.

To further validate the Debye length analysis, a single composition 3:1 IZO TFT with the same channel thickness (15 nm) was analyzed as a control device. The extracted L_D was approximately 5.0 nm, which is consistent value with gradient channel TFT, as shown in Table S3. This result indicates that the calculated L_D is not unique to the gradient structure and is not an artifact arising from the compositional gradient. Despite the comparable L_D values, the gradient channel TFT exhibited significantly enhanced electrical performance, suggesting that the improvement originates from the engineered vertical cation distribution and interfacial band alignment rather than from differences in the Debye screening length itself.

Consequently, the gradient channel engineering approach enables effective control of carrier distribution and transport characteristics through the vertical modulation of channel composition. When the L_D becomes comparable to the thickness of the In-rich front channel layer, the dominant conduction path is formed near the gate dielectric/channel interface, resulting in enhanced electrical performance. These findings provide insight into the relationship between channel-depth composition profiles and interfacial carrier transport, highlighting the importance of channel engineering for high-performance oxide TFTs.

4. Conclusions

This study demonstrated two key approaches for analyzing gradient channel architecture. First, the compositional band engineering enabled by the vertically graded cation distribution from the 5:1 to 2:1 IZO layers controls the carrier distribution and establishes a dominant conduction path within the high-mobility front channel region through engineered interfacial band alignment, thereby enabling efficient carrier transport without compromising switching characteristics. XPS analysis revealed the compositional and chemical properties of the single layer IZO films, whereas UPS, SE, and TCAD analyses provided the energy band alignment of the gradient structure, indicating the formation of a dominant conduction path in the front channel region. Second, a thickness dependent analysis based on Debye screening revealed the existence of an optimal channel thickness where the gate-induced field and conduction depth were properly balanced. When the channel thickness exceeds the L_D , a residual region beyond the effective field penetration depth contributes to bulk conduction and performance degradation. By tailoring the vertical composition and channel thickness, the optimized gradient channel TFT achieved a high mobility of $54 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, a V_{th} of 0 V, and an ultra-low S.S of 0.079 V dec^{-1} . As a result, carrier transport in the gradient channel is predominantly localized within the front channel region, whereas the back channel region plays a critical role in regulating carrier density and electrical stability.

These findings provide fundamental insight into the relationship between vertical cation distribution, interfacial electronic structure, gate-field screening, and carrier transport in oxide semiconductor channels. Furthermore, this work highlights the importance of interface engineering as a strategy for controlling carrier transport pathways in advanced oxide electronic devices.

AI Declaration

No AI-assisted technologies were used in the preparation of this manuscript.

CRediT authorship contribution statement

Tae Hwan Boo: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Seunghyeon Shin:** Investigation, Software, Visualization, Validation, Formal analysis, Data curation. **Hwa Young Kim:** Writing – review & editing, Visualization, Investigation, Formal analysis, Data curation. **Sunghwan Park:** Writing – review & editing, Investigation, Formal analysis, Visualization, Validation. **Sang-Hee Ko Park:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

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.2026.110385](https://doi.org/10.1016/j.surfin.2026.110385).

Data availability

Data will be made available on request.

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