

Interfacial effects of mo-based alloy electrodes on channel shortening and mobility extraction in oxide thin-film transistors

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ABSTRACT

This study investigates the impact of source/drain materials on channel shortening in back-channel-etched (BCE) oxide thin-film transistors (TFTs) employing an indium-tin-based oxide semiconductor. Molybdenum (Mo) and Molybdenum-aluminum-titanium (MoAlTi) electrodes are systematically compared to evaluate their effects on channel shortening and device performance. Combined electrical characterization and materials analyses indicate that MoAlTi electrodes induce stronger contact-related interfacial effects, resulting in more pronounced effective channel length reduction and consequent overestimation of field-effect mobility. Temperature-dependent TLM analysis suggests that thermally activated defect-mediated processes are involved in the observed channel shortening behavior, although the diffusing species cannot be uniquely identified from the activation energy alone. TEM and XPS analyses further support stronger interfacial oxidation and oxygen-vacancy-related bonding changes in the MoAlTi contact system compared to the Mo contact system. These findings underscore the necessity of accounting for effective channel length reduction in mobility extraction and highlight the critical role of electrode/oxide interfacial reactions in scaled oxide TFTs.

1. Introduction

Thin-film transistors (TFTs) based on amorphous oxide semiconductors (AOS) have emerged as promising candidates for backplane devices in active-matrix displays due to their favorable electrical characteristics, including high field-effect mobility (μ_{FE}) and good stability with excellent uniformity over large areas [1,2]. These properties have enabled their widespread adoption in commercial display applications, such as televisions and mobile devices. Furthermore, their compatibility with low-temperature processing makes oxide TFTs particularly attractive for next-generation form factors, such as flexible and paper-based electronics [3–5].

As demand increases for higher resolution and faster response times, ongoing efforts to optimize the performance of oxide TFTs remain crucial. Among various performance challenges, the scaling of TFTs to short channels is of particular importance in enabling the miniaturization and high-density integration of devices. Short-channel scaling also

offers the potential to improve on-current (I_{ON}) due to the reduced channel resistance. However, oxide TFTs with short channels are often affected by contact-induced phenomena, in which interactions between the source/drain metal electrodes and the oxide semiconductor reduce the effective channel length (channel shortening). For example, previous studies have shown that interfacial interactions between Mo source/drain electrodes and IZO channels can affect contact properties and effective channel length in oxide TFTs [6]. Channel shortening can lead to mobility overestimation, increased off-current, and a negative shift in threshold voltage (V_{th}), thereby degrading the switching characteristics. Recent studies on amorphous metal-oxide TFT modeling and scaled device architectures have also emphasized that accurate interpretation of mobility, threshold voltage, and reliability requires careful consideration of channel-length-dependent effects, contact structures, and interface-related effects [7,8]. Addressing this issue is critical, especially for oxide semiconductors with high mobility, where the interaction between metal electrodes and the channel can strongly influence device

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characteristics.

In high-performance display backplanes, low-resistance metals such as copper (Cu) are attractive for minimizing power loss and improving signal speed [9,10]. Nevertheless, Cu readily diffuses into oxide semiconductors and degrades device reliability [11,12]. To overcome this issue, several Cu metallization strategies have been investigated, including the insertion of diffusion-barrier interlayers and the use of Cu-based alloy electrodes. In particular, Cu-Cr-Zr alloy systems have been reported as promising electrode materials because they can improve the thermal stability, adhesion, and diffusion-barrier characteristics of Cu metallization while maintaining relatively low resistivity [13,14]. In parallel, refractory-metal barrier electrodes such as Mo and Mo-based alloys are commonly adopted to suppress Cu diffusion while maintaining low contact resistance. Among these candidates, MoAlTi alloys have been proposed as promising Cu barrier materials for oxide TFT metallization [15–17]. However, reactive alloying elements in such metal-alloy electrodes may also modify the electrode/oxide interface, potentially leading to contact-induced defect formation and effective channel shortening.

Despite these advances, previous studies on oxide TFT metallization have mainly focused on conventional metallization metrics, such as Cu diffusion-barrier capability, electrical resistivity, contact resistance, and adhesion. In contrast, the influence of alloy-electrode-induced interfacial reactions on effective channel length reduction and mobility extraction remains insufficiently understood. In this study, we investigate back-channel-etched (BCE) oxide TFTs employing an indium-tin-based oxide semiconductor. We systematically compare Mo and MoAlTi source/drain electrodes and quantify channel shortening using the transmission line method (TLM). By combining electrical characterization with structural and materials analyses, we clarify how electrode materials influence contact-induced interfacial reactions, effective channel length reduction, and mobility extraction.

2. Experimental

Fig. 1 shows a schematic and a cross-sectional image of the fabricated BCE TFT. Each composite layer was aligned using photolithography and wet etching process. First, a 100 nm Mo gate electrode was deposited by DC sputtering. A 200 nm SiO₂ layer was then deposited by plasma-enhanced chemical vapor deposition (PECVD) as the gate insulator. Subsequently, a 30 nm Al-doped InSnZnO (Al:ITZO) active layer was deposited by RF sputtering. Al:ITZO was selected due to its chemical robustness, which minimizes process-induced damage [18]. After patterning, the active layer was pre-annealed at 350 °C for 2 h in an O₂ ambient to reduce defects and optimize carrier concentration. For the source/drain electrodes, 100-nm-thick Mo and MoAlTi (Mo:Al:Ti = 70:25:5 at%) layers were deposited by DC sputtering under identical conditions: an Ar flow rate of 10 sccm, a working pressure of 5 mTorr, and a sputtering power of 200 W. Finally, a 100-nm-thick SiO₂ passivation layer was deposited by PECVD at 300 °C. To examine channel shortening caused by lateral diffusion from the source/drain contact

region, the TFTs were post-annealed from 300 to 350 °C at 10 °C intervals for 2 h under vacuum.

Electrical characterization was performed using a semiconductor parameter analyzer. To evaluate channel shortening, the transmission line method (TLM) was employed by analyzing the total device resistance as a function of the physical channel length under various gate voltages. The channel width was fixed at 20 μm, and the channel length was varied from 5 to 30 μm in 5 μm increments. For accurate extraction of the effective channel length reduction, precise channel dimensions were measured using an optical microscope. Structural and chemical analyses were conducted using high-resolution transmission electron microscopy (HR-TEM) and X-ray photoelectron spectroscopy (XPS).

3. Results and discussions

The representative transfer curves of the BCE structured TFTs depending on the source/drain materials with various annealing temperatures are depicted in Fig. 2. The transfer characteristics were measured with gate voltage (V_g) swept from −15 to 20 V in 0.25 V increments at a fixed drain voltage (V_d) of 0.1 V. The evaluated devices had a channel width and length of 20 and 15 μm, respectively. The average values and standard deviation of the electrical parameters extracted from four devices under various annealing temperatures are summarized in Table 1. The transfer curves for measured devices annealed at 300 °C are provided in Fig. S1. The threshold voltage (V_{th}) was extracted by linearly fitting the high-conductance linear region of the I_d - V_g curve and extrapolating the fitted line to $I_d = 0$. The field-effect mobility (μ_{FE}) was calculated using the following equation:

$$\mu_{FE} = \frac{g_m}{(W/L)C_i V_d}, \left(\text{where } g_m \equiv \frac{\partial I_d}{\partial V_g} \right) \quad (1)$$

where W and L denote the channel width and length, respectively. C_i is the capacitance of the gate insulator and was measured to be about 1.7×10^{-4} F/m². The devices exhibit distinct differences in electrical properties depending on the source/drain materials. The device annealed at 300 °C with MoAlTi source/drain electrodes exhibits a relatively large μ_{FE} of 66.0 cm²V^{−1}s^{−1} and a negatively shifted V_{th} of 2.37 V, whereas the device with Mo source/drain electrodes exhibits μ_{FE} of 44.4 cm²V^{−1}s^{−1} and V_{th} of 3.75 V. Because the devices were fabricated under identical conditions except for the source/drain electrodes, these differences are attributed to the source/drain material.

According to the transfer curves in Fig. 2, all devices shift in the negative direction as the annealing temperature increases. After annealing at 350 °C, the BCE TFTs with MoAlTi shift significantly in the negative direction, while the devices with Mo source/drain electrodes have a V_{th} of −2.10 V. The negative shift of transfer curves in oxide TFTs induced by thermal annealing is typically attributed to an increase in carrier concentration due to hydrogen incorporation or oxygen vacancies (V_O) acting as donors originating from the gate insulator or passivation layer [19,20]. In this study, all devices use the same gate insulator and passivation materials and process, so additional factors

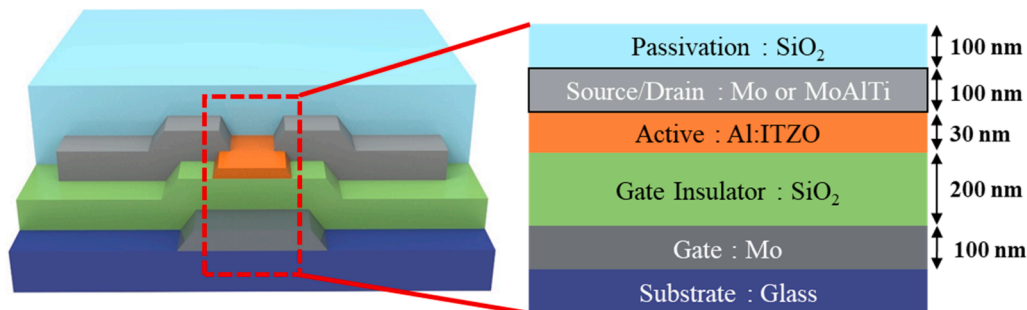


Fig. 1. Schematic and cross-sectional structure of the fabricated bottom-gate coplanar (BCE) TFT with Mo or MoAlTi source/drain electrodes.

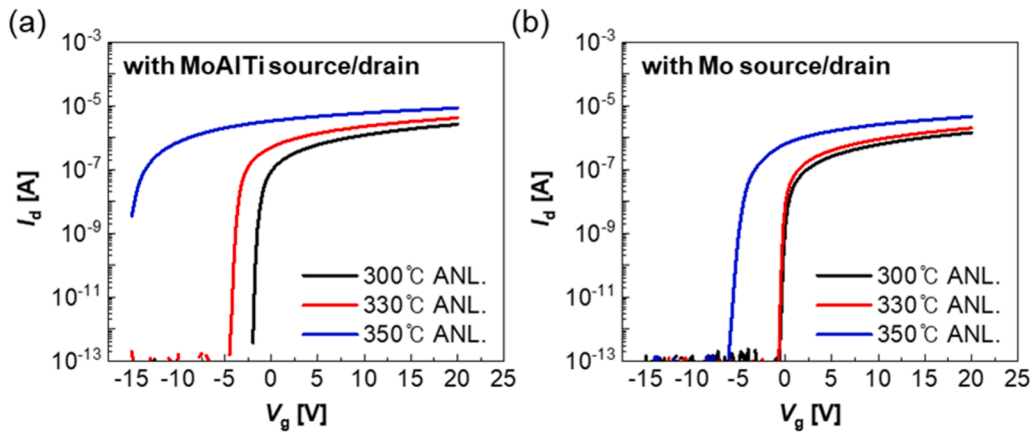


Fig. 2. Transfer characteristics of BCE-structured TFTs with (a) MoAlTi and (b) Mo source/drain electrodes measured at a drain voltage of 0.1 V after post-annealing at different temperatures.

Table 1

Summary of the electrical parameters of BCE-structured TFTs with MoAlTi and Mo source/drain electrodes after post-annealing at different temperatures. (* μ_{lin} may be overestimated due to channel length reduction.).

Annealing temperature	S/D materials	S.S [V/dec]	V _{th} [V]	ON/OFF Ratio [× 10 ⁸]	μ_{lin}^* [cm ² V ⁻¹ s ⁻¹]
300 °C	MoAlTi	0.12 ± 0.01	2.37 ± 0.06	2.59 ± 0.01	66.0 ± 0.4
	Mo	0.15 ± 0.02	3.75 ± 0.22	1.60 ± 0.15	44.4 ± 5.4
330 °C	MoAlTi	0.16 ± 0.02	-2.00 ± 0.23	4.25 ± 0.30	85.9 ± 3.7
	Mo	0.13 ± 0.02	2.69 ± 0.04	2.08 ± 0.07	54.4 ± 1.8
350 °C	MoAlTi	N/A	N/A	N/A	117.7 ± 3.1
	Mo	0.27 ± 0.02	-2.10 ± 1.38	4.31 ± 0.44	86.9 ± 3.0

may contribute to carrier generation.

Notably, the magnitude of the negative shift differs depending on the source/drain material. Therefore, the negative shift in the transfer curves is attributed to channel shortening owing to the formation and lateral diffusion of donor-like species from the source/drain region [21, 22]. Consequently, the apparent increase in mobility and the negative shift in V_{th} originate from the lateral diffusion of donor-like states from the source/drain contact regions, and channel shortening should be considered. Additionally, the extracted mobility values are likely

significantly overestimated because they were calculated based on the channel dimensions defined by the mask design. Fig. 3(a) and (b) show the transfer curves of the 350 °C-annealed BCE TFTs with MoAlTi and Mo source/drain electrodes, respectively, as a function of channel length. As shown in Fig. 3, the devices exhibit distinct difference in V_{th} depending on the channel length. Because the contact geometry is identical for all devices, the observed channel-length dependence is unlikely to be dominated by Schottky barrier effects at the contacts; [23] instead, it is consistent with an effective channel length reduction. To quantify channel shortening as a function of source/drain material, we extracted the effective channel length reduction (ΔL) using the transmission line method (TLM) [24,25]. The total resistance (R_{tot}) was extracted at $V_d = 0.1$ V as a function of the physical channel length (L_p) measured by optical microscope. Under small V_d conditions, R_{tot} can be expressed as follows: [26]

$$R_{tot} = \frac{V_d}{I_d} = \frac{L_p - \Delta L}{W\mu C_i(V_g - V_{th})} + R_{SD}(V_d < V_g - V_{th}) \quad (2)$$

where, R_{SD} is the source/drain contact resistance. When the $R_{tot} - L_p$ plots are obtained for devices with various L_p under different V_g conditions, the lines intersect at a single point, from which ΔL can be extracted. Fig. 4 shows the $R_{tot} - L_p$ plots for the BCE TFTs depending on the source/drain materials and annealing temperature. It should be noted that the TLM plots shown in Fig. 4 correspond to selected representative annealing temperatures, whereas the full ΔL extraction was performed at six post-annealing temperatures from 300 to 350 °C with a 10 °C interval, namely 300, 310, 320, 330, 340, and 350 °C. As depicted

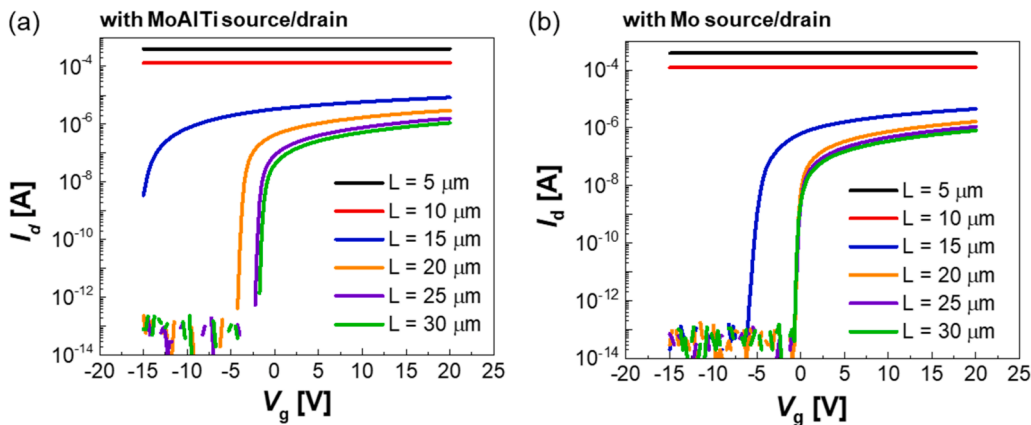


Fig. 3. Transfer characteristics of BCE-structured TFTs annealed at 350 °C with (a) MoAlTi and (b) Mo source/drain electrodes as a function of channel length.

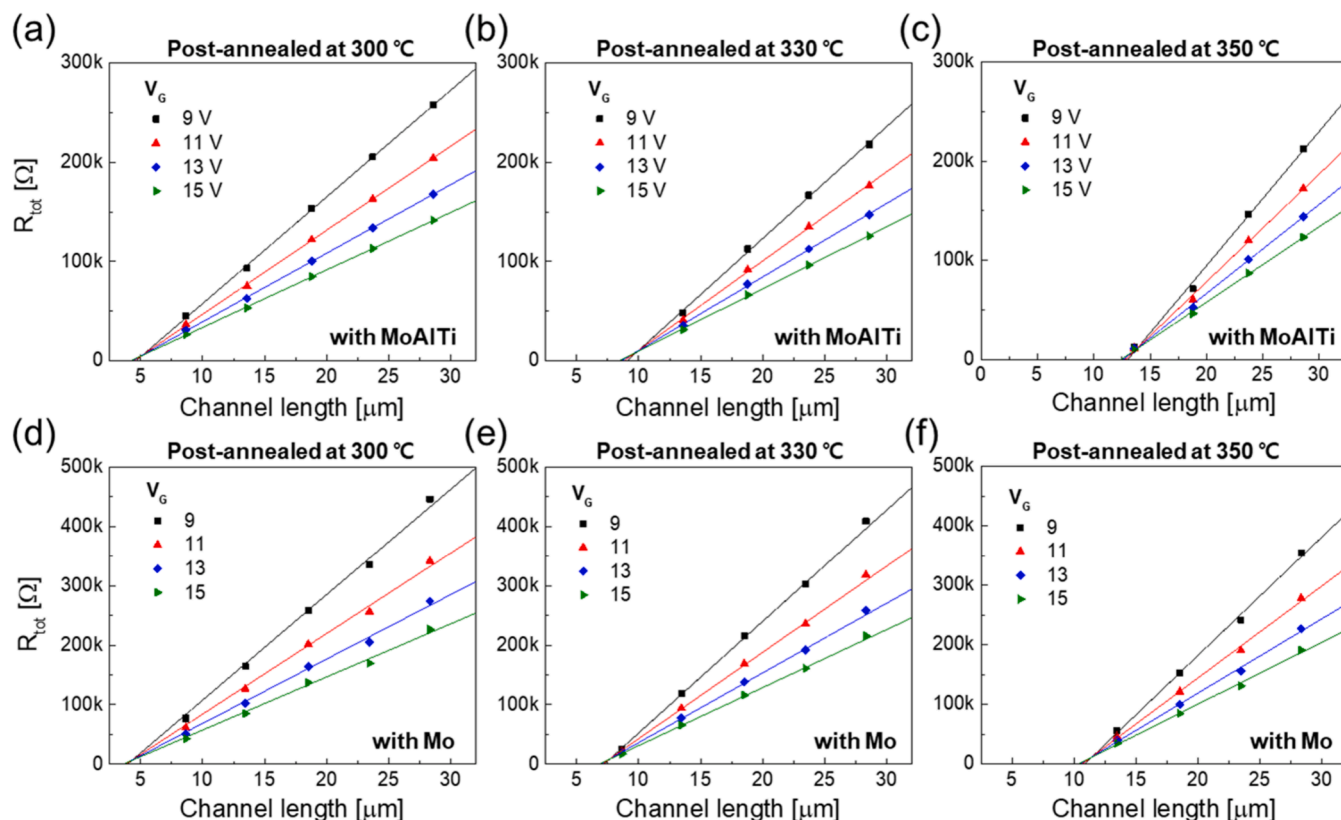


Fig. 4. Total resistance (R_{tot}) as a function of channel length (L_p) measured at different gate voltages for BCE TFTs with (a–c) MoAlTi and (d–f) Mo source/drain electrodes after post-annealing at 300, 330, and 350 °C. The linear fits converge to a single intersection point, from which the effective channel length reduction (ΔL) is extracted.

in graphs, R_{tot} has a good linear relationship with L_p , under various V_G conditions, and the fitted lines converge to a single point, indicating that this method is suitable for extracting ΔL . As shown in Fig. 4, ΔL increases with increasing annealing temperature. For each annealing condition, 18 devices were analyzed to extract ΔL , and the results obtained from all six annealing temperatures are summarized in Fig. 5(a) with error bars, demonstrating good statistical reliability. The R_{tot} - L_p plots for all measured devices are provided in Fig. S2 and S3, and demonstrate good reproducibility. As indicated in Fig. 5(a), the BCE TFTs with MoAlTi source/drain electrodes exhibit a larger increase in ΔL with annealing temperature than those with Mo source/drain electrodes.

Using the extracted ΔL , the μ_{FE} can be calculated without overestimation by employing the effective channel length ($L_p - \Delta L$). Without accounting for channel shortening, abnormally high mobility values are obtained, as discussed in Table 1. Fig. 5(b) shows the μ_{FE} as a function of the L_p with (solid lines) and without (dashed lines) the effective channel length correction. When channel shortening is not considered, large variations in mobility are observed even for the same oxide semiconductor, and these variations depend on both the channel dimensions and the source/drain materials. This indicates that effective channel shortening is a major source of mobility overestimation in the present devices. In contrast, when channel shortening is considered, similar mobility values are obtained regardless of channel length and the

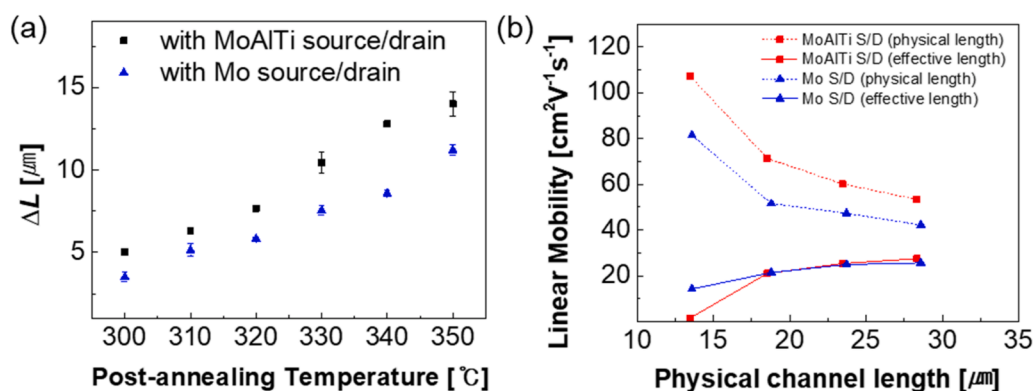


Fig. 5. (a) Extracted effective channel length reduction (ΔL) as a function of post-annealing temperature for BCE TFTs with MoAlTi and Mo source/drain electrodes. (b) Field-effect mobility as a function of physical channel length, calculated with (solid lines) and without (dashed lines) effective channel length correction ($L_p - \Delta L$).

source/drain materials. The BCE TFTs fabricated in this work exhibit a mobility of approximately $25 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, which is substantially lower than the overestimated values. Therefore, channel shortening should be considered for accurate device and circuit design. Furthermore, because the mobility values corrected using ΔL are reasonable, the TLM-based extraction of ΔL is considered reliable.

Despite using the effective channel length, a slight decrease in mobility is observed as the channel length decreases. This is because the contribution of the R_{SD} to R_{tot} increases as the channel length decreases [27]. The extracted R_{tot} , channel resistance (R_{ch}) and R_{SD} as a function of gate overdrive voltage for channel lengths of 30 and 15 μm are shown in Fig. S4. As shown in Fig. S4(a) and (b), R_{SD} is negligible compared with R_{tot} and R_{ch} for long-channel (30 μm) devices. In contrast, for the short-channel (15 μm) devices, R_{SD} becomes comparable to R_{ch} , as shown in Fig. S4(c) and (d), leading to a decrease in the extracted mobility.

Because the devices were fabricated under identical conditions except for the source/drain materials, the different channel shortening behavior is attributed to contact-induced processes near the source/drain region, such as donor-like defect generation, diffusion-related effects, or metal-induced interfacial states. To further support this interpretation, additional TLM measurements were performed after post-annealing at 250 $^{\circ}\text{C}$ as a practical low-thermal-budget baseline. This was the lowest temperature at which stable and reproducible transfer characteristics were obtained. The as-fabricated devices exhibited unstable and nonuniform transfer characteristics, which can be attributed to plasma-process-induced degradation during the PECVD SiO_2 passivation performed directly on the oxide semiconductor. This degraded initial state made quantitative TLM extraction unreliable (Fig. S5(a-d)). Importantly, the 250 $^{\circ}\text{C}$ annealing temperature is substantially lower than the deposition temperatures of the gate insulator and passivation layers (350 and 300 $^{\circ}\text{C}$, respectively). Therefore, additional thermally activated contributions from hydrogen or other species originating from the adjacent layers are expected to be relatively limited under the 250 $^{\circ}\text{C}$ annealing condition [28]. Thus, the 250 $^{\circ}\text{C}$ -annealed devices provide a practical low-thermal-budget baseline for evaluating the initial source/drain-electrode-dependent channel-shortening behavior. As shown in Fig. S5 (e, f), the 250 $^{\circ}\text{C}$ -annealed devices showed clear R_{tot} - L_p linearity, with extracted ΔL values of 1.6 μm for Mo and 3.2 μm for MoAlTi. This result suggests that the larger effective channel length reduction in the MoAlTi-contacted devices appears even under the lowest reliable annealing condition, supporting the source/drain-electrode-dependent origin of the channel-shortening

behavior.

Since direct observation of the lateral defect distribution is experimentally challenging, we analyzed the temperature dependence of the extracted effective ΔL to evaluate the thermally activated nature of the contact-induced channel shortening behavior. The diffusion length (L_d) and diffusivity (D) were derived from ΔL to investigate the underlying diffusion mechanism [29]. A schematic representation of the lateral diffusion process and the definition of the relevant parameters are illustrated in Fig. 6(a). According to Fick's second law, the impurity concentration profile is described by:

$$C_x(x, t) = C_s \text{erfc} \left(\frac{x}{2\sqrt{Dt}} \right) \quad (3)$$

where C_x and C_s are the impurity concentration at position x and at the surface, respectively. In our case, the surface corresponds to the contact interface between the source/drain electrode and the oxide semiconductor, x denotes the lateral diffusion distance into the channel center, and t denotes the diffusion time (i.e., the post-annealing duration), as depicted in Fig. 6(a). Assuming that the oxide semiconductor becomes conductive when the impurity concentration exceeds a critical value C_{crit} , the diffusion length L_d can be defined as

$$C(L_d, t) = C_{crit} = C_s \text{erfc} \left(\frac{L_d}{2\sqrt{Dt}} \right) = C_s \text{erfc} \left(\frac{\Delta L}{4\sqrt{Dt}} \right) \quad (4)$$

Because ΔL includes the reduced channel length on both the source and drain sides, $\Delta L/2$ was taken as the L_d . Rearranging the above equation yields

$$\Delta L = 4\sqrt{Dt} \text{erfc}^{-1}(C_{crit}/C_s) = K\sqrt{Dt}, K \equiv 4\text{erfc}^{-1}(C_{crit}/C_s) \quad (5)$$

which gives

$$K^2 D = \frac{(\Delta L)^2}{t} \quad (6)$$

Because the exact values of C_s and C_{crit} are difficult to determine experimentally, we treated $K^2 D$ as an effective parameter and analyzed its dependence on annealing temperature to infer the diffusion behavior. As shown in Fig. 6(b), a plot of $K^2 D$ (log scale) versus reciprocal temperature exhibits a linear trend, indicating Arrhenius-type behavior: [30]

$$K^2 D(T) = K^2 D_0 \exp \left(-\frac{E_a}{kT} \right) \quad (7)$$

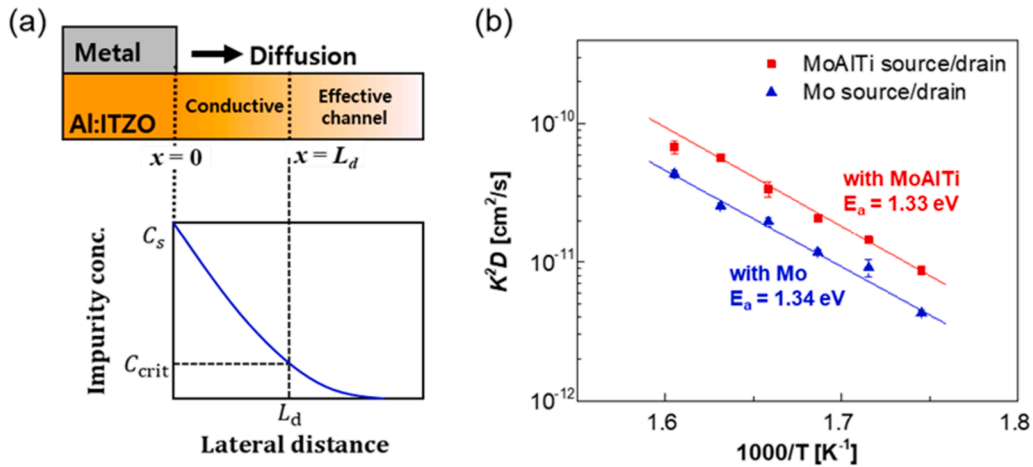


Fig. 6. (a) Schematic illustration of the lateral diffusion model at the contact region, defining the diffusion length (L_d), surface concentration (C_s), and critical concentration (C_{crit}) of donor-like defects that determine the effective channel length. (b) Arrhenius plot of the effective diffusion parameter $K^2 D$ as a function of reciprocal temperature for BCE TFTs with MoAlTi and Mo source/drain electrodes.

where, D_0 , E_a and k denote the diffusion prefactor, apparent activation energy and Boltzmann constant, respectively. From the slope of the Arrhenius plot, the apparent activation energies were extracted as 1.33 eV for the MoAlTi electrode system and 1.34 eV for the Mo electrode system, suggesting that both cases exhibit similar thermal activation behavior. Because both devices employ the same oxide semiconductor, the similar apparent activation energies suggest that the effective channel-shortening process is governed by a similar thermally activated defect-related process. However, the activation energy alone does not uniquely identify the diffusing species, and possible contributions from hydrogen-related effects, metal-induced defect states, or local Al/Ti-related interfacial effects in the MoAlTi system cannot be completely excluded. Therefore, oxygen-vacancy-related defects are considered a plausible contributor to the observed behavior, but they should not be regarded as the only possible origin. Furthermore, reported activation energies for oxygen diffusion in oxide semiconductors range from 0.45 to 2.56 eV [23,31,32]. Because the extracted apparent activation energies are within the broad range reported for oxygen-related defect migration in oxide semiconductors, the present results are consistent with oxygen-vacancy-related processes, while not excluding other defect-mediated contributions. It should be noted that, because C_{crit} may depend on annealing temperature, the extracted activation energies should be interpreted as apparent values rather than absolute activation energies. To estimate the possible influence of this assumption, we considered a $\pm 50\%$ variation in C_{crit} over the 300–350 °C range, using $C_{crit}/C_s = 0.005$ as a representative value based on previous diffusion-model analyses [23]. The resulting variation in the apparent activation energy was approximately 0.05 eV. Therefore, possible variation in C_{crit} may introduce uncertainty in the absolute activation energy, but it does not affect the comparative conclusion that the MoAlTi and Mo electrode systems exhibit similar apparent activation energies. Furthermore, even with this uncertainty, the recalculated values remain within the reported activation-energy range for oxygen diffusion in oxide semiconductors (0.45–2.56 eV) [23,31,32].

In addition, the MoAlTi electrode system exhibits a higher y-

intercept in the Arrhenius plot than the Mo electrode system. In this context, the y-intercept corresponds to $\ln(K^2D_0)$. The pre-factor D_0 is influenced by various factors, including the vibrational properties of the diffusing species, the entropy of migration and vacancy formation, solute-vacancy binding energy, and structural characteristics; that is, it reflects the nature of the diffusion mechanism and the host system [33]. Given the nearly identical apparent activation energies, the two systems may involve similar thermally activated defect-mediated processes; however, the exact diffusing species cannot be uniquely determined from the present analysis. Therefore, the higher y-intercept for the MoAlTi contact system suggests a larger effective diffusion-related prefactor, which may be associated with stronger interfacial reactions and/or a higher effective interfacial defect concentration near the contact region. Accordingly, the Arrhenius analysis suggests that the MoAlTi electrode enhances the effective contact-induced channel-shortening process, consistent with stronger interfacial reactions.

To support this interpretation, we performed a structural and materials analysis of the interface between the metal electrodes and the oxide semiconductor. According to previous studies, Ti and Al components in Mo-based alloys can significantly affect the contact states at the metal/oxide semiconductor interface [34]. In particular, Ti and Al can be easily oxidized by extracting oxygen from the oxide semiconductor owing to their relatively low oxide formation energies (i.e., more negative ΔG_{rxn}^0 for oxidation) [34–36]. Therefore, MoAlTi source/drain electrodes may induce oxygen-vacancy-related bonding changes near the contact interface through interfacial oxygen-scavenging reactions, which may contribute to local electrical modification near the contact region. To investigate the contact region between oxide semiconductor and the metal electrodes, structural analysis was conducted using high-resolution TEM. Fig. 7(a) and (b) show cross-sectional images of the oxide semiconductors (Al:ITZO)/MoAlTi and Al:ITZO/Mo stacks, respectively. In contrast to the Al:ITZO/Mo, an interlayer is clearly observed when MoAlTi is deposited on the oxide semiconductors. Because EDS has limited spatial resolution for ultrathin interlayers, it was difficult to unambiguously identify whether this interlayer

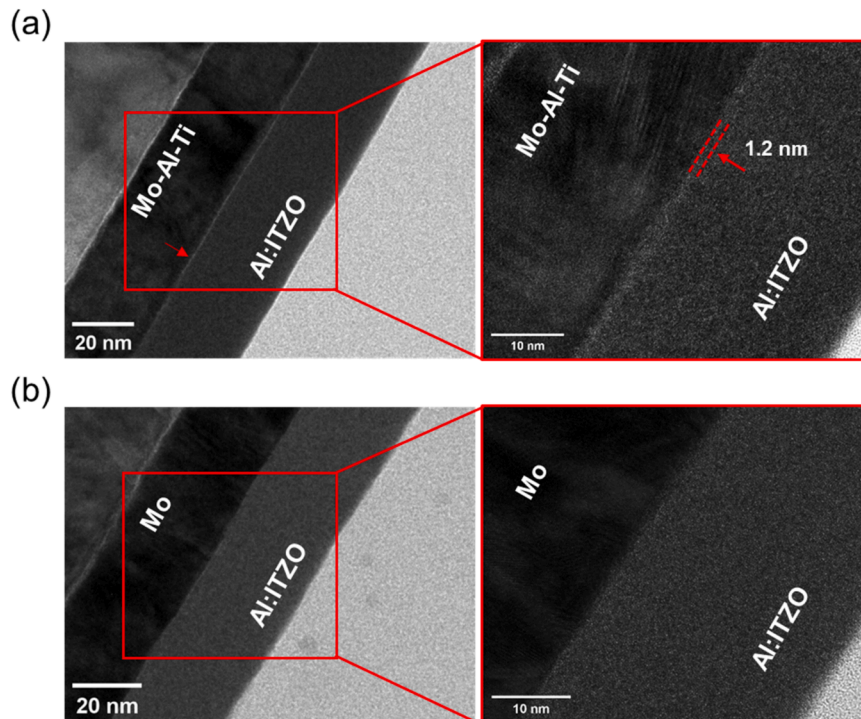


Fig. 7. Cross-sectional high-resolution TEM images of the contact interface between the oxide semiconductor and metal electrodes: (a) Al:ITZO/MoAlTi and (b) Al:ITZO/Mo stacks.

consisted of AlOx, TiOx, or MoOx based solely on the EDS results. Nevertheless, from a thermodynamic perspective, it is highly likely that a metal-oxide layer forms at the interface. The thermodynamic stability of metal oxidation can be evaluated using the standard Gibbs free energy of formation. The Gibbs free energy (ΔG_{rxn}^0) for the oxidation reactions in the temperature range of 400 to 1100 K are given as follows: [37]

$$2/3\text{Mo}_{(s)} + \text{O}_{2(g)} = 2/3\text{MoO}_{3(s)} \quad \Delta G_{rxn}^0 = -502.1 + 0.1686T(\text{kJ/mol}) \quad (8)$$

$$\text{Ti}_{(s)} + \text{O}_{2(g)} = \text{TiO}_{2(s)} \quad \Delta G_{rxn}^0 = -943.5 + 0.1791T(\text{kJ/mol}) \quad (9)$$

$$4/3\text{Al}_{(s)} + \text{O}_{2(g)} = 2/3\text{Al}_2\text{O}_{3(s)} \quad \Delta G_{rxn}^0 = -1115.5 + 0.1791T(\text{kJ/mol}) \quad (10)$$

The Gibbs free energies for the oxidation reactions of Al and Ti are more negative than that of Mo. Therefore, formation of Al_2O_3 and TiO_2 is more thermodynamically stable than that of MoO_3 , so the interlayer was more apparent in the cross-sectional TEM images in the case of Al:ITZO/MoAlTi due to the metal oxidation. Therefore, in BCE TFTs, MoAlTi source/drain electrodes are expected to induce stronger oxygen-scavenging reactions and oxygen-vacancy-related bonding changes than Mo source/drain electrodes owing to the favorable oxidation of Al and Ti in the MoAlTi alloy.

To investigate the oxygen bonding states in oxide semiconductors, O 1s XPS spectra were analyzed, as shown in Fig. 8. The O 1s peak was deconvoluted into the three Gaussian components assigned to lattice oxygen (O_L , M-O), oxygen-vacancy-related component (O_V), and chemisorbed oxygen species (O_C ; e.g., -OH), centered at 529.8 ± 0.1 eV, 531.0 ± 0.1 eV, and 532 ± 0.1 eV, respectively. The relative area ratios of the deconvoluted components are summarized in Fig. 8(d) to compare

the oxygen bonding states for different contact materials. The O_V -related peak area fraction of the bare oxide semiconductor surface was 11.0%. After deposition of Mo or MoAlTi on the oxide semiconductors and post-annealing at 350 °C, the O_V -related peak area fraction increased to 17.3% and 20.1%, respectively. This suggests that, during metal deposition and subsequent thermal annealing, oxygen may be partially consumed from the oxide semiconductor near the metal/oxide interface, leading to interfacial oxidation of the metal. To examine possible metal oxidation, the main metal peaks of Mo and MoAlTi on oxide semiconductors were investigated in bulk and interface regions as shown in Fig. 8(e) and (f). The “bulk” and “interface” regions were identified during XPS depth profiling by monitoring the relative Mo and In signal intensities. For the Al:ITZO/Mo stack, the Mo 3d_{3/2} and 3d_{5/2} peaks are observed at binding energies of 231.0 and 227.5 eV, respectively, in the bulk region (black line). At the interface region, the Mo 3d peak positions and line shape change barely, without pronounced additional peaks or shoulder, indicating that Mo is minimally oxidized upon contact with oxide semiconductors and subsequent annealing. For the MoAlTi electrode, the Mo 3d spectra show a similar trend with Mo stack (Fig. S6); however, the Al 2p spectra exhibit additional higher binding energy components at the interfaces, consistent with the formation of Al_2O_3 . These results support that oxidation of MoAlTi, particularly Al, promotes oxygen-vacancy-related bonding changes in the oxide semiconductor by consuming oxygen near the interface. These results indicate that MoAlTi, particularly the Al component, undergoes stronger interfacial oxidation than Mo, which is consistent with the larger O_V -related component observed in the oxide semiconductor. Although these results do not uniquely identify the diffusing species responsible for channel shortening, they support the interpretation that MoAlTi electrodes promote stronger contact-induced interfacial reactions and

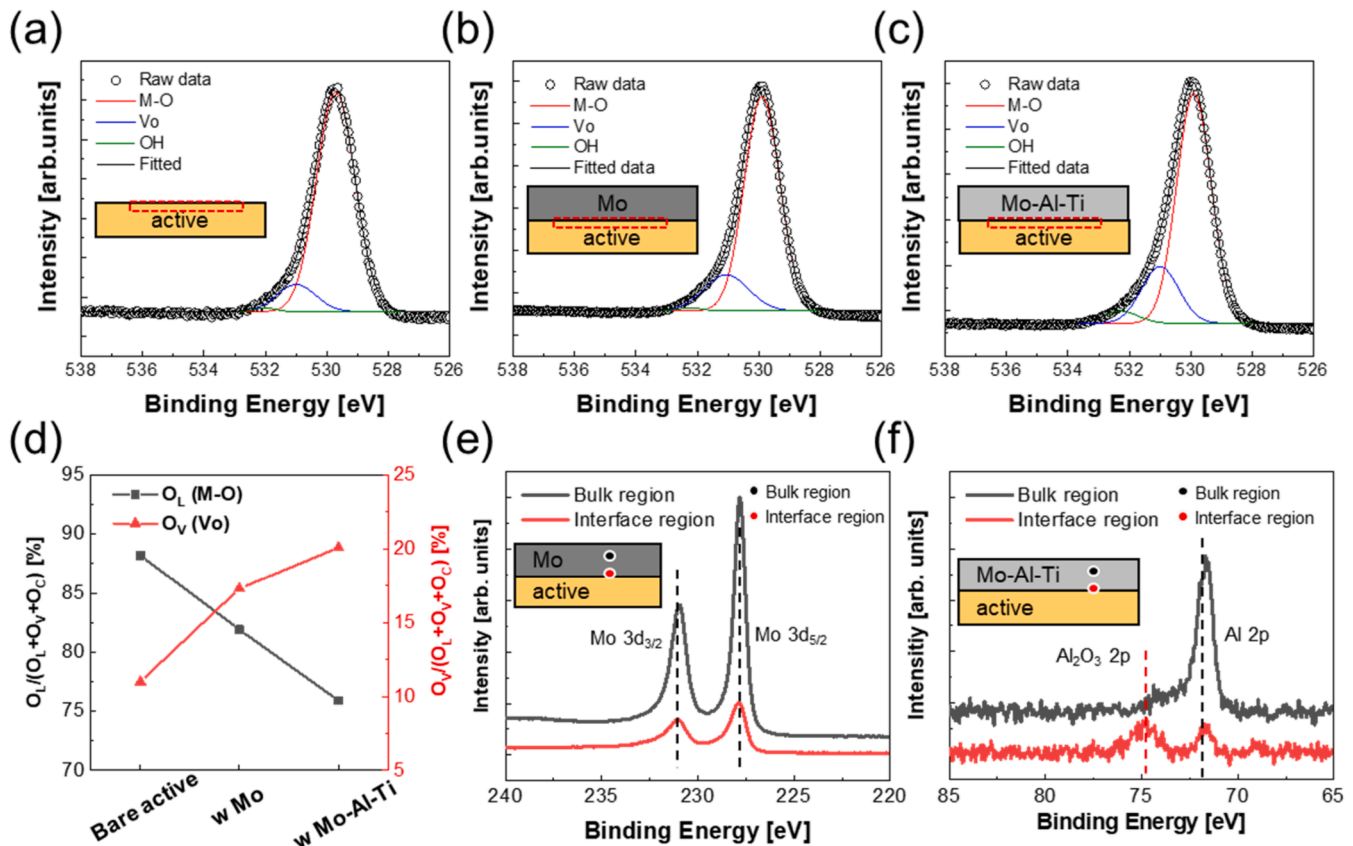


Fig. 8. XPS analysis of oxygen bonding states and interfacial chemistry in Al:ITZO films with different contact materials. (a–c) O 1s spectra of (a) bare Al:ITZO, (b) Al:ITZO/Mo, and (c) Al:ITZO/MoAlTi after post-annealing at 350 °C. (d) Relative area ratios of the lattice oxygen (O_L) and oxygen-vacancy-related component (O_V). (e) Mo 3d spectra of the Al:ITZO/Mo stack and (f) Al 2p spectra of the Al:ITZO/MoAlTi stack measured in the bulk and interface regions.

oxygen-vacancy-related bonding changes. This result further suggests that the Mo/Al/Ti compositional ratio can influence contact-induced interfacial reactions and effective channel shortening. Therefore, future optimization of the MoAlTi composition should balance Cu diffusion-barrier capability and suppression of contact-induced channel shortening.

4. Conclusions

This study highlights the significant impact of source/drain electrode materials on effective channel length reduction in BCE-structured oxide TFTs, emphasizing contact-induced interfacial reactions at Mo-based alloy/oxide semiconductor interfaces. By systematically comparing Mo and MoAlTi electrodes, we show that MoAlTi electrodes induce stronger interfacial oxidation and larger effective channel length reduction than Mo electrodes. High-resolution TEM and XPS analyses further indicate that oxidation of Al in MoAlTi alloys contributes to oxygen-vacancy-related bonding changes in the oxide semiconductor, consistent with the formation of interfacial Al_2O_3 -related layers. Electrical characterization and TLM-based analysis show that devices with MoAlTi electrodes exhibit larger reductions in effective channel length, which can lead to mobility overestimation if channel shortening is not properly accounted for. After correcting for the effective channel length, the extracted mobility values are reduced to approximately $25 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and show much smaller variation across different channel lengths. The effective diffusion-related parameters and apparent activation energies derived from ΔL measurements indicate that the contact-induced channel-shortening behavior is thermally activated, with apparent activation energies of 1.33 eV for MoAlTi and 1.34 eV for Mo electrodes.

Overall, this work underscores the necessity of accounting for channel shortening effects in mobility extraction and device design, particularly when employing reactive alloys such as MoAlTi as copper barrier materials. In addition, the present results suggest that the Mo/Al/Ti compositional ratio should be further optimized to balance Cu diffusion-barrier capability and suppression of contact-induced channel shortening. Thus, this work expands the design framework for Mo-based alloy electrodes beyond conventional metallization performance by emphasizing effective-channel-length-related device considerations. These findings indicate that, for scaled oxide TFTs, future alloy electrodes should be evaluated not only in terms of Cu diffusion-barrier capability, electrical resistivity, contact resistance, and adhesion, but also in terms of suppressed interfacial reactivity, reduced contact-induced channel shortening, and mobility extraction accuracy. These insights are expected to aid electrode selection and improve the reliability of scaled oxide TFTs for high-resolution display applications.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that no generative AI or AI-assisted technologies were used in the manuscript preparation process.

CRediT authorship contribution statement

Seong-Jae Kim: Validation, Investigation, Formal analysis, Conceptualization. **Hye-In Yeom:** Writing – original draft, Visualization. **Tae Kyu Nam:** Investigation. **Jin Kim:** Writing – review & editing. **Ji-Hwan Ha:** Writing – review & editing. **Sang-Hee Ko Park:** Writing – review & editing. **Jong Beom Ko:** Writing – review & editing, Supervision, Resources, 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

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Data availability

Data will be made available on request.

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