Recent Progress, Opportunities and Properties in Polycrystalline Oxide TFTs

*Gwang-Bok Kim, Sang Won Chung and Jae Kyeong Jeong**
Hanyang University, Seoul, Republic of Korea
E-mail: jkjeong1@hanyang.ac.kr

Abstract

This study explores advanced crystallization methods to enhance oxide TFT performance, addressing the demand for high-mobility, reliable semiconductors in large, ultra-high-resolution OLEDs. While a-IGZO TFTs dominate current applications, evolving technologies necessitate improved crystalline quality, including optimized grain size and orientation. We highlight innovative manufacturing approaches and material science insights that offer potential solutions to the challenges of crystalline oxide semiconductors, paving the way for next-generation display technologies.

Author Keywords

Crystallization; indium zinc tin oxide; thin-film transistor (TFT); OLED

1. Introduction

Amorphous IGZO (*a*-IGZO) has gained prominence since 2004 due to its high field-effect mobility ($\mu_{FE} \geq 10$ cm^2/V·s), low off-current (<1 pA), and compatibility with low-temperature processing. *a*-IGZO TFTs have replaced *a*-Si TFTs in AM-LCDs and OLEDs and are now the standard backplane electronics for AMOLED televisions. However, mobile AMOLED panels still rely on low-temperature polycrystalline silicon (LTPS) due to its superior mobility ($\geq$ 80 cm^2/V·s) and reliability [1-2]. To meet the demand for higher pixel density and reduced power consumption in smartphones, low-temperature polycrystalline oxide (LTPO) technology integrates LTPS and IGZO TFTs. This reduces power consumption through variable frame-rate driving. However, LTPO faces challenges such as high manufacturing costs and low yields due to its complex structure [3]. High-mobility oxide TFTs ($\geq$ 80 cm^2/V·s) offer a promising alternative, simplifying AMOLED fabrication and enabling application in AR, VR, and extended reality (XR).

Efforts to develop high-performance oxide TFTs include multi-component doping, channel crystallization, and dual-gate designs [2]. Crystalline oxides, such as In_2O_3-based bixbyite structures, exhibit promising properties, including high mobility and free-carrier density via percolation conduction. Effective dopants like Ga can suppress carrier traps while promoting crystallization, addressing issues such as threshold voltage (V_{TH}) non-uniformity and leakage currents. Advanced crystallization techniques, both catalyst-free and catalyst-induced, are critical for fabricating oxide TFTs at low temperatures. Catalyst-free methods rely on post-deposition annealing, while catalyst-induced approaches expand processing margins by facilitating structural ordering.

This paper focuses on cutting-edge crystalline oxides and their potential for high-performance TFTs, emphasizing material properties and innovative crystallization methods essential for reliable, scalable devices. Recent studies on bixbyite IGTO and spinel IZTO TFTs, which utilize catalyst-free direct crystallization and catalyst-induced approach, respectively, will also be discussed.

2. Result and Discussion

The crystallization method for semiconducting oxide films can be classified into catalyst-free and catalyst-induced varieties. In catalyst-free crystallization, the composition of cations and anions in a given metal oxide and subsequent post-deposition annealing (PDA) are key factors that determine the microstructure and device performance of crystalline films. The advantages of catalysis-free crystallization lie in processing simplicity. Semiconducting metal oxide films are deposited primarily through physical vapor deposition (PVD) methods such as sputtering or pulsed laser ablation. Although the performance and reliability of multicomponent metal oxide TFTs have been subject to multiple cation composition–dependent investigations, their main focus has been the amorphous phase of the metal channel layer [4-5]. Catalyst-free cation composition–dependent crystallization was recently reported in an IGZO system using ALD [6-8]. The cation composition in ALD can be easily tailored by adjusting the subcycle duty in the supercycle, with different subcycle numbers of binary indium oxide, gallium oxide, and zinc oxide films during ALD growth ensuring the in situ controllability of constituent indium, gallium, and zinc cations in the IGZO film. In general, on-set crystallization of multi-component metal oxides tends to increase with the component number because the diversity of configuration entropy makes it difficult to induce lattice ordering. Because the on-set crystallization temperature for the IGZO system with In:Ga:Zn = 1:1:1 is high ($\geq$ 600 °C), it is important to consider the element of X and relative cation/anion composition in quaternary an In-Ga-X-O system. Our group investigated the evolution of structural properties of IGTO thin-films depending on PO_2 values at a T_{PDA} of 400 °C [9]. An indium-rich IGTO system with a cation composition of In:Ga:Sn = 75:23:2 at% was chosen for catalyst-free low-temperature crystallization. IGTO films prepared at PO_2 values of 10%, and 20% had weakly crystallized and amorphous phases, respectively (**Figure 1(a)-(b)**). Conversely, IGTO film grown at a PO_2 of 0% exhibited the (222) preferential orientation in bixbyite structure (**Figure 1(c)**). The IGTO TFTs at PO_2 of 20% showed a μ_{FE} of 49.3 cm^2 V^{-1} s^{-1}, an *SS* of 0.23 V decade^{-1}, and a V_{TH} of 0.68 V as shown in **Figure 1(d)**. The device performance was improved with decreasing PO_2 value (see **Figure 1(e)**). The best performance was observed for the IGTO TFTs at PO_2 of 0%: they exhibited a high μ_{FE} of 116.5 cm^2 V^{-1} s^{-1}, an *SS* of 0.13 V decade^{-1}, and a V_{TH} of 0.47 V (**Figure 1(f)**). The PBTS instabilities were examined for these IGTO TFTs under the following condition: $V_{DS,ST}$ = 5.1 V, $V_{GS,ST} = V_{TH} + 20$ V and 60 °C for 3,600 s. The ΔV_{TH} values for the amorphous IGTO TFT at PO_2 = 20% after PBTS duration was 1.1 V as shown in **Figure 1(g)**. In contrast, a remarkable ΔV_{TH} of +0.17 V was achieved under the identical PBTS conditions (**Figure 1(i)**).

ISSN 0097-996X/25/5602-0734-$1.00 © 2025

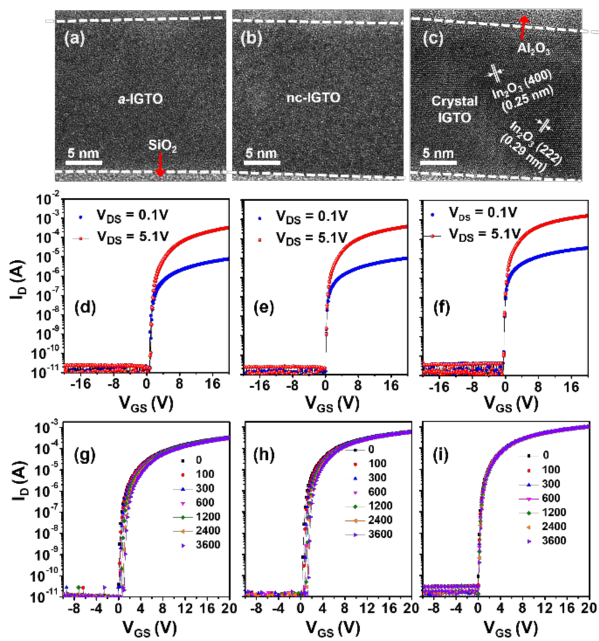

Figure 1. Cross-sectional HR-TEM images of 400 °C-annealed IGTO films at the oxygen flow ratios of (a) 20, (b) 10 and (c) 0%. Representative transfer characteristics of the IGTO TFTs at the oxygen flow ratios of (d) 20, (e) 10 and (f) 0%. Evolution of the transfer characteristics under PBTS for the IGTO TFTs at the oxygen flow ratios of (g) 20, (h) 10 and (i) 0%. Data adapted from reference [9].

However, on-set crystallization temperatures for metal oxides with high zinc or gallium cation contents tend to be relatively high, potentially limiting the thermodynamic crystallization process margin for a variety of multi-component oxide systems. Low-temperature crystallization of multi-component metal oxide substances can be facilitated through catalytic-induced ordering. The conventional method of calcinating metal oxide materials, particularly zinc-based oxide compounds, at high temperatures to transition them from an amorphous to a crystalline state has drawbacks, including the promotion of inter-particle sintering and a need for substantial energy input. An alternative approach, known as metal-induced crystallization (MIC), can crystallize amorphous materials at temperatures ≤ 400 °C. MIC was first reported in 1969 by Oki et al. [10], who demonstrated the crystallization of amorphous germanium using aluminum and noble metals as a capping layer. Since then, research into crystallization induced by MIC has expanded to include *a*-Si [11], titania [12], and various metal oxide semiconductors. Recent studies have focused on developing high-performance metal oxide semiconductor devices using MIC. The underlying principle involves placing a catalytic metal layer in contact with metal oxide semiconductors. This catalytic layer aids in breaking and rearranging weak bonds between cations and oxygen within the oxide layer during PDA [13].

Despite the improved electrical characteristics made possible by the MIC method, a metal capping layer that could overestimate the electrical parameters had not been removed. Our group designed crystalline IZTO films with tantalum capping layer 10 nm thick covering 60% of the channel area, producing TFTs at a low temperature of 300 °C [14], depending on the cation compositions of the Zn/Sn ratios, with the indium fraction fixed at 22 at% to confirm the relationships between microstructure, cation composition and device performance in an $InO_{0.5}$-ZnO-SnO_2 ternary system. To allow for crystallization at a low temperature, a tantalum thin-film 10 nm thick was sputtered on an IZTO channel layer 17 nm thick between S/D electrodes, followed by T_{PDA} at 300 °C for 1 h in ambient O_2. Discernible crystalline structures in three phases (bixbyite, spinel, and rutile SnO_2), two phases (spinel and homologous compounds) and single phase (spinel) were obtained by adjusting the zinc fraction using co-sputtering of In_2O_3, ZnO, and SnO_2 targets, as shown in **Figure 2(a)–(c)**. At an intermediate zinc fraction of 55 at%, a highly aligned spinel single-phase structure was favored. The resulting TFT with a spinel single phase exhibited a μ_{FE} of 83.2 $cm^2 V^{-1} s^{-1}$, an *SS* of 0.15 V $decade^{-1}$, a V_{TH} of −0.14 V, as shown in **Figure 2(d)**, a ΔV_{TH} of +0.19 (−0.22) V under the PBTS and negative bias temperature stress (NBTS) conditions, and excellent V_{TH} uniformity of 0.22 V (for the set of 128 devices). Conversely, The TFT with three phases of a polycrystalline $In_{0.22}Zn_{0.39}Sn_{0.39}O_{1.50}$ channel had an inferior μ_{FE} of 12.5 $cm^2 V^{-1} s^{-1}$, an *SS* of 0.31 V $decade^{-1}$, a V_{TH} of −0.10 V, and a V_{TH} uniformity of 0.7 V. Based on experimental and analytical results, TFTs with multiple phases exhibited degraded performance and reliability, which can be attributed to the presence of adverse GB defects between different crystal phases. Finally, the unnecessary metal capping layer was etched to confirm crystallinity effect of IZTO TFTs with a spinel single phase. The TaO_x-etched TFTs exhibited excellent performance and reliability, similar to those of tantalum-capped IZTO with spinel single phase, as illustrated in **Figure 2(e)–(h)**.

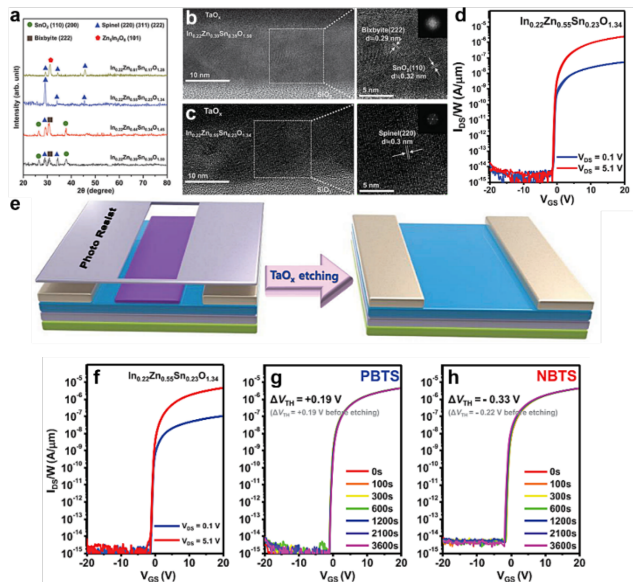

Figure 2. (a) XRD profiles of tantalum-capped crystalline IZTO thin-films with different zinc fractions. Cross-sectional HR-TEM images of IZTO thin-films with zinc fractions of (b) 39 and (c) 55 at%. (d) Representative transfer characteristics of IZTO TFTs with a zinc fraction of 55 at%. (e) Schematic of fabricated IZTO TFT with a zinc fraction of 55 at% before/after reactive ion etching (RIE). (f) Representative transfer characteristics of IZTO TFTs after RIE. (g) PBTS and (h) NBTS results of IZTO TFTs after RIE. Data adapted from reference [14].

.

3. Impact of Your Research

We demonstrated the supeior performance of the polycrystalline bixbyite IGTO and spinel IZTO TFTs fabricated

at a low temperture of ≤ 400 °C through precise cation composition control and a transition metal-assisted crystallization strategy. These polycrystalline oxide TFTs exhibit field-effect mobilities and electrical stabilities comparable to those of low-temperature polycrystalline silicon TFTs, a signficant advancement enabled by their highly ordered crystalline structure. Additionally, the wide bandgap nature of these oxides and their inherently low hole carrier density contributes to ultra-low off-state current, a challenge for polycrystalline Si TFTs. These finding position crystalline oxide backplane technology as a promising altenative to current expensive LTPO technology for IT OLED application on Generation 8 substrates, offering a path toward enhanced peroformanc and energy efficiency in advanced display systems.

4. Acknowledgements

This work was supported by the Industry Technology R&D program (20006400) funded by the Ministry of Trade, Industry & Energy (Korea) and the National Research Foundation of Korea(NRF) grant funded by the Korea government (MSIT) (No. RS-2023-00260527). This work was also supported by Institute of Information & communications Technology Planning & Evaluation (IITP) under the artificial intelligence semiconductor support program to nurture the best talents (IITP-2023-RS-2023-00253914) grant funded by the Korea government.

5. References

1. Nomura K, Ohta H, Takagi A, Kamiya T, Hirano M, Hosono H. Room-temperature fabrication of transparent flexible thin-film transistors using amorphous oxide semiconductors. *Nature* 2004; **432**: 488-492.
2. Kim T et al. Progress, challenge, and opportunities in oxide semiconductor devices: a key building block for application ranging from display backplanes to 3D integrated semiconductor chips. *Adv. Mater.* 2023; **35**: 2204663.
3. Cho M H et al. Recent progress and perspectives on atomic-layer-deposited semiconducting oxides for transistor applications. *J. Soc. Inf. Disp.* 2022; **30**: 175–97
4. Park J et al. Compositional engineering of Hf-doped InZnSnO films for high-performance and stability amorphous oxide semiconductor thin film transistors. *Adv. Elect. Mater.* 21; **7:** 2001216.
5. Jeong J K et al. High performance thin film transistors with cosputtered amorphous indium gallium zinc oxide channel. *Appl. Phys. Lett.* 2007; **91**: 113505.
6. Lee H Y et al. Comparative study on indium precursors for plasma-enhanced atomic layer deposition of In_2O_3 and application to high-performance field-effect transistors. *ACS Appl. Mater. Interfaces* 2023; **15**: 51399–410.
7. Yang H J et al. High-performance thin-film transistors with an atomic-layer-deposited indium gallium oxide channel: a cation combinatorial approach. *ACS Appl. Mater. Interfaces* 2020; **12**: 52937–51.
8. Hur J S et al. High-performance thin-film transistor with atomic layer deposition-derived indium–gallium oxide channel for back-end-of-line compatible transistor applications: cation combinatorial approach *ACS Appl. Mater. Interfaces* 2022; **14**: 48857–67.
9. Kim B K et al. Polycrystalline indium gallium tin oxide thin-film transistors with high mobility exceeding 100 cm^2/Vs *IEEE Electron Device Lett.* 2021; **42**: 347–50.
10. Oki F et al. Effect of deposited metals on the crystallization temperature of amorphous germanium film. *Jpn. J. Appl. Phys.* 1969; **8**: 1056.
11. Bosnell J R and Voisey U C, The influence of contact materials on the conduction crystallization temperature and electrical properties of amorphous germanium, silicon and boron films *Thin Solid Films* 1970; **6**: 161–6.
12. Zhang Y, Li J and Wang J, 2006 Substrate-assisted crystallization and photocatalytic properties of mesoporous TiO_2 thin films. *Chem. Mater.* 2006; **18**: 2917–23.
13. Shin Y et al. The mobility enhancement of indium gallium zinc oxide transistors via low-temperature crystallization using a tantalum catalytic layer. *Sci Rep* 2017; **7**: 10885.
14. Kim G-B et al. High mobility IZTO thin-film transistors based on spinel phase formation at low temperature through a catalytic chemical reaction. *Small Methods* 2023; **7**: 2201522.