Improved electrical performance of solution-processed zinc oxide-based thin-film transistors with bilayer structures

Kazuyori Oura, Hideo Wada, Masatoshi Koyama, Toshihiko Maemoto and Shigehiko Sasa
Nanomaterials Microdevices Research Center, Osaka Institute of Technology, Osaka, Japan

ABSTRACT
A bilayer thin-film transistor (TFT) structure with ZnO and Al-doped ZnO (AZO) was fabricated using a solution process. The film thickness and sintering atmosphere of ZnO and AZO were controlled and then evaluated by measuring their electrical characteristics. By changing the sintering atmosphere, carriers attributed to oxygen vacancies in the thin film increased. Moreover, the ZnO single-layer TFT sintered in N₂ exhibited good electrical characteristics. In the ZnO/AZO bilayer TFT laminated with the ZnO sintered in N₂ and high-resistance AZO thin films, electrical characteristics, such as the On/Off ratio and subthreshold swing, improved compared to those of the ZnO-TFT. The On/Off ratio of the ZnO/AZO-TFT using the AZO thin film sintered in an O₂ atmosphere notably improved to $3.7 \times 10^5$ compared to that of the ZnO-TFT ($1.7 \times 10^4$). In addition, the subthreshold swing in the ZnO/AZO-TFT was 0.36 V/dec, while the field-effect mobility was $2.2 \times 10^{-1}$ cm²/Vs, thereby exhibiting the best electrical characteristics among the fabricated samples. According to the grazing-incidence X-ray diffraction measurement, the ZnO particle size and crystallinity of the ZnO/AZO bilayer were higher than those of the ZnO single layer. Therefore, improvement of the electrical characteristics was confirmed.

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1. Introduction
Amorphous oxide semiconductors have recently been developed for the acquisition of next-generation flat panel displays (FPDs), such as large-area, high-definition, transparent, flexible, and micro-LED displays. These next-generation FPDs are used in various fields and applications including automobiles, medical care, and IoT devices [1–4]. To develop next-generation displays, it is necessary to reduce the cost of devices and improve their mobility. A solution-based non-vacuum film-forming process that enables easy composition control seems to offer a cost-effective method. In the case of printed electronics, a solution process is used in combination with a conventional printing technology, triggering the development of lower-cost, process-saving, and larger-area devices when compared to conventional ones. Production that takes into account environmental concerns, such as resource used and energy conservation as well as the reduced use of hazardous substances, has become feasible [5,6].

Scientific articles on printed electronics include numerous reports on the use of organic semiconductors, but only a few have focused on oxide semiconductors, which exhibit favorable properties such as high electron mobility and effective heat resistance. Oxide semiconductors offer numerous advantages, including high electron mobility and transparency in the amorphous phase. Therefore, oxide semiconductors are expected to form a part of the active layers in the backplanes of thin-film transistors (TFTs) [7,8]. Typical examples include ZnO, In₂O₃, indium zinc oxide (IZO), indium gallium oxide (IGO), and indium gallium zinc oxide (IGZO) [9–13]. Bilayer structure devices composed of different oxide semiconductors have recently been developed, and such devices are expected to improve the drivability and stability of carrier mobility in TFTs [14,15]. Recent progress in materials and film-forming techniques has also led to improvements in the characteristics of bilayer structures such as those of ZnO: H/ZnO, ZnO/In₂O₃, In₂O₃/IZO, In₂O₃/IGO, In₂O₃/IGZO, and IZO/IGZO [16–21].

Al-doped ZnO (AZO), which does not contain rare metals such as In or Ga, has been studied as a candidate material for TFTs. The structure and electrical characteristics of AZO thin films having different amounts of incorporated Al have been previously reported [22]. Recently, the development of ZnO/AZO bilayer channel...
TFTs using the atomic layer deposition technique and the improvement of TFT characteristics have been reported [23,24]. However, only a few detailed reports have investigated the relationship between the heat-treatment conditions of the bilayer structure and film thickness.

In this report, we fabricated bilayer TFTs composed of high-resistance AZO thin films and channel layers of ZnO thin films using a solution process. We found that TFTs fabricated using bilayer AZO and ZnO thin films exhibit enhanced characteristics compared with TFTs fabricated using ZnO thin films. Furthermore, the dependence of the high-resistance AZO layer on the heat-treatment conditions and film thickness was evaluated.

### 2. Experimental design

A ZnO precursor solution was prepared at a concentration of 0.5 mol/L of zinc acetate dihydrate (FUJIFILM Wako Pure Chemical Corp.), monoethanolamine (FUJIFILM Wako Pure Chemical Corp.), and 2-methoxyethanol (FUJIFILM Wako Pure Chemical Corp.). The amounts of aluminum chloride hexahydrate (FUJIFILM Wako Pure Chemical Corp.) and zinc acetate dihydrate used to prepare the AZO precursor solutions were adjusted so that the Zn/Al molar ratio changed from 99/1 to 94/6. The prepared precursor solution was stirred at 60°C for over 3 h.

The thin films were formed via the spin-coating method using the prepared precursor solution. EAGLE XG (Corning Corp.) substrate was sequentially cleaned with toluene, acetone, and isopropanol. The solution was then dropped onto the glass substrate, which was first rotated at 500 rpm for 5 s, and then at 2500 rpm for 20 s. The spin-coated samples were dried on a hotplate at 100°C for 1 min and then on a hotplate at 240°C for 9 min. This process was performed once or twice. Finally, the thin films were sintered under a nitrogen or oxygen atmosphere for 2 h at 500°C. The thickness of the obtained films varied in the range of 30–50 nm with a single coating. Thin films with a thickness of 70–90 nm were obtained using double coating.

Single-layer and bilayer TFTs with a top-gate spacer structure were fabricated using ZnO-based oxide thin films. Ti/Au (50/50 nm) was deposited as the source–drain ohmic electrode, HfO₂ (70 nm) was deposited as a gate insulating film, and Ti/Au (20/100 nm) was deposited as the gate electrode. The electrodes and insulating films were formed using electron-beam evaporation. The fabricated TFT had a gate length \( L_G \) of 2 µm, a spacer length \( L_S \) of 2 µm, and a channel width \( W \) of 50 µm.

The electrical characteristics of the obtained TFT (Agilent, 4156C) were measured. For the output characteristics, the drain current was measured when the gate voltage was applied from −5 to 5 V and the drain voltage was applied from 0 to 10 V. For the transfer characteristics, the drain current was measured when a drain voltage of 10 V was swept and a gate voltage was applied from −5 to 5 V. Surface chemical analysis was performed using X-ray photoelectron spectroscopy (XPS) (Shimadzu KRATOS, AXIS Ultra). Mg-Kα (1253.6 eV) radiation was used as the excitation source. Crystal analysis was performed using grazing-incidence X-ray diffraction (GI-XRD) measurement (Rigaku, Smart lab). The X-ray wavelength of Cu-Kα (\( \lambda = 1.5406 \) Å) was used to reveal the microstructure of the thin films.

### 3. Results and discussion

Figure 1 shows the measurement results of sheet resistance \( R_{sh} \) of AZO thin films having different Al contents, fabricated by double coating. The \( R_{sh} \) values of ZnO thin films annealed in nitrogen and oxygen atmosphere were \( 4.0 \times 10^7 \) and \( 4.1 \times 10^9 \) Ω/sq., respectively. We consider that nitrogen sintering causes oxygen defects in the thin film and increases the number of carriers [25]. An AZO thin film incorporated with 2 mol% Al was observed to have the lowest \( R_{sh} \) of \( 2.8 \times 10^5 \) Ω/sq. By increasing the Al content, a decrease in \( R_{sh} \) was observed. The minimum value was observed at 2 mol%, but as the Al concentration was increased further, the increase in \( R_{sh} \) due to the formation of Al oxides became more apparent than the doping effect.

To reduce the Off-current of the TFTs, we fabricated a bilayer TFT by inserting a high-resistivity AZO thin film with 6 mol% Al between the glass, taking advantage of the large resistance change caused by the change...
in Al content in the ZnO films. Hereinafter, AZO indicates ZnO incorporated with 6 mol% Al. In addition, the AZO precursor solution was prepared at a concentration of 0.3 mol/L to control the film thickness. The thickness of the obtained films was approximately 30 nm with a single coating and approximately 50 nm with double coating. Figure 2 shows schematic diagrams of the fabricated ZnO-TFTs and AZO-TFTs with different film thicknesses and sintering atmospheres. The film thickness of ZnO was approximately 40 nm for a single coat and approximately 70 nm for double coating.

Figure 3 shows the electrical characteristics of the ZnO-TFTs. Figure 3(a–c) shows the transfer and output characteristics of the ZnO-TFTs sintered in N$_2$ atmosphere, and Figure 3(d–f) shows the transfer and output characteristics of the ZnO-TFTs sintered in O$_2$ atmosphere. Table 1 summarizes the results of the ZnO-TFTs. The transconductance ($g_m$), threshold voltage ($V_{th}$), sub-threshold swing (S.S.), the field-effect mobility ($\mu_{FE}$), sheet carrier density ($n_{sh}$), and trap density ($D_{SG}$) in the bandgap are estimated using the following equations

$$g_m = \frac{\Delta I_D}{\Delta V_{GS}}$$

(1)

$$S.S. = \frac{dV_{GS}}{d\log_{10}I_D}$$

(2)
Table 1. Parameters calculated from the transfer characteristics of ZnO-TFT with sintering in N\textsubscript{2} or O\textsubscript{2} atmosphere.

| Sample             | \(g_m\) (\(\mu\)S) | \(On/Off\) \(V_{th}\) (V) | S.S. (V/dec) | \(R_{sh}\) (\(\Omega\)/\(\Omega\)) | \(\mu_{FE}\) (cm\(^2\)/Vs) | \(n_s\) (cm\(^{-2}\)) | \(D_{SG}\) (cm\(^{-2}\))/eV |
|--------------------|-------------------|--------------------------|-------------|-----------------|-----------------|----------------|-----------------|
| ZnO (1 coat, N\textsubscript{2}) | \(4.3 \times 10^{-3}\) | \(4.8 \times 10^4\) | \(-0.9\) | 0.50            | \(2.4 \times 10^{10}\) | \(1.1 \times 10^{-3}\) | \(2.1 \times 10^{10}\) |
| ZnO (2 coats, N\textsubscript{2}) | \(1.2 \times 10^{-1}\) | \(1.7 \times 10^6\) | \(-1.2\) | 0.48            | \(9.9 \times 10^{8}\) | \(2.1 \times 10^{-2}\) | \(1.8 \times 10^9\) |
| ZnO (1 coat, O\textsubscript{2}) | \(1.5 \times 10^{-4}\) | \(2.1 \times 10^2\) | \(-0.1\) | 0.68            | \(3.3 \times 10^{11}\) | \(1.4 \times 10^{-4}\) | \(5.5 \times 10^9\) |
| ZnO (2 coats, O\textsubscript{2}) | \(1.3 \times 10^{-3}\) | \(1.0 \times 10^1\) | \(-0.3\) | 0.36            | \(3.8 \times 10^{10}\) | \(1.5 \times 10^{-3}\) | \(1.7 \times 10^9\) |

\[ \mu_{FE} = \frac{2L_G}{W \cdot C_G} \cdot \frac{I_D}{(V_{GS} - V_{th})^2} \]  

\[ n_s = \frac{1}{q \cdot \mu_{FE} \cdot R_{sh}} \]  

\[ D_{SG} = \frac{C_G}{q} \cdot \left( \frac{S.S.}{\ln 10 \cdot \frac{K T}{q}} - 1 \right) \]

where \(C_G\) is the specific capacitance of the gate dielectric per unit area (1.89 mF/m\(^2\)), \(q\) is the electron charge, \(K\) is Boltzmann’s constant, \(T\) is the absolute temperature, and \(R_{sh}\) is the sheet resistance calculated using the transfer length method measurements. The \(On\)-current and \(Off\)-current of the ZnO-TFT sintered in the N\textsubscript{2} atmosphere were higher than those of the ZnO-TFT sintered in O\textsubscript{2} atmosphere. The \(V_{th}\) was shifted to negative values. For ZnO (2 coats, N\textsubscript{2}) with the lowest sheet resistance, \(\mu_{FE}\) was \(2.1 \times 10^{-2}\) cm\(^2\)/Vs, and the \(n_s\) was \(4.2 \times 10^{11}\) cm\(^{-2}\). The AZO-TFT did not operate as a TFT in any of the sintering atmospheres because the AZO thin film has high resistance and low carrier concentration. Based on these results, a high-resistance AZO was inserted between the glass substrate and the active channel layer to improve the TFT characteristics.

Therefore, a TFT with a bilayer structure of ZnO and AZO was fabricated. Figure 4 shows the schematic diagrams of the fabricated ZnO/AZO-TFTs with different sintering atmospheres and film thicknesses. Table 2 lists the conditions for the ZnO/AZO-TFTs. The ZnO thin film with double coating was sintered in an N\textsubscript{2} atmosphere, and the film thickness was approximately 70 nm.

Figure 5 shows the output and transfer characteristics of the ZnO/AZO bilayer TFT using an AZO thin film sintered in N\textsubscript{2} or O\textsubscript{2} atmosphere. Figure 5(a–c) shows the transfer and output characteristics of the ZnO/AZO-TFTs using an AZO thin film sintered in N\textsubscript{2} atmosphere, while Figure 5(d–f) shows the transfer and output characteristics of the ZnO/AZO-TFTs using an AZO thin film sintered in O\textsubscript{2} atmosphere. Table 3 summarizes the results for the ZnO/AZO-TFTs. On-current increased regardless of the sintering atmosphere of the AZO thin film. The On/Off ratio was \(7.0 \times 10^4\) for ZnO/AZO (2 coats, N\textsubscript{2}) and \(3.7 \times 10^5\) for ZnO/AZO (2 coats, O\textsubscript{2}). In contrast, the drain current did not decrease steeply, and the tail of the drain current was observed even when a higher gate voltage was applied. The sheet carrier concentration increased while employing the bilayer structure compared to ZnO-TFT; \(\mu_{FE}\) of ZnO/AZO (2 coats, O\textsubscript{2}) was \(2.2 \times 10^{-1}\) cm\(^2\)/Vs while its \(n_s\) was \(1.6 \times 10^{12}\) cm\(^{-2}\). The sheet resistance of the ZnO/AZO bilayer structure decreased regardless of the sintering atmosphere, and the sheet resistance of ZnO/AZO (2 coats, O\textsubscript{2}) was the lowest at \(2.4 \times 10^7\) \(\Omega\)/sq. Mobility tended to increase as the film thickness of the ZnO layer of the ZnO-TFT increased.

Table 2. Condition of fabricated ZnO/AZO-TFT with different sintering atmospheres and film thicknesses.

| Sample             | Sintered | Deposition | Thickness |
|--------------------|----------|------------|-----------|
|                    | ZnO      | AZO        | ZnO       | AZO       |
| (a) ZnO/AZO (1 coat, N\textsubscript{2}) | N\textsubscript{2} | N\textsubscript{2} | 2 | 1 | 70 nm | 30 nm |
| (b) ZnO/AZO (2 coats, N\textsubscript{2}) | N\textsubscript{2} | N\textsubscript{2} | 2 | 2 | 70 nm | 50 nm |
| (c) ZnO/AZO (1 coat, O\textsubscript{2}) | N\textsubscript{2} | O\textsubscript{2} | 2 | 1 | 70 nm | 30 nm |
| (d) ZnO/AZO (2 coats, O\textsubscript{2}) | N\textsubscript{2} | O\textsubscript{2} | 2 | 2 | 70 nm | 50 nm |
and the AZO layer of the ZnO/AZO-TFT increased. The sheet carrier concentration did not change significantly regardless of the film thickness of AZO. In addition, the sheet carrier concentration of the ZnO/AZO bilayer structure was higher than that of the ZnO (2 coats, N$_2$) used in the channel layer. In fact, the sheet carrier concentration of ZnO/AZO (2 coats, O$_2$) exhibited a good TFT characteristic of $1.6 \times 10^{12}$ cm$^{-2}$. It has been reported that a layer with a high electron concentration due to two-dimensional electron gas is formed.
Figure 7. Results of XPS measurement of AZO thin film sintered in (a) N₂ or (b) O₂ atmosphere.

**Table 3.** Parameters calculated from the transfer characteristics of ZnO/AZO-TFT with different sintering atmospheres and film thicknesses.

| Sample                  | gₘ (µS) | On/Off | Vₘ (V) | S.S. (V/dec) | Rₛ (Ω/sq.) | μₑ (cm²/V·s) | nₑ (cm⁻²) | Dₑg (cm⁻²/eV) |
|-------------------------|---------|--------|--------|-------------|------------|-------------|-----------|--------------|
| ZnO/AZO (1 coat, N₂)    | 2.0 × 10⁻¹ | 3.9 × 10⁴ | −1.6   | 0.52        | 1.2 × 10⁸  | 1.5 × 10⁻²  | 1.5 × 10¹  | 9.1 × 10¹²   |
| ZnO/AZO (2 coats, N₂)   | 2.4 × 10⁻¹ | 7.0 × 10⁴ | −1.3   | 0.44        | 5.4 × 10⁷  | 1.1 × 10⁻¹  | 1.2 × 10¹  | 7.5 × 10¹²   |
| ZnO/AZO (1 coat, O₂)    | 2.2 × 10⁻¹ | 6.1 × 10⁴ | −0.3   | 0.34        | 9.6 × 10⁷  | 1.0 × 10⁻¹  | 6.9 × 10⁹  | 5.5 × 10¹²   |
| ZnO/AZO (2 coats, O₂)   | 3.1 × 10⁰  | 3.7 × 10⁵ | −0.6   | 0.36        | 2.4 × 10⁷  | 2.2 × 10⁻¹  | 2.2 × 10¹⁰ | 5.9 × 10¹²   |

near the heterointerface as a result of a band alignment in a heterojunction bilayer TFT [26]. To investigate the band structure of the ZnO/AZO bilayer structure, transmittance and UPS were measured. Figure 6(a) shows results of transmittance measurement and optical bandgap estimation for ZnO and AZO. The absorption coefficient α was estimated using the following equation

$$\alpha = -\frac{1}{d} \ln T$$

where d is the thickness of the thin film and T is the film transmittance. The optical bandgap $E_g$ was calculated using the following equation,

$$\alpha hν = A(hν - E_g)^\frac{1}{2}$$

where $h$ is Planck's constant, $ν$ is a wavenumber, and $A$ is a function of the refractive index of a material [27]. Transmittance measurements showed that both films have a high transmittance of 90% in the visible-wavelength region (380–780 nm). It was also confirmed that the position of the absorption edge shifts to the ultraviolet wavelength region due to the uptake of Al. The optical bandgaps were also calculated, and the bandgaps of ZnO and AZO were 7.50 and 7.20 eV. Thus, a potential at the upper end of a valence band and bottom of a conduction band increases with increasing incorporation of Al. Figure 6(b) shows the ultraviolet photoelectron spectroscopy (UPS) measurement results for ZnO and AZO. UPS measurements show that the ionization potential of ZnO and AZO are 7.50 and 7.20 eV. Thus, a potential at the upper end of a valence band and bottom of a conduction band increases with increasing incorporation of Al. Figure 6(c) shows band-structure diagrams estimated by combining the results of transmittance and UPS measurements. The band discontinuity $ΔE$ of the conduction band occurs at 0.35 eV for ZnO/AZO. However, the AZO buffer layer has a low carrier concentration and high resistivity, although we have not been able to clarify the existence of highly concentrated 2D electrons in this structure. In order to investigate the factors that improve electrical characteristics by inserting the lower buffer layer, the surface condition and crystallinity were investigated in detail based on the results of the single-layer and bilayer TFTs.

XPS measurements were performed on the AZO thin film to investigate the effect of the sintering atmosphere. Figure 7 shows the results of the XPS measurements for the O1s orbitals of the AZO thin films sintered in N₂ or O₂ atmosphere. The O1s spectra were decomposed into OH-induced surface contamination (OH: 533.4 eV) as an effect of the adsorption of CO and water molecules, oxygen vacancies (Oᵥ: 532.2 eV), and the bonding of the metal (Zn²⁺) and O²⁻ (M-O: 531.6 eV) in the AZO thin film [28]. The amount of oxygen vacancies was significantly suppressed by O₂ sintering compared to N₂ sintering. This suggests that inserting the AZO thin film sintered in O₂ atmosphere between ZnO and the substrate suppresses interface defects and shifts $V_{th}$ positively [29].

GI-XRD measurements were performed to investigate the change in crystallinity resulting from the bilayer structure. Figure 8 shows the results of the GI-XRD measurements of the AZO, ZnO, and ZnO/AZO thin films. Figure 8(a) shows the XRD pattern of the AZO thin film with a single coat. Figure 8(b) shows the XRD pattern of the AZO thin film with double coating. In addition, the crystal grain size was evaluated for (002) plane using Debye Scherrer’s equation [30]. It was observed that the AZO thin films were slightly crystallized, while the ZnO thin film was mainly oriented in the (002) and (103) planes. The incorporated Al³⁺ ions were smaller than the Zn²⁺ ions, and the Al³⁺ ions were replaced with Zn²⁺ in the ZnO lattice, resulting in a decrease in the AZO crystallite size [31,32]. Additionally, the diffraction peak on the (002) plane of the ZnO thin film, which was
formed on the micro-crystallized AZO thin film, was significantly improved. The grain size of the ZnO/AZO film was larger than that of the ZnO thin film, regardless of the thickness of the AZO thin films. Furthermore, Figure 8(c) presents a cross-sectional TEM image of ZnO/AZO sintered in O2 atmosphere with double coating. The grain size distribution of ZnO on the AZO (6 mol%) thin film was 40–50 nm, and the grain size of the AZO (6 mol%) was approximately 10 nm. Crystal size reduction was observed in the cross-sectional TEM image after incorporating Al. From this experiment, the bilayer TFT characteristics were improved following the enhanced \( R_{th} \) and \( \mu_{FE} \) results. We attribute this to the enhanced crystallinity of the ZnO channel layer, the increased size of the crystal grains, and reduced grain boundaries when using the micro-crystallized AZO buffer layer as the lower layer.

4. Conclusion

ZnO/AZO bilayer TFTs were fabricated using a solution process. The dependence of the AZO thin film’s electrical characteristics on the sintering atmosphere and film thickness was evaluated. Although the On-current is improved by laminating the AZO thin films compared to a ZnO-TFT, \( V_{th} \) and S.S. are affected by the sintering atmosphere of the AZO thin film. By using the AZO thin film sintered in O2 with double coating, the On/Off ratio becomes \( 3.7 \times 10^5 \), S.S. is \( 0.36 \) V/dec, and \( \mu_{FE} \) is \( 2.2 \times 10^{-1} \) cm²/Vs, thus achieving an optimum condition. The GI-XRD measurements obtained show that the ZnO particle size and crystallinity of the ZnO/AZO bilayer were higher than those of the ZnO single layer. Consequently, the electrical characteristics were improved.

![Figure 8. GI-XRD patterns of ZnO, AZO, and ZnO/AZO thin films using AZO thin film with (a) 1 coat and (b) 2 coats and (c) cross-sectional TEM image of ZnO/AZO (2 coats, O2) sample.](image)
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Notes on contributors
Kazuyori Oura received his B.S. and M.S. degree from the Department of Electrical and Electronic System Engineering and major in Electrical, Electronic and Mechanical Engineering at Osaka Institute of Technology, Osaka, Japan, in 2016 and 2018, respectively. His research interests are focused on solution-processed metal oxide-based thin-film transistors.

Hideo Wada received his Doctoral Degree in Electrical Engineering in 1991 from Tokyo University of Science. He subsequently engaged in research on infrared devices in the Sensors Research Division of the Electronic Systems Research Center of the Ministry of Defense for 25 years. In 2019, he was inaugurated as a professor at the Nanomaterials Microdevices Research Center of Osaka Institute of Technology. His main research areas cover the development and evaluation of infrared functional material and devices.

Masatoshi Koyama received his PhD degree from Osaka Institute of Technology (Osaka, Japan) in 2009. He then worked as a GaN-HEMT Process Development and Integration Engineer for Eudyna Device (now Sumitomo Electric Device Innovations, Inc.). In 2015, he became an Assistant Professor at Osaka Institute of Technology (Osaka, Japan). From 2019 to 2020, while remaining in this position, he joined Millimeter-Wave Electronics Group at ETH Zurich (Zurich, Switzerland) as an academic guest. In 2021, he became an Associate Professor at Osaka Institute of Technology (Osaka, Japan). His research interests are focused on the design, process development, fabrication and characterization of GaN-HEMTs and oxide semiconductor devices for RF amplifiers and power devices.

Toshihiko Maemoto received his Doctoral Degree in Electrical and Electronic Engineering from Osaka Institute of Technology in 1995. He joined Osaka Institute of Technology Junior College in 1995 as a lecturer. He subsequently moved to Osaka Institute of Technology as an Associate Professor in 2003. He was inaugurated as a Professor at the Department of Electrical and Electronic Systems Engineering in 2014. He has been researching flexible oxide thin-film transistors and functional device technology for hybrid flexible electronics.

References
[1] J.Y. Choi, and S.Y. Lee, J. Korean Phys. Soc. 71 (5), 516–527 (2017).
[2] H.-H. Hsieh, H.-H. Lu, H.-C. Ting, C.-S. Chuang, C.-Y. Chen, and Y. Lin, J. Inf. Disp. 11 (4), 160–164 (2010).
[3] L. Petti, N. Münzenrieder, C. Vogt, H. Faber, L. Büthe, G. Cantarella, F. Bottacchi, T.D. Anthopoulos, and G. Tröster, Appl. Phys. Rev. 3, 021303 (2016).
[4] T. Wu, C.-W. Sher, Y. Lin, C.-F. Lee, S. Liant, Y. Lu, S.-W. H. Chen, W. Guo, H.-C. Kuo, and Z. Chen, Appl. Sci. 8, 1557 (2018).
[5] S.J. Kim, S. Yoon, and H.J. Kim, Jpn. J. Appl. Phys. 53, 02BA02 (2014).
[6] C.C.-Raya, Z.Z. Denchev, S.F. Cruz, and J.C. Viana, Appl. Mater. Today 15, 416–430 (2019).
[7] K. Nomura, H. Ohta, K. Ueda, T. Kamiya, M. Hirano, and H. Hosono, Science 300, 1269–1272 (2003).
[8] E. Fortunato, P. Barquinha, and R. Martins, Adv. Mater. 24 (22), 2945–2986 (2012).
[9] C.-S. Li, Y.-N. Li, Y.-L. Wu, B.-S. Ong, and R.-O. Loufty, J. Mater. Chem. 19, 1626–1634 (2009).
[10] Y. Meng, G. Liu, A. Liu, H. Song, Y. Hou, B. Shin, and F. Shan, RSC Adv. 5, 37807–37813 (2015).
[11] C.Y. Koo, K. Song, T. Jun, D. Kim, Y. Jeong, S.-H. Kim, J. Ha, and J. Moon, J. Electrochem. Soc. 157 (4), J111–J115 (2010).
[12] S. Jeong, J.-Y. Lee, M.-H. Ham, K. Song, J. Moon, Y.-H. Seo, B.-H. Ryu, and Y. Choi, Superlatt Microstruct 59, 21–28 (2013).
[13] D.I. Kim, D.L. Kim, Y.S. Rim, C.H. Kim, WH. Jeong, H.S. Lim, and H.J. Kim, ACS Appl. Mater. Interfaces 4, 4001–4005 (2012).
[14] J.-S. Seo, and B.-S. Bae, ACS Appl. Mater. Interfaces 6, 15335–15343 (2014).
[15] Y. Li, C. Zhao, D. Zhu, P. Cao, S. Han, Y. Lu, M. Fang, W. Liu, and W. Xu, Nanomaterials 10 (5), 965 (2020).
[16] A. Abliz, C.-W. Huang, J. Wang, L. Xu, L. Liao, X. Xiao, W.-W. Wu, Z. Fan, C. Jiang, J. Li, S. Guo, C. Liu, and T. Guo, ACS Appl. Mater. Interfaces 8, 7862–7868 (2016).
[17] D. Khim, Y.-H. Lin, and T.D. Anthopoulos, Adv. Funct. Mater. 2019, 29, 28, 1902591 (2019).
[18] G.X. Liu, A. Liu, F.K. Shan, Y. Meng, B.C. Shin, E. Fortunato, and R. Martins, Appl. Phys. Lett. 105, 113509 (2014).
[19] X. Yu, N. Zhou, J. Smith, H. Lin, K. Stallings, J. Yu, T.J. Marks, and A. Facchetti, ACS Appl. Mater. Interfaces 5, 7983–7988 (2013).
[20] K. Liang, Y. Wang, S. Shao, M. Luo, V. Pecunia, L. Shao, J. Zhao, Z. Chen, L. Moe, and Z. Cuia, J. Mater. Chem. C 7, 6169–6177 (2019).
[21] N. Tiwari, R.N. Chauhan, P.-T. Liu, and H.-P.D. Shieh, RSC Adv. 6, 75693–75698 (2016).
[22] Y. Ammaih, A. Lfakir, B. Hartiti, A. Ridah, P. Thevenin, and M. Siadat, Opt Quant Electron 46, 229–234 (2014).
[23] S.W. Cho, M.G. Yun, C.H. Ahn, S.H. Kim, and H.K. Cho, Electron. Mater. Lett. 11, 198–205 (2015).
[24] H. Li, D. Han, L. Liu, J. Dong, G. Cui, S. Zhang, X. Zhang, and Y. Wang, N Nanoscale Res. Lett. 12, 223 (2017).
[25] J. Wang, R. Chen, L. Xiang, and S. Komarneni, Ceram. Int. 44, 7357–7377 (2018).
[26] L.-C. Cheng, B.-S. Wang, H.-H. Hou, and J.-Z. Chen, ECS Trans. 50 (8), 83–93 (2012).
[27] Y.-J. Choi, S.C. Gong, D.C. Johnson, S. Golledge, G.Y. Yeom, and H.-H. Park, Appl. Surf. Sci. 269, 92 (2013).
[28] Y.S. Rim, W.H. Jeong, D.L. Kim, H.S. Lim, K.M. Kim, and H.J. Kim, J. Mater. Chem. 22, 12491–12497 (2012).
[29] V. Sarangi, and S. Gandla, J. Mod. Mater. 3 (1), 14–23 (2017).
[30] G. Kaur, A. Mitra, and K.L. Yadav, Prog. Nat. Sci. 25, 12–21 (2015).
[31] A.J. Ghazai, E.A. Salman, and Z.A. Jabbar, Am. Sci. Res. J. Eng. Technol. Sci. 26 (3), 202–211 (2016).
[32] P.L. Sari, H. Munawaroh, S. Wahyuningsih, and A.H. Ramelan, Indones. J. Chem. 20 (1), 54–59 (2020).