Aluminum (Al)-doped indium zinc magnesium oxide (Al:IZMO)-based transparent conductive oxide (TCO) films with a tunable conduction band structure are developed via deposition at room temperature under radio-frequency (RF) magnetron co-sputtering for the application of highly efficient photovoltaic devices. First, at the amorphous phase region with the [In]/([In] + [Zn]) compositional ratio of 0.5–0.8, Al-doped indium zinc oxide (Al:IZO) films obtained by introducing a small amount of aluminum oxide (Al$_2$O$_3$) exhibit higher Hall mobility and lower carrier density than those of indium zinc oxide (IZO) without Al doping. Second, adding magnesium oxide (MgO) to Al:IZO allows the optical bandgap ($E_g$) control, with constant ionization energy of $-7.31$ eV, which can be expressed by $E_g = 0.83y + 3.33$ (eV) as a function of $[\text{Mg}]/([\text{Zn}] + [\text{Mg}])$ compositional ratio ($y$) in the $y$ value region of 0–0.12. This result suggests that the conduction band minimum can be tuned by 0.067 eV under the 8% Mg substitution into the Zn site in the Al:IZMO films while remaining valence band maximum. Al:IZMO-based TCO films with conduction band controllability are deposited at room temperature for preventing thermal damage. These findings contribute to the device design and development of emerging photovoltaic applications.

1. Introduction

Transparent conductive oxide (TCO) films have been widely applied in the development of organic light-emitting diodes, photovoltaic solar cell devices, and thin-film transistors. For applications in various photovoltaics, such as crystalline-silicon, chalcogenide (e.g., Cu(In, Ga)Se$_2$, Cu(In, Ga)S$_2$, and Cu(In, Ga)(S, Se)$_2$), perovskite, and CdTe solar cells, high transparency, low resistivity, and tunable energy band structure in the TCO films are essential for developing the highly efficient devices. TCO films should possess high carrier mobility to be applied in the solar cells. High carrier mobility affords a low sheet resistance and a low carrier density, suppressing free-carrier absorption and high transparency in the visible and near-infrared regions.$^{[1,2]}$ For a high collection efficiency of minority carriers and large built-in potential in the solar cell devices, the conduction band minimum (CBM) for the TCO layers should be tuned according to that of the absorber and electron transport (or n-type buffer) layers. CBM tuning by varying $[\text{Mg}]/([\text{Mg}]+[\text{Zn}])$ compositional ratio in the Al-doped zinc magnesium oxide (Al:Zn, MgO) or boron (B)-doped zinc magnesium oxide (B:Zn, MgO) TCO layers suppress carrier recombination caused by the reduced CBM offset at the heterojunction interface for the Cu(In, Ga)(S, Se)$_2$ and Cu(In, Ga)S$_2$ solar cells.$^{[6]}$ Furthermore, built-in potential in the $pn$-junction can be enhanced according to the CBM shift toward the vacuum level, which is related to the Fermi levels, by varying the $[\text{Mg}]/([\text{Mg}]+[\text{Zn}])$ compositional ratio in the Al:Zn, MgO applied as an n-type TCO layer, boosting the open-circuit voltage for the Cu(In, Ga)S$_2$ solar cells.$^{[6]}$ Therefore, developing the CBM control techniques for TCO films is crucial for photovoltaic device applications.

Low-temperature deposition technique for developing TCO films is highly desirable because it prevents thermal damage during the production of photovoltaic devices, comprising stacked multilayers including heat-sensitive materials (e.g., silicon hetero-junctions,$^{[3–5]}$ Cu(In, Ga)Se$_2$,$^{[6–11]}$ and Cu(In, Ga)(S, Se)$_2$) solar cells). In particular, in the recently opened emerging photovoltaic markets, e.g., building-integrated photovoltaics (BIPV),$^{[14–16]}$ vehicle integrated photovoltaics (VIPV)$^{[14,17–19]}$ and wearable power sources,$^{[20,21]}$ the development of the flexible and...
lightweight thin-film solar cells has remarkably progressed. Flexible perovskite solar cells fabricated on heat-sensitive substrates with high flexibility, such as polyethylene terephthalate (PET) and polyethylene naphthalate (PEN), have been reported. Moreover, despite the high growth temperature of 500–600 °C for Cu(In, Ga)Se₂, by applying the device- peeling technique using MoSe₂ atomic layers, flexible and bifacial Cu(In,Ga)Se₂ solar cells have been developed, which were transferred to ethylene tetrafluoroethylene (ETFE) or fluorinated ethylene propylene (FEP) films with low heat resistance temperature of 150–200 °C as the alternative flexible substrates. Al-doped zinc oxide (AZO) and indium tin oxide (ITO) deposited at room temperature after device-peeling for the back contact electrode of their flexible and bifacial Cu(In, Ga)Se₂ solar cells. According to this recent research progress on photovoltaic devices, the requirement for low-temperature deposition techniques for TCO layers is considerably increasing. Hence, in this study, the TCO films with controllable CBM are developed for applying high-efficient photovoltaics, which can be deposited at room temperature for preventing thermal damages to the devices.

A transparent amorphous oxide is free from grain boundaries and can accommodate large bond angle distributions. Therefore, the amorphous/poly crystalline semiconductor interface had a lower defect density than that in the conventional polycrystalline/poly crystalline semiconductor interfaces; thus, the transparent amorphous oxide materials are useful for developing TCO layers in the solar cells. Amorphous indium zinc oxide (α-IZO) is a promising TCO layer with the highest carrier mobility of ∼60 cm² V⁻¹ s⁻¹[30,31] deposited evenly at room temperature. In IZO, the vacant 5s orbitals in indium cations, which is a posttransition heavy metal element, form the large band dispersion owing to their large spatial overlap in the neighboring atoms; therefore, affording an electron conduction path and the high mobility despite the amorphous phase deposited at low temperature.[32,33] Via the elemental substitution, the electrical properties and energy band structure in IZO can be controlled so that they can be applied as the TCO layers for developing high-performance photovoltaic devices. In the Al-doped a-IZO matrix,[34–36] an increase in the Hall mobility caused by co-sputtering Al₂O₃ and IZO was reported, which can be attributed to extra conduction paths formed by Al cations in the network of In cations.[34] To deposit an electrically stable IZO, Al atoms for the stabilizer ions were doped as a carrier suppressor, thereby reducing oxygen deficiencies.[37] Furthermore, MgO has a wide optical band gap (Eg) of ∼7.9 eV [38] thereby facilitating band structure controllability by mixing in the oxide-based compound semiconductor. Optical Eg can be controlled from 3.6 to 3.8 eV by varying the Mg content x of 0–0.5 in InₙOₓ(Zn₁₋ₓMgₓ) deposited at a temperature of 300 °C[39] where InₓOₙ(ZnO)ₓ₋ₙ is an InₓOₙ(ZnO)ₙ (k = 3–9, 11, 13, and 15) family with a homologous structure and comprises cubic-bixbyite-structured InO₁₋ₚ and wurtzite-structured 4In₁₋ₚZnₚO₁₋ₚₚ layers repeatedly stacked along the c-axis.

The TCO films with continuously tunable CBM deposited at room temperature developed for the solar cell application is the only Al(Zn,Mg)O films.[34,36,40] In this study, the TCO materials deposited at room temperature with CBM controllability are investigated with a focus on the IZO-based materials, where higher mobility can be expected. Based on the comparison between InₓOₙ−ZnO (without Al₂O₃) and InₓOₙ−AZO (with Al₂O₃) systems, the effect of Al-doping into the IZO films deposited at room temperature via co-sputtering is comprehensively discussed for a [In]/([In] + [Zn]) compositional ratio of 0–1.0. Then, for the Al-doped amorphous IZO films (Al:α-IZO) with the highest mobility at the [In]/([In] + [Zn]) compositional ratio of 0.55–0.65, the energy band structure obtained by Mg addition is systematically investigated based on the optical Eg and ionization energy. Finally, room-temperature deposition of developed Al-doped indium zinc magnesium oxide (Al:IZMO) films with tunable CBM on a heat-sensitive flexible FEP substrate is demonstrated. These findings contribute to the realization of high-performance solar cell devices and the development of emerging photovoltaic applications.

2. Results and Discussion

2.1. Effect of Al-Doping on InₓOₙ−ZnO Systems

Two IZO films were co-sputtered using InₓO₃ and ZnO or AZO (Al₂O₃: 2 wt%) targets for discussing the correlation between Al-doping and electrical properties. Figure 1 depicts the XRD spectrum associated with the TCO films: a) InₓOₙ−ZnO and b) InₓOₙ−AZO systems deposited at room temperature via
an RF-magnetron co-sputtering system. The TCO samples with 
\([\text{In}] / ([\text{In}] + [\text{Zn}])\) compositional ratio of 0 and 1.0 were identified as wurzite and bixbyite structures, respectively, where the PDF Card #01-075-0533 (ZnO) and #00-006-0416 (In$_2$O$_3$) were referenced. The homologous phases were observed in both the In$_2$O$_3$–ZnO and In$_2$O$_3$–AZO systems at the region with a 
\([\text{In}] / ([\text{In}] + [\text{Zn}])\) compositional ratio of 0.3–0.4 [\#00-020-1441 (Zn$_2$In$_2$O$_{10}$) and #00-020-1440 (Zn$_3$In$_3$O$_{18}$)] and the amorphous phases are observed at the region with a 
\([\text{In}] / ([\text{In}] + [\text{Zn}])\) compositional ratio of 0.5–0.8. Figure 2 shows Hall effect measurement of: a) resistivity, b) mobility, and c) carrier density for TCO films of In$_2$O$_3$–ZnO and In$_2$O$_3$–AZO systems as a function of 
\([\text{In}] / ([\text{In}] + [\text{Zn}])\) compositional ratio. Mobility of In$_2$O$_3$–ZnO system increased from 12.2 to 20.0 cm$^2$ V$^{-1}$s$^{-1}$ when the 
\([\text{In}] / ([\text{In}] + [\text{Zn}])\) compositional ratio increased from 0 to 0.60 and declined to 9.8 cm$^2$ V$^{-1}$s$^{-1}$ when the 
\([\text{In}] / ([\text{In}] + [\text{Zn}])\) reached to 1.0. The carrier density increased from 6.55 × 10$^{20}$ to 1.14 × 10$^{21}$ cm$^{-3}$ with the 
\([\text{In}] / ([\text{In}] + [\text{Zn}])\) compositional ratio from 0 to 0.76. This trend is consistent with the reported results.[41] Because the bond strength of In–O is lower than that of Zn–O, oxygen vacancies increased with the 
\([\text{In}] / ([\text{In}] + [\text{Zn}])\) compositional ratio, affording higher carrier density in IZO.

Remarkably, lower and higher carrier mobilities with the In$_2$O$_3$–AZO system, compared to the In$_2$O$_3$–ZnO system, were observed at the regions of the 
\([\text{In}] / ([\text{In}] + [\text{Zn}])\) compositional ratio of 0.3–0.4 (homologous) and 0.5–0.8 (amorphous), respectively. In the amorphous region with the 
\([\text{In}] / ([\text{In}] + [\text{Zn}])\) compositional ratio of 0.5–0.8 in the In$_2$O$_3$–AZO system, carrier mobility was improved because of the following two factors. First, the extra conduction pathways were formed via Al$_2$O$_3$ doping. The overlap between neighboring In 5s orbitals in IZO affords high carrier mobility despite an amorphous phase.[32,33] Furthermore, by co-sputtering Al$_2$O$_3$ and IZO targets, Hall mobility was improved because of the extra electron conduction pathways formed by Al 3s orbitals in the network of In cations, affording higher mobility.[34] Second, oxygen vacancies were reduced by Al-doping, suppressing the scattering of carriers by ionized impurities. Higher chemical bonding energy of Al with O atoms, rather than In and Zn atoms, affords reduced oxygen vacancies.[37,42] In particular, in this study, oxygen gas was not introduced during the IZO sputtering process. Therefore, the effect of suppression for the excess oxygen vacancies by Al-doping as a carrier suppressor was notably observed in the In$_2$O$_3$–AZO system. At the 
\([\text{In}] / ([\text{In}] + [\text{Zn}])\) compositional ratio exceeding 0.4, carrier density was lower in the In$_2$O$_3$–AZO than that in In$_2$O$_3$–ZnO systems (Figure 2c), implying the reduced oxygen vacancies caused by Al-doping. Finally, at the 
\([\text{In}] / ([\text{In}] + [\text{Zn}])\) ratio of 0.65, the highest mobility of 32.6 cm$^2$ V$^{-1}$s$^{-1}$ was realized for the Al:a-IZO films with a suppressed carrier density of 2.12 × 10$^{20}$ cm$^{-3}$, affording a resistivity of 7.19 × 10$^{-4}$ Ωcm. Hall mobility for the Al:a-IZO films in the region with a 
\([\text{In}] / ([\text{In}] + [\text{Zn}])\) compositional ratio of 0.55–0.65 was high compared to AZO films. Figure 3 depicts the transmittance (T) of the TCO films of: a) In$_2$O$_3$–ZnO and b) In$_2$O$_3$–AZO systems as well as c) average T at the wavelength region of 700–1300 nm and d) optical $E_g$ as a function of the 
\([\text{In}] / ([\text{In}] + [\text{Zn}])\) compositional ratio (x) for the TCO samples of In$_2$O$_3$–ZnO and In$_2$O$_3$–AZO systems deposited at room temperature via RF-magnetron sputtering system. The average T was examined in a long-wavelength region from 700 to 1300 nm since the free-carrier absorption is clearly observed in the range. The average T at the wavelength region of 700–1300 nm in Figure 3c was estimated based on data depicted in Figure 3a, b. The optical $E_g$ in Figure 3d was extracted by the (εhν)$^2$ plot as a function of hν, as shown in the supporting information (Figure S2, Supporting Information). For In$_2$O$_3$–AZO and In$_2$O$_3$–ZnO systems, the $E_g$ at 
\([\text{In}] / ([\text{In}] + [\text{Zn}])\) compositional ratio below 0.4 was decreased with In content. Zn$_3$In$_2$O$_8$, a material in In$_2$O$_3$–ZnO systems with an 
\([\text{In}] / ([\text{In}] + [\text{Zn}])\) compositional ratio of 0.5, had $E_g$ of 2.9 eV lower than that of 3.3 eV in ZnO.[29] Therefore, the $E_g$ was reduced by incorporating In into ZnO. At the region of the 
\([\text{In}] / ([\text{In}] + [\text{Zn}])\) compositional ratio below 0.4, average T at the wavelength region of 700–1300 nm was low (Figure 3c) and optical $E_g$ was high (Figure 3d) in the In$_2$O$_3$–AZO system compared to the In$_2$O$_3$–ZnO system. Al atom act as a donor in the ZnO.[30,43,44] Hence, at the 
\([\text{In}] / ([\text{In}] + [\text{Zn}])\) compositional ratio of 0, Al-doping affords a higher carrier density of 4.50 × 10$^{20}$ cm$^{-3}$ (AZO) in the In$_2$O$_3$–AZO system than that of 6.55 × 10$^{20}$ cm$^{-3}$ (ZnO) in the In$_2$O$_3$–ZnO system (Figure 2c). Therefore, free-carrier absorption afforded reduced average T.

Figure 2. a) Resistivity, b) mobility, and c) carrier concentration performed via the Hall effect measurement for the TCO films of the In$_2$O$_3$–ZnO and In$_2$O$_3$–AZO systems as a function of 
\([\text{In}] / ([\text{In}] + [\text{Zn}])\) compositional ratio.
at the wavelength of 700–1300 nm in low [In]/([In] + [Zn]) compositional ratios below 0.4. Moreover, optical $E_g$ widening occurred because of Burstein–Moss effect observed in the heavily doped degenerated semiconductors.[45] At the [In]/([In] + [Zn]) compositional ratio exceeding 0.7, the transmittance at the wide wavelength region of 400–1300 nm was reduced in both cases of the $\text{In}_2\text{O}_3$–ZnO and $\text{In}_2\text{O}_3$–Al:IZO systems (Figure 3a–c). A metal-like dark film is formed under the zero or low oxygen partial pressure during the sputtering process caused by the oxygen-deficient in $\text{In}_2\text{O}_3$–ZnO–SnO$_2$.[46,47] Therefore, because oxygen gas did not flow in this work, the oxygen deficiency results in a low transmittance in the In-rich condition with the [In]/([In] + [Zn]) ratio exceeding 0.7 due to the bond strength of In–O weaker than that of Zn–O. By least-squares fitting at the region with a [In]/([In] + [Zn]) compositional ratio value ($x$) from 0 to 1.0, the variation in optical $E_g$ for the $\text{In}_2\text{O}_3$–ZnO and $\text{In}_2\text{O}_3$–Al:IZO systems (Figure 3d) can be expressed as the following equations

\begin{align}
\text{In}_2\text{O}_3 – \text{ZnO}: E_g &= 0.715x^2 - 0.408x + 3.27 \\
\text{In}_2\text{O}_3 – \text{AZO}: E_g &= 1.25x^2 - 1.27x + 3.60
\end{align}

Finally, relatively high carrier mobility and transparency in the $\text{In}_2\text{O}_3$–Al:IZO TCO films deposited at room temperature compared with the conventional AZO TCO were obtained at the amorphous phase region with an optimum [In]/([In] + [Zn]) compositional ratio of 0.55–0.65. The next section discussed the influence of Mg addition to Al:IZO films on controlling the CBM band structure.

### 2.2. Conduction Band Tuning of Al-Doped IZO Films via Mg Addition

To realize the CBM controllability for the TCO films, MgO was added to the Al:IZO films by co-sputtering using $\text{In}_2\text{O}_3$, AZO, and MgO targets. Mg atoms replace Zn atoms in Al:IZO films. In this section, structural, electrical, and optical properties are discussed for the Al:IZMO films with the [In]/([In] + [Zn] + [Mg]) compositional ratio of 0.67 ± 0.05 while varying the [Mg]/([Zn] + [Mg]) ratio. Figure 4 depicts: a) mobility, b) carrier density, c) sheet resistance performed using the Hall effect measurement system, d) XRD spectrum, and e) optical $E_g$ and ionization energy (IE) as a function of [Mg]/([Zn] + [Mg]) ratio ($\nu$) for the Al:IZMO films. The optical $E_g$ and IE were extracted from the plots of ($ahu$)$^2$ as a function of $hu$ (Figure S3, Supporting Information) and $Y^{1/3}$ as a function of $hu$ ($Y$: photoemission yield intensity) (Figure S5, Supporting Information), respectively, as shown in the supporting information. In the Hall mobility and carrier density, there was no clear trend at the [Mg]/([Zn] + [Mg]) ratio below 0.1; however, they decreased at the [Mg]/([Zn] + [Mg]) ratio exceeding 0.1. Therefore, sheet resistance of the Al:IZMO films were increased at an [Mg]/([Zn] + [Mg]) compositional ratio exceeding 0.1 (Figure 4c). Hence, the Al:IZMO films with the [Mg]/([Zn] + [Mg]) compositional ratio of 0–0.10 should be stable when used as a TCO layer in the photovoltaic devices because the sheet resistance is below 10 Ω sq.−1. In the XRD spectrum, the Al:IZMO films crystallized and became the homologous phase by Mg addition (Figure 4d). This crystallization mechanism should be investigated in more detail. However, one of
the possible reasons is energy induced by the additional sputtering power for the Mg targets, causing the promoted crystallization. In Figure 4e, optical $E_g$ was monotonically increased and the IE was constant. By linear least-squares fitting at the region with the $[\text{Mg}] / ([\text{Zn}] + [\text{Mg}])$ compositional ratio value ($y$) from 0 to 0.12, the variation in $E_g$ and IE for Al:IZMO films can be expressed using the following equations

$$E_g = 0.83y + 3.33$$

$$IE = -0.05y - 7.31$$

The optical $E_g$ is widening because of the Mg addition rather than Burstein–Moss effect owing to decreasing trend in the carrier density with the $[\text{Mg}] / ([\text{Zn}] + [\text{Mg}])$ ratio depicted in Figure 4b. Moreover, because the IE was estimated to be an almost constant value of $-7.31$ eV, the valence band maximum (VBM) was fixed. By contrast, CBM was shifted by 0.067 eV toward the vacuum level under the Mg substitution into the Zn site by 8%. This finding helps the design of the highly efficient solar cells considering the energy band structure. This $E_g$ widening affords enhanced activation energy for donor-related shallow defect states, hindering the climbing of the carriers to the conduction band.\cite{48,49} Furthermore, MgO has high formation energy of oxygen vacancies of 9.8 eV,\cite{48} thus reducing the oxygen vacancies in Al:IZMO with increasing $[\text{Mg}] / ([\text{Zn}] + [\text{Mg}])$ compositional ratio. For these reasons, carrier density was decreased at the $[\text{Mg}] / ([\text{Zn}] + [\text{Mg}])$ compositional ratio exceeding 0.1, as shown in Figure 4b. For demonstrating the usefulness of the solar cell application, developed Al:IZMO films were deposited at room temperature on a heat-sensitive flexible FEP substrate. Figure 5 depicts transmittance and photograph of the Al:IZMO films with the thicknesses of $\approx$1000 nm and a $[\text{Mg}] / ([\text{Zn}] + [\text{Mg}])$ compositional ratio of 0.12 deposited on (a,b) glass and (c,d) heat-sensitive flexible 250 µm thick FEP substrates. In the substrate cases of glass and flexible FEP substrates, high transmittance of $\approx$80% at the wavelength region of 400–1300 nm was observed. Thus, Al:IZMO films can be formed on flexible FEP

![Figure 4](image1.png)

![Figure 5](image2.png)
with a heat-resistant temperature of 150–200 °C, preventing thermal damages during sputtering process.

The Al:IZMO-based TCO layers with the stable conductivity by the Al-doping and tunable CBM via Mg addition were realized. Moreover, their room-temperature deposition on heat-sensitive flexible FEP substrate prevented thermal damage during the fabrication process. Based on these findings, the device design of the solar cell structures and emerging photovoltaic applications are developed.

3. Conclusions

For highly efficient photovoltaic application, Al:IZMO-based TCO films with tunable CBM were developed, which can be deposited at room temperature for preventing thermal damages. First, at the amorphous region with [In]/([In] + [Zn]) compositional ratio of 0.6–0.7, Al:IZO films had higher Hall mobility and lower carrier density compared to a-IZO without Al-doping, achieving the highest carrier mobility of 32.6 cm V⁻¹ s⁻¹. Second, MgO addition into the Al:IZO led to control of the $E_g$, which can be expressed by $E_g = 0.83y + 3.33$ (eV) as a function of $[Mg]/([Zn] + [Mg])$ compositional ratio ($y$) at the y value region of 0–0.12 while remaining $IE$ of −7.31 eV. This result suggests that VBM was fixed with the Mg addition while the CBM was shifted by 0.067 eV toward the vacuum level under the Mg substitution into the Zn site by 8% in the Al:IZMO films. Finally, Al:IZMO films with the $[Mg]/([Zn] + [Mg])$ compositional ratio of 0.12 on the heat-sensitive flexible FEP substrates, which have a heat-resistant temperature of 150–200 °C, were demonstrated, implying that thermal damages were prevented during the deposition process. These findings will facilitate the device design of the solar cells, developing the emerging photovoltaic applications.

4. Experimental Section

First, the influence of Al-doping on the IZO films is discussed. 1000 nm thick TCO films of In$_2$O$_3$–ZnO (without Al-doping) and In$_2$O$_3$–AZO (with Al-doping) systems were deposited on glass substrates at room temperature via a radio-frequency (RF) magnetron co-sputtering system. In$_2$O$_3$ and ZnO targets in the In$_2$O$_3$–ZnO system or In$_2$O$_3$ and AZO (Al$_2$O$_3$; 2 wt% doped) targets in the In$_2$O$_3$–AZO system were used. The [In]/([In] + [Zn]) compositional ratio was changed from 0 to 1.0 by varying the sputtering power applied to In$_2$O$_3$ and ZnO (or AZO) targets from 0 to 140 W. Second, the effect of Mg addition on the Al:IZO films is discussed. The In$_2$O$_3$, AZO, and MgO targets were used in this section. $[Mg]/([Zn] + [Mg])$ compositional ratio was controlled from 0 to 0.12 by changing the sputtering power from 0 to 140 W. All applied targets had a diameter of 76.2 mm and 99.99% (4 N) purity. The background pressure before the deposition, working pressure, and pure Ar gas flow rate were 2.0 × 10⁻⁴ Pa, 0.25 Pa, and 10 sccm, respectively. The elemental composition was estimated using energy-dispersive X-ray spectrometry (EDX) (EMAX x, act, HORIBA) under an acceleration voltage of 4 kV via scanning electron microscopy. The X-ray diffraction (XRD) θ–2θ scan was conducted using Cu Kα radiation with a wavelength of 1.5405 Å using a measurement system (X’Pert PRO, PANalytical). Optical $E_g$ was estimated from the plot of the $(a/b^2) \times 10^6$ as a function of photon energy ($h\nu$), where the absorption coefficient of the films (α) was calculated from transmittance and reflectance spectra measured using an ultraviolet/visible near-infrared spectrophotometer (UV-3600, Shimazu). The electrical properties and the ionization energy were investigated using a Hall effect measurement system (ResiT Test 8400, TOYO) and by the $Y^{1/3}$ plot as a function of $h\nu$ using the photoelectron yield spectroscopy (PYS) system (BIP-KV221K, Bunkoukeiki), where the Y is photoemission yield intensity, respectively.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.

Keywords

AZO, conduction band, IZO, MgO, mobility, room-temperature deposition, solar cells

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