Research Article

Fabrication and Characterization of Copper System Compound Semiconductor Solar Cells

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Copper system compound semiconductor solar cells were produced by a spin-coating method, and their cell performance and structures were investigated. Copper indium disulfide- (CIS-) based solar cells with titanium dioxide (TiO_2) were produced on F-doped SnO_2 (FTO). A device based on an FTO/CIS/ TiO_2 structure provided better cell performance compared to that based on FTO/ TiO_2 /CIS structure. Cupric oxide- (CuO -) and cuprous oxide- (Cu_2O -) based solar cells with fullerene (C_{60}) were also fabricated on FTO and indium tin oxide (ITO). The microstructure and cell performance of the CuO/C_{60} heterojunction and the $\text{Cu}_2\text{O}:\text{C}_{60}$ bulk heterojunction structure were investigated. The photovoltaic devices based on FTO/ CuO/C_{60} and ITO/ $\text{Cu}_2\text{O}:\text{C}_{60}$ structures provided short-circuit current density of 0.015 mAcm^{-2} and 0.11 mAcm^{-2} , and open-circuit voltage of 0.045 V and 0.17 V under an Air Mass 1.5 illumination, respectively. The microstructures of the active layers were examined by X-ray diffraction and transmission electron microscopy.

1. Introduction

Chalcopyrite semiconductors are expected as one of the alternative materials to silicon solar cells. The features of chalcopyrite semiconductors include high optical absorption efficiency, low light degradation, and high radiation resistance. Copper indium disulfide, CuInS_2 (CIS) is a well-known p-type chalcopyrite semiconductor. CIS is a suitable material for high-efficiency solar cells because its bandgap (1.5 eV) is close to the ideal energy gap, which is well matched with the solar spectrum. In addition, the band structure shows direct transition, which provides a high efficiency. The highest efficiency of 12% as the absorber layer has been obtained for the CIS solar cells by using the expensive vacuum evaporation technique [1]. Most of the efficient CIS-based solar cells have been prepared by using CdS as buffer layers.

Cd-free CIS-based solar cells with TiO_2 and In_2O_3 have been fabricated by an evaporation method [2–4] and reported to show efficiencies of 3~9.5% [3, 4]. Titanium

dioxide (TiO_2) as an n-type semiconductor has also been used as electrode materials for dye-sensitized solar cells [5]. TiO_2 is also a safe and low-cost material for environmentally harmonized solar cells. A low-cost method is essential for the mass production of CIS-based solar cells, and spin coating is a more economical method compared with vacuum evaporation [6–8]. CIS thin films deposited by sol-gel spin-coating methods have also been investigated and reported [9, 10]. The resulting structure closely resembles that of polymeric bulk heterojunction cells (polymer/ C_{60}) fabricated using organic materials [11–13]. The bulk heterojunction structures contribute to increase the p-n heterojunction interface for photoelectric conversion region in the devices. The aim of the present work was to investigate whether the TiO_2 /CIS structure by penetration of CIS nanocrystals into the porous TiO_2 layer could function as a bulk heterojunction structure.

Oxide semiconductors are one of the alternatives to silicon solar cells. Features of oxide semiconductors are high optical absorption and low cost of raw materials. Copper oxides (CuO and Cu_2O) are well-known p-type

FIGURE 1: Structures of (a) FTO/TiO₂/CIS/Al, (b) FTO/CIS/TiO₂/Al, (c) FTO/CuO/C₆₀/Al heterojunction solar cells, and (d) ITO/PEDOT:PSS/Cu₂O:C₆₀/Al bulk heterojunction solar cells.

oxide semiconductors. CuO and Cu₂O are suitable materials for high-efficiency solar cells because those direct bandgaps (~ 1.5 eV and ~ 2.0 eV) are close to the ideal energy gap for solar cells, and are well matched with the solar spectrum. The highest efficiency of $\sim 2\%$ has been obtained for Cu₂O solar cells by using a high-temperature annealing method and an expensive vacuum evaporation technique [14]. Heterojunction solar cells with Cu₂O and ZnO have been fabricated by electrodeposition and photochemical deposition methods [15–17], and an efficiency of $\sim 0.001\%$ was reported [17]. However, p-n heterojunction interface area for photoelectric conversion is small. One of improvements is to increase the p-n heterojunction interface by blending of p-type and n-type semiconductors, which are called bulk heterojunction solar cells [6–8]. Although CuO is used as a hole transfer layer and a barrier layer for dye-sensitized solar cells [18, 19], few solar cells with CuO used as a p-type semiconductor active layer have been investigated. The advantage of CuO is a simple production method.

Fullerene (C₆₀) is a good acceptor material for solar cells, and has been used as n-type semiconductor active layer for

organic thin film solar cells [12, 20]. A low-cost method is essential for mass production of CuO-based solar cells, and spin coating is a more economical method compared to vacuum evaporation [6, 7]. CuO thin films deposited by sol-gel spin-coating methods have also been investigated and reported [21].

The purpose of the present work was to prepare copper-based semiconductor solar cells by using a spin-coating method, and to investigate the microstructures and photovoltaic properties for TiO₂/CIS and CuO/C₆₀ and Cu₂O:C₆₀ structures. The solar cells were investigated by microstructure analysis, optical absorption, and electronic property measurements.

2. Experimental Procedures

2.1. Fabrication of Dioxide/Copper Indium Disulfide Solar Cells. Two types of solar cells with TiO₂/CIS and CIS/TiO₂ structures were fabricated as shown in Figures 1(a) and 1(b), respectively. TiO₂ and CIS layers were coated on precleaned F-doped SnO₂ (FTO) glass plates (Asahi Glass, $\sim 9.3 \Omega/\square$) by

TABLE 1: Measured parameters of solar cells.

Layered samples	FTO/TiO ₂ /CIS/Al	FTO/CIS/TiO ₂ /Al	FTO/CuO/C ₆₀ /Al	ITO/PEDOT:PSS/Cu ₂ O:C ₆₀ /Al
V _{OC} (V)	1.1×10^{-3}	0.010	0.045	0.17
J _{SC} (mA/cm ²)	3.6×10^{-4}	6.0×10^{-3}	0.015	0.11
FF	0.25	0.25	0.25	0.23
η (%)	1.0×10^{-7}	1.5×10^{-5}	1.7×10^{-4}	4.3×10^{-3}

using a spin-coating method. TiO₂ layers with a thickness of $\sim 10 \mu\text{m}$ were prepared by squeegee coating using a TiO₂ paste (0.6 g/mL) of fine TiO₂ powders (P25, Sigma Aldrich) in an acetylacetone/polyethylene glycol solution and were annealed at 450°C for 30 minutes in air [22]. Copper acetate monohydrate, Cu(CH₃COO)₂ · H₂O (0.5 mol/L, Sigma Aldrich, 99.99%) and indium acetate, In(CH₃COO)₃ (0.5 mol/L, Sigma Aldrich, 99.99%) were dissolved into 2-propanol/monoethanolamine with a ratio of 4:1 and 1-propanol/diethanolamine with a ratio of 4:1, respectively, and the two solutions were then mixed. The molar ratio of Cu:In was 1:1. Cu-In layers of CIS precursor substance were prepared by spin coating at 1000 rpm using a mixed Cu-In solution. The Cu-In films were annealed at 200°C under an N₂ atmosphere for 30 minutes. The films were sulfurated by dipping in sulfur solution (1.0 mol/L) in *o*-dichlorobenzene. After annealing at 500°C for 30 minutes in a N₂(95%)/H₂(5%) mixture gas, CIS layers with a thickness of $\sim 100 \text{ nm}$ were formed from the Cu-In films.

2.2. Fabrication of Copper Oxide/Fullerene Solar Cells. CuO and C₆₀ layers were coated on precleaned FTO glass plates (Asahi Glass, $\sim 9.3 \Omega/\square$) by using a spin-coating method. Copper acetate monohydrate, Cu(CH₃COO)₂ · H₂O (0.5 mol/L, Sigma Aldrich, 99.99%) was dissolved into 2-propanol/monoethanolamine. Cu layers of CuO precursor substance were prepared by spin coating at 1000 rpm using the mixture Cu solution. After annealing at 300°C under air atmosphere for 3 hours, CuO layers with a thickness of $\sim 100 \text{ nm}$ were formed from the Cu(II) films. C₆₀ layers with a thickness of $\sim 100 \text{ nm}$ were prepared on a CuO layer by spin coating using a C₆₀ solution (16 mg/mL) with C₆₀ powders (Material Technologies Research, 99.98%) in *o*-dichlorobenzene, and were annealed at 100°C for 30 minutes in N₂ atmosphere.

Cu₂O nanoparticles were synthesized by reducing copper-amine complex with 1-heptanol in the presence of tetramethyl ammonium hydroxide. The details of the synthesis scheme were as follows: Copper acetate and oleylamine were introduced into 1-heptanol and heated under a nitrogen atmosphere at 120°C for one hour to remove the moisture in the system. Then, tetramethyl ammonium hydroxide (TMAOH) dissolved in 1-heptanol ($\sim 150^\circ\text{C}$) was introduced and the suspension was heated at 150°C for 2 hours. Next, the suspension was cooled to room temperature and Cu₂O nanoparticles were recovered by centrifuging. Finally, the Cu₂O nanoparticles were washed with methanol to remove excess oleylamine, and the Cu₂O nanoparticles ($\sim 100 \text{ mg}$) were dispersed in toluene (10 mL).

A thin layer of polyethylenedioxythiophene doped with polystyrene-sulfonic acid (PEDOT:PSS) (Sigma Aldrich) was spin-coated at 2000 rpm on precleaned indium tin oxide (ITO) glass plates (Geomatec Co., Ltd., $\sim 10 \Omega/\square$). After annealing at 100°C for 10 minutes in N₂ atmosphere, semiconductor layers were prepared on a PEDOT layer by spin coating using a mixed solution of a toluene with Cu₂O nanoparticle and a C₆₀ solution (16 mg/mL) with C₆₀ powders (Material Technologies Research, 99.98%) in *o*-dichlorobenzene. The thickness of the bulk heterojunction structure was approximately $\sim 150 \text{ nm}$. The Cu₂O:C₆₀ layers were annealed at 100°C for 30 minutes in N₂ atmosphere.

For all the present copper system compound semiconductor solar cells, aluminum (Al) metal contacts with a thickness of $\sim 100 \text{ nm}$ were deposited as top electrodes, and annealed at 140°C for 20 minutes in N₂ atmosphere. Schematic illustrations of the present solar cells are shown in Figure 1.

2.3. Measurements of Solar Cells. The current density-voltage (*J*-*V*) characteristics (Hokuto Denko Corp., HSV-100) of the solar cells were measured both in the dark and under illumination at 100 mW/cm² by using an AM 1.5 solar simulator (San-ei Electric, XES-301S) in N₂ atmosphere. The solar cells were illuminated through the side of the FTO and ITO substrates, and the illuminated area was 0.16 cm². Optical absorption of the solar cells was investigated by means of UV-visible spectroscopy (Hitachi, Ltd., U-4100). The microstructures of the CIS, copper oxides, and C₆₀ thin films were investigated by X-ray diffractometer (XRD, PHILIPS X'Pert-MPD System) with CuK α radiation operating at 40 kV and 40 mA, scanning electron microscopy (SEM, Hitachi, Ltd., S-3200N), energy dispersive X-ray analysis (EDX, EMAX-5770W), and transmission electron microscopy (TEM) operating at 200 kV (Hitachi, Ltd., H-8100).

3. Results and Discussion

3.1. CIS/TiO₂ Solar Cells. The *J*-*V* characteristics of the TiO₂/CIS and CIS/TiO₂ structures in the dark and under illumination were measured. The photocurrent was observed under illumination and both structures showed characteristic curves with open-circuit voltage and short-circuit current. The measured parameters of these solar cells are summarized in Table 1. A solar cell with the CIS/TiO₂ structure provided power conversion efficiency (η) of $1.5 \times 10^{-5}\%$, fill factor (FF) of 0.25, short-circuit current density (*J*_{SC}) of $6.0 \times 10^{-3} \text{ mA/cm}^2$, and open-circuit voltage (*V*_{OC}) of $1.0 \times 10^{-2} \text{ V}$, which is better than those of the TiO₂/CIS device.

FIGURE 2: Optical absorption of CIS/TiO₂ heterojunction solar cells.

Figure 2 shows the measured optical absorption of the solar cells. The TiO₂/CIS structure shows high absorption at 444, 510, 606, and 738 nm, which correspond to 2.8, 2.4, 2.0, and 1.7 eV, respectively. The CIS/TiO₂ structure also shows high optical absorption at 420, 488, 590, and 710 nm, which correspond to 2.6, 2.5, 2.1, and 1.7 eV, respectively. The absorption peaks at 444 nm and 420 nm for the TiO₂/CIS and CIS/TiO₂ structures were due to TiO₂, and the other peaks were due to CIS. As shown in Figure 2, the optical absorption between 400 nm and 800 nm for the TiO₂/CIS solar cell is higher than that of CIS/TiO₂ structure. The increase in film thickness of the CIS layer in the TiO₂/CIS structure through the penetration of the CIS nanocrystals into the porous TiO₂ layer results in the increase in the optical absorption of solar cells in the TiO₂/CIS structure.

Microstructures of the CIS thin film were investigated by XRD, as shown in Figure 3(a). Diffraction peaks corresponding to CIS and indium oxide (In₂O₃) were observed for the CIS thin film. The crystallite size was estimated using the Scherrer equation: $D = 0.9 \lambda / B \cos \theta$, where λ , B , and θ represent the wavelength of the X-ray source, the full width at half maximum (FWHM), and the Bragg angle, respectively [23]. From the FWHM of the 112 peak, the crystallite size of CIS was determined to be 13.1 nm. Elemental analysis of the CIS thin film was investigated by SEM and EDX. The atomic concentrations of the CIS thin film were copper (28.0%), indium (26.0%) and sulfur (46.0%).

Preparation conditions of the TiO₂/CIS structure were different from those of the CIS/TiO₂ structure, and influence of different annealing temperatures of the TiO₂ layer was investigated. Figures 3(b) and 3(c) show X-ray diffraction patterns of the TiO₂ thin films on the glass substrates annealed at 450°C for 30 minutes in air, and 500°C for 30 minutes in N₂/H₂ atmosphere and annealed at 450°C for 30 minutes in air, respectively. The X-ray diffraction patterns

FIGURE 3: XRD pattern of (a) CIS thin film and (b) TiO₂ thin film annealed at 450°C for 30 minutes in air and 500°C for 30 minutes in N₂/H₂ atmosphere and (c) TiO₂ thin film annealed at 450°C for 30 minutes in air.

indicate an anatase phase with a tetragonal system, and there was a slight amount of the rutile phase. The particle size of the anatase phase was estimated to be 26.1 nm from the Scherrer's equation. No differences between Figures 3(b) and 3(c) were observed on the crystalline structures of the TiO₂ layer.

FIGURE 4: (a) TEM image and (b) electron diffraction pattern of TiO₂/CIS structure. (c) Enlarged HREM images of TiO₂ in (a) and (d) CIS in (a).

Figures 4(a) and 4(b) show a TEM image and an electron diffraction pattern of the TiO₂/CIS composite film, respectively. The TEM image indicated TiO₂ nanocrystals in the CIS matrix. Debye-Scherrer rings, which indicate polycrystalline structures of TiO₂ and 112 reflection of the CIS crystal can be seen in Figure 4(b). Enlarged high-resolution electron microscopy (HREM) images of the TiO₂ and CIS in Figure 4(a) are shown in Figures 4(c) and 4(d), respectively, revealing the lattice fringes of the 101 of the TiO₂ and the 112 of the CIS crystals.

Figures 5(a) and 5(b) show the microstructures of FTO/TiO₂/CIS/Al and FTO/CIS/TiO₂/Al, respectively. As shown in Figure 5(a), the porous TiO₂ layer has a composite structure with CIS nanocrystals. Therefore, the p-n junction interface area, which is the photoelectron conversion region in the TiO₂/CIS solar cells, becomes larger compared to the ordinary heterojunction structure, leading to an increase in efficiency. As shown in Figure 2, the optical absorption between 400 nm and 800 nm for the TiO₂/CIS solar cell is higher than that of CIS/TiO₂ structure. The increase of the CIS layer thickness in the TiO₂/CIS structure through the penetration of the CIS nanocrystals into the porous TiO₂ layer would result in the increase of the optical absorption of TiO₂/CIS solar cells. Charge separation for the TiO₂/CIS solar cell would be higher from high optical absorption. However, the carrier recombination of electrons and holes

would occur at the FTO/TiO₂ interface for the TiO₂/CIS structure, and the energy conversion efficiency would not be improved by an increase of the p-n heterojunction interface in the present work.

Energy level diagrams of TiO₂/CIS and CIS/TiO₂ solar cells are summarized as shown in Figures 5(c) and 5(d), respectively. Previously reported values were used for the energy levels [24, 25]. It has been reported that V_{OC} is nearly proportional to the bandgap of the semiconductors [26].

Compared to a Si semiconductor with an indirect transition band structure, the CIS with a direct transition band structure is the more suitable for the optical absorption property. In addition, the ultrathin film of the CIS layers could provide an efficient charge injection because of the high optical absorption. Although Cu(In_xGa_{1-x})Se₂ (CIGS) has been mainly used as a p-type inorganic semiconductor for solar cells [27], CIS was applied instead of CIGS in the present work. Advantages of the present CIS are the low-cost reagent and the simple fabrication process. TiO₂ and CIS have stable properties against sunlight, and prevent photodeterioration for the solar cells. CIS-based solar cells are expected to provide a long life time.

CIS-based solar cells prepared by a spin-coating method without vacuum evaporation were investigated in the present work. The low conversion efficiency of the present solar

FIGURE 5: Schematic microstructures of (a) FTO/TiO₂/CIS/Al and (b) FTO/CIS/TiO₂/Al solar cells. Energy level diagrams of (a) TiO₂/CIS and (b) CIS/TiO₂ heterojunction solar cells.

FIGURE 6: Optical absorption of CuO/C₆₀ heterojunction solar cell.

cells is due to presence of impure compounds in the active layer. The defects produced by inadequate crystals would cause carrier recombination. Optimization of the CIS microstructures can increase the efficiency of solar cells. There could be carrier recombination of electrons and holes at the rear surface of the n-type electrode (FTO). Solar cells with a buffer layer fabricated by addition of ultrathin TiO₂ or ZnO n-type semiconductor layers between FTO and TiO₂ have been reported [28, 29]. Energy conversion efficiency could be improved by addition of the buffer layers to inhibit carrier recombination at the contact surfaces.

3.2. CuO/C₆₀ Solar Cells. *J-V* characteristics of the CuO/C₆₀ structures in the dark and under illumination were investigated. The photocurrent was observed under illumination, and the CuO/C₆₀ structure showed characteristic curves with short-circuit current and open-circuit voltage. Measured parameters of these solar cells are summarized in Table 1. A solar cell with a CuO/C₆₀ structure provided η of $1.7 \times 10^{-4}\%$, FF of 0.25, J_{SC} of 0.015 mAcm^{-2} , and V_{OC} of 0.045 V.

Figure 6 shows the measured optical absorption of the CuO/C₆₀ solar cell. The absorption peaks around 350 nm in the CuO/C₆₀ structure were due to CuO, and absorption peaks around 338 nm, 440 nm, and 606 nm correspond to C₆₀.

Figure 7 shows an X-ray diffraction pattern of the CuO thin films on glass substrates annealed at 300°C for 3 hours in air. Diffraction peaks corresponding to CuO were observed for the CuO thin film, which consisted of a tenorite phase with monoclinic system (space group of C2/c and lattice parameters of $a = 0.4653 \text{ nm}$, $b = 0.3410 \text{ nm}$, $c = 0.5108 \text{ nm}$, and $\beta = 99.48^\circ$). The crystallite size was estimated using Scherrer's equation. From the FWHM of the -111 peak, the crystallite size of CuO was determined

FIGURE 7: XRD patterns of CuO thin films annealed at 300°C for 3 hours in air.

to be 16.0 nm. Figures 8(a) and 8(b) show a TEM image and an electron diffraction pattern of the CuO thin film annealed at 300°C, respectively. The TEM image indicated CuO nanocrystals with sizes of 10~20 nm, which agree well with XRD results. Debye-Scherrer rings in Figure 8(b) indicate polycrystalline structures of CuO.

Energy level diagram of CuO/C₆₀ solar cells is summarized as shown in Figure 9. Previously reported values were used for the energy levels [20, 30, 31]. Compared to the Si semiconductor with an indirect transition band structure, CuO with a direct transition bandgap is more suitable for the optical absorption property. Although Cu₂O has been mainly used as a p-type oxide semiconductor for solar cells [14–17], CuO was applied instead of Cu₂O in the present work. The advantages of the present CuO are low-cost reagent and the simple fabrication process.

CuO-based solar cells prepared by a spin-coating method without vacuum evaporation were investigated in the present work. The low conversion efficiency of the present solar cells would be due to carrier recombination by the defects produced by inadequate crystalline, and presence of CuO compounds with heterogeneous grain size in the active layer. Formation of the high-quality CuO thin films could increase the efficiency of solar cells.

3.3. Cu₂O:C₆₀ Solar Cells. The CuO/C₆₀ solar cell was a heterojunction structure. To increase the interfacial area of p-n junction, Cu₂O/C₆₀ bulk heterojunction solar cells were prepared. The *J-V* characteristics of the Cu₂O:C₆₀ structure in the dark and under illumination were measured. The photocurrent was observed under illumination, and the Cu₂O:C₆₀ structure showed photovoltaic properties. The measured parameters of the solar cells are summarized in Table 1. A solar cell with a Cu₂O:C₆₀ structure provided η of $4.3 \times 10^{-3}\%$, FF of 0.23, J_{SC} of 0.11 mAcm^{-2} and V_{OC} of 0.17 V.

TABLE 2: Comparison of copper oxide-based solar cells.

Sample	η (%)	Fabrication process	Annealing temperatures ($^{\circ}\text{C}$)	References
Heterojunction $\text{Cu}_2\text{O}/\text{ZnO}$	2.01	Evaporation and annealing	1000	[1]
Heterojunction CuO/C_{60}	1.7×10^{-4}	Spin coating	300	Present work
Bulk heterojunction $\text{Cu}_2\text{O}:\text{C}_{60}$	4.3×10^{-3}	Spin coating	140	Present work

FIGURE 8: (a) TEM image and (b) electron diffraction pattern of CuO structure.

Figure 10 shows optical absorption of the $\text{Cu}_2\text{O}:\text{C}_{60}$ solar cells. An absorption peak around 324 nm for the $\text{Cu}_2\text{O}:\text{C}_{60}$ structure is due to Cu_2O , and the absorption peak around 362 nm and 476 nm corresponds to C_{60} .

Microstructures of the $\text{Cu}_2\text{O}:\text{C}_{60}$ thin films were investigated by XRD, as shown in Figure 11. Diffraction peaks corresponding to Cu_2O and C_{60} were observed for the $\text{Cu}_2\text{O}:\text{C}_{60}$ thin film, and they consisted of a cuprite phase with cubic system (space group of $\text{Pn}3\text{m}$ and a lattice parameter of $a = 0.4250 \text{ nm}$), and a C_{60} phase with cubic system (space group of $\text{Fm}3\text{m}$ and a lattice parameter of $a = 1.4166 \text{ nm}$). The crystallite sizes of Cu_2O and C_{60} were determined to be 7.2 nm and 25.7 nm, respectively.

Figures 12(a) and 12(b) show a TEM image and a selected area diffraction pattern of the $\text{Cu}_2\text{O}:\text{C}_{60}$ thin film annealed at 100°C , respectively. The TEM image indicated aggregated Cu_2O nanocrystals with sizes of 10~20 nm. Line broadening of the Debye-Scherrer rings in Figure 12(b) indicates

FIGURE 9: Energy level diagram of FTO/CuO/C₆₀/Al heterojunction solar cells. FIGURE 10: Optical absorption of $\text{Cu}_2\text{O}:\text{C}_{60}$ bulk heterojunction solar cells.

nanocrystal structures of Cu_2O . C_{60} peaks [32] were not observed in this pattern, which would be due to dispersion of C_{60} crystals. Optimization of the nanocomposite structure with Cu_2O and C_{60} would increase the efficiencies of the solar cells.

FIGURE 11: XRD pattern of $\text{Cu}_2\text{O}:\text{C}_{60}$ thin film.

(a)

(b)

FIGURE 12: (a) TEM image and (b) electron diffraction pattern of $\text{Cu}_2\text{O}:\text{C}_{60}$ structure.

Energy level diagram of the $\text{Cu}_2\text{O}:\text{C}_{60}$ solar cell is summarized as shown in Figure 13. Previously reported values were used for the energy levels [11, 31, 33]. Cu_2O with a direct transition bandgap is more suitable for the optical absorption property compared to Si. Although ZnO has been mainly used as an n-type oxide semiconductor for solar cells

FIGURE 13: Energy level diagram of ITO/PEDOT:PSS/ $\text{Cu}_2\text{O}:\text{C}_{60}$ /Al bulk heterojunction solar cells.

[14–17], C_{60} was applied instead of ZnO in the present work. Advantages of the present C_{60} are a good acceptor for solar cells and the simple fabrication process.

Compared to previously reported Cu_2O -based heterojunction solar cells [14], copper oxide-based bulk heterojunction and heterojunction solar cells prepared by a spin-coating method without a vacuum system were investigated in the present work, as listed in Table 2. The present copper oxide-based bulk heterojunction and heterojunction solar cells have simple fabrication process and good cost performance.

The low conversion efficiency of the present solar cells would be due to aggregation of Cu_2O nanoparticle in the active layer, which would cause carrier recombination. Formation of the $\text{Cu}_2\text{O}:\text{C}_{60}$ thin films with homogeneous distribution of Cu_2O nanoparticles could increase the efficiency of solar cells.

4. Conclusions

Copper system compound semiconductor solar cells were produced and characterized. A device based on the CIS/ TiO_2 structure provided η of $1.5 \times 10^{-5}\%$, FF of 0.25, J_{SC} of $6.0 \times 10^{-3} \text{ mA/cm}^2$, and V_{OC} of $1.0 \times 10^{-2} \text{ V}$, which showed better performance compared to that of a device based on the TiO_2/CIS structure. The devices based on the CuO/C_{60} and $\text{Cu}_2\text{O}:\text{C}_{60}$ structures were fabricated by a spin-coating method which provided η of $1.7 \times 10^{-4}\%$ and $4.3 \times 10^{-3}\%$, FF of 0.25 and 0.23, J_{SC} of 0.015 mAcm^{-2} and 0.11 mAcm^{-2} , and V_{OC} of 0.045 V and 0.17 V, respectively. X-ray diffraction analysis indicated the formation of CIS, CuO, and Cu_2O nanocrystal structures, respectively.

Energy level diagrams of CIS/ TiO_2 , CuO/C_{60} , and $\text{Cu}_2\text{O}:\text{C}_{60}$ solar cells were proposed. Separated holes could transfer from the valence band of the copper system

compound semiconductors to the transparent conducting oxide electrodes, and separated electrons could transfer from the conduction band of the copper system compound semiconductors to the Al electrodes, respectively.

Formation of the high-quality in active layers with inorganic nanoparticles would improve the efficiencies of the solar cells. The bulk heterojunction structure with dispersed inorganic nanoparticles in present work was effective for the improvement of current density.

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