

A Study on the Band Structure of ZnO/CdS Heterojunction for CIGS Solar-Cell Application

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Abstract—In this paper, ZnO films were prepared by atomic layer deposition (ALD) and CdS films were deposited using chemical bath deposition (CBD) to form ZnO/CdS heterojunction. More accurate mapping of band arrangement of the ZnO/CdS heterojunction has been performed by analyzing its electrical and optical characteristics in depth by various methods including transmittance, x-ray photoemission spectroscopy (XPS), and ultraviolet photoemission spectroscopy (UPS). The optical bandgap energies (E_g) of ZnO and CdS were 3.27 eV and 2.34 eV, respectively. UPS was capable of extracting the ionization potential energies (IPEs) of the materials, which turned out to be 8.69 eV and 7.30 eV, respectively. The electron affinity (EA) values of ZnO and CdS calculated from IPE and E_g were 5.42 eV and 4.96 eV, respectively. Energy-band structures of the heterojunction could be accurately drawn from these parameters taking the conduction band offset (CBO) into account, which will substantially help acquisition of the full band structures of the thin films in the CIGS solar-cell device and contribute to the optimal device designs.

Index Terms—CIGS solar cell, atomic layer deposition, chemical bath deposition, ZnO, CdS, heterojunction, transmittance, XPS, UPS, ionization potential energy, conduction band offset

Manuscript received Sep. 17, 2014; accepted Mar. 3, 2015.

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I. INTRODUCTION

Most of solar-energy technology manufacturers have great deal of interests in bulk-material-based solar cell technology that has benefits of cost-effectiveness and process maturity. To continue increasing the conversion efficiency, various types of thin-film solar cells are being developed. Second-generation thin-film solar cells, compared with the first-generation bulk-type crystalline solar cells, are increasingly studied by simple fabrication processing by deposition of an absorber layer of several-micrometer thickness onto a suitable substrate such as glass and plastic for thin-film transistor (TFT) circuit and flexible electronics applications [1-5].

In general, the thin-film Cu(InGa)Se₂ (CIGS) solar cells are fabricated in a *p-n* junction configuration consisting of molybdenum (Mo) as the bottom electrode (BE), CIGS thin film as the absorber layer, CdS thin film as the buffer layer, and intrinsic zinc oxide (*i*-ZnO) and Al-doped ZnO (AZO) layers as the window layers [6, 7]. The CIGS thin-film absorber layer has I-III-VI group chalcopyrite composition and its energy bandgap (E_g) is in the range of 1.04 - 1.68 eV, depending on the composition of individual atoms [8]. The E_g of the window layer is around 3.3 eV, and a lattice mismatch or inconsistency is usually observed between the window layer and absorber layer, that is, the CIGS layer [9]. Also, the CdS thin film of which E_g is approximately 2.4 eV acts as a bandgap buffer [10, 11].

As shown in Fig. 1, there exists a difference between the conduction band minima (E_C 's) of CdS and CIGS, a conduction band offset (CBO). E_C of CdS is higher than that of CIGS, by which an energy barrier is observed by the conduction electrons in the CIGS toward the CdS

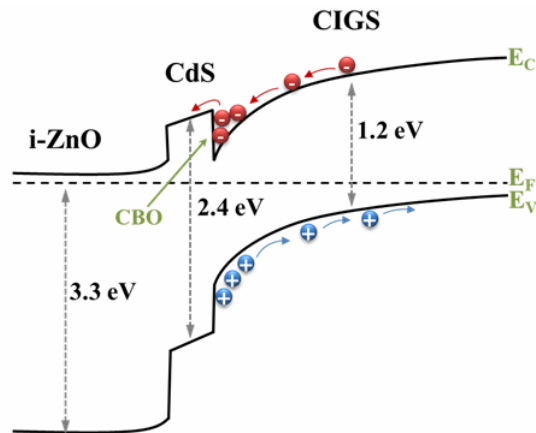


Fig. 1. Energy-band diagram of a CIGS solar cell.

region. The appropriate CBO value required for the movement of electrons from CIGS to CdS is in the range of 0.3 - 0.4 eV. Although short-circuit current (J_{sc}) can be reduced by the CBO seen from CIGS toward CdS, the CBO has an effect of increasing the open-circuit voltage (V_{oc}) of the CIGS solar cell. For these reasons, a thin CdS layer is introduced in the solar cell and its thickness is precisely controlled to maximize the fill factor (FF) [12, 13]. However, extracting the exact E_g values of the solar-cell materials using the conventional optical methods is quite challenging since they usually require preparation of samples with extremely thin films which is not easily achievable in a CIGS solar cell having bulky grains, which calls for different approaches. In this study, as a part of a closer investigation into the energy-band alignments among materials comprising a CIGS solar cell, the CBO between the ZnO window and the CdS buffer layers has been extracted using complementary optical methods.

II. THIN-FILM PROCESSING AND ANALYSIS TECHNIQUES

ZnO thin film deposition was performed by atomic layer deposition (ALD) under the process conditions shown in Table 1, where diethylzinc (DEZn, $(C_2H_5)_2Zn$) and H_2O were used as the precursors. A slide-glass substrate with an area of 30×20 mm and a thickness of 1 mm was used to measure transmittance, and a Si wafer substrate with 1000-Å gold deposited by an e-beam evaporator was used for the ultraviolet photoelectron

Table 1. ALD process conditions for the ZnO thin film

Process Parameters	Conditions
Precursors	DEZn(diethylzinc), H_2O
Substrate materials	Slide glass, gold/wafer
Substrate size	30×20 mm
Glass thickness	1 mm
Base pressure	10 mTorr
Ar flow rate	300 sccm
H_2O injection time	1 sec
DEZn injection time	1 sec
Ar purge time	4 sec
Substrate temperature	$120^\circ C$

Table 2. CBD process conditions for the CdS thin film

Process Parameters	Conditions
Chemical solutions	$CdSO_4$: 2.2×10^{-4} M, 132 mL
	$CS(NH_2)_2$: 1.1×10^{-2} M, 132 mL
	NH_4OH : 1.4 M, 168 mL
	DI water: 900 mL
Substrate materials	soda-lime glass, gold/wafer
Substrate size	30×20 mm, 4-in. diameter
Glass thickness	1 mm
Bath water temperature	$65^\circ C$
Deposition time	12 min
Number of CBD cycles	3
Solution temperature	$65^\circ C$
Annealing condition	20 min at $200^\circ C$

spectroscopy (UPS) analysis. Gold was deposited onto the substrate in order to prevent the destruction of the thin film by electron charging while the optical analyses. The base vacuum and substrate temperature were maintained at 10 mTorr and $120^\circ C$, respectively, and the injection of each precursor was performed for 1 s. The chamber was purged with Ar gas for 4 s, while the partial pressure was maintained at 300 sccm.

CdS thin film was prepared by chemical bath deposition (CBD) with the process conditions in Table 2. $CdSO_4$, $CS(NH_2)_2$, NH_4OH , and DI water were used as the solution elements for the deposition. Water in a container was heated to $65^\circ C$ by a hot plate, and the container was then introduced into the chemical bath. DI water at $65^\circ C$ was injected, followed by the introduction of $CdSO_4$ and NH_4OH solution. A sample was then soaked and the elapsed time was measured. $CS(NH_2)_2$ solution was injected as 1 min passed. The sample was removed after 12 min, passed through cyclic cleaning 3 times, and subjected to post annealing. The

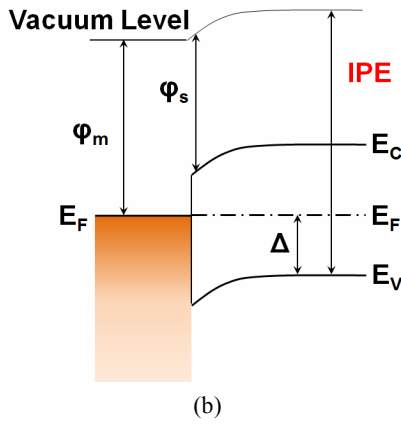
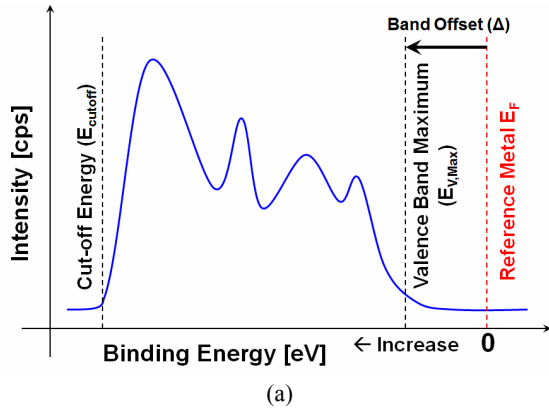


Fig. 2. Exploring the valence-band structure by UPS technique (a) Intensity-energy curve, (b) energy-band diagram.

transmittances of the prepared ZnO and CdS thin films were measured using an UV-visible spectrophotometer. The measured transmittance values were expressed in terms of the absorption coefficient α , using Eq. (1).

$$\alpha = 1 - R^2, \quad \alpha^2 = [1 - (1 - T)^2]^2 \quad (1)$$

where R and T are reflectance and transmittance, respectively. α is in the range of $0 < \alpha < 1$, and in order to make the change more distinguishable, α^2 was plotted. The linear extrapolation was performed at the wavelength where its maximum derivative was obtained, in order to extract the cut-off wavelength of a material, which will be made clearer in the later section. E_g is obtained from the extracted cut-off wavelength by Eq. (2) [14].

$$E_g = \frac{1.24}{\lambda}, \quad E_g \text{ in eV for } \lambda \text{ in } \mu\text{m units.} \quad (2)$$

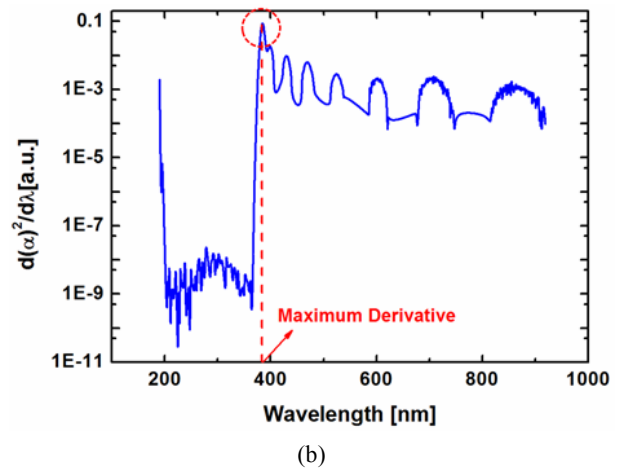
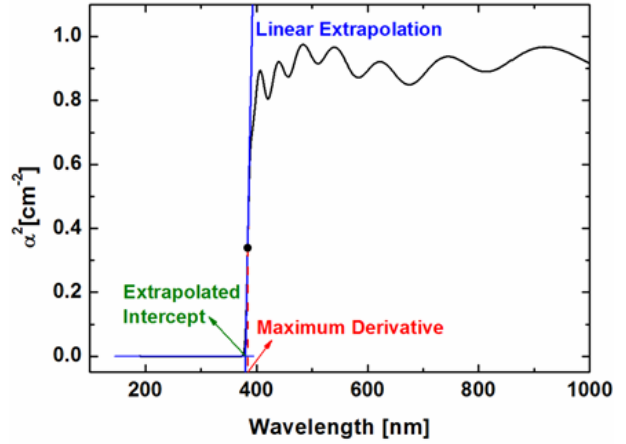


Fig. 3. Extraction of the E_g of ZnO using the transmittance measurement results (a) Extraction of cut-off wavelength by the linear extrapolation, (b) Location of the maximum first derivative.

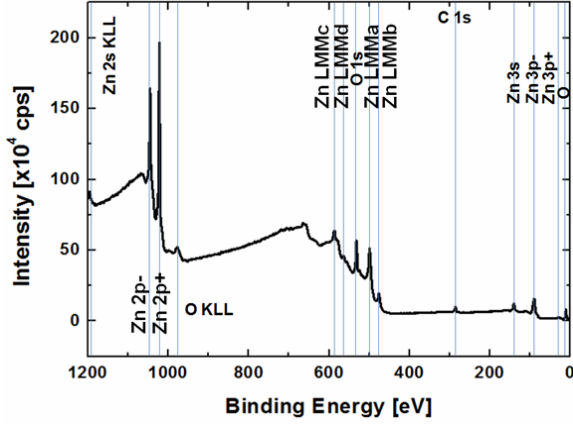
The composition of materials was validated using an x-ray photoelectron spectroscopy (XPS), and the valence band structure was identified using UPS relatively more suitable to low-energy analysis below 20 eV [15].

The band structures of materials were explored by calculating the ionization potential energy (IPE) and electron affinity (EA) obtained from the analyses. Fig. 2 illustrates the principle of calculating IPE from the UPS analysis. Here, ϕ_m and ϕ_s are EAs of metal and semiconductor, respectively.

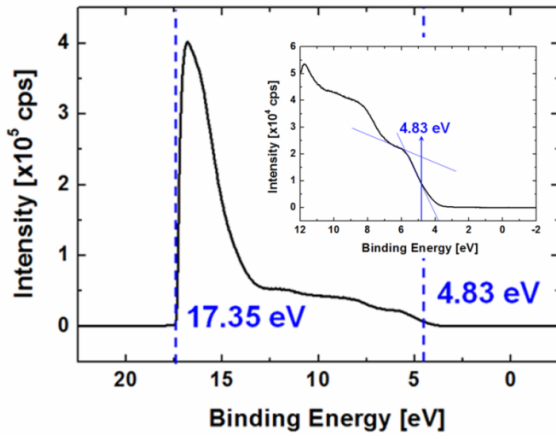
III. RESULT AND DISCUSSION

1. ZnO Thin Film Analysis

Fig. 3 shows the process of calculating the optical E_g



(a)



(b)

Fig. 4. Photoelectron spectroscopy analyses of ZnO thin film. (a) Wide-scan XPS analysis, (b) UPS analysis on confinement energy distribution of valence electrons.

of ZnO thin film based on transmittance measured by an UV-visible spectrophotometer.

The measured T values are converted to α^2 by Eq. (1) and plotted in Fig. 3(a). After taking the wavelength where the maximum first derivative of α^2 occurs (Fig. 3(b)), the linear extrapolation is performed at the wavelength as shown in Fig. 3(a). The extrapolated intercept, the cut-off wavelength, is then translated into energy by Eq. (2). The extracted optical E_g was 3.27 eV.

Fig. 4(a) shows the wide-scan XPS analysis on the ZnO prepared by ALD, where it is confirmed that the thin film consists of Zn and O dominantly, and native C usually found in an air-exposed sample. IPE is the minimum energy required for the valence electrons to jump to the vacuum level (Fig. 2(b)), which can be expressed simply as follows:

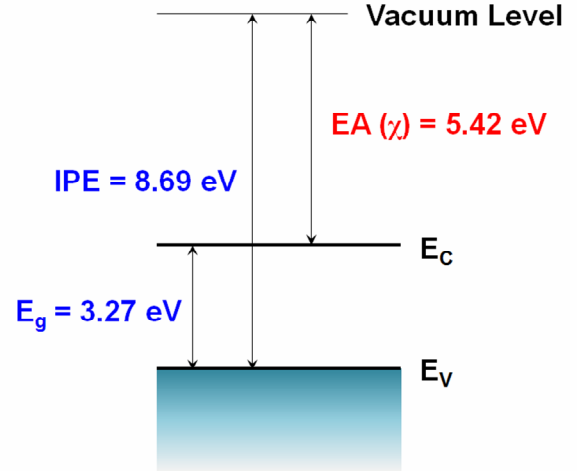


Fig. 5. Energy-band diagram of the *i*-ZnO based on the empirically extracted parameters.

$$\text{IPE} = h\nu - (E_{\text{cutoff}} - E_{V,\text{Max}}) \quad (3)$$

By employing the confinement energy distribution of the valence electrons and plugging the measured energy values to Eq. (3), the IPE of ZnO thin film is calculated to be 8.69 eV as shown in Eq. (4).

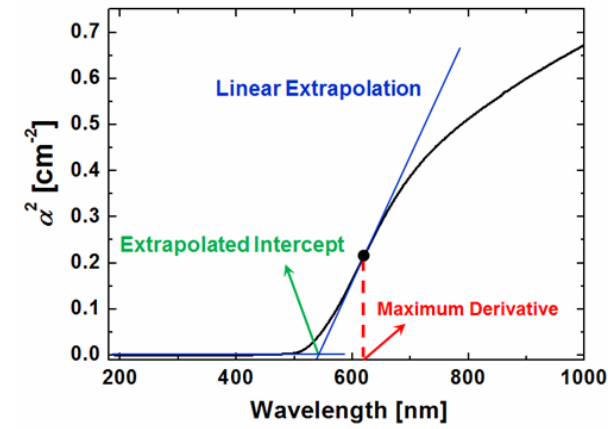
$$\begin{aligned} \text{IPE} &= h\nu - (E_{\text{cutoff}} - E_{V,\text{Max}}) \\ &= 21.21 - (17.35 - 4.83) = 8.69 \text{ eV} \end{aligned} \quad (4)$$

E_g and IPE have been extracted by transmittance and UPS analyses. EA, by its physical definition, is expressed by the difference between IPE and E_g and the calculated EA of *i*-ZnO was 5.42 eV. Fig. 5 demonstrates the energy-band diagram of the prepared *i*-ZnO with the extracted parameters.

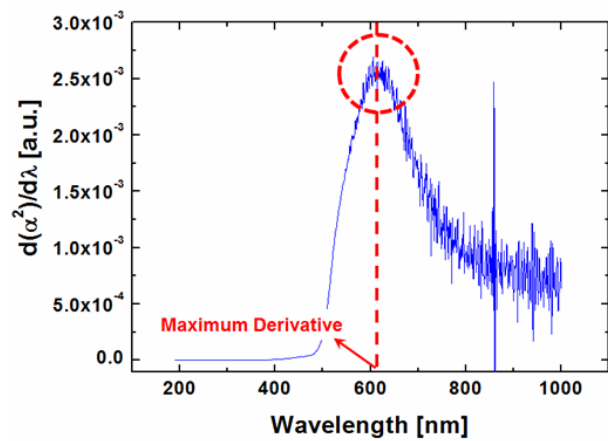
2. CdS Thin Film Analysis

The procedures to obtain cut-off wavelength of the CBD-prepared CdS thin film are the same with those employed in the previous section, by which transmittances was measured and converted to the absorption coefficients (Eq. (1)), and $\lambda = 530$ nm was extracted as the extrapolated intercept, as shown in Figs. 6(a) and (b). E_g of the thin film is calculated by Eq. (2).

$$E_g = \frac{1.24}{\lambda} \approx \frac{1.24}{0.530} = 2.34 \text{ eV} \quad (5)$$

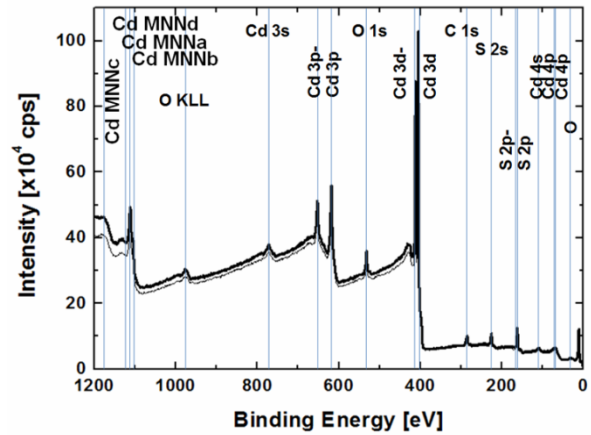


(a)

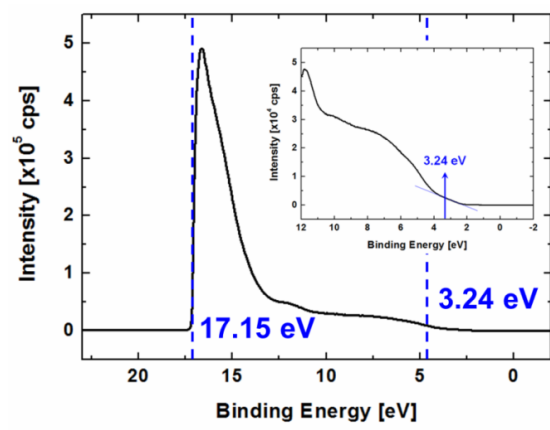


(b)

Fig. 6. Extraction of the E_g of CdS using the transmittance measurement results (a) Extraction of cut-off wavelength by the linear extrapolation, (b) Location of the maximum first derivative.



(a)



(b)

Fig. 7. Photoelectron spectroscopy analyses of CdS thin film (a) Wide-scan XPS analysis, (b) UPS analysis on confinement energy distribution of valence electrons.

Fig. 7(a) shows the wide scan results of XPS. The CdS thin film deposited by CBD consists of pure Cd and S dominantly, and native C and O elements. The confinement energy distribution of valence electrons in the CdS thin film was validated by UPS, as shown in Fig. 7(b). Using Eq. (3), the IPE was extracted for valence band analysis as follows.

$$\begin{aligned} \text{IPE} &= h\nu - (E_{\text{cutoff}} - E_{V, \text{Max}}) \\ &= 21.21 - (17.15 - 3.24) = 7.30 \text{ eV} \end{aligned} \quad (6)$$

The IPE of CdS thin film is calculated to be 7.30 eV. Based on the empirically obtained E_g , 2.34 eV, and IPE = 7.30 eV, the EA is calculated as their difference, 4.96 eV. Fig. 8 demonstrates the energy-band diagrams of CBD-prepared CdS with the physical parameters.

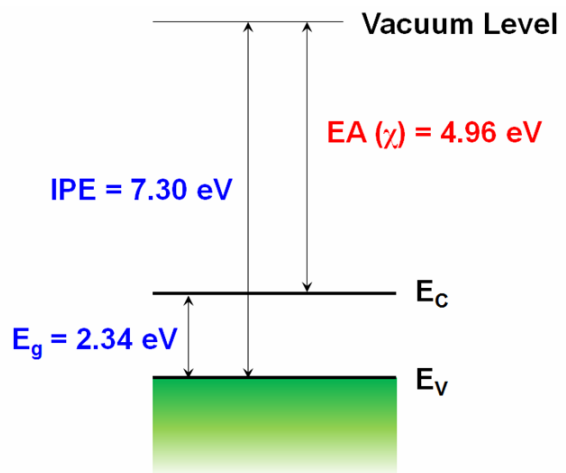


Fig. 8. Energy-band diagram of the CdS based on the empirically extracted parameters.

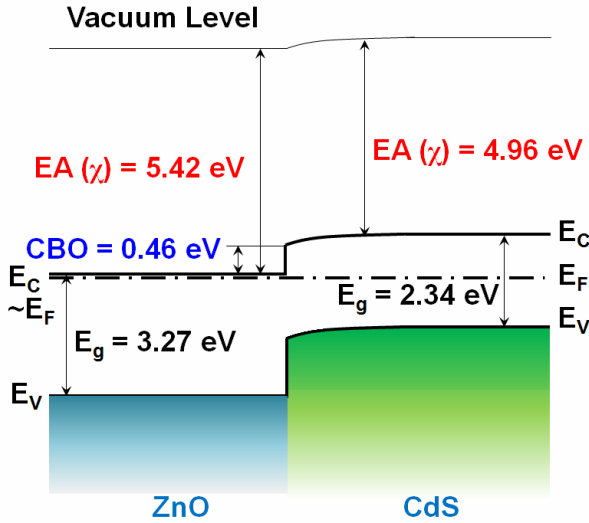


Fig. 9. Energy-band diagram of ZnO/CdS heterojunction.

3. Energy-Band Alignment of ZnO/CdS Heterojunction

ZnO and CdS thin films comprise a part of the *p-i-n* structure of CIGS solar cells. In adopting thin-film materials, their conduction and valence band offsets need to be studied in advance, since the carrier conduction and photovoltaic efficiency are significantly determined by the offsets. If the band arrangements among materials are not favorable to electron and hole conduction, the external quantum efficiency (EQE) of a solar cell drops even though an active material with high internal quantum efficiency (IQE) is being adopted. Thus, when it comes to a heterojunction solar cell, geometrical device design should be preceded by accurate energy-band arrangements. The E_g values cannot solely provide the full information on band alignment. The band arrangement of the ZnO/CdS heterojunction can be identified by mapping the parameters obtained in the previous sections, in reference to vacuum level.

Figs. 5 and 8 have confirmed the energy-band structures of ZnO and CdS. As these materials are brought to form a heterojunction, deformation of the energy band would occur accompanying Fermi-level (E_F) alignment as shown in Fig. 9.

As shown in the figure, the E_F of ZnO is drawn near the conduction band minimum, E_C , assuming that the conductivity of *i*-ZnO is assumed to be very high (degenerate state). It should be mentioned that the ZnO intrinsically has a large number of mobile electrons [16], and *i*-ZnO can be always understood as an *n*-type

Table 3. E_g and IPE values of ZnO and CdS

	ZnO	CdS
E_g	3.25-3.28 eV [20]	2.5 eV [22]
	3.3 eV [21]	2.31-2.32 eV [23]
IPE	~ 8 eV [24]	Not reported
	7.85-8.41 eV [25]	Not reported

semiconductor material not depending on whether the notation *i* (intrinsic) is used or omitted. The cause of this unintentional *n*-type conductivity has been widely discussed in the literature, and has often been attributed to the presence of native point defects such as oxygen vacancies and zinc interstitials. However, it is more likely that the *n*-type conductivity observed in as-grown bulk ZnO single crystals is caused by the unintentional incorporation of impurities, with H being a plausible candidate since it is difficult to avoid its presence in most growth and annealing environments [17]. For this reason, although the exact position of E_F can be changed depending on the measurement accuracy, it would fall between E_C and mid-bandgap of *i*-ZnO. The non-degenerate state would reduce the CBO. Considering these details comprehensively, CBO = 0.46 eV is not the absolute value but is suggested as the maximum value that a ZnO/CdS heterojunction can have. Intrinsic CdS is also an *n*-type material and gets its *n*-type conductivity due to the presence of sulfur vacancies (native defects formed during processing), which act as ionized donors. Typical donor concentration of $10^{16} - 10^{17} \text{ cm}^{-3}$ are obtained [18]. Also, the conduction band effective density of states (DOS) and the intrinsic carrier concentration of CdS obtained by a method were reported to be $N_c = 2 \times 10^{18} \text{ cm}^{-3}$ and $n = 1.2 \times 10^{17} \text{ cm}^{-3}$, respectively [19], by which the intrinsic Fermi level is located approximately 0.07 eV above the midgap of CdS. Due to this energy-band configuration, the electrons are injected into the ZnO without loss once the electrons generated by sunlight in the active layer of a CIGS solar cell reach the CdS buffer layer. Table 3 summarizes the E_g and IPE values of ZnO and CdS in the previous works and it is supported that the experimentally obtained values in this work do not show a significant difference from the reported ones. Particularly, there has been no report on the IPE of CdS and our empirical value can be a plausible reference to the related researches.

IV. CONCLUSION

In this study, experiments and analyses have been performed to identify the band structure of ZnO/CdS heterostructure in the CIGS solar cells. The ZnO and CdS thin films were prepared by ALD and CBD techniques, respectively. Transmittance, XPS, and UPS were used cooperatively to map the band arrangements more accurately. The optical E_g 's of ZnO and CdS were 3.27 eV and 2.34 eV, respectively. The energy distribution of valence electrons could be identified by the UPS, which successfully provided IPE and EA values of each thin film. The CBO is obtained to be 0.46 eV as the difference between EAs of ZnO (5.42 eV) and CdS (4.96 eV), which would help optimum design of a CIGS solar cell with higher accuracy and play a role as the reference value to validate empirical CBO values of ZnO/CdS heterojunction found from CIGS solar cells in the related researches.

ACKNOWLEDGEMENT

This work was supported by the Gachon University research fund of 2014 (GCU-2014-0118) and also supported by Nano-Material Technology Development Program through the National Research Foundation of Korea (NRF) funded by the Korean Ministry of Science, ICT & Future Planning (2009-0082580).

REFERENCES

- [1] M. C. Scharber, D. Mühlbacher, M. Koppe, P. Denk, C. Waldauf, A. J. Heeger, and C. J. Brabec, "Design Rules for Donors in Bulk-Heterojunction Solar Cells - Towards 10 % Energy-Conversion Efficiency," *Adv. Mater.*, vol. 18, no. 6, pp. 789 - 794, Mar. 2006.
- [2] J. Cárabe and J. J. Gandia, "Thin-film-silicon solar cells," *Opto-Electron. Rev.*, vol. 12, no. 1, pp. 1 - 6, Mar. 2004.
- [3] A. Romeo, M. Terheggen, D. Abou-Ras, D. L. Bätzner, F.-J. Haug, M. Kälin, D. Rudmann, and A. N. Tiwari, "Development of Thin-Film Cu(In,Ga)Se₂ and CdTe Solar Cells," *Prog. Photovoltaics Res. Appl.*, vol. 12, no. 2 - 3, pp. 93 - 111, Mar. - May 2004.
- [4] P. Choi, H. Kim, D. Baek, and B. Choi, "A Study on the Electrical Characteristic Analysis of c-Si Solar Cell Diodes," *J. Semicond. Technol. Sci.*, vol. 12, no. 1, pp. 59 - 65, Mar. 2012.
- [5] S.-K. Oh, H.-S. Shin, K.-S. Jeong, M. Li, H. Lee, K. Han, Y. Lee, G.-W. Lee, and H.-D. Lee, "Process Temperature Dependence of Al₂O₃ Film Deposited by Thermal ALD as a Passivation Layer for c-Si Solar Cells," *J. Semicond. Technol. Sci.*, vol. 13, no. 6, pp. 581 - 588, Dec. 2013.
- [6] J. Nelson, *The Physics of Solar Cells*, Imperial College Press, London, UK, 2003, pp. 245 - 246.
- [7] F. J. Pem, L. Mansfield, C. DeHart, S. H. Glick, F. Yan, and R. Noufi, "Thickness Effect of Al-Doped ZnO Window Layer on Damp-Hear Stability of CuInGaSe₂ Solar Cells," *Proc. The 37th IEEE Photovoltaic Specialists Conference (PVSC 37)*, pp. 1 - 6, Seattle, Washinton, Jun. 19 - 24, 2011.
- [8] U. Rau and H. W. Schock, "Electronic properties of Cu(In,Ga)Se₂ heterojunction solar cells - recent achievements, current understanding, and future challenges," *Appl. Phys. A*, vol. 69, no. 2, pp. 131 - 147, Aug. 1999.
- [9] N. Fujimura, T. Nishihara, S. Goto, J. Xu, and T. Ito, "Control of preferred orientation for ZnO_x films: control of self-texture," *J. Cryst. Growth*, vol. 130, no. 1 - 2, pp. 269 - 279, May 1993.
- [10] S. M. Kong, Y. Xiao, E. H. Kim, and C. W. Chung, "Growth Mechanism of CdS Nano Films Prepared by Chemical Bath Deposition," *J. Nanosci. Nanotechnol.*, vol. 11, no. 12, pp. 6287 - 6292, Dec. 2011.
- [11] K. S. Ramaiah, R. D. Pilkington, A. E. Hill, R. D. Tomlinson, and A. K. Bhatnagar, "Structural and optical investigations on CdS thin films grown by chemical bath technique," *Mater. Chem. Phys.*, vol. 68, no. 1 - 3, pp. 22 - 30, Feb. 2011.
- [12] A. O. Pudov, *Impact of Secondary Barriers on CuIn_{1-x}Ga_xSe₂ Solar-Cell Operation*, Ph.D. Dissertation, Colorado State University, 2005.
- [13] T. Ericson, J. J. Scragg, A. Hultqvist, J. T. Wätjen, P. Szaniawski, T. Törndahl, C. P.-Björkman, "Zn(O,S) Buffer Layers and Thickness Variations of CdS Buffer for Cu₂ZnSnS₄ Solar Cells," *IEEE J. Photovoltaics*, vol. 4, no. 1, pp. 465 - 469, Jan. 2014.
- [14] S. O. Kasap, *Optoelectronics and Photonics: Principles and Practices*, 2/e, Pearson Education,

London, UK, 2013, p. 388.

- [15] C. R. Brundle, C. A. Evans, Jr., and S. Wilson, *Encyclopedia of Materials Characterization: Surfaces, Interfaces, Thin Films*, Butterworth-Heinemann, Stoneham, USA, 1992, pp. 300 - 309.
- [16] D.-H. Kim, G.-W. Lee, and Y.-C. Kim, "Interaction of zinc interstitial with oxygen vacancy in zinc oxide: An origin of n-type doping," *Solid State Commun.*, vol. 152, no. 18, pp. 1711 - 1714, Sep. 2012.
- [17] A. Janotti and C. G. V. de Walle, "Fundamentals of zinc oxide as a semiconductor," *Rep. Prog. Phys.*, vol. 72, no. 12, pp. 1 - 29, Oct. 2009.
- [18] B. R. Tetali, Stability studies of CdTe/CdS thin film solar cells, Ph.D. Dissertation, University of South Florida, 2005.
- [19] L. Kronik, L. Burstein, M. Leibovitch, Y. Shapira, D. Gal, E. Moons, J. Beier, G. Hodes, D. Cahen, D. Hariskos, R. Klenk, and H.-W. Schock, "Band diagram of the polycrystalline CdS/Cu(In,Ga)Se₂ heterojunction," *Appl. Phys. Lett.*, vol. 67, no. 10, pp. 1405 - 1407, Sep. 1995.
- [20] F. K. Shan and Y. S. Yu, "Band gap energy of pure and Al-doped ZnO thin films," *J. Eur. Ceram. Soc.*, vol. 24, no. 6, pp. 1869 - 1872, Jun. 2004.
- [21] V. Srikant and D. R. Clarke, "On the optical band gap of zinc oxide," *J. Appl. Phys.*, vol. 83, no. 10, pp. 5447 - 5451, May 1998.
- [22] R. Das and S. Pandey, "Comparison of Optical Properties of Bulk and Nano Crystalline Thin Films of CdS Using Different Precursors," *Int. J. Mater. Sci.*, vol. 1, no. 1, pp. 35 - 40, Jan. 2011.
- [23] A. I. Oliva, O. Solís-Canto, R. Castro-Rodríguez, and P. Quintana, "Formation of the band gap energy on CdS thin films growth by two different techniques," *Thin Solid Films*, vol. 391, no. 1-2, pp. 28 - 35, Jul. 2001.
- [24] A. Wadeasa, "Heterojunctions between zinc oxide nanostructures and organic semiconductor," Ph.D. Dissertation, Linköpings Universitet, 2011.
- [25] N. R. D'Amico, F. Cantele, C. A. Perroni, and D. Ninno, "Electronic properties and Schottky barriers at ZnO-metal interfaces from first principles," *J. Phys: Condens. Matter*, vol. 27, no. 1, pp. 1 - 13, Jan. 2015.



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