Surface passivation of AZOY/n-Si interface of heterojunction solar cells with NH4F solution treatment

Na-Fu Wang1,3 *, Yu-Zen Tsai1 and Yu-Song Cheng2

1 Department of Electronic Engineering, Center for Environmental Toxin and Emerging-Contaminant Research, Super Micro Mass Research & Technology Center, Cheng Shiu University, 840 Chengcing Rd., Niaosong District, Kaohsiung City 833, Taiwan
2 National Synchrotron Radiation Research Center, Materials Science Group, 101 Hsin-Ann Road, Hsinchu Science Park, Hsinchu 30076, Taiwan
3 Author to whom any correspondence should be addressed.

E-mail: nafuwang@gcloud.csu.edu.tw

Keywords: heterojunction solar cells, AZOY, conversion efficiency, ammonium fluoride (NH4F), interface state density

Abstract

This study reports the fabrication of n-type aluminum- and yttrium-codoped zinc oxide (AZOY) on n-Si (AZOY/n-Si) heterojunction solar cells (HJSCs) by using RF magnetron sputtering at various working pressure. AZOY thin films deposited on glass and n-Si substrates at various working pressure were evaluated for optoelectrical properties and performance. At a working pressure of 3 mTorr, the AZOY films showed the lowest resistivity of $8.11 \times 10^{-2} \Omega \text{cm}$ and visible transmittance (400–800 nm) of 84.64%, and AZOY/n-Si HJSCs achieved a high conversion efficiency of 11.83% ($V_{oc}$: 498 mV, $J_{sc}$: 35.89 mA cm$^{-2}$, and FF: 0.662). Repeating the optimal working pressure, the n-Si substrate was immersed in ammonium fluoride (NH4F) solution to improve the AZOY/n-Si interface state. The fluorine atom had the strongest electron negativity for effective passivation of the silicon dangling bond, and the device’s performance was able to further increase conversion efficiency to 12.64% ($V_{oc}$: 523 mV, $J_{sc}$: 36.79 mA cm$^{-2}$, and FF: 0.657). Moreover, NH4F solution treatment of the silicon surface can increase the thinness of the SiOx layer from 1.27 to 0.79 nm and reduce the interface state density from $8.59 \times 10^{11}$ to $1.13 \times 10^{11}$ cm$^{-2}$.

1. Introduction

Transparent conducting oxide (TCO) thin film as a window layer deposited on a silicon wafer represents a promising Si-based heterojunction solar cell (HJSC) because of its simple device structure, low product cost, and low processing temperature [1, 2]. In terms of the n-type and p-type silicon properties, n-Si has a higher efficiency compared with p-Si in producing silicon-based photovoltaics (PVs) because n-Si is a stable, high diffusion length material owing to its reduced recombination activity of metal impurities and other nonmetallic defects [3]. Kobayashi et al [2] produced an indium tin oxide (ITO) on n-Si HJSC and achieved conversion efficiencies in the range of 9%–15% by using spray pyrolysis [4–7]. Because indium is a precious metal, fabrication of PV devices with indium would entail a high cost [2, 8, 9]. ZnO represents an alternative material to ITO films because of their surface texture ability, low cost, abundance, and excellent electrical and optical properties [10, 11]. Kobayashi et al also demonstrated a conversion efficiency of 6.9% for a ZnO/n-Si HJSC. However, HJSC devices with fill factor (FF) and open circuit voltage ($V_{oc}$) are subject to TCO resistivity and discrepancies in operation between the semiconductor and TCO. Therefore, the higher sheet resistance and lower work function of undoped ZnO thin films have been the main problems affecting FF (0.56) and $V_{oc}$ (410 mV), leading to a lower conversion efficiency for ZnO/n-Si than for ITO/n-Si HJSCs. Thus, to overcome the disadvantages of ZnO films, Al-doped ZnO (AZO) thin films have been widely used as an emitter layer in Si-based HJSC solar cell applications [11–14].

In previous studies [15, 16], we investigated a novel Al–Y-codoped ZnO (AZOY) transparent conducting thin film deposited through DC sputtering at a low cost, with results indicating a high conversion efficiency of
9.4% ($V_{oc}$: 429 mV, $J_{sc}$: 35.289 mA cm$^{-2}$, and FF: 0.618). However, the non-ideal FF and $V_{oc}$ of ZnO/n-Si are attributable to their thick SiO$_x$ layer and high interface state density ($D_{it}$) [17], as follows: (i) a higher working temperature increases SiO$_x$ layer thickness and causes carrier tunneling obstruction, thus reducing FF and $V_{oc}$ [18–20]; (ii) a high interface state density ($D_{it}$) results in Fermi-level pinning and carrier trap [21, 22]. Therefore, decreasing the working temperature to inhibit SiO$_x$ layer thickness and passivating the silicon surface are necessary to achieve high efficiency in a AZOY/n-Si PV device. However, the predominant electrical properties of AZOY thin films depend on a high working temperature, and SiO$_x$ layer thickness is directly proportional to working temperature. Therefore, we propose a low-cost, rapid, effective method of silicon surface passivation and a different approach to improving AZOY thin film resistivity.

In this study, we proceed from the fact that the fluorine atom is widely used for surface passivation [23–27] and that the resistivity of AZOY thin films is strongly dependent on working temperature. We therefore propose two methods to resolve the high resistivity of AZOY thin films at low working temperatures and the non-ideal AZOY/n-Si interface. The first is adjustment of sputtering working pressure. We discuss ion energy transfers to assist in improving AZOY thin film crystal quality to mitigate grain boundary scattering. Second, given that fluorine atoms have the strongest electron negativity (EN) for effective passivation of the silicon dangling bond, we use an ammonium fluoride (NH$_4$F) solution to provide fluorine atoms for decreased $D_{it}$ density and SiO$_x$ layer thickness.

2. Experimental

AZOY thin films were deposited on glass and silicon substrates through RF magnetron sputtering by using an AZOY ceramic target containing 2.0 wt% Al$_2$O$_3$ and 0.33 wt% Y$_2$O$_3$ (GfE Metalle und Materialien GmbH). The glass and (100)-oriented n-type silicon substrates first underwent the standard cleaning procedures (acetone and methanol) and were then rinsed in deionized water. Next, the n-Si was immersed in 0.1 M of NH$_4$F solution for 5 min at room temperature. Before AZOY thin film deposition, the vacuum system was evacuated using a turbo-molecular pump to a base pressure of approximately $4 \times 10^{-6}$ Torr, and pre-sputtering was implemented for 10 min to clean any pollution on the target surface. For AZOY thin film deposition, a 100 W sputtering source was used, and the working temperature was fixed at 150 °C. To investigate the effects of working pressure on AZOY films, the working pressure was varied in the 3–9 mTorr range with Ar ambient gas (fixed at 50 sccm), and the thickness of all the AZOY films was fixed at 250 nm.

The chemical composition and bonding states of Si, O, and F were analyzed using x-ray photoelectron spectroscopy (XPS; JEOL JAMP-9500F AES/XPS), after which the AZOY films were etched for 20 seconds to remove adsorbed surface water. The crystalline properties of the AZOY thin films were determined using x-ray diffraction (XRD; Philips PW3710), and their electrical properties were obtained through Hall effect measurement (HL 5500U) using Van der Pauw’s method at room temperature. The surface morphology of AZOY thin films was examined using high-resolution field-emission scanning electron microscopy (Hitachi SU8000), and their transmittance spectra were measured using a UV-visible spectrophotometer (Hitachi U-4100) in the wavelength range of 300–1500 nm. High-resolution transmission electron microscopy (TEM) was employed to verify the interface state. The PV characteristics of the device were tested using an AM 1.5 standard Newport #96000 solar simulator (Peccell PEC-L11) with an illumination intensity of 100 mW/cm$^2$.

3. Results and discussion

3.1. AZOY thin films of properties

Figure 1(a) shows the optical properties of AZOY thin films at various working pressures. The average visible transmittance (400–800 nm) of the AZOY thin films increased slightly from 84.64% to 85.38% with increasing working pressure from 3 to 9 mTorr. In addition, sharp of material absorb edge was obtained in the ultraviolet region. Figure 1(b) displays the optical Eg of the AZOY thin films, which was determined by plotting $(\alpha h\nu)^{1/2}$ versus $h\nu$ (where $\alpha$ is the absorption coefficient and $h\nu$ is the photon energy). All Eg samples were estimated at between 3.38 and 3.4 eV, which is close to the ZnO bulk band gap of 3.37 eV. However, the Eg of all AZOY thin-films were larger than that of standard ZnO thin films. The larger Eg may be explained by the Burstein–Moss (B–M) shift. The Fermi level into the conduction band of the degenerate semiconductor leads to the broadening effect of the Eg. The widening of Eg is directly proportional to carrier concentration $n^{2/3}$ which is dependent on the resistivity of AZOY films. The Fermi level position in energy band diagram of AZOY/n-Si is also dependent on carrier concentration. Figure 2(a) shows the XRD pattern of AZOY films deposited at various working pressures, with a strong, narrow ZnO (002) peak for all the investigated samples. In addition, the ZnO (002) diffraction angle was at 34.45° and was not significantly shifted, indicating that highly energetic argon ion bombardment of the growing films was irrelevant to the working pressure range [28]. In addition, figure 2(b)
shows that the full width at half maximum of the ZnO (002) diffraction peak increased from 0.371 to 0.415 with increasing working pressure. Using the Scherrer equation \[29\], grain sizes of the AZOY thin films were estimated at 22.45 nm (3 mTorr), 21.66 nm (5 mTorr), 20.62 nm (7 mTorr), and 20.05 nm (9 mTorr). These results indicate that grain size depends on working pressure. This is because the sputtered particle is related to the probability of collisions (mean free path \(\lambda_{\text{MFP}}\)), as described by equation \[2\] \[30\], where \(\delta\) is the atomic diameter (Ar: 0.367 nm), \(P\) is the gas pressure (Pa), \(N_a\) is Avogadro’s constant, and \(T\) is the temperature (K). At low working pressures, a larger \(\lambda_{\text{MFP}}\) of sputtered particles produces greater kinetic energy, because of the sputtered particles and gas molecule collision probability can be mitigation, increasing the \(\lambda_{\text{MFP}}\) of the sputtered particles. Therefore, the highest crystal quality can be correlated with a higher kinetic energy of sputtered particles, providing the materials with sufficient energy surface mobility to aggregate and grow. This result also corresponds to the Hall effect measurement, because carrier concentration and mobility are an inextricable part of business. The electrical resistivity \(\rho\), carrier concentration \(n\), and carrier mobility \(\mu\) of AZOY thin films deposited at various working pressures are shown in table 1. Carrier mobility clearly improves with increasing working pressure. The carrier mobility of the films is primarily affected by several scattering mechanisms, namely, ionized impurity, grain boundary, lattice vibration, and neutral impurity scattering \[31\]. According to the XRD and Hall effect measurement results, high carrier concentration can be attributed to the greater kinetic energy provided by the dopant atoms (Al\(^{3+}\) and Y\(^{3+}\)) substituted for Zn\(^{2+}\) sites at lower working pressures. In theory, high carrier concentration will cause impurity scattering and reduce carrier mobility; however, in all the investigated samples, carrier mobility and concentration increased simultaneously at lower working pressures. This can be attributed to the high crystal quality of AZOY films, which reduces grain boundary scattering and increases the carrier mobility path even with increased impurity scattering.
3.2. AZOY/n-Si HJSC of properties

Figure 3 shows TEM and XPS details for the AZOY/n-Si interface. In figures 3(a) and (b), a clear interfacial layer is obtained at the interface and is thinner than one without NH4F solution treatment. Figures 3(c) and (d) shows the strong core level of the Si2p peak observed at 99.22 eV, which is characteristic of bulk silicon wafer [32, 33]. When n-Si was treated with NH4F solution, Si–O and Si–F peaks were observed at a binding energy of 103.1 and 101.5 eV, respectively [32]. Thus, formation of a SiOx layer in the interfacial layer was confirmed and can be attributed to the metal oxide target used in the sputtering system; the target material was bombarded by argon ions to silicon substrate form nucleation AZOY films. The Si atom primarily combines with an O atom to form a SiOx layer because the bond energy of Si–O (452 kJ mol$^{-1}$) is larger than that of Zn–O (256 kJ mol$^{-1}$) [34–37].

However, an Si–F bond was observed, and the SiOx layer could be thinning (figure 3(b)). The EN of fluorine is known to be greater than that of other atoms commonly used for silicon passivation, such as hydrogen, oxygen, and iodine. Moreover, the Si–F bond (582 kJ mol$^{-1}$) [38] indicated that fluorine atoms can effectively passivate and inhibit the SiOx layer [39]. Figure 4 shows the photocapacitance–voltage (C–V) characteristic for AZOY/n-Si HJSCs at room temperature. The interface state (Dit) is described by equation 3 [34, 40], where Curo is the insulator layer capacitance, ΔV is the voltage shift caused by a photo-induced change in charges in the Si surface state, q is the electric charge, and Eg is the silicon substrate’s band gap. The Dit value decreased from $8.59 \times 10^{11}$ to $1.13 \times 10^{11}$ cm$^{-2}$. When silicon (5.43 Å) and zinc oxide (3.25 Å) [41], the AZOY/n-Si heterojunction lattice mismatch was 40%, indicating that many trapping the states in the AZOY/n-Si interface to cause

![Figure 3](https://example.com/image3.png)

Figure 3. High-resolution TEM cross section images and XPS of interface properties for AZOY/n-Si structures (a and b) without NH4F solution treatment or (c and d) with such treatment.

| Working pressure | Resistivity $\Omega$cm | Mobility cm$^2$V$^{-1}$S$^{-1}$ | Concentration cm$^{-3}$ |
|------------------|-----------------------|-------------------------------|------------------------|
| 3 mTorr          | $8.11 \times 10^{-3}$ | 8.32                          | $-9.26 \times 10^{19}$ |
| 5 mTorr          | $21.78 \times 10^{-2}$ | 4.57                          | $-6.28 \times 10^{18}$ |
| 7 mTorr          | $34.79 \times 10^{-2}$ | 3.23                          | $-5.57 \times 10^{18}$ |
| 9 mTorr          | $69.55 \times 10^{-2}$ | 2.23                          | $-4.03 \times 10^{18}$ |

Table 1. Electrical properties of AZOY thin films.
recombination. Thus, when electron–hole pairs are generated in the depletion region, the carrier can easily recombine because the available interface state energy levels have a lower density at higher energy \[42–44\].

Figure 5 depicts the dark and light current–voltage (I–V) curves at various working pressures, among which the optimal parameter was used in the repeated process with 0.1 M NH₄F solution for 5 min at room temperature.

Table 2 shows that PV device performance improved at various working pressures from 9 to 3 mTorr, of which a working pressure of 3 mTorr yielded the highest conversion efficiency; this could be further increased using fluorine passivation. Moreover, the diode was evaluated by calculating the saturation current, interface recombination velocity, and ideal factor using equations 4 and 5, and all of the device details for dark I–V curves are listed in Table 3, where \(J\) is the forward current, \(J_0\) is the saturation current, \(q\) is the electric charge, \(K\) is Boltzmann’s constant, \(T\) is the temperature (in K), \(n\) is the ideal factor, \(V\) is the applied voltage, \(N_c\) is the effective

![Figure 4. Photoresponsive C–V measurements of AZOY/n-Si HJSCs produced at various working pressures.](image1)

![Figure 5. (a) Light current density–voltage (J–V) curves at various working pressures and silicon passivation before sputtering with NH₄F solution treatment; (b) AZOY/n-Si dark J–V curves at various working pressures and NH₄F solution treatment at 3 mTorr.](image2)

**Table 2. Efficiency of AZOY/n-Si HJSCs at various working pressures and NH₄F solution treatments.**

| Working pressure | Current density (mA/cm²) | Open circuit voltage (mV) | Fill factor (%) | Efficiency (%) | Series resistance (Ω·cm²) | Shunt resistance (Ω·cm²) |
|------------------|--------------------------|---------------------------|----------------|---------------|---------------------------|--------------------------|
| 3 mTorr with NH₄F | 36.79                    | 523                       | 65.7           | 12.64         | 169.01                    | 1822.31                  |
| 3 mTorr          | 35.89                    | 498                       | 66.2           | 11.83         | 163.25                    | 1796.43                  |
| 5 mTorr          | 34.39                    | 453                       | 55.1           | 8.59          | 163.34                    | 1433.68                  |
| 7 mTorr          | 33.01                    | 384                       | 54.4           | 6.90          | 178.43                    | 1364.04                  |
| 9 mTorr          | 33.82                    | 369                       | 34.8           | 4.34          | 186.91                    | 1255.73                  |

recombination. Thus, when electron–hole pairs are generated in the depletion region, the carrier can easily recombine because the available interface state energy levels have a lower density at higher energy [42–44]. Figure 5 depicts the dark and light current–voltage (I–V) curves at various working pressures, among which the optimal parameter was used in the repeated process with 0.1 M NH₄F solution for 5 min at room temperature. Table 2 shows that PV device performance improved at various working pressures from 9 to 3 mTorr, of which a working pressure of 3 mTorr yielded the highest conversion efficiency; this could be further increased using fluorine passivation. Moreover, the diode was evaluated by calculating the saturation current, interface recombination velocity, and ideal factor using equations 4 and 5, and all of the device details for dark I–V curves are listed in table 3, where \(J\) is the forward current, \(J_0\) is the saturation current, \(q\) is the electric charge, \(K\) is Boltzmann’s constant, \(T\) is the temperature (in K), \(n\) is the ideal factor, \(V\) is the applied voltage, \(N_c\) is the effective
state density in the n-Si conduction band, and \( s \) is the AZOY/n-Si interface recombination velocity. In this study, at a working pressure of 3 mTorr, the AZOY/n-Si diode turn-on voltage \( V_{on} \) improved from 504 to 552 mV. This could be explained by Fermi-level pinning on the semiconductor surface because of the high interface state. When the interface state is sufficiently high a double layer forms on the semiconductor surface, leading to formation of a surface state charge and space charges of opposite signs \[22\]. Thus, this phenomenon causes built-in potential \( V_{bi} \) and cannot produce the theoretical value \( f_{AZOY} - f_{n-Si} \). However, the interface mitigated the charge effect at the surface, indicating that recombination velocity can be mitigated by the NH4F solution treatment. The \( V_{on} \) and surface recombination velocity thus improved, these resulted are agreement C-V and AZOY/n-Si HJSC conversion efficiency.

4. Conclusion

In this study, optimal AZOY/n-Si HJSCs were used to fabricate ZnO/n-Si–based HJSCs with the highest conversion efficiency. Prior to deposition of AZOY films, NH4F solution was used to provide fluorine atoms for passivating the silicon surface dangling bond. XPS analysis results revealed that the AZOY/n-Si interface had Si–F and Si–O bonds, and the TEM image also indicated that fluorine passivation inhibited SiOx layer thickness. Moreover, the C–V characteristic revealed that the AZOY/n-Si interface trap density was reduced from \( 8.59 \times 10^{11} \) to \( 1.13 \times 10^{11} \) cm\(^{-2}\). This also increased the AZOY/n-Si HJSC conversion efficiency from 11.83% to 12.64%. The interface recombination velocity was also be reduced from \( 2.401 \times 10^{3} \) to \( 1.628 \times 10^{3} \) cm s\(^{-1}\).

### Table 3. Diode parameters of the Al/AZOY/n-Si/Al structure measured in dark conditions.

| Working pressure \( \text{NH}_4\text{F} \) | Leakage current \( I_L \) (A) | Ideal factor \( I_d \) | Recombination velocity \( V_{on} \) (V) | Turn on voltage \( V_{bi} \) (V) |
|---------|-----------------|-----------------|-----------------|-----------------|
| 3 mTorr | \( 32.61 \times 10^{-6} \) | 2.86 | 1628 | 0.552 |
| 3 mTorr | \( 38.34 \times 10^{-6} \) | 3.28 | 2401 | 0.504 |
| 5 mTorr | \( 71.43 \times 10^{-6} \) | 3.46 | 2590 | 0.489 |
| 7 mTorr | \( 30.22 \times 10^{-3} \) | 3.56 | 2873 | 0.459 |
| 9 mTorr | \( 88.46 \times 10^{-3} \) | 3.65 | 2945 | 0.428 |

Acknowledgments

This work was supported by the National Science Council of Taiwan under Contract Number NSC107-2221-E-230-005.

ORCID iDs

Na-Fu Wang \( \text{https://orcid.org/0000-0003-3027-0506} \)

References

[1] Kobayashi H, Kogetsu Y, Ishida T and Nakato Y 1993 Increases in photovoltage of ‘indium tin oxide/silicon oxide/mat-textured n-silicon’ junction solar cells by silicon preoxidation and annealing processes J. Appl. Phys. 74 4756
[2] Kobayashi H, Mori H, Ishida T and Nakato Y 1995 Zinc oxide/n-Si junction solar cells produced by spray-pyrolysis method J. Appl. Phys. 77 1301
[3] Schmiga C, Nagel H and Schmidt J 2006 19% efficient n-type Czochralski silicon solar cells with screen-printed aluminium–alloyed rear emitter Progr. Photovoltaic: Res. Appl. 14 533–9
[4] Kobayashi H, Ishida T, Nakato Y and Tsusbomura H 1991 Mechanism of carrier transport in highly efficient solar cells having indium tin oxide/ Si junctions J. Appl. Phys. 69 1736

[5] Kobayashi H, Tachibana S, Yamanaka K, Nakato Y and Yuneda K 1997 Improvement of <indium-tin-oxide/silicon oxide/>-n-Si> junction solar cell characteristics by cyanide treatment J. Appl. Phys. 81 7630

[6] Manifacier J C and Szpessy I 1977 Efficient sprayed In,O,Sn n-type silicon heterojunction solar cell Appl. Phys. Lett. 31 459

[7] Vasu V and Subrahmanyan A 1992 Photovoltaic properties of spray pyrolytic grown indium tin oxide (ITO)/silicon junctions depending on substrate temperature Semicond. Sci. Technol. 7 1473

[8] Baik D G and Cho S M 1999 Application of sol-gel derived films for ZnO/n-Si junction solar cells Thin Solid Films 354 227

[9] Ihn S G et al ITTO-free inverted polymer solar cells using a ZGO cathode modified by ZnO Sol. Energy Mater. Sol. Cells 95 2011 1160

[10] Wang Z A, Chu J B, Zhu H B, Sun Z, Chen Y W and Huang S M 2009 Growth of ZnO:Al films by RF sputtering at room temperature for solar cell applications Solid-State Electron. 53 1149

[11] Aref E, Hefnawi S H, Elia A Y, Abdel-Naby M M and Ahmed N M 2005 Realization and characterization of ZnO/n-Si solar cells by spray pyrolysis Egypt. J. Sol. Systs. 28 243 (https://researchgate.net/profile/Aref_Elia/publication/268184103_Realization_and_Characterization_of_ZnO-nSi_Solar-Cells_by_Spray-Pyrolysis/links/56cc524608ace3e5e4536e5/Realization-and-Characterization-of-ZnO-n-Si-Solar-Cells-by-Spray-Pyrolysis.pdf)

[12] Song D, Xia J, Eun-Chel C and Aberle, A G 2002 Comparative study of ZnO:Al films on Si and glass prepared by rf magnetron sputtering at room temperature Photovoltaic Specialists Conf., Conf. Record of the Twenty-Ninth IEEE (New Orleans, USA) p 239

[13] Kim J, Yun J H, Park Y C and Anderson W A 2012 Transparent and crystalline Al-doped ZnO film-embedded heterojunction Si solar cell Mater. Lett. 75 99

[14] Song D and Guo B 2009 Electrical properties and carrier transport mechanisms of n-ZnO/SiOx/n-Si isotype heterojunctions with native or thermal oxide interlayers J. Phys. D: Appl. Phys. 42 025103

[15] Hsu F H, Wang N F, Tsai Y Z, Chuang M C, Cheng Y S and Houn M P 2013 Study of working pressure on the optoelectrical properties of Al-y codoped ZnO thin-film deposited using DC magnetron sputtering for solar cell applications Appl. Surf. Sci. 280 104–8

[16] Tsai Y Z, Wang N F, Tseng M R and Hsu F H 2010 Transparent conducting Al and Y codoped ZnO thin film deposited by DC sputtering Mater. Chem. Phys. 123 300

[17] Hsu F H, Wang N F, Tsai Y Z, Cheng Y S, Yang C F and Houn M P 2014 Interfacial layer effect on novel p-Ni1-xSn1+xO thin-film deposited World Academy of Science, Engineering and Technology 8 683–6

[18] Fang H W, Hsieh T E and Juang J Y 2013 Influences of SiOx-layer thickness on the characteristics of In–Zn–O/SiOx/n-Si heterojunction structure solar cells Surf. Coat. Technol. 231 214–8

[19] Fang H W, Hsieh T E and Juang J Y 2014 Effects of indium concentration on the efficiency of amorphous In–Zn–O/SiOx/n-Si heterojunction solar cells Sol. Energy Mater. Sol. Cells 121 176–81

[20] Fang H W, Hsieh T E and Juang J Y 2015 Photo-electric detection characteristics of In–Zn–O/SiOx/n-Si hetero-junctions Appl. Surf. Sci. 345 295–300

[21] Stemsans A and Afnas’ev V V 2002 Si dangling-bond-type defects at the interface of (100)Si with ultrathin layers of SiOx, Al2O3, and ZrO2 Appl. Phys. Lett. 80 1957

[22] Bardeen J 1947 Surface states and rectification at a metal semi-conductor contact Phys. Rev. 71 717

[23] Jung W S, Park J H, Nainani A, Nam D and Saraswat K C 2012 Fluorine passivation of vacancy defects in bulk germanium for Ge-Metal-oxide-semiconductor field-effect transistor application Appl. Phys. Lett. 101 072104

[24] Ye Z and Wong M 2012 Characteristics of thin-film transistors fabricated on fluorinated zinc oxide IEEE, Electron Device Lett. 33 4

[25] Callaby B D 1997 Elements of X-Ray Diffraction 2nd ed. (Menlo Park, CA: Addison-Wesley)

[26] Kittel C 1969 Thermal Physics (New York: Wiley)

[27] Lu J G, Ye Z Z, Zeng Y J, Zhu L P, Wang L, Yuan J, Zhao B and Liang Q L 2006 Structural, optical, and electrical properties of Al2O3/n-Si solar cell thin-film transistors J. Mater. Chem. A 4 2016 11844

[28] Chen P C, Chiu Y C, Liou G L, Zheng Z W, Cheng C H and Wu Y H 2017 Performance enhancements in p-type Al-doped tin-oxide thin film transistors by using fluorine plasma treatment IEEE, Electron Device Lett. 38 2

[29] Kappertz O, Drese R, Nganuiya J M and Wutting M 2005 Reactive sputter deposition of zinc oxide: employing respattering effects to tailor film properties Thin Solid Films 484 64

[30] Callaby B D 1997 Elements of X-Ray Diffraction 2nd ed. (Menlo Park, CA: Addison-Wesley)

[31] Kittel C 1969 Thermal Physics (New York: Wiley)

[32] Lu J G, Ye Z Z, Zeng Y J, Zhu L P, Wang L, Yuan J, Zhao B and Liang Q L 2006 Structural, optical, and electrical properties of (Zn,Al)O films over a wide range of compositions J. Appl. Phys. 100 073714

[33] Matsuo P I, Standaert T E F M, Allen S D and Oehreleib G S 1999 Characterization of Al, Cu, and TiN surface cleaning following a low-K dielectric etch Journal of Vacuum Science & Technology B, Nanotechnology and Micromechanics: Materials, Processing, Measurement, and Phenomena 17 1435

[34] Wagner C D, Riggins W M, Davis L E and Mouldner J F 1979 Handbook of X-ray Photoelectron Spectroscopy ed G E Mullenburg (Eden Prairie, MN: Perkin-Elmer) (https://doi.org/10.1002/sia.724030412)

[35] Fang H W, Hsieh T E and Juang J Y 2014 Effects of indium concentration on the efficiency of amorphous In–Zn–O/SiOx/n-Si heterojunction solar cells Solar Energy Materials & Solar Cells 121 176–81

[36] Choi NS, Yew K H, Lee K Y, Sung M, Kim H and Kim SS 2006 Effect of fluoroethylene carbonate additive on interfacial properties of silicon thin-film electrode J. Power Sources 161 1254–9

[37] Kim K, Kim H S, Hwang D K, Lim J H and Park S J 2003 Realization of type ZnO thin films via phosphorus doping and thermal activation of the dopant Appl. Phys. Lett. 83 63

[38] Wenas W G and Riyadi S 2006 Carrier transport in high-efficiency ZnO/SiOx/n-Si solar cells Solar Energy Materials & Solar Cells 90 2261–7

[39] Decken A, LeBlanc F A, Passmore J and Wang X 2006 Cyclodimethylsiloxane (Me2SiO)m (m = 3–6) Ring transformations on reactions with Ag(2)Br2 crystal structure of Ag(Me2SiO)nBr2, Eur. J. Inorg. Chem. 4033–6

[40] Ju M, Lee J Y, Lee K, Han C, Jo Y and Yi J 2012 Effectiveness of iodine termination for ultrahigh efficiency solar cells as a means of chemical surface passivation Japan. J. Appl. Phys. 51 09MA03

[41] Tam J, Dass M K, Cooper J A Jr and Melloch M R 1997 Metal-oxide-semiconductor capacitors formed by oxidation of polycrystalline silicon on SiC Appl. Phys. Lett. 70 2280–1
[41] Muthukumaran S and Gopalakrishnan R 2012 Structural, FTIR and photoluminescence studies of Cu doped ZnO nanopowders by co-precipitation method Opt. Mater. 34 1946–53
[42] Resfa A, Bourzig Y S and Menezla B R 2011 Study and modeling of the transport mechanism in a Schottky diode on the basis of a GaAs semiinsulator J. Semicond. 32 1 12004
[43] Gupta R K, Ghosh K and Kahol P K 2009 Effect of temperature on current–voltage characteristics of Cu2O/p-Si Schottky diode Physica E 41 876
[44] Yu W, Wang C S, La W B and Cui S K 2007 Deposition of n-type nanocrystalline SiC films and current transport mechanisms in nanocrystalline SiC/crystalline Si heterojunctions Solid State Commun. 143 228