Improved open-circuit voltage in Cu(In,Ga)Se₂ solar cells with high work function transparent electrodes

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Hydrogenated indium oxide (IOH) is implemented as transparent front contact in Cu(In,Ga)Se₂ (CIGS) solar cells, leading to an open circuit voltage V_{OC} enhanced by ~ 20 mV as compared to reference devices with ZnO:Al (AZO) electrodes. This effect is reproducible in a wide range of contact sheet resistances corresponding to various IOH thicknesses. We present the detailed electrical characterization of glass/Mo/CIGS/CdS/intrinsic ZnO (i-ZnO)/transparent conductive oxide (TCO) with different IOH/AZO ratios in the front TCO contact in order to identify possible reasons for the enhanced V_{OC} . Temperature and illumination intensity-dependent current-voltage measurements indicate that the dominant recombination path does not change when AZO is replaced by IOH, and it is mainly limited to recombination in the space charge region and at the junction interface of the solar cell. The main finding is that the introduction of even a 5 nm-thin IOH layer at the i-ZnO/TCO interface already results in a step-like increase in V_{OC} . Two possible explanations are proposed and verified by one-dimensional simulations using the SCAPS software. First, a higher work function of IOH as compared to AZO is simulated to yield an V_{OC} increase by 21 mV. Second, a lower defect density in the i-ZnO layer as a result of the reduced sputter damage during milder sputter-deposition of IOH can also add to a maximum enhanced V_{OC} of 25 mV. Our results demonstrate that the proper choice of the front TCO contact can reduce the parasitic recombination and boost the efficiency of CIGS cells with improved corrosion stability. © 2015 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4922351>]

I. INTRODUCTION

Transparent electrodes for solar cells are usually heavily doped metal-oxides based on In₂O₃, SnO₂, ZnO, TiO₂, and CdO.^{1–4} The industrially most relevant transparent conductive oxide (TCO) is indium tin oxide (ITO), which is frequently implemented in silicon based solar cells,³ flat-panel displays,¹ and low-emissive coatings.⁵ Amorphous TCOs, such as In-Zn-O,^{6–8} Zn-Sn-O,⁹ and In-Ga-Zn-O (Refs. 9–11), have emerged as valuable alternatives. Among the growing family of amorphous TCOs, hydrogenated indium oxide (In₂O₃:H or simply IOH)^{12–14} with hydrogen as a shallow donor^{15–17} exhibits a high carrier mobility even in the as-deposited state without intentional heating. IOH front contacts have been tested in microcrystalline Si,^{18,19} silicon hetero-junction,^{19,20} tandem micromorph silicon,²¹ and Cu(In,Ga)Se₂ (CIGS)²² solar cells.

In all record-efficiency CIGS solar cells, ZnO:Al (AZO) is the standard front electrode.^{23–27} However recently, it was found that the implementation of IOH as transparent front contacts in glass/Mo/CIGS/CdS/intrinsic ZnO (i-ZnO)/IOH solar cells with Na post-deposition treated absorbers leads to an increased open circuit voltage (V_{OC}) yielding an overall

improved power conversion efficiency compared to the reference AZO electrodes.²⁸ Here, a systematic electrical investigation of CIGS solar cells with IOH front contacts and the role of this TCO contact for an increased V_{OC} are presented.

In general, the maximum open circuit voltage V_{OC} obtained from the detailed balance limit, well-known as the Shockley-Queisser limit,²⁹ is ~ 890 mV for CIGS solar cells with a band gap of 1.15 eV.³⁰ This value is well above the V_{OC} of ~ 750 mV for current record efficiency CIGS cells.²³ V_{OC} loss can be attributed to parasitic non-radiative recombination processes that occur at various places in the hetero-junction cell - in the bulk, at grain boundaries of the polycrystalline absorber, as well as at several hetero-interfaces in the Mo/CIGS/CdS/i-ZnO/TCO stack.³¹ Several strategies to reduce the detrimental electron-hole recombination were found to be, among others, an increased hole concentration in the absorber³¹ and the use of highly resistive buffers, such as i-ZnO or Zn_xMg_{1-x}O especially for rough CIGS cells.³² Our results demonstrate that the engineering of the front TCO contact can be yet another promising approach for reducing the parasitic recombination and boosting the efficiency of CIGS cells.

We examine possible material properties and processing effects that could explain the higher V_{OC} observed in IOH-containing cells. First, the primary function of IOH as the transparent conductor is tested by changing the bulk IOH

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thickness and hence the front electrode sheet resistance. Next, the effect of an IOH interlayer at the i-ZnO/TCO interface is investigated for a series of solar cells with varying IOH/AZO ratio in the front TCO electrode. The dominant recombination mechanism of these devices is determined from temperature and illumination intensity-dependent current-voltage measurements, whereas defect levels of solar cells with different IOH/AZO ratios are analyzed by admittance spectroscopy (AS). Finally, we propose two possible explanations for the observed increase in V_{OC} and verify them using the SCAPS software,³³ namely, a higher work-function of IOH and a lower defect density in the i-ZnO layer thanks to a reduced sputter damage during the mild sputter-deposition of IOH, which can both yield an improved V_{OC} .

II. EXPERIMENTAL DETAILS

Thin films of hydrogenated indium oxide were sputter-deposited with H_2O vapor as the doping source.²⁸ Planar magnetrons in an unbalanced configuration were located confocal towards the substrate. The applied sputter power density to ceramic In_2O_3 (2 in. diameter, 99.99%) targets was 3.0 W/cm^2 at a total pressure of 0.6 Pa. H_2O vapor was injected via a needle valve with a partial pressure of $9 \times 10^{-5}\text{ Pa}$ yielding a H concentration of $\sim 4\%$ estimated from elastic recoil detection analysis.²⁸ The AZO reference front electrodes were deposited in another sputtering system from a ceramic AZO target (4 in. diameter, 99.995%, 2 wt. % of Al_2O_3 in ZnO) facing directly the substrate at a power density of 2.5 W/cm^2 and a total pressure of 0.15 Pa. Both TCOs were deposited without intentional heating. Right after a deposition, the substrate temperature was measured to be below 40°C for both IOH and AZO. We assume therefore that the bulk substrate heating during the sputtering should not be detrimental to the CIGS/CdS heterojunction. However, the actual surface temperature and, importantly, the energetic particle flux are different for IOH and AZO experiments since different sputter geometries were employed. The energetic particle flux, and hence the sputter damage is expected to be lower in the case of IOH because of the confocal target configuration, the higher total pressure, and a larger target-to-substrate distance.

Work function offsets were measured by Kelvin probe force microscopy (KPFM) with a modified NanoScan high-resolution magnetic force microscope using a 50 nm Pt-coated Team Nanotec LRCH250 probe at a pressure of $6 \times 10^{-4}\text{ Pa}$. The compensated bias potential was extracted from the bias dependent frequency shift on each sample.

Thin film $Cu(In,Ga)Se_2$ absorbers were deposited on Mo coated soda lime glass in a three-stage co-evaporation process with a composition of $[Cu]/[In + Ga] = 0.83$ and $[Ga]/[In + Ga] = 0.41$, where for each absorber a NaF post-deposition treatment (PDT) was carried out *in-situ*. CdS buffer layer was grown by chemical bath deposition, followed by sputter-depositing 70 nm of i-ZnO. CIGS solar cells were investigated using front contacts consisting of IOH layers in the range from 40 to 330 nm and of the reference AZO contact of 176 nm. Front contacts with different

IOH/AZO ratios were fabricated at a deposition rate of 2 and 32 nm/min for IOH and AZO, respectively, where the thickness of each TCO stack was adjusted to achieve a total sheet resistance of $\sim 75\ \Omega/\square$ on CIGS solar cells. The photovoltaic (PV) parameters of Mo/CIGS/CdS/i-ZnO/TCO solar cells were measured under simulated standard-test conditions (1000 W m^{-2} , AM 1.5 G illumination, 25°C , LOT-Oriel). Current density-voltage (J - V) curves were acquired with a Keithley 2400 source meter and four-terminal sensing. Temperature-dependent J - V curves were obtained in a cryostat with liquid nitrogen cooling. The light intensity from the halogen lamp was calibrated for the same J_{SC} as measured under simulated standard condition. The activation energy E_A of the reverse saturation current density J_0 and the diode ideality factor A were determined from J_{SC} - V_{OC} data at different illumination intensities using various neutral density filters in the temperature range from 120 K to 300 K.^{34,35}

Capacitance-voltage (C - V) measurements and AS were performed with an Agilent E4980A LCR meter at temperatures from 125 K to 300 K assuming a parallel circuit model. Before cooling with liquid nitrogen, the samples were left in dark for at least 30 min in order to relax photo-excited states. The frequency range for AS measurements was 200 Hz–2 MHz.

One-dimensional solar cell simulations for calculating J - V curves under AM 1.5 G illumination at 300 K were performed with the software SCAPS (version 3.2.01).³³ The simulated solar cells consisted of a stack of CIGS/CdS/i-ZnO/TCO, where the parameters used in SCAPS are given in Table I.

III. EXPERIMENTAL RESULTS

A. Enhanced V_{OC} observed for IOH-containing CIGS solar cells

In order to test the persistence of the higher V_{OC} for CIGS solar cells with IOH front contacts, two series of

TABLE I. Parameters used for SCAPS simulations: film thickness (d), band gap (E_g), electron affinity (χ), shallow donor density (N_D) and acceptor (N_A) density, effective states of conduction (N_C) and valence (N_V) bands, electron (μ_e) and hole (μ_h) mobilities, and relative dielectric permittivity (ϵ/ϵ_0). An interface defect between the CIGS and CdS layer was introduced energetically located 0.8 eV above the valence band maximum (VBM) with listed total density (N_{defect}) and capture cross section (σ_c) for electrons and holes.

	CIGS	CdS	i-ZnO	AZO	IOH
d (nm)	2000	50	70	300	300
E_g (eV)	1.2	2.4	3.4	3.4	3.4
χ (eV)	4.5	4.45	4.55	4.6	4.81
N_D (cm^{-3})	—	1×10^{14}	1×10^{16}	4.4×10^{20}	2.3×10^{20}
N_A (cm^{-3})	5.5×10^{15}	—	—	—	—
N_C (cm^{-3})	2×10^{18}	2×10^{18}	4×10^{18}	4×10^{18}	4×10^{18}
N_V (cm^{-3})	2×10^{18}	1.5×10^{19}	9×10^{18}	9×10^{18}	9×10^{18}
μ_e (cm^2/Vs)	50	50	50	50	50
μ_h (cm^2/Vs)	20	20	20	20	20
ϵ/ϵ_0	10	10	10	10	10
	Interface defect		—	—	—
N_{defect} (cm^{-2})	1×10^{11}		—	—	—
σ_c (cm^2)	1×10^{-14}		—	—	—

devices with different IOH sheet resistance using film thicknesses between 330 and 40 nm were fabricated together with reference AZO-containing solar cells. The enhanced V_{OC} is observed for all devices with IOH contacts in the range from 50 to 350 $\Omega/\square$ as compared to the reference AZO device (Fig. 1(a)). For each series, the short-circuit current J_{SC} is increasing for higher IOH resistance (Fig. 1(b)) because thinner IOH layers have lower optical absorption and, hence, can yield a higher photocurrent. The reference AZO device exhibits a higher photocurrent than IOH cells, which can be explained by a wider optical band gap of AZO.²⁸ For similar sheet resistances of the TCO, comparable fill factor FF values are measured for both IOH and AZO devices with a general trend of decreasing FF for high sheet resistance (Fig. 1(c)). The average power conversion efficiency η can be enhanced by absolute 0.5% when replacing AZO for IOH, primarily thanks to the higher V_{OC} .

B. Evolution of PV parameters for IOH/AZO bilayers

In order to distinguish if the beneficial effect of IOH electrode is related to the bulk TCO properties or any interface phenomena are also involved, solar cell devices with front contacts consisting of IOH/AZO bilayers with different thickness ratios but a similar total sheet resistance of $73 \pm 14 \Omega/\square$ were fabricated. The IOH fractions 0, 0.03, 0.11, 0.29, 0.51, and 1 correspond to IOH (AZO) film thicknesses of 0 (176), 5 (173), 20 (158), 50 (125), 90 (85), and 290 (0) nm. As can be clearly seen from Fig. 2(a), a step-like improvement of the V_{OC} is already observed once a thin $\text{In}_2\text{O}_3\text{:H}$ layer of ~ 5 nm is introduced at the i-ZnO/TCO interface, and V_{OC} increases further for higher IOH/AZO ratios. The device with 5 nm of IOH followed by

173 nm of AZO (i.e., IOH/AZO thickness fraction of 0.03) yields an average V_{OC} of 16 mV higher than the reference device with 176 nm AZO. The cell series with an IOH/AZO fraction of 0.11, which exhibits a somewhat increased statistical deviation due to a decreased FF , still shows the average V_{OC} improvement by 10 mV. For IOH-containing devices, the J_{SC} in Fig. 2(b) decreases continuously for higher IOH fractions, whereas the reference AZO cells show values lower than devices with a 5 nm IOH layer. The FF in Fig. 2(c) is rather independent of the IOH fraction except for two series with IOH fractions of 0.03 and 0.11 that exhibit broader deviations possibly due to inhomogeneities in cell grids. The similar average FF of solar cells with pure IOH or AZO front contacts is in agreement with earlier observations.²⁸ The overall power conversion efficiency could be increased by as much as absolute $\sim 0.5\%$ by completely replacing AZO for IOH, but also by the introduction of a thin IOH layer.

C. Temperature-dependent J-V characterization

The enhanced V_{OC} , in essence, indicates the reduced recombination for a p - n junction of fixed work functions. In order to investigate dominant thermally-activated recombination paths, current density–voltage (J - V) curves of CIGS solar cells with front contacts of different IOH fractions were measured at temperatures between 300 K and 120 K, Fig. 3. The enhanced V_{OC} is clearly visible in the inset of Fig. 3(a) for samples measured at room temperature. The FF is also somewhat improved when increasing the IOH fraction and the same trend is observed for the lower temperature of 120 K. A roll-over of J - V curves is observed for all samples at 120 K regardless the IOH fraction (Fig. 3(b)). The

FIG. 1. Photovoltaic parameters of two series of CIGS solar cells (squares and circles) with AZO and IOH front contacts of different sheet resistance: (a) open circuit voltage V_{OC} , (b) short-circuit current density J_{SC} , (c) FF , and (d) solar cell efficiency η . Average values and standard deviation are given for nine cells (cell area 0.3 cm^2).

FIG. 2. Photovoltaic parameters of CIGS solar cells with TCO front contacts consisting of IOH/AZO bilayers that have a constant total sheet resistance of $73 \pm 14 \Omega/\square$. The IOH fraction is given as the thickness ratio $d_{\text{IOH}}/(d_{\text{IOH}} + d_{\text{AZO}})$. Average values and standard deviation are given for 6–9 cells (cell area 0.3 cm^2).

appearance of this roll-over is often attributed to the presence of the so-called “N1” defect in CIGS solar cells, which is not related to the front contact but can rather be explained by a secondary diode at the CIGS/Mo interface.⁷

The dominant recombination mechanism can be determined from $J_{\text{SC}}-V_{\text{OC}}$ measurements at different temperatures and illumination intensities, which yield the activation energy E_A , the reverse saturation current density J_0 , and the diode ideality factor A .³⁵ The temperature dependence of the reverse saturation current density J_0 is assumed to be

$$J_0 = J_{00} \cdot \exp\left(\frac{-E_A}{k_B T}\right),$$

where J_{00} is a weakly dependent pre-factor and k_B is the Boltzmann constant.

The activation energy E_A and the diode ideality factor A , which are extracted from the J - V curves of one representative cell for each IOH fraction, remain rather constant for the whole range of IOH fractions from 0 to 1 (Fig. 4). The E_A value remains around 1.2 eV, which is close to the measured minimum CIGS band gap of 1.16 eV. If Fermi level pinning is present, this would suggest that the dominant recombination losses occur in the space charge region (SCR) or the quasi-neutral region (QNR) of the absorber. However,

FIG. 3. Current density–voltage (J - V) curves of CIGS solar cells with front contacts of different IOH fractions (0–1) measured at (a) 300 K and (b) 120 K. Inset (a): Scale-up showing the increase in V_{OC} for higher IOH fractions.

FIG. 4. Activation energy E_A of the reverse saturation current density J_0 and diode ideality factor A determined from $J_{\text{SC}}-V_{\text{OC}}$ data at different illumination intensities in the temperature range from 120 K to 300 K. The diode ideality factor A is plotted for a temperature of 300 K.

electron-hole recombination in the QNR is not expected to dominate in high efficiency solar cells.³¹ On the other hand, if the Fermi level is not pinned, interface recombination through defects can limit the diode current although an activation energy close to the band gap energy of the absorber would be measured. In that case, the activation energy E_A is not equivalent to the hole barrier at the interface.³⁶ Hence the hole barrier can be increased, for instance by an enhanced built-in voltage, yielding decreased recombination without a change in E_A . The diode ideality factor depends on the recombination mechanism and is equal to 2 in case of recombination in the SCR and, if the Fermi level is not pinned, $A = 1$ for interface recombination.^{31,36} A similar ideality factor A of ~ 1.4 is observed for all IOH fractions. The temperature dependence of A^{-1} (not shown) deviates only weakly from a linear behavior, indicating that tunneling contributes only to a small part to the recombination current.^{37,38} One can conclude that the dominant recombination mechanism remains to be within the SCR and at the junction interface for all IOH fractions.

D. Admittance spectroscopy of defect levels

Detrimental electron-hole recombination occurs primarily at deep defect states within the band gap, and in the CIGS absorber, these defects are thought to be mainly Cu_{In} , Cu_{Ga} , and Se related defects.^{39–41} In order to correlate defect states to V_{OC} , the defect density N_T was estimated from AS as a function of the exciting energy E_ω for CIGS solar cells with different IOH fractions, depicted in Fig. 5. A large defect signal is apparent between 0.1 and 0.15 eV for all devices and is attributed to the well-known defect N1.³⁴ For increasing IOH content, a second peak is evolving with a shifting energy up to 0.25 eV for pure IOH as front contact. Admittance spectroscopy was performed at zero bias voltage for all the solar cells and is sensitive to defects states inside the SCR where the Fermi level crosses the defect level. A shifting AS signal therefore means that either the energy level of that defect is changing or that the band bending is modified by the presence of the various applied TCOs. The fact that recombination is reduced for higher IOH fraction favors the latter and suggests that this defect is present in all of the devices, but is detected by AS at different exciting energies or not at all.

IV. DISCUSSION

The detailed electrical characterization of glass/Mo/CIGS/CdS/i-ZnO/TCO heterostructure solar cells with IOH front TCO electrode has repeatedly confirmed the improvement in the open circuit voltage V_{OC} by ~ 20 mV as compared to the reference AZO electrode. The step-like V_{OC} raise is already observed when a very thin IOH layer of 5 nm is inserted at the i-ZnO/AZO interface, and the voltage is further increased by increasing the IOH thickness. Temperature- and illumination dependent measurements show that the introduction of the IOH does not alter the dominant recombination path, which remains to be confined to the SCR and the interface of the p - n junction.

We propose two hypotheses of how the introduction of the IOH layer can lead to the observed V_{OC} improvement.

FIG. 5. Defect density N_T as a function of the exciting energy E_ω obtained by admittance spectroscopy for CIGS solar cells with front contacts of different IOH fractions (0–1) measured from 125 K to 300 K in the frequency range between 200 Hz and 2 MHz.

These two hypotheses are verified using one-dimensional simulations with the SCAPS software. For these simulations, we set an acceptor-like defect at the CIGS/CdS interface 0.8 eV above the valence band with a total density of $1.0 \times 10^{11} \text{ cm}^{-2}$ and a capture cross section of $1.0 \times 10^{-14} \text{ cm}^2$ for electrons and holes. Experimentally, a deep defect centered around 0.8 eV above the valence band was observed by several methods,^{42–44} whereupon the chemical formation and the spatial location of this defect are not clear.^{45,46} The resulting energy band diagrams for AZO and IOH front contacts, which correspond to the J - V simulations in Fig. 7(b) at zero bias voltage, are depicted in Fig. 6(b).

FIG. 6. (a) Schematic of CIGS solar cells with front contacts consisting of AZO, IOH, and IOH/AZO bilayers of different ratios. (b) Resulting energy band diagrams for AZO and IOH front contacts corresponding to the J - V simulations in Fig. 7(b) at zero bias voltage with depicted conduction (E_C) and valence (E_V) bands, electron ($E_{F,n}$) and hole ($E_{F,p}$) quasi Fermi levels, and interface defect between the CIGS and CdS layer.

FIG. 7. SCAPS simulations of CIGS solar cells with an acceptor-like defect at the CIGS/CdS interface, energetically set 0.8 eV above the valence band: (a) Effect of the TCO electron affinity on the V_{OC} for different donor doping densities. (b) Calculated $J-V$ curves cells using TCOs with free carrier densities determined from Hall measurements and a chosen electron affinity offset of 0.21 eV yielding a difference in V_{OC} of 21 mV.

First, IOH differs from AZO electrically by a higher work function,⁴⁷ a lower optical band gap, and by a lower carrier density and a higher mobility.²⁸ Using KPFM on pre-cleaned TCO surfaces, we measured the difference in the work function between IOH and AZO to be 0.21 eV. The work function offset of i-ZnO/IOH can yield a Schottky-like barrier, but which does not lead to a significant hindrance for electron transport confirmed by a similar cell series resistance. The influence of the work function of the TCO on the PV parameters was simulated by varying the electron affinity in the range from 4.6 to 4.81 eV, where the effect of the Fermi level was tested by changing the doping (donor density) and the conduction band minimum was assumed to be constant. In Fig. 7(a), the V_{OC} increases significantly for an offset of $>0.1 \text{ eV}$ slightly dependent of the free carrier density of the TCO. The resulting $J-V$ curves of cells using TCOs with an electron affinity offset of 0.21 eV (chosen based on the determined work function offset by Kelvin probe) and free carrier densities of IOH and AZO determined from Hall measurements are given in Fig. 7(b), yielding a difference in V_{OC} of 21 mV. The higher work function shifts up the Fermi level at the $p-n$ junction and increases the hole barrier by an enhanced built-in electric field, which reduces electron-hole recombination through the interface defect. The fact that the activation energy E_A was measured to be constant with $E_A \approx E_{g,\text{CIGS}}$ (Fig. 4) for different IOH fractions is not contradicting an enhanced hole barrier for IOH-containing devices because for unpinned Fermi levels at the junction, the hole barrier height depends on the quasi-Fermi levels of the absorber and the n -type part.³⁶

The second hypothesis considers also a work function offset of the TCO but includes high energetic bombardment of the i-ZnO layer. The high energetic particle flux towards the i-ZnO is much higher due to a direct facing target and a lower sputtering pressure for AZO than IOH films, which introduces a higher defect density in the top layer of i-ZnO and possibly creating oxygen vacancies yielding a higher donor density. In Fig. 8(a), the influence of the donor density of the first 10 nm i-ZnO (penetration depth estimated with the software SRIM,⁴⁸ total i-ZnO thickness is 70 nm) on the V_{OC} is shown for different TCO electron affinities. The shift of the Fermi level leading to reduced recombination through the interface defect is apparent for lower donor densities of the i-ZnO and depends strongly on the offset of the electron affinity. The resulting $J-V$ curves for the extreme case with $N_{\text{i-ZnO(AZO)}}/N_{\text{i-ZnO(IOH)}} = 10^3$ and $\Delta\chi = 0.21 \text{ eV}$ are depicted in Fig. 8(b), exhibiting a V_{OC} difference of 25 mV.

Both scenarios depend on the $p-n$ junction properties, such as band bending and defect states. The underlying mechanism can be understood as a remote controlling of the Fermi level position at the $p-n$ junction. Apparently, such effects can only be expected in the case of an unpinned junction Fermi level. It was shown that for interface defect densities around 10^{11} cm^{-2} , as in our case, the Fermi level should not be pinned.⁴⁹ Indeed, the situation is different for solar cells with potassium post-deposition treated absorbers, where the CIGS surface at the CdS interface is thought to be inverted due to Cd_{Cu} donor defects.³⁴ In this case, the V_{OC} could not be improved by the introduction of IOH and the average PV parameters of six cells with their standard deviation exhibited $V_{OC} = 715 \pm 3 \text{ V}$, $J_{SC} = 34 \pm 0.1 \text{ mA/cm}^2$, $FF = 76.1 \pm 0.4\%$, and $\eta = 18.5 \pm 0.1\%$,

FIG. 8. SCAPS simulations of CIGS solar cells with an acceptor-like defect at the CIGS/CdS interface, energetically set 0.8 eV above the valence band: (a) Effect of the donor density in the i-ZnO layer (first 10 nm) on the V_{OC} for different TCO electron affinities. (b) Calculated $J-V$ curves cells using i-ZnO layers with $N_{\text{i-ZnO(AZO)}}/N_{\text{i-ZnO(IOH)}} = 10^3$ and a chosen electron affinity offset of 0.21 eV yielding a difference in V_{OC} of 25 mV.

compared to $V_{OC} = 719 \pm 3$ V, $J_{SC} = 34.7 \pm 0.2$ mA/cm², $FF = 75.7 \pm 0.3\%$, and $\eta = 18.9 \pm 0.1\%$ for pure AZO electrodes. The junction in CIGS based solar cells is highly investigated and further progress is expected. Thus, the possibility to modify the Fermi level position at that junction by the proper choice of the front TCO contact might become a promising tool to reduce parasitic recombination.

V. CONCLUSIONS

Hydrogenated In₂O₃ was demonstrated to be a suitable front contact in CIGS solar cells with enhanced PV performance. The interface between the i-ZnO and the TCO was found to be crucial for the enhanced V_{OC} and showed improved functionality due to a higher work function of IOH and a lower bombardment by energetic species during the sputter-deposition of the TCO.

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