Graphical Abstract

Controlled Activation of ZnTe:Cu Contacted CdTe Solar Cells Using Rapid Thermal Processing

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Abstract

Back contacts can significantly limit CdTe solar cell performance, reducing both open circuit voltage (V_{oc}) and fill factor (FF). Copper is an essential component of effective back contacts, but its presence in the CdTe absorber creates detrimental recombination centers. Rapid thermal processing (RTP) is demonstrated as a highly effective approach for reducing back contact barriers in CdTe solar cells contacted with ZnTe:Cu buffer layers, substantially improving both FF (>73%) and V_{oc} (>850 mV). Current density and quantum efficiency remain essentially unchanged, but a five-fold increase in minority carrier lifetime is observed which is attributed to passivation of recombination sites in the back contact region. Quantitative analysis of secondary ion mass spectrometry shows that the majority of Cu segregates to the Au metallization layer and that the ZnTe buffer appears to inhibit the Cu diffusion into CdTe. 3D imaging of the back contact region using atom probe tomography shows that optimized devices are characterized by preferential segregation of copper to both the Au/ZnTe and CdTe/ZnTe interfaces, perhaps in the form of Cu_xTe . With its low thermal budget the RTP process has been successfully applied to multiple device architectures. ~~including devices with certified efficiencies in excess of 16%.~~

Keywords: solar cells, CdTe, thin film, back contact, RTP

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1. Introduction

A notorious challenge for CdTe solar cell technology is the formation of high quality ohmic back contacts [1]. The large electron affinity of CdTe coupled with its inability to be highly doped leads to the formation of a Schottky barrier when contacted directly with a metal. Consequences of such barriers involve loss of open circuit voltage (V_{oc}) and fill factor (FF), which are often manifested by the presence of roll over behavior in J-V curves [2]. A common strategy to address this problem is through the insertion of a thin interfacial layer between the CdTe and metal contact [3]. One such **back** buffer layer is Cu_xTe ($1 < x < 2$), which may be formed by the deposition of Cu followed by thermal treatments. Such contacts reduce the series resistance and have resulted in high efficiency devices [4, 5], but copper migration to the front contact can lead to shunting and loss of efficiency [6, 7]. Another commonly used **back** buffer layer is copper doped zinc telluride (ZnTe:Cu), where the copper doping level is in the range of 1-5 wt % [8]. ZnTe is chemically compatible with CdTe and offers a number of advantages. First, its valence band maximum is well aligned with that of CdTe, facilitating hole collection [9]. With a band gap of the ~2.2 eV ZnTe also provides a back contact reflector for electrons which is proposed to reduce recombination at the back contact, particularly in thin or fully depleted device structures [10]. Lastly, ZnTe can be highly doped ($> 10^{20} \text{ cm}^{-3}$) [11] to provide an effective tunnel junction to the metal layer [12]. First Solar recently revealed that it has integrated a ZnTe buffer into its current product line, crediting this layer for recent improvements in both champion cell efficiency and module reliability [13].

As most commonly practiced, ZnTe:Cu layers are deposited by sputtering at elevated temperature (240–360 °C) in processes whose duration are on the order of hours [14, 15]. The amount of copper is controlled by varying the composition of the sputter target or the layer

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4 thickness. It is well known that copper is a fast diffuser, with reported coefficients of $\sim 10^{-9} \text{ cm}^2/\text{s}$
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6 at the temperatures employed [16, 17]. In addition to limiting throughput, another drawback of
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8 this procedure is that deposition and diffusion occur simultaneously, making process control
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10 difficult and resulting in copper migration throughout the device [15]. In bulk CdTe a very small
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12 amount of copper may be beneficial [18, 19], however excessive amounts lead to deep level
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14 defects and recombination centers [20-22].
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18 In this paper we describe a new process in which deposition and activation of ZnTe:Cu are
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20 decoupled. The ZnTe:Cu buffer and Au metallization layers are first deposited by evaporation at
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22 low temperature, followed by rapid thermal processing (RTP) to precisely control activation.
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24 Despite RTP's apparent suitability for CdTe device fabrication there are very limited reports of
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26 its use. RTP has been demonstrated to facilitate grain growth and improve crystallinity of
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28 evaporated CdTe [23], but we are unaware of its application in back contact preparation. RTP
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30 offers a number of important advantages for this purpose. First, it is expected that high
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32 temperature-short time processes should be selective to Cu activation over diffusion based on
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34 energetics. The diffusion process is weakly activated, with reported activation energies of 0.3–
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36 0.7 eV [16, 17, 24]. In contrast, the enthalpies of formation for copper doping states range from
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38 1.5–2.5 eV [25]. Second, RTP offers high throughput and precise control over time-temperature
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40 trajectories. Lastly, the low thermal budgets involved should not disturb the optimization of
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42 preceding processes used in front contact formation or absorber deposition, making this process
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44 easily adaptable to multiple device fabrication platforms.
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53 In this work the dramatic improvements in device performance afforded by this RTP process
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55 are quantified and interpreted through measurements of current-voltage (J-V), quantum
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57 efficiency (QE), carrier density (N_A) and minority carrier lifetime (τ). The redistribution of
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copper during RTP is examined using secondary ion mass spectrometry (SIMS) and atom probe tomography (APT). SIMS is used to quantify the extent of Cu diffusion into the CdTe absorber while APT is employed to characterize the back contact region with nanoscale resolution. These measurements are combined to postulate the changes in band structure that occur in the back contact region under optimal process conditions.

2. Materials and Methods

2.1 Device Fabrication

Devices were fabricated using two different superstrate/front contact combinations to demonstrate the flexibility of the RTP back contact process. The first employed fluorine-doped tin oxide coated glass (TEC-15, Pilkington) that was coated with 150 nm of CdS deposited by thermal evaporation at 150 °C. The second superstrate consisted of Corning 7059 glass coated with a SnO₂:F (FTO)/SnO₂ (TO) transparent conductive oxide (TCO) bilayers deposited by metal-organic chemical vapor deposition followed by 100 nm of CdS:O deposited by reactive sputtering at room temperature [26]. The remaining processing was identical. For all devices a ~3 micron CdTe absorber layer was grown by vapor transport deposition at T = 450 °C [27]. The samples were exposed to CdCl₂ in a close spaced sublimation geometry in a tube furnace at 400 °C for 30 min using a 50%-50% O₂/N₂ ambient. The back surface was etched in a 0.5% (v/v) Br₂/CH₃OH solution for 10 s and rinsed with methanol prior to back contact preparation. A 200 nm ZnTe:Cu buffer layer was deposited by thermal co-evaporation at 100°C to avoid moisture contamination. Quartz crystal monitors (QCM) were used to control the evaporation rates of both sources, and the total copper content was 3.4 wt%. Devices with an area of 0.079 cm² were defined by evaporation of 150 nm of Au using a shadow mask. Individual devices were isolated

by scribing along the perimeter of the Au through the semiconductors down to the transparent conductor. After device fabrication, samples were subjected to 30 s RTP treatments under flowing Ar to activate the back contact. Devices were placed on a thin AlN susceptor and illuminated from all sides. The nominal temperature reported is from a thermocouple placed in direct contact with the base of the AlN susceptor. Further details on the optimization of buffer layer composition and RTP process conditions are provided in the literature [28].

2.2 Device Characterization

The solar cell performance was measured under simulated AM1.5 radiation using a commercial tool that is calibrated using a certified silicon standard (PV Measurements). Quantum efficiency (QE) was measured on a custom system with a grating monochromator and lock-in amplifier detection. For these measurements no intentional white light bias is added to the mechanically chopped monochromatic light. Results are calibrated by comparison to a standard silicon solar cell previously measured at the National Renewable Energy Laboratory (NREL). Capacitance Voltage (CV) was measured on an Agilent HP4284A precision LCR meter controlled by Labview at 100 kHz and with a 10 mV AC signal. Time resolved photoluminescence (TRPL) measurements used to determine minority carrier lifetime were performed at NREL using 650 nm pulsed laser excitation.[29] Dynamic SIMS was performed using an ION-TOF Model IV, and the copper density was quantified by normalizing the measured Cu/Te ratio to the copper content in the as-deposited sample which was quantified by APT. APT analyses were performed on a Cameca LEAP 4000X Si local electrode atom probe instrument using parameters optimized for quantitative evaluation of these materials.[30] Additionally, transmission electron microscopy (TEM) images before and after APT analyses

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4 were acquired with a Philips CM200 TEM using a holder specifically designed for imaging APT
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6 specimens.[31]
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10 11 **3. Results**

12 13 *3.1 Opto-electronic Properties*

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15 The CdTe cells used in these studies were fabricated using the conventional superstrate
16 architecture as detailed in the experimental section. Throughout this work comparisons are made
17 among sets of three devices in which the fabrication steps through deposition of the back contact
18 were identical, with the only parameter varied being the nature of the RTP treatment. “As-
19 deposited” samples refer to devices that were contacted with a ZnTe:Cu|Au bilayer, but not
20 subjected to RTP annealing. “Optimal” samples were subjected to a 30 s RTP treatment at an
21 optimized setpoint temperature that was 300-340 °C depending on the specific superstrate
22 employed. “Overheated” samples received an additional 30 s RTP treatment at slightly elevated
23 temperature.
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27 Figure 1a provides box plots comparing the efficiency obtained from 8-10 devices in the as-
28 deposited state, after an optimal RTP treatment, and from an overheated sample. Figure 1b
29 provides representative J-V curves from this set of devices and the associated device parameters
30 are summarized in Table 1. For these samples, which employed the Corning 7059 front contact,
31 the optimal RTP treatment consisted of a single 30 s treatment at a setpoint temperature of 300
32 °C. The overheated sample was exposed to an additional 30 s treatment at 320 °C. Note that
33 nominally identical results were observed for devices employing the TEC15/CdS front
34 contact.^[28] The as-deposited device showed good current collection, but the efficiency was just
35 10% due to the low open circuit voltage of just 636 mV. After the optimal RTP treatment there
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were significant improvements in both V_{OC} (852 mV) and FF (73.7%) that are consistent with the elimination of back contact barriers. The J_{sc} value remains essentially unchanged, and thus the overall efficiency was elevated to 15.3%. After receiving the second 30 s RTP treatment the efficiency was greatly attenuated (8.9%), with losses in V_{oc} , FF, and J_{sc} . The significant decrease in J_{sc} could be attributed to the presence of excess Cu in the CdTe that form defects that serve as recombination centers. Another possibility is shunting, which is commonly observed when significant Cu has diffused to the CdS layer, thus degrading the quality of the heterojunction. These possibilities are discussed below.

Figure 1. Influence of RTP treatment on a) device efficiency as shown in a box plots based on 8-10 devices at each condition. 50% of the measurements fall within the box, while the position of the error bars reflect the maximum and minimum obtained from each sample. b) J-V curves representative of ZnTe:Cu contacted devices in the as-deposited state, after optimal RTP treatment, and overheated.

Table 1. Summary of device parameters in the three states.

Sample	V_{OC} [mV]	J_{sc} [mA/cm ²]	FF [%]	Efficiency [%]
As-deposited	636	25.4	62.2	10.0
Optimal	852	24.3	73.7	15.3
Overheated	793	19.4	54	8.3

Measurements of quantum efficiency, carrier density and lifetime are consistent with the J-V behavior. Figure 2 compares the QE response obtained from devices prepared in the as-deposited, optimal, and overheated states. The QE of the as-deposited and optimally processed devices were quite similar as would be expected from their J_{sc} values, showing that the optimal RTP treatment does not significantly impact the properties of the front contact or the CdTe absorber. In contrast, excessive heating is deleterious to current collection throughout the visible spectrum. In particular, significant QE loss is observed in the red portion of the spectrum, behavior which has previously been correlated with copper content and ascribed to related defects that cause voltage-dependent collection [32].

Figure 2. Comparison of external quantum efficiency spectra for the 3 representative devices.

The carrier density (N_A) profile as a function of the depletion width (W) is calculated by

$$N_A(W) = \frac{2}{q\epsilon} \left[\frac{d(1/C^2)}{dV} \right]^{-1} \quad (1)$$

where $W = \epsilon/C$, q is the elemental charge, ϵ is the permittivity, C is the specific capacitance, and V is the bias voltage. Figure 3a compares the carrier density profile for the as-deposited and optimally processed samples. The overheated sample displayed very high leakage current, providing unreasonable results and as such was excluded from this comparison. Both of the remaining samples display U-shape profiles characteristic of CdTe/CdS solar cells.^[33] The carrier concentrations were estimated from the bases of these curves to avoid the complications that can occur at both forward and reverse bias. The results are somewhat surprising, in that the apparent acceptor density actually declined after optimal RTP treatment from 10^{14} to $4 \times 10^{13} \text{ cm}^{-3}$. However these changes are small, and suggest that the observed device improvements are not due to copper doping of the CdTe.

Figure 3. a) Net acceptor density, N_A vs. depletion width, W , as derived from C-V measurements for the as-deposited device and after optimal RTP treatment; b) Comparison of TRPL measurements of minority carrier lifetime from three representative devices.

Figure 3b compares TRPL measurements which were used to extract minority carrier lifetimes (τ) for these samples. After optimal RTP treatment, τ jumped by a factor of five from 0.3 ns in the as-deposited sample to 1.5 ns. With excessive heating τ declined to values less than the as-deposited case. Open circuit voltage has been strongly correlated with lifetime [34],

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4 although the underlying reasons for this relationship are not fully understood. For devices
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6 contacted with Cu_xTe it was observed that lifetimes declined with increasing copper, which was
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8 attributed to the formation of defects in the bulk or near the CdS/CdTe heterojunction that serve
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10 as recombination centers [32]. In contrast, for devices contacted with ZnTe:Cu lifetimes
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12 increased to an optimal value that was a strong function of contacting temperature,^[14] not
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14 dissimilar from the behavior observed here. Recently it has been shown that 1 photon TRPL
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16 using excitation above the band gap may be more sensitive to surface than bulk recombination,
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18 particularly in thin film devices [35]. The addition of buffer layers is expected to introduce
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20 interface defect states that can create dipole layers [3]. The resulting fields would oppose the
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22 built-in field associated with the junction, and thus their removal by post-deposition processes
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24 such as RTP would increase the energy of collected carriers. An optimally formed ZnTe:Cu
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26 back contact will also have a large conduction band offset at the CdTe/ZnTe interface, creating
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28 an electron reflector that keep electrons from getting to the ZnTe/metal interface. It is postulated
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30 that the large increase in τ and V_{OC} observed under optimal RTP conditions is due to
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32 modification or passivation of these interface states, and an associated reduction in
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34 recombination and barriers in the back contact region.
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47 3.2 Copper Distribution

48 3.2.1 Secondary Ion Mass Spectrometry

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50 To better understand how copper migration may be influencing the results described above, its
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52 distribution was measured using SIMS and APT using a set of TEC15/CdS based devices. The
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54 former provides an averaged 1D profile throughout the device structure, while APT was used to
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56 create 3D reconstructions of the structure and elemental distribution in the back contact region.
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Figure 4 displays SIMS profiles confirming systematic variation in Cu diffusion into the CdTe layer as a result of RTP treatment. The as-deposited case shows that copper is uniformly distributed through the ZnTe layer in a step profile as expected. Upon RTP treatment copper diffuses out of the ZnTe layer into both the CdTe absorber as well as into the gold contact (the first ~150 nm of the depth profile). The latter is not surprising since copper and gold form completely miscible solid solutions. Also as expected, successive RTP treatments further deplete the ZnTe layer and increase the extent of copper diffusion into the device. For the optimal device Cu extends ~1 μm into the CdTe before falling below the sensitivity limit of the instrument. The overheated sample displays higher Cu levels in the CdTe, and there is also some evidence of copper accumulation in the CdS layer, which would be consistent with the shunting behavior observed in those devices (Fig. 1b).

Figure 4. Quantified SIMS depth profiles of Cu concentration from the Au/ZnTe:Cu/CdTe/CdS devices considered in this work. The smooth curves through the RTP samples are solutions to Fick's law using Eq. (2).

The smooth curves running through the data are Gaussian profiles that are the solutions to Fick's second law, approximating the initial Cu distribution as a delta function:

$$C(x,t) = \frac{Q_T}{\sqrt{\pi Dt}} \exp\left(\frac{-x^2}{4Dt}\right) \quad (2)$$

where the two adjustable parameters are the initial dose, Q_T , and a characteristic diffusion length $\sqrt{Dt}$. For both profiles the dose was fixed at $Q_T = 2 \times 10^{16} \text{ cm}^{-2}$ and the diffusion lengths were 0.13 and 0.21 μm for the optimal and overheated samples, respectively. These simple analytical solutions do a relatively good job of modeling the experimental profiles, and the parameters employed provide insight into the processes that are occurring. The total dose of copper provided in the as-deposited ZnTe:Cu layer was $1 \times 10^{17} \text{ cm}^{-2}$. The lower value of $2 \times 10^{16} \text{ cm}^{-2}$ that was found to best fit both diffusion profiles reflects the fact that a significant fraction, perhaps the majority, of copper provided in the buffer layer accumulates in the gold contact. Based on the RTP times employed one extracts diffusion coefficients that are on the order of $5 \times 10^{-12} \text{ cm}^2/\text{s}$. These are surprisingly low values, and using the Arrhenius relationships for copper diffusion coefficients available in the literature [16, 17] it would suggest that the temperature of the sample was $\sim 150^\circ\text{C}$, significantly below the nominal RTP setpoint recorded by a thermocouple in contact with the susceptor. This contradicts evidence that suggest that during RTP processing the effective temperature of the CdTe layer is actually hotter than the value recorded by the thermocouple in contact with the AlN susceptor. At the short time scales involved radiation is selectively absorbed in the CdTe layer with the glass superstrate and AlN susceptor serving as heat sinks. Evidence in support of this hypothesis comes from our observation that the RTP temperature setpoint must be reduced in order to achieve optimal performance when the thickness of the glass superstrate is reduced or when devices are

intentionally placed in poor thermal contact with the susceptor. Assuming the CdTe layer is at temperature greater than **or** equal to that recorded by the thermocouple these results suggest that barriers at the ZnTe interface may inhibit Cu diffusion into the CdTe, accounting for the low effective diffusion coefficients observed. Such behavior would be consistent with recent reports of improved reliability with the use of ZnTe buffer layers [13].

3.2.2 Atom Probe Tomography

SIMS is very useful for providing an overview of the distribution throughout the device, but it provides profiles that are radially averaged due to the sputtering spot size. Atom probe tomography has been demonstrated to be a powerful tool for characterizing polycrystalline solar cells [36], and in particular its 3D capability has been recently deployed to characterize the segregation of impurities at the grain boundaries in CdTe devices [37]. Here we apply APT to characterize the structure and composition of the three representative samples as shown in Figure 5. Each of these figures includes a TEM image of the sample before APT, the resulting elemental reconstruction, and volume averaged 1D concentration profiles down the tip axis, which was approximately orthogonal to the layers. The original samples prepared by FIB contained a small portion of the Au contact (~5 – 10 nm) at the apex, but this layer popped off during specimen turn on, likely due to the lower evaporation field for ZnTe than for Au. Therefore, zero on the x axis of the concentration profiles corresponds to the Au|ZnTe interface. In the APT images Cd is represented as black, Zn is grey, Cu is orange, and Te is excluded for clarity. Note that the images provided in Figure 5 are just 2D representations of the full 3D reconstructions. Videos displaying the full 3D elemental distributions for these samples are provided in the

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4 supplementary information. A sharp ZnTe|CdTe interface is observed in all samples, demarked
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6 by the grey/black border. Significant heterogeneity in the copper distribution is observed in all
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8 samples as discussed below.
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11 Fig. 5a displays the results for the as-deposited sample. During co-evaporation the intent was
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13 to deposit copper uniformly throughout the buffer layer sample, though in this sample higher
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15 levels are observed near the CdTe interface. The non-uniform profile is attributed to the
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17 challenges of the co-evaporation process. The evaporation rates of both constituents are
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19 controlled by independent power supplies and monitored by two QCMs. However the nominal
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21 evaporation rate of Cu is $0.5 \text{ \AA/s}$, which is near the lower limit of the QCM's sensitivity, making
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23 control challenging. It is straightforward to control the total amount of copper deposited, but the
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25 variations observed in this APT sample are attributed to our ability to precisely control the local
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27 Cu evaporation rate. However, we note that while the RTP process is sensitive to the total
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29 fraction of copper in the buffer layer, but not significantly influenced by its initial distribution.
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31 Previously we demonstrated that device results achieved with ZnTe|Cu bilayers were nominally
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33 identical to co-evaporated buffers [28]. The volume-averaged copper content in the as-deposited
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35 buffer was 9.8 at. % (3.4 wt %), which is quite comparable to the nominal composition of ZnTe:
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37 Cu targets used in sputter deposition [14].
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(a) As-deposited

(b) Optimal

(c) Overheated

Figure 5. TEM images of samples before APT processing, 2D images of the resulting elemental reconstruction, and 1D volume averaged concentration profiles of the back contact region obtained from a) the as-deposited; b) optimally-processed and c) the overheated samples. Note that $z = 0$ in the APT reconstructions corresponds to the position of the ZnTe/Au interface. Click on the following hyperlinks to access videos displaying the full 3D elemental reconstruction of the [as-deposited](#), [optimal](#), and [overheated](#) samples. In the videos and images above the threshold values used for the isoconcentration surfaces – are 25 at% for Cd (black), 25 at% for Zn (grey), and 10 at% for Cu (orange).

Figure 5b shows the APT reconstruction of a sample processed with an optimal RTP treatment. In this case APT reveals considerable segregation of copper toward both the Au and CdTe interfaces. Comparison of Figs. 4 and 5 highlight the power of APT for nanoscale analysis of these interfacial regions that are so critical to controlling the performance of thin film photovoltaic devices. The SIMS profile for these samples indicate that Cu is uniformly distributed throughout the ZnTe, where in reality it is highly localized with some individual regions exceeding 50 at. %. These images suggest that copper redistribution within the ZnTe region is controlled primarily by thermodynamic parameters such as solubility and partition functions as opposed to Fickian diffusion. The high localized levels of Cu suggest the possibility of Cu_xTe formation, as the regions with elevated Cu content are well-correlated to displacement of Zn. This finding is perhaps not surprising given that the formation energy of Cu_2Te is close to zero.^[25] So while Cu_xTe and ZnTe:Cu have been previously considered to be distinct buffer layers, these results suggest that they may share some notable similarities, at least when processed using RTP.

Finally Figure 5c shows the APT reconstruction of a sample that has been overheated during RTP treatment. It is remarkable that the application of just 30 s of additional RTP treatment beyond the optimized condition results in significant depletion of Cu from the ZnTe buffer layer. Characteristics of the Cu_xTe phase remain at the CdTe interface, but it is largely diminished at

the Au interface. Significant Cd diffusion from the absorber layer is also observed. This is also seen in the optimal sample, but in the overheated sample the alloying process appears complete with a uniform density of ~4 at. % Cd throughout the ZnTe layer. In addition, significant Te and Cd accumulations at the Au interface are observed, which may be another contributing factor to the substantial decline in performance of the overheated sample.

4. Discussion

It is somewhat surprising that the heterogeneous structure produced under optimal RTP processing was correlated to such dramatic improvements in device performance. Figure 6 displays proposed band diagrams of the back contact region illustrating the changes that occur in the optimized RTP process. The electronic structure of the back contact region in the as-deposited state was based on the work of Späth et al. [38], who constructed their band diagram of this heterojunction using ultraviolet photoelectron spectroscopy (UPS) measurements of the valence band maximum position relative to the Fermi level obtained from CdTe and after subsequent sputter deposition of ZnTe. We assume that the Fermi level in the as-deposited ZnTe:Cu is similar to their value, because although Cu is present, it has not been thermally activated. In this structure there is a negligible valence band offset (~0.1 eV) at the ZnTe|CdTe interface, but a significant Schottky barrier is present at the gold interface. In addition, since these layers are deposited at low temperature it is expected that there are significant densities of defects and trap states at the interface. Indeed it was suggested in the previous UPS work that defects must be present at this interface to ensure charge neutrality and explain why band bending only occurs in the CdTe layer [38]. After optimal RTP treatment we postulate two

Figure 6. Postulated band diagrams of the back contact region for these devices in the a) as-deposited state and b) after application of an optimized RTP treatment.

major changes. First, the ZnTe:Cu layer becomes more *p*-type due to activation of Cu dopants, which shifts the valence band offset into a position that eliminates any barriers to hole transport at the ZnTe|CdTe interface.[38] Second, it is postulated that the Cu migration to the interfaces observed by APT is critical for passivation of defect states, which allows band bending to occur on both sides of the ZnTe|CdTe interface. Note that a Schottky junction remains at the gold interface after RTP treatment, but the activation of dopants creates an efficient tunnel junction for charge transfer into the Au metallization layer. Finally this structure presents a formidable barrier to electron transport, which should minimize recombination in the back contact region.

Rapid thermal processing is critical to enable the benefits shown in this work. The staggering changes that occur in the ZnTe buffer region after 30 s RTP treatments suggest that its structure is determined by thermodynamic quantities such as solubility and stability of the relevant phases. It is highly unlikely that the unique non-equilibrium structures observed in this work that are correlated with high performance could be achieved through conventional thermal processing. Decoupling buffer deposition and activation, combined with the precise control imparted by RTP, are identified as the key enablers. Finally, the low thermal budgets employed

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4 suggest that this process should be readily adapted to other systems. This attribute was recently
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6 demonstrated when the back contact procedure described here was applied to devices fabricated
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8 by the National Renewable Energy Laboratory based on 100 μm flexible glass superstrates.[39]
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10 Application of the RTP back contact contributed to elevating the certified efficiency of devices
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12 fabricated on this platform from 14% to >16%.[40]
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18 **5. Conclusions**

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20 It is demonstrated that RTP is a highly effective approach to activate ZnTe:Cu-based back
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22 contacts, providing significant improvements in V_{oc} , FF, and efficiency. The dramatic
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24 improvements in V_{oc} and τ are attributed to the elimination of barriers and mitigation of surface
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26 recombination in the back contact region. Analysis of SIMS profiles suggest that the Au
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28 metallization layer serves as a sink for much of the Cu supplied in the buffer, and that the degree
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30 of copper migration into the CdTe is substantially reduced relative to conventional thermal
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32 activation. As such, the impact of optimal RTP on the bulk CdTe device structure is minimal,
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34 which is confirmed by the observation of negligible changes in parameters such as N_A , QE, or J_{sc} .
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36 APT reveals the nanoscale heterogeneity of this back contact and the dramatic elemental
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38 redistribution that occurs during brief RTP treatments. Under optimal conditions Cu displays
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40 heterogeneous local enrichment including segregation to both the CdTe and Au interfaces,
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42 perhaps in the form of Cu_xTe , which is suggested as one of the underlying reasons for the
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44 dramatic improvements in back contact performance. This process has been demonstrated to be
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46 beneficial on multiple device structures, as the low thermal budget of RTP facilitates its adoption
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48 without impacting the optimization of upstream processing.
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