Transmission Electron Microscopy Study on Microstructure of Degraded CdTe Modules

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Abstract — **In this work we employ transmission electron microscopy (TEM) coupled with energy-dispersive X-ray spectrometry (EDS) to study the structure and chemistry of cadmium telluride (CdTe) thin-film solar cells with different extents of degradation. The regions studies originate from the same photovoltaic mini-module, which was subjected to one-sun light exposure at a temperature of 100 °C for 400 h to induce light and heat degradation. EDS maps reveal a discontinuous CdS layer and particles rich in O and S but Te-depleted within the CdTe absorber layer after the light and heat stress. These features could act as enhanced recombination centers resulting in decreased photovoltaic conversion efficiency. Additionally, the most-degraded CdTe sample shows a strong accumulation of Na precisely localized in the discontinuous part of the CdS layer. The local Na concentration is determined to be ~16 at.%. In addition, appreciable Na accumulation is observed at the soda-lime glass (SLG)/transparent conductive oxide (TCO) interface in both degraded CdTe solar cells. The microstructure of the baseline CdTe mini-module without any stress was also investigated to demonstrate that the structure difference was caused by the light and heat induced degradation, instead of module fabrication. These results highlight the need to control the distribution of Na in fielded CdTe modules to sustain long-term high-power output.**

Index Terms — **transmission electron microscopy, CdTe mini-modules, Na accumulation, light and heat induced degradation, S diffusion, energy-dispersive X-ray spectrometry.**

I. Introduction

The long-term reliability of photovoltaic (PV) technologies has attracted increasing attention from both researchers and manufacturers, because of the power loss and failure of the entire modules in the field [1]. The degradation mechanism known as potential induced degradation (PID) of crystalline silicon modules has been intensively studied and the root cause appears to be the diffusion of sodium ions at high voltage, which causes aggregation in the antireflective coatings and ultimately penetration into stacking faults or planar defects, resulting in shunting of the p-n junction [2]–[7]. The degradation mechanism of copper indium gallium diselenide (CIGS) thin-film modules is also closely related to Na migration. Recent work using dynamic secondary-ion mass spectrometry (D-SIMS) and glow-discharge optical emission spectroscopy (GD-OES) reveals Na migration from soda-lime glass (SLG) and accumulation in the transparent conductive oxide (TCO) layer and CdS layer of CIGS solar cells. This is a result of the solar cells experiencing negative voltage bias at elevated temperatures [8,9], or of being simultaneously exposed to damp heat and illumination [10].

In cadmium telluride (CdTe) thin-film modules, the diffusion of Cu from the back contact to the CdTe layer is a known cause of performance degradation [11-13]. Time-of-flight SIMS (TOF-SIMS) indicates a correlation between the Cu concentration at the front interface and the amount of degradation observed by photoluminescence (PL) images [14]. However, change in the microstructure of these degraded CdTe samples and a baseline sample has not yet been reported. SLG is used as the superstrate in the CdTe modules and Na is known to be highly mobile with a small activation energy to migrate [15]; however, relatively few studies have reported the effect of Na on the CdTe solar cell performance. Significant amounts of Na have been detected at the CdTe/CdS and CdS/TCO interfaces and CdTe layer by using SIMS [16,17]. Molva *et al.* showed that Na introduces shallow acceptor levels in CdTe [15] which helps the *p*-type conductivity, while using first-principles band structure methods Wei *et al*. found that the shallow defects Na_{Cd}(-/0) and Na_i(0/+) can result in a deep Na_{Cd}(-)/Na_i(+) defect via self-compensation [18]. Such a defect could explain the variations in PL intensity reported in reference [14]. Kranz *et al.* reported detrimental effects of Na on the solar cell performance via strongly enhancing CdS-CdTe intermixing and leading to CdS island formation which results in direct contacts between absorber and TCO [19]. However, the spatial distribution of Na resulting from heat and light stress and how this distribution affects the module performance during the stress are still unclear. Transmission electron microscopy (TEM) has the capability to precisely probe the structural and chemical information at the atomic-scale to provide details on the behavior of Na during the degradation. In this work, we used TEM coupled with energy-dispersive X-ray spectrometry (EDS) to study the structure and chemistry of CdTe thin-film solar cells with different extents of degradation from the same mini-module.

II. Experimental

We used an acceleration test by stressing a commercial 6-inch CdTe mini-module at the condition of one-sun light exposure at a temperature of 100 °C for 400 h for the light and elevated temperature induced degradation. The module interiors were always several degrees hotter than the outer perimeter, and thus different degradation rates were always observed in a given sample. This approach however did allow for studying different levels of degradation through testing a single mini-module. Based on the previously reported photoluminescence (PL), electroluminescence (EL), and dark lock-in thermography (DLIT) images [14], we isolated regions exhibiting the least degraded and most significant degradation from the mini-module using a technique based on a diamond-based coring bit and drill [20]. The PL intensity of the most-degraded sample is ~40% of the least-degraded sample. Detailed information can be found in [14]. To study the structure and chemistry of the baseline module, one sample was cut from an unstressed CdTe sample.

A Pt capping layer was deposited on the surface of the samples to protect the thin-film structure. TEM foils were prepared by the standard focused ion beam (FIB) lift-out technique and followed by Ga ion milling to reduce the final thickness to less than 100 nm. Then, a Fischione Nanomill was used to remove preparation damage on the TEM foils using low energy cleaning at 500 eV under vacuum of 10^{-7} torr at -170 °C for ±10°. TEM observations were performed on an FEI Tecnai ST30 TEM at an acceleration voltage of 300 kV. Chemical analysis was done using an FEI Tecnai F20 TEM equipped with energy-dispersive X-ray spectrometry (EDS) in the high-angle annular dark-field (HAADF)-scanning TEM (STEM) mode.

III. Results and Discussion

Figures 1(a), 1(b), and 1(c) show the cross-sectional bright-field (BF) TEM images of the most-degraded, least-degraded sample, and baseline sample, respectively. Submicron-sized polycrystalline CdTe grains with a high density of twins are observed, due to the low stacking-fault formation energy of CdTe, *i.e.*, (9 ± 1) mJ/m^2 [21]. The twins are identified on the {111} plane, consistent with previous reports [22-24]. Note the existence of pinholes with bright contrast in the BFTEM images at the CdS layer in all the samples, as indicated by the red arrows. A relatively thin CdS layer can often lead to the formation of pinholes or voids, resulting in reduced performance of CdTe solar cells [25]. Figures 1(d) and 1(e) are the HAADF-STEM images of the most-degraded and least-degraded sample, respectively. The contrast of the HAADF image is highly sensitive to the variations in atomic number, or composition variation in the sample. Therefore, each layer in the CdTe thin-film can be clearly distinguished, according to the contrast difference. In addition, several dark gray spots are randomly distributed in the CdTe layer, indicating a variation in the local compositions, *i.e.*, a Te-depleted phase as shown in the following EDS result. Moreover, the dark spots in the CdS layer shown in the HAADF image are voids that correspond to pinholes with bright contrast in the BFTEM image. Overall, there is no significant difference in the microstructural character of the regions with different extents of degradation based on these TEM observations.

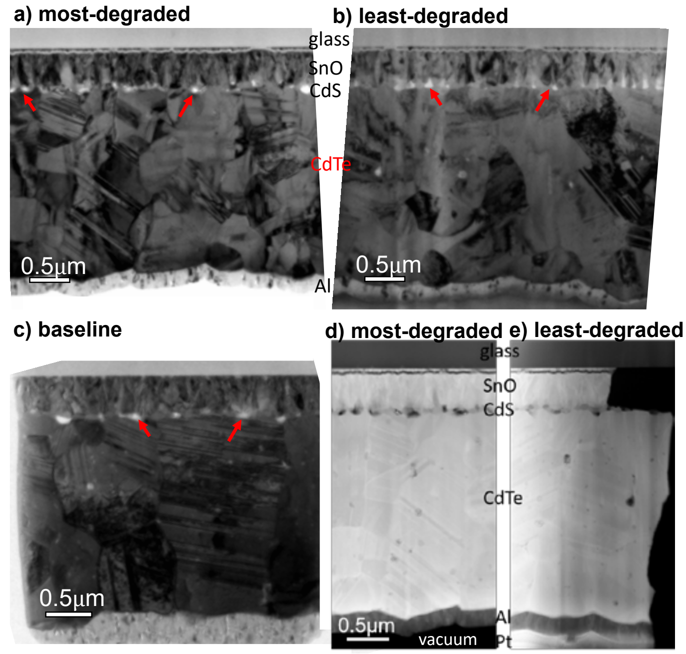


Fig. 1. Cross-sectional BFTEM images of (a) the most-degraded, (b) least-degraded, and (c) baseline sample. HAADF-STEM images of (d) the most-degraded and (e) least-degraded sample.

Figure 2 shows the EDS elemental maps of the front interface in the least-degraded sample. The CdS layer is discontinuous and appears in the form of CdS islands in the S and Cd maps. This results in the direct contact between the *p*-type CdTe absorber and TCO layer as indicated by the red circles in the Sn and Cd maps. Electrical shunts can be produced via this direct contact, causing adverse effects on the photovoltaic performance by reducing open circuit voltage (V_{OC}) and fill factor (FF) [22,26,27]. There are particles exhibiting an O- and S-rich and Te-depleted composition in the CdTe layer. The evidence of a discontinuous CdS layer suggests that S diffuses from the CdS layer into the CdTe layer and forms the O- and S-rich particles [28-30]. EDS analysis on these particles indicates a rough composition of 55% O, 16% S, 18% Cd, and 10% Te, which is very close to previous findings of $CdSO_3$ precipitates in the $CdCl_2$-treated CdTe solar cells [30].

Although the majority of the Na is detected in the SLG, an apparent Na layer with stronger contrast appears at the SLG/TCO interface but close to the TCO layer because there is a clear contrast gap between this Na layer and the Na in the SLG. Si and O show a separate thin layer located exactly at the Na layer, whereas a separate Sn thin layer appears at the above-mentioned gap. This results in a SLG/Sn-O/Si-O/TCO structure between SLG and TCO. The Sn-O layer is very thin and not continuous as indicated by the red arrows. The Si-O layer is also very thin and act as a barrier layer for Na out-diffusion from SLG [31]. From the Na map in Figure 2, the Si-O barrier layer appears to successfully block further Na diffusion in the least-degraded sample. However, it is believed that the de-adhesion of the tin oxide from the SLG can be caused by sodium accumulation near the SLG/TCO interface and this electrochemical process can be greatly accelerated by elevated temperature and humidity [32,33]. Our observations of Na behavior provide direct evidence to support this hypothesis. Considering that only light and heat stress was applied on the CdTe solar cells, the de-adhesion of TCO from the SLG could be even more severe in the field given that high-voltage bias on a PV module accelerates Na ion migration. Also note that Cl was found to segregate at the CdS/CdTe interface.

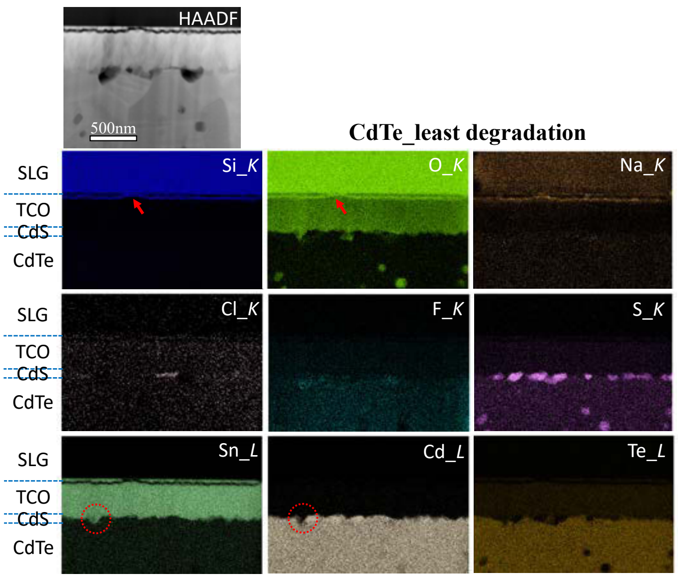


Fig. 2. HAADF image and corresponding EDS elemental mappings of the front interface in the least-degraded sample.

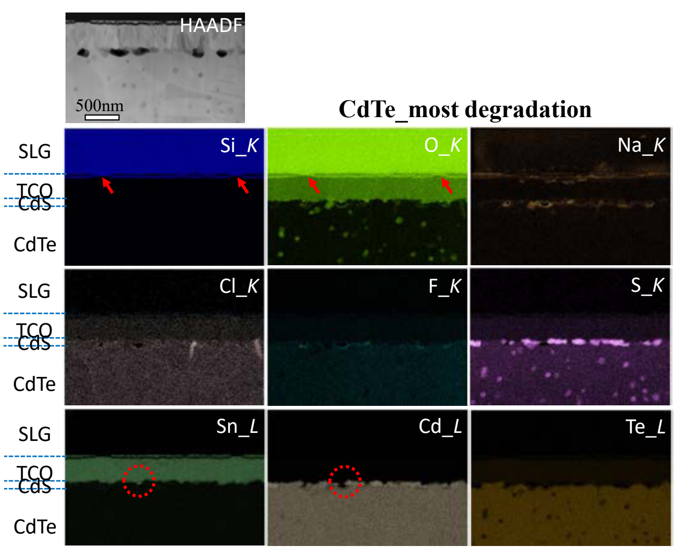
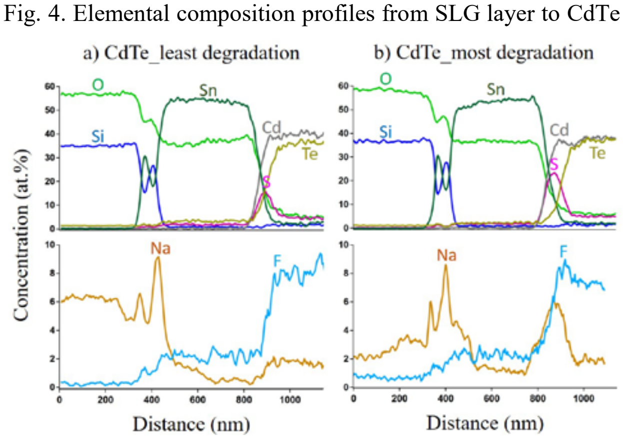


Fig. 3. HAADF image and corresponding EDS elemental mappings of the front interface in the most-degraded sample.

Figures 3 shows the EDS elemental maps of the front interface in the most-degraded sample. The same features can be seen as in the least-degraded sample except for the Na behavior. The Na not only accumulates at the SLG/Sn-O/Si-O/TCO, but it also moves beyond the Si-O barrier layer and across the tin oxide layer forming a noticeable Na layer in the CdS layer. This indicates that the Na can diffuse through the Si-O barrier layer in the most-degraded sample. The CdS layer acts as a sink for Na, as previously reported in CIGS solar cells [9]. The high Na concentration in the window layer can significantly decrease the performance of the CdTe solar cells [19], and it could be related to the relatively low PL intensity in the most-degraded sample. Moreover, the number density of O- and S-rich particles obviously increases in the most-degraded sample. Comparing the HAADF images with corresponding O and S maps, we can see that the O- and S-rich particles are randomly distributed, either in the grains or on the grain boundaries. In addition, Cl segregates at the CdS/CdTe interface as well as along the CdTe grain boundaries. Cu is not detected in both samples due to the detection limit of EDS.

Figures 4(a) and 4(b) are the elemental composition profiles from the SLG layer to the CdTe layer perpendicular to the interfaces obtained from EDS analysis on the least-degraded and most-degraded sample, respectively. An obvious shift of peaks and valleys in Si and Sn profiles can be seen between the SLG and tin oxide layer, which clearly indicates the SLG/Sn-O/Si-O/TCO structure. Na accumulates at both Sn-O and Si-O layers, but more at the Si-O layer. A strong Na peak with a sharp Na/Sn interface appears in the least-degraded sample. In contrast, the Na profile of the most-degraded sample at the same region shows a peak with a broad shoulder extending into the Sn layer. As expected, the Na accumulation in the CdS layer is expressed by another peak in the Na profile in Figure 4(b). The Na concentration in the CdS layer is determined to be ~5.9 at.%. Considering the average effect of the composition profile, the local Na concentration should be even higher.

Fig. 4. Elemental composition profiles from SLG layer to CdTe layer



of the (a) least-degraded and (b) most-degraded sample.

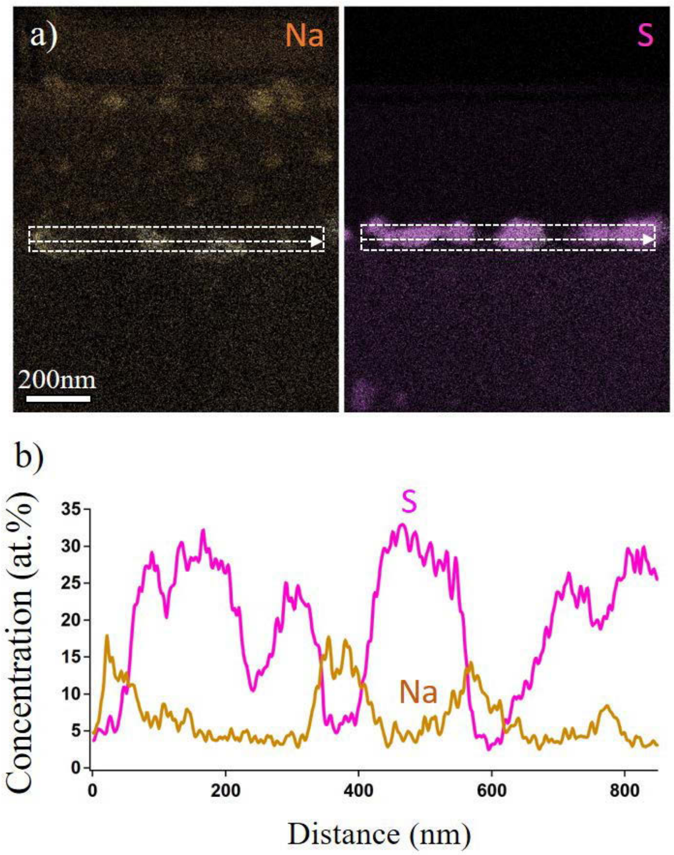


Fig. 5. (a) Na and S mappings from the most-degraded sample. (b) Na and S composition profiles in the CdS layer obtained from the selected white box in 5(a).

Figure 5(a) shows high magnification Na and S maps from the most-degraded sample and Figure 5(b) is the Na and S composition profiles in the CdS layer obtained from the selected white box in Figure 5(a). The peak value of the local Na concentration is ~16 at.%. In addition, a shift of peaks and valleys in Na and S profiles occurs. Given the evidence that S is discontinuous, the exact location where Na accumulates should be in the discontinuous part of the CdS layer, which was also confirmed by the Na and S maps.

To distinguish whether the observed structural difference is caused by stress or module fabrication, we also studied the microstructure of the baseline CdTe solar cells without any stress. Figure 6 shows EDS elemental maps of the front interface in the baseline sample. There is no clear evidence of S diffusion occurring during module fabrication. However, similar to the degraded samples, the CdS layer in the baseline sample is also discontinuous, which could be an indirect clue of the well-known phenomenon, *i.e.,* CdS-CdTe intermixing during the annealing treatment of the module fabrication [19,25,26,28,30]. It is possible that there is some S diffusion into the CdTe layer, but if so it is at a level below the EDS sensitivity. The O- and S-rich particles are not formed yet and Te is uniformly distributed in the CdTe layer, which suggests that the stress promotes the formation of the O- and S-rich and Te-depleted particles. In addition, only a weak contrast of Na can be discerned in the SLG layer, even though the Na map contrast is already enhanced.

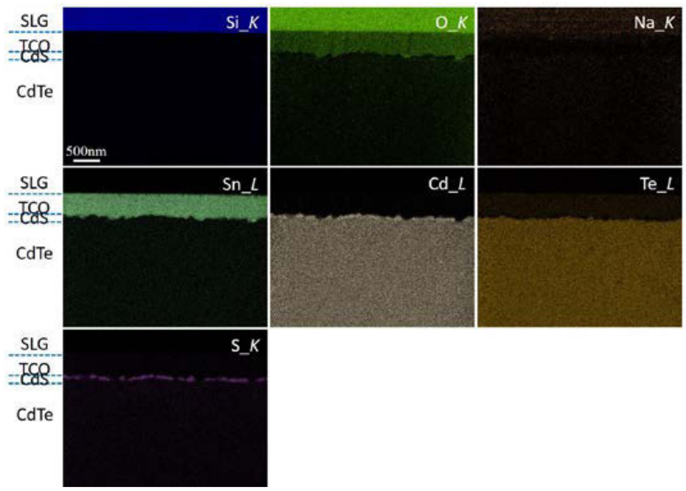


Fig. 6. EDS elemental mappings of the front interface in the baseline sample.

The two important findings in this work are summarized as follows: 1) Clear correlations between O- and S-rich particle formation under heat and light stress; 2) Heat and light stress govern Na diffusion behavior in CdTe mini-modules. The O- and S-rich particles are not clearly visible in the baseline sample. It is only with stress that the O- and S-rich and Te-depleted particles appear in the CdTe layer, which suggests that stress promotes the S diffusion from CdS into the CdTe. The number density of these particle clearly increases with the extent of the stress/degradation (Figures 2 and 3). The formation of these particles has two adverse influences on the CdTe solar cell performance. First, the consumption of CdS due to S diffusion leads to direct contact between the CdTe absorber layer and TCO and the formation of shunts [19,22]. Secondly, as a model of a defect or inclusion contributing a localized continuum of states [34], the interfaces between the O- and S-rich particles and the CdTe matrix likely act as non-radiative recombination centers, significantly affecting the previously reported PL intensity.

There is no obvious out-diffusion of Na from SLG in the baseline sample. When the CdTe mini-module is stressed by light and heat, Na gradually migrates and accumulates at the Si-O barrier layer. Eventually, Na diffuses through the Si-O barrier and enters the CdS window layer and accumulates at the discontinuous part of the CdS layer. Although Na occupying a Cd site is a shallow acceptor, self-compensation changes it to a deep level because the Na interstitial site is more stable regardless of Na acting as a *p*-type or *n*-type dopant [18]. This deep level could also explain the low PL intensity in the degraded regions. The Na accumulation at the CdS layer, together with high number density of O- and S-rich particles, accounts for the relatively low PL intensity of the most-degraded sample through reducing light emission and leading to non-radiative recombination, which will deteriorate the long-term device performance. Considering only gentle stress, *i.e.,* light and heat, is applied on the CdTe mini-module in this work, the field degradation caused by high-voltage bias could be even more serious.

IV. Conclusions

We have reported on the structural and chemical nature of CdTe thin-film solar cells with different extents of degradation resulting from exposure to elevated temperature and light. TEM imaging coupled with EDS mapping in the most-degraded CdTe solar cells revealed that Na accumulates in the discontinuous portion of the CdS layer. The peak value of the local concentration of Na is determined to be ~16 at.%. In addition, another notable Na layer accumulates at the SLG/Sn-O/Si-O/TCO structure. We have shown that a Si-O barrier layer does not effectively block Na diffusion; therefore, we suggest using glass with low sodium content, e.g., borosilicate glass (BSG), or at least SLG with a more effective barrier layer to provide resistance to Na diffusion. We also observed the formation of particles with an O- and S-rich and Te-depleted composition that are likely to act as non-radiative recombination centers within the CdTe absorber. The number density of these particles clearly increased proportional to the level of degradation. Future studies should focus on solving the issue of Na diffusion and O- and S-rich and Te-depleted particle formation under heat and light stress to improve long-term CdTe module performance.

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References

[1] W. Luo, Y. S. Khoo, P. Hacke, V. Naumann, D. Lausch, S. P. Harvey, J. P. Singh, J. Chai, Y. Wang, and A. G. Aberle, "Potential-induced degradation in photovoltaic modules: a critical review," *Energy & Environmental Science*, vol. 10, pp. 43-68, 2017.

[2] V. Naumann, D. Lausch, S. Großer, M. Werner, S. Swatek, C. Hagendorf, and J. Bagdahn, "Microstructural analysis of crystal defects leading to potential-induced degradation (PID) of Si solar cells," *Energy Procedia*, vol. 33, pp. 76-83, 2013.

[3] V. Naumann, D. Lausch, A. Hähnel, J. Bauer, O. Breitenstein, A. Graff, M. Werner, S. Swatek, S. Großer, J. Bagdahn, and C. Hagendorf, "Explanation of potential-induced degradation of the shunting type by Na decoration of stacking faults in Si solar cells," *Solar Energy Materials and Solar Cells*, vol. 120, pp. 383-389, 2014.

[4] V. Naumann, C. Hagendorf, S. Grosser, M. Werner, and J. Bagdahn, "Micro structural root cause analysis of potential induced degradation in c-Si solar cells," *Energy Procedia*, vol. 27, pp. 1-6, 2012.

[5] D. Lausch, V. Naumann, A. Graff, A. Hähnel, O. Breitenstein, C. Hagendorf, and J. Bagdahn, "Sodium outdiffusion from stacking faults as root cause for the recovery process of potential-induced degradation (PID)," *Energy Procedia*, vol. 55, pp. 486-493, 2014.

[6] J. Bauer, V. Naumann, S. Großer, C. Hagendorf, M. Schütze, and O. Breitenstein, "On the mechanism of potential-induced degradation in crystalline silicon solar cells," *physica status solidi (RRL) – Rapid Research Letters*, vol. 6, pp. 331-333, 2012.

[7] S. P. Harvey, J. A. Aguiar, P. Hacke, H. Guthrey, S. Johnston, and M. Al-Jassim, "Sodium accumulation at potential-induced degradation shunted areas in polycrystalline silicon modules," *IEEE Journal of Photovoltaics*, vol. 6, pp. 1440-1445, 2016.

[8] S. Yamaguchi, S. Jonai, K. Hara, H. Komaki, Y. Shimizu-Kamikawa, H. Shibata, S. Niki, Y. Kawakami, and A. Masuda, "Potential-induced degradation of $Cu(In,Ga)Se_2$ photovoltaic modules," *Japanese Journal of Applied Physics*, vol. 54, pp. 08KC13, 2015.

[9] V. Fjällström, P. Szaniawski, B. Vermang, P. M. P. Salomé, F. Rostvall, U. Zimmermann, and M. Edoff, "Recovery after potential-induced degradation of $CuIn_{1-x}Ga_xSe_2$ solar cells with CdS and Zn(O,S) buffer layers," *IEEE Journal of Photovoltaics*, vol. 5, pp. 664-669, 2015.

[10] M. Theelen, V. Hans, N. Barreau, H. Steijvers, Z. Vroon, and M. Zeman, "The impact of alkali elements on the degradation of CIGS solar cells," *Progress in Photovoltaics: Research and Applications*, vol. 23, pp. 537-545, 2015.

[11] C. R. Corwine, A. O. Pudov, M. Cloeckler, S. H. Demtsu, and J. R. Sites, "Copper inclusion and migration from the back contact in CdTe solar cells," *Solar Energy Materials and Solar Cells,* vol. 82, pp. 481-489, 2004.

[12] S. H. Demtsu, D. S. Albin, J. R. Sites. W. K. Metzger, and A. Duda, "Cu-related recombination in CdS/CdTe solar cells," *Thin Solid Films*, vol. 516, pp. 2251-2254, 2008.

[13] T. D. Dzhafarov, S. S. Yesilkaya, N. Yilmaz Canli, and M. Caliskan, "Diffusion and influence of Cu on properties of CdTe thin films and CdTe/CdS cells", *Solar Energy Materials and Solar Cells,* vol. 85, pp. 371-383, 2005.

[14] S. Johnston, D. Albin, P. Hacke, S. P. Harvey, H. Moutinho, C.-S. Jiang, C. Xiao, A. Parikh, M. Nardone, M. Al-Jassim, and W. K. Metzger, "Imaging, microscopic analysis, and modeling of a CdTe module degraded by heat and light", *Solar Energy Materials and Solar Cells*, vol. 178, pp. 46-51, 2018.

[15] E. Molva, J. P. Chamonal, and J. L. Pautrat, "Shallow acceptors in cadmium telluride", *Physica Status Solidi B*, Vol. 109, pp. 635-644, 1982.

[16] M. Emiane, K. Durose, D. P. Halliday, N. Romeo, and A. Bosio, "The distribution of impurities in the interfaces and window layers of thin-film solar cells", *Journal of Applied Physics*, Vol. 97, pp. 114910, 2005.

[17] K. Durose, M. A. Cousins, D. S. Boyle, J. Beier, and D. Bonnet, "Grain boundaries and impurities in CdTe/CdS solar cells", *Thin Solid Films*, vol. 403-404, pp. 396-404, 2002.

[18] S.-H. Wei, and S. B. Zhang, "Chemical trends of defect formation and doping limit in II-VI semiconductors: the case of CdTe", *Physical Review B*, vol. 66, pp. 155211, 2002.

[19] L. Kranz, J. Perrenoud, F. Pianezzi, C. Gretener, P. Rossbach, S. Buecheler, A. N. Tiwari. "Effect of sodium on recrystallization and photovoltaic properties of CdTe solar cells", *Solar Energy Materials and Solar Cells*, Vol. 105, pp. 213-219, 2012.

[20] S. Johnston, M. Al-Jassim, P. Hacke, S. P. Harvey, C.-S. Jiang, A. Gerber, H. Guthrey, H. Moutinho, D. Albin, B. To, J. Tynan, J. Moseley, J. Aguiar, C. Xiao, J. Waddle, and M. Nardone, "Module degradation mechanisms studied by a multi-scale approach", in *Proceeding of the 43rd IEEE Photovoltaic Specialist Conference,* 2016.

[21] S. Tekeuchi, and K. Suzuki, "Stacking fault Energies of tetrahedrally coordinated crystals", *Physica Status Solidi,* vol. 171, pp. 99-103, 1999.

[22] M. Terheggen, H. Heinrich, G. Kostorz, D. Baetzner, A. Romeo, and A. N. Tiwari, "Analysis of bulk and interface phenomena in CdTe/CdS thin-film solar cells", Interface Science, Vol. 12, pp. 259-266, 2004.

[23] C. Sun, N. Lu, J. Wang, J. Lee, X. Peng, R. F. Klie, and M. J. Kim, "Creating a single twin boundary between two CdTe (111) wafers with controlled rotation angle by wafer bonding", *Applied Physics Letters*, vol. 103, pp. 252104, 2013.

[24] T. Paulauskas, C. Buurma, E. Colegrove, Z. Guo, S. Sivananthan, M. K. Y. Chan, and R. F. Klie, "Atomic-resolution characterization of the effects of $CdCl_2$ treatment on poly-crystalline CdTe thin films", *Applied Physics Letters*, vol. 105, pp. 071910, 2014.

[25] A. Romeo, D. L. Bätzner, H. Zogg, C. Vignali, and A. N. Tiwari, "Influence of CdS growth process on structural and photovoltaic properties of CdTe/CdS solar cells", *Solar Energy Materials & Solar Cell*, vol. 67, pp. 311-321, 2001.

[26] K. W. Böer, "CdS enhances V_{OC} and fill factor in CdS/CdTe and CdS/$CuInSe_2$ solar cells", *Journal of Applied Physics*, Vol. 107, pp. 023701-023706, 2010.

[27] K. Nakamura, M. Gotoh, T. Fujihara, T. Toyama, and H. Okamoto, "Influence of CdS window layer on 2-µm thick CdS/CdTe thin film solar cells", *Solar Energy Materials and Solar Cells*, Vol. 75, pp. 185-192, 2003.

[28] D. S. Albin, "Accelerated stress testing and diagnostic analysis of degradation in CdTe solar cells", in *SPIE Optics + Photonics Meeting Reliability of Photovoltaic Cells, Modules, Components and Systems,* 2008.

[29] A. Bosio, N. Romeo, A. Podestà, S. Mazzamuto, and V. Canevari, "Why $CuInGaSe_2$ and CdTe ploycrystalline thin film solar cells are more efficient than the corresponding single crystal?", *Crystal Research and Technology*, vol. 40, pp. 1048-1053, 2005.

[30] C. Li, J. Poplawsky, N. Paudel, T. J. Pennycook, S. J. Haigh, M. M. Al-Jassim, Y. Yan, and S. J. Pennycook, "S-Te interdiffusion within grains and grain boundaries in CdTe solar cells", *IEEE Journal of Photovoltaics*, vol. 4, pp. 1636-1643, 2014.

[31] Y. Yan, X. Li, R. Dhere, M. Al-Jassim, K. Jones, M. Young, and M. Scott, "SiO_2 as barrier layer for Na out-diffusion from soda-lime glass", in *Proceeding of the 36rd IEEE Photovoltaic Specialist Conference,* 2010.

[32] D. E. Carlson, R. Romero, F. Willing, D. Meakin, L. Gonzalez, R. Murphy, H. R. Moutinho, and M. Al-Jassim, "Corrosion effects in thin-film photovoltaic modules", *Progress in Photovoltaics: Research and Applications*, vol. 11, pp. 377-386, 2003.

[33] C. R. Osterwald, T. J. McMahon, J. A. del Cueto, "Electrochemical corrosion of SnO_2:F transparent conducting layer in thin-film photovoltaic modules", *Solar Energy Materials and Solar Cells*, Vol. 79, pp. 21-33, 2003.

[34] J. I. Pankove, "Optical process in semiconductors", Dover Publications, Inc., pp. 165, 1975.