Non-Uniformities in Thin-Film Cadmium Telluride Solar Cells Using Electroluminescence and Photoluminescence

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Katherine Zaunbrecher
Colorado State University and National Renewable Energy Laboratory

James Sites
Colorado State University

Steve Johnston and Fei Yan
National Renewable Energy Laboratory

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NON-UNIFORMITIES IN THIN-FILM CADMIUM TELLURIDE SOLAR CELLS USING ELECTROLUMINESCENCE AND PHOTOLUMINESCENCE

Katherine Zaunbrecher[1,2], Steve Johnston[2], Fei Yan[2], James Sites[1]
[1]Colorado State University, Fort Collins, CO, 80526, USA
[2]National Renewable Energy Laboratory, Golden, CO, 80401, USA

ABSTRACT

It is the purpose of this research to develop specific imaging techniques that have the potential to be fast, in-line tools for quality control in thin-film CdTe solar cells. Electroluminescence (EL) and photoluminescence (PL) are two techniques that are currently under investigation on CdTe small area devices made at Colorado State University. It is our hope to significantly advance the understanding of EL and PL measurements as applied to CdTe. Qualitative analysis of defects and non-uniformities is underway on CdTe using EL, PL, and other imaging techniques.

INTRODUCTION

Not all data acquisition techniques are created equal. Some provide detailed, quantitative information that may require several hours to procure, while others may furnish high-resolution spatial data in a matter of seconds. One example of the latter is imaging. Several imaging techniques have been developed in order to qualitatively assess material quality and the manufacturing process. It is our purpose to advance specific imaging measurements used for quality control in the production of thin-film CdTe solar cells. Electroluminescence (EL) and photoluminescence (PL) are two such techniques that are currently under investigation on CdTe solar cells made at Colorado State University's (CSU) Materials Engineering Laboratory. [1-8] These two imaging methods are reasonably well understood with regard to analysis of Si solar cells, but much less so for thin-film cells. It is our hope to significantly advance the understanding of EL and PL measurements as applied to CdTe while emphasizing overall cell uniformity and defect analysis.

ACQUIRING IMAGES

Imaging is a powerful diagnostic tool that can be used for defect characterization, evaluating device performance, and determining overall material quality. To that effect, EL and PL images have been acquired on CdTe solar cells made at CSU. Images were taken at the National Renewable Energy Laboratory (NREL) using a Si charge-coupled device (CCD) camera with 1024 x 1024 pixels.

For PL imaging, an optical excitation source composed of four 5-Watt red light-emitting diode (LED) arrays centered at 630 nm is used. The LEDs emit from opposite angles to provide uniform excitation over the area of the sample. The camera then detects PL emissions as the excess carriers generated by the 630-nm excitation source recombine. Various illumination intensities were used for PL measurements, although an illumination of one sun is typical. RG1000 Schott glass filters are mounted to the camera lens to block reflected light from the sample and stage area.

The Schott glass filters are removed for EL imaging, and the sample is connected to a power supply where a forward- or reverse-bias voltage can be placed across the cell. Again, the camera detects a signal where carriers are radiatively recombining, while dark regions exist where little or no carriers accumulate. Varying current densities can be used to acquire EL images. Values as low as 1–2 mA/cm^2 were used as a minimum, while current densities corresponding to nearly half of the short-circuit current densities (J_{SC}) were used as maximum values.

Illuminated lock-in thermography (ILIT) and dark lock-in thermography (DLIT) were also used as evaluation techniques. [9-11] Lock-in thermography images were acquired using a FLIR/Cedip Silver SC5600 InSb infrared camera with built-in lock-in detection and 640 x 512 pixels. An 808-nm laser diode optical excitation source was used for ILIT. The light source (for ILIT), the applied voltage (DLIT), and the camera's lock-in electronics (for both DLIT and ILIT) were set to acquire frames at a frequency of 6.7 Hz. A forward bias is applied to the cell for DLIT in order to evaluate current flow through the device. This current causes a rise in temperature in the cell that is detected by the camera. In this way, the uniformity of the current can be examined. In the case of shunt detection, a reverse-bias voltage is used during the DLIT measurements. For a cell under reverse bias, shunts can create paths for larger currents, which can significantly heat up the region where a shunt is located.

ANALYSIS

The current focus of this research, after having acquired images, is evaluating cell uniformity and identifying non-uniformities that may appear. These characteristics include a variation in EL and PL intensities over the entire area of the cell as well as local defects that appear as both dark and bright regions and vary in size and shape. While these non-uniformities are present using both techniques, there are few features that overlap in PL and EL.

Progress has been made to categorize the general types of features seen in CdTe using EL and PL imaging. On one hand, one can look at the overall uniformity and note the linearity of the EL and PL intensity based on current density and illumination intensity, respectively. On the other hand, local defects and their origins can be identified. When examining these features, one can often recognize that their origins are due either to the inherent properties of the material or as a result of the fabrication process. However, these two categories are not necessarily mutually exclusive.

While examining the overall uniformity of each cell, there is a linear response of the EL intensity with the amount of current through the cell; the PL intensity is also linear with the illumination level, as seen in Figures 1 and 2. This intensity, used to characterize the brightness of the signal, is determined by the average pixel counts. A baseline parameter has also been developed to characterize the overall uniformity of a cell—the full-width at half-maximum of the intensity distribution over the peak intensity. When plotted against current density, it shows a positive slope for each device. The curves from different cells, however, do not overlap one another as in the case of EL intensity versus current density.

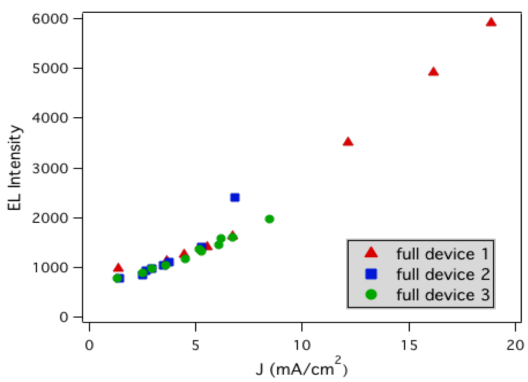

Figure 1. EL intensity versus illumination level for three different devices

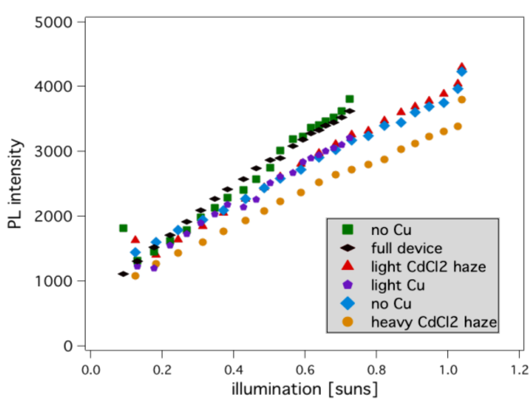

Figure 2. PL intensity versus illumination level of cells with varying processing steps

ILIT was another imaging technique used to look at cell uniformity. However, contrary to PL and forward-bias EL, it was not a useful technique to characterize current uniformity. The ILIT images revealed little spatial variation, except when resulting from non-uniformity in the light source shining on the cells.

When comparing the overall effectiveness of the images in determining cell uniformity, it is interesting to note that EL images tend to display more detail than PL counterparts. Both have been seen to contain gradients in intensity as well as local defects and other features; however, there is a sense of higher resolution of certain defects when using EL that appears to be due to properties of cell materials.

Turning from uniformity analysis to feature characterization, some common local defects that are seen in both PL and forward-bias EL images include scratches on the glass, patterns on the transparent conducting oxide (TCO) from detergent residues and diverse artifacts from the cleaning process, and local gradients due to material quality. There are also various dark points on the images where there is a lack of carrier accumulation in those regions. This may occur as a result of a high number of defect states being present or conductive paths due to weak diodes or shunts. Some features also act as simple optical obstructions and thus block the signal to the camera.

EL and PL, however, may give different qualitative information for certain features. For instance, there are bright spots in some of the forward-bias EL images that do not appear in PL. They appear in areas of higher current density where response to the bias current is greater than that of the overall cell. These spots are located mostly around the edges of the devices and typically saturate the camera. Some may be attributed to shunts at the cell edge, while the few appearing in the inner part of the cells may be areas of better local performance or decreased performance due to shunting. In order to see what fraction of these spots were caused by shunting, both reverse-bias EL and DLIT images were compared to the forward-bias EL images containing the spots; it was found that less than half of these areas correspond to shunts. When comparing the two methods, however, more shunts were found using DLIT than reverse-bias EL. And while some shunts appeared much more severe than others in the same cell using one technique, this was not necessarily true of the other.

Although the effect of defects on device performance has not yet been quantitatively evaluated for CdTe solar cells using EL and PL imaging, preliminary analysis shows correlation between intensity and select performance parameters. For the case of several devices processed with various treatments, there was a correlation between the EL intensity and fill factor for all of the cells that had not yet undergone the full Cu treatment or the final annealing and then another correlation for the cells that were made with these final treatments. A similar correlation was also found between EL intensity and cell efficiency. These data are shown in Figures 3 and 4.

Once initial EL and PL measurements were taken on CdTe solar cells made at CSU, a set of devices was made in order to aid in identifying defect origins and to begin cataloging defect types. Intentional scratching and deposition of impurities were the first few types of defects studied. These scratches and impurities were placed on the TCO, in the CdS, and in the CdTe before the placement of the back contact on several different substrates. The scratches were made with various materials. Intentional impurities included dust particles, fingerprints, and detergent residue.

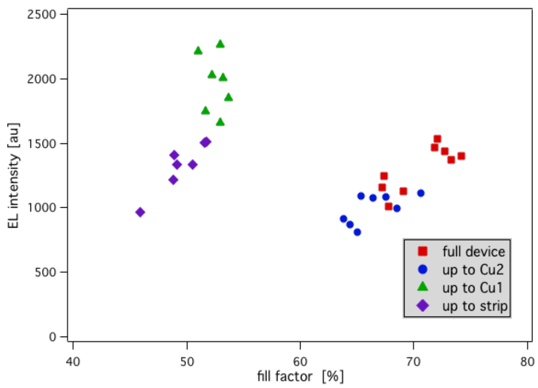

Figure 3. EL intensity versus fill factor for devices with varying processing steps

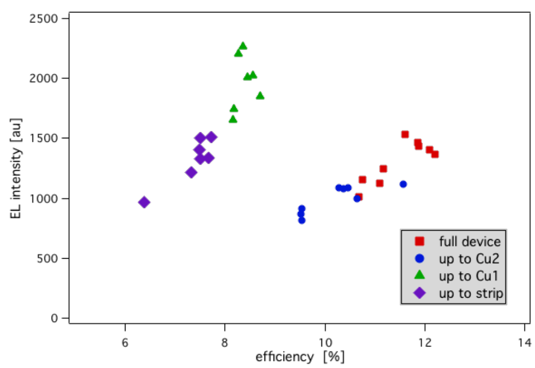

Figure 4. EL intensity versus efficiency for devices with varying processing steps

In the case of scratches made using glass, metal, and ceramic, there are regions that appear dark in the EL images where material has been completely removed. There are also brighter areas around the edges of the scratches in the EL images where material may have been partially removed and current is focused in those regions. The use of other imaging techniques such as reverse-bias DLIT helped to identify shunts in these regions. Most of the shunting appeared to be a result of the metal scratches and dust placed on the TCO before CdS deposition. The dust also appeared as bright regions in PL. The graphite scratch was, for the most part, an optical obstruction that blocked any PL and EL signal generated in that region. Most of the regions where the material had been scratched by ceramic appeared dark in both PL and EL. Glass scratches and the fingerprints placed on the TCO had bright and dark features in both EL and PL images. And in the regions where detergent residue was left, EL revealed bright and dark regions, while PL produced the dark patterns that were often seen in images that had been previously taken. Examples of metal, graphite, and glass scratches and their effects on PL, EL, and reverse-bias DLIT are shown in Figure 5.

In an attempt to see how PL measurements would fare as an in-line instrument for early material quality evaluation, five unfinished substrates were fabricated at CSU and then imaged at NREL. These substrates included a film that had only the TCO, CdS and CdTe, one with a $CdCl_2$ treatment after CdTe deposition, and films with varying Cu and annealing treatments. After the initial PL imaging, the films were then made into full devices. They were then imaged again using PL, EL, and DLIT. The images of the unfinished films and finished devices were then compared. While features could be detected as early as the CdTe deposition, PL signal greatly increased after the $CdCl_2$ treatment, and the contrast was such that most features were more distinct and more detailed characteristics were easily seen. And features that appeared in the initial PL imaging of the films could be seen in the images of the finished device.

With all of the data collected over the past year in hand, the next stages of detailed analysis can begin. Particularly illuminating is that even during the initial stages of imaging CdTe devices, beginning with identifying features and drawing qualitative conclusions, these techniques do indeed provide reasonably informative spatial information. As a next step, particular focus will be placed on defect and uniformity analysis. Quantitative impacts of defects that more commonly occur during the fabrication processes will be given particular attention. Areas of decreased performance will be examined in-depth as well in an attempt to distinguish between weak diode effects, variation in series resistance, and increased local recombination due to shunting.

SUMMARY

Qualitative analysis of defects and non-uniformities in CdTe is underway using EL and PL imaging techniques. In order to evaluate the capability of both techniques to characterize the overall quality of the cells, we examine the EL and PL intensities and compare them to cell performance. PL and EL intensities are plotted as a function of illumination intensity and current density, respectively, with both showing linear responses. EL intensity is also plotted against fill factor and efficiency, with correlations present for devices made with similar processing. Studies of defects and their imaging signatures were also performed, and an example of a cell made with intentional scratches. Identifying the origins and effects of defects and non-uniformities to EL and PL may lead to better devices in the future.

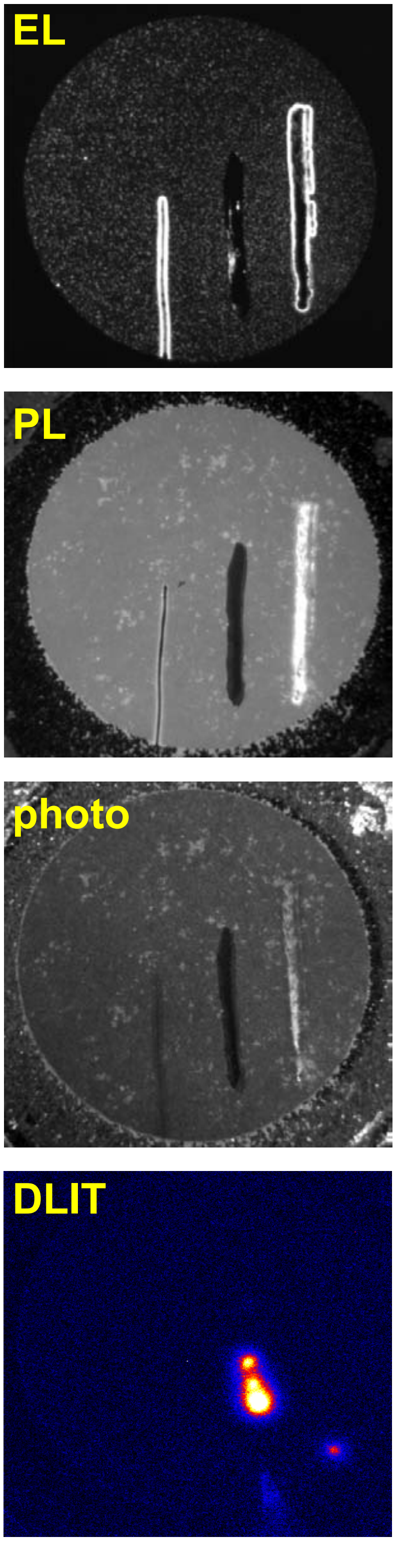

Figure 5. Metal, graphite, and glass scratches imaged (from top to bottom): (a) EL, 6.6 mA/cm^2, 30 s exposure; (b) PL, one sun, 30 s exposure; (c) room light with 2RG1000 Schott glass filters; and (d) DLIT

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