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Identification and Analysis of Distinct Features in Imaging Thin-film Solar Cells

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***ABSTRACT* — Electroluminescence and photoluminescence (EL and PL) are two imaging techniques employed at NREL that are used to qualitatively evaluate solar cells. In this work, imaging lab-scale CdTe and CIGS devices provides information about small-area PV response, which will aid in determining the effects of non-uniformities on cell performance. EL, PL, and dark lock-in thermography signatures are first catalogued. Their responses to varying conditions are then studied. Further analysis includes acquiring spectral data, making microscopy measurements, and correlating luminescence to device performance. The goal of this work is to quantitatively determine non-uniformity effects on cell performance using rapid imaging techniques.**

***Index Terms* — electroluminescence, photoluminescence, imaging, photovoltaic cells, thin films.**

I. Introduction

Imaging as a method to characterize and evaluate solar cell performance is well underway at the National Renewable Energy Laboratory (NREL). In this study, particular emphasis is placed on $Cu(In,Ga)Se_2$ (CIGS) and CdTe devices, recognizing the potential for imaging thin-film technologies and the challenge of fully exploiting these techniques.

Electroluminescence (EL), photoluminescence (PL), and dark lock-in thermography (DLIT) measurements at NREL were initially reported in 2009 [1]. The setup for EL and PL includes a Princeton Instruments PIXIS 1024BR Si charge-coupled device (CCD) camera with 1024x1024 pixels housed in a light-tight box. A power supply is used to place the cells in forward bias during EL imaging. The optical excitation sources used for PL include four 5-watt light-emitting diode (LED) arrays centered at 630 nm for CdTe samples and four 30-watt 808 nm laser diodes for CIGS. RG1000 Schott glass filters are mounted on the camera lens to block reflected light from the sample area. DLIT is done using an InSb infrared camera with built-in lock-in detection and 640 x 512 pixels. The camera picks up heat signatures given off by a sample that is placed in forward or reverse bias.

II. Small Area PV Response

EL, PL, and DLIT provide qualitative spatial maps of the current flow, voltage distribution, and radiative recombination occurring in photovoltaic devices [2]-[10]. One may use these measurements to determine the overall uniformity of a cell as well as locate defects. Imaging at NREL has been successful in doing both for CIGS and CdTe small-area devices. Using lab-size samples allows us to examine the features we believe to be due to small-scale variations in semiconductor material parameters. This highlights our focus on the basic physical properties of the semiconductor material, especially non-uniformities inherent in the materials as well as those which arise as a result of the manufacturing process. Some of the signatures specific to both luminescence techniques (EL and PL) and to both technologies are discussed below.

A. Distinct features in luminescence

Once images of solar cells are acquired, luminescence features can be documented and their origins and effects on device performance identified. Particular care in cataloguing and describing features has been taken here, as this will help in determining the physical causes of non-uniformities that can be seen by variations in luminescence. When physical defects are linked to specific signatures, these techniques may replace slower and more complicated measurements as a means of identifying cells that have severe shunting, low efficiency, or other non-uniformity issues.

While the types of luminescence features in both CdTe and CIGS cells can be numerous, only a few specific ones will be discussed here. Before the details of these signatures are mentioned, it should be noted that there is a significant difference in luminescence images of CdTe and CIGS cells. There is a strong overlap in features that appear in EL and PL images of CIGS cells. On the other hand, EL imaging provides far more detail than PL for CdTe cells, as seen in Fig. 1. This may be due to the lack of appropriate optical filters for PL measurements on CdTe. A set of more suitable filters is being made at NREL which will hopefully resolve this issue. It is also worth noting that many of the more subtle patterns seen in EL images of CdTe are from inhomogeneities in the transparent conducting oxide (TCO).

One particular luminescence feature seen in both technologies is a local reduction of signal. (Local in this case means less than 10% of a cell's area.) The feature is due to a lack of luminescence and appears as small, black holes in the images, varying in size from 50 to 500 microns. In CdTe devices, these dark spots do not appear as large or as greatly contrasted in PL images as they do in EL. In CIGS, the sizes and overall contrast of these features are mostly comparable in both EL and PL. Some of these dark spots appear as bright spots in forward-bias DLIT and are not visible in reverse bias, implying diode turn-on and low voltage, often referred to as weak-diode behavior [11]. (See Fig. 2.)

A second feature of interest is an increase in the EL signal which occurs only in CdTe cells. These bright spots show up at higher current densities and appear throughout the cell but are more prevalent around the edges. An example of this can be seen in the EL image in Fig. 1. A third luminescence signature is the increase in EL signal with current around the gridlines on the front of CIGS cells (seen later in Fig. 5). Both are discussed in subsequent analysis.

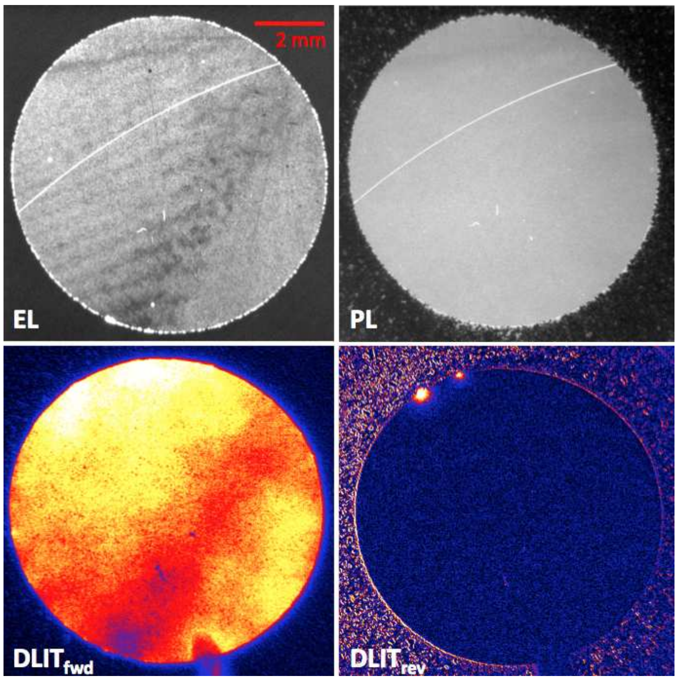

Fig. 1. *Left to right, top to bottom:* EL, PL, and forward- and reverse-bias DLIT measurements of a CdTe device. Note the level of detail present in the EL image that does not appear in PL.

B. Shunts and weak diodes

Defects such as weak diodes and shunts affect voltage and current distribution in the cell. This change in voltage across the devices should presumably affect the EL and PL signals (however differently). For weak diodes, we expect an increase in current through the compromised CdS window layer. The EL signature from a shunt may have little or no current going directly through the shunt path itself, but may direct a lot of the surrounding current toward it. The presence of either defect will affect the voltage across the cell at the surrounding areas. Both types of defects have been seen in CIGS cells [11]. Although the detailed explanation of the effects in CdTe imaging are yet unknown, some non-uniformities that may correlate to these defects are under investigation using EL, DLIT, and microscopy.

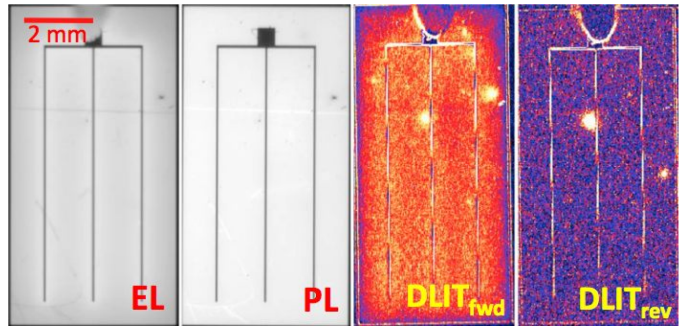

Fig. 2. *Left to right:* EL, PL, and forward- and reverse-bias DLIT measurements of a CIGS device. Overlapping features can be seen in all four techniques.

III. Analysis

Previous studies discussed uniform luminescence in CdTe small-area devices and its response to varying current and injection levels [12]. For the current work, focus is on specific luminescence signatures, such as those shown in Figs. 1 and 2. Analysis of these features may lead to determining their effects on device performance, which in turn would lead to finding a connection between luminescence intensities (including defect sizes, distributions, and densities) and device parameters such as open-circuit voltage and efficiency. Analysis includes taking line cuts of luminescence images to quantify the signal across a specific region, studying the luminescence response to varying current through the cells, and determining the spectral responses of specific EL signatures in CdTe.

A. Local regions of reduced luminescence

The dark spots in CdTe and those in CIGS that exhibit weak-diode behavior exhibit luminescence directly around the dark spots and show no distinct response to increasing current. This means that these regions of little or no signal are not affecting the voltage distributions of the surrounding regions.

There are also dark spotted areas in CIGS that are visible in both luminescence techniques. When these images are compared to light-beam-induced current (LBIC) maps and DLIT images, as in Fig. 3, the broader, lower-contrast areas (in EL and PL images) correspond to a reduction in quantum efficiency (QE) in the unbiased LBIC map. Reverse-bias LBIC revealed an even greater decrease in QE in most of these regions while displaying more severe drops in QE in other regions which correspond to areas of decreased luminescence in EL and PL. Variations seen in forward-bias DLIT typically corresponded to patterns seen in luminescence images, while reverse-bias DLIT revealed hot spots most likely due to shunts. These spots often coincided with local dark regions in EL and PL.

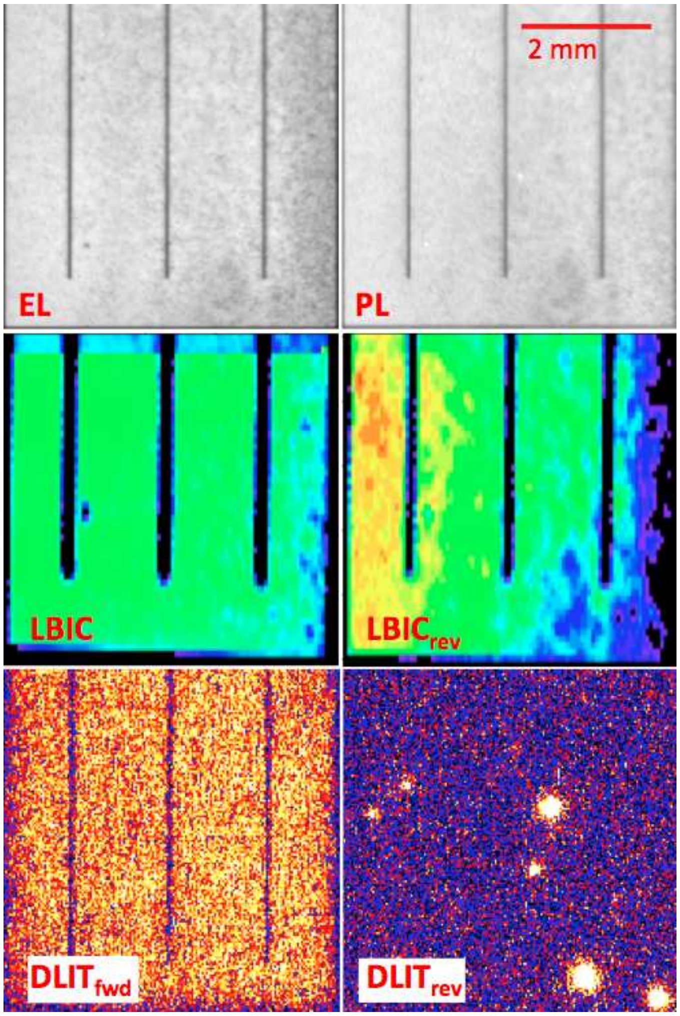

Fig. 3. *Left to right, top to bottom:* EL, PL, unbiased LBIC, LBIC at reverse bias, and forward- and reverse-bias DLIT measurements of part of a CIGS device.

B. Local regions of increased luminescence

The bright spots that appear in EL images of CdTe do so at high current densities. They begin to appear at 4 mA/cm^2 but are quite visible at 10 mA/cm^2 (around ½ J_{SC}). These regions do not have a linear response to current density as do the luminescence in uniform regions. Instead, it is a much more sensitive response. When looking at these bright features and their spectral response, the decrease in luminescence with the increasing cut-on wavelength of the filters is the same as regions of the cell with uniform luminescence, as seen in Fig. 4. In the case of bright spots that occur inside the cell, normalized EL intensity of a line cut across the spot shows an incremental decrease between the peak intensity and the luminescence of the area surrounding the spot as the cut-on wavelength increases. This shows that the entire luminescence signal (the bright region and the areas surrounding it) is being blocked by the filters. In addition, the spread of the peak stays constant as the filters change.

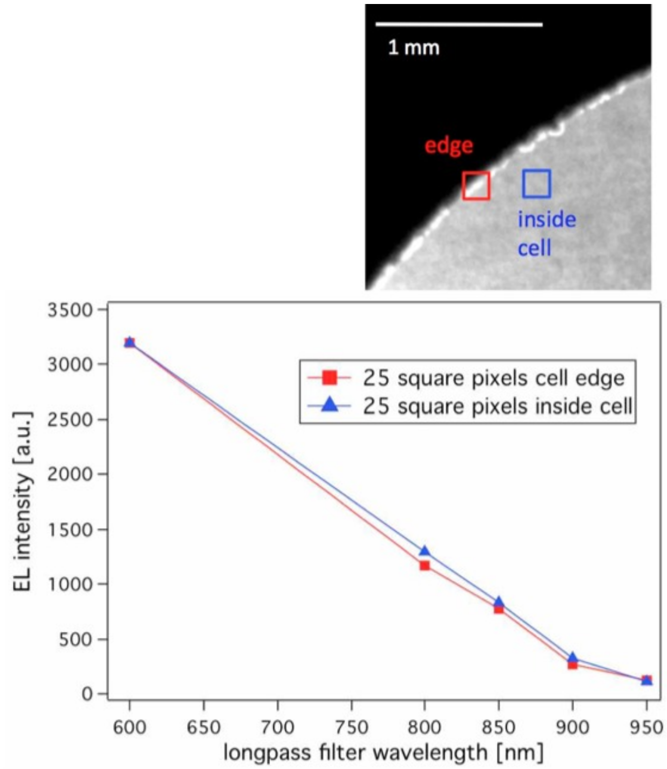

Fig. 4. *Top:* An EL image of a CdTe cell edge that exhibits bright edge effects. The two boxed regions were selected for a rough spectral study using longpass filters. *Bottom:* The resulting EL intensity as a function of longpass filter wavelength.

C. Variations in EL around gridlines in CIGS

The last signature of interest is the variation in luminescence intensity surrounding the gridlines of the CIGS cells, seen in Fig. 5. This variation is recognizable at 10 mA/cm^2 and becomes very apparent at 20 mA/cm^2. A line cut across the three gridlines (Fig. 6) shows that the luminescence intensity increases as the distance to the gridline decreases. Closer to the top of the cell where the three gridlines connect, the change in intensity becomes smaller. This particular characteristic shows that the presence of the gridlines affects the voltage across the cell in that region—as the current through the cell increases, the voltage across the device in the region directly surrounding the gridlines increases more than in other areas.

D. Microscopy

One way to confirm the physical causes of the non-uniformities described above is with microscopy as previously reported for several types of defects in CIGS cells [11]. It was shown that weak diodes visible in forward-bias DLIT result from voids in the CIGS and CdS layers. On the other hand, shunts detected by reverse-bias DLIT show that the deposition of the CIGS, CdS, and top ZnO layers were disrupted. Progress is currently being made in locating regions of interest in CdTe cells for scanning electron microscopy (SEM) and transmission electron microscopy (TEM) measurements. Preliminary results include an SEM scan of a region in a CdTe cell that had no EL signal in a significant portion of its area (Fig. 7). The SEM images show no disruption in the CdS or CdTe layers. They do, however, show large voids (~10 μm) in the back contact, as seen in Fig. 8. These voids may somewhat divert the current around that area, but they do not fully explain the decrease in EL signal in such a large portion of the cell.

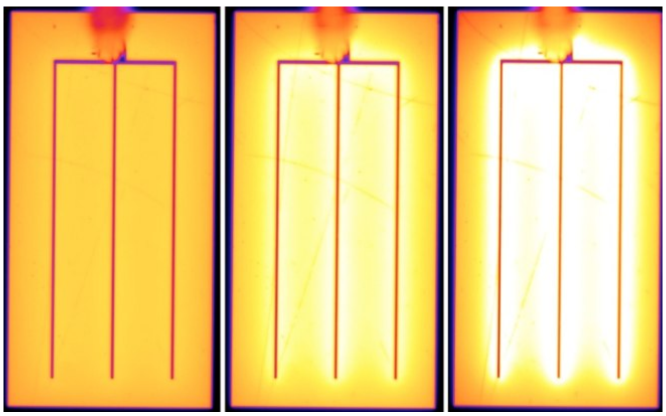

Fig. 5. *Left to right:* EL images of a CIGS cell taken at 4, 10, and 20 mA/cm^2. The color scale was chosen to obtain better contrast within the cell.

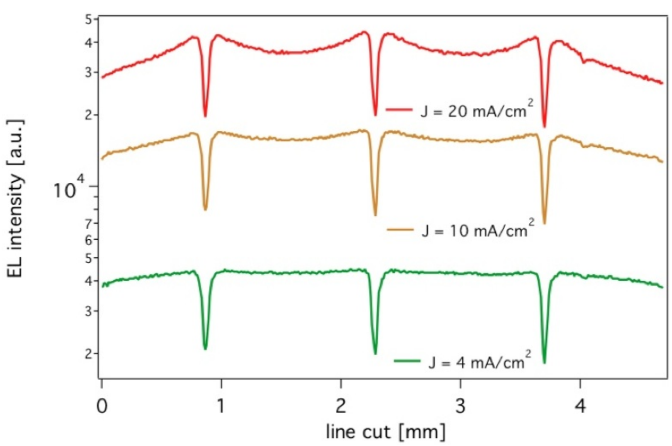

Fig. 6. Line cuts taken across the CIGS cell shown in Fig. 5 at three current densities. The line cuts include the gridlines that run along the length of the cell.

IV. Conclusion

Luminescence imaging can provide high-resolution spatial information about the performance of solar cells. Some spatial non-uniformities are easily distinguished using EL, PL, and DLIT imaging. Although no specific method of identification of features has yet been established, we are continuing to study imaging in hopes of linking specific luminescence signatures to defects in both CdTe and CIGS thin-film solar cells.

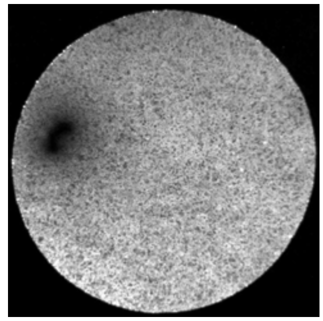

Fig. 7. An EL image of a CdTe device showing a lack of signal in a significant portion of the cell.

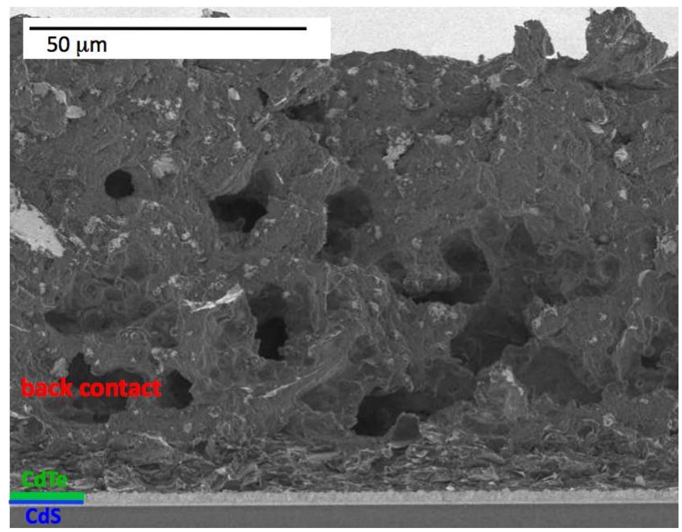

Fig. 8. SEM cross-section of a CdTe small-area device showing voids in the back contact.

The origins of some features such as the bright spots in EL images of CdTe have yet to be explained. But spectral analysis shows the same response in the tail of the luminescence signal, despite these regions being much more responsive to increased current. These bright features are not seen in images of CIGS cells. Various shunt and weak-diode features, however, have been identified in CIGS cells using microscopy. Current and future work will hopefully do the same for CdTe cells. Many local non-uniformities, including bright and dark regions in EL and PL, do not significantly affect the surrounding current (by comparing luminescence with DLIT). And EL may be useful in identifying spatial variations in the cell voltage, as shown in the case of the varying luminescence around the gridlines of CIGS cells. The techniques discussed above are rapid measurements that reveal information about thin-film cells that are becoming increasingly useful in the evaluation of their performance.

V. Summary

EL, PL, and DLIT can be used in the identification of non-uniformities in thin-film CdTe and CIGS solar cells. Specific luminescence signatures include weak diodes and shunts. The three distinct features discussed in this work are dark regions that are present in EL and PL imaging of both CdTe and CIGS, bright spots which occur in CdTe and were seen at higher current densities in EL, and an increase in EL intensity around the front gridlines of CIGS cells. These features affect the luminescence signals in various ways. The response of their luminescence was further analyzed by varying operating conditions and obtaining spectral dependences of EL using longpass filters. This analysis showed that local spots of increased or decreased luminescence was just that—local. It did not affect surrounding areas. A variation in EL signal in CIGS also showed that the front gridlines on the cells cause variations in the voltage.

Besides looking at voltage and current distributions due to non-uniformities and spectral analysis of these features, microscopy can also be used to identify physical causes of luminescence signatures. Past microscopy work includes measurements which identified shunt and weak-diode defects in CIGS cells, and current work includes SEM to identify defects seen in images of CdTe devices.

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