Light-Beam-Induced-Current Characterization of CdTe Solar Cells

Russell M. Geisthardt and James R. Sites

Colorado State University, Fort Collins, CO, 80523, USA

Abstract—In this work, light-beam-induced-current (LBIC) measurements are discussed as a characterization tool for nonuniformities in solar cells. A modification of the measurement procedure has reduced the measurement time by at least a factor of 5, which results in a 10 minute scan time for a 10,000-pixel image. A general strategy for using LBIC and electroluminescence as a nonuniformity characterization suite is presented, which allows for thorough characterization of nonuniformities and identification of their causes. These tools are presented in the specific context of CdTe solar cells.

Index Terms—cadmium compounds, current measurement, electroluminescence, photovoltaic cells.

I. INTRODUCTION

One significant problem facing solar cells, especially thin-film cells, is nonuniformity. For nonuniformities which affect the short-circuit current of a cell, local quantum efficiency can be measured using light-beam-induced current (LBIC).

A common problem with LBIC, which has limited its industrial applicability, is the long measurement time. A procedure has been developed and is described in this work for on-the-fly measurement as the cell is moving. This procedure allows for a significant reduction in measurement time, by at least a factor of 5.

With the measurement time reduced, it becomes easier to make many measurements of the same cell using different wavelengths, biases, and resolutions. The variation of these different parameters allows for detailed characterization of nonuniformities in cells, ideally with the result of determination of the cause of the nonuniformities. LBIC can also be paired with electroluminescence (EL) into a nonuniformity characterization suite.

In this work, the faster procedure and resulting measurements will be described. A general strategy for nonuniformity characterization using LBIC and EL will be presented. This discussion will be applied to the specific context of CdTe solar cells.

II. EXPERIMENTAL

The LBIC system at CSU has been described in [1] and [2]. The light for LBIC measurements is provided by laser diodes which are pigtailed into a fiber optic. Wavelengths of 405, 638, 830, and 850 nm were selected to match key wavelength regions of the CdTe cell. An attenuator controls the light intensity to keep it near 100 mW/cm². The output from the fiber is split, and 10% of the beam power is monitored using an amplified photodiode. The remaining beam is optically chopped and steered with mirrors to a microscope objective, which focuses the light onto the cell. Focusing is controlled by changing the height of the objective using stepper motors.

The position of the cell is also controlled using stepper motors. Signal out of the cell is amplified, and then read using a lock-in amplifier, which is locked onto the optical chopper. The entire system is controlled using custom-built LabView software.

Several upgrades were recently made to this system. The 405-nm laser was added to look at nonuniformities in the window layer. A new optical chopper was installed to reduce noise. The monitor photodiode system was upgraded to improve accuracy. Several software additions were also made.

The EL system at CSU consists of an Apogee Alta 8300 camera and a Zeiss 50 mm macro lens with extension tubes. The system is in a darkened enclosure to reduce background light. Cells are forward biased using a DC power supply at a constant current of 40 mA/cm² and imaged for 100 seconds. The system is further described in [3].

The cells studied in this work were manufactured in the CSU PV Manufacturing Lab. CdS and CdTe were deposited on TEC10 glass using closed-space sublimation (CSS). CdCl₂ and copper post-treatments were also done using CSS. Layers of graphite and nickel paint were sprayed on for the back contact. The plate is delineated into 9 circular devices, each approximately 1 cm in diameter [4].

III. REDUCED LBIC MEASUREMENT TIME

Under the previous measurement procedure, a standard square measurement area of 10,000 points took 45 minutes. This procedure required the system to stop at each point to make a measurement. This led to long wait times to ensure that the motors arrived at the correct point before measuring.

Fig. 1. Schematic of slower stepped process and faster continuous process.
After a point was measured, a new motion command was sent and the process repeated. This procedure was replaced by an on-the-fly procedure, as illustrated schematically in Fig. 1. The motion command is sent to move all the way across the cell. As the cell is moving, measurements are taken at regular intervals. The results of the modified procedure are shown in Fig. 2. The 45 minute scan time was the old standard using the stepped process. The 10 minute scan time is the new standard using the continuous process. There is little obvious loss of position accuracy between the two scans. Due to variations in processing speed, the data can be collected unevenly in time, which can result in variations in distance between data points. To correct for this, a fixed-measurement-cycle-time option was added, which is the 15 minute scan. It was also possible to reduce each step to a bare minimum number of software tasks, which can reduce the measurement time further, as seen in the 5 minute scan. However, this procedure introduces distortions due to nonlinearities in the motion of the stepper motors. The distortions can be corrected, as has been done in the displayed scan data. However, the correction adds additional user time, so is generally only used for screening purposes. All four of these settings are available in the software, so that the user has the choice between greater speed and greater accuracy.

Fig. 2. Scan results of same area using different scanning procedures: stepped (45 minute), fixed-time (15 minute), continuous (10 minute), and screening (5 minute)

IV. NONUNIFORMITY CHARACTERIZATION

A. Pairing EL with LBIC

Electroluminescence and light-beam-induced current are both powerful uniformity characterization tools on their own [2] [3]. However, they can be combined into a powerful uniformity characterization suite. Since the two tools operate by different mechanisms, and the cells are measured at different points on the J-V curve, the two techniques provide different information. EL has been shown to be related to open-circuit voltage [3], while LBIC is a measure of QE, and is therefore related to short-circuit current. This difference of information makes them complimentary, rather than redundant, tools.

EL is a fast technique, with imaging time around 100 seconds and independent of imaging area. LBIC, although significantly slower than EL, provides much greater depth of information, since parameters such as wavelength and voltage bias can be varied. This has led to a procedure where EL is used for imaging a large number of samples. Samples which merit further study based on their EL images are then measured using LBIC to attempt to determine the causes of nonuniformities.

Fig. 3 shows a comparison between an EL image and LBIC maps of the same cell. The region which was scanned with LBIC was expanded in the top-right EL image for direct comparison. From this figure, we can see that the forward-bias LBIC shares a stronger overlap of features with EL than the zero-bias LBIC. For example, the feature labeled 1 in the EL image is visible in both LBIC scans, while the feature labeled 2 is visible only at forward bias. Since feature 1 reduces performance across a range of voltage bias conditions, it is likely more harmful to the cell performance than feature 2, which only reduces performance at forward bias.

B. Parameter Variation in LBIC

Several parameters can be varied in the LBIC measurement to provide a greater depth of information. These parameters include wavelength, voltage bias, resolution, and image contrast.

The different layers of the cell are sensitive to different wavelengths of light. A standard wavelength has been 638 nm, because this is strongly absorbed by most absorber layers, including CdTe. Longer wavelengths, 830 and 850 nm, are
also used with CdTe because they are near the CdTe band gap. The 830 nm light will be absorbed farther into the layer, so it can be sensitive to nonuniformities towards the back of the CdTe. The 850 nm light is near the band edge of CdTe, so it will be particularly sensitive to shifts in the local band gap. An additional wavelength, 405 nm, has been added to the system. This wavelength is strongly absorbed by the CdS window layer, but does not contribute to the collected current of the cell. This laser is therefore sensitive to local variations in the thickness of the CdS layer, with a higher response caused by a thinner layer.

Voltage bias can also be used to reveal additional nonuniformities which are not visible at short-circuit conditions. This can include features such as weak diodes which have little impact at zero bias, but can significantly reduce performance at forward bias. Local series resistance or barrier effects can also be identified using forward-bias LBIC.

Fig. 4 shows a cell which had several nonuniformities in EL (upper left). The cell was then measured using four different LBIC wavelengths at two or three different voltage bias conditions. The scales have been removed from the LBIC images for the sake of space, and the range varies by scan, but the color scale is shared, with high QE represented by red and low QE represented by purple. The position scales have also been removed, but the cell diameter is approximately 1 cm. From this figure, it is clear how different types of features can have different LBIC signatures which can be used to identify the causes of the feature. For example, the line which is primarily visible in forward-bias LBIC is likely a scratch in the TCO which increases local series resistance. Likewise, a high-QE area in the 405-nm LBIC is a thin CdS spot which impacts performance at other wavelengths.

Nonuniformities exist on many different scales, so it is useful to change the resolution of the LBIC system. The system is designed to routinely use 100, 10, or 1 µm spot sizes. When applied to a standard 10,000 point area, with step size half of spot size, this maps areas of 5000 x 5000, 500 x 500, and 50 x 50 µm x µm, respectively. Fig. 5 shows the results of scanning at these different resolutions. At the 10-µm spot size, the defect which features prominently in the scan is shown to have internal features which were not visible at the lower resolution. Small nonuniformities also appear which were not visible at the lowest resolution. The 1-µm spot size further emphasizes these small nonuniformities, which are about 30 µm in size and vary in QE by 10%.

Varying contrast in the image can be a useful technique for identifying the size and magnitude of a feature. Fig. 6 shows an LBIC scan of a feature which is likely a shunt under two different QE graphing ranges. With a large range (low contrast), it is clear that the physical size of the shunt is relatively small. The dark spots in this scan are caused by scratches during contacting. One of these scratches may have produced the shunt. With a small range (high contrast), the large area of effect from the shunt becomes clear. Although the physical size of the shunt is limited, it reduces performance over a much larger area.
V. Conclusion

The LBIC setup at CSU has been improved through hardware and software upgrades. A new measurement procedure increased the working speed of the system by a factor of 5 with little loss of position accuracy. The faster system enables easy characterization of many parameters of a cell, including variations in wavelength response, voltage bias response, and mapping of uniformity at different resolutions. LBIC has also been paired with EL to form a powerful uniformity characterization suite. Ultimately, these tools can lead to identification and correction of nonuniformities.

Acknowledgment

Thank you to J. Drayton and K. Cameron for making cells, and to D. Swanson and J. Raguse for valuable discussions. This work was supported by the NSF I/UCRC for Next Generation Photovoltaics and the U.S. Department of Energy SunShot Program, F-PACE Award DE-EE0005399.

References