LUMINESCENCE SHUNT IMAGING: QUALITATIVE AND QUANTITATIVE SHUNT IMAGES USING PHOTOLUMINESCENCE IMAGING

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ABSTRACT: In this paper, we present a proof of concept study for a quantitative method for shunt detection in silicon solar cells using photoluminescence imaging. The method is based on interpretation of the luminescence intensity around a local shunt in terms of the extracted current density. The theoretical relationship between the PL signal and the shunt current is derived. Experimental results on specifically prepared test structures, on intentionally shunted monocrystalline cells and on shunted industrial multicrystalline cells are presented and compared to shunt values from dark IV, SunsVoc and Lock in thermography. Good agreement is found for the test structures and for the intentionally shunted cells. For the multicrystalline cells the shunt values calculated from PL images agree to within a factor of two with shunt values obtained from other methods.

Keywords: Photoluminescence, Shunts, Silicon Solar Cell

1 INTRODUCTION

Shunting in solar cells refers to local internal short circuits, which can reduce the cell efficiency, manufacturing yield and module lifetime. Current methods for spatially resolved shunt detection include CELLO \cite{1}, Corescan \cite{2}, electron and light beam induced current (EBIC/LBIC) \cite{3, 4} and lock-in thermography (LIT) \cite{5}. Photoluminescence (PL) imaging \cite{6} has the potential to provide a contactless method of shunt imaging, with a measurement time of seconds. Work previously presented on this topic \cite{7, 8} has been largely qualitative. In this paper, we present a proof of concept for a method of determining quantitative shunt values from PL images.

2 BACKGROUND

2.1 Theory

Photoluminescence (PL) Imaging measures the spatially resolved radiative recombination of an illuminated sample. The photoluminescence (PL) signal averaged over an area A of a silicon solar cell is given by \cite{9-11} as:

\[ PL_{A_{\text{corr}}} = C \cdot \exp \left( \frac{V_{d,A}}{V_t} \right) \]

(1)

where C is a calibration constant depending on the optical properties, geometry and carrier lifetime of the cell, \( V_{d,A} \) is the diode (junction) voltage of the region A and \( V_t \) is the thermal voltage (25.8mV at 25\textdegree C). \( PL_{A_{\text{corr}}} \) is the PL signal corrected for diffusion limited carriers, as described in \cite{12, 13}. This correction is done by subtracting a separate luminescence image taken at zero or moderate reverse bias from images taken at other operating points. Unless otherwise stated, it has been applied to all luminescence images in this paper.

The shunt resistance \( R_{sh} \) of a solar cell region is obtained from the voltage and current across the shunt, \( V_{sh} \) and \( I_{sh} \), respectively. The diode voltage at the shunt \( V_{sh} \) can be obtained from the PL image. It is calculated from Equation 1, using the lowest PL signal in the shunted region. The proportionality constant C can be calculated with sufficient accuracy using an open circuit PL image and the cell Voc, where the PL term in Equation 1 is given by the PL intensity in a non-shunted region. Due to the exponential relationship between PL intensity and diode voltage small lateral variations in the cell characteristic of a solar cell can be written as:

\[ J_{d,A} = J_{d,0} \cdot \left( PL_{A_{\text{corr}}} \right)^{\frac{1}{n}} \]

(2)

where \( J_{d,0} \) is the diode dark current density of an area A of the cell, \( J_{d,0} \) is the dark saturation current density and n is the diode ideality factor. Now, the current voltage characteristic of a solar cell can be written as:

\[ J_{\text{ex}}(V_{d,A}) = J_L - J_{d,A}(V_{d,A}) \]

(3)

The light generated current density, \( J_L \), is assumed constant across the whole cell. \( J_{\text{ex}} \) is the extracted current density, defined as the current density generated in an area A which does not recombine locally. For an ideal diode (n = 1) combining equations (2) and (3), gives:

\[ PL_{A_{\text{corr}}} = \frac{C}{J_{d,0}} \left( J_L - J_{\text{ex},A} \right) \]

(4)

which says that for n = 1, the luminescence signal decreases in proportion to the current density extracted from a specific area. This proportionality can be used to calculate \( I_{sh}\), the current through a local shunt, as follows.

A local shunt in an illuminated cell represents a local current sink. The shunt itself is often microscopic, much smaller then a single pixel and thus not visible in large area images. A PL image will only show the effect of the shunt on the surrounding non-shunted cell region. The method introduced here relies on the fact that a shunt extracts current from the surrounding non-shunted area through the emitter, which reduces the PL signal according to Equation 4. This typically results in the
circular or elliptical blurred regions of reduced luminescence around a point like shunt, as described previously by Kasemann et al [14]. The unknown ratio \( J_{01} / C \) from Equation 4 is assumed to be constant across the entire cell. It is determined from the PL signal in a non-shunted region with zero current extraction, given by:

\[
PL_{\text{NonRsh}} = \frac{C}{J_{01}} \frac{I_L}{A_{\text{cell}}} \quad (5)
\]

From the above description we can conclude that the total missing PL signal around a shunted region compared to an equivalent non-shunted region is proportional to the shunt current, \( I_{Rsh} \). To obtain the total current flowing into the shunt we thus need to average the PL signal over the entire area impacted by the shunt. This approach is similar to the thermography methodology proposed by Breitenstein et al, which relies on averaging over an area large enough to capture the total heat dissipated in a shunt [15]. Finally, combining Equations 4 and 5 results in:

\[
\frac{(PL_{\text{NonShunted}}) - (PL_{\text{Shunted}})}{(PL_{\text{NonShunted}})} \frac{A_{Rsh}}{A_{\text{Cell}}} \cdot I_L = I_{Rsh} \quad (6)
\]

which allows the shunt current of a local shunt to be calculated using only a single corrected PL image and \( I_L \). The shunt resistance is then calculated by dividing \( V_{Rsh} \) by the shunt current, \( I_{Rsh} \).

2.2 Shunt values in finished cells and in test samples were obtained from Suns-Voc [16, 17] and dark IV measurements. PL imaging and Dark Lock In Thermography (DLIT) were also used.

PL images were measured with illumination from a 50W, 808nm diode laser. The PL emission of the cells was imaged using a commercially available one megapixel CCD camera. Optical filters were used between the CCD and the sample to prevent reflected laser light from contributing to the measured signal. PL images with current extraction were taken using the setup described in [18]. A deconvolution algorithm was applied to the measured images to mitigate various sources of light spreading.

Dark lock-in thermography (DLIT) is an established technique for shunt detection [19]. It was used here as a comparison for shunt images and values obtained using PL imaging. A Thermosensorik [20] TDL 384M system with image resolution of 384 x 288 pixels was used.

3 EXPERIMENTAL

3.1 Relationship between \( I_{\text{ext}} \) and \( PL_{\text{corr}} \)

This experiment was performed to experimentally verify the relationship derived in Equation (4) between the PL signal and the extracted current density.

PL images were taken on 6-inch industrial multicrystalline silicon solar cells with constant illumination and at various operating points. As an example Fig.1 shows the average PL intensity as a function of the extracted current \( (I_{\text{ext}}) \) for one specific cell.

![Comparison between PL signal and extracted current](image)

Figure 1. Relationship between the average PL signal from an industrial multicrystalline silicon solar cell and the current extracted from the cell, measured with the same illumination intensity but at different operating points between open circuit and short circuit. The dashed line is a linear fit to the data.

For all cells investigated here, the area averaged PL signal was linearly proportional to the extracted current, which agrees with Eq.4, and supports the assumption of an ideality factor of unity for these cells. Variations in the optical properties, dark saturation current density and the shunt resistance between cells were reflected in variations in the gradients of PL versus extracted current curves.

3.2 Quantification of artificially introduced shunts

The previous experiment confirmed the expected linear relationship between the average PL signal and extracted current for the entire cell area. The following experiment was performed to measure the effect of local current extraction on the PL signal and to obtain quantitative shunt currents as described in Section 2 above. A solar cell structure was fabricated, with full rear metallisation, but only a single metalized square contact (side length 500 μm) on the front surface. A variable artificial local shunt was created by externally connecting a resistor of known value in parallel with the cell, i.e. between the rear metallization and the point contact on the front. A PL image and SunsVoc measurement were taken for external resistor values between 1 and 400 Ohms. The PL images were not corrected for diffusion limited carriers, since the cell did not have a full front metallisation.

Figure 2 shows two PL images of the test structure with (a) 120Ω and (b) 1Ω resistors connected in parallel. The images are plotted on the same scale, and demonstrate the effect of the shunt on the PL signal as the shunt resistance is decreased, as previously modelled by [14]. The tip of the probe that was used to contact the front contact is visible in both images.
3.4 Application to industrial multicrystalline solar cells

In a further set of experiments we applied this PL shunt calculation technique to a number of shunted industrial multicrystalline cells. In this experiment, shunt images and local shunt currents were calculated from the PL images for a number of cells, and the results were compared with DLIT measurements of the same cell.

Figure 5(a) shows a photoluminescence shunt image. The image was calculated by applying Equation 6 to each pixel of the open circuit PL image of the cell, and shows the percentage of light generated current extracted from each pixel. Figures 5(b) and (c) are the forward and reverse bias DLIT images of the same cell, respectively. The comparison of Figures 4(b) and 4(c) shows that most shunts in this cell are Ohmic shunts, since they appear in both the forward and reverse DLIT.

There is good agreement between the locations and intensities of the shunted regions in the forward bias DLIT image and the PL image. Similar agreement was observed for a large number of shunted industrial cells in this study.

It is evident, by comparison with the reverse bias image, that we are currently unable to distinguish between ohmic and non ohmic shunts in the PL image analysis. This is expected within the methodology presented, since a single PL image measured at a single operating point is unable to distinguish between the local IV behaviour of a shunt or a recombination centre.

Quantitative values for the shunt resistances for individual shunted regions can be obtained from the DLIT images using the method proposed by Breitenstein et al [15]. Shunt resistances were calculated for 20 local regions in 10 shunted industrial cells, and compared to the values calculated using the PL method. The results are presented in Figure 6. Shunt values calculated by both methods agreed to within a factor of 2. The values unambiguously assigned to the intentionally introduced local shunts. The shunt values were calculated from the PL images using the method described above, and were compared to the shunt values from dark IV measurements. The introduced shunt resistances ranged from approximately 150 – 1500 Ohms.

Figure 4 shows the shunt values calculated from the PL images in comparison to the shunt values measured by dark IV. The dashed line has a gradient of one and passes through the origin. The PL-calculated values are consistent with the values measured by dark IV with maximum deviations by a factor of 2.

3.3 Quantification of shunts on finished cells

To test a more practical case, single shunts were introduced into previously non shunted 3cm x 7cm crystalline laboratory buried contact solar cells. Shunts were produced by depositing small silver droplets onto the surface or into surface scratches, followed by drive in with a laser. The cells were characterised with dark IV, SunsVoc and PL imaging before and after shunting. Typical shunt values prior to shunting were on the order of tens of thousands of Ohms, allowing the much smaller shunt values measured after local shunting to be unambiguously assigned to the intentionally introduced local shunts. The shunt values were calculated from the PL images using the method described above, and were compared to the shunt values from dark IV measurements. The introduced shunt resistances ranged from approximately 150 – 1500 Ohms.

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We observed a non-zero y intercept of 23 Ohms measured in the initial data. Comparison with Suns-Voc measurement indicates that this is due to the contact resistance of the setup.

Additionally, SunsVoc measured a parallel resistance of 115 Ω with the external circuit at open circuit. This is currently attributed to either the inherent shunt resistance of the fabricated sample or the effect of shading from the probe (as modelled by [21]), and is being investigated. The data in Figure 2 has been corrected for this parallel resistance.

With these corrections, there is a good agreement between PL calculated and SunsVoc measured resistances, with a maximum error of 14%.

The shunt values were calculated from these PL images for the above range of resistances and compared to SunsVoc data (Fig.3).

Figure 3. Comparison of shunt values calculated from PL images (y axis) with the SunsVoc measured resistance (x axis). The dashed line is y = x. Maximum deviation from known resistances was 14%. Data has been corrected for the inherent shunt resistance in the sample. The non zero y intercept is due to the contact resistance of the setup.

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with the largest error were either non ohmic shunts or non localised shunts.

Figure 5. (a) An image showing percentage of generated current extracted from each pixel, calculated from a PL image using the method described in this paper. A forward bias (b) and reverse bias (c) DLIT image of the same cell, and a colorbar indicative of the image scaling (d).

Figure 6. Comparison of shunt resistances calculated from PL images (y axis) and DLIT images (x axis). The dashed line is $y = x$. All calculated resistances agree to within a factor of 2. The three weakest shunts (top right) are non-ohmic.

4 DISCUSSION AND CONCLUSIONS

4.1 Discussion

There are several factors which can limit the accuracy of the method for shunt detection and quantification discussed in this paper. These factors include current extraction through the front metal grid, inaccurate selection of the non shunted region, and non-ideal diode behaviour.

Variations of the shape of the stronger shunts introduced into the previously non shunted cells (Section 3.3) indicated that current extraction through the cell fingers affected the appearance of shunts in the PL images. Specifically, that part of a local shunt current that is extracted via the metal fingers will not unambiguously be detectable as reduced PL signal, and will therefore generally not detected in our method. This effect has previously been modelled by Kasemann et al [14]. Further work will focus on developing and analysing methods for quantitatively correcting these distortions based on the influence of the sheet resistance and the relative position to grid lines.

Calculation of the shunt current depends on the difference in PL intensity between the shunted region and a non shunted cell region (Equation 6). Therefore, to accurately calculate the shunt current, the non shunted cell region should have the same average PL signal as the shunted region would have in the absence of the shunt. In practice, finding such a region can be difficult, and introduces errors, particularly in multicrystalline cells.

Finally, this method assumes an ideal diode, i.e. $n = 1$. For all cells in this experiment, including strongly shunted multicrystalline cells, the assumption was confirmed. The method benefits from the fact that images are measured and interpreted at operating points close to open circuit conditions, whereas large deviations from $n=1$ often appear only at lower voltages.

4.2 Conclusions

This paper presents a proof of concept study for calculating quantitative shunt values from PL images. The method is based on interpreting the reduced PL signal that is observed around a shunted region in terms of the current extracted by a shunt from its surroundings. Good quantitative agreement was found on test structures with known shunt resistance and for intentionally shunted monocrystalline cells. For multicrystalline cells various limitations currently reduce the accuracy of this method, as seen in comparison with lock in thermography data, which gave deviations of up to a factor two.

Future work will focus on further improving the accuracy of this method by a systematic analysis of the impact of non unity diode ideality factor and of the influence of the proximity of shunts to grid metal lines. Given that previous luminescence based shunt analysis was largely qualitative the method presented here represents a significant step towards a quantitative shunt analysis of luminescence images.

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References