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Improved local efficiency imaging via photoluminescence for silicon solar cells

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ABSTRACT

We present an improved method that uses photoluminescence images to calculate the spatially-resolved efficiency in addition to other performance parameters of silicon solar cells. This new method is simpler than our previously-presented two-diode method, using only one diode with a variable ideality factor. Experimental results show that the simplified method is more tolerant of very large variations in local series resistance, a characteristic commonly seen in silicon cells. Using dark lock-in thermography techniques, we quantitatively verify the efficiency images produced by our improved method.

1. Introduction

The measurement of solar cell efficiency has previously been limited to a determination of the terminal characteristics of the cell, which represent an average of the spatially-varying properties of the device. Spatially-resolved efficiency images recently became available with the work of Shen et al. [1], led by the work of Glatthaar et al. [2]. Simultaneously, Breitenstein [3] published a technique based on dark lock-in thermography (DLIT) that calculated an efficiency image incorporating shunt influence, whereas Shen [1] did not include this explicitly. After Shen et al. [4] validated their results qualitatively with CELLO measurements [5], Shen's and Breitenstein's methods were compared [6]. The comparison showed that Shen's efficiency image was incorrectly affected by high series resistance (R_s) impact on the dark saturation current of the second diode J_{02}. Inspired by Glatthaar et al. [2] again, we present an improved method based on [1,2] to generate a set of images that show increased accuracy around the maximum power point of the cell. The images are inherently self-consistent and appear to have overcome the previous problems of the R_s influence on other parameters [6]. This paper introduces the theory in Section 2, the calculated images in Section 3 and a comparison and discussion in Section 4.

2. Theory

Our algorithm uses a minimum of four photoluminescence (PL) images at different electrical bias and illumination conditions as inputs. The output images are the calibration constant C_{xy}, series resistance $R_{s,xy}$, the local voltage $V_{oc,xy}$ at a terminal open circuit, the local voltage $V_{mpp,xy}$ at a terminal maximum power point (MPP), the local current density $J_{mpp,xy}$ at the terminal MPP, dark saturation current density $J_{0,xy}$, and power density P_{xy} or, equivalently, efficiency η_{xy}. In this context, the subscripts xy are the coordinates of a pixel on the CCD camera, which define a "point" on the cell.

The equations are similar to those used in our previous work [4]. The commonly accepted correlations between the luminescence photon flux $\phi_{PL,xy}$ (i.e., the PL images) and the local voltage V_{xy} [7,8] are shown in Eqs. (1) and (2a). C_{xy} is a calibration constant containing unknown optical parameters and other scaling constants. It is assumed to be independent of electrical bias and illumination conditions. Eq. (2a) calculates the net PL photon flux $\phi_{net,xy}$ that is used in Eq. (1). Eq. (2b) depicts Glatthaar's [2] approximation that only one image $\phi_{offset,xy,1sun}$ at short circuit and one sun illumination condition are required to determine the offset photon flux $\phi_{offset,xy}$. This flux is primarily caused by diffusion-limited carrier recombination [7]. To calculate $\phi_{offset,xy}$ at different illumination intensities, a scaling factor β_{sun} is used. For example, for half-sun intensity, β_{sun} is 0.5. The thermal voltage V_T is kT/q, where k is Boltzmann's constant, T is the cell

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temperature and q is the charge of an electron. The local current density J_{xy} is defined by the Shockley diode equation [9] with a single ideality factor n and light-generated current density J_{light}; see Eq. (3). This parameter is assumed to be uniform throughout the cell and equals the short circuit current density. This assumption is common to most of the PL imaging techniques, but still remains controversial. The ideality factor n is also assumed to be uniform across the cell. However, the local variations in efficiency caused by diode properties will still be reflected by variations in $J_{0,xy}$. Therefore, the dark current will be reasonably correct. Eq. (4) describes the current density J_{xy}, which is defined by the voltage drop between the local voltage V_{xy} and terminal voltage V_{term} through the local series resistance $R_{s,xy}$. J_{xy} is therefore the local current density that contributes to the terminal current.

$$V_{xy} = V_T \ln\left(\frac{\phi_{net,xy}}{C_{xy}}\right) \tag{1}$$

$$\phi_{net,xy} = \phi_{PL,xy} - \phi_{offset,xy} \tag{2a}$$

$$\phi_{offset,xy} = \beta_{sun}\phi_{offset,xy,1sun} \tag{2b}$$

$$J_{xy} = -J_{0,xy}(e^{(V_{xy}/nV_T)} - 1) + J_{light} \tag{3}$$

$$J_{xy} = \frac{V_{xy} - V_{term}}{R_{s,xy}} \tag{4}$$

Eq. (5) is obtained by combining Eqs. (1), (3) and (4):

$$\underbrace{V_T \cdot \ln(\phi_{net,xy}) - V_{term}}_{a_{xy}} = \underbrace{V_T \ln C_{xy}}_{X_{xy}} + \underbrace{R_{s,xy}}_{Y_{xy}}\underbrace{J_{light}}_{b_{xy}} - \underbrace{\frac{J_{0,xy}R_{s,xy}}{\sqrt[n]{C_{xy}}}}_{Z_{xy}}\underbrace{\sqrt[n]{\phi_{net,xy}}}_{C_{xy}} \tag{5}$$

2.1. Calculation

The calculation consists of eight steps and is summarized in two stages A and B, described in the flow chart in Fig. 1.

Stage A. The first stage is to find a global ideality factor n and condition independent images C_{xy}, $R_{s,xy}$ and $J_{0,xy}$. The ideality factor n is assumed to be uniform across the cell and calculated via an iterative loop. For example, an initial value of $n=1.2$ (illuminated) may be assumed. Then steps 2–5 are repeated until the averaged current density J_{xy} of each point matches the measured global current density J_{global} at the maximum power point. In this case the calculated global ideality factor n and condition-independent images C_{xy}, $R_{s,xy}$ and $J_{0,xy}$ will be passed on to stage B. Although the assumption of a uniform ideality factor does not distinguish the diode feature of each point (into J_{01} or J_{02} described in [4]), the overall diode properties will still be reflected in $J_{0,xy}$ as well as the overall recombination current (the first term in Eq. (3)). Hence, the overall efficiency will still be sensitive to individual local diode properties. The efficiency image will be reasonably correct because at a particular point (MPP), only the current density is used to calculate the efficiency, and the current density relies on the combination of $J_{0,xy}$ and n instead of only n; see Eq. (3). In addition, since the average calculated current density is always equal to the global current density, the efficiency map is more adaptable to cells with large R_s variation according to our experiments.

In step 3, sections of the upper expression in Eq. (5) are substituted into known parameters a_{xy}, b_{xy} and c_{xy} and unknown parameters X_{xy}, Y_{xy}, and Z_{xy}. Each PL image, identified by an index i, will generate one set of variables $a_{i,xy}$, $b_{i,xy}$ and $c_{i,xy}$. These can be seen as a coordinate triplet in a three-dimensional space. All images will generate points in this space. A least-square-fit-based linear

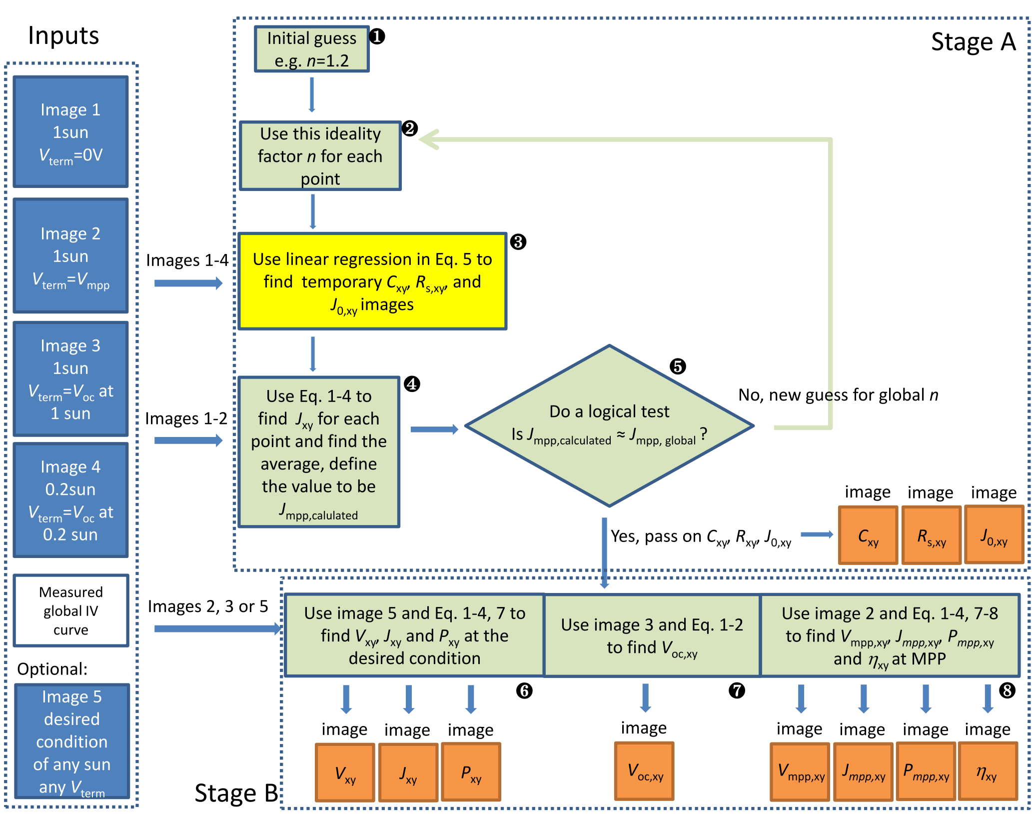

Fig. 1. The schematic flow chart of the algorithm. It has two stages. Eight individual steps are marked with black circled numbers. Blue images represent input images and orange images represent output images. The main calculation step is step 3, which is marked in yellow. Note that in stage B, the OC and MPP means that the terminal voltage is at open circuit and maximum power point condition.