Contents lists available at ScienceDirect

# Solar Energy Materials & Solar Cells

CrossMark

# Photoluminescence based open circuit voltage and effective lifetime images re-interpretation for solar cells: The influence of horizontal balancing currents

Chao Shen *, Henner Kampwerth, Martin A. Green

*University of New South Wales, Sydney, NSW 2036, Australia*

ABSTRACT

We present a method to display photoluminescence imaging results in a different way for open circuit voltage for metallised solar cells. This method virtually eliminates the influence of horizontal balancing currents, which have limited the validity of previously reported methods. It is achieved by creating a "virtual static" situation. At this virtual situation, there is no horizontal current flowing and the calculation of local open circuit voltage can be more reliable. Then effective lifetime image can be calculated more accurately. Compared to other spatially resolved lifetime measurement methods, this method does not require calibration. It is made more convenient by only using one laser wavelength and existing photoluminescence systems. The total measurement time of 2–3 min increases its practicability. Moreover, it is free of horizontal balancing current and the accuracy is experimentally verified.

© 2014 Elsevier B.V. All rights reserved.

## 1. Introduction

Open circuit voltage $V_{oc}$ and effective minority carrier lifetime ($\tau_{eff}$) are important parameters for solar cells. $V_{oc}$ imaging was previously calculated and explained by [1–4,14]. Some techniques were based on photoluminescence (PL) but they are affected by horizontal balancing current [1–3,14]. The method by Breitenstein [4] is free of horizontal balancing current but the practicability is much reduced by complicated experimental setup and long data acquisition time.

For a solar cell before metallisation, carrier lifetime can be determined by various existing techniques. However, only very few techniques work well on metallised cells. A high free carrier density in metals and a lack of optical transparency are the main constraints for wafer lifetime measurement techniques such as [5–7]. They use different techniques with [5] using QSSPC based lifetime measurement, [6] using microwave reflection measurements, and [7] using calibrated QSSPL. Electroluminescence (EL) [8] achieved fast and high definition qualitative diffusion length images, but it seems to be inaccurate, pointed out by [9]. The method described in Würfel et al. [9] records at least two luminescence images in different wavelength ranges to calculate effective diffusion length. Method [9] seems to be convincing but the experimental setup must be altered during the data acquisition period, which is inconvenient. None of the above techniques directly measure the spatially resolved quantitative lifetime. However, Giesecke et al. [10] developed a $\tau_{eff}$ imaging method based on quasi-steady-state photoluminescence (QSSPL). This method is well demonstrated but requires additional calibration.

Although $V_{oc}$ and $\tau_{eff}$ can be well indicated by the above luminescence-based techniques, they neglect horizontal balancing currents within the cell. Our analysis and experimental results show that even for open-circuited cells, horizontal balancing currents can play a significant role. With these horizontal balancing currents, each point on the cell is not strictly open-circuited even when the cell terminals are open-circuited. Therefore, the $V_{oc}$ and $\tau_{eff}$ image obtained from the above methods are affected.

There are two established alternative possibilities to display $V_{oc}$ data. The first being the local voltage when the cell terminal is at open circuit condition. The second being the local voltage when each point is at open circuit condition, which is the $V_{oc}$ potential image in [4,13]. This paper will explain in detail the calculation of "$V_{oc}$ potential" image by one diode model and its practical usefulness. Firstly, we create a "virtual static" situation to calculate the $V_{oc}$ potential image. With this image, $\tau_{eff}$ can then be calculated for given cell thickness and doping level without the influence of horizontal balancing currents. Moreover, no additional calibrations or equipment modifications are required. Finally, the accuracy of the $V_{oc}$ potential image is experimentally verified.

* Corresponding author. Tel.: +61 433666505.
E-mail address: hunterchaoshen@gmail.com (C. Shen).

## 2. Theory

To explain the influence of the horizontal balancing currents, a current density image calculated by a PL based method [2] is shown in Fig. 1. It shows that although the overall current at the terminal is zero, horizontal balancing currents are significant.

Horizontal balancing currents have a significant impact on a non-uniform cell that increases with higher non-uniformity. These include non-uniform series resistance $R_s$ and saturation current density $J_0$, which will be explained in Figs. 2 and 3 below. To eliminate these influences, a calculation of $V_{oc}$ potential from each point is used. Instead of direct conversion (see Eq. (1) [11]) from open-circuit PL image via a calibration constant used previously by Shen et al. [1,2] the proposed method finds $V_{oc}$ from the local $J$–$V$ curve of each point. Subscript $xy$ stands for each point on a cell. $V_T$ is the thermal voltage, and equals $kT/q$, where $k$ is Boltzmann's constant, $T$ is the cell temperature and $q$ is the elementary charge of an electron. Photon flux $\phi_{net,xy}$ is the total photon collected by the camera per second for each unit/pixel on the camera. $C_{xy}$ is a voltage dependent calibration constant, which accounts for locally varying optical properties and variations in the luminescence signal of the cell due to variations in the local diffusion length of minority carriers.[8]

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

The first essential step is collect local $J$–$V$ curve data of each point. For example, by the method given in [2], dark saturation current density $J_{0,xy}$, light generated current density $J_{light}$ and global ideality factor $n$ are obtained. We can therefore draw the local $J$–$V$ curve of each point on the cell:

$$J_{xy} = -J_{0,xy} \times \left(e^{\frac{V_{xy}}{nV_T}} - 1\right) + J_{light} \quad (2)$$

This local $J$–$V$ curve describes the local feature of this point, and determines whether this spatial point is producing or withdrawing current at the local voltage. If each point on the cell is set to zero local current, then this cell will be in a "virtual static" situation. In this situation, Fig. 1 will become a uniform image with zero current density everywhere. Note that this "virtual static" situation will never be obtained in a real cell as interactions between points will always exist. The local open circuit voltage can then be found:

$$V_{oc,xy} = n \times V_T \times \ln\left(\frac{J_{light}}{J_{0,xy}} + 1\right) \quad (3)$$

Since the current of each point is set to be 0, there will be no current sources in the cell, and horizontal balancing currents will not exist. The local $V_{oc}$ image calculated from this step is the $V_{oc}$ potential voltage. If the net doping concentration $N$ and the cell thickness $W$ are known, the effective carrier lifetime $\tau_{eff}$ can be calculated via Eqs. (4) and (5) by assuming the $V_{oc}$ potential is equal to the implied one:

$$V_{oc} = V_T \times \ln\left(\frac{1}{n_i^2}(\Delta n + \frac{n_i}{N})(\Delta n + N)\right) \quad (4)$$

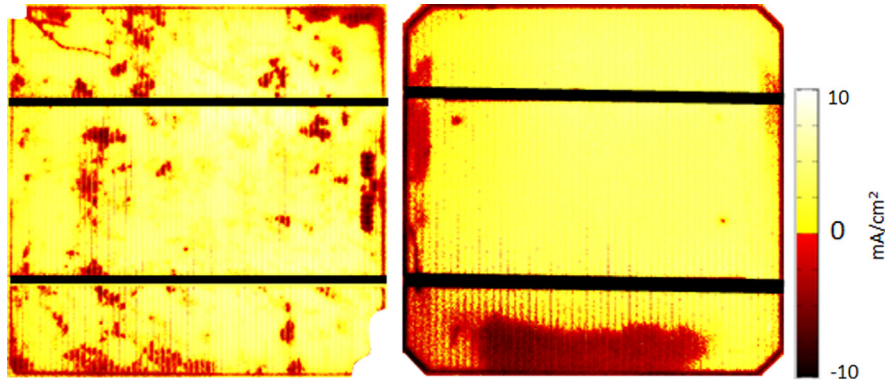$$\tau_{eff} = \frac{\Delta n \times q \times W}{J_{light}} \quad (5)$$



**Fig. 1.** Current density image at open-circuit for an industrial multi-crystalline cell (left) and a mono-crystalline cell (right). The semi-binary colour bar is chosen to separate clearly positive and negative current. Under open-circuit conditions, bright regions are producing current and dark regions are withdrawing current.
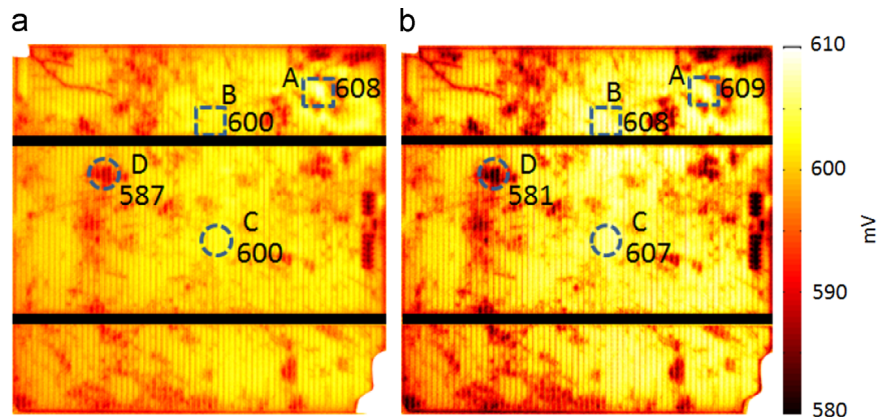


**Fig. 2.** The comparison of local voltages when the terminals (a) or each single point (b) are open-circuited. It can be seen that the $V_{oc}$ potential image is more discriminating, as visualised in Fig. 3. On the other hand, (a) is less discriminating because the horizontal current flow partially rebalanced the local voltage.