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Fast separation of front and bulk defects via photoluminescence on silicon solar cells

Chao Shen*, Kai Wang, Martin A. Green

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

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ABSTRACT

Electroluminescence and photoluminescence imaging provide spatially resolved lifetime information of solar cells with short measurement time. Its high resolution feature validates good visualization of local defects. However, the luminescence image for finished cells is a 2-dimensional image. An extension to 3-dimensional image should be included. This paper proposed a fast technique for separating front and bulk effects. "Front" in this paper refers to front surface, emitter and junction. Its quality can be varied a lot during processing and it is a most interesting region for most of the cells. Experimental results show that the method achieved a clear separation for various cells. It helped to optimize the cell processing and developing techniques. Therefore, it could become a popular characterization technique in the laboratory based on its fast, reliable and 3-demensional spatially resolved features.

1. Introduction

Photoluminescence (PL) imaging on large solar wafers was first demonstrated by Trupke et al. [1]. Parameters imaging techniques based on PL images at different voltage bias or illumination conditions were also published in recent years; see [2–10]. However, these techniques are 2-dimensional modelling based since they use one pixel value to represent a stack of layers. After Würfel et al. [5] used 3-dimensional modelling for cells, 3-dimensional wafer characterization techniques were published by Michl et al. [11] and Giesecke et al. [12]. The latter also explained a method to calculate the rear surface and bulk diffusion length of the cells via electroluminescence (EL). Although this method is limited by series resistance disturbance and complication of experimental setup, it shows good vertical characterization of finished cells. We present a fast front and bulk separation method for finished cells by focusing on the PL image at open circuit and short circuit conditions. It first tells whether the defects are at front surface, emitter or junction. It also tells whether the defects are at the rear surface and in the bulk. The advantages are that it only requires a total time of 8 s and can be readily used in the laboratory and industry.

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

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2. Theory

To achieve the separation, open circuit PL (OC-PL) image and short circuit PL (SC-PL) image are compared. The OC-PL image is the PL image when there is no applied electrical bias. The SC-PL image is the PL image when the cell is biased at zero voltage. It is actually a combination of PL and EL. In order to study the OC and SC PL images more, we establish a one-dimensional model for the excess minority carrier density (hereinafter "carrier density" for simplicity). Under low level injection condition, neglecting the emitter for the wavelength of interest, the continuity equation [13] for steady state carrier density, $\Delta n(z)$, can be expressed as

$$D\frac{d^2\Delta n(z)}{dz^2} - \frac{n(z)}{\tau_b} + G(z) = 0 \tag{1}$$

where D stands for the minority carrier diffusivity. τ_b is the bulk minority carrier lifetime, which is assumed to be uniform along the depth (see justification in [14]). The generation profile $G(z)$ is given by

$$G(z) = \alpha F\exp(-\alpha z/\cos(\theta)) \tag{2}$$

where α is the absorption coefficient of excitation wavelength, F is the photon flux and θ is the angle of light propagation. As for the rear side boundary condition, $z = W$, it can be expressed as

$$D\left.\frac{d\Delta n(z)}{dz}\right|_{z=W} = -S_W\Delta n(W) \tag{3}$$

Eqs. (1) and (3) are essentially the same for OC and short-circuit PL conditions. However, the front boundary conditions are different. As pointed out by Shockley [15], the carrier density at $z = 0$ is defined by the external voltage applied, V_{appl}

$$\Delta n(0) = \frac{n_i^2}{N_A}\left[\exp\left(\frac{V_{appl}}{V_T}\right) - 1\right] \tag{4}$$

where n_i is the intrinsic carrier density, N_A is the background doping density and V_T is the thermal voltage. As a result, under SC condition, the rear boundary condition follows:

$$\Delta n(0) = 0 \tag{5}$$

As for OC condition, we follow the assumption made by Bothe and Hinken [16] that all the current losses due to the junction, emitter and front surface recombination should be lumped into an effective surface recombination velocity, S_{eff}, at $z = 0$. Therefore, under OC condition, the rear boundary condition reads

$$D\left.\frac{d\Delta n(z)}{dz}\right|_{z=0} = S_{eff}\Delta n(0) \tag{6}$$

Combining Eqs. (1)–(6), we could simulate $\Delta n(z)$ under SC and OC conditions for two samples, as can be seen in Fig. 1a.

The value of the PL image is significantly dependent on the total carrier density Δn which could be approximated by the total area under each curve at the long-wavelength involved (see details in [17]). Therefore, it is established from Fig. 1a that the change of front quality will change the OC-PL value but not the SC-PL value. By comparing these two images, we can determine whether a defect is located at front or not. "Front" in this paper refers to front surface, emitter and junction. It could also be proved from Fig. 1b that the value of SC-PL image is dependent on the bulk and rear surface. Therefore, SC-PL image could characterize the combined quality of bulk and rear surface. Defects such as dislocations or grain boundaries that extend through both regions will suppress minority carrier concentrations in their vicinity showing features in both OC and SC images.

3. Experimental results and discussion

3.1. Detailed discussion based on one sample

Since PL signal is largely dependent on the excess carriers, it also can be seen from Fig. 1 that the received luminescence signal by the camera (PL counts) should be much less than the one received under the OC condition. This is experimentally shown in Fig. 2. Although the signal is weak, the dynamic resolution is sufficient to see the defects. By comparison, it can be noticed that the two images represent the quality of the cell for different areas. The OC-PL image represents the quality of the cell of all the depth layers and SC-PL image represents the quality of the cell at the rear surface and in the bulk. Their similarity and difference can be used to interpret the quality of the cell at different layers.

First, both images show similar typical defects of multi-crystalline cells, such as grain boundaries and dislocation centers. Some of them are boxed in region B. They also both show the lifetime drop in the crack, as marked in region C. Since crack and grain boundaries strongly lower the bulk quality, the similarity of the two images proves that they both have the ability to check the bulk quality. There are also two obvious differences. First, the

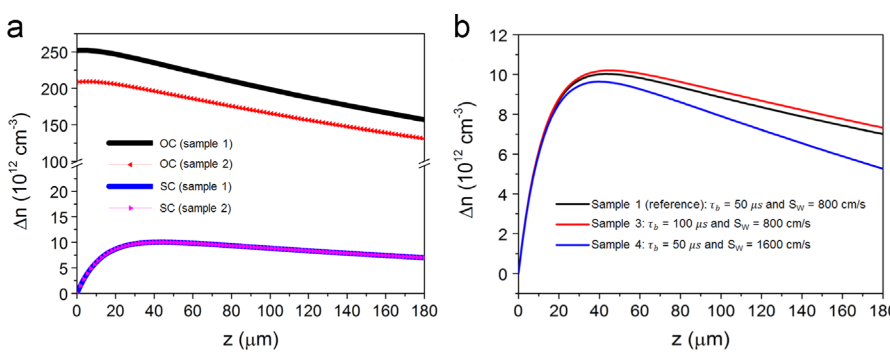

Fig. 1. (a) Simulated minority carrier density as a function of depth under OC and SC conditions. Parameters used for both sample 1 and sample 2 are: $D = 26.92$ cm^2/s (corresponding to N_A of 1.5×10^{16} cm^{-3}), $\tau_b = 50$ μs, $\alpha/\cos(\theta) = 790$ cm^{-1}, $F = 2.5 \times 10^{17}$ cm/s, $W = 180$ μm and $S_W = 800$ cm/s. The only difference is that $S_{eff} = 200$ cm/s for sample 1 and $S_{eff} = 400$ cm/s for sample 2. The wavelength used is always 808 nm. Note reabsorption, rear reflection and some other less influential factors are neglected in this simulation. (b) Simulated minority carrier density as a function of depth under SC conditions. All the unmentioned parameters are the same as sample 1.

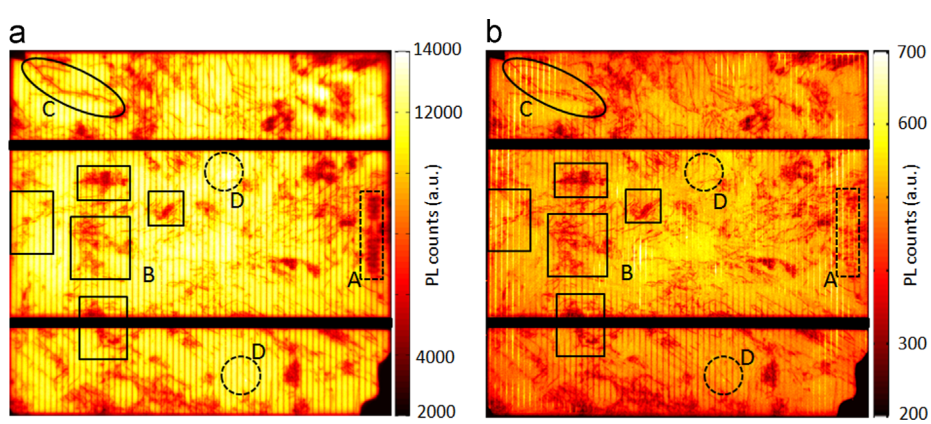

Fig. 2. (a) and (b) The OC-PL and SC-PL images for a multi-c silicon commercial cell. Both images are normalized to 1 s exposure time. It can be seen that both images shows similar defect regions. Region A is the only one obvious difference for the two images. From OC-PL image, an obvious laser tagged series number can be seen, which is contrastively dark compared to neighboring area.