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Injection intensity-dependent recombination at various grain boundary types in multicrystalline silicon solar cells

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ABSTRACT

If the ratio of two open circuit photoluminescence (V_{oc}-PL) images taken at two different light intensities is displayed, some grain boundaries (GBs) may show up as bright lines. This indicates that these special GBs show distinct injection intensity-dependent recombination properties. It will be shown here that this results in an apparent ideality factor of the light emission smaller than unity. The effect is reproduced with numerical device simulations using a usual distribution of defects in the band gap along grain boundaries. Quantitative imaging of this apparent luminescence ideality factor by PL imaging is complicated by the lateral horizontal balancing currents flowing at open circuit. The local voltage response of an inhomogeneous solar cell at different injection levels under open circuit is modelled by Griddler simulations, based on PL investigations of this cell. The evaluation of V_{oc}-PL images at different illumination intensities allows us to conclude that the apparent luminescence ideality factor at the special GBs is about 0.89, whereas in the other regions it is between 0.94 and 0.95. Reverse bias electroluminescence showed no pre-breakdown sites, and hyperspectral PL imaging showed only in one of the investigated GBs particular defect luminescence. TEM investigations of two GBs, one showing distinct injection intensity-dependent recombination and the other one showing none, revealed that the investigated special GB is a large-angle GB whereas the GB not showing this effect is a small-angle GB.

1. Introduction

Electroluminescence (EL) and photoluminescence (PL) imaging are standard tools to study local electronic properties of solar cells. This holds in particular for cells made from multicrystalline (mc) silicon material, which still represent the major part of all solar cells produced today. Therefore a comprehensive study of the electronic properties of the extended crystal defects in mc-Si material and cells is necessary, since these defects are governing the energy conversion losses in these cells. Grain boundaries (GBs) and dislocation networks represent the significant contribution to these extended defects. It is well-known that different types of GBs in mc-Si show different recombination properties. For example, twins on (111) planes usually show little or no recombination activity, whereas low-angle GBs may show a high recombination activity [1]. These low-angle GBs are basically rows of dislocations. It was shown recently that, even within one and the same low-angle GB, regions of different recombination activity may exist, which differ in their type of dislocations representing the GB [2].

In this contribution we show by evaluating PL images of mc-Si solar cells that different GBs may show different degrees of injection intensity-dependent recombination activity. It will be shown by a simplified analytic analysis that this property can be described by an apparent ideality factor of the luminescence n_{lum} smaller than unity, which corresponds to a bulk recombination current ideality factor n_1 larger than unity. The effect is reproduced with numerical device simulations using a usual distribution of defects in the band gap along grain boundaries. In principle, n_{lum} can be imaged by evaluating V_{oc}-PL images taken at different illumination intensities. The difference between the applied bias and the local diode voltages due to horizontal balancing currents may be regarded at least approximately by applying a recently introduced correction method evaluating V_{oc}-PL images at two illumination intensities [3]. In this work this correction method is extended to the evaluation of images taken at 4 different intensities. Based on this knowledge and on 2-dimensional finite element simulations of the cell using an independently measured J_{01} distribution, n_{lum} of the special GBs are measured. By transmission electron microscopy (TEM) the crystallographic structure of one of these GBs showing and one GB not showing injection-dependent recombination was

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determined. It was checked by reverse bias electroluminescence (ReBEL) [4] and hyperspectral PL imaging [5] whether these special GBs show particular defect luminescence.

2. Photoluminescence results

Two cells from different producers were investigated here, both being industrial standard technology Al-BSF (full-area back surface field) type multicrystalline (mc) cells with 3 busbars, 156 × 156 mm^2 in size. It should be noted that the special GBs reported here have been found also on several other cells of this type, hence they seem to be quite common at least in this type of solar cells. PL measurements have been performed under open circuit and short circuit conditions by using a custom built PL system employing LED illumination at 850 nm (870 nm short-pass filtered) and 950–1000 nm bandpass filtering in front of the thermoelectric-cooled ANDOR iKon-M PV-Inspector camera used with a LINOS inspec.x M NIR 1.4/50 mm objective. All open circuit (V_{oc})-PL images shown and evaluated here are net PL images, hence from all of them a short circuit (J_{sc})-PL image taken at the same illumination intensity and acquisition time was subtracted, see [6]. This procedure makes the PL images equivalent to EL images for the same local diode voltage [7] and corrects for the baseline and residuals of the excitation illumination. For (V_{oc})-PL images the luminescence correction is very minor, but the baseline and illumination light correction remains important. Usually deconvolution of the luminescence images is applied for correcting photon scatter in the detector [8,9]. We have shown recently [10] that, for our band-pass filtered luminescence images, deconvolution leads to minor improvements of the spatial resolution but may degrade the signal-to-noise ratio. Therefore we have not applied spatial deconvolution for most of our results. Only the final result of the image of the luminescence ideality factor will be presented either without or including spatial deconvolution of the luminescence images.

Fig. 1(a) shows a net V_{oc}-PL image of the first investigated cell taken at 0.5 sun equivalent intensity (measured by the nominal I_{sc}) together with an enlarged insert below. The same images measured at 0.1 sun intensity looked visually very similar. However, when the ratio of the 0.5 to the 0.1 suns images is displayed in Fig. 1(b), some bright lines appear in the enlarged insert, see white arrows. These lines are in the locations of certain isolated lying recombination-active grain boundaries, which look in a) very similar to other grain boundaries. In the ratio image (Fig. 1(b)) other separately lying grain boundaries become invisible, see e.g. dashed white arrows. These GBs obviously show an injection-independent recombination. Some cracks in the lower left of the enlarged region (black arrows) and all regions of a high local density of GBs, which may be considered as extended regions with increased recombination, appear dark in the ratio image b), see circle. This is an effect of the lateral series resistance as will be modelled in the next Section. Note that under V_{oc} condition, in defect regions of high bulk recombination current density J_{01}, the dark current dominates, whereas in "good" regions the photocurrent dominates. This leads to lateral balancing currents and thus to lateral diode voltage differences. In defect regions the local diode voltage is always smaller than in good cell regions, and these differences increase with increasing illumination intensity (linear response principle, see [11]). Therefore in these defect regions the local voltage is reduced more strongly at 0.5 suns than at 0.1 suns, leading to the dark contrast in these regions in the ratio image Fig. 1(b).

3. The apparent ideality factor of light emission

3.1. General considerations

It is well-known that Shockley-Read-Hall (SRH) recombination levels having unequal capture cross sections leads to a lifetime τ, which depends on the excess carrier concentration n. This dependency can be approximated in a restricted injection range by (see e.g. [12]):

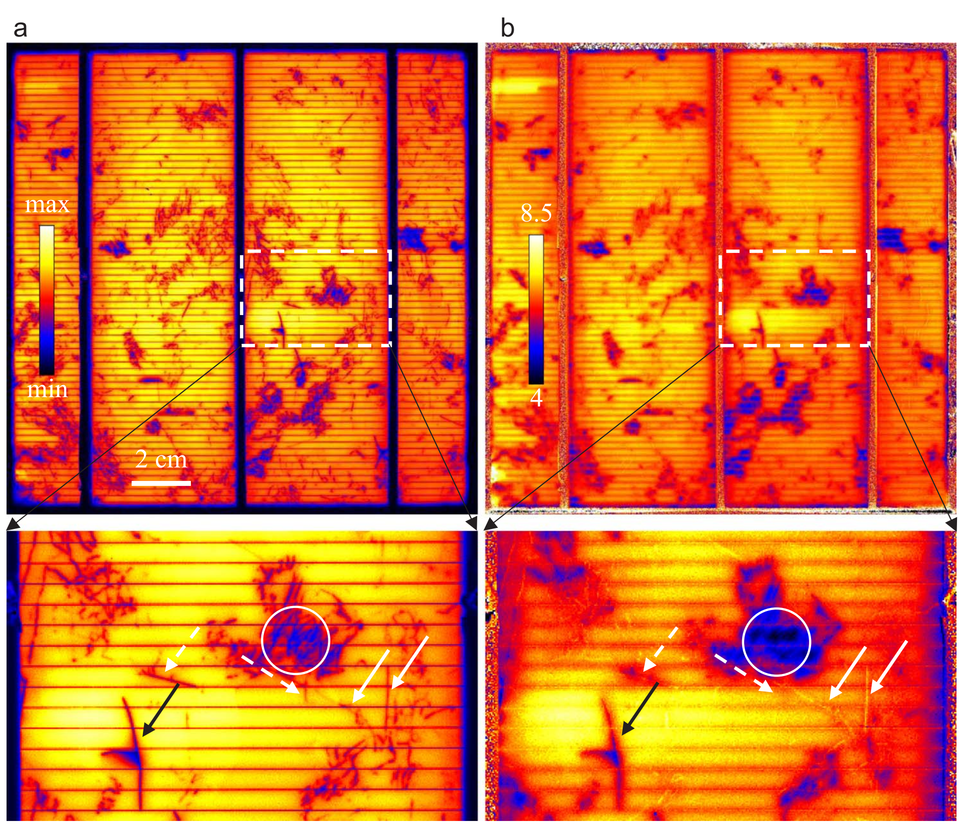

Fig. 1. a) V_{oc}-PL image of the first investigated cell at 0.5 sun [colors in a.u.], b) ratio of V_{oc}-PL images at 0.5 and at 0.1 suns intensity.