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Quality control method based on photoluminescence imaging for the performance prediction of c-Si/a-Si:H heterojunction solar cells in industrial production lines

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ABSTRACT

Photoluminescence (PL) imaging is a fast and contactless technique that allows visualizing defective regions of a solar cell where local carrier lifetime is reduced. In this paper we present a PL based method for the quantification of such defective areas in the case of a-Si:H/c-Si heterojunction solar cells produced in an industrial pilot line. After a description of the methodology used for obtaining a "defectivity parameter" G_d from the open-circuit PL images, we show that the efficiency of non-metallized cells produced in this line can be predicted from their G_d value with absolute deviations lower than 0.2%. Numerical calculations based on the two-diodes model are then used together with experimental results to investigate the impact of the defective regions on the cells performance. Finally, we focus on some defective regions using high resolution characterization tools such as SEM, EDX and μ-PL, and show that they can emanate from microscopic defects induced by the wafering step.

1. Introduction

Inline quality controls are of great importance to optimize and ensure stability of a silicon solar cell production line. In order to limit performance failure, defective substrates such as silicon (Si) wafers exhibiting cracks or dislocations are generally rejected prior to any process step. However, some intra-grain defects are revealed only after the solar cells have been processed like for instance, certain impurity clusters responsible for Shockley–Read–Hall (SRH) recombination currents in the device. In particular, wire sawing of mono- and/or multi-crystalline Si bricks used for the production of Si wafers is a key step wherein the sliced wafers surface is impregnated with residues of cutting fluid slurry or metallic species coming from the wire saw [1,2]. This kind of contamination is highly detrimental for the solar cell fill factor (*FF*) and therefore, a cleaning step prior to any deposition process is crucial to achieve high device efficiencies. This is even more important in the case of a-Si:H/c-Si heterojunction (HET) solar cells, where the interface quality (*i.e.* wafer surface quality) governs mainly the device performance [3,4]. Hence, all wafers containing a high density of defects that induce severe performance losses should be rejected as soon as possible from the production line in order to avoid additional costly processing steps like, for instance, producing the metallization grid.

In this context, photoluminescence (PL) imaging has been demonstrated to be a very powerful technique for the inline monitoring of solar cell fabrication steps. Indeed, the aforementioned recombination defects induce a decrease of the minority carriers effective lifetime leading to a low PL response. Furthermore, PL imaging is a contactless, fast and easy-to-implement technique which allows determining information about the main solar cell parameters: A few number of calibrated PL images of a solar cell, performed at open-circuit voltage (V_{oc}) conditions and at different generation rates, enable the construction of a pseudo-light *I–V* curve and the spatially resolved determination of the minority carrier lifetime [5]. This method is applicable to non-metalized solar cells. Peloso et al. used PL hyperspectral imaging to determine spatially resolved images of the diffusion lengths of minority charge carriers in silicon wafer solar cells [6]. Other methods use a set of several PL images taken under different electrical bias and illumination conditions to determine mappings of the series resistance (R_s), V_{oc}, J_{sc}, *FF* and efficiency (η) of metalized solar cells [7–9]. Detection and quantification of shunts in solar cells by means of PL imaging have also been demonstrated [10,11], even though only strong linear shunts are clearly detectable and shunt defects can hardly be distinguished from other types of recombination defects [12]. A contactless PL method for

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the mapping of recombination currents in a GaAs solar cell is presented in [13]. In this method, maps of PL spectra are taken using a hyperspectral imager to determine the quasi-Fermi level splitting under different illumination conditions. A fitting procedure using a two diode model is then applied to obtain the diode current saturation maps that allows predicting the cell efficiency using the superposition principle (diode ideal factors $n_1=1$ and $n_2=2$ are fixed and shunt and series resistance effects are neglected). A more simple method is proposed in [14] wherein the average intensity values of the PL images, taken under 1 sun illumination and at open-circuit conditions, of a sample set of Cu(In, Ga)Se_2 thin film solar cells are correlated with their main parameters *i.e.* V_{oc}, *FF* and η. In this latter case, the correlations show a high uncertainty except for the case of V_{oc}. Yan et al. applied a similar procedure to predict the performance of multicrystalline Si solar cells by correlating the cells efficiency with the defect area percentage, determined using a threshold value, of their respective PL images [15]. However, to our knowledge, there exist no works based on PL imaging that allow predicting the performance of non-metallized HET solar cells on monocrystalline Si wafers.

In the first part of this paper, we present a method enabling prediction of fill factor and efficiency losses for HET solar cells prior to their metallization step. This method combines the acquisition of a unique PL image in open-circuit conditions and a coarse graining image treatment. This method can be applied to non-metalized cells; the original PL image, M_0, is decoupled into two matrices: a "base PL image", M_b, which is the original PL image free of defective areas and a "defectivity PL image", M_d, which is the resulting image from the ratio $M_d=M_0/M_b$. A "defectivity parameter", G_d, which quantifies the impact of defective areas on the average PL signal, is determined from M_d for each measured solar cell. Said parameter G_d shows good correlation with calculated fill factor losses of the tested solar cells, attributed to SRH recombination in the space-charge region (J_{02} recombination currents). Using the historical current density–voltage data of the solar cells produced in our production line, we show that it is possible to predict with reasonable accuracy (absolute deviations of $\pm 0.2\%$) the performance of a solar cell, prior to its metallization step, from its G_d value.

The second part is dedicated to the in-depth study of the defects revealed by PL imaging on our samples, with a special focus on wire sawing induced defects. Electron microscopy, μ-PL imaging and surface chemical analysis have been performed for this purpose. The influence of different pre-texturing treatments applied to the as cut Si wafers on some defects reduction is also investigated.

2. Experimental details

All heterojunction a-Si:H/c-Si solar cells shown in this work have the structure shown in Fig. 1 and were fabricated in a pilot line under the same process conditions. Experimental details regarding the deposition process conditions can be found in [16,17]. The c-Si wafers $<100>$ oriented used for the production of said solar cells were supplied by the same manufacturer. Such wafers were sliced using diamond plated wires from equivalent quality mono-crystalline silicon ingots and have a nominal wafer resistivity $\rho_{c\text{-}Si}=3\ \Omega\,\text{cm}$ and a carrier lifetime $\tau>2$ ms for an injection level of $10^{15}\ \text{cm}^{-3}$. Wafer texturization was performed using a KOH alkaline based solution. Some wafers have been subjected to different pre-texturing treatments prior to the texturization step. More details on the pre-treatments are presented in Section 4.3. Finally, after texturization, the wafers were cleaned by industrial ozone-based cleaning [18] and dipped in a hydrofluoric acid solution to deoxidize the surfaces.

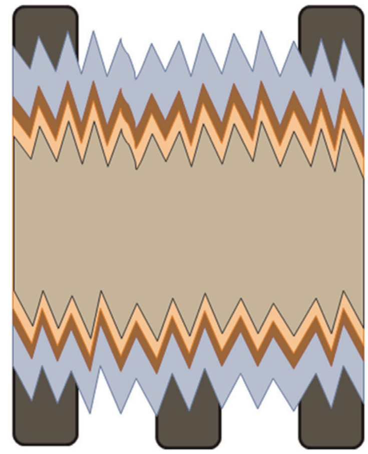

Fig. 1. Schematic diagram of the heterojunction a-Si:H/c-Si solar cells used in this study.

The cells performance was measured using a solar spectrum simulator integrated at the back end of the production line under AM 1.5 conditions. PL images of the solar cells were taken with a *BT Imaging LIS-R2* equipment at open circuit conditions and using a laser intensity equivalent to an illumination of 1 sun. The excitation time was fixed to 0.01 s for all PL acquisitions. Scanning electron microscopy (SEM) images and energy-dispersive x-ray (EDX) analysis of defective areas of the tested solar cells were taken using a *Nova NanoSEM 630* microscope equipped with an *INCA* X-ray microanalysis system from Oxford Instruments. The impact of wire sawing induced defects on the device PL local response was examined by means of micro-PL using a confocal microscope (*Witec alpha300R*) with a frequency-doubled NdYag laser operating at 532 nm as excitation source with up to 20 mW continuous wave output power. The expected lateral spatial resolution in the *x*–*y* plane is around 1 μm.

3. PL imaging based quality control method

3.1. PL defectivity quantification: G_d parameter

Defects responsible of recombination currents in a solar cell will appear as dark spots (*i.e.* areas with lower PL intensity) in its corresponding PL image. An image analysis tool has been developed in order to quantify the amount of local recombining defects observed in the PL images. The image treatment process is detailed in Fig. 2: a matrix M_0 which corresponds to the original PL image (Fig. 2a) is divided into a number S of sub-matrices like those depicted in the inset of Fig. 2a. Afterwards, the PL intensity value of the central pixel, $\varphi_{j,central}$, of each sub-matrix j ($j=1\ldots S$) is substituted by the highest PL intensity value, $\varphi_{j,max}$, of said sub-matrix pixels. Next, all pixels in each sub-matrix j are considered to have non-defined intensity values, except for $\varphi_{j,central}$. In this way, the tool generates a new matrix M_b with S defined values for those pixels located at the center of each sub-matrix j, $\varphi_{j,central}=\varphi_{j,max}$, while the rest of the pixels have a non-defined value. A new PL intensity value is then given to these non-defined pixels by interpolation. A smart choice of the sub-matrices size guarantees that the resulting matrix M_b, shown in Fig. 2b, is the "base PL image" that is to say, the PL image that would be obtained if all local defects of the solar cell were suppressed. The optimal sub-matrices size is the minimal one that guarantees that the PL loss from all local defects in M_0 will be filtered by the coarse graining and interpolation process used to create M_b. In our case, the sub-matrices size was set to 20 pixels ($3.2\times3.2\ \text{mm}^2$ approximately).