Photoluminescence imaging of solar grade mc-Si wafers and solar cells as a tool for efficiency qualification

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Abstract

The photoluminescence imaging (PLi) technique allows for the fast qualification of mc-Si wafers and solar cells, giving information of the presence and distribution of carrier capture centres, which obviously affect the final efficiencies. In this work, we characterize a wide collection of solar cells by PLi, correlating some aspects extracted from the PL images to their efficiencies. The desired goal of this approach is to provide a tool allowing a robust prediction of solar cell efficiency from the PL images of the wafers.

Introduction

The photovoltaic industry is, nowadays, dominated by crystalline silicon, on the form of mono-crystalline (c-Si), or multi-crystalline (mc-Si) material. The use of mc-Si grown from casting processes is preferential for cost effectiveness, in spite of their high concentration of intrinsic structural defects. The efficiency losses in mc-Si are mainly caused by the structural defects inherent to the growth, e.g. grain boundaries (GBs), dislocations, and incorporation of impurities [1-3]. In particular, in the case of solar grade material, this can be a critical point, due to the high amount of impurities [4]. These defects act as charge traps, killing the minority carrier lifetime (τ), and shortening the diffusion length (L_{diff}), which negatively affects the conversion efficiency [2, 3].
An important effort is being carried out in the last years in the development of characterization tools allowing the screening of the mc-Si wafers and solar cells. Both scanning and imaging techniques have been developed. One of the most promising experimental tools for a fast qualification of mc-Si wafers is the PL imaging (PLi) technique, which permits to acquire in a short time a wafer panoramic view of the main carrier capture centres [5]. This technique is very promising for the fast in-line screening of the wafers. A very interesting characteristic of the technique would be to infer an estimation of the final efficiency of the solar cell from the alone PLi of the wafer. In this work, we have analysed in detail the PLi of several solar cells of known efficiencies, observing a very good correlation between the colour lookup table (LUT) extracted from the PL images and the solar cell efficiencies. The difficulties to extrapolate the data extracted from the PL images of the wafers to the cell efficiency are discussed.

Experimental and samples

The PLi set-up consists of a dedicated in-house built system. The whole wafers/solar cells were excited with four laser diodes (λ= 808 nm, optical output power of 25 W). The luminescence emission was collected with a Peltier-cooled Si-CCD camera (PCO1300-Solar, 12 bits, 1392 x 1040 pixels). Several filters were used to suppress the laser spurious light and the background light. A 12.5 mm optical objective was coupled to the camera allowing the acquisition of the PL image from a whole wafer or cell. The exposure time can be shorter than 2 s in the case of solar cells (using front-side illumination and front-side collection), being of the order of 1-2 min for obtaining the full wafer PL image (using front-side illumination and back-side collection); these time can be largely shortened by improving the experimental set-up.
Both solar grade mc-Si wafers grown by conventional casting and solar cells fabricated from them following standard BSF industrial methods have been investigated. P-type mc-Si bricks (B-doped) were grown, conventional square shaped wafers (156x156 mm^2) were cut from these bricks. Solar cells were performed using HNO_3/HF-based texturing processes and a typical H-patterned screen-printing metallization. P-diffusion was performed by offline ($POCl_3$) method.

Results and discussion

PLi has the advantage of the fast inspection of the mc-Si wafers or solar cells, allowing a rapid identification of areas with trapping activity. Fig.1 show the PL image of a mc-Si wafer in which one can observe a very inhomogeneous distribution of the dark luminescence (quenched) zones. Such features correspond to the typical non-radiative recombination pattern revealed on mc-Si; the inhomogeneous distribution being related to the presence of GBs, and a high density of dislocations [6]. The GBs, by themselves, are not the main electrical active defects in mc-Si [7], but their electrical activity depends on their decoration by impurities. These features make mc-Si material very inhomogeneous in terms of local charge trapping activity. This can be especially critical in the case of solar grade mc-Si.

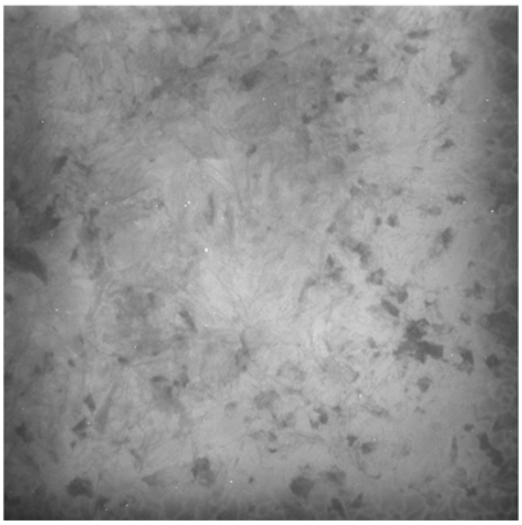

Figure 1. PL image of a mc-Si wafer.

PLi can be used to qualify the mc-Si wafers with the aim of establishing a relation between the PL response and the efficiency once the wafer has been processed into cell.

In order to quantify this correlation, PL images of a set of solar cells with known efficiencies were analysed. Three sets of 10 different solar cells, processed in the same way from similar wafers (solar grade mc-Si), were analysed, with average efficiencies for each cell lot of 16.4, 16.8 and 17.4%, respectively. Fig. 2 shows two representative PL images of solar cells with the lowest and highest average efficiencies, respectively. The LUT level intensity observed in the PL images matched well with the efficiencies; the solar cell with lower efficiency showed, in average, darker LUT levels in the PL image. Fig. 3 shows the obtained correlation between the average LUT levels and efficiencies for the three set of solar cells with low, medium and high efficiency, showing that the PL images seem to give a quantified information with respect to the final efficiencies.

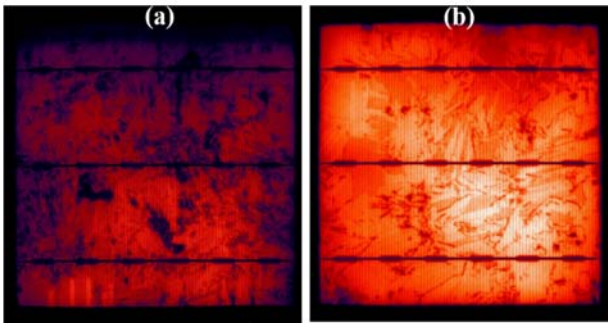

Figure 2. PL images of solar cells with efficiencies of 16.4% (a) and 17.4% (b) (average efficiencies). LUT contrast is the same in both images.

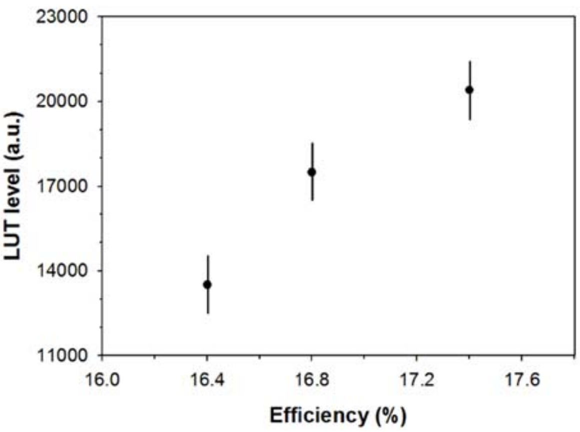

Figure 3. LUT levels obtained from the PL images of the three set of solar cells investigated, with low (16.4%), medium (16.8%) and high (17.4%) efficiencies.

The correlation obtained is valid since all the solar cells have been processed in the same way with the only difference of the initial wafer quality and characterized by PL using the same parameters. In this sense, the LUT levels extracted from the PL images are supplying information about the influence of the defects present in the wafers and their impact on the final efficiency. In particular, it is worth noting to mention the very high sensitivity of the PLi technique, since we observed a variation of 6000 a.u. of the LUT intensity correlated to a variation of 1% in cell efficiency. Although these data are still preliminary, the trend observed is believed to be likely related to the deleterious character of the impurities in these solar grade mc-Si solar cells.

The next step would be to quantify also the PL images of the wafers (Fig. 1) and to provide a prediction of the efficiency expected from wafers using a well-established solar cell technology. In fact, this procedure only makes sense when comparing solar cells processed with the same technology. Some drawbacks to be mentioned here are related to the use of a Si CCD camera, giving typical times for wafers PLi acquisition in the range of 1 minute. In addtion, problems related to inhomogeneous excitation of the wafers can be also critical. Moreover, and pretending the PLi technique to be an in-line tool, such long times must be drastically reduced. Nevertheless, significant time reductions can be achieved by adjusting the experimental set-up, with more sensitive detectors like InGaAs cameras, and/or higher power lasers. The design of a quantitative procedure to perform the wafer classification from PL images shall be very useful, being nowadays the subject of intense research [8, 9].

Conclusions

PLi is a fast tool allowing to catch information about the presence and distribution of carrier capture centres in both silicon wafers and solar cells. A good correlation between the LUT levels extracted from the PL images and the efficiency of three set of solar cells has been observed, providing a high sensitivity to the efficiency variations. The PLi technique appears as a promising in-line tool for fast qualification of wafers and cells.

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