FAST PHOTOLUMINESCENCE IMAGING OF SILICON WAFERS

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ABSTRACT

Photoluminescence (PL) imaging is demonstrated as a fast characterization tool allowing variations of the minority carrier lifetime within large area silicon wafers to be measured with high spatial resolution and with a data acquisition time of only one second. PL imaging is contactless and can therefore be applied to silicon solar cells before and after every processing stage including fully processed cells and bare, unpassivated mc-Si wafers, which makes it an extremely effective process monitoring tool that is ideally suited for inline applications in the PV industry. The combination of PL imaging with electroluminescence imaging and the application of PL imaging with external bias control are demonstrated to give very quick access to additional valuable information about local series resistance variations.

INTRODUCTION

Characterization techniques that allow the spatial variation of the material quality to be assessed quantitatively, quickly and without being affected by artifacts can be invaluable tools in the development of high efficiency solar cells and for effective process monitoring. To apply such techniques inline on each wafer in industrial manufacturing a data acquisition time of at most a few seconds per wafer can be tolerated. Mapping techniques are orders of magnitude too slow to meet this requirement, even with only moderate spatial resolution. *Imaging* techniques that have emerged over the last few years include the two related Infrared Lifetime Mapping [1] (ILM) and Carrier Density Imaging [2] (CDI) techniques and also Electroluminescence (EL) Imaging [3]. While ILM/CDI are faster than mapping techniques, it has been shown that to measure in one second and with an acceptable signal to noise ratio an industrial size silicon wafer with a minority carrier lifetime of 1μs the spatial resolution has to be reduced to 1 cm [4]. Most spatial information is obviously lost in that case. In addition the wafer must be heated to a temperature of ~70 degrees in order to achieve that sensitivity and those techniques are also affected by both minority carrier trapping and by excess carriers in space charge regions.

Injection level dependent quasi-steady-state photoluminescence (QSS-PL) lifetime measurements on silicon are unaffected by these artifacts [5, 6] and have also been shown to be extremely sensitive. An imaging technique based on luminescence thus seems ideal to characterize silicon wafers. It has been shown that in electroluminescence (EL) imaging the emission from silicon solar cells under forward bias can be captured by a commercially available silicon CCD camera and that the counts per pixel are correlated with the local diffusion length [3]. However there exist several limitations to the application of that method. Firstly it requires electrical contacts to the device and as such it is only applicable to fully processed solar cells. Secondly, the quantitative interpretation of the images is complicated by series resistance effects. Experimental results presented in this paper demonstrate that the simplistic assumption of a diffusion length that is linearly related to the counts per pixel can result in a misinterpretation of EL images.

PL imaging [7] combines the above mentioned advantages of QSS-PL with high resolution spatial information about the wafer quality. PL Imaging can be applied to both unfinished and fully processed silicon solar cells of any practical size, it is contactless and non-destructive, it is applicable to both planar and textured samples and it measures the sample at room temperature. A practical advantage of PL/EL imaging over ILM/CDI is that commercially available and generally cheaper and higher performance silicon CCD cameras can be used instead of very high cost infrared cameras.

EFFICIENT PROCESS MONITORING

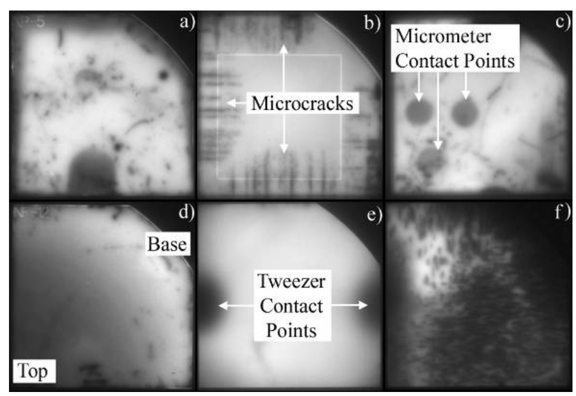

Fig.1 *Various examples of process induced defects identified with PL imaging. See text for details.*

In initial experimental work it has been demonstrated that with PL imaging the effective minority carrier lifetime of a passivated 8.5x8.5 cm^2 mc-Si wafer with lifetime variations between 20μs and 180μs can be measured with a total data acquisition time of only 1.5s with a resolution of 130 μm per pixel and at an illumination intensity equivalent to one Sun [7]. Very good agreement with the results from an independently calibrated CDI measurement on the same wafer was observed [7],

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demonstrating the feasibility of using PL imaging to quantitatively determine the spatial variation of the minority carrier lifetime.

In *qualitative* PL imaging only the relative variation of the intensity across a sample is investigated. Such qualitative PL imaging has been applied extensively by the buried contact solar cell group at UNSW and has revealed information about a unexpectedly rich variety of processing induced defects and problems with standard processing methods. Some examples from that work, that are discussed in more detail in [8, 9] are shown in Fig.1. The images shown were made on differently processed, 1 Ω.cm float zoned, 4-inch wafer quarters with a data acquisition time of one second or less per sample. Bright areas in those images correspond to a large luminescence signal and thus to a high local minority carrier lifetime and vice versa. In Fig.1a the influence of a dome shaped dent in the substrate holder of a PECVD SiN deposition system is clearly visible at the bottom of the wafer. Fig.1b shows micro-cracks resulting from poor laser scribing and subsequent cleaving of the sample. Fig.1c shows the effect of a micrometer used to measure the sample thickness in various positions. Fig.1d shows the influence of a temperature gradient across the wafer during furnace annealing. Fig.1e shows the effect of wafer handling with RCA cleaned plastic tweezers during wafer drying prior to high-temperature furnace processing. Fig.1f shows the image of an unintentionally contaminated wafer.

These and various other defects that have been identified with PL imaging result not only in large and highly unpredictable variations in the electrical properties of finished cells but also in substantial efficiency losses, which clearly complicates a systematic improvement of process parameters and the development of new device designs. For example, in a current investigation of a new contacting scheme an entire batch of wafers recently suffered from microcracks around the cleaved edge (as shown in Fig.1b) as a result of non optimal laser scribing [10]. Without PL imaging the significantly deteriorated final device performance measured across that entire batch would have led to incorrect conclusions about the influence of the actual processing step being investigated in that study and thereby could have led the further development in a wrong direction. PL-imaging of industrially processed solar cells, supplied by various commercial manufacturers, has yielded the discovery of many similar detrimental effects. In many cases the presence of these effects was previously unknown. With knowledge of the processing used and the spatial information provided by PL imaging the source of such detrimental effects can be rectified quickly and effectively. PL imaging is thus a very efficient tool for fault analysis in production lines, particularly during the initial developmental stages of new processing lines.

QUALITY CONTROL OF WAFERS

In Fig.2 the PL image of a finished 12.5x12.5 cm^2 industrial screen printed solar cell (Fig.2a) is compared to the PL image of an unprocessed (i.e. unpassivated) neighboring silicon wafer (Fig.2b). Despite the fact that the effective minority carrier lifetime within the unprocessed wafer is strongly dominated by surface recombination the PL image still shows a significant variation of the effective lifetime across that wafer (roughly by a factor two between good and bad areas), which is caused by lateral variations in the bulk properties. This is confirmed by the correlation between the PL image of the finished cell with the PL image of the unprocessed wafer. The images from Fig.2 were taken with data acquisition times of one second (finished cell) and five seconds (bare wafer), respectively. The resolution is 125μm and 250μm, respectively. Some modifications of the experimental set up that are currently being installed at UNSW will allow an estimated further reduction in data acquisition time by a factor five to ten. PL imaging is the only technique currently available that can provide high resolution images of raw material with such short data acquisition times.

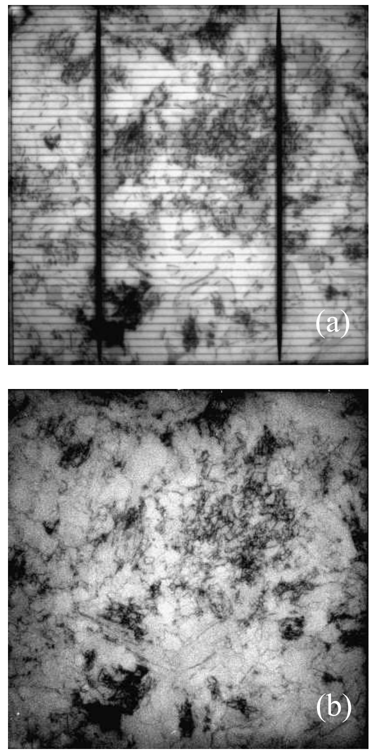

Fig.2 *PL image of (a) an industrial screen printed solar cell and (b) of the unpassivated neighbouring wafer.*

Using either analytical models or empirical comparisons of PL images of bare wafers with the electrical performance of finished devices may allow such images to be used to predict the electrical performance of finished devices already at the beginning of processing. As a result wafer or solar cell manufacturers could use PL imaging on every wafer as a fast and effective quality control tool for raw silicon wafers.

Such fast characterization of unprocessed and partially processed wafers can be applied to a variety of silicon substrates and importantly, at any processing stage. For example PL imaging was applied to partially processed string ribbon wafers to evaluate potential advantages of n-type over p-type string ribbon substrates [11].

Fig.3 *PL image of an n-type (left) and a p-type (right) string ribbon silicon wafer side by side.*

An example of a PL image of two 2.5 Ω.cm n-type (left) and p-type (right) string ribbon wafers after phosphorous doping and SiN firing is shown in Fig.3. Data acquisition time for that measurement was 1s.

ELECTROLUMINESCENCE (EL) IMAGING

In EL imaging the excitation of luminescence is achieved by a forward bias applied to a finished cell. We find that such experiments are severely influenced by two fundamental effects, firstly a smearing of the contrast between good and bad quality areas and secondly an artificial contrast due to lateral variations of the series

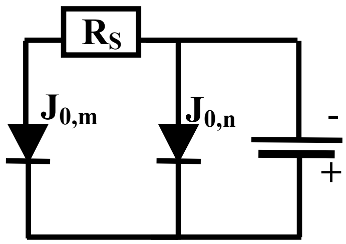

Fig.4 *Equivalent circuit of a solar cell with two areas of different material quality) that are connected to each other in parallel via a series resistance R_S.*

resistance. Fig.3 shows a simplified circuit diagram that allows these effects to be discussed. A solar cell with a good and a bad quality area is modelled as two diodes with different saturation currents ($J_{0,n}$ and $J_{0,m}$, respectively) connected in parallel. In an ideal cell all series resistances are negligible (R_S=0) and in that case the same voltage is applied to the junction in all parts of the cell. Provided the diffusion length in both parts of the cell is larger than the thickness, the separation of the quasi-Fermi energies $\Delta\eta$ is then almost constant throughout the entire volume of the cell resulting in no or only very poor contrast in the luminescence image. Only if the diffusion length is smaller in at least one part of the cell will $\Delta\eta$ decrease noticeably with increasing distance from the junction in that area resulting in the luminescent contrast observed in [3]. In high efficiency cell development diffusion lengths are typically much larger than the cell thickness, even in areas with locally reduced lifetime, which shows that EL imaging is not very practical in that case. The smearing between good and bad areas occurs in both EL and PL imaging on all samples that have an emitter and metal contacts connecting different parts of the cell in parallel. PL imaging is advantageous because it can be applied to samples prior to the emitter or contact formation allowing lateral lifetime variations in the material quality to be determined more readily.

The second fundamental effect occurs only in EL images and makes it difficult to distinguish whether the contrast in a specific EL image is due to series resistance variations or due to locally enhanced recombination. This effect can be described in Fig.4 if we assume that the two parts of the cell have the same material quality (i.e. $J_{0,n}$=$J_{0,m}$) but one part is connected to the rest of the cell via a finite series resistance (Rs). The latter could be the result of a lateral series resistance, e.g. due to a limited conductance of the emitter around that area or due to a vertical series resistance, e.g. due to a poor Ohmic contact on either side. The series resistance causes a voltage drop, resulting in different voltages across $J_{0,n}$ and $J_{0,m}$. As a result the EL image will appear darker in the region of $J_{0,m}$ despite homogeneous bulk properties.

We observed such series resistance effects in a variety of industrial cells. Fig.5 shows three luminescence images each taken with a data acquisition time of one second and

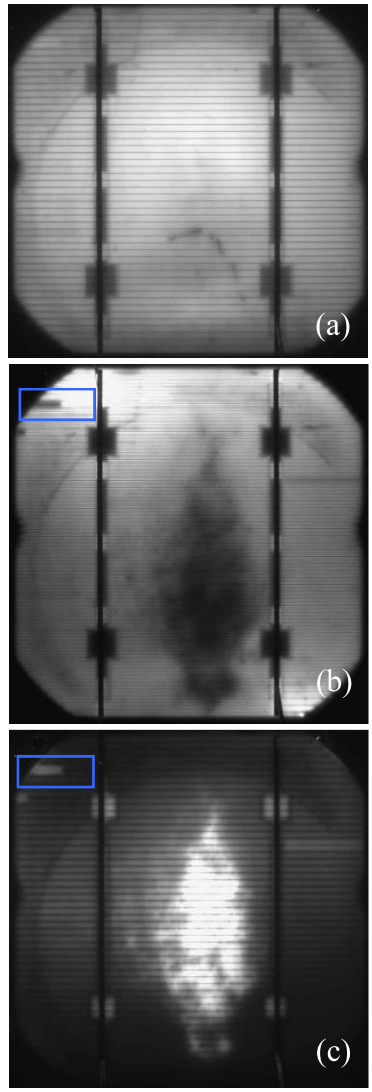

Fig.5 *Luminescence images of an industrial screen printed solar cell: (a) PL with ~1 Sun illumination, (b) EL with 25mA/cm^2 current density, (c) PL with external short circuit.*

with 125μm resolution on the same 12.5x12.5 cm^2 industrial screen printed silicon solar cell. Fig.5a shows a PL image measured with approximately one Sun equivalent illumination intensity. Fig.5b is an EL image measured with a current density of 25mA/cm^{-2}. Fig.5c shows a PL image taken with one Sun illumination but with two contact probes located on the bottom side of the two busbars short circuiting the cell externally (for clarity we denote that PL mode PL_{SC}). The images reveal a surprising amount of variation of the material quality across the cell. Both EL and PL show reduced lifetime in the areas in which the rear side of the cell is metallised with silver and hence is locally missing a back surface field. In an improved cell design the size of those areas clearly should be minimised. Both the EL and the PL image also show a degraded area outside a circular pattern, the origin of which is not clarified yet, but which can most likely be associated with a specific processing step known by the manufacturer. Two localised low quality regions on the left and on the right hand side of the cell observed in the PL and in the EL image point towards a handling problem. Two additional distinct features with reduced intensity appear in the EL image but *not* in the PL image, firstly the area around specific grid fingers (e.g. blue square in the top left) and secondly a very large area in the middle of the cell with a characteristic pattern that was observed on various cells from that batch. While the standard interpretation of EL as discussed in [3] suggests a reduced minority carrier diffusion length, the PL image clearly shows that the lifetime and thus diffusion length is not deteriorated in those areas. This apparent discrepancy is caused by series resistance effects leading to an artificial contrast in the EL image as discussed above. This interpretation is conclusively confirmed by the PL_{SC} measurement (Fig.5c). The areas that are well connected to the busbars appear dark in that case because photo-generated carriers are effectively removed through the external circuit dragging down the local voltage. Only the resistively connected parts of the cell that appear dark in the EL image but not in the PL image still appear bright in the PL_{SC} image because the extraction of the carriers is impeded by the series resistance leaving these areas at a higher local voltage. In contrast to EL imaging alone, PL imaging in combination with EL imaging or PL imaging with external bias control thus allows distinguishing unambiguously between poorly connected or electrically isolated regions and degraded areas of lower lifetime within a solar cell. PL imaging under one Sun illumination and with external short circuit as qualitatively discussed here is just one example of an entire new field of applications, where luminescence images are measured with variable light intensity and with variable external bias control. Combined with theoretical modelling such experiments will allow a more quantitative determination of series resistance variations across a solar cell.

It was concluded that the dark area in the centre of the cell shown in Fig.5b is caused by a locally enhanced contact resistance at the front. These areas lead to a quite substantial reduction in fill factor from 76.5% in good cells from that batch to 68.3% in this particular cell and thereby to a reduction in efficiency from 16.2% to 14.4%.

Elongated areas (dark in EL, bright in PL_{SC}) around specific grid fingers were observed in images from many screen printed cells from various manufacturers and often occurred in the same location on different cells from the same batch. Inspection of these cells under an optical microscope revealed a clear correlation of those areas with broken metal grid fingers causing the area around that finger to be poorly connected electrically to the rest of the cell. EL imaging or PL_{SC} imaging thus allows a fast identification of problems with the screen printing process, for example a congested or contaminated screen.

SUMMARY

The benefit of PL imaging for efficient process development and for the development of new cell designs cannot be overestimated. Only a few months after its introduction PL imaging has revolutionized process monitoring in the buried contact solar cell group at UNSW and it is now used routinely on an almost daily basis for all process and cell development. It has already lead to significant modifications of a variety of standard processing techniques that had previously been used for many years.

The combination of high resolution spatial information about the material quality in large area samples with extremely short data acquisition times of only one second per wafer makes PL imaging a very efficient and powerful process monitoring tool that is ideally suited for inline industrial applications. Characteristic patterns in the PL image give even inexperienced users invaluable and easy to interpret clues about the origin of specific processing problems allowing these problems to be rectified quickly and effectively. Because even bare wafers can be measured within a few seconds PL imaging can be used for inline process monitoring before and after every processing step, thereby allowing the influence of each step on the material properties be monitored. The combination of PL imaging with EL imaging of finished cells gives further information about cell performance losses, specifically about locally enhanced contact resistances.

These and many other practical advantages of PL imaging over existing characterisation techniques that have been discussed above make PL imaging an ideal tool that should find a variety of applications in research and in the industry.

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