4.6 PHOTOCONDUCTIVITY AND DEVICE CHARACTERISATION

4.6.1 Photoluminescence based characterisation of silicon

4.6.1.1 Background
In photoluminescence (PL) imaging an intense light source is used to illuminate large area samples such as silicon bricks, wafers or complete solar cells homogeneously with typically one-sun equivalent illumination intensity. A CCD camera captures a high resolution picture of the luminescent light that the sample emits. Figure 4.6.1.1 shows a schematic diagram of a luminescence imaging system. The power supply that is shown on the bottom left can be used as an excitation source in electroluminescence (EL) imaging experiments on finished cells [4.6.1.3] and also for applications in which a solar cell is held at specific operating points under external illumination, such as the series resistance imaging methods that were introduced by our group [4.6.1.4-4.6.1.6].

High resolution (typical one megapixel) luminescence images can be captured within seconds or even fractions of a second, allowing very fast and detailed studies of specific material and device properties. Over the last five years PL imaging has seen the development of a range of specific applications and also rapid adoption by the PV community. Specific applications that are applicable across the PV value chain are now available and the number of these applications is growing rapidly. Examples include series resistance imaging and diffusion length imaging on fully processed cells. The research of the PL group at UNSW continues to contribute significantly to these developments. This year the research by our group was focussed on the application of the photoluminescence intensity ratio method for measurements of the bulk lifetime on silicon bricks (Section 4.6.1.2), proof of concept studies on an application of luminescence imaging for measuring the emitter sheet resistance on diffused wafers (4.6.1.4) and on analysing local shunt or defect currents from PL images on metallised and non-metallised samples in a quantitative fashion (4.6.1.5).

The commercialisation of PL imaging by UNSW spin-off company BT Imaging Pty Ltd has also made significant progress, with a growing number of leading wafer and cell manufacturers and research institutes worldwide now using the BTi-R1 R&D tool that was introduced into the market in 2008. In addition, as-cut wafer inspection with PL imaging (see Section 4.6.1.3) is increasingly recognised as an ideal tool for incoming wafer inspection in solar cell production or for outgoing quality control in wafer manufacturing [4.6.1.2, 4.6.1.7-4.6.1.8]. New in-line PL imaging tools that are fast enough to keep up with typical production line throughput at full one megapixel image
resolution were introduced by BT Imaging in 2010 and are currently entering the market.

4.6.1.2 PL imaging on Si bricks

Photoluminescence imaging is an ideal tool for fast characterisation of silicon bricks, giving instant information about the position of low lifetime regions that are commonly observed near the bottom and top of a brick and also exposing areas of high structural defect density. This information can be used as valuable feedback during the production of silicon wafers. Initial work on luminescence imaging on bricks showed excellent qualitative correlation between the as measured PL intensity and for example μ-PCD effective minority carrier lifetime maps [4.6.1.9]. More recently we also demonstrated a quantitative interpretation of the PL signal in terms of the bulk minority carrier lifetime $\mu_n$. The bulk lifetime is a more useful parameter than the effective lifetime, especially in unpassivated samples, where the measurement result is strongly influenced by surface recombination. PL imaging thus has advantages compared to other measurement techniques such as μ-PCD, which have commonly been used to date for the characterisation of bricks in production, and which report only effective lifetime values.

In our previous approach to measure bulk lifetime from PL images we converted the measured PL intensity form a single PL image into bulk lifetime using a pre-determined tool specific transfer function. While that approach proved to be a reliable approach for obtaining bulk lifetime on a number of samples and without the need for additional calibration, one disadvantage is the fact that it requires a separate doping density measurement. The PL intensity in low injection conditions is given as $PL\propto N_n N_D$, i.e. it is proportional to both the effective lifetime and the background doping density $N_n$. Normalising the measurement for doping variations is required in order to obtain information on $\Delta n$ and thereby the lifetime.

Recent work in the Photoluminescence Group focussed on a modified approach for bulk lifetime measurements on silicon bricks, which avoids the need for a separate resistivity measurement. The method is based on analysing the photoluminescence intensity ratio (PLIR) between two PL images taken with different spectral filters mounted in front of the camera [4.6.1.10–4.6.1.11]. It is equivalent to the diffusion length imaging method proposed and first demonstrated at UNSW by Peter Würfel on finished solar cells using electroluminescence imaging [4.6.1.12]. In fact, the elimination of voltage variations from a diffusion length image that is achieved in the PLIR method on cells is in perfect analogy to the elimination of doping density variations when applying this method to PL images on bricks. Silicon bricks represent an ideal test case for the PLIR method, since uncertainties associated with variations in surface texture and with the optical and electronic properties of the rear surface are almost completely avoided. In cells and wafers these uncertainties can lead to large experimental errors.

Figure 4.6.1.2 shows a comparison of two bulk lifetime images obtained from a doping normalised PL image and from the PL intensity ratio, respectively. The latter image was obtained using a transfer function that was calculated taking into account sample temperature and the exact spectral properties of the measurement system. Deviations are observed near the low lifetime edges at the bottom and top, where the PLIR overestimates the bulk lifetime (see also Fig.4.6.1.3, showing a comparison of cross sections through the two bulk lifetime images). Defect luminescence contributions, which become more noticeable in the low lifetime regions with reduced band to band luminescence signal is currently believed to cause those deviations. Spectral PL measurements currently under way will shed more light on this issue. Several approaches to mitigate the impact of the above measurement errors in the PLIR near the bottom and top regions are currently under investigation.

Schematic diagram of a luminescence imaging system. In photoluminescence (PL) imaging an intense laser is used to illuminate the entire sample and a sensitive IR camera then captures the luminescent emission from the sample. In PL imaging the sample can be a brick prior to wafering, an as-cut or partially processed wafer or a fully processed solar cell (as shown). A power supply is used in electroluminescence imaging on finished solar cells and in combination with the light source in series resistance imaging techniques.

Figure 4.6.1.1

Bulk lifetime images obtained from a single doping density normalised PL image (upper) and from the PLIR (lower), see text for details.

Figure 4.6.1.2

Cross sections through the bulk lifetime images from Fig. 4.6.1.2, showing good agreement in the centre and artefacts near the bottom and top regions.

Figure 4.6.1.3
Very good quantitative agreement is observed between the two measurements in the central part, i.e. across the majority of the brick. This region is the section of the brick that is supposed to be used for wafer manufacturing (the very low lifetime top and bottom regions are supposed to be removed from the ingot).

4.6.1.3 Raw wafer inspection
Wafer quality in industrial manufacturing of silicon solar cells varies substantially and can have a strong impact on the efficiency of solar cells, particularly in the case of multicrystalline silicon. As-cut wafer inspection of incoming quality control (IQC) in solar cell production is therefore indispensable in order to maintain high efficiencies at high yield in production. To date IQC in production typically includes optical inspection for cracks and large chips, thickness and total thickness variation, surface morphology, resistivity measurements and in some cases \( \mu \)-PCD lifetime scanning. A problem with these techniques is that the electrical cell performance does not correlate sufficiently strongly with the data resulting from these measurements. One main reason is surface recombination dominating total recombination (and thus effective lifetime) in as-cut wafers. Only wafers with very low bulk lifetime (<10 \( \mu s \)) or specific areas exhibiting very low bulk lifetime show up sufficiently strongly in average or spatially resolved lifetime. While this complicates the analysis of spatially averaged lifetime values and makes correlation with final cell efficiency less reliable, particularly for wafers with overall high lifetime, it is beneficial since such areas are generally expected to also have the strongest impact on final cell efficiency. In other words, features that are visible with significant contrast in effective lifetime images are very recombination active and have bulk lifetime of only a few \( \mu s \) or below one \( \mu s \).

The dominant spatial features that are commonly observed in mc-Si as-cut wafers are dislocation networks, recombination active grain boundaries and impurity rich regions in edge/corner and top/bottom wafers. Figure 4.6.1.4 shows four typical examples, (a) a wafer from a center brick with low dislocation density, (b) a wafer from a center brick with high dislocation density, (c) a wafer from the impurity rich area at the bottom and (d) a wafer from a corner brick with low dislocation density [4.6.1.2]. All spatial features that appear dark in these images are indicative of highly recombination active regions within the wafers. Automated image processing methods allow determining wafer quality metrics that are related to the area fraction of those features and finally correlation with cell efficiency parameters such as \( I_{SC} \) and \( V_{OC} \) [4.6.1.1, 4.6.1.7, 4.6.1.13]. An example for such correlation is shown in Fig. 4.6.1.5, showing the correlation between the cell efficiency, \( V_{OC} \) and (given in relative numbers, normalised to unity) and the dislocation density as measured on the as cut wafers for a number of cells. A strong correlation is observed.

The observed correlation of these metrics with cell performance data, which will depend on the detailed processing conditions, can then be used for a range of actions, all aiming at higher yield, and higher average efficiency in production: (i) wafer rejection, (ii) wafer quality based pricing, (iii) wafer quality specific processing, or (iv) assignment of specific types of wafers to specially tuned production lines. Separating specific wafers for high efficiency processing lines such as a selective emitter line, which requires higher quality wafers to realise the full efficiency potential and may not be as robust against specific types of defects as the common screen printed process, is one specific example for that latter application.

The PL intensity emitted from as-cut silicon wafers is extremely low, a result of the strong dominance of surface recombination, resulting in luminescence quantum efficiencies on the order of \( 10^{-5} \) (i.e. one luminescence photon is emitted for 100 million incident photons). This low photoluminescence intensity is a result of the strong surface recombination activity.
of the luminescence that is emitted from that area. The filter passes effectively all (>99.9%) incident light from the illumination source. The filter is placed in close proximity to the sample with theoretical modelling. A 1-inch circular long pass filter is used to obtain the PL intensity variation, in combination with non-uniform illumination and obtain the emitter sheet resistance information from the PL images.

4.6.1.4 Emitter sheet resistance imaging

In solar cell production, the value of the emitter resistance typically needs to be maintained within tight specifications in order to avoid subsequent problems with contact formation such as shunting or high contact resistance. Previous work in the PL group focused on luminescence based emitter sheet resistance imaging measurements on fully processed metallised solar cells. In a new approach, the aim is to measure the emitter sheet resistance in a contactless fashion from PL images on non-metallised samples, which would allow application of that method immediately after the emitter diffusion in production. Since the emitter sheet resistance is not expected to exhibit lateral variations over short distances, a method with comparatively low spatial resolution is sufficient. Here we investigated the principle of using a PL image for a coarse measurement of the emitter sheet resistance, providing a single average data point for a large area.

The measurement principle is to take a PL image with non-uniform illumination and obtain the emitter sheet resistance information from the resulting PL intensity variation, in combination with theoretical modelling. A 1-inch circular long pass filter is placed in close proximity to the sample during the PL imaging measurement. The filter blocks effectively all (>99.9%) incident light from the area underneath the filter and transmits >98% of the luminescence that is emitted from that area. The luminescence from the non-illuminated area is generated by lateral flow of excess carriers from the illuminated into the non-illuminated parts of the wafer, in other words, electroluminescence is generated in a contactless fashion from that region, as reported previously elsewhere [4.6.1.14]. The illumination intensity and the emitter sheet resistance have a strong impact on the carrier redistribution via lateral carrier flows and thereby on the steady state excess carrier concentration, the latter reflected in the luminescence intensity. Combined with theoretical modelling this allows interpretation of the luminescence intensity distribution in terms of the emitter sheet resistance.

An example of a PL image taken on a diffused wafer with 60 \(\Omega/\text{sq}\) is shown in Figure 4.6.1.7. The circular filter is visible in the centre of the wafer. The luminescence signal from underneath the filter represents contactless electroluminescence as described above. Figure 4.6.1.8 shows three PL intensity profiles from the centre of the filter to the outside region taken on three different samples with emitter sheet resistivities ranging between 30 \(\Omega/\text{sq}\) and 100 \(\Omega/\text{sq}\). With increasing emitter resistance the PL intensity decays with a steeper slope towards the centre of the non-illuminated region, which is a result of the limited ability of the emitter to transport current laterally. An analytical model for that relative PL profile was developed and used to fit the measured data within the non-illuminated part of the image. Resulting emitter sheet resistance values were found to agree with eddy current measurements of the emitter sheet resistance.

The analytical model so far describes only the PL profile in the non-illuminated filter region. Further work will aim to extend that model to the illuminated part of the wafer, resulting in increased accuracy. The impact of the wafer background doping density on the measurement results is another topic for further work.

![BT Imaging W1 PL imaging system, with integrated automated image processing algorithms and a current throughput of up to 2400 wafers per hour with full one megapixel image resolution.](image1)

![PL image of a diffused silicon wafer taken with a 1-inch circular long pass filter located in close proximity to the wafer surface. The luminescence signal emitted from underneath the filter is caused by lateral current injection from the illuminated wafer area via the emitter.](image2)

![Cross section of the normalised PL intensity from the centre of the filter (x=0) to the outside region through PL images as shown in Fig 4.6.1.7 for different samples with variable emitter sheet resistance.](image3)
4.6.1.5 Luminescence based shunt imaging

Qualitative shunt detection from luminescence images has been demonstrated in the past by the UNSW PL group (amongst others) [4.6.1.15-4.6.1.17]. The vicinity of shunted areas typically appears as a blurred region of reduced luminescence intensity in both PL and EL images. This blurring is caused by voltage drops associated with lateral current flow through the emitter and the front surface grid.

A luminescence imaging based method for determining quantitative shunt values in silicon solar cells from open circuit photoluminescence images has been developed and demonstrated in collaboration with the Max Planck Institute for Microstructure Physics, Halle, Germany. The method is based on interpretation of the luminescence intensity around a local shunt in terms of the extracted current density [4.6.1.18]. Under the assumption of a unity ideality factor the local reduction in PL count rate in the vicinity of a shunt or local defect is proportional to the current being extracted. The theoretical framework for quantifying the total current extracted by a local defect by integrating the reduction of the PL signal in the surrounding of the shunt or defect and by applying suitable calibration procedures was developed.

Experimental verification of the method was achieved using a specifically prepared test structure, i.e. a solar cell structure with single point contact on the front surface. That structure allowed generating local shunts with variable and well defined external shunt resistance. Figure 4.6.9 shows two PL images of that structure with a high (left) and low (right) Ohmic resistor connected in parallel with that structure. Figure 4.6.1.10 shows the extracted current, as obtained from the above methodology as a function of the current flowing across the resistor, as measured with a multimeter. Excellent agreement is observed. Combining the above current measurement technique with an interpretation of the local luminescence signal in terms of the diode voltage near a shunt site allows quantification of individual local shunts.

Applications of this method to finished cells are affected by current extraction via the metal grid, which causes experimental errors. The impact of this effect was assessed experimentally using specific test structures, where the relative position with respect to the nearest grid finger of artificially introduced shunts could be varied. These experiments indicate that the above experimental errors in fully processed cells can at least partially be corrected using empirically determined look up tables.

When applied to partially processed cells prior to metallisation the method can be used to quantify local shunts, to determine the total recombination current in local and distributed defects and also to quantify recombination channels that are introduced by specific processing steps such as laser processing.

4.6.1.6 Summary

An exceptional variety of material and solar cell parameters can be measured on silicon bricks, silicon wafers and silicon solar cells with high lateral spatial resolution and short measurement time using luminescence imaging techniques. The range of applications continues to grow, with new applications for PL imaging being developed at UNSW, and increasingly also in other research institutes and by R&D groups in PV companies. PL imaging, introduced at UNSW only five years ago, has now been broadly adopted as a standard characterisation method, with PL tools now in use at virtually all leading research institutes worldwide and also by leading wafer and solar cell manufacturers. A range of opportunities for in-line quality control, process monitoring and process control are enabled by the high resolution and speed of PL imaging. Demonstration by UNSW spin-off company BT Imaging of those applications in beta trials at several company sites is currently in progress.
4.6.2 General Characterisation

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The range of research undertaken by the Centre involves a variety of measurement techniques for the characterisation of photovoltaic materials and devices. Understanding and utilising these techniques appropriately, and improving them where possible, is crucial in order to maintain the world-class reputation of our research output.

Improvements to measurement techniques with the goal of producing more accurate and meaningful results will have a direct impact both on research activities and on the optimization of procedures used in manufacturing. The time and number of experiments needed to understand a certain phenomena can be greatly reduced. The need to measure parameters of interest more precisely, without the possibility of misinterpretation, is therefore high. The General Characterisation group was formed in July 2010 to address this need.

The group primarily focuses on optical characterization methods such as photoluminescence spectroscopy and absorption spectroscopy. In recent years, it has been shown that these optical measurements can be used to extract a large number of material and device properties. In addition the ability to perform contactless non-destructive probing of small areas down to a few ten micrometers in diameter makes optical measurement techniques very attractive for samples that cannot be measured otherwise.

In addition, the group will review some commonly used measurement methods with the aim of automating parameter extraction from measurement data. It is common that less experienced researchers misinterpret data and draw incorrect conclusions. Computer programs that assist in various levels of interpretation therefore can prove their value. Some computer programs written in the course of this work will be made available for public use.

References


