COMPARING MDP, QSSPC AND PL IMAGING FOR THE PRODUCTION CONTROL OF HETEROJUNCTION SOLAR CELLS

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ABSTRACT: Minority carrier lifetime is a valuable parameter for quality control of the early production steps in solar cell manufacturing. It is particularly powerful for heterojunction technology as passivation of the amorphous silicon (aSi) layers is fully established directly after PECVD without further activation steps (as e.g. in the PERC process). This allows sensitive quality assessment especially if lifetime is measured injection-dependently and/or spatially resolved. Quasi-steady-state photoconductance (QSSPC), photoluminescence (PL) imaging and microwave-detected photoconductivity (MDP) are fast and contactless techniques that allow lifetime measurements inline. Each technique has its own strengths and weaknesses regarding carrier injection resolution, spatial information, quantitative accuracy, and signal understanding. At Fraunhofer ISE, each of the systems is installed in our inline wafer inspection system FWIS which allows direct comparison of the results for each wafer on a statistical scale. We present here such a comparison of QSSPC, PL and MDP on a set of 4000 silicon heterojunction precursors. We observe strong correlation between the three techniques, indicating good qualitative agreement of the measured lifetimes. Despite MDP being designed for measurement of differential lifetime over a steady-state bias injection level, even high-power MDP measurements without bias injection agree quantitatively with QSSPC measured at a carrier injection level of 10^{16} cm^{-3}, suggesting that this may be taken as the effective carrier injection density of the MDP tool for the given setup. By calibrating the instruments against each other, we are thus able to gain spatially and injection-resolved lifetime data for each individual wafer in a production environment.
Keywords: Microwave-detected photoconductivity, carrier lifetime, silicon heterojunction solar cells

1 INTRODUCTION

The global photovoltaic power installation capacity is growing by 174 GWp/a and accelerating by 48 GWp/a^2 (data from end of 2021). 95% of this is c-Si technology [1]. Silicon single-junction cell efficiency is approaching its theoretical limit [2], and to gain further incremental improvements, individual process steps during production need to be fine-tuned efficiently. Improving overall production efficiency by upscaling, as well as by reducing waste and machine downtime during repairs, can additionally increase cost efficiency.

To meet these requirements during cell manufacturing, automatic inline characterisation of cell precursors between production steps is highly beneficial. The data gathered enables tight feedback loops for optimisation of individual processes and early detection of faulty wafers.

For many of the process steps, a variety of important quality parameters can be tested with inline characterisation tools. To assess the quality of the junction formation and surface passivation steps, for example, minority carrier lifetime is one such parameter: It can be used to predict the final cell performance without the influence of the grid and contacts, by calculating the implied open-circuit voltage (V_{oc}).

Resolving lifetime measurements spatially across the wafer surface as well as for different injection levels provides detailed information about the previous processes. Values measured at multiple injection levels show the relative strengths of the various recombination mechanisms: at low levels, defect-enabled Shockley-Read-Hall recombination dominates, whereas at high levels the interaction between excited carriers increases, which causes Auger recombination to dominate [3]. Peak lifetime values usually occur in an intermediate range of injection levels, in which radiative recombination has a higher contribution.

Lifetime maps measured across the surface of each wafer with high spatial resolution further allow for differentiating between different sources of defects, such as impurities introduced through handling or spatial inhomogeneities of deposition and diffusion processes.

In this work, we compare different techniques for the inline lifetime measurement of silicon heterojunction (SHJ) solar cell precursors. The aim is to demonstrate the agreement between the measured data from the different techniques on a wafer-by-wafer basis. The combination of these techniques can therefore provide spatially and injection-resolved lifetime data for each wafer, suitable for rapid, robust, reliable and meaningful inline quality control.

2 BACKGROUND

In the quasi-steady-state photoconductance (QSSPC) method, established by Sinton et al. in 1996 [4], free carriers are excited by a flash lamp of decaying intensity. In steady-state mode, the decay time of the flash intensity is long compared to the carrier lifetime, while it is short in transient mode. The change of inductance caused by the density of excess carriers is measured via an inductively coupled coil and converted to lifetime with prior knowledge of the doping density. As the measurement runs continuously during the intensity decay of the lamp, lifetime values at different injection levels are recorded, the injection-dependent lifetime curve providing insight into the type of limitations and performance at different operating conditions. Our IL-800 QSSPC tool from Sinton Instruments takes one measurement at the centre of each wafer, and it has an integration area with a diameter of about 8 cm due to the size of the coil and the flash lamp. Thus, this technique provides an averaged lifetime without spatial resolution. It is, however, a well-understood and widely used technique for contactless lifetime measurement.

Photoluminescence (PL) imaging [5,6] is an equally well understood method, capable of capturing high-resolution images of the radiative recombination intensity in a semiconductor due to concurrent laser excitation. Our inline PL tool from Meyer Burger creates images from on-the-fly line scans. As the illumination occurs only locally via the line laser, lateral carrier diffusion prevents us from knowing the local injection level at the detection point precisely. Nor can the brightness of the PL image be directly translated into lifetime values, as it depends not only on the excess minority carrier density but also on the net background doping and the optical properties of each sample. Nevertheless, a calibrated lifetime map can be generated by scaling each PL image to the lifetime value measured by means of QSSPC [7–10] or MDP [11] across their respective integration regions on the same wafer.

Finally, microwave-detected photoconductivity (MDP) [11] uses laser diodes to excite the sample to steady-state conditions. During and after this pulse of light, the photoconductivity is measured via its effect on the reflectance of microwaves in a resonant cavity. The lifetime can be inferred from the transient decay of photoconductivity after the light has been switched off. Our MDP-Linescan tool from Freiberg Instruments has an integration area with a diameter of 1.1 mm, and it performs a single line scan down the middle of each wafer as it passes underneath on the fly. The MDP data therefore contain more spatial information than those from QSSPC, but less than PL images. As with QSSPC, carrier lifetime can be calculated directly; but unlike QSSPC, the value is computed over the entire slope of the photoconductance decay curve. As we discuss later in Section 4.1, this makes it difficult to determine an injection level directly.

In summary, QSSPC gives high injection resolution but low spatial resolution, PL imaging is the other way around, and MDP is intermediate in both categories. The combination of these tools, if calibrated well, could deliver comprehensive lifetime data for each wafer with high resolution both spatially and in terms of injection levels.

The conventional way to calibrate different instruments against each other is to use reference samples. In our case, these would have to be pristine, uniform solar cell precursors without any defects, be it from handling, process inhomogeneities or other sources. Such samples take great effort to produce and can easily be damaged, so relying on them can be expensive. Our approach relies instead on comparing a large enough population of production samples to gain a representative statistical distribution of values for each instrument. The correlation of these distributions can then be used to see, in the first instance, whether two instruments are actually measuring the same physical property, and if so, to then calibrate one instrument against the other.

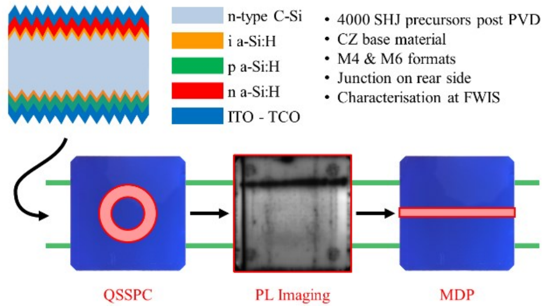


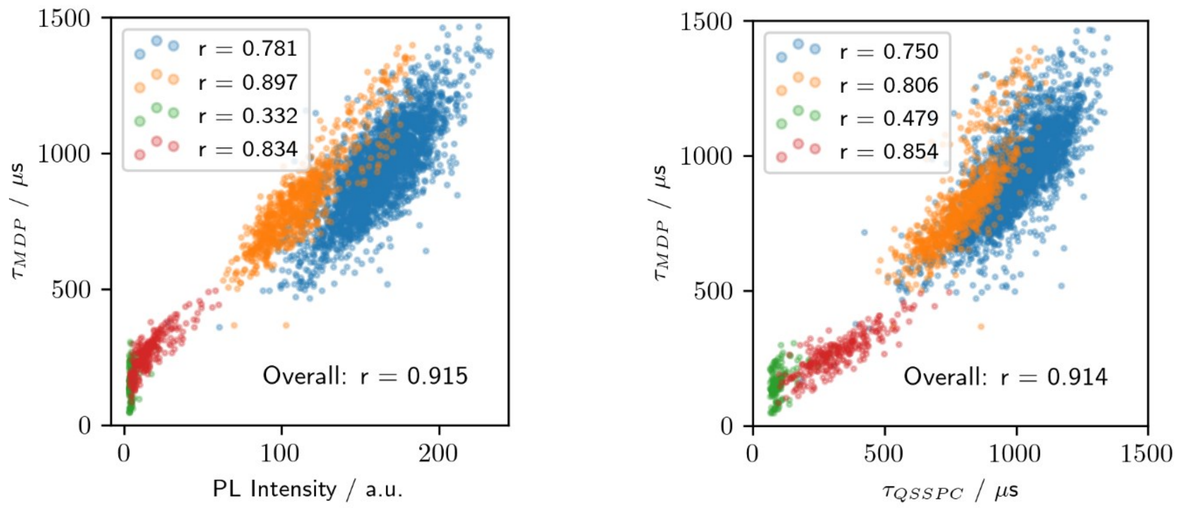
Figure 1: Layer stack of the textured SHJ precursors and process flow of the inline lifetime measurements. Wafers are placed onto the conveyor belt and automatically measured using QSSPC, PL imaging and MDP tools. The integration areas of the individual techniques are highlighted red in the sketch.

3 EXPERIMENTAL

Figure 1 shows the process flow of the inline lifetime measurements performed at our frontend wafer inspection system (FWIS) at Fraunhofer ISE; this system allows us to characterise solar cell precursors inline as it could be implemented in production. To gain the statistical data for this work, 4164 textured SHJ precursors were loaded onto the conveyor belt and passed by the various contactless characterisation tools. The stop-and-go motion of the belt facilitates both on-the-fly scanning and stationary measurements, depending on the requirements of each instrument.

Three of the instruments installed in the FWIS can be used for lifetime measurements: (i) the Sinton IL-800 QSSPC tool, (ii) the Meyer-Burger PL imaging tool, and (iii) the MDPlinescan tool from Freiberg Instruments. The first operates in stationary mode, while the latter two record their data on the fly. The data from each tool are initially collected by the respective control computer and then passed on to a central machine, where they are consolidated and processed. The areas of data acquisition are indicated in Figure 1 by the red outlines.

For the statistical comparison of the three methods of lifetime measurement, a representative lifetime value was calculated for each wafer and each method. Geometrical consistency was achieved by averaging sections of the PL image that corresponded to the integration area of each of the other two tools when comparing with them (an annulus for QSSPC and a strip for MDP).



(a) (b)

Figure 2: MDP lifetime (averaged over the full trace) plotted against (a) mean PL intensity and (b) QSSPC lifetime at $1 \times 10^{16} cm^{-3}$ carrier density. The different coloured clusters correspond to the same groups as in Figure 3.

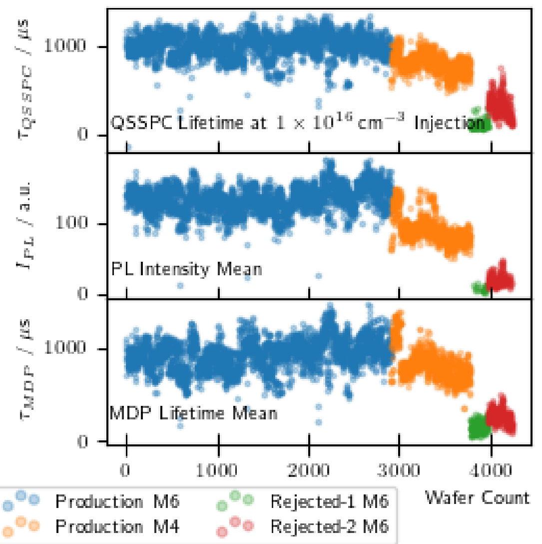


Figure 3: QSSPC (top), PL (middle) and MDP (bottom) data averaged for each wafer and plotted chronologically for 4164 SHJ precursors. Groups from different production batches are colour-coded.

4 RESULTS AND CONCLUSIONS

Figure 3 shows average values for the three lifetime tools plotted as a function of wafer count. The top subplot shows QSSPC lifetime in the central region at an injection level of $1 \times 10^{16} cm^{-3}$. The middle subplot shows PL image intensity averaged over the full surface of each wafer. The bottom subplot shows lifetime measured by MDP.

The wafers are sorted in no particular order. However, four groups of wafers can be distinguished by the different colours in the plot. The blue and orange groups were production-quality precursors of M6 and M4 sizes, respectively. The green and red groups were wafers from two different batches, rejected from the production line due to their low performance in previous inline characterisation.

It is already visible that all three datasets correlate well with each other, and that the QSSPC and MDP values are even in good absolute agreement. Further details can be seen by plotting the lifetimes against each other, as has been done in Figure 2. Here, we see that the different groups form distinguishable clusters, but that the correlations between MDP lifetime (on each y-axis) and the other two methods (on each x-axis) are generally good for groups with significant spread in both parameters, and excellent ($r > 0.9$) overall.

4.1 Injection levels

The level of excess carrier injection influences the measured lifetime substantially. QSSPC lifetime data for the best wafers range from 1 ms at $1 \times 10^{14} cm^{-3}$ and at $1 \times 10^{16} cm^{-3}$ to over 3 ms at $1 \times 10^{15} cm^{-3}$.

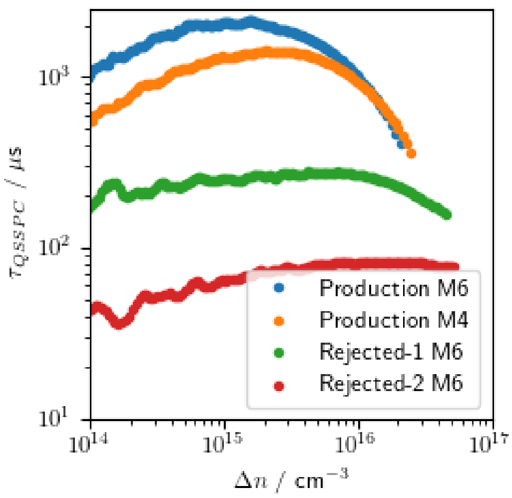


Figure 4: QSSPC lifetime vs. minority carrier injection level for the different production batches.

This can be seen in the plotted QSSPC lifetimes versus injection level for representative wafers from each production batch in Figure 4. Note that the strong oscillations at low Δn are artifacts of data processing and do not represent actual trends. Note also that the positions of positive and negative slope shift between wafers of different quality: at $\Delta n = 5 \times 10^{15} cm^{-3}$ the red and green curves are still rising while the orange and blue curves are falling.

Resolving the injection level of QSSPC measurements is possible because data are collected continuously during the brightness decay of the excitation lamp, and the gradient at each point of the decay curve can be determined to yield a separate lifetime value.

MDP, on the other hand, is designed as a differential method of lifetime measurement: A steady-state homogeneous injection level is to be set by a bias light, and the laser adds a perturbance to the carrier density. As long as this perturbance is small, the decay curve is linear in the semi-logarithmic plot, and so a fit over the entire range can yield accurate results. Even so, the so-obtained differential lifetimes would actually need to be integrated over all bias light intensity levels to calculate true absolute lifetimes.

Bias light series were not implemented in our inline MDP setup at the time of this experiment. Instead, a stronger laser pulse was used to enable noise-free measurement. However, this introduced a significant uncertainty in the lifetime and injection level as calculated from the entire decay slope for two reasons: Firstly due to the strong and wafer-specific injection dependence of lifetime; and secondly due to significant diffusion of carriers away from the excitation spot during the measurement, which effectively dampens the injection density as a function of time since the start of the transient.

We can estimate an upper limit on the steady-state injection level from the known power (500 mW), wavelength (925 nm) and spot size (1.1 mm) of the laser excitation; this gives us a value of $2.5 \times 10^{19} cm^{-3}$. However, in our current setup this is serves only as a rough guide.

Bias light series and integration of differential lifetimes will solve this problem and are currently in development, to be published in future works. In absence of this, our statistical survey can be used for a practical and empirical relation of MDP lifetime to injection level by plotting the MDP lifetime against the QSSPC lifetime at different injection levels, as has been done in Figure 5. The red, orange and yellow datasets correspond to injection levels of $1 \times 10^{15} cm^{-3}$, $5 \times 10^{15} cm^{-3}$, and $1 \times 10^{16} cm^{-3}$, respectively. As we can see, not only is the correlation best for $10^{16} cm^{-3}$, the datapoints also line up well with the 1:1 line, indicating good absolute correspondence of the values. This suggests that $10^{16} cm^{-3}$ may be treated as the effective injection level at which the lifetime is measured with MDP.

4.2 Region of interest selection

A PL image contains a brightness value of radiative recombination for each pixel, which corresponds to a resolution of about 150 µm on the sample. The MDP tool records a line scan down the centre of the wafer, with a resolution of about 1 cm. In order to compare these methods with each other, the different measurement locations must be considered.

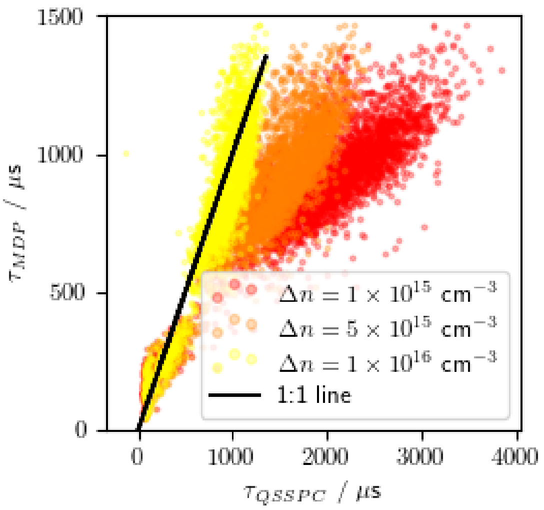


Figure 5: MDP lifetime plotted against QSSPC lifetime at different injection levels. The line of 1:1 proportionality is shown in black.

Figure 6 shows MDP lifetime averages plotted against different types of PL intensity averages. In the purple and red groups, the arithmetic mean *A* was computed over the whole wafer and a stripe corresponding to the MDP detection area, respectively. The correlation is better for the stripe subset ($r = 0.915$ vs 0.835), indicating on the one hand that matching the integration areas allows for a more precise comparison between tools. On the other hand, it shows that this narrow stripe is generally not a representative sample of the lifetime inhomogeneities across each wafer. This means that despite sampling a whole cross-section of the wafer surface, MDPlinescan is no replacement for PL imaging in terms of spatial resolution.

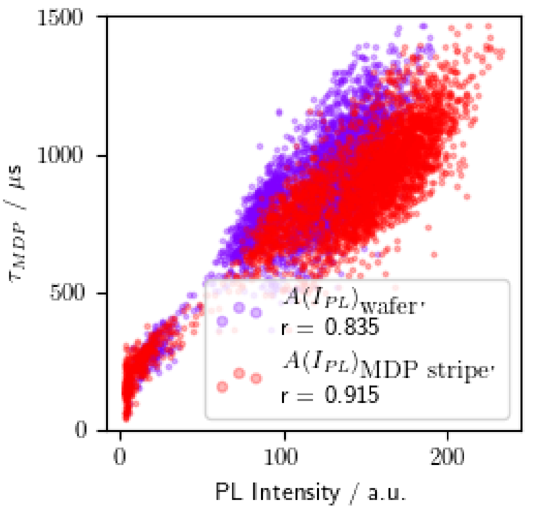


Figure 6: MDP lifetime plotted against different averagings of the PL intensity images. The blue and orange clouds, respectively, show the arithmetic mean A of each whole wafer, and a stripe matching the integration area of the MDP linescan.

4.3 Calibration of PL images

Our standard and most accurate method for converting PL images into lifetime maps is by calibrating the pixel values of each image against the QSSPC lifetime measured for that wafer. Being able to calibrate each wafer individually is one of the benefits of having both measurement devices installed as inline tools in the production line.

However, if space or budget allows for only one tool for lifetime measurement to be installed inline, lifetime maps can still be generated with acceptable accuracy using an inline PL and calibrating it via other methods.

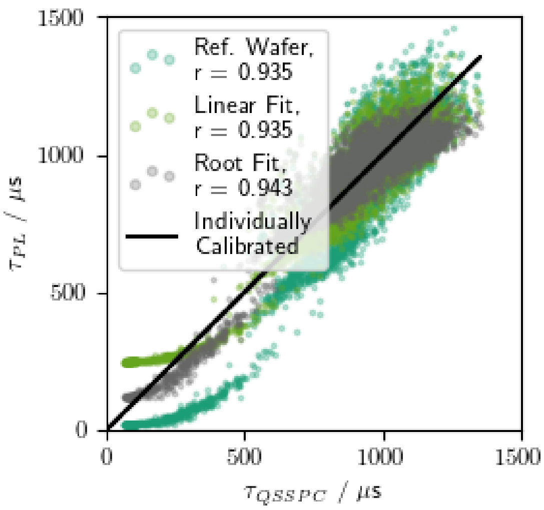


Figure 7: PL lifetime calculated via different methods of calibration against QSSPC.

Figure 7 shows mean PL lifetimes calibrated by different methods against the corresponding QSSPC lifetimes. The black line indicates the calibration against QSSPC for each individual wafer. By definition, this is the identity relation.

The blue-green dots arose from calibration against the QSSPC lifetime of a single reference wafer, picked from the centre of the correlation cloud of mean PL values versus QSSPC lifetime. With this simple method, a single representative wafer can be measured by offline QSSPC to generate a constant scaling factor for all PL measurements.

The olive-green dots show a two-parameter calibration using an affine linear fit ($\tau(I_{PL}) = A + B \cdot I_{PL}$) of the mapping of QSSPC lifetime to mean PL intensity. Although the correlation coefficients are the same, clearly this calibration yields more accurate mean PL lifetimes than the single-wafer calibration (blue dots), as it accounts for differences in signal offset from stray light or other sources. This method could be used in production if there is capacity to measure QSSPC not just on a single wafer but on a larger selection.

An even better match with the individual QSSPC values is achieved by fitting a square root function ($\tau(I_{PL}) = A + B \cdot \sqrt{I_{PL} - C}$) (grey dots). This is expected from the theoretical τ^2-dependence of PL intensity over large ranges of τ.

4.4 Conclusion

In conclusion, we have demonstrated that QSSPC, MDP and PL imaging are compatible methods for inline measurements of minority charge carrier lifetimes in silicon solar cell precursors. Their data, averaged over corresponding areas of each sample, correlate well with each other over a wide range of lifetime values. QSSPC directly offers absolute lifetime values with a high injection level resolution. However, it provides little spatial information. MDP, designed for measuring differential lifetime over a series of bias light intensities, can nevertheless provide a value that corresponds fairly well to absolute lifetime even from a single measurement with a powerful laser excitation, without using the bias light. We were able to show that an effective injection level may be inferred for the MDP measurements from the statistical correlation with QSSPC measurements, with a value of $10^{16} cm^{-3}$ in the case of our MDP setup. Compared to QSSPC, the MDP line scan provides more detailed spatial information.

When comparing methods of different integration geometries, we show that comparing only matching areal subsets of the data yields more precise results. PL imaging by itself yields high-resolution maps of relative carrier lifetime; the excellent correlation of mean PL intensity with QSSPC lifetime justifies calibration of PL images against QSSPC, which can yield highly resolved *absolute* lifetime maps. [7]

Finally, we demonstrated that although measuring each wafer with a reference method such as QSSPC yields the most accurate calibration of PL images, more cost-effective methods offer acceptable results as well: in order of accuracy, one may apply (a) a scale factor, (b) a linear function or (c) a square-root function to PL values. These require only (a) one typical reference wafer or (b,c) a selection of reference wafers to be measured by QSSPC.

In future work we intend to establish inline MDP bias light series in order to measure differential lifetime with accurate and precise knowledge of the corresponding injection level. Injection series of absolute lifetime may then be determined by integration and compared directly with those of QSSPC.

Furthermore, we aim to extend the statistical comparison to measurements of the finished solar cell parameters. This will help us to quantify the predictive power of precursor lifetime measurements by the different methods.

Acknowledgments: This work was funded by the German Federal Ministry for Economic Affairs and Climate Action within the project SALSA under contract number 03EE1096A.

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