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Fast, high resolution, inline contactless electrical semiconductor characterization for photovoltaic applications by MDP

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Abstract

The state-of-the art lifetime measurement technique MDP (microwave detected photoconductivity) is presented with its latest developments in sensitivity, measurement speed and data simulation. Several applications and examples in the field of inline material characterization, defect recognition and real time statistical process control in silicon bricks and wafers are presented, demonstrating the practical use of MDP measurements and of the data obtained by it. The measured lifetime itself combined with its spatial distribution and the measured steady state photoconductivity enable a good correlation to the cell efficiency. Furthermore, the paper presents a detailed summary of the properties of steady state and non-steady state microwave based minority carrier lifetime measurement techniques to complete this extensive study.

Keywords: lifetime, silicon, contactless characterization, photoconductivity, SPC - statistical process control, photovoltaic

1. Introduction

In addition to processing techniques, the properties of electronic devices, such as solar cells, strongly depend on the inherent electrical properties of the material. For example, the simple diode equation for a solar cell requires electrical properties such as the minority carrier lifetime as starting parameters. Good correlations between the open circuit voltage and short circuit current with the minority carrier lifetime of solar cells were demonstrated experimentally in a variety of approaches [1]. It is obvious that measurements of the carrier lifetime are most useful if they are performed as early as possible in the production chain, starting with mono-crystalline or multi-crystalline bricks and not passivated wafers.

An important factor is the measurement strategy for the carrier lifetime. For inline applications, these measurements must be contactless with high speed and high spatial resolution. Furthermore, the lifetime data must quantitatively reflect the bulk recombination lifetime, to represent the material quality and not only the surface quality.

Among the different measurement strategies for the minority carrier lifetime, microwave detected photoconductivity (MDP) meets all requirements. It uses a steady state measurement regime, but avoids the resolution problems inherent in other steady state measurement techniques. It is much less influenced by surface recombination than, e.g., µPCD (microwave detected photoconductive decay) [2, 3]. In contrast to from photoluminescence techniques, MDP data are inherently quantitative.

In this paper, high resolution lifetime maps together with contactless resistivity measurements of bricks are presented, which were obtained in less than a minute for each brick side. Examples of the information that can be gained by these measurements are given, such as the precise automatic cutting criteria or the over compensated n-type areas in the brick. The data provide instantaneous information for statistical process control and the optimization of processing steps, such as furnace operation.

MDP wafer measurement tools provide full wafer maps on as grown multi-crystalline wafers with a resolution of better than two millimeters in less than one second, which was presented in a previous paper [4]. This technique is particularly useful for standard process control and the prediction of expected cell efficiencies. Surface recombination is a major concern when performing lifetime measurements on wafers [5]. However, in this paper, the prediction of cell efficiencies based on lifetime values in combination with an evaluation of the spatial lifetime distribution is presented.

2. Methods

The standard materials under investigation are multi- and mono-crystalline silicon bricks and unpassivated wafers for photovoltaic production with resistivities of 0.5 to 3 Ωcm.

The MDP method applied here measures the photoconductivity during and after a rectangular laser pulse by microwave (9-10 GHz) absorption via a resonant microwave cavity [6]. The sample is located just outside the microwave cavity and its complex dielectric constant influences the resonant frequency and the loss properties of the cavity. This setup yields a superior detection sensitivity compared to conventional setups. The high sensitivity enables injection dependent measurements over 8 orders of magnitude, e.g., in low injection to investigate trapping [7]. Furthermore, very thin layers (<10 µm) or metalized solar cells can also be measured [8]. Another consequence is that a very high measurement speed is possible because it is not necessary to average over many measurements to gain a good signal to noise ratio. Using more than one laser and cavity additionally increases the measurement speed.

Carrier excitation is performed by laser diodes at 980 nm with a photon energy slightly exceeding the band gap of silicon. The laser pulse duration can be varied from 0.2 µs to several milliseconds. For example, for brick measurements, long excitation pulses are applied to obtain a large influence from the bulk. If information about the surface is wanted, short pulses can be applied. Such short pulses cause a high carrier concentration close to the surface, which results in a strong influence of surface recombination [2]. However, the goal is generally to obtain a successful correlation between the measured lifetime values for the material in an early production step and the properties of the final product, e.g., the cell efficiency. This correlation strictly implies that the lifetime should be measured under the conditions of the final product under normal operation. For solar cells, the lifetime should be measured under the steady state conditions as created by the sun in the solar cell. Hence, a laser pulse of moderate intensity is applied for a sufficiently long time to allow the sample to reach a steady state. After switching off the light, the photoconductivity immediately exhibits the characteristic lifetime transient (Fig 1.a).

Another well-known approach is the µPCD technique, where the photoconductivity as initiated by a very high intensity laser pulse (13-16 W) of typically 200 ns is detected via microwave reflection measurements. This detection method usually causes relatively high microwave signals, which are easily detected. However, the laser pulse causes a condition in the sample that is far from steady state. Hence, the data are obscured by carrier diffusion, trap filling, carrier mobility effects, and recombination effects at various carrier concentrations. All of these effects together give rise to the surprising effect that the signal still increases after the light is switch off, as shown in Fig. 1.b.

A further widely used method is the quasi steady state photoconductivity (QSSPC). This method is especially suited for injection dependent measurements and brick measurements because, it has a much higher penetration depth than the two methods mentioned above. However, the QSSPC method is limited by resolution due to the excitation by a flash lamp, which is a considerable drawback, especially for multi-crystalline and mono-like silicon characterization.

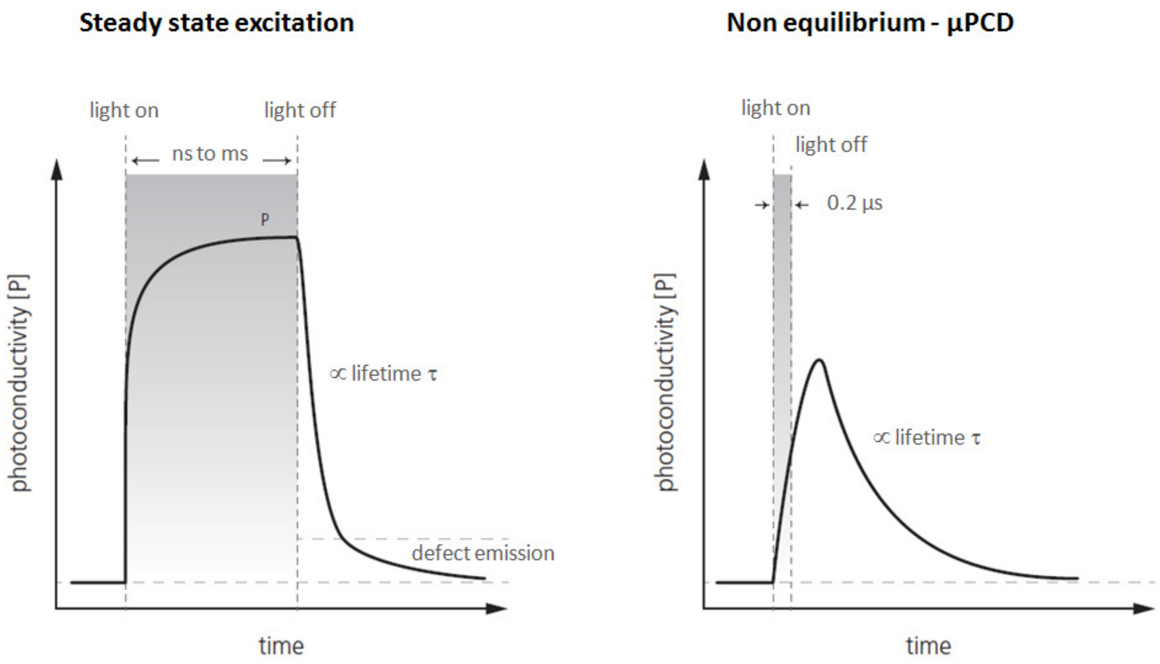

Fig. 1. Comparison of a typical steady state (MDP) and non-equilibrium (µPCD) measurement signal

A completely different approach is used in photoluminescence methods. Instead of measuring the photoconductivity as in the methods mentioned before, the photoluminescence intensity is measured. The key advantage of the optical methods is the high spatial resolution combined with a high measurement speed. Many attempts were made to observe correlations between the carrier lifetime values as obtained by electrical characterization and photoluminescence imaging techniques [9-12]. However, for silicon as an indirect semiconductor, luminescence is a second order effect. The optical lifetime results depend on the doping and sample thickness. A calibration of the data by electrical methods such as QSSPC, µPCD or MDP [13] is necessary. However, for this calibration a single spot on the sample or even an average over a larger area are not really sufficient. The influence of material inhomogeneities such as doping variation, different defect and recombination center concentrations and differences between grains and grain boundaries in multi- or mono-crystalline silicon is significant. One must be very careful when taking luminescence data as a quantitative measure for the recombination lifetime of the excess carrier concentration in the conduction band. For a reliable calibration an entire lifetime map obtained by microwave-based techniques is necessary [14].

In table 1, the most important properties of the different lifetime measurement approaches are summarized and compared.

Tab. 1. Comparison of the most important properties of different lifetime measurement strategies.

	MDP	**µPCD**	**QSSPC**	**PL**
dynamics	steady state	non-equilibrium	quasi steady state	steady state
excitation	laser pulse	laser pulse	flash	LED
	0.2 µs to > 1 s	0.2 µs		
measured value	τ_{eff} (bulk dominated)	τ_{eff} (surface dominated)	photoconductivity	luminescence
	photoconductivity			intensity
resolution	< 100 µm	< 100 µm	area: 6 x 30 mm^2	CCD resolution
	depending on diffusion	depending on diffusion		
	length	length		
speed				
wafer map	high	slow	-	high
brick map	high	slow	medium	high

For the production of semiconductor crystals, the control of segregation effects is a major concern and calls for reliable resistivity measurements as an integral part of the MDP equipment with no degradation of the overall system performance, in particular, the measurement speed. Eddy current-based sensors are used. However, with these sensors the measured effect strongly depends on the distance from the sensor to the sample surface, in particular, the brick surface. Any mechanical contact of the sensor with the surface is unacceptable. Therefore, the eddy sensor comprises a high precision distance sensor as an integral part, and the system uses a combined distance and resistivity calibration matrix. This technique altogether results in an excellent maintenance free, long term stability of the system. The typical repeatability is better than 3% without recalibration for three years. As a by-product, the system provides a precise geometrical map of the object under investigation, which allows for an automatic check of the mechanical integrity of the brick, for example.

3. Theory and calculation

The high level development of measurement tools and the correct interpretation of the measurement results require a detailed understanding and a quantitative calculation facility for any measurement strategy under all conditions of interest. For this purpose, a system of generalized rate equations was established, which starts from first principles and uses almost no approximations. It was presented in detail in [15].

The generalized rate equation system accounts for the influence of an unlimited number of decoupled defect levels, which overcome the limitations of the Shockley Read Hall (SRH) approaches [16-18]. With this simulation tool, the time dependent change of the conduction and valence band occupation ($\dot{n}, \dot{p}$) as well as the occupation of defect levels ($\dot{n}_{Tj}$) can be modeled. All allowed transitions between defect levels in the forbidden gap and the bands of a semiconductor are described by transition rates without any approximation. Only some basic values, which characterize the semiconductor and the electrical properties of the defects therein, are needed as input parameters, e.g., the band gap energy, the effective density of states for the conduction and valence bands, and the mobility of the carriers. Each defect level, including donors and acceptors to simulate doping density, is characterized by its density, its energy position within the bandgap, its capture cross sections for electrons and holes, and its charge state [19].

First, the thermal equilibrium occupation of the bands and every defect level are computed, yielding the Fermi level and the conductivity. In a second step, the time dependence of all of these parameters upon a light induced perturbation of the system (e.g., a laser pulse) is calculated. Based on the simulated time dependent carrier concentrations, the photoconductivity can be calculated using the mobility model of Dorkel and Leturcq [20]. Hence, with these simulations, the measurement results as obtained by MDP, µPCD or QSSPC can be considered quantitatively and compared to each other precisely, particularly with respect to their practical usefulness [15].

In previous papers, this simulation tool has already been applied to investigate the influence of trap levels on the accuracy of different lifetime measurement methods and on the analysis algorithms, which are used to determine the lifetime from the measurement data [21], and the influence of trap levels on the accuracy of iron density measurements by lifetime measurements [22].

Additionally, transport equations have been used to simulate the developing carrier profiles in thick samples to investigate the bulk and surface influence on different lifetime measuring methods.

Second order effects, such as photoluminescence, are not included in the theory, which would require detailed knowledge of the wave functions of the defects and a well-established theory to calculate the optical transitions between defects including all phonon effects. This is, however, far beyond the scope of the theoretical approaches above.

4. Results

Several applications and examples in the field of inline material characterization, defect recognition and real time statistical process control in silicon bricks and wafers are presented below

The first examples of the usefulness of fast, inline MDP measurements are demonstrated by brick measurements. The comparison between the lifetime results of µPCD and MDP on bricks show a huge difference, especially in the good quality part of the bricks (Fig. 3.a). These differences can be explained by simulating the carrier profiles developing in the sample during a µPCD or MDP measurement.

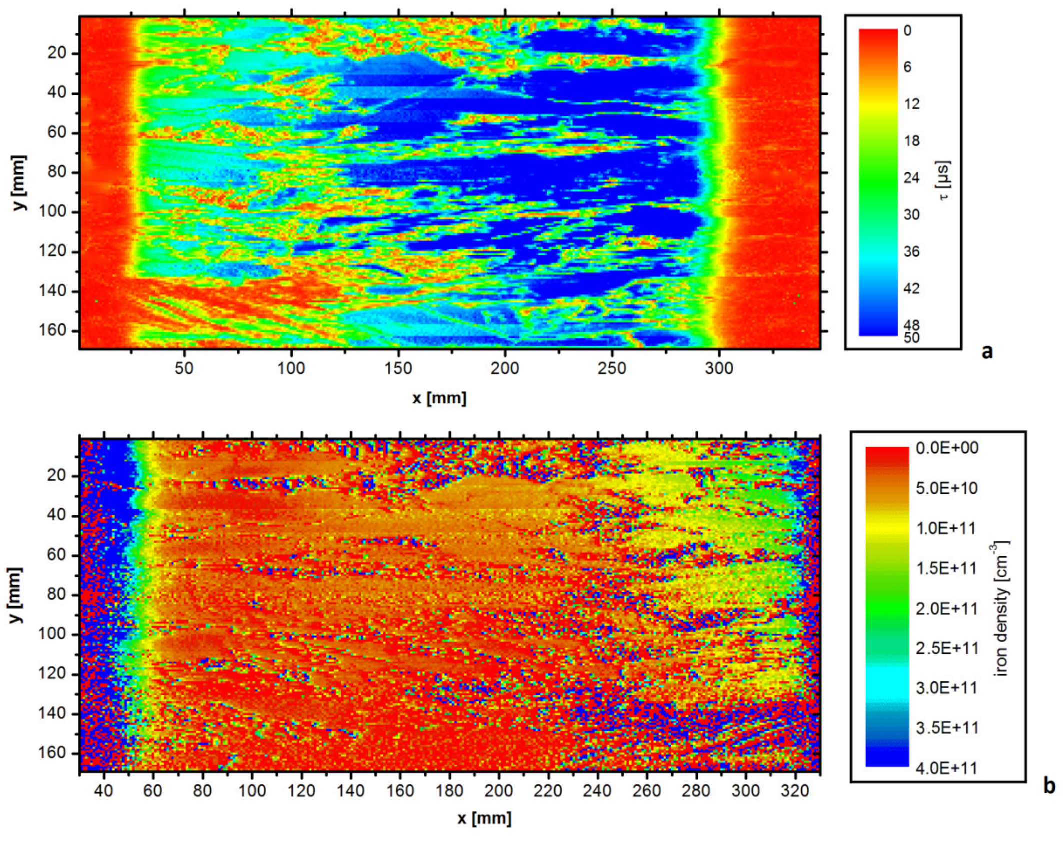

Fig. 2: (a) exemplary lifetime and (b) iron density map of a brick, measured within less than 2 min

The calculated depth profile of the charge carriers clearly shows the surface recombination limitations on the effective lifetime by non-steady state µPCD measurements with a 0.2 µs laser excitation pulse [2]. Such limitations are not present for steady state measurements with MDP or QSSPC. These methods result in a deep carrier profile with the consequence that the main recombination is dominated by the bulk. A direct consequence of this higher bulk influence is that iron measurements on bricks are enabled [23]. The effect of iron on the measured lifetime is also clear in the lifetime linescan shown here (Fig. 3.a). The lifetime decay towards the top of the mc-silicon bricks is typical for iron because, it segregates strongly at the top of the brick. A map of the iron content can be obtained with a resolution of 1 mm within less than two minutes for a 156x156x500 mm brick. No special surface treatment of the brick is required. This method is already used in inline applications in state-of-the-art production applications to characterize each individual brick. An exemplary lifetime and iron density map of a brick, which were measured inline, are presented in figure 2. A typical measurement time for one brick surface is less than 20 seconds, which enables the collection of very many reliable data within short timescales, which is a prerequisite for modern statistical process control. These measurement possibilities are crucial for, e.g., the optimization of furnaces and crystallization processes, and they are important for establishing a realistic prediction of the final solar cell efficiencies on the basis of material bulk lifetimes.

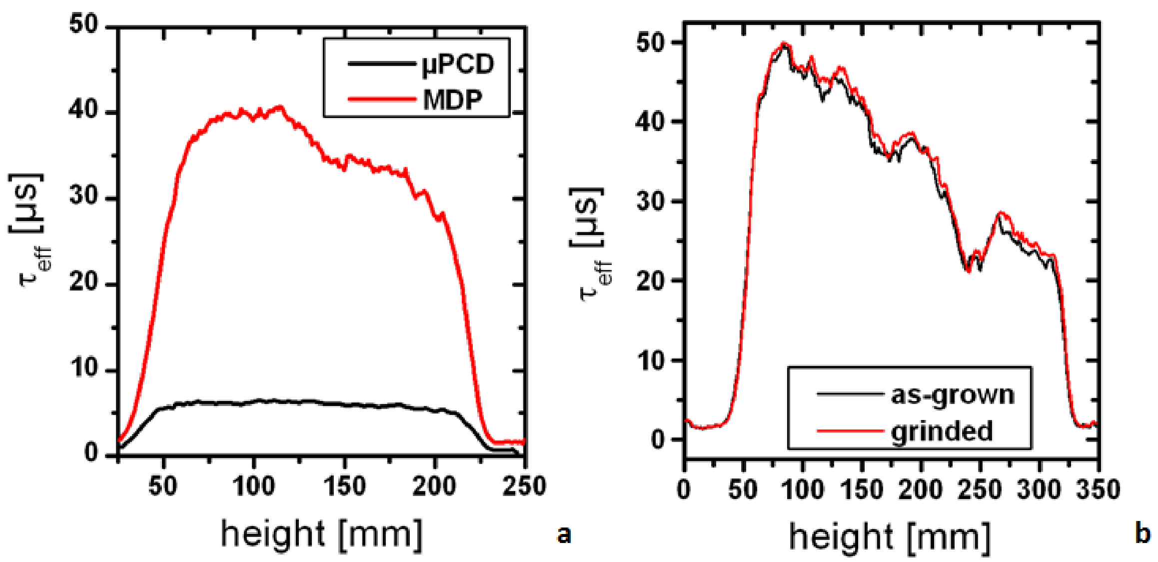

Fig. 3. (a) steady state MDP linescan in comparison to non equilibrium µPCD linescan on the same brick. (b) comparison of MDP steady state measurement before and after the grinding of the brick surface.

To demonstrate this effect with MDP measurements, internal structures well below the brick surface are resolved. Fig. 3.b. shows a comparison of a MDP lifetime measurement on a typical mc-Si brick before and after its surface was ground. It exhibits almost no effect of the surface treatment within experimental error.

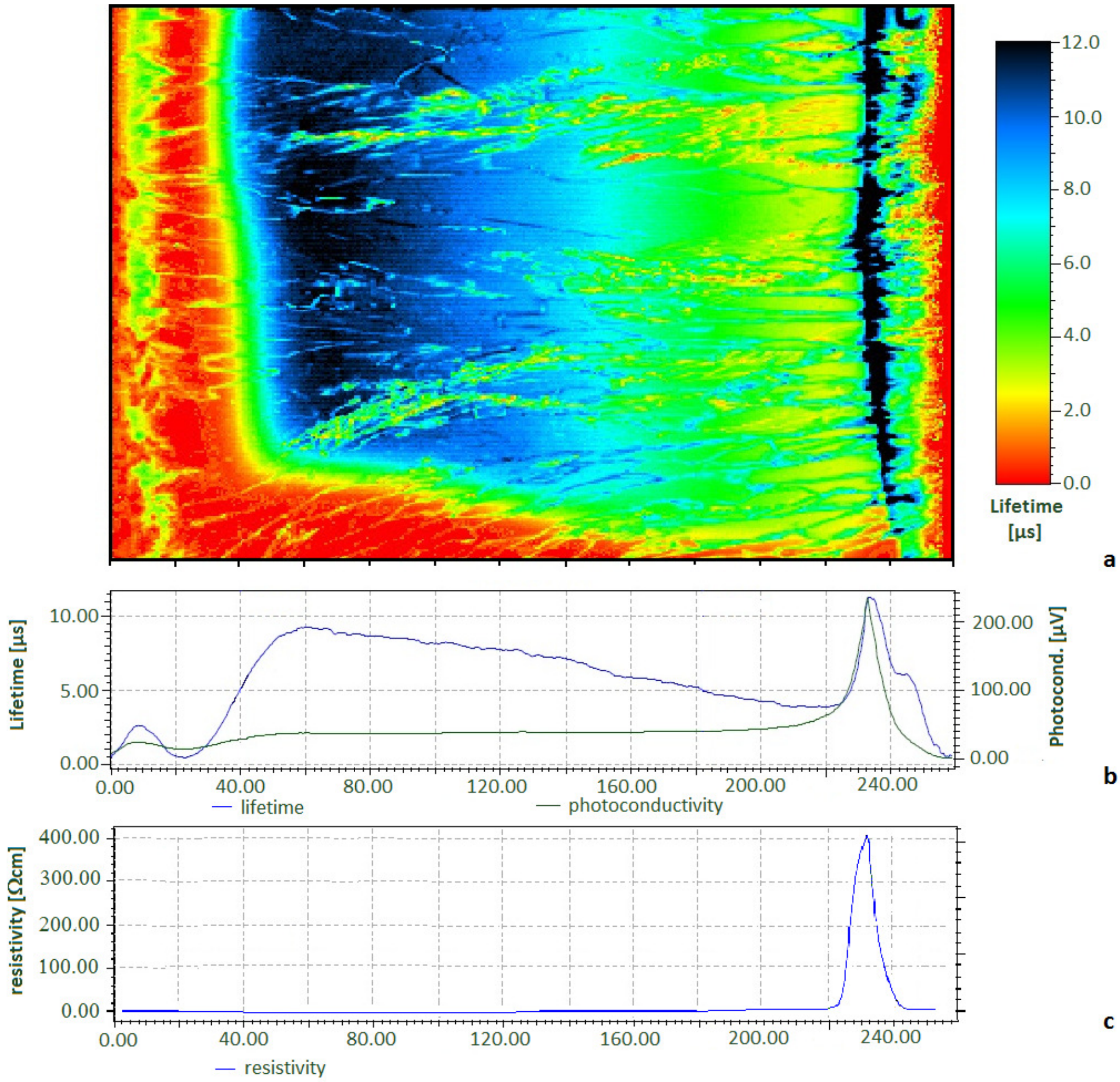

Fig. 4. (a) MDP lifetime map of a mc brick at 1mm resolution; the measurement time is 20 s within a normal production environment. (b) typical photoconductivity and minority carrier lifetime scans along the height of the brick. (c) resistivity linescan with a strong rise in the compensated region

Another example for a standard application of the measurement possibilities discussed above is the characterization of mc-silicon bricks for photovoltaic applications, which exhibit a change in the conduction type due to a high phosphor concentration in the top. Fig. 4.a presents a typical minority carrier lifetime map of a mc-silicon brick. Additionally, a resistivity, lifetime and photoconductivity linescan is shown. In the linescans, the strong increase in resistivity and, as a consequence, in lifetime and photoconductivity becomes obvious due to the highly compensated material in the region where the conduction type changes from p to n. Such a change can be automatically detected with an accuracy of 1 mm by applying a clever computer algorithm to the measurement results [24].

One advantage of steady state measurement regimes, such as MDP that was already implied above is that the minority carrier lifetime and additionally the photoconductivity are measured simultaneously. The steady state photoconductivity $\Delta\sigma$ correlates to mobility μ and the lifetime itself and, hence, to the square of the diffusion length.

$$\Delta\sigma = eG_{opt}\tau\left(\mu_n + \mu_p\right) \tag{1}$$

$$L_{n/p} \propto \sqrt{\tau\mu_{n/p}} \tag{2}$$

Thus, one also obtains also information on the mobility and the diffusion length of the excess carriers, which is otherwise hard to obtain. This information can be used, e.g., to find and to locate compensated areas in a brick, as shown in Fig. 4.b and for correlations with cell efficiency.

Fast MDP lifetime measurements with 1 mm resolution on wafers are no longer a problem, as demonstrated in [4]. However, the interpretation of the data is not as straightforward as for bricks due to the surface recombination effects. Despite these limitations, a correlation of the lifetime data with the cell efficiency is still possible with MDP. It is, however, essential that lifetime maps with sufficient resolution are available, which allow a statistical evaluation of spatial lifetime distribution patterns for each wafer. Using the measured lifetime together with a newly developed inhomogeneity parameter allows the wafers that will yield in solar cells with low efficiency to be sorted. In other words, it becomes possible to classify the material of the as-grown wafers.

Fig. 5 indicates the results obtained for standard as grown 180 µm mc-silicon wafers. Maps with up to 10000 pixels were taken at a measurement speed of less than one second per wafer. For statistical evaluation purposes, at least 500 wafer maps should be included, which would take less than 10 minutes of total time in a state-of-the-art production plant. According to Fig. 5, it is evident that the lifetime values alone do not have the potential for a satisfactory cell efficiency prediction. However, the inhomogeneity information alone is not useful either, but with the combination of these two parameters, a wafer classification becomes possible.

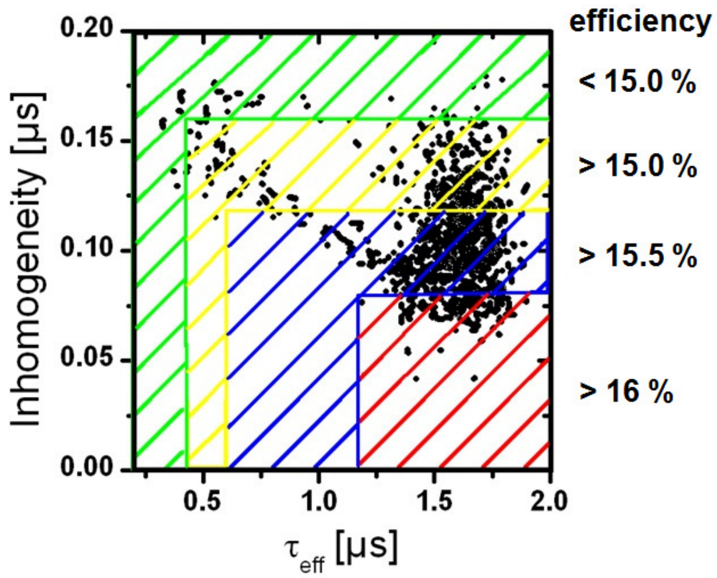

Fig. 5. Cell efficiency for as-grown mc silicon wafers as a function of MDP lifetime and lifetime distribution (inhomogeneity).

5. Conclusions

Microwave detected photoconductivity (MDP) as a state-of-the-art technique with a unique sensitivity and measurement speed is most suitable for high performance material quality evaluation in production environments and for research purposes. In production environments, the most stringent criteria for the value of a lifetime measurement technique are the practical usefulness of the data obtained, the measurement speed, and the cost effectiveness. In the meantime, there is much evidence that MDP as a steady state measurement strategy in combination with high level electronics includes or exceeds the benefits of other existing lifetime measurement strategies. In addition, camera-based techniques are no longer a valuable alternative. The main advantage of MDP is the combination of measurement speed and resolution together with the advanced analysis and interpretation of the data that makes a true correlation with the quality of the final product (cell efficiency) possible.

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