NEW SPATIAL RESOLVED INLINE METROLOGY ON MULTICRYSTALLINE SILICON FOR PV

K. Dornich[1], N. Schüler[1], D. Mittelstraß[1], A. Krause[3], B. Gründig-Wendrock[3], K. Niemietz[2] and J.R. Niklas[1]
[1]Freiberg Instruments GmbH, Am St. Niclas Schacht 13, 09599 Freiberg, Germany Sachsen
[2]TU Bergakademie Freiberg, Institut für Experimentelle Physik, Leipziger Str. 23, 09599 Freiberg, Germany Sachsen
[3]Solar World Innovations GmbH, Berthelsdorfer Str. 111A, 09599 Freiberg, Germany Sachsen
correspondence to: dornich@freiberginstruments.com, phone:+49 3731 41954 0

ABSTRACT: Non-destructive measurements of minority carrier lifetime are well established and widely used for process control and characterization of defects in crystalline silicon. In this paper the novel method MDP (microwave detected photoconductivity) will be introduced to the field of contact less inline metrology. It enables to map the minority carrier lifetime with a so far unsurpassed combination of spatial resolution, sensitivity and measurement speed. New inline metrology tools for high resolution maps of wafers or even ingots will be presented, along with measurement results of long time studies. Correlations with shunts and other crystallographic defects demonstrate the potential of these tools, e.g. investigation of passivation homogeneity, statistical monitoring and process control or monitoring of furnace properties.

keywords: characterization, multicrystalline silicon, lifetime, photoconductivity

1 INTRODUCTION

The minority carrier lifetime is a key parameter for the performance of solar cells. Therefore it is a suitable criterion for classifying wafers by means of quality. Taking it one step further, inline ingot measurements allow to sort out low quality parts of the ingot before sawing wafers. The non-destructive methods µPCD (microwave detected photo conductance decay) and QSSPC (quasi steady state photo conductivity) are widely used in the field of inline metrology. In this paper the novel contact less and destruction free method MDP will be presented. It enables investigations with a so far unsurpassed combination of spatial resolution, sensitivity and speed, making MDP a favorable tool particularly for inline applications. MDP inline tools enable whole wafer maps up to (156 x 156 mm) in less than one second or simultaneous two surface maps of an ingot with a resolution of 1 mm within less than 2 minutes comprising maps of lifetime, p/n- behavior, resistivity and surface geometry.

In the following sections measurement results and correlations are presented of inline wafer and ingot measurements.

2 METHOD

Owing to the sensitivity of MDP, measurements may take place down to extremely low injection levels with no longer any restriction of laser pulse lengths. This, in turn, enables photoconductivity measurements under steady state along with lifetime measurements out of a steady state regime. A combination of these together with measurements as a function of injection provides new pieces of information on lifetime and defect or trap properties. Also trapping behavior of carriers can be investigated. This also provides a new look to the tremendous influence of measurement conditions and defects such as traps on the results of lifetime measurements. In the following, however, the focus is set primarily on inline and hence technological applications.

The microwave spectrometers used to work at about 10 GHz. They employ a resonant microwave cavity with the sample being electrically part of it. The sample is, however, geometrically outside of the measurement system to allow for scanning. The physical information is extracted from a time dependent measurement of the full complex dielectric constant of the sample.

The inline measurements take full advantage of the main above mentioned features. This leads to inline maps of parameters at timescales which fit completely into the normal production processes.

Wafer maps were performed with a resolution of 2.8 mm, where as all ingot measurements were performed with a 1 mm resolution. This, however, is not at all a technological limit.

3 RESULTS

3.1 Inline wafer measurements

Inline mappings of as-grown wafers are a versatile tool for the detection of e.g. crystallization defects early in the production process. With the MDP tool a full electrical wafer characterization at up to one wafer per second is possible. Along with the effective minority carrier lifetime also the resistivity is measured. With these investigations of each individual wafer, a huge variety of applications are possible like process control, yield and process improvement as well as a fast ramping up of any new production line or process. One must keep in mind, that an automatic measurement of each wafer provides an extremely large amount of data in a likewise short time. A statistical evaluation of these data, in turn, provides surprisingly precise pieces of information. Furthermore, the inline measurements are suitable for monitoring the material quality of outgoing or incoming wafers as well as identification of crystallization problems at wafer level. Some examples will be given in the following sections.

When it comes to the measurement of raw wafers it has to be taken into account, that not the actual bulk lifetime, but the effective lifetime, which consists of the surface and the bulk recombination, is measured. The following simplified equation shows the relationship between bulk lifetime τ_{bulk}, diffusion coefficient D_n and wafer thickness W for as-grown silicon wafers.

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_{bulk}} + D_n\left(\frac{\pi}{W}\right)^2 \qquad (1)$$

Therefore the measured lifetime of an as-grown wafer with a thickness of 200 µm is limited to approximately 1.5 µs. However if the bulk lifetime is very small, it will dominate the effective lifetime, so that a low quality can be recognized. Figure 1 displays the lifetime map of an as-grown multicrystalline wafer from the edge of a cast. The low quality edge, due to the contact with the crucible, can be easily distinguished from the better parts.

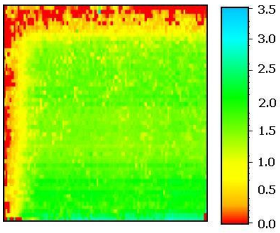

Figure 1: lifetime map of a mc-Si wafer from the edge of a cast ingot

The measurement range of the wafer inline tool is between 0.1 and 2 µs for as-grown wafers or between 0.1 and over 50 ms for passivated wafers. Note that these limits can be expanded if necessary.

3.1.1 Material classification

The MDP inline tool is able to classify wafers in up to 15 quality classes. For that, different characteristic parameters are taken into account, like arithmetic average, harmonic average, average according to J. Isenberg [1], median and standard deviation. Note that a direct correlation between the effective lifetime and the efficiency of the solar cells is not present, because of the cell process which affects single regions in ingots differently.

The software equipment developed for this tool also determines a variety of process relevant parameters and low quality edge areas of the wafers.

The combination of lifetime averages and standard deviation enables a very good classification of the material quality. Figure 2 showcases an exemplary classification of three wafers from the bottom, middle and top part of an ingot.

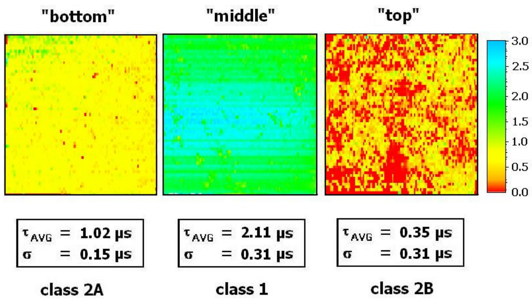

Figure 2: Exemplary classification of three wafers of bottom (a), the middle (b) and top(c) of an ingot.

As can be seen in figure 2, it is even possible to distinguish wafers of the bottom from those of the top part of the ingot. Wafer of the bottom often have higher oxygen and defect concentration, which results in a lower average lifetime. Wafers from the top often have a low lifetime, because of metallic impurities, a high nitrogen and carbon concentration and segregations of SiC, Si_3N_4 and other crystallization defects.

3.1.2 Monitoring and recognition of crystal defects

For the monitoring and recognition of crystal defects an extensive study was carried out, where specific wafers with special defect constellations were measured. In this study characteristic results for different crystallographic defects were determined.

One of the most abundant defects are Si_3N_4 and SiC segregates, which lead to shunts in the solar cell. In the MDP lifetime maps these defects lead to a very high inhomogeneity and a high percentage of pixels with a lifetime under 0.2 µs. The second most abundant crystal defects are *micro*crystalline structures in the wafer. These structures lead to a very low lifetime, together with a low inhomogeneity. In combination with a crack tester these microcrystalline wafers can be recognized and distinguished from the wafers with segregates.

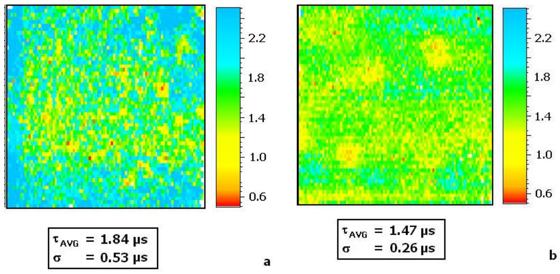

Figure 3: Si_3N_4 and SiC segregates (a); microcrystalline wafer (b)

3.1.3 Furnace monitoring

Another useful application is the monitoring of furnace properties. Complications in the growth process can be detected and furnace properties can be optimized.

Figure 4 and 5 show two examples of the above mentioned possible applications.

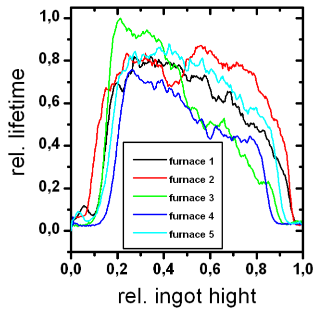

Figure 4: lifetime average versus ingot height for 5 ingots grown in different furnaces

In figure 4 the average of 5 ingots, which were grown in different furnaces, were plotted versus the ingot height. It becomes obvious, that different furnace properties lead to different slopes in the bottom and top part of the ingots. For example furnace 2 and 5 differ by about 30 % in the bottom slope and furnace 2 and 4 by about 50 % in the top slope. With this information an optimization of the furnace is possible.

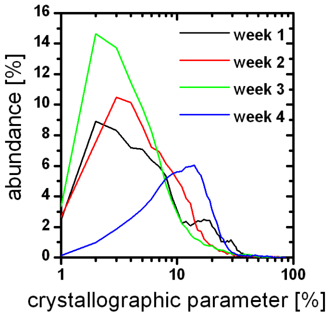

Figure 5: histogram of the crystallographic parameter of different weeks

Figure 5 displays the abundance of a crystallographic parameter, which is characteristic for the material quality. A high value indicates a low quality and vice versa. The abundance of this parameter is displayed for the wafers of different weeks of production. Several thousand wafers were analyzed. Week 4 shows a higher percentage of wafers with a high crystallographic parameter. Apparently there have been contaminations in the feedstock or something influences the growth process, which can be detected with the MDP measurements. In such a way problems can be traced back to their origin and thus can be eliminated efficiently.

3.1.4 Passivation homogeneity

The strong influence of the surface recombination can be used to investigate the passivation homogeneity. A local deficiency of the passivation leads to a much lower measured lifetime.

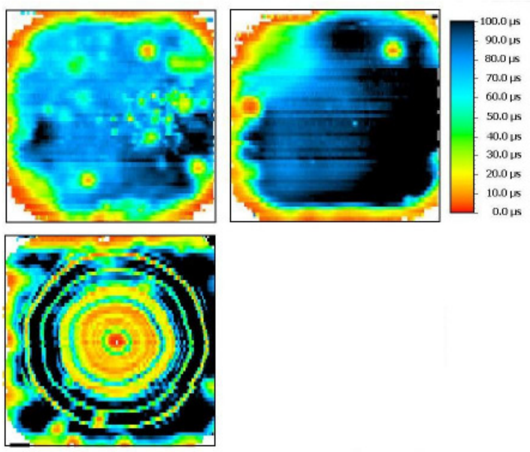

Figure 6: examples of an inhomogeneous passivation and striations

Figure 6 shows three different inline lifetime maps of monocrystalline silicon wafers passivated with thermal oxide.

3.2 Inline ingot measurements

In order to investigate the quality of the material as early as possible in the production process, the best way are inline measurements of ingots. Most of the before mentioned applications are also possible at ingots.

Solely lifetime measurements out of a steady state regime exhibit only a small surface influence, as was proven by simulations of carrier profiles [2]. By lifetime mappings it is possible to determine the cutting parameters for the low quality parts at the bottom and the top of the ingot.

3.2.1 pn detection

One useful application of inline ingot measurements is the spatial detection of changes in the conduction type. Changes in the conduction type of a multicrystalline ingot may occur depending on the material used for the cast process. The inline detection of these changes is made possible among others via steady state lifetime measurements.

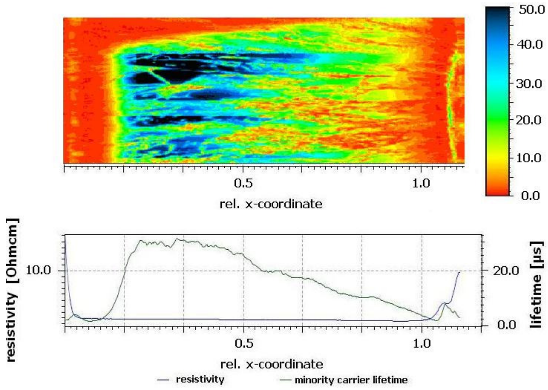

Figure 7: exemplary lifetime map of an ingot with a change in conduction type

Figure 7 displays the lifetime map of an ingot exhibiting a change in the conduction type from p to n in the top region. As can be seen, in the line scan the lifetime rises at the conduction change as well as the resistivity and falls again in the n-type region. This is used for the pn detection via an automatic algorithm. This will be addressed in a forthcoming paper.

4 CONCLUSION

The novel method MDP enables the measurement of lifetime also under steady state conditions together with a so far not achieved combination of spatial resolution, sensitivity and measurement speed. In inline applications, this opens an entire spectrum of new possibilities towards a highly efficient optimization of products and production processes together with an improvement of yield.

6 REFERENCES

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