Integral characterization: Traceability from feedstock to cell

Dennis Schaffarzik & **Dirk Zickermann**, Calisolar GmbH, Berlin, Germany; **Jean Hummel**, Calisolar Inc., Sunnyvale, USA

ABSTRACT

For a vertically integrated solar cell production starting with purification of silicon feedstock and ending with the production of solar cells, it is necessary to have control over all possible parameters that may affect yield, efficiency and product quality. This paper presents an approach for tracking products with minimal effort using a contactless technique. The method allows wafers to be virtually reconstructed into bricks and ingots, as well as recognizing the precursor wafer for each solar cell.

Introduction

Increasingly, cost reduction plays a major role in solar cell production, and yet there are also demands for continuous improvement of the quality of the cells. Yield improvement is one approach to tackling this balancing act: it has been used in the semiconductor industry but is also transferable to solar cell production. Yield improvement can be done by effective process optimization, but is only possible if the boundary conditions are well known and if as many parameters as possible are measured and can be assigned to individual products. In addition, it is necessary to separate the whole solar cell process into single process steps in order to realize the full potential of the benefits of process control and optimization. The knowledge of all parameters – including production- and material-related properties, measurements, electrical data, and quality data for each single wafer and cell – allows an insight into the complex interaction between feedstock quality, crystallization, wafering and cell processes. For example, the influence of defect density in the wafer in connection with the feedstock used, and of crystallization parameters and process steps later in the cell process, can all impact final cell performance.

Detailed product tracking becomes quite complex because production scenarios often interrupt a perfect linear product flow. Disturbances occur when splitting wafer batches or when changing from batch to in-line processes. If detailed product history is needed, complex recording is usually required at each production stage.

Single wafer tracking in the semiconductor industry [1] is the traditional approach used to improve quality and therefore yield and production cost. Laser-marking methods [2,3] are known techniques for tracking solar cell production from ingot crystallization to single wafer and/or cell. This paper presents a novel approach permitting traceability from feedstock to finished solar cell, allowing simple data collection across the production line and then identification and optimization of the relevant and important process parameters.

Tracking solution

The tracking begins with the application of product identifiers to each feedstock batch so that all detailed process and measurement data (e.g. ICP-MS data) can then be saved and tagged with the corresponding feedstock number. After crystallization, an ingot is created and each one gets a unique ingot identifier, which is saved with all its corresponding process data. At the bricking process step, the ingot number is used when saving the process data, and an additional brick-identifier suffix is applied to each of the 25 bricks. The wafering process data are saved with the corresponding ingot and brick identifier. All the combined data are transferred and saved to a manufacturing execution system (MES).

After wire sawing, the wafers are separated singly from the stack using a machine that has two loading entries for the sawed bricks. Each brick of wafers is loaded into four lanes (see red and green wafers in Fig. 1a). In summary, all wafers are transported in eight lanes into a wafer clean bench and recombined into a single lane at the exit of this wafer clean system. Due to the manner of this handling, the order of the wafers is lost: this is illustrated by different colours of the wafers in Fig. 1(a). The blue wafers of one brick from the right-hand side are completed, and the green wafers follow at the right-hand side. During this time, the red wafers from the left-hand side are still being processed. In this case the system mixes wafers from three different bricks (see blue, red and green wafers in Fig. 1a).

> “The complete wafer-tracking system consists of a matrix camera, special illumination to obtain a high contrast of the grain structure of the wafers, and proprietary software.”

The important information on the position of the wafers within the bricks and the tracking of the wafers gets lost. To recover this information, a system called Gemini [4] was implemented. Developed by Intego GmbH, a specialist in vision systems, Gemini essentially

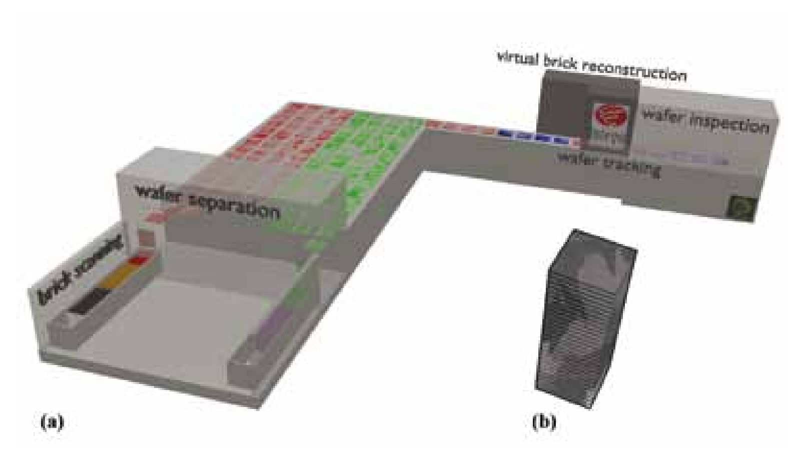

Figure 1. (a) Wafer separation. (b) Drawing of similar grain structure in a sawed brick.

delivers virtual brick reconstruction using intelligent image recognition. This system is able to virtually re-sort the wafers into the sequence of their precursor brick by using the principle that the grain structures of neighbouring wafers within a brick are almost identical (see illustration of wire-sawn brick in Fig. 1b). The complete wafer-tracking system consists of a matrix camera, special illumination to obtain a high contrast of the grain structure of the wafers, and proprietary software. The integration of a brick-scanning system at the entry of the wafer separation is used to transfer the brick and ingot number of loaded bricks to the wafer-tracking system. The pictures of each wafer at the end of the single lane are taken by the wafer-tracking system and transferred to the brick-reconstruction system, with an additional arbitrary incremental virtual serial number for each wafer, and the corresponding ingot and brick number. The software of the brick-reconstruction system is able to detect the grain structure of the wafers and summarizes this feature in a compact file. A fast recognition algorithm is able to calculate a correlation value between any two images and thus allow the system to reconstruct the order of the wafers within a brick and also distinguish different bricks. The information on the position and serial number of each wafer, together with the ingot and brick number, is then transferred by the brick-reconstruction system to the MES. With the stored information of ingot number, brick number and wafer position within the brick, a virtual rebuild of single wafers into the brick's precursor ingot is possible.

The wafer-tracking station transfers the arbitrary serial number of each wafer to the wafer-inspection system as well, which itself associates this serial number with the corresponding wafer measurement data prior to transferring to the MES.

> “Even though a lot of the information of the surface is lost, the system is still able to find the correct precursor wafer for each cell.”

Because of the combination of in-line and batch processes in cell production, the order of the wafers will get lost within the process. The in-line process needs a constant flow and a carrier change is needed after the filling of one carrier at the end of the in-line process. During this period of time the in-line process must store some wafers in buffers and will reload them if space becomes available due to process-related missing wafers (see Fig. 2).

Figure 2. Change from in-line to batch.

Due to the change of the aspect (colour, contrast, morphology, reflection, etc.) of the wafer surface through the different processes, the recognition rate becomes very low with this brick-reconstruction system. However, a correlation between cells and wafers is sufficient at this stage of production. To this end, a cell-to-wafer tracking system has been co-developed with Intego GmbH. Based on the brick-reconstruction software, the detected patterns of the wafers after each process step are compared with the as-cut wafers to determine the correlation between cells and wafers.

The largest impact on the wafer appearance is acidic texturization. This process dramatically reduces the contrast of the grain structure of the wafer surface, compared to the as-cut wafer. The software detects and identifies the grain structure of the acidic-texturized wafers as well, but, compared to the grain structure of the as-cut wafers, much information of the grain structure is lost. This loss of information is reflected in the correlation values after the texturization, which are lower than those of the as-cut wafers (see Fig. 3).

Each consecutive process reduces the information that can be derived from the wafer surface and with it the matching correlation values. Nevertheless, the comparison of processed wafer 3 with as-cut wafers 1, 2 and 3 after each process step still shows the highest correlation value for only the as-cut wafer 3 comparison (see Fig. 3). Even though a lot of the information of the surface is lost, the system is still able to find the correct precursor wafer for each cell. The matrix camera for the cell-to-wafer matching system is utilized in the print/colour inspection. For each detected cell, the system uses the same serial number as the one for the wafer, and transfers this number and the print/colour measurement result of each cell to the MES. In the same way, the serial number is also transferred to the cell tester unit, which then uses it in saving all measurement values of each cell and transfers the data to the MES.

Visualization

For a better visualization of all process parameters and process steps, especially for the ingot crystallization, it is helpful to generate a 3D model of the whole ingot using data from wafers or cells. Therefore a procedure has been developed that allows the creation of a 3D representation of wafers or cells with the given coordinates

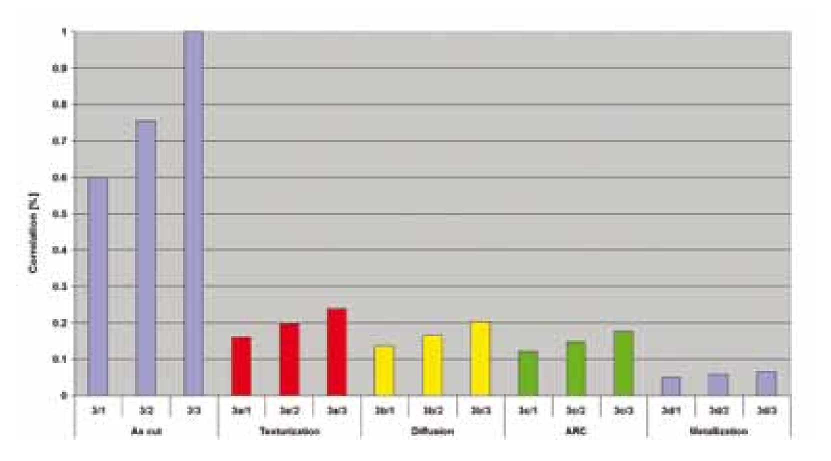

Figure 3. Comparing as-cut and processed wafers with as-cut wafer 3.

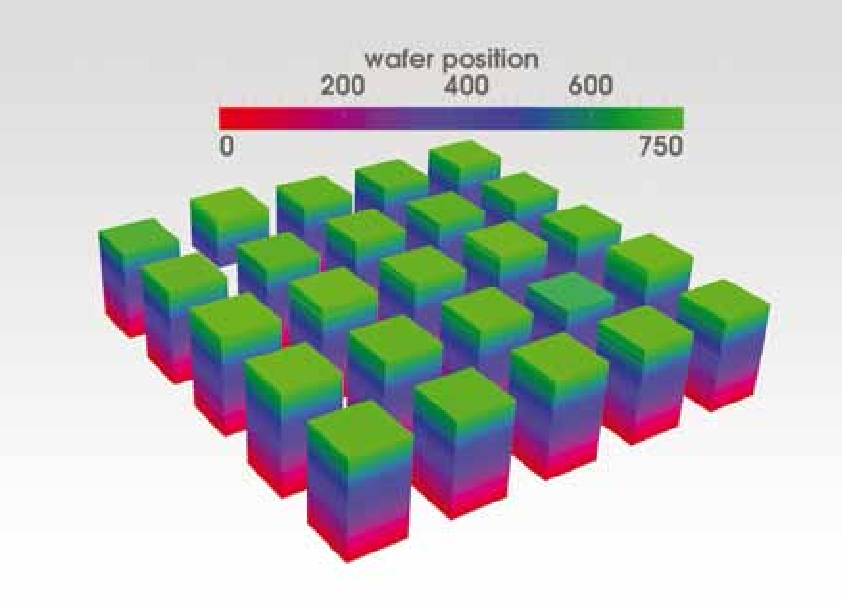

Figure 4. 3D view of an ingot rebuilt from single wafers.

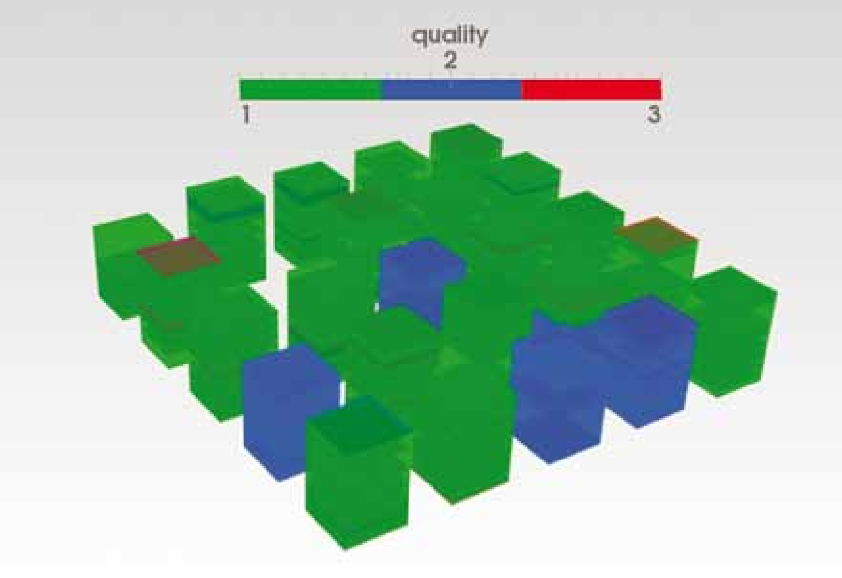

Figure 5. Wafer quality – Example 1.

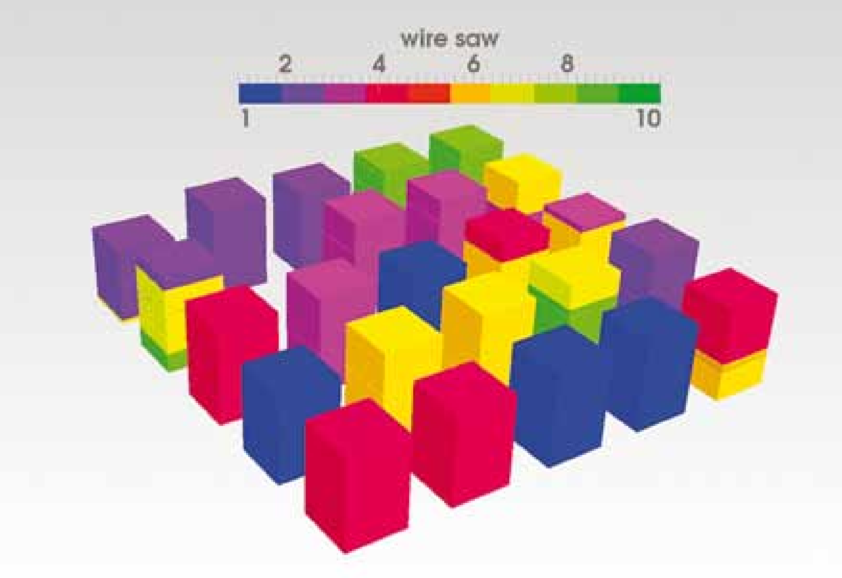

Figure 6. Wire saw number – Example 1.

x and *y* from the brick number and *z* from the height position within the brick. For each wafer or cell, a virtual ingot data model will be automatically constructed with the calculated information of its height within the brick and its position in the ingot. In addition, a colour range can be applied to one parameter to encode measurement results on wafers and cells or process data at single product stages. In Fig. 4 such an ingot reconstruction is shown for the wafer position parameter of each wafer within the 25 bricks.

Results

Example 1: Failure analysis

With this full-tracking solution it is possible to analyze all process parameters, measurement data and binning information corresponding to each wafer or each cell re-positioned into its precursor ingot. Continuous access of these data enables real-time assessment of yield and quality-controlling factors, allowing a fast analysis of the yield/loss mechanism and a fast corrective action in manufacturing.

An example of a yield analysis of low wafer quality is shown in Figs. 5 and 6. The wafer quality parameter is plotted for one ingot in Fig. 5. Most of the quality 2 wafers are located in the four blue bricks. Due to the fact that four bricks are cut at once with each wire saw, it could be that the process of wafering was not under control for a particular wire saw. This can be easily checked if the same wafers of the ingot are plotted against the information on the wire saw with which the wafers were cut (see Fig. 6).

By analyzing in this manner, the correlation between quality 2 and wire saw number 1 (blue bricks) is confirmed and the problem with the wire saw can be investigated and solved. Without such spatial differentiation, the identification of the problem would be rather difficult because the only available information would be that roughly 2500 wafers have quality 2.

Example 2: Experiment observations

To improve production yield some experiments in the production process are necessary. Such experiments may significantly disturb the production because a special handling and tracking of test lots within the production line is necessary. In contrast, the availability of a full-tracking system can avoid additional work within the production, and experiments are easily performed and data extracted using only the MES, as shown in this example (Fig. 7).

A variation of different wire diameters and different pitches was evaluated for wire saws 6 and 9 (dark green and orange bricks, respectively, in Fig. 7). To verify the resulting wafer thickness, the same ingot need only be visualized with a colouring scheme for the measured wafer thickness obtained from the wafer-inspection system. In Fig. 8 the resulting thicker wafers (dark red) can be identified and traced back to the wire saws. Furthermore, the possible influence on cell performance, for example the resulting efficiency, of the same ingot can be checked as shown in Fig. 9.

Example 3: Reverse analysis

An analysis such as previously described can be also done in reverse to detect the process influence at the level of single 'products', these being feedstock, ingot, bricks, wafers and cells. The reverse analysis starts from the results of the cell efficiency plotted per ingot. In this example of one ingot, a slight decrease in efficiency was observed in the bottom region of some of the bricks (see Fig. 10). Since each parameter at each product stage can be controlled, it can be seen how the slight decrease in efficiencies matches the lower lifetime values obtained for the wafer level in the bottom region of the bricks (see Fig. 11).

> "Integral tracking of feedstock, crystallization, wafer and cell data is a powerful tool for quality management, process control, process development, and research and development tasks."

Conclusions

3D models of ingots were reconstructed from brick, wafer and cell tracking data. The advantages are found in the visualization of process parameters through brick and ingot reconstruction. This allows a differentiation of the effects of the different components, such as feedstock, crystallization characteristics, wafer processes and cell processes. The quality of the cells can be directly compared to the properties of the corresponding wafers. It is possible to extract the influence of the precursor feedstock on solar cells from the brick and ingot information. Integral tracking of feedstock, crystallization, wafer and cell data is a powerful tool for quality management, process control, process development, and research and development tasks. The influence of feedstock and process parameters on the end product – the solar cell – can be quickly ascertained (and corrective action taken) by one-to-one tracking of wafer and cell data.

Acknowledgements

The authors thank S. Herbrecher and A. Eckl (Intego GmbH) for their valuable cooperation in this project, C. Strümpel

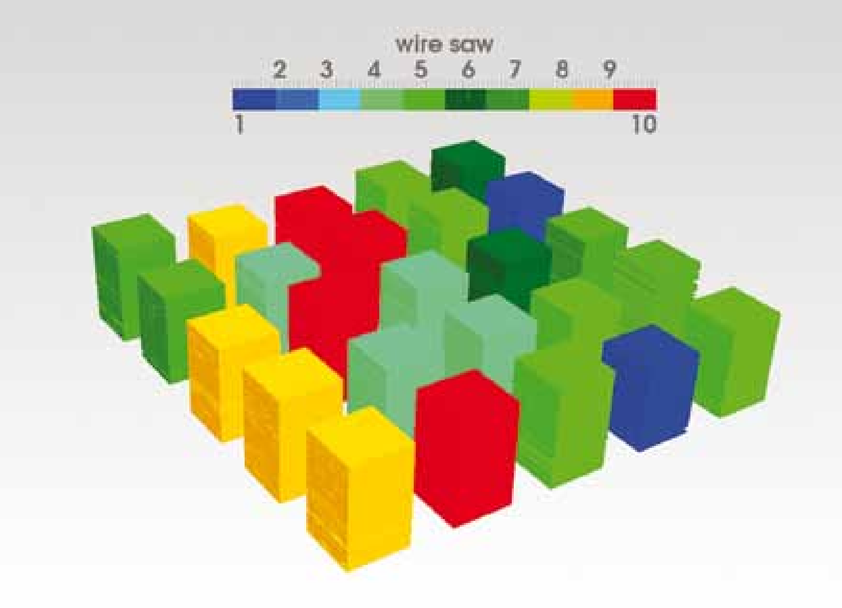

Figure 7. Wire saw number – Example 2.

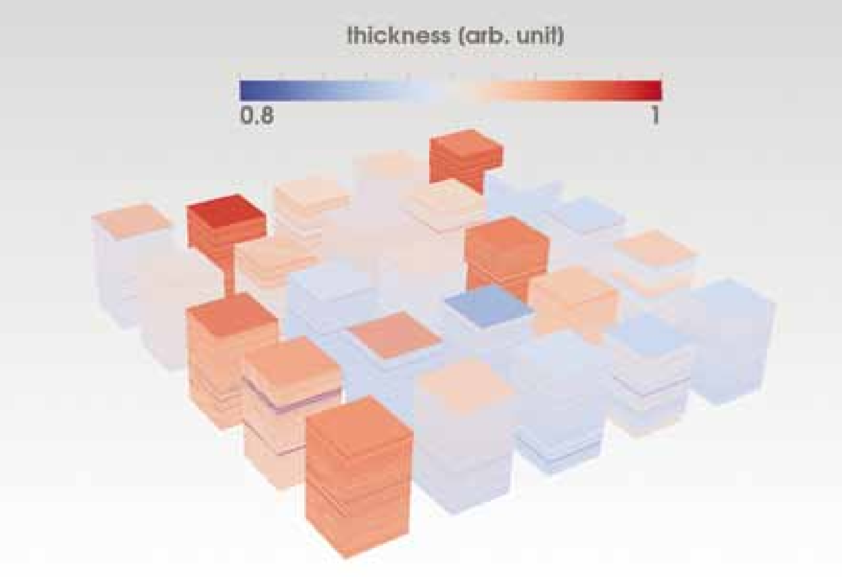

Figure 8. Wafer thickness – Example 2.

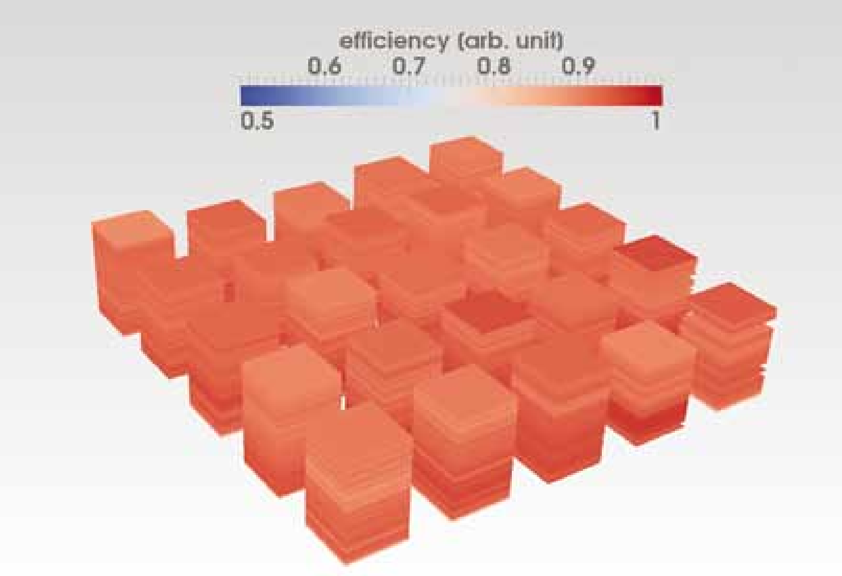

Figure 9. Cell efficiency – Example 2.

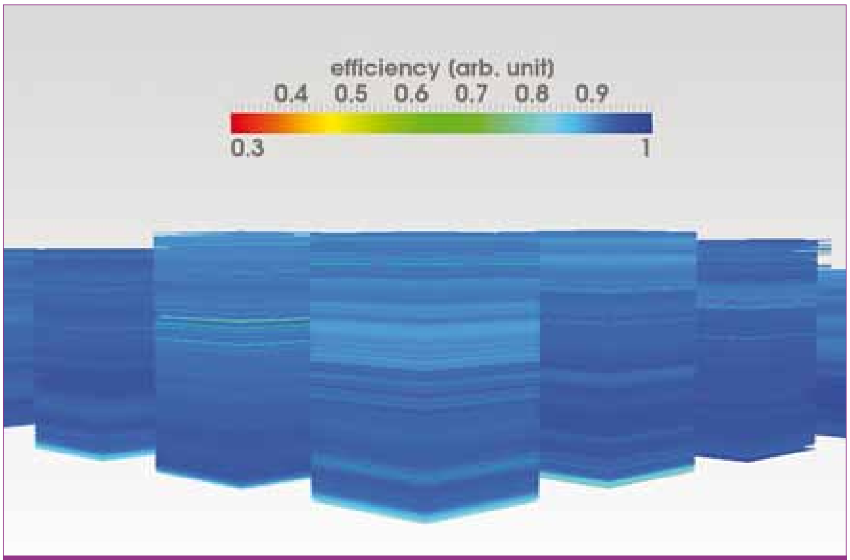

Figure 10. Cell efficiency – Example 3.

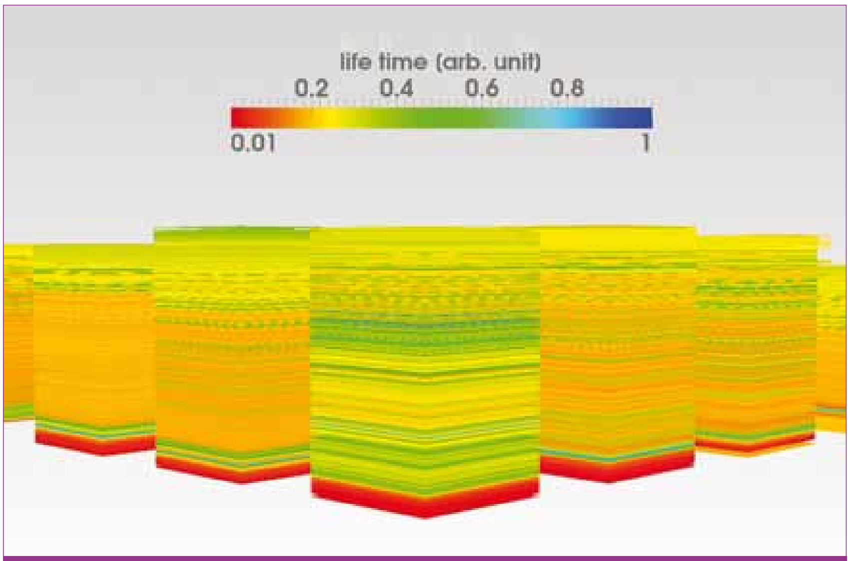

Figure 11. Wafer lifetime – Example 3.

(formerly of Calisolar Inc.) for additional implementation into the cell production and M. Heuer (Calisolar GmbH) for fruitful discussions.

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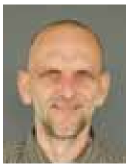
About the Authors



Dennis Schaffarzik worked on surface photovoltage based characterization of silicon solar cells at the former Hahn-Meitner-Institute, after studying physics at Humboldt University, Berlin. Dennis has been with Calisolar Berlin since 2007, and his current work includes new metrology implementation for process and product control at Calisolar's integrated plant in California.

Dirk Zickermann studied physics at the University of Osnabrück and was awarded a diploma for investigations of selective emitters for solar cells. After working on coating technologies at Fraunhofer IST Braunschweig, he joined Calisolar Berlin in 2007. Currently Dirk focuses on data evaluation and simulation for silicon and cell production.

Jean Hummel is the director of equipment at Calisolar, where he has managed tool installation and ramped production to 75MW/yr. He has 20 years' experience in PV, including 15 years with Solarworld in the USA. Jean holds a diplôme ingénieur from ENSI in Poitiers, France, and a master's in mechanical engineering from Stanford University.

Enquiries

D. Schaffarzik
Calisolar GmbH
Magnusstrasse 11
Berlin 12489
Germany
Tel: +49 (0) 30 6392 4588
Email: schaffarzik@calisolar.com
Web: www.calisolar.com