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Final testing: a secure release gate towards module manufacturing

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ABSTRACT

Among all of the tests performed in the production chain of solar cells, each with the scope of production control and the aim of driving engineering improvements, the electrical final test is certainly the most important. The final test defines the gate to module manufacturing and has a direct impact on finances and customer satisfaction. The test procedure itself is well known and continues to undergo constant further development, but that shall not be the scope of this article. This paper will elucidate on the issues faced by bringing these tests into high volume production, highlighting some issues on measurement accuracy and degradation of the internal calibration standards. In addition to pure electrical testing, the paper will discuss the Q-Cells approach to identifying hot spots and subsequent binning of the affected cells without adding process time to the test procedure, and will show their straightforward correlation to heat generation of these hot spots in real-life condition-encapsulated module tests.

Final test procedure

The test usually focuses on the parameters used to describe the cell according to standard test conditions (STC), namely P_{mpp} and the derived conversion efficiency (η), V_{oc}, I_{sc}, and the fill factor (FF). Beyond these measurements, other factors are recorded such as a better prediction of the behaviour of the cell in the module and field conditions, shunt resistances and dark operating curve parameters as reverse bias currents at voltages that might occur when a module is partially shaded.

Nevertheless, these parameters have not proven sufficient for protection of modules from losses and securing stable efficiency over the complete lifetime of the module. It is also essential to sort out cells that are suffering from local defects. Unfortunately, the influence of these defects would hardly be measureable during the integral electrical assessment of the cell at its first exposure to both light and current flow. Finally, modules should look uniform in colour and cells have to be sorted accordingly, even if electrical parameters are unchanged by these differences in the anti-reflection coating.

For those engineers dedicated to constantly improving line performance, process stability and cell technology, the final test results come to full power only if they can be correlated on an individual wafer basis against all the factors that influence the conversion efficiency η. Fig. 1 illustrates how sharp the usually very broad distribution of η becomes if it is plotted against the wafers' original position in the ingot or brick. Any smaller

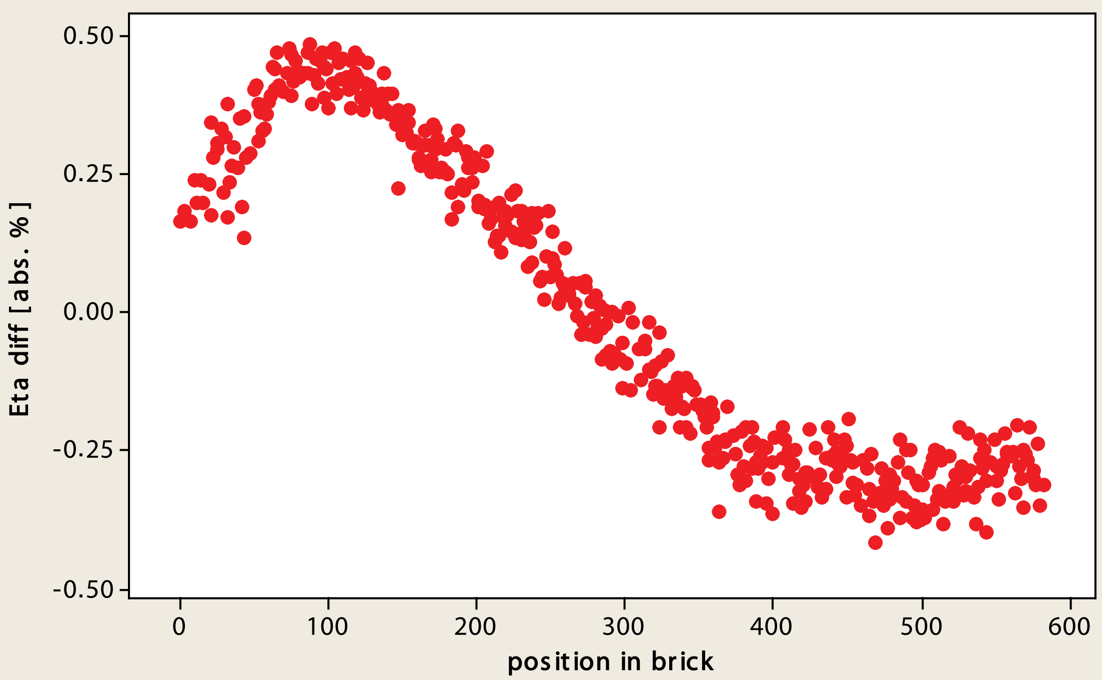

Figure 1. The usually rather broad distribution of cell efficiencies measured at the cell tester becomes much sharper if correlated against their major predictors, i.e. the ingot or brick position. MES systems maintain the data relation throughout the entire line. Exploiting this, incremental improvements and small deviations of less than one-tenth % can quickly and unambiguously be identified and levered.

deviation can now be detected and incremental improvement potentials levered. The issue with these correlations is less the knowledge of their existence than the precise tracking of the material all the way down into modules.

Finally and most importantly, cells are binned into boxes of different classes. Each class of box comes into module manufacturing with a commitment to minimal performance of the cells it contains. Confirming the importance of proper tester calibration, we will discuss the robustness of module yield manufactured out of these boxes.

As a prerequisite to the discussion later, we need to briefly revisit the testing procedure itself. After identification of the cell, it is fed into the dark test chamber where it is properly aligned and lifted onto rear contacts, which in turn hold the wafers against multiple contact beams over the bus bars. In order to yield good contacts and a rigid construction, the bars are a little wider than the bus bars, also precisely defining the shaded area subtracted from the active area for efficiency calculation, tolerating a certain misalignment. Then, operating curves are recorded, both under dark, low light and full STC conditions. Test temperature is actively maintained and monitored values are used to correct the data in voltage and current due to small remaining temperature offsets to the standard temperature. Light is provided by a distant, homogeneous and high-power flasher system providing proper illumination conditions during a period of some milliseconds long enough to acquire the complete operating curve. Any remaining flash intensity fluctuations during curve measurement are again recorded by a monitor cell and both currents and voltages are corrected accordingly. If the spectrum of this light is not perfectly similar to the STC AM1.5g, care must be taken to ensure that spectral mismatch can be minimized by setting a spectrally matched calibration standard at the centre of the current production window for each significant cell type.

As reported earlier in the sixth edition of *Photovoltaics International* [1], advances in cell design and even smaller improvements usually lever the thus-far less exploited violet and infrared ends' potentials in the quantum efficiency characteristic of the cell. The cell's convolution with the standard spectrum and the flasher spectrum, respectively, leads to changes in the mismatch factor that must be rolled out to production test with process changes of this category.

A frequent source of misunderstanding is the repeatability of a single measurement against the precision that can be obtained once sufficient statistics are used. Fig. 2 illustrates this problem showing the differences between five subsequent measurements of a batch of 100 cells on a production test system. Each measurement is compared against the same cell's result in the first batch run. The comparison reveals a superimposed noise added to the mean result, which is perfectly Gaussian distributed and independent from the test sequence or wafer properties. Positively speaking, we superimpose random noise with the measurement and are thus able to eliminate its influence sufficiently by applying some statistics to all calibration routines perfectly reproducing mean values. Secondly, as distribution width is rather small and constant, proper guard bands in testing secure test bins from containing significantly deviating low-flyers.

Calibration

A sophisticated task on its own is the calibration of the testers against the WPVS primary standards provided by the national institutes of standardization (e.g. the PTB, Physikalisch-technische Bundesanstalt in Germany), as the spectrum cannot be as easily materialized and transported as for other physical properties like length or electrical resistance. Q-Cells SE aims to very conservatively distribute the standard across all flashers at all production sites with the procedure outlined in the following section.

Standard encapsulated cells are delivered by PTB and re-circulated for calibration bi-annually to PTB. Several standards are used concurrently to ensure stability over time and alert on any incompatible finding. Using this verified standard, a solar simulator AM1.5g Grade A illumination source is checked every

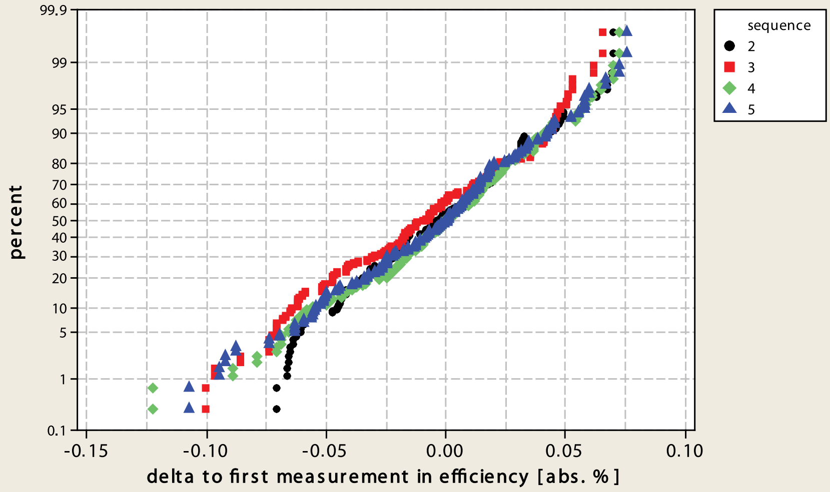

Figure 2. Reproducibility of a standard production flasher test. Cells are tracked individually through the five batch runs, and the differences to the first measurement are plotted against a normal distribution scale. They show independent normal distribution of similar width and very reproducible position.

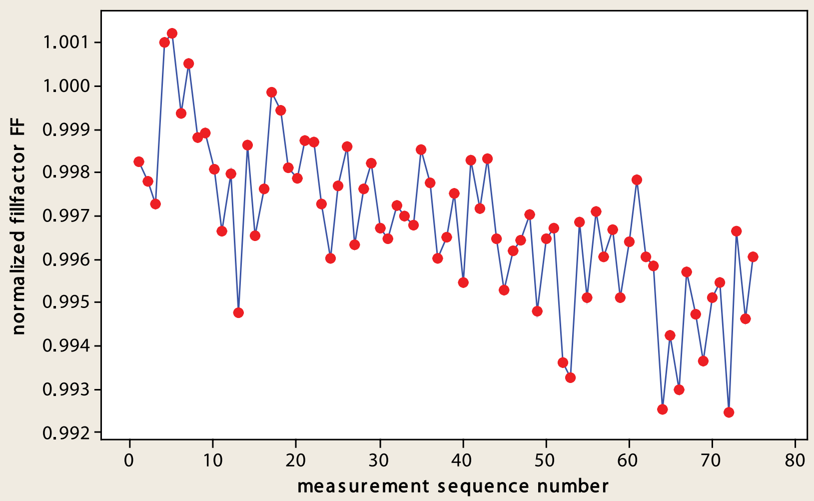

Figure 3. Degradation in fill factor of a 150-wafer batch contacted and measured repeatedly.

morning, and before calibration of internal secondary standards, to precisely deliver a standard 1 sun flux and spectrum at homogeneity across a 6" wafer. Here, a first re-confirmation loop is established by checking results with full-width wafers from ISE CalLab. Using this internal calibration standard, working and reference batches are measured using carefully optically degraded cells representing the centre of the production. Reference batches will be tested as few times as possible as they are designated to give reference against working batches to be produced for the future calibration runs over time. The working batch is used to calibrate all testers at the beginning of the calibration period.

The other testers are checked daily to ensure they still give similar results, with production batches produced on a certain predefined master-tester that has been checked with the previous reference batch. Degraded cells are stored in the tester and fed into the measurement position every hour to additionally contain any deviation that might occur in between. As and when suspicious test results occur in either of the verification runs, the tester is immediately re-calibrated using the working batch. After the end of their duty cycle, both the working and reference batches are returned to the lab to confirm their proper settings closing the second verification loop.

The predominant wear-out mechanism of reference or working batches is the frequent contacting which leads to a loss in fill factor (Fig. 3). As calibration is made to adjust on a point close to mpp (in addition to I_{sc} and V_{oc}) , leaving this batch for calibration a little longer is tempting as it would shift production to better efficiencies. Insufficiently pre-degraded batches would have the same effect.

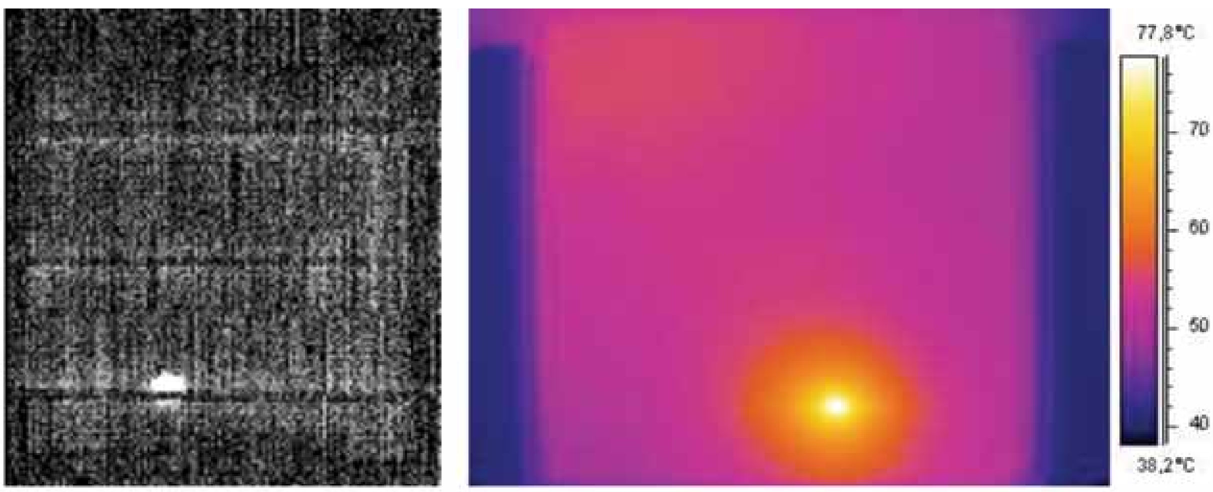

Figure 4. Diffential IR image of a cell under test, taken within fractions of a second. This image correlates well to a hot-spot that developed after assembly of that cell into a module and exposing it to field conditions for some time. Note that the cell is seen from the sunny side in the cell tester and inspected from the rear side during module operation.

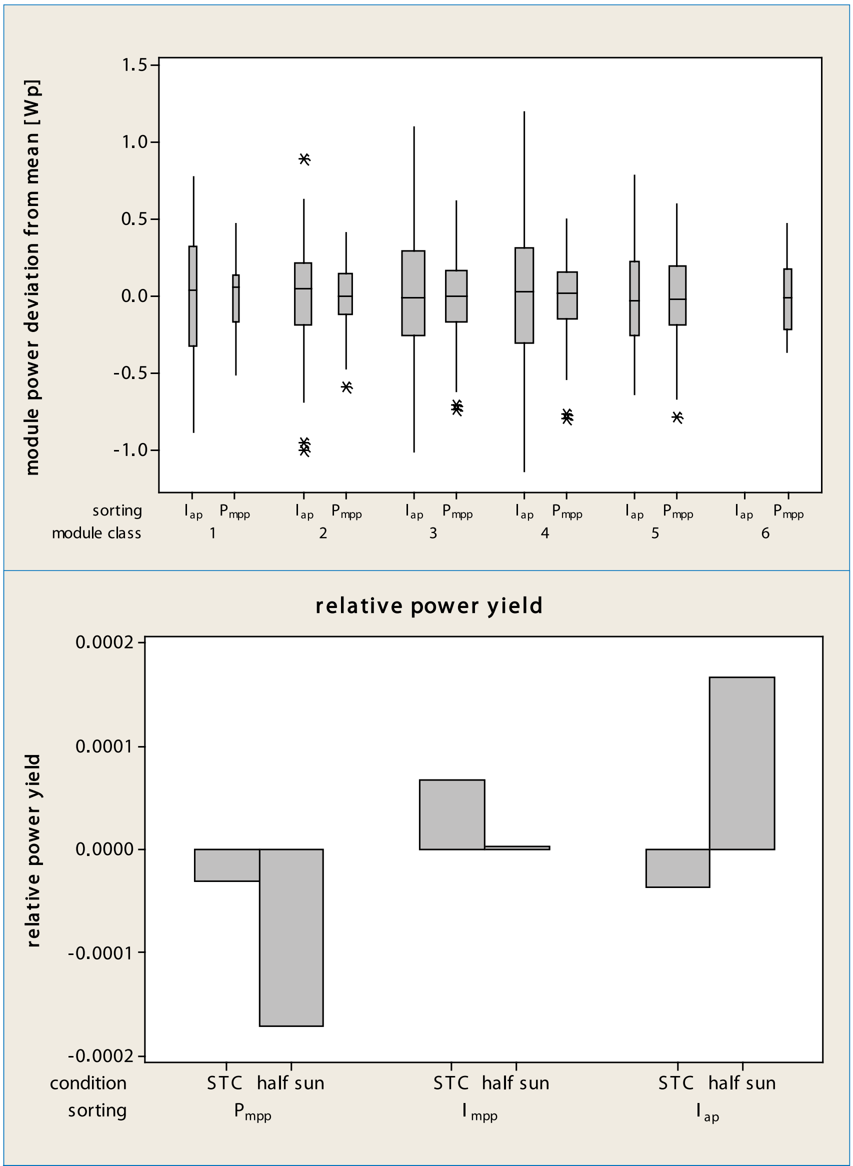

Figure 5. Simulation results of artificially assembled modules by combining 47,500 real measured cell operation curves to 3 × 20-cell-modules. The box plot shows that sorting according to the power at the maximum power point (P_{mpp}) leads to the best prediction for the power of the modules assembled of the sorted cells. In turn, the bar graph displays a slight advantage in total module power output for sorting according to the current at a fixed voltage (500mV, I_{ap}) for full- (1000W/m², STC) and half-sun (500W/m²) irradiation, yet differences are in the one-ten-thousandths range.

Hot-spot inspection and binning

As pointed out before, local defects such as shunts are hardly visible in the integral measurement of the entire cell. However, local heating and unfavourable operating conditions might lead to a self-amplification of that defect resulting in hot-spot temperatures that will irreversibly destroy the encapsulation of the module at that spot. On the other hand, the test must not decrease throughput at the final test insertion allowing the hot-spot enough time to go into the self-amplification regime. Our test engineers have developed a method to quickly detect and discriminate small local temperature increases that correlate well to failure seen in long-term module tests. Fig. 4 illustrates an example.

This method benefits from the fact that the sample is contacted anyway inside the tester, which means that in the same step as testing, power can be dissipated electrically into the cell under test. The resulting lateral distribution of temperature increase is measured with a differential IR-camera image. Test modules have been built from specially sorted cells covering all ranges of hot-spot patterns and intensities as well as increased reverse-bias currents. Accelerated real-life condition tests are then used to determine thresholds for the IR-camera patterns detected during final test. In addition, spatially resolved assessment of the patterns helps to classify the hot-spots and trace them down to process issues to be eliminated.

After being sorted by the IR camera tests and other quality criteria into the top category, the cells need to be binned. The ultimate goal of the binning is to not jeopardize any power generation capability of the cell to mismatches of the cells stringed together to a module. In this step, all the caution and effort spent on the accurate calibration of the cell tester pays off. Only using this procedure can it be guaranteed that all boxes labelled the same actually contain equivalently matching cells.

> "Total power achievable with the given collection of cells only changes by far less than one-thousandth of the total power for the proposed sorting schemes."

Other manufacturers take different approaches to this sorting step. We have performed simulations testing different binning schemes of 47,500 measured real operating curves, and subsequently randomly combining these cells to modules (see Fig. 5). Ignoring other influences of module manufacturing itself, the module operating curves and individual P_{mpps} were calculated from the superposition of the individual cell curves, not just by adding the cell's P_{mpps}. I_{mpp} distribution does not broaden, regardless of whether or not it is binned according to the current at a fixed voltage (500mV, I_{ap}) or by P_{mpp}. Total power achievable with the given collection of cells only changes by far less than one-thousandth of the total power for the proposed sorting schemes. This is far below the uncertainty one has due to the slightly different early light-induced degradation which is not yet accessible to cell test, and impacts of the module assembly itself.

Outlook

Looking forward, a new challenge arises with improving cell efficiencies further by using material excelling in longer lifetime. With the longer lifetime of the minority charge carriers, it takes the cell longer to go back to equilibrium when the operation condition is changed. Standard measurement times are already in that regime when entering high efficiency classes. The effect of staying in non-equilibrium shows up in the hysteresis when running through the operation curve in both directions, as shown in Fig. 5. Only longer settle time per measurement point can overcome this pitfall, and clever segmenting of the test range helps to keep test times short enough to fit into the stable plateau of a flash, extending the current test methodology to the next generation of cells.

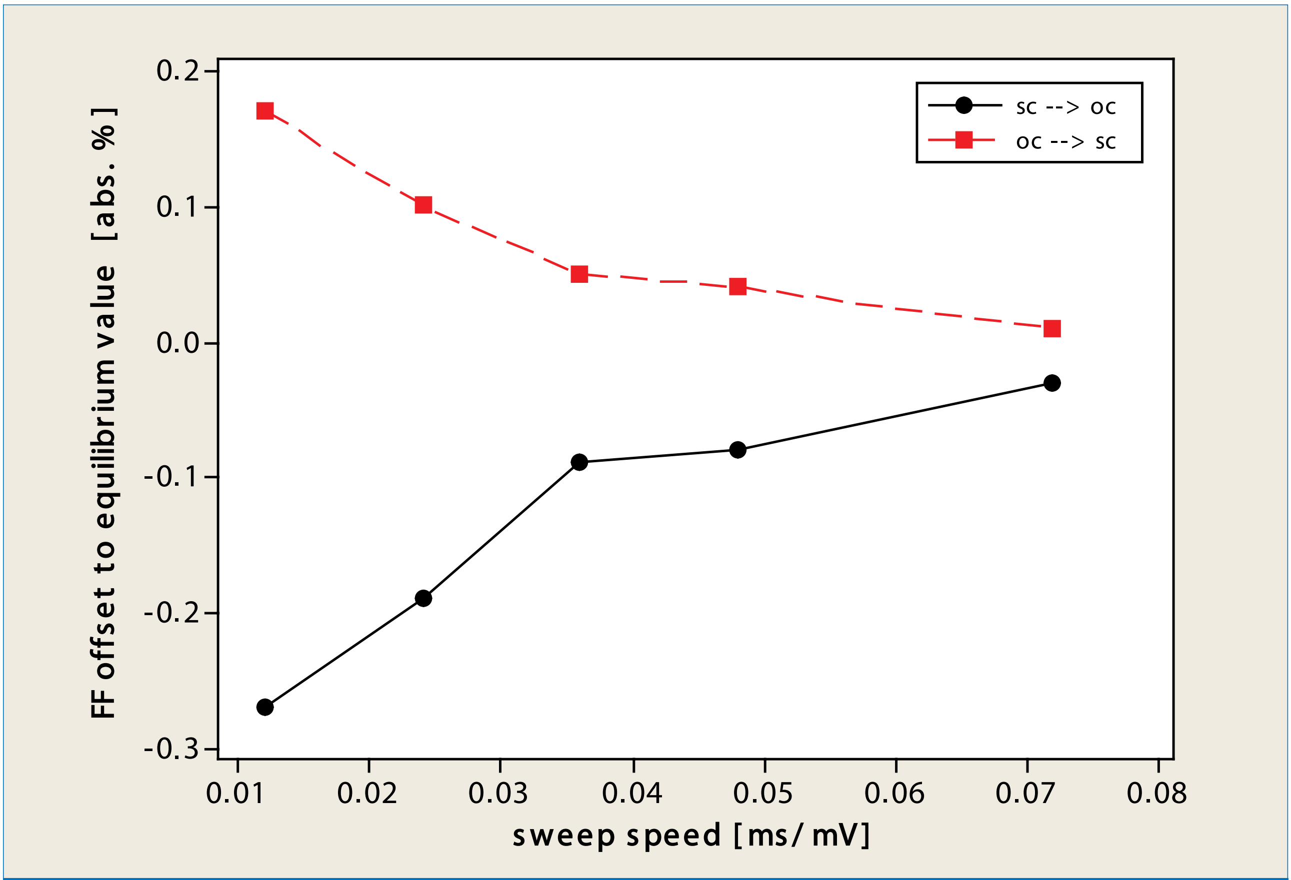

Figure 6. This graph shows the offset due to fast sweeping through the operating curve converging to the equilibrium value for slower sweep rates. Using measurements that are too fast poses the risk of over- or underestimation of the performance of the cell, respectively.

Reference

[1] Kux, A. & Müller, J. 2009, "Increasing the efficiency of multicrystalline silicon solar cells", *Photovoltaics International*, Edition 6, p. 66.

About the Authors

Nico Ackermann received his diploma degree in technical physics from the University of Duisburg-Essen. While studying he gained experience in photovoltaics at the Fraunhofer ISE. He joined Q-Cells in 2005 and has responsibility in the field of characterization and physical analysis.

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