Yield management at the highest quality level

Ralf Lüdemann, Ute Mareck & Michael Eberspächer, SolarWorld, Freiberg, Germany

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ABSTRACT

Yield and quality of a production process and quality of the final product are closely linked. To further improve yield and quality, cutting-edge technology and best-practice productions are necessary. Technology development and continuous improvement require, however, in-depth understanding of all materials, processes and equipment as well as their interactions. We propose a system of comprehensive quality assurance on different levels and both within and between all production steps along the value-added chain. Optimisation or changes in interstage products, i.e. supplies, must focus on the quality of the final product. For this reason, we must look at the production chain as a whole, from raw material to final product.

Setting the stage for quality and improvement

Quality matters; quality sells; quality is all-dominant. This simple principle can be applied to myriad situations, but for PV modules, which come with long-term warranties and bring a high degree of public awareness, quality is a vital criterion. Of course, cost is a major factor in this process, but ultimately, production cost and product quality do not conflict. Together with technology development and continuous improvement, cost and quality have the same roots and prerequisites. Quality assurance and yield management go hand-in-hand and improve product quality and production cost at the same time.

Besides a clear level of commitment and well-educated staff, a good set of tools and conditions is necessary to ensure high levels of quality in the technology industry. The most important basic condition is to know what you are doing and how it affects the final product. This sounds obvious, but is far from simple or even common in real-life mass production. Placing oneself in that (starting) position, one must establish:

- quality assurance on process level
- quality assurance on product level
- both within and between each value-added step.

Quality assurance on different levels

Quality control of products is common to all production scenarios. As suppliers and customers agree on a certain specification of the goods to be exchanged, testing against this specification is part of the business. However, specifications often arise from producibility considerations and, to a lesser extent, from specifications of the customer's customer. As is often the case, the guiding idea is 'what is possible' instead of 'what is necessary,' because it is not entirely known what level of influence properties of a supply material have on the processes during production and therefore on the quality of the production itself. Yield and productivity are very sensitive to

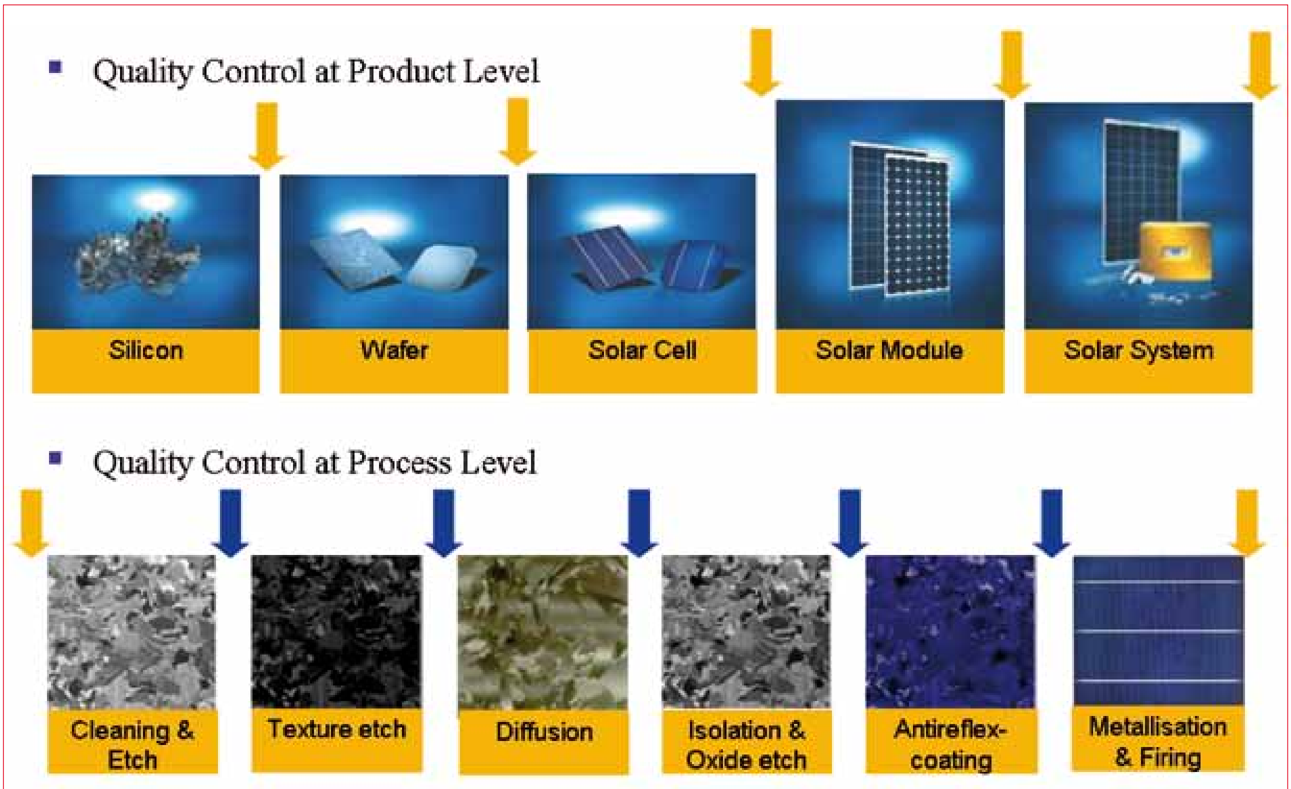

Figure 1. Quality assurance between the different product stages of the entire value-added chain and within one value-added step (solar cell production in this case).

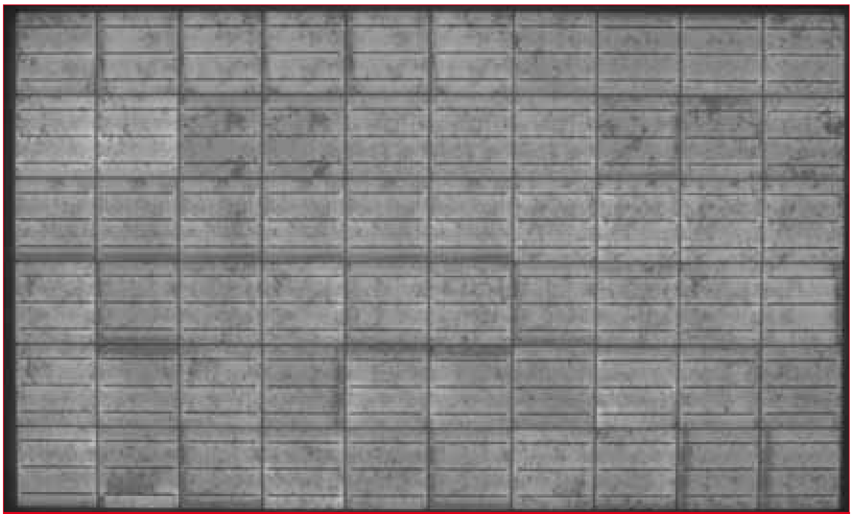

Figure 2. Electroluminescence image of a solar module.

some (but not all) properties as well as to variations of properties of input material.

Quality control of all processes during production has therefore a two-fold importance: control of every single process step is necessary to secure a stable production by identifying variations of even minuscule extent. With this control, preventive maintenance of equipment, readjustment of processes, and reject (or rework) of deficient products can then be performed at the earliest possible stage, which is the basis of high overall equipment efficiency (OEE), high product quality and low yield costs, as deficient products are not treated further before being rejected in the final inspection. In addition, comprehensive quality control at process level is the only way of identifying important material properties and the impact of their variations.

A high-quality product is made out of high-quality supplies in a quality-oriented way. Since all supplies are products of upstream productions, the interaction of productions along the value chain becomes apparent. All products are considered interstage products on the way to the final product for the end-user. Therefore, it is advantageous – if not even necessary – to be a fully-integrated company or at least to have access to the whole production chain, from raw material to final product.

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In the following section, we provide an insight into quality assurance and yield management along the PV value chain, starting at the finished product, the solar module.

Yield management in module production

Both in terms of cost and technology, the solar module is the core of photovoltaic systems. Only a long-lasting functionality and durable high energy yield over several years can guarantee the calculated return on the entire investment. Consequently, particular stress should be placed on ensuring the longevity and quality of each individual solar module.

Function and longevity of the solar module

Numerous climate chambers are employed at SolarWorld's module factories to assess any possible fault sources that could potentially reduce the service life of the modules. Up to 14 modules are randomly selected from the production line, placed in a climate chamber that has been connected to the end of the production line, and subjected to rigorous, all-inclusive inspections based on the IEC 61215 certification. All modules that pass the several-weeks-long inspection process are then checked for possible errors in their entirety. As a result, faults can be reacted to in a prompt manner and the respective measures can be undertaken accordingly. In addition, further climate chambers are set up to simulate environmental influences such as heat, frost and humidity for even more thorough analysis. At SolarWorld, a separate company for global technology development and quality assurance supports the production companies in this regard, subjecting the modules to elaborate processes in which they are inspected for process or material changes before being granted approval for production.

However, important simulations of the natural aging process are for quality assurance of the production process; they are insufficient in terms of controlling all possible faults on a PV module. Subsequently, we utilize additional methods of quality control. One very novel method involves electroluminescence measurements. Taking advantage of the properties of solar cells, electrical stimulation involves light being emitted from all functioning cell parts. It is thus possible to create an image that describes the functioning of the individual cells both during the current flow through the solar module as well as during inverse operation.

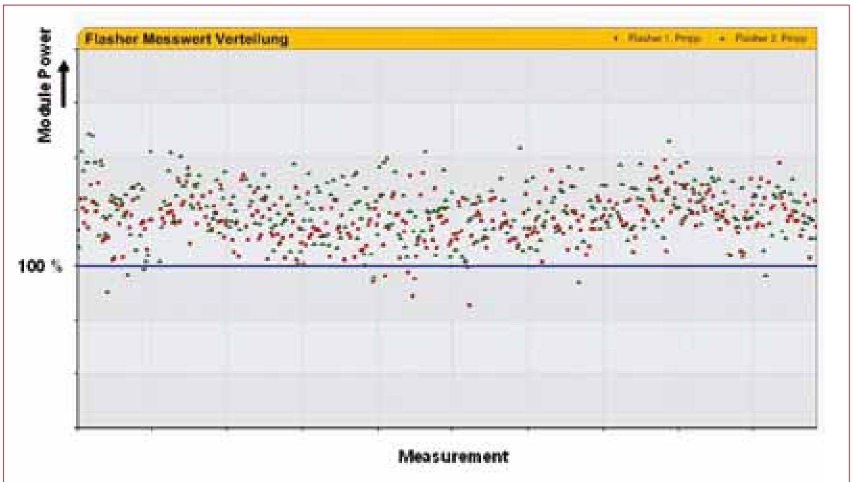

Figure 3. Trend chart of the measured module output on two flashers.

Figure 4. Device for performing a pull-off test on soldered solar cells.

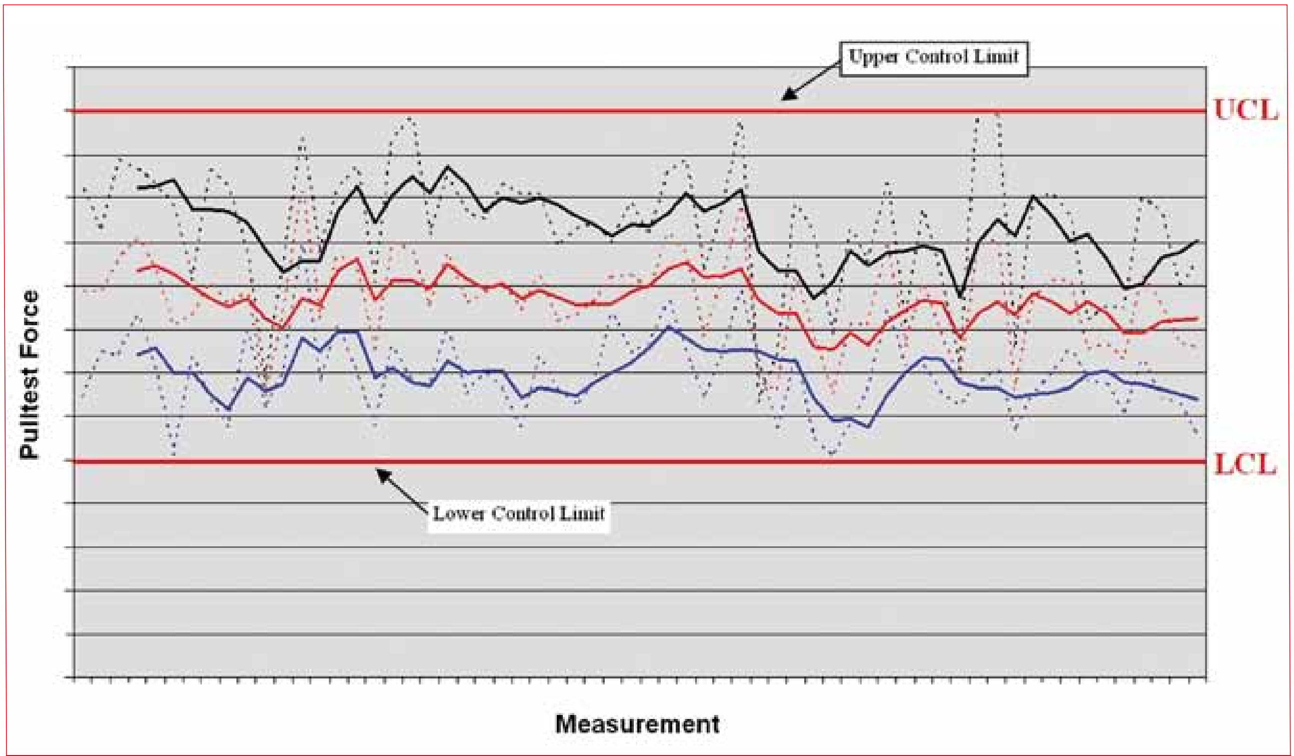

Figure 5. Process controls of the pull-off values on the front and rear side of the module.

If any solar modules are found to possess cells with breakage, shunts or other faults, we will subsequently remove them from production and they will not be sold.

The sun simulator: the most important measuring instrument

An essential parameter for customers is the module's output, which, in the end, influences the cost of the entire PV system. At the very minimum, all SolarWorld customers generally receive the output for which they paid. That is why, alongside practicing plus sorting (all 220W modules are always equipped with more than 220W), special emphasis is placed on the function and configurations of the sun simulator, or so-called flasher. External institutes regularly confirm the measured module output based on routine precision measurements. The continuous observation of the power curve of the produced modules ensures that the entire measuring system is functioning at all times. Several flashers are compared to one another via software and any deviations are automatically reported to the responsible engineer.

Continuous process controls

Good quality and performance cannot be 'tested into' a product; it must be manufactured. In consequence, each component of the solar module and every relevant production process are carefully observed, the primary responsibility of the employees at the highly automated factories. As soon as the solar cells are soldered to a so-called string, factory employees perform a 100% control through which any possible faults are discovered immediately. This is combined with camera inspections. The adhesiveness of the copper strips used to connect cells is routinely measured and documented via a measuring device specially developed in-house. Predetermined minimum requirements must be met. If not, the soldering system or the respective material must be decommissioned and the cause of the fault must be determined.

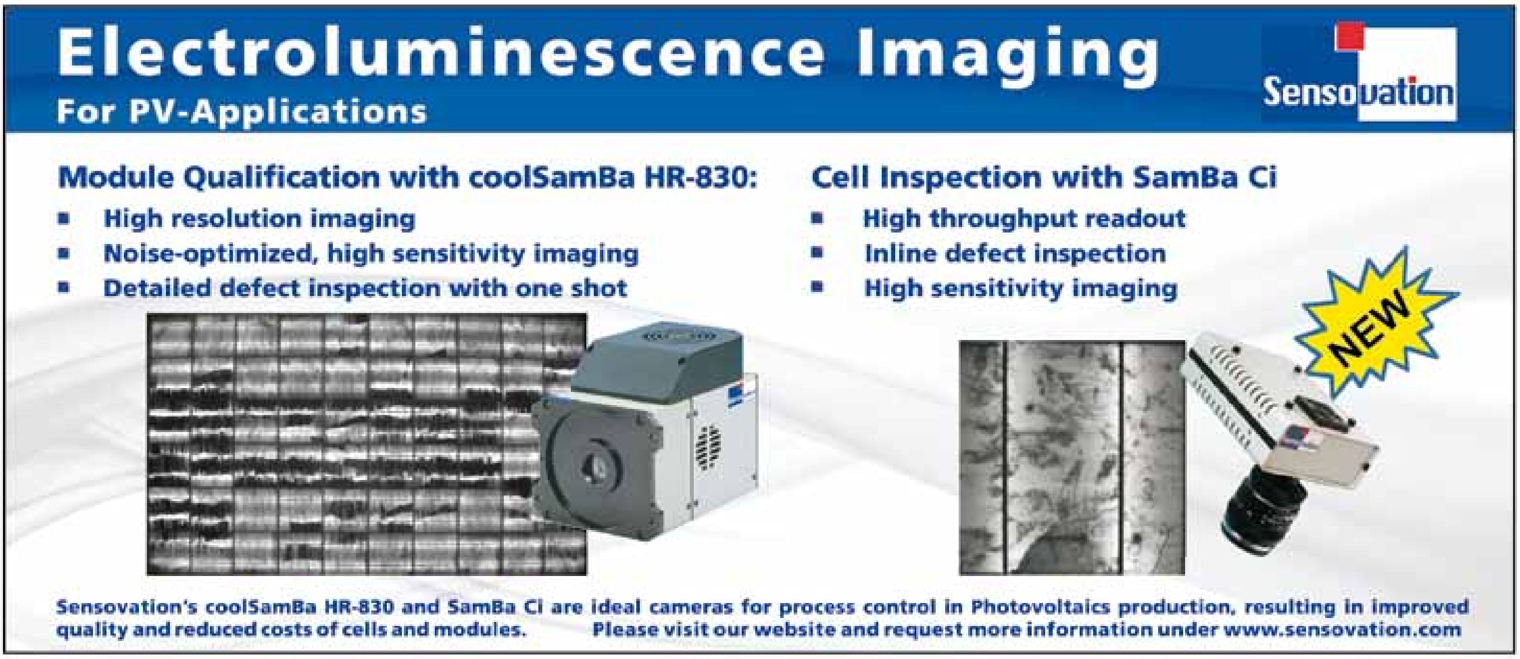

Figure 6. Qualification of uncured EVA film as part of the inspection of incoming goods.

Such inspections are constantly performed during the entire production process up until final production of the module. Whether soldering, laminating or placing the connections socket or frame, inspections are always required to demonstrate that the processes are stable and that their results are within the predetermined parameters – for each and every solar module. The results are continuously recorded, saved in a production control system and made available to the company for evaluation and control via intelligent presentations.

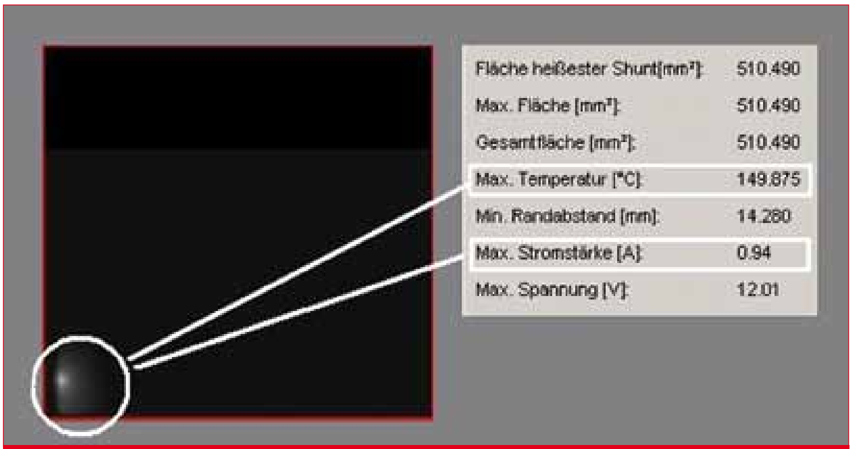

Figure 7. This specific cell passed all other final inspection tests but was rejected by a thermographic test for hot spot risk at the cell edge. The resulting test temperature here was 149°C.

Alongside these processes, the ‘ingredients’ are also decisive for the quality of the end product. For this reason, all essential product properties are precisely defined in quality agreements and specifications agreed upon with suppliers. High-quality products can only be consistently produced in a highly automated factory when stable materials are used within the permissible tolerances. The agreed properties of the components such as films, glass or frames are continuously ensured through internal measurements. Specially trained personnel with no other productive responsibilities are on duty around the clock specifically for this purpose.

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The specially developed batch tracing allows the tracing of the materials in each

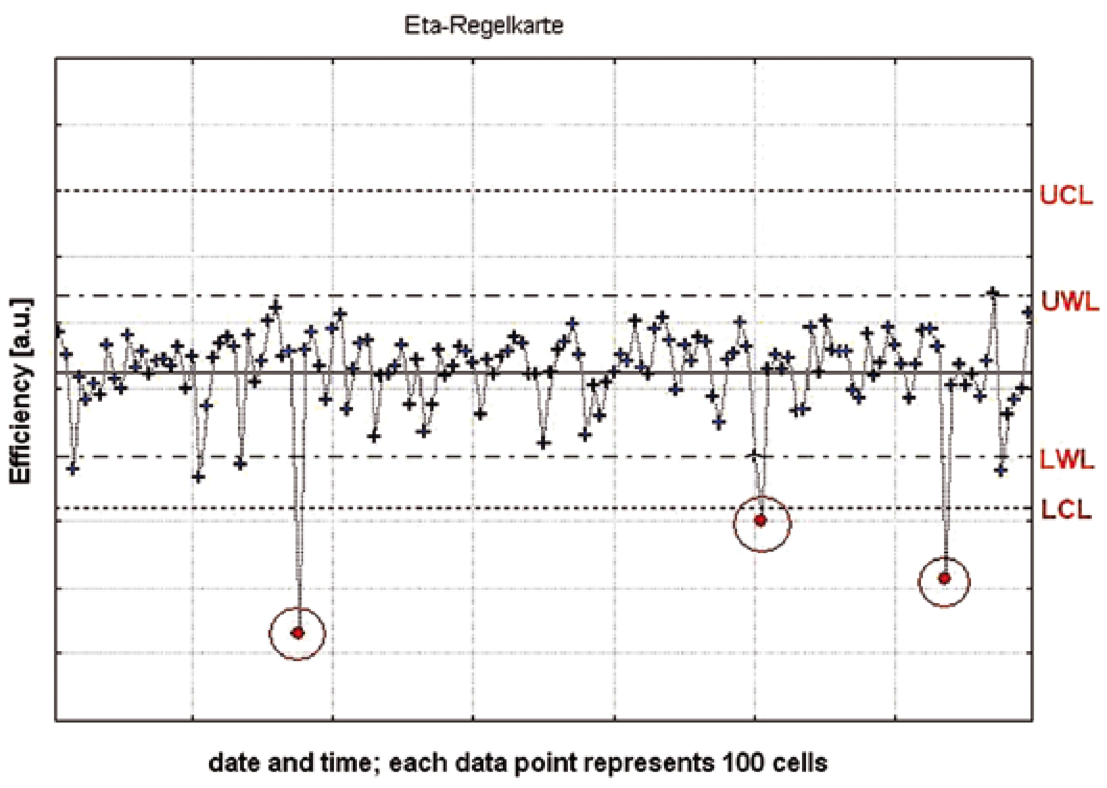

Figure 8. Real-time efficiency SPC control indicates an out-of-control situation but not the root cause.

module up to the batch number of the suppliers. The module factories maintain intensive cooperation with the solar cell productions, which are mostly located in the immediate vicinity, in terms of both current and future products. The concept of a comprehensive value-added chain and being a fully integrated corporate group pays off well.

Yield management in solar cell production

Solar cells are the core of crystalline silicon modules and the most important supply for module production. Their functionality basically determines both the module power as well as long-term behaviour of the modules. The best way of maintaining cell quality under control is by keeping each process step and the incoming material quality under control. SolarWorld cell manufacturing supports the quality control with an integrated MES and SPC system over the whole process chain.

Outgoing quality control

Before any cell leaves the solar cell manufacturing process for the module

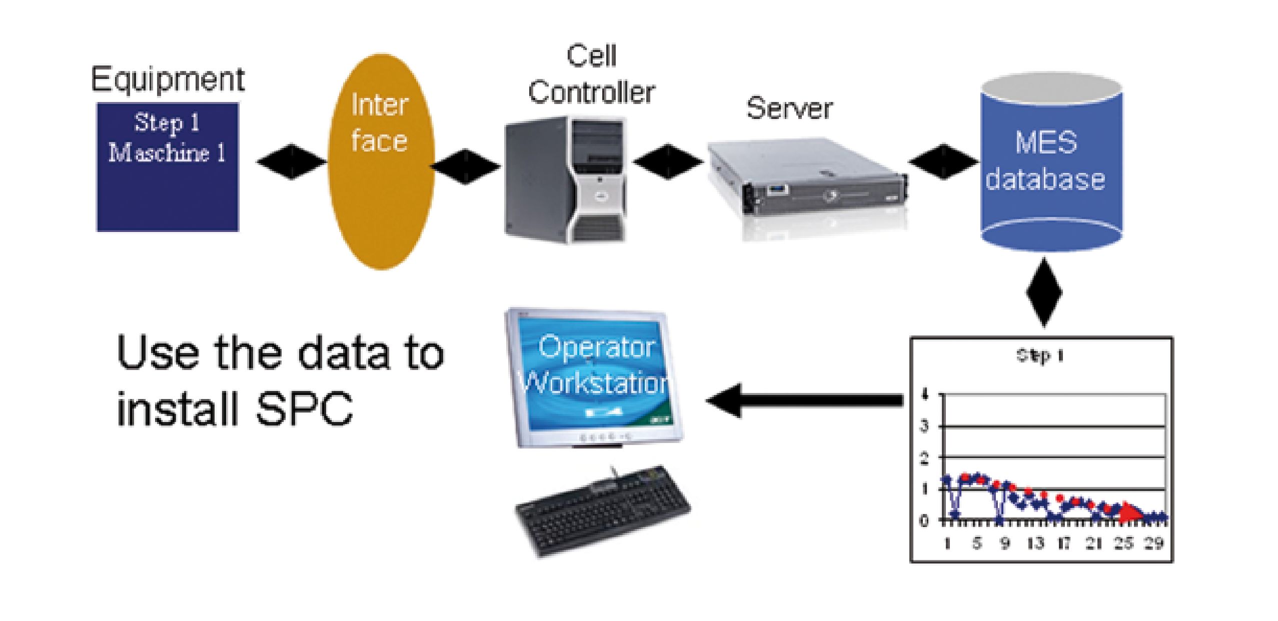

Figure 9. All measured data are collected in a database.

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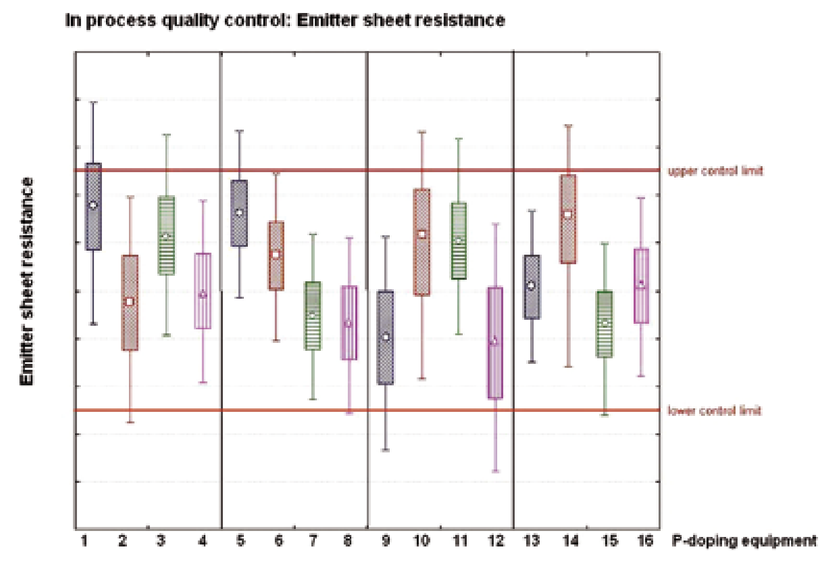

Figure 10. An automated variation analysis enables keeping different equipments of one process step under control.

manufacturing process, a final quality control takes place. This includes the measurement of its output power, the evaluation of its optical appearance and final breakage inspection. All data are stored to a database and can be recovered by reference to their shipping box.

Having passed all these tests, a solar cell still may have a small risk of generating hot spots when it is operated under the reverse current condition, for example, partial shading as a result of falling leaves or just a tree that casts a shadow. SolarWorld applies a thermographic test method to detect and reject such cells.

In-process quality control

The SPC control of completed solar cells just indicates out-of-control situations, but cannot support the root cause analysis. This can be done only with real time SPC for critical process parameters of individual process steps.

Following this approach, the SolarWorld cell manufacturing is covered with inline process control for each process step. All measured data are collected in a database. Key parameters automatically undergo analysis of variance (ANOVA) for the different equipments, with SPC or other analytic methods based on the data submitted to the MES database. This approach enables keeping several items of production equipment under control and supports the continuous improvement process.

As a result of having all individual process steps under control, the outcome in terms of yield and efficiency is very stable and predictable.

Incoming quality control and tracking

Wafer quality is key to cell quality. There

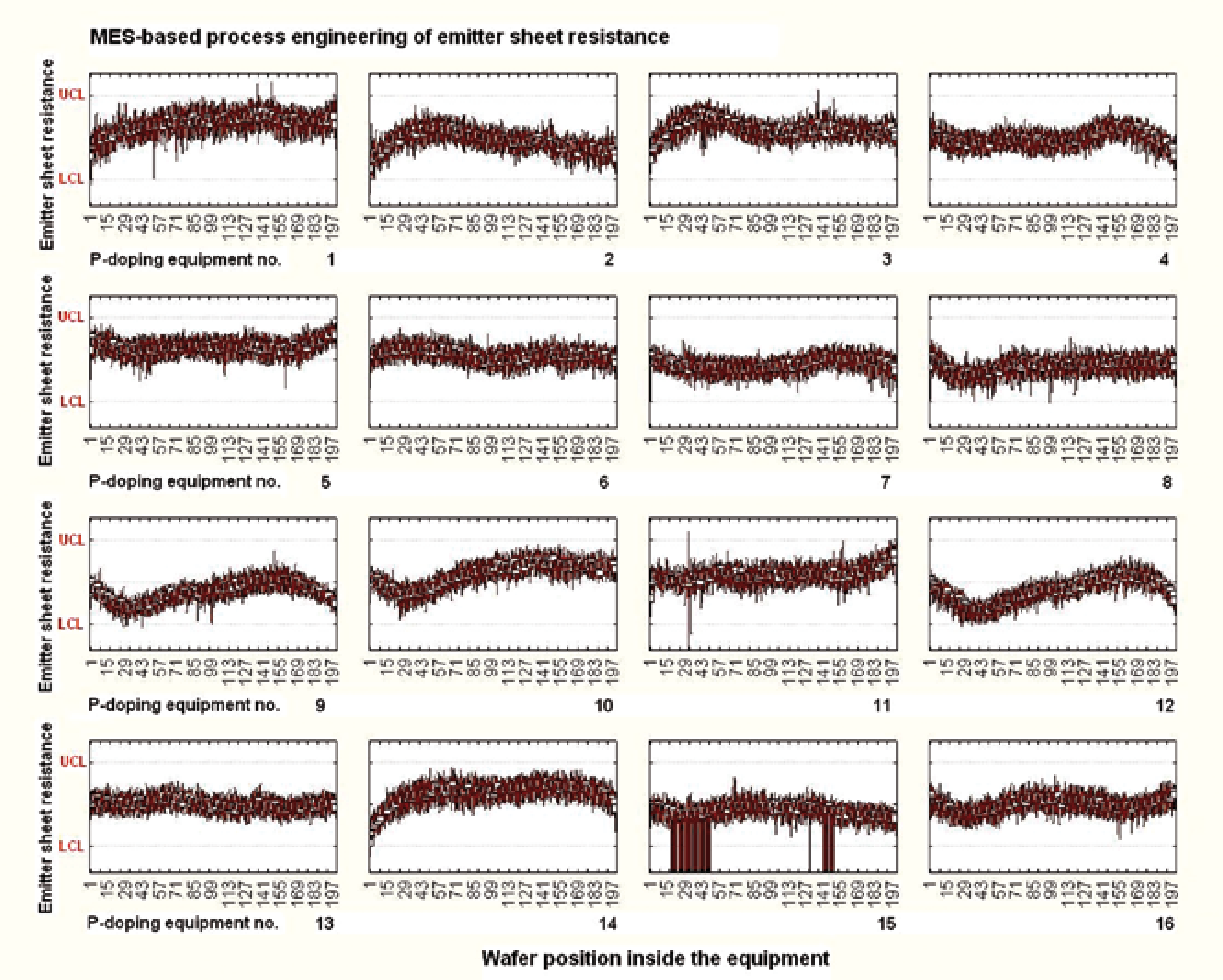

Figure 11. With MES support it is possible to visualize the wafer-to-wafer emitter sheet resistance within one process batch or as an average of many processed batches.

are different inspection tools available to inspect wafer quality characteristics such as dimension, resistivity, charge carrier lifetime (as an indicator to cell power), and micro crack (for breakage prevention). A standard approach, like in other industries, involves a final inspection on the part of the wafer supplier of the product quality. Together with our suppliers, we define and develop techniques and parameters and we audit our supplier regularly.

After incoming inspection, all of the wafers get a virtual identification number and a description of their wafer history when they are checked in to the cell manufacturing process. Wafer performance is thus tracked and in case of any deficiency followed up with its supplier.

Requirements for equipment

Yield management and quality assurance techniques and processes need production equipment that enables stable production processes and process controlling. The production equipment itself has to comply with highest quality standards: quality products can only be made using high-quality equipment.

Integrated equipment structure

First of all, the integration of quality control equipment into all process and handling equipment is mandatory. Integration means not only a physical build-in, but also a logical integration into the process control (rather than only a data connection), since a lot of hand-shaking between process, handling and quality control equipment is necessary. A production unit for a certain production step consists of several sub-units or equipments. However, it must work and feel like a unit, i.e. the user interface should be uniform and the manufacturing execution system should be connected via a single interface to the equipment, including all sub equipments.

> "Working under pressure to get a tool up and running, problems can be fixed ineffectually, and changes can be shoddily documented, or not documented at all."

First pass yield and documentation

Nevertheless, even more basic requirements exist. The PV industry is still such a young and rapidly changing industry, and standards are rare. In addition, issues in yield or productivity in production often arise from errors during installation of the production line. The following set of rules must be adhered to in order to ensure a first pass yield for equipment:

- Equipment is built as specified (all deviations from guidelines or specifications have to be approved)
- All test protocols are available before installation (safety guidelines, process and equipment functions, etc.)
- After installation the equipment is ready for process start-up (no software corrections etc. necessary)
- Communications between sub-tools and other tools are tested before delivery
- MES communication is tested in-house.

Often, a kind of on-site development starts after installation of production equipment. This not only leads to delays in ramp-up, but can hamper production permanently. The manufacturer can only know what is happening in a process (first bullet point above) if they know how the tools work. Working under pressure to get a tool up and running, problems can be fixed ineffectually, and changes can be shoddily documented, or not documented at all.

Documentation can not be underestimated. It has to be prepared before shipment and should (at the very least) contain:

- Risk and hazard analysis; electrical and functional plans

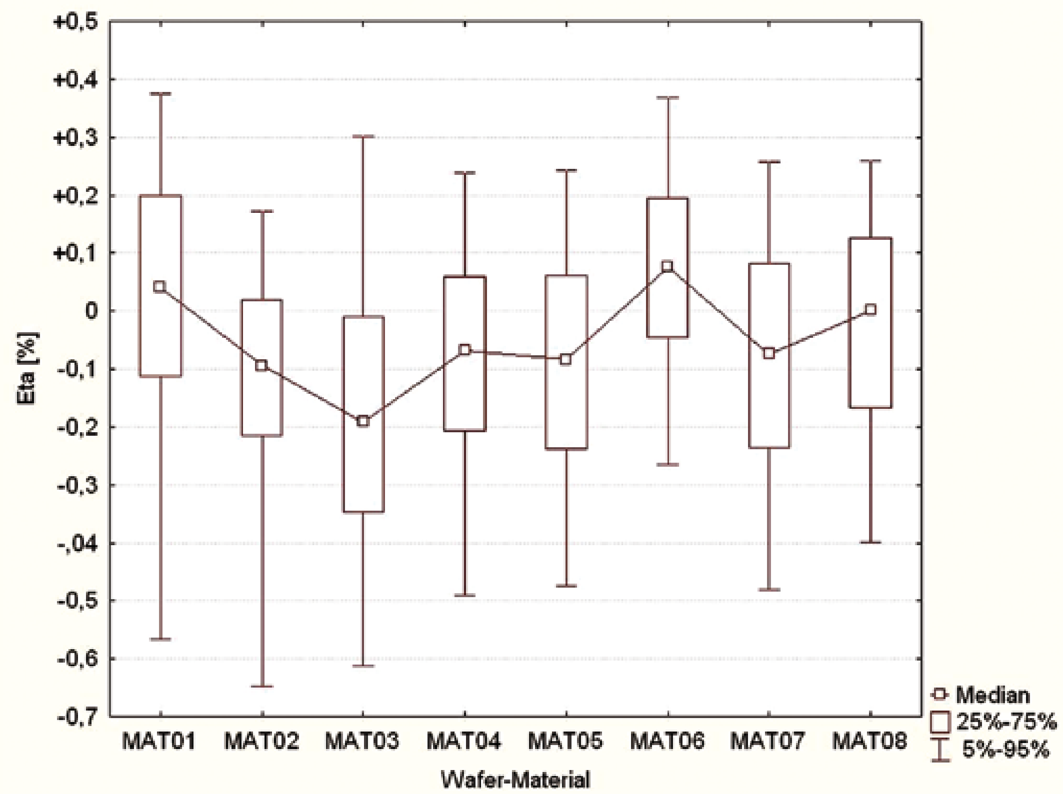

Figure 12. Tracing back cells to their wafer origin enables a real wafer quality control.

- Operating instructions, process and equipment functions, interface and hand-shaking protocol
- Maintenance plans and instructions, and detailed spare part lists with MTBF.

Support

To ensure the highest possible quality of a product, the producer and supplier must work together closely. What is true for material suppliers is also true for equipment suppliers, and this cooperation should not stop after the equipment acceptance test. A high-quality production needs qualified support, including qualified training of equipment engineers, service technicians, and operators (of all shifts) as well as on-site service at least in the first months after ramp-up and a 24-hour hotline, service response and spare parts delivery.

Outlook

Thirst for knowledge and the drive to establish solar energy supply at a competitive price have improved technology in photovoltaics in the past. With bright and dedicated people with good ideas, techniques for fabrication and for quality assurance have been established and yield management techniques have been adapted. At SolarWorld, we were the first to establish a sustainable quality assurance along the whole value-added chain, from silicon to system, by quality control of all (interstage) products and supplies as well as after every single process step. Together with comprehensive MES and thorough SPC in mass production, statistically sound analysis from individual process steps to the overall manufacturing is possible. We not only know what we are doing, we even control it. And a lot of others in the PV industry follow this approach.

Economical pressure is forcing all players in the industry to follow this route to higher quality and higher yield at an ever-increasing pace. Not only is there room for improvement; there is a burning need for improvement. The interdependency of supply material, process equipment and end-product is so important that the interaction between supplier and customer, between equipment manufacturer and production company, between the different stages in the value-added chain will increase further and the optimisation of all products and processes will strictly focus on the final product for the end-user. This customer-oriented, quality-focused, integral approach is the basis for yield management at the highest quality level in mass photovoltaics production.

About the Authors

Ralf Lüdemann is Managing Director of SolarWorld Innovations and SolarWorld Industries Deutschland. Within the SolarWorld Group, he is responsible for global R&D and strategic technology and product development. Prior to this role, he was in charge of establishing and operating SolarWorld's solar cell production Deutsche Cell. Ralf Lüdemann is curator of several research institutions and gives lectures at the University of Freiberg.

Dr. Ute Mareck, Dr. rer. nat. studied chemistry and semiconductor materials at the University of Leipzig. From 1992-2007 she worked on wafer technology and quality assurance in the semiconductor industry. Since 2007 she has been responsible for quality assurance at Deutsche Cell, the German cell manufacturing company of SolarWorld.

Michael Eberspächer has a diploma in electrical engineering and completed his postgraduate studies with an M.B.A. For over six years, he has worked at Solar Factory GmbH, the module producing company of the SolarWorld Group. In his current position as Head of Quality Assurance (Module Production), he is responsible for, among other aspects, the MES (Manufacturing Execution System) and statistical evaluation.

Enquiries

SolarWorld Innovations GmbH
Berthelsdorfer Strasse 111a
D-09599 Freiberg
Germany
Email: info@sw-innovations.de
Website: www.solarworld.de