Wafer, cell and module quality requirements

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ABSTRACT

Standardized requirements for the quality of PV modules, solar cells and wafers are given in the according IEC norms (e.g., IEC 61215, 61646, and IEC 61730 for modules). However, the manufacturers of cells purchasing wafers and the module manufacturers purchasing cells want information beyond the final check of the product and to monitor each step during the production process to identify harsh handling and/or machine faults at the earliest stage possible. With consequential improvements of the process enabled, continuous improvements in throughput and yield improvement of the factory are likely, also allowing an early feedback on quality issues to the raw material supplier. Furthermore, by knowing all characteristics and factors of the cell and the module, prediction of electrical energy yield during the life cycle of a PV power plant is becoming more accurate and more reliable.

Conventional production process

Conventional quality control during the production process of wafers

During the production process, the typical quality monitoring, like the resistivity measurements before and after crystallization, have a limited µ-PCD lifetime determination (see Figure 1). A weight control of the wafers at the end of the process allows checking of the dimensions of the wafer (length, width, and in particular, thickness) and mechanical defects (e.g., torn edges). By using a visual inspection unit, relatively large cracks and severe process irregularities can be detected. These checks cannot identify micro-cracks in the final wafer which are crucial for the performance of the final solar cell and its vulnerability to mechanical stress within operation lifetime.

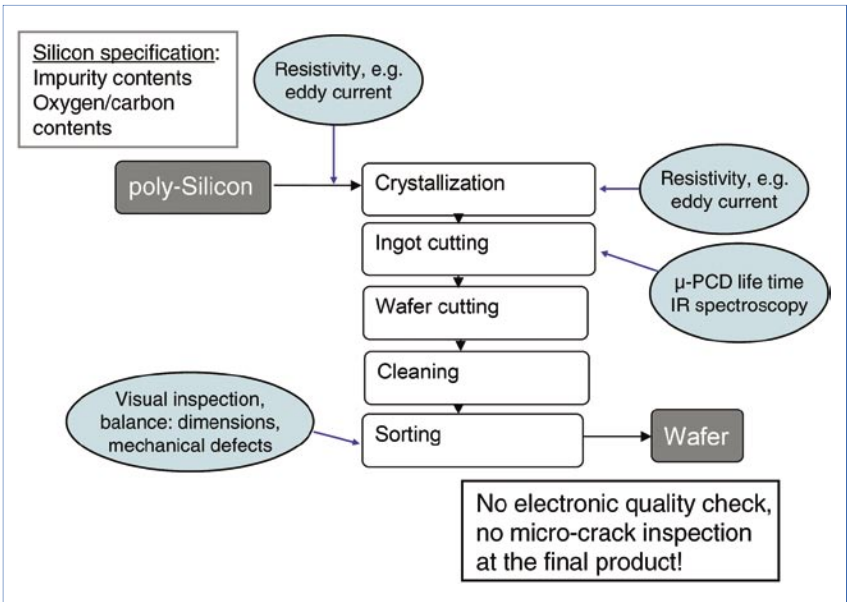

Figure1. Conventional quality control at wafer production.

Conventional Quality control during the production process of cells

During the production process, which is shown in Figure 2, typical quality monitoring is rather limited. At delivery, the incoming wafers are checked for mechanical defects and their dimensions. After wet etching (in order to take away the damaged area from sawing) and the diffusion process (usually where an *n*-type dopant such a phosphor is diffused into a *p*-type substrate), electric sheet resistivity is measured to control the correct amount of doping and diffusion. After de-oxidation (the wafer has been oxidized during its treatment the diffusion furnace) and edge isolation, silicon nitride (SiN_x) is applied as an anti-reflective coating (ARC) on the cell. While the wavelength of maximum absorption (minimum reflection) is given by the thickness of the ARC layer, the reflected part changes its visual appearance (by a slight change in color) that is typically used as a control method for the layer thickness. Also, the quality of the screen-printing process is controlled mainly visually. At the final stage, the cell is flashed to determine its maximum power output P_{max}, the short circuit current I_{sc}, the open circuit voltage V_{oc}, the series resistance R_{series} and the internal shunt resistance R_{shunt}. A supplier feedback can be given only after these test stages.

Quality control via electroluminescence (EL) and photoluminescence (PL)

Principle of EL and PL

Electroluminescence (EL) is the use of a solar cell in a reverse format as it was originally designed. Instead of converting irradiance into electricity, at EL, electricity (supplied via the cell's electrical contacts) is converted into IR-radiation that is emitted via the cell's surface. The intensity of the radiation emission is an indicator for the local efficiency and quality of the conversion process. This method works well for cells and modules, but not for wafers. However, with wafers the radiation emission can be provoked by absorbed photons at a smaller wavelength: the so-called photo-luminescence (PL).

History

PL was discovered at first as a tool for the detection of faults and defects at wafers and solar cells [1]; however, older publications exist that discuss photoemission microscopy (PEM) for failure analysis in microelectronics. During the last two years, a considerable increase in popularity and application of EL and PL could be observed [2]. Meanwhile, EL and PL are even used to identify specific defects, e.g., using PL for the exposure of problems with grid fingers and the related screen-printing process [3], or for the selective identification of defects and faults in cells via electroluminescence

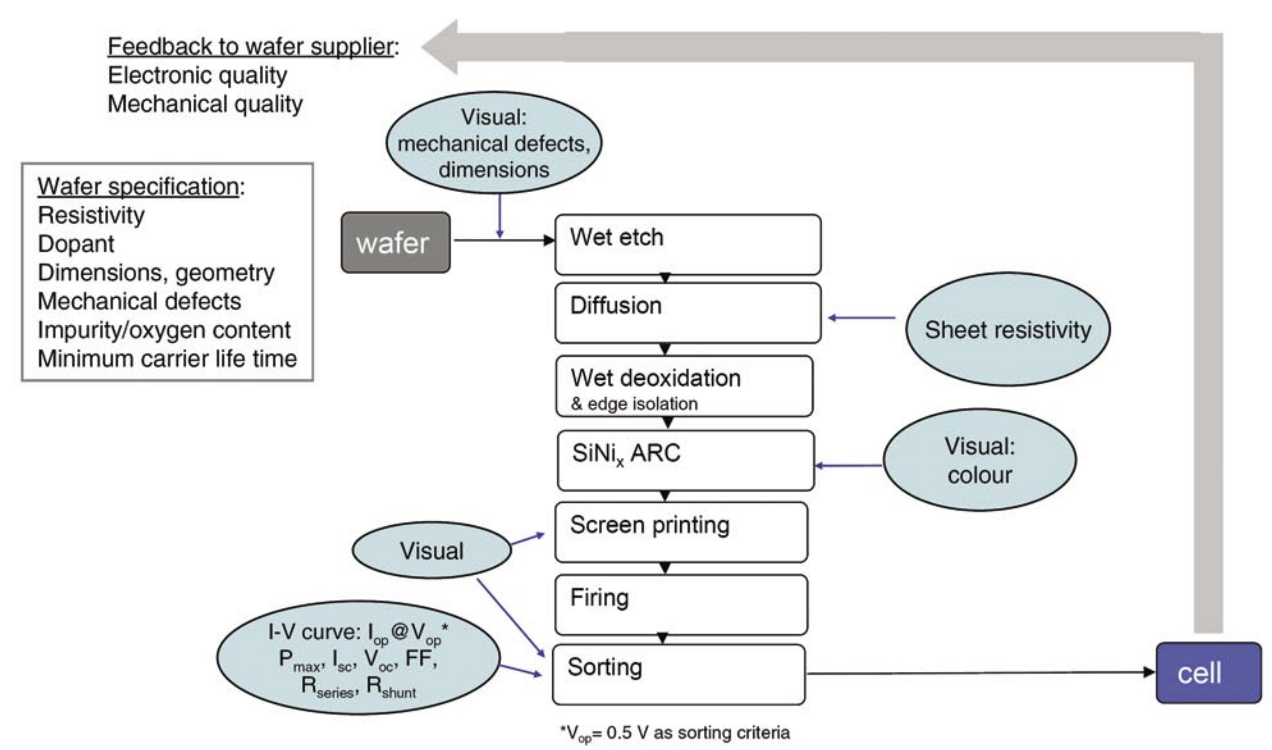

Figure 2. Conventional quality control at cell production: feedback to supplier of wafers only after finished cell; no intermediate quality control possible.

differentiated in temperature [4]. A further method [5] strove to find defects by the detection of longer wavelengths. The original electroluminescence radiation works mainly for cells but not for modules, while the cover glass of the module is opaque for wavelengths longer than 1,200nm.

Application of EL and PL

This section shows effective applications of EL and PL in a production line to quickly diagnose typical problems as shown in Figure 3, to reduce stop times and increase production yield. It allows fast feedback to the operators, production equipment manufacturers and suppliers of raw materials.

The consequent use of PL and EL along the production process of a cell is demonstrated in Figure 5. As early as at delivery, the incoming wafers can be checked for hidden micro-cracks or poor electronic quality via PL; in the case of insufficient wafer quality the wafers can be returned straight away to the supplier, thus saving time and money, as the following processing steps are aborted in a very early stage. The same is true for the result of every subsequent treatment (diffusion, wet etching, ARC application, screen printing, firing). If errors are detected via PL, the location of the processing station where the faults are caused is identified at once, and action to solve the problem can be taken immediately.

The suggested locations for the use of EL cameras within quality control during module production are shown in Figure 6.

As for cell production, a quality check at the delivery of the incoming cells is carried out.

Cost-benefit ratio of tools and methods for quality control

Even relatively small gains in power output and energy yield are advantageous, though the suggested methods are relatively cheap, especially taking into consideration the actual costs and production output of state-of-the-art production lines for cells and modules.

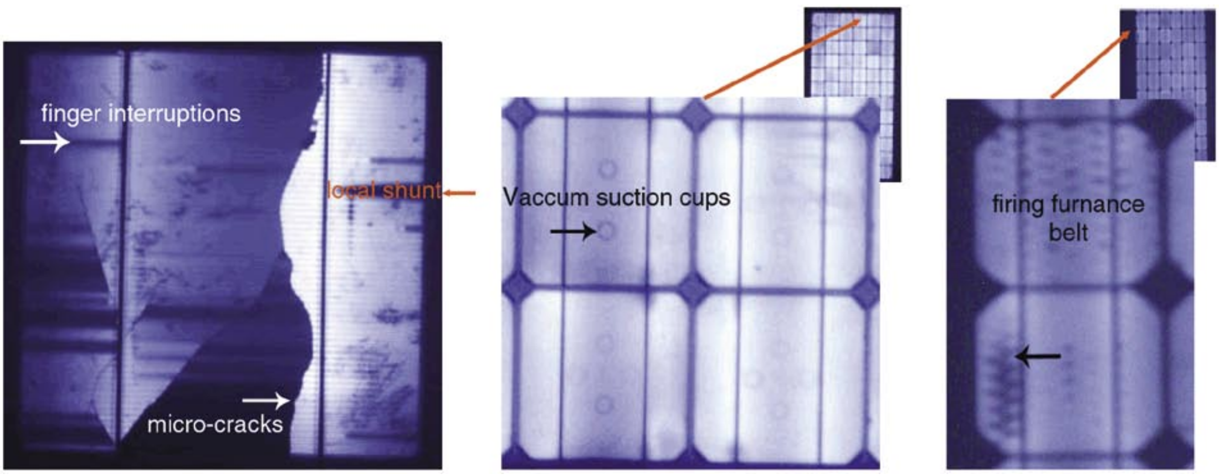

Figure 3. Examples for electroluminescence (EL) as a useful tool for the detection of suboptimal production processes and inadequate cell handling (close-up images of entire module EL photos).

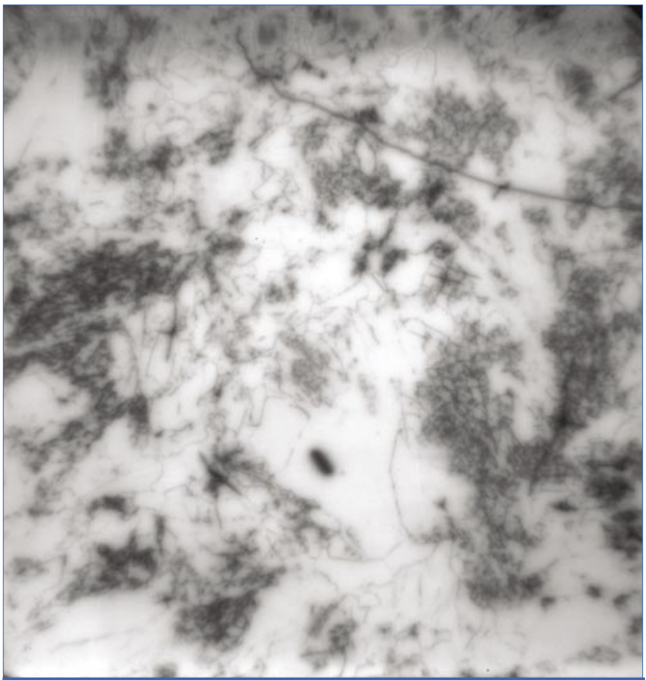

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Figure 4. Photoluminescence (PL) as a tool for the detection of suboptimal production processes and inadequate cell handling (see T. Trupke et al [2]).

Example

A prominent illustration of the positive results of quality control via a closer monitoring of production is the binning of cells or modules in power classes, thus reducing mismatch reduction in the module or in the system and increasing power output and yield. Cell sorting in 0.2% steps for cells between 14%-17% leads to 3% more in average module power. The price for such a sorter is within 3% of total investment costs. At present, cell prices for crystalline cells (ex-factory) are about €2/Wp, while module prices are approximately €3/Wp. For a factory with a production capacity of 30MWp per annum, the gain of 3% more saleable power is a gain of 0.9MWp, worth €2.7 million per annum.

Cost-benefit ratio for PL and EL

The threshold for an investment (e.g., for EL equipment) of €100,000 per annum to achieve a positive cost-benefit ratio is reached for a yield improvement of 0.1%. For an expected lifetime of the system of five years, and an increase of 65% of the product price as implementation and operation cost, a produce price of €300,000 is covered by the 0.1% yield increase.

Results

The procedure for energy yield simulation is shown in Figure 9. The accurate simulation of direct and diffuse irradiance via their spectral-spatial appearance allows for an accurate representation of the module reaching irradiance. After passing the different layers of the encapsulation, being reflected according to the Fresnel laws - considering actual incidence angles and refractive indices - this irradiance forms the cell-reaching spectrum. The photo-electric conversion efficiency depends on matching of the cell-reaching spectrum with the cell's spectral response and the actual operating cell temperature (which is derived from a balance of energy flows of absorbed irradiance, electricity generation, and heat dissipation).

An example of the course of conversion efficiency during a single clear day is shown in Figure 10 for a multi-crystalline Si-module installed in Northern Africa. An interesting effect is that the inclination angle of the module is not influencing the irradiance on the plane of the module, but also has a significant effect on the convective heat transfer of the module. For horizontal mounting (module elevation angle: 0°), the convection capability and convective heat transfer at the module are reduced, thus causing high operating cell temperatures and a considerable dip in conversion efficiency around noon. This

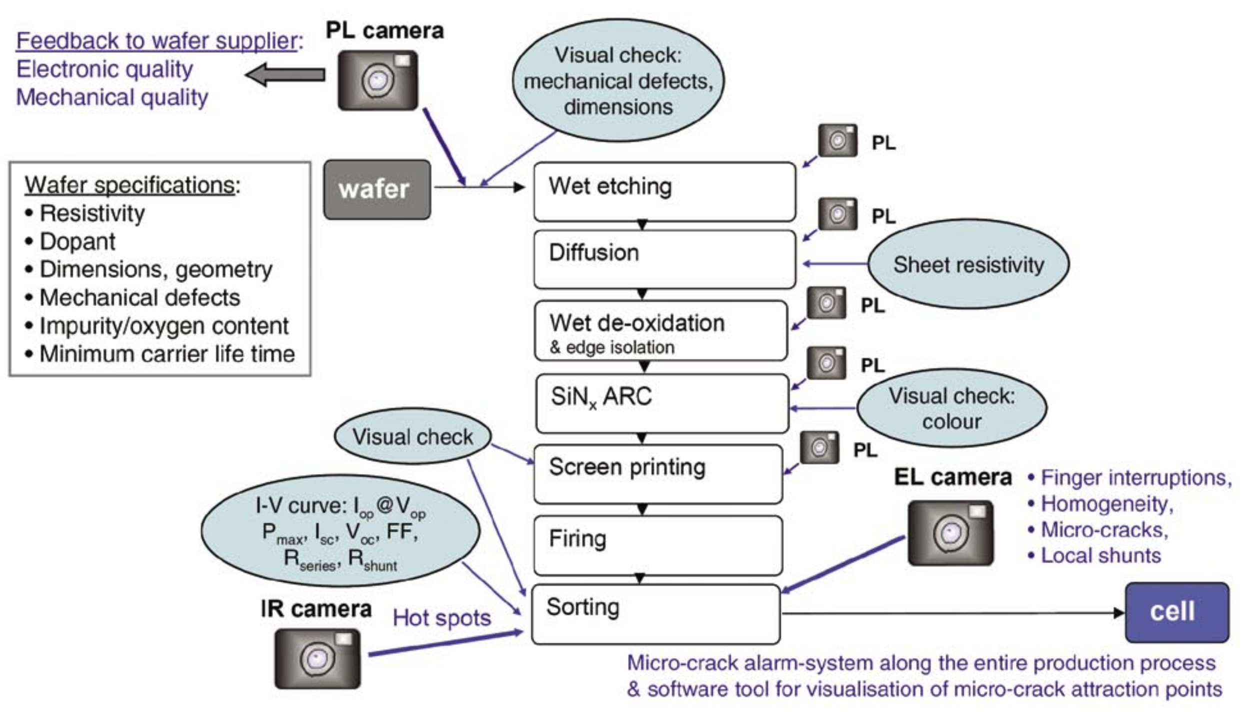

Figure 5. Enhanced quality control during cell production process via Electroluminescence cameras (EL) and Photoluminescence (PL) cameras.

dip is drastically reduced for more inclined modules, allowing an effective flow of air and convection along the module.

The minima of conversion efficiencies 20 minutes after sunrise at 6 a.m. and 20 minutes before sunrise at 6 p.m. can be explained by the extremely flat angle of incidence of the direct irradiance during that part of the day. This example shows how the quality of yield prediction depends rather on the comprehension of the entire optical-thermal-electrical composition of the installed PV panel than on the knowledge of an isolated PV module.

Conclusion

The tools presented offer an excellent cost-benefit ratio. The expected minimum yield improvement is in the vicinity of 1%, but already a yield improvement of 0.1% would justify the investment of €100,000 in a 30MW combined c-Si cell and module line at today's (2008) pricings.

Electro- and photoluminescence are powerful tools for fast in-line imaging of electronic and mechanical properties on wafers, cells and modules, allowing for a fast detection of process faults and handling errors and enabling a quick feedback (with a proofing image) to the suppliers of raw materials and to the providers of production and handling equipment.

Thus, the highest benefit is expected for micro-crack detection, in particular

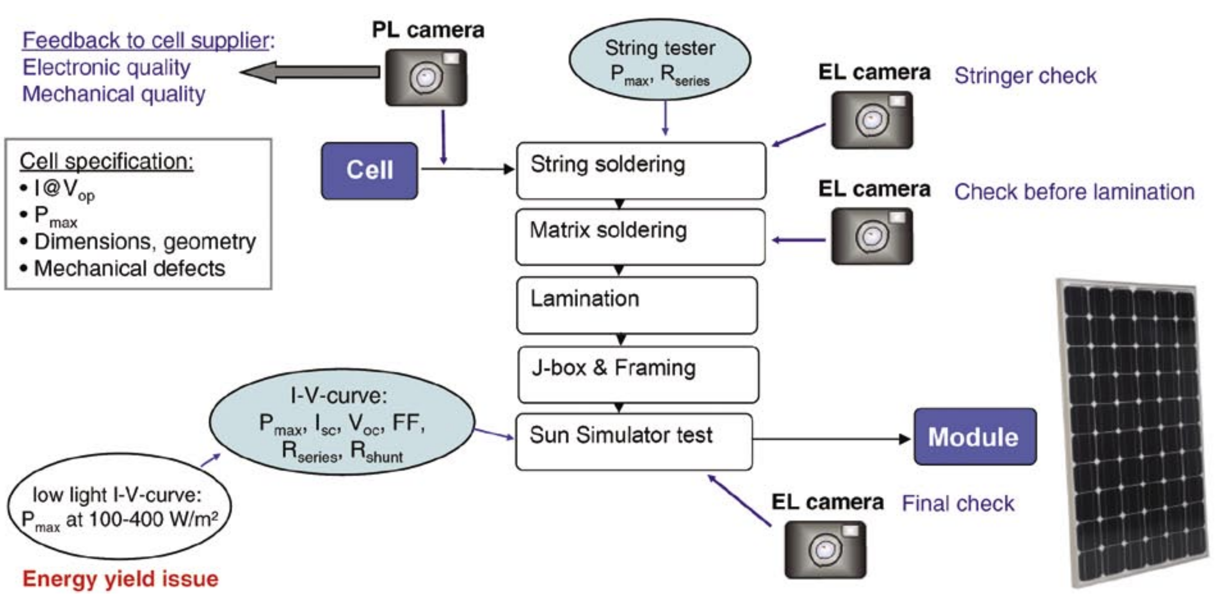

Figure 6. Enhanced quality control and collection of yield parameters at module production via three electroluminescence cameras (EL) and one photoluminescence (PL) camera.

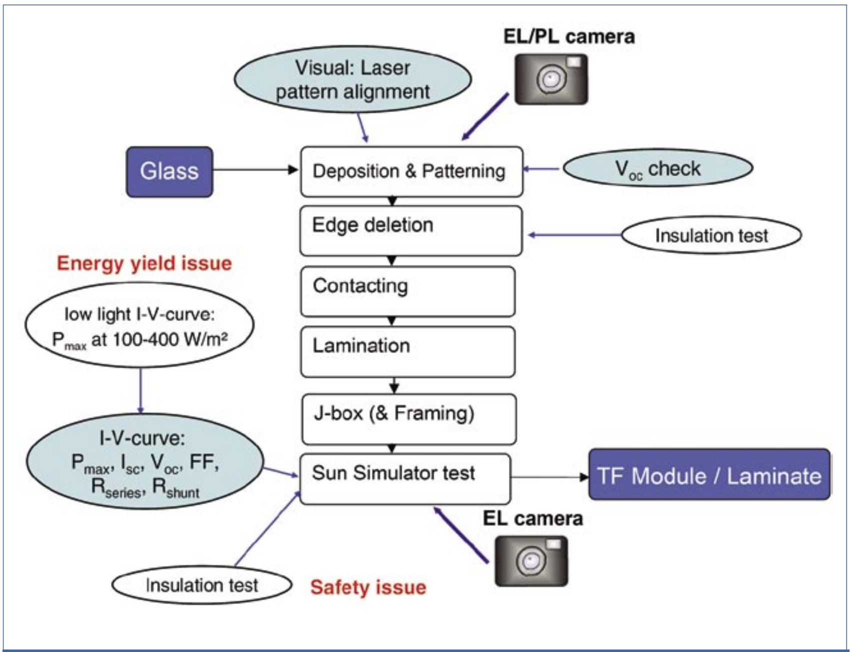

Figure 7. Enhanced quality control and collection of yield parameters during thin-film (TF) module production process via electroluminescence (EL) and photoluminescence (PL) cameras.

for highly automated production lines. As CCD cameras are used, they can be combined with or replace conventional visual inspection stations.

Outlook

Safety risks (i.e., hot spot and isolation) and energy yield potential of the finished modules are important product properties in the field and should be covered with similar investment efforts (recommended product strategy).

Electro- and photoluminescence are powerful tools for fast in-line imaging of electronic and mechanical properties on wafers, cells and modules.

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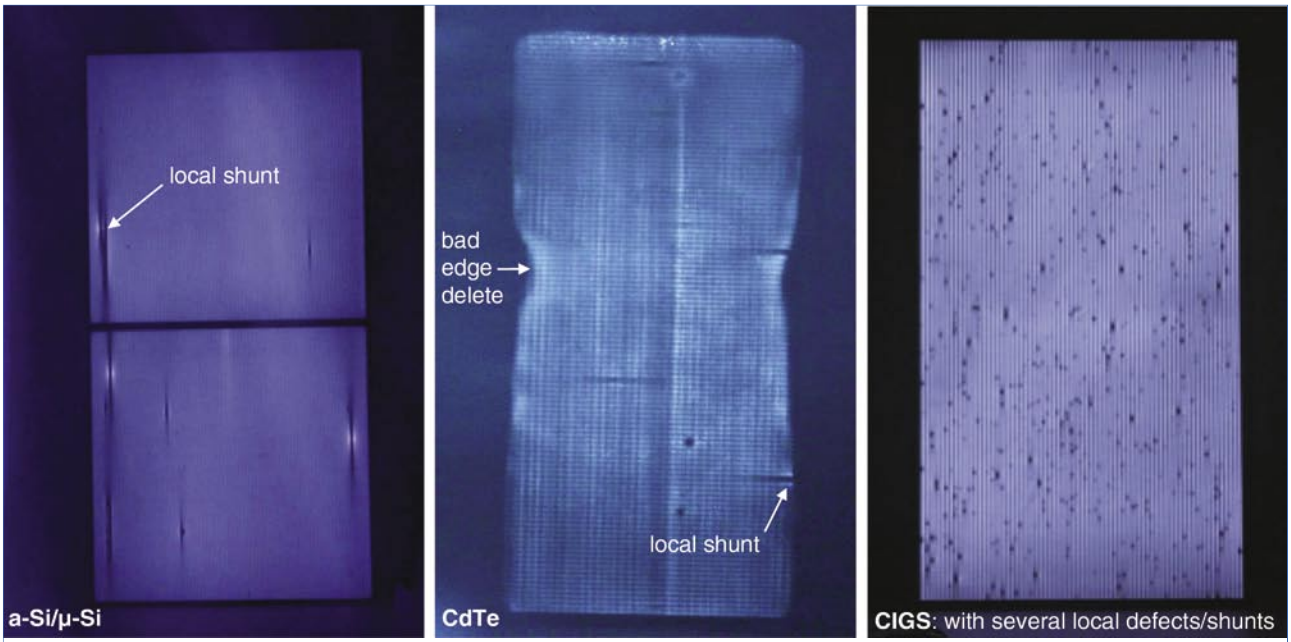

Figure 8. Electroluminescence (EL) pictures and visibility of process faults during production of thin-film modules with different technologies (a-Si/μSi, CdTe, and CIGS).

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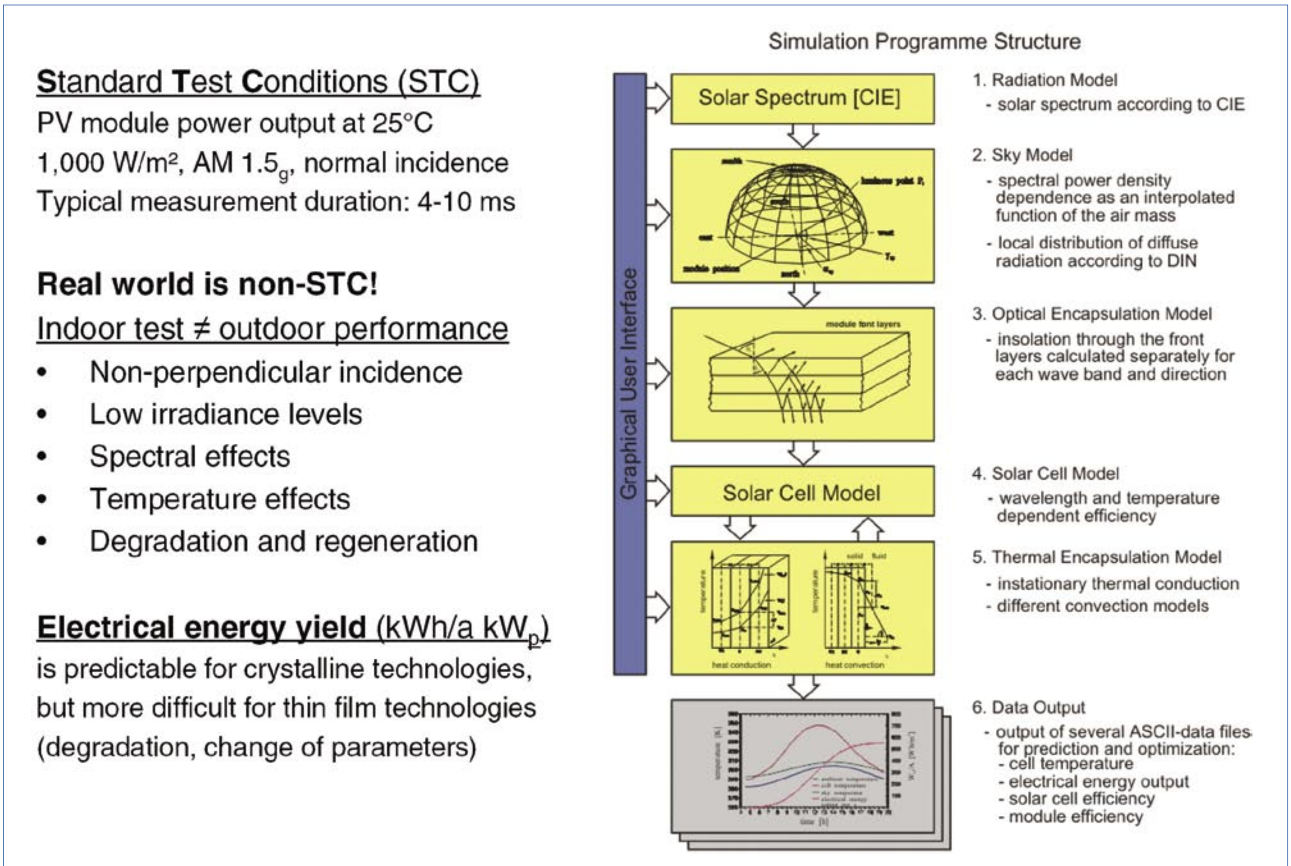

Figure 9. Yield becomes more important than power output at STC: Structure of a state-of-the-art simulation.

About the Authors

Prof. Stefan Krauter received his Ph.D. in electrical engineering from the University of Technology Berlin (TUB) in 1993. In 1996 he co-founded Solon, and 10 years later – after a visiting professorship at UFRJ and UECE in Brazil – he co-founded the Photovoltaic Institute Berlin, for which organisation he acts as a senior consultant and sits on the board of directors.

Dr. Grunow received his Ph.D. in physics from the Meitner Institute and Free University Berlin (FU-Berlin), and carried out his post-doc studies on thin-film solar cells at the Federal University of Rio de Janeiro in Brazil (UFRJ-COPPE). He co-founded Solon AG in 1996 and, together with Reiner Lemoine, founded Q-Cells AG in 1998. In 2006 he co-founded the Photovoltaic Institute Berlin where he sits on the board of directors and acts as a senior consultant. He also is a lecturer at the University of Applied Sciences for Technology and Economics Berlin (FHTW).

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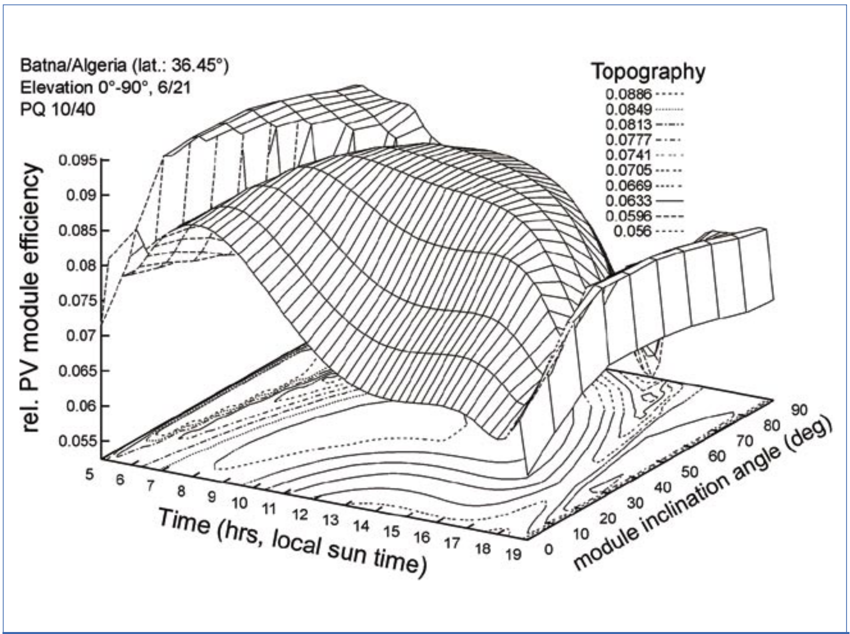

Figure 10. Results of a real-world simulation of a PV module showing the course of PV conversion efficiency during a day as a function of inclination angle of the module.