



Photo: KLA Tencor

A print inspection system integrated into a screen printing machine. The system had to be designed with a 90 degree angle in order to fit into the machine's housing.

## Optimum optics

**Optical inspection systems for cell production (inline):** These systems work without contact, are quick and can provide vital information to solar producers. Despite the prowess these systems have, there are still certain issues in need of rectification. How does one assess these systems?

Ten years ago marked the beginning of the age of automated production of solar cells in Germany. Centrotherm and M+W Zander delivered the first turnkey production plant to Deutsche Cell and shortly thereafter, Q-Cells began installing automated production lines at breathtaking speed. This rapid expansion of production volume was only possible with reliable production technology whose processes could be minutely regulated and controlled. Even today, these traits are the essential basis for the incredible growth in production capacity of crystalline silicon solar cells. Process reliability must not be traded off against a safety margin. Processes must instead be opti-

mized to the limits of feasibility. At today's prices, an increase in cell efficiency of 0.1 percent absolute in a 50-megawatt-per-year production line translates to an annual cost saving for the cell manufacturer of over 200,000 euros. An increase in yield of one percent absolute brings an additional profit of over 350,000 euros per year. Processes must therefore be monitored directly and immediately; process fluctuations must be detected as soon as they occur, and locations where there is a risk of wafer breakage be identified as early as possible. Optical inspection systems are contactless measuring systems that can be integrated into automatic production machines, making them ideally

suited to carry out the monitoring function. However, optical inspection systems are capable of much more. They are generally connected to powerful computers that can collect, store, process and export data and images. In cell production, optical inspection systems are therefore an important tool used by process engineers to characterize the process by means of data and to quickly identify process variations on the basis of meaningful random samples, a capability essential to systematic process optimization.

### Powerful data processing machines

The particular strength of optical inspection systems is their ability to capture the



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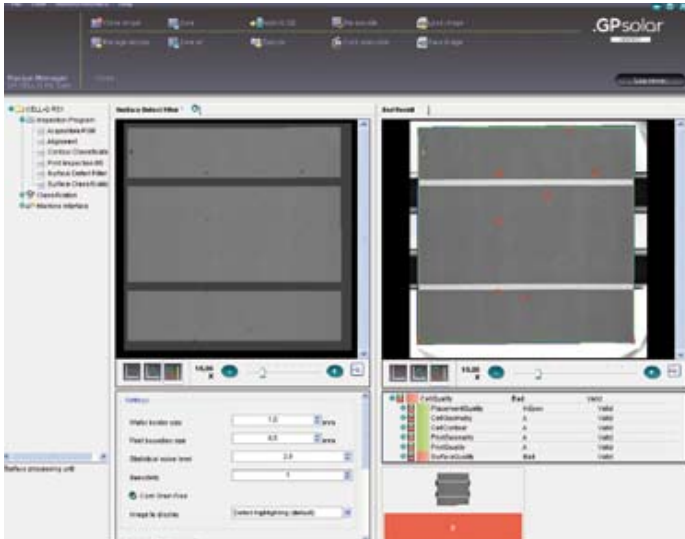


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Photos: GP Solar



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The monitor screen of an optical inspection system provides plenty of information on defects and defect statistics. It is necessary to present the data in an easy-to-grasp manner.

Details of a grid finger as seen by an optical inspection system. Writing software algorithms for producing a sensible reading for the finger width requires a good understanding of the printing process.

entire wafer or cell in a single step at production speed, and to evaluate the image information. This requires large-format cameras and powerful computers. The largest cameras are generally used for inspecting the frontside printed image. These are cameras with up to eleven million pixels (eight bits). With a cycle time of 1.5 seconds, this means a processing capability of about eight megabytes per second. The processing itself is generally extremely demanding and requires complex algorithms and many memory access operations. The processing software is highly sophisticated and extremely costly to develop. Optical inspection systems therefore carry a hefty price tag (50,000 to 120,000 euros) and are seldom used anywhere where simpler sensors and/or statistical process control will do the job.

**Locations**

- Typical locations of use and tasks are:
- Wafer inspection in the wafer stack splitter at the start of the production line; inspection of the wafer geometry, outside contour and surface flaws
  - Microcrack inspection in the wafer stack splitter at the start of the production line; search for hairline cracks and SiC inclusions in the wafer interior
  - Measurement of the SiN layer thickness and homogeneity following SiN coating after off-loading from the SiN process

- Inspection of the frontside printing on the metallization line; measurement of the finger width and print position; search for finger interruptions, paste stains and finger knots; check of outside contour to ensure it is intact
- Optional inspection of the backside print
- Inspection of the frontside of the cell in the cell tester at the end of the production line; optical assessment of color homogeneity, coloring, print image, outside contour and surface defects
- Optional inspection of backside

**Integration is the key**

To keep the cost of a production line as low as possible and minimize its footprint, optical inspection systems are integrated into the process equipment in the most efficient manner possible. Moreover, the closer the inspection is linked to the production process, the better the feedback to the process is. Machine builders therefore want optical inspection systems to be as small as possible.

Unfortunately, the laws of optics make extremely small optical inspection systems impossible. Lenses with low image distortions require an object distance of a few hundred millimeters. The inspection task often requires a particular light geometry that allows a high-contrast display of the object properties to be measured. Light generation is also subject to the laws of optics and thus often requires

adequate distance from the object. Optical inspection systems are therefore generally large boxes in which cameras, wiring, power supply units, and possibly lighting fixtures are housed and which shield the camera and solar cell from outside light as far as possible. Homogeneous background lighting is generally required, and must be integrated into the machine design.

An optical inspection system must be integrated into a production machine's process flow as well as its physical structure. The measurement results must be accurately attributed to the inspected cell. That may sound trivial, but it isn't. An optical inspection system uses highly complex internal software processes that are not always predictable in terms of duration and result. The software interface between the optical inspection system on the one hand and the machine into which it is integrated on the other must have an extremely robust design and be capable of handling any event that could possibly occur during operation. In fact, the biggest challenge in this respect comes from people, who intervene in the process and create conditions unforeseen by software programmers.

An optical inspection system should always be carefully selected in consultation with the supplier of the target machine. The measurement setup (lighting, camera, solar cell) must be capable of being integrated into a production envi-

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ronment, such as make laboratory conditions not required. The integration work must be planned with extreme care, and responsibility for the integration must be clearly established.

**Two peas in a pod**

Solar cells are normally produced in several similar, independent production lines set up in parallel in a factory. One line produces between 30 and 80 megawatts annually. A solar cell manufacturer therefore generally operates several optical inspection systems of the same type. It is natural to want identical systems to behave similarly in every respect. In practice, this means that a manufacturer's desire is to equip all same-type systems with identical inspection recipes, which are logically managed independently of the system.

Even with the most careful production and integration of the inspection systems, this desire remains unfulfilled. Production tolerances for cameras, lighting and mechanical components make it impossible to copy systems exactly. Manufacturers of optical inspection systems have therefore developed a strategy for controlling disparities among systems that are actually alike. Recipes are divided up into a device-dependent portion and a device-independent portion. The device-

dependent portion essentially comprises the calibration of all relevant measurements and dimensions, that is, the code for translating device-dependent data into device-independent data. This calibration should be recipe-independent.

Calibrations must be checked on a regular basis and repeated as necessary to maintain the reliability of the inspection systems. Optical inspection systems that have not resolved the issue of calibration and the use of device-independent recipes satisfactorily and in a manner that can be implemented in a practical setting are not suited for large-scale production with many production lines.

**How do I configure?**

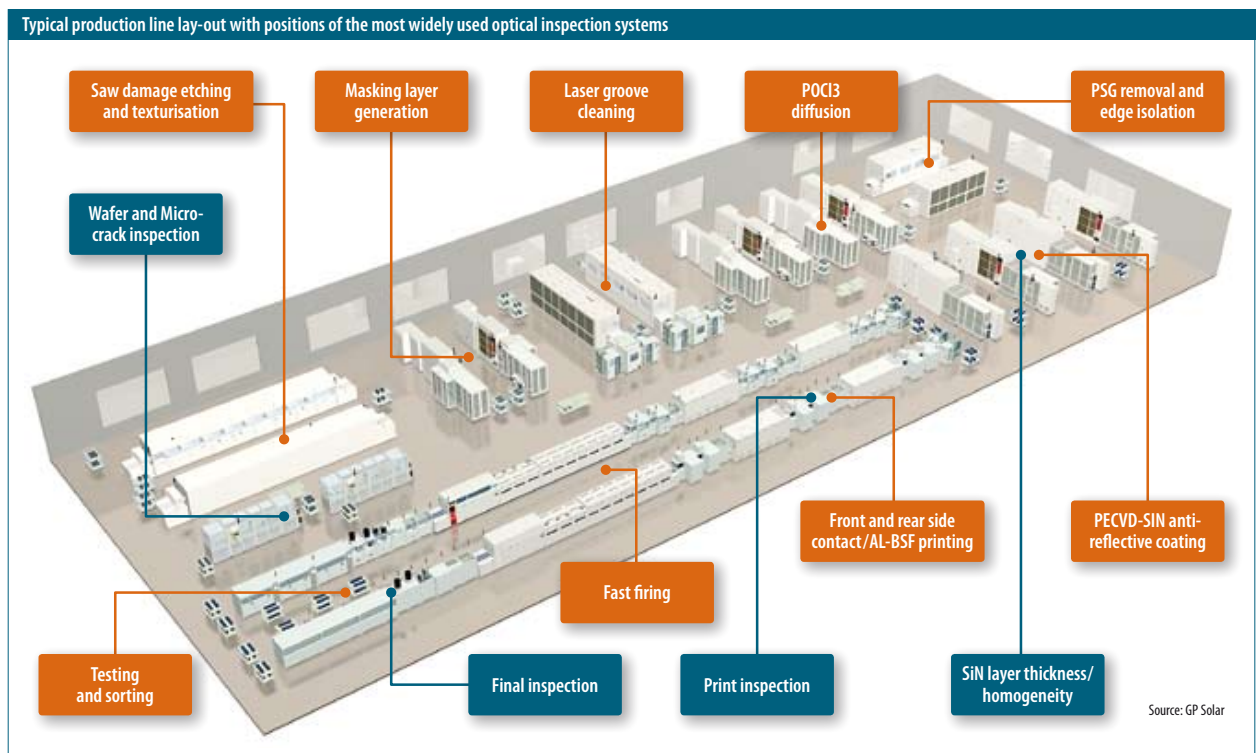
For the evaluation and assessment of images, the optical inspection system often rivals the most highly-developed human abilities to inspect images for defects and to evaluate these defects. One example: an optical inspection system is superior to the human eye in measuring the length of a finger interruption. However, the optical inspection system has difficulty capturing the optical impression evoked in the human observer by a cluster of finger interruptions on the solar cell.

The evaluation and assessment of the image takes place in several stages. The defects on the cell (finger interruptions

in our example) are detected and measured individually. In our example, the length of the interruption and its position on the cell are calculated. When all defects have been measured, the second stage, cell classification, begins. Based on the number, size, and position of the defects, any number of rules can be formulated, resulting in a classification. For example, one can define that cells with up to three finger interruptions below 0.1 millimeters (mm) in length belong to class A, but only if the finger interruptions do not form an "optical cluster," that is, only if they are not concentrated on one part of the cell. This is only one simple example. In real-world applications, any number of complicated rules of this type exist.

Alongside the difficult task of pouring these rules into software, the question arises for manufacturers of optical inspection systems as to how device users formulate the classification rules and communicate them to the device. Moreover, a suitable method must be found for logging the classification once completed, preferably exporting it as data, and presenting it to the user in an intelligible manner.

Finally, images or image details must store individual data and their relationships and present them in an organized manner. Each manufacturer has his own



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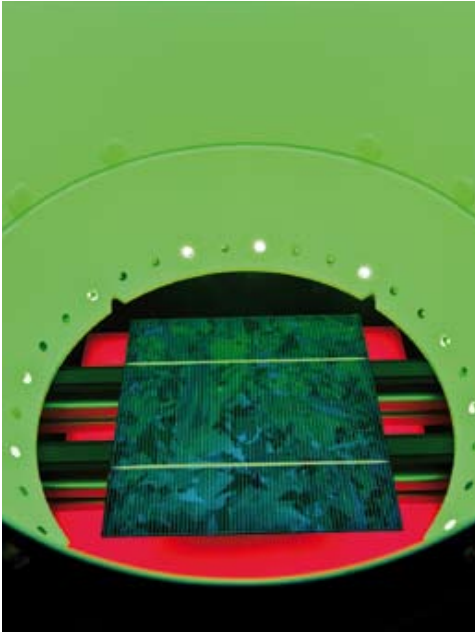
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The light-dome used by GP Solar represents a very consequent transfer of a typical laboratory set-up into the production line. The light-dome is a modified version of an Ulbricht sphere designed to create a homogeneous surface illumination. The shape is bound to be rather bulky.

method for solving this problem. There is even a variant that uses standard database formats as the input and output format. This is certainly the most elegant and sensible solution, but also the most challenging one in terms of the software technology.

### Nobody is perfect

Like all measuring systems, optical inspection systems have limited measurement accuracy. With a visual field of at least 160 mm in width, this accuracy is often at the limit of what is acceptable, despite ultra-high resolution cameras. Knots or nodes on the contact fingers printed with silver paste on the front-side of the solar cell, for example, can be measured with an eleven-megapixel camera only with a three-sigma accuracy of  $\pm 0.05$  mm. The tolerance limit is typically at around 0.2 mm, meaning that if a finger becomes wider than 0.2 mm locally, the cell must be placed in a lower quality category. It is likely that a trained human eye can more accurately assess finger knots.

Measurement accuracy is easy to determine if dimensions are being measured and if the measurement is within the measurement range. Repeatability, reproducibility and accuracy can be deter-

mined in the context of systematic measurement series. Serious manufacturers also state these values in their specifications or provide them on request. Based on these values, the “decision confidence” of the device can be estimated statistically, meaning that the reliability with which the optical inspection system will decide whether a measured value is on the “good” side or the “bad” side of a tolerance limit can be predicted. If a good reading is classified as bad, this is known as over-reject; the opposite case is called under-reject. In general, an attempt is made to keep both values as small as possible, with preference given to a smaller under-reject rate in cases of doubt. Cells that are rejected on the basis of over-reject can be manually reclassified, in principle.

More difficult and equally important is the question of where the limits of the measurement ranges lie and whether the system is even capable of capturing and measuring certain characteristics of the cell at all. With a standard contact finger width of just 0.06 mm, it is advisable to inquire specifically how a manufacturer believes this can be reliably measured with a pixel resolution of 0.06 mm. There do exist so-called “sub-pixel algorithms,” which permit measurements in the sub-pixel range. However, their suitability must be carefully determined in real-world applications.

An even more critical example is the detection of so-called microcracks – hairline cracks in the wafer interior with a gap width of zero to one micrometer. These cannot be seen with visible light. It is therefore difficult to determine whether an optical inspection system is reliably finding these cracks. Incidentally, the question of over-rejects and under-rejects is particularly critical in this case. A wafer with a crack can still be made into a good solar cell; such a wafer therefore does not necessarily need to be found and culled out. We know only that the wafer breakage rate drops significantly when such wafers are not introduced into the production process.

Conversely, a wafer that does not have a crack but is mistakenly culled out means a loss of raw material and value equivalent to the loss that occurs in the event of breaking. In such a case, therefore, contrary to the general rule, a certain level of under-reject is accepted, since a significant over-reject rate would call into

question the sense of using a microcrack inspection system.

### Summary

Optical inspection systems are a helpful and necessary tool for quality control and process control in solar manufacturing. It is important for this tool to be used effectively by process engineers. This requires a thorough understanding of system capabilities and their limits. Particular attention must be paid to integration in the machine environment and the systematic determination of repeatability and accuracy. A number of suppliers offer high-quality, tested optical inspection systems. When assessing these systems, it is advisable to consider the following questions:

- Is the system capable of detecting the required characteristics; is the measurement range appropriate for the requirements; are repeatability and accuracy adequate?
- Can the measurement setup be integrated into a production environment? Are there convincing concepts for what exactly is involved in integration?
- Does the system have “real-time capability,” that is, can it perform all of the required measurements in synchrony with the production cycle, and also store data and images, and export and display them online if necessary?
- Does the system support the required interface for exporting data and images?
- Does the system, and particularly its user interface, offer the capability of efficiently and clearly defining all desired tolerances and classification characteristics and to read the results equally efficiently?
- Are over-reject and under-reject estimations known?
- Can the system easily be reproduced, that is, can same-type systems be integrated into similar production lines without increasing operating effort?

Finally, it is important to keep a view on the technical roadmap. The solar cell community is implementing new process enhancements such as thinner grid fingers or fancy geometries for bus-bar and grid. With the introduction of double print and selective emitter tools new alignment requirements arise. It is important that suppliers of optical inspection systems present solutions to these new challenges soon. ◆

Stephanus Wansleben

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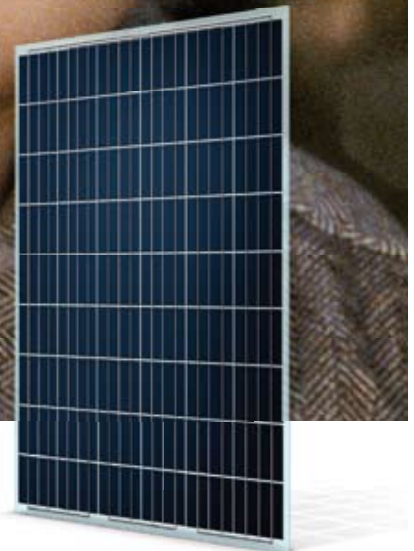


Photo: KLA-Tencor



Pieter Vandewalle is Senior Marketing Director at KLA-Tencor where he is responsible for the Marketing and Product Management of the ICOS Division's product lines for Solar PV Inspection and Semiconductor Package Inspection. Before joining the company in 2004, he held positions at Alcatel's Network and Service Division as a Marketing Director and at Price-WaterhouseCoopers as a Management Consultant. He has earned a Masters Degree in Engineering at the Katholieke Universiteit of Leuven, Belgium and an MBA at the Vlerick Leuven Gent Management School, Belgium and the University of Rochester, New York, USA.

## Portraying development from a product point of view

**Interview:** With increasing importance being placed on optical inspection in the bid to raise quality, the systems that are already in the market are offering more. **pv magazine** spoke with KLA-Tencor ICOS Division's Senior Marketing Director, Pieter Vandewalle, on what the inspection and metrology tools supplier has on its plate and in the works.

### *Which in-line optical inspection systems does ICOS offer?*

KLA-Tencor's ICOS Division was a pioneer in automated optical inspection of PV wafers and cells. The first generation of the tool was released in the year 2001; the latest generation is the ICOS PVI-6, which is currently holding the market leading position. The inline optical inspection module is utilized for inspection of photovoltaic (PV) wafers and cells at various stages of the production process.

Applications for the PVI-6 tool include bare wafer inspection, micro-crack inspection, SiN coating inspection (after the anti-reflective coating process), print inspection (FSPI, front side print inspection, and BSPI, back side print inspection), and cell classification (FSCC, front side cell classifier, and BSCC, back side cell classifier).

Additionally, as solar cell manufacturing ramps up to meet market demands, the next-generation high-volume solar fabs

*“One of the important challenges is the change in print patterns to reach higher efficiency.”*

will need to coordinate the operation of hundreds of production tools within multiple lines.

Overall process management goals cannot be achieved with a piecemeal approach of individually controlling the tools. A comprehensive approach with integrated, centralized process management is essential.

The Central Module Manager (CMM) software developed by

KLA-Tencor, enables the use of one central location to monitor the statuses of all modules, inspections and classifications, as well as storing recipes, results and classifications. Another software package, Tune 1000, provides off-line optimization of inspection recipes in the different process steps. This then allows for efficient

and timely updates and deployment of recipes as well as tracking of trends/charts as well as communication with industry-standard MES systems.

In terms of production worthiness, the PVI-6 series was the first in the industry to encompass a unified calibration kit, golden cell for periodic accuracy verification, offline recipe optimization and management system across multiple production lines. All these features have ensured successful replacement of manual inspection with highest level of consistency and repeatability in a high-volume production environment.

**What are the most important markets?**

Adoption of the ICOS PVI technology has been especially strong in the critical solar cell regions, namely, Taiwan, China, and Europe, as well as the U.S., Korea and India, with more than 1,300 inspection units including the ICOS PVI-6 and prior generation modules. The rapid adoption of these products has been largely driven by the superior reliability and repeatability of automated inspection compared to manual inspection methods.

**Which of the systems is most popular?**

KLA-Tencor's most widely used systems in solar manufacturing are categorized within the following inspection process stages: 1) print inspection process, including front-side steps (silver) and back-side steps (silver and aluminum paste), where key problem areas are paste defects, blisters, busbar defects, finger knots and finger interrupts; 2) final cell classification for optimizing overall yields and correct binning of the different cell classes; optical inspection results are combined with electrical test data.

We're also seeing bare wafer inspection and SiN coating inspection (after the anti-reflective coating process) gaining importance with our customers.

Deploying process control throughout the solar fab line has become popular because cell manufactures have realized that process control systems can help improve efficiency, yield and thus overall profitability.

As an example, monitoring print defects and coating thickness deviations is critical because they have a direct impact on final cell efficiency; recently a cell efficiency improvement of up to 0.4 percent in absolute terms was achieved after introducing automated inspection in the print lines of a cell manufacturer.

**Where do you see the biggest technical challenges in the current offerings?**

One of the important challenges is the change in print patterns to reach higher efficiency. Line widths are decreasing for single and double print and require higher resolution inspection, as well as the use of advanced sub-pixel inspection algorithms. Especially for double print applications, it is important to monitor the alignment of both print layers since such defects may jeopardize the cell manufacturer's investment in an additional print step.

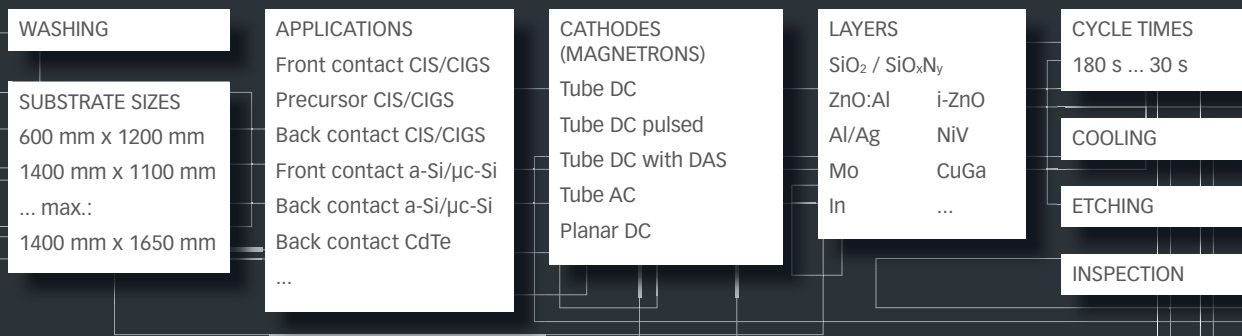
Another challenge is in the area of microcrack inspection in several process steps, especially for polycrystalline cells. It is important to distinguish grain boundaries from microcracks; this requires the use of advanced algorithms and image processing.

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Furthermore, as manufactures scale output to meet the strong demand in the market, production lines are becoming more expensive and complex. In such an environment, the old paradigm of manual inspections and ad-hoc quality is no longer cost-effective and sustainable. Thus customers have to move to automated in-line systems with real-time predictive analysis of their process.



Adoption of ICOS PVI technology has been especially strong in the critical solar cell regions of Taiwan, China, and Europe, as well as the U.S., Korea and India.

***Do you think your customers are taking best advantage of the functionality you offer, or would you advise a change in the way they use the systems?***

We've proven, and proven to numerous customers, that significant manufacturing efficiency and yield improvements can be achieved by deploying comprehensive process control methodology.

Continued success will require a much higher degree of inline automation, comprehensive tightly integrated process control, and high-volume yield improvements. We see that cell manufacturers who have a loose set-up of the inspection tools, suffer more often from yield and efficiency loss.

For example, we recently had a major Chinese solar cell manufacturer, with PVI-6 FSPI (front-side print inspection) modules, completely remove manual inspection from its print-line, and dispatch manual inspection resources to other process tasks. This alleviated a significant labor shortage issue. The modules also enabled this customer to fine-tune and systematically characterize its double print process.

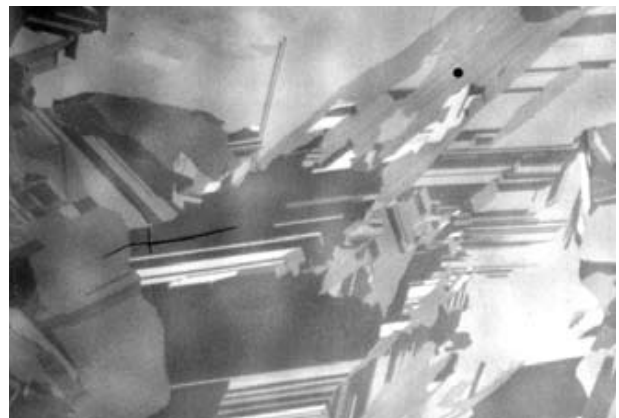
***New requirements are in the pipeline for optical inspection systems. Grid fingers are getting thinner, the busbar and fingers are in fancy geometric shapes. With the introduction of double print and selective emitter new alignment requirements arise. Multi-layered anti-reflective coating is getting popular. Where do you see the biggest challenges and how can optical inspections systems cope with these new requirements?***

As indicated earlier, there is a constant change of print patterns; this is the case for several cell technologies like double printed cells, metal-wrap-through (MWT) and other back-contact cell technologies.

KLA-Tencor's PVI-6 tool utilizes a unique CAD model approach and smart algorithms that best mimic heuristics behind manual quality control. This offers maximum flexibility to cover the ever-evolving print patterns. Besides, several Selective Emitter (SE) technologies require accurate alignment of the doping material with the print pattern.

In addition, the evolving and increasingly advanced customer needs in the PV manufacturing market now require a comprehensive yield management strategy to drive to higher efficiencies through collecting and analyzing all defect data. ♦

Interview by Stephanus Wansleben



PVI-6 offers validation of the structural integrity of bare wafers for cracks, foreign material inclusions, and pitting.