Process quality control in the photovoltaic industry

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Abstract
Solar industry is booming. In the last decade photovoltaic market has increased with a rate of about 40% per year. Manufacturing industry is rushing to meet the growing demand and is investing in processes, materials and research trying to reach the scale required to reduce the cost of the electricity produced by photovoltaic to the grid parity. In order to reach this target high throughput PV-production lines are required. However, these lines have to be controlled in an efficient way to insure high quality end-products, to reduce production down times and material loss due to process deviations. This paper reports a review of some fast inline characterisation and analysis tools for quality control.

Introduction
The photovoltaic industry has grown and it is expected to grow also in the next five years with an annual growth rate of about 30% [1]. By the end of 2012 a global cumulative capacity of 44 GWp could be achieved. For that period it is expected that the grid parity will be achieved in different south Europe countries. But the resulting economy of scale effects are not enough to achieve the grid parity on their own. In order to reduce the production cost automated and stable processes, highly integrated factories and ad-hoc production control systems for continually optimise the process are requested.

Cell and module manufacturers want information about wafers and cells quality beyond the final check of the product and to monitor each step during the production process to identify line problems at the earliest stage possible.

The new highly integrated photovoltaic factories will reach cycle time of the order of 20 seconds [2]; every 20 seconds a module is produced and the final quality will depend on the process quality control developed in the line which are based on fast in-line characterisation and analysis tools from the starting material up to the module. The feed-back time for an in-line quality control tool must be below three seconds (best case one second!).

Unluckily, nowadays there are not many tools available to industry. Although many prototype instruments for material and device characterization are in use in an R&D mode [3, 4], few of these instruments are available in high-volume and in-line configurations.

In this paper some characterization techniques proposed for in-line characterization for silicon wafer based solar cells are reviewed.

Characterization tools for in-line control
Characterization tools are not enough if a good criteria in order to keep only good wafers and reject which will reduce the module efficiency is not available [5, 6] but more and new efficient equipments for automated, in-line monitoring and testing are desirable.

Several manufacturers are also developing and inventing adapted automated systems for in-line measurements but the cost of new in-line control tools must be cover by a sufficient efficiency gain or less process deviation. Another limitation to a faster transfer of the lab-scale instrument to large scale industrial production is the limited standard wafer size or cell design to handle.

Moreover, only dozens of instruments are required for a complete in-line control and this is a strong disincentive for equipment manufacturers who might provide in-line test equipment for industry. However the strong increase of the photovoltaic market will attract their interest.

A research project for developing in-line characterization methods and tools has been financed in the past by the European Community (Fast-IQ Project) and some characterization tools were successfully introduced in the production line [6]. In the following two of the characterization tools developed are reported.

X-ray application for crack detection
Mechanical breakage in the PV industry involves a large fraction, about 5%-10%, of the wafers. This rather low yield is in part the result of using larger and thinner wafers. Therefore, the breakage issue has become more important than the cell efficiency. There is an urgent need for some sensitive, nondestructive way for measuring wafer interior stresses and for detecting microcracks.

In the current photovoltaic line productions are already available tools for detection of the wafer and cell integrity. However these techniques, based essentially on visual analysis, can detect major edge defects. Micro-cracks inside the wafer or cell are not detectable but these defects are responsible for the wafer crack during processing. In the Fast-IQ EEC Program we studied the possibility to use X-Ray technique for crack detection [6].

Although X-ray technique are widely used in research and production for the study of crystal defects and crack and other fault in metals, it is not applied in the PV industry. However, an in-line X-ray characterisation of solar cells is potentially capable to detect all kind of these failures in both the as grown material and in solar cell, thus providing a mean for achieving a total quality control of the production.

The instrument developed within the Fast-IQ EEC Program combines the techniques of x-ray topography and x-ray radiography. More details about the technique can be find in [7], here are reported some results obtained. With the prototype developed edge defects (breakage, flaking) and defects inside the cell (points with highest density, internal fractures and broken bars) were observed.

In general edge defects are regions where fairly large fragments of material have flaked away. Fragment loss causes a break in electric contact and hence the system fails to operate. In this case, either standard optical or x-ray analyses can come in useful.

Figure 1 (A) X-ray image of edge defect. (B) Holes and macro fractures in block-casted solar cell.

For an in-line identification of these defects in cell production, it is only necessary to determine the real perimeter and then compare it with the corrected perimeter. Figure 1 A shows an x-ray radiography of a edge broken cell which can easily detected. Thickening or depletion of the material are more difficult to reveal but can be clearly observed on a radiograph, by adopting the principle of absorption and phase [7] contrast (Figure 1 B).

The X-ray system is able to observe some types of defects (holes, broken string, cracks and gaps) starting from a fine focus x-ray tube of 5 - 10 watts. Software, applicable to this instrument for the identification of defective cells using non-linear geometry, can perform image analysis in about 1-2 second. The low energy and low power (<22 KeV, < 0.4 mA) required are sufficient safety for in-line application in solar cell production.

FAST LBIC for in-line characterization

In the Fast-IQ EEC Program was also explored the possibility to use Light Beam Induced (LBIC) technique as in line tool for cell, string and module characterisation, in terms of speed and reliability.

The interest is in individuating off-specs elements and ensure quality control of the process. Within this frame an open problem is the optimisation of solar cell selection for series connection in strings and modules, to avoid power losses from cell mismatch.

LBIC technique is a non-destructive, high spatial resolution technique suitable to detect areas of efficiency losses in multicrystalline solar cells [8]. In its classical configuration LBIC offers an high spatial resolution (about or less 1 \( \mu \)m) but it is time consuming.

The Large Area Fast-LBIC [9] is a system which allows the measurement of laser beam induced photo-current of photovoltaic devices of large area (up to about 150×150 cm). Its working principle is basilar (Figure 2): a chopped laser source generates electron-holes pairs in the test specimen and the collected carriers generate the photocurrent signal which is measured by a lock-in amplifier. The main unit of the system is a computer-controlled head which can steer the light beam by use of two perpendicular galvanometric mirrors. The use of such a device intrinsically introduces a distortion in the image that is not observed with moving XY stages but, at the same time, allows the probing of larger areas. The introduction of a motorized variable lens synchronized with the mirrors allows the control of both focus and spherical distortion. The linear resolution depends on the distance between the device and the probe, and is defined in 65000 points/10°. With respect to a conventional LBIC system,
the spot size is larger (typically ranging from roughly 50-60 μm at 15 cm to about 1 mm² at 3 meters from the device under test), but the acquisition time is order of magnitude higher. An array of 30×30 points has been measured in less than 3 seconds [10].

**Figure 2** Schematic diagram of the Fast LBIC system.

The Fast LBIC can be used as an off-line tool for deep analysis of defective cell, sting or module. Figure 3 (A) reports an example of the results obtained using the 780 nm laser in 30 minutes. For in-line application higher scan speed are requested. Figure 3 (B) reports also an example of fast scan. Although a loss of details regarding the cell microstructure is observed in the Fast-LBIC imaging, the most probable photocurrent values are still consistent with the cell specifications.

**Figure 1** High (600x600 pts in 30 min) and low resolution (50x50 pts in 7 sec) maps for a standard block-casted cell using the 780 nm laser.

It was also demonstrated that a scan speed of 3 sec per wafer is sufficient for a reliable quality control. This speed was than used to characterized a set of finished solar cells of different quality. The fast-LBIC can be also applied to the string analysis. A line scan composed by 2200 points can be acquired in less than 3 seconds. In the non defected string the signal between cell to cell does not change significantly. In this case of the bad string the distribution of the average photocurrent signal across each cell is uneven and defective cells in the string can be detected.

The Fast LBIC has proven to be a characterisation system suitable for inline application where a rapid check of series connected cells were required, such as in the final steps of module packaging. Its limitation consists in the fact that detection capabilities rely on, and is limited to, poor shunt resistance or photocurrent. Since the relevant information to measure is the average LBIC signal over the cell, there are great margins for improvement of the system.

The Fast-LBIC technique as not already introduced as in-line characterization tool essentially for the limitation reported. However, recently we demonstrate the possibility to apply this technique for the analysis of the laser edge isolation quality [11].

In fact, the most popular new edge isolation process [12] is laser scribing. It is naturally suitable for inline processing and the wafer doesn’t need to be touched, which is an important requirement for the handling of thin wafers. To validate the scribing process I-V characteristics can be used but local information are not available. The Fast-LBIC technique in high resolution configuration can be used as diagnostic tool during the optimization of the laser scribing procedure. Figure 4 reports an high resolution Fast LBIC maps of a solar cell where the laser edge isolation fails. This part is localized in the solar cell corner where the laser speed must be controlled in accurate way.
Figure 2 High resolution Fast LBIC maps of a bad laser edge isolated solar cell.

For a fast in-line characterization it is possible to use a single square scan near the solar cell edge. The photocurrent collected is inversely linked to the isolation quality. Tests in this direction are in progress.

Conclusions

The PV industry request of in-line, manufacturing-compatible, non-contact techniques is growing. Relatively small gains in power output and energy yield are also accepted if the suggested methods are cheap. The threshold for an investment of 100000 € per annum to achieve a positive cost-benefit ratio is reached for a yield improvement of 0.1% in a 30MW combined c-Si cell and module line at today’s pricings.

It is not easy to foresee which techniques will be implemented in the future production lines. Many manufacturers consider sufficient a regular control of selected wafers/cells. However in the future raw material supplied to the industries (solar grade silicon) will be highly variable and it will be really difficult to adjust effectively the process parameters for a good final solar cell.

This evolution will ask for efficient in-line characterisation tools but also for wafer tracking and elaborate statistical control process procedures.

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