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# REVIEW OF TOOLS AND APPROACHES FOR INLINE QUALITY CONTROL IN HIGH EFFICIENCY SILICON SOLAR CELL PRODUCTION

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ABSTRACT: Multiple tools and methods for the optical and electrical quality control of high efficiency silicon solar cells during their industrial production are available on the market, even more are discussed in the literature. We summarize the possibilities of these tools along the value chain from wafer to cell for the case of passivated emitter and rear cells (PERC) and discuss some showcases. We recommend a broad inline quality control before solar cell production in order to discard wafers with insufficient quality. Especially PL-Imaging can reveal material defects and process variations and thus acts as a versatile tool for the whole production chain. An economic evaluation shows that a CAPEX spending of 250,000 EUR for metrology equipment is already justified if cell efficiency is increased by only 0.03 %abs from a reference efficiency 20.61 % to 20.64 %. Combining technological and economical aspects, this paper gives an overview over recent inline metrology tools and upcoming challenges.

Keywords: solar cell, quality, metrology, PL-Imaging, economics

## 1 INTRODUCTION

In the photovoltaic industry, each market player faces extreme competition. Solar cell and module manufacturers aim at reducing their costs and use of consumables and at the same time at improving throughput and uptime, yield, process stability, solar cell reliability and solar cell output power. However, the higher potential of novel devices goes along with a higher sensitivity towards material and process variations. Concerning material quality, a certain kind of incoming test is highly prioritized by cell manufacturers. Especially geometrical properties can be precisely tested at the beginning of the cell production line or at the end of the wafer production line in order to prevent off-spec material to enter the production chain.

To better control variations during the production process and in order to find further potential of process improvements, an intelligent use of inline characterization techniques ideally combines the required investigation of material and device properties with real-time process and production control. In general, the most challenging question for cell manufacturers and metrology suppliers concerning inline metrology is which tools and methods are required and economically advisable. The central question is how to control and improve the yield, the reliability, the mean cell efficiency and the scattering of the efficiency distribution at which cost.

To be able to discuss these questions, different tools and approaches are discussed in this article including an economic assessment. While this article gives an overview, more details are published elsewhere [1].

## 2 APPROACH

In the Photovoltaic Technology Evaluation Center PVTEC [2] at Fraunhofer ISE, a broad pool of inline and off-line metrology tools is available and used for characterization and quality control during solar cell production. Most experiments in the PVTEC include systematic variations of process parameters which need to be quantified and correlated to the resulting IV parameters of the solar cells. Other experiments include broad variations of material quality or are done without variation in order to analyze process fluctuations. The data from these experiments provide information about the process variations which may be detected by means of the various metrology tools and about their relevance for the output parameters of the final solar cell. From this, the economic benefit of the different tools may be assessed, strongly depending on the cell concept under test.

## 3 INCOMING CONTROL

The electrical and mechanical quality of wafers can be checked during final inspection of wafer production or during incoming inspection of solar cell production. Poor quality wafers should be identified and discarded at an early stage in the process to avoid unnecessary costs. Inline accessible mechanical wafer properties are wafer thickness and its variation, the size and geometry, saw marks and roughness, chipping, holes and cracks. Inline-accessible electrical properties are base resistivity, effective lifetime and crystal defects [3, 4]. In addition, surface contamination and reflectivity are optical properties which are worth to be investigated. The measurement procedure of most of these properties is covered by recent SEMI standards.

The wafer thickness is typically measured capacitance-based. Tools measuring e.g. three traces with several hundreds of measurement points each allow to detect not only the mean thickness (typically ~180µm), but also the total thickness variation (~20µm) and more details of the wafer's shape (see Figure 1).

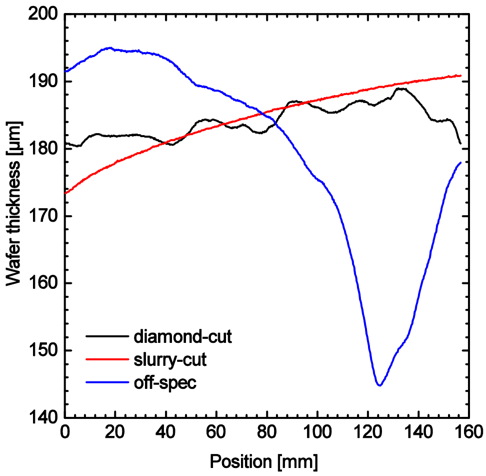

Figure 1. Three examples of thickness profiles. The diamond-cut wafer shows a typical large-scale saw mark structure, the slurry-cut wafers shows a strong gradient, while the off-spec wafer shows a very strong saw mark.

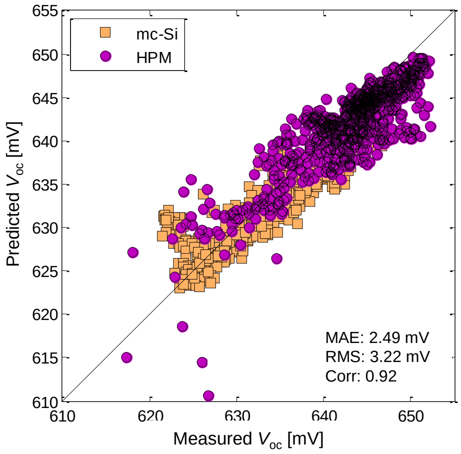

Figure 2. Prediction results of the open-circuit voltage $V_{OC}$ for more than 1300 passivated emitter and rear cells (PERC) obtained with a regularized regression model based on empirical data, adapted from Ref [5].

The bulk lifetime of minority charge carriers is one of the most important parameters to characterize the electrical quality of wafers. Unfortunately, in the as-cut state, only an effective lifetime can be measured which is strongly limited by surface recombination and thus does not allow a correlation to final solar cell parameters. Only wafers with very low lifetime (e.g. due to crucible contaminations) can be identified and sorted out. Nevertheless, lifetime measuring systems based on microwave-detected photoconductivity (MPD, [6]), microwave-detected photoconductance decay (MW-PCD, [7]) and quasi-steady-state photoconductance (QSSPC, [9]) measurements are available. To overcome the limit of surface recombination, these techniques can be used to inspect the lifetime in later process stages (e.g. after diffusion or passivation). Nevertheless, there is a very promising approach for material quality rating in the as-cut stage which has yielded excellent results on multicrystalline wafers [8]. It is based on the analysis of PL images and Figure 2 shows the predicted open circuit voltages plotted against the measured ones on the final cells, showing a very good prediction accuracy [5, 8].

## 4 PRODUCTION PROCESS

Inline quality control between the incoming test of the as-cut wafers and the final outcoming test of the finished solar cells is not known to be very widespread. It is nevertheless a prerequisite to quickly detect arising problems during production and to constantly achieve high solar cell conversion efficiencies, which gains importance as the efficiency potential of the cell structures increases. Many of the following methods require the combination of several measurements (*e.g.* resistivity and wafer thickness, or resistivity as-cut and after diffusion). Thus, the data need to be assigned to one another wafer-specifically. For this purpose, single-wafer-tracking methods e.g. using data-matrix-codes have been developed [10, 11].

During texturing, the concentration of chemicals in the bath can be controlled continuously using near-infrared spectroscopy. Acidic (HF, HNO3) and alkaline (KOH, organic additives) baths typically used in silicon photovoltaics can be analyzed [12, 13]. After the texturization process, the reflectance and the thickness of the wafer can be measured and used to control the quality of the reflection properties and of the silicon removal, respectively. Figure 3 depicts photoluminescence images that are taken after three different process stages. From these, recombination-active defects that are induced or activated within the different steps can be detected spatially resolved, which often allows to identify their origin [14, 15]. An overview of the inline metrology for emitter diffusion and the following process steps can be found in Ref [1].

## 4 FINISHED SOLAR CELL

After contact formation on finished solar cells, extensive inline characterization is available. The most important inline characterization for finished solar cells is the measurement of the current-voltage (IV) characteristics under standard test conditions (25°C, 1000 W/m² illumination with AM1.5g spectrum), from which the energy conversion efficiency can be deduced and the cells can be sorted into the corresponding bins. Due to mismatch effects [16], the choice of the reference cells, which are calibrated in the CalLab [17], can have a significant impact on the measured values of short-circuit current and conversion efficiency and needs to be closely adjusted to the cell technology under test. Besides the measurement under constant illumination, also the suns-$V_{oc}$ characteristic as well as the forward and reverse IV characteristics in the dark can be measured, which allow a basic analysis of non-ideal recombination, series resistance, ohmic and non-linear shunting, and hot-spot danger [18].

Line or matrix cameras are used for visual inspection of the front side of the cells to detect paste residuals and chipping defects, measure the finger width and the cell dimensions and the color of the anti-reflection coating [19]. By inspecting the rear of the PERC cells with full-area Al print, the darkening of the aluminum at the local contact openings due to silicon alloying during the contact formation can be detected, which may be used to detect inhomogeneous formation of the local back-surface field. For bifacial solar cells, the visual inspection of the cell’s rear is in principle the same as that of the cell’s front: paste residuals, chipping, finger width and color can be detected.

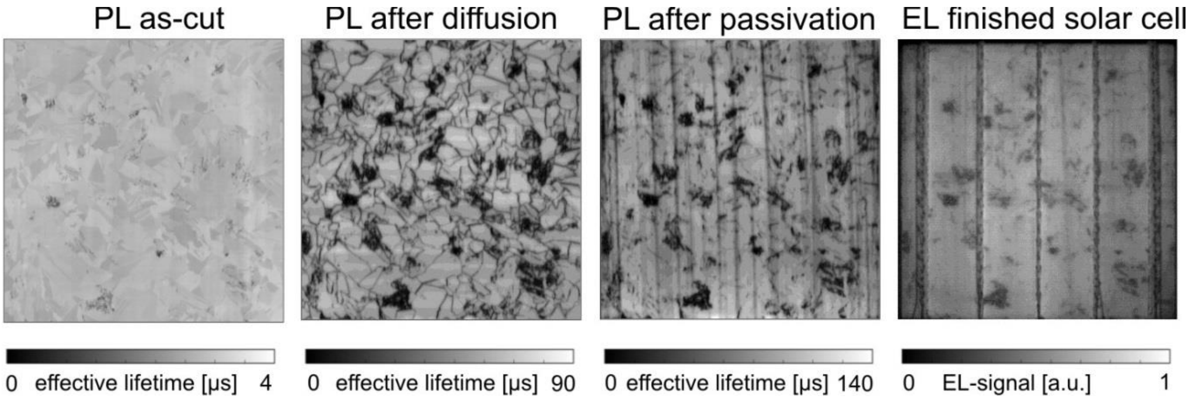

Figure 3: Photoluminescence (PL) and electroluminescence (EL) images of a mc-Si wafer at different stages of the PERC production sequence. In the as-cut state, dislocations and grain boundaries are visible that become even more pronounced after emitter formation. After surface passivation, line-shaped defects possibly induced by saw marks become apparent. In the finished cell, several material- and process-induced defects (possibly saw marks, crystal dislocations, finger interruptions, edge shunts) overlie.

Besides the measurement of the IV characteristics of the solar cells, advanced upgrades for the IV testers are available. Electroluminescence (see Figure 3) and photoluminescence imaging allow to detect cracks, finger interruptions and dark areas [20, 21]. Thermography is used to detect cells with hot spots and to predict their temperature behavior in the finished module [22]. Such a local analysis is preferable compared to an analysis of the global dark reverse current because inhomogeneous reverse current and power dissipation within the cell is the reality, not the exception. This is exemplified in Figure 4, where the thermography image of an mc-Si PERC cell shows a significant temperature increase of 5 K after only 40 ms reverse current load, which is likely to damage the module. Since the cell's reverse current at -12 V is below 2 A, this hot spot danger cannot be predicted from only the IV characteristics [23]. A systematic comparison of inline hot spot detection and evaluation via the above mentioned cell's reverse current, temperature increases in short-term measurements and two more advanced approaches is presented in Ref. [24].

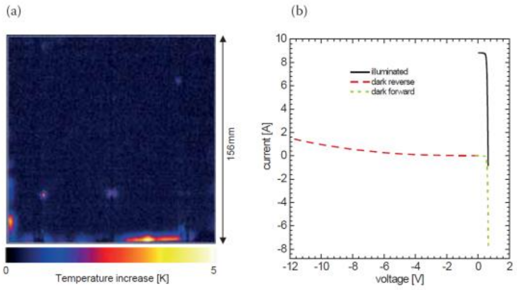

Figure 4. (a) Thermography image of an mc-Si PERC cell with a severe temperature increase of up to 5 K after applying a reverse voltage of -12 V for only 40 ms, indicating hot spot danger for the module. (b) IV characteristics of the same cell showing only a moderate reverse current < 2 A at -12 V reverse voltage.

## 5 ECONOMIC ASSESSMENT

One of the cell and module manufacturers main concerns is the expected return of investment, when they are faced with decisions to invest in advanced inline characterization techniques. Looking at real production environments, parameters like the uptime or the yield of a production tool are randomly influenced by failures, consumables, wafer quality, and other factors. So, it often seems not to be clear how to distinguish between positive effects of inline quality control and other factors influencing the performance of a production tool. This makes it difficult to appropriately prepare an investment decision for an inline characterization technique.

To better understand the economic impacts of an integration of inline characterization techniques into a production environment, a 500 MWp/year monocrystalline PERC cell production process was simulated and examined with our cost of ownership (COO) calculation tool 'SCost' [25]. We calculated the essential productivity improvement (in terms of cell efficiency gain) for the cell manufacturer with respect to the prospected capital expenditures (CAPEX) on inline characterization in the production line, i.e., how much CAPEX can be spent to break even the expected production performance enhancement.

Figure 5 shows the resulting break-even analysis based on the $W_P$-cost equivalence before and after the application of the inline characterization techniques for a timeframe of five years. If the cell manufacturer realizes a higher cell efficiency by using the inline characterization technique, the all-in cell costs (all-in module costs) decrease compared to the reference value. This influence of cell efficiency enhancement to the all-in cell costs is analyzed in Figure 6.

This finding shows how small the efficiency increase is to justify inline metrology, but also confirms that a well-founded investment decision requires the metrology-induced efficiency gain to be demonstrated. However, as inline metrology can also improve other production parameters, such as production yield, equipment uptime and consumable utilization, it often may turn to account also without induced efficiency gains. Such effects may be very tool-specific and thus have to be assessed individually.

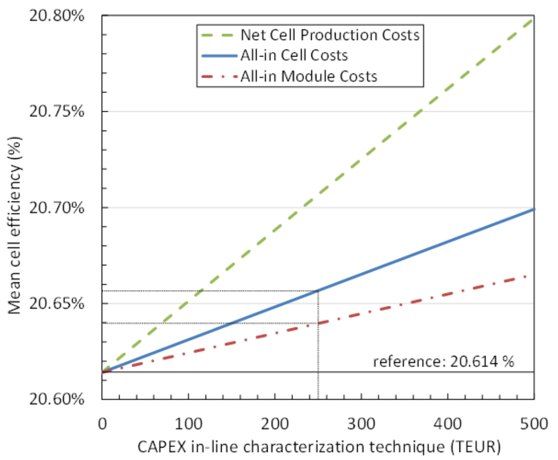

Figure 5. Break-even analysis of an inline characterization technique, integrated into a 500 MWp/year monocrystalline PERC cell production line. The three lines indicate for the ‘net cell production costs’, the ‘all-in cell costs’ and the ‘all-in module costs’ the respective gain in mean cell efficiency to be reached by the characterization technique in order to break even within five years the expended costs for the additional characterization technique.

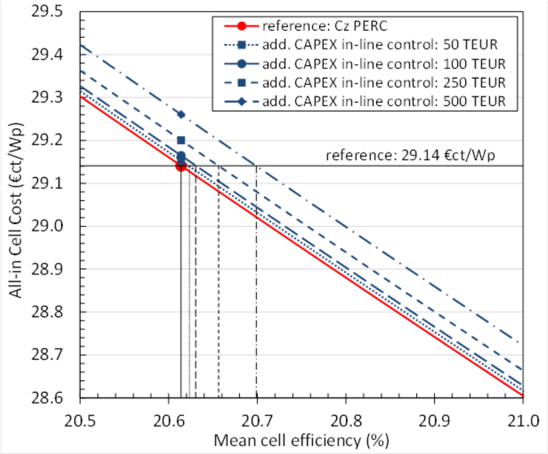

Figure 6. Sensitivity analysis of the mean cell efficiency influence on ‘All-in Cell Costs’. The red line indicates the costs of the Cz PERC reference and the red dot the reference cell efficiency of 20,61 %, respectively. The dashed blue lines indicate the costs including additional CAPEX for inline characterization. All figures are calculated for a 500 MWp/year monocrystalline PERC cell production.

## 6 OUTLOOK

After the fire incident in the PVTEC laboratory at Fraunhofer ISE, new and updated inline characterization tools will be available soon for test and service. The automated inspection system for as-cut wafers will be equipped with 16 different measurement systems, including waferidentification, tools for optical and geometrical inspection, photolumineszence imaging, a new tool for microcrack detection and a tool for grain structure analysis in mc-Si wafers. The system will be able to measure not only standard but also diamond-wire-cut wafers with shiny surface more accurately. Partially processed wafers will be able to be measured in a separate inspection system which is equipped among other techniques with lifetime calibrated photoluminescence imaging, combining high spatial resolution and physical relevance of the data. For finished solar cells, an inline cell tester will be available with IV, spectral response, thermography, electroluminescence, combined electro- and photoluminescence and high-resolution print inspection units which will allow inline in-depth analysis with high spatial resolution. Beyond the high-quality measurement equipment, the system will be able to handle not only standard cells, but also bifacial, busbarless and back-contacted solar cells.

## 7 CONCLUSION

In this article, we gave an overview over state-of-the-art inline metrology for material and process control. We recommend incoming inspection during solar cell production or outgoing inspection during wafer production as a very important step for quality control, as wafers with insufficient mechanical or electrical properties can be detected and discarded. During solar cell processing, inline metrology helps to quickly identify upcoming problems, and appropriate tools can be applied after each production step. All finished solar cells need to be IV-tested. Different approaches to analyze IV curves are available, as well as additional metrology tools to monitor spatially resolved specific defects such as cracks or hot-spots. While during process optimization extensive characterization is necessary, even a running production can benefit from a comprehensive metrology as the quality of the individual processes has to be known on a statistically relevant basis to be able to reduce variations and increase the standards and thus to improve the overall efficiency gain. Economic and technological challenges are addressed to answer the question how much gain in efficiency can be justified from investments in metrology.

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