Combining highest throughput and precision in IV measurements of high-efficiency bifacial silicon solar cells

Abstract: we analyze available measurement time in a sun simulator in highest-throughput production of silicon solar cells. We explain how this time is distributed on the different measurements, which need to be performed to characterize a solar cell. For high-efficiency solar cells, we elaborate how it is possible to reduce the required measurement time to determine their *IV* characteristics such that throughput requirements can be met in all cases. We find that a combination of voltage sweep speed adaptation and advanced hysteresis evaluation is suited for highest throughput without compromising measurement accuracy even for highest-capacitance heterojunction (HJ) cells.

Introduction

Modern solar cell production lines run at high throughput with cycle times of 1 s or below. For the near future, cycle times as low as 800 ms, translating to a throughput of up to 4500 wafers/hour, have to be achieved on a single line of a solar cell tester and sorter.

To allow such short cycle times, handling and measurement times need to meet strict requirements.

At the same time, Si-solar cell efficiency is constantly improving, thereby increasing cell capacity due to higher effective charge carrier lifetime. As a result, the required time for a device to achieve quasi-steady-state conditions after a change in operating conditions, a prerequisite for accurate power rating of solar cells, increases. During *IV* measurements, the applied voltage is varied from 0 V to open-circuit conditions and beyond, i.e. the operating conditions are modified drastically.

Thus, the time that is necessary to measure the steady-state *IV* curve of highest V_{oc} cells like HJ cells or TopCon cells on n-type material may reach several seconds. The recent breakthrough of bifacial solar cell technology adds another challenge. In addition to the light *IV* measurement at standard test conditions (STC front), STC rear and true bifacial measurements are performed routinely in solar cell production, thereby tripling the light *IV* measurement time.

The three requirements, long measurement times, an increasing number of measurement types and highest throughput, represent a conflict of objectives. A solution that sacrifices measurement precision is no option. Therefore, this conflict of objectives can only be solved using advanced solutions.

We analyze the available time for a light *IV* measurement in high-throughput production of modern bifacial devices and explain measurement strategies which allow obtaining precise steady-state *IV* curves even for highest-capacity HJ cells within the available time.

Timing analysis

Figure 1 shows one measurement cycle including handling time in a typical station of a sun simulator for electrical measurements like *IV*, electroluminescence (EL) or thermography. The cycle splits into different tasks, which need to be performed sequentially. First, the cell is transported into the measurement position, then the contact elements are closed in order to achieve electrical contact required for the measurements.

During the measurement time (contacts closed, no cell movement), the actual measurements need to be performed. Finally, the contacting elements are opened again. With the next cell transport sequence, the next cycle starts. Due to mechanical restrictions, wafer transport and contacting time cannot be minimized endlessly. In modern production lines 550 ms for all three steps at a cell size of 210 mm is already at the edge of the mechanical feasibility.

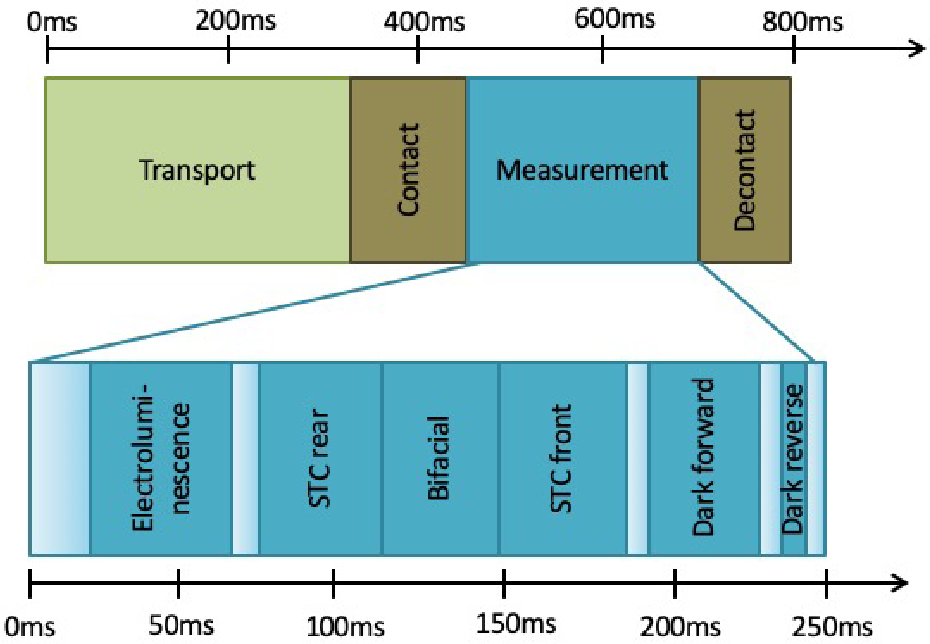

Figure 1a: Time breakdown of a cycle for a solar cell *IV* measurement in production. One cycle comprises a transport, a contacting, a measurement and a decontacting step.
Figure 1b: The bottom sketch shows the split-up of the measurement step into different measurement types. The time spans marked in dark blue are net measurement times while those marked in light blue represent additional time that is necessary to switch between measurement types.

Step	Time [ms]
Transport	330
Contact	120
Measurement	250
Decontact	100
Sum	**800**

Table 1: Example for a time breakdown for one cycle of a solar cell measurement. The handling time sums up to 550 ms leaving 250 ms for the actual measure-ment. A total cycle time of 800 ms is assumed (4500 wafers/h).

330 ms are required for wafer transport and about 120 ms for contacting and 100 ms for decontacting. This leaves as much as 250 ms for all measurements. Please note that 550 ms handling time is an assumed optimum.

A throughput of 4500 wafers/h allows for 250 ms of measurement time. Obviously, longer measurement times reduce the throughput, while shorter times leave room to increase it.

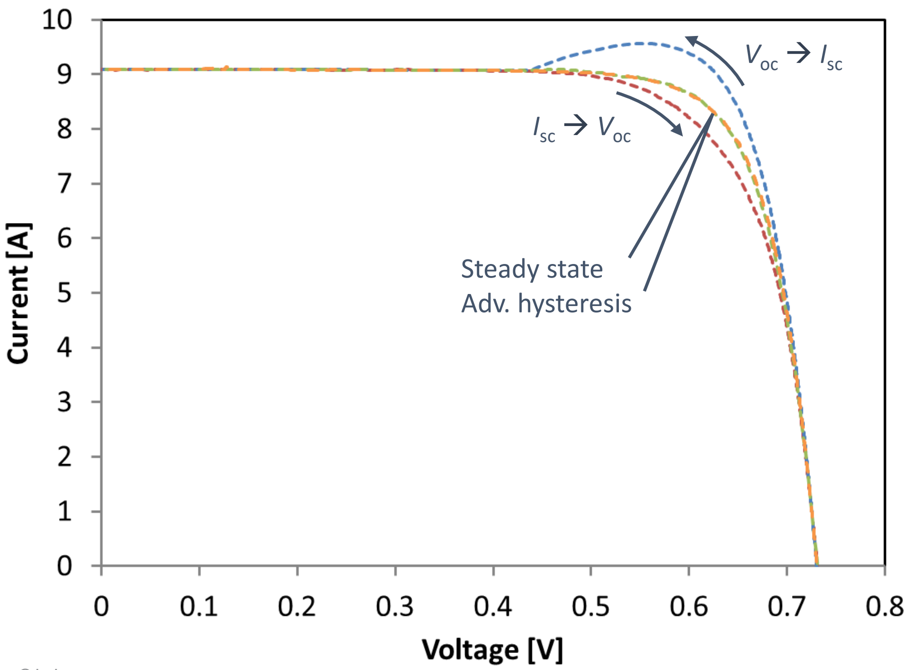

Figure 2: Current-voltage characteristics of a high-efficiency solar cell (*Voc* 734 mV). The $I_{sc} \rightarrow V_{oc}$ and the $V_{oc} \rightarrow I_{sc}$ sweeps are performed within 28 ms. The root cause for the deviation of these curves from the steady-state curve is explained in the text.

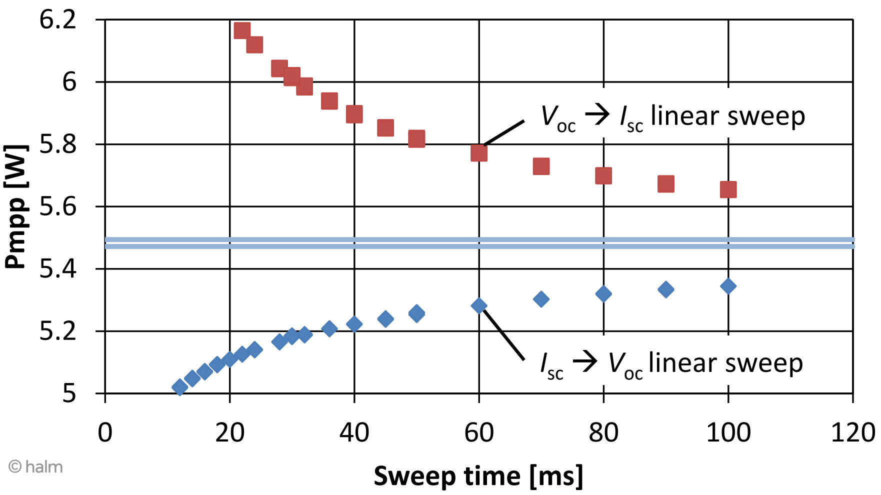

Figure 3: *IV* measurement results for a HJ solar cell for sweep times up to 100 ms using a linear voltage ramp.

State-of-the-art measurements that are necessary to characterize a bifacial solar cell allowing process and quality control include

- 3-level light *IV* (STC rear, true bifacial, STC front) for bifacial cells
- dark-forward *IV*
- dark-reverse *IV* and
- electroluminescence measurement

Having only 250 ms for the total measurements, no measurement times larger than approximately 40 ms are allowed for the three light *IV* and the dark-forward measurements, the ones that are affected by cell capacity. This leaves approximately 90 ms for reverse *IV* and EL measurements, switching times between the measurements and handshake communication.

A breakdown of the total of 250 ms measurement time into the different individual measurements, as well as switching times and communication time, is shown in Figure 1b. Data evaluation time is not shown as the data evaluation is performed in parallel to the handling time.

Measurement Strategies

In the following, we focus on optimizing the measurement time of the light and dark-forward *IV* measurement. Current-voltage characteristics of a high-efficiency solar cell are shown in Figure 2. It shows the *IV* curve of a measurement with a forward voltage sweep from 0 *V* to V_{OC} ($I_{SC} \rightarrow V_{OC}$) and with a reverse voltage sweep from V_{OC} to 0 *V* ($V_{OC} \rightarrow I_{SC}$). In addition, the steady-state *IV* curve is shown. The $I_{SC} \rightarrow V_{OC}$ curve shows a lower FF and the $V_{OC} \rightarrow I_{SC}$ curve a higher FF compared to the steady-state curve. This can be attributed to the minority charge carriers, which are stored in the silicon volume, usually referred to as cell capacitance. Accordingly, this cell capacitance is not constant but varies with the cell voltage. When the voltage is increased during the voltage sweep, the capacitance is loaded and the current that is necessary to charge the cell capacitance is not delivered to the cell terminals.

Similarly, when the voltage is decreased, the cell capacity is discharged. The discharge current is additionally delivered to the cell terminals and current values higher than the steady-state value at the same operating condition are measured. As the effect can be attributed to the cell capacitance, the differences between the measured *IV* curves and the steady-state curve increase with increasing cell capacitance and faster sweep rate. As fast sweep rates are necessary for high-throughput measurements, advanced solutions are required for precise *IV* measurements of high-efficiency solar cells.

To analyze measurement accuracy under the time limitations presented above, we perform *IV* measurements of a HJ cell as a function of the *IV* measurement time in the two cases of $I_{SC} \rightarrow V_{OC}$ sweep and $V_{OC} \rightarrow I_{SC}$ sweep. The cell has an open-circuit voltage of 734 mV and thus a very high capacitance. The results are displayed in Figure 3. Two horizontal lines represent the desired accuracy level +/-0.2% around the steady-state efficiency.

Measurement results should ideally lie within these lines. Otherwise, the accuracy requirements are not met. It is obvious that all measurements are quite far out, even for measurement times as large as 100 ms. At 40 ms measurement time, the measurement-time limit determined above, a deviation of larger than 4.5% from the steady-state value is observed which is far beyond any precision requirements.

Sometimes it is proposed to adapt the voltage sweep speed during the measurement time in order to achieve more precise measurement results. The sweep speed is reduced close to V_{MPP} to decrease the transient effects and increased at low voltages. Using such an approach, the deviation between steady-state measurement result and transient result can be decreased as displayed in Figure 4.

However, even with optimized settings, the deviation from steady-state at 40 ms sweep time is still larger than 1% and at 100 ms measurement time the steady-state value is missed by 0.5%.

The solution to achieve the desired accuracy in short measurement times is the usage of two sweeps performed in one single flash, sweeping from $I_{SC} \rightarrow V_{OC}$ first and then back from $V_{OC} \rightarrow I_{SC}$. In this way, two *IV* curves are measured. The difference between the two curves is characteristic of the cells transient behavior. It can therefore be used to

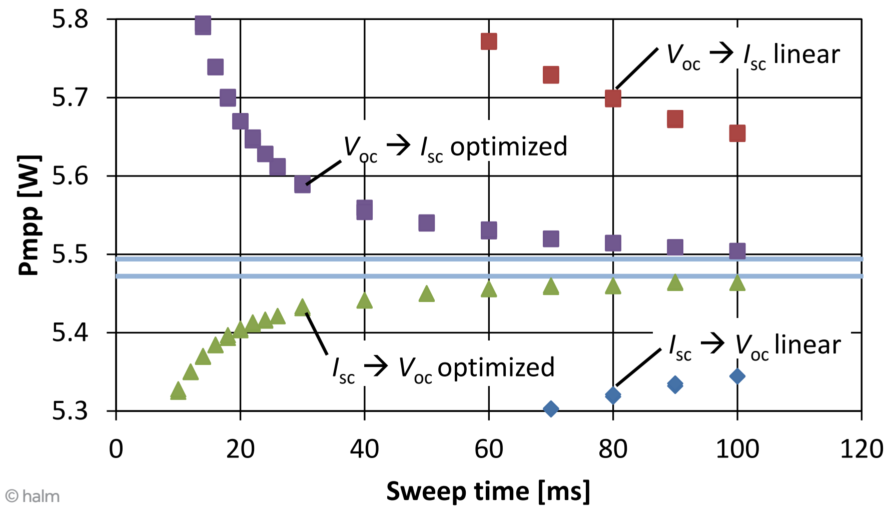

Figure 4: P_{MPP} values achieved in single-sweep measurements with optimized non-linear and linear sweep settings. Even at 100 ms sweep time, the desired accuracy is not reached while at 40 ms the deviation is still larger than 1%.

'We have shown that advanced hysteresis in combination with an optimized sweep form allows for meeting this requirement without sacrificing measurement accuracy.'

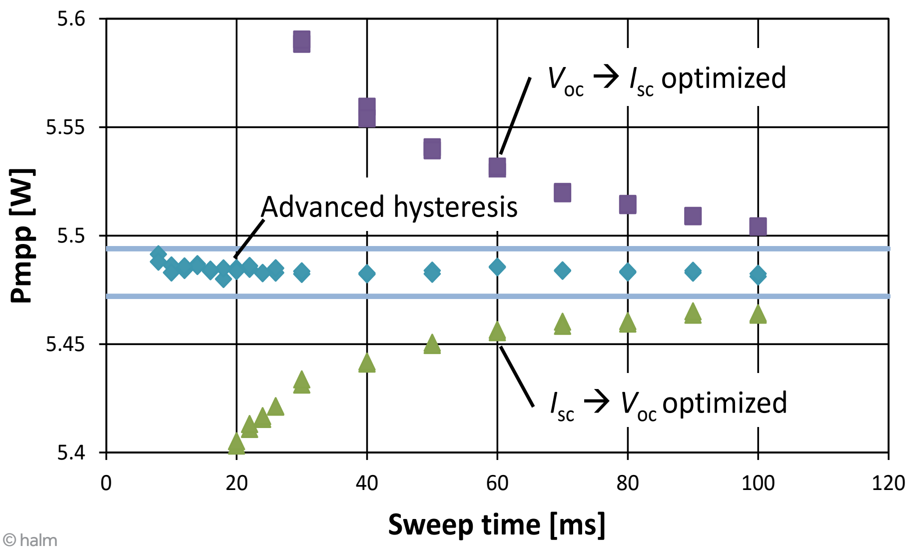

Figure 5: Measurement results including advanced hysteresis analysis (blue diamonds). Even for very short measurement times, all efficiency values fall within the band of desired accuracy. Note: The results from the linear sweep do not fall into the range displayed in this graph.

calculate the true steady-state *IV* curve, based on the measured curves and the knowledge about the physical origin of the observed splitting between them.

This is performed by the h.a.l.m. advanced hysteresis approach. Please note, as two sweeps are required for each measurement, the available sweep time in a 40 ms flash segment is reduced to about 17 ms per sweep. Figure 5 displays the results achieved using advanced hysteresis evaluation in combination with an optimized voltage sweep ramp, together with the single sweep results already shown in Figure 4.

For all measurement times from 2x8 ms up two 2x100 ms, the results closely agree with the steady-state value and fall within the band of desired accuracy. This demonstrates how the precision of fast measurements on highly capacitive devices is increased using advanced hysteresis analysis. Deviations from the desired steady-state value are only observable at very short measurement times. For these conditions, distortions in the *IV* curves at voltages below V_{MPP} are observed for high-capacitance devices, which is why very short sweep times are not recommended by h.a.l.m. for such measurements.

Accordingly, we recommend our customers to use the whole 40 ms measurement time for highest-capacitance solar cells. This ensures precise measurement results and delivers not only the steady-state output power but also the whole steady-state *IV* curve and thus allows precise determination of important cell parameters like series resistance or diode saturation currents. A time diagram of the three light *IV* measurements for a bifacial cell is presented in Figure 6. As can be seen, all light *IV* measurements of a bifacial solar cell can be performed within 120 ms.

Conclusion

Modern high-throughput solar cell production requires fast measurements that are performed in no more than about 250 ms. As several measurements are needed for solar cell characterization, in particular for bifacial devices, the maximum allowed measurement time for one *IV* measurement is about 40 ms.

We have shown that advanced hysteresis in combination with an optimized sweep form allows for meeting this requirement without sacrificing measurement accuracy. The required flash pulse length of 40 ms for each measurement condition of a highly capacitive bifacial solar cell (rear STC, true bifacial, front STC) allows for two voltage sweeps to determine the $I_{SC} \rightarrow V_{OC}$ and the $V_{OC} \rightarrow I_{SC}$ curve. A sophisticated algorithm that uses both curves together with a physical model results in an *IV* curve that precisely matches the steady-state *IV* curve.

www.halm.de

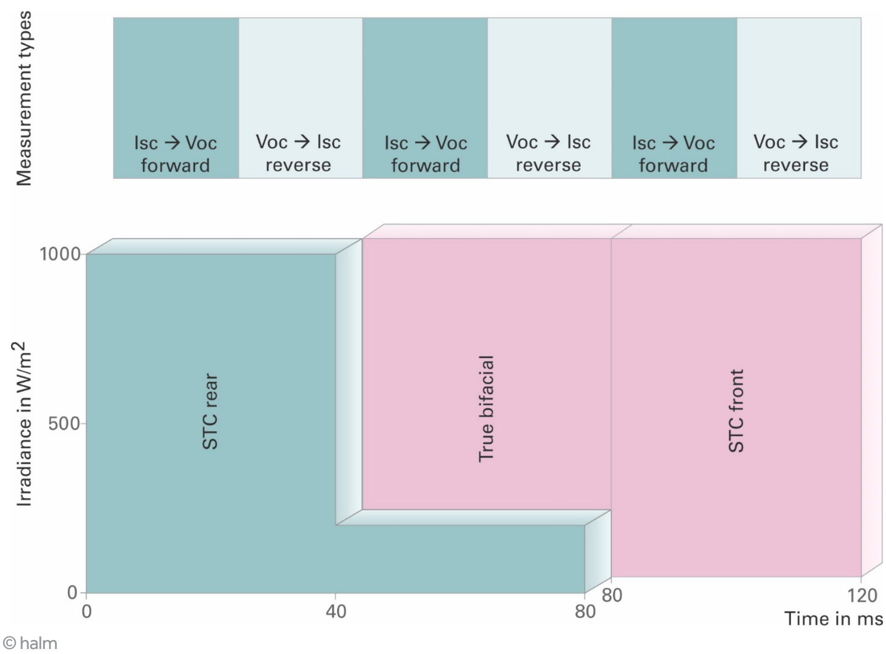

Figure 6: Sketch of the light *IV* measurement sequence of a bifacial solar cell using single-flash hysteresis for all three measurement conditions. The bottom graph shows the irradiance levels of the front and rear flash as a function of time. As can be seen, the first measurement is performed at rear STC, the second at true bifacial conditions and the third at front STC. Within each flash level, the *IV* characteristics are determined with a forward ($I_{SC} \rightarrow V_{OC}$) and a reverse ($V_{OC} \rightarrow I_{SC}$) sweep (single-flash hysteresis).