Accurate flash testing of high-efficiency solar cells and modules using Capacitance Compensation

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Introduction

Due to their high throughput, flash testers are ideal for measuring and sorting of solar cells or modules at manufacture lines. During flash testing, a current-voltage (IV) curve is obtained by sweeping the output voltage from open-circuit to short-circuit conditions (or vice versa) while recording the output current induced by flash illumination. Generally, the voltage sweep time is limited by the throughput requirement of the manufacture line.

High-efficiency solar cells such as the passivated emitter and rear contact (PERC) cell, the heterojunction technology (HJT) cell, and the interdigitated back-contact (IBC) cell are currently gaining in production volume and market share. Due to well passivated surfaces and high effective minority carrier lifetimes, these architectures store a considerable amount of charge mainly in the quasi-neutral regions of the device. Consequently, charging and discharging of this region during voltage sweeps can produce transient artefacts in the measured IV-curve when relatively high sweep rates typical to flash testing are applied. Suitable methods to correct these artefacts are required for accurate measurement of the steady-state IV-curve with flash testers.

Measurement artefacts due to storage of charge in high-efficiency solar cells

Figure 1 illustrates uncorrected IV-curves simulated with the PC1D software [1] using model parameters corresponding to a high-efficiency solar cell with an open-circuit voltage of ~0.72 V. A linear sweep of the output voltage, V_{out}, with a duration of 20 ms was applied both in the forward direction (FW, from short- to open-circuit) and in the reverse direction (REV). The measurement artefacts due to capacitive charge storage in the solar cell are visible around the maximum power point (MP) as an underestimated output current, I_{out}, during the FW sweep, and an overestimated I_{out} during the REV sweep as compared to the simulated steady-state IV-curve, $I_{\mathrm{out,s-s}}$.

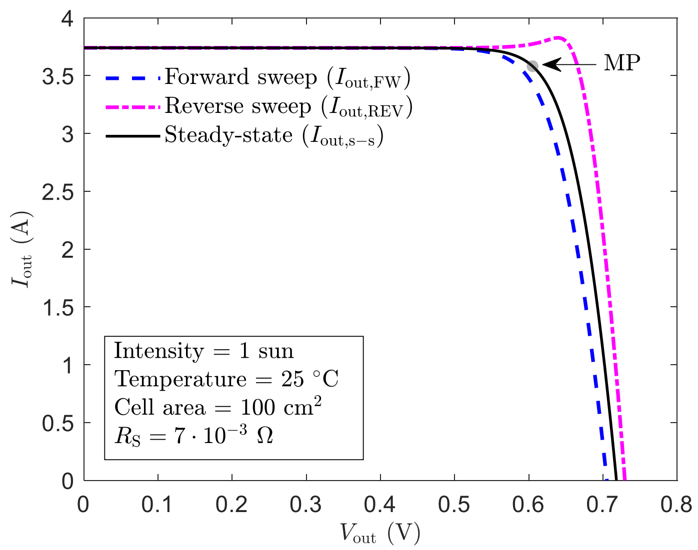

Figure 1: IV-curves simulated using the PC1D software with model parameters corresponding to a high-efficiency solar cell with an open-circuit voltage of ~0.72 V. An output voltage sweep length of 20 ms was applied both in the forward direction (from short- to open-circuit) and in the reverse direction. Further, a steady-state IV-curve was simulated using a very long sweep duration.

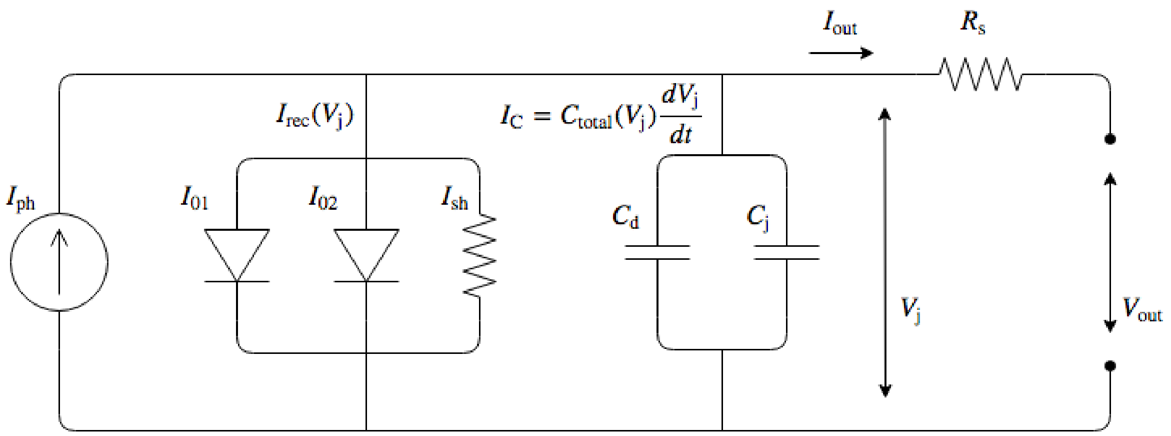

Figure 2: Equivalent circuit of a high-efficiency solar cell. Capacitors parallel to the recombination diodes are included to take charge storage in the solar cell or module into account.

Table 1: Summary of symbols in Fig. 2.

I_{ph}: photocurrent	I_{rec}: total recombination current	I_C: capacitive current	I_{out}: output current
	I_{01}: current of recombination diode 1	C_{total}: total capacitance	V_{out}: output voltage
	I_{02}: current of recombination diode 2	C_d: diffusion capacitance	V_j: junction voltage
	I_{sh}: shunt current	C_j: junction capacitance	R_S: series resistance

Correction of measurement artefacts through equivalent circuit analysis

The mathematical form of current components that produce the transient artefacts can be examined further using equivalent circuit analysis. According to the equivalent circuit in Figure 2, the output current of a solar cell can be written as

$$I_{out} = I_{ph} - \underbrace{(I_{01} + I_{02} + I_{sh})}_{I_{rec}} - \underbrace{C_{total}(V_j)\frac{dV_j}{dt}}_{I_C}. \quad (1)$$

The current pathways in the solar cell can be divided into two groups based on whether they are of steady-state or transient nature. In Eq. (1), I_{rec} corresponds to the steady-state V_j-dependent current loss, whereas the current due to capacitive charge storage, I_C, depends not only on V_j but also on its rate of change, dV_j/dt. Hence, the current I_C is responsible for the transient artefacts observed during fast voltage sweeps.

Transient artefacts during IV-measurement can be corrected using a so-called Capacitance Compensation (CAC) method. This method utilizes two IV-curves that are measured in opposite V_{out} sweep directions. First, each V_{out} point of the measured IV-curves is converted into junction voltage V_j through

$$V_j = R_s I_{out} + V_{out}. \quad (2)$$

This is followed by a subtraction of the FW- and REV-swept currents at each junction voltage point,

$$I_{out,REV}(V_j) - I_{out,FW}(V_j) = I_{C,FW} - I_{C,REV} = C_{total}(V_j)\left(\left.\frac{dV_j}{dt}\right|_{FW} - \left.\frac{dV_j}{dt}\right|_{REV}\right), \quad (3)$$

which factors out all steady-state current components. Hence, the total capacitance, C_{total}, can be solved from Eq. (3) as

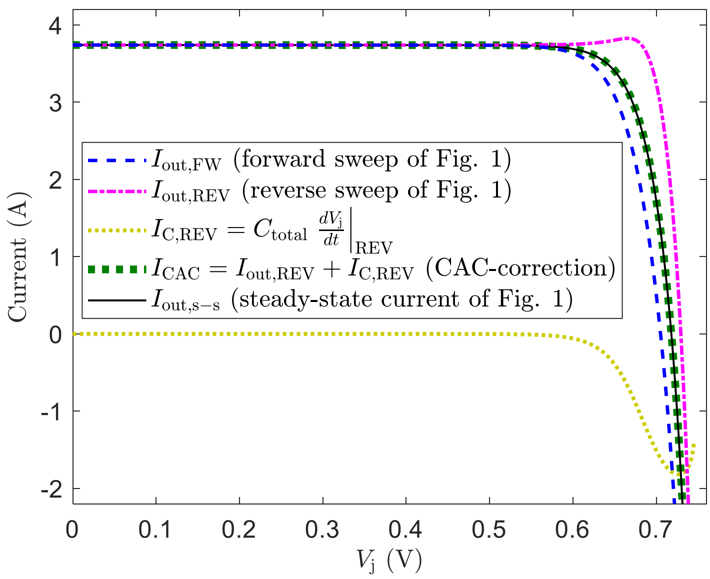

Figure 3: IV-curves of Fig. 1 with output voltages V_{out} converted into junction voltages V_j. The Capacitance Compensation (CAC) method was applied to obtain $I_{C,REV}(V_j)$, and consequently the CAC-corrected current, I_{CAC}, was calculated. The coincidence of I_{CAC} with $I_{out,s-s}$ means that the CAC-corrected current is free from transient artefacts.

$$C_{total}(V_j) = \frac{I_{out,REV}(V_j) - I_{out,FW}(V_j)}{\frac{dV_j}{dt}\Big|_{FW} - \frac{dV_j}{dt}\Big|_{REV}}, \quad (4)$$

where the time derivatives of V_j in the denominator are obtained from recorded time information of $V_{out}(t)$ and $I_{out}(t)$, and Eq. (2). Since both $C_{total}(V_j)$ and dV_j/dt are now known, the capacitive current corresponding to either of the examined IV-curves, $I_{C,FW}$ or $I_{C,REV}$, can be calculated. This capacitive current is consequently added to the corresponding IV-curve to yield an output current that is theoretically free from the transient artefacts [see Eq. (1)] [2].

As an example of the correction procedure according to the CAC method, Figure 3 shows both $I_{out,FW}$ and $I_{out,REV}$ of Figure 1 with their output voltage points V_{out} converted into junction voltages V_j through Eq. (2). Also illustrated is the charge storage current $I_{C,REV}(V_j)$ that was determined as described above using $C_{total}(V_j)$ calculated based Eq. (4). Consequently, $I_{C,REV}(V_j)$ was added to $I_{out,REV}(V_j)$, which yields the CAC-corrected current, I_{CAC}. Since I_{CAC} coincides exactly with $I_{out,s-s}$ (the steady-state IV-curve of Figure 1 whose V_{out} points were also converted into V_j and plotted in Figure 3), the CAC method reproduces an IV-curve that is free from transient artefacts due to charge storage. To obtain the final corrected form of the IV-curve, the series resistance is reintroduced into I_{CAC} by converting each of the junction voltage points back to output voltage V_{out}.

Accurate evaluation of steady-state efficiency with CAC method

The accuracy of the CAC method in correcting experimental data was evaluated using a state-of-the-art high-efficiency solar cell with an open-circuit voltage of ~0.72 V. Forward and reverse-swept IV-curves were measured and used to obtain both the CAC-corrected current and a V_{out} point-wise averaged IV-curve (denoted as simple average). The deviation of the efficiencies determined from these IV-curves from the approximate steady-state efficiency are compared in Figure 4 (in $\%_{rel}$) at different V_{out} sweep times. Importantly, the efficiency determined with the CAC method stays within

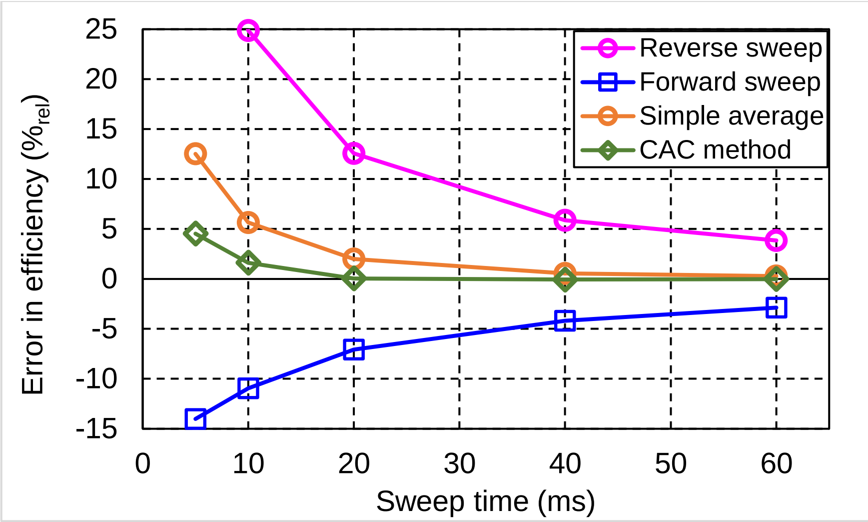

Figure 4: Relative deviation of the solar cell efficiency (in $\%_{rel}$) from the steady-state efficiency at different V_{out} sweep times. Forward- and reverse-swept IV-curves were utilized to calculate the efficiency both from the CAC-corrected current and from V_{out} point-wise averaged IV-curves (simple average).

< 0.1 $\%_{rel}$ error from the V_{out} sweep time of 20 ms upward. On the other hand, the efficiency determined by the simple averaging of the IV-curves approaches the steady-state efficiency with increasing sweep time but introduces a significant error (> 0.1 $\%_{rel}$) below 60 ms. Therefore, the CAC method provides a considerable improvement in comparison to the simple V_{out} point-wise averaging of the IV-curves.

It is important to note that since each of the individual forward and reverse sweeps were recorded within a single flash, the IV-curves corrected with the CAC method and the simple averaging both involve two separate flashes and output voltage sweeps. However, since the CAC method allows decreasing the sweep time below 20 ms even in the case of the investigated state-of-the-art solar cell with a high open-circuit voltage of ~0.72 V, both sweeps could also easily be measured within a single flash, which would result in a notable decrease in the total measurement time.

The above-presented cell results are fully transferrable to module level. Hence, the CAC method allows accurate determination of steady-state IV parameters even from state-of-the-art high-efficiency solar cells and modules whose open-circuit voltage exceeds 0.7 V/cell.

References

[1] H. Haug, and J. Greulich, *Energy Procedia* 92, 60 (2016).
[2] R. A. Sinton, H. W. Wilterdink, and A. L. Blum, *IEEE Journal of Photovoltaics* 7, 1591 (2017).