FLASH TESTING HIGH-EFFICIENCY SILICON SOLAR CELLS AND MODULES

Ronald A. Sinton[1], Denis De Ceuster[2], Karen Wilson[2], Laetitia Rodrigues Barbosa[2]
[1]Sinton Consulting, Inc., 1132 Green Circle, Boulder, CO USA 80305, email: ron@sintonconsulting.com
[2]SunPower Corp., Sunnyvale CA USA

ABSTRACT: A number of new, high-efficiency silicon solar cell technologies have been entering the market in the last decade. These include the BP Saturn, Sanyo HIT, and SunPower backside-contact solar cell technologies. The more traditional solar cell designs are also improving, so that they operate at higher voltages than previous generations of similar designs. These high-voltage solar cells can have internal capacitance that is orders of magnitude higher than typical industrial silicon solar cells manufactured in the last decade. This capacitance can lead to time delays in the cell response to changing light or voltage. These delays can lead to serious measurement artifacts in all methods of cell and module measurement. This work will discuss the device physics of flash-test measurement of high-efficiency cells and modules. An accurate flash-test methodology for high-efficiency silicon cells is demonstrated.
Keywords: Crystalline, Silicon, Capacitance, Flash-test, High-efficiency, Module, Back-contact

1 OVERVIEW

Unlike many of the thin films, the transient properties of high-efficiency silicon cells are very predictable from device physics simulations. In this paper, computer simulations were used to identify ideal conditions for accurate flash-testing of high efficiency silicon solar cells and modules. The trends in these simulations are verified with data from high-efficiency modules that were fabricated from backside-contact solar cells.

The main effect is due to charge storage in high-efficiency silicon solar cells. If this charge is discharged during the measurement, the measured currents are inflated relative to the steady-state measurements. If the stored charge is increased during the measurement, then the measured current is low compared to the steady state. These trends are well known and have been documented [1,2]. The usual solution to this problem is to measure one IV point per flash, while holding the voltage constant throughout the measurement to limit the effects of the capacitance[2]. This is commonly referred to as the “multiflash” technique, which has been used for high-efficiency cell measurements since at least the early 80’s.

This is the approach used in this work. With constant voltage at the terminals of the solar cell or module, second order effects become evident. These are documented and discussed here.

For perspective, this differential capacitance is shown as a function of the substrate doping type, doping density, and junction voltage for cells under open-circuit conditions in Fig. 1. The vast majority of existing solar cells have a maximum power point voltage of about 500 mV and a p-type substrate doping in the 1 to 3 ohm-cm range. From Figure 1, this cell design would have less than 1 $\mu F/cm^2$ of cell area.

Currently, there are high-efficiency silicon solar cells from SunPower and Sanyo, for example, which have junction voltages at the maximum power point that approach 600 mV. These cells are also fabricated on n-type wafers instead of p-type. From Figure 1, these solar cells could have 30 to 100 μF/cm2 of differential capacitance at the maximum power point, about 100 times more than most existing solar cells. This means that the time response of these new generations of solar cells could be 100 times slower than typical industrial solar cells from the last decade. As the trends towards higher efficiency in the entire industry continue, most silicon solar cells will evolve towards higher voltages at the maximum power point. Therefore, this issue affecting a few cell types today may grow to affect most solar cells in the future.

As the silicon photovoltaic manufacturing industry matures, more in-line characterization is being implemented within the manufacturing lines. Flash-testing of modules has been primarily used to certify specifications. There is great promise that with a more detailed device physics basis for flash tests these measurements can be used for accurate diagnostic process control and optimization. Detailed techniques usually reserved for R&D studies on solar cells can be applied to the measurements of module electrical characteristics.

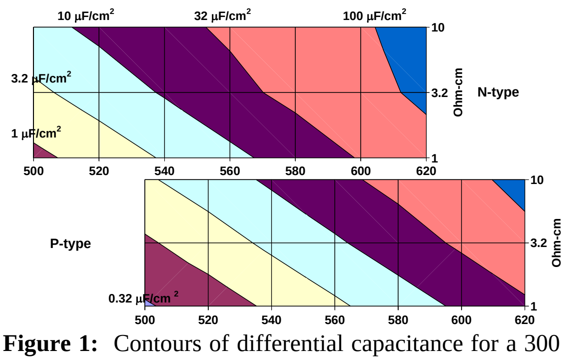

Figure 1: Contours of differential capacitance for a 300 μm-thick solar cell as a function of voltage at V_{oc} in mV.

2 MODELING OF THE TRANSIENT FLASH-TEST PROBLEM

An illustration of the capacitance is shown in Fig. 2, based on a PC1D simulation of a 1D approximation of a SunPower high-efficiency solar cell. There are two main components of the charge. One is determined primarily by the junction voltage, and is uniform throughout the cell under conditions of long diffusion length and good

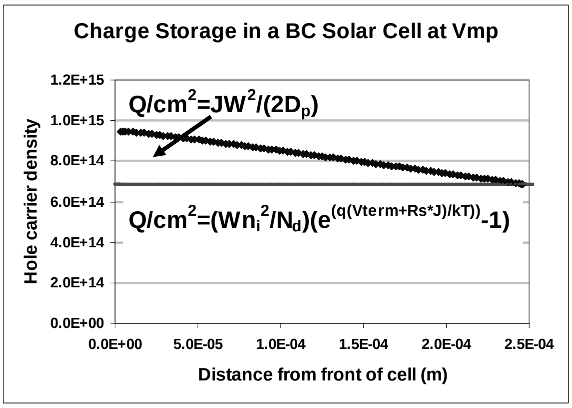

Figure 2: A PC1D[3] simulation of the charge (holes) in a high-efficiency n-type backside-contact solar cell. It has two parts, a uniform carrier density component dictated by the junction voltage at the back of the cell, and a "transit" component that depends on the carrier-density gradients that drive the current.

surface passivation. This is the component shown in the contour plots in Figure 1. The second component is due to the gradient in carrier density that drives the current. This charge is present even at short circuit current conditions, and is primarily significant in solar cell designs where the photogeneration can be some distance from the collecting junction.

The implications of this charge storage to flash-test measurements are well illustrated by PC1D[3,4] simulations of these tests, shown in Fig. 3 and Fig. 4, for two common flashlamp intensity-time profiles. The terminal voltage of the solar cell was held constant, at the steady-state maximum power point for 1 sun.

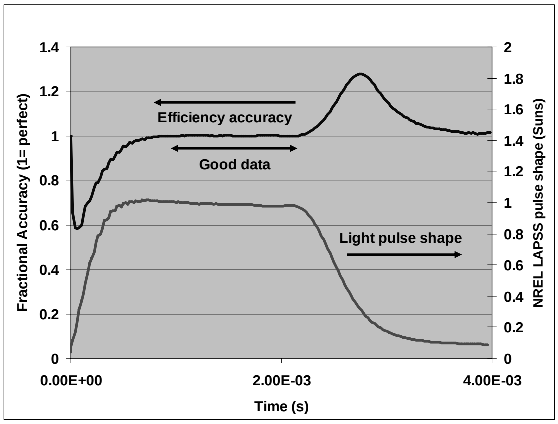

Figure 3: The instantaneous efficiency that would be measured at each point in time for a common flashlamp time-intensity pulse shape[5]. The efficiency is normalized by the true steady-state efficiency at each light intensity.

In Fig. 3, the reported efficiency is shown normalized to the steady-state efficiency for that light intensity at each point in time. During the rise time and for about 200 μs after a constant intensity is achieved, the measured efficiency is low. Soon after the light pulse begins to drop off, the measured efficiency peaks at nearly 30% higher than the steady state value. With the terminals of the solar cell held at constant voltage, it might seem that the charge storage in the cell would be constant, not permitting inflated or low measurements of the current. Two things are not constant though.

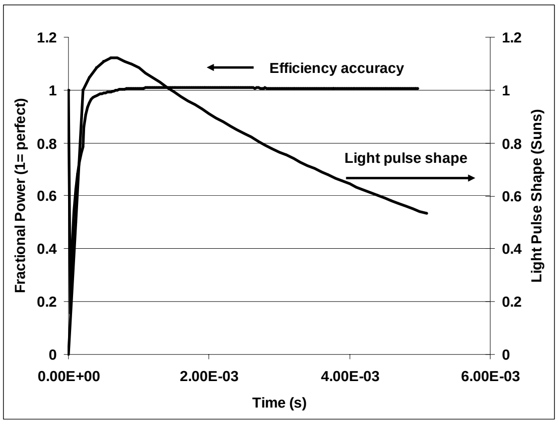

Figure 4: The modeled result for another common flashlamp pulse shape. During the long decay of the light intensity, the measured efficiency is 1% high.

1) The current is changing nearly proportionally to the illumination intensity, changing the "transit" charge shown in Fig. 1.

2) The junction voltage is still modulated during the measurement by a factor of Rs*(dJ/dt).

Fig. 4 shows the same type of simulation for another common flashlamp pulse shape. In this case, there is a fast rise time in the light intensity, and then a slow exponential fall. The efficiency is measured low until a few hundred μs after the peak intensity, and then is measured at 1% high during the slow light decay.

3 EXPERIMENTAL

We investigated the use of the pulse shape shown in Figure 4 in detail with measurements on modules fabricated from SunPower cells.

The downward ramp rates in intensity varied from a maximum rate of -735 suns/sec at one sun, to a minimum rate of -197 suns/sec.

The resulting measured curve parameters are shown in Fig. 6, normalized to their values extrapolated to the steady-state case (intensity ramp of 0 suns/sec). The parameters, efficiency, Jsc, and FF are all linear in the light-intensity ramp rate for this regime of light ramp rates comparable to or longer than the effective minority-carrier lifetime in the cells (before recombination or collection at the junction). The open circuit voltage is independent of the intensity ramp rate. The open-circuit voltage data was taken under open-circuit conditions rather than at constant voltage. In addition, the open-circuit voltage case is a simplified special case for which the transient correction has been derived[6]. This correction was applied here.

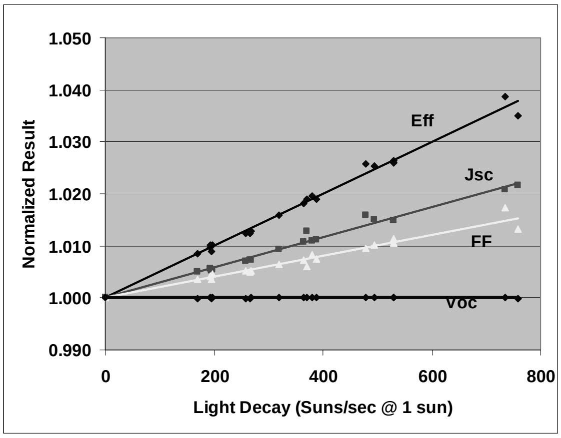

Figure 5: The curve parameters measured by the multiflash method with constant voltage at V_{mp} and a pulse shape similar to that in Fig. 4. The values are normalized by their extrapolated intercepts for light decay rate = 0.

The dependence of the short circuit current on the light-intensity ramp rate is likely to be due to the "transit" component of the stored charge shown in Fig. 2. This charge is stored even under short circuit conditions and is independent of the junction voltage. The FF dependence is due to the modulation of the junction voltage by the change in current and the series resistance. At the maximum light intensity ramp rate of -735 suns/sec this results in -25 V/sec of voltage ramping at the junction.

At the slowest intensity ramp rate, the error in the measured efficiency is less than 1% relative. Very importantly, if two or more ramp rates are used this transient error can be precisely determined and corrected. This can be done in-situ for any module or all modules measured.

Another interesting point is that much of the dependence upon the intensity ramp rate is due to the J_{sc} dependence. This is particular to the backside junction design of the SunPower solar cells. In front junction solar cells, this component is much reduced or absent.

If the reference cell for the measurement of light intensity were of the same technology, design, and nominal thickness as the cells in the module, then there would be no apparent dependence of the measured short-circuit current on the light ramp rate because there would be identical errors in the intensity and current measurements, canceling out in the calculation of current at one sun. The dependence of the measured efficiency on the light ramp rate would be reduced to less than half of that shown in Fig. 5.

Fig. 6 shows a detail of the J-V curve taken under the lowest and highest ramp rates used in this study. The transient effects shift the current upwards at each voltage. At the maximum power point, the shift is the 4% in power seen in Fig. 5.

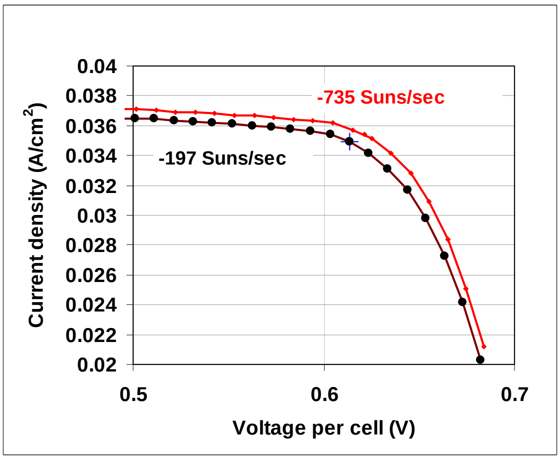

Figure 6: Contours of differential capacitance for a 300 mm-thick solar cell as a function of voltage at V_{oc}.

4 APPLICATIONS OF THE SUNS-VOC CURVE

When using the multi-flash method, one flash is required to obtain the open-circuit voltage. For a pulse shape as shown in Fig. 4, this voltage is obtained at a wide range of intensities. Rather than using the single point, V_{oc} at one sun, the entire Suns-Voc curve has been shown to contain significant information that is relevant to the interpretation of IV curves[6,7].

Figure 7 shows an example of the clear utility of the Suns-Voc curve. This curve (constructed from the illumination-V_{oc} curve by using the measured J_{sc} to convert light intensity to current) is shown along with the J-V data points from a multiflash measurement taken at the slowest light ramp rate shown in Fig. 5. The Suns-Voc curve represents the upper bound on the efficiency that would be possible for the solar cells in this module, if there were no series resistance or cell mismatch.

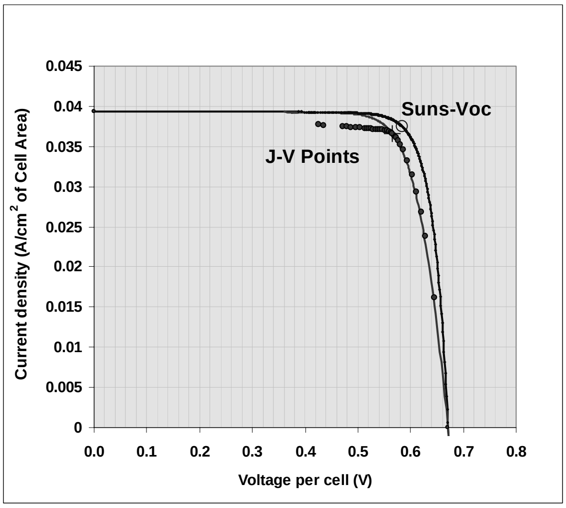

Figure 7: The J-V data points shown relative to the Suns-Voc curve, and a modeled curve constructed by shifting the Suns-Voc curve by the series resistance as determined at Jmp by the difference between the curves. The Suns-Voc data already includes any losses due to bulk recombination, surface recombination, and shunting.

A comparison of the IV point at the maximum power and the Suns-Voc curve at the same current density gives the most relevant measure of the series resistance loss. This is shown in the figure by the modeled curve, shifting the Suns-Voc curve by the series resistance measured in this way at Jmp.

Since the Suns-Voc curve already includes any shunting effects in the cells in this module (there is no evidence of shunting), then it is clear that the "notch" in the J-V curve on the short-circuit side of the maximum power point is due to non-uniform illumination or current mismatch in the solar cells.

Similarly, if there were significant shunting showing in the Suns-Voc curve, then it would be clear that this was not due to distributed series resistance effects.

In this way, the use of the Suns-Voc curve to complement the J-V curve can give more unique determination and separation of the effects due to:

-shunting
-bulk defects
-surface recombination
-lumped and distributed series resistance
-illumination non-uniformity
-mismatched cells in a module

Except for the last two in this list, this extra functionality can be useful at either cell test or module test.

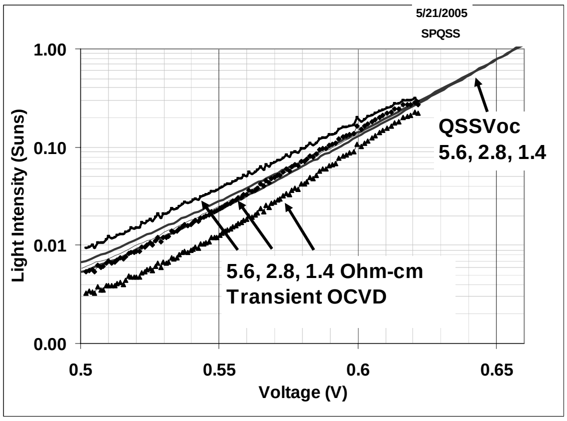

Figure 8: A comparison of illumination-Voc curves constructed from QSS data (light-pulse as shown in Fig. 4), and transient OCVD data. The case for different substrate resistivities is shown.

Another useful application of this Suns-Voc curve is shown in Fig. 8. Following the analysis of Kerr, J-V curves can be constructed from Qusasi-Steady-State and transient (OCVD) illumination-Voltage curves as well as from the steady state data. When this is done, there is a very strong dependence on the substrate doping in the transient case and very little dependence in the QSS case with a slowly varying light pulse. The transient and QSS curves will only agree for the correct choice of substrate doping. This can be used as a method to measure the substrate doping.

Specific knowledge of the substrate doping for each wafer at the end of the process could allow more sophisticated device physics and process control to be done using industrial J-V curve data from the cell test or the module test stage. Often there is the problem that only the nominal substrate doping is known. In this case, the nominal range of substrate doping could account for a rather large variation in the J-V characteristics obscuring the sensitivity to other parameters.

Knowing the substrate doping could also permit a more sophisticated assignment of cells into modules. An industrially important example of this might be the case of B-doped CZ cells. Instead of binning by current alone, the cells could be binned by current and substrate doping in order to ensure that the cells within a single module would remain better current matched AFTER degradation as well as at the end of the cell fabrication.

5 CONCLUSION

SunPower modules have been characterized by flash-testing. The main trends in the time response are predicted by computer modeling using an approximate 1D model of the solar cells. Accurate testing is possible using modest intensity-time flash profiles if the terminal voltage of the cell or module is held constant during the measurement. This is not sufficient to completely eliminate the transient effects. Instead, these effects should be characterized and monitored. A methodology for doing this was demonstrated. These techniques are general to any crystalline-silicon solar cell.

When using the multi-flash method for characterizing cells or modules, one flash is required for the open-circuit voltage. This entire data curve, the "Suns-Voc" curve, can provide additional data for device physics analysis and process control.

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5.2 References

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