IMPLIED-V_{OC} AND SUNS-V_{OC} MEASUREMENTS IN MULTICRYSTALLINE SOLAR CELLS

S. Bowden, V. Yelundur and A. Rohatgi
University Center of Excellence in Photovoltaics
School of Electrical and Computer Engineering
Georgia Institute of Technology, Atlanta, GA 30332–0250 USA

ABSTRACT

Identifying loss mechanisms and predicting device performance are key goals of device and process characterization. Photoconductance measurements allow the extraction of the Implied V_{oc} and Suns V_{oc}, which together can be used for process monitoring, for loss analysis and to identify the potential device performance in the absence of unwanted defects. In this paper, we measure the Implied V_{oc} and Suns V_{oc} from solar cells with a range of different substrates and at different stages in processing. These measurements are used to analyze the correlation with the actual V_{oc} to determine the impact of both non-idealities such as depletion region recombination, and expected effects such as lifetime changes, both during processing and in the final devices.

INTRODUCTION

The I-V curve and the open circuit voltage of a solar cell not only specify device performance, but also reflect the dominant recombination mechanisms. However, using the I-V curve has several disadvantages. Firstly, the measurement of the IV curve requires a completed solar cell, and secondly parasitic effects may mask the desired effects. Both of these problems can be circumvented by using a combination of Implied-V_{oc} and Suns-V_{oc} techniques, provided that the match between the Implied-V_{oc} and other techniques can be demonstrated. In this paper we show that for solar cells with uniform and ideal (i.e., m=1) recombination, the Implied-V_{oc} matches well. However, for solar cells with substantial non-ideal recombination components, Implied-V_{oc} results are not sensitive to the non-ideal recombination.

MEASUREMENT TECHNIQUES

Actual-Voc

The term actual-Voc is used to denote the V_{oc} as measured with a standard IV tester with a lamp spectrum approximating AM 1.5. The wafers are on a temperature controlled block at 25°C but poor thermal contact may cause the wafer temperature to deviate by 1-2°C and V_{oc} by up to 5 mV.

Suns-V_{oc}

Suns-V_{oc} [1] directly measures V_{oc} as a function of the light intensity, typically from a few suns to just below 0.1 suns. Since it is a direct electrical measurement with an electrical contact, the V_{oc} measured at one sun should exactly match that from an IV tester assuming that the cell temperature is constant and that the spectrum of the lamp is similar. The results can be interpreted in a number of ways; the most important for this work is that of local ideality factor, m, as derived from the following equation:

$$suns \cdot Jsc = J_0 \exp\left(\frac{qV_{oc}}{mkT}\right), \tag{1}$$

where suns is the light intensity, J_{sc} is the cell short circuit current at one sun and is a constant for a particular cell, V_{oc} is the open circuit voltage and is a function of light intensity, J_0 is the dark saturation current and kT/q is thermal voltage (25.69 mV at 25°C). By taking the natural log of both sides the ideality factor is then the inverse of the slope at each point divided by the thermal voltage. Although J_{sc} appears in Eqn 1 it does not affect the slope, so it does not need to be known. The Suns-V_{oc} measurement follows the Dark IV curve but without the effects of series resistance.

Implied-V_{oc}

Quasi-steady-state-photoconductance (QSS-PC) measures the average excess carrier concentration. Assuming the carrier concentration is constant through the base, the effective minority carrier lifetime, τ_{eff}, can be determined and is commonly used for characterisation. An alternative interpretation of the minority carrier lifetime is to determine the voltage [2] of the device if contacts were applied.

This parameter is called Implied-V_{oc} and is determined from the carrier concentrations at the edge of the depletion region. In low level injection:

$$\text{Implied}\, V_{oc} = \frac{kT}{q} \ln\left(\frac{n\ N_A}{n_i^2}\right), \tag{2}$$

where n is the minority carrier concentration at the junction edge and n_i is the intrinsic carrier concentration (8.6×10^9 cm^{-3} at 25°C). The base doping, N_A, has a strong effect on Implied-Voc and so must be measured on each wafer. The base resistivity is determined using the same RF system as for the PC measurement and is preferable to a four-point probe where grain boundaries are a problem.

MODELING IMPLIED V_{OC} WITH PC1D

The QSS-PC system only measures the *average* minority carrier density, whereas accurate determination of Implied-Voc using Eqn. 2 requires the minority carrier density at the *junction edge*. If the surface recombination velocities are high or the diffusion length in the base is low, the assumption that the average carrier density is the same as that at the junction edge may no longer hold. While there are many ways to calculate the carrier profile, the easiest is via the simulation program PC1D. The simulation procedure outlined here closely models the operation of the QSS-PC tester and the same analysis spreadsheet is used with only slight modifications.

A light generation file for PC1D was calculated from typical flash properties. PC1D uses W/cm^2 so the generation file values are multiplied by 10 for the analysis sheet (accomplished by setting V/Sun to 0.1). In PC1D, the excitation is set to transient, the number of steps to that of the analysis spreadsheet (125) and the time step to that in the light generation file. The resistance on the base circuit is set to 10 M Ω so the cell operates at V_{oc}. The auxiliary data is set to cumulative excess conductivity at a distance from the front equal to the wafer thickness. This follows the real case where the RF coil also measures excess conductivity. The graphs in PC1D are set to base voltage vs time and Auxiliary data vs time. After a simulation is run, the contents of the cumulative excess conductivity are copied directly to the conductivity column of the analysis spreadsheet. The base V_{oc} is copied to the spreadsheet so that the Implied-Voc calculated by the lifetime analysis spreadsheet can be compared to the voltage directly determined by PC1D.

COMPARISON OF IMPLIED-V_{OC} AND ACTUAL-V_{OC}

Finished solar cells were measured for actual-V_{oc} and SunsV_{oc}. Next, the highly conductive metal aluminium rear surface was removed in hydrochloric acid to allow for a measurement of the photoconductance. Measurements on similar cells with the Suns-V_{oc} system show that removing the rear Al metal has no effect on V_{oc}. The float zone and cast multicrystalline cells are fabricated on 4 in wafers with nine 2 x 2 cm cells on each wafer. The String Ribbon samples are 5 x 8 cm with six 2 x 2 cm cells on each wafer. All cells have an emitter diffused to 45 Ω/□, an Al-alloyed BSF and a front contact fired through a SiN top surface passivation layer.

For the Implied-V_{oc} measurements, a bias light of 0.3 to 1 sun was added to correct for trapping [3]. In the tables, the final column denoted *Simple PC1D Correction* is the Implied-Voc measurements corrected using PC1D simulations outlined above. The simulations only correct for the carrier profiles through the device, they do not correct for two dimension effects such as variation in lifetime across the device and the other diode non-idealities discussed below.

Float-Zone material

The three FZ solar cells of Table 1 show a close correlation between the V_{oc} measurements. Cell FZ2 is nearly ideal with resistivity of 2 Ωcm, with a good quality BSF and a long base lifetime. Modeling the device with PC1D showed the real V_{oc} should be 4 mV higher than the V_{oc} determined from conductivity measurements. For FZ2 there is almost an exact match between the three methods with only 2 mV between the results.

The cells FZ750 and FZ775 are similar to FZ2 but were fabricated with non-optimal firing conditions. The small differences between the Suns-Voc and the IV tester are doubt due to either temperature effects or spectral mismatch between the lamps. The Implied-Voc measurements closely match the SunsVoc results however simple modeling shows the Implied-V_{oc} should be increased by 4 mV. However, the PC1D modeling does not take into account non idealities in the diode. For well behaved single crystalline cells with a low rear surface recombination velocity the differences between V_{oc} measurements are due to temperature effects.

Table 1. Comparison of V_{oc} measurements for cells fabricated on FZ material

Wafer	actual-Voc*	Suns-Voc	Implied-Voc	Simple PC1D
FZ2	625	626	620	624
FZ750	617	621	622	627
FZ775	622	623	623	628

Cast Multicrystalline Material

In sample H1.5 with a base resistivity of 1.5 Ωcm, the Implied-Voc is 10 mV high than the actual-Voc and the Simple PC1D correction is 20 mV higher. However, in this sample there is a wider variation in cell V_{oc}s. The highest cell on the wafer V_{oc} is 592 mV and the lowest V_{oc} is 573 mV. Averaging the photoconductance may not be the same as averaging the actual solar cell V_{oc}s, especially since the coil size is much large than the cell size. In addition, Suns-V_{oc} measurements show a high ideality factor of 1.3 at one-sun. This indicates the cell V_{oc} is being reduced by junction recombination, that the Simple PC1D correction is invalid in and that Implied-Voc overestimates actual-Voc. For more details on the effect of junction recombination, see the String Ribbon case below.

Table 2. Comparison of actual-Voc, one-sun Suns-Voc and Implied-Voc measurements on multicrystalline substrates

Wafer Res.	actual-Voc*	Suns-Voc	Implied-Voc	Simple PC1D
H1.5	581	580	592	602
H0.2	610	605	625	635

Cell H0.2 is fabricated from 0.2 Ωcm material and is a highly non-ideal device. Not only is the ideality factor at one-sun high at 1.33, but there is also an extra hump in the ideality factor curve. This indicates a high level of localized recombination and that cell V_{oc} is no longer simply limited by recombination in the bulk and emitter.

String Ribbon Cells

For the String Ribbon samples, two sets of samples were identically processed. The only difference between the sets of samples is that one set used a high frequency 13.56 MHz SiN depositions like all the other samples in this study, while a second set used a lower frequency kHz SiN deposition. Sample thickness varied from 200 to 300 µm while resistivity ranged from 1 to 5 Ωcm.

Table 3. Wafers fabricated with kHz SiN on String Ribbon substrates. The cells have ideality factors of close to one indicating ideal recombination mechanisms such as SRH in the bulk.

Wafer	actual-Voc	Implied-Voc	Simple PC1D correction
d3	583	586	592
d4	582	578	584
a3	580	578	584

The cells with the kHz SiN were measured to have a final bulk lifetime of 20 µsec. From this value, modeling in PC1D suggests that the Implied-V_{oc} should be 6 mV higher. Table 3 shows good correlation between V_{oc} measurements of String Ribbon cell with kHz SiN, even though they are multicrystalline with grain boundaries present.

Table 4. Wafers fabricated with 13.56 MHz SiN on String Ribbon substrates.

Wafer	actual-Voc	Implied-Voc	Simple PC1D correction
a1	540	562	572
a2	541	577	587
b1	557	553	563

For the cells with a MHz SiN, the actual-V_{oc} is up to 40 mV lower than similarly processed samples with the kHz SiN. The best cell (b1) was measured to have m=1 around V_{oc}. The low bulk lifetime of b1 (≈ 10 µs, half that of above) explains the lower V_{oc}. However, as in the kHz nitride case, there is a good match in V_{oc}. The PC1D corrected Implied-Voc is 6 mV higher than the actual either due to variation in recombination across the device or a higher temperature during the actual V_{oc} measurement.

Effect of Junction Recombination on Implied-V_{oc}

Wafers a1 and a2 have a very low actual-Voc of 540 mV, and a quite different Implied-Voc that is ≈ 25 mV higher. A simple correction of these results with PC1D makes the situation even worse, giving a corrected V_{oc} ≈ 40 mV higher than the actual values. A closer examination of these devices reveals highly non-ideal behavior. Fig. 1 shows the ideality factor as a function of voltage. In this cell the ideality factor is still at 1.4 at one-sun V_{oc} (open circle). The high ideality factor is probably caused by extra recombination in the depletion region (junction). While a comprehensive study of ideality factors [4] suggests that recombination in the junction is typically overestimated, it seems a suitable explanation in this case where the material is highly defected.

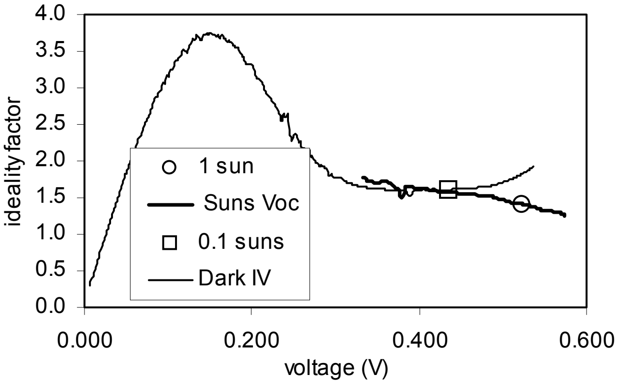

Fig. 1. Experimental Ideality factor of a String Ribbon cell with a high frequency deposited nitride layer. The high values below 0.3 V are from the shunt resistance and can be discounted.

Junction recombination was modeled in PC1D by placing a diode with an ideality factor of two in parallel with the junction. While junction recombination is highly complex [4] an ideality factor of two is assumed here to show the general effect of junction recombination on Implied-Voc. The effect of junction recombination is shown in Fig. 2. Where the Implied-Voc values calculated from the excess conductance are higher than the PC1D calculated values. Recombination in the junction reduces the carrier concentrations around the junction and this in turn lowers the device V_{oc}. However, the Implied-Voc measurement relies on the average carrier concentration, which in this case is higher than at the junction causing an overestimate V_{oc}. An additional problem is that the procedure for correcting for trapping by applying a bias light breaks down in this case causing an even higher Implied-Voc.

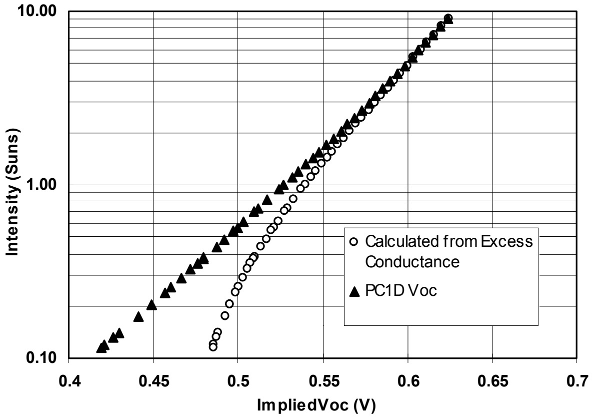

Fig. 2. Simulated effect of junction recombination on Implied-Voc. The values calculated from excess conductance are what would be predicted by a QSS-PC measurement (Implied-V_{oc}). The PC1D V_{oc} is what would be measured by an IV tester (actual-V_{oc}).

PROCESS MONITORING

The String Ribbon wafers were also measured throughout the process to demonstrate how Implied-V_{oc} can be used for process monitoring. Prior to processing, the samples have extremely low lifetime leading to very low and highly variable lifetime. This is partly due to the lack of surface passivation at this stage. After the $POCl_3$ diffusion, the surfaces are sufficiently passivated so that the Implied-Voc at this point is a good measure of the bulk properties. In commercial processing, if a sample at this point was found to have a very low Implied-Voc after diffusion it could be removed from the process.

Deposition of a kHz SiN layer on one side of the sample increased the Implied-Voc significantly. This is unlikely to come from improved surface passivation since the deposition is only on one side and low frequency SiN has a poorer passivation the high frequency SiN. It shows that even during SiN deposition at low temperatures of ≈400°C, the hydrogen has sufficient mobility to diffuse into the substrate and passivate defects. After deposition of the metal contacts and firing the V_{oc}s of all three cells increase to the same value.

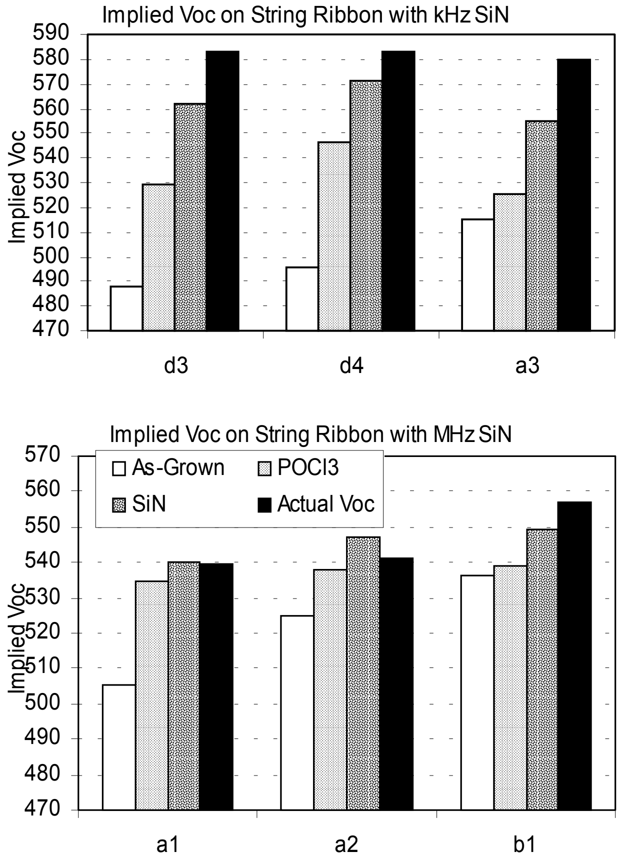

Fig. 3 Implied-Voc measurements during processing for String Ribbon material above. The legend is the same for both figures. The x axis is sample label.

The other set of samples with MHz SiN do not show the same improvement in Implied-V_{oc} after the SiN deposition. Additionally, the two poorest samples show a decrease in Implied V_{oc} after metal addition and firing. These samples are not reaching their full potential V_{oc} due to the junction recombination discussed earlier.

DEVIATIONS IN IMPLIED-V_{OC} FROM ACTUAL-V_{OC}

1. Recombination in the bulk causes Implied-Voc to underestimate actual-Voc. This can easily be corrected with PC1D. For a cell with a BSF this correction is minor.

2. If the lifetime varies (e.g. multicrystalline material) Implied-Voc typically overestimates actual-Voc

3. Recombination in the depletion region of the cell causes Implied-Voc to overestimate actual-Voc.

In the cells studied with a BSF and a diffusion length greater than half the substrate thickness it is found that the effects of 1 and 2 balance each other so no correction in Implied-Voc is necessary. In multicrystalline samples, cells with the lowest lifetime typically also have the greatest variation in lifetime.

CONCLUSION

For solar cells with an ideality factor equal to one, Implied-Voc matches the actual cell V_{oc} even on multicrystalline substrates. PC1D can be used to correct for variations in carrier concentration through the device thickness but the correction is small (4-8 mV) for most samples with a BSF. High recombination in the depletion region causes significant deviation in Implied-V_{oc} measurements but these cases are easily identified by measuring the ideality with the Suns-V_{oc} system.

REFERENCES

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