16th European Photovoltaic Solar Energy Conference, 1-5 May 2000, Glasgow, UK

NON–IDEAL RESISTIVE EFFECTS IN SILICON SOLAR CELLS

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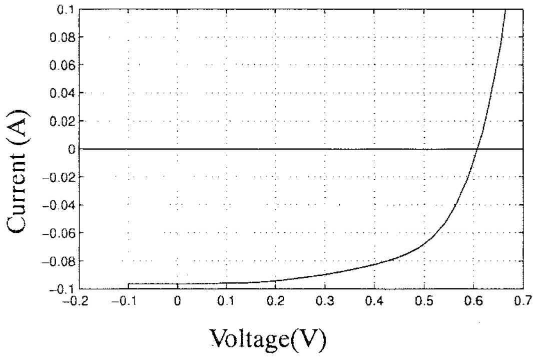
ABSTRACT: Two mechanisms which cause 'soft' fill factors in silicon solar cells have been identified. Each of these result from non–ideal resistive losses, despite apparently good series resistance and shunt resistance at V_{oc} and I_{sc} respectively. Each mechanism can produce qualitatively similar illuminated IV curves. The cause of each of the non–ideal resistive losses can be identified by investigating the IV curves at different illumination levels. One mechanism consists of a schottky diode in series with a resistance in parallel with the cell. The cell does not appear shunted due in reverse bias due to the presence of the diode. This can lead to significant loss of open circuit voltage due to current leakage. The second is caused by some regions of the cell experiencing high series resistance with the remainder of the cell has more typcial low resistance. This is equivalent to connecting a cell with good resistnace and a cell with poor resistance in parallel. Recognition of the cause of the 'soft' fill factor enables processing to be modified to minimise these non–ideal resistive losses.

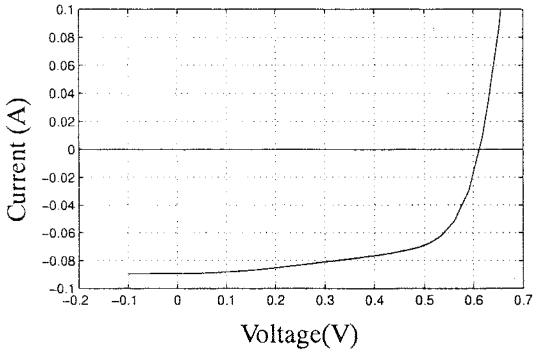
Keywords: Resistive Losses –1: Shunts –2: Silicon–3.

1. INTRODUCTION

Analysis of the illuminated IV curve of a silicon solar cell will often include investigation of the resistive losses in order to identify causes of power loss. The typical model for resistive losses in a silicon solar cell consists of a resistance in series with the cell and a second shunt resistance in parallel. The values for these two resistances are usually obtained from a measurement of the illuminated IV curve for the cell. Resistive losses in well behaved cells can be modelled with accurate prediction of fill factor possible [1].



Cell A



(Cell B)

Figure 1. Cell A and B. Multicrystalline silicon solar cell with 'soft' fill factor. Despite the similiarity of the curves, different mechanisms cause the non–ideal resistive losses.

However, cells can sometimes differ significantly from this simple model. Deviations from this model are sometimes described as a 'soft' fill factor [2]. The cell may have excellent shunt resistance in reverse bias and low series resistance near open circuit voltage, but fill factor is significantly lower than predicted by the model.

Typical examples of this can be seen in the IV curves in Figure 1. These cells demonstrate a near linear increase in current between 100–400mV and the maximum power voltage. This causes a loss in potential cell power, characterised by the poor fill factor. The IV curve of the cells demonstrated good shunt resistances in reverse bias (>1000Ω) and relatively low series resistance near open circuit voltage. The poor fill factors were independent of the quality of the cell current and voltage.

Our investigations have shown that this type of IV curve can be caused by two different non–ideal resistive mechanisms. This paper reports models which explain the loss in power caused by these non–ideal resistive losses and their possible causes. Identifying the cause of these losses can allow the manufacturing process to be modified to prevent these problems arising, and enable immediate improvements in cell efficiency.

2. IV CHARACTERISTICS UNDER VARYING ILLUMINATION

Further information on the behaviour of the substrates was obtained by investigating the cell's IV characteristics at different light intensities. Illumination intensity was varied from one seventh of a sun to one and a half suns. This led to decreases in fill factor on cell A from 70%, to 56%. Behaviour of cell B was markedly different, with fill factors increasing from 34% to 67%. Clearly, two different mechanisms were influencing cell behaviour.

The improvement in fill factor with illumination on cell B pointed towards shunt like behaviour in the cell (despite the lack of a shunt in reverse bias). Currents in the dark and illuminated IV curves were similar below 500mV with differences in the curves at higher voltages caused by series resistance losses (Figure 2). Qualitatively, the shape of the curves where they overlap is similar to that expected from a shunt. However, the curves could not be modelled with a shunt resistance in parallel with the cell. The reverse current was very small indicating a shunt resistance greater than 2000Ω in reverse bias.

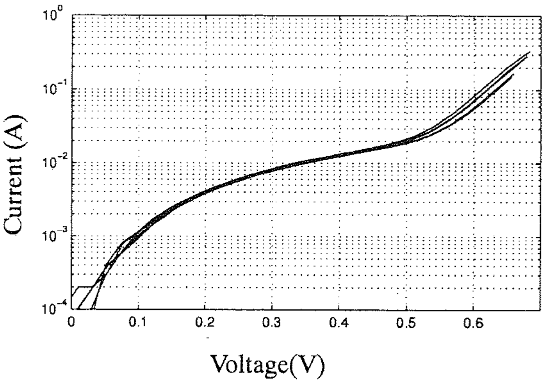


Figure 2. IV curves for cell B. Illumination was varied though dark, 1/7, 1 and $1^1/_2$ suns. Cell characteristics were similar below 500mV with variations at higher voltage due to series resistance.

In contrast, cell A had IV curves which differed significantly with changes in illumination (Figure 3). The curve at a low illumination level is similar to the dark IV curve. As the illumination level increases the curves diverge, with the greatest divergence at lower currents. This suggested that the resistive loss was related to a series–like resistance.

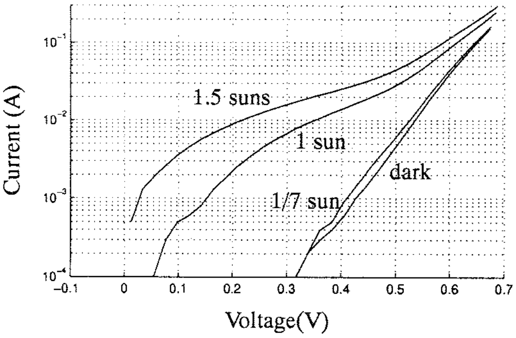


Figure 3. IV curves for cell A. The curves differ significantly as illumination levels vary.

3. SCHOTTKY SHUNT

Despite the shunt–like appearance of the forward bias region of the IV curve, the IV curve of cell B cannot be fitted with a simple shunt resistance. Figure 4 is a comparison of various shunt resistances to the dark IV curve of cell B. The curve approached the curves for the higher shunt resistances at lower voltages, gradually approaching lower values of shunt resistance at higher voltages.

It appeared that a small voltage was required to turn on the shunt, and that the shunt was switched off in reverse bias. This indicated that the shunt was in series with a diode. The cell was modelled with the equivalent circuit in Figure 5.

The diode and the shunt resistance was fitted to the low voltage regions of the IV curve (Figure 6). The model provided excellent agreement with the cell measurements. The cell current was dominated by the diode/shunt until 400mV when the current from the cell diode starts to become significant. At higher voltages(>600mV), the current is dominated by the cell diode and the diode/shunt has little effect on cell performance.

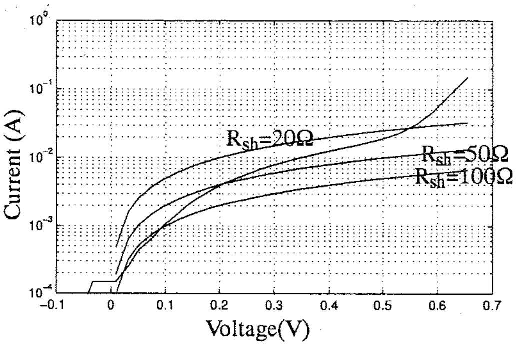


Figure 4. Comparison of dark IV curve for cell B and modelled shunt behaviour. The forward bias current of cell B at low currents is not well modelled by pure shunt resistance. In reverse bias, the cell demonstrates currents less than 0.5mA at 1V (i.e. R_{sh}>2000Ω)

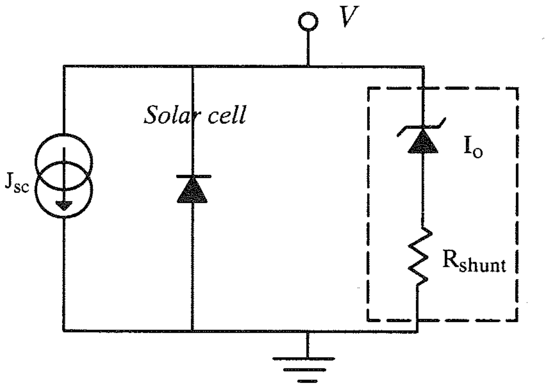


Figure 5. Model of solar cell with schottky shunt. The model consists of a solar cell in parallel with a shunt resistance and a diode with a low turn on voltage. The region in the dashed box was fitted to the low current region of the dark IV curve.

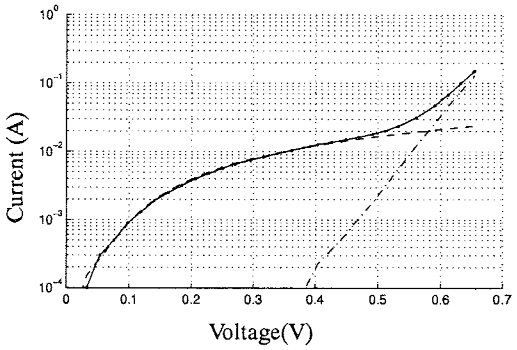


Figure 6. The modelled fit of the shunt in series with a diode for cell B.

—— dark IV
- - -modelled shunt/diode
- - dark IV –modelled shunt/diode

The shunt/diode model explained the cell behaviour at low forward currents. Excellent reverse bias shunt resistance was provided by the shunt diode. The behaviour of the cell and the model at low currents was independent from illumination level.

Other cells which showed similar behaviour were also modelled. The shunt resistance in cells which showed this behaviour varied greatly between substrates leading to large differences in fill factors (table 1). The shunt resistance can be sufficiently small to significantly reduce the open circuit voltage of the device. Subtracting the shunt/diode current from the illuminated IV curve leads to the conclusion that the 35Ω shunt had little effect on the open circuit voltage of s57aa while the 4.5Ω shunt in s57c decreased the open circuit voltage by 75mV.

Cell ID	Rsh (Ω)	Diode I_o (A)	FF	V_{oc} (mV)	V_{oc} loss (mV)
s59e	20.6	$4\ 10^{-5}$	67%	611	11
s57aa	35	10^{-6}	73%	635	4
s57c	4.5	10^{-4}	38%	568	75

Table 1. Modelled shunt resistance and diode saturation current to fit cell current voltage characteristics.

The very low turn on voltages for the diode point towards a Schottky–type metal silicon contact. There is a trend of increasing diode saturation current with decreasing shunt resistance suggesting a relationship between the area of the Schottky diode and the shunt resistance. The behaviour was confirmed by making cells which deliberately included a schottky contact to the substrate of a cell outside the emitter area. These cells showed the modelled schottky shunt behaviour. The schottky shunt was diced from the cell, and the cell fill factor improved to values expected

The prevalence of the shunt/diode on multicrystalline silicon substrates may be due to the roughness of the multicrystalline silicon surface, since the substrates were not polished. This can lead to damage to the emitter junction during handling with the consequence that the front contact directly contacts the p–type substrate. Photolithographic defects are also more prevalent on the rough multicrystalline silicon substrates which can lead to defects in the emitter such that the front metallisation can directly contact the lightly doped substrate.

The schottky shunt is not restricted to multicrystalline silicon substrates. The schottky shunt was also common in earlier single crystal silicon concentrator cells manufactured for trough concentrator systems at the ANU [3]. Cell measurements showed 'soft' fill factors which improved under increased illumination. Improved handling and deeper diffusions have virtually eliminated schottky shunts from completed cells.

4. DISTRIBUTED SERIES RESISTANCE

Despite the similarity of the shapes of the IV curves, the poor fill factor in cell A was not due to the diode/shunt behaviour. Fill factors were observed to decrease with increasing illumination, indicating a series resistance problem, rather than a shunt. The dark IV curves for different illumination levels on cell A in figure 3 differed greatly at low voltages suggesting large series resistance losses in the cells but the series resistance near open circuit voltage appeared to be low. This was confirmed by comparing the IV curve of cell A at one sun illumination to modelling for a range of resistances in series with a two diode model fit of I_{sc} versus V_{oc} (to eliminate series resistance effects), which can be seen in Figure 7. Around open circuit voltage, the one sun IV curve was bounded by models for 0.25Ω and 0.5Ω series resistance while at lower voltages the current was bounded by 2Ω and 4Ω models.

Such behaviour indicated that the cell had a region of high series resistance and other areas of more typical low series resistance. At low applied voltages, the bad regions were driven further into forward bias by the photogenerated current flowing through the region of high resistance, leading to decreased current. As the photogenerated current increased due to increased illumination, the bad region was forward biased at lower applied voltages leading to lower fill factors. As the applied voltage increased beyond open circuit voltage, both regions of the cell were in forward bias. The majority of the current then flowed through the good region of the cell where the resistance was lower. The resistance then approaches the resistance of the good and bad regions in parallel. Consequently the cell would appear to have relatively good series resistance at higher voltages while having poor apparent series resistance at lower voltages.

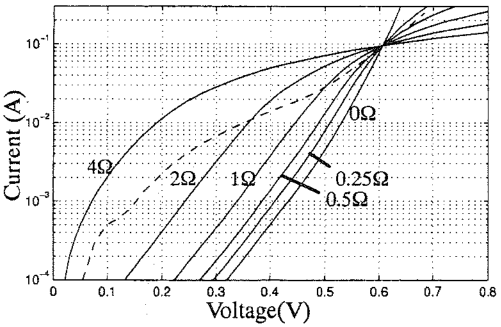


Figure 7. Modelled effect of varying a single global series resistance on cell behaviour at one sun illumination. Cell behaviour is not well described by a single series resistance. At higher voltages the cell current is bounded by the models for 0.25Ω and 0.5Ω while at low voltages, the cell current is bounded by the 2Ω and 4Ω models.

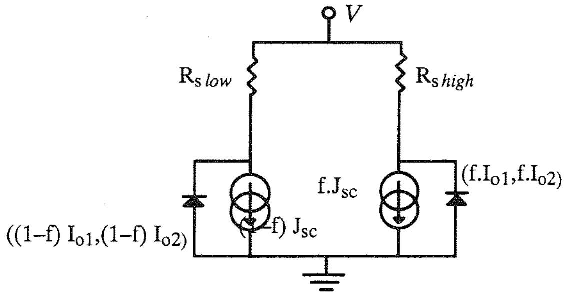


Figure 8. Model for distributed series resistance. The model consisted a solar cell in series with a low resistance in parallel with a solar cell in series with a high resistance. A fraction, f, of the total solar cell area is in series with the high resistance, with current and dark saturation currents appropriately scaled.

This effect was modelled analytically. The model used can be seen in figure 8. A fraction of the cell, f, is connected to a high series resistance in parallel with the remainder of the cell, which is in series with a low series resistance. The model resistances and poor fraction, f, of the cell were adjusted to fit the one sun IV curve. The poor fraction, f, was found to be 30% with a series resistance of 3.5Ω while the remainder of the cell was found to have a relatively low resistance of 0.2Ω. Adjusting the short circuit current fo r the level of illumination showed good agreement with the cell behaviour at different light intensities, as shown in figure 9.

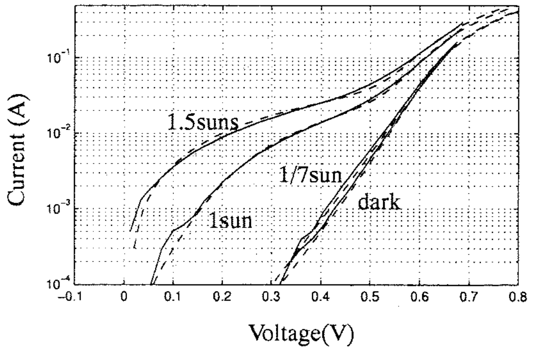


Figure 9. Measured and modelled IV curves for a cell A with distributed series resistance for a range of illumination intensities.

--- measured
—— modelled

The dark IV curve is not well fitted with an n=1,n=2 two diode model. Despite this the cell behaviour is well described by 30% of the cell having a high series resistance (3.5Ω) with the remainder of the cell having a low resistance (0.2Ω).

Distributed series resistance is not a new idea. Researches appreciated during the eighties that a single lumped series resistance was insufficient to explain the resistive losses in a real solar cell, typically looking at the emitter and metal fingers [4,5,6]. These studies typically looked at only small perturbations from the ideal case (single lumped series resistance). The fill factor in cell A deviated significantly from the ideal model.

The cause of the high series resistance in a large region of the cell was a poorly defined front metal grid. The grid was poorly defined during photolithography with breaks visible under the microscope in almost all the metal fingers after electroplating. Measurements of the resistance from the bus bar to other areas of the grid varied from less than 0.1Ω near the bus bar up to 40Ω at points on the grid at the opposite end of the cell. The good region/bad region model was therefore oversimplified, with the cell broken into many more regions with different series resistance, but provided the basis for explaining the observed behaviour.

5. CONLCUSIONS

Two mechanisms which cause non–ideal resistive losses in silicon cells have been identified in otherwise apparently well–behaved cells. Appropriate models have been developed which explain the observed current–voltage relationships in these cells.

One mechanism is a schottky diode in series with a shunt. This leads to a loss in fill factor due to leakage of current through the shunt when the solar cell is in forward bias. In extreme cases, the open circuit voltage of the cell is deminished. The second mechanism is a distributed series resistance where a fraction of the cell has a significantly higher series resistance than the remainder. This effect is similar to that observed when connecting cells with good and poor series resistance in parallel.

Comparisons of the dark and light IV curves of affected cells enable the quick identification of which of the two mechanisms may be responsible for the cells poor fill factor. Manufacturing approaches can then be modified to prevent these losses from occurring with immediate improvements in cell efficiencies.

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