# *Modelling shading on amorphous silicon single and double junction modules*

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# MODELLING SHADING ON AMORPHOUS SILICON SINGLE AND DOUBLE JUNCTION MODULES

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## ABSTRACT

The effect of shading amorphous silicon mini-modules is investigated by means of measurements and simulation. Several devices are measured under varying degrees of shading and the reverse bias behaviour is investigated, including the reverse breakdown voltage. A simulation using a modified single diode model for amorphous silicon is presented, in which the Bishop extension of the shunt resistance is used to simulate the behaviour of shaded devices. The differences between the effect of shading on amorphous silicon and on crystalline silicon devices are investigated based on measurements and simulations. It is shown that the thin film cells do not develop hot spots in the same manner as crystalline silicon devices; they always break down at the interconnection to the adjacent cell.

## 1 INTRODUCTION

Photovoltaic systems are commonly integrated into buildings in an urban environment and this frequently results in device shading. The power loss due to shading is non-linear and typically affects the performance of a system to a significant degree. Thus, it is an important matter to be considered in the design of photovoltaic systems in an urban context. The behaviour of crystalline silicon devices has been investigated extensively and models exist for the description of their behaviour (e.g.[1]). A range of thin film solar cells, in particular those using single and multi-junction amorphous silicon (a-Si), are widely available in the market. The performance of these materials is known to be different from crystalline silicon and differences in series operation and hot spot formation can also be expected. This is borne out in a direct comparison of different technologies, as discussed e.g. in [2]. No comprehensive modelling study has been undertaken to date, although initial work was published recently by Kawamura [3]. The work presented here provides further measurements and an initial model for the simulation of shaded modules produced from amorphous silicon (a-Si).

## 2 MEASUREMENTS

Measurements were taken in the solar simulator at the Centre for Renewable Energy Systems Technology (CREST). The sample is illuminated using a ScienceTech solar simulator. Devices are mounted on a thermally controlled chuck, the temperature is kept stable within one tenth of a degree. The electrical measurements are taken using a Keithley 2420 source measure unit. Scans were carried out with a minimum of 200 I-V points.

Initially, it is important to understand the difference of behaviour between the amorphous devices to be investigated and conventional crystalline devices. Experiments were carried out for 3 different kinds of cells: one single junction with a relatively low shunt resistance, one single junction with an extremely high shunt resistance and a double junction with a very high shunt resistance. The investigation was carried out on cells without any protective back contacting as this allowed the behaviour of each cell in the mini-modules to be investigated separately. The reverse bias characteristic was investigated and the breakdown voltage measured for each individual cell. Typically this led to the destruction of the cell. A significant difference between a-Si devices and c-Si devices became apparent. Crystalline silicon devices exhibit a low number of hot spots, typically a single spot is formed although in rare cases up to three hot spots have been observed in a single cell [4]. These hot spots can occur anywhere on the cell, although there is an increased possibility of occurrence at the boundaries. In contrast, all tested a-Si cells formed 'hot strips' when being subjected to reverse biasing rather than hot spots. This is illustrated in Figure 1, where the front of a small plate is shown after all 6 cells were subjected to reverse biasing. The hot strips always form at the laser grooves separating/interconnecting the cells, indicating that this is the weak spot in the mini module.

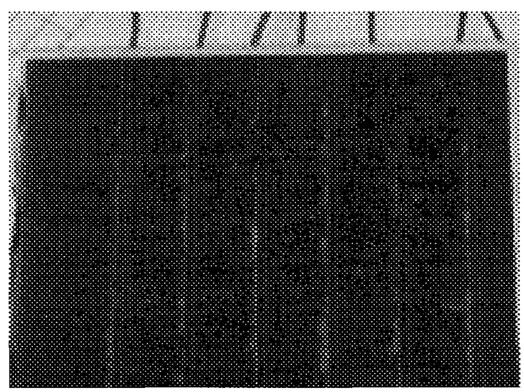

Figure 1: Effect of Reverse Biasing on an a-Si Module.

A second difference is found in the breakdown voltage of the different devices. In the case of c-Si devices, this is expected to be around 10 V. A test carried out on 25 cells showed that this value is never reached for single junction a-Si devices. The frequency of breakdown voltages achieved in tests of single junction devices is shown in Figure 2. There appear to be two centres of concentration in this plot, one around 6.5 V and one around 7.5 V. The variation of this breakdown voltage is investigated in more detail in the lower plot in Figure 2, which to some extent

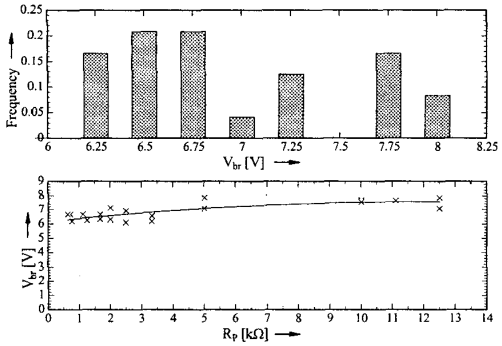


Figure 2: Histogram of Breakdown Voltages (upper plot) and dependence of the breakdown voltage on the parallel resistance.

explains this grouping in the histogram. Interpreting low shunt resistance as the presence of faults within the material creates electrically weak spots. These areas will be more likely to be affected by reverse biasing and thus cells with a high shunt resistance will have a higher breakdown voltage.

## 3 MODEL FOR AMORPHOUS SILICON DEVICES

Shaded solar cells are commonly modelled by assuming the average irradiance on the whole cell G' can be calculated as:

$$G' = \frac{A_u}{A_c} G_u + \frac{A_{sh}}{A_c} G_{sh} \tag{1}$$

where $A_U$ is the unshaded area, $A_C$ is the area of the cell, $A_{sh}$ is the shaded area and $G_U$ and $G_{sh}$ are the irradiance in the unshaded and shaded parts of the cell respectively. In the laboratory environment here $G_U$ equals zero but in realistic operation it may not be so, as diffuse irradiance might still reach the device.

This assumption means that the short circuit current should scale with incident irradiance, a fact which was shown to be true for a-Si in the past [5].

In the following, it will be investigated whether a module will perform similarly, when one of the constituent cells is partially shaded. Here the most interesting case of a high quality single junction with a

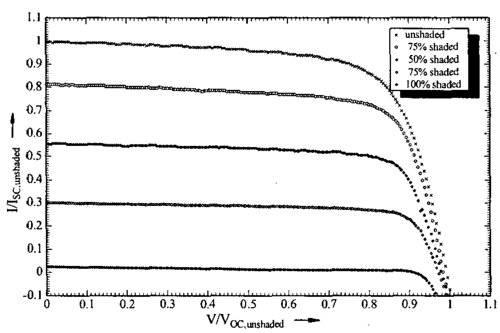


Figure 3: Measurement of the effect of shading a single cell in the mini-module.

very high shunt resistance and very high diode quality (i.e. diode ideality factor between one and two), as shown in the lower graph in Figure 2, is investigated in more detail. The near perfect scaling with average irradiance for the shaded cell, as seen for the single device, appears to be true. There is a small deviation for high levels of shading. This could be due to a measurement inaccuracy but is also borne out by the simulations presented below, validating these measurements.

Amorphous silicon solar cells can be modelled for realistically occurring operating conditions using a modified single diode model. This is given as:

$$I = -I_{ph} + I_D\left(\exp\frac{eV_j}{nkT} - 1\right) + \frac{V_j}{R_P} \tag{2}$$

where I is the current through the device, $V_j$ is the voltage at the junction, T is the temperature at the junction, e is the elementary charge and k is the Boltzmann constant. The behaviour of the solar cell is described through the photocurrent $I_{ph}$, diode saturation current $I_D$, diode ideality factor n, series resistance $R_S$ and the parallel resistance $R_P$. The voltage at the junction is calculated as:

$$V_j = V - IR_S \tag{3}$$

Merten et al. [6] implemented the additional loss term in this model. This model results in a modification of the photocurrent given in equation (2), which is calculated as [6]:

$$I_{ph} = I'_{ph}\left(\frac{1}{\frac{\mu\tau}{d_i^2}\left(V_{fb} - V_j\right)} - 1\right) \tag{4}$$

where the first term models the additional recombination term. It is described through the ratio of the mobility μ and lifetime τ to the square of the thickness of the intrinsic layer $d_i$. The voltage dependence is included by considering the relation of $V_j$ to the flatband voltage $V_{fb}$.

This method is valid for the forward characteristic, the reverse characteristic can be modelled based on avalanche breakdown. This can be achieved by extending the term modelling the current through the shunt resistance $I_{sh}$ using the method presented by Bishop [7]. This is given as:

$$I_{Sh} = \frac{V_j}{R_{Sh}}\left[1 + a\left(1 - \frac{V_j}{V_{br}}\right)^{-m}\right] \tag{5}$$

where $V_{br}$ is the breakdown voltage. The two empirical parameters a and m describe the shape of the reverse bias characteristic.

Equations (2)-(5) allow the modelling of the I-V characteristic of a single cell, but does not deal with the interconnection of cells. Combining equations (2)-(5) yields an implicit function that cannot be solved analytically. An iterative procedure using the VanWijngaarden-Dekker-Brent method given by Press et al. [8] is used to solve this equation. This solution to the I-V equation of a single cell is referred to as the inner iteration in the following discussion.

Connecting cells in series will have an influence on the device performance if the cells are not identical. The effects of interconnection follow Kirchhoff's laws. The measurements presented here are for series connections only; hence the solution presented here is for series connections. Each cell produces the current $I_i$ and the voltage $V_i$, which are linked to the string voltage $V_{string}$ and string current $I_{string}$ through:

$$I_{string} = I_i \tag{6}$$

and

$$V_{string} = \sum_{i=1}^{n} V_i \tag{7}$$

The I-V characteristic of a series connection can then be constructed simply by supplying a current and calculating the corresponding voltages of all individual cells. The calculation of some basic properties of this interconnection, such as short circuit current or maximum power point (MPP), require a second (outer) iteration. Finding the MPP can be achieved by iteration. Finding $I_{SC}$ is more difficult. In this work, the real value is bracketed, i.e. the maximum and minimum values possible are determined as $I_{SC}$ of the unshaded device and zero. These are used as initial guesses for the current and the resulting voltage is calculated for each of them. In the majority of cases the resulting voltage will not be zero and thus the current needs to be adjusted. Using a second (outer) VanWijngaarden-Dekker-Brent iteration as given by Press et al. [8] allows an accurate and rapid determination of the real $I_{SC}$. A similar procedure can be used for a parallel connection, when exchanging currents and voltages in equations (6) and (7).

It is apparent the performance of a mini-module will change according to how many cells are connected in series. This is not immediately intuitive but is due to the change of the voltage applied to the shaded cell. This has been confirmed by measurements carried out in the laboratory, but not presented here. A higher number of unshaded cells will result in a higher voltage appearing across the shaded cell, driving it further into reverse bias. Thus the voltage loss will be lower, as each cell will lose a smaller proportion of its energy. This is consistent with the prediction that the power loss generated by a single cell will be lower for larger modules. Figure 4 shows the effect of shading one single cell in a series connected module, for different numbers of cells; the underlying parameters are the same as before.

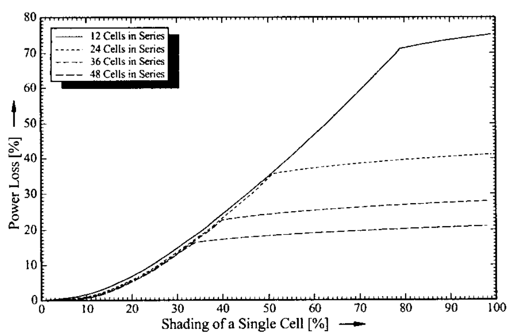


Figure 4: Power Loss Due to Shading of a Single Cell in a Module

It is apparent that the most significant energy loss is experienced by the module with the smallest number of cells in series and the lowest loss occurs in the module with the highest number of cells. It is clear, though, that the danger of cell damage due to a hot spot is much higher in the module with the higher number of cells; thus an optimisation of the number of cells in series would appear to be prudent. The energy loss due to shading appears to fall into three sections: initially it is barely noticeable, then there is a region of linear increase and finally a levelling off. The loss in the case of low shading is compensated for quite easily by the shunt current and does not cause significant losses. In the mid range, the effect of shading is much more pronounced and increases approximately linearly, followed by a slow but steady increase. The reasons for this plateau will be investigated later.

It is important to keep in mind that the case shown here is quite extreme, as the cell is being operated at full STC irradiance with the exception of the single cell that is fully shaded. This case is not so common, as significant shading tends to occur when the sun is low in the sky when the irradiance is low. The influence of irradiance and level of shading on power production is resolved in Figure 5. Here the power loss is calculated for a module of 36 cells in series using irradiances from 1 to 1000 W/m$^2$ and shading factors from 0 to 100%, split into 100 points each. The exact shape of the resulting surface will depend very strongly on the specific device parameters.

It is apparent from Figure 5 that for low irradiance conditions, there is no significant influence of shading.

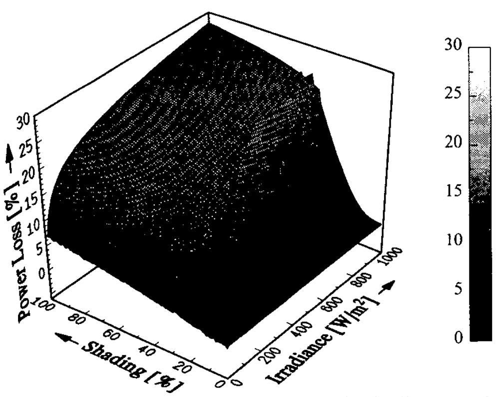


Figure 5: Influence of Irradiance and Shading on the Power Loss.

Even one single cell being shaded to 100% does not cause a significant loss of power (less than 10%). Once the irradiance increases, the effect of shading increases significantly until it reaches the plateau also illustrated in Figure 4. Similarly, for low levels of shading, there is not a significant impact on the module performance. With increasing irradiance there is a near linear increase which stops once a certain plateau is reached. The reasons for this plateau are not immediately apparent and warrant further investigation.

The reasons for the sudden levelling off of the losses is identified when investigating the voltage across the shaded device, illustrated in Figure 7. The voltages shown here are the ones achieved at maximum power operation. For low irradiance conditions, the voltages across the shaded device are relatively low. The device has, as shown in Figure 3, a relatively low shunt current, that does not increase significantly in reverse bias operations. The current mismatch of the shaded cell can be compensated for in the forward bias and there is no significant impact. An increase in shading causes a change in the maximum power point avoiding the cell being driven into reverse bias. There is, however, a point when this is no longer

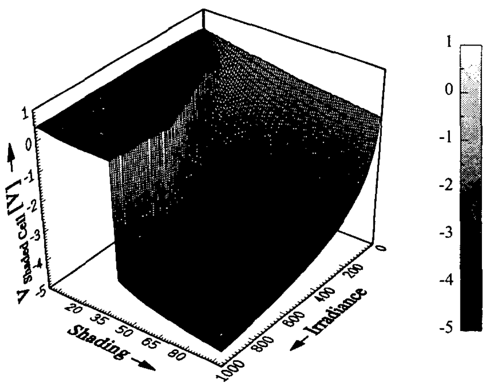


Figure 7: Voltage at the Shaded Cell

possible and, at maximum power operation, the shaded cell will be driven into reverse bias. As the cell initially has a very limited slope of the reverse bias current-voltage characteristic, the voltage change will be dramatic, as shown in the step in the shown surface. This will depend, as shown in [5], strongly on the chosen value of a in equation (5) as this strongly influences the behaviour around $I_{SC}$.

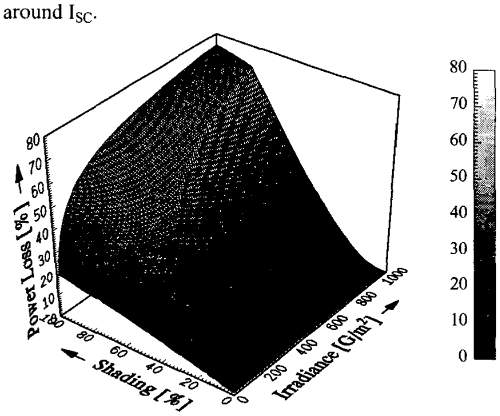


Figure 6: Power Loss of 36 Modules Connected in Series with 3 Cells Shaded.

Finally, the effect of different cell numbers being shaded is illustrated in Figure 6, where the same system of 36 cells as in Figure 4is simulated, shading 3 cells this time. The power loss itself is much higher than for single cell shading only. The point of reverse biasing one cell is reached even later. This behaviour is a difference to conventional crystalline devices, where typically the worst cell determines the overall output. It appears that in the case of a-Si, the number of bad cells is of importance as well.

## 4 CONCLUSIONS

This work investigates the shading characteristics for a-Si devices. Appropriate measurements have been made and the differences between a-Si and c-Si investigated. Measurements are also presented for different a-Si technologies, indicating clear differences between these. In order to understand the behaviour of the devices better, a model is presented that includes the effect of shading on the performance of a-Si devices. Estimation of realistic device parameters from the measurements facilitates empirically based simulation of device behaviour and can be used to predict cell damage. It is shown on the basis of simulations, that fully shading a single cell does not necessarily mean that the output of the overall module will be reduced to zero. Although significant losses occur, the simulated devices are able to cope with low shading percentages reasonably well. There is only a low risk of cell damage in the case presented. It is shown that the power loss due to shading decreases with increasing length of the series connection although, on the other hand, this does increase the risk of cell damage. Further investigations are planned to investigate more precisely the conditions giving rise to cell damage.

## 5 ACKNOWLEDGEMENTS

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