MODELLING OF SLIVER® MODULES INCORPORATING A LAMBERTIAN REAR REFLECTOR

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ABSTRACT: Modules incorporating cells which are bifacial and narrow can make use of rear reflectors to capture most of the incident sunlight while covering only a fraction of the module area with cells. Sliver® cells, invented and developed at the ANU, meet these criteria. In this paper we analyse the performance limits of such modules for the case where a diffuse (lambertian) reflector is used. The analysis is carried out for various cell thicknesses, cell spacings and reflectivities of the lambertian reflector. The results show that excellent performance can be realised despite the simplicity of the structure. A module with a 50% coverage with 70μm thick cells can capture up to 84% of the light entering the module. Importantly, the performance of this kind of module is insensitive to module orientation. The results of the analytical model are compared with ray tracing studies and measurements and are shown to be in good agreement. It is concluded that significant module cost reductions can be achieved for only modest reductions in performance by covering half or less of the module surface with cells.
Keywords: Si-Films, Modeling, Optical Properties

1 INTRODUCTION

Silicon wafer based modules currently dominate the PV market. It is well known that the silicon cells are the single biggest cost component of these modules. A possible approach to reduce the cost of such modules is therefore to cover only a fraction of the module area with cells and to incorporate a reflector in the module structure. It is then necessary to ensure that a significant fraction of the light that is incident upon the reflector is eventually absorbed by the cells.

In principle, such modules can be fabricated with standard, monofacial cells. In practice, in order to ensure that most of the light is absorbed by the cells and to keep the module dimensions acceptable (in other words, a total module thickness of no more than a few mm) it is necessary that the cells used are both bifacial and very narrow (with a width of at most several mm). These requirements have ruled out the commercial manufacture of such modules to date, since such cells have not been available.

However, recently some novel approaches have been presented which allow such narrow, bifacial cells to be fabricated such as the Sliver® cells [1] and the LASE process [2], which were invented and developed to their present stage at the ANU. Sliver® cells, in particular, are perfectly bifacial as well as long and narrow, being typically only 1mm wide and 60-100mm long, and are thus perfectly suited to the incorporation of a rear reflector.

Figure 1 illustrates a module incorporating narrow, bifacial cells together with a rear reflector. Sunlight incident in the space between the cells is reflected and may be absorbed by the cells, or may reach the front surface of the module where it is either totally internally reflected or coupled out of the module and lost.

One of the simplest reflectors to analyse is a perfectly diffuse (lambertian) surface. This is also one of the simplest reflectors to realize in practice, using, for example, a white paint or white film.

In this paper, the performance of modules incorporating narrow, bifacial cells and lambertian reflectors is analysed. A simple analytical model is used to determine the performance limits of this structure as a function of cell thickness, cell coverage fraction and lambertian reflectivity. The results are compared with ray tracing and measurements. All the work presented here was carried out at the ANU.

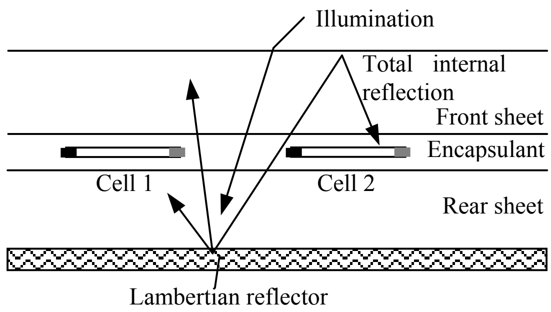


Figure 1: Cross sectional structure of a module incorporating narrow, bifacial cells and a lambertian reflector.

2 LIMITS TO THE CONCENTRATION RATIO

The structure shown in fig. 1 can be considered to be a concentrator with an acceptance angle of 90 degrees. If the concentration ratio is defined as the ratio of the intensity of the light incident upon the cells in the concentrator compared to a structure with 100% cell coverage, then the limit to the concentration ratio achievable using bifacial cells is given by:

$$C = 2n^2/\sin^2(\theta)$$

where n is the refractive index of the concentrator structure. In the case considered here, $\theta = 90^o$ and $n \sim 1.5$, giving a limit to the concentration ratio of 4.5. The factor of 2 results from the fact that the cells are bifacial – in other words, the use of bifacial cells doubles the theoretically achievable concentration ratio. However, the limit is only achieved when the cells are spaced infinitely far apart, resulting in a module efficiency of zero. In practice, significantly lower concentration ratios must be used.

3 ANALYTICAL MODEL

The structure to be modeled is shown in fig 2. Bifacial, textured cells are encapsulated behind transparent front and rear sheets. The cells have a width of W and are regularly spaced with a gap G between cells so that a fraction $F = W/(G+W)$ of the module surface covered with cells. A lambertian reflector is positioned at the rear of the cell which reflects and scatters a fraction R of the incident light, and absorbs the remainder.

The reflector results in a perfectly lambertian distribution of light within the reflector material. In general, the lambertian distribution will be modified at the reflector/glass interface, according to Snell's Law. In this model, it is assumed that the refractive index of the reflector and the glass are the same, so that the lambertian distribution is maintained in the glass.

The texture of the cells is assumed to result in a lambertian distribution of light within the cells. (Optical transmission and reflection measurements on textured Sliver® cells have shown nearly perfectly lambertian behaviour.) Further, a perfect antireflection coating is assumed so that no light incident on the cell/encapsulant interface from outside the cells is reflected, while reflection of light incident on the cell/encapsulant interface from inside the cells only occurs by total internal reflection.

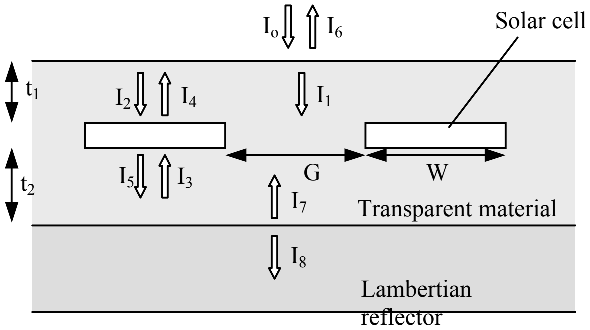


Figure 2: The module to be modeled

The thicknesses t_1 and t_2 are assumed to be infinite. This means that the fraction of light incident upon the cells is independent of the position where the light originated at both the glass/air or glass/reflector interface, and is only a function of the surface coverage fraction F. While this assumption is obviously unrealisic in practice, ray tracing analyis has shown that it introduces little error provided $t_1 \geq W$ and $t_2 \geq 2W$. The various fluxes shown in fig. 3 can be expressed in terms of a set of 8 coupled equations:

$$I_1 = (1-F)(1-T_2)I_7 + (1-T_2)I_4 + T_1I_0$$
$$I_2 = FI_1$$
$$I_3 = FI_7$$
$$I_4 = P_1I_3 + P_2I_2$$
$$I_5 = P_1I_2 + P_2I_3$$
$$I_6 = (1-F)T_2I_7 + T_2I_4$$
$$I_7 = (1-F)RI_1 + RI_5$$
$$I_8 = (1-F)(1-R)I_1 + (1-R)I_5$$

Here, T_1 is the transmission coefficient of the incident sunlight through the air/encapsulant interface, T_2 is the transmission coefficient of the diffuse (perfectly lambertian) light within the encapsulant that is incident on the air/encapsulant interface, and P_1 and P_2 are wavelength dependent coefficients which account for the fact that a fraction of the light that is absorbed through one surface will exit again through the same or the opposite surface. In general, $T_1 \neq T_2$ since the spatial distribution of sunlight does not follow a lambertian distribution.

Solution of the above equations at each wavelength allows determination of the amount of light absorbed within the silicon, given by

$$I_{abs} = I_0 - I_6 - I_8$$

To obtain an assessment of the performance of the module relative to a module with 100% surface coverage and infinitely thick silicon cells, T_1 can be set equal to 1. The relative performance, or performance ratio of the module, is then given by $PR = I_{abs}/I_0$. T_2 is given by $T_2 = 1/n_{enc}^2$. P_1 and P_2 are determined by analysing a layer of silicon of thickness w.

The above equations were solved and the performance ratio calculated for a range of values for the coverage fraction F and the silicon cell thickness, using the AM1.5G specturm. The refractive index of the encapsulant was set to n=1.5. The results are shown in fig. 3.

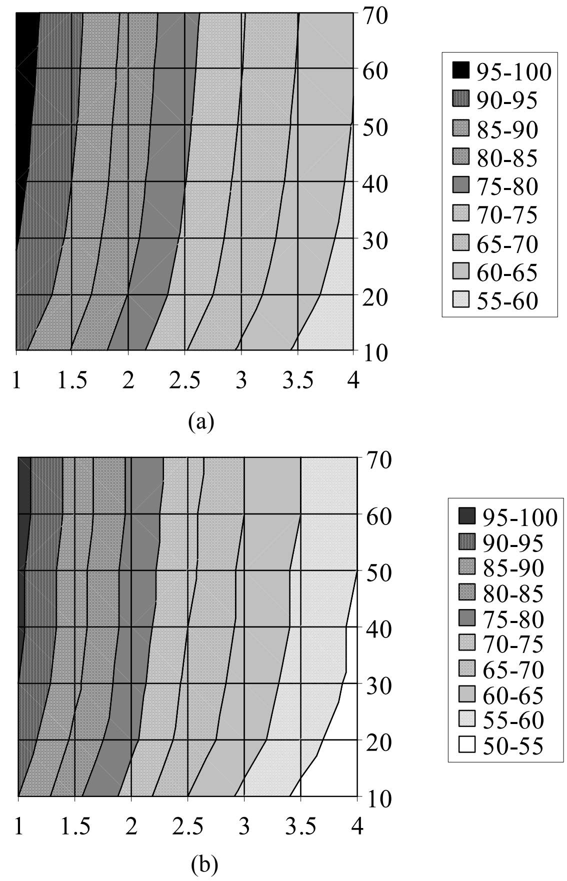


Figure 3: Performance ratio in percent as a function of the inverse of the coverage fraction, 1/F (horizontal axis), and the cell thickness in μm (vertical axis) for a reflector with (a) 100% and (b) 90% reflectivity.

The analytical model will slightly underestimate the performance limits, since it effectively assumes a perfect antireflection coating on the front module surface, so that the reflection of light within the glass at the glass/air interface is by total internal reflection only.

It can be seen from the results that, given good light trapping, the cell thickness can be reduced to 30µm or less with relatively little efficiency penalty. On the other hand, decreasing the surface coverage fraction leads to a significant decrease in efficiency, but also leads to a substantial reduction in module costs since not only the silicon but also the cell fabrication costs per unit module area are reduced.

4 RAY TRACING

4.1 Effect of front/rear sheet thickness and cell width

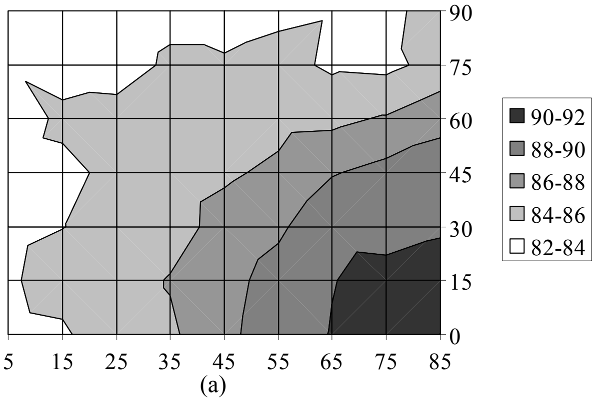
Ray tracing was carried out using the software package OptiCAD™. This allows the effect of finite front and rear sheets to be investigated. The cells are modeled to be perfectly absorbing (infinite thickness and perfect AR coating). The rear reflector is perfectly lambertian, with a reflectivity of 100%. 3 module structures with different combinations of front and rear sheet thicknesses were investigated, namely 1mm/3mm, 3mm/1mm and 3mm/3mm. The cell width was varied from 1 to 2mm, and surface coverage fraction was varied from 0.33 to 0.66.

The modeling indicates that, for a cell width of 1mm, the performance ratio is independent (to within 1%) of front sheet thickness and direction of incidence of sunlight for a rear sheet thickness of 3mm. The results for this case are in agreement with the analytical model, with a predicted performance ratio of 87% and 74% for a coverage fraction of 0.5 and 0.33, respectively. For a rear sheet thickness of 1mm, the module response shows some dependence on direction of incidence of sunlight and reduced overall performance, fig. 4(a).

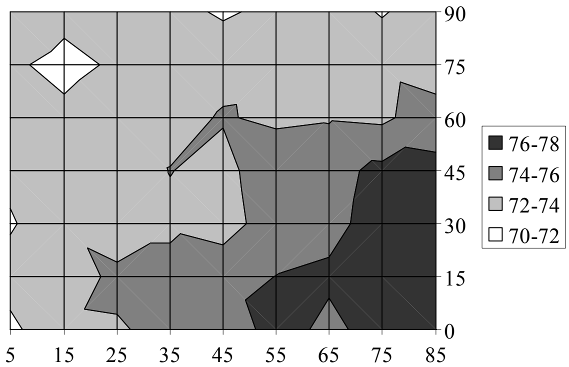
As the cell width is increased to 2mm, the module response becomes dependent on the direction of incidence of light, even for a rear sheet thickness of 3mm. This effect becomes more pronounced for lower surface coverage fractions. Fig. 4(b) shows the results for a cell width of 2mm and a coverage fraction of 0.33.

4.2 Effect of lambertian material refractive index

The refractive index of the lambertian reflector has an effect on module performance. A refractive index different from than that of the other materials which make up the module will result in a non-lambertian distribution of light in the module. This effect was investigated using OptiCAD. A lambertian reflectivity of 100% or 90% was used. Fig. 5 shows that a refractive index lower than that of the rest of the module results in a reduction in module performance as the light is restricted to a narrower range of angles, leading to a reduction in the amount of light that is totally internally reflected.



(a)



(b)

Figure 4: Module performance ratio (in percent) as a function of elevation angle (horizontal axis) and azimuth angle (vertical axis) of the incident light. An elevation angle of 0 degrees corresponds to light vertically incident on the module. An azimuth angle of 0 degrees corresponds to the plane of incidence of the light being perpendicular to the long dimension of the cell. (a) 1mm wide cells, with 3mm thick front and 1mm thick rear sheet and a coverage fraction of 50%, (b) 2mm wide cells, with 1mm thick front and 3mm thick rear sheet and a coverage fraction of 33%.

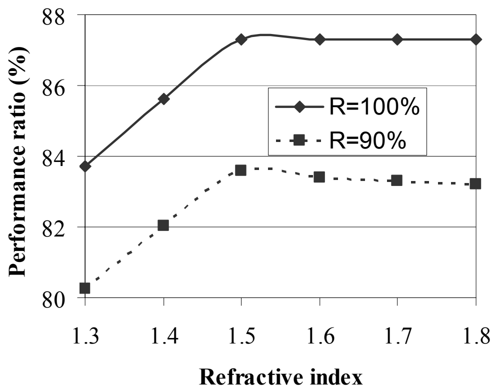


Figure 5: The influence of lambertian refractive index on the performance ratio for different lambertian reflectivities.

5 EXPERIMENTAL RESULTS

5.1 Effect of module orientation

$10x10cm^2$ modules were constructed using 1mm wide cells, 1mm thick front and 3mm thick rear glass sheets and several different lambertian reflector materials. The lambertian reflectors were optically coupled to the same module in succession, using glycerine for optical contact. In this way, direct and quantitative comparison of different reflectors is possible. EVA was used as the encapsulant. The surface coverage was 50%. Cells in the centre of the module were electrically connected to enable measurement of cell current and voltage, while cells around the periphery were left unconnected. This avoids edge effects which would be encountered if all the cells in the module were electrically active. These edge effects would be significant for such a small module size and would make accurate determination of module performance difficult.

The module was exposed to a beam of collimated light and tilted such that the long dimension of the cells was parallel to the axis of module tilt. Fig. 6 shows the results for 3 lambertian materials. For an ideal lambertian reflector, the normalised module response would be expected to be independent of tilt angle. The data shows that all 3 materials approximate an ideal reflector. Modelling indicates that the slightly higher response at high tilt angles for material 1 could be due to a lower refractive index of about 1.3.

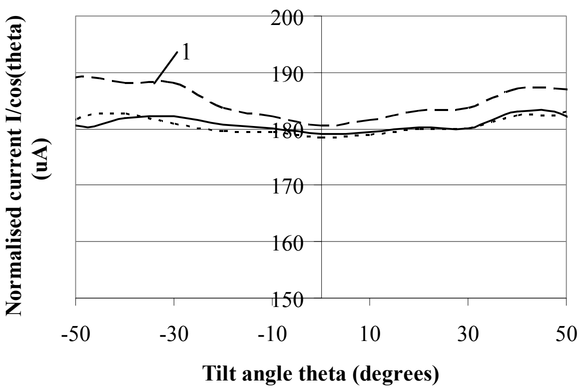


Figure 6: Module response as a function of tilt angle for 3 different lambertian reflector materials.

5.2 Measured performance ratio

To measure the performance ratio, $10x10cm^2$ modules were constructed using 1mm thick front glass and 3mm thick rear glass, and EVA as the encapsulant. Cells in the centre of the module were electrically connected to enable measurement of cell current, while cells around the periphery were left unconnected. To determine the performance ratio, the module current was first measured with black felt behind the module. This will result in virtually all of the light that reaches the rear of the module being lost. The black felt was then removed, a suitable lambertian reflector was applied and the module current was remeasured. All measurements were carried out on a clear day with perpendicular incidence of light.

The performance ratio of the module can be calculated as:

$$PR = I_{lamb}*F/I_{black}$$

where F is the surface coverage and I_{lamb} and I_{black} are the values for the module current with the lambertian reflector and black felt, respectively. The results are summarised in table I. The predicted values were calculated using the analytical model and assuming a refractive index of 1.45, a paint reflectivity of 95% and a cell thickness of 50µm. There is good agreement between the measured and predicted value at a coverage fraction of 0.5. However, at lower coverage fractions, the measured performance is significantly less than predicted. Further investigations are required to determine the cause of the discrepancy. One contributing factor is likely to be the fact that the measurements will underestimate the value of PR slightly, since the black felt is not optically coupled to the rear of the module, thus resulting in some reflection of light at the rear glass/air/felt interface. This effect would become more pronounced at lower coverage fractions.

Coverage fraction F	PR, predicted	PR, measured
0.5	79.4	79
0.4	71.8	68.7
0.33	65.4	61.5

Table I: Predicted and measured performance ratios of prototype modules

6 CONCLUSIONS

The results presented in this paper demonstrate that module structures incorporating narrow, bifacial cells can achieve good performance with substantially less than 100% cell coverage through the use of suitable rear reflectors. This allows a reduction in the overall module cost in $\$/W_P$. By combining the results from a simple analytical model with the results from ray tracing studies, the performance limits of this type of module structure, as well as the performance of real modules, can be predicted with good accuracy.

7 ACKNOWLDEGMENTS

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8 REFERENCES

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