SLIVER® CELLS FOR CONCENTRATOR SYSTEMS

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ABSTRACT: One of the fundamental principles of concentrator PV systems is that expensive solar cells can be replaced by less expensive optics. However, the proliferation of concentrator systems has been somewhat held up by the fact that cells remain a significant component of total concentrator system cost. Current research in concentrator PV is focused in the area of high concentration systems which employ a smaller number of high efficiency triple junction cells. Sliver® cells, developed at The Australian National University, utilize a novel method for micromachining narrow, thin cells from conventional silicon wafers. The technology gives rise to a marked increase in active solar cell area per wafer processed. The cells were originally designed for non-concentrating PV applications, though it is possible to modify the design of the cells such that they are capable of operating at low-medium concentration ratios. Modelling has been used to determine the optimum set of design parameters for concentrator sliver® cells. This forms the basis for cell fabrication. Development of low cost concentrator solar cells can provide a pathway to cost-effective low to medium concentration ratio PV systems.
Keywords: monocrystalline, concentrator cells,

1 SLIVER® CELL TECHNOLOGY

Thin, single crystal silicon cell solar cells have been manufactured through the use of a novel micromachining process at The Australian National University [1]. Narrow grooves are formed through the wafer. Cells are manufactured on the resulting silicon strips. These cells have a much greater surface area than the original wafer, leading to large decreases in processing effort and silicon usage. The size, thickness and bifacial nature of the cells create the opportunity for a wide variety of module architectures and applications.

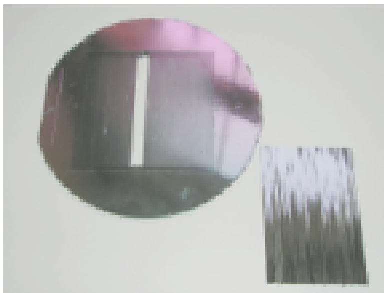

Figure 1: Sliver® cells extracted from an 800µm thick wafer.

Under concentrated light, the typical output current of an individual Sliver® cell at a concentration of 3W/cm2 (30 suns) is of the order of 300mA. The cells can be arranged in series connected strings that would build voltage at a rate of around 5 – 10V per linear cm. The string size can then be chosen to give a desired output voltage. High voltage and low current outputs result in reduced losses.

2 CONCENTRATOR SLIVER® CELL MODELLING

Concentrator Sliver® cells are modelled using Dessis semiconductor modelling software from ISE / TCAD [2]. The software package allows the user to define any semiconductor solar cell geometry and complete set of material properties and then solves the set of coupled non-linear semiconductor equations with a defined set of boundary conditions. Typical boundary conditions for solution of the semiconductor equations include surface recombination velocities at silicon/dielectric interfaces and at silicon/metal interfaces, relative electrostatic potential at user-defined metal contact points or current flows through user-defined metal contacts. Cell design parameters varied in this study are shown in figure 2.

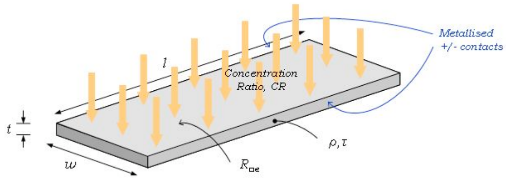

Figure 2: Concentrator Sliver® cell with modelled design parameters shown.

Carrier generation is handled via the ISE / TCAD Optik command which takes as inputs the material properties, such as silicon bandgap and wavelength dependant absorption coefficients, and the incident spectrum intensity. The modelling in this paper uses the AM1.5D spectrum normalized to 100mW/cm^2. Front and rear reflectance values are carefully defined so that the appropriate degree of light-trapping is simulated without the need for computationally intensive ray-tracing on every occasion. The equivalent of two extreme light-trapping scenarios are used: light trapping for polished surfaces, and for lamertian surfaces. The relationship between short circuit current and cell thickness for the two cases matches those calculated by Johnson et. al for rear metallised cells [3]. Corresponding curves for Sliver® cells are represented in figure 3.

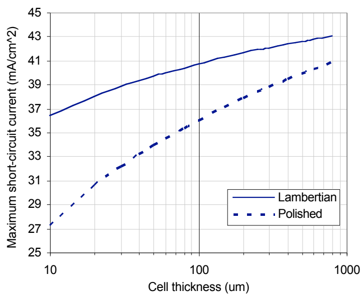

Figure 3 . Maximum Sliver® cell short circuit current for light trapping scenarios with lambertian and polished surfaces.

Auger recombination, SRH recombination, surface recombination and band-gap narrowing are all considered in the modelling. Bulk SRH lifetimes have been selected for given material doping levels based on typical values for float-zone wafers.

Apart from producing IV curves for the modelled cells (figure 3), Dessis is able to produce 2D or 3D plots of variables at any operating point. For example, figure 4 shows plots of normalised electron current density in the p-type bulk region of a Sliver® cell illuminated from the front side only. In this case the three scenarios, with rising illumination intensity, highlight the increase in current density in the bulk of the cell as a greater number of minority carriers diffuse to the rear emitter junction.

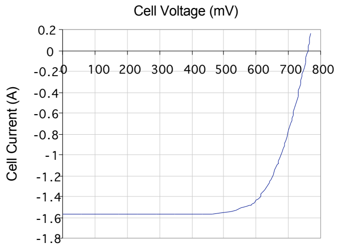

Figure 3. IV curve of a modelled cell at 4W/cm2

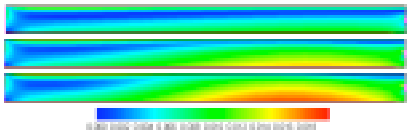

Figure 4 2D cross-section plots of normalised minority carrier current density in sliver® cells, illuminated from the 'front' (top) side only at 1, 3 and 5 W/cm^2.

3 OPTIMUM CELL DESIGN

3.1 Material quality and bulk resistivity

One of the simplest design parameters which can be varied for the production of concentrator Sliver® cells is the bulk resistivity of the starting wafer. The remainder of the process remains practically identical but the variation of bulk resistivity can greatly affect cell behaviour. It is thus a good starting point for analysing cell design variables and determining the optimum design.

Cells are modelled for a range of bulk resistivity values and over a range of illumination intensities. The cells are initially assumed to have been fabricated from high purity float-zone wafers with good electronic lifetimes. The minority carrier lifetimes used for this study are shown in table 1.

Table 1. Minority carrier lifetimes used for modelling.

Resistivity (Ω.cm)	0.033	0.1	0.25	0.5	1	2.5	5	10
Lifetime (_s)	9	14	50	100	300	500	700	1000

An efficiency contour plot for concentrator Sliver® cells illuminated at 2W/cm^2 (CR = 20) for a range of bulk resistivities and cell thicknesses is depicted in figure 5. There exists a clear relationship between bulk resistivity and cell efficiency. An efficiency plateau exists for a range of low resistivities, efficiency dropping off for both higher and lower resistivies. The centre of the optimal range varies slightly with cell thickness, and is in fact alos dependant upon illumination intensity. Maximum efficiency for most scenarios occurs at a bulk resistivity of around 0.1 to 0.3 Ω.cm. Higher bulk resistivities result in efficiency reduction via bulk resistance related fill-factor losses. This is particularly evident for low cell thicknesses since the effective series resistance of the bulk region is inversely proportional to thickness. At lower resistivities the fill-factor is always high but the reduced minority carrier lifetime results in both lower short-circuit curent and open-circuit voltage.

For cells with low resistivity bulk and of reasonable thickness any series resistance related fill-factor losses are due almost entirely to the emitters. Low resistivity substrates are desirable, but are carrier lifetime limited.

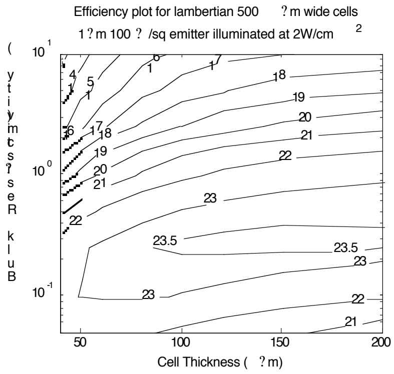

Figure 5: Efficiency for a range of bulk resistivity and cell thicknesses.

Modelling reveals that it is desirable to use float-zone silicon. Figure 6 demonstrates the relationship between efficiency and minority carrier lifetime for 0.1 Ω.cm bulk resistivity cells (thicknesses of 50 μm and 100 μm) for both polished and lambertian light trapping schemes. A minority carrier lifetime of at least 10 μs is desirable to ensure high efficiency.

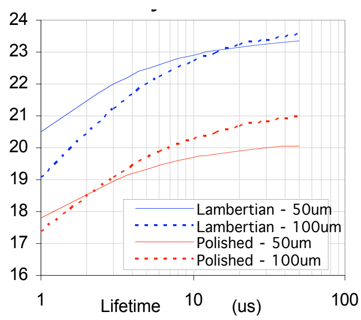

Figure 6: Efficiency versus carrier lifetime for cells with 0.1 Ω .cm bulk resistivity.

3.2 Cell thickness

The thickness of a fabricated Sliver® cell is determined by the pitch of the micromachined grooves. The more closely spaced these grooves are the greater the number of cells that can be produced from a single wafer. In this respect alone it is desirable to make cells as thin as practically possible.

From a cell performance perspective an upper limit on cell thickness is determined by the minority carrier lifetime and diffusion length and their impact upon IQE. Modelling shows that even minority carriers generated in the bulk quite near to the front emitter junction diffuse to the rear emitter and so a diffusion length at least equal to the cell thickness is required. Diffusion lengths for 0.1 Ω .cm float-zone silicon of greater than 100 μm are attainable. Cells produced from wafers of higher resistivity have larger upper thickness limits.

A performance based lower limit on cell thickness is imposed by the quality of the light-trapping scheme, which is introduced during the cell fabrication. Good light-trapping schemes are capable of providing high quantum efficiency for thickness down to around 30µm. The Sliver® cell thickness is more likely to be limited by the practicalities of wafer handling.

3.3 Emitter diffusion

Altering the front and rear emitter diffusions has a significant impact on cell performance. Making such a change is in practice relatively simple: requiring an altered deposition time and temperature and an altered diffusion drive-in time. A heavier emitter diffusion results in a lower sheet resistance meaning that the series resistance of the cell is correspondingly reduced. However, an increased concentration of dopant atoms at the surface results in poorer surface passivation leading to higher rates of surface recombination, increases band-gap narrowing induced recombination as well as the probability of trap-assisted SRH recombination and auger recombination. This leads to both lower open-circuit voltage and short-circuit current, via reduced emitter transparency.

For conventional high efficiency cells it is important to ensure than high emitter transparency is maintained. Emitter diffusions are always light, typically at or above 100 Ω/_. Such a sheet resistance, almost regardless of the junction depth, will ensure close to 100% IQE at short wavelengths. For a conventional cell the only advantage in making the sheet resistance low is that it allows for wider finger spacing (but also wider fingers). The analogy for concentrator Sliver® cells is a larger cell width: a far greater advantage provided the gain can easily offset losses due to reduced short-circuit current.

The effectiveness of deep and heavy emitter diffusions in mitigating fill-factor losses is variable, depending upon cell width and concentration ratio. The wider the cell and the higher the concentration ratio, the greater the effect of heavy diffusions. The modelled cell efficiency contour plot of figure 7, for varied sheet resistance and emitter depth is for a 500 _m wide cell at an illuminaiton intensity of 4 W/cm^2 (CR = 40). A distinct maximum occurs for a sheet resistance of around 50 Ω/_ and for large junction depths. A broader plateau exists for sheet resistance in the range of 50 to 70 Ω/_ and for depths of at least greater than 1.5 _m.

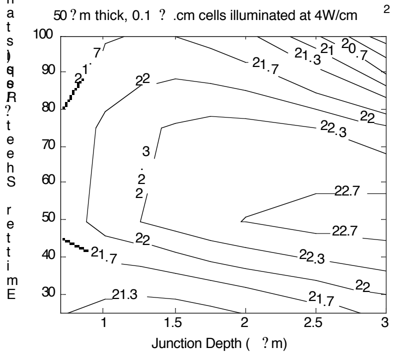

Figure 7: Effect of emitter diffusion magnitude and depth (for Gaussian profile) on cell efficiency.

For most scenarios a deeply driven-in, heavy emitter diffusion is beneficial.

3.4 Cell width and concentration ratio

Sliver® cell width is determined by the starting thickness of the processed wafer. For cost-effective processing and handling it is desirable to have the cells as wide as possible. However, the series resistance of Sliver® cells increases with width, as does the current which must travel across the width. To minimise effects of series resistance, cell width should therfore be kept as low as possible. A practical balance between these competing constraints can be found for given operating conditions.

Figure 8 is an efficiency contour plot with both concentration ratio and cell width as varied parameters. The modelled cell has ideal light-trapping, is based on 0.1 Ω.cm bulk resistivity, is 50 _m thick and has moderately driven-in emitter diffusions of 50 Ω/_.

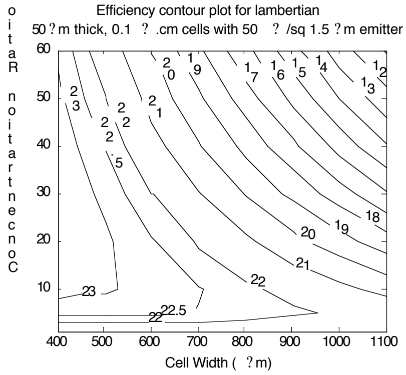

Figure 8: Dependance of cell efficiency on cell width and concentration ratio

The major influence on performance for varied concentration ratios and widths is undoubtedly the front and rear emitter resistance. The effect is amplified by both increasing width and concentration ratio and results in considerable fill-factor reduction. The maximum cell efficiency occurs for a concentration ratio of around 5 to 10 and, for any given illumination intensity, is highest for low widths. The corresponding plots for cells with different emitter diffusions exhibit the same pattern. Concentrator Sliver® cells are can be made at widths of up to 1000 _m provided they are operated at low concentration ratios, or if fabricated at low widths they can operate with good efficiency at concentration ratios of up to 60 or 70.

Fill-factor losses, which are dominated by emitter resistance, can be reduced if the current load is shared evenly between the front and rear emitters. For cells illuminated from one side only the rear emitter may only carry between 10% and 40% of the current load, whilst load is shared uniformly for cells illuminated from both sides. A feature of the concentrator Sliver® cell is that they are perfectly bifacial. An efficiency increase of between one half and one percent absolute is typical if the cells are illuminated from both sides.

4 CONCENTRATOR SYSTEM COST

To determine the most favourable concentrator system market opportunities for concentrator Sliver® cells, a simple analytical model is used which approximates the cell efficiency dependance upon width and illumination intensity. This is incorporated into a cost model which takes accounts for cell fabrication costs and system module costs.

Cell efficiency can be approximated by expression (1), where K_V and K_I are fractions of open circuit voltage and short circuit current respectively for an ideal, zero-resistance solar cell, ΔP_{max} is the change in power output resulting from the addition of series resistance, and P_{sun} is the power incident upon the cell. Power loss due to series resistance, ΔP_{max} is in turn approximated by expression (2) where Rs_{bulk} and Rs_{emit} are equivalent resistances of the bulk and emitter regions. K_f accounts for non-uniform current sharing between the front and rear emitters. A plot of efficiency versus concentration ratio and cell width, using this approximation for a chosen open circuit voltage and sort-circuit current reveals a very close match to the plot of figure 8.

$$\eta = \frac{K_V V_{OC}.K_I I_{SC} - \Delta P_{\max}}{P_{sun}} \quad (1)$$

$$\Delta P_{\max} \cong (K_I I_{SC})^2 R_{S_{BULK}} + (K_I I_{SC})^2 K_F . R_{S_{EMIT}} \quad (2)$$

$$R_{S_{emit}} \cong \frac{1}{3} R_{sq_e} \frac{w}{l}, \quad R_{S_{bulk}} \cong \frac{1}{3} \rho_B \frac{w}{l.t} \quad (3)$$

The fabrication cost of concentrator Sliver® cells can be calculated by taking into account material costs, fabrication costs and cell efficiency:

$$\$/W = \frac{(t + t_{mach}).(C_p + C_w (w + w_{kerf}))}{Y.D_{eff}.P_{CR=1}.w.l.CR.\eta_{(w,CR)}} \quad (4)$$

where C_p is processing costs per wafer, C_w is wafer costs per unit length and w_{kerf} is kerf losses, Y is the yield fraction, and D_{eff} is the width of the machined area. The combined equations can be used to either derive a total system cost ($/W) by adding cost data for other concentrator system components, or to define a budget in $/m^2 for all other system components in order to meet a total system cost target. Figure 9 shows the resulting budget for the balance of concentrator system components in order to meet a US$2/W total cost target for a Sliver® cell based concentrator system.

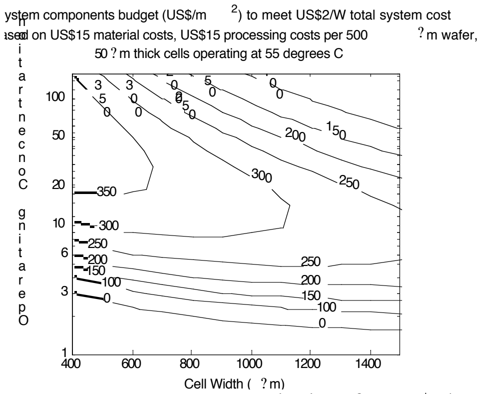

Figure 9: System components budget for US$2/W total system cost.

An indicative total system cost is arrived at by using an appropriate cost model for all system components other than cells. Based on assumptions for small sized concentrator PV plants made by Swanson [4], the cost model depicted in figure 10 is used.

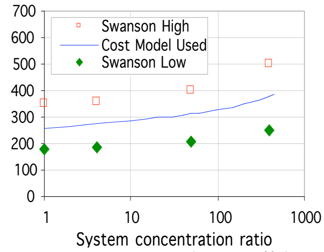

Figure 10: System component (non-cells) cost model.

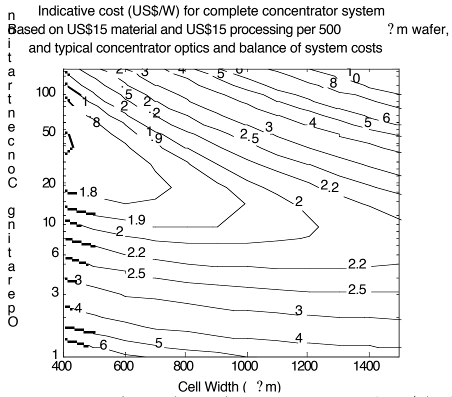

Figure 11: Projected total system costs (US$/W) for concentrator Sliver® cell system, based on cost model.

Total system costs using these cost assumptions is depicted in figure 11. Both contour plots exhibit a definite region of lower costs. The actual values are dependant upon cost assumptions although the same pattern is evident regardless. The most cost effective application of concentrator Sliver® cells is to use low width cells (400_m to 700_m) in systems operating at concentration ratios in the order of 20 to 60.

5 CELL FABRICATION AND TESTING

Concentrator Sliver® cells are currently being made at the ANU. An elegant and short fabrication process has been developed. Early results for concentrator cells are promising, and will improve further when an identified series resistance is removed in the next batch. Figure 12 shows measured IV data typical of early batches of concentrator Sliver® cells; these cells are 600_m wide polished cells without anti-reflection coating.

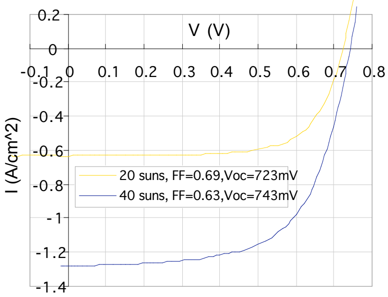

Figure 12: Preliminary IV curves for 600_m wide polished cells without AR coating.

6 REFERENCES

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