Concentrator Sliver® Cells for CHAPS Concentrator Systems

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Abstract

The Centre for Sustainable Energy Systems (CSES) at The Australian National University, with Origin Energy, has developed a novel cell fabrication process for single crystal silicon PV. The Sliver® cell fabrication process produces narrow and long cells. With some modifications to the current fabrication process it is possible to produce Sliver® cells suitable for concentrator systems with low to medium concentration ratios (10 to 40 suns). Such a concentrator cell may be considerably less costly to produce per unit area than conventional silicon concentrator cells. Already under development at CSES is a solar concentrator technology which is a suitable candidate for concentrator sliver® cells. The existing Combined Heat and Power Solar (CHAPS) systems operates at a concentration of around 30 suns, using mirrors to focus light onto solar cells. Following development of concentrator Sliver® cells it is proposed that the conventional cells be replaced by strings of series connected concentrator Sliver® cells. The strings of cells will be high voltage, low current devices.

In this paper designs for cells suitable for concentrated sunlight applications are investigated using 2D semiconductor device modelling software and the application of concentrator Sliver® cells to the current solar concentrator technology is explored. It is expected that the successful production of concentrator Sliver® cells will also pave the way for new concentrator PV technologies at ANU.

INTRODUCTION

The primary objective of photovoltaic concentrator systems is to reduce the per unit energy costs via reduction in solar cell costs. This is, of course, achieved through large reductions in photovoltaic cell area. For concentrator systems designed to produce very high concentration ratios (several hundred) this allows the use of considerably more expensive photovoltaic technologies such as high efficiency, triple junction GaAs-based cells. Concentrator systems with more moderate concentration ratios (10 – 50 suns) require larger areas of photovoltaic cells, and economic constraints generally discount the possibility of using advanced photovoltaic technologies. However, high efficiency mono-crystalline silicon solar cells are well suited to such concentrator applications.

The Australian National University is currently developing the Combined Heat And Power Solar (CHAPS) system for generation of heat and electricity (Coventry, 2002). The system consists of parabolic trough mirrors to concentrate sunlight onto a receiver consisting of a strip of mono-crystalline silicon solar cells (figure 1). The solar cells are thermally bonded to a channel through which water is pumped, thus providing active cooling whilst at the same time a providing a supply of low temperature hot water which can be used for domestic purposes. The cells are 40mm wide and 50mm long. The average concentration ratio peaks at around 30 suns during the middle of the day. Each cell operates at a maximum power current of around 16 Amps and a maximum power voltage of around 600mV. The cells are connected in series so that a reasonable voltage can be built up for DC to AC inversion. The output for one 28-cell receiver is around 17 volts and 16 amps.

A string of series connected solar cells has its output limited by the least illuminated cell by virtue of the fact that the maximum permissible current for a series connection is equal to the minimum short circuit current of any of the cells. Such a scenario occurs due to lengthwise mirror imperfections, shading by support structures or buildings and trees, loss of illumination due to small gaps between adjacent mirrors, or through degradation of cells. The cells are currently made at ANU using high quality wafers, light diffusions and annealed oxide surface passivation, localised front and rear diffusions under silver contacts which are produced by multistep photolithography and metal evaporation. The cells are still a considerable fraction of the expense of the entire system.
A new solar cell manufacturing technology has been developed at ANU in conjunction with Origin Energy. Sliver® technology is a novel fabrication process which aims at addressing the issues of high material and manufacturing costs by making the same quantity of silicon cover a larger area. The new technology allows for a large reduction in silicon usage and also a large reduction in the number of wafers processed per unit area of photovoltaic coverage. Details of the sliver® cell and the manufacturing technology has been described previously by other authors (Stocks, 2003; Blakers, 2003). The cells are typically in the order of 1mm wide, 50µm thick and 5-10cm long. They are bifacial in nature and can be illuminated from either side or from both sides simultaneously. Sliver® cells tested under 1 sun illumination have already recorded open circuit voltages of around 685mV and 19% efficiency.

All of the advantages associated with the sliver® cells designed for one sun applications apply equally well to cells designed for concentrated sunlight applications: reduced per unit area silicon usage and wafer processing costs, high voltage and low current outputs. In addition there are other possible advantages in terms of toleration of the non-uniform illumination typical of concentrator systems. Sliver® cells currently being produced for one-sun applications do not perform very well at higher concentrations. However, it is possible to select design parameters so that a concentrator sliver® cell can be produced with very little variation in the fabrication process. In this paper Dessis semiconductor modelling software (ISE, 2000) is used to examine the performance of cells under low to medium concentration, and to select optimum design parameters.

One potential application for concentrator sliver® cells is to replace the concentrator cells in a CHAPS receiver with strings of series connected 40mm long sliver® cells. The strings of cells would have the same width as a conventional concentrator cell but would operate at high voltage and low current. The use of 1mm wide sliver® cells could, for example, produce a string of cells with maximum power point current of approximately 350mA, and output voltage of about 6V per linear cm.

**CONCENTRATOR SLIVER® CELL MODELLING**

Sliver® cells are modelled using Dessis semiconductor modelling software from ISE / TCAD. The software allows the user to define a solar cell geometry and complete set of material properties and then solves the full set of coupled non-linear semiconductor equations with a defined set of boundary conditions. The coupled equations can be written and solved for a 3, 2 or 1 dimensional device. The concentrator sliver® cells have been modelled in this paper as 2D devices.

Carrier generation is handled via the ISE / TCAD Optik command which takes as inputs the material properties, such as silicon bandgap and absorption, and the incident optical spectrum intensity and placement definition. The modelling in this paper uses the AM1.5G spectrum normalized to 100mW/cm² at 1 sun, and incident upon either one entire side of the sliver® cell only (monofacial mode) or incident upon both sides uniformly (bifacial mode). Both the front and rear light accepting surfaces of the cell are coated with an antireflection coating. Auger recombination, SRH defect-level recombination, surface recombination and band-gap narrowing are all included in the modelling. Bulk SRH lifetimes have been selected for given material doping levels based on typical values for float-zone mono-crystalline wafers.
Various simulated IV curves for a range of cell parameters is given in figure 3, for an emitter sheet resistivity of 1000Ω/cm² and at an illumination level of 2W/cm² (20 suns). Low resistivity bases provide the best option for concentrator sliver® cells, in the order of 0.1Ωcm. Cells based upon high resistivity wafers exhibit characteristics of high series resistance. This is due to significant ohmic losses in the long, narrow (in the order of 100µm thick) bulk region. Low resistivity wafers have shorter minority carrier lifetimes and lower mobilities, which places an upper limit on the bulk doping level and also on sliver® cell thickness. It is necessary to ensure that minority carrier diffusion lengths in the bulk comfortably exceed sliver® cell thickness so that internal quantum efficiency remains high. A lower limit on cell thickness is only determined by the light-trapping regime employed and by handling requirements: if the cell is made too thin then the carrier generation efficiency will start to drop. Thin cells maximise the advantage of the sliver® technology by maximising silicon usage.

For low resistivity sliver® cells the main loss mechanism when operating at high illumination levels becomes resistance losses in the emitter. Electrons generated in the emitter or diffusing into the emitter from the base are required to travel, on average, half the width of the cell to reach the negative contact. The emitter sheet resistance is significant. Normally for a high efficiency concentrator cell it is important to guarantee emitter transparency; that is to make sure that all minority carriers generated near the top surface of the silicon are transported across the pn junction. Generally speaking, a sheet resistance of 1000Ω/? will produce a transparent emitter. However, for concentrator sliver® cells it may actually be worth sacrificing emitter collection efficiency in order to reduce emitter sheet resistance significantly. For a given cell width a 50% reduction in emitter sheet resistivity produces close to a 50% reduction in fill-factor losses due to emitter resistance. Reduced sheet resistivity, whilst still maintaining high emitter collection efficiency, can be achieved by utilising deeply driven-in emitter diffusions. A 500Ω/cm² phosphorous diffusion with Gaussian profile and having surface concentration of 2 x 10¹⁹ cm⁻³, junction depth of 1.3µm and good surface passivation (SRV = 1000cm/s) has been modelled to have an emitter collection efficiency of greater than 94% for wavelength, ? = 400nm and a
total internal quantum efficiency of greater than 98% for the entire AM1.5G spectrum. Such a diffusion profile could be formed, after a suitable phosphorous pre-deposition step, with an 1100°C drive-in for 50 minutes (Jaeger, 1993). The relationship between efficiency and cell width, and efficiency and concentration ratio are shown in figure 4 for a sliver® cell based on 0.1Ocm bulk resistivity, 100µm thick with emitter diffusions described above.

Cell performance drops off as cell width is increased or as concentration is increased past the optimum. The drop in fill factor is due to emitter resistance losses which increase linearly with concentration and with the square of cell width. Bifacially illuminated cells perform better because more of the current load is shared between the front and rear emitters. From a manufacturing perspective the advantage of the sliver® technology is maximised if the cells are manufactured as wide as possible and as thin as possible, since the total photovoltaic coverage area is increased for the same amount of wafer processing. A delicate trade-off exists between sliver® cell width, sheet resistance and emitter efficiency and allowable concentration ratios. The ultimate selection of optimal parameters depends upon a detailed economic analysis of processing costs and the value of electricity generation for a given set of operating conditions.

CONCENTRATOR SLIVER® CELLS IN THE CHAPS SYSTEM

Conventional cells used for the CHAPS system are produced from mono-crystalline silicon wafers. Efficiencies of around 20-21% are normally achieved. Each cell measure 40m wide x 50mm long and typically produces maximum power point current and voltage of 16A and 600mV respectively for normal concentrator operation. A CHAPS receiver (see figure 1) typically consists of around 30 of these cells connected in series. A potential application for concentrator sliver® cells is to replace the conventional concentrator cells with strings of series connected concentrator sliver® cells.

Since each sliver® cell operates at a small current, the strings of cells can be configured so that they are have a low current and high voltage output. For example, if the individual concentrator sliver® cells are 500µm wide and 40mm long then the output current at maximum power point will be around 180mA, and voltage will build linearly along the receiver at a rate of around 10V per cm. The strings of series connected cells can then be configured at a given length to meet desired voltage output requirements. If the sliver® cells are manufactured at a thickness of 50µm, then a single 100mm diameter, 500µm thick wafer could cover a length of approximately 60cm of a CHAPS receiver (an area of 240cm²). The present concentrator cells cover a receiver length of 10cm (or an area of 40cm²).

CONCLUSIONS

Modelling has revealed that it is possible to produce sliver® cells capable of operating at low to medium concentration ratios, and that the correct choice of design parameters for such cells is crucial. Good concentrator sliver® cells can be produced from low resistivity wafers, provided that the material is of sufficient quality to ensure diffusion length is greater than the cell thickness. The cells should be made as thin as possible to maximise silicon usage, but this is limited by the light-trapping scheme that is used.
The emitter sheet resistance dominates the fill-factor losses in a concentrator sliver® cell for low resistivity substrates, and so cell width needs to be kept to a minimum for highest efficiency. Emitter sheet resistance can be reduced by using deeply driven-in emitter diffusions with only small associated reduction in internal quantum efficiency. There is a delicate trade-off between cell performance’s dependence upon cell width and emitter diffusions, and the benefits of the sliver® processing technology. The optimum combination of emitter diffusion and cell width for a given operating illumination intensity relies upon a detailed economic analysis of processing costs and electricity generation revenue.

Concentrator sliver® cells can be manufactured and assembled in strings of series-connected cells to take the role of conventional concentrator cells in the CHAPS systems. Concentrator sliver® cells could be used to produce six times the coverage of conventional cells for the processing of a single wafer.

Production of several batches of concentrator sliver® cells will commence initially using low resistivity boron doped p-type float-zone wafers with a cell thickness and width range of approximately 50-150µm and 500-1000µm respectively, and for a range of emitter diffusions. 3D modelling will be conducted to investigate the effects of end-cuts and non-uniform illumination on cell performance.

REFERENCES