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# EFFICIENT 20-50 SUN CONCENTRATOR CELLS

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ABSTRACT: The Australian National University, together with commercial partners, has developed a Photovoltaic / Trough concentration system. It comprises two-axis sun-tracking parabolic glass mirrors and a receiver with solar cells placed along the focal line. The cells are under 20-30 suns concentration, and are cooled either actively or passively. A 20 kW prototype system has been constructed in Perth in Western Australia. The ANU fabricated 2,500 cells of 20 $cm^2$ for the prototype system. Average cell efficiency was 22% under 30 suns, while the best cells reached 24%. They were made on 0.5 ohm-cm, 300 micron thick 100 mm diameter float zone silicon wafers using an elegant processing sequence. The design has high efficiency potential under both concentrated and non-concentrated sunlight and yet is potentially no more complex or costly to fabricate commercially than conventional one sun designs.

KEYWORDS: Concentrator - 1: High-efficiency - 2: Silicon – 3

## 1. INTRODUCTION

Concentrator systems have a number of important advantages over conventional PV systems, the main one being that a cheap reflective or refractive surface is substituted for most of the solar cells. The inability of concentrators to use direct beam sunlight is compensated for by the sun-tracking of the system. In sunny locations such as central Australia direct beam radiation is a high proportion of global radiation. Provided that regular maintenance is available, concentrator systems could have a substantial advantage in such locations. An excellent review paper of concentrator systems has recently been published [1].

The major problem for concentrator systems hitherto has been that a suitable market does not exist. PV concentrators cannot compete directly with electricity from state grids and lack the niche markets that have accommodated conventional photovoltaic modules. If and when a suitable market for large scale PV systems opens, whether driven by subsidies or by other means, it is expected that concentrator systems will compete well with conventional PV systems.

The Australian National University has developed a Photovoltaic / Trough Concentration System for use in the Australian outback. The system comprises two-axis sun-tracking parabolic glass mirrors and a receiver at the focal line of the trough with cells mounted on the under surface. An aluminium passive heat sink provides cell cooling. A 20 kW prototype system has been installed in Rockingham near Perth in Western Australia [2].

Solar cells for use in mid-range concentrators (20-50 suns) are not readily available. BP Solarex produced Buried Grid solar cells for the 480 kW PV/Trough concentrator system that was built recently in Tenerife in the Canary Islands. The cells were reported to be up to 18% efficient under concentration.

Point focus concentrators can afford highly efficient (> 26%) cells even if they are expensive. Trough concentrators operating at 20-50 suns can’t economically use such cells. However, cells in the efficiency range 22 to 24% under concentration are much less expensive than cells designed for point focus concentrator. Economic analysis indicates that such cells can be afforded for trough concentrators. Roughly speaking, a relative improvement in solar cell efficiency of 10% in the ANU PV/Trough concentrator system allows an increase in cell costs of 30%.

As part of the development of its PV/Trough system, ANU has developed an efficient mid-range concentrator solar cell with a remarkably simple fabrication process.

## 2. CONCENTRATOR CELL DESIGN

Pioneering work in the area of high performance concentrator solar cells was done at Stanford University and at the Universite Catholique de Louvain. The aim of that work was a solar cell with both n and p contacts on the rear for application in point focus concentrators with system illumination intensities above 100 suns. The Point Contact cell has been commercialised by SunPower Corporation, who produce cells with efficiencies above 26%.

The standard point contact cell required an expensive manufacturing process with several aligned photolithography steps. A considerable simplification became possible by using a novel self aligned process [3]. In this design $n^+$ and $p^+$ regions are adjacent to each other. Control of doping profiles avoids shorting between the two regions. The surface doping concentrations need to be sufficiently low to avoid a short, but high enough to allow ohmic contacts to be made to the silicon (particularly in the case of the n-contact).

The major advantage of the back contact cell is that no metal is located on the front surface, which eliminates metal reflection losses. Another advantage is that if metal is being deposited by evaporation then only a single step is needed to coat both n and p contacts. There are, however, a number of disadvantages for the rear contact approach, including the following:

**1. Electron & hole transport:** Both electrons and holes must be transported to the rear surface. The low mobility of holes means that the wafer should be thin (< 150 microns) to avoid sublinearities under concentration. Thinner wafers require a thinning step and are more difficult to handle during processing. Another disadvantage of thinner wafers is that they absorb slightly less light than thicker wafers. Conventional $n^+/p$ cells on low resistivity wafers (< 2 ohm-cm) must transport holes but not electrons to the rear surface. The cells remain in low injection for intensities below 50 suns or so, and the holes are transported as majority carriers with only small resistive losses even in 300 micron thick wafers.

**2. Rear surface metallisation**: Both the n and p contact metals must share the rear surface, meaning that the thickness of each metal must be much greater than the rear metal required for a conventional bifacially contacted cell. For large area cells (5x4 $cm^2$) for linear concentrators at 20-50 suns the metal thickness will need to be above 5 microns, which can warp the wafer or result in metal peeling off the cell surface due to thermal expansion mismatch.

The thickness of metal needed in back contact 5x4 $cm^2$ 30 sun cells is much larger than for 1 $cm^2$ back contact cells for use in point focus concentrators at 300 suns because the current is extracted from only two edges rather than four, and because the cells are larger. If an interdigitated metal grid is used on the rear surface then the problem is acute: the ratio of metal thickness required for equivalent resistance losses in the rear metal is 13 (factors of 2, $8^2$ and 1/10 for two sides of extraction rather than four, 8 times longer fingers and lower solar intensity respectively).

An alternative approach is to overlay the two metallisations and extract current from both sides for each polarity of current, using a pinhole free material in between (eg polyimide). This increases the cost of cell mounting but reduces the rear metal resistance losses by a factor of four.

**3. Other aspects:** Care (and expense) must be taken to avoid short circuits between the n and p contact metals when mounting the cell on the heat sink.

If one of the contact types (n or p) is recessed then heat sinking is more difficult, since less than 100% of the surface will contact the heat sink unless a planarisation step is done. Any insulation layers between metallisations will increase the thermal resistance of the cell.

In the case of the simplified back contact cell the entire rear surface is doped heavily, either p or n type. This increases surface recombination relative to a cell in which the surface is either lightly phosphorus doped or is undoped.

Detailed analysis shows that there is almost no difference in the efficiency potential of 5 x 4 $cm^2$ back contact cells and conventional cells designed to operate at 20 to 50 suns except in the case of sophisticated rear metallisation schemes [4]. At high concentrations back contact cells have a clear advantage.

One reason for the good performance of conventional cells relative to back contact cells is that the optical loss of a silver electroplated front metal grid after encapsulation is less than one third of that expected from geometrical calculations. The trapping of light reflected from silver electroplated fingers has been comprehensively characterised at the ANU. It has been numerically calculated, measured with an integrating sphere and measured by observing solar cell short circuit currents as a function of finger plating thickness. All three techniques agree. More than 65% of the light incident on a silver electroplated finger on an encapsulated solar cell will be absorbed by the silicon rather than escape [4]. This reduces the combined reflection and resistance losses associated with the front surface metal grid, the emitter and the rear surface metallisation in a 30 sun 20 $cm^2$ concentrator cell to a total of about 8%.

## 3. A NEW CONCENTRATOR SOLAR CELL

Careful attention to clean processing results in large minority carrier lifetimes when using FZ wafers. With suitable precautions it is relatively straightforward and inexpensive to maintain high minority carrier lifetimes even in a production setting. However, highly efficient cells require sophisticated processing in order to suppress surface recombination and optical reflection and to enhance light trapping. Such processing is costly. Fortunately carefully chosen simplifications can yield efficiencies only a few percent (absolute) below the best silicon solar cells.

An elegant $n^+pp^+$ concentrator cell process sequence has been developed at ANU. No photolithographic alignment, laser grooving or other unusual steps are required. The wafers are 250-350 microns thick FZ, 0.5 to 1 ohm-cm. Recombination at metal contacts is suppressed by minimising contact area and by heavily doping. Heavy doping also suppresses contact resistance losses. Front surface recombination is minimised by the use of a high-quality thermal oxide in combination with a light phosphorus doping. Silver electroplated metal fingers on the front surface have high conductivity and low effective shading after encapsulation

The metal-silicon contacts occupy approximately 2% on both the front and rear surfaces. In addition the two metal busbars on the front surface have a contact area of 5%. This can be reduced by interposing an oxide between the metal and silicon, but only at the cost of a significant increase in process complexity. As an alternative a new pattern is being designed to reduce the busbar area to about 2%.

Dicing of cells from the wafer is being done with a dicing saw, which cuts directly through the pn junction. This leads to a significant efficiency loss since the perimeter area in a 300 micron thick 5x4 $cm^2$ cell is 1.4% of the total surface area of the cell, and it is entirely unpassivated or diffused. The loss is less than in a small high-concentration cell since the perimeter area is a smaller fraction of total surface area.

At present there is a silicon dioxide antireflection coating. This is ineffective after encapsulation. An SiN system has recently been acquired and an improvement of 1% absolute in cell efficiency is expected by straightforward reflection reduction.

Random texturing is used in the cells. This leads to a higher surface recombination rate than polished or inverted pyramid surfaces but is strongly preferred for cost reasons. Effective light trapping is also obtained, particularly after encapsulation. Howver, since the cells are 250-350 microns thick, excellent light trapping is a marginal issue.

The cells are being tested for environmental stability. UV, humidity/heat, salt tolerance, elevated temperature and thermal cycling tests are being carried out on bare cells, tabbed cells and encapsulated cells. Early results are favourable.

The processing complexity and cost of the new cell design is equivalent to the buried contact cell produced by BP Solarex. However, cell efficiencies are substantially higher. This is partly due to the use of high-quality float zone wafers and partly due to an inherently more efficient cell design. Buried contact concentrator cells have a relatively large metal-silicon contact area (about 20% of the total cell surface area) since groove spacing needs to be 400 microns or less. The x-sectional area of the groove is much less than the x-sectional area of metal required for each finger, and so most of the metal spills out of the top of the groove. The shading loss of the front surface metallisation is almost identical to that of a conventional cell with silver plated metal fingers after encapsulation [4].

Some 2,500 cells were fabricated for the ANU 20 kW PV/Trough system. Typical cell parameters after encapsulation behind glass at 30 suns concentration ratio were a Voc of 750-770 mV, a fill factor of 0.77 to 0.80, a current density around 38 $mA/cm^2$ per sun and a cell efficiency of 22-23%. The best cells reached 24 percent efficiency. Cell efficiency is almost constant in the range 15 to 60 suns (provided that metal finger thickness is adjusted appropriately). It seems likely that efficiencies of up to 25% at 30 suns will be obtainable while retaining process simplicity. The temperature coefficients of performance for efficiency and Voc are 0.32%/degree and 1.7 mV/degree respectively.

The cells are not as efficient as SunPower Point Contact cells but are considerably cheaper to fabricate. Even in a laboratory setting costs are compatible with commercial sales. Experience gained in fabricating 2,500 cells shows that yields rapidly improved and the spread of cell efficiencies tightened and moved to the upper end of the efficiency range.

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