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Concentrator Silicon Cell Research

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CONCENTRATOR SILICON CELL RESEARCH

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ABSTRACT

This project continued the development of high-efficiency silicon concentrator solar cells with the goal of achieving a cell efficiency in the 26 to 27 percent range at a concentration level of 150 suns or greater. The target efficiency was achieved with the new PERL (passivated emitter, rear locally diffused) cell structure, but only at low concentration levels around 20 suns. The PERL structure combines oxide passivation of both top and rear surfaces of the cells with small area contact to heavily doped regions on the top and rear surfaces. Efficiency in the 22 to 23 percent range was also demonstrated for large-area concentrator cells fabricated with the buried contact solar cell processing sequence, either when combined with prismatic covers or with other innovative approaches to reduce top contact shadowing.

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SECTION 1

1. SUMMARY

1.1 Objectives

The aim of this project conducted over the period from February, 1989 to August, 1990 was to continue the development of high efficiency silicon concentrator cells. One major objective was to demonstrate an efficiency in the 26-27% range at concentration levels of 150 suns or greater. This was to be achieved by the concurrent investigation of several approaches involving both the optimization of established sequences and innovative approaches such as passivated emitter and rear cell structures.

1.2 Major Results

At the commencement of the project, the University of New South Wales (UNSW) had demonstrated concentrator silicon solar cell technology capable of producing large quantities of 24% efficient cells at sunlight concentration levels in the 100-150 suns range, with a peak efficiency of 25.2% measured [1].

Several hundred cells of this performance level designed for use in conjunction with prismatic covers had been supplied to Sandia for use in experimental modules [2]. Very promising results had also been obtained with a new approach to passivating the rear surface of silicon cells with one-sun efficiencies up to 21.8% independently confirmed [1].

Early in the present project, rapid progress was made with this new approach with 22%, 23% and finally 24% one-sun cell efficiency successively surpassed [3]. Accordingly, the present project focussed upon adapting this new approach for use under

concentrated sunlight. Due to an emerging commercial interest for concentrator cell use, considerable effort was also expended in investigating the potential of low-cost, large-area laser grooved cells for use in low concentration ratio applications.

Using the new PERL (passivated emitter, rear locally-diffused) cell structure and cells designed for use with prismatic covers to reduce the effects of metallization shadowing, promising efficiencies were demonstrated under concentration prior to application of the covers. Some difficulty was experienced with the subsequent application of the covers externally to UNSW. Consequently, the full benefits of covers were not observed during the project. The best covered cell efficiency was 26.0% under 20 suns concentration, with efficiencies up to 23.7% demonstrated at 150 suns, both for 1.6-cm² area cells. Higher efficiency is feasible with this technology with improved cover application and further reduction of cell series resistance.

Good results are also reported with cells fabricated with the laser grooved processing approach. This technology has previously been primarily of interest for non-concentrating cell applications although also of considerable interest for low-cost, low concentration ratio cell use. This is due to the very low finger and contact resistance achievable with this approach. Efficiencies above 22% are reported for 20-cm² cells after application of prismatic covers at 10-20 suns concentration. By innovative cell processing, even higher efficiencies up to 22.6% were demonstrated for large-area cells without these covers, at similar concentration levels.

Other results are reported relating to the optical and electronic characterization of cells, particularly in the area of rear reflectance.

The cell performance results given in this report are based on the calibration standard used by Sandia prior to 1991. All cell currents, efficiencies, and responsivities should be multiplied by 0.952 to convert these figures to the standard currently in use at Sandia.

SECTION 2

2. PERL CELLS

2.1 Introduction

Previous reports [1,3] document the development of an improved passivated emitter, rear-locally diffused (PERL) silicon solar cell (Figure 2.1). This structure arose basically by combining the strong performance features of the passivated emitter solar cell (PESC) [1,2] with the improved surface passivation as demonstrated in solar cells developed at Stanford University [4]. Physically, the main difference from earlier PESC cells is the replacement of an alloyed aluminum rear contact by the oxide-passivated structure shown. From the processing point of view, extensive use is made of chlorine-based processing to preserve bulk material quality while simultaneously improving surface passivation [3]. Another high performance feature is the high level of "light-trapping" due to the combination of the "inverted pyramid" top surface structure and the "dielectrically-displaced" rear surface reflector [5].

These features combined to give excellent "one-sun" performance. However, a major disadvantage for concentrator cells compared to the earlier PESC approach is the way contact is made at intermittent points along the rear surface. This reduces contact area and forces current to flow laterally through the bulk of the cell. Both effects increase resistive contributions. Consequently, there are considerably more "trade-offs" involved in designing PERL cells for concentrator use. Although considerable progress was made in adapting this design for concentrator applications during the course of the present project, further work remains in this area.

Figure 2.1: PERL Cell (Passivated Emitter, Rear Locally-Diffused Cell).

Figure 2.2: Mask design for present PERL cells [2].

2.2 PERL Concentrator Cells

Due to the developmental nature of the present project, an existing top contact mask design was used as shown in Figure 2.2. This design is intended for use with prismatic covers, with metallization fingers covering 15% of the designed illumination area [2]. Extensive experience has been gained with PESC cells fabricated with this mask. Upon application of prismatic covers, an average boost in performance of 13% has been observed under concentration for several dozen cells so covered [2].

For the rear contact to the cells, several different masks were used with contact areas spaced uniformly over the rear surface. Excessive rear contact area can result in open-circuit voltage reduction, due to the non-ideal properties of the heavily diffused contact areas. Too small a contact area can lead to increased series resistance, either contact resistance or bulk resistance due to lateral current flow over too large a distance. Resistive contributions have been discussed elsewhere [1]. Due to continual processing improvements, further work is required to definitively specify the optimum rear contact design.

Several batches of high-performance PERL concentrator cells were produced during the project with very high energy conversion efficiency demonstrated. However, although considerable improvement was made during the course of the project, PERL cells invariably peaked in performance at concentration levels well below PESC cells using the same mask design.

Some of the highest performance and most thoroughly characterized cells came from batches Z253 and Z255 with processing details given in Table 2.1. Two cells from these batches will be discussed in some detail. Cells were first measured without prismatic covers at Sandia in February, 1990. At one sun, they

demonstrated efficiencies around 20-21% as indicated in Table 2.2. Under concentration, cell Z255-1 gave the highest overall efficiency of above 24%, while cell Z252-1 gave the best result in the designed concentration region.

The cells were then sent to ENTECH to have prismatic covers applied [6]. These covers steer light away from the cell metallization, boosting the current output [1,2]. As previously noted, an average boost of 13% has been demonstrated in the past for the present cell top contact design. However, in the present case, a lower boost was observed as shown in Table 2.2. The observed boost was only 9.5% for cell Z252-1 and 11% for cell Z255-1. This was sufficient, however, to improve the one-sun performance of cell Z255-1 to 23.4% under the direct AM1.5 spectrum at 25°C (23.6% under the global AM1.5 spectrum). Under concentration, apparent efficiencies up to 26.7% were observed at low concentration [7].

Subsequent more detailed evaluation showed that fill factors were inflated at low concentration levels due to a sweep rate dependence in tracing the cell output curve. When corrected for this effect, efficiency at low concentration levels reduced slightly although still above 26% for the best cells. Tables 2.3 and 2.4 show the output characteristics of cell Z252-1 and Z255-1 under concentration.

As noted, cell efficiency was disadvantaged by a less than ideal boost upon application of prismatic covers. Although cell Z255-1 had the highest boost of 11%, there were still deficiencies in the prismatic cover that was applied. A laser scan of the 5 mm x 5 mm section of the cell after application of the prismatic cover is shown in Figure 2.3. The large black segments are attributed to bubbles in the prismatic cover or its adhesive layer which prevent it from working ideally. An additional boost in performance up to 6% for cell Z252-1 and 4% for cell Z255-1 might have been expected.

Table 2.1: Processing Sequence for PERL Concentrator Cells (Z252-1 fabricated on 0.2- Ω -cm substrate, Z255-1 on 0.5- Ω -cm, both cells used 10 x 10 micron rear contact holes on 250 micron spacing)

<u>STEP</u>	<u>PARAMETERS</u>
1. Wafer Selection	0.2-0.5 Ω cm, (100), FZ, p-type. Boron doped, 280 micron thick, Φ = 50.8 mm. Both sides polished
2. Oxide Growth	1000°C, 1.5 hr, 2% TCA in O ₂
3. Oxide Patterning	Inverted pyramids, active area
4. Surface Etching	KOH:H ₂ O = 8:100 (w/v), 70°C.
5. Rounding	NH ₄ F:HNO ₃ = 1:30, 1 min.
6. Oxide Removal	HF:H ₂ O = 1:5, 2 min.
7. Rounding	NH ₄ F:HNO ₃ = 1:30, 1 min.
8. Oxide Growth	1070°C, 3 hr., 2% TCA in O ₂
9. Oxide Patterning	Rear boron windows (30 x 30 micron)
10. Boron Diffusion	BBr ₃ source 900°C then 3 hr. at 1080°C in 5% O ₂ in N ₂
11. Deglaze	HF:H ₂ O = 1:20, ~ 6 min.
12. Oxide Growth	1070°C, 3 hr., 2% TCA in O ₂
13. Oxide Patterning	Fat finger pattern
14. Heavy N ⁺ Diffusion	Phosphorus solid source, 910°C, 30 min., 10 $\Omega/\square$
15. Deglaze	HF:H ₂ O = 1:20, 1 min.
16. Oxide Growth	1050°C, 1 hr., 2% TCA in O ₂
17. Oxide Patterning	Emitter junction definition
18. Light N ⁺ Diffusion	820°C, 20 min., 300 $\Omega/\square$
19. Deglaze	HF:H ₂ O = 1:20, 3 min.
20. Passivation Oxide Growth	1000°C, 95 min., 2% TCA in O ₂ . 15 min. annealing in Ar
21. Oxide Patterning	Metal finger pattern, rear contact holes
22. Photoresist Patterning	Busbar area without HF etching
23. Top Contact Metal	Ti/Pd:600/600Å, lift off
24. Rear Contact Metal	Al:2 micron
25. Ag Plating Top	Electrolytic, 8 micron
26. Sinter	400°C, 30 min., 4% H ₂ in Ar

Table 2.2: One-sun efficiencies of cells Z252-1 and Z255-1 before and after application of prismatic covers (Direct AM1.5 spectrum, 25°C, cell area 1.56-cm², measurements courtesy of Sandia National Laboratories).

Cell	Cover	V _{oc} (mV)	J _{sc} (mA/cm ²)	FF (%)	Effic. (%)
Z253-1	No	680	36.2	79.5	19.6
	Yes	683	39.6	79.4	21.5
Boost		3 mV	9.5%	-	-
Z255-1	No	687	36.9	32.6	20.9
	Yes	690	41.0	82.7	23.4
Boost		3 mV	11.1%		

Table 2.3: Efficiency of cell Z252-1 under concentrated sunlight after application of prismatic covers. (One sun performance remeasured 7 months after those of Table 2.2). One sun responsivity 0.400 A/W. (Direct AM1.5 spectrum, 25°C, cell area 1.56-cm², measurements courtesy of Sandia National Laboratories).

Suns	V _{oc} (mV)	FF (%)	Effic. (%)
1	683	79.4	21.7
30	772	82.9	25.6
150	804	73.5	23.7

Table 2.4: Efficiency of cell Z255-1 under concentrated sunlight after application of prismatic covers. (One sun performance remeasured 7 months after those of Table 2.2). One sun responsivity 0.410 A/W. (Direct AM1.5, 25°C, cell area 1.56-cm², measurements courtesy of Sandia National Laboratories).

Suns	V _{oc} (mV)	FF (%)	Effic. (%)
1	690	82.7	23.4
20	762	83.1	26.0
145	802	63.0	20.7

Figure 2.3: Laser scan of a 5 mm x 5 mm area of prismatic covered cell Z255-1. Five grey tones are used to display responsivity between 80% to 100% of maximum. Darkest areas show response below 80%, with response as low as 20% recorded in the center of some regions. Grey area near lower edge may be an artefact due to laser stabilization.

2.3 Optical Characterization of Cells

Preliminary optical characterization of PERL cells has been reported elsewhere [3,5]. One parameter of interest has been the reflectance of the rear surface of the cell. The rear surface reflector, consisting of a layer of aluminum displaced from the silicon surface by a layer of silicon dioxide, should act as a very efficient reflector of light. Figure 2.4 shows the calculated reflectance at 1.2 microns (free space wavelength) as a function of oxide thickness for several different incidence angles from within the silicon [8].

The calculations show three reflectance regions depending upon the angle of incidence. Below the critical angle for the Si/SiO₂ interface (24.7°), normal interference layer effects predominate with a cyclical change in reflectance as a function of wavelength. Near the critical angle for the thickness range shown, minimum reflectance occurs. Above the critical angle, very high reflectance becomes possible with the thickest oxides giving the best results.

This rear reflectance is of prime importance since it determines the effectiveness of "light-trapping" schemes. Once the bulk absorption per optical pass across the cell falls significantly below the loss per rear reflection, light-trapping will become increasingly less effective. At infrared wavelengths beyond 1.2 microns where silicon is relatively non-absorbing, the cell reflectance itself gives considerable information on the rear surface reflectance properties as well as the effectiveness of light-trapping schemes.

At such wavelengths, PERL cells with planar, non-textured top surfaces typically give reflectance of 90-91%. With microgrooved (slat) top surfaces, this decreases to about 82%, and with inverted pyramid top surfaces it decreases further to the 60-70% range [5].

The reflectance of planar cells, in particular, is lower than expected given the results of Figure 2.4. To eliminate complications in interpreting results due to the top metal contacts and free carrier absorption in doped regions of the cells, optical test structures were fabricated upon high-resistivity substrates (1000- Ω -cm) which excluded such contacts and heavily doped regions. The reflectance of these samples were measured to an absolute accuracy of about 0.5% within the Sandia Thermo-Physical Properties Measurement group.

The results for a planar structure with typical oxide thicknesses on top and rear surfaces (circa 1,000 Å) are shown in Figure 2.5(a). At wavelengths below 1 micron, the silicon is relatively strongly absorbing and the reflectance measured is basically that from the top surface of the cell. Beyond 1.2 microns, silicon is essentially transparent and a combination of top surface and rear surface reflectance is measured. At intermediate wavelengths, the absorption within the cell becomes important. For a planar structure, the overall top surface reflectance R can be calculated as:

$$R = \rho_{fe} + \frac{(1 - \rho_{fe})^2 \rho_b e^{-2\alpha W}}{(1 - \rho_{fe} \rho_b e^{-2\alpha W})} \quad (2.1)$$

where ρ_{fe} is the reflectance of the top surface alone, ρ_b is that of the rear surface, α is the absorption coefficient of silicon and W is the sample thickness.

Applying this equation to the smoothed raw data for Figure 2.5(a) gives a rear reflectance for perpendicular light of 95.3%, 94.9% and 94.5% at free space wavelengths of 1.2, 1.8 and 2.4 microns respectively. This is in good agreement with the calculated results of Figure 2.4, which gives a value of 95.8% for a 1,000 Å thick oxide at 1.2 microns wavelength. This increases confidence in the accuracy of the other calculated results.

Figure 2.4: Calculated reflectance from the rear PERL cell reflector as a function of oxide thickness for the different incidence angles shown [8].

Figure 2.5(b) shows the measured reflectance for an almost identical test structure except it is fabricated on a more heavily doped 0.2- Ω -cm substrate. The most apparent difference is the steady decrease in reflectance from 1.2 to 2.4 microns. This is due to free carrier absorption in this specimen. By rearranging Equation (2.1) and applying to both specimens, accurate values of the free carrier absorption coefficient (α_{pfc}) can be deduced as 0.370(38), 0.878(45) and 1.503(58) at 1.2, 1.8 and 2.4 microns respectively (the numbers in brackets are the estimated one standard deviation uncertainties in the last two digits). At 1.2 microns, the main uncertainty arises from reflectance measurement repeatability (estimated 0.2% standard deviation) while at 2.4 microns it is uncertainty in the sample thickness (estimated 3% standard deviation). These results are consistent with the expression [9] :

$$\alpha_{pfc} = A \lambda^2 p \quad (2.2)$$

where p is the hole concentration. The value of A deduced is $2.8(2) \times 10^{-18} \text{ cm}^3/\text{micron}^2$ in good agreement with the value of 2.7×10^{-18} deduced from measurements at 4-10 micron wavelengths [9].

Figure 2.6 shows a similar result to that of Figure 2.5(a), this time when an inverted pyramid structure is applied to the top surface. There is considerable reduction in reflection at all wavelengths. At wavelengths below 1.0 microns, the reflectance very nearly equals R^2 , where R was the reflectance measured for the planar structure of Figure 2.5(a). This is due to the double bounce experienced by light reflected from the side of an inverted pyramid. Beyond 1.2 microns, the reflectance is again relatively constant with a value of about 68%. The decreased reflection in this case is due to light-trapping within the cell which increases the opportunities for absorption in the rear aluminum. Due to the oblique coupling of the

Figure 2.5(a): Hemispherical reflection from a planar test structure fabricated on a 1000- Ω -cm substrate with surface oxide thickness of 988 Å.

Figure 2.5(b): Hemispherical reflection from a planar test structure fabricated on a 0.2- Ω -cm substrate with 972 Å oxide thickness.

light into the cell, the main incidence angle at first reflection is 41.3° . This increases the calculated reflectance to 98.3%. Some light may also strike at closer to zero incidence due to imperfect flat borders or rounded regions between the inverted pyramids but light coupled in on the second top surface reflection will strike the rear more obliquely. On reaching the top surface, about 45% of the obliquely coupled light will strike the top surface at an angle where it can be coupled straight out of the cell (some will be reflected). Most of the remainder will be totally internally reflected back to the rear of the cell which, (according to P. Campbell) it will strike at incidence angles primarily of 54° and 58° . On subsequent passages, a myriad of possible incidence angles will be built up by second order interactions, some of which have been already described. However, due to the escape of the largest bundle of light after the first double pass, it is probably not possible to accurately model the light-trapping scheme as Lambertian.

There is scope for improving cell performance by increasing rear surface reflectance. Options identified as worthy of investigation include replacing the dielectric by a lower index material, use of a higher reflectivity metal, or the use of low-absorbance dielectric stacks. The rear surface has to be reflective for a range of incidence angles, complicating the design. Aluminum also has processing advantages in that a low temperature "anneal" step is incorporated in the processing to reduce rear surface state density.

Modification of the rear dielectric properties could be relatively simply implemented. Insertion of a layer of a low index material such as magnesium fluoride between the rear silicon dioxide and aluminum should increase the rear surface reflectance. This would be by giving more flexibility in interference design, as well as decreased critical angle and improved scope for use of very thick layers. As a first step, planar test structures were fabricated incorporating a $1200 \text{ \AA}$ layer of magnesium fluoride deposited on

top of the rear oxide before rear surface aluminum deposition. As shown in Figure 2.7, an increase in reflectance was noted for wavelengths beyond 1.2 microns for perpendicularly incident light. Little can be said about oblique light performance. Further work is required to quantify design advantages possible with this approach.

2.4 Spectral Response Characterization

An ingenious technique for extracting optical and material properties by analysis of the reflectance and spectral response of a general solar cell has been developed by P.A. Basore of Sandia [10,11].

Basically, the technique involves plotting the inverse of the internal quantum efficiency of the device as a function of the absorption length of the light in silicon (the inverse of the absorption coefficient). This is an established technique for measuring diffusion lengths in cells. The difference in the present case is the extension of the technique to absorption lengths much longer than the cell thickness and the interpretation of the information thereby gained. For experimental cells, the resulting plot can often be split into two linear regions as shown in Figure 2.8.

The region near the origin corresponds to light absorbed relatively quickly in the silicon. The response in these regions does not depend on rear surface reflection. The inverse slope of the straight line to this region gives a length parameter, L_{IQE} . Knowing the angle of the passage of light across the cell, this parameter can be related to an "effective diffusion length", L_{eff} , of physical significance [11]. At larger values of the absorption depth, the optical properties of the rear of the cell become important. It is possible to fit a second linear region to the higher absorption length values, with a second length parameter W_{IQE} defined as the inverse slope at these high absorption length values. The

Figure 2.6: Hemispherical reflection from a test structure with inverted pyramids on the top surface and a planar rear reflector structure (1000- Ω -cm resistivity, 990 Å oxide thickness).

Figure 2.7: Hemispherical reflection from a planar test structure with 1200 Å of MgF₂ between rear oxide and Al reflector (1000- Ω -cm, 995 Å oxide).

Points plotted at 20 nm increments from 1000 nm to 1140 nm

All QE data adjusted upwards by 5%

Figure 2.8: Inverse internal quantum efficiency plotted as a function of inverse absorption coefficient for UNSW cell F0806-1, a laser grooved/PERC hybrid. (Measurements and data extraction courtesy of P.A. Basore, Sandia National Laboratories).

extrapolated intercept with the zero absorption length axis corresponds to an internal quantum efficiency, η_c , the collection efficiency for uniformly-generated light [11]. W_{IGE} is an effective photogeneration thickness, taking into account photon path angles, carrier collection losses and rear surface reflectance [10].

The effective number of optical passes, Z , is the ratio of the response of the ratio of this thickness, corrected for the effects noted, to the actual cell thickness [10]:

$$Z = \frac{W_{IGE}}{\eta_c W} \cdot \frac{1 - R_{sub}}{1 - \rho_{fe}} \quad (2.3)$$

where R_{sub} is the sub-bandgap reflection from the cell surface.

Hence, from measurement of the internal quantum efficiency and the cell reflectance versus wavelength, Z can be extracted. By the auxiliary equation [11]:

$$W_{IGE} = \frac{W \eta_c}{\cos \theta} \cdot \frac{1 + \rho_b}{1 - \rho_b} \quad (2.4)$$

where θ is the angle of passage of light across the cell, the rear surface reflectance can also be derived.

Table 2.5 shows the parameters extracted by this technique from several UNSW cells over this period. The technique appears capable of discriminating between different cell types. In particular, it gives high optical pathlength enhancement factors for cells in the 13-23 range for cells designed for light-trapping, a low Z factor for a planar laser grooved/PERL hybrid cell ($Z = 2$ as expected theoretically), and an intermediate Z factor ($Z \approx 5$) for cells with alloyed rear aluminum reflectors. Relatively high rear surface reflectivity is measured for cells with dielectrically

displaced reflectors (86-94%), with a high internal reflectance from the top silicon surface also measured for cells with inverted pyramids along the surface ($\rho_{fi} = 75-89\%$). All cells were measured to have diffusion lengths significantly greater than the cell thickness, with diffusion lengths in the 0.6-4.5 mm range measured. Perhaps the parameter showing least correlation with that expected from the cell design was the uniform generation rate collection efficiency, η_c , which lay in the 80-100% range for the cells shown. For example, it is difficult to see why a planar cell should have a value significantly higher than a cell with inverted pyramids along the top surface, but otherwise structurally similar.

Table 2.5: Data extracted from the extended spectral response technique for a variety of UNSW cells (data courtesy of P.A. Basore, Sandia National Laboratories, LG = laser grooved).

Cell	Description	W (micron)	Z	L_{eff} (mm)	ρ_b (%)	ρ_{fi} (%)	η_c (%)
Z255-1	PERL, textured	285	15	1.2	86	87	94
F0806-12	LG, textured, alloyed Al	400	5	0.6	47	85	80
FC-125	LG, textured, alloyed Al	390	5	0.7	50	75	85
PERL-IR	PERL, textured	280	23	3.4	94	89	90
F0806-1	LG/PERL hybrid, textured	400	13	4.5	86	85	91
F9093-5	LG/PERL hybrid, planar	440	2	-	91	19	100

The technique is expected to be very sensitive to the absolute accuracy of the cell's spectral response measurement and the value of the absorption coefficient used in analysis, particularly at the longer wavelengths (wavelengths out to 1.14 microns were used in the analysis). The latter would imply accurate knowledge of the

temperature at which the spectral response measurements were made. The technique also makes assumptions about the nature of the light-trapping scheme used in the cell to extract values of ρ_b and ρ_{fl} . It essentially assumes that all passes of light across the cell are of the same length and that these values are not angularly sensitive. Nonetheless, if applied consistently at the same laboratory, it would be expected to be able to identify important differences between different cell designs.

SECTION 3

3. LASER GROOVED CONCENTRATOR CELLS

3.1 Introduction

The laser grooved solar cell structure of Figure 3.1 offers the opportunity for high cell efficiency at low cost. Energy conversion efficiencies in the 17.5-18.0% range have been reported in pilot commercial production for large-area, one-sun cells [12,13].

Compared to cells fabricated by the standard screen printing process, the previous standard for one-sun cells, laser grooved cells have several advantages that make them of interest in concentrator applications. The cells have much lower resistance per unit finger length due to the use of high conductivity copper instead of fired silver paste, and the much larger cross sectional areas which are possible by locating the fingers in deep grooves. The cells also use plated nickel as the contact metal which gives much lower specific contact resistance than silver paste. The contact is also made to heavily diffused groove regions of large contact area which further accentuates the contact resistance advantage. Screen printed cells have therefore not proven suitable for use even at relatively low sunlight concentration levels, even when combined with prismatic covers which allow up to 50% of the top surface to be metallized [14].

The only alternative process which has proven capable of producing cells operating at concentration has been that based on space cell metallization technology as for the previous PERL cells [15]. This approach is unlikely to be consistent with obtaining low cell cost.

Figure 3.1: Laser grooved, buried contact solar cell.

Figure 3.2: Concentrator cell metallization design. Actual cells were half the length shown.

3.2 Prismatic Cover Cells

Large-area cells were fabricated to the design of Figure 3.2. (Due to limitations on the size of the starting wafer which could be handled at UNSW, actual cells were half the length shown). This is a standard design intended for subsequent application of prismatic covers developed by ENTECH [16]. The cells are designed for concentration levels of 20 suns.

Laser grooved cells were fabricated with the sequence of Table 3.1. Prior to the application of the covers, these gave efficiencies up to 21% under concentration. Application of covers at ENTECH further boosted performance by steering incoming light away from the cell metallization fingers. The results for the best cell after cover application are shown in Table 3.2, with peak efficiencies above 22% demonstrated. With further optimization, efficiency above 23% in the design concentration range appears feasible with this approach.

Cells of a similar contact design but of 19% efficiency resulted in nominally 17% module efficiency for the 300 kW system installed at Austin, Texas by ENTECH [16]. Replacing these cells by cells of the present performance may well result in 20% module efficiency.

3.3 Advanced Laser Processing

As noted in the previous section, good performance was obtained for laser grooved cells even without application of prismatic covers. Due to the advantages previously cited, this approach has far more potential for producing high efficiency, large-area concentrator cells than either screen printed technology previously discussed or "space cell" technology (relying on photo-lithographically defined metal lying across the top surface of the cell). Accordingly, concentrator cells were fabricated with a similar metallization

Table 3.1: Standard process sequence for large-area laser-grooved, buried contact solar cells.

<u>STEP</u>	<u>PARAMETER</u>
1. Wafer Selection	(100) Float-zone, 10-cm diameter
2. Saw Damage Removal	30% NaOH at 85-90°C
3. Texture Etch	2% NaOH at 90°C
4. Wafer Clean	Standard RCA clean
5. Top Phosphorus Diffusion	845°C for 10 minutes
6. Wet Oxidation	Masking oxide and AR coat
7. Laser Groove	Grooves up to 70 micron depth; 20 micron width
8. Groove Clean	NaOH; DI water
9. Groove Phosphorus Diffusion	950°C for 90 minutes
10. Rear Al Deposition	2-micron thickness
11. Al Alloying	950°C-1020°C in O ₂ during entry followed by N ₂
12. Top and Rear Metallization	Electroless Ni, Cu (and Ag)*
13. Wafer Scribe	Rear scribe 60-120 micron
* Optional	

Table 3.2: Efficiency of large-area laser-grooved concentrator cell as a function of concentration ratio for 0.5- Ω -cm float-zoned substrate. Cell responsivity is 0.401 A/W. (Direct AM1.5 spectrum, 25°C, measurements courtesy of Sandia National Laboratories).

Suns	V _{oc} (mV)	FF (%)	Effic. (%)
1	635	79.9	20.4
5.0	679	81.0	22.1
10.2	697	80.1	22.4
15.0	706	78.3	22.2
20.0	711	75.6	21.6
25.0	716	73.3	21.1
29.6	719	71.8	20.7
34.8	723	69.6	20.2

Table 3.3: Efficiency of a large-area concentrator cell (no prismatic cover) fabricated with advanced laser processing. Cell area is 20.0-cm² and responsivity is 0.398 A/W (Direct AM1.5 spectrum, 25°C, measurements courtesy of Sandia National Laboratories).

Suns	V _{oc} (mV)	FF (%)	Effic. (%)
1	644	81.3	20.9
5.1	686	81.7	22.3
10.2	703	80.9	22.6
20.0	719	77.7	22.2
44.0	737	73.9	21.6

pattern to that of Figure 3.2, but with sufficiently low metal coverage that prismatic covers were not required.

One concept investigated was a double groove approach of Figure 3.3(a). The aim in this case is to locate the metallization finger towards the base of the groove. Light reflected from the metallization finger therefore will have a second chance of striking the cell surface as shown, reducing the effective metallization coverage optical loss.

For the present cells, the metal was located within the groove by a second laser scribing of the cell surface closely aligned to that of the original groove. A slight misalignment is not disastrous since it still produces beneficial effects as shown in Figure 3.3(b). Although this approach requires an additional laser grooving step, no extra diffusions are required if the first groove is formed early in the processing sequence.

The other high performance feature incorporated into the present cells was the use of laser defined "macrogrooves" in the cell top surface [17-19] running perpendicularly to the cell fingers. As opposed to the photolithographically defined "microgrooves" used in PESC cells [1,2] which have typical widths of 10 microns, the laser defined "macrogrooves" have typical widths of 50-100 microns. Macrogrooves have all the advantages of microgrooves, as well as features which increase the collection probability at long wavelengths, particularly for low quality substrate material [17-19].

The best cell fabricated with these improvements (FC-125) demonstrated an efficiency of 20.9% at one sun, peaking at 22.6% efficiency at 10 suns and maintaining an efficiency above 22% at the design concentration level of 20 suns as shown in Table 3.3. Note that these results were obtained without application of prismatic

Figure 3.3: (a) Double groove approach to reducing effective metallization coverage. By locating metal in groove, reflected light can still be captured; (b) misalignment of second groove still gives substantial benefits.

cover and represent the highest efficiencies demonstrated for a concentrator cell of the present size (20-cm²).

Figure 3.4 shows the results of a laser beam induced current scan across the surface of the cell. The effective finger width deduced from this scan is 14 microns, roughly half that of the width of the actual grooves. The measured spacing of the fingers was 508 microns giving an effective shading loss in the cell due to the fingers of only 2.8%. This confirms the effectiveness of the double groove strategy of Figure 3.3.

3.4 Double Sided Grooving

Although not investigated in the present project, the double-sided laser grooved structure of Figure 3.5 offers further opportunities for performance improvement in the medium term. Effectively, it is an implementation of the PERL structure which does not require photolithographic processing. Similar performance to that demonstrated by prismatic covered PERL cells is expected with the present innovations which could have important implications for large-area, low concentration ratio cells.

Data for Sample: unsw fc-125
 Collected 12 SEP 90 at 9:29:00a
 632.8 nm laser, 10 μm spot size, 5.0 μm step size

Figure 3.4: Laser scan across the fingers of the high efficiency cell of Table 3.3. Effective finger width is smaller than groove width.

Figure 3.5: Double-sided laser grooved cell structure with the potential for very high performance at low cost.

SECTION 4

4. CONCLUSION

The target efficiency of 26-27% efficiency was attained for PERL cells during the present project, but only at concentration levels lower than the 150 suns concentration specified. Given the non-ideal nature of the prismatic covers applied to the cells during the project and the on-going evolution of this technology, the target specifications are feasible.

An examination of the optical properties of cells has shown much lower reflectance of sub-bandgap wavelength light than expected from theoretical modelling. A detailed examination of this effect has failed to identify the reason for the discrepancy, since specially fabricated test structures performed close to ideally.

A new technique developed by Paul Basore of Sandia based on the analysis of the reflectance and spectral response of experimental cells was shown capable of differentiating between different UNSW cell designs. In particular, PERL cells with "inverted pyramid" top surface structure showed an effective number of optical passes of about 20, laser grooved cells with textured top surfaces and alloyed aluminum rear surfaces showed factors of 5, and planar PERL cells values of 2.

Large-area laser grooved concentrator cells also demonstrated improved results during the present project. Using a standard approach in combination with a prismatic cover, efficiencies of 22.4% and 21.6% were demonstrated at 10 and 20 suns concentration respectively.

An alternative approach based on locating the contact metal at the base of grooves combined with "macrogrooved" top surface

structure demonstrated even better results. Efficiencies of 22.6% and 22.2% were demonstrated at the previous concentration levels without requiring prismatic covers. The effective metal finger coverage was less than 3% in these designs. Further work with a double sided laser grooved structure should push these large-area cell efficiencies even closer to those demonstrated by the smaller area PERL cells.

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