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Development of Manufacturing Capability for High-Concentration, High-Efficiency Silicon Solar Cells

R.A. Sinton, P.J. Verlinden, R.A. Crane, and R.M. Swanson

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ABSTRACT

This report presents a summary of the major results from a program to develop a manufacturable, high-efficiency silicon concentrator solar cell and a cost-effective manufacturing facility. The program was jointly funded by the Electric Power Research Institute, Sandia National Laboratories through the Concentrator Initiative, and SunPower Corporation. The key achievements of the program include the demonstration of 26%-efficient silicon concentrator solar cells with design-point (20 W/cm^2) efficiencies over 25%. High-performance front-surface passivations that were developed to achieve this result were verified to be absolutely stable against degradation by 475 days of field exposure at twice the design concentration. SunPower demonstrated pilot production of more than 1500 of these cells. This cell technology was also applied to pilot production to supply 7000 17.7-cm^2 one-sun cells (3500 yielded wafers) that demonstrated exceptional quality control. The average efficiency of 21.3% for these cells approaches the peak efficiency ever demonstrated for a single small laboratory cell within 2% (absolute). Extensive cost models were developed through this program and calibrated by the pilot-production project. The production levels achieved indicate that SunPower could produce 7-10 MW of concentrator cells per year in the current facility based upon the cell performance demonstrated during the program.

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Acknowledgments

We would like to acknowledge all of the people at SunPower that participated in the development of the processes and facilities, and that worked the long hours to fabricate the devices reported here. In addition to the SunPower team, we would like to thank people at Stanford University, Sandia National Laboratories, Cummings Engineering, and Daedalus Associates for their varied contributions.

This complexities of this joint EPRI/Sandia program required all of the skills of SunPower's administrative, financial, and accounting staff as well. We appreciate their efforts.

Finally, we would like to thank Frank Goodman at EPRI and James Gee at Sandia National Laboratories for their technical and administrative expertise.

Summary

This report covers a cooperative program in high-efficiency solar cell research and development at SunPower Corporation of Sunnyvale, California. This project was simultaneously supported by the Electric Power Research Institute, of Palo Alto, California and the Department of Energy through Sandia National Laboratories in Albuquerque, New Mexico. In addition, SunPower Corporation provided cost sharing. Through close cooperation, the institutions funded complementary areas in the research and development of high-efficiency solar cell design, fabrication, and manufacture.

Early in the project, SunPower focused on developing highly manufacturable, high-efficiency cells. The process schedules, originally from work at Stanford University, were completely revised in order to convert to cost-effective batch processes. One of the primary achievements was to eliminate the use of pyrophoric gases in the process. This major modification allowed the cells to be made in a much simpler facility due to the elimination of the inherent danger of self-igniting gases.

This process was installed in SunPower's fabrication facility. This facility was designed specifically for the manufacture of cost-effective, high-efficiency solar cells. The work in converting the process to simpler technology prior to installing it at SunPower allowed for very informed, specific equipment purchases. This pilot production facility was targeted to take full advantage of the similarities of the solar cell fabrication to integrated circuit-fabrication, while avoiding equipment specialized for VLSI technology considerations that were not required.

A full testing and characterization capability was developed at SunPower. An indoor facility included all of the standard test equipment for integrated-circuit quality control. Additionally, equipment was custom designed, fabricated, and installed that allowed the measurement of solar cell efficiency at concentrations from one-sun to 1000 suns. A computerized photoconductivity-decay diagnostics system was used for research on the cell process development and quality-control diagnostics for the processes once installed.

An outdoor testing facility was installed with a large tracker, suitable for simultaneously supporting several characterization and reliability studies. An EPRI 48-cell Fresnel module was installed and used continuously over the course of the program to field test the solar cells in order to optimize the designs for reliability and stability against degradation.

By December 1992, SunPower had developed concentrator cells with efficiencies over 26% at 90 suns. Some of these cells were tested in the outdoor module at

two times the design-point concentration and found to be entirely stable against degradation after 475 days of exposure. This verified the successful development of a high-performance stable passivation, a major goal of this program. A detailed study of four mature cell designs and four high-performance passivations was done. This study encompassed multiple cell fabrication runs and high-concentration testing at four laboratories. Of over 1500 cells fabricated, nearly 100 cells were involved in this extended characterization. Over 300 of these high-performance cells were delivered to EPRI for qualification during the Spring of 1993.

A commercial opportunity arose in 1993 allowing the direct, practical application of the processes developed for this project. Over 7000 17.7-cm^2 one-sun cells were fabricated for Honda R&D Co. for use in their solar race car, the "Dream". The average efficiency of the delivered cells was 21.3%, within 2% (absolute) of the best single silicon laboratory-demonstration cell of any size. Some of these cells were subsequently applied in an 862 cm^2 one-sun module that set a new world-record efficiency of 21.7%. The car won the 3013-km World Solar Challenge race across Australia.

To accomplish this task, SunPower applied the original baseline process developed for this program, modified for the special demands of this particular application. It is more difficult in most respects to fabricate one-sun cells with a tight distribution approaching the theoretical limit than it is to fabricate concentrator cells. This successful project demonstrated exceptional process optimization and quality control.

The project produced over 3500 yielded wafers. An extrapolation of the production rate achieved indicates that the SunPower Cell Pilot Line fabrication facility could produce 7-10 MW per year of concentrator cells of the type and performance demonstrated in this report. A detailed cost model has been developed and refined during the course of the contract and calibrated with real data at moderate production levels during the pilot-production projects.

1. Cell Pilot Line

1.1 General Description of SunPower Cell Pilot Line

SunPower has a Cell Pilot Line optimized for the production of high-efficiency concentrator solar cells. This Cell Pilot Line is a 4000-ft^2 facility with 1700-ft^2 of Class-100 clean-room area.

At the initiation of this contract, SunPower was searching for such a facility. The goal of the contracted work, as well as a central and necessary goal of SunPower was to develop a cost-effective source of high-efficiency solar cells. The solar cells that had been demonstrated at Stanford University were fabricated in an integrated-circuit facility. These cells were much more similar to an integrated circuit than to a conventional flat-plate one-sun solar cell. However, it is not sufficient for the long-term goal of producing competitive solar power to have a proof-of-concept, high-efficiency cell fabricated in an integrated-circuit line. The solar cell has to be fabricated at a much lower cost per unit area than a typical integrated circuit.

There are many important differences between these solar cells and integrated circuits. In many ways, the solar cell is more demanding of the facility than an integrated circuit. Most notably, the solar cell demands extremely pure chemicals, gases, and wafer handling in order to maintain the long minority-carrier lifetime in the finished devices after the high-temperature processing. Just as important are those aspects of state-of-the-art integrated-circuit fabrication that are not required for solar cells. Some of these are extremely fine dimensions, low particle counts and defect densities, and precision dopant quantities for threshold control.

The challenge in developing a cost-effective solar cell fabrication facility is to choose appropriate technology. It is important to take full advantage of the manufacturing, materials experience, and the vendor-service availability of the integrated-circuit industry. It is also important to use the least costly machines and processes that will meet the requirements of solar cell manufacture.

SunPower found a small, abandoned fabrication facility, filled it with equipment selected specifically for its suitability for solar cell manufacture, and rebuilt and customized this equipment as necessary. A floor plan layout of this facility is shown in Figure 1.1.

A baseline process was established on this equipment and subsequently evolved over the course of this work. The result is a facility and a process that is small and simple, but very complete. It has all of the necessary equipment to fabricate solar cells and a wide range of silicon devices from the silicon chip through to a packaged part. As such, it provided the opportunity to fully optimize a solar cell fabrication line vertically for the lowest possible cost. It is significant that this small lab, essentially with one of each necessary piece of equipment, would be capable when fully utilized of producing the solar cells for several megawatts of power per year (See Section 7, Pilot Production).

SunPower leased the space on April 1, 1991. Equipment had previously been purchased, as available at a good price. The facility needed several upgrades. This included the installation of a new exhaust system for the wet benches, modification of the existing air ducting, and rebuilding of the PVDF de-ionized water distribution system. Further projects included modification of the high-purity gas system to accept new process gases, and the creation of a new gowning area. Walls were moved and doors were installed as required.

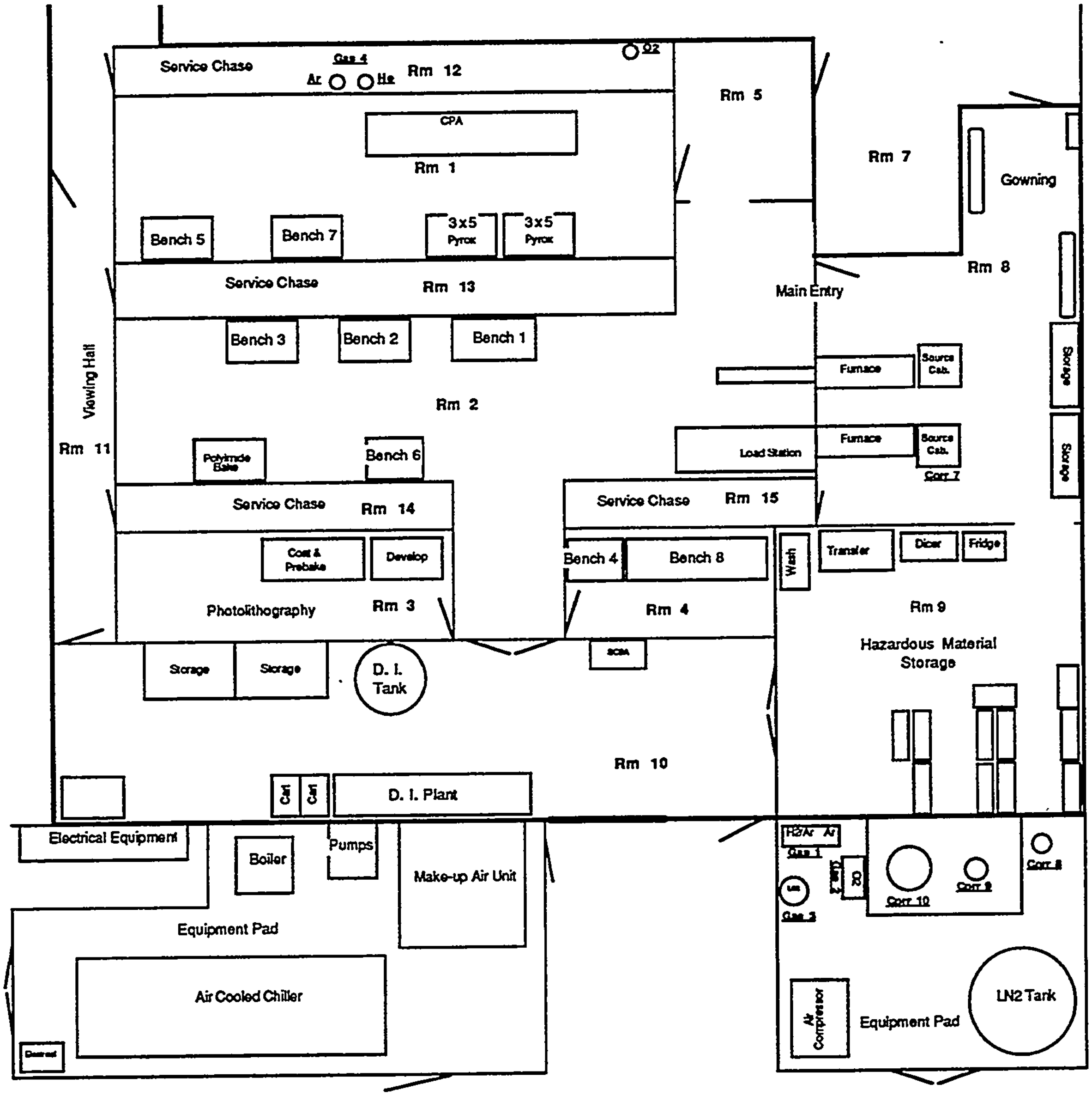


Figure 1.1. Floor plan for the Cell Pilot Line.

Following the facility improvements, all of the equipment was installed. Physically, this was largely completed by September 1991. Operationally, it continued to evolve through June of 1992, with another phase of upgrades for the pilot production project accomplished in 1993.

A significant fraction of the effort to bring up the facility was involved in obtaining the various permits. Figure 1.2 shows the basic structure of the tasks involved in coordinating various vendors, projects and consultants in order to obtain the occupancy permit that allows the use of this space as a fabrication facility. This was done during the course of the 9 months following obtaining the lease on April 1, 1991. The actual work in bringing up the facility was just the tip of the iceberg, with the permitting process contributing an incredible time sink and unpredictability to the planning and time-lines. Useful byproducts of the permitting process were that very detailed documentation of chemical usage, storage, disposal and facilities details were constructed. This provided the base of information later used in planning and costing the process, as well as designing for the least toxic chemicals and processes.

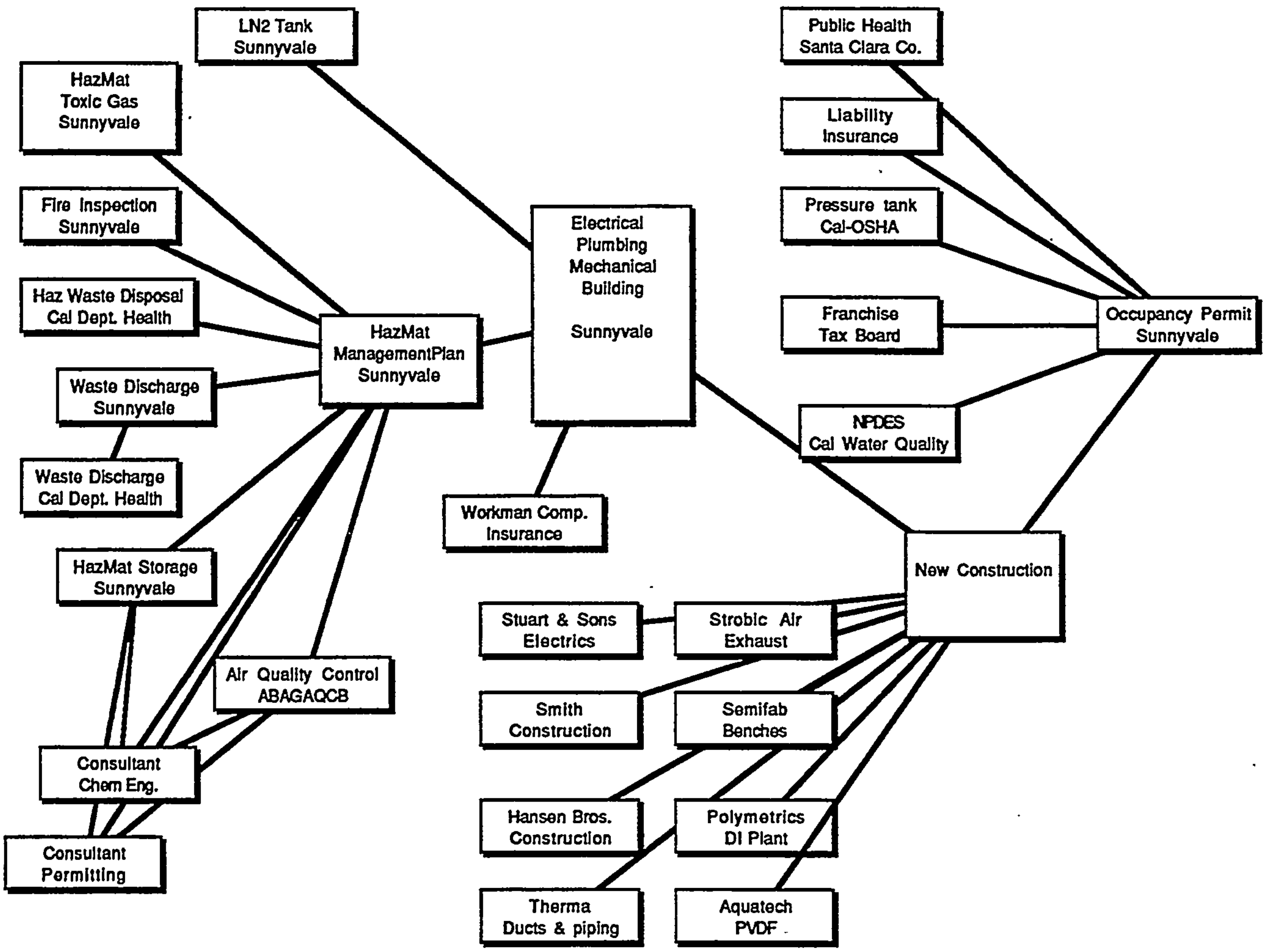


Figure 1.2. A flow chart indicating the coordination necessary to bring the Cell Pilot Line into operational status.

1.2 Significant Dates in the Facility and Process Qualification

It is interesting to look back at a very busy period of time and see when the equipment and processes actually came on-line at SunPower.

Deionized water	September, 1991
All permits in	October, 1991
Photolithography	October, 1991
Ni-Au plating	November, 1991
Resist Strip	November, 1991
Polyimide	November, 1991
Wafer thinning	December, 1991
Wafer texture	December, 1991
BOE etch	December, 1991
Saw	January, 1992
Sputtering	January, 1992
Diffusion/oxidation	April, 1992
AR coat	April, 1992
Mature Passivation	September, 1992

2. Testing Capability

2.1 General Description of Test Facilities

SunPower installed the capability to be largely self-sufficient in evaluating solar cells for performance and degradation. Measurement techniques for obtaining the photoconductivity-decay lifetime and emitter saturation current density, sublinearity of the current density vs. concentration, short-circuit current vs. open-circuit voltage, open-circuit voltage decay, and sheet resistance were established in an indoor test facility. With the exception of the sheet resistance, these measurements have been automated using data acquisition directly into a computer for analysis.

An outdoor tracker continuously tracking the sun was also installed by Dave Gorman of Advanced Thermal Systems, Inc. of Englewood, Colorado. This tracker is used for systems evaluation, and also for on-sun characterization of cells at one-sun and under concentrated sunlight. Measurements under concentration are done using an EPRI Mod-1 module. This module is also used for long-term qualification of the cells, including the stability under concentrated sunlight. The outdoor tracker also functions to evaluate one-sun responsivities for SunPower cells by comparison with a Sandia National Laboratories calibrated reference cell. An automated data acquisition I-V curve tracer and load was purchased from Endecon of San Ramon, California in order to perform steady-state measurements of SunPower cells, modules, and systems. A photograph of the EPRI module on the SunPower tracker is shown in Figure 2.1.

Figure 2.1. A photograph of the EPRI module on the outdoor tracker.

Most of the test equipment and techniques used are rather standard and similar to those that were used at Stanford[1,2] as well as elsewhere. Exceptions are the indoor tests for fill-factor and series resistance, and the sublinearity measurement. The major difference was the added requirement of the ability to screen large numbers of devices. Not only was detailed information on a few devices needed in order to evaluate the cell design and process, but the ability to do quality control, statistics, and qualification of batches of cells was also required.

Towards this end, SunPower designed and fabricated an automated data acquisition system that determines the fill-factor, open-circuit voltage vs. short-circuit current, maximum power voltage, and series resistance of a solar cell without a heat sink at any concentration of light up to 1000-2000 suns. In its current configuration, the cell is placed into a mount, four flashes of a strobe are used, then the data is converted by the computer into the fill-factor and voltages at current densities representative of 100 and 200 suns. The series resistance is also calculated. A block diagram of the actual test apparatus is shown in Figure 2.2.

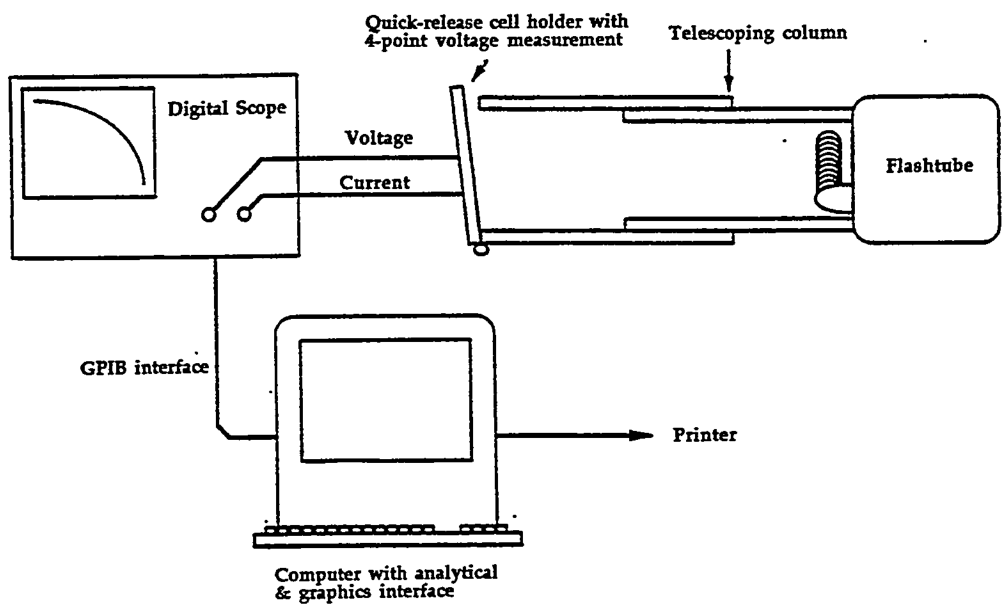


Figure 2.2. The indoor cell test apparatus. The solder-mounted cell is inserted into a holder that incorporates four-point voltage probing. The flashlamp built into the housing is then used as the light source for intensities up to 2000 suns.

An additional flash is then used to determine the sublinearity of current with respect to the incident power density for the solar cell at all concentrations.

An example of these measurements is shown for a cell from the archives, labeled H-157. This cell was fabricated at Stanford in 1989, and had a detailed characterization in the outdoor test facility at Stanford at that time[1]. As such, the abbreviated indoor test sequence can be directly compared to outdoor test data. In this case, the outdoor test facility was a heliostat combined with a long focal length mirror that gave a very uniform beam over the width of the solar cell. The comparison is shown in Figure 2.3 and Table 2.1.

First, notice the tight distribution of the indoor test measurements. For example, in five measurements, the difference between the highest and lowest result for the fill factor at 8 amperes is less than 2%. The standard deviation over 5 measurements is 0.7%. Similarly, the scatter in the results for open-circuit and maximum power voltages are comparable or less than those typical from steady-state outdoor test measurements.

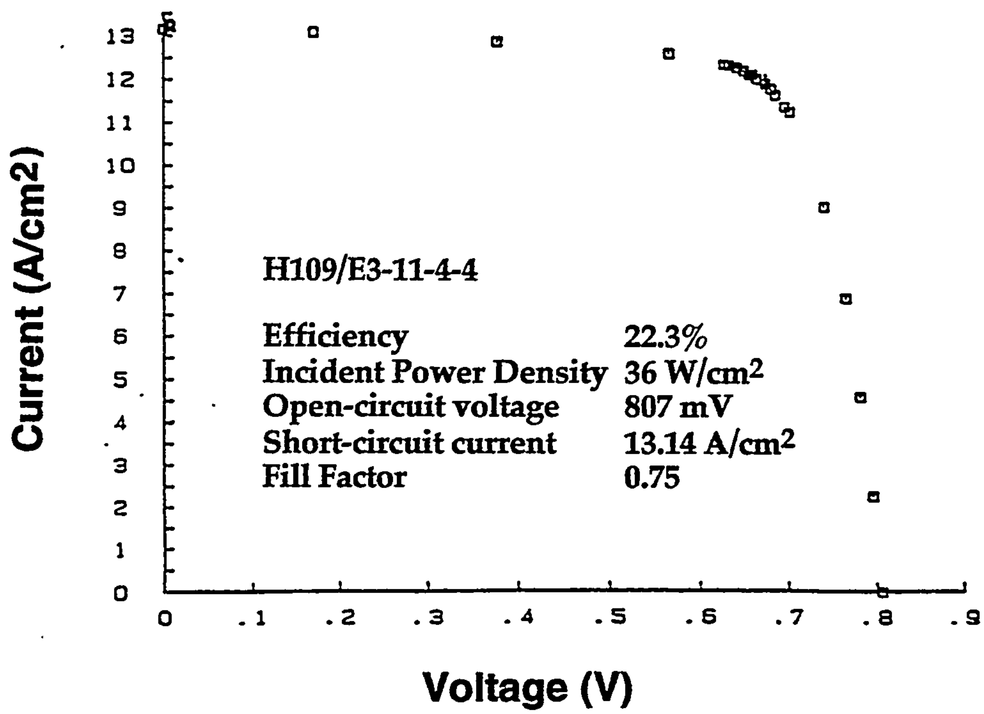


Figure 2.3. A measurement taken outdoors at Stanford University using a long focal length parabolic mirror to achieve the concentration.

EPRI III Cell H-157

Indoor Test Results

8 Amperes Short-Circuit Current			4.4 Amperes Short-Circuit Current		
Fill Factor %	Open-Circuit Voltage (mV)	Maximum Power Voltage (mV)	Fill Factor %	Open-Circuit Voltage (mV)	Maximum Power Voltage (mV)
76.4	811	662	79.1	791	678
76.4	812	675	79.3	792	675
75.7	812	666	79.3	792	667
77.1	811	671	79.6	797	674
76.3	812	676	78.8	798	664
76.4±0.5	811±0.5	670±6	79.2±0.3	794±3	672±5

Outdoor Test Results

8.2 Amperes Short-Circuit Current			3.5 Amperes Short-Circuit Current		
Fill Factor %	Open-Circuit Voltage (mV)	Maximum Power Voltage (mV)	Fill Factor %	Open-Circuit Voltage (mV)	Maximum Power Voltage (mV)
76.6	811	669	79.3	789	678

Table 2.1. Indoor (top) and outdoor test results.

Because the indoor and outdoor test results shown here are at slightly different concentrations, the most comparable figures are the fill factors at the high and low concentrations. These are in absolute agreement, well within the uncertainty of either measurement.

2.2 Standard Test Procedure

The procedure for testing SunPower concentrator solar cells involved separating them from the wafer with the wafer saw, soldering them onto electrodes, and then doing the following tests.

Indoor

1) Series resistance, fill factor, and voltages at incident intensities corresponding to 100 and 200 suns.

2) Sublinearity vs. concentration. The ratio of short-circuit current to incident power is often used to indicate the incident power density during concentrator cell measurements, since the current is easily measured. However, for backside contact cells, this ratio is generally lower at high concentration than at one

sun making the current "sublinear" with concentration. The short-circuit current may be sublinear or superlinear with concentration for other cell designs. For accurate measurements of concentrator cells, the assumption that the current is proportional to the concentration can lead to measurement errors.

Outdoor

1) One-sun responsivity relative to a Sandia-calibrated standard cell.

These three measurements allowed the calculation of the efficiency at 100 and 200 suns.

Next, select cells were x-rayed, I-V curves were constructed (if required), and open-circuit voltage decays were measured. Some cells were mounted into the EPRI module for on-sun steady-state measurements and qualification studies. These on-sun studies included stability.

These tests were complemented by the measurements available from Sandia National Laboratories. Typically, these include full one-sun measurements, and IV curves at current densities representing 100 suns. Select cells then are measured for full efficiency vs. concentration including sublinearity, spectral response, internal quantum efficiency, reflection vs. wavelength, soldering studies, and UV degradation studies.

Beginning with Run 17 in September of 1991, the first "baseline" process was established. This run was characterized in detail at Sandia National Laboratories. The efficiency was 22% at 100 suns dropping to 21.4% at 200 suns. The current density at one-sun for this cell was 38.64 mA/cm^2 with an open-circuit voltage of 773 mV at 100 suns and 789 mV at 200 suns. The sublinearity measured at SunPower was 95% at 100 suns and 90% at 200 suns.

This Run 17 was also coincident with the establishment of the baseline testing regimen. Forty cells were measured at SunPower, then sent to Sandia. The agreement between the measurements at the two laboratories was quite good. Ratios of the key parameters illustrate these results. The SunPower measurements divided by the Sandia measurements for each parameter show:

1) V_{oc}	0.9992	
2) FF	1.0076	
3) J_{sc}, 1-sun	1.033	
4) Sublinearity	1.01	(100 suns)
5) Sublinearity	0.993	(200 suns)

In order to maintain good agreement in one-sun outdoor responsivity, reference cells were periodically exchanged between SunPower and Sandia National Laboratories.

3. Cell Design

3.1 SunPower First-Generation Cell Design

The first task in this project was to design a new cell for use in Fresnel-lens modules. A consensus in the EPRI program was that a larger area cell was desirable. This would have several effects upon the performance. First, using a larger cell with the same lens would lower the sunlight concentration at the cell. This lower concentration would be more near the concentration where the cell has its peak efficiency, 100-200 suns. Second, a larger active area would reduce the cell temperature since the same heat (for a fixed lens size) would pass through a larger area at the alumina voltage isolator. The observed temperature drop across this voltage isolator, (about 10 °C) could potentially be reduced to 2 - 3 °C. This would also require a different electrode pattern in order to allow a more ideal heat spreading at the copper electrode level prior to the alumina. Another consideration was to minimize perimeter loss, which occurs when the sawcut edges are too near the active area. Last, it was important to minimize the die area for any given cell to reduce the cost by allowing the maximum number of cells from each wafer.

In choosing a process design and technology, several other issues came into play. For example, although thin solar cells are more efficient, thick wafers are easier to process and promise higher yield. A summary of modeled effects of various optimizations upon the cell performance is shown in Table 3.1. Physical dimensions for the particular cells modeled are shown in Figure 3.1.

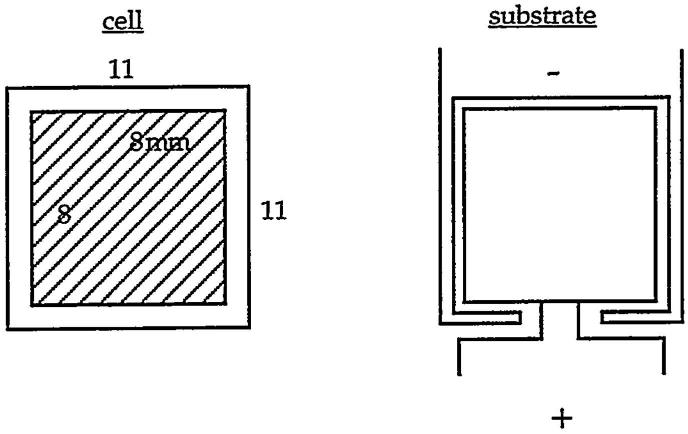
Table 3.1. Efficiency (relative) and cost implications of design changes

	Better Heat Dissipation	Perimeter loss	Lower Concentration		AR coating	High-Performance Passivation		Cost
Baseline EPRI 8mm active area 11 mm die size	Baseline	Baseline	Base-line	6.9 % loss	3.0 %	6.0 %	4.0 %	Baseline
10mm on 11 mm	1.2-2.0 %	1 to 2 % loss	1.6 %	3.6 % loss	3.0 %	6.0 %	4.0 %	Baseline
11mm on 12 mm	1.6-2 %	3.0 % loss	1.2 %	1.6 % loss	3.0 %	5.0 %	5.0 %	20 % higher
12.5 mm on 14 mm	1.9-2 %	1.4 % loss	1.6 %	1.2 % loss	3.0 %	6.0 %	5.0 %	62 % higher
			90 μm	130μm		90 μm	130μ	

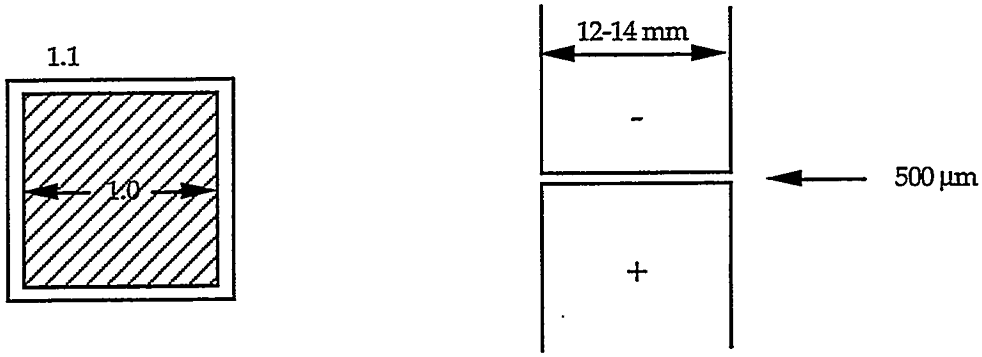
Baseline case:

8 mm active area on 11 mm die
23% efficient at 25 C
360 suns nominal operating point

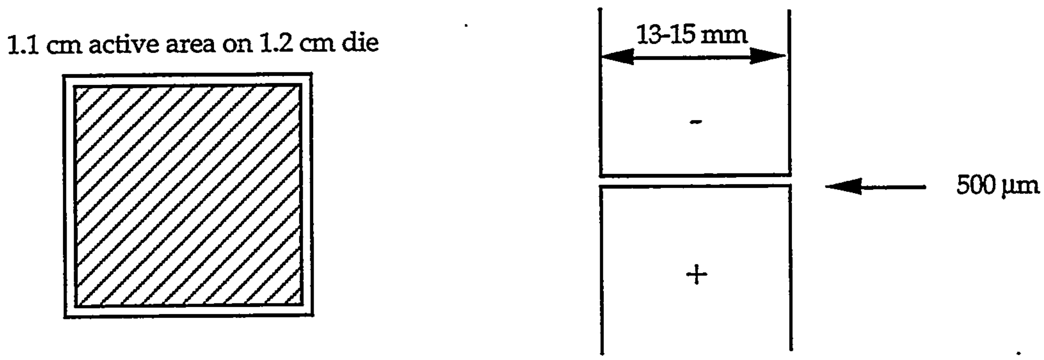
1) 1989 Stanford/EPRI 500 X cell (1.1 cm die)



2) A proposed 320 X cell (1.1 cm die)



3) A proposed 260 X cell (1.2 cm die)



4) Same as (3), 1.25-cm active area on 1.4 cm die (205 X)

Figure 3.1. The cell and substrate design for the 1989 Stanford stable module-ready cells and three designs considered for first-generation SunPower cells.

The primary boundary condition on this optimization was the 7-inch lens size. This fixed the cell current independent of the size of the cell chosen. This choice of size allowed the cell to be compatible with both the EPRI modules, the Sandia Baseline III module, and other modules based upon these designs such as that from Solar Kinetics, Inc. of Dallas, Texas.

The first line in Table 3.1 shows the expected effects of several design and process changes upon the existing cells that had been fabricated at Stanford and demonstrated in outdoor tests in EPRI modules[1,5] and Sandia National Laboratories Concept 90 modules[4]. The Sandia Concept 90 module in particular had demonstrated a very high efficiency of 20.5% for a cell temperature of 25 C and 18.5% under operating temperatures. This was a 0.64 cm^2 cell on a 1.21 cm^2 die. The efficiency vs. concentration for this cell as measured in 1990 is shown in Figure 3.2.

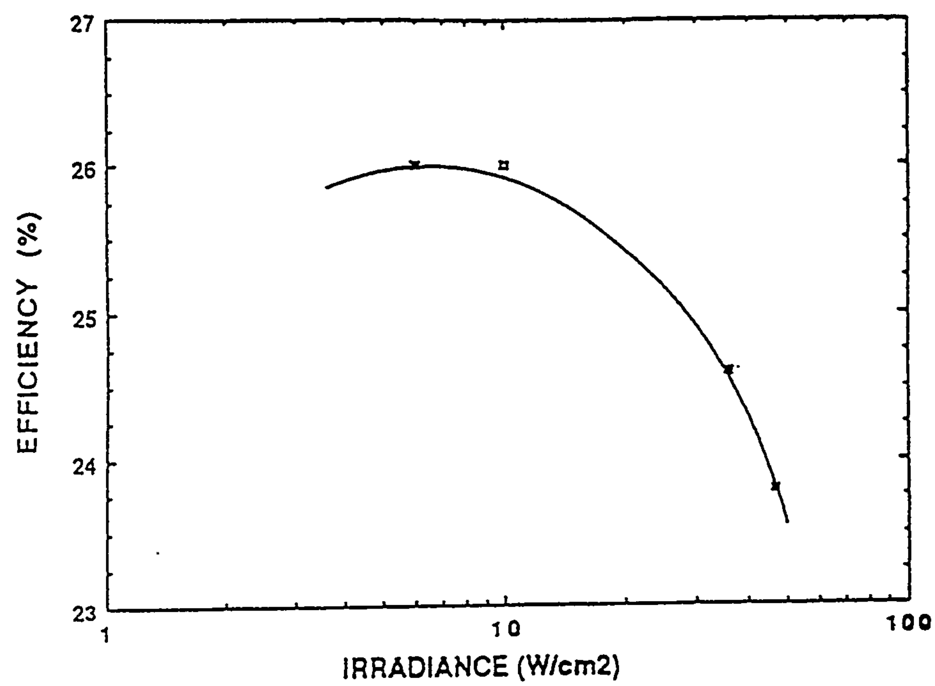


Figure 3.2. The efficiency vs. incident power density for cells of the type used in the EPRI module and the Sandia Concept-90 module. These were the 0.64 cm^2 cells shown in Figure 3.1.

The optimization was for an operating condition of the EPRI module. Some results from such a module are shown in Figure 3.3. The module was roughly 18.5% efficient, based upon the lens areas and corrected to 25 C. This module was

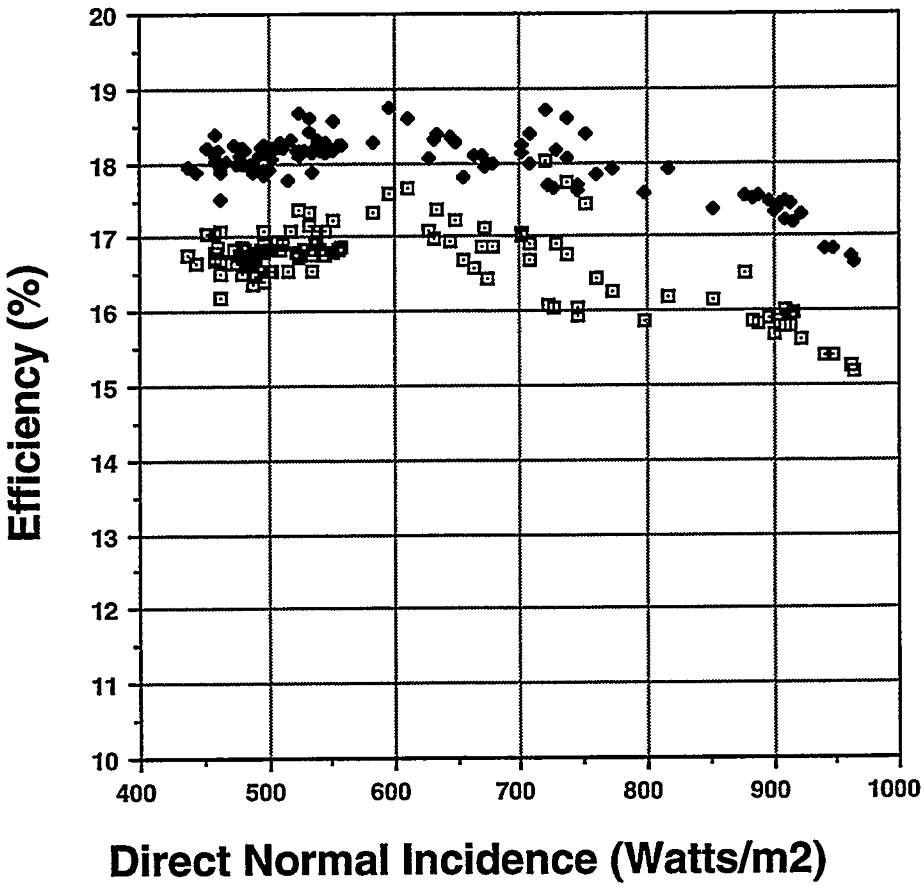


Figure 3.3. Results for an EPRI Mod-1 module. The upper data-set is corrected to 25 C. The lower data-set is at actual temperature. These efficiencies are based upon the total lens area.

very nearly ideal, in the sense that measurement of the individual cells in the string showed that currents were matched within better than 2% and the power from each of twelve strings of four cells was matched to within 5% (best to worst)[5]. A plot of the efficiency distribution for devices used in this module is shown in Figure 3.4. These efficiencies are shown for the design concentration, with 360 suns incident upon the cell.

Expected changes from the use of this cell in the EPRI Mod-1 module are shown in the Table 3.1. The first line shows the deviation from the performance of the 1989 Stanford cell that would be expected from changes in several parameters. If the cell were thicker, 130 micrometers rather than 90, the efficiency would drop by 6.8% (relative). An anti-reflection coating would give an expected improvement of about 3%. Stability improvements, based upon obtaining ideal front diffusions as investigated in[2], could be expected to improve the performance 6% for the thin cell and 4% for a thicker cell.

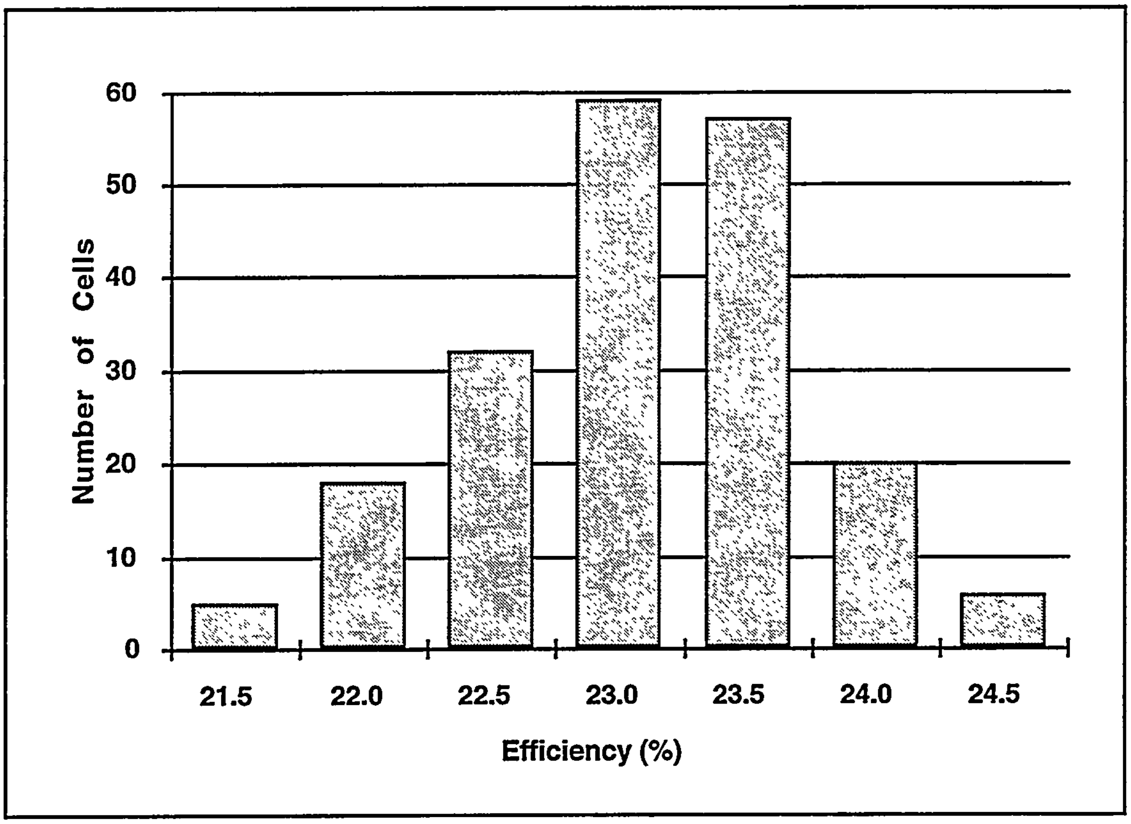


Figure 3.4. The efficiency distribution for cells from two fabrication runs used in the module of Figure 3.3. Lower efficiency cells than shown here brought the yield of good cells to 70% from those wafers that finished the process.

The second line in Table 3.1 indicates the results for a design that used the same die size, holding the cost constant, but had a larger active area (1.0 cm^2) within the die. The first effect is that the cell would run cooler, since the heat will pass through a larger area of alumina voltage isolator. This gives an estimated 1-2% efficiency improvement. Some of this improvement is lost in perimeter recombination, the loss of current due to having the sawcut die edges near the active area. The lower concentration improves the cell efficiency by 1.6% if the cell is thin. The thicker cell, however, would still lose 3.6% in efficiency even at the lower concentration. Note that the efficiency improvements in going to larger cells in order to lower the concentration are not as large as might be expected from looking at the efficiency curve in Figure 3.2. This is because the measured efficiency in Figure 3.2 is not at constant current. The lower concentrations had less current, leading to less series resistance losses. This improvement would only be possible if the lens size were reduced in order to reach lower concentrations rather than just making larger cells. Note that the metalization series resistance of a cell, in ohms, is constant independent of the size of the cell for a fixed metalization design. So for a fixed lens size, the metalization series resistance is fixed independent of the chosen cell size.

The third row in Table 3.1 shows a third option, a slightly larger die size with a larger active area as well. This was an 11-mm active area on a 12-mm die. The advantage of larger cells is that the area utilization of the die is better, and the concentration is lower. But the cost of the die is roughly proportional to the area so the cost is of course higher.

The last option is a much larger cell. A 12.5-mm cell on a 14-mm die was proposed by Dick Cummings of Cummings Engineering, in order to operate at the optimum cell concentration as shown in Figure 3.2, and also give bigger tolerances for cell and module alignments and tracking accuracy. This cost of this cell would be 62% more expensive than the baseline case based upon the die area alone.

Other important effects were not quantified here. One of these is the effect of non-uniform light distribution on the die. This impacts the series resistance losses, heating losses, and front surface recombination losses. These effects generally favor the use of lower concentrations. The goal of designing for high yield is yet another factor that is difficult to anticipate. Yield could depend upon die size, as well as design rules and process complexity.

The design on the 12-mm die was chosen based upon this analysis. This cell costs only slightly more than the baseline case, but because of the lower operating concentration it is more tolerant of thicker substrates, hence promises benefits in manufacturability that could easily offset the increased cost of the larger die area.

The microscopic cell design of the diffusion geometries similar to that used at Stanford for the previous EPRI cells[1,3,6] was chosen as a starting point for SunPower's first generation cell designs. A cross section of this cell design is shown in Figure 3.5. A primary goal of SunPower was to achieve a low-cost, highly manufacturable, yet high-efficiency cell design. The design in Figure 3.5 has major advantages towards these goals. Importantly, it has the potential to be fabricated in an entirely self-aligned manner, reducing or eliminating the expensive photolithographic steps[6]. In the shorter term, when photolithographic masks are used, some of the same features have the effect of improving the yield. This can be described relative to Figure 3.5. The metalization that contacts the n^+ diffusion only runs over n^+ diffusion area. Similarly for the p^+ metalization. Hence the danger of shorts between layers is essentially eliminated. Pinhole defects in the layer between the silicon and the metalization have little or no effect upon the cell performance. Also, the definition of the metalization at the step in the silicon improves the yield since this Al is the thinnest here, and is generally cracked across this step .

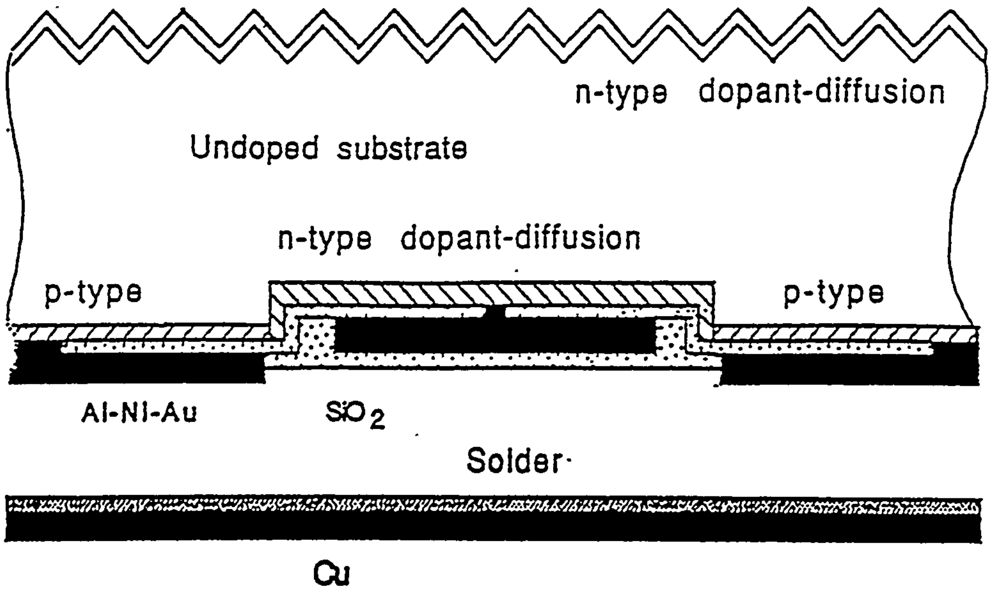


Figure 3.5. A cross-section indicating the 1989 Stanford/EPRI 0.64 cm^2 cell design, the first in Figure 3.1.

An additional advantage of this design is that the cell performance is tolerant of very large features. The metalization lines can be quite wide before efficiency drops due to current crowding effects within the silicon[6] would become evident. This was an important consideration potentially impacting the manufacturing yield, cost, and performance. Large features allow the use of larger tolerances, for example in the photolithographic alignment and the wet-etch processing. This in turn allows the use of less expensive equipment, and promises very robust process sequences. Also, widely spaced diffusions allow wider Al busbars. This decreases the amount of via space between busbars, increasing the cell backside reflectivity and lowering the series resistance of the cell. These coarse patterns also relaxed the dimensional requirements for our planned use of polyimide dielectrics to replace the deposited silicon dioxide layers in the cell as described in Section 4, Process Development. A diffusion spacing was chosen that gave a modeled efficiency loss due to increased current crowding within the silicon of 0.5% in absolute efficiency, relative to the cells previously fabricated at Stanford. On the first mask sets, cells with larger diffusion spacings were laid out in order to confirm the modeled results for this important trend, essentially manufacturing tolerance vs. efficiency.

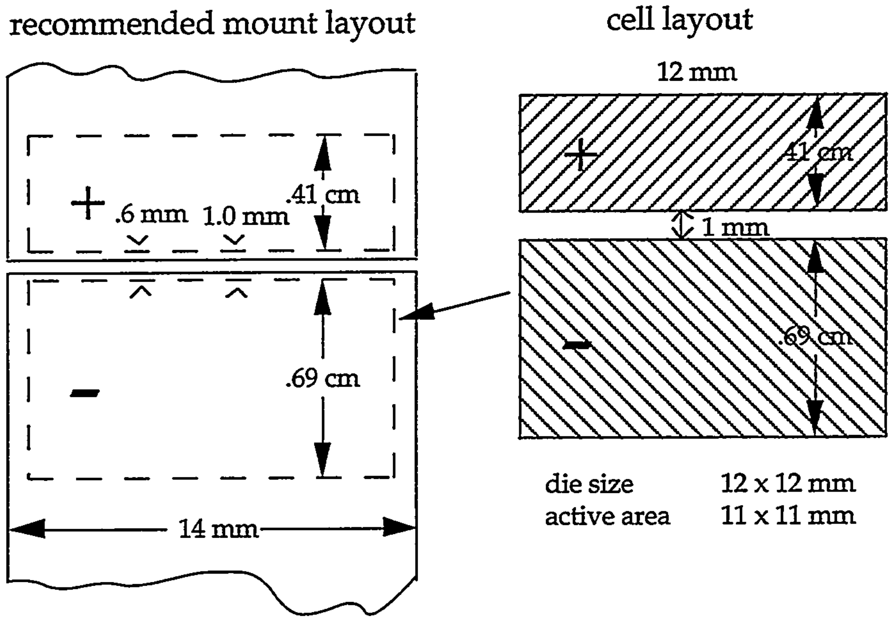


Figure 3.6. The SunPower first-generation mount design. The key elements in this design were the simplicity for high yield and good heat spreading.

The electrode pattern is shown in Figure 3.7. This pattern was designed especially for simplicity of soldering. There are only two pads, with a minimal border susceptible to shorting. This was to insure that the yield be even better than on the previous design. With this single separation between pads, the unsoldered area under the cell is minimized, optimizing the heat transfer. Also, compared to the previous design, the heat spreading in the copper electrode is not impeded by the isolation.

A plot of cell efficiencies vs. cell design and major laboratory activities at SunPower is shown in Figure 3.7. The first generation SunPower cell design was used during the development phases to change the entire process to different dopant and metalization dielectric technologies. Subsequently, it remained the baseline while the processes were transferred into the Cell Pilot Line at SunPower. These activities spanned all of 1991 into the first half of 1992.

As the processes became more optimized, the efficiency improved. By April of 1992, the peak efficiency was 23%, with an efficiency for concentrations that would result from the EPRI lens of 21%.

3.2 Second-Generation SunPower Cell Design

With the processes approaching maturity, the design of a second generation SunPower cell design was started. The first generation design was not yet

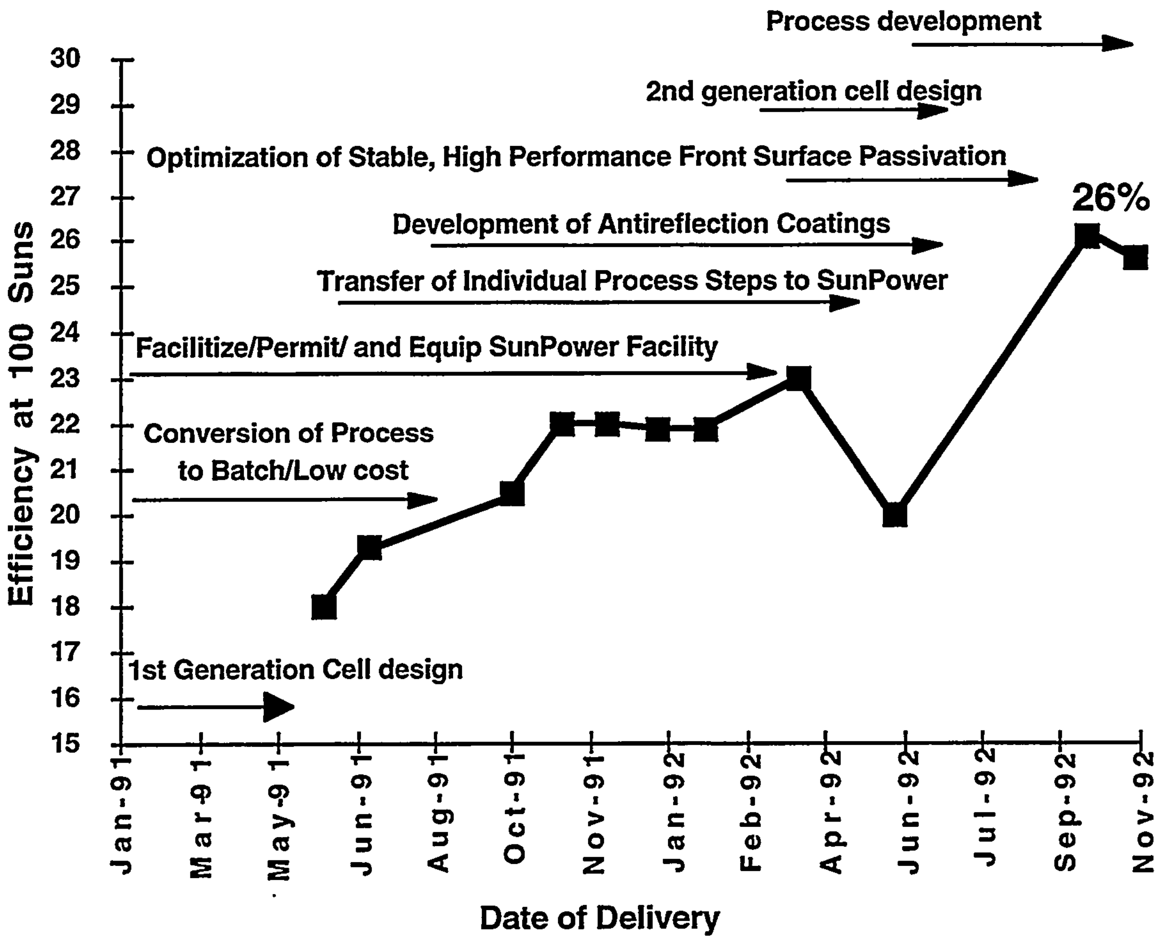


Figure 3.7. A time line of major activities at SunPower superimposed upon a plot of efficiency achieved vs. date.

optimized up to the performance levels of the previous simplified cells demonstrated earlier with the doped oxide processes, even accounting for the 0.5 absolute percent lower efficiency expected for courser feature size.

Although major performance improvements were expected to result when the antireflection coatings and the high-performance passivations became available over the next few months, these simple designs were not expected to exceed 25% in efficiency.

A pie chart indicating the current state (in Spring 1992) of the cell efficiency at the EPRI concentration is shown in Figure 3.8. An improvement of 2% (absolute) was expected with improved passivations, and another 1% with antireflection coatings. Some additional improvement was anticipated from an improved electrode layout that would lower the metalization resistance. The net efficiency would be in the 24-25% range.

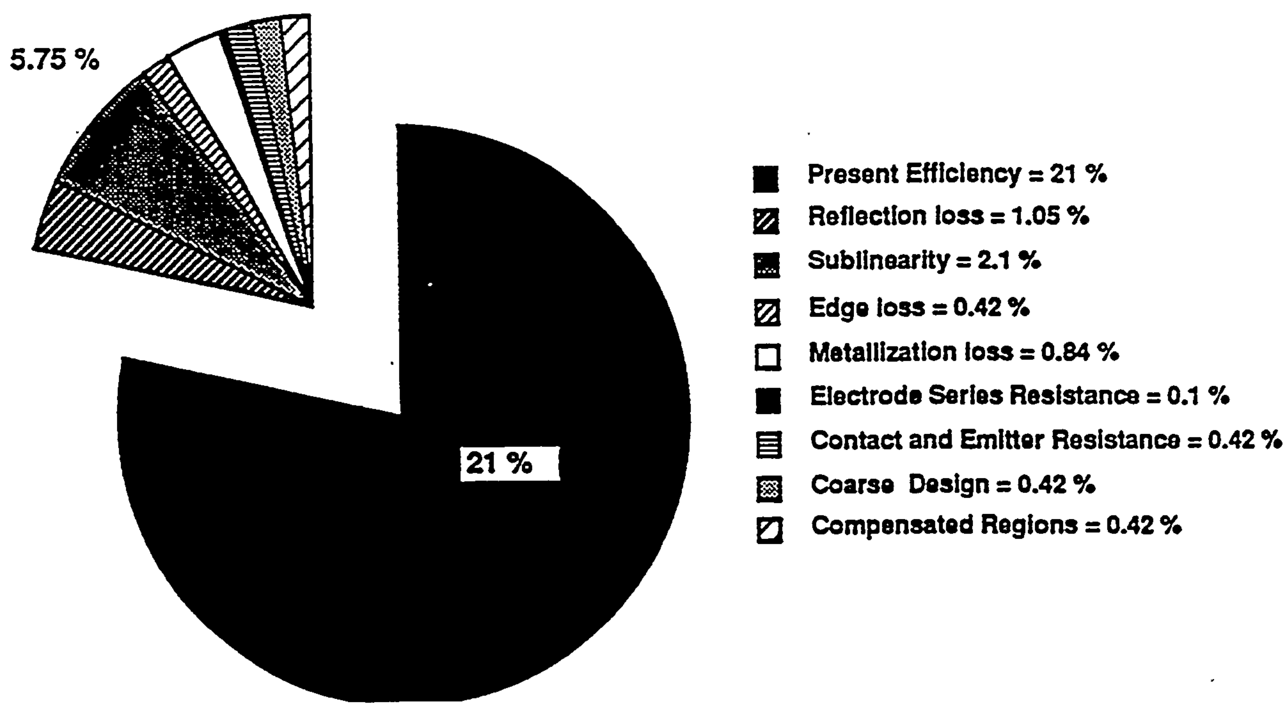


Figure 3.8. A graphic display indicating the efficiency at 200 suns for the first generation cells fabricated in April, 1992, and the various possibilities for improvement based upon modeling and measurements.

Having achieved the major goals of process development and transfer with the simple design, it was decided to switch strategies and approach the optimum cost and performance design from the high-efficiency side rather than from the low-cost side. The EPRI procurements were heavily performance driven, with a requirement for 26%-efficient cells at the design concentration of about 200 suns. For perspective, the difficulty in meeting this efficiency specification can be seen by comparing it to the best concentrator cell efficiency achieved to date. A 26% cell as measured in 1993 would be the rough equivalent of a 27.4% cell measured in 1987 due to a calibration shift at Sandia National Laboratories[7]. This is very near the peak efficiencies (27.5-28%) measured at that time on small 0.15 cm^2 laboratory cells that did not need to meet the demands of cell mounting, heat-sinking, and large power outputs[1].

The second-generation design included four versions of point-contact solar cells, with varying dimensions so that the performance and yield sensitivities could be determined. All four designs would be fabricated on each wafer, giving well-controlled comparison data. In addition, these masks were laid out so that the simplified designs could also be compared to the point-contact cells. These simplified designs also had a range of dimensions so that the performance/yield sensitivities could be determined. Changes were also made in the electrode patterns to reduce the cell metalization series resistance. This new electrode pattern is shown in Figure 3.9. In soldering the first-generation designs, few cells were shorted across the spacing between positive and negative pads. By adding a pad, the series resistance in the metalization was reduced substantially by shortening the metalization distance to a contact pad.

A detailed discussion of the results from these cells is given in the Section 5, Cell Results. The simultaneous introduction of high-performance passivations, anti-reflection coatings, and the new designs resulted in 26% cells by December of 1992.

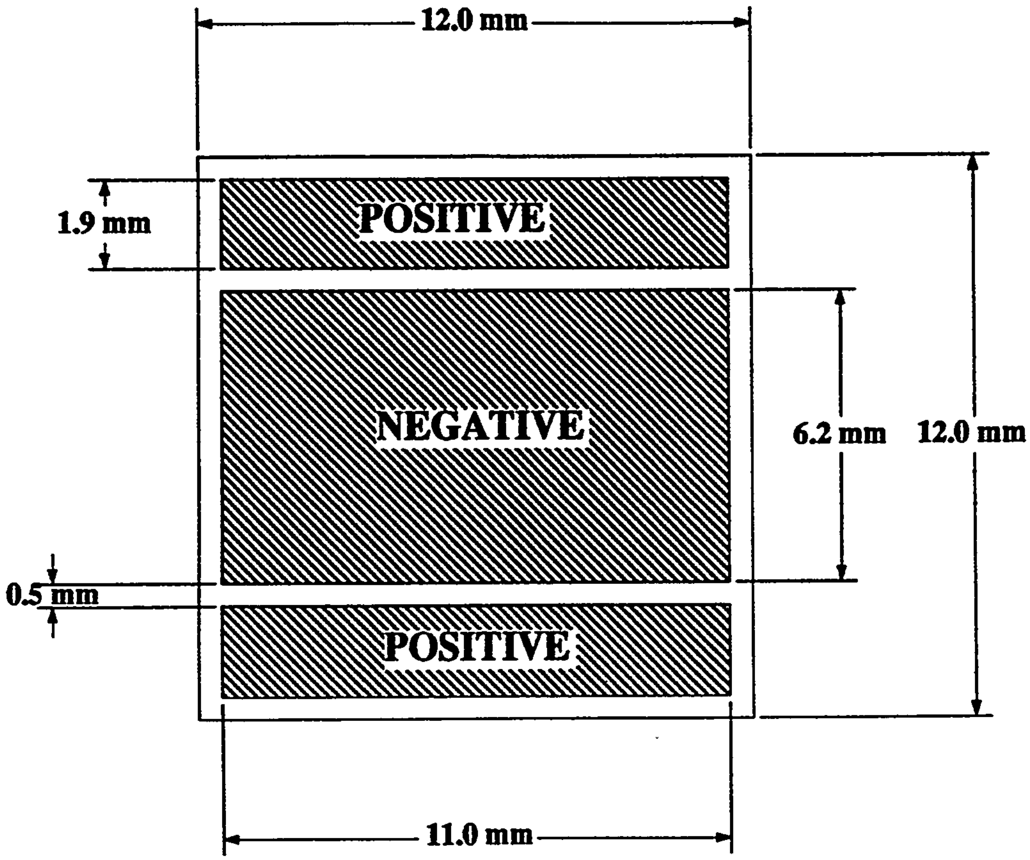


Figure 3.9. The electrode layout for the SunPower second-generation cell design.

4. Process Development

4.1 Introduction

A central goal of this joint-research program was to develop a cost-effective, high-efficiency cell fabrication capability. In order to meet cost goals, the cell design, process schedule and facility all needed to be optimized for high yield at low cost. The high-concentration solar cells developed at Stanford University were more similar to integrated circuits than to conventional flat-plate solar cells. So an obvious first cut for an optimized facility would be an integrated-circuit facility. Much of the research at Stanford was done in such an integrated-circuit laboratory. However, simply duplicating a modern VLSI fabrication facility is very expensive. Many of the cost drivers in a VLSI production facility such as sub-micron photolithography and the measures taken to eliminate particle defects are not necessary for solar cells.

As discussed in Section 1, the facility and process were designed to be state-of-the-art with respect to high-lifetime, contamination-free processing. In other areas, the equipment requirements were not so strict. Often previous-generation integrated-circuit equipment was perfect for the tasks and cost goals. As described in the previous section, the cell was designed specifically to achieve high manufacturing yields. This high yield was an absolute requirement in attaining low cost. Additionally, the facility was designed to incorporate low-cost processing techniques.

One of the major process decisions was to eliminate the use of pyrophoric (self-igniting) gases in the fabrication process. Previously, silane, diborane, and phosphine were used in the wafer-doping processes as well as for depositing oxides as dielectric layers needed in backside-contact solar cells. These gases are highly toxic and explosive. Their elimination allowed a safer manufacturing facility, without the costs involved in engineering the necessary safeguards for minimizing the risks involved in the use of the pyrophorics.

To accomplish this goal, a switch to BBr_3 and $POCl_3$ liquid-source dopants was made. This substituted for the deposited oxides that had previously been used in the doping process[1]. Additionally, the interlevel dielectric in the metalization that had also been a doped oxide in the previous process was replaced. This was done by developing a process for the use of an organic polymer, polyimide, instead.

In order to achieve an even more general goal, each toxic material that was used in the process was assessed for possible substitutes in order that the process and facility that was developed would be as ready for scaling up as possible.

4.2 Dopant-diffusion optimization

The characterization of the dopant diffusion processes was one of the major efforts in 1991, and continued to be an important area throughout 1992. Within the constraints of the cell designs described in the last section, there were numerous diffusion parameters to be optimized. First, each diffusion needed to meet the most basic criteria of maintaining the high lifetime in the substrate, having a low emitter saturation current density, requiring a sufficient surface concentration for contacts, and having the correct junction depth.

The next challenge was to integrate the dopant diffusion into the process. The simplest cell design requires three independent diffusions. The diffusion on the front side was ideally shallow, with a moderate surface concentration, while the phosphorus and boron diffusions on the backside needed to be more heavily doped to attain low contact resistance, and deeper for ideal emitter saturation current densities.

The difficulties came in integrating these diffusions into the process. The junction depths are determined by the total time at temperature that each diffusion sees. The total dose and lifetime parameters for each diffusion depend upon the detailed time, temperature, and ambient gas flow during the predeposition steps. Since the masking oxide is thermally grown, a careful optimization of masking thickness vs. dopant junction depth and surface concentration is required. The effectiveness of this mask against the predeposition of dopants depends upon the exact predeposition ambient, temperature, and time at high temperature.

Additional difficulties arise in the silicon etch steps. The effectiveness of the thermally-grown mask against wet-etching depends upon the thickness and dopant content. Wet-chemical silicon etching depends upon the dopant type and concentration. Hence the texture and trench steps in the process depend critically upon the wafer processing up to the etch step. The last consideration in optimizing a dopant process sequence was to minimize the number of steps, especially photolithographic steps, that are required in order to achieve the desired structure. This is done by using a logical sequence where oxides already existing in the process are used in subsequent masking steps.

Originally at Stanford, the structure shown in Figure 3.5 was implemented using doped oxides[1,3,6]. The advantage of the doped-oxide diffusion sources was that the single-sided processing of the wafer was automatic when the doped oxide source was an APCVD reactor depositing onto a platen. Furthermore, the masking oxide thickness was independent of the junction depth since this masking oxide could be deposited to any thickness at low temperature. The desire to eliminate pyrophorics from the process required that we abandon these advantages.

At Stanford in 1989 and 1990, a hybrid process had been optimized using boron-deposited oxides in conjunction with a $POCl_3$ predeposition to achieve the three diffusions[8]. This process was especially elegant in its use of the characteristics of the dopant sources. The boron diffusion was first, and therefore deepest and single-sided since it came from a deposited oxide. The $POCl_3$ diffusion was shallow, being last, and could have the high surface concentration required for low contact resistance. Since $POCl_3$ deposits on both sides of the wafer, the result was that these two diffusion steps resulted in all three of the desired diffusions. About 40 large-area ($35cm^2$) one-sun cells were delivered to Sandia National Laboratories that were fabricated on this schedule. They were found to have very high performance and yield[8].

This process provided the starting point for this work at SunPower. Many extensions were required. First, the boron-doped deposited oxide needed to be replaced by a BBr_3 process, that could in some way accomplish the same single-sided doping with equivalent characteristics. Second, the dopant parameters needed to be re-optimized for concentrator applications. The backside dopant diffusions needed to be significantly heavier in order to meet the series-resistance and emitter saturation current density goals despite more metal-silicon contact area. The sunward-side diffusion had to be significantly more optimized for a concentrator cell than for a one-sun cell. Early work on this contract focused on finding the best compromise; the single n^+ diffusion that could be used simultaneously on the front and back of the cell. However, it was not found. It was decided that this compromise costs too much in performance and therefore the n^+ diffusions on each side needed to be independently optimized.

Specifically, cells that were made with the same n^+ diffusion on both sides had an excessive sublinearity. The emitter saturation current density for the diffusion with the characteristics needed for the backside contact is too high for use as front-surface field for a concentrator cell.

Several proposed schemes were investigated. These each used one of several methods to achieve the three independent diffusions. Some worked well and some did not. The methods tested were to:

1) Stack the wafers back-to-back in the boat during oxidation in order to obtain different masking oxide thickness on the front and back prior to doping.

2) Stack the wafers back-to-back during BBr_3 doping.

3) Dope the wafers back-to-back during $POCl_3$ doping.

4) Grow an oxide, coat one side with photoresist, etch the other side. Then during doping the wafer will be doped on only one side.

5) Do the doping predeposition, etch the doping oxide off of the wafer with a single-sided etching technique, then do an additional drive-in.

6) Do the doping predeposition, grow an oxide, etch the doping oxide off of one side, etch the silicon to remove the doped layer, then do a second predeposition.

7) Dope the wafer, grow an oxide, coat with resist, etch the oxide, do a second predeposition.

In each case, the critical parameters in the procedure were different for boron and phosphorus, and depended upon the previous history of the wafer. Each of these methods was tried and optimized to a certain extent before a preferred technique was chosen. By September 1991, this procedure was fixed and settled down to small deviations from a preferred runsheet schedule. As a result, the baseline process essentially became established at this time, with Run 17. Runs 18, 19, 20, and 21 (through December 1991) nominally used this baseline process schedule.

When these processes were installed at SunPower, they were altered to requalify them on the new equipment. In addition to the criteria discussed above, an additional goal was achieved. The processes were designed for minimal use of the liquid doping sources. There are three motivations for this direction, all directly or indirectly related to cost.

1) Low usage of dopant source minimizes the chemical handling of replenishment, and minimizes the total volume of hazardous material on the premises. The chemical cost is reduced.

2) The frequency of tube cleaning was minimized for lower source usage.

3) Wafer yield for thin wafers was determined to improve when a minimum of BBr_3 was used.

The lifetime and sheet resistance for both the phosphorus and the boron depositions were found to be very sensitive to the conditions of gas flow and the pressure differentials around the tube and loading areas. The heat baffles, quartzware fittings, and the gas-filter chemical compatibility and placement also affected the dopant uniformity and lifetime.

The phosphorus diffusions were more easily transferred to the Cell Pilot Line than the boron diffusions. Very careful process control and optimization was required before repeatable lifetimes greater than 200 μs were achieved from the BBr_3 sources at SunPower.

4.3 Wafer thinning

At the beginning of this SunPower project, the wafer thinning was a well characterized process. Starting in October of 1991, this process was transferred to the Cell Pilot Line. All of the wafers (150) for Runs 19, 20, and 21 (December 1991) were thinned in the Cell Pilot Line. All subsequent wafer etching was done at the SunPower facility.

4.4 Polyimide

In Figure 3.5, a silicon dioxide layer was used to define the areas to be directly solder-bonded to the header. The desire to eliminate silane from the laboratory required the elimination of this oxide.

In previous processes, this oxide had several problems. The oxide was deposited at atmospheric pressure using silane and oxygen in nitrogen. This oxide typically has pinholes, and at the deposition temperature of 400 °C the Al formed hillocks, creating a topography that could crack the oxide or penetrate it. As a result, this process had yield problems[9].

The new process needed to address these problems. It required high yield, high reliability, use of non-pyrophoric sources, and environmental safety. A spin-on organic polymer, polyimide, was chosen to meet these criteria. Polyimide is pinhole free. It is widely used in similar integrated-circuits-industry applications. It is spun on in a way similar to photoresist, and is cured at a relatively low temperature of 350 °C. It can provide a thick layer, capable of good step coverage and planarization. Additional advantages are that it requires no special equipment, no pyrophorics, and can be patterned using relatively low-tech wet-etching techniques.

The drawbacks of polyimide are that it is relatively expensive and absorbs chemicals. This second point can (and did) cause problems in subsequent wafer processing. A variety of polyimides are available. The major criteria used to choose the appropriate polyimide were cost, viscosity (to determine the layer thickness), thermal-expansion matching to silicon, adhesion properties, and the possibility for wet processing. The more conventional (and more expensive) way to pattern polyimide is to use plasma etching.

This polyimide process was fully developed early in 1991, using the Stanford University facilities. The key milestones in this development were the choice and qualification of a polyimide with respect to stress, planarization, and adhesion, a demonstration of sufficient resolution in a wet-etch patterning technique, a high yield in the resulting devices, and finally a demonstration that the polyimide process, including the 350 °C cure, caused no efficiency degradation in finished solar cells. This was accomplished by March, 1991. In November, the process was transferred to the Cell Pilot Line. This was especially significant since it involved developing a batch process for the first time. At Stanford, a single-wafer process was used through the polyimide coat, expose, develop, and resist strip. The polyimide cure was followed by another single wafer-process, the Ni- and Au-plating of the wafers. The equipment at the Cell Pilot Line was designed with the proposed batch process in mind. This conversion went quite smoothly.

Subsequent work at SunPower established the process control and parameters required to achieve nearly 100% yield for this step for each of the cell designs requiring differing dimensional control of the polyimide.

4.5 Wafer texture

SunPower's high-efficiency cells were designed to have a textured front surface. Early in this development program, it was decided to use inverted pyramids instead of upright pyramids. The cells that had been fabricated at Stanford in 1989 for the EPRI and Sandia Concept 90 modules had upright pyramids. However, in work on one-sun cells in 1990 it had been found that the inverted pyramids contribute an additional 0.5 mA/cm^2 of current compared to identically processed wafers with upright pyramids and offered superior process control[8]. This work followed work by other groups that had found similar results[10]. Random pyramid texture was also fully characterized at the SunPower facility as a lower-cost alternative to the photolithographically-defined inverted texture.

The investigations that were performed during 1991 at SunPower primarily concerned the integration of the texture into the process. This was largely a strategic question involving cost, complexity, and yield. The approach with the highest yield was initially to texture the wafers at the very beginning of the process. When this was done, the process through the middle, where the layers are aligned to each other, was the shortest. However, texturing at the beginning required the growth and masking of an additional oxide to those that are necessary for the doping sequence.

A shorter overall sequence used one of the oxides grown during an intermediate step as the mask for the texture etch. This strategy also had some pitfalls. One is that masking and etching defects were then present in the doped layer, as mentioned above. Second, the etching behavior of the surface after doping is highly dopant dependent and had to be carefully characterized. A third concern is that this silicon etch step thinned the oxide mask which still has to be thick enough to be a barrier in subsequent dopant masking. In this way, the texture had an influence on the already-too-complex dopant sequence optimization.

Both approaches have been used. By carefully addressing the yield problems, the second approach became the preferred alternative in most cases.

4.6 Metal Sputtering Deposition

During the course of this work, metal-sputtering deposition was used to metalize the cells. This has its own special difficulties with thin wafers. The metalization thickness that was used is sufficient to bow the wafers and make them incompatible with the automatic transports commonly integral in these sputtering machines. A machine and process were installed at the Cell Pilot Line that took these problems fully into account. Installation began in December of 1991. Starting in February of 1992, all depositions of metal for SunPower's cells were done with this machine, a CPA 9300. The breakage yield for this process was confirmed as negligible.

4.7 Photolithography

The photolithographic line was installed during the Fall of 1991. Beginning in December of 1991, all of the photolithography was performed in the Cell Pilot Line. The required sequences were fully specified including positive resist and polyimide processing during the next few months. By the end of 1991, all lithography was done at this facility.

4.8 Antireflection coatings

A series of deposition techniques was evaluated for antireflection coatings by using vendor services. Some of these coatings were found to be compatible with our process, however, the vendors were not able to continue providing the service.

SunPower developed a proprietary process in April, 1992. These films were characterized and found to improve the cell responsivity by close to 4% in initial experiments. As a result, SunPower had an in-house capability for depositing antireflection coatings. Cells subsequent to mid-year of 1992 had single- or double-layer antireflection coatings. These coatings were optimized either for encapsulated or unencapsulated applications as required.

4.9 Sawing

A wafer saw was installed at the Cell Pilot Line in order to separate the die for mounting. This saw was installed during October and November, and fully specified in December, 1991.

4.10 Solderable Metalization

At Stanford University, the Ni and Au plating was a single-wafer process. It was slow and temperamental. It had proven barely sufficient for fabrication of the cells that were used in EPRI and Sandia Concept 90 modules in 1989.

The introduction of the polyimide dielectric in place of the silicon dioxide dielectric required significant additional development. The major problem appeared to be the absorption of chemicals into the polyimide. An additional problem was achieving an extremely clean surface after photoresist stripping subsequent to the polyimide patterning. Overly aggressive cleans at this stage prior to the polyimide cure will strip the polyimide. Any organic not cleaned from the wafer at this stage becomes baked on by the 350 °C cure.

This problem required significant work in February and March of 1991, but was solved. No problems were observed in the plating quality in runs processed since that time.

Another solution that addressed both these problems and the hazardous material use of gold cyanide was to eliminate the process entirely and institute a solderable sputtered metalization in its place. This goal was achieved with the development of a Cu-based second-level metalization during 1992[11].

4.11 Soldering

During this contract period, a close collaboration between SunPower and Tom Hund at Sandia National Laboratories investigated the solder-bond techniques and reliability of the evolving SunPower cell designs, mount designs, and soldering processes.

Following the fabrication and sawing of the cells, initial cells were mounted onto electrode assemblies provided by Cummings Engineering of Wilmington, Massachusetts. The first of these mounts arrived in April, 1991, and virtually 100% yield was attained in the soldering operation. In September, trouble appeared in the form of increased void density. Eventually, this was traced to a quality control problem in the electrode mounts. A soft copper had been used rather than the usual alloy, and as a result the electrode surfaces where the cell was to be soldered were not flat to various degrees. The problem was not debugged until December. As a result, all of the cell results between September and December 31, 1991 were significantly confused by the variability in the solder-joint quality.

Several tests were performed in an effort to understand the soldering problems during this period. They involved different weights during soldering, and different solder thicknesses. The results were assessed by two measured parameters. The first was the void density as determined by x-rays, and the second was measurements of the series resistance. No real trends were observed relating the soldering techniques to these results. However, another interesting observation was made. The sublinearity was very well correlated with the series resistance. Devices with high series resistance also had large sublinearities. This meant that a cell with a high void density would have a poor sublinearity as well as a high series resistance. This is demonstrated in Figure 4.1. This figure suggests that without solder voids, the series resistance could be as low as 5 mΩ-cm^2 and the sublinearity limited to 95%.

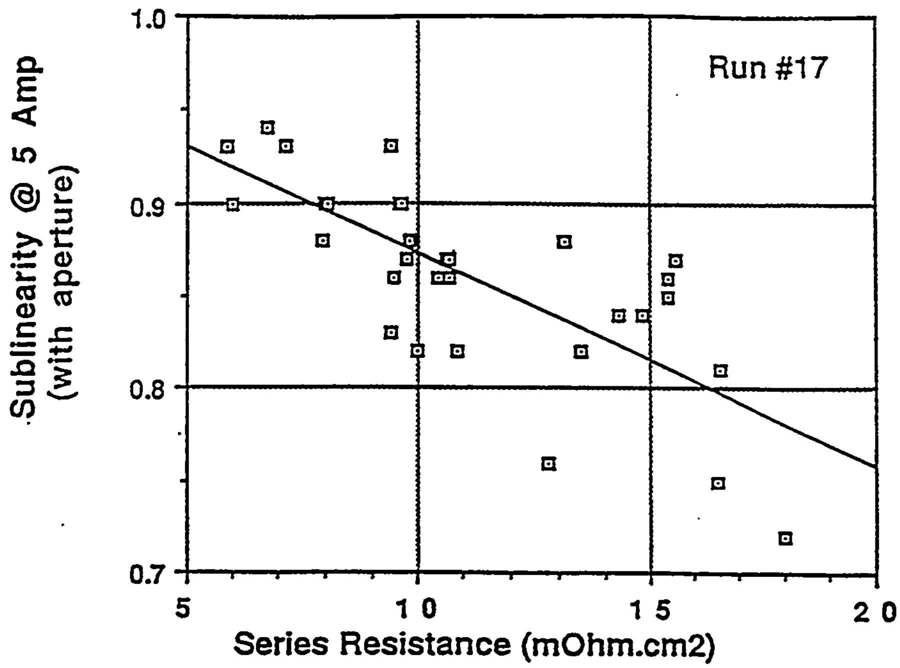


Figure 4.1. A plot illustrating the correlation between the sublinearity and the series resistance for a group of cells (Nov. 1991). It was hypothesized that the common variable controlling both parameters was the solder void density.

SunPower's initial cell design used a single-level metalization with individual fingers soldered onto a header. Tests performed up to May of 1992 at Sandia National Laboratories indicated that this design was quite susceptible to solder fatigue. The metalization fingers with less soldered area failed first, followed by the larger-coverage-fraction areas. Interestingly, it was found that thin solder layers produced more reliable bonds than thicker solder.

Better results were obtained for directly soldering the cell onto the alumina voltage isolator, without the copper electrodes between the cell and the alumina. Alumina has a thermal-expansion coefficient much better-matched to silicon than Cu does. Some of the results for cells soldered directly to the alumina are shown in Figure 4.2a and 4.2b.

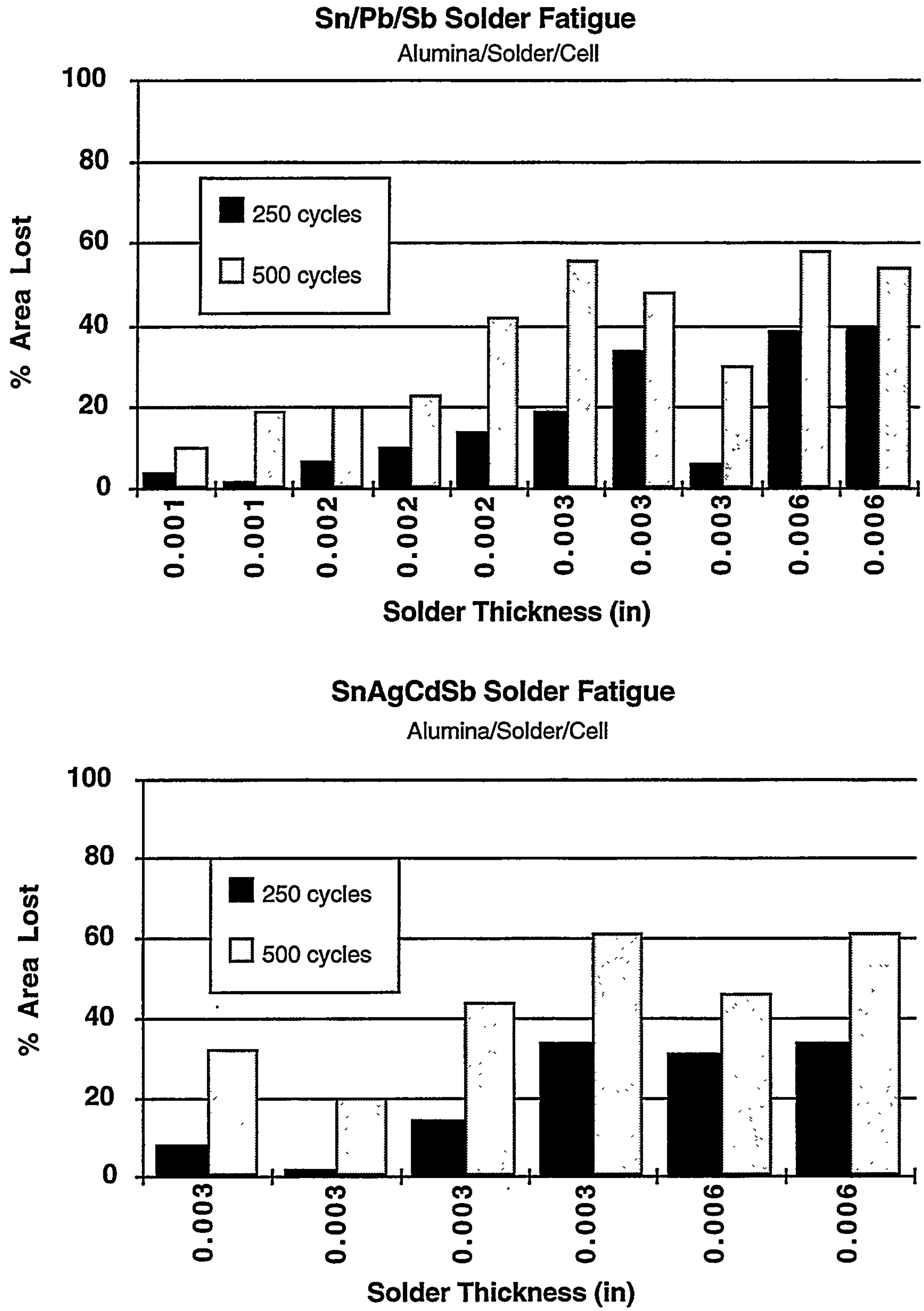


Figure 4.2. The solder-fatigue performance of SunPower first generation cells as a function of solder thickness for Sn/Pb and Sn/Ag/Cd/Sb solder. The figure of merit is the percentage of solder-bond area lost after thermal cycling.

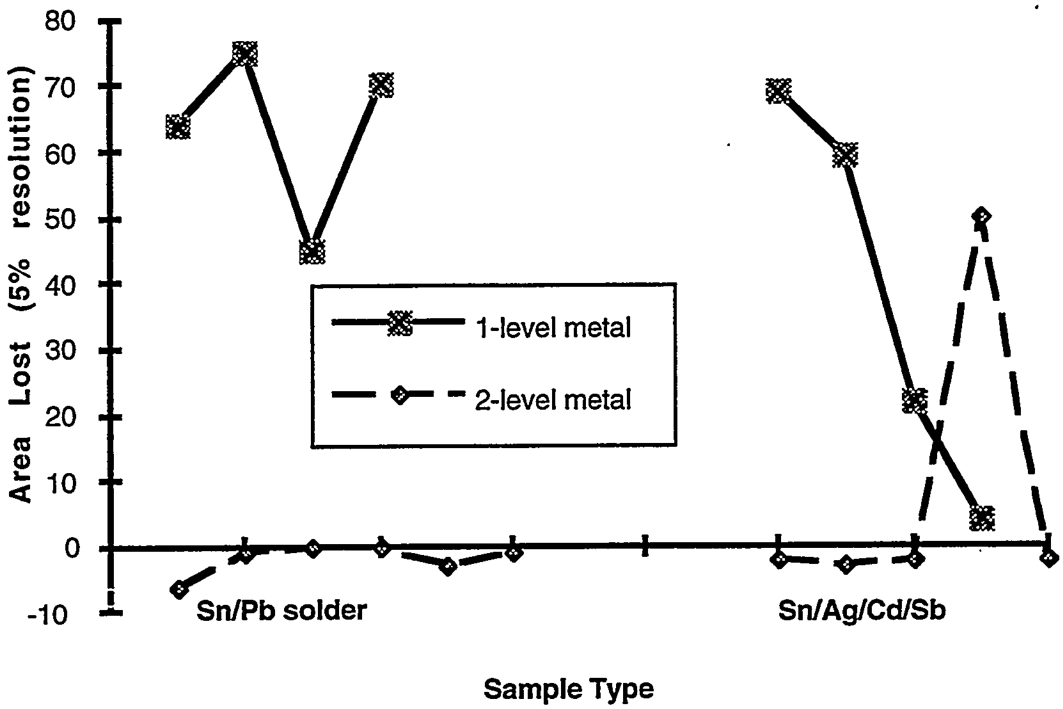


Figure 4.3. The area loss after 250 thermal cycles for single-level metal and double-level metal solar cells. Both Sn/Pb and Sn/Ag/Cd/Sb solders were tested. Identically -prepared samples are connected by lines to guide the eye.

A double-level metalization was developed in order to address the problem of void-growth due to solder fatigue. In comparison tests performed at Sandia National Laboratories in August, 1992, eleven cells with double-level metalization showed no solder-area loss in 250 cycles. One cell with a high initial void density did show a significant loss. The control case of cells with single-level metalization had cells that were largely delaminated from their mounts. This result is shown in Figure 4.3.

Additional tests reported in March of 1993 confirmed that the solder contact-area losses were less than 10% for double-level metal designs with smaller solder-pad dimensions than the original double-level cells measured in August. Another Sandia test at this same time determined that the alumina-aluminum heat spreader joint was another critical interface. This test indicated that the 3-

mil-thick Sn/Pb solder was superior to Sn/Ag/Cd/Sb solder at this interface (Figure 4.4).

Following these results, SunPower standardized on a process specification using double-level metalizations in conjunction with Sn/Pb solder in order to insure good reliability.

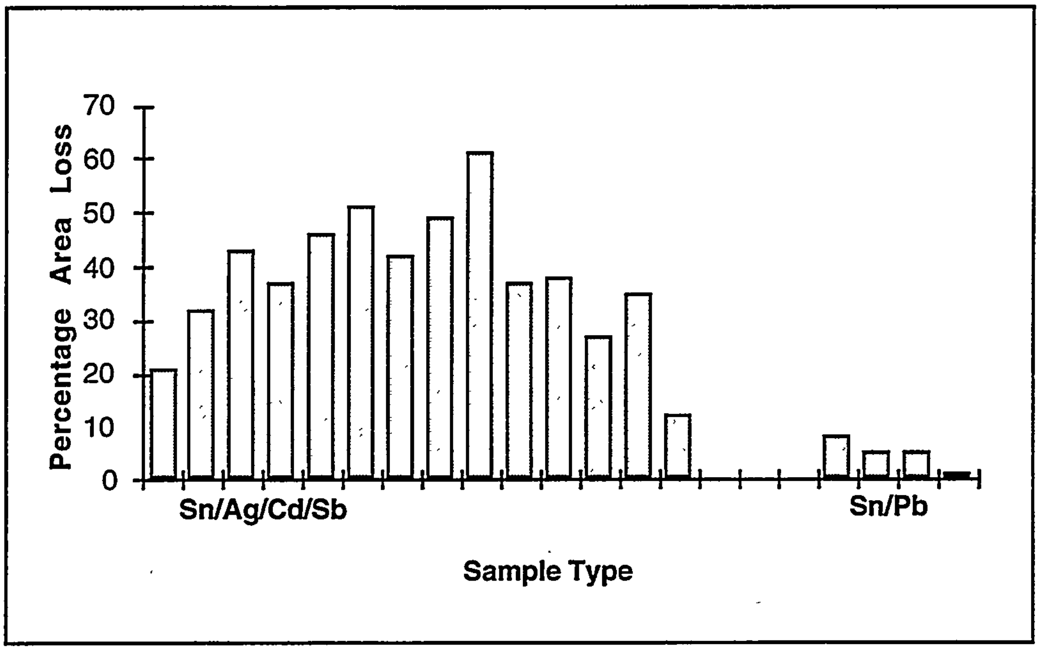


Figure 4.4. The solder bond performance comparing the use of two solders at the alumina/Ni-plated aluminum heat spreader interface. The solder-area loss after 250 cycles is shown.

5. Cell Results

5.1 Introduction

The progress as measured by cell results closely followed the major activities at SunPower. A timeline of major efforts at SunPower is superimposed on a plot of efficiency for cells delivered to Sandia National Laboratories in Figure 5.1.

5.2 Process Development and Transfer Stage

Initially after placement of the contracts, the major efforts went into conversion of the doped-oxide-based process schedule to a liquid-dopant source process that was anticipated to be installed at SunPower. In parallel with this activity, a first generation SunPower cell design was modeled and the Computer-Aided-Design for the photolithographic masks was done.

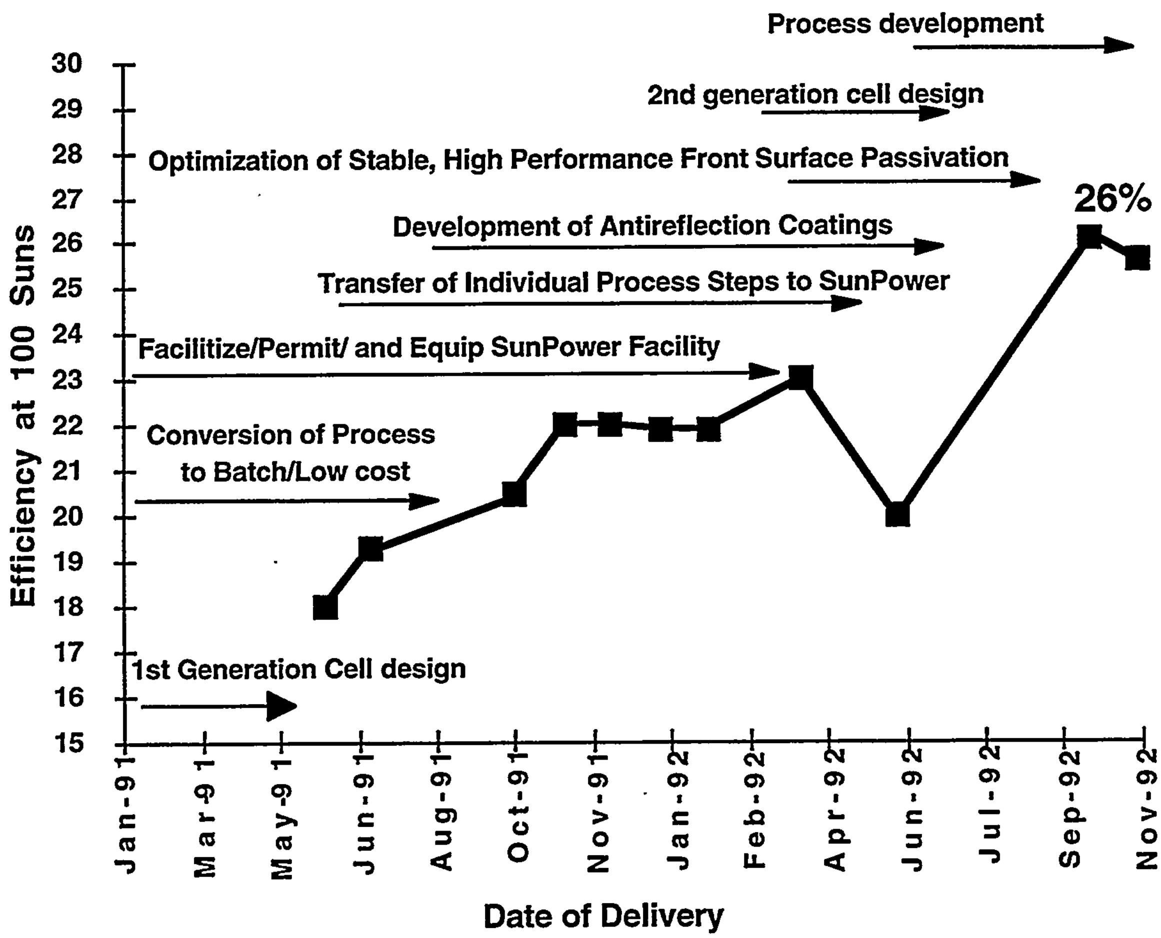


Figure 5.1. A time line superimposed on a plot of cell efficiency at 100 suns. The efficiencies are for cells delivered to Sandia National Laboratories.

These masks became available in May of 1991. At this point, with initial runs, an efficiency milestone of 18% at 100 suns was set. The primary focus of the research at this stage was on optimizing individual processes.

The initial results essentially checked out the mask set, as well as early optimizations for the new doping processes. The first runs utilized small variants upon the existing one-sun process schedules. These schedules used a single doping step to place a dopant on both the front and the back of the cell. Since the backside dopant-diffusion needed to be highly doped to attain low contact resistance, the frontside dopant-diffusion was more heavily-doped than was optimal.

The front-surface recombination was very high under concentrated sunlight. As a result, cells fabricated in May, 1991, typically had a sublinearity in the short-circuit current of 88% (a 12% loss) at the EPRI design point. This excess front-surface recombination also limited the open-circuit voltage of the cells.

By July, 1991, the loss in current at high concentration due to the front dopant-diffusion had been cut in half by carefully optimizing this single diffusion. It had to be as shallow as possible in order to best meet the required compromise between the desired properties for the front and back. However, the best result obtained for this single diffusion compromised the cell performance substantially, degrading the cell efficiency by approximately 10%.

Subsequently, SunPower optimized a process that included different dopant diffusions for the front and the back of the cells. This work extended through September of 1991. This improvement allowed the cell efficiencies to rise to 22%.

During the period from October, 1991 through May, 1992, the process steps were transferred step by step into the SunPower facility as described in Section 4, Process Development. The process was also transformed into a batch process with detailed specifications so that the cells could be fabricated by process engineers and technicians. Previously, all SunPower cells had been fabricated by Ron Sinton and Pierre Verlinden. The cell results shown as efficiency in Figure 5.1 were entirely secondary during this period of intensive process-development, training, and equipment debugging.

5.3 A Technology Demonstration

The successful implementation of liquid-source dopants was well established by late summer of 1991. Even at this early stage in the process, before anti-reflection coatings and high-performance passivations were available, the technology was applied to a SunPower project related to the EPRI/Sandia work. A dense array module was fabricated using the existing process.

This dense array was a proof-of-concept for a wafer-scale integration of an entire module. An exploded view of the module is shown in Figure 5.2. The silicon module, called the monolithic cells in Figure 5.2, are series-connected on the wafer using a patented SunPower process.

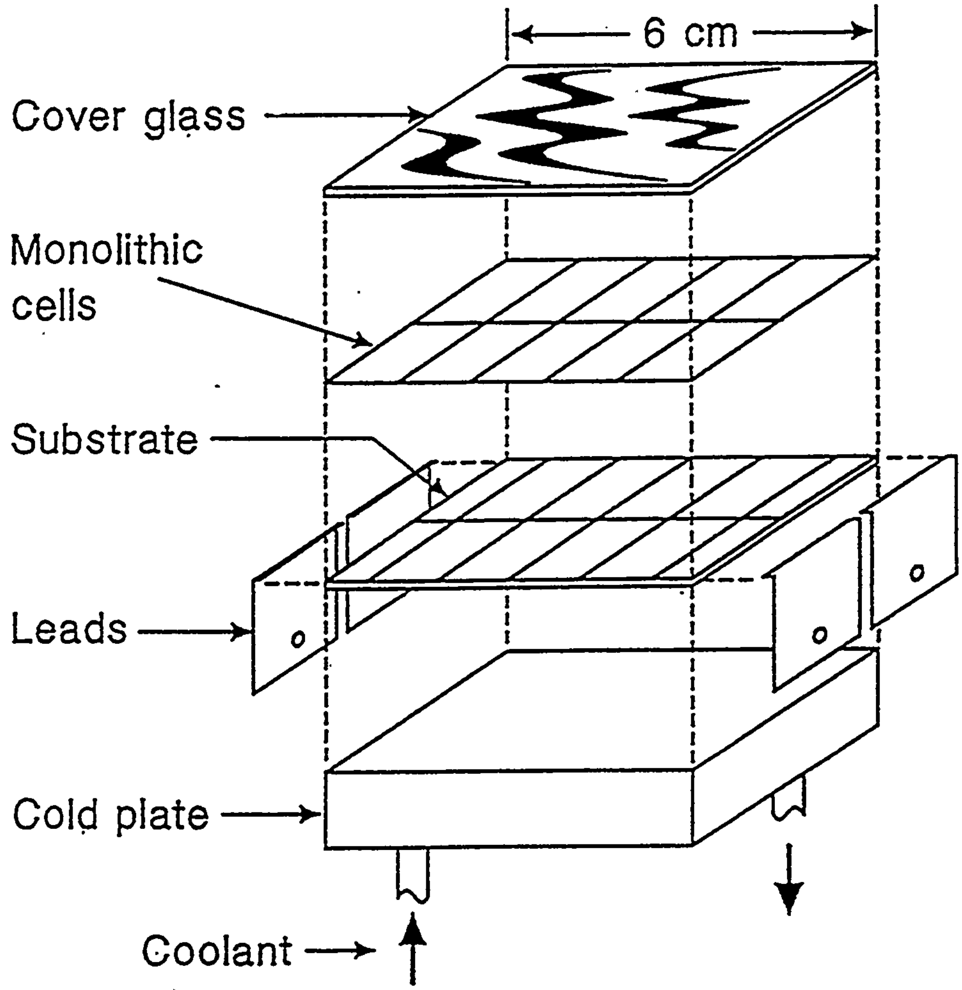


Figure 5.2. An exploded view of a SunPower wafer-scale module.

The characteristics of this module are shown in Figure 5.3. Using SunPower's flash-testing apparatus, the measured efficiency of the dense array closely tracked the efficiency of the process at that time, indicated by the 22% Fresnel cells in October, 1991 in Figure 5.1. The module produced more than 140 W under 200 suns of illumination.

This same dense array was packaged with a cold plate as indicated in Figure 5.2 and tested under steady-state illumination in a parabolic dish reflector. These results are shown in Figure 5.4. The cell temperature is shown for each cell current. The temperatures are indicative of the ability of the package with water cooling to remove the heat from the array[12].

MODULE 22 - R17 @ 25°C

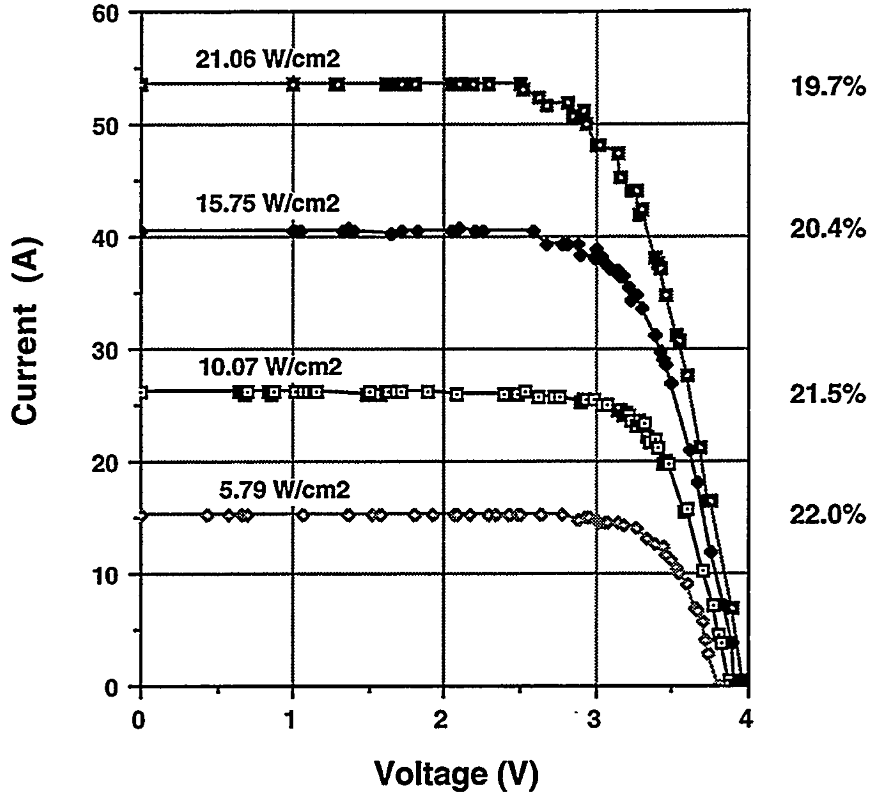


Figure 5.3. Flash-test results for a 36 cm² wafer-scale module.

5.4 Demonstration of High-Efficiency Cells

During the first half of 1991, the emphasis in the laboratory shifted into transferring each step of the cell process into the new SunPower facility. This was completed with the characterization of the furnaces in April of 1992, as discussed in the chapter on Process Development.

At this point, the focus returned to improving the cell efficiency. This effort had three thrusts:

1) A new cell design and layout.

2) Development of new, high-performance stable surface passivations.

3) Characterization of SunPower's antireflection coatings.

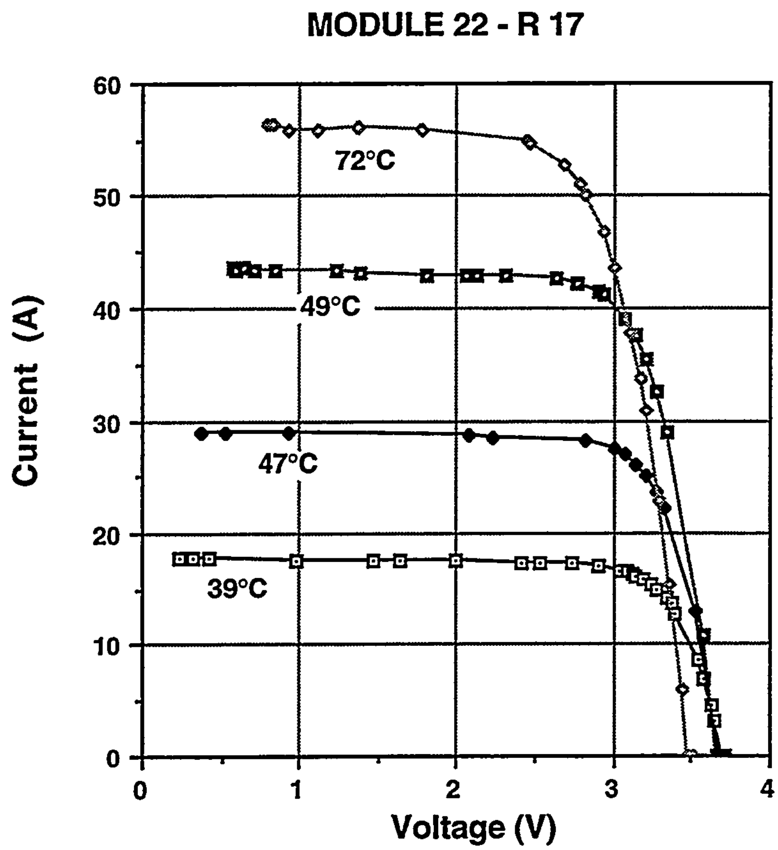


Figure 5.4. On-sun results for a 36 cm² wafer-scale module operating in the steady -state under sunlight concentrated by a parabolic-dish reflector.

The remainder of this section will discuss the results of the fabrication runs of the new design. Section 6, Stable High-Performance Passivation, will look at the passivation issue in detail.

The new cell design included four different cell types on each wafer. The four designs, A, B, C, and D were each based upon a point-contact process with deep localized diffusions. In general, "B" had larger feature sizes, "C" and "D" had the smallest, and "A" was intermediate although many parameters differed between the designs. The details of these designs are proprietary to the Electric Power Research Institute.

By having all four types of cells on each wafer, the performance differences could be evaluated in well-controlled experiments. This was especially important since the experiment was also simultaneously evaluating four different high-performance passivations. The net result was that 16 different cell types were entered into an extended experiment.

Between October, 1992 and June, 1993, these variables were evaluated using cells from successive runs. Measurements were done at four different test facilities. The first tests were done at SunPower, using the techniques described in Section 2, Testing Capabilities. Some of these cells were subsequently sent to Sandia National Laboratories. They have the facilities to do flash-testing using an entirely different method. Also, they maintain standards with all of the major laboratories in the world and have full facilities to perform optical and spectral-response measurements.

Cell were also sent to two of EPRI's contractors to measure. The first of these was Daedalus Associates of Mountain View, California. They used an EPRI "minimodule" with 2 standard EPRI lenses. The cell under test was measured side by side with a standard cell traceable to Sandia National Laboratories. The second subcontractor was Cummings Engineering of Wilmington, Massachusetts. Cummings Engineering performed a steady-state measurement with a solar simulator that utilized an arc lamp.

Note that the four tests were not necessarily the same. Each had different light uniformity and spectral content of incident light. Since each test group of cells was an independent experiment, the results are displayed independently. In each case, the efficiency shown is that for the measured concentration closest to 200 suns. Additionally, the Daedalus measurements were steady-state measurements using reflective secondary elements mounted onto the cells. The Cummings measurements were steady-state, with an entirely different optics. Flux non-uniformities could cause localized heating and series resistance in the cells that would not be evident from flash-test measurements. These effects could be especially significant in the presence of any solder voids. This sort of detailed testing involving four test laboratories is virtually unprecedented for concentrator cell research and presented a unique opportunity to evaluate the detailed performance of these cells. In addition to these measurements discussed here, long-term exposure and on-sun tests were performed in an EPRI module at SunPower. The results from nearly 500 days of exposure are presented in the next chapter on cell stability.

In each case, the comparisons of cells done at the same facility can be used to rate each cell type relative to all others measured at the same time.

The first of these results is shown in Figure 5.5. These measurements from September of 1992 indicate excellent agreement between SunPower and Sandia National Laboratories. Discarding the two low cells, the efficiencies are nominally 24.5% at 200 suns. Comparing the four designs, the main conclusion is that the design "A" may be slightly inferior to the other three in performance, but within 0.4 absolute percent.

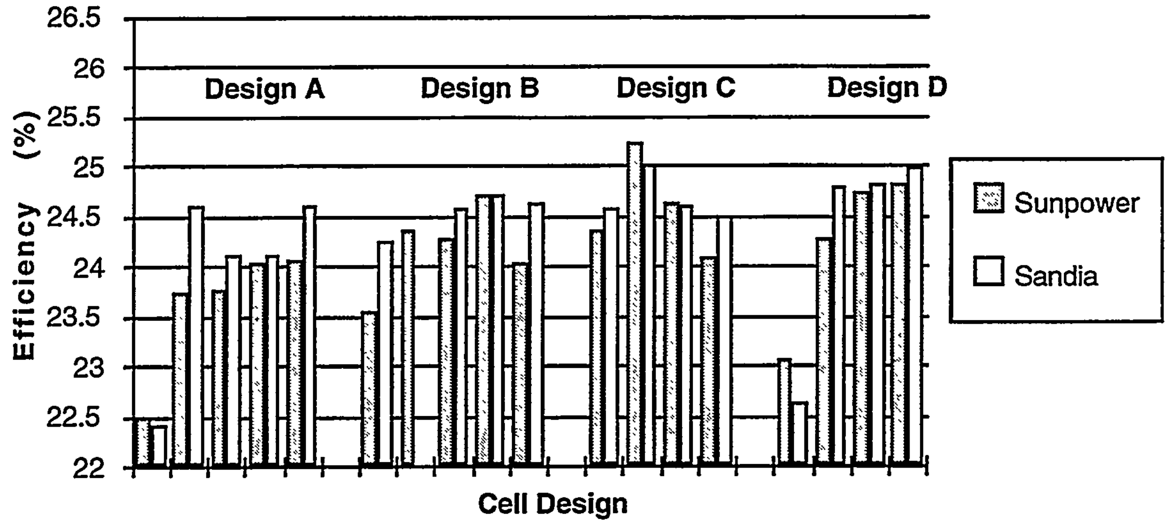


Figure 5.5. Test results for the first batch of cells of the new design, with new passivation technology and antireflection coating. Measurements are from Sept., 1992.

Figures 5.6, 5.7, 5.8, 5.9, and 5.10 show the results of all of the experiments with significant numbers of cells to date.

Figure 5.6 shows the results for a group of ten cells sent to Daedalus Associates. All of these cells were of the type "C" or "D". If the one low cell of type "C" is discarded from the data, the mean efficiency for both SunPower and Daedalus data is 24.8%. The difference between the efficiency for the two types of cells is not statistically significant. Figure 5.7 shows similar data from the next delivery.

Figure 5.8 shows results measured at Sandia National Laboratories in February of 1993. This time, the sublinearity was not measured and no correction was made for spectral mismatch. SunPower measurements indicate that the sublinearities for these cells all were between 0.95 and 0.99. This indicates that under 200 suns of concentration, the ratio of short-circuit current to incident power is 95-99% of its value at one sun. The cells efficiencies need to be corrected for this effect. The spectral mismatch correction for previous deliveries of cells was +1.7%. So the Sandia data should be corrected by a net -3.3 to + 0.7% (relative) or -0.8-+0.2% (absolute) at 200 suns, bringing the Sandia and SunPower data into substantial agreement. The data in Figures 5.9 and 5.10 are similar to that in Figure 5.8.

The relative performance between designs B, C, and D are the same for SunPower and Sandia measurements, with design "D" being superior to "B" by approximately 0.4 absolute percent and with "C" intermediate between the two. This result seems fairly consistent with the data from all of the individual tests.

The cells from the run shown in Figure 5.8 were the first cells mounted on an improved copper header. Sandia measurements indicated that the best cell was 26.1% efficient at 90 suns. At this concentration, the sublinearity and spectral mismatch corrections should approximately cancel.

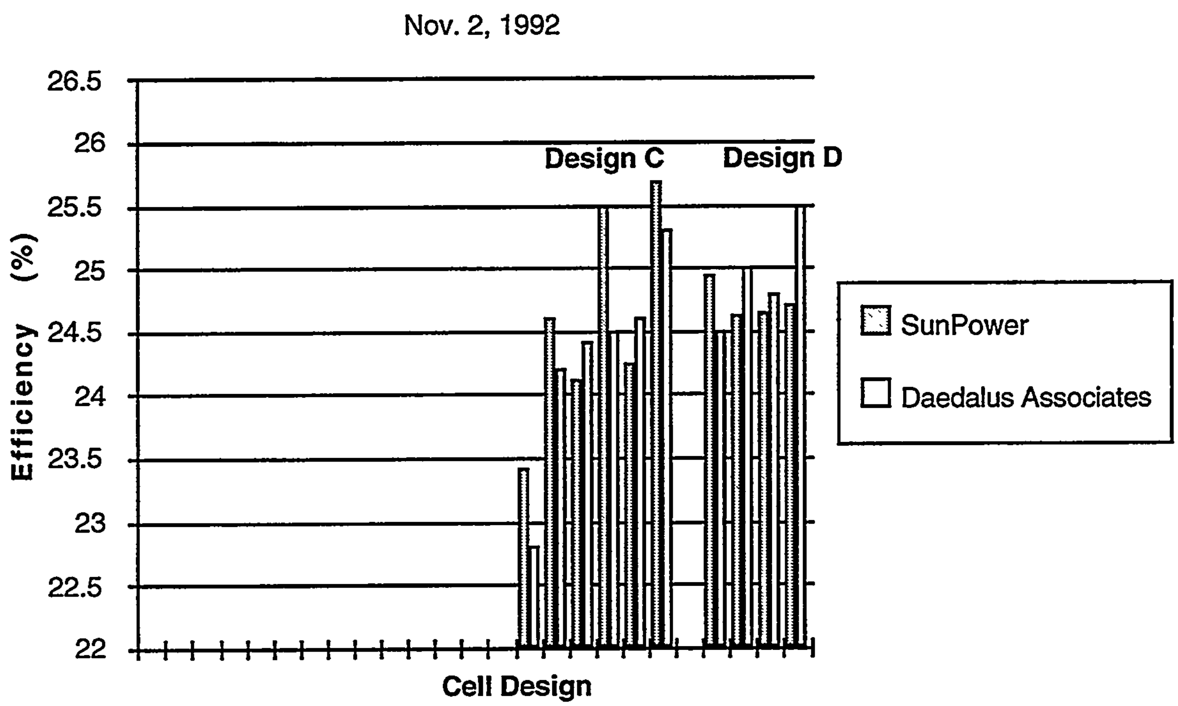


Figure 5.6. Test results measured at Daedalus Associates under steady-state measurements using sunlight concentrated by a Fresnel lens.

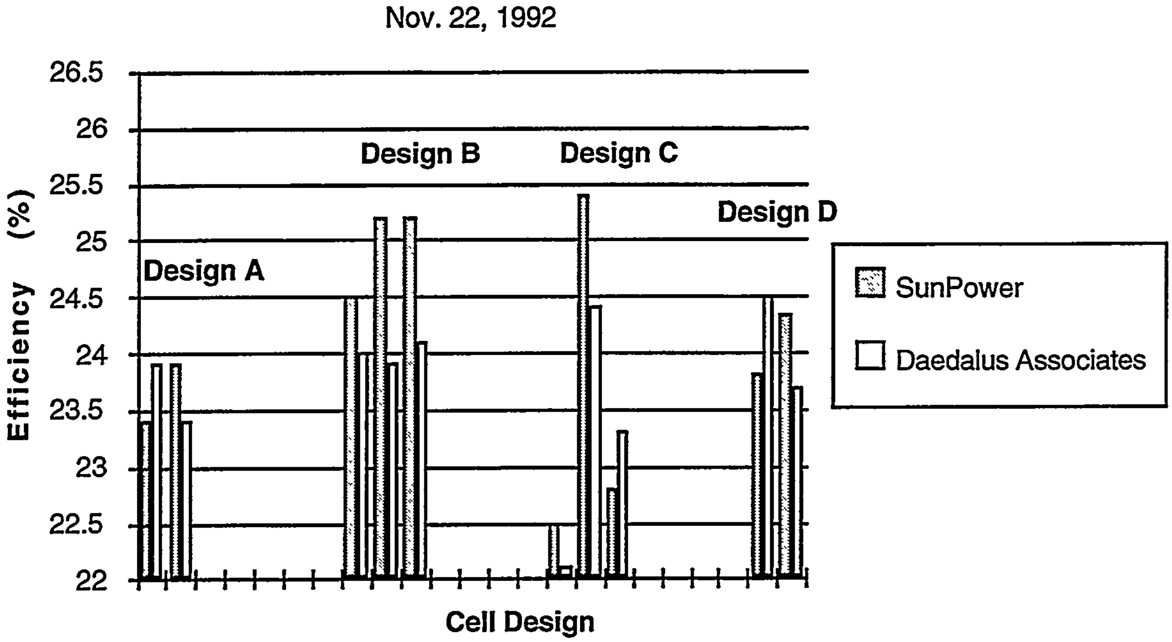


Figure 5.7. Measurements at Daedalus Associates.

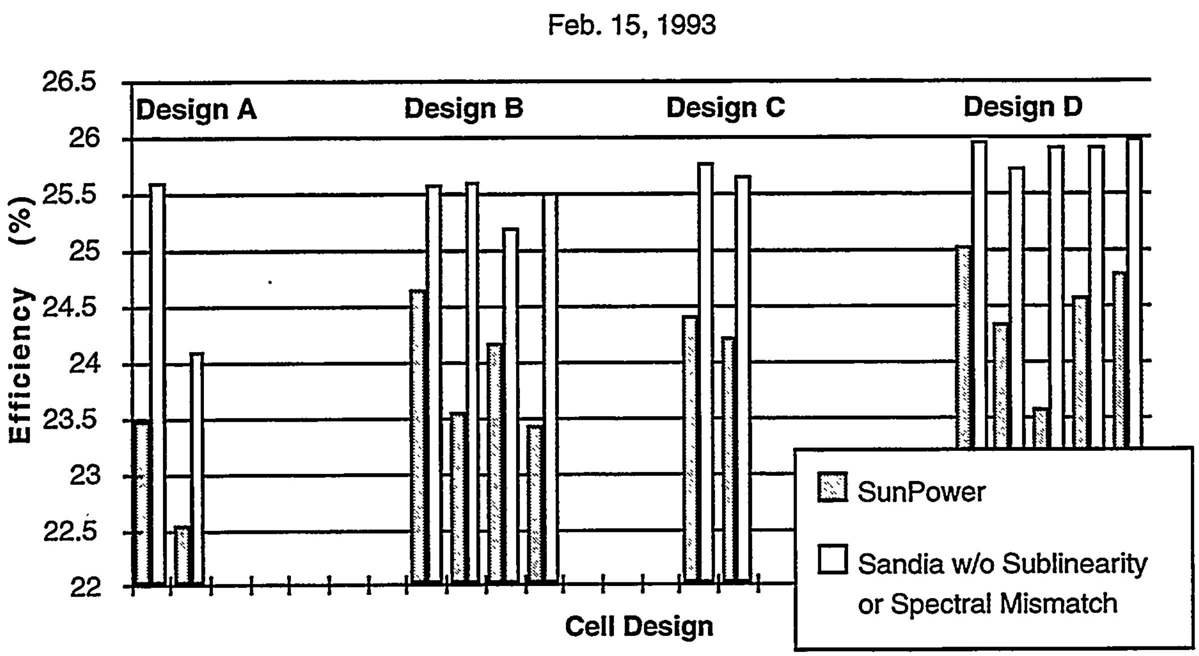


Figure 5.8. Test results from SunPower and Sandia National Laboratories. The Sandia measurements did not include spectral mismatch or sublinearity.

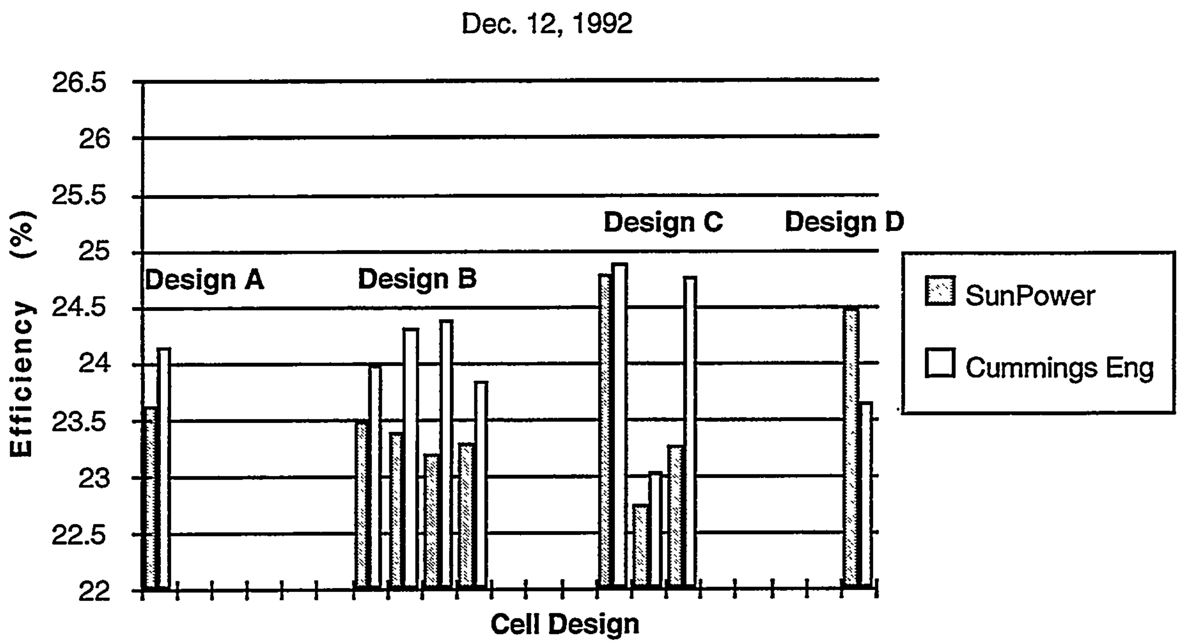


Figure 5.9. Test results measured at Cummings Engineering.

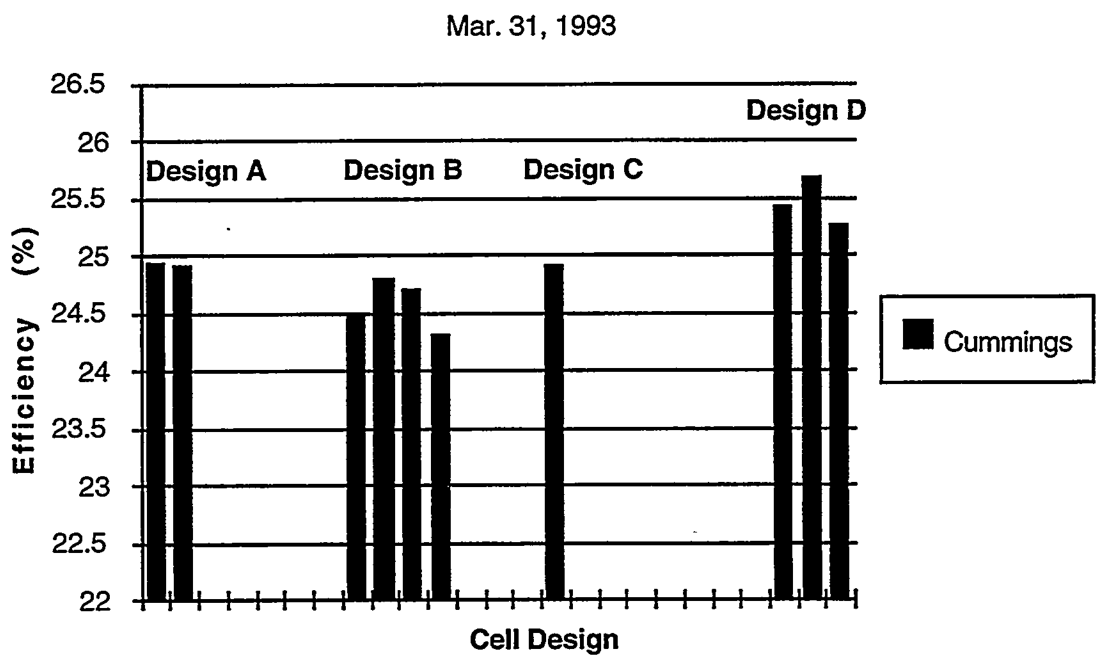


Figure 5.10. Test results measured at Cummings Engineering.

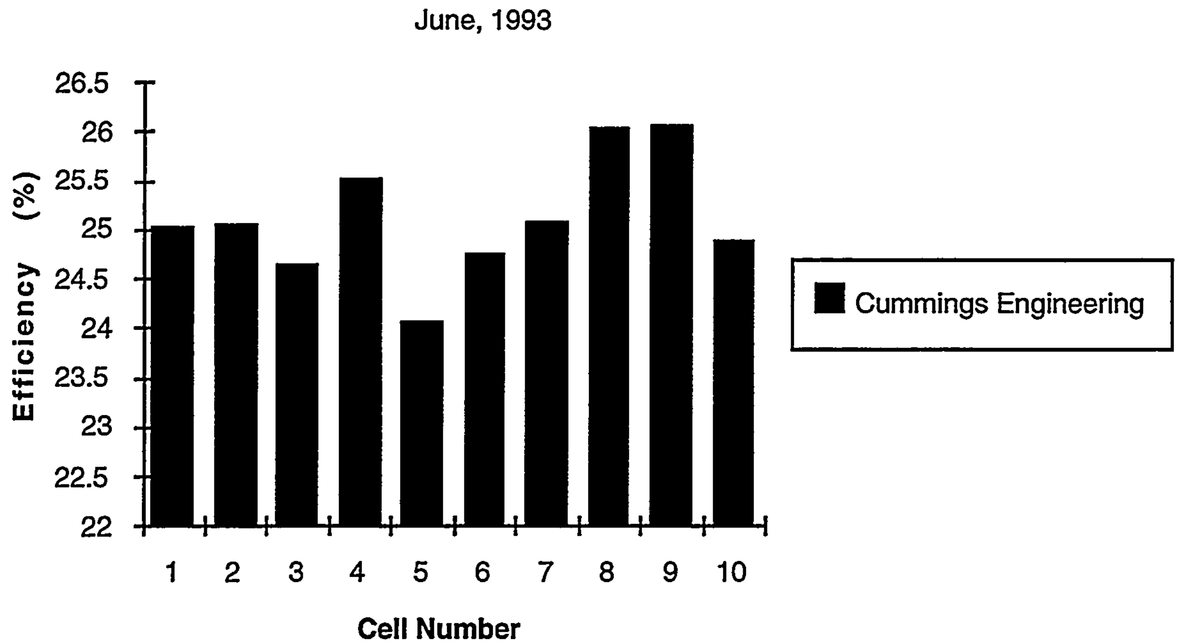


Figure 5.11. Test results measured at Cummings Engineering for the final delivery of EPRI cells. These efficiencies are indicative of the efficiency distribution for 300 cells delivered to EPRI during the Spring of 1993.

During the Spring of 1993, 300 cells were delivered to EPRI for evaluation for use in the EPRI Fresnel module program. At EPRI's request, these cells were unmounted, however, the distribution of efficiencies for these cells should be identical to the mounted cells delivered to Cummings Engineering in June, 1993. The efficiency distribution for these cells is shown in Figure 5.11.

For more detailed information on a particular cell, Sandia provided full measurements for the efficiency, voltages, and fill factors for several individual cells. The curves for one particular cell are shown in Figure 5.12[11]. The efficiency reaches 23% by 2 suns. It then exceeds 25% between 10 and 200 suns. The cells have very impressive optical characteristics (Figure 5.13). Sandia National Laboratories analyzed the optical data[13] and determined that the light trapping is very effective, with the equivalent number of passes across the cell for long-wavelength light of 26. This is accomplished by a back-surface reflectivity of 93.4% and an internal frontside reflectance of 91.7%.

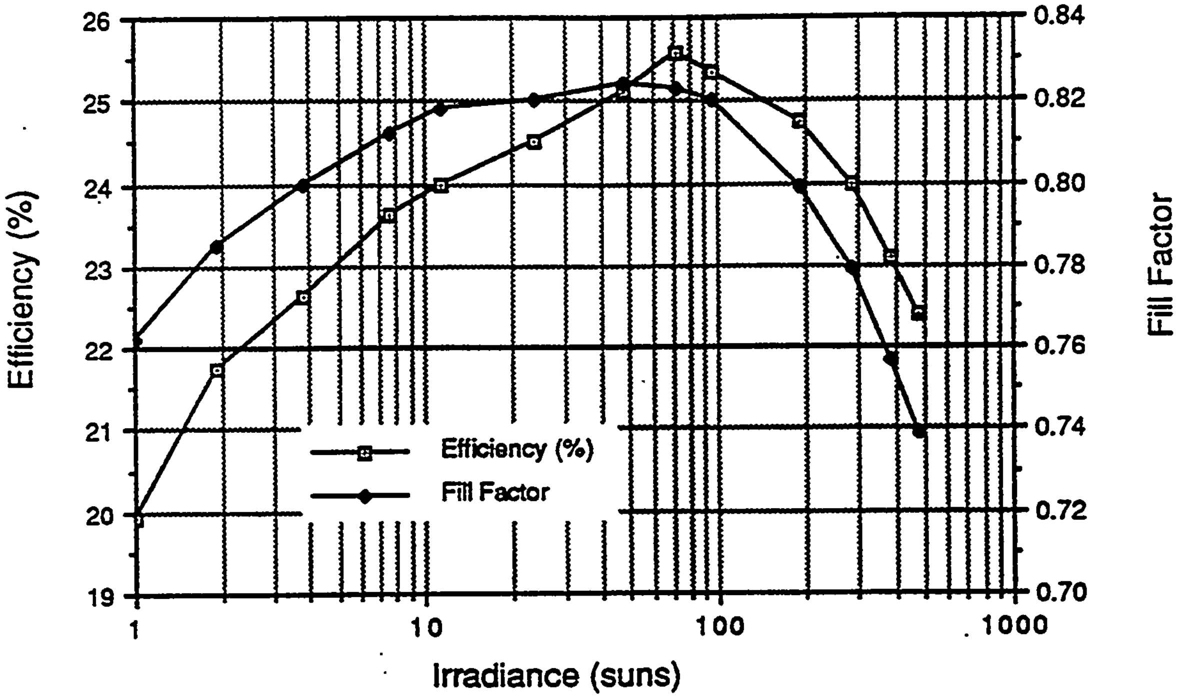


Figure 5.12. The efficiency vs. concentration as measured at Sandia National Laboratories.

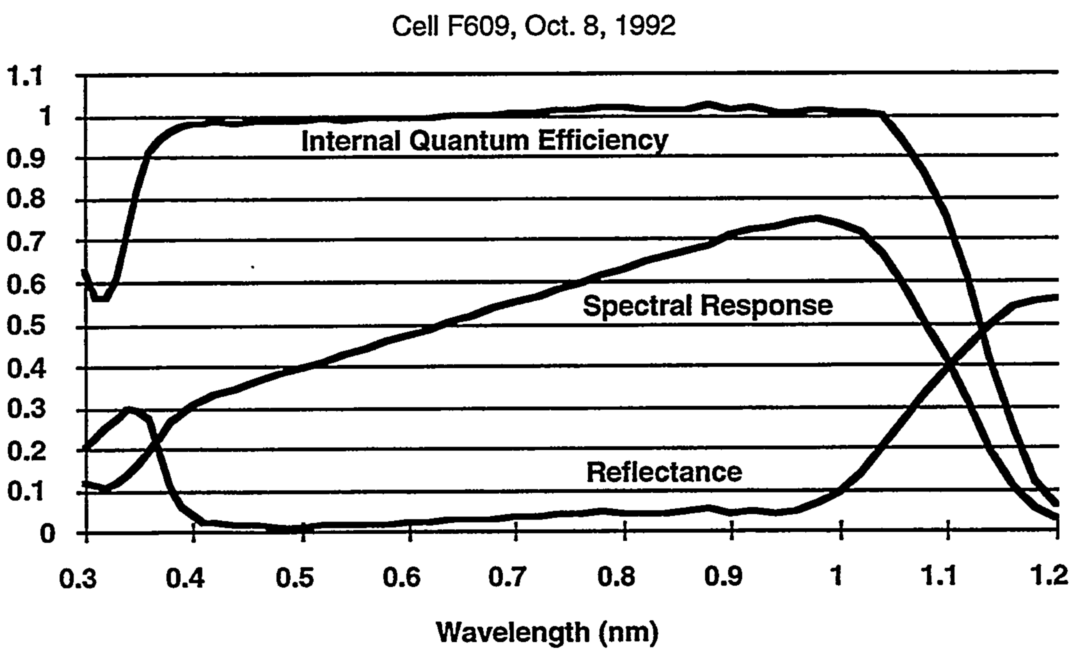


Figure 5.13. Spectral response measurements from Sandia National Laboratories.

6. Stable High-Performance Passivation

6.1 Introduction

One very important focus of research at SunPower was an effort to develop a stable front-surface passivation that offered the performance characteristics of the laboratory cells that had demonstrated 28% efficiencies. The passivations on the record breaking 28% cells demonstrated in 1987 were found to degrade when exposed to highly-concentrated light.

In previous work at Stanford University, stable passivations had been developed and incorporated into module-ready solar cells. These resulted in the stable modules shown in Figure 3.3. However, this stable passivation compromised the beginning-of-life efficiency of the solar cells. A comparison of the modeled efficiency of a cell with a stable passivation compared to the efficiency of the record cells is shown in Figure 6.1. The stable cell has a n^+-type dopant diffusion creating a front-surface field that makes the cell insensitive to damage to the oxide interface. The cell with the stable diffusion drops off in efficiency at high concentrations.

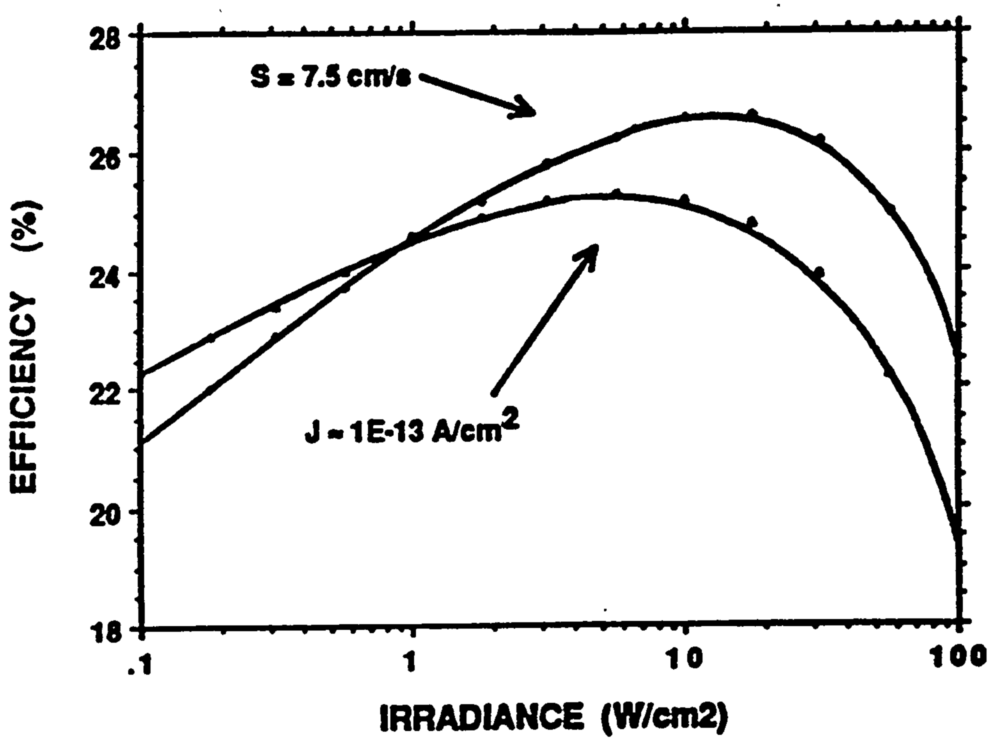


Figure 6.1. A modeled comparison of a cell with the passivation used in the 1987 record-breaking cells and the passivation used in EPRI's stable modules.

A summary of the previous work on stability is contained in an EPRI report [1]. In addition to the technique of using doped surfaces to achieve passivation stability, the previous work discovered novel structures based upon polysilicon and thin dielectrics that were also stable[14,15].

SunPower made an early decision to report efficiencies only on cells that had stable passivations. This created somewhat of a perception handicap, in that these efficiencies would, at first, be significantly lower than the 28% number considered to represent "state-of-the-art" silicon concentrator cells. To close this perception gap, an aggressive program was pursued in order to develop higher-performance front-surface passivations. This effort also required the implementation of outdoor exposure testing in order to qualify the new processes.

6.2 Development of Improved Passivations

The research continued over the entire contract period. At first, the efforts were focused upon optimizing the previous solutions to the degradation problem and verifying that they could be reproduced even as the process was switched from doped-oxide dopant sources to liquid sources. This work was accelerated in June of 1992, after SunPower's oxidation and dopant-diffusion furnaces were installed and characterized allowing more intensive study under better-controlled conditions. In addition, SunPower's antireflection coatings became available at this time, allowing a full integration of the passivation research into the mature cell-design process and fabrication.

The initial screening of candidate passivations was based entirely upon passivation performance parameters as determined by photoconductivity decay measurements. The candidate processes were chosen based upon previous experience in stable solar cell passivations [1] as well as processes from the literature known to be resistant to hot-electron effects and u-v degradation.

6.3 Testing of Cell Stability and Efficiency

Four passivations (referred to here as A, B, C, and D) were chosen for extended tests on solar cells. These were applied to the first run of the second-generation SunPower cell design in September, 1992. These cells were immediately mounted into an EPRI module for extended exposure tests under a geometric concentration ratio of 500X. The incident power density on the cells was nominally 36 W/cm^2. This represents an accelerated test by nearly a factor of two, since these cells were designed for use at nominally 20 W/cm^2. For mounting, the cells were soldered onto electrodes and heat spreaders. As this report was being prepared, the cells have accumulated nearly 500 days of exposure. One cell was chosen as a control, and the lens for this cell was covered except during the short period of testing for that single cell. Three or four cells of each passivation type were involved in the test. A detailed description of each passivation is not included here, as a patent study is in progress at EPRI.

Initial and periodic on-sun measurements were made of the responsivity at 200 suns concentration. The responsivity is subject to degradation from many effects, including any solder disbonding that may occur. As discussed in Section 4, Process Development, SunPower dramatically improved the solder bond performance of the cells a few months after this experiment was started.
The responsivity and the sublinearity of the current for the cell under high concentration are extremely sensitive to surface passivation quality. The sublinearity in the short-circuit current was determined by taking the ratio of the current with and without a screen in front of the Fresnel lens to determine the ratio of current for a fixed ratio in incident power.

The measured responsivity changes and sublinearity degradation for this test are shown in Figs. 6.2 and 6.3. From the plot of responsivity changes out to 475 days of exposure, the cells appear to be absolutely stable within a measurement variation of approximately ± 2% (relative). One cell with a D-type passivation degraded by 9.5%, while the other D-type cells were stable within ± 0.6%. Thus the apparent degradation of these cells was probably unrelated to passivation. The sublinearity degradation at high concentration also shows little variation.

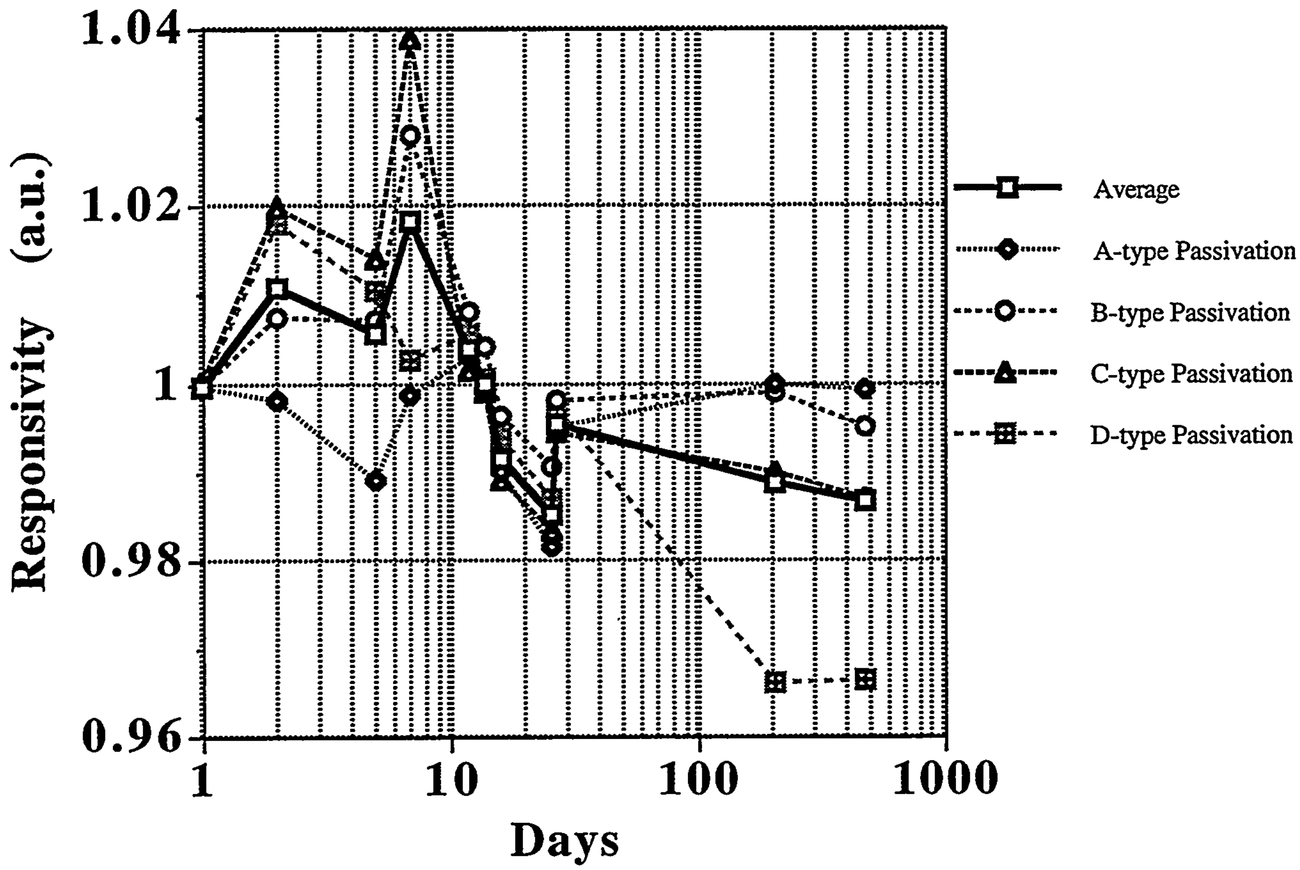


Figure 6.2. Responsivity changes as a function of the exposure time.

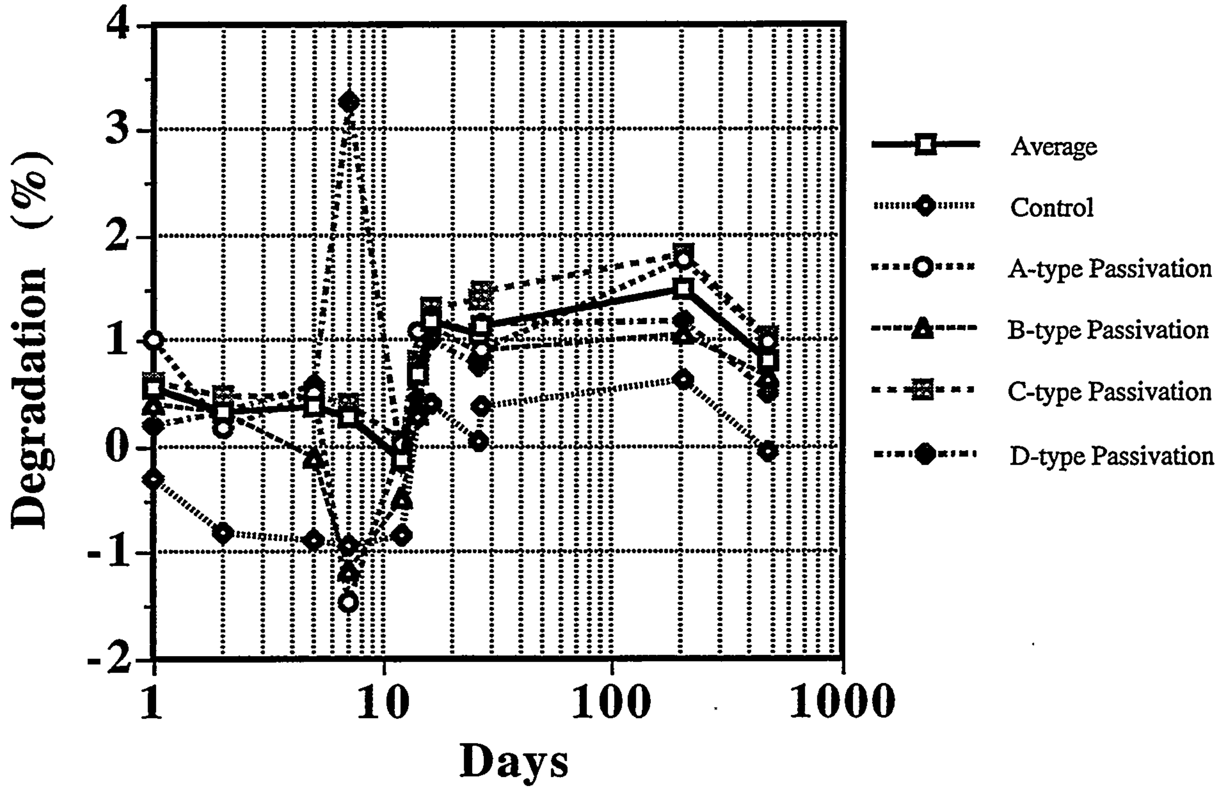


Figure 6.3. Sublinearity degradation vs. exposure time.

On the basis of Figures 6.2 and 6.3, little discrimination between the passivation stabilities could be made, since no significant degradation was observed. More controlled data on the performance qualities of the cells was assembled from the extensive measurements done at SunPower, Sandia, and Daedalus Associates on these cells.

Figure 6.4 shows performance comparison of the four passivation types based upon indoor test data taken at SunPower and Sandia National Laboratories. No statistically significant difference between the passivations can be seen. The real significant result evident in this figure is shown by the arrow. This is the performance improvement that can be accounted for by the passivation improvement alone. All four new stable passivations offer approximately a 1.7 percent (absolute) improvement in cell efficiency over the previous passivation technology.

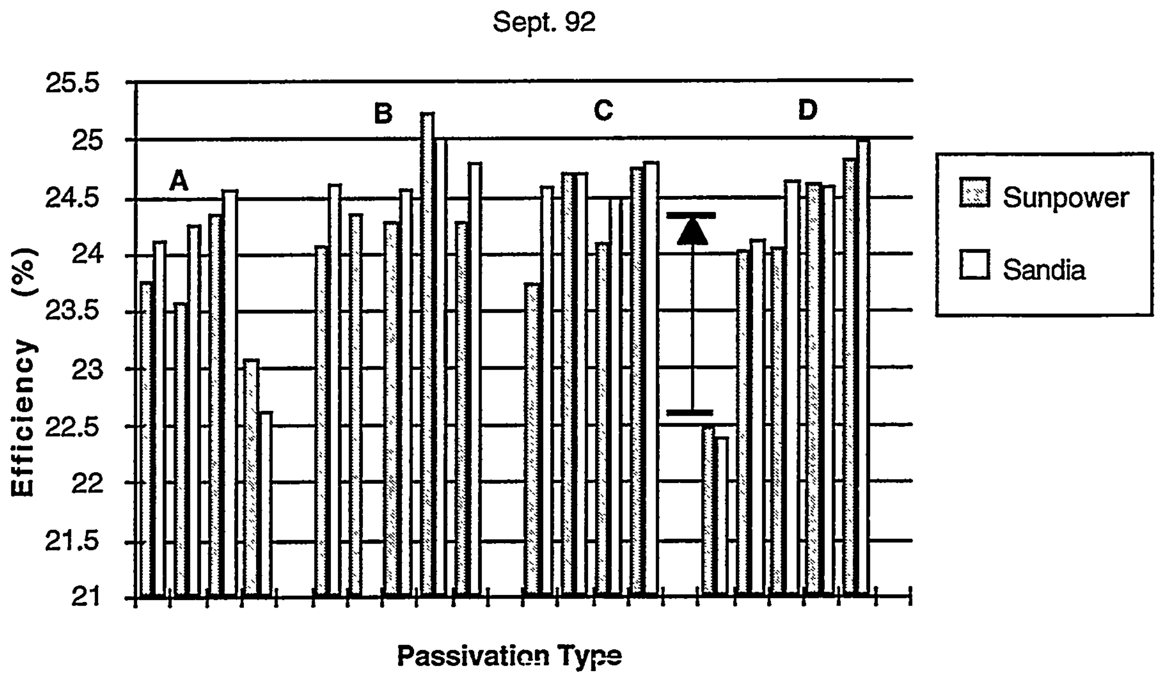


Figure 6.4. Cell performance vs. passivation for four different passivations.

Further results (Figure 6.5 and 6.6) are shown for two additional cell deliveries measured at SunPower and Daedalus Associates. The results are similar to those in Figure 6.4. No significant difference between the passivations was obvious. For subsequent deliveries, including the large number of cells delivered to EPRI during the Spring of 1993, the passivation B was used based upon processing considerations.

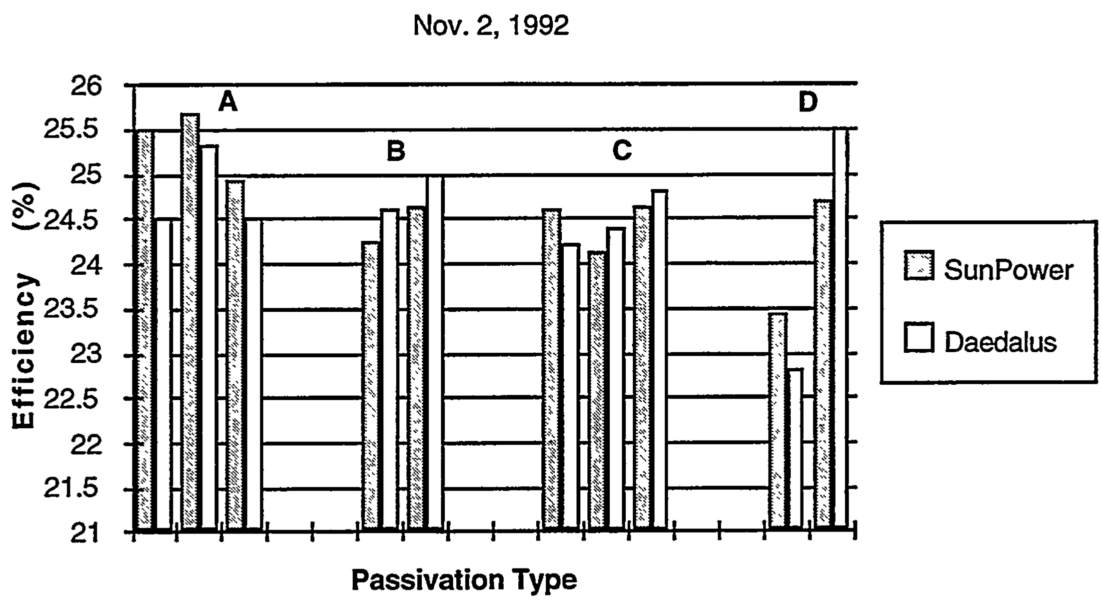


Figure 6.5. Cell performance vs. passivation

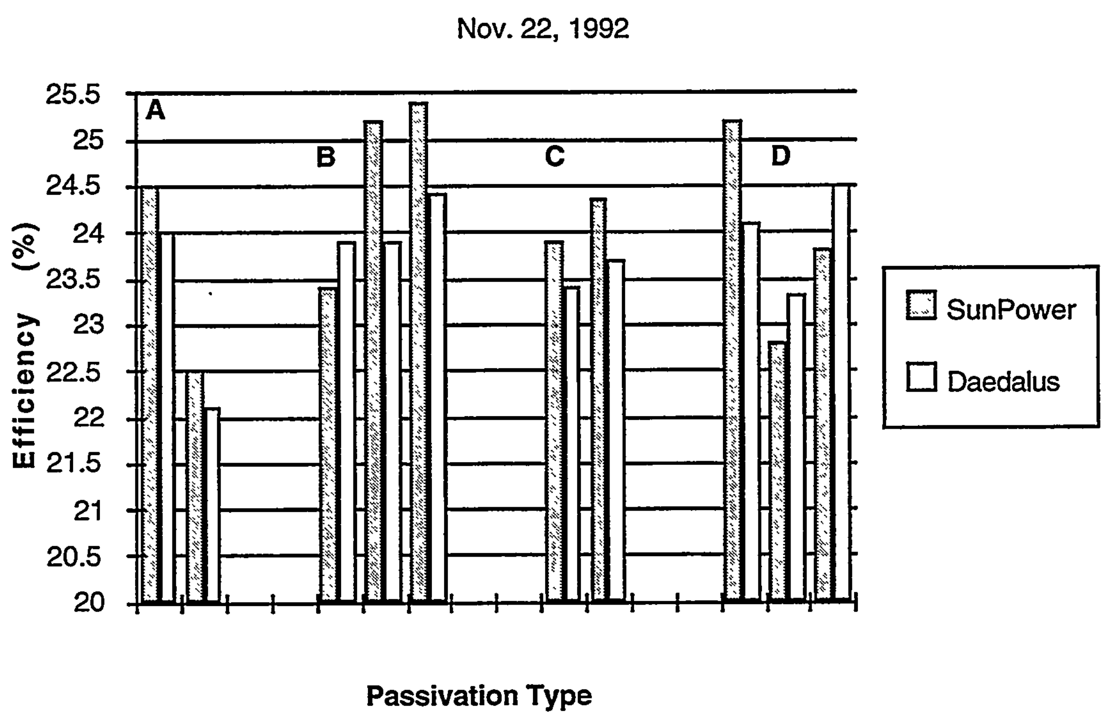


Figure 6.6. Cell performance vs. passivation

7. Pilot Production

7.1 Introduction

Early in 1993, SunPower obtained the opportunity to test its production capability in order to deliver 7000 17.7-cm^2 one-sun cells for Honda R&D Company, Ltd. These cells were produced within 7 months and averaged 21.1% efficiency under 1-sun conditions[16]. Subsequently, the car built with these cells, the Honda Dream, won the 1993 World Solar Challenge 3013-km solar car race across Australia from Darwin to Adelaide[16]. Cells from this same production run were also used in fabricating a world-record 21.6%-efficient 862-cm^2 flat-plate module[17].

For this project, SunPower chose to use it's first-generation Fresnel-cell process technology in conjunction with the simplified one-sun cell designs demonstrated previously[6,18]. This project required an extensive program of quality control in order to maintain a tight efficiency distribution and a high fabrication yield. This project also tested and calibrated the manufacturing-cost models developed during the EPRI/Sandia contract period under conditions of moderate-scale production.

Slightly-thicker wafers are permissible for high-efficiency one-sun cells than for concentrator cells. In most other ways, a tight distribution of efficiencies for one-sun cells is more difficult to achieve than for concentrator cells. Concentrator cells are tolerant to wider variations in the dopant-diffused regions and substrate lifetimes than the one-sun cells. This is demonstrated in Figure 7.1 that shows the efficiency limit determined by substrate lifetime for cells with all other parameters at the best currently attainable.

For concentrator cells, the efficiency saturates within 0.5 absolute percent of ideal for bulk lifetimes greater than 0.5 ms. In contrast, one-sun cells are sensitive to bulk lifetime until several ms lifetimes are attained. This sensitivity to the lifetime is indicative of the unique quality control challenges that had to be overcome in order to produce a large quantity of cells with a very-tight efficiency distribution. Notice that the average efficiency attained for this large number of wafers is within two absolute percent of the best efficiency ever recorded for a small laboratory silicon cell that had been measured prior to separation from the wafer[19].

This production run is essentially equivalent to a run of 800 kW of concentrator cells of the size and performance demonstrated elsewhere in this report. The demonstrated production levels, yields, and resulting cell parameters from this project extrapolate to a capability of producing 7-10 MW/yr. of concentrator cells using three shifts in the existing Cell Pilot Line.

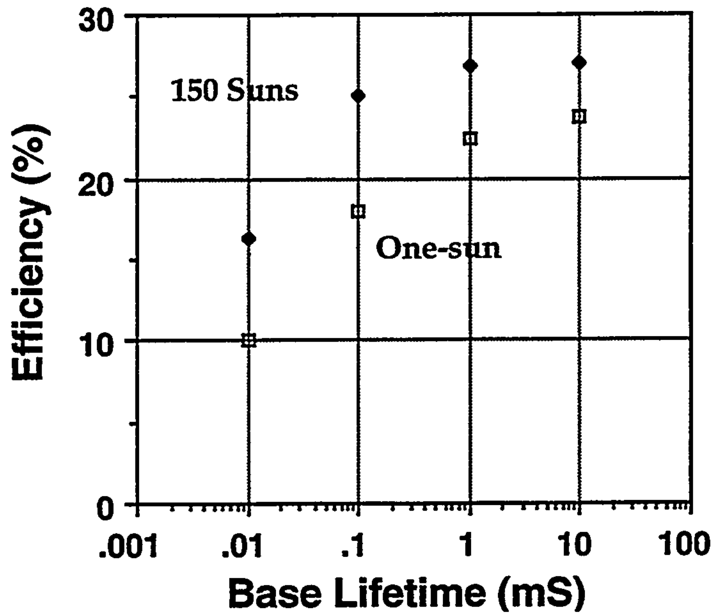


Figure 7.1. The modeled efficiency for a one-sun cell and a concentrator cell as a function of the substrate lifetime assuming ideal parameters for all other cell parameters.

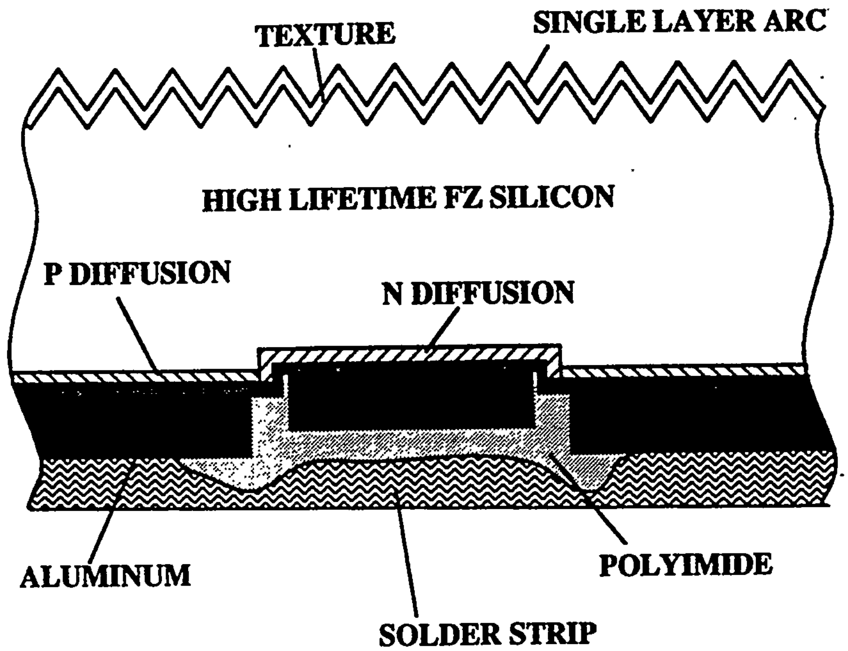


Figure 7.2. A cross section of a simplified backside-contact solar cell.

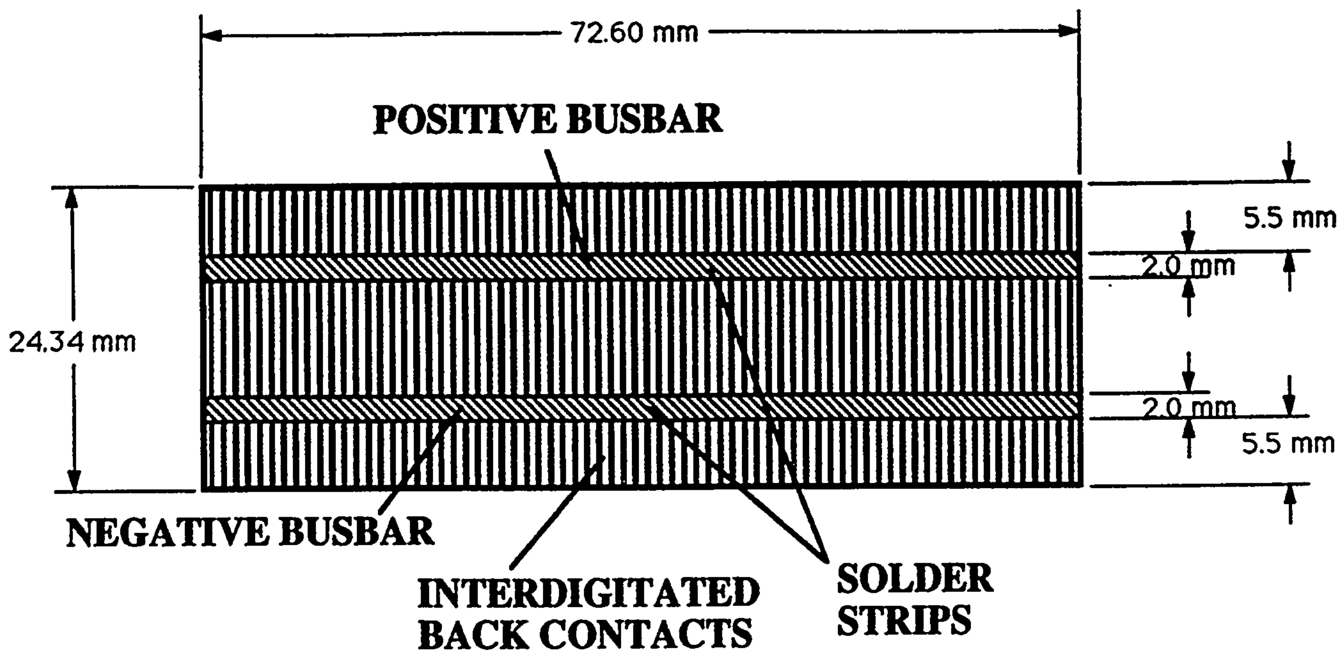


Figure 7.3. Backside configuration of the SunPower RACE solar cell

7.2 Race Solar Cell Structure

A cross section of the solar cell design is shown in Figure 7.2. These cells were fabricated on float-zone, n-type, <100>, 200 Ω-cm silicon wafers. The external dimensions are 72.5 by 24.4 mm, allowing the fabrication of two cells on each four-inch wafer. Interdigitated fingers contact both the n-type and p-type diffusions. These fingers are covered by a polyimide dielectric layer. Windows in the polyimide are opened and contacted by two large copper busbars that are deposited onto the cell. These busbars allow for simple solder attachment of leads. This backside cell layout is shown in Figure 7.3.

The frontside of the 160-μm-thick cell is textured for optimal light-trapping and covered with a single-level antireflection coating optimized for use in an encapsulated module.

7.3 Production

One of the most important challenges in scaling up the production volume at SunPower for this project was to train the new operators in high-lifetime processing techniques on thin wafers. Their previous experience had been on thick (500 μm) wafers. In addition, it was more usual to fabricate devices for which the elimination of particle defects was a primary goal and exceptional minority-carrier lifetimes were not required. Additionally, new wafer handling equipment was acquired specifically for this project and needed to be qualified for thin-wafer handling. The qualification test was a successful handling of 500 80-μm-thick wafers without any breakage.

The production volume varied from 500-600 wafer-starts per week, with a wafer moving from start to finish (including testing and packaging) in about five weeks.

During the production, the inventory was kept at 1500-2000 wafers. A computerized WIP (work-in-progress) tracking system was used to control wafer flow and set daily priorities. The entire process flow involved 34 steps. In order to meet the time requirements, 2400 wafer-steps were required per day. In order to meet these aggressive goals, the wafer flow was carefully monitored. This insured that critical bottlenecks were always fed with wafers, and wafers didn't pile up at any point in the process.

7.4 Quality Control

In addition to the obvious demands of scaling up a research project into a two-shift production operation, quality control was a major issue. During this production project, 65 process parameters were recorded on the runcards[20]. Examples of these parameters were the bath temperatures, etch rate at each etch step, dopant-diffusion sheet resistivity, critical dimension line-widths, and which equipment was used for each step. This information was made available for analysis.

An important example of the usefulness of this database presented itself during the scale-up. Twelve lots of cells had an unusually high rate of shorted cells. This was traced to a mask defect, and all of the affected cells were flagged by serial number. Some had shown high efficiencies despite their predisposition to failure during module manufacture and could have caused major problems if not identified.

Independent of the parameters measured on the cells, the pilot line itself was monitored on a weekly basis. Wafers were cleaned and oxidized in each furnace tube. The carrier lifetime, surface recombination velocity and emitter saturation current densities for the doped regions were monitored by photoconductivity decay. If any parameter was out of bounds, the production was halted until the engineering staff could identify the source of the contamination.

Each cell was measured, inspected, attached to a protective tape and individually packaged. The specification sheets included a full listing of electrical parameters from each cell, including open-circuit voltage, short-circuit current, maximum-power voltage and current, fill factor, and power. These measurements were made on a custom-built simulator with an Extra Long Hours (ELH) quartz halogen light. Two cells from the production run were calibrated at Sandia National Laboratories and used as transfer standards. One of these cells was used only to periodically check the reference cell. With tight control instituted using these reference cells, the measurements were repeatable to within 1.5% (relative). A comparison of SunPower cells from a single run between Sandia, NREL, and the Fraunhofer Institute showed that the measurements were within agreement to 3% (relative).

7.5 Fabrication Yield

Since individual cells had been fabricated with the required efficiency prior to this project, the major uncertainty facing SunPower in taking on this project was the projected fabrication yield.

The total yield can be defined as the product of:

i) The *production line yield* due to wafer breakage and process problems.

ii) The *efficiency yield* of cells with efficiency greater than 20%.

iii) The *cosmetic yield* due to cosmetic defects.

SunPower's goal to achieve an overall yield of 75% anticipated a production yield of 90%, a cosmetic yield of 100% and an efficiency yield of 84%. These goals were exceeded by carefully studying the causes of low yield. The technique of Quality Improvement was used in this research[21]. Figure 7.4 shows the Ishikawa (fishbone) diagram for the root causes of low yield.

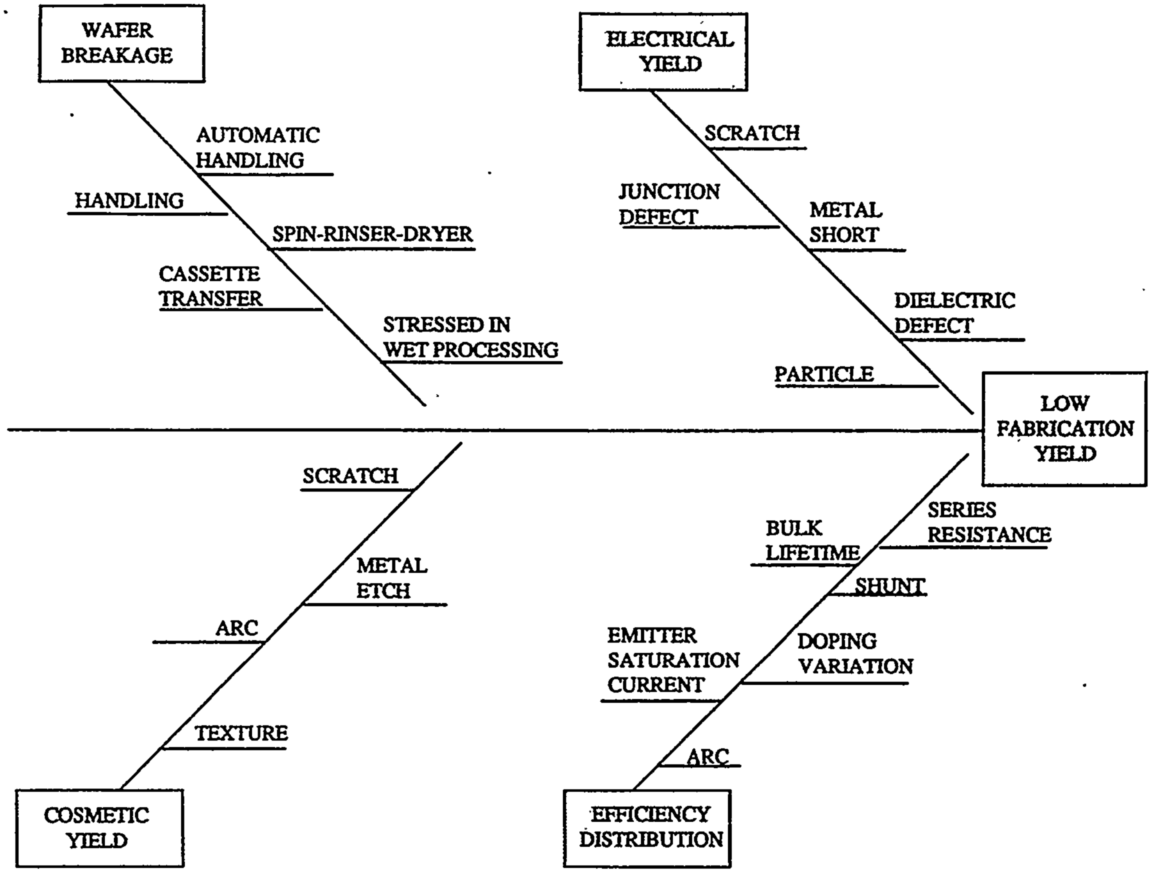


Figure 7.4. The Ishikawa (fishbone) diagram for the root causes of low yield.

7.6 Results

The average efficiency of the cells fabricated was 21.3%. The best cells had an efficiency (not independently confirmed) of 22.1% with a 0.395 A/W responsivity, a 0.690 Volt open-circuit voltage and an 81% fill factor. Figure 7.5 shows the distribution of efficiencies for the production project. The cumulative distribution for cells-to-date is shown as a function of the week into the production. The distribution of efficiencies for the initial 2 weeks peaked at 21.1%. In the third week, this shifted up to 21.3%, where it remained for all subsequent weeks.

Figure 7.6 shows the average lot values for efficiency, short-circuit current, and open-circuit voltage. Each of these parameters was controlled to within a very tight band of values. The efficiency increase with experience is more obvious in Figure 7.6 than in Figure 7.5. Towards the end of the production schedule, there is a high frequency of lots approaching an average efficiency of 22%.

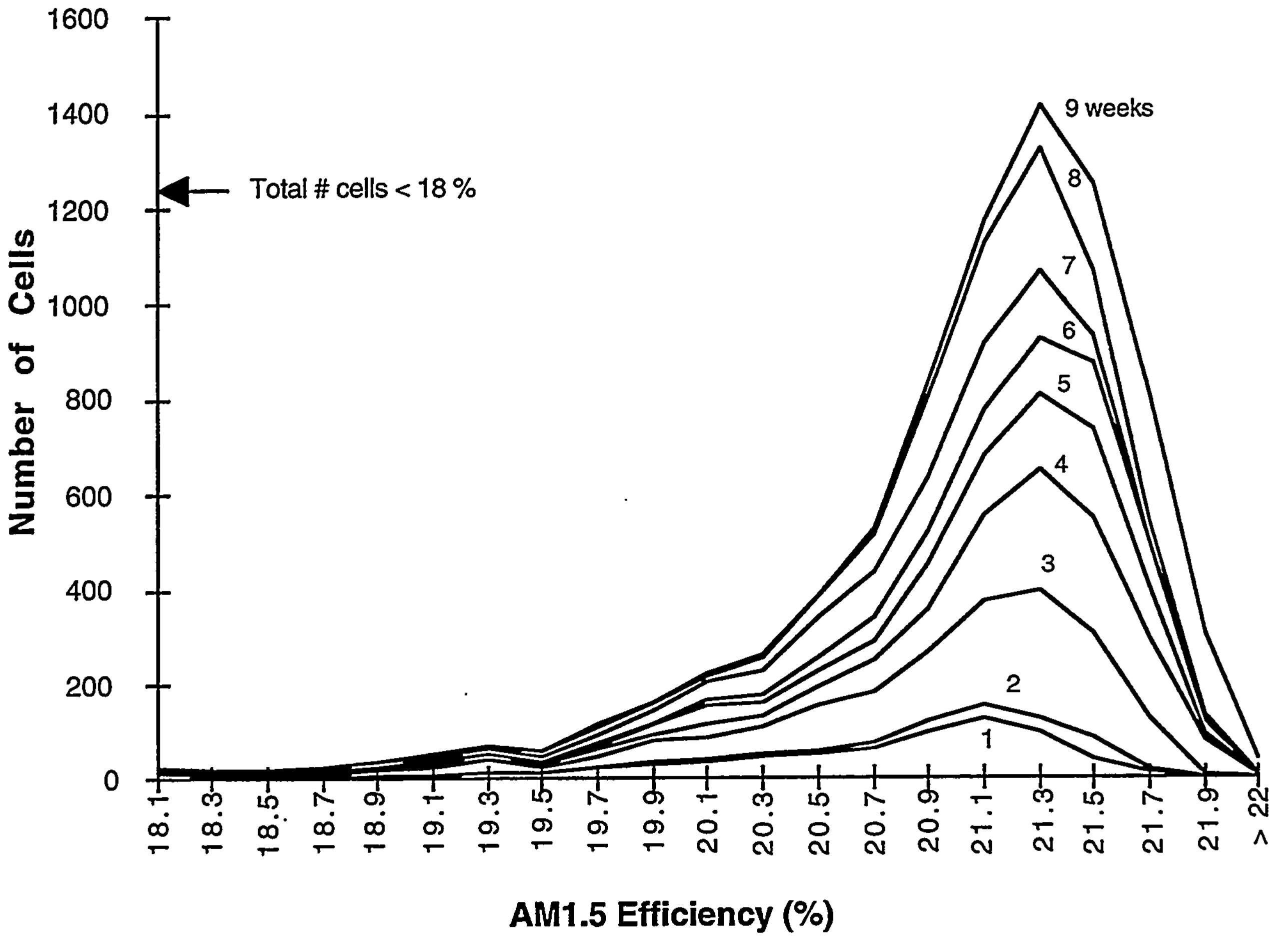
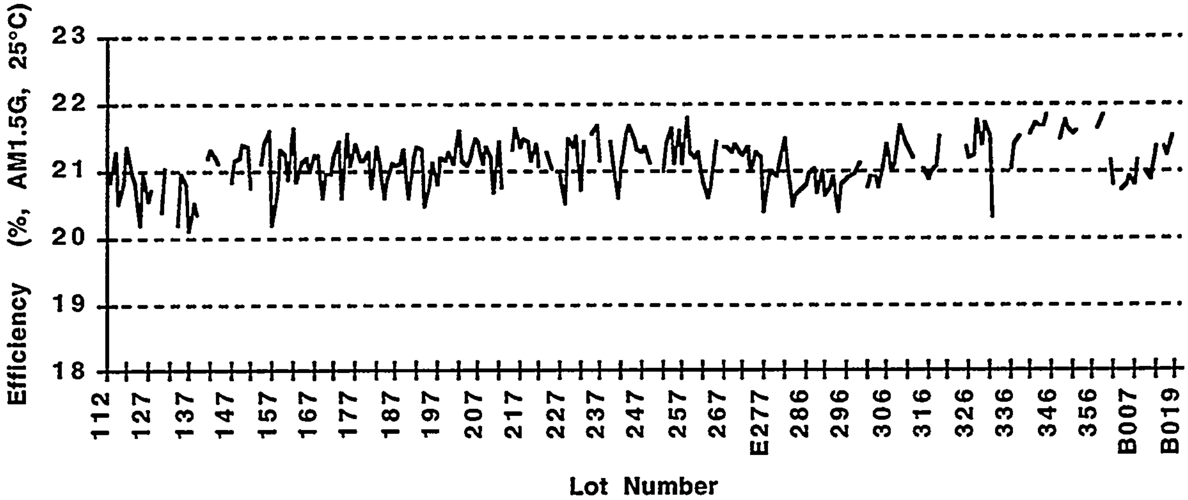
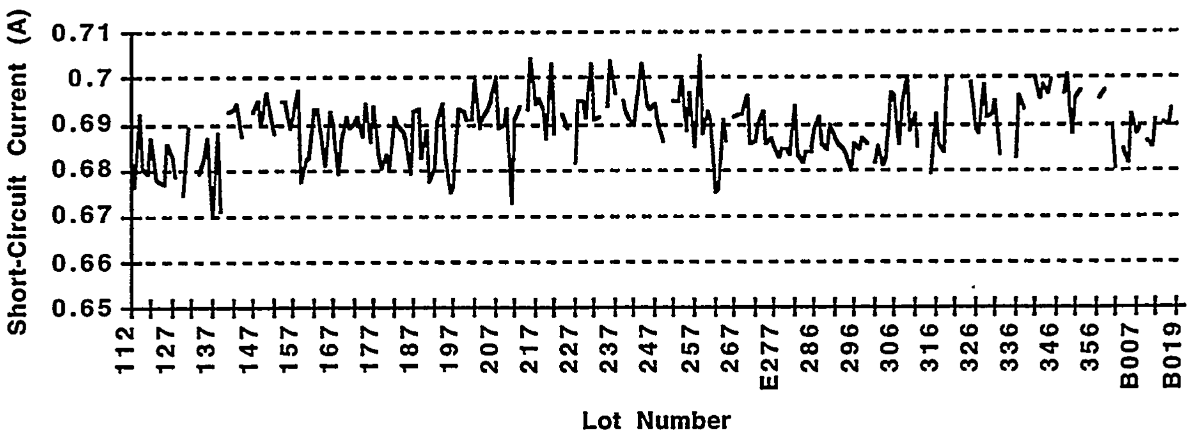


Figure 7.5. The cumulative efficiency distribution as a function of week into the production schedule .





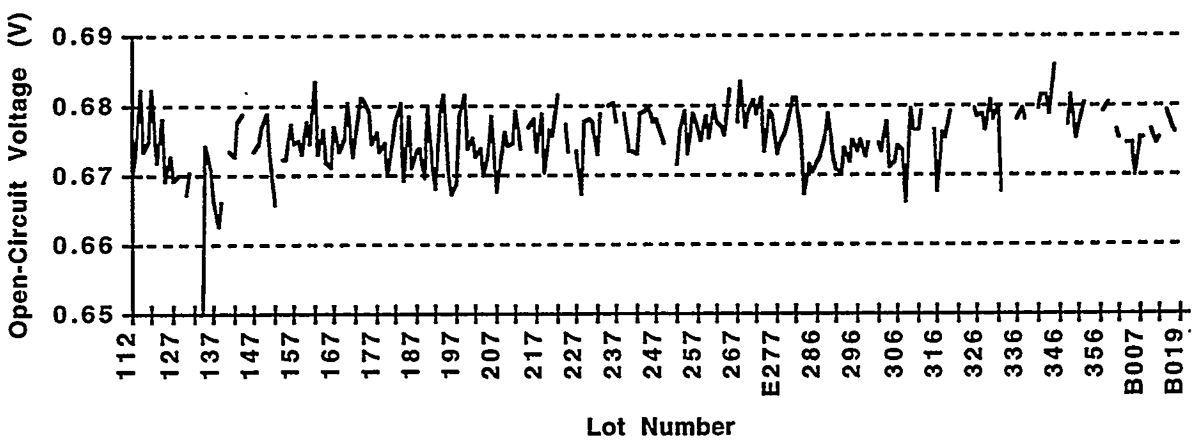


Figure 7.6. Average parameters as measured at SunPower plotted for each lot of the production.

A table indicating the results of a cell measurement exchange with Sandia National Laboratories, NREL, and the Fraunhofer Institute is shown in Table 7.1. An I-V curve from NREL is given in Figure 7.7.

Cell no.	V_{OC} (V)	J_{SC} (mA cm^{-2})	Fill factor	Efficiency (%)	Laboratory
2071	0.681	38.81	0.813	21.5	FSE
2813	0.686	37.91	0.811	21.1	NREL
2818	0.685	38.46	0.810	21.3	NREL
2830	0.681	38.93	0.804	21.3	Sandia
5710	0.679	38.92	0.806	21.3	Sandia
5714	0.679	39.01	0.805	21.3	Sandia
9264	0.690	38.18	0.811	21.4	NREL

Table 7.1. Characteristics of Measurements from Sandia National Laboratories, NREL, and the Fraunhofer Institute for Solar Energy

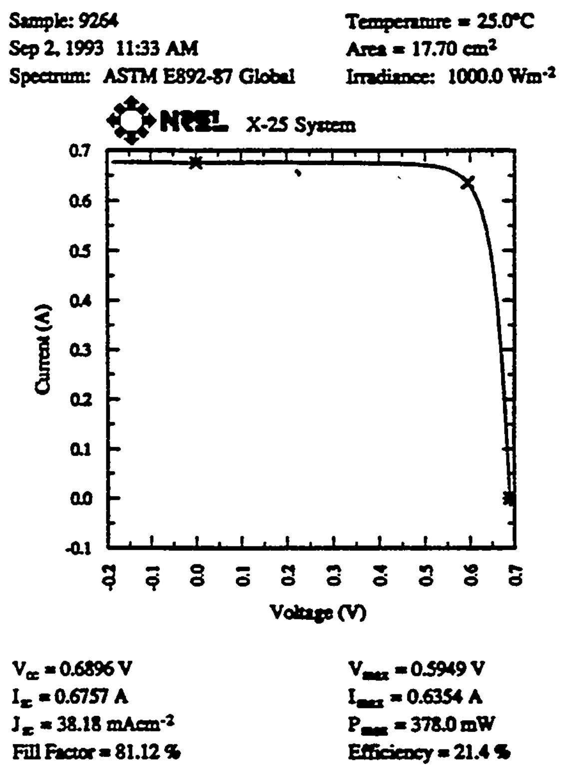


Figure 7.7. The I-V curve of a cell measured at NREL

Some of these cells were subsequently encapsulated by Honda into a 862-cm^2 module. Measurements at Sandia National Laboratories ranged from 21.53 to 21.73% (AM1.5, 25 °C). This rates as the highest-efficiency silicon one-sun module to date, improving over the 20.5% 743-cm^2 module reported by the University of New South Wales in 1993[22].

7.7 Manufacturing-Cost Modeling

SunPower did not complete a detailed manufacturing model for large-scale production prior to termination of the project. However, by tracking the expenses through the production of one-sun cells for Honda, SunPower was able to realistically calibrate a manufacturing-cost model in its small, existing fabrication facility. These costs are specifically for the SunPower facility and process. The cost model is based upon the cost of each "activity" (wafer step) that the wafer was subjected to over the length of the process. Each is costed individually in order to accurately reflect the materials, chemical, gas, and labor cost of each step. A comparison of the cost breakdown of the production of the one-sun cells at two production levels is shown in Figure 7.8 and 7.9.

Figure 7.8 shows the cost breakdown per wafers of operating the Cell Pilot Line at 150 wafers per week, about 12% of capacity. Figure 7.9 show the same breakdown at the peak production levels achieved during the project, about 500 wafers per week. In increasing the production, the cost per wafer of indirect labor (maintenance staff), labor, utilities and rent decreased significantly, as expected. The cost per wafer decreased by a factor of 2.1. Further increasing the production to the pilot-line capacity of 1200 wafers per week would decrease the manufacturing cost per wafer by approximately another 25%.

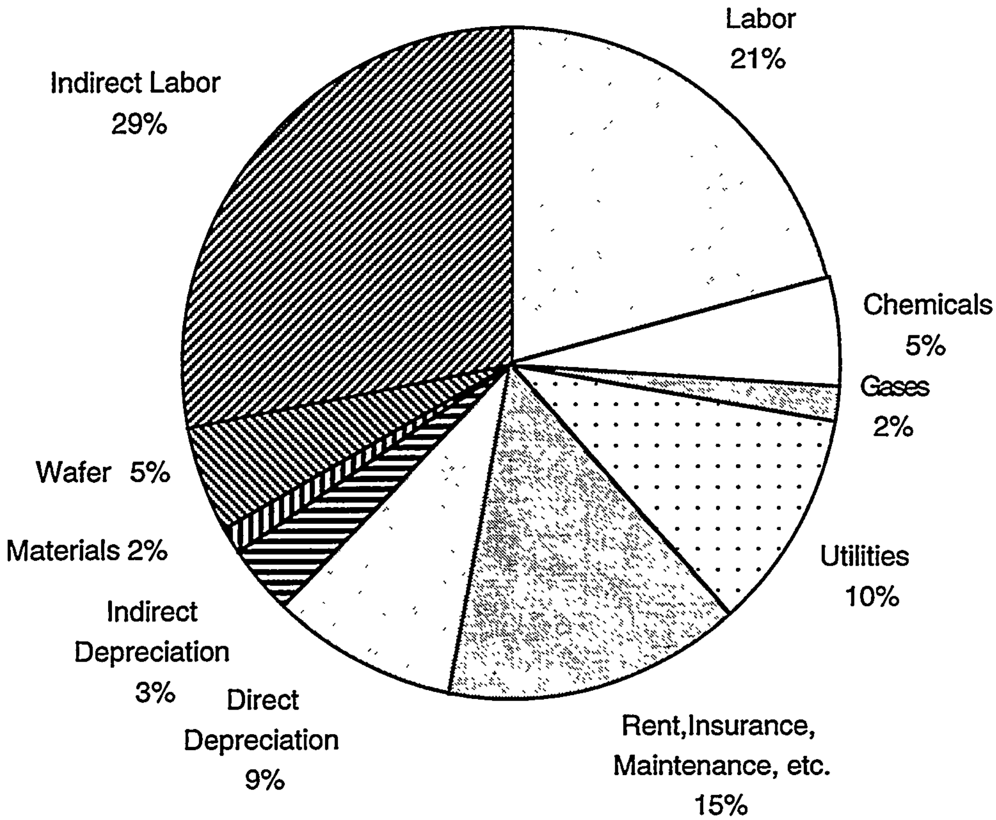


Figure 7.8. The per-wafer cost breakdown of manufacturing one-sun cells. at low production volume (17% of capacity)

7.8 Implications of This Project for Concentrator-Cell Manufacturing

These state-of-the-art one-sun race car cells were fabricated with essentially a full-blown concentrator-cell process schedule. Both the cost and the yield data gathered from this project are directly applicable to concentrator cell production. By accounting for the differences between the fabrication process at each step in the process, the cost from this project can be converted to an equivalent production of concentrator cells. For the dimensions and efficiencies for the concentrator cells reported in Section 5, 150 wafers per week is an annual

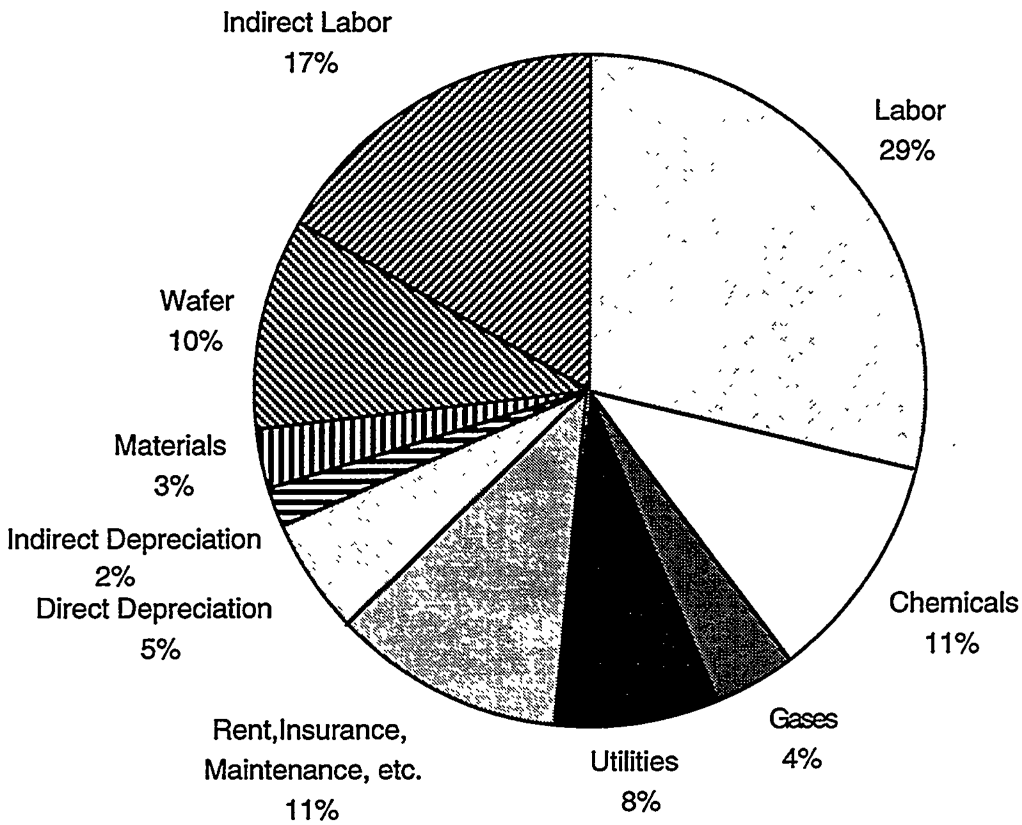


Figure 7.9. The per-wafer cost breakdown of manufacturing one-sun cells. at medium production volume (58% of capacity). This corresponds to 600 wafers per week.

production volume of 1 MW. The production level shown in Figure 7.9 corresponds to 4 MW. The full capacity of the SunPower pilot line is 10 MW per year, with 15 MW possible for higher-concentration cells.

These are immediate-term, realistic numbers based upon actual cost data for a project of similar size. At full-production capacity, the manufacturing cost of these 200X concentrator cells would fall to approximately $0.30/Watt. Further reduction in cost could be achieved even in this small facility by simplifying the process, optimizing for cost, and more significantly by increasing the wafer size to 5-inch. Additional reductions could be expected following construction of an optimized larger facility, such as 100 MW/year.

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Appendix I: Work Statements

This contract report summarized work on a project funded jointly by the Electric Power Research Institute of Palo Alto, CA. and the U. S. Department of Energy through Sandia National Laboratories. The tasks were coordinated into a project originally conceived to be 41 months in length with joint project reviews, monthly reports and other overall reporting. Although both funding agencies required funding reductions on this work, the major goals for the project were achieved nonetheless.

The overall goal of the program was to transform previous laboratory-type cell designs into a highly manufacturable, high-efficiency cell and to develop a process and production facility capable of cost-effectively supplying moderate quantities of these cells to companies which were developing concentrator systems. This appendix lists the tasks as originally conceived for this project:

Sandia National Laboratories

Task 1. Procure and fabricate necessary processing equipment.

Task 2. Establish baseline cell process.

Task 3. Improve manufacturability.

Task 4. Deliver cells. 20 cells per month (10 to EPRI, 10 to Sandia) were to be delivered starting after 1 year. Near the end of the program, a demonstration project of at least 1000 concentrator cells was planned in order to verify pilot-production capability.

Task 5. Demonstrate long-term reliability, utilizing Sandia National Laboratories solder fatigue testing capability.

Task 6. Develop a manufacturing cost model.

Task 7. Monthly, annual and final reports.

Electric Power Research Institute

Task 1. Cell modeling and design.

Task 2. Implement process characterization capability.

Task 3. Fabricate and deliver baseline cells.

Task 4. Develop and implement cell testing capability.

Task 5. Research on methods for improving cell performance.

Task 6. Research on passivation layers with improved performance and stability.

Task 7. Monthly, annual, and final reports.

Task 8. Same as Sandia Task 4.

This report presented SunPower's results in a logical, topical organization rather than by task. The completion of Sandia task 1-3 and 5 were covered in detail in sections 1, 4, and 7. Certainly the demonstration of a manufacturable high-efficiency solar cell process implicit in these tasks was presented in Section 7, Pilot Production, as well as in Section 5, cell results. During the manufacturing project described in Section 7, the actual costs of production using SunPower's facility at 42% of capacity were tracked. This allowed an unusually realistic calibration for SunPower's manufacturing-cost modeling.

The cell design Task 1 for EPRI was described in detail in Section 3. The cell testing was presented in Section 2, Testing Capability. The development of several new cell passivation technologies is described in Section 6, Stable High-Performance Passivations. Extensive testing indicates that these new passivations are stable and have performance comparable to the best unstable passivations ever demonstrated. The other EPRI tasks were necessary in order to deliver over 300 high-efficiency cells to EPRI during the Fall of 1992 and the Spring of 1993.

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