MANUFACTURE OF SOLAR CELLS WITH 21% EFFICIENCY

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ABSTRACT: This paper reports recent progress by SunPower Corporation to commercialize silicon solar cells with efficiency greater than 20%. Large-area (149cm^2) cells with efficiency as high as 21.5% (confirmed by NREL) have been made on a 1 MW/yr pilot line, and a production line with 25 MW/yr capacity has been constructed. Using a back-contact cell design and novel manufacturing techniques, cells with efficiency over 21% were produced with techniques suitable for high-volume manufacturing using Photovoltaic-grade Float Zone (PVFZ) silicon. Modules have been built. All test sequences for IEEE 1262 qualification have been passed and a 5kW demonstration array has been installed. Advantages of the cell design include a grid-less front surface and n-type starting material that does not suffer the initial light-induced degradation of commonly-used p-type wafers. Additional technical information about cell design and experiment results is also provided.

Keywords: High-efficiency, c-Si, back contact

1 INTRODUCTION

SunPower Corporation is commercializing novel high-efficiency silicon solar cells that can lower the cost and accelerate the growth of photovoltaics. The advantages of high efficiency silicon solar cells in general and SunPower's back-contact cell in particular have been previously published [1]. These advantages include reduced silicon cost on a per-watt basis and reduced per-watt module construction and installation costs. With higher cell efficiency, there is more power generated per silicon wafer. Because ingot growth and wafering accounts for almost half of the finish module cost, this is a very significant cost savings. Similarly, higher cell efficiency leverages per-watt cost savings in cell processing capital, labour, and chemical consumption, although these savings are offset by the slightly more complicated processing required to make high-efficiency cells. There are also area-related cost saving in module manufacturing because it takes the same amount of materials (glass, EVA, etc.) to make a module with higher output power. Finally, higher module efficiency leads lowers PV system costs because installation and materials costs are somewhat dependent on module area.

SunPower Corporation has previously announced the achievement of a silicon solar cell with greater than 20% efficiency using a process that was suitable for mass-production [2]. This paper reports progress to increase cell efficiency and initial module results. SunPower has built a 25MW/yr production line in the Philippines and is now in the process of ramping this factory to production levels. This facility has space to expand to 100 MW/yr production capacity.

2 TECHNOLOGY

2.1 Device design

SunPower's back-contact solar cell design is depicted schematically in Figure 1. Interdigitated n+ and p+ diffusions and grid lines are used to collect photogenerated entirely from the back of the cell.

Key design features that contribute to high efficiency include localized back contacts which reduce contact recombination losses, a grid-less front surface which permits optimization of light trapping and passivation, and a back-side metallization approach that provides internal rear-surface reflection and very low series-resistance loss.

2.2 Silicon

Because minority carriers must diffuse through the entire wafer thickness to reach the collecting junctions at the rear, this cell design requires extraordinarily high lifetime silicon starting material. SunPower requires wafers with lifetime > 1 ms. SunPower is using low-cost photovoltaic float-zone silicon starting material (PV-FZ), recently available from Topsil [3] that can meet these stringent lifetime requirements.

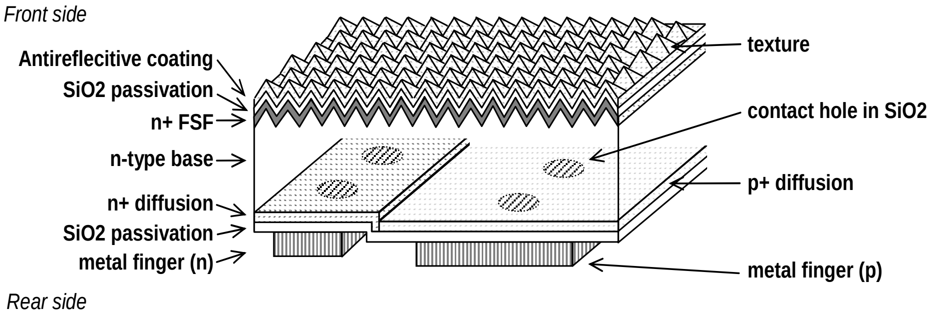


Figure 1: Schematic diagram of SunPower's A-300 solar cell (not to scale).

2.3 Cell processing

Historically, SunPower's high-efficiency back-contact solar cells have been fabricated with conventional semiconductor processing technology, including photolithography. Using such processing, SunPower produces cells with one-sun efficiencies approaching 23% but at costs affordable to just a few niche applications, such as solar airplanes and solar cars.

To reduce fabrication costs, SunPower has developed low cost screen-printing technology to replace photolithography in the fabrication the rear contact solar cells. SunPower has also adapted other low-cost solar cell processing equipment to meet our needs, such as diffusion furnaces, wet etching, and cleaning equipment.

3 PILOT PRODUCTION

3.1 Pilot line

In late 2002 SunPower began construction of a 1 MW/year pilot line in an existing Cypress Semiconductor building in Round Rock, Texas (SunPower is now a subsidiary of Cypress Semiconductor). In 2003, SunPower started pilot production of solar cells in this facility. This facility allowed the production of 125mm flat-to-flat semi-square solar cells. Our previous California facility was limited to smaller, round wafers.

3.2 Cell aesthetics

A picture of the front and back side of the cell is shown in figure 2. Note the lack of grids on the front surface. In addition to the efficiency benefits described in section 2.1, the grid-less front provides a non-reflective, pleasing appearance that enables some new applications.

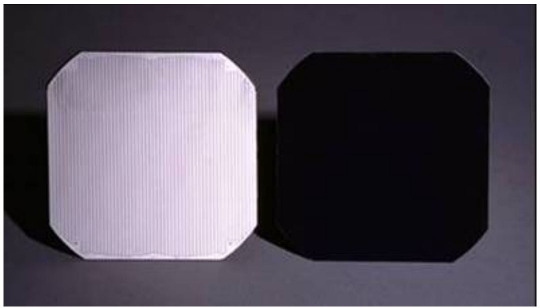


Figure 2: Back and front of back-contact 149cm^2 solar cell.

3.3 Efficiency results

Table I shows the test results for a champion cell that was made on SunPower's Texas pilot line. It was fabricated entirely by production operators using low-cost processing (no photo-lithography). Reported below are test results as measured by the National Renewable Energy Laboratory (NREL).

Table I: NREL-reported parameters of low-cost back-contact solar cell at 100 mW/cm^2, AM1.5g, 25 °C:

Area (cm2)	Silicon	Voc (mV)	Jsc (mA/cm^2)	FF	Efficiency (%)
148.9	PV-FZ	678	39.5	0.803	21.5

3.4 Spectral response

The high current (>40 mA/cm^2) is illustrated by Figure 3, which plots the spectral response (or relative external quantum efficiency). Our solar cell has a much broader spectral response than a conventional cell for several reasons. The short-wavelength response is enhanced because the cell has a lightly doped front diffusion, which avoids the dead-layer associated with the heavy diffusions of conventional cells. And the long-wavelength response is enhanced because of the excellent passivation afforded by the SiO2, which coats the rear surface except at the point contacts. The long-wavelength response is also enhanced by the excellent optics, which make the optical thickness of the cell about 6 times its actual thickness [4]. The broad spectral response increases the energy delivered per peak watt.

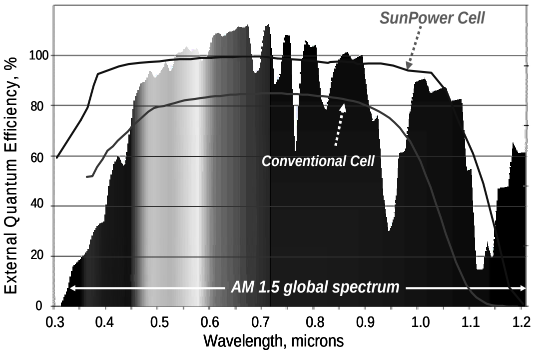


Figure 3: Spectral response of SunPower cell.

3.5 Loss mechanism

Figure 4 shows the photon and recombination loss mechanisms for the cell at the maximum power point as determined by modeling supplemented with experimental characterization. Good device modeling and extensive characterization are essential to understanding the key loss mechanisms. This knowledge is then used to guide cell process and design optimization.

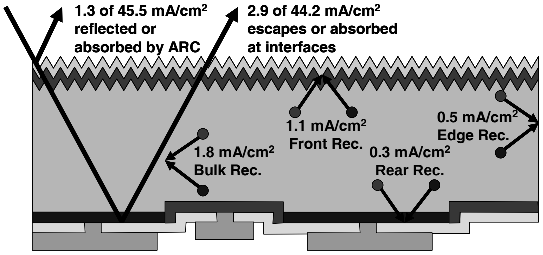


Figure 4: Breakdown of photon and recombination loss mechanisms at the maximum power point.

3.6 Temperature coefficient

The ratio of the open-circuit voltage to the intrinsic band gap is the primary predictor of the temperature coefficient of a solar cell. The high Voc of these cells (~667mV) produces a temperature coefficient on power of approximately 0.38 %/ºC. This provides a greater energy delivery per STC rated watt as compared to traditional solar cells which have a temperature coefficient of about 0.5%/ºC. Open circuit voltage versus temperature data is shown in figure 5.

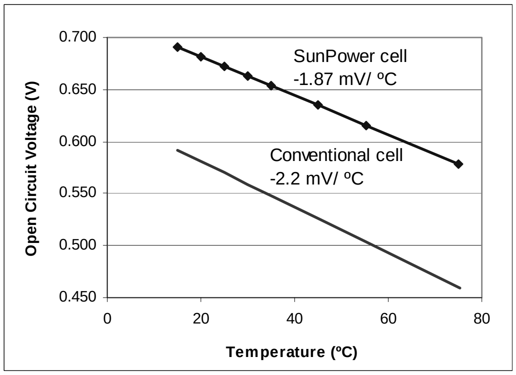


Figure 5: Temperature dependence of Voc

3.7 Stability

Modules made with cells from our pilot line have passed all sequences for IEC 61215 / IEEE 1262 qualification, including damp heat, humidity freeze, temperature cycling, hot spot, and UV soak. Notably SunPower's n-type PV-FZ cells do not exhibit the light-induced degradation (LID) effect typically seen in p-type Czochralski silicon cells.

3.8 Development methodology

Since the above NREL-confirmed value, we have continued to refine processes on the pilot line to provide the transfer-process to ramp the production facility.

We use a rigorous process development strategy based on statistical process control (SPC) and design of experiments (DOE). At the beginning of the development process, designers set targets and specification limits for each process step based on modeling or prior process knowledge. This the baseline from which the development can begin. SPC control charts are immediately set up to begin early data collection. Next, a well planned fractional factorial recipe screening DOE is done. We investigate as many input variables as practical to determine which factors have the biggest impact. For example, for SiN deposition such factors might include temperature, gas flow rates, pressure, and power. At the same time, we conduct a coefficient of variables (COV) analysis that determines the biggest sources of random variation in the process outputs and a metrology sampling plan that captures most of that variation. Once the key input variables are determined, a second optimization DOE is done to more fully map out the response surface and then retarget at the optimum process parameters.

We experimentally verify that our specification limits are set correctly by manufacturing product at and beyond the specification limits. This is done for every process step in isolation and also for several steps together where critical interactions may exist. The results of this testing is fed back into the design models.

SunPower targets a minimum process capability index (Cpk) of at least 1.3 for all processes. When Cpk significantly exceeds 1.3 we tighten the specification limits, taking advantage of the low variation to improve quality. Figure 6 shows an example SPC chart.

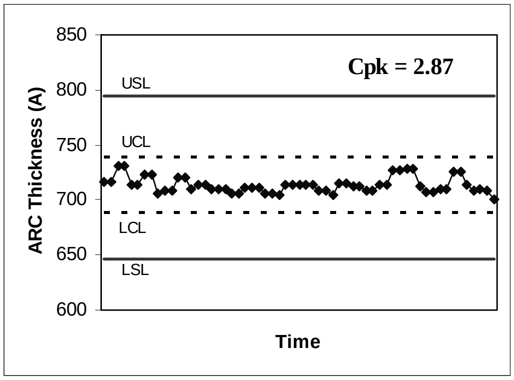


Figure 6: Example control chart (SiN ARC thickness) from SunPower's pilot line.

4 MODULES AND FIELD DEMONSTRATION

Both 32-cell and 72-cell modules have been built. SunPower's 72 cell SPW-210 module was first deployed in September 2003 at NASA's Dryden Flight Research Center, located at Edwards, Calif.

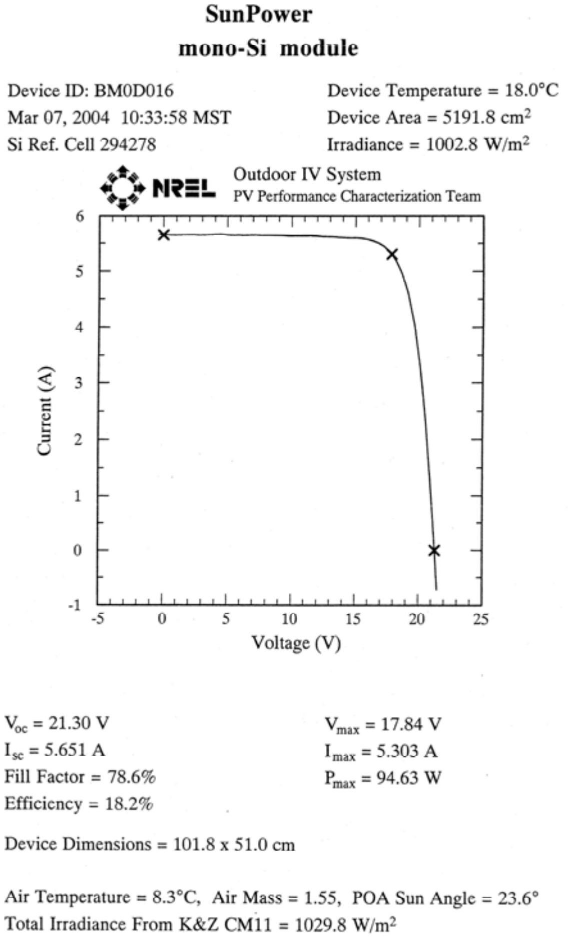
The five-kilowatt solar array (fig. 7) located at NASA Dryden is a technology transfer and commercialization success for NASA and SunPower. The Environmental Research and Sensor Technology (ERAST) program helped finance technology development that eventually evolved into the A-300 solar cell.

Figure 7: NASA Dryden Flight Research Center's solar array site. (NASA photo by Tom Tschida)

The experimental site consists of two fixed-angle solar arrays and one single-axis tracking array. One of the fixed arrays contains typical, less efficient cells, and is being used as a baseline comparison for the newer fixed-cell array. The sun-tracking array tilts to follow the sun using an advanced "real-time" tracking device rather than normal pre-programmed mechanism. Part of the demonstration is to compare the actual energy delivery and system cost with the array output modeling program established by Sandia National Laboratory.

Figure 8 shows the test results for a 32-cell module that was made with cells produced on SunPower's Texas pilot line. The module has an aperture area efficiency of

18.2% and produces 95W.



SunPower
mono-Si module

Device ID: BM0D016
Mar 07, 2004 10:33:58 MST
Si Ref. Cell 294278

Device Temperature = 18.0°C
Device Area = 5191.8 cm^2
Irradiance = 1002.8 W/m^2

NREL Outdoor IV System
PV Performance Characterization Team

V_{oc} = 21.30 V
I_{sc} = 5.651 A
Fill Factor = 78.6%
Efficiency = 18.2%

V_{max} = 17.84 V
I_{max} = 5.303 A
P_{max} = 94.63 W

Device Dimensions = 101.8 x 51.0 cm

Air Temperature = 8.3°C, Air Mass = 1.55, POA Sun Angle = 23.6°
Total Irradiance From K&Z CM11 = 1029.8 W/m^2

Figure 8: IV Curve 18.2% efficient 32-cell module tested by NREL.

5 LARGE-SCALE MANUFACTURING

Based on the results of the pilot line, SunPower designed a 25 MW/year factory. Construction began in November 2003 and was completed May 2004. Most of the equipment is now installed and cells up to 19.9% efficiency have already been produced with most of the steps performed on the full-scale equipment. The outside of the building, which is located in the Philippines, is shown in Figure 9. A picture of the manufacturing area is shown in Figure 10.

6 SUMMARY

SunPower is commercializing a back-contact solar cell with 20% minimum efficiency and outstanding visual appeal. We have reported a maximum cell efficiency of 21.5% for a large-area cell manufactured with a low-cost process in a production environment. SunPower has built a 25MW factory in the Philippines and is in the process of ramping that factory to full production. Modules built with SunPower cells have achieved 18.2% efficiency and are currently being field-tested.

Figure 9: Production facility building

Figure 10: SunPower manufacturing facility

7 REFERENCES

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