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The Path to 25% Silicon Solar Cell Efficiency: History of Silicon Cell Evolution

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The first silicon solar cell was reported in 1941 and had less than 1% energy conversion efficiency compared to the 25% efficiency milestone reported in this paper. Standardisation of past measurements shows there has been a 57% improvement between confirmed results in 1983 and the present result. The features of the cell structure responsible for the most recent performance increase are described and the history of crystalline and multicrystalline silicon cell efficiency evolution is documented. Copyright © 2009 John Wiley & Sons, Ltd.

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INTRODUCTION

Since the first silicon solar cell was reported in 1941,[1] there have been substantial improvements in silicon cell performance, culminating in the 25·0% value reported in the present paper. Since 1983, key results have been independently measured at recognised testing centres.[2] Over the same period there has been ongoing refinement and standardisation of cell measurement techniques. The most recent refinement has been in April 2008 with the acceptance by the International Electrochemical Commission (IEC) of a revised global AM1·5 spectrum (IEC 60904-3: Ed. 2 equivalent to ASTM G173).[3–5] A unified history of the evolution of silicon cell performance is presented, normalised to present reporting conditions. The commonly cited National Renewable Energy Laboratory (NREL) graph of 'Best Research-Cell Efficiencies'[6,7] is shown to have overlooked several key results over the 1983–1990 timeframe.

TWENTY-FIVE PER CENT EFFICIENT PERL CELL

The recent revision of the internationally accepted reference solar spectrum[3–5] has resulted in the achievement of the major 25% efficiency milestone by a passivated emitter, rear locally diffused (PERL) cell shown in Figure 1. Referenced to the new spectrum, output parameters of this 4 cm^2 cell are 706 mV, 42·7 mA/cm^2, 82·8 and 25·0% for V_{oc}, I_{sc}, fill factor and efficiency, respectively. This cell had an efficiency of 24·7% under the now-obsolete IEC 60904-3: Ed. 1 spectrum.[8]

The new reference spectrum has more energy at both blue and red ends of the spectrum, with relatively less energy at intermediate green wavelengths.[3] The exceptionally strong response of the PERL cell at both blue and red wavelengths increases its performance margin over less highly performing devices. The strong

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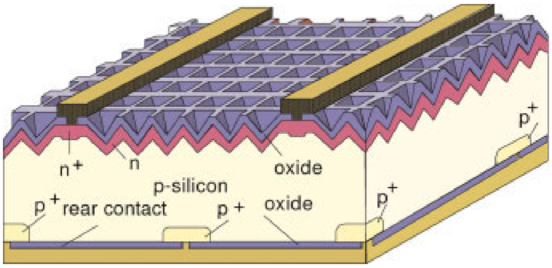

Figure 1. PERL cell

blue response of PERL cells stem from the lightly doped top surface (estimated $4 \times 10^{18}/cm^3$ P concentration[9]) and the retention of a thin annealed oxide under the overlying double layer antireflection (DLAR) coating.[10] This gives essentially 100% internal quantum efficiency (IQE) at blue wavelengths with impact ionisation increasing the IQE above 100% at wavelengths below 370 nm.[11] External quantum efficiency (EQE), however, is reduced at such wavelengths both by increased reflection due to the rapidly increasing complex refractive index of silicon as wavelength decreases[12] and by absorption in the high-index ZnS component of the DLAR.

The good red response is a consequence of the high carrier lifetimes,[8] effective 'tiler's pattern' inverted pyramid light-trapping scheme,[13] the dielectrically enhanced metallic rear Al reflector,[14] reduced free carrier absorption by low bulk doping, high mobility in the n-type layer of Figure 1 and minimal volume of n^+ and p^+ diffusions,[14] together with the relatively large cell thickness (nominally 400–450 μm).

MEASUREMENT HISTORY

The 25% cell result represents the latest step in the 60-plus year history of silicon cell development. Over the last two decades of this history, terrestrial cell measurements have evolved to the stage where independent laboratories measure the same result for standard silicon cells within 1–2%.[15,16] However, most key results have been reported under conditions different from the recently revised IEC standards.

In the 1970s and 1980s, international leadership in photovoltaics resided in the US with NASA taking the early lead in cell measurements. Techniques for AM0 cell calibration to an estimated accuracy of 1% have been established for some time.[17] Although such AM0 reference cells have since been shown to give accurate terrestrial measurements with appropriate spectral corrections,[17] in 1977 NASA chose an independent technique for terrestrial cell calibration under a direct normal (DN) AM1·5 spectrum.[18] In this methodology, NASA was designated as the sole source of reference cells and supplied cells to many groups, both in the US and internationally. Many years were to pass before these terrestrial calibrations were shown to be inconsistent with the AM0 calibrations.[19,20]

As a result of early initiatives by SERI (Solar Energy Research Institute, now NREL) that encouraged the development of high-efficiency silicon cells, several key silicon cell results were measured at SERI in the early 1980s,[21] the beginning of what will be referred to as the 'modern phase' of silicon cell development. Prior to 1985, these measurements were at 28°C relative to NASA-calibrated reference cell N265 under a Spectrolab X-25 simulator, without spectral mismatch correction. In 1984, SERI began calibrating its own reference cells using a technique incorporating spectral correction.[17] A large difference from the NASA calibration was noted, as subsequently reported.[19,20]

From May to September 1985, SERI reported measurements under the NASA DN spectrum[18] relative to both NASA and SERI calibrated cells, as well as under the ASTM E891-82 DN and ASTM E892-82 global spectra.[22] From October 1985, all one-sun measurements were relative to the ASTM global AM1·5 spectrum at 25°C referenced to SERI calibrated cells. The ASTM standard was first published in 1985 then adopted by the International Electrotechnical Commission (IEC) in 1989 as IEC 60904-3 Ed. 1.

To refer earlier measurements to this standard spectrum, several factors have to be taken into account. Measurements on UNSW cells during 1985 when cells were measured with both techniques show that an average 5·3% reduction in current was required to incorporate spectral mismatch correction and the difference from the NASA calibration. Conversion from the NASA DN to the ASTM E892 global spectrum produced a 0·6% current increase for good cells. A 0·2% decrease would result from the reduced measurement temperature, giving an overall 4·9% decrease in current. Less than 2% of this difference can be explained by spectral correction errors. *V*oc would increase a net 5 mV with fill factor unaltered, to measurement accuracy, resulting in approximately 3·7% reduction in efficiency. Uncertainty in this

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conversion process is estimated as 1% (relative), additional to normal measurement errors.

Sandia was next to become active in high efficiency silicon cell measurements. Prior to 1987, these were under the NASA DN spectrum,[18] reflecting Sandia's involvement with concentrating photovoltaics. Measurements were referenced to NASA calibrated cell Y49 under a XT-10 simulator without spectral mismatch correction. After these corrections were incorporated, measurements were reported relative to either the ASTM E891-82 DN or ASTM E892-82 global spectrum, with spectral correction to account for the different calibration spectrum of the NASA reference cell. Measurements under the ASTM global spectrum were generally 2–3% less conservative than earlier measurements under the NASA DN spectrum, depending upon the cell's spectral response.

An interchange of UNSW cells between Sandia and SERI in 1990 brought to light a much larger measurement difference than in earlier such interchanges. To resolve this difference, Sandia developed its own primary cell calibration technique rather than relying on NASA calibrated cells. Round robin comparisons of cells calibrated with this new technique showed no systematic differences from SERI calibrated cells, despite the difference in calibration approach.[2]

A prolonged period of nearly 20 years stability in cell measurement followed. For reasons explained elsewhere,[23,24] but due mainly to perceived deficiencies in the ASTM E891-82 DN spectrum, a new global and DN spectra were developed by the appropriate ASTM sub-committee and released in 2003 as ASTM G173-03. In April 2008, the IEC voted to accept the new global spectrum as IEC 60904-3 Ed. 2. Solar cell testing centres began converting to the new spectrum from mid-2008.

Based on the above discussion, Figure 2 shows the factor by which past reported short-circuit currents must be multiplied to convert to present standards. The shaded areas indicate estimated uncertainty in this transformation due to differences in the spectral responses of the cells involved. Normal measurement errors must be superimposed. Table I shows the evolution of silicon cell efficiency over the modern period of development standardised on the basis of this discussion (or further refined where additional information is available). This table documents a massive 57% relative increase in silicon cell efficiency over this period. Note that several key results in this history do not appear on a widely used NREL chart showing cell efficiency improvements,[6,7] including neglect of such milestones as the attainment of the first 20% silicon cell in 1985.

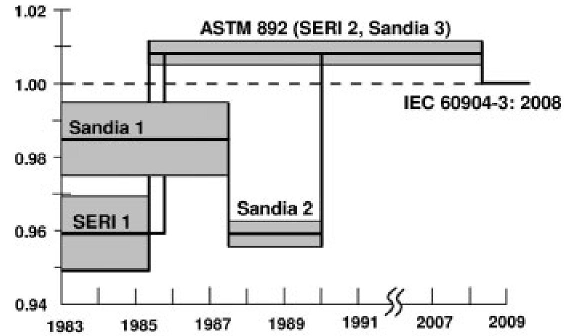

Figure 2. Calibration factor multiplier allowing conversion of past short-circuit current measurements to present standards

Also listed in Table I is the basis on which the area of the cell is defined. Three different area definitions are presently used by test centres as discussed in detail elsewhere.[25] These are total area, where the total area of the cell is used, the aperture area, where a mask is used to define the cell area, with all active cell components lying within this area, and the designated illumination area where some components, normally busbars, lie outside the masked area. Before 1985, most cells were measured on a total area basis. This created some difficulties due to rough cell edges since some test centres, rather than measuring the total projected area of the cell,[26] believed that a maximum packing density area (such as might be measured by vernier callipers[21]) was more appropriate. This discriminated strongly against cells measured on this basis compared to cells where areas were precisely defined by masks or photolithography. Optimal sizing and alignment of masks present additional challenges for test centres so most of the most recent results in Table I have been measured on a 'designated illumination area' basis. In such measurements, the cell area is precisely defined by a 'picture frame' metal busbar with a non-critically aligned external mask also used to eliminate stray light response.

EARLIER HISTORY

The first silicon cells were described by Ohl in 1941 using melt grown junctions.[1] From the description of these devices, efficiency is assessed as less than 1%. The next step forward was reported in 1952 when

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Table I. History of silicon cell improvement (>1 cm^2 area) over the modern era normalised to present standard test conditions (25°C, 1000 W/m^2, IEC 60904-3: 2008 global spectrum, equivalent to ASTM G173-03 global spectrum)

Date	Reported efficiency (%)	Test conditions*	Corrected efficiency (%)	Cell description
1/83	16·5	SERI 1 (t)	15·9	ORNL
5/83	17·1	SERI 1 (t)	16·5	ASEC
8/83	17·1	SERI 1 (ap)	16·5	Westinghouse
9/83	18·0	SERI 1 (t)	17·4	Spire textured
	18·7	SERI 1 (t)	18·1	UNSW MINP
12/83	19·1	SERI 1 (t)	18·4	UNSW PESC
5/85	19·8	SERI 1 (ap)	19·1	UNSW PESC
10/85	20·0	SERI 2 (ap)	20·2	UNSW μg PESC
7/86	20·6	SERI 2 (da)	20·8	UNSW μg PESC
4/88	21·4	SANDIA 2 (ap)	21·0	UNSW μg PESC
9/88	22·3	SERI 2 (ap)	22·5	Stanford
6/89	23·2	SANDIA 2 (ap)	22·6	UNSW PERC
12/89	23·0	SERI 2 (ap)	23·2	UNSW PERL
2/90	24·2	SANDIA 2 (ap)	23·4	UNSW PERL
3/94	23·5	ASTM E892 (ap)	23·7	UNSW PERL
9/94	24·0	ASTM E892 (ap)	24·2	UNSW PERL
2/98	24·4	ASTM E892 (da)	24·7	UNSW PERL
11/98	24·5	ASTM E892 (da)	24·7	UNSW PERL
3/99	24·7	ASTM E892 (da)	25·0	UNSW PERL

*(t) = total area, (ap) = aperture area, (da) = designated illumination area.

Kingsbury and Ohl reported devices with junctions formed by helium ion bombardment.[27] These devices showed reasonable spectral responsivity and, although measurements were not reported under sunlight, would have been expected to show an efficiency of about 1%.

Cell efficiency then evolved rapidly with the introduction of diffused junctions. Bell Laboratories fabricated a cell with 4·5% efficiency in 1953[28] and 6% in 1954.[29,30] The 10% efficiency mark was exceeded within 18 months.[31] In 1961, a 14·5% terrestrial cell efficiency was measured for a commercial cell fabricated upon a phosphorus doped substrate.[32] With the switch to boron doped substrates about this time, lower efficiency was obtained, but a higher radiation tolerance in space. It was not until the early 1970's that efficiencies on boron-doped substrates approached this 14·5% figure.

The first cell to convincingly exceed this 14·5% figure was the 'violet' cell developed at Comsat Laboratories in the early 1970s[33] introducing a second phase of cell development. Terrestrial cell measurements are reported by Rittner and Arndt,[34] although possibly not for the highest performing cells. Based on an AMO efficiency of 13·7%, an AM1·5 efficiency of over 15% would be expected for these cells. This mark was soon exceeded by the Comsat non-reflecting cell using textured surfaces.[35] These displayed efficiencies above 15% under the AMO spectrum. Terrestrial measurements gave efficiency up to 16·7%,[34] although again this may have not been for the best cells produced. Based on an AMO efficiency approaching 15·5%, a champion cell efficiency of 17·3% under terrestrial conditions is assigned.

For the next decade, no cell convincingly demonstrated higher efficiency. The next improvement was in 1983 when the UNSW MINP cell demonstrated 18% efficiency for the first time,[36] introducing the modern period of cell development. From this date, Table I documents subsequent improvements, with the leading cell technology transitioning from MINP to PESC, to rear point contact cells, to PERC cells and ultimately to the PERL cell of Figure 1.

MULTICRYSTALLINE CELLS

Although the early cells made by Ohl in 1941[1] and subsequently[22] were based on multicrystalline silicon formed by directional solidification, the modern interest in this approach stems from two papers presented sequentially at the 12th IEEE Photovoltaic Specialists Conference in Orlando in 1976.[39,40]

Solarex (since assimilated into BP Solar) reported achievement of 10% AM1 efficiency with this approach, while AEG Telefunken/Wacker reported efficiencies of up to 12·5% (AM0) and 14·5% (AM1).

Table II. Early evolution of silicon solar cell efficiency (>1 cm^2 area) nominally under the IEC 60904-3: 2008 global or ASTM G173-03, global AM1·5 spectrum at 25°C and 1000 W/m^2 illumination intensity (all cells measured on total area basis; most measurements 'in-house')

Date	Efficiency (%)	Cell structure	Organisation	Reference
3/41	<1	Melt grown junction	Bell laboratories	1
3/52	~1	He bombardment	Bell laboratories	27
~12/53	~4·5	Li diffused wraparound	Bell laboratories	28
1/54	~6	B diffused wraparound	Bell laboratories	29
11/54	~8	B diffused wraparound	Bell laboratories	30
5/55	~11	B diffused wraparound	Bell laboratories	31
~12/57	~12·5	$0{\cdot}5 \times 2\,cm^2$ B diffused	Hoffman electronics	37
8/59	~14	Grid-contact B diffused	Hoffman electronics	38
8/61	~14·5	B diff. AR coat, gridded	Commercial, USASRDL	32
1/73	~15·3	Violet cell	Comsat laboratories	33,34
9/74	~17·3	Textured non-reflecting	Comsat laboratories	35,36
9/83	18·1	MINP cell	University of NSW	36

At the next conference in this series,[41] Solarex reported 16% AM1 efficiency, a value later confirmed at SERI under the then prevailing test conditions.

The history since then (Table III) roughly parallels that of crystalline cell development. Again the widely referenced NREL chart[6,7] overlooks several key results in this history over the 1984–1990 period.

The consolidated set of results from Tables I–III are plotted in Figure 3.

SUMMARY

A milestone efficiency of 25% is reported for a silicon solar cell as measured under the revised IEC 60904-3: Ed. 2 reference spectrum introduced as the international standard in April 2008 (equivalent to ASTM G173-03 introduced in January 2003).

Although solar cell efficiency measurements historically were quite laboratory-dependent, improvements in calibration approaches and increased inter-laboratory comparisons had reduced inter-laboratory differences by the early 1990s. Interchange of cells suggests that any systematic difference between cell calibrations between recognised test centres are generally less than 1% or so, with random measurement error being of about the same magnitude.

A consolidated history of silicon cell development shows three major phases in the evolution of this efficiency. The first major improvements in efficiencies occurred in the early 1950s with the development of both crystal growth and junction diffusion techniques and the refinement of cell and contact design. Another

Table III. History of multicrystalline silicon cell improvement (>1 cm^2 area) over the modern era normalised to present standard test conditions (25°C, 1000 W/m^2, IEC 60904-3:2008 global, equivalent to ASTM G173-03 global spectrum)

Date	Reported efficiency (%)	Test conditions*	Corrected efficiency (%)	Cell description
12/75	10	AM1 (in house) (t)	~9	SOLAREX
5/76	14·5	AM1 (in house) (t)	~14	AEG/Wacker
9/77	16	AM1 (in house) (t)	~15·3	SOLAREX
5/84	16·2	SERI 1 (t)	15·7	SOLAREX
3/86	15·9	SERI 2 (t)	16·1	UNSW PESC
2/89	17·8	SANDIA 2 (t)	17·3	UNSW PESC
8/89	17·3	SERI 2 (t)	17·5	UNSW PESC
1/92	17·7	ASTM E892(ap)	17·9	GEORGIA Tech PESC
3/94	17·8	ASTM E892 (ap)	18·0	GEORGIA Tech PESC
2/95	18·6	ASTM E892 (ap)	18·8	GEORGIA Tech PESC
2/98	19.8	ASTM E892 (ap)	20.0	UNSW PERL
5/04	20·3	ASTM E892 (ap)	20·4	FhG-ISE Laser PERC

*(t) = total area, (ap) = aperture area.

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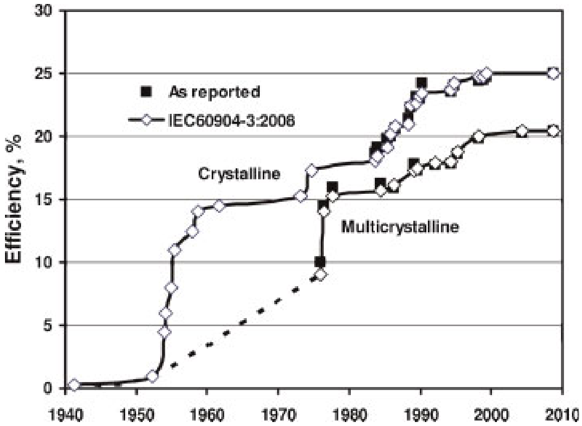

Figure 3. Evolution of crystalline and multicrystalline silicon solar cell efficiency

phase occurred in the 1970s with the development of shallow junctions, photolithographically defined metallisation, improved antireflection coatings and surface texturing. The third phase began in the early 1980s and resulted from improvements in surface passivation, bulk lifetimes, contact passivation and light trapping in the cell.

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