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Research

SHORT COMMUNICATION

Solar Cell Efficiency Tables (Version 27)

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Consolidated tables showing an extensive listing of the highest independently confirmed efficiencies for solar cells and modules are presented. Guidelines for inclusion of results into these tables are outlined and new entries since July, 2005 are reviewed.

KEY WORDS: solar cell efficiency; photovoltaic efficiency; energy conversion efficiency

INTRODUCTION

Since January, 1993, 'Progress in Photovoltaics' has published 6 monthly listings of the highest confirmed efficiencies for a range of photovoltaic cell and module technologies.[1–3] By providing guidelines for the inclusion of results into these tables, this not only provides an authoritative summary of the current state of the art but also encourages researchers to seek independent confirmation of results and to report results on a standardised basis. In the present article, new results since July, 2005 are briefly reviewed.

The most important criterion for inclusion of results into the tables is that they must have been measured by a recognised test centre listed in an earlier issue.[2] A distinction is made between three different eligible areas: total area; aperture area and designated illumination area.[1] 'Active area' efficiencies are not included. There are also certain minimum values of the area sought for the different device types (above 0.05 cm^2 for a concentrator cell, 1 cm^2 for a one-sun cell, and 800 cm^2 for a module).[1]

Results are reported for cells and modules made from different semiconductors and for sub-categories within each semiconductor grouping (e.g. crystalline, polycrystalline and thin film).

NEW RESULTS

Highest confirmed cell and module results are reported in Tables I, II and IV. Any changes in the tables from those previously published[3] are set in bold type. Table I summarises the best measurements for cells and submodules, Table II shows the best results for modules and Table IV shows the best results for concentrator cells and concentrator modules. Table III contains what might be described as 'notable exceptions'. While not

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Table I. Confirmed terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 Wm^{-2}) at 25°C

Classification[a]	Effic.[b] (%)	Area[c] (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF[d] (%)	Test Centre[e] (and Date)	Description
Silicon							
Si (crystalline)	24.7 ± 0.5	4.00 (da)	0.706	42.2	82.8	Sandia (3/99)	UNSW PERL[9]
Si (multicrystalline)	20.3 ± 0.5	1.002 (ap)	0.664	37.7	80.9	NREL (5/04)	FhG-ISE[10]
Si (thin film transfer)	16.6 ± 0.4	4.017 (ap)	0.645	32.8	78.2	FhG-ISE (7/01)	U. Stuttgart (45 μm thick)[11]
III–V Cells							
GaAs (crystalline)	25.1 ± 0.8	3.91 (t)	1.022	28.2	87.1	NREL (3/90)	Kopin, AlGaAs window[12]
GaAs (thin film)	24.5 ± 0.5	1.002 (t)	1.029	28.8	82.5	FhG-ISE (5/05)	Radboud U., NL[13]
GaAs (multicrystalline)	18.2 ± 0.5	4.011 (t)	0.994	23.0	79.7	NREL (11/95)	RTI, Ge substrate[14]
InP (crystalline)	21.9 ± 0.7	4.02 (t)	0.878	29.3	85.4	NREL (4/90)	Spire, epitaxial[15]
Thin film chalcogenide							
CIGS (cell)	18.4 ± 0.5[f]	1.04(ap)	0.669	35.7	77.0	NREL (2/01)	NREL, CIGS on glass[16]
CIGS (submodule)	16.6 ± 0.4	16.0 (ap)	2.643	8.35	75.1	FhG-ISE (3/00)	U. Uppsala, 4 serial cells[17]
CdTe (cell)	16.5 ± 0.5[f]	1.032 (ap)	0.845	25.9	75.5	NREL (9/01)	NREL, mesa on glass[18]
Amorphous/ nanocrystalline Si							
Si (amorphous)[g]	9.5 ± 0.3	1.070 (ap)	0.859	17.5	63.0	NREL (4/03)	U. Neuchatel[19]
Si (nanocrystalline)	10.1 ± 0.2	1.199 (ap)	0.539	24.4	76.6	JQA (12/97)	Kaneka (2 μm on glass)[20]
Photochemical							
Nanocrystalline dye	**10.4 ± 0.3**	**1.004(ap)**	**0.729**	**21.8**	**65.2**	**AIST (8/05)**	**Sharp[5]**
Nanocrystalline dye (submodule)	4.7 ± 0.2	141.4 (ap)	0.795	11.3	59.2	FhG-ISE (2/98)	INAP
Multijunction devices							
GaInP/GaAs/Ge	32.0 ± 1.5	3.989(t)	2.622	14.37	85.0	NREL (1/03)	Spectrolab (monolithic)
GaInP/GaAs	30.3	4.0 (t)	2.488	14.22	85.6	JQA (4/96)	Japan Energy (monolithic)[21]
GaAs/CIS (thin film)	25.8 ± 1.3	4.00 (t)	—	—	—	NREL (11/89)	Kopin/Boeing (4 terminal)
a-Si/CIGS (thin film)[h]	14.6 ± 0.7	2.40 (ap)	—	—	—	NREL (6/88)	ARCO (4 terminal)[22]
a-Si/μc-Si (thin submodule)[i]	11.7 ± 0.4	14.23(ap)	5.462	2.99	71.3	AIST (9/04)	Kaneka (thin film)[23]

[a]CIGS = $CuInGaSe_2$; a-Si = amorphous silicon/hydrogen alloy.
[b]Effic. = efficiency.
[c](ap) = aperture area; (t) = total area; (da) = designated illumination area.
[d]FF = fill factor.
[e]FhG-ISE = Fraunhofer-Insitut für Solare Energiesysteme; JQA = Japan Quality Assurance; AIST = Japanese National Institute of Advanced Industrial Science and Technology.
[f]Not measured at an external laboratory.
[g]Stabilised by 800 h, 1 sun AM1.5 illumination at a cell temperature of 50°C.
[h]Unstabilised results.
[i]Stabilised by 174 h, 1-sun illumination after 20 h, 5-sun illumination at a sample temperature of 50°C.

conforming to the requirements to be recognised as a class record, the cells and modules in this Table have notable characteristics that will be of interest to sections of the photovoltaic community with entries based on their significance and timeliness. In most cases, a literature reference is provided that describes either the result reported or a similar result.

To ensure discrimination, Table III is limited to 10 entries with the present authors having voted for their preferences for inclusion. Readers who have suggestions of results for inclusion into this Table are welcome to contact any of the authors with full details. Suggestions conforming to the guidelines will be included on the voting list for a future issue. (A smaller number of 'notable exceptions' for concentrator cells and modules additionally is included in Table IV, as are results under a recently proposed low aerosol optical depth direct-beam spectrum[4]).

Table II. Confirmed terrestrial module efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at a cell temperature of 25°C

Classification[a]	Effic.[b] (%)	Area[c] (cm^2)	V_{oc} (V)	I_{sc} (A)	FF[d] (%)	Test Centre (and Date)	Description
Si (crystalline)	22.7 ± 0.6	778 (da)	5.60	3.93	80.3	Sandia (9/96)	UNSW/Gochermann[24]
Si (multicrystalline)	15.3 ± 0.4[e]	1017 (ap)	14.6	1.36	78.6	Sandia (10/94)	Sandia/HEM[25]
Si (thin-film polycrystalline)	8.2 ± 0.2	661(ap)	25.0	0.318	68.0	Sandia (7/02)	Pacific Solar (1–2 μm on glass)[25]
CIGSS	13.4 ± 0.7	3459 (ap)	31.2	2.16	68.9	NREL (8/02)	Showa Shell (Cd free)[27]
CdTe	10.7 ± 0.5	4874 (ap)	26.21	3.205	62.3	NREL (4/00)	BP Solarex[28]
a-Si/a-SiGe/a-SiGe (tandem)[f]	10.4 ± 0.5	905 (ap)	4.353	3.285	66.0	NREL (10/98)	USSC (a-Si/a-Si/a-Si:Ge)[29]

[a]CIGSS = CuInGaSSe; a-Si = amorphous silicon/hydrogen alloy; a-SiGe = amorphous silicon/germanium/hydrogen alloy.
[b]Effic. = efficiency.
[c](ap) = aperture area; (da) = designated illumination area.
[d]FF = fill factor.
[e]Not measured at an external laboratory.
[f]Light soaked at NREL for 1000 h at 50°C, nominally 1-sun illumination.

The first new result is in Table I where an efficiency of 10.4% is reported for a 1 cm^2 nanocrystalline dye cell fabricated by Sharp and measured at the Japanese National Institute of Advanced Industrial Science and Technology (AIST).

The second new result is for a large area, commercial-size multicrystalline silicon cell and is reported in Table III as a 'notable exception'. An efficiency of 18.1% has been confirmed by the Fraunhofer Institute for Solar Energy Systems (FhG-ISE) for a large area (137.7 cm^2) laser grooved, buried contact cell fabricated by the University of Kontanz, improving substantially on the University's earlier 17.6% result.[6]

Three new concentrator results are reported in Table IV. Record single-junction concentrator cell performance of 27.6% is reported in Table IV for a back contacted cell fabricated by Amonix[7] and measured at the Fraunhofer Institute for Solar Energy Systems (FhG-ISE) under a concentrated low aerosol

Table III. 'Notable exceptions': 'Top ten' confirmed cell and module results, not class records (Global AM1.5 spectrum, 1000 Wm^{-2}, 25°C)

Classification[a]	Effic.[b] (%)	Area[c] (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	Test Centre (and Date)	Description
Cells (Silicon)							
Si (MCZ crystalline)	24.5 ± 0.5	4.0 (da)	0.704	41.6	83.5	Sandia (7/99)	UNSW PERL, SEH MCZ substrate [30]
Si (moderate area)	23.7 ± 0.5	22.1(da)	0.704	41.5	81.0	Sandia (8/96)	UNSW PERL[24], FZ substrate
Si (large FZ crystalline)	21.5 ± 0.6	148.9(t)	0.678	39.5	80.3	NREL (9/03)	Sunpower FZ substrate[31]
Si (large CZ crystalline)	21.5 ± 0.3	100.3(t)	0.712	38.3	78.7	AIST (12/04)	Sanyo HIT, n-type CZ substrate[32]
Si (large CZ crystalline)	18.3 ± 0.5	147.5(t)	0.625	36.3	80.6	FhG-ISE (9/02)	BP Solar, laser grooved[33]
Si (large multicrystalline)	**18.1 ± 0.5**	**137.7(t)**	**0.636**	**36.9**	**77.0**	**FhG-ISE (8/05)**	**U. Konstanz, laser grooved[6]**
Cells (Other)							
GaInP/GaInAs/Ge tandem)	31.3 ± 1.5	4.0 (t)	2.392	16.0	81.9	NREL (1/03)	Spectrolab, monolithic metamorphic
CIGS (thin film)	19.5 ± 0.6	0.410(ap)	0.693	35.3	79.4	FhG-ISE (9/04)	NREL, CIGS on glass[34]
a-Si/a-Si/a-SiGe (tandem)	12.1 ± 0.7	0.27 (da)	2.297	7.56	69.7	NREL (10/96)	USSC stabilised (monolithic)[35]
Photoelectrochemical	11.0 ± 0.5	0.25(ap)	0.795	19.4	71.0	FhG-ISE (12/96)	EPFL, nanocrystalline dye[36]

[a]CIGS = $CuInGaSe_2$.
[b]Effic. = efficiency.
[c](ap) = aperture area; (t) = total area; (da) = designated illumination area.

Table IV. Terrestrial concentrator cell and module efficiencies measured under the direct beam AM1.5 spectrum at a cell temperature of 25°C

Classification	Effic.[a] (%)	Area[b] (cm^2)	Intensity[c] (suns)	Test centre (and Date)	Description
Single cells					
GaAs	27.6 ± 1.0	0.126 (da)	255	Sandia (5/91)	Spire[37]
GaInAsP	27.5 ± 1.4[d]	0.075 (da)	171	NREL (2/91)	NREL, Entech cover
Si	26.8 ± 0.8	1.60 (da)	96	FhG-ISE (10/95)	SunPower back-contact[38]
InP	24.3 ± 1.2[d]	0.075 (da)	99	NREL (2/91)	NREL, Entech cover[39]
CIGS (thin film)	21.5 ± 1.5[d]	0.102 (da)	14	NREL (2/01)	NREL
2-cell stacks					
GaAs/GaSb (4 terminal)	32.6 ± 1.7	0.053 (da)	100	Sandia[e] (10/89)	Boeing, mechanical stack[40]
InP/GaInAs (3 terminal)	31.8 ± 1.6[d]	0.063 (da)	50	NREL (8/90)	NREL, monolithic[41]
GaInP/GaInAs (2-terminal)	30.2 ± 1.2	0.1326 (da)	300	NREL/FhG-ISE (6/01)	Fraunhofer, monolithic[42]
GaInP/GaAs (2 terminal)	30.2 ± 1.4	0.103 (da)	180	Sandia (3/94)	NREL, monolithic[43]
GaAs/Si (large) (4-terminal)	29.6 ± 1.5[d]	0.317 (da)	350	Sandia[e] (9/88)	Varian/Stanford/ Sandia, mech. Stack[44]
3-cell stacks					
GaInP/GaAs/Ge (2-terminal)	34.7 ± 1.7	0.2665(da)	333	NREL (9/03)	Spectrolab, monolithic
Submodules					
GaInP/GaAs/Ge	27.0 ± 1.5	34 (ap)	10	NREL (5/00)	ENTECH[45]
GaAs/GaSb	25.1 ± 1.4	41.4 (ap)	57	Sandia (3/93)	Boeing, 3 mech. stack units[46]
Modules					
Si	20.3 ± 0.8[d]	1875 (ap)	80	Sandia (4/89)	Sandia/UNSW/ ENTECH (12 cells)[47]
Low-AOD spectrum[f]					
GaInP/GaInAs/Ge (2-terminal)	**39.0 ± 2.3[f]**	**0.2691 (da)**	**236**	**NREL (5/05)**	**Spectrolab, low-AOD spectrum[8]**
Si	27.6 ± 1.0	1.00 (da)	92	FhG-ISE (11/04)	Amonix back-contact[7]
'Notable exceptions'					
GaInP/GaInAs/Ge (2-terminal)	**38.8 ± 2.3[f]**	**0.254(da)**	**241**	**NREL (5/05)**	**Spectrolab, metamorphic[8]**
Si (large)	21.6 ± 0.7	20.0 (da)	11	Sandia[e] (9/90)	UNSW laser grooved[48]
GaAs (Si substrate)	21.3 ± 0.8	0.126 (da)	237	Sandia (5/91)	Spire[37]
InP (GaAs substrate)	21.0 ± 1.1[d]	0.075 (da)	88	NREL (2/91)	NREL, Entech cover[49]

[a]Effic. = efficiency.
[b](da) = designated illumination area; (ap) = aperture area.
[c]One sun corresponds to an intensity of 1000 Wm^{-2}.
[d]Not measured at an external laboratory.
[e]Measurements corrected from originally measured values due to Sandia recalibration in January, 1991.
[f]Low aerosol optical depth direct beam AM1.5 spectrum.

density AM1.5 direct-beam spectrum.[4] Two further improvements are reported for multiple junction cells. The first is the demonstration of 39% efficiency at 236 suns concentration for a 0.27 cm^2 GaInP/GaInAs/Ge triple junction cell fabricated by Spectrolab[8] and measured at the US National Renewable Energy Laboratory (NREL), again under the low aerosol density AM1.5 spectrum. Metamorphic cells with the same nominal structure but with 8% indium in the middle cell, producing 0.5% lattice mismatch, gave nearly identical results with efficiencies up to 38.8% demonstrated under the same spectrum[8] and recorded in Table IV as a 'notable exception'.

Finally, Figure 1 shows, for several key cell categories, the evolution of the efficiency values reported in these Tables over the 1993–2006 period. The monolithic III–V stacked concentrator cells have shown the largest gains, with efficiency increasing from below 30% to close to 40% over this period. CIGS technology also showed very rapid progress over the first part of this period, with good recent progress shown for nanocrystalline dye cells of a qualifying size (at least 1 cm^2).

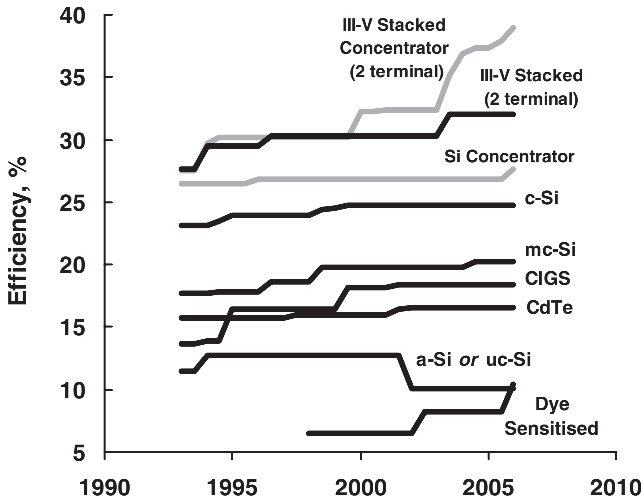

Figure 1. Evolution of solar cell efficiency over the 1993–2006 timeframe for several major cell categories as reflected by values reported in these Tables (the apparent decrease for 'a-Si *or* μc-Si' cells is due to a change in reporting from 'unstabilised' to 'stabilised' results, reflecting commercial practice)

DISCLAIMER

While the information provided in the tables is provided in good faith, the authors, editors and publishers cannot accept direct responsibility for any errors or omissions.

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