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Research

SHORT COMMUNICATION

Solar Cell Efficiency Tables (Version 22)

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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 January 2003 are reviewed. Copyright © 2003 John Wiley & Sons, Ltd.

INTRODUCTION

Since January 1993, *Progress in Photovoltaics* has published six-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 standardized basis. In the present article, new results since January 2003 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 $0{\cdot}05\,cm^2$ 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 summarizes 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 conforming to the requirements to be recognized 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

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Table I. Confirmed terrestrial cell and submodule efficiencies measured under the global AM1·5 spectrum (1000 W m^{-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 cells							
Si (crystalline)	24·7 ± 0·5	4·00 (da)	0·706	42·2	82·8	Sandia (3/99)	UNSW PERL[7]
Si (multicrystalline)	19·8 ± 0·5	1·09 (ap)	0·654	38·1	79·5	Sandia (2/98)	UNSW/Eurosolare[7]
Si (thin film transfer)	16·6 ± 0·4	4·017 (ap)	0·645	32·8	78·2	FhG-ISE (7/01)	University of Stuttgart (45 μm thick)[8]
III–V cells							
GaAs (crystalline)	25·1 ± 0·8	3·91 (t)	1·022	28·2	87·1	NREL (3/90)	Kopin, AlGaAs window
GaAs (thin film)	23·3 ± 0·7	4·00 (ap)	1·011	27·6	83·8	NREL (4/90)	Kopin, 5 mm CLEFT[9]
GaAs (multicrystalline)	18·2 ± 0·5	4·011 (t)	0·994	23·0	79·7	NREL (11/95)	RTI, Ge substrate[10]
InP (crystalline)	21·9 ± 0·7	4·02 (t)	0·878	29·3	85·4	NREL (4/90)	Spire, epitaxial[11]
Polycrystalline thin film							
CIGS (cell)	18·4 ± 0·5[f]	1·04 (ap)	0·669	35·7	77·0	NREL (2/01)	NREL, CIGS on glass[12]
CIGS (submodule)	16·6 ± 0·4	16·0 (ap)	2·643	8·35	75·1	FhG-ISE (3/00)	University of Uppsala, 4 serial cells[13]
CdTe (cell)	16·5 ± 0·5[f]	1·032 (ap)	0·845	25·9	75·5	NREL (9/01)	NREL, mesa on glass[14]
Amorphous/nanocrystalline Si							
Si (nanocrystalline)	10·1 ± 0·2	1·199 (ap)	0·539	24·4	76·6	JQA (12/97)	Kaneka (2 μm on glass)[15]
Photochemical							
Nanocrystalline dye	8·2 ± 0·3	2·36 (ap)	0·726	15·8	71·2	FhG-ISE (7/01)	ECN[16]
Nanocrystalline dye (submodule)	4·7 ± 0·2	141·4 (ap)	0·795	11·3	59·2	FhG-ISE (2/98)	INAP
Multijunction cells							
GaInP/GaAs	30·3	4·0 (t)	2·488	14·22	85·6	JQA (4/96)	Japan Energy (monolithic)[17]
GaInP/GaAs/Ge	**32·0 ± 1·5**	**3·989 (t)**	**2·622**	**14·37**	**85·0**	**NREL (1/03)**	**Spectrolab (monolithic)[4]**
GaAs/CIS (thin film)	25·8 ± 1·3	4·00 (t)				NREL (11/89)	Kopin/Boeing (4 terminal)
a-Si/CIGS (thin film)[g]	14·6 ± 0·7	2·40 (ap)				NREL (6/88)	ARCO (4 terminal)[18]

[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.
[f]Not measured at external laboratory.
[g]Unstabilized results.

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[19]
Si (multicrystalline)[e]	15·3 ± 0·4[e]	1017 (ap)	14·6	1·36	78·6	Sandia (10/94)	Sandia/HEM[20]
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)[21]
CIGSS	13·4 ± 0·7	3459 (ap)	31·2	2·16	68·9	NREL (8/02)	Showa Shell (Cd-free)[22]
CdTe	10·7 ± 0·5	4874 (ap)	26·21	3·205	62·3	NREL (4/00)	BP Solarex[23]
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)[24]

[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.

Table III. 'Notable exceptions': 'Top ten' confirmed cell and module results, not class records (global AM1·5 spectrum, 1000 W/m^{-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[25]
Si (moderate area)	23·7 ± 0·5	22·1 (da)	0·704	41·5	81·0	Sandia (8/96)	UNSW PERL[19]
Si (large CZ crystalline)	21·0 ± (0·3	100 (t)	0·714	37·6	78·1	JQA (3/01)	Sanyo HIT, *n*-type CZ substrate
Si (large multicrystalline)	**17·6 ± 0·5**	**144 (t)**	**0·632**	**35·9**	**77·7**	**FhG-ISE (x/03)**	**University of Konstanz, BP Solar, Photowatt wafer (mechanically textured)[5]**
Si (supported film)	16·6 ± 0·5	0·98 (ap)	0·608	33·5	81·5	NREL (3/97)	AstroPower (Si film)[26]
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[4]**
CIGS (thin film)	18·9 ± 0·6	0·4049 (ap)	0·696	34·8	78·0	FhG-ISE (7/01)	NREL, CIGS on glass[12]
a-Si/a-Si/a-SiGe[d] (tandem)	13·5 ± 0·7	0·27 (da)	2·375	7·72	74·4	NREL (10/96)	USSC (monolithic)[27]
Photoelectrochemical	11·0 ± 0·5	0·25 (ap)	0·795	19·4	71·0	FhG-ISE (12/96)	EPFL, nanocrystalline dye[28]
Module							
CdTe (large)	10·5 ± 0·5	8670 (ap)	46·45	3·07	64·3	NREL (5/00)	BP Solar[23]

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

significance and timeliness. Where available, 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).

A major new result is reported in Table I in the present version of these tables. This is a new record for solar cell efficiency under unconcentrated sunlight of 32·0% for a 4 cm^2 triple-junction, monolithic GaInP/GaAs/Ge cell fabricated by Spectrolab and measured at the National Renewable Energy Laboratory (NREL).[4]

A closely related new result is the demonstration of 31·3% efficiency for a similar cell also fabricated by Spectrolab, but with the upper cells mismatched to the Ge substrate. In principle, this $Ga_{0\cdot44}In_{0\cdot56}P$/$Ga_{0\cdot92}In_{0\cdot08}As$/Ge device should give even higher efficiency than the lattice-matched device. This is because the lower bandgaps in the upper devices should provide higher current output, better matched to that from the Ge cell. A GaInAs buffer layer of graded composition on top of the Ge cell reduces the impact of the lattice mismatch. This new result appears in Table III as a 'notable exception', since it is not an outright efficiency record, although it does seem likely this approach will soon produce such a record.[4]

Another new result in Table III is the improvement of the efficiency of a large-area 144 cm^2 multicrystalline silicon cell to 17·6%. This was achieved as a combined effort of the University of Konstanz and BP Solar, using the buried contact approach,[5] with the cell measured by the Fraunhofer Institute for Solar Energy Systems (FhG-ISE).

A final new result for a very-high-performance concentrator cell appears in Table IV. A lattice-matched GaInP/GaAs/Ge cell again fabricated by Spectrolab[4] has been measured to have an efficiency of 35·2% under 66 suns concentration, when measured by NREL under a new low aerosol optical depth direct-beam AM1·5 spectrum.[6] Although this spectrum is a better match to measured spectra than the ASTM E 89I AM1·5 direct-beam spectrum used for the other measurements of Table IV, there is disagreement amongst the authors

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[29]
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[30]
InP	24·3 ± 1·2[d]	0·075 (da)	99	NREL (2/91)	NREL, Entech cover[31]
CIGS (thin film)	21·5 ± 1·5[d]	0·102 (da)	14	NREL (2/01)	NREL
Two-cell stacks					
GaAs/GaSb (4 terminal)	32·6 ± 1·7	0·053 (da)	100	Sandia[e] (10/89)	Boeing, mechanical stack[32]
InP/GaInAs (3 terminal)	31·8 ± 1·6[d]	0·063 (da)	50	NREL (8/90)	NREL, monolithic[33]
GaInP/GaInAs (2-terminal)	30·2 ± 1·2	0·1326 (da)	300	NREL/FhG-ISE (6/01)	Fraunhofer, monolithic[34]
GaInP/GaAs (2 terminal)	30·2 ± 1·4	0·103 (da)	180	Sandia (3/94)	NREL, monolithic[35]
GaAs/Si (large) (4-terminal)	29·6 ± 1·5[d]	0·317 (da)	350	Sandia[e] (9/88)	Varian/Stanford/Sandia, mechanical stack[36]
Three-cell stacks					
GaInP/GaInAs/GaSb(4-term.)	33·5 ± 1·7[d]	0·1326 (da)	308	FhG-ISE (6/01)	Fraunhofer, mechanical stack[34]
GaInP/GaAs/Ge (2-terminal)	32·4 ± 2·0	0·1025 (da)	414	NREL (6/00)	Spectrolab, monolithic[37]
GaInP/GaAs/Ge (large)	30·6 ± 1·5	1·050 (da)	234	NREL (9/00)	Spectrolab, monolithic
Submodules					
GaAs/GaSb	25·1 ± 1·4	41·4 (ap)	57	Sandia (3/93)	Boeing, three mechanical stack units[38]
GaInP/GaAs/Ge	27·0 ± 1·5	34 (ap)	10	NREL (5/00)	ENTECH[39]
Modules					
Si	20·3 ± 0·8[d]	1875 (ap)	80	Sandia (4/89)	Sandia/UNSW/ENTECH (12 cells)[40]
Low-AOD spectrum[f]					
GaInP/GaAs/Ge (two-terminal)	**35·2 ± 1·5[f]**	**0·266 (da)**	**66·3**	**NREL (2/03)**	**Spectrolab, low-AOD spectrum[4]**
'notable exceptions'					
Si (large)	21·6 ± 0·7	20·0 (da)	11	Sandia[e] (9/90)	UNSW laser-grooved[41]
GaAs (Si substrate)	21·3 ± 0·8	0·126 (da)	237	Sandia (5/91)	Spire[29]
InP (GaAs substrate)	21·0 ± 1·1[d]	0·075 (da)	88	NREL (2/91)	NREL, Entech cover[42]

[a]Effic. = efficiency.
[b](da) = designated illumination area; (ap) = aperture area.
[c]One sun corresponds to an intensity of 1000 W/m^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.[6]

of the present article as to which represents a better choice for predicting annual energy output. Until a consensus is obtained, a separate category will be maintained for cells measured under the new spectrum.

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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