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Research *SHORT COMMUNICATION*

Solar Cell Efficiency Tables (Version 32)

Martin A. Green[1*,†], Keith Emery[2], Yoshihiro Hishikawa[3] and Wilhelm Warta[4]
[1]*ARC Photovoltaics Centre of Excellence, University of New South Wales, Sydney, 2052, Australia*
[2]*National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, CO 80401, USA*
[3]*National Institute of Advanced Industrial Science and Technology (AIST), Research Center for Photovoltaics (RCPV), Central 2, Umezono 1-1-1, Tsukuba, Ibaraki, Japan*
[4]*Department of Solar Cells—Materials and Technology, Fraunhofer-Institute for Solar Energy Systems, Heidenhofstr. 2, D-79110 Freiburg, Germany*

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 2008 are reviewed.

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

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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 standardised basis. In the present paper, new results since January 2008 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 1-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. In most cases, a literature reference is provided that describes either the result reported or a similar result. 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 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.

To ensure discrimination, Table III is limited to nominally 10 entries with the present authors having voted for their preferences for inclusion. Readers who

* Correspondence to: Martin A. Green, ARC Photovoltaics Centre of Excellence, University of New South Wales, Sydney 2052, Australia.
†E-mail: m.green@unsw.edu.au

Table I. Confirmed terrestrial cell and submodule efficiencies measured under the global AM1·5 spectrum (1000 W/m^2) at 25°C

Classification[*]	Effic.[†] (%)	Area[‡] (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF[§] (%)	Test centre[‖] (and date)	Description
Silicon							
Si (crystalline)	24·7 ± 0·5	4·00 (da)	0·706	42·2	82·8	Sandia (3/99)	UNSW PERL[10]
Si (multicrystalline‘)	20·3 ± 0·5	1·002 (ap)	0·664	37·7	80·9	NREL (5/04)	FhG-ISE[11]
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)[12]
Si (thin-film submodule)	10·4 ± 0·3	94·0 (ap)	0·492[¶]	29·5[¶]	72·1	FhG-ISE (8/07)	CSG Solar (1–2 μm on glass; 20 cells)[13]
III–V cells							
GaAs (crystalline)	**25·9 ± 0·8**	**0·998 (ap)**	**1·038**	**29·4**	**84·7**	**FhG-ISE (12/07)**	**Radboud U. Nijmegen[5]**
GaAs (thin film)	24·5 ± 0·5	1·002 (t)	1·029	28·8	82·5	FhG-ISE (5/05)	Radboud U. Nijmegen[5]
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)	**19·2 ± 0·6[#]**	**0·994(ap)**	**0·716**	**33·3**	**80·3**	**NREL (1/08)**	**NREL, CIGS on glass[6]**
CIGS (submodule)	16·6 ± 0·4	16·0 (ap)	0·661[¶]	33·4[¶]	75·1	FhG-ISE (3/00)	U. Uppsala, four serial cells[16]
CdTe (cell)	16·5 ± 0·5[#]	1·032 (ap)	0·845	25·9	75·5	NREL (9/01)	NREL, mesa on glass[17]
Amorphous/nanocrystalline Si							
Si (amorphous)[**]	9·5 ± 0·3	1·070 (ap)	0·859	17·5	63·0	NREL (4/03)	U. Neuchatel[18]
Si (nanocrystalline)	10·1 ± 0·2	1·199 (ap)	0·539	24·4	76·6	JQA (12/97)	Kaneka (2 μm on glass)[19]
Photochemical							
Dye sensitised[††]	10·4 ± 0·3	1·004(ap)	0·729	21·8	65·2	AIST (8/05)	Sharp[20]
Dye sensitised (submodule)[††]	**8·2 ± 0·3**	**25·45 (ap)**	**0·703[¶]**	**19·0[¶]**	**61·2**	**AIST (12/07)**	**Sharp, nine serial cells[7]**
Dye sensitised (submodule)[††]	**8·2 ± 0·3**	**18·50 (ap)**	**0·659[¶]**	**19·8[¶]**	**62·9**	**AIST (6/08)**	**Sony, eight serial cells[8]**
Organic							
Organic polymer[††]	5·15 ± 0·3	1·021(ap)	0·876	9·40	62·5	NREL(12/06)	Konarka[21]
Organic (submodule)[††]	**1·1 ± 0·3**	**232·8 (ap)**	**29·3**	**0·072**	**51·2**	**NREL (3/08)**	**Plextronics (P3HT/PCBM)[9]**
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)[22]
GaAs/CIS (thin film)	25·8 ± 1·3	4·00 (t)	—	—	—	NREL (11/89)	Kopin/Boeing (4-terminal)[23]
a-Si/μc-Si (thin submodule)[‡‡]	11·7 ± 0·4	14·23(ap)	5·462	2·99	71·3	AIST (9/04)	Kaneka (thin film)[24]

[*]CIGS, CuInGaSe2; a-Si, amorphous silicon/hydrogen alloy.
[†]Effic., efficiency.
[‡](ap), aperture area; (t), total area; (da), designated illumination area.
[§]FF, fill factor.
[‖]FhG-ISE, Fraunhofer Institut für Solare Energiesysteme; JQA, Japan Quality Assurance; AIST, Japanese National Institute of Advanced Industrial Science and Technology.
[¶]Reported on a ‘per cell’ basis.
[#]Not measured at an external laboratory.
[**]Stabilised by 800 h, 1 sun AM1·5 illumination at a cell temperature of 50°C.
[††]Stability not investigated.
[‡‡]Stabilised by 174 h, 1 sun illumination after 20 h, 5 sun illumination at a sample temperature of 50°C.

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 relatively new low aerosol optical depth direct-beam spectrum[4]).

Six new results are reported in the present versions of the tables, only slightly down from the record number of eight in the previous version.[3]

The first new result appears in Table I. An efficiency of 25·9% was measured at the Fraunhofer Institute for Solar Energy Systems (FhG-ISE) for a 1 cm^2 GaAs cell fabricated by Radboud University Nijmegen of the Netherlands. This result displaced one of the oldest

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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*	Effic.† (%)	Area‡ (cm^2)	V_{oc} (V)	I_{sc} (A)	FF§ (%)	Test centre (and date)	Description
Si (crystalline)	22·7 ± 0·6	778 (da)	5·60	3·93	80·3	Sandia (9/96)	UNSW/Gochermann[25]
Si (large crystalline)	20·1 ± 0·6	16 300 (ap)	66·1	6·30	78·7	Sandia (8/07)	SunPower[26]
Si (multicrystalline)	15·3 ± 0·4‖	1017 (ap)	14·6	1·36	78·6	Sandia (10/94)	Sandia/HEM[27]
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)[28]
CIGSS	13·4 ± 0·7	3459 (ap)	31·2	2·16	68·9	NREL (8/02)	Showa Shell (Cd free)[29]
CdTe	10·7 ± 0·5	4874 (ap)	26·21	3·205	62·3	NREL (4/00)	BP Solarex[30]
a-Si/a-SiGe/a-SiGe (tandem)¶	10·4 ± 0·5	905 (ap)	4·353	3·285	66·0	NREL (10/98)	USSC (a-Si/a-Si/a-Si:Ge)[31]

*CIGSS, CuInGaSSe; a-Si, amorphous silicon/hydrogen alloy; a-SiGe, amorphous silicon/germanium/hydrogen alloy.
†Effic., efficiency.
‡(ap), aperture area; (da), designated illumination area.
§FF, fill factor.
‖Not measured at an external laboratory.
¶Light soaked at NREL for 1000 h at 50°C, nominally 1 sun illumination.

results in the previous editions of these tables, a 25·1% efficient cell made by the Kopin Corporation in 1990. Radboud University also have previously fabricated the best thin-film GaAs cell listed in Table I.[5] A paper on this work is in preparation.

The second new result also appears in Table I where efficiency improvement to 19·2% is reported for a 1 cm^2 thin-film polycrystalline CIGS (copper indium gallium diselenide) cell fabricated and measured by the National Renewable Energy Laboratory (NREL)[6] improving on the Laboratory's earlier 18·8% result.

The third new result again appears in Table I where 8·2% efficiency is reported for a 25 cm^2 dye sensitised cell submodule fabricated by Sharp[7] and measured by the Japanese National Institute of Advanced Industrial Science and Technology (AIST). This improves the company's previous benchmark of 7·9% efficiency for such a submodule.

The fourth new result is also reported for the same category in Table I where an 8·2% efficiency is also reported for a similarly sized dye sensitised cell submodule (18·5 cm^2) fabricated by Sony[8] and measured by AIST.

Table III. 'Notable exceptions': 'top 10' confirmed cell and module results, not class records (global AM1·5 spectrum, 1000 W/m^2, 25°C)

Classification*	Effic.† (%)	Area‡ (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[32]
Si (moderate area)	23·7 ± 0·5	22·1 (da)	0·704	41·5	81·0	Sandia (8/96)	UNSW PERL, FZ substrate[25]
Si (large FZ crystalline)	21·8 ± 0·7	147·4 (t)	0·677	40·0	80·6	FhG-ISE (3/06)	SunPower FZ substrate[33]
Si (large CZ crystalline)	22·3 ± 0·6	100·5 (t)	0·725	39·1	79·1	AIST (7/07)	Sanyo HIT, *n*-type CZ substrate[34]
Si (large multicrystalline)	18·1 ± 0·5	137·7 (t)	0·636	36·9	77·0	FhG-ISE (8/05)	U. Konstanz, laser grooved[35]
Cells (other)							
GaInP/GaInAs/GaInAs (tandem)	33·8 ± 1·5‖	0·25 (ap)	2·960	13·1	86·8	NREL (1/07)	NREL, monolithic[36]
CIGS (thin film)	19·9 ± 0·6‖	0·419 (ap)	0·692	35·5	81·0	NREL (10/07)	NREL, CIGS on glass[37]
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)[38]
Photoelectrochemical§	11·1 ± 0·3	0·219 (ap)	0·736	20·9	72·2	AIST (3/06)	Sharp, dye sensitised[39]
Organic	5·4 ± 0·3§	0·096 (ap)	0·856	9·70	65·3	NREL (7/07)	Plextronics[9]

*CIGS, $CuInGaSe_2$.
†Effic., efficiency.
‡(ap), aperture area; (t), total area; (da), designated illumination area.
§Stability not investigated.
‖Not measured at an external laboratory.

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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.* (%)	Area† (cm^2)	Intensity‡ (suns)	Test centre (and date)	Description
Single Cells					
GaAs	27·8 ± 1·0	0·203 (da)	216	Sandia§ (8/88)	Varian, Entech cover[40]
Si	27·3 ± 1·0	1·00 (da)	93	FhG-ISE (9/07)	Amonix back-contact[41]
CIGS (thin film)	21·5 ± 1·5‖	0·102 (da)	14	NREL (2/01)	NREL
Multijunction cells					
GaInP/GaAs/Ge (2-terminal)	34·7 ± 1·7	0·267(da)	333	NREL (9/03)	Spectrolab, monolithic
Submodules					
GaInP/GaAs/Ge	27·0 ± 1·5	34 (ap)	10	NREL (5/00)	ENTECH[42]
Modules					
Si	20·3 ± 0·8‖	1875 (ap)	80	Sandia (4/89)	Sandia/UNSW/ENTECH (12 cells)[43]
Low-AOD spectrum					
GaInP/GaInAs/Ge (2-terminal)	40·7 ± 2·4¶	0·267 (da)	240	NREL (9/06)	Spectrolab, lattice-mismatched[44]
GaInP/GaAs/GaInAs	**40.1 ± 2.4**	**0.0976 (da)**	**143**	**NREL (4/08)**	**NREL, inverted monolithic**
Si	27·6 ± 1·0¶	1·00 (da)	92	FhG-ISE (11/04)	Amonix back-contact[45]
'Notable exceptions'					
GaAs/GaSb (4-terminal)	32·6 ± 1·7	0·053 (da)	100	Sandia§ (10/89)	Boeing, mechanical stack[46]
InP/GaInAs (3-terminal)	31·8 ± 1·6‖	0·063 (da)	50	NREL (8/90)	NREL, monolithic[47]
GaInP/GaInAs (2-terminal)	30·2 ± 1·2	0·1330 (da)	300	NREL/FhG-ISE (6/01)	Fraunhofer, monolithic[48]
GaAs (high concentration)	26·2 ± 1·0	0·203 (da)	1000	Sandia§ (8/88)	Varian[49]
Si (large area)	21·6 ± :0·7	20·0 (da)	11	Sandia§ (9/90)	UNSW laser grooved[50]

*Effic., efficiency.
†(da), designated illumination area; (ap), aperture area.
‡One sun corresponds to direct irradiance of 1000 W/m^2.
§Measurements corrected from originally measured values due to Sandia recalibration in January 1991.
‖Not measured at an external laboratory.

The fifth new result also appears in Table I where a landmark efficiency of 1·1% is reported for a large (233 cm^2) organic submodule[9] fabricated by Plextronics and measured by NREL.

The final new result is reported in Table IV and introduces the second entry into the Tables with efficiency above 40%. An efficiency of 40.1% has been measured at 143 suns concentration (more precisely, 143 kW/m^2 direct irradiance) for a cell fabricated by and measured at NREL with an inverted, monolithic GaInP/GaAs/GaInAs structure and a low stress metamorphic bottom junction (see reference for 33.8% cell in Table III for more details).

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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