

ACCELERATED PUBLICATION

Solar cell efficiency tables (version 49)

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ABSTRACT

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 June 2016 are reviewed. Copyright © 2016 John Wiley & Sons, Ltd.

KEYWORDS

solar cell efficiency; photovoltaic efficiency; energy conversion efficiency

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1. 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 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 version 33 of these Tables [2], results were updated to the new internationally accepted reference spectrum (International Electrotechnical Commission IEC 60904-3, Ed. 2, 2008), where this was possible.

The most important criterion for inclusion of results into the tables is that they must have been independently measured by a recognised test centre listed elsewhere [1]. A distinction is made between three different eligible definitions of cell area: total area, aperture area and designated illumination area, as also defined elsewhere [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 cm² for a concentrator cell, 1 cm² for a one-sun cell and 800 cm² for a module).

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). From version 36 onwards, spectral response information is included when available in the form of a plot of the external quantum efficiency (EQE) versus wavelength, either as absolute values or normalised to the peak measured value. Current–voltage (IV) curves have also been included where possible from version 38 onwards.

2. NEW RESULTS

Highest confirmed 'one-sun' cell and module results are reported in Tables I–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 (readers identifying improved references are welcome to submit to the lead

Table I. Confirmed single-junction terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m²) at 25 °C (IEC 60904-3: 2008, ASTM G-173-03 global).

Classification	Efficiency (%)	Area (cm ²)	V _{oc} (V)	J _{sc} (mA/cm ²)	Fill factor (%)	Test centre (date)	Description
Silicon							
Si (crystalline cell)	26.3 ± 0.5	180.43 (da)	0.7438	42.25^a	83.8	FhG-ISE (7/16)	Kaneka, rear junction [4]
Si (multicrystalline cell)	21.3 ± 0.4	242.74 (t)	0.6678	39.80 ^b	80.0	FhG-ISE (11/15)	Trina Solar [19]
Si (thin transfer submodule)	21.2 ± 0.4	239.7 (ap)	0.687 ^c	38.50 ^c	80.3	NREL (4/14)	Solixel (35 µm thick) [20]
Si (thin film minimodule)	10.5 ± 0.3	94.0 (ap)	0.492 ^c	29.7 ^c	72.1	FhG-ISE (8/07) ^e	CSG Solar (<2 µm on glass) [21]
III-V Cells							
GaAs (thin film cell)	28.8 ± 0.9	0.9927 (ap)	1.122	29.68 ^f	86.5	NREL (5/12)	Alta Devices [22]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95) ^d	RTI, Ge substrate [23]
InP (crystalline cell)	22.1 ± 0.7	4.02 (t)	0.878	29.5	85.4	NREL (4/90) ^d	Spire, epitaxial [24]
Thin Film Chalcogenide							
CIGS (cell)	21.0 ± 0.6	0.9927 (ap)	0.757	35.70 ^g	77.6	FhG-ISE (4/14)	Solibro, on glass [25]
CIGS (minimodule)	18.7 ± 0.6	15.892 (da)	0.701 ^c	35.29 ^c	75.6	FhG-ISE (9/13)	Solibro, 4 serial cells [26]
CdTe (cell)	21.0 ± 0.4	1.0623 (ap)	0.8759	30.25 ^d	79.4	Newport (8/14)	First Solar, on glass [27]
CZTSSe (cell)	9.8 ± 0.2	1.115 (da)	0.5073	31.95 ^j	60.2	Newport (4/16)	IMRA Europe [28]
CZTS (cell)	7.6 ± 0.1	1.067 (da)	0.6585	20.43 ⁱ	56.7	NREL (4/16)	UNSW [14]
Amorphous/Microcrystalline							
Si (amorphous cell)	10.2 ± 0.3 ^k	1.001 (da)	0.896	16.36 ^d	69.8	AIST (7/14)	AIST [29]
Si (microcrystalline cell)	11.8 ± 0.3 ^k	1.044 (da)	0.548	29.39 ^g	73.1	AIST (10/14)	AIST [30]
Perovskite							
Perovskite (cell)	19.7 ± 0.6 ^l	0.9917 (da)	1.104	24.67 ⁱ	72.3	Newport (3/16)	KRICT/UNIST [31]
Perovskite (minimodule)	12.1 ± 0.6^l	36.13 (da)	0.836^c	20.20^c	71.5	AIST (9/16)	SJTU/NIMS, 10 serial cells [5]
Dye sensitised							
Dye (cell)	11.9 ± 0.4 ^m	1.005 (da)	0.744	22.47 ^m	71.2	AIST (9/12)	Sharp [32]
Dye (minimodule)	10.7 ± 0.4 ^m	26.55 (da)	0.754 ^c	20.19 ^c	69.9	AIST (2/15)	Sharp, 7 serial cells [32]
Dye (submodule)	8.8 ± 0.3 ^m	398.8 (da)	0.697 ^c	18.42 ^c	68.7	AIST (9/12)	Sharp, 26 serial cells [33]
Organic							
Organic (cell)	11.2 ± 0.3 ^o	0.992 (da)	0.780	19.30 ^d	74.2	AIST (10/15)	Toshiba [34]
Organic (minimodule)	9.7 ± 0.3 ^o	26.14 (da)	0.806	16.47 ^c	73.2	AIST (2/15)	Toshiba (8 series cells) [35]

Any changes in the tables from those previously published [3] are set in bold type. CIGS, CuIn_{1-y}Ga_ySe₂; a-Si, amorphous silicon/hydrogen alloy; nc-Si, nano-crystalline or microcrystalline silicon; CZTSS, Cu₂ZnSnS_{4-y}Se_y; CZTS, Cu₂ZnSnS₄; (ap), aperture area; (t), total area; (da), designated illumination area; FhG-ISE, Fraunhofer Institut für Solare Energiesysteme; AIST, Japanese National Institute of Advanced Industrial Science and Technology, NREL, National Renewable Energy Laboratory.

^aSpectral response and current–voltage curve reported in the present version of these tables.

^bSpectral response and current–voltage curve reported in version 47 of these tables.

^cReported on a 'per cell' basis.

^dSpectral responses and current–voltage curve reported in version 45 of these tables.

^eRecalibrated from original measurement.

^fSpectral response and current–voltage curve reported in version 40 of these tables.

^gSpectral response and current–voltage curve reported in version 46 of these tables.

^hSpectral response and current–voltage curve reported in version 43 of these tables.

ⁱSpectral response and current–voltage curve reported in version 48 of these tables.

^jStabilised by 1000 h exposure to one sun light at 50 °C.

^kNot measured at an external laboratory.

^lNot stabilised, initial efficiency. Reference [36] reviews the stability of similar devices.

^mInitial performance (not stabilised). Reference [37] reviews the stability of similar devices.

ⁿSpectral response and current–voltage curve reported in version 41 of these tables.

^oInitial performance (not stabilised). References [38] and [39] review the stability of similar devices.

^pSpectral response and/or current–voltage curve reported in version 42 of these tables.

Table II. Confirmed multiple-junction terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m²) at 25 °C (IEC 60904-3: 2008, ASTM G-173-03 global).

Classification	Efficiency (%)	Area (cm ²)	Voc (V)	Jsc (mA/cm ²)	Fill factor (%)	Test centre (date)	Description
III-V Multijunctions							
Five-junction cell (bonded) (2.17/1.68/1.40/1.06/0.73 eV)	38.8 ± 1.2	1.021 (ap)	4.767	9.564	85.2	NREL (7/13)	Spectrolab [40]
InGaP/GaAs/InGaAs	37.9 ± 1.2	1.047 (ap)	3.065	14.27 ^a	86.7	AIST (2/13)	Sharp [41]
GaInP/GaAs (monolithic)	31.6 ± 1.5	0.999 (ap)	2.538	14.18 ^b	87.7	NREL (1/16)	Alta Devices [42]
Multijunctions with c-Si							
GaInP/GaInAs/Ge; Si (spectral split minimodule)	34.5 ± 2.0	27.83 (ap)	2.66/0.65	13.1/9.3	85.6/79.0	NREL (4/16)	UNSW/AzurTrina [43]
GaInP/Si (mech. stack)	30.5 ± 2.0^c	1.005 (da)	1.45/0.69	15.3/21.5^d	85.1/78.2	NREL (9/16)	NREL/CSEM, 4-terminal [6]
GaInP/GaAs/Si (wafer bonded)	30.2 ± 1.1^c	3.963 (ap)	3.046	11.9^d	83.0	FhG-ISE (6/16)	Fraunhofer ISE [7]
GaInP/GaAs/Si (monolithic)	19.7 ± 0.7^c	3.943 (ap)	2.323	10.0^d	84.3	FhG-ISE (8/16)	Fraunhofer ISE
Perovskite/Si (monolithic)	23.6 ± 0.6^e	0.990 (ap)	1.651	18.09^d	79.0	NREL (8/16)	Stanford/ASU [8]
a-Si/nc-Si Multijunctions							
a-Si/nc-Si/nc-Si (thin-film)	14.0 ± 0.4^f	1.045 (da)	1.922	9.94^f	73.4	AIST (5/16)	AIST [9]
a-Si/nc-Si (thin-film cell)	12.7 ± 0.4% ^f	1.000 (da)	1.342	13.45 ^g	70.2	AIST (10/14)	AIST 29.30]

Any changes in the tables from those previously published [3] are set in bold type. a-Si, amorphous silicon/hydrogen alloy; nc-Si, nanocrystalline or microcrystalline silicon; (ap), aperture area; (t), total area; (da), designated illumination area; FhG-ISE, Fraunhofer Institut für Solare Energiesysteme; AIST, Japanese National Institute of Advanced Industrial Science and Technology; NREL, National Renewable Energy Laboratory.

^aSpectral response and current-voltage curve reported in version 42 of these tables.

^bSpectral response and current-voltage curve reported in version 48 of these tables.

^cNot measured at an external laboratory.

^dSpectral response and current-voltage curve reported in the present version of these tables.

^eNot stabilised, initial efficiency. Reference 36 reviews the stability of similar devices.

^fStabilised by 1000 h exposure to one sun light at 50 °C.

^gSpectral responses and current-voltage curve reported in version 45 of these tables.

Table III. Confirmed terrestrial module efficiencies measured under the global AM1.5 spectrum (1000 W/m²) at a cell temperature of 25 °C (IEC 60904-3: 2008, ASTM G-173-03 global).

Classification	Effic. (%)	Area (cm ²)	V _{oc} (V)	I _{sc} (A)	FF (%)	Test centre (date)	Description
Si (crystalline)	24.4 ± 0.5	13 177 (da)	79.5	5.04^a	80.1	AIST (9/16)	Kaneka (108 cells) [4]
Si (multicrystalline)	19.9 ± 0.4	15 143 (ap)	78.87	4.795^a	79.5	FhG-ISE (10/16)	Trina Solar (120 cells) [10]
GaAs (thin film)	24.1 ± 1.0	858.5 (ap)	10.89	2.255 ^b	84.2	NREL (11/12)	Alta Devices [44]
CdTe (thin-film)	18.6 ± 0.6	7038.8 (ap)	110.6	1.533 ^c	74.2	NREL (4/15)	First Solar, monolithic [45]
CIGS (Cd free)	17.5 ± 0.5	808 (da)	47.6	0.408 ^d	72.8	AIST (6/14)	Solar Frontier (70 cells) [46]
CIGS (large)	15.7 ± 0.5	9703 (ap)	28.24	7.254 ^e	72.5	NREL (11/10)	Miasole [47]
a-Si/nc-Si (tandem)	12.3 ± 0.3 ^f	14 322 (t)	280.1	0.902 ^g	69.9	ESTI (9/14)	TEL Solar, Trubbach Labs [48]
Organic	8.7 ± 0.3 ^h	802 (da)	17.47	0.569 ^c	70.4	AIST (5/14)	Toshiba [35]
Multijunction							
InGaP/GaAs/InGaAs	31.2 ± 1.2	968 (da)	23.95	1.506	83.6	AIST (2/16)	Sharp (32 cells) [49]

Any changes in the tables from those previously published [3] are set in bold type. CIGSS, CuInGaSSe; a-Si, amorphous silicon/hydrogen alloy; a-SiGe, amorphous silicon/germanium/hydrogen alloy; nc-Si, nanocrystalline or microcrystalline silicon; Effic., efficiency; (t), total area; (ap), aperture area; (da), designated illumination area; FF, fill factor; FhG-ISE, Fraunhofer Institut für Solare Energiesysteme; AIST, Japanese National Institute of Advanced Industrial Science and Technology; NREL, National Renewable Energy Laboratory; ESTI, European Solar Test Installation. ^aSpectral response and/or current–voltage curve reported in the present version of these tables.

^bSpectral response and current–voltage curve reported in version 41 of these tables.

^cSpectral response and/or current–voltage curve reported in version 48 of these tables.

^dSpectral response and/or current–voltage curve reported in version 45 of these tables.

^eSpectral response reported in version 37 of these tables.

^fStabilised at the manufacturer to the 2% level following IEC procedure of repeated measurements.

^gSpectral response and/or current–voltage curve reported in version 46 of these tables.

^hInitial performance (not stabilised).

author). Table I summarises the best-reported measurements for ‘one-sun’ (non-concentrator) single-junction cells and submodules. Table II is new to the present issue of these tables and summarises the growing number of cell and submodule results involving high efficiency, one-sun multiple-junction devices, with these previously reported in Table I. Table III shows the best results for one-sun modules. Table IV contains what might be described as ‘notable exceptions’. While not conforming to the requirements to be recognised as a class record, the one-sun 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 encourage discrimination, Table IV is limited to nominally 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.

Table V shows the best results for concentrator cells and concentrator modules (a smaller number of ‘notable exceptions’ for concentrator cells and modules additionally is included in Table V).

Sixteen new results are reported in the present version of these Tables. The first new result in Table I is a new efficiency record for a large area (180 cm² designated illumination area) silicon solar cell. An efficiency of 26.3% has been measured by the Fraunhofer Institute for Solar Energy Systems (FhG-ISE) for a cell fabricated by Kaneka

using an amorphous silicon heterojunction interdigitated back contact approach [4]. Efficiency was a creditable 25.6% on a total area basis.

Table I also reports the first certified results for perovskite minimodules. An efficiency of 11.5% was reported in August for a 16-cm² four-cell minimodule fabricated by the University of New South Wales and measured by the Newport Technology and Applications Center. This was surpassed in September with an efficiency of 12.1% reported for a 36-cm² 10-cell minimodule fabricated by Shanghai Jiao Tong University in conjunction with the Japanese National Institute of Materials Science [5] with the module measured by the Japanese National Institute of Advanced Industrial Science and Technology (AIST). This is an initial efficiency in both cases, with the stability of these devices not investigated.

Five new results are reported in the new Table II relating to one-sun, multijunction devices. The first new result is for a two-junction (2j), four-terminal GaInP/Si mechanically stacked device with an efficiency of 30.5% measured for a 1-cm² device with the GaInP cell fabricated by the National Renewable Energy Laboratory (NREL) and the silicon cell by the Swiss Center for Electronics and Microtechnology, Neuchatel, with the stacked device measured by NREL [6].

A similar efficiency of 30.2% has been confirmed for a 4-cm² two-terminal, three-junction, wafer bonded GaInP/GaAs/Si cell fabricated and measured at FhG-ISE [7]. Here, the GaInP/GaAs cells have not been directly grown on the Si but grown inverted on a GaAs substrate and transferred to the Si bottom cell via wafer bonding.

Table IV. 'Notable Exceptions': 'Top ten' confirmed cell and module results, not class records measured under the global AM1.5 spectrum (1000 W m^{-2}) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global).

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill factor (%)	Test centre (date)	Description
Cells (silicon)							
Si (crystalline)	25.0 ± 0.5	4.00 (da)	0.706	42.7^a	82.8	Sandia (3/99) ^b	UNSW p-type PERC top/rear contacts [50]
Si (crystalline)	25.3 ± 0.3^c	4.014 (da)	0.7180	42.50^d	82.8	FhG-ISE (8/16)	FhG-ISE, n-type top/rear contacts [11]
Cells (III-V)							
GaNP	21.4 ± 0.3	0.2504 (ap)	1.4932	16.31^d	87.7	NREL (9/16)	LG Electronics, high bandgap [12]
Cells (chalcogenide)							
CIGS (thin-film)	22.6 ± 0.5	0.4092 (da)	0.7411	37.78^d	80.6	FhG-ISE (5/16)	ZSW on glass [13]
CIGSS (Cd free)	22.0 ± 0.5	0.512 (da)	0.7170	39.45^e	77.8	FhG-ISE (3/16)	Solar Frontier on glass [51]
CdTe (thin-film)	22.1 ± 0.5	0.4798 (da)	0.8872	31.69 ^h	78.5	Newport (11/15)	First Solar on glass [52]
CZTS (thin-film)	12.6 ± 0.3	0.4209 (ap)	0.5134	35.21 ^g	69.8	Newport (7/13)	IBM solution grown [53]
CZTS (thin-film)	9.5 ± 0.2	0.2379 (da)	0.6732	21.25^h	66.3	NREL (9/16)	UNSW on glass [14]
Cells (other)							
Perovskite (thin-film)	22.1 ± 0.7^i	0.0946 (ap)	1.105	24.97 ^e	80.3	Newport (3/16)	KRICT/UNIST [31]

Any changes in the tables from those previously published [3] are set in bold type. CIGSS, CuInGaSSe ; CZTSS, $\text{Cu}_2\text{ZnSnS}_{4-x}\text{Se}_x$; CZTS, $\text{Cu}_2\text{ZnSnS}_4$ (ap), aperture area; (t), total area; (da), designated illumination area; AIST, Japanese National Institute of Advanced Industrial Science and Technology; NREL, National Renewable Energy Laboratory; FhG-ISE, Fraunhofer-Institut für Solare Energiesysteme; IBM, International Business Machines Corporation; UNSW, University of New South Wales; ZSW, Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg. ^aSpectral response reported in version 36 of these tables.

^bRecalibrated from original measurement.

^cNot measured at an external laboratory.

^dSpectral response and current-voltage curves reported in the present version of these tables.

^eSpectral response and current-voltage curves of this or similar cell reported in version 48 of these tables.

^fSpectral response and current-voltage curves reported in version 45 of these tables.

^gSpectral response and current-voltage curves reported in version 44 of these tables.

^hSpectral response and/or current-voltage curves reported in version 46 of these tables.

ⁱStability not investigated. Reference 36 documents stability of similar devices.

Table V. Terrestrial concentrator cell and module efficiencies measured under the ASTM G-173-03 direct beam AM1.5 spectrum at a cell temperature of 25 °C.

Classification	Effic. (%)	Area (cm ²)	Intensity ^a (suns)	Test centre (date)	Description
Single Cells					
GaAs	29.3 ± 0.7^b	0.09359 (da)	49.9	NREL (10/16)	LG Electronics
Si	27.6 ± 1.2 ^c	1.00 (da)	92	FhG-ISE (11/04)	Amonix back-contact [54]
CIGS (thin-film)	23.3 ± 1.2 ^d	0.09902 (ap)	15	NREL (3/14)	NREL [55]
Multijunction cells					
GalnP/GaAs; GaInAsP/GaInAs	46.0 ± 2.2 ^f	0.0520 (da)	508	AIST (10/14)	Soitec/CEA/FhG-ISE 4j bonded [56]
GalnP/GaAs/GaInAs/GaInAs	45.7 ± 2.3 ^d	0.09709 (da)	234	NREL (9/14)	NREL, 4j monolithic [57]
InGaP/GaAs/InGaAs	44.4 ± 2.6 ^h	0.1652 (da)	302	FhG-ISE (4/13)	Sharp, 3j inverted metamorphic [58]
GalnP/GaInAs	34.2 ± 1.7^b	0.05361 (da)	460	FhG-ISE (4/16)	Fraunhofer ISE 2j [18]
Minimodule					
GalnP/GaAs; GaInAsP/GaInAs	43.4 ± 2.4 ^d	18.2 (ap)	340 ^j	FhG-ISE (7/15)	Fraunhofer ISE 4j (lens/cell) [59]
Submodule					
GalnP/GaInAs/Ge; Si	40.6 ± 2.0 ^j	287 (ap)	365	NREL (4/16)	UNSW 4j split spectrum [60]
Modules					
Si	20.5 ± 0.8 ^d	1875 (ap)	79	Sandia (4/89) ^k	Sandia/UNSW/ENTECH (12 cells) [61]
Three junction (3j)	35.9 ± 1.8 ^l	1092 (ap)	N/A	NREL (8/13)	Amonix [62]
Four junction (4j)	38.9 ± 2.5 ^m	812.3 (ap)	333	FhG-ISE (4/15)	Soitec [63]
'Notable exceptions'					
Si (large area)	21.7 ± 0.7	20.0 (da)	11	Sandia (9/90) ^k	UNSW laser grooved [64]
Luminescent minimodule	7.1 ± 0.2	25(ap)	2.5 ^j	ESTI (9/08)	ECN Petten, GaAs cells [65]

Any changes in the tables from those previously published [3] are set in bold type. CIGS, CuInGaSe₂; Effic., efficiency; (da), designated illumination area; (ap), aperture area; NREL, National Renewable Energy Laboratory; FhG-ISE, Fraunhofer-Institut für Solare Energiesysteme; AIST, Japanese National Institute of Advanced Industrial Science and Technology; UNSW, University of New South Wales; ESTI, European Solar Test Installation; ECN, Energy Research Centre of the Netherlands.

^aOne sun corresponds to direct irradiance of 1000 W/m².

^bSpectral response and current-voltage curve reported in the present version of these tables.

^cMeasured under a low aerosol optical depth spectrum similar to ASTM G-173-03 direct [66].

^dNot measured at an external laboratory.

^eSpectral response and current-voltage curve reported in version 44 of these tables.

^fSpectral response and current-voltage curve reported in version 45 of these tables.

^gSpectral response and current-voltage curve reported in version 46 of these tables.

^hSpectral response and current-voltage curve reported in version 42 of these tables.

ⁱDetermined at IEC 62670-1 CSTC reference conditions.

^jGeometric concentration.

^kRecalibrated from original measurement.

^lReferenced to 1000 W/m² direct irradiance and 25 °C cell temperature using the prevailing solar spectrum and an in-house procedure for temperature translation.

^mMeasured under IEC 62670-1 reference conditions following the current IEC power rating draft 62670-3.

An efficiency of 19.7% also has been confirmed for a 4-cm² monolithic GaInP/GaAs/Si cell again fabricated and measured at FhG-ISE, with the GaInP/GaAs cells directly grown on the Si.

The fourth new result in Table II is for a 1-cm², 23.6% efficient monolithic perovskite-on-silicon tandem cell fabricated by combining an infrared-tuned silicon heterojunction bottom cell developed at Arizona State University with a Cs_{0.17}FA_{0.83}Pb(Br_{0.17}I_{0.83})₃ perovskite top cell deposited at Stanford University with the final device measured at NREL [8]. Finally, 14.0% efficiency for a 1-cm² thin-film a-Si/nc-Si/nc-Si triple junction cell fabricated and measured at AIST is reported [9].

Two significant new module results are reported in Table III. Following the battle for supremacy for a large area crystalline-Si module reported in the previous versions of these tables [3], two groups reported confirmed large-area module efficiencies above 24% during the reporting period. First, SunPower reported an efficiency of 24.1% in June exceeded by Kaneka in September with an aperture area efficiency of 24.4% reported for

a 1.3-m² interdigitated back contact module measured by AIST [4].

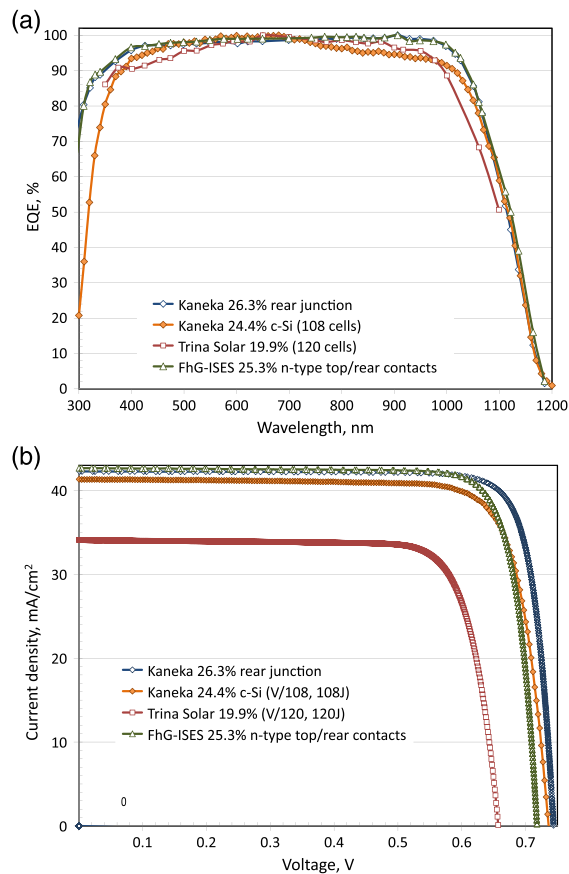


Figure 1. (a) Normalised external quantum efficiency (EQE) for the new silicon cell and module results reported in this issue and (b) corresponding current density–voltage (JV) curves for the same devices. FhG-ISES, Fraunhofer-Institut für Solare Energiesysteme.

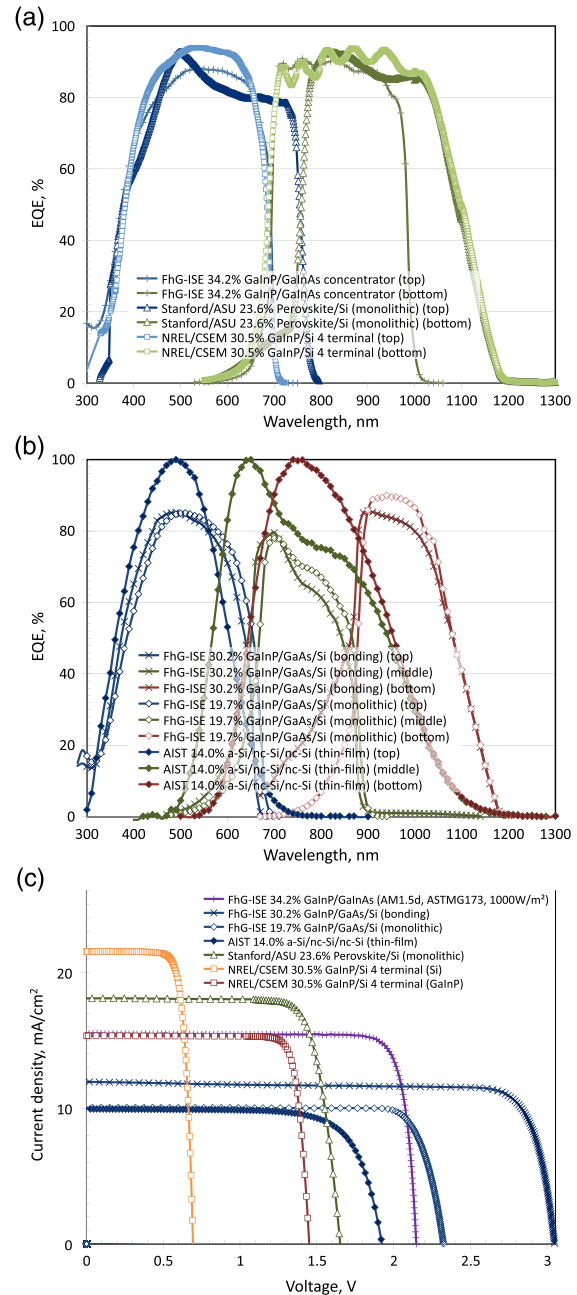


Figure 2. (a) External quantum efficiency (EQE) for the new two-junction multijunction cell results reported in this issue; (b) external quantum efficiency (EQE) for the new three-junction multijunction cell results reported in this issue (mixed normalised and absolute results); and (c) corresponding current density–voltage (JV) curves. AIST, Japanese National Institute of Advanced Industrial Science and Technology; CSEM, Swiss Center for Electronics and Microtechnology; FhG-ISE, Fraunhofer-Institut für Solare Energiesysteme; NREL, National Renewable Energy Laboratory.

An increase to 19.9% aperture area efficiency is also reported for a larger (1.5 m^2) multicrystalline module fabricated by Trina Solar [10] and measured at the FhG-ISE. This module included a number of advanced cell and module technologies, including half-cell, high-performance multi-crystalline silicon wafers with a high minority carrier lifetime, high-efficiency passivated emitter and rear cell technology and highly efficient light trapping.

Five new results are reported as 'notable exceptions' in Table IV. An efficiency of 25.3% has been confirmed for a 4-cm^2 n-type silicon cell with both top and rear contacts, fabricated and measured at FhG-ISE, a record for a cell with this traditional type of contacting [11]. The efficiency of a wide bandgap GaInP cell has been increased to 21.4% for a small area (0.25 cm^2) cell fabricated by LG Electronics and measured at NREL [12]. Yet another increase in CIGS ($\text{CuIn}_{1-x}\text{Ga}_x\text{Se}_2$) cell efficiency to 22.6% is reported for a small area (0.4 cm^2) cell fabricated by Zentrum für

Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg and measured at FhG-ISE [13]. For a Cd-free CIGSS device of similar area, efficiency was increased to 22.0% for a cell fabricated by Solar Frontier and also measured at FhG-ISE. Finally, an efficiency of 9.5% has also been measured for a small (0.24 cm^2) pure sulfide CZTS ($\text{Cu}_2\text{ZnSnS}_4$) cell fabricated by the University of New South Wales and measured at Newport [14]. For the previous four cells, cell area is too small for classification as an outright record. Solar cell efficiency targets in governmental research programmes generally have been specified in terms of a cell area of 1 cm^2 or larger [15–17].

Two new concentrator cell results are reported in Table V. The first is improvement in efficiency to 29.3% for a small area (0.09 cm^2) cell fabricated by LG Electronics and measured at NREL. The final new result in Table V is a new efficiency level of 34.2% for a small area (0.05 cm^2), two-junction GaInP/GaInAs concentrator cell fabricated and measured by FhG-ISE [18], slightly higher in measured efficiency than a similar device fabricated and measured at NREL in 2014.

The EQE spectra for the new silicon cell and module results reported in the present issue of these Tables are shown in Figure 1(a). Figure 1(b) shows the current density–voltage (JV) curves for the same devices. Figure 2(a) and (b) shows the EQE for the new two-junction and three-junction multijunction cell results, respectively with Figure 2(c) showing their current density–voltage (JV) curves. Figure 3(a) and (b) shows the corresponding EQE and JV curves for the new perovskite minimodule, together with the new GaInP, CIGS, CZTS and GaAs concentrator cell results.

For the case of modules, the measured current–voltage data have been reported on a 'per cell' basis (measured voltage has been divided by the known or estimated number of cells in series, while measured current has been multiplied by this quantity and divided by the module area).

3. 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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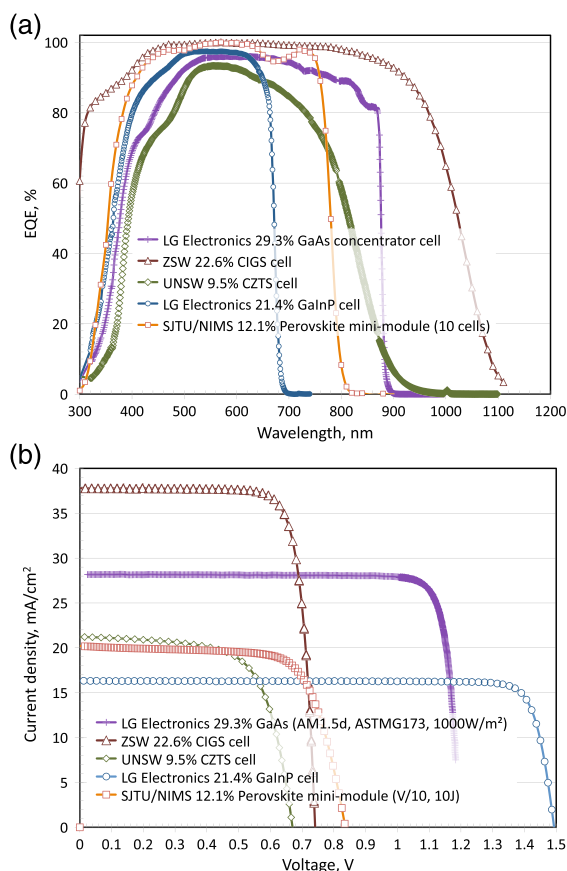


Figure 3. (a) External quantum efficiency (EQE) for the new perovskite minimodule results reported in this issue together with the new GaInP, CIGS, CZTS and GaAs concentrator cell results (mixed normalised and absolute results) and (b) corresponding current density–voltage (JV) curves. CIGS, $\text{CuIn}_{1-x}\text{Ga}_x\text{Se}_2$; CZTS, $\text{Cu}_2\text{ZnSnS}_4$; UNSW, University of New South Wales; ZSW, Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg; SJTU, Shanghai Jiao Tong University; NIMS, Japanese National Institute of Materials Science.

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REFERENCES

- Green MA, Emery K, Hishikawa Y, Warta W, Dunlop ED. Solar cell efficiency tables (Version 39). *Progress in Photovoltaics: Research and Applications* 2012; **20**: 12–20
- Green MA, Emery K, Hishikawa Y, Warta W. Solar cell efficiency tables (Version 33). *Progress in Photovoltaics: Research and Applications* 2009; **17**: 85–94
- Green MA, Emery K, Hishikawa Y, Warta W, Dunlop ED. Solar cell efficiency tables (Version 48). *Progress in Photovoltaics: Research and Applications* 2016; **24**: 905–913
- http://www.kaneka.co.jp/kaneka-e/images/topics/1473811995/1473811995_101.pdf (accessed 25 October 2016).
- <http://en.sjtu.edu.cn/news/a-breakthrough-in-large-area-perovskite-solar-panels-by-sjtu-team/> (accessed 25 October 2016).
- Essig S, Steiner MA, Alleb'e C, Geisz JF, Paviet-Salomon B, Ward S, Descoeudres A, LaSalvia V, Barraud L, Badel N, Faes A, Levrat J, Despeisse M, Ballif C, Stradins P, Young DL. Realization of GaInP/Si dual-junction solar cells with 29.8% 1-sun efficiency. *IEEE Journal of Photovoltaics* 2016; **6**: 1012–1019. DOI:10.1109/JPHOTOV.2016.2549746
- Cariou R, Benick J, Beutel P, Razek N, Flötgen CH, Hermle M, Lackner D, Glunz S, Bett AW, Wimplinger M, Dimroth F. Monolithic 2-terminal III-V//Si triple-junction solar cells with 30.2% efficiency under 1-sun AM1.5 g. *IEEE Journal of Photovoltaics*, accepted for publication, 2016.
- <http://web.stanford.edu/group/mcgehee/research.html>.
- Sai H, Matsui T, Koida T, Matsubara K, Kondo M, Sugiyama S, Katayama H, Takeuchi Y, Yoshida I. Triple-junction thin-film silicon solar cell fabricated on periodically textured substrate with a stabilized efficiency of 13.6%. *Applied Physics Letters* 2015; **106**: 213902. DOI:10.1063/1.4921794
- Verlinden PJ et al. *Will We Have > 22% Efficient Multi-Crystalline Silicon Solar Cells?* PVSEC 26: Singapore, 2016. 24–28.
- Glunz SW, Feldmann F, Richter A, Bivour M, Reichel C, Steinkemper H, Benick J, Hermle M. The irresistible charm of a simple current flow pattern –25% with a solar cell featuring a full-area back contact. Paper 2BP.1.1, *European Photovoltaic Solar Energy Conference 2015*, Hamburg, September 2015.
- Kim S, Hwang ST, Yoon W, Lee HM. High performance GaAs solar cell using heterojunction emitter and its further improvement by ELO technique. Paper 4CV.1.27, *European Photovoltaic Solar Energy Conference 2016*, Munich, June 2016.
- https://www.zsw-bw.de/fileadmin/user_upload/PDFs/Pressemitteilungen/2016/pr09-2016-ZSW-WorldRecordCIGS.pdf (accessed 25 October 2016).
- Sun K, Yan C, Liu F, Huang J, Zhou F, Stride JA, Green M, Hao X. Over 9% efficient kesterite $\text{Cu}_2\text{ZnSnS}_4$ solar cell fabricated by using $\text{Zn}_{1-x}\text{Cd}_x\text{S}$ buffer layer. *Advanced Energy Materials* 2016; **6**: 1600046. DOI:10.1002/aenm.201600046.
- Program milestones and decision points for single junction thin films. *Annual Progress Report 1984, Photovoltaics, Solar Energy Research Institute, Report DOE/CE-0128*, June 1985; 7.
- Sakata I, Tanaka Y, Koizawa K. Japan's new National R&D Program for Photovoltaics. *Photovoltaic Energy Conversion, Conference Record of the 2006 IEEE 4th World Conference*, 2008; **1**: 1–4
- Jäger-Waldau A (Ed). *PVNET: European Roadmap for PV R&D*. EUR 21087 EN, 2004, p.27.
- Ohlmann J, Martinez Sanchez JF, Lackner D, Förster P, Steine M, Fallisch A, Dimroth F. Recent development in direct generation of hydrogen using multi-junction solar cells. *AIP Conf. Proc.* 2016; **1766**: 080004. DOI:10.1063/1.4962102
- Zhang S, Pan X, Jiao H, Deng W, Xu J, Chen Y, Altermatt PP, Feng Z, Verlinden PJ. 335 watt world record p-type mono-crystalline module with 20.6% efficient PERC solar cells. *IEEE Journal of Photovoltaics*, to be published.
- Moslehi MM, Kapur P, Kramer J, Rana V, Seutter S, Deshpande A, Stalcup T, Kommera S, Ashjaee J, Calcaterra A, Grupp D, Dutton D, Brown R. World-record 20.6% efficiency 156 mm × 156 mm full-square solar cells using low-cost kerfless ultrathin epitaxial silicon & porous silicon lift-off technology for industry-leading high-performance smart PV modules. *PV Asia Pacific Conference (APVIA/PVAP)*, 24 October 2012.
- Keevers MJ, Young TL, Schubert U, Green MA. 10% efficient CSG minimodules. *22nd European Photovoltaic Solar Energy Conference*, Milan, September 2007.
- Kayes BM, Nie H, Twist R, Spruytte SG, Reinhardt F, Kizilyalli IC, Higashi GS. 27.6% conversion efficiency, a new record for single-junction solar cells under 1 sun illumination. *Proceedings of the 37th IEEE Photovoltaic Specialists Conference*, 2011.
- Venkatasubramanian R, O'Quinn BC, Hills JS, Sharps PR, Timmons ML, Hutchby JA, Field H, Ahrenkiel A, Keyes B. 18.2% (AM1.5) efficient GaAs solar cell on

- optical-grade polycrystalline Ge substrate. *Conference Record, 25th IEEE Photovoltaic Specialists Conference*, Washington, May 1997, 31–36.
24. Keavney CJ, Haven VE, Vernon SM. Emitter structures in MOCVD InP solar cells. *Conference Record, 21st IEEE Photovoltaic Specialists Conference*, Kissimmee, May, 1990, 141–144.
 25. Solibro press release, “Solibro beats world record for solar cells”, dated 12 June 2014.
 26. Wallin E, Malm U, Jarmar T, Lundberg O, Edoff M, Stolt L. World-record Cu(In,Ga)Se₂-based thin-film sub-module with 17.4% efficiency. *Progress in Photovoltaics: Research and Applications* 2012; **20**: 851–854.
 27. First solar press release, First Solar builds the highest efficiency thin film PV cell on record, 5 August 2014.
 28. Larramona G, Levchenko S, Bourdais S, Jacob A, Choné C, Delatouche B, Moisan C, Unold T, Dennler G. Fine-tuning the Sn content in CZTSSe thin films to achieve 10.8% solar cell efficiency from spray-deposited water–ethanol-based colloidal inks. *Advanced Energy Materials* 2015; **5**: 1501404.
 29. Matsui T, Sai H, Suezaki T, Matsumoto M, Saito K, Yoshida I, Kondo M. Development of highly stable and efficient amorphous silicon based solar cells. *Proc. 28th European Photovoltaic Solar Energy Conference* 2013; 2213–2217.
 30. Sai H, Maejima K, Matsui T, Koida T, Kondo M, Nakao S, Takeuchi Y, Katayama H, Yoshida I. High-efficiency microcrystalline silicon solar cells on honeycomb textured substrates grown with high-rate VHF plasma-enhanced chemical vapor deposition. *Japanese Journal of Applied Physics* 2015; **54**: 08KB05.
 31. Yang WS, Noh JH, Jeon NJ, Kim YC, Ryu S, Seo J, Seok SI. High-performance photovoltaic perovskite layers fabricated through intramolecular exchange. *Science* 2015; **348**(6240): 1234–1237.
 32. Komiya R, Fukui A, Murofushi N, Koide N, Yamanaka R and Katayama H. Improvement of the conversion efficiency of a monolithic type dye-sensitized solar cell module. *Technical Digest, 21st International Photovoltaic Science and Engineering Conference*, Fukuoka, November 2011; 2C-50-08.
 33. Kawai M High-durability dye improves efficiency of dye-sensitized solar cells. *Nikkei Electronics* 2013; Feb. 1 (http://techon.nikkeibp.co.jp/english/NEWS_EN/20130131/263532/) (accessed 23 October, 2013)
 34. Mori S, Oh-oka H, Nakao H, Gotanda T, Nakano Y, Jung H, Iida A, Hayase R, Shida N, Saito M, Todoriki K, Asakura T, Matsui A, Hosoya M. Organic photovoltaic module development with inverted device structure. *MRS Proceedings* 2015; **1737**: . DOI:10.1557/opl.2015.540
 35. Hosoya M, Oooka H, Nakao H, Gotanda T, Mori S, Shida N, Hayase R, Nakano Y, Saito M. Organic thin film photovoltaic modules. *Proceedings of the 93rd Annual Meeting of the Chemical Society of Japan* 2013; 21–37.
 36. Han Y, Meyer S, Dkhissi Y, Weber K, Pringle JM, Bach U, Spiccia L, Cheng YB. Degradation observations of encapsulated planar CH₃NH₃PbI₃ perovskite solar cells at high temperatures and humidity. *Journal of Materials Chemistry A* 2015; **3**: 8139–8147
 37. Krašovec UO, Bokalič M, Topič M. Ageing of DSSC studied by electroluminescence and transmission imaging. *Solar Energy Materials and Solar Cells* 2013; **117**: 67–72.
 38. Tanenbaum DM, Hermenau M, Voroshazi E, Lloyd MT, Galagan Y, Zimmermann B, Hoesel M, Dam HF, Jørgensen M, Gevorgyan SA, Kudret S, Maes W, Lutsen L, Vanderzande D, Wuerfel U, Andriessen R, Roesch R, Hopper H, Teran-Escobar G, Lira-Cantu M, Rivaton A, Uzunoğlu GY, Germack D, Andreasen B, Madsen MV, Norrmany K, Krebs FC. The ISOS-3 inter-laboratory collaboration focused on the stability of a variety of organic photovoltaic devices. *RSC Advances* 2012; **2**: 882–893.
 39. a Krebs FC (Ed). *Stability and Degradation of Organic and Polymer Solar cells*. Wiley: Chichester, 2012; b Jorgensen M, Norrman K, Gevorgyan SA, Tromholt T, Andreasen B, Krebs FC. Stability of polymer solar cells. *Advanced Materials* 2012; **24**: 580–612.
 40. Chiu PT, Law DL, Woo RL, Singer S, Bhusari D, Hong WD, Zakaria A, Boisvert JC, Mesropian S, King RR, Karam NH. 35.8% space and 38.8% terrestrial 5 J direct bonded cells. *Proc. 40th IEEE Photovoltaic Specialist Conference*, Denver, June 2014; 11–13.
 41. Sasaki K, Agui T, Nakaido K, Takahashi N, Onitsuka R, Takamoto T. *Proceedings, 9th International Conference on Concentrating Photovoltaics Systems*. Miyazaki: Japan, 2013.
 42. Kayes BM, Zhang L, Twist R, Ding IK, Higashi GS. Flexible thin-film tandem solar cells with >30% efficiency. *IEEE Journal of Photovoltaics* 2014; **4**: 729–733.
 43. Green MA, Keevers MJ, Concha Ramon B, Jiang Y, Thomas I, Lasich JB, Verlinden, PJ, Yang Y, Zhang X, Emery K, Moriarty T, King RR, Bensch W. Improvements in sunlight to electricity conversion efficiency: above 40% for direct sunlight and over 30% for global. Paper 1AP.1.2, *European Photovoltaic Solar Energy Conference 2015*, Hamburg, September 2015.
 44. Mattos LS, Scully SR, Syfu M, Olson E, Yang L, Ling C, Kayes BM, He G. New module efficiency record: 23.5% under 1-sun illumination using thin-film

- single-junction GaAs solar cells. *Proceedings of the 38th IEEE Photovoltaic Specialists Conference*, 2012.
45. First solar press release. First Solar achieves world record 18.6 % thin film module conversion efficiency, 15 June 2015.
 46. Sugimoto H High efficiency and large volume production of CIS-based modules. *40th IEEE Photovoltaic Specialists Conference*, Denver, June 2014.
 47. <http://www.miasole.com> (accessed 22 May, 2015).
 48. Cashmore JS, Apolloni M, Braga A, Caglar O, Cervetto V, Fenner Y, Goldbach-Aschemann S, Goury C, Hötzel JE, Iwahashi T, Kalas J, Kitamura M, Klindworth M, Kupich M, Leu GF, Lin J, Lindic MH, Losio PA, Mates T, Matsunaga D, Mereu B, Nguyen XV, Psimoulis I, Ristau S, Roschek T, Salabas A, Salabas EL, Sinicco I. Improved conversion efficiencies of thin-film silicon tandem (MICROMORPHTM) photovoltaic modules. *Solar Energy Materials and Solar Cells* 2016; **144**: 84–95. DOI:10.1016/j.solmat.2015.08.022.
 49. Takamoto T. Application of InGaP/GaAs/InGaAs triple junction solar cells to space use and concentrator photovoltaic. *40th IEEE Photovoltaic Specialists Conference*, Denver, June 2014.
 50. Zhao J, Wang A, Green MA, Ferrazza F. Novel 19.8% efficient “honeycomb” textured multicrystalline and 24.4% monocrystalline silicon solar cells. *Applied Physics Letters* 1998; **73**: 1991–1993.
 51. Solar frontier press release. Solar Frontier achieves world record thin-film solar cell efficiency: 22.3%, 8 December 2015.
 52. First solar press release. First Solar Achieves yet another cell conversion efficiency world record, 24 February 2016.
 53. Wang W, Winkler MT, Gunawan O, Gokmen T, Todorov TK, Zhu Y, Mitzi DB. Device characteristics of CZTSSe thin-film solar cells with 12.6% efficiency. *Advanced Energy Materials* 2013. DOI:10.1002/aenm.201301465.
 54. Slade A, Garboushian V. 27.6% efficient silicon concentrator cell for mass production. *Technical Digest, 15th International Photovoltaic Science and Engineering Conference*, Shanghai, October 2005; 701.
 55. Ward JS, Ramanathan K, Hasoon FS, Coutts TJ, Keane J, Contreras MA, Moriarty T, Noufi R. A 21.5% efficient Cu(In,Ga)Se₂ thin-film concentrator solar cell. *Progress in Photovoltaics: Research and Applications* 2002; **10**: 41–46.
 56. Press release, Fraunhofer Institute for Solar Energy Systems, 1 December 2014 (accessed at <http://www.ise.fraunhofer.de/en/press-and-media/press-releases/press-releases-2014/new-world-record-for-solar-cell-efficiency-at-46-percent> on 7 December 2014).
 57. NREL press release NR-4514, 16 December 2014.
 58. Press release, Sharp Corporation, 31 May 2012 (accessed at <http://sharp-world.com/corporate/news/120531.html> on 5 June 2013).
 59. Steiner M, Siefert G, Schmidt T, Wiesenfarth M, Dimroth F, Bett AW. 43 % sun light to electricity conversion efficiency using CPV. *IEEE Journal of Photovoltaics*, submitted.
 60. Green MA, Keevers MJ, Thomas I, Lasich JB, Emery K, King RR. 40% efficient sunlight to electricity conversion. *Progress in Photovoltaics: Research and Applications* 2015; **23**(6): 685–691.
 61. Chiang CJ and Richards EH. A 20% efficient photovoltaic concentrator module. *Conf. Record, 21st IEEE Photovoltaic Specialists Conference*, Kissimmee, May 1990: 861–863.
 62. <http://amonix.com/pressreleases/amonix-achieves-world-record-359-module-efficiency-rating-nrel-4> (accessed 23 October 2013).
 63. van Riesen S, Neubauer M, Boos A, Rico MM, Gourdel C, Wanka S, Krause R, Guernard P, Gombert A. New module design with 4-junction solar cells for high efficiencies. *Proceedings of the 11th Conference on Concentrator Photovoltaic Systems*, 2015.
 64. Zhang F, Wenham SR, Green MA. Large area, concentrator buried contact solar cells. *IEEE Transactions on Electron Devices* 1995; **42**: 144–149.
 65. Slooff LH, Bende EE, Burgers AR, Budel T, Pravettoni M, Kenny RP, Dunlop ED, Buechtemann A. A luminescent solar concentrator with 7.1% power conversion efficiency. *Physica Status Solidi (RRL)* 2008; **2**(6): 257–259.
 66. Gueymard CA, Myers D, Emery K. Proposed reference irradiance spectra for solar energy systems testing. *Solar Energy* 2002; **73**: 443–467.