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ACCELERATED PUBLICATION

Solar cell efficiency tables (version 47)

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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 July 2015 are reviewed. Copyright © 2015 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 provides not only 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 cm^2 for a concentrator cell, 1 cm^2 for a one sun cell and 800 cm^2 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 and II. 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 author). Table I summarises the best reported measurements for cells and submodules, while Table II shows the best results for 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, which will be of

Table I. Confirmed terrestrial cell and submodule efficiencies 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)	Jsc (mA/cm^2)	Fill factor (%)	Test centre (date)	Description
Silicon							
Si (crystalline)	25.6 ± 0.5	143.7 (da)	0.740	41.8[a]	82.7	AIST (2/14)	Panasonic HIT, rear junction [15]
Si (multicrystalline)	**21.25 ± 0.4**	**242.74 (t)**	**0.6678**	**39.80[b]**	**80.0**	**FhG-ISE (11/15)**	**Trina Solar** [5]
Si (thin transfer submodule)	21.2 ± 0.4	239.7 (ap)	0.687[c]	38.50[c,d]	80.3	NREL (4/14)	Solexel (35 μm thick) [16]
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; 20 cells) [17]
III-V cells							
GaAs (thin film)	28.8 ± 0.9	0.9927 (ap)	1.122	29.68[f]	86.5	NREL (5/12)	Alta Devices [18]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95)[d]	RTI, Ge substrate [19]
InP (crystalline)	22.1 ± 0.7	4.02 (t)	0.878	29.5	85.4	NREL (4/90)[d]	Spire, epitaxial [20]
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 [21]
CIGS (minimodule)	18.7 ± 0.6	15.892 (da)	0.701[c]	35.29[c,h]	75.6	FhG-ISE (9/13)	Solibro, 4 serial cells [22]
CdTe (cell)	21.0 ± 0.4	1.0623 (ap)	0.8759	30.25[d]	79.4	Newport (8/14)	First Solar, on glass [23]
Amorphous/microcrystalline Si							
Si (amorphous)	10.2 ± 0.3[i,j]	1.001 (da)	0.896	16.36[d]	69.8	AIST (7/14)	AIST [24]
Si (microcrystalline)	11.8 ± 0.3[j]	1.044 (da)	0.548	29.39[g]	73.1	AIST (10/14)	AIST [25]
Dye sensitised							
Dye	11.9 ± 0.4[k]	1.005 (da)	0.744	22.47[l]	71.2	AIST (9/12)	Sharp [26]
Dye (minimodule)	10.7 ± 0.4[k]	26.55 (da)	0.754[c]	20.19[c,g]	69.9	AIST (2/15)	Sharp, 7 serial cells [26]
Dye (submodule)	8.8 ± 0.3[k]	398.8 (da)	0.697[c]	18.42[c,h]	68.7	AIST (9/12)	Sharp, 26 serial cells [27]
Organic							
Organic thin-film	11.0 ± 0.3[m]	0.993 (da)	0.793	19.40[d]	71.4	AIST (9/14)	Toshiba [28]
Organic (minimodule)	9.7 ± 0.3[m]	26.14 (da)	0.806	16.47[c,g]	73.2	AIST (2/15)	Toshiba (8 series cells) [28]
Perovskite							
Perovskite thin-film	**15.6 ± 0.6[n]**	**1.020 (da)**	**1.074**	**19.29[b]**	**75.1**	**AIST (6/15)**	**NIMS [6]**
Multijunction							
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 [29]
InGaP/GaAs/InGaAs	37.9 ± 1.2	1.047 (ap)	3.065	14.27[o]	86.7	AIST (2/13)	Sharp [30]
GaInP/Si (mech. stack)	**29.8 ± 1.5[j]**	**1.006 (da)**	**1.46/0.68**	**14.1/22.7[b]**	**87.9/76.2**	**NREL (10/15)**	**NREL, 4-terminal**
a-Si/nc-Si/nc-Si (thin-film)	13.6 ± 0.4[i,j]	1.043 (da)	1.901	9.92[g]	72.1	AIST (1/15)	AIST [31]
a-Si/nc-Si (thin-film cell)	12.7 ± 0.4[i,j]	1.000 (da)	1.342	13.45[d]	70.2	AIST (10/14)	AIST [24,25]

CIGS, $CuInGaSe_2$; 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.

[a]Spectral response and current–voltage curve reported in version 44 of these tables.

[b]Spectral response and current–voltage curve reported in the present version of these tables.

[c]Reported on a 'per cell' basis.

[d]Spectral responses and current-voltage curve reported in version 45 of these tables.

[e]Recalibrated from original measurement.

[f]Spectral response and current–voltage curve reported in version 40 of these tables.

[g]Spectral response and current–voltage curve reported in version 46 of these tables.

[h]Spectral response and current–voltage curve reported in version 43 of these tables.

[i]Stabilised by 1000 h exposure to 1 sun light at 50°C.

[j]Not measured at an external laboratory.

[k]Initial performance (not stabilised). Reference 56 reviews the stability of similar devices.

[l]Spectral response and current–voltage curve reported in version 41 of these tables.

[m]Initial performance (not stabilised). References 57 and 58 review the stability of similar devices.

[n]Not stabilised, initial efficiency

[o]Spectral response and/or current–voltage curve reported in version 42 of these tables.

Table II. Confirmed terrestrial module efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at a cell temperature of 25°C (IEC 60904-3: 2008, ASTM G-173-03 global).

Classification	Effic. (%)	Area (cm2)	V_{oc} (V)	I_{sc} (A)	FF (%)	Test centre (date)	Description
Si (crystalline)	22.9 ± 0.6	778 (da)	5.60	3.97	80.3	Sandia (9/96)[a]	UNSW/Gochermann [32]
Si (large crystalline)	**22.8 ± 0.6**	**15738.9 (ap)**	**69.36**	**6.459[b]**	**80.0**	**NREL (6/15)**	**SunPower (96 serial cells) [8]**
Si (multicrystalline)	**19.2 ± 0.4**	**15126.5 (ap)**	**77.93**	**4.726[b]**	**78.93**	**FhG-ISE (6/15)**	**Trina Solar (120 serial cells) [9]**
GaAs (thin-film)	24.1 ± 1.0	858.5 (ap)	10.89	2.255[c]	84.2	NREL (11/12)	Alta Devices [33]
CdTe (thin-film)	**18.6 ± 0.6**	**7038.8 (ap)**	**110.6**	**1.533[b]**	**74.2**	**NREL (4/15)**	**First Solar, monolithic [10]**
CIGS (Cd free)	17.5 ± 0.5	808 (da)	47.6	0.408[d]	72.8	AIST (6/14)	Solar Frontier (70 cells) [34]
CIGS (thin-film)	15.7 ± 0.5	9703 (ap)	28.24	7.254[e]	72.5	NREL (11/10)	Miasole [35]
a-Si/nc-Si (tandem)	12.3 ± 0.3[f]	14322 (t)	280.1	0.902[g]	69.9	ESTI (9/14)	TEL Solar, Trubbach Labs [36]
Organic	8.7 ± 0.3[h]	802 (da)	17.47	**0.569[d]**	70.4	AIST (5/14)	Toshiba [28]

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.

[a]Recalibrated from original measurement.

[b]Spectral response and/or current voltage curve reported in the present version of these tables.

[c]Spectral response and current–voltage curve reported in version 41 of these tables.

[d]Spectral response and/or current–voltage curve reported in version 45 of these tables.

[e]Spectral response reported in version 37 of these tables.

[f]Stabilised at the manufacturer to the 2% level following IEC procedure of repeated measurements.

[g]Spectral response and/or current–voltage curve reported in version 46 of these tables.

[h]Initial performance (not stabilised).

interest to sections of the photovoltaic community, with entries based on their significance and timeliness.

To encourage discrimination, Table III 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 IV 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 IV).

Eleven new results are reported in the present version of these tables and five more corrected from the previous version. The first new result in Table I is a new efficiency record for a multicrystalline silicon solar cell. A total area efficiency of 21.25% has been measured by the Fraunhofer Institute for Solar Energy Systems (FhG-ISE) for a large area (243 cm^2) cell fabricated by Trina Solar (Changzhou, Jiangsu, China) [5], improving on the company's earlier record. The first corrected result relates to voltage and current values for the 9.7% efficient organic minimodule reported in the previous issue [3,4].

The second new entry is an improved result for an organic–inorganic lead halide perovskite cell of greater than 1-cm^2 area. An efficiency of 15.6% has been measured at the Japanese National Institute of Advanced Industrial Science and Technology (AIST) for a 1.02-cm^2 perovskite cell fabricated by the National Institute of Materials Science, Tsukuba, Japan [6], again improving on this group's earlier result. This is the efficiency as initially measured, with subsequent degradation not investigated.

A third new result in Table I is for a mechanically stacked, four-terminal GaInP/Si tandem solar cell, with 29.8% efficiency reported for a 1-cm^2 device fabricated and measured by the US National Renewable Energy Laboratory.

Three significant new module results are reported in Table II. The first new result for a large area crystalline module occurred in two steps. In May 2015, a record aperture area efficiency of 22.5% was measured at AIST for a large area module fabricated by Panasonic (Kadoma, Osaka, Japan) [7]. The following month, an aperture area efficiency of 22.8% was measured at NREL for a large area (1.6 m^2) module fabricated by SunPower (San Jose, CA, USA) [8], reclaiming the record.

A substantial increase to 19.2% aperture area efficiency is reported for a large (1.5 m^2) multicrystalline module fabricated by Trina Solar [9] and measured at FhG-ISE. An even larger increase to 18.6% aperture area efficiency is reported for a smaller (0.7 m^2) CdTe module fabricated by First Solar (Tempe, AZ, USA) [10] and measured by NREL. This is the highest confirmed efficiency for any thin-film polycrystalline module.

Three new silicon cell results are reported as 'notable exceptions' in Table III. An efficiency of 25.1% has been confirmed for a 4-cm^2 n-type silicon cell fabricated by and measured at FhG-ISE [11]. An identical efficiency of 25.1% has also been confirmed by FhG-ISE for a larger 152-cm^2 n-type silicon cell fabricated by Kaneka (Osaka, Japan) [12]. The common 25.1% efficiency is the highest that has been demonstrated for a silicon cell with the two different polarity contacts on opposite cell surfaces. A slightly higher efficiency of 25.2% on a total area basis has been reported for a similarly sized 153-cm^2 rear

Table III. '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 PERL top/rear contacts [37]
Si (crystalline)	**25.1 ± 0.5[c]**	**4.01 (da)**	**0.7177**	**42.07[d]**	**83.24**	**FhG-ISE (8/15)**	**Fraunhofer n-type top/rear contacts [11]**
Si (large crystalline)	**25.1 ± 0.5**	**151.88 (ap)**	**0.7375**	**40.79[d]**	**83.49**	**FhG-ISE (9/15)**	**Kaneka, n-type top/rear contacts [12]**
Si (large crystalline)	**25.2 ± 0.5**	**153.49 (t)**	**0.7370**	**41.33[d]**	**82.71**	**FhG-ISE (10/15)**	**SunPower, n-type rear junction [8]**
Cells (III-V)							
GaInP	20.8 ± 0.6	0.2491 (ap)	1.4550	16.04[e]	89.3	NREL (5/13)	NREL, high bandgap [38]
Cells (chalcogenide)							
CIGS (thin-film)	21.7 ± 0.7	0.4972 (da)	0.7463	36.59[f]	79.3	FhG-ISE (**9/14**)	ZSW on glass [39]
CIGSS (Cd free)	20.9 ± 0.7	0.5192 (ap)	0.6858	39.91[g]	76.4	FhG-ISE (3/14)	Showa Shell, on glass [40]
CdTe (thin-film)	21.5 ± 0.4	0.3455 (da)	0.8774	30.44[h]	79.2	Newport (12/14)	First Solar on glass [41]
CZTSS (thin-film)	12.6 ± 0.3	0.4209 (ap)	0.5134	35.21[g]	69.8	Newport (7/13)	IBM solution grown [42]
CZTS (thin-film)	9.1 ± 0.2	0.2409 (da)	0.701	**20.84[h]**	62.5	AIST (12/14)	Toyota Central R&D Labs [43]
Cells (other)							
Perovskite (thin-film)	20.1 ± 0.4[i]	0. 0955 (ap)	1.059	24.65[f]	77.0	Newport (11/14)	KRICT[j] [44]
Organic (thin-film)	**11.5 ± 0.3[i]**	**0.0429 (ap)**	**0.7907**	**19.74[d]**	**73.5**	**Newport (5/15)**	**Hong Kong UST [45]**

CIGSS, CuInGaSSe; CZTSS, $Cu_2ZnSnS_{4-y}Se_y$; CZTS, Cu_2ZnSnS_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; ESTI, European Solar Test Installation.

[a]Spectral response reported in version 36 of these tables.
[b]Recalibrated from original measurement.
[c]Not measured at an external laboratory.
[d]Spectral response and/or current–voltage curves reported in the present version of these tables.
[e]Spectral response and current–voltage curves reported in version 42 of these tables.
[f]Spectral response and current–voltage curves reported in version 45 of these tables.
[g]Spectral response and current–voltage curves reported in version 44 of these tables.
[h]Spectral response and/or current–voltage curves reported in version 46 of these tables.
[i]Stability not investigated.
[j]Korean Research Institute of Chemical Technology.

junction n-type cell fabricated by SunPower [8] and also measured at FhG-ISE. This is the highest total area cell result reported for a silicon cell. Two further corrections have been made to entries in the previous version of Table III [3,4] (the measurement date of the 21.7% small area CIGS cell and the current density of the small area CZTS cell have been corrected). A final new result in Table III is a new efficiency result for a very small-area organic solar cell. An efficiency of 11.5% was measured by Newport Technology and Applications Center for a cell fabricated by the Hong Kong University of Science and Technology (Hong Kong UST) when masked by a 0.04-cm^2 aperture. The cell was fabricated using a donor polymer with temperature aggregation properties that gave a favourable morphology of reasonably small but highly crystalline and pure polymer domains (see reference in Table III). Again, stability was not investigated. We will require future entries into Table III to have larger area.

One new result in Table IV is a new efficiency level of 43.4% for the conversion of sunlight to electricity for a minimodule of 18.2-cm^2 aperture area, consisting of a single full glass lens and a wafer-bonded GaInP/GaAs; GAInAsP/GaInAs cell [13]. The module was fabricated and measured at FhG-ISE.

A final correction is made in Table IV. The concentrator module of 38.9% efficiency and 812-cm^2 aperture area reported in the earlier version of these tables was actually fabricated by Soitec Solar GmbH, Bernin, France [14] and independently measured at FhG-ISE. This is the highest efficiency reported for a photovoltaic module of this size, although not directly comparable with the non-concentrator results of Table II because of the neglect of diffuse light in the calculation of conversion efficiency for concentrator cells and modules.

The EQE spectra for the new perovskite result reported in the present issue of these tables are shown in Figure 1

Table IV. 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	29.1 ± 1.3[b]	0.0505 (da)	117	FhG-ISE (3/10)	Fraunhofer ISE
Si	27.6 ± 1.2[d]	1.00 (da)	92	FhG-ISE (11/04)	Amonix back-contact [46]
CIGS (thin-film)	23.3 ± 1.2[b]	0.09902 (ap)	15	NREL (3/14)	NREL [47]
Multijunction cells					
GaInP/GaAs; GaInAsP/GaInAs	46.0 ± 2.2[f]	0.0520 (da)	508	AIST (10/14)	Soitec/CEA/FhG-ISE bonded [48]
GaInP/GaAs/GaInAs/GaInAs	45.7 ± 2.3[b]	0.09709 (da)	234	NREL (9/14)	NREL, 4 J monolithic [49]
InGaP/GaAs/InGaAs	44.4 ± 2.6[h]	0.1652 (da)	302	FhG-ISE (4/13)	Sharp, inverted metamorphic [50]
Minimodule					
GaInP/GaAs; GaInAsP/GaInAs	**43.4 ± 2.4[b]**	**18.2 (ap)**	**340[j]**	**FhG-ISE (7/15)**	**Fraunhofer ISE (lens/cell) [13]**
Submodule					
GaInP/GaInAs/Ge; Si	40.4 ± 2.8[i]	287 (ap)	365[j]	NREL (11/14)	UNSW split spectrum [51]
Modules					
Si	20.5 ± 0.8[b]	1875 (ap)	79	Sandia (4/89)[k]	Sandia/UNSW/ENTECH (12 cells) [52]
Three junction	35.9 ± 1.8[l]	1092 (ap)	N/A	NREL (8/13)	Amonix [53]
Four junction	38.9 ± **2.5[m]**	812.3 (ap)	333	FhG-ISE (4/15)	**Soitec [14]**
'Notable exceptions'					
Si (large area)	21.7 ± 0.7	20.0 (da)	11	Sandia (9/90)[k]	UNSW laser grooved [54]
Luminescent submodule	7.1 ± 0.2	25 (ap)	2.5[j]	ESTI (9/08)	ECN Petten, GaAs cells [55]

CIGS, $CuInGaSe_2$; Effic., efficiency; (da), designated illumination area; (ap), aperture area; NREL, National Renewable Energy Laboratory; FhG-ISE, Fraunhofer-Institut für Solare Energiesysteme.
[a]One sun corresponds to direct irradiance of 1000 Wm^{-2}.
[b]Not measured at an external laboratory.
[c]Spectral response reported in version 36 of these tables.
[d]Measured under a low aerosol optical depth spectrum similar to ASTM G-173-03 direct[59].
[e]Spectral response and current–voltage curve reported in version 44 of these tables.
[f]Spectral response and current–voltage curve reported in version 45 of these tables.
[g]Spectral response and current–voltage curve reported in version 46 of these tables.
[h]Spectral response and current–voltage curve reported in version 42 of these tables.
[i]Determined at IEC 62670-1 CSTC reference conditions.
[j]Geometric concentration.
[k]Recalibrated from original measurement.
[l]Referenced to 1000 W/m^2 direct irradiance and 25 °C cell temperature using the prevailing solar spectrum and an in-house procedure for temperature translation.
[m]Measured under IEC 62670-1 reference conditions following the current IEC power rating draft 62670-3.

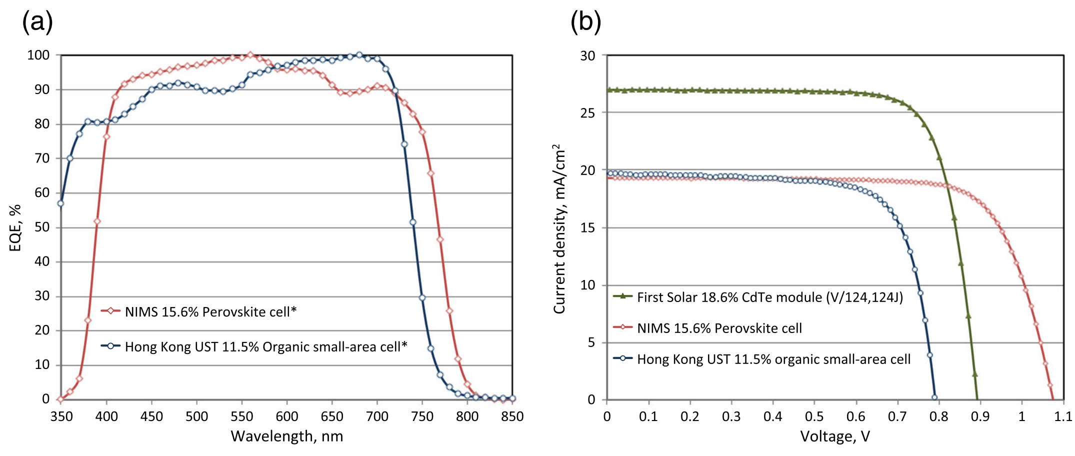

Figure 1. (a) External quantum efficiency (EQE) for the new perovskite and organic cell results reported in this issue. (b) Corresponding current density–voltage (JV) curves for the same devices together with that of the new CdTe module. NIMS, National Institute of Materials Science.

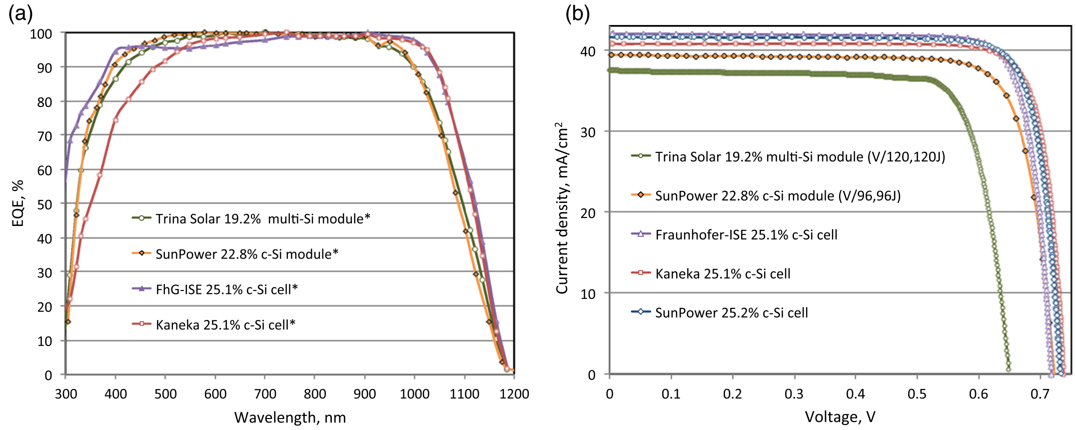

Figure 2. (a) External quantum efficiency (EQE) for the new silicon cell and module results in this issue. (b) Corresponding current density–voltage (JV) curves.

(a). Figure 1(b) shows the current density–voltage (JV) curves for the same device together with that of the new CdTe module. Figure 2(a) shows the EQE for the new silicon cell and module results, with Figure 2(b) showing their JV curves.

For the case of modules and tandem cells, 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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REFERENCES

1. 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.
2. Green MA, Emery K, Hishikawa Y, Warta W. Solar cell efficiency tables (version 33). *Progress in Photovoltaics: Research and Applications* 2009; **17**: 85–94.
3. Green MA, Emery K, Hishikawa Y, Warta W, Dunlop ED. Solar cell efficiency tables (version 46). *Progress in Photovoltaics: Research and Applications* 2015; **23**: 805–812.
4. Green MA. Corrigendum to 'solar cell efficiency tables (version 46)' [*Progress in Photovoltaics: Research and Applications*: 2015; **23**: 805–812]. *Progress in Photovoltaics: Research and Applications* 2015; **23**: 1202.
5. Deng W, Chen D, Xiong Z, Verlinden PJ, Dong JW, Ye F, Li H, Zhu HJ, Zhong M, Yang Y, Chen YF, Feng ZQ, Altermatt P. 20.8% PERC Solar Cell on 156 mm x 156 mm P-Type Multicrystalline Silicon Substrate. *IEEE J. Photovoltaics* 2015, available in early view.
6. http://www.nims.go.jp/group/g_dye-sensitizes-solar-cells/index_e.html. [see also: Kaneko K. *NIMS achieves 15% efficiency with perovskite PV cell*. Nikkei Business Publications, Inc., 12 May 2015 (http://techon.nikkeibp.co.jp/english/NEWS_EN/20150512/417866/?ST=msbe; accessed 22 May, 2015)].
7. Clover I. Panasonic announces 22.5% module-level efficiency solar panel. *PV Magazine*, 6 October 2015.
8. Swanson R The role of modeling in SunPower's commercialization efforts. *Presented at challenges in PV science, technology, and manufacturing: a workshop on the role of theory, modeling and simulation*, Purdue University, August 2–3, 2012.
9. 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%

 Prog. Photovolt: Res. Appl. 2016; **24**:3–11 © 2015 John Wiley & Sons, Ltd.
DOI: 10.1002/pip

efficient PERC solar cells. *IEEE Journal of Photovoltaics* (to be published).
10. First Solar Press Release. *First solar achieves world record 18.6 % thin film module conversion efficiency*, 15 June 2015.
11. 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.
12. Yamamoto K. 25.1% efficiency Cu metallized heterojunction crystalline Si solar cell. *25th International Photovoltaic Science and Engineering Conference*, Busan, Korea, November 2015.
13. Steiner M, Siefer G, Schmidt T, Wiesenfarth M, Dimroth F, Bett AW. 43 % sun light to electricity conversion efficiency using CPV. *IEEE Journal of Photovoltaics*, submitted.
14. 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.
15. Masuko K, Shigematsu M, Hashiguchi T, Fujishima D, Kai M, Yoshimura N, Yamaguchi T, Ichihashi Y, Yamanishi T, Takahama T, Taguchi M, Maruyama E, Okamoto S. Achievement of more than 25% conversion efficiency with crystalline silicon heterojunction solar cell. *IEEE Journal of Photovoltaics* 2014; **4**: 1433–1435.
16. 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 x 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.
17. Keevers MJ, Young TL, Schubert U, Green MA. 10% efficient CSG minimodules. *22nd European Photovoltaic Solar Energy Conference*, Milan, September 2007.
18. 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.
19. Venkatasubramanian R, O'Quinn BC, Hills JS, Sharps PR, Timmons ML, Hutchby JA, Field H, Ahrenkiel A and 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.
20. Keavney CJ, Haven VE, Vernon SM. Emitter structures in MOCVD InP solar cells. *Conference Record, 21st IEEE Photovoltaic Specialists Conference*, Kissimimee, May, 1990, 141–144.
21. Solibro Press Release, "*Solibro beats world record for solar cells*", dated 12 June 2014.
22. Wallin E, Malm U, Jarmar T, Lundberg O, Edoff M, Stolt L. World-record Cu(In,Ga)Se_2-based thin-film sub-module with 17.4% efficiency. *Progress in Photovoltaics: Research and Applications* 2012; **20**: 851–854.
23. First Solar Press Release, *First Solar builds the highest efficiency thin film PV cell on record*, 5 August 2014.
24. 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.
25. 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* in press.
26. Komiya R, Fukui A, Murofushi N, Koide N, Yamanaka R, 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-5O-08.
27. 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)
28. 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.
29. Chiu PT, Law DL, Woo RL, Singer S, Hong WD, Zakaria A, Boisvert JC, Mesropian S, King RR, Karam NH. Continued progress on direct bonded 5J space and terrestrial cells. *Proc. 40th IEEE PVSC* 2014.
30. Sasaki K, Agui T, Nakaido K, Takahashi N, Onitsuka R, Takamoto T. *Proceedings, 9th International Conference on Concentrating Photovoltaics Systems*, Miyazaki, Japan 2013.
31. 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).

32. Zhao J, Wang A, Yun F, Zhang G, Roche DM, Wenham SR, Green MA. 20,000 PERL silicon cells for the "1996 world solar challenge" solar car race. *Progress in Photovoltaics* 1997; **5**: 269–276.
33. 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.
34. Sugimoto H. High efficiency and large volume production of CIS-based modules. *40th IEEE Photovoltaic Specialists Conference*, Denver, June 2014.
35. http://www.miasole.com (accessed 22 May, 2015).
36. *TEL solar press release*, *July 9*, 2014.
37. 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.
38. Geisz JF, Steiner MA, Garcia I, Kurtz SR, Friedman DJ. Enhanced external radiative efficiency for 20.8% efficient single-junction GaInP solar cells. *Applied Physics Letters* 2013; **103**(4): 041118.
39. Powalla M, Jackson P, Hariskos D, Paetel S, Witte W, Wuerz R, Lotter E, Menner R, Wischmann W. CIGS thin-film solar cells with an improved efficiency of 20.8%. *29th European Photovoltaic Solar Energy Conference*, 3AO.4.2, Amsterdam, September 2014.
40. Nakamura M, Yamaguchi K, Chiba, Y, Hakuma H, Kobayashi T, Nakada T. Achievement of 19.7% efficiency with a small-sized $Cu(InGa)(SeS)_2$ solar cells prepared by sulfurization after selenizaion process with Zn-based buffer. *39th IEEE PVSC, Tampa, USA*, June 18, 2013.
41. *PV magazine, First Solar raises bar for CdTe with 21.5% efficiency record*, 6 February 2015.
42. 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).
43. Tajima S, Asahi R, Isheim D, Seidman DN, Itoh T, Hasegawa M, Ohishi K. Atom-probe tomographic study of interfaces of Cu_2ZnSnS_4 photovoltaic cells. *Citation: Applied Physics Letters* 2014; **105**: 093901 (DOI: 10.1063/1.4894858).
44. Noh JH, Im SH, Heo JH, Mandal TH, Seok SI. Chemical management for colorful, efficient, and stable inorganic–organic hybrid nanostructured solar cells. *Nano Letters* 2013; **13**: 1764–1769.
45. Hu H, Jiang K, Yang G, Li Z, Lin H, Liu Y, Zhao J, Zhang J, Huang F, Qu Q, Ma W, Yan H. Terthiophene-based D-A polymer with an asymmetric arrangement of alkyl chains that enables efficient polymer solar cells. *Journal of the American Chemical Society* 2015; published online, (DOI: 10.1021/jacs.5b08556).
46. 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.
47. 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.
48. 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).
49. NREL. *Press Release NR-4514, 16*. December 2014.
50. Press Release, Sharp Corporation, 31 May 2012 (accessed at http://sharp-world.com/corporate/news/120531.html on 5 June 2013).
51. 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.
52. Chiang CJ, Richards EH. A 20% efficient photovoltaic concentrator module. *Conf. Record, 21st IEEE Photovoltaic Specialists Conference*, Kissimimee, May 1990: 861–863.
53. http://amonix.com/pressreleases/amonix-achieves-world-record-359-module-efficiency-rating-nrel-4 (accessed 23 October 2013).
54. Zhang F, Wenham SR, Green MA. Large area, concentrator buried contact solar cells. *IEEE Trans. on Electron Devices* 1995; **42**: 144–149.
55. 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. *Phys. Stat. Sol*. (*RRL*) 2008; **2**(6): 257–259.
56. 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.
57. 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.

58. 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.
59. Gueymard CA, Myers D, Emery K. Proposed reference irradiance spectra for solar energy systems testing. *Solar Energy* 2002; **73**: 443–467.