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ACCELERATED PUBLICATION

Solar cell efficiency tables (version 46)

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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 January 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 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 version 33 of these Tables [2], results were updated to the new internationally accepted reference spectrum (International Electrotechnical Commision (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 recognized 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 subcategories 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 normalized to the peak measured value. Current–voltage 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 summarizes the best 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

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)	J_{sc} (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 [21]
Si (multicrystalline)	20.8 ± 0.5	243.9 (t)	0.6626	39.03[b]	80.3	FhG-ISE (11/14)	Trina Solar [22]
Si (thin transfer submodule)	21.2 ± 0.4	239.7 (ap)	0.687[c]	38.50[b,c]	80.3	NREL (4/14)	Solexel (35-μm thick) [23]
Si (thin-film minimodule)	10.5 ± 0.3	94.0 (ap)	0.492[c]	29.7[c]	72.1	FhG-ISE (8/07)[d]	CSG Solar (<2 μm on glass; 20 cells) [24]
III–V cells							
GaAs (thin film)	28.8 ± 0.9	0.9927 (ap)	1.122	29.68[e]	86.5	NREL (5/12)	Alta Devices [25]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95)[d]	RTI, Ge substrate [26]
InP (crystalline)	22.1 ± 0.7	4.02 (t)	0.878	29.5	85.4	NREL (4/90)[d]	Spire, epitaxial [27]
Thin-film chalcogenide							
CIGS (cell)	**21.0 ± 0.6**	**0.9927 (ap)**	**0.757**	**35.70**[f]	**77.6**	**FhG-ISE (4/14)**	**Solibro, on glass** [4]
CIGS (minimodule)	18.7 ± 0.6	15.892 (da)	0.701[c]	35.29[c,g]	75.6	FhG-ISE (9/13)	Solibro, four serial cells [28]
CdTe (cell)	21.0 ± 0.4	1.0623 (ap)	0.8759	30.25[b]	79.4	Newport (8/14)	First Solar, on glass [29]
Amorphous/microcrystalline Si							
Si (amorphous)	10.2 ± 0.3[h,i]	1.001 (da)	0.896	16.36[b]	69.8	AIST (7/14)	AIST [6]
Si (microcrystalline)	**11.8 ± 0.3**[i]	**1.044 (da)**	**0.548**	**29.39**[f]	**73.1**	**AIST (10/14)**	**AIST** [5]
Dye sensitized							
Dye	11.9 ± 0.4[j]	1.005 (da)	0.744	22.47[k]	71.2	AIST (9/12)	Sharp [7]
Dye (minimodule)	**10.7 ± 0.4**[j]	**26.55 (da)**	**0.754**[c]	**20.19**[c,f]	**69.9**	**AIST (2/15)**	**Sharp, seven serial cells** [7]
Dye (submodule)	8.8 ± 0.3[j]	398.8 (da)	0.697[c]	18.42[c,g]	68.7	AIST (9/12)	Sharp, 26 serial cells [30]
Organic							
Organic thin film	11.0 ± 0.3[l]	0.993 (da)	0.793	19.40[b]	71.4	AIST (9/14)	Toshiba [8]
Organic (minimodule)	**9.7 ± 0.3**[l]	**26.14 (da)**	**0.686**[c]	**11.47**[c,f]	**73.2**	**AIST (2/15)**	**Toshiba (eight series cells)** [8]
Perovskite							
Perovskite thin-film	**15.0 ± 0.6**[m]	**1.017 (ap)**	**1.090**	**20.61**[f]	**66.8**	**AIST (2/15)**	**NIMS** [12]
Multijunction devices							
Five-junction cell (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** [13]
InGaP/GaAs/InGaAs	37.9 ± 1.2	1.047 (ap)	3.065	14.27[m]	86.7	AIST (2/13)	Sharp [31]
a-Si/nc-Si/nc-Si (thin film)	**13.6 ± 0.4**[i]	**1.043 (da)**	**1.901**	**9.92**[f]	**72.1**	**AIST (1/15)**	**AIST** [5,6]
a-Si/nc-Si (thin-film cell)	12.7 ± 0.4%[h]	1.000 (da)	1.342	13.45[b]	70.2	AIST (10/14)	AIST [5,6]

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; NREL = National Renewable Energy Laboratory.

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

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

[c]Reported on a "per-cell" basis.

[d]Recalibrated from original measurement.

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

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

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

[h]Stabilized by 1000-h exposure to one-sun light at 50 °C.

[i]Not measured at an external laboratory.

[j]Initial performance (not stabilized). Reference [9] reviews the stability of similar devices.

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

[l]Initial performance (not stabilized). References [10] and [11] review the stability of similar devices.

[m]Not stabilized, initial efficiency.

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

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 significance and timeliness.

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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 (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)	22.9 ± 0.6	778 (da)	5.60	3.97	80.3	Sandia (9/96)[a]	UNSW/Gochermann [32]
Si (large crystalline)	22.4 ± 0.6	15 775 (ap)	69.57	6.341[b]	80.1	NREL (8/12)	SunPower [33]
Si (multicrystalline)	18.5 ± 0.4	14 661 (ap)	38.97	9.149[c]	76.2	FhG-ISE (1/12)	Q-Cells (60 serial cells) [34]
GaAs (thin film)	24.1 ± 1.0	858.5 (ap)	10.89	2.255[d]	84.2	NREL (11/12)	Alta Devices [35]
CdTe (thin film)	17.5 ± 0.7	7021 (ap)	103.1	1.553[e]	76.6	NREL (2/14)	First Solar, monolithic [36]
CIGS (Cd free)	17.5 ± 0.5	808 (da)	47.6	0.408[f]	72.8	AIST (6/14)	Solar Frontier (70 cells) [37]
CIGS (thin film)	15.7 ± 0.5	9703 (ap)	28.24	7.254[g]	72.5	NREL (11/10)	Miasole [38]
a-Si/nc-Si (tandem)	**12.3 ± 0.3**[h]	**14 322 (t)**	**280.1**	**0.902**[i]	**69.9**	**ESTI (9/14)**	**TEL Solar, Trubbach Labs** [39]
Organic	8.7 ± 0.3[j]	802 (da)	17.47	0.1065[f]	70.4	AIST (5/14)	Toshiba [8]

CIGS = $CuInGaSe_2$; 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 current–voltage curve reported in version 42 of these tables.

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

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

[e]Current–voltage curve reported in version 44 of these tables.

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

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

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

[i]Spectral response and/or current-voltage curve reported in current version of these tables.

[j]Initial performance (not stabilized).

Table III. "Notable exceptions": "top ten" confirmed cell and module results, not class records measured under the global AM1.5 spectrum (1000 Wm^{-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 PERL top/rear contacts [40]
Si (large crystalline)	25.0 ± 0.7	120.94 (ap)	0.726	41.5[c]	82.8	FhG ISE (2/14)	SunPower rear junction [41]
Cells (III–V)							
GaInP	20.8 ± 0.6	0.2491 (ap)	1.4550	16.04[d]	89.3	NREL (5/13)	NREL, high bandgap [42]
Cells (chalcogenide)							
CIGS (thin film)	21.7 ± 0.7	0.4972 (da)	**0.7463**	36.59[e]	79.3	FhG-ISE (93/14)	ZSW on glass [43]
CIGSS (Cd free)	20.9 ± 0.7	0.5192 (ap)	0.6858	39.91[c]	76.4	FhG-ISE (3/14)	Showa Shell, on glass [44]
CdTe (thin film)	**21.5 ± 0.4**	**0.3455 (da)**	**0.8774**	**30.94**[f]	**79.2**	**Newport (12/14)**	**First Solar on glass** [14]
CZTSS (thin film)	12.6 ± 0.3	0.4209 (ap)	0.5134	35.21[c]	69.8	Newport (7/13)	IBM solution grown [45]
CZTS (thin film)	**9.1 ± 0.2**	**0.2409(da)**	**0.701**	**20.64**[f]	**62.5**	**AIST (12/14)**	**Toyota Central R&D Labs** [15]
Cells (other)							
Perovskite (thin film)	20.1 ± 0.4[g]	0. 0955 (ap)	1.059	24.65[e]	77.0	Newport (11/14)	KRICT[h] [46]
Organic (thin film)	11.1 ± 0.3[g]	0.159 (ap)	0.867	17.81[i]	72.2	AIST (10/12)	Mitsubishi Chemical [47]

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]Spectral response and current–voltage curves reported in version 44 of these tables.

[d]Spectral response and current–voltage curves reported in version 42 of these tables.

[e]Spectral response and current–voltage curves reported in version 45 of these tables.

[f]Spectral response and/or current–voltage curves reported in the present version of these tables.

[g]Stability not investigated.

[h]Korean Research Institute of Chemical Technology.

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

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,c]	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 [48]
CIGS (thin film)	23.3 ± 1.2[b,e]	0.09902 (ap)	15	NREL (3/14)	NREL [49]
Multijunction cells					
GaInP/GaAs, GaInAsP/GaIn	46.0 ± 2.2[f]	0.0520 (da)	508	AIST (10/14)	Soitec/CEA/FhG-ISE bonded [50]
GaInP/GaAs/GaInAs/GaInAs	**45.7 ± 2.3[b,g]**	**0.09709 (da)**	**234**	**NREL (9/14)**	**NREL, 4J monolithic** [19]
InGaP/GaAs/InGaAs	44.4 ± 2.6[h]	0.1652 (da)	302	FhG-ISE (4/13)	Sharp, inverted metamorphic [51]
Submodule					
GaInP/GaAs, GaInAsP/Ge, Si	40.4 ± 2.8	287 (ap)	365	NREL (11/14)	UNSW split spectrum [52]
Modules					
Si	20.5 ± 0.8[b]	1875 (ap)	79	Sandia (4/89)[i]	Sandia/UNSW/ENTECH (12 cells) [53]
Three junction	35.9 ± 1.8[j]	1092 (ap)	N/A	NREL (8/13)	Amonix [54]
Four junction	**38.9 ± 2.5[b,k]**	**812.3 (ap)**	**333**	**FhG-ISE (4/15)**	**Fraunhofer ISE** [20]
"Notable exceptions"					
Si (large area)	21.7 ± 0.7	20.0 (da)	11	Sandia (9/90)[i]	UNSW laser grooved [55]
Luminescent submodule	7.1 ± 0.2	25 (ap)	2.5[l]	ESTI (9/08)	ECN Petten, GaAs cells [56]

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[57].
[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 present version of these tables.
[h]Spectral response and current–voltage curve reported in version 42 of these tables.
[i]Recalibrated from original measurement.
[j]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.
[k]Measured under IEC 62670-1 reference conditions following the current IEC power rating draft 62670-3.
[l]Geometric concentration.

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).

Twelve new results are reported in the present version of these tables. The first new result in Table I reports result overlooked in the previous issue [3]. An improved efficiency of 21.0% has been measured by the Fraunhofer Institute for Solar Energy Systems (FhG-ISE) for a 1-cm^2 polycrystalline thin film fabricated by Solibro Research in Uppsala, Sweden [4].

Improved results are also reported for both individual microcrystalline silicon thin-film cells and tandem cells where these are combined with amorphous silicon. An efficiency of 11.8% is reported for a 1-cm^2 microcrystalline silicon cell (also, perhaps more accurately, known as a nanocrystalline, nc-Si, cell) fabricated and measured by the Japanese National Institute of Advanced Industrial Science and Technology (AIST), improving slightly upon the previous result from the same group [5]. This improvement doubtlessly contributed to another new result in Table I by the same institute, the demonstration of 13.6% stabilized efficiency for a 1-cm^2 a-Si/nc-Si/nc-Si triple-junction tandem cell [6].

Another improvement to 10.7% initial efficiency is reported for a 27-cm^2 dye-sensitized thin-film minimodule fabricated by Sharp, Japan and measured by AIST [7]. A small increase to 9.7% initial efficiency is also reported for a 26-cm^2 organic thin-film minimodule fabricated by Toshiba and measured by AIST, improving upon the company's previous result [8]. Along with other emerging technology devices, the stabilities of the dye-sensitized and organic devices were not investigated, although the stability of related devices is reported elsewhere [9–11].

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Another new entry is the first result for an organic-inorganic lead halide perovskite cell of greater than 1-cm^2 area. An efficiency of 15.0% has been measured at AIST for a 1.02-cm^2 perovskite cell fabricated by the National Institute of Materials Science (NIMS), Tsukuba, Japan [12]. Once more, this is the efficiency as initially measured, with subsequent degradation not investigated.

The final new result in Table I represents a new record for conversion of global sunlight, again overlooked in previous issues [3]. An efficiency of 38.8% has been measured for a 1-cm^2, five-junction tandem device fabricated by Spectrolab [13] and measured by the National Renewable Energy Laboratory.

One new module result is reported in Table II. A slight improvement of 12.3% total area, stabilised efficiency is reported for a large-area (1.4 m^2) a-Si/nc-Si module fabricated by TEL Solar, Trubbach Labs, Switzerland and measured at the European Solar Test Installation (ESTI).

Table III, "notable exceptions", reports two new results for small-area (less than 0.4 cm^2) cells. The first new result documents an increase to 21.5% efficiency for a small-area 0.35-cm^2 cadmium telluride (CdTe) cell fabricated by First Solar, USA [14] and measured at Newport Technology and Applications Center. The second new result in Table III is 9.1% efficiency for a similarly small-area 0.2-cm^2 copper zinc tin sulphide cell fabricated by Toyota Central R&D Laboratories, Nagakute, Japan [15] and measured by AIST. In both cases, cell area is too small for classification as an outright record. Solar cell efficiency targets in governmental research programs generally have been specified in terms of a cell area of 1 cm^2 or larger, for example, in US [16], Japanese [17], and European [18] programs. Cells of smaller area bypass some of the contacting and material uniformity issues encountered with larger area devices, as well as being more prone to measurement error because of peripheral effects.

As has been apparent from earlier versions of these tables [1–3], very rapid progress has been made over the recent years in improving the efficiency of series-connected multiple-junction solar cell stacks operating under concentrated sunlight. Table IV reports two new results for concentrating cells and modules. Following on

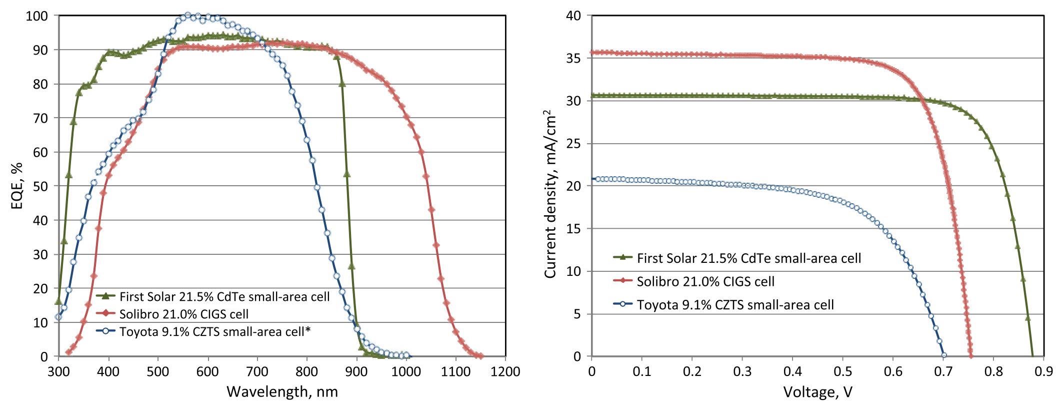

Figure 1. (a) External quantum efficiency (EQE) for the new CdTe, CIGS, and CZTS results in this issue and (b) corresponding current density–voltage curves.

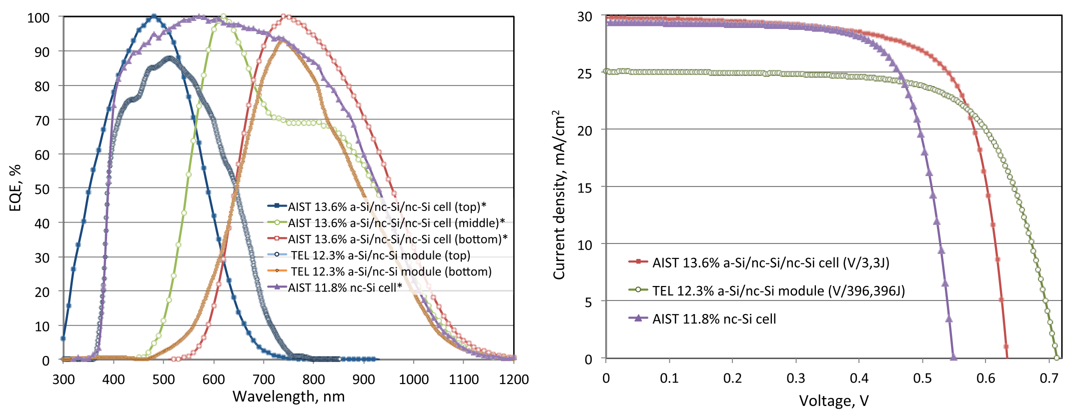

Figure 2. (a) External quantum efficiency (EQE) for the new nanocrystalline (nc-Si) silicon, a-Si/nc-Si and a-Si/nc-Si/nc-Si tandem cell and module results in this issue and (b) corresponding current density–voltage curves. AIST, Japanese National Institute of Advanced Industrial Science and Technology.

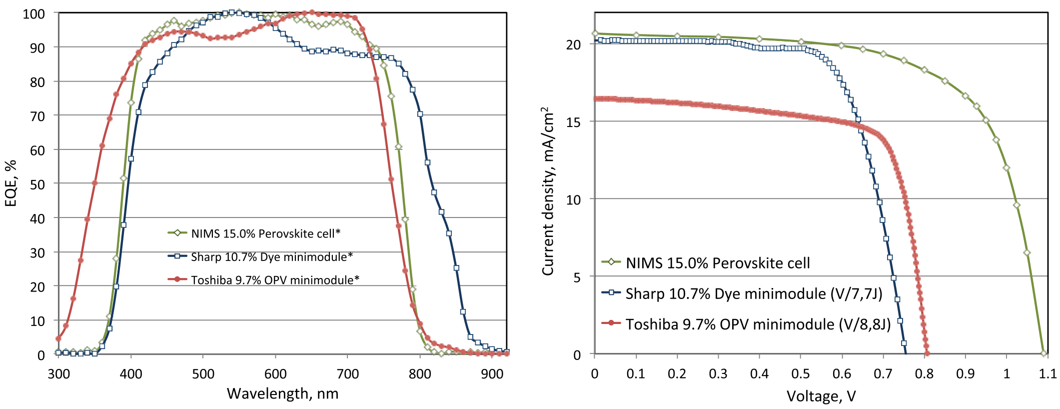

Figure 3. (a) External quantum efficiency (EQE) for the new perovskite, dye-sensitized and organic (OPV) results in this issue and (b) corresponding current density–voltage curves.

from the 46.0% result reported in the previous version of these tables [3] for a four-junction wafer-bonded device, a similar efficiency of 45.7% is reported for a four-junction monolithic device fabricated and measured by National Renewable Energy Laboratory [19]. A new record of 38.9% is reported for an 812-cm^2 photovoltaic module using a four-cell, wafer-bonded stack [20]. The module was fabricated and measured at the Fraunhofer Institute for Solar Energy Systems (FhG-ISE). This is the highest efficiency for any reasonably sized solar energy converter to date.

The EQE spectra for CdTe, $CuInGaSe_2$, and copper zinc tin sulphide 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) shows the EQE for the new nc-Si, a-Si/nc-Si and a-Si/nc-Si/n-Si cell and module results, with Figure 2(b) showing their JV curves. Figure 3(a) shows the EQE for the new perovskite, organic and dye-sensitized results, while Figure 3(b) shows the corresponding 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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