

## RESEARCH: SHORT COMMUNICATION

**Solar cell efficiency tables (version 36)**Martin A. Green<sup>1\*</sup>, Keith Emery<sup>2</sup>, Yoshihiro Hishikawa<sup>3</sup> and Wilhelm Warta<sup>4</sup><sup>1</sup> ARC Photovoltaics Centre of Excellence, University of New South Wales, Sydney, NSW 2052, Australia<sup>2</sup> National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, CO 80401, USA<sup>3</sup> National Institute of Advanced Industrial Science and Technology (AIST), Research Center for Photovoltaics (RCPV), Central 2, Umezono 1-1-1, Tsukuba, Ibaraki 305-8568 Japan<sup>4</sup> Department of Solar Cells—Materials and Technology, Fraunhofer Institute for Solar Energy Systems, Heidenhofstr. 2; D-79110 Freiburg, Germany**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 2010 are reviewed. Copyright © 2010 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 [1,2,3]. By providing guidelines for the inclusion of results into these tables, this not only provides an authoritative summary of the current state of the art but also encourages researchers to seek independent confirmation of results and to report results on a standardized basis. In a recent version of these Tables (Version 33) [2], results were updated to the new internationally accepted reference spectrum (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 measured by a recognized test centre listed elsewhere [1]. A distinction is made between three different eligible areas: total area; aperture area and designated illumination area [1]. 'Active area' efficiencies are not included. There are also certain minimum values of the area sought for the different device types (above 0.05 cm<sup>2</sup> for a concentrator cell, 1 cm<sup>2</sup> for a one-sun cell and 800 cm<sup>2</sup> for a module) [1].

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 the present version onwards, spectral

response information will be included in the form of a plot of the external quantum efficiency (EQE) versus wavelength, normalized to the peak measured value.

**2. NEW RESULTS**

Highest confirmed cell and module results are reported in Tables I, II and IV. Any changes in the tables from those previously published [3] are set in bold type. In most of the cases, a literature reference is provided that describes either the result reported or a similar result. Table I summarizes the best measurements for cells and submodules, Table II shows the best results for modules and Table IV shows the best results for concentrator cells and concentrator modules. Table III contains what might be described as 'notable exceptions'. While not conforming to the requirements to be recognized as a class record, the cells and modules in this table have notable characteristics that will be of interest to sections of the photovoltaic community with entries based on their significance and timeliness.

To ensure discrimination, Table III is limited to nominally 10 entries with the present authors having voted for their preferences for inclusion. Readers who have suggestions of results for inclusion into this table are

**Table I.** Confirmed terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m<sup>2</sup>) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global).

Classification <sup>a</sup>	Effic. <sup>b</sup> (%)	Area <sup>c</sup> (cm <sup>2</sup> )	V <sub>oc</sub> (V)	J <sub>sc</sub> (mA/cm <sup>2</sup> )	FF <sup>d</sup> (%)	Test centre <sup>e</sup> (and date)	Description
Silicon							
Si (crystalline)	25.0 ± 0.5	4.00 (da)	0.706	42.7	82.8	Sandia (3/99) <sup>f</sup>	UNSW PERL [10]
Si (multicrystalline)	20.4 ± 0.5	1.002 (ap)	0.664	38.0	80.9	NREL (5/04) <sup>f</sup>	FhG-ISE [11]
Si (thin film transfer)	16.7 ± 0.4	4.017 (ap)	0.645	33.0	78.2	FhG-ISE (7/01) <sup>f</sup>	U. Stuttgart (45 μm thick) [12]
Si (thin film submodule)	10.5 ± 0.3	94.0 (ap)	0.492 <sup>g</sup>	29.7 <sup>g</sup>	72.1	FhG-ISE (8/07) <sup>f</sup>	CSG Solar (1–2 μm on glass; 20 cells) [13]
III-V Cells							
<b>GaAs (crystalline)</b>	<b>26.4 ± 0.8</b>	<b>1.006 (t)</b>	<b>1.030</b>	<b>29.8</b>	<b>86.0</b>	<b>FhG-ISE (3/10)</b>	<b>Fraunhofer ISE</b>
GaAs (thin film)	26.1 ± 0.8	1.001 (ap)	1.045	29.6	84.6	FhG-ISE (7/08) <sup>f</sup>	Radboud U. Nijmegen [14]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95) <sup>f</sup>	RTI, Ge substrate [15]
InP (crystalline)	22.1 ± 0.7	4.02 (t)	0.878	29.5	85.4	NREL (4/90) <sup>f</sup>	Spire, epitaxial [16]
Thin Film Chalcogenide							
CIGS (cell)	19.4 ± 0.6 <sup>h</sup>	0.994 (ap)	0.716	33.7	80.3	NREL (1/08) <sup>f</sup>	NREL, CIGS on glass [17]
CIGS (submodule)	16.7 ± 0.4	16.0 (ap)	0.661 <sup>g</sup>	33.6 <sup>g</sup>	75.1	FhG-ISE (3/00) <sup>f</sup>	U. Uppsala, 4 serial cells [18]
CdTe (cell)	16.7 ± 0.5 <sup>h</sup>	1.032 (ap)	0.845	26.1	75.5	NREL (9/01) <sup>f</sup>	NREL, mesa on glass [19]
Amorphous/Nanocrystalline Si							
<b>Si (amorphous)</b>	<b>10.1 ± 0.3<sup>i</sup></b>	<b>1.036 (ap)</b>	<b>0.886</b>	<b>16.75</b>	<b>67.0</b>	<b>NREL (7/09)</b>	<b>Oerliken Solar Lab, Neuchatel [4]</b>
Si (nanocrystalline)	10.1 ± 0.2 <sup>j</sup>	1.199 (ap)	0.539	24.4	76.6	JQA (12/97)	Kaneka (2 μm on glass) [20]
Photochemical							
Dye sensitized	10.4 ± 0.3 <sup>k</sup>	1.004 (ap)	0.729	22.0	65.2	AIST (8/05) <sup>f</sup>	Sharp [21]
<b>Dye sensitized (submodule)</b>	<b>9.2 ± 0.4<sup>k</sup></b>	<b>17.19 (ap)</b>	<b>0.712<sup>g</sup></b>	<b>19.4<sup>g</sup></b>	<b>66.4</b>	<b>AIST (2/10)</b>	<b>Sony, 8 parallel cells [5]</b>
Organic							
Organic polymer	5.15 ± 0.3 <sup>k</sup>	1.021 (ap)	0.876	9.39	62.5	NREL (12/06) <sup>f</sup>	Konarka [22]
Organic (submodule)	3.5 ± 0.3 <sup>k</sup>	208.4 (ap)	8.620	0.847	48.3	NREL (7/09)	Solarmer [23]
Multijunction Devices							
GaInP/GaAs/Ge	32.0 ± 1.5 <sup>j</sup>	3.989 (t)	2.622	14.37	85.0	NREL (1/03)	Spectrolab (monolithic)
GaInP/GaAs	30.3 <sup>j</sup>	4.0 (t)	2.488	14.22	85.6	JQA (4/96)	Japan Energy (monolithic) [24]
GaAs/CIS (thin film)	25.8 ± 1.3 <sup>j</sup>	4.00 (t)	—	—	—	NREL (11/89)	Kopin/Boeing (4 terminal) [25]
a-Si/μc-Si (thin submodule) <sup>l</sup>	11.7 ± 0.4 <sup>l</sup>	14.23 (ap)	5.462	2.99	71.3	AIST (9/04)	Kaneka (thin film) [26]
Organic (2-cell tandem)	6.1 ± 0.2 <sup>k</sup>	1.989	1.589	6.18	61.9	FhG-ISE (7/09)	Heliatek [27]

<sup>a</sup> CIGS = CuInGaSe<sub>2</sub>; a-Si = amorphous silicon/hydrogen alloy.

<sup>b</sup> Effic. = efficiency.

<sup>c</sup> (ap) = aperture area; (t) = total area; (da) = designated illumination area.

<sup>d</sup> FF = fill factor.

<sup>e</sup> FhG-ISE = Fraunhofer Institut für Solare Energiesysteme; JQA = Japan Quality Assurance; AIST = Japanese National Institute of Advanced Industrial Science and Technology.

<sup>f</sup> Recalibrated from original measurement.

<sup>g</sup> Reported on a 'per cell' basis.

<sup>h</sup> Not measured at an external laboratory.

<sup>i</sup> Light soaked at Oerliken prior to testing at NREL (1000 h, 1 sun, 50°C).

<sup>j</sup> Measured under IEC 60904-3 Ed. 1: 1989 reference spectrum.

<sup>k</sup> Stability not investigated. References [28] and [29] review the stability of similar devices.

<sup>l</sup> Stabilized by 174 h, 1 sun illumination after 20 h, 5 sun illumination at a sample temperature of 50°C.

welcome to contact any of the authors with full details. Suggestions conforming to the guidelines will be included in the voting list for a future issue. (A smaller number of 'notable exceptions' for concentrator cells and modules is additionally included in Table IV.)

Ten new results are reported in the present version of these tables.

The first new result in Table I is a new record for a single-junction cell of any type under non-concentrated

sunlight. An efficiency of 26.4% is reported for a 1 cm<sup>2</sup> GaAs cell fabricated and measured by the Fraunhofer Institute for Solar Energy Systems (FhG-ISE).

Another significant new result in Table I is the first single-junction amorphous silicon cell with stabilized efficiency above 10%. An efficiency of 10.1% is reported for a 1 cm<sup>2</sup> cell fabricated by the Oerliken Solar Laboratory, Neuchatel [4] measured by the National Renewable Energy Laboratory (NREL) after stabilization at Oerliken.

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

Classification <sup>a</sup>	Effic. <sup>b</sup> (%)	Area <sup>c</sup> (cm <sup>2</sup> )	V <sub>oc</sub> (V)	I <sub>sc</sub> (A)	FF <sup>d</sup> (%)	Test centre (and date)	Description
Si (crystalline)	22.9 ± 0.6	778 (da)	5.60	3.97	80.3	Sandia (9/96) <sup>e</sup>	UNSW/Gochermann [30]
Si (large crystalline)	21.4 ± 0.6	15780 (ap)	68.6	6.293	78.4	NREL (10/09)	SunPower [31]
<b>Si (multicrystalline)</b>	<b>17.3 ± 0.5</b>	<b>12753 (ap)</b>	<b>33.6</b>	<b>8.63</b>	<b>76.1</b>	<b>AIST (x/10)</b>	<b>Kyocera</b>
Si (thin-film polycrystalline)	8.2 ± 0.2	661 (ap)	25.0	0.320	68.0	Sandia (7/02) <sup>e</sup>	Pacific Solar (1–2 μm on glass) [32]
<b>CIGS</b>	<b>13.8 ± 0.5</b>	<b>9762 (ap)</b>	<b>26.34</b>	<b>7.167</b>	<b>71.2</b>	<b>NREL (4/10)</b>	<b>Miasole</b> [6]
CIGSS (Cd free)	13.5 ± 0.7	3459 (ap)	31.2	2.18	68.9	NREL (8/02) <sup>e</sup>	Showa Shell [33]
CdTe	10.9 ± 0.5	4874 (ap)	26.21	3.24	62.3	NREL (4/00) <sup>e</sup>	BP Solarex [34]
a-Si/a-SiGe/a-SiGe (tandem) <sup>f</sup>	10.4 ± 0.5 <sup>g</sup>	905 (ap)	4.353	3.285	66.0	NREL (10/98) <sup>e</sup>	USSC [35]

<sup>a</sup> CIGSS = CuInGaSSe; a-Si = amorphous silicon/hydrogen alloy; a-SiGe = amorphous silicon/germanium/hydrogen alloy.

<sup>b</sup> Effic. = efficiency.

<sup>c</sup> (ap) = aperture area; (da) = designated illumination area.

<sup>d</sup> FF = fill factor.

<sup>e</sup> Recalibrated from original measurement.

<sup>f</sup> Light soaked at NREL for 1000 h at 50°C, nominally 1-sun illumination.

<sup>g</sup> Measured under IEC 60904-3 Ed. 1: 1989 reference spectrum.

The final new result in Table I is another increase (third in a row) to 9.2% efficiency for a 17 cm<sup>2</sup> dye-sensitized submodule fabricated by Sony [5] and measured by the Japanese National Institute of Advanced Industrial Science and Technology (AIST).

Following the burst of activity in the multicrystalline silicon module area reported in the last version of these tables, where three groups exceeded the previous record for module efficiency over the reporting period,

a fourth group has done even better. In Table II, a new efficiency record of 17.3% is reported for a large (1.3 m<sup>2</sup> aperture area) module fabricated by Kyocera and measured by AIST.

Also reported in Table II is a record result for a thin-film module, with 13.8% reported for a 1 m<sup>2</sup> CIGS module fabricated by Miasole and measured by NREL [6].

The first new result in Table III also relates to improved multicrystalline silicon cells. An efficiency increase to

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

Classification <sup>a</sup>	Effic. <sup>b</sup> (%)	Area <sup>c</sup> (cm <sup>2</sup> )	V <sub>oc</sub> (V)	J <sub>sc</sub> (mA/cm <sup>2</sup> )	FF (%)	Test centre (and date)	Description
Cells (silicon)							
Si (MCZ crystalline)	24.7 ± 0.5	4.0 (da)	0.704	42.0	83.5	Sandia (7/99) <sup>d</sup>	UNSW PERL, SEH MCZ substrate [36]
Si (moderate area)	23.9 ± 0.5	22.1 (da)	0.704	41.9	81.0	Sandia (8/96) <sup>d</sup>	UNSW PERL, FZ substrate [30]
Si (large crystalline)	23.0 ± 0.6	100.4 (t)	0.729	39.6	80.0	AIST (2/09)	Sanyo HIT, n-type substrate [37]
Si (large crystalline)	22.0 ± 0.7	147.4 (t)	0.677	40.3	80.6	FhG-ISE (3/06) <sup>d</sup>	Sunpower n-type substrate [38]
<b>Si (large multicrystalline)</b>	<b>19.3 ± 0.5</b>	<b>217.7 (t)</b>	<b>0.651</b>	<b>38.8</b>	<b>76.4</b>	<b>AIST (7/09)</b>	<b>Mitsubishi Electric honeycomb</b> [7]
Cells (other)							
GaInP/GaAs/GaInAs (tandem)	35.8 ± 1.5	0.880 (ap)	3.012	13.9	85.3	AIST (9/09)	Sharp, monolithic [39]
<b>CIGS (thin film)</b>	<b>20.1 ± 0.6</b>	<b>0.503 (t)</b>	<b>0.720</b>	<b>36.3</b>	<b>76.8</b>	<b>FhG-ISE (4/10)</b>	<b>ZSW Stuttgart, CIGS on glass</b>
a-Si/nc-Si/nc-Si (tandem)	12.5 ± 0.7 <sup>e</sup>	0.27 (da)	2.010	9.11	68.4	NREL (3/09)	United Solar stabilized [40]
Dye-sensitized	11.2 ± 0.3 <sup>f</sup>	0.219 (ap)	0.736	21.0	72.2	AIST (3/06) <sup>d</sup>	Sharp [41]
Organic	7.9 ± 0.3 <sup>fg</sup>	0.0441 (ap)	0.756	14.7	70.9	NREL (11/09)	Solarmer [23]

<sup>a</sup> CIGS = CuInGaSe<sub>2</sub>.

<sup>b</sup> Effic. = efficiency.

<sup>c</sup> (ap) = aperture area; (t) = total area; (da) = designated illumination area.

<sup>d</sup> Recalibrated from original measurement.

<sup>e</sup> Light soaked under 100 mW/cm<sup>2</sup> white light at 50°C for 1000 h.

<sup>f</sup> Stability not investigated. References [28] and [29] review the stability of similar devices.

<sup>g</sup> Light soaked under simulated AM1.5 for about 140 h prior to shipment to NREL.

**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. <sup>a</sup> (%)	Area <sup>b</sup> (cm <sup>2</sup> )	Intensity <sup>c</sup> (suns)	Test centre (and date)	Description
Single Cells					
<b>GaAs</b>	<b>29.1 ± 1.3<sup>d</sup></b>	<b>0.0505 (da)</b>	<b>117</b>	<b>FhG-ISE (3/10)</b>	<b>Fraunhofer ISE</b>
Si	27.6 ± 1.0 <sup>e</sup>	1.00 (da)	92	FhG-ISE (11/04)	Amonix back-contact [42]
CIGS (thin film)	21.8 ± 1.5 <sup>df</sup>	0.102 (da)	14	NREL (2/01) <sup>g</sup>	NREL
Multijunction cells					
GaInP/GaInAs/Ge (2-terminal)	41.6 ± 2.5	0.3174 (da)	364	NREL (8/09)	Spectrolab, lattice-matched [43]
Submodules					
GaInP/GaAs; GaInAsP/GaInAs	36.1 ± 2.2	0.313 (ap)	30	NREL (8/09)	U. Delaware, split spectrum [44]
GaInP/GaAs/Ge	27.0 ± 1.5 <sup>h</sup>	34 (ap)	10	NREL (5/00)	ENTECH [45]
Modules					
Si	20.5 ± 0.8 <sup>d</sup>	1875 (ap)	79	Sandia (4/89) <sup>g</sup>	Sandia/UNSW/ENTECH (12 cells) [46]
Notable exceptions					
<b>InGaP/GaAs/InGaAs (2-terminal)</b>	<b>41.3 ± 2.5</b>	<b>1.008 (ap)</b>	<b>343</b>	<b>NREL (3/10)</b>	<b>Spire, bi-facial epigrowth</b> [8]
<b>GaInP/GaAs (2-terminal)</b>	<b>32.6 ± 2.0<sup>e</sup></b>	<b>0.010 (da)</b>	<b>1026</b>	<b>FhG-ISE (9/08)</b>	<b>U. Polytechnica de Madrid</b> [9]
Si (large area)	21.7 ± 0.7	20.0 (da)	11	Sandia (9/90) <sup>g</sup>	UNSW laser grooved [47]

<sup>a</sup> Effic. = efficiency.<sup>b</sup> (da) = designated illumination area; (ap) = aperture area.<sup>c</sup> One sun corresponds to direct irradiance of 1000 W/m<sup>2</sup>.<sup>d</sup> Not measured at an external laboratory.<sup>e</sup> Measured under a low aerosol optical depth spectrum similar to ASTM G-173-03 direct [48].<sup>f</sup> Measured under old ASTM E891-87 reference spectrum.<sup>g</sup> Recalibrated from original measurement.

19.3% has been confirmed by AIST for a large 218 cm<sup>2</sup> multicrystalline silicon cell fabricated by Mitsubishi Electric [7].

Another new result in Table III is the improvement of a small area (0.50 cm<sup>2</sup>) CIGS cell fabricated by Zentrum für Sonnenenergie-und Wasserstoff-Forschung (ZSW), Stuttgart to 20.1% efficiency as measured by FhG-ISE. This cell is slightly bigger with a slightly higher measured efficiency than for the previous 20.0% result, but the cell is still smaller than the 1 cm<sup>2</sup> size required for classification as an outright record.

The EQE normalized to the peak EQE values for seven of the above devices are shown in Figures 1(a) and (b).

Concentrator cell and module results (Table IV) are now referenced against the direct normal spectrum tabulated in ASTM G173-03 (except where otherwise noted). Three new results are reported.

The first is an increase in the efficiency to 29.1% at 117 suns for a GaAs cell fabricated and measured by FhG-ISE under the new reference spectrum, paralleling the new 1-sun result reported in Table I.

The second new result is a notable exception. An efficiency of 41.3% under 343 suns concentration is reported for a relatively large 1 cm<sup>2</sup> triple-junction cell fabricated by Spire Semiconductor [8] and measured by NREL. This result is only slightly lower than the 41.6% outright concentrator cell record. The interesting feature is

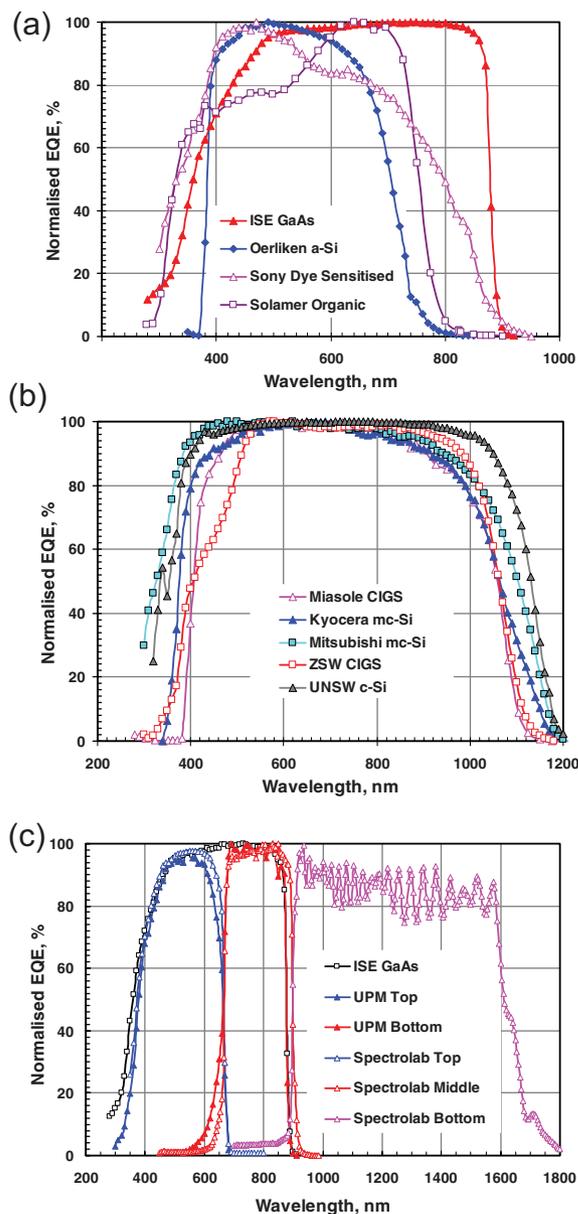
that the cell was fabricated by a new technique for a device of this level of performance. The top two cells (InGaP and GaAs) were grown epitaxially on one side of a GaAs wafer. The wafer had been flipped with the third cell, a 0.95 eV bandgap InGaAs cell, previously grown epitaxially on the opposite side [8].

Finally, a small (0.01 cm<sup>2</sup>) GaInP/GaAs tandem solar cell fabricated by the Universitat Politecnica de Madrid [9] and measured by FhG-ISE has shown exceptional performance at high sunlight concentration levels with 32.6% efficiency demonstrated from 500–1000 suns concentration (0.5–1 kW/m<sup>2</sup> irradiance). This eclipses several previous results for double junction devices.

Figure 1(b) shows the normalized EQE of first and third of these concentrator cells, with the response of the two cells of the tandem stack shown separately. Also shown is the EQE similarly plotted for the 41.6% efficient triple-junction device reported in the previous version of these tables [3]. More information on the EQE of other entries will be published in future issues.

### 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.



**Figure 1.** (a) Normalized external quantum efficiency (EQE) of three of the new non-concentrator cell entries in this issue plus the Solamer 'notable exception' cell from the previous version [3]; (b) Normalized EQE of four of the new non-concentrator cell entries in this issue plus the 25% efficient Si cell from Table I; (c) Normalized EQE of two of the new concentrator cell entries together with that of the record 41.6% device reported in the previous version [3].

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