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ACCELERATED PUBLICATION

Solar cell efficiency tables (version 40)

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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 2012 are reviewed. Copyright © 2012 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]. By providing guidelines for the inclusion of results into these tables, this not only provides an authoritative summary of the current state-of-the-art but also encourages researchers to seek independent confirmation of results and to report results on a standardised basis. In 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 independently measured by a recognised test centre listed elsewhere [1]. A distinction is made between three different eligible areas: 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 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 [1] are set in bold type. In most cases, a literature reference is provided that describes either the result reported, or a similar result. Table I summarises the best measurements for cells and submodules, whereas Table II shows the best results for modules. Table III contains what might be described as 'notable exceptions'. Although not conforming to the requirements to be recognised as a class record, the cells and modules in this Table have notable characteristics

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[a]	Effic.[b] (%)	Area[c] (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF[d] (%)	Test centre[e] (and date)	Description
Silicon							
Si (crystalline)	25.0 ± 0.5	4.00 (da)	0.706	42.7[f]	82.8	Sandia (3/99)[g]	UNSW PERL [12]
Si (multicrystalline)	20.4 ± 0.5	1.002 (ap)	0.664	38.0	80.9	NREL (5/04)[g]	FhG-ISE [13]
Si (thin film transfer)	19.1 ± 0.4	3.983 (ap)	0.650	37.8[h]	77.6	FhG-ISE (2/11)	ISFH (43 μm thick) [14]
Si (thin film submodule)	10.5 ± 0.3	94.0 (ap)	0.492[i]	29.7[i]	72.1	FhG-ISE (8/07)[g]	CSG Solar (1–2 μm on glass; 20 cells) [15]
III-V Cells							
GaAs (thin film)	**28.8 ± 0.9**	**0.9927 (ap)**	**1.122**	**29.68[j]**	**86.5**	**NREL (5/12)**	**Alta Devices** [3]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95)[g]	RTI, Ge substrate [16]
InP (crystalline)	22.1 ± 0.7	4.02 (t)	0.878	29.5	85.4	NREL (4/90)[g]	Spire, epitaxial [17]
Thin film chalcogenide							
CIGS (cell)	19.6 ± 0.6[k]	0.996 (ap)	0.713	34.8[l]	79.2	NREL (4/09)	NREL, on glass [18]
CIGS (submodule)	17.4 ± 0.5	15.993 (da)	0.6815[i]	33.84[i]	75.5	FhG-ISE (10/11)	Solibro, four serial cells [19]
CdTe (cell)	**17.3 ± 0.5**	**1.066 (ap)**	**0.842**	**28.99[j]**	**75.6**	**NREL (7/11)**	**First Solar, on glass** [4]
Amorphous/ nanocrystalline Si							
Si (amorphous)	10.1 ± 0.3[m]	1.036 (ap)	0.886	16.75[f]	67.0	NREL (7/09)	Oerlikon Solar Lab, Neuchatel [20]
Si (nanocrystalline)	10.1 ± 0.2[n]	1.199 (ap)	0.539	24.4	76.6	JQA (12/97)	Kaneka (2 μm on glass) [21]
Photochemical							
Dye sensitised	11.0 ± 0.3[o]	1.007 (da)	0.714	21.93[h]	70.3	AIST (9/11)	Sharp [22]
Dye sensitised (submodule)	9.9 ±0.4[o]	17.11 (ap)	0.719[i]	19.4[i]	71.4	AIST (8/10)	Sony, eight parallel cells [23]
Organic							
Organic thin-film	10.0 ± 0.3[o]	1.021 (ap)	0.899	16.75[p]	66.1	AIST (10/11)	Mitsubishi Chemical [24]
Organic (submodule)	**5.2 ± 0.2[o]**	**294.5 (ap)**	**0.689**	**11.73[i]**	**64.2**	**AIST (3/12)**	**Sumitomo (15 series cells)** [5]
Multijunction devices							
InGaP/GaAs/InGaAs	**37.5 ± 1.3**	**1.046 (ap)**	**3.015**	**14.56[j]**	**85.5**	**AIST (2/12)**	**Sharp** [6]
a-Si/nc-Si/nc-Si (thin film)	12.4 ± 0.7[q]	1.050 (ap)	1.936	8.96[h]	71.5	NREL (3/11)	United Solar [25]
a-Si/nc-Si (thin film cell)	12.3 ± 0.3%[r]	0.962(ap)	1.365	12.93[p]	69.4	AIST (7/11)	Kaneka [26]
a-Si/nc-Si (thin film submodule)	11.7 ± 0.4[n]	14.23 (ap)	5.462	2.99	71.3	AIST (9/04)	Kaneka [27]

[a]CIGS = $CuInGaSe_2$

[b]Effic. = efficiency

[c](ap) = aperture area; (t) = total area; (da) = designated illumination area

[d]FF = fill factor

[e]FhG-ISE = Fraunhofer Institut für Solare Energiesysteme; JQA = Japan Quality Assurance; AIST = Japanese National Institute of Advanced Industrial Science and Technology

[f]Spectral response reported in Version 36 of these Tables

[g]Recalibrated from original measurement

[h]Spectral response and current-voltage curve reported in Version 38 of these Tables

[i]Reported on a 'per cell' basis

[j]Spectral response and/or current-voltage curve reported in present version of these Tables.

[k]Not measured at an external laboratory

[l]Spectral response reported in Version 37 of these Tables

[m]Light soaked at Oerlikon prior to testing at NREL (1000 h, one sun, 50 °C)

[n]Measured under IEC 60904-3 Ed. 1: 1989 reference spectrum

[o]Stability not investigated. References [28] and [29] review the stability of similar devices

[p]Spectral response and current-voltage curve reported in Version 39 of these Tables

[q]Light soaked under 100 mW/cm^2 white light at 50 °C for over 1000 h

[r]Stabilised by manufacturer

[s]Stabilised by 174 h, one sun illumination after 20 h, five sun illumination at a sample temperature of 50 °C.

that will be of 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

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[a]	Effic.[b] (%)	Area[c] (cm^2)	V_{oc} (V)	I_{sc} (A)	FF[d] (%)	Test centre (and date)	Description
Si (crystalline)	22.9 ± 0.6	778 (da)	5.60	3.97	80.3	Sandia (9/96)[e]	UNSW/Gochermann [30]
Si (large crystalline)	21.4 ± 0.6	15780 (ap)	68.6	6.293	78.4	NREL (10/09)	SunPower [31]
Si (multicrystalline)	**18.5 ± 0.4**	**14661 (ap)**	**38.97**	**9.149**[f]	**76.2**	**FhG-ISE (1/12)**	**Q-Cells (60 serial cells)** [7]
Si (thin-film polycrystalline)	8.2 ± 0.2	661(ap)	25.0	0.320	68.0	Sandia (7/02)[e]	Pacific Solar (1–2 μm on glass) [32]
GaAs (thin film)	23.5 ± 0.7	856.8 (ap)	10.77	2.222[g]	84.0	NREL (12/11)	Alta Devices [3]
CIGS	15.7 ± 0.5	9703 (ap)	28.24	7.254[h]	72.5	NREL (11/10)	Miasole [33]
CIGSS (Cd free)	13.5 ± 0.7	3459 (ap)	31.2	2.18	68.9	NREL (8/02)[e]	Showa Shell [34]
CdTe	**15.3 ± 0.5**	**6750.9 (ap)**	**64.97**	**2.183**[f]	**72.9**	**NREL (1/12)**	**First Solar** [8]
a-Si/a-SiGe/a-SiGe (tandem)	10.4 ± 0.5[i,j]	905 (ap)	4.353	3.285	66.0	NREL (10/98)[e]	USSC [35]

[a]CIGSS = CuInGaSSe; a-Si = amorphous silicon/hydrogen alloy; a-SiGe = amorphous silicon/germanium/hydrogen alloy
[b]Effic. = efficiency
[c](ap) = aperture area; (da) = designated illumination area
[d]FF = fill factor
[e]Recalibrated from original measurement
[f]Spectral response and/or current-voltage curve reported in present version of these Tables
[g]Spectral response and current-voltage curve reported in Version 37 of these Tables
[h]Spectral response reported in Version 37 of these Tables.
[i]Light soaked at NREL for 1000 h at 50 °C, nominally onesun illumination
[j]Measured under IEC 60904-3 Ed. 1: 1989 reference spectrum

Table III. 'Notable exceptions': 'Top 10' 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[a]	Effic.[b] (%)	Area[c] (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	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)[d]	UNSW PERL, SEH MCZ substrate [36]
Si (large crystalline)	24.2 ± 0.7	155.1(t)	0.721	40.5[e]	82.9	NREL (5/10)	Sunpower n-type CZ substrate [37]
Si (large crystalline)	**23.9 ± 0.6**	**102.7(t)**	**0.748**	**38.89[f]**	**82.2**	**AIST (2/12)**	**Panasonic HIT, n-type** [9]
Si (large multicrystalline)	19.5 ± 0.4	242.7(t)	0.652	39.0[e]	76.7	FhG ISE (3/11)	Q-Cells, laser fired contacts [38]
Cells (other)							
CIGS (thin film)	20.3 ± 0.6	0.5015 (ap)	0.740	35.4[e]	77.5	FhG-ISE (6/10)	ZSW Stuttgart, CIGS on glass [39]
CZTSS (thin film)	11.1 ± 0.3	0.4496 (ap)	0.4598	34.54[f]	69.8	Newport (2/12)	IBM solution grown [40]
a-Si/nc-Si/nc-Si (tandem)	**12.5 ± 0.7[i]**	**0.27 (da)**	**2.010**	**9.11**	**68.4**	**NREL (3/09)**	**United Solar stabilised** [41]
Dye-sensitised	11.4 ± 0.3[j]	0.231 (ap)	0.743	21.34[h]	72.2	AIST (6/11)	NIMS [42]
Organic (tandem)	**10.6 ± 0.3[j]**	**0.103 (ap)**	**1.5306**	**10.08[f]**	**68.5**	**NREL (1/12)**	**UCLA-Sumitomo** [10]
Luminescent submodule	7.1 ± 0.2	25(ap)	1.008	8.84[e]	79.5	ESTI (9/08)	ECN Petten, GaAs cells [43]

[a]CIGS = $CuInGaSe_2$; CZTSS = $Cu_2ZnSnS_{4-y}Se_y$

[b]Effic. = efficiency

[c](ap) = aperture area; (t) = total area; (da) = designated illumination area

[d]Recalibrated from original measurement

[e]Spectral response reported in Version 37 of these Tables

[f]Spectral response and current-voltage curve reported in the present version of these Tables

[g]Spectral response and current-voltage curves reported in Version 39 of these Tables

[h]Spectral response and current-voltage curves reported in Version 38 of these Tables

[i]Light soaked under 100 mW/cm^2 white light at 50 °C for 1000 h

[j]Stability not investigated

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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).

Ten new results are reported in the present version of these Tables. The first new result in Table I is an outright record for solar conversion by any single-junction photovoltaic device, increasing the 28.3% result reported in the previous version of these Tables [1]. An efficiency of 28.8% has been measured at the National Renewable Energy Laboratory (NREL) for a 1-cm^2 thin film GaAs device fabricated by Alta Devices, Inc. Alta Devices is a Santa Clara-based 'start-up' seeking to develop low cost, 30% efficient solar modules [3].

The second new result is for a 1-cm^2 CdTe cell with 17.3% efficiency reported for a cell fabricated by First Solar [4] and measured by NREL.

Another new result in Table I is an improvement in efficiency to 5.2% for a 295-cm^2 organic cell submodule fabricated by Sumitomo Chemical [5] and measured by the Japanese National Institute of Advanced Industrial Science and Technology (AIST). The improvement over the previous record from the same company came as a result of greatly increased fill factor. The stability of this device, as with that of some of the other newer technologies, was not investigated.

Another major new result in Table 1 is a new record for energy conversion efficiency for any photovoltaic converter that does not use sunlight concentration. An efficiency of 37.5% is reported for a 1 cm^2 InGaP/GaAs/InGaAs multijunction cell fabricated by Sharp [6] and again measured by AIST.

Following a vigorous burst of activity in the multicrystalline silicon module area reported in the five previous versions of these Tables, where five separate groups exceeded the previous record for module efficiency seven times over a 2–3 year period, one of these groups has carried out even better. In Table II, a new efficiency record of 18.5% is reported for a large (1.5-m^2 aperture area) module fabricated by Q-Cells [7] and measured by the Fraunhofer-Institut für Solare Energiesysteme (FhG-ISE).

Also, reported in Table II is a new record for a thin film CdTe module. An efficiency of 15.3% was measured by NREL for a 0.7-m^2 area module fabricated by First Solar [8]. The company has earlier reported this result as 14.4% efficiency [8], more demandingly

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.[a] (%)	Area[b] (cm^2)	Intensity[c] (suns)	Test centre (and date)	Description
Single Cells					
GaAs	29.1 ± 1.3[d]	0.0505 (da)	117	FhG-ISE (3/10)	Fraunhofer ISE
Si	27.6 ± 1.0[f]	1.00 (da)	92	FhG-ISE (11/04)	Amonix back-contact [44]
Multijunction cells					
GaInP/GaAs/GaInNAs (2-terminal)	43.5 ± 2.6	0.3124 (ap)	418	NREL (3/11)	Solar Junction, Triple Cell [45]
GaInP/GaInAs/Ge (2-terminal)	41.6 ± 2.5[e]	0.3174(da)	364	NREL (8/09)	Spectrolab, lattice-matched [46]
Submodules					
GaInP/GaAs; GaInAsP/GaInAs	38.5 ± 1.9[g]	0.202 (ap)	20	NREL (8/08)	DuPont et al., split spectrum [47]
GaInP/GaAs/Ge	27.0 ± 1.5[h]	34 (ap)	10	NREL (5/00)	ENTECH [48]
Modules					
Si	20.5 ± 0.8[d]	1875 (ap)	79	Sandia (4/89)[i]	Sandia/UNSW/ENTECH (12 cells) [49]
Triple Junction	**33.5 ± 0.5[j]**	**10,674.8 (ap)**	**N/A**	**NREL (5/12)**	**Amonix** [11]
'Notable Exceptions'					
Si (large area)	21.7 ± 0.7	20.0 (da)	11	Sandia (9/90)[i]	UNSW laser grooved [50]

[a]Effic. = efficiency

[b](da) = designated illumination area; (ap) = aperture area

[c]One sun corresponds to direct irradiance of 1000 Wm^{-2}

[d]Not measured at an external laboratory

[e]Spectral response reported in Version 36 of these Tables

[f]Measured under a low aerosol optical depth spectrum similar to ASTM G-173-03 direct [51]

[g]Spectral response reported in Version 37 of these Tables

[h]Measured under old ASTM E891-87 reference spectrum

[i]Recalibrated from original measurement

[j]Based on ASTM E2527 rating, May 2012 (850 W/m^2 direct irradiance, 20 °C ambient, 4 m/s wind speed)

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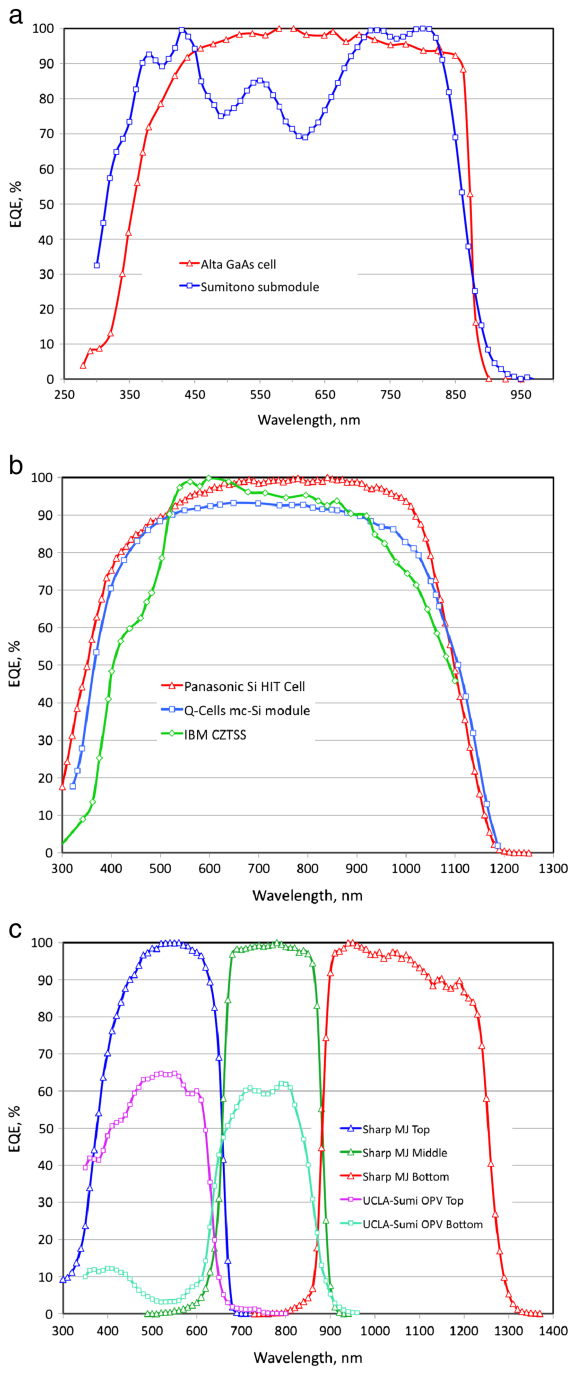

Figure 1. (a) External quantum efficiency (EQE) for the new GaAs cell and organic submodule results in this issue; (b) EQE for the new silicon and CZTSS cell and silicon module entries in this issue; (c) EQE for the new III-V and organic multijunction cells in this issue (Normalised data in most cases).

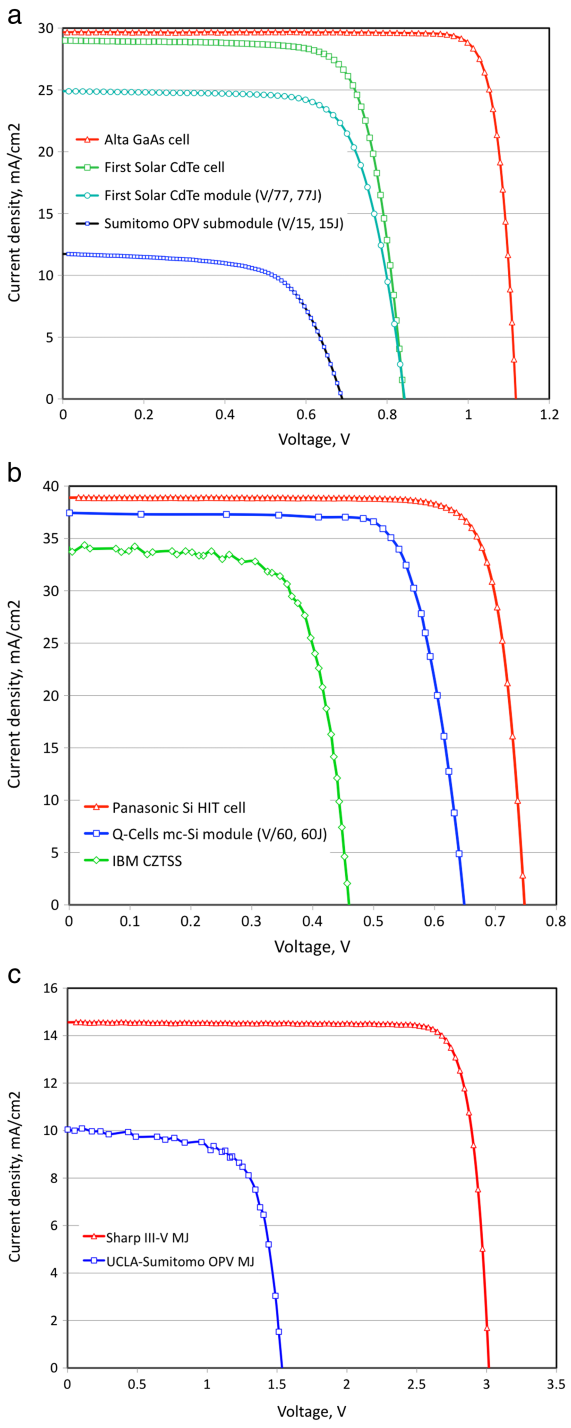

Figure 2. (a) Current density—voltage (JV) curve for the new GaAs cell and organic submodule results in this issue; (b) JV curves for the new silicon and CZTSS cell and silicon module entries in this issue; (c) JV curves for the new multijunction cells in this issue (cells per series string estimated in some cases).

based on the total area of the module rather than the aperture area more commonly used for modules reported in these Tables.

The first new result in Table III relates to an efficiency increase to 23.9% for a large 100-cm^2 crystalline silicon cell fabricated by Panasonic (formerly Sanyo) [9] and measured by AIST. The cell uses Panasonic's HIT cell structure (Heterojunction with Intrinsic Thin layer).

The second new result in Table III relates to an efficiency increase to 11.1% for a small area (0.5-cm superscript 2) CZTSS solar cell fabricated by IBM and measured by Newport Laboratories. This cell is too small in area to be classified as an outright record.

A third new notable exception in Table III is for a small area 0.1-cm^2 organic thin film cell of 10.6% efficiency fabricated by UCLA (University of California, Los Angeles) using material supplied by Sumitomo Chemical [10] and measured by NREL. This cell is much smaller than the 1-cm^2 size required for classification as an outright record.

Table IV reports the final new result, the confirmed measurement of a large area photovoltaic module with energy conversion efficiency above 30%. An efficiency of well above this at 33.5% was measured by NREL for a 1-m^2 aperture area concentrating photovoltaic module fabricated by Amonix [11]. This efficiency was based on the ASTM E2527 rating of the module as measured in May 2012 at NREL (850-W/m^2 direct irradiance, 20 °C ambient temperature and 4-m/s wind speed).

The external quantum efficiencies for the new GaAs cell and organic submodule results of Table I are shown in Figure 1(a). Figure 1(b) shows the EQE of the new silicon and CZTSS cell and silicon module results in the present issue of these Tables. Figure 1(c) shows the EQE of the constituent cells for the new III-V and organic multijunction cell results.

Figure 2 shows the current density—voltage (JV) curves for the corresponding devices and for some additional devices for which the EQE is not shown. For the case of modules, the measured current—voltage data has been reported on a 'per cell' basis (measured voltage has been divided by the number of cells in series per series string, whereas measured current has been multiplied by this quantity and divided by the module area). For the First Solar module, the number of cells per series string has been assumed to be the same as in the company's present commercial 'Series 3' modules.

3. DISCLAIMER

Although 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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