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RESEARCH: SHORT COMMUNICATION: ACCELERATED PUBLICATION

Solar cell efficiency tables (version 37)

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ABSTRACT

Consolidated tables showing an extensive listing of the highest independently confirmed efficiencies for solar cells and modules are presented. Guidelines for inclusion of results into these tables are outlined and new entries since June 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 [1–3]. 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 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 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 [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) [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 Version 36 onwards, spectral response information has been included when available 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 ‘‘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. Table I summarises 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 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

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

Classification[a]	Effic.[b] (%)	Area[c] (cm^2)	*Voc* (V)	*Jsc* (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 [17]
Si (multicrystalline)	20.4 ± 0.5	1.002 (ap)	0.664	38.0	80.9	NREL (5/04)[g]	FhG-ISE [18]
Si (thin film transfer)	16.7 ± 0.4	4.017 (ap)	0.645	33.0	78.2	FhG-ISE (7/01)[g]	U. Stuttgart (45 μm thick) [19]
Si (thin film submodule)	10.5 ± 0.3	94.0 (ap)	0.492[h]	29.7[h]	72.1	FhG-ISE (8/07)[g]	CSG Solar (1–2 μm on glass; 20 cells) [20]
III–V cells							
GaAs (thin film)	**27.6 ± 0.8**	**0.9989 (ap)**	**1.107**	**29.6**[j]	**84.1**	**NREL (11/10)**	**Alta Devices** [4]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95)[g]	RTI, Ge substrate [21]
InP (crystalline)	22.1 ± 0.7	4.02 (t)	0.878	29.5	85.4	NREL (4/90)[g]	Spire, epitaxial [22]
Thin Film Chalcogenide							
CIGS (cell)	**19.6 ± 0.6**[i]	**0.996 (ap)**	**0.713**	**34.8**[j]	**79.2**	**NREL (4/09)**	**NREL, CIGS on glass** [5,23]
CIGS (submodule)	16.7 ± 0.4	16.0 (ap)	0.661[h]	33.6[h]	75.1	FhG-ISE (3/00)[g]	U. Uppsala, 4 serial cells [24]
CdTe (cell)	16.7 ± 0.5[h]	1.032 (ap)	0.845	26.1	75.5	NREL (9/01)[g]	NREL, mesa on glass [25]
CdTe (submodule)	**12.5 ± 0.4**	**35.03 (ap)**	**0.838**	**21.2**[j]	**70.5**	**NREL (9/10)**	**ASP Hangzhou, 8 serial cells**
Amorphous/nanocrystalline Si							
Si (amorphous)	10.1 ± 0.3[k]	1.036 (ap)	0.886	16.75[f]	67	NREL (7/09)	Oerlikon Solar Lab, Neuchatel [26]
Si (nanocrystalline)	10.1 ± 0.2[l]	1.199 (ap)	0.539	24.4	76.6	JQA (12/97)	Kaneka (2 μm on glass) [27]
Photochemical							
Dye sensitised	10.4 ± 0.3[m]	1.004(ap)	0.729	22	65.2	AIST (8/05)[g]	Sharp [28]
Dye sensitized (submodule)	**9.9 ± 0.4**[m]	**17.11 (ap)**	**0.719**[h]	**19.4**[h,j]	**71.4**	**AIST (8/10)**	**Sony, 8 parallel cells** [6]
Organic							
Organic polymer	**8.3 ± 0.3**[m]	**1.031 (ap)**	**0.816**	**14.46**[j]	**70.2**	**NREL(11/10)**	**Konarka** [7]

(*Continues*)

Table I. (Continued)

Classification[a]	Effic.[b] (%)	Area[c] (cm^2)	*V*oc (V)	*J*sc (mA/cm^2)	FF[d] (%)	Test Centre[e] (and Date)	Description
Organic (submodule)	3.5 ± 0.3[m]	208.4 (ap)	8.62	0.847	48.3	NREL (7/09)	Solarmer [29]
Multijunction devices							
GaInP/GaAs/Ge	32.0 ± 1.5[l]	3.989 (t)	2.622	14.37	85	NREL (1/03)	Spectrolab (monolithic)
GaAs/CIS (thin film)	25.8 ± 1.3[l]	4.00 (t)	—	—	—	NREL (11/89)	Kopin/Boeing (4 terminal) [30]
a-Si/μc-Si (thin film cell)	**11.9 ± 0.8**[n]	**1.227**	**1.346**	**12.92**[j]	**68.5**	**NREL (8/10)**	**Oerlikon Solar Lab, Neuchatel** [8]
a-Si/μc-Si (thin film submodule)[j,l]	11.7 ± 0.4[l,o]	14.23 (ap)	5.462	2.99	71.3	AIST (9/04)	Kaneka (thin film) [31]
Organic (2-cell tandem)	**8.3 ± 0.3**[m]	**1.087 (ap)**	**1.733**	**8.03**[j]	**59.5**	**FhG-ISE (10/10)**	**Heliatek** [9]

[a] CIGS = CuInGaSe2; a-Si = amorphous silicon/hydrogen alloy.
[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] Reported on a 'per cell' basis.
[i] Not measured at an external laboratory.
[j] Spectral response reported in present version of these tables.
[k] Light soaked at Oerlikon prior to testing at NREL (1000 h, 1 sun, 50°C).
[l] Measured under IEC 60904–3 Ed. 1: 1989 reference spectrum.
[m] Stability not investigated. References [32] and [33] review the stability of similar devices.
[n] Stabilised by 1000 h, 1 sun illumination at a sample temperature of 50°C.
[o] Stabilised by 174 h, 1 sun illumination after 20 h, 5 sun illumination at a sample temperature of 50°C.

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

Classification[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)	5.6	3.97	80.3	Sandia (9/96)[e]	UNSW/Gochermann [34]
Si (large crystalline)	21.4 ± 0.6	15780 (ap)	68.6	6.293	78.4	NREL (10/09)	SunPower [35]
Si (multicrystalline)	**17.55 ± 0.5**	**14701 (ap)**	**38.31**	**8.94**[f]	**75.3**	**ESTI (8/10)**	**Schott Solar (60 serial cells)** [10]
Si (thin-film polycrystalline)	8.2 ± 0.2	661(ap)	25	0.32	68	Sandia (7/02)[e]	Pacific Solar (1–2 μm on glass) [36]
CIGS	**15.7 ± 0.5**	**9703 (ap)**	**28.24**	**7.254**[f]	**72.5**	**NREL (11/10)**	**Miasole** [11]
CIGSS (Cd free)	13.5 ± 0.7	3459 (ap)	31.2	2.18	68.9	NREL (8/02)[e]	Showa Shell [37]
CdTe	10.9 ± 0.5	4874 (ap)	26.21	3.24	62.3	NREL (4/00)[e]	BP Solarex [38]
a-Si/a-SiGe/a-SiGe (tandem)	10.4 ± 0.5[g,h]	905 (ap)	4.353	3.285	66	NREL (10/98)[e]	USSC [39]

[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 reported in present version of these tables.
[g] Lightsoaked at NREL for 1000 h at 50°C, nominally 1-sun illumination.
[h] Measured under IEC 60904–3 Ed. 1: 1989 reference spectrum.

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[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	83.5	Sandia (7/99)[d]	UNSW PERL, SEH MCZ substrate [40]
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** [12]
Si (large crystalline)	23.0 ± 0.6	100.4(t)	0.729	39.6	80	AIST (2/09)	Sanyo HIT, n-type substrate [41]
Si (large multicrystalline)	19.3 ± 0.5	217.7(t)	0.651	38.8[f]	76.4	AIST (7/09)	Mitsubishi Electric honeycomb [42]
Cells (other)							
GaInP/GaAs/GaInAs (tandem)	35.8 ± 1.5	0.880 (ap)	3.012	13.9	85.3	AIST (9/09)	Sharp, monolithic [43]
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** [13]
a-Si/nc-Si/nc-Si (tandem)	12.5 ± 0.7 [g]	0.27 (da)	2.01	9.11	68.4	NREL (3/09)	United Solar stabilised [44]
Dye-sensitised	11.2 ± 0.3[h]	0.219 (ap)	0.736	21	72.2	AIST (3/06)[d]	Sharp [45]
Luminescent submodule	**7.1 ± 0.2**[h]	**25(ap)**	**1.008**	**8.84**	**79.5**	**ESTI (9/08)**	**ECN Petten, GaAs cells** [14]

[a] CIGS = $CuInGaSe_2$.
[b] Effic. = efficiency.
[c] (ap)= aperture area; (t) = total area; (da) = designated illumination area.
[d] Recalibrated from original measurement.
[e] Spectral response reported in present version of these tables.
[f] Spectral response reported in Version 36 of these tables.
[g] Light soaked under $100 mW/cm^2$ white light at 50°C for 1000 h.
[h] Stability not investigated.

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,e]	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 [46]
Multijunction cells					
InGaP/GaAs/InGaAs (2-terminal)	**42.3 ± 2.5**[i]	**0.9756 (ap)**	**406**	**NREL (9/10)**	**Spire, bi-facial epigrowth** [15]
GaInP/GaInAs/Ge (2-terminal)	41.6 ± 2.5[e]	0.3174(da)	364	NREL (8/09)	Spectrolab, lattice-matched [47]
Submodules					
GaInP/GaAs; GaInAsP/GaInAs	**38.5 ± 1.9**[i]	**0.202 (ap)**	**20**	**NREL (8/08)**	**DuPont *et al.*, split spectrum** [16]
GaInP/GaAs/Ge	27.0 ± 1.5[g]	34 (ap)	10	NREL (5/00)	ENTECH [48]
Modules					
Si	20.5 ± 0.8[d]	1875 (ap)	79	Sandia (4/89)[h]	Sandia/UNSW/ENTECH (12 cells) [49]
Notable exceptions					
GaInP/GaAs (2-terminal)	32.6 ± 2.0[e]	0.010 (da)	1026	FhG-ISE (9/08)	U. Polytecnica de Madrid [50]
Si (large area)	21.7 ± 0.7	20.0 (da)	11	Sandia (9/90)[h]	UNSW laser grooved [51]

[a] Effic. = efficiency.
[b] (da) = designated illumination area; (ap) = aperture area.
[c] One sun corresponds to direct irradiance of 1000 W/m.
[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[52].
[g] Measured under old ASTM E891–87 reference spectrum.
[h] Recalibrated from original measurement.
[i] Spectral response reported in the present version of these tables.

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).

Fourteen 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. An efficiency of 27.6% 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 [4].

The second new result in Table I is an efficiency improvement to 19.6% for a 1 cm^2 single-junction copper–indium–gallium–selenide (CIGS) cell fabricated by and measured at NREL [5]. Although CIGS efficiency of 20% and higher has been reported previously by two groups (see Table III), this has been for cells appreciably less than 1 cm^2 in area, the minimum considered reasonable for efficiency comparisons in these Tables and for milestones in most of the international programs.

A third new result in Table I is 12.5% efficiency for an eight cell 35 cm^2 CdTe submodule fabricated by Advanced Solar Power (ASP) Hangzhou, also measured by NREL.

A fourth new result in Table I is for a dye sensitized submodule with efficiency of 9.9% reported for a 17 cm^2 submodule fabricated by Sony [6] and measured by the Japanese National Institute of Advanced Industrial Science and Technology (AIST). This is quite close to the record of 10.4% efficiency for the best individual dye sensitised cell yet confirmed (of more that 1 cm^2 area).

Another outstanding new result is the measurement of 8.3% efficiency at NREL for a 1cm^2 organic cell fabricated by Konarka [7], representing a massive improvement over the company's previous 5.15% record entry. An intermediate result of 6.5% was measured in July 2010.

Another new result in Table I is for a double-junction amorphous/microcrystalline silicon cell with stabilized efficiency of 11.9% reported for a 1.2 cm^2 cell fabricated by Oerlikon and Corning [8] and again measured by NREL, after stabilization.

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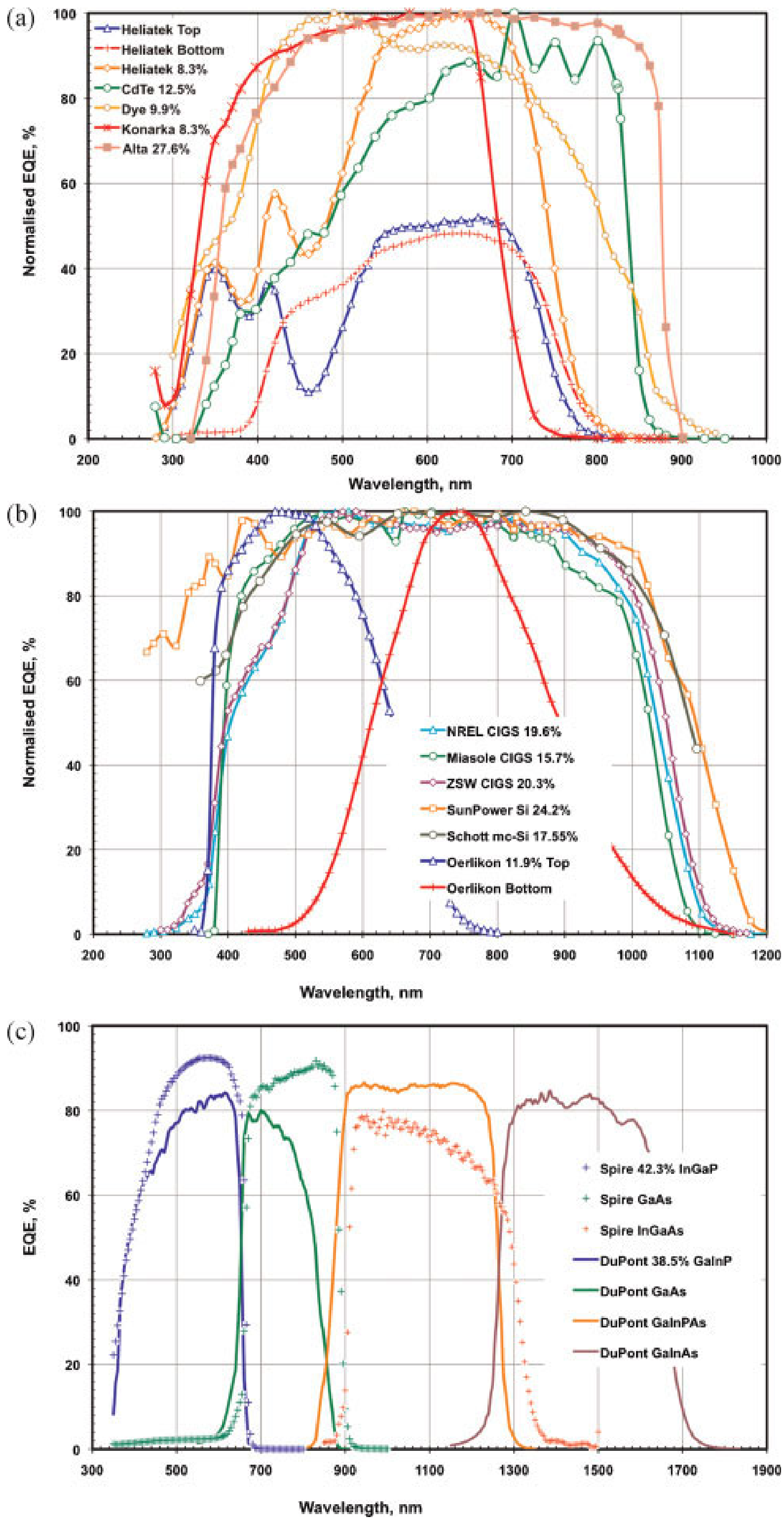

Figure 1. (a) Normalised external quantum efficiency (EQE) for the new organic and GaAs cell results in this issue and for the new CdTe and dye-sensitised submodule results; (b) Normalised EQE for the three new CIGS cell and module entries in this issue plus for the three new silicon cell and module results; (c) EQE of the composite cells for the new concentrator cell and submodule entries in the present issue.

The final new result in Table I is for a double-junction organic solar cell with 8.3% efficiency measured for a 1.1 cm^2 cell fabricated by Heliatek [9] and measured by the Fraunhofer Institute for Solar Energy Systems (FhG-ISE). This represents rapid progress from the 6.1% result from Heliatek measured in June last year and reported in the previous version of these Tables. An intermediate result of 7.7% was measured in March 2010.

Following a similarly vigorous burst of activity in the multicrystalline silicon module area reported in the two previous versions of these Tables, where four groups exceeded the previous record for module efficiency over the two reporting periods, a fifth group has done even better. In Table II, a new efficiency record of 17.55% is reported for a large (1.5 m^2 aperture area) module fabricated by Schott Solar [10] and measured by the European Solar Test Installation, Ispra (ESTI).

Also reported in Table II is a record result for a thin-film module, with a large improvement to 15.7% reported for a 1 m^2 CIGS module fabricated by Miasole [11] and measured by NREL.

The first new result in Table III relates to an efficiency increase to 24.2% for a large 155 cm^2 silicon cell fabricated on an n-type Czochralski grown wafer, with the cell fabricated by SunPower [12] and also measured by NREL.

Another new result in Table III is the further improvement of a small area (0.5 cm^2) CIGS cell fabricated by Zentrum für Sonnenenergie- und Wasserstoff- Forschung (ZSW), Stuttgart [13] to 20.3% efficiency as measured by FhG-ISE. This cell is smaller than the 1 cm^2 size required for classification as an outright record, as previously discussed.

The final new result in Table III is for a luminescent concentrating submodule using high performance GaAs cells placed along the edge of a luminescent plate to convert the collected luminescent radiation. An efficiency of 7.1% was confirmed for a 25 cm^2 test device fabricated by ECN, Netherlands [14] and measured by ESTI.

Two more new results are reported in Table IV for more conventional concentrator cells and systems. The first is a new efficiency record for any photovoltaic cell with 42.3% efficiency measured by NREL at 406 suns concentration (irradiance) for a 1 cm^2 cell fabricated by the Spire Corporation [15]. A new approach was used whereby a low bandgap InGaAs cell was grown on one side of a GaAs wafer, with the wafer then flipped over and an intermediate bandgap GaAs followed by a high bandgap InGaP cell grown on the other side.

The final new result represents a new record for the conversion of sunlight to electricity by any means. An efficiency of 38.5% was measured by NREL for a very small area (0.2 cm^2) spectral-splitting submodule at about 20 suns concentration as the result of a multi-institutional effort headed by DuPont [16]. This complete lens/cell assembly uses a dichroic reflector to steer light to two different two-cell stacks, one on a GaAs substrate and one on an InP substrate.

The external quantum efficiencies (EQE) normalized to the peak EQE values for the new organic cell results of Table I are shown in Figure 1(a) as well as the response for the GaAs cell and CdTe and dye-sensitised submodules of Table I. Also shown is the decomposition into the top and bottom cell response for the 8.3% Heliatek tandem cell of Table I. Interestingly, both cells in the stack have largely overlapping spectral response range, although complementary in some aspects.

Figure 1(b) shows the normalized EQE of the new CIGS and silicon results in the present issue of these tables. Quite striking is the almost identical responses of the NREL and ZSW CIGS cells with the higher current from the ZSW cell attributed to a slightly lower bandgap edge. The normalized responses of both cells in the Oerliken/Corning micromorph tandem cell are also shown.

Figure 1(c) shows the absolute EQE for the different cells contributing to the new concentrator cell and submodule results of Table IV. The much narrower response bandwidth of the bottom InGaAs cell in the 42.3% Spire monolithic stack compared to the response of the bottom Ge in the 41.6% Spectrolab device [3] reflects a higher bandgap. This gives a higher voltage output that contributes to the improved performance. The EQE for the 38.5% submodule differs slightly from results reported elsewhere [16] due to incorporation of the effect of the dichroic reflector used in this system. Each of the four cells in this system is contacted separately, removing the need for current matching.

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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