ECN

Energy research Centre of the Netherlands

Organic photovoltaic efficiency as a technical challenge

Jan Kroon, ECN Solar Energy

OBPV – Efficiency & costs

Long term target for power applications < 0.5 € /W_p

- Reduce module costs (< €/m^2)
- Increase efficiency (>W_p/m^2)

Module costs (€/m²)	1000	750	500	250	100	75	50	25
Module η(%)								
2	50.00	37.50	25.00	12.50	5.00	3.75	2.50	1.25
4	25.00	18.75	12.50	6.25	2.50	1.88	1.25	0.63
6	16.67	12.50	8.33	4.17	1.67	1.25	0.83	0.42
8	12.50	9.38	6.25	3.13	1.25	0.94	0.63	0.31
10	10.00	7.50	5.00	2.50	1.00	0.75	0.50	0.25
12	8.33	6.25	4.17	2.08	0.83	0.63	0.42	0.21
14	7.14	5.36	3.57	1.79	0.71	0.54	0.36	0.18

€/Wp

Contents

- Introduction
- Standard and adapted measuring procedures for OBPV
- State of the art
- Efficiency potential for OBPV
- Conclusion and recommendations

Photovoltaic power conversion efficiency

$$\eta\ (\%) = (P_{out}/P_{in}) \times 100 = (FF \times V_{oc} \times J_{sc}) / P_{in}$$

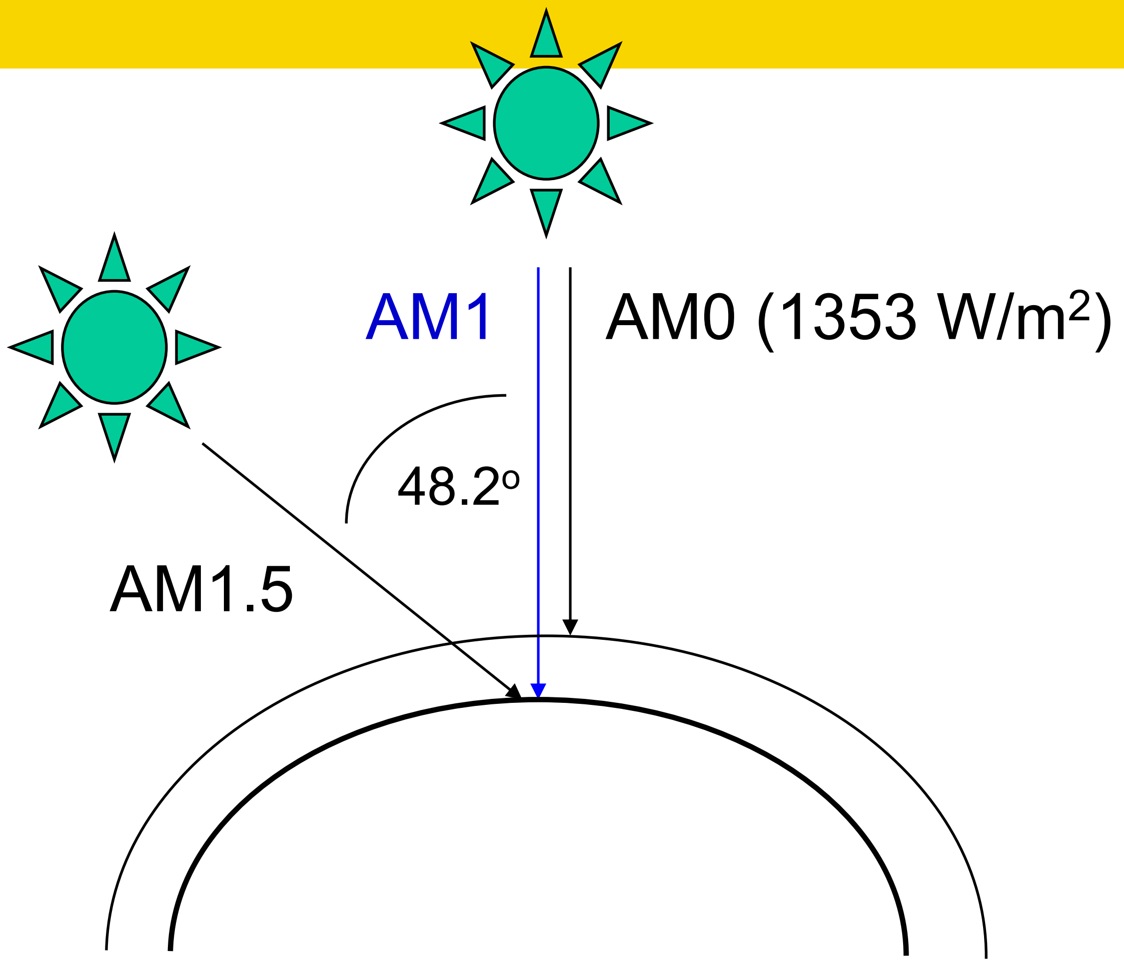
η depends on

- Temperature
- Illumination power
- Spectral distribution light source

For a meaningful comparison of results:
Efficiencies independent of measuring institute and technique

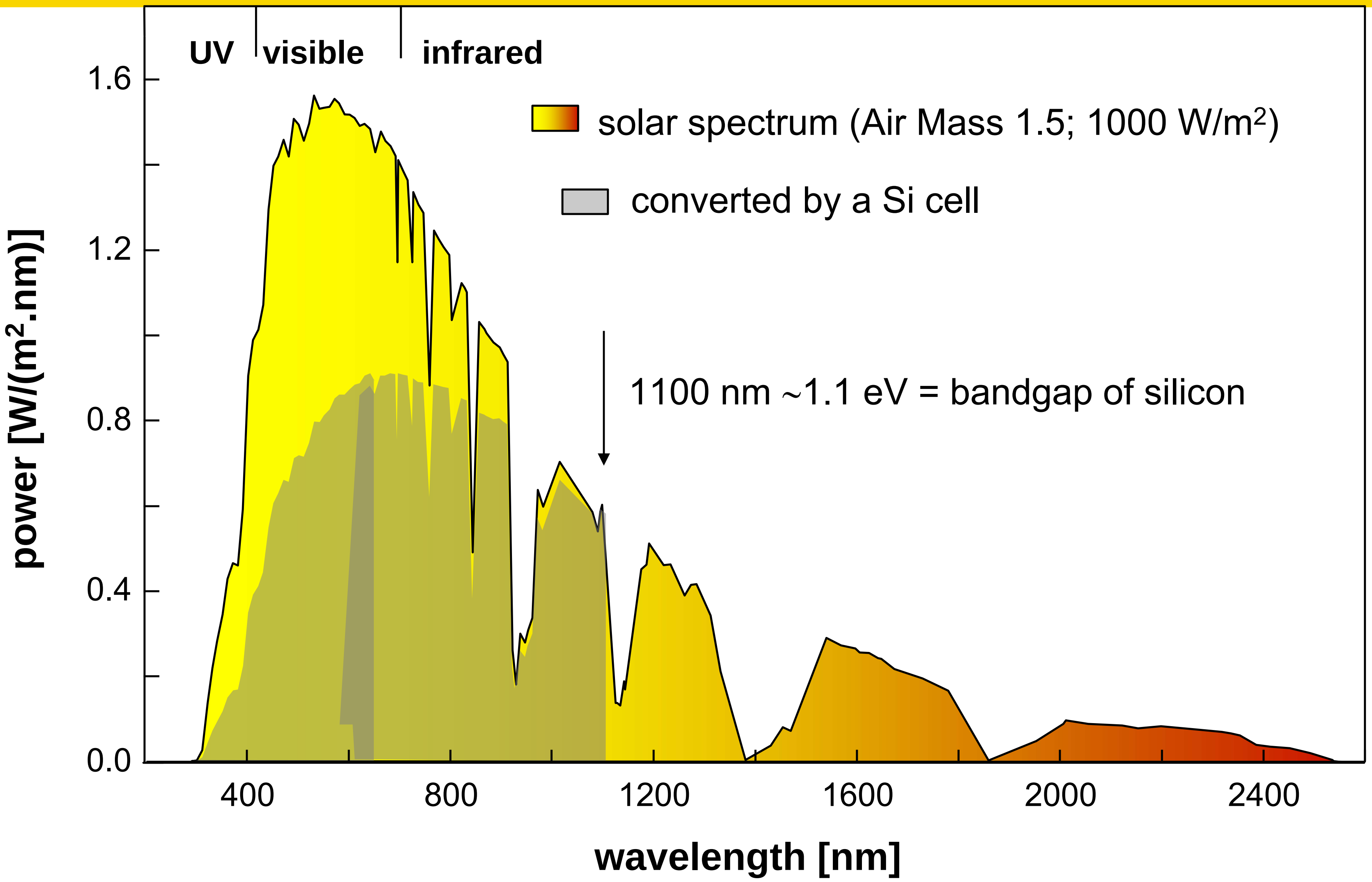
Definition of Standard Reporting Conditions

Radiant intensity:	1000 W/m^2
Spectral irradiance distribution:	AM1.5 global (ASTM G173)
Cell temperature:	25 ^{o}C

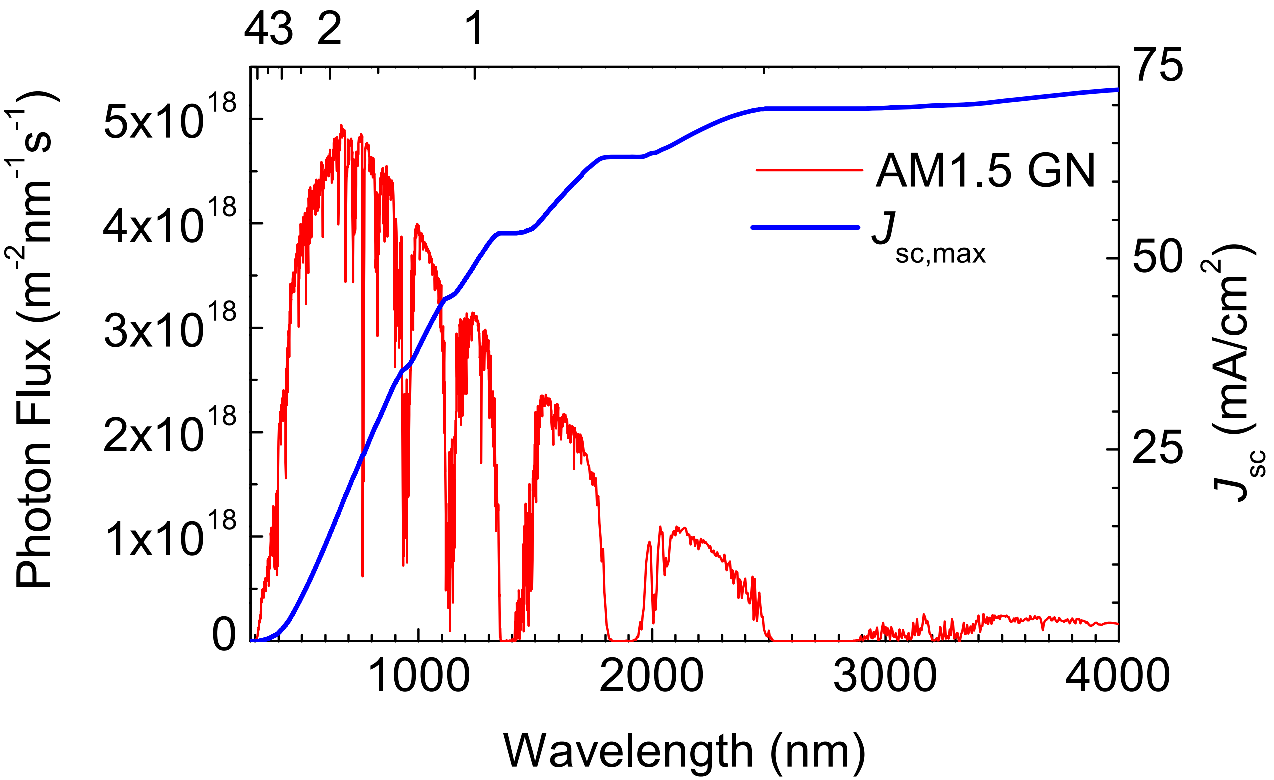


Global = Direct + Diffuse

Air mass = $1/\cos\theta$


UV
visible
infrared
solar spectrum (Air Mass 1.5; 1000 W/m²)
converted by a Si cell
1100 nm ~1.1 eV = bandgap of silicon
power [W/(m².nm)]
1.6
1.2
0.8
0.4
0.0
400
800
1200
1600
2000
2400
wavelength [nm]

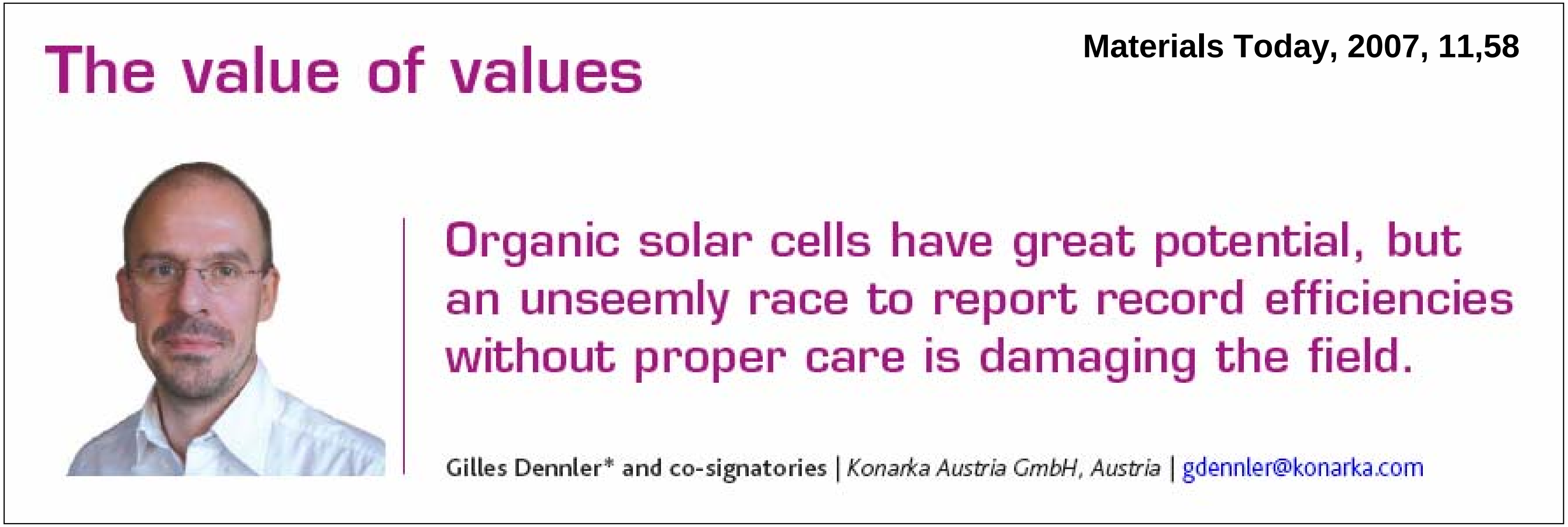
Solar Spectrum and available photocurrent



However, in spite of the existence of SRC…..

For OBPV, norms are seldom followed at the research level:

- reported efficiencies under various testing conditions
- comparison of efficiency values not possible.



Materials Today, 2007, 11,58

The value of values

Organic solar cells have great potential, but an unseemly race to report record efficiencies without proper care is damaging the field.

Gilles Dennler* and co-signatories | *Konarka Austria GmbH, Austria* | gdennler@konarka.com

Reasons:

- lack of awareness of the standard procedures
- inadequate measuring equipment
- specific features of OBPV require adapted protocols
- small active areas
- edge effects and device layout leads to overestimation η
- no temperature control

Better understanding required how to measure and report accurate efficiencies

Procedure efficiency measurement at SRC

Required:

- Solar simulator, preferably Class A (usually Xe-lamp with AM1.5 filter)
- Calibrated reference cell to adjust the intensity of the simulator

Errors are introduced:

- Mismatch simulator spectrum and AM1.5 GN reference spectrum (ASTM G173)
- Deviations of Spectral Response (SR) test cell and reference cell

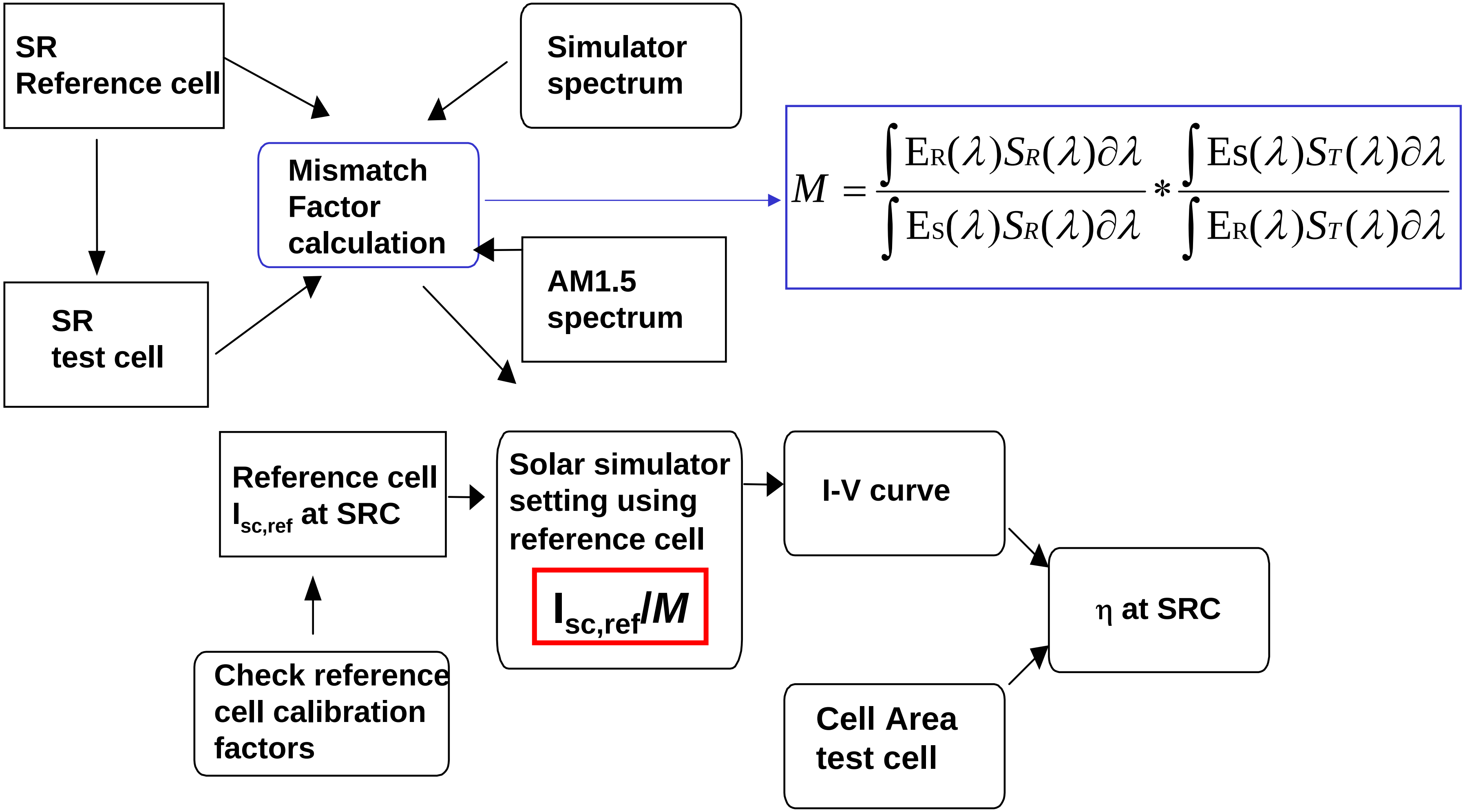
Reference cells are based on Silicon or GaAs

For novel type of solar cells:

- no stable reference cell with same SR and geometrical design

Correction for spectral mismatch is necessary !!

Procedure efficiency measurement at SRC



SR Reference cell

Simulator spectrum

Mismatch Factor calculation

$$M = \frac{\int E_R(\lambda) S_R(\lambda)\partial\lambda}{\int E_S(\lambda) S_R(\lambda)\partial\lambda} * \frac{\int E_S(\lambda) S_T(\lambda)\partial\lambda}{\int E_R(\lambda) S_T(\lambda)\partial\lambda}$$

AM1.5 spectrum

SR test cell

Reference cell $I_{sc,ref}$ at SRC

Check reference cell calibration factors

Solar simulator setting using reference cell

$\boxed{I_{sc,ref}/M}$

I-V curve

Cell Area test cell

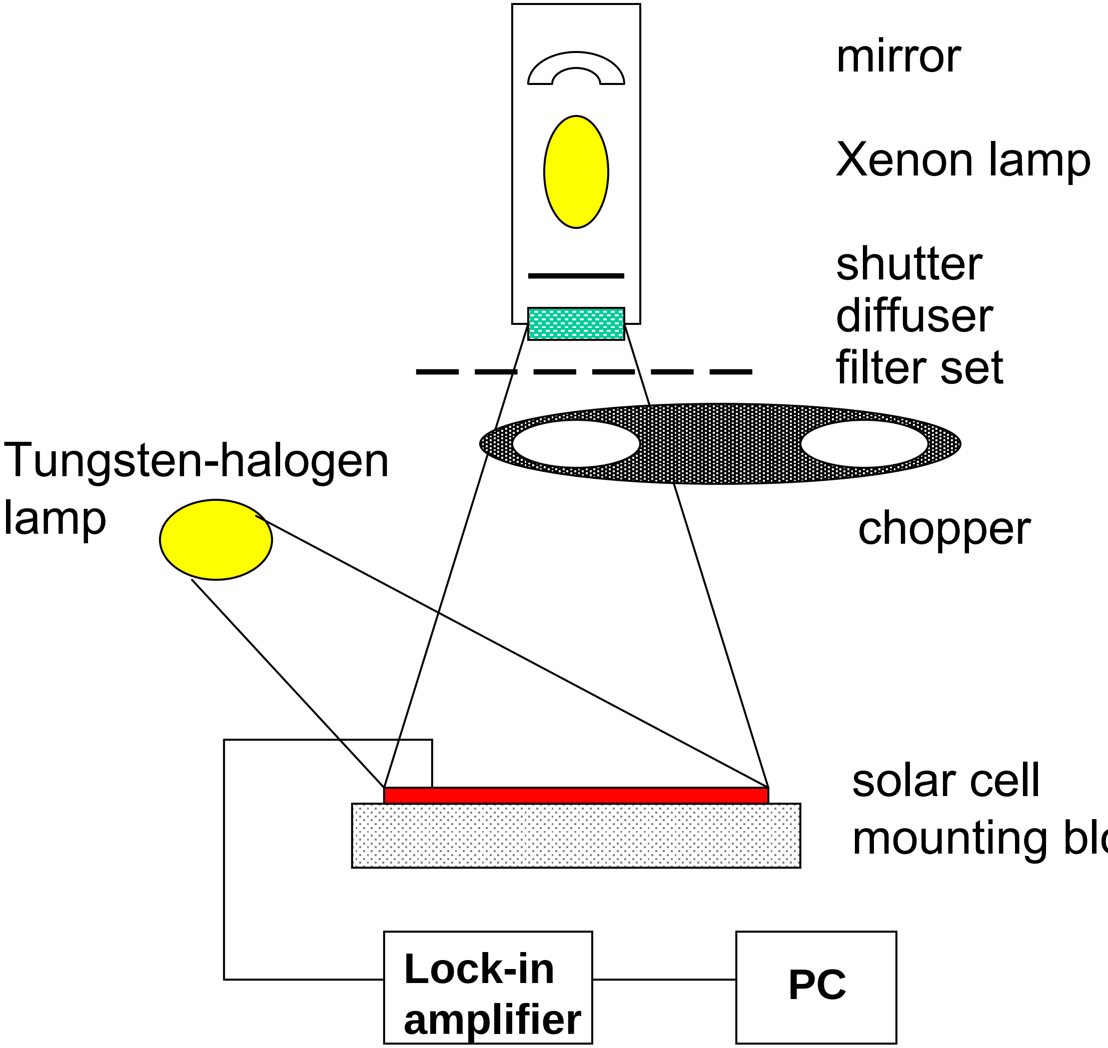
η at SRC

Procedure efficiency measurement at SRC

- For Silicon, M close to unity
- M can significantly deviate from 1 for new types of solar cells
- SR and size of test and reference cells should match as close as possible: Si-diodes with KG filters preferred
- This procedure can be used using relative SR
- Each broad radiant source with known relative spectral irradiance can be used

If mismatch is ignored, error is M-1

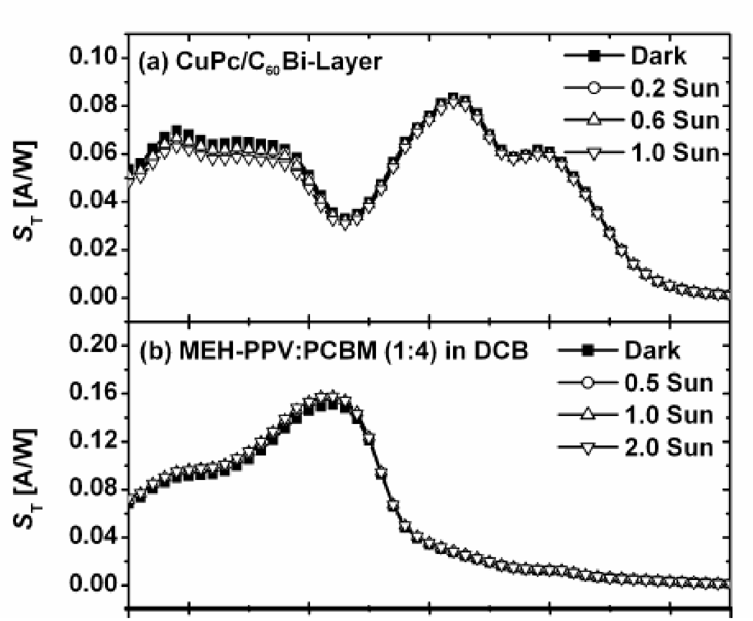
Spectral Response following ASTM E1021-84 norm



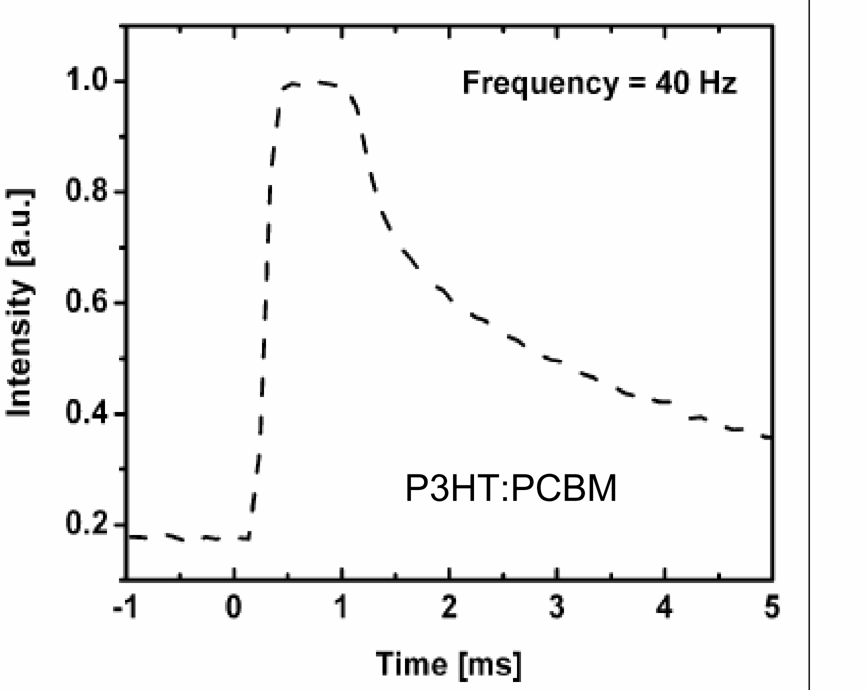
SR(A/W)=[q/hc] x λ x EQE

- Pulsed monochromatic light
- White bias light
- Lock-in amplifier
- Reference cell is used
- $\tau_{response}$ << 1/chopper rate

SR under varying bias light intensities and response time for solid state organic cells



Shape SR and *M* independent of bias-light intensity



At 40 Hz, $\tau_{response} < 1$ ms
fast response up to 150 Hz

V. Shrotriya et al. AFM, 2006, 16, 2016

Special features of photoelectrochemical DSC

slow temporal response

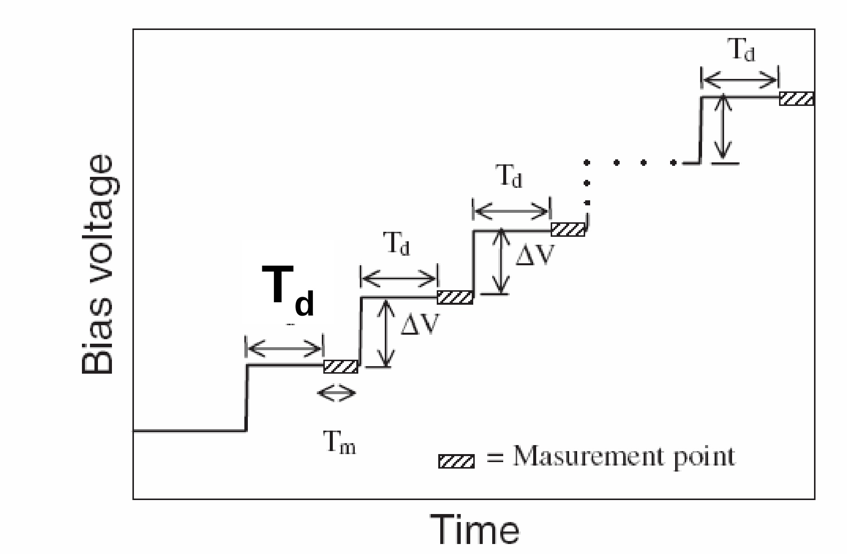
1. Mass transport: diffusion of ions → IV
2. Slow charge transport through TiO_2 (trapping and detrapping of electrons in surface states) → SR

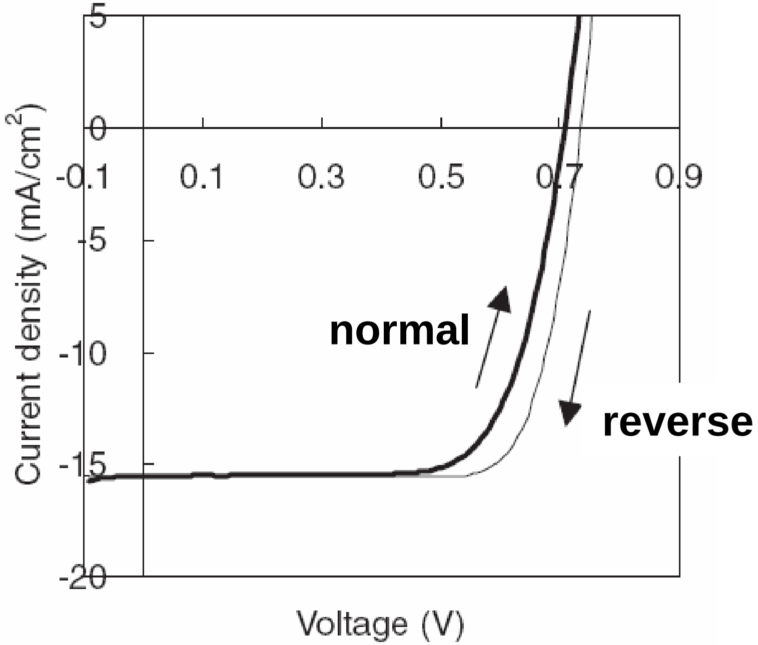
Dependent on device structure DSC

Implications for IV measurement:

- IV curve dependent on voltage sweep direction (I_{sc}→V_{oc} or V_{oc}→I_{sc})
- Scanning time: > 20 s required to minimize the error
- No flashing of modules

Sharp studies





T_d = sampling delay time varied
T_m = measuring integration time = 50 ms
ΔV = 10 mV

Requirement: T_d > 4 x time constant

- T_d = 1 ms (like Si solar cells)
- Sweep time = 5 sec
- Hysteresis observed
- Recommended: T_d = 40 ms
- Averaging data two scans

N.Koide et al., Jpn. J. Appl. Phys., 2005, 44, 4176

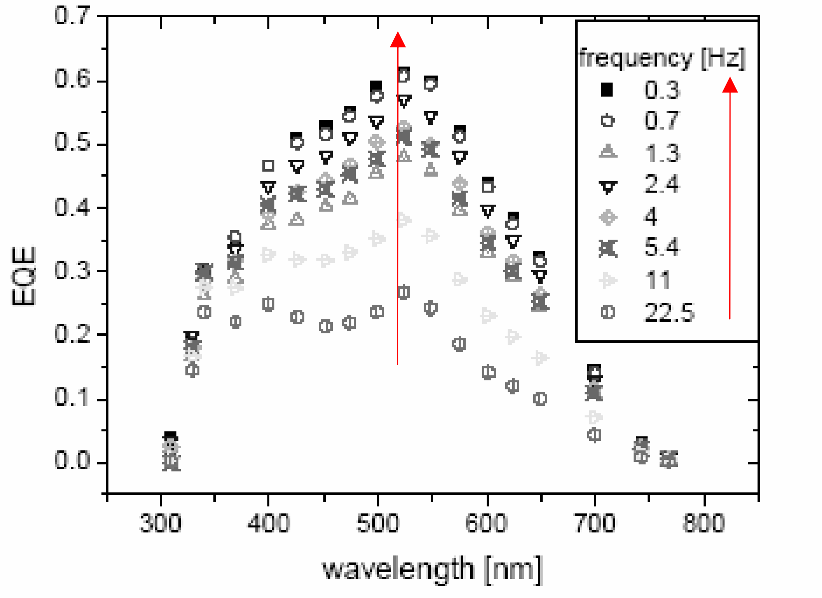
Special features of photoelectrochemical DSC

slow temporal response

Implication for Spectral Response (SR) measurements

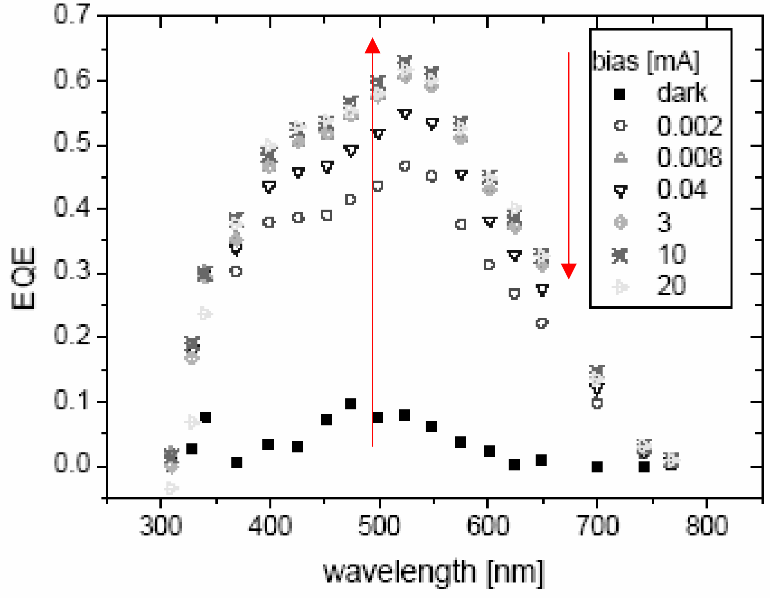
- Measured SR depends on bias light intensity
- Measured SR depends on pulse frequency:
  - low frequencies < 10 Hz tolerated
  - DC high intensity monochromatic light

FhG ISE studies



EQE at constant bias illumination and different chopper frequencies.

only low frequencies are tolerated



EQE at different bias illuminations with a chopper frequency of 0.7 Hz.

Bias light leads to increased trap filling and faster response

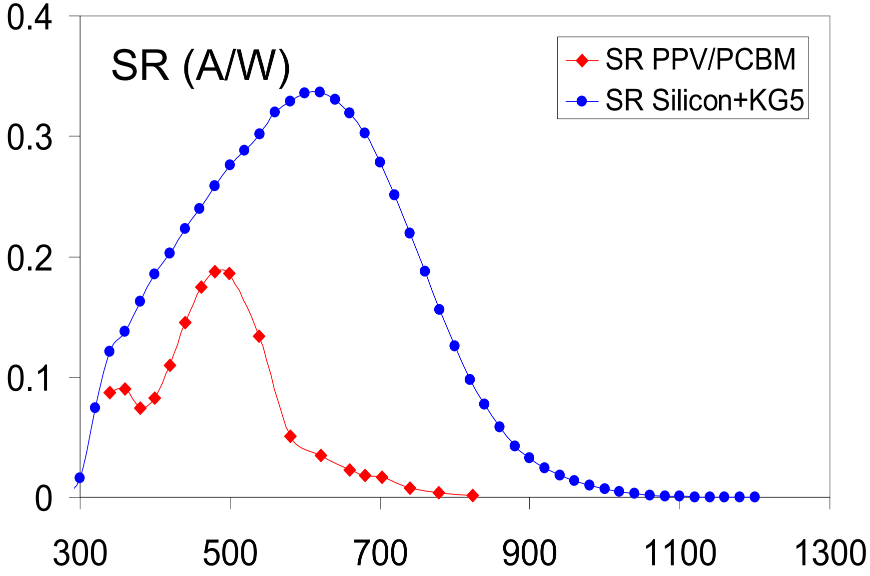
Hohl-Ebinger et al. Proc. EUPVSEC 2004, Paris

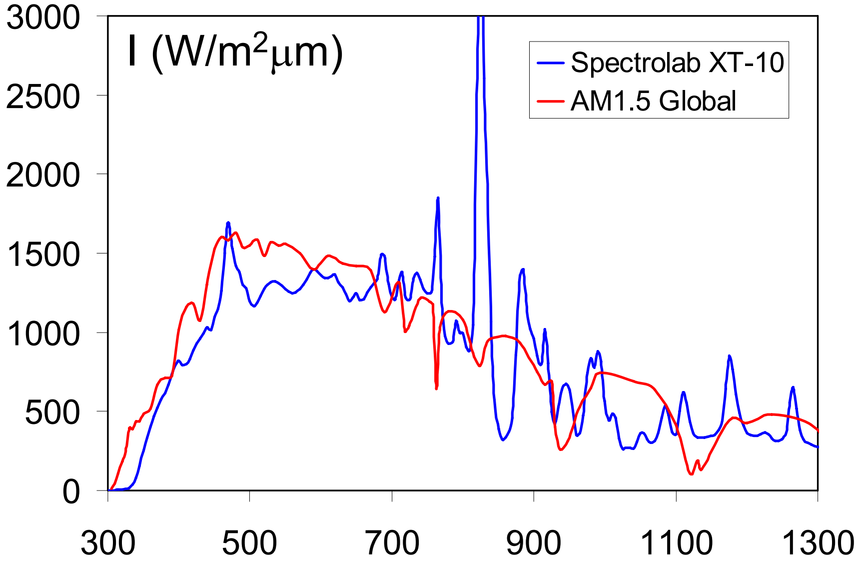
Important check when performing IV and SR measurements!

Compare calculated J_{sc} from overlap integral SR and AM1.5 spectrum with the measured J_{sc} under solar simulator:

$J_{sc,\ calc} \approx J_{sc,\ meas}$

Example 1: Test cell MDMO-PPV / PCBM device
Reference cell: monocrystalline Silicon + KG5 filter
Solar Simulator: Spectrolab XT-10 (Xe-lamp)



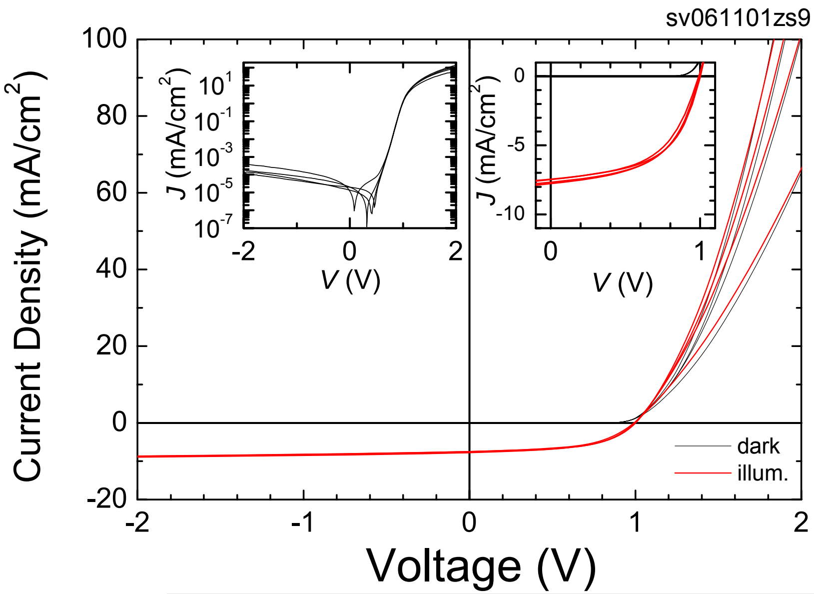


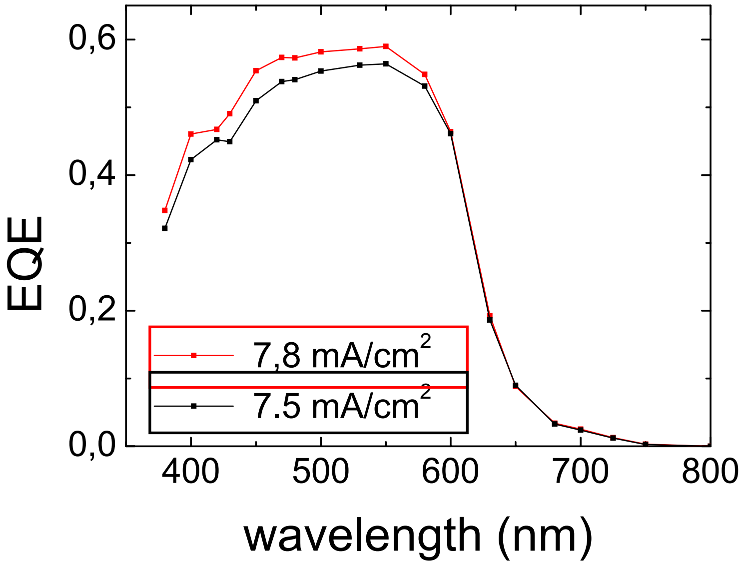
$$M = \frac{\int E_R(\lambda) S_R(\lambda)\partial\lambda}{\int E_S(\lambda) S_R(\lambda)\partial\lambda} * \frac{\int E_S(\lambda) S_T(\lambda)\partial\lambda}{\int E_R(\lambda) S_T(\lambda)\partial\lambda}$$

→ **M = 0.9**

J.M. Kroon et al., TSF, 2002, 403-404, 223-228

Example 2: Test cell PFTBT / PCBM
Reference cell: monocrystalline Silicon + KG5 filter
Solar Simulator: WACOM WXS-300S-50 (Xe-lamp); M = 0.993





active area cm^2:	**0.36**	**1.00**
V_{oc} (V)	**0.999**	**0.995**
FF	**54**	**53**
J_{sc} (mA/cm^2)	**7.7**	**7.5**
AM1.5 efficiency (%)	**4.2**	**3.9**

Slooff et al. APL ***90*** *143506 (2007)*

What is often going wrong in characterization of Organic based solar cells?

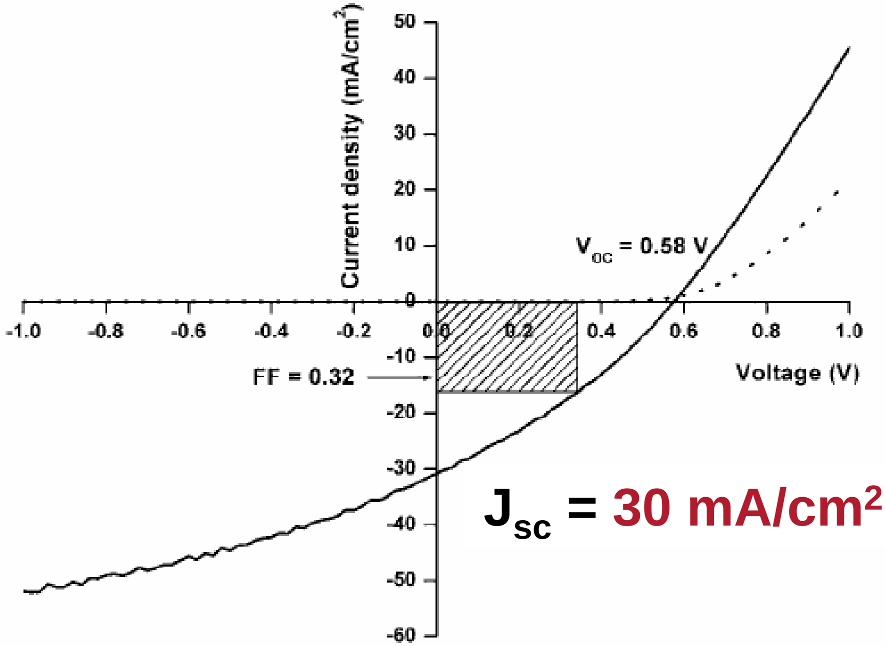
Too high current densities claimed at “AM1.5” conditions

- No mismatch correction
- Measuring small cells:
  - inaccurate determination of surface area
  - edge effects and device layout, “cross talking”
  - effects of device masking

Examples from literature

Molecular Solar Cells

- Claim of **30 mA/cm²**
and η = 5.58 %
- No Spectral Response



J_{sc} = **30 mA/cm²**

FIG. 5. Current density-voltage characteristics of dual doped devices in the dark and under illumination of 100 mW/cm².

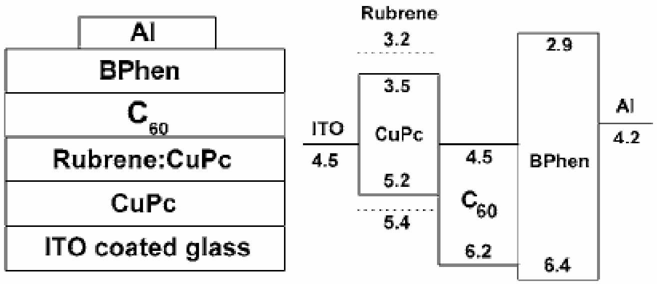


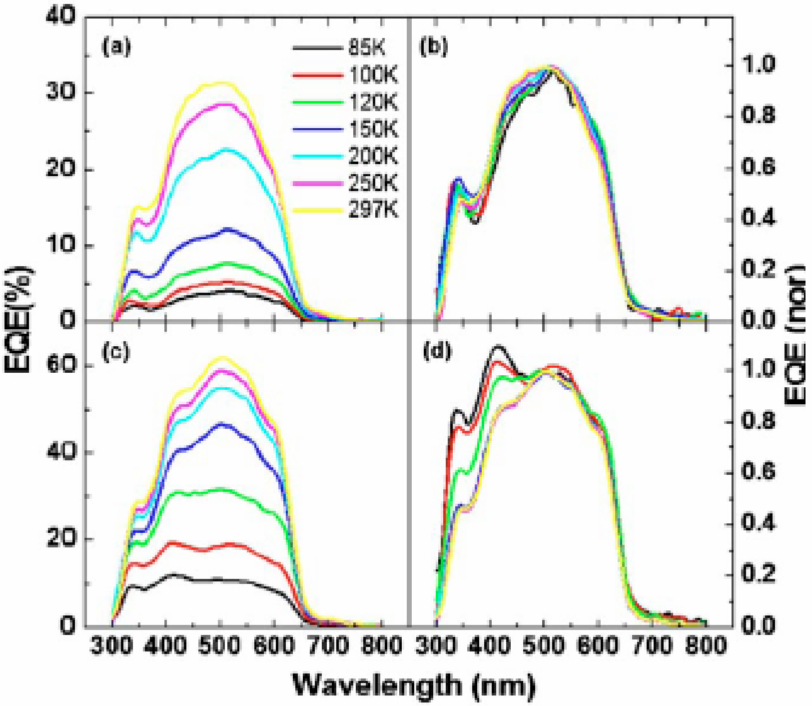
FIG. 1. Schematic structure and energy level diagram of doped CuPc device. Dash lines represent the energy levels of rubrene.

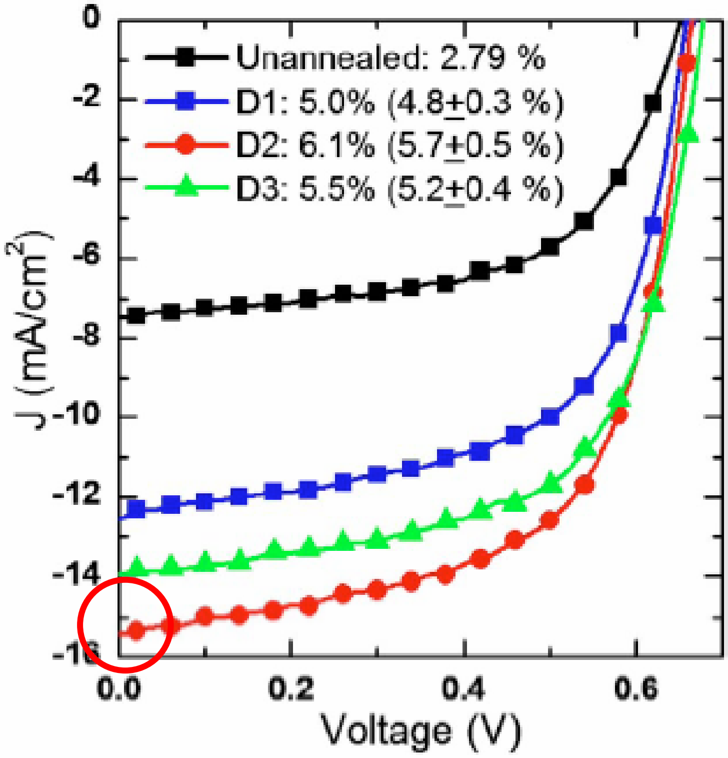
Appl. Phys. Lett. **90**, 023504 (2007)

Polymer solar cells: P3HT:PCBM

$J_{sc,calc}$ = 7-9 mA/cm^2 << $J_{measured}$ = 12-15.5 mA/cm^2

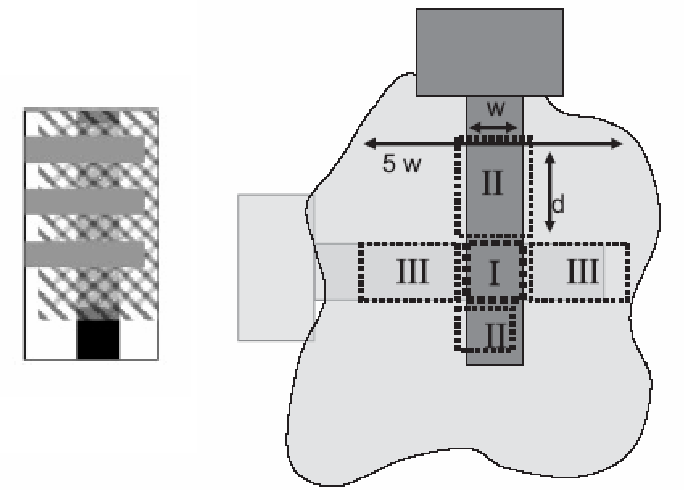
η = 3-3.5 % η ~ 5-6 %

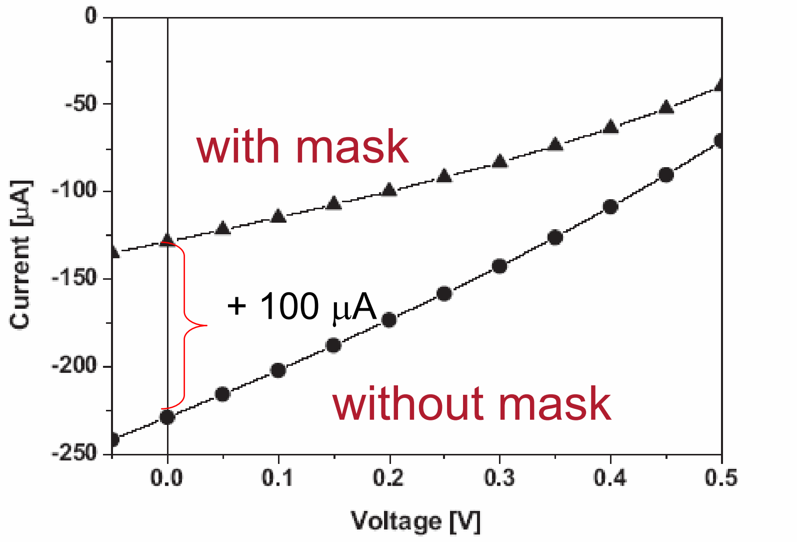




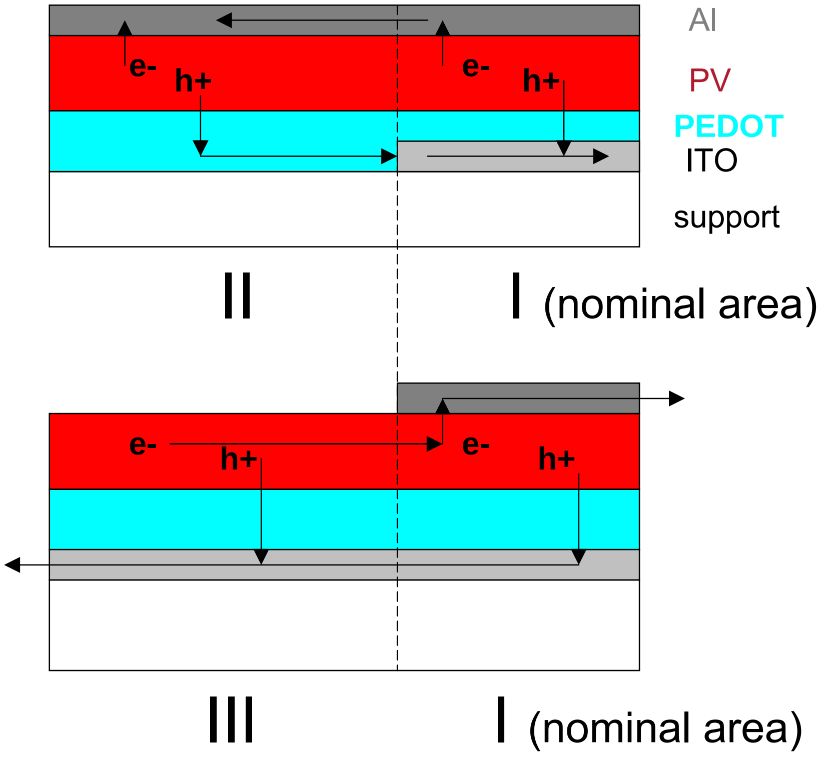
Appl. Phys. Lett. 90, 163511 (2007)

Edge effects and device layout in all organic cells



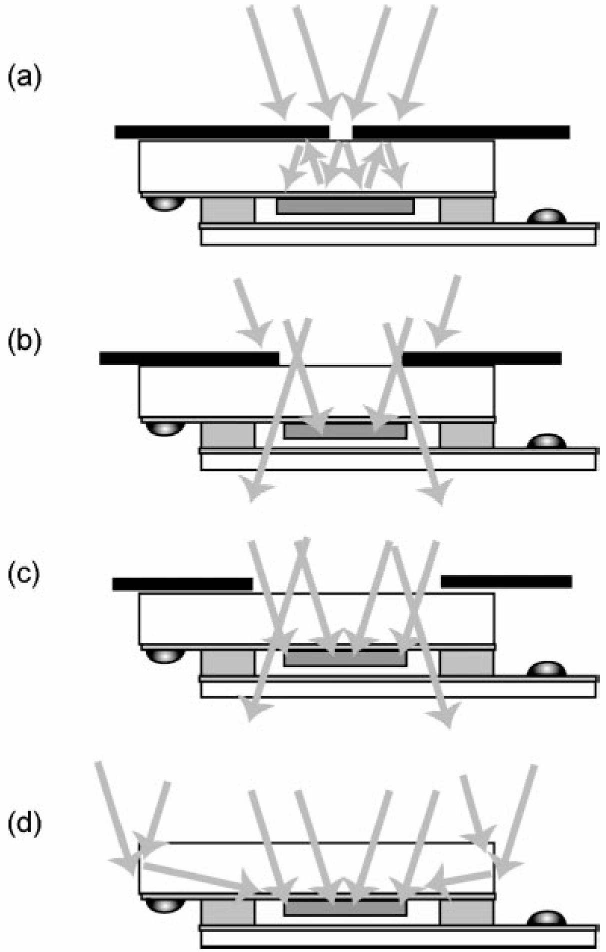


Device configuration:
ITO/PEDOT/BHJ/Al

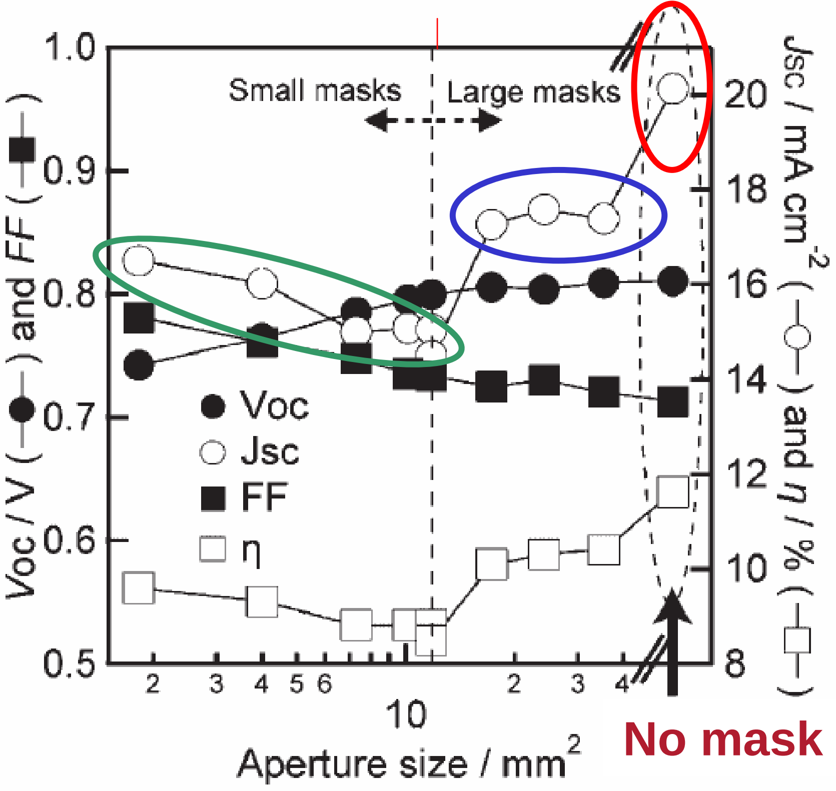


A. Cravino et al., AFM, 2007, 17, 3906

Measuring small devices – effects of masking/DSC



active area



No mask

S.Ito et al., PIP, 2006, 14, 589

Record and confirmed efficiencies for the different OBPV technologies ?

Look in Solar Efficiency tables in Progress in Photovoltaics

- Cell areas should be > 1 cm^2
- Cell areas < 1 cm^2 notable exceptions
- Certification Labs: NREL (US), AIST(Japan), FhG-ISE (Germany),..
- No confirmed efficiencies for MSC yet

From solar efficiency tables (Version 31): PIP, 2008, 16, 61-67

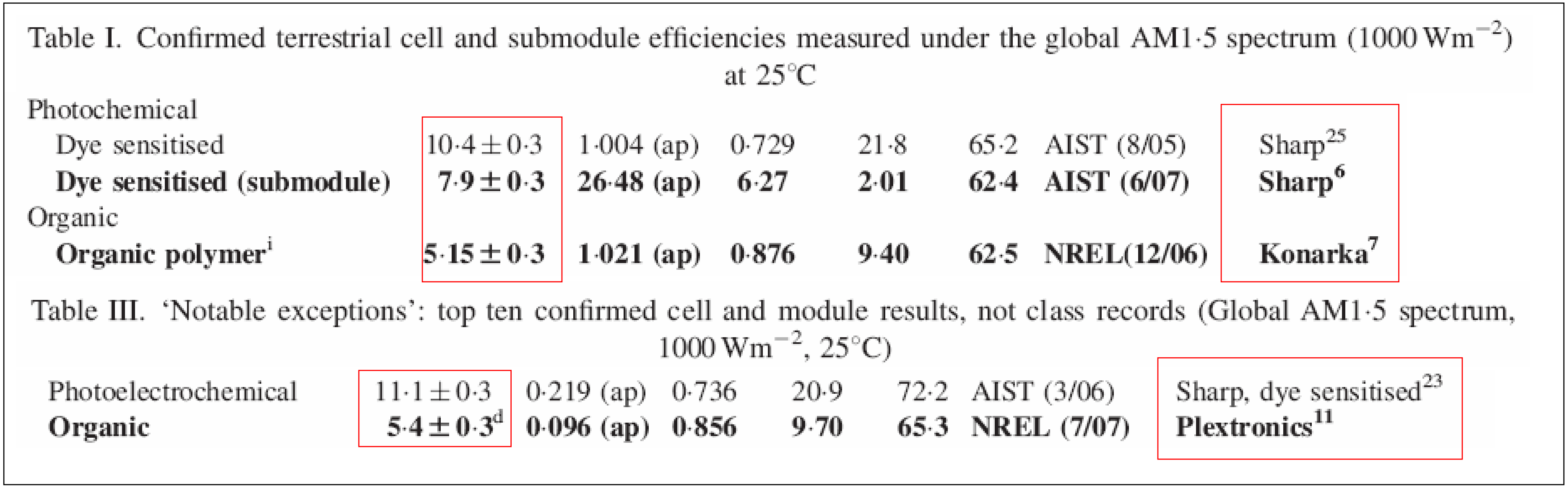


Table I. Confirmed terrestrial cell and submodule efficiencies measured under the global AM1·5 spectrum (1000 Wm^{-2}) at 25°C

Photochemical							
Dye sensitised	10·4 ± 0·3	1·004 (ap)	0·729	21·8	65·2	AIST (8/05)	Sharp[25]
Dye sensitised (submodule)	**7·9 ± 0·3**	**26·48 (ap)**	**6·27**	**2·01**	**62·4**	**AIST (6/07)**	**Sharp[6]**
Organic							
Organic polymer[i]	**5·15 ± 0·3**	**1·021 (ap)**	**0·876**	**9·40**	**62·5**	**NREL(12/06)**	**Konarka[7]**

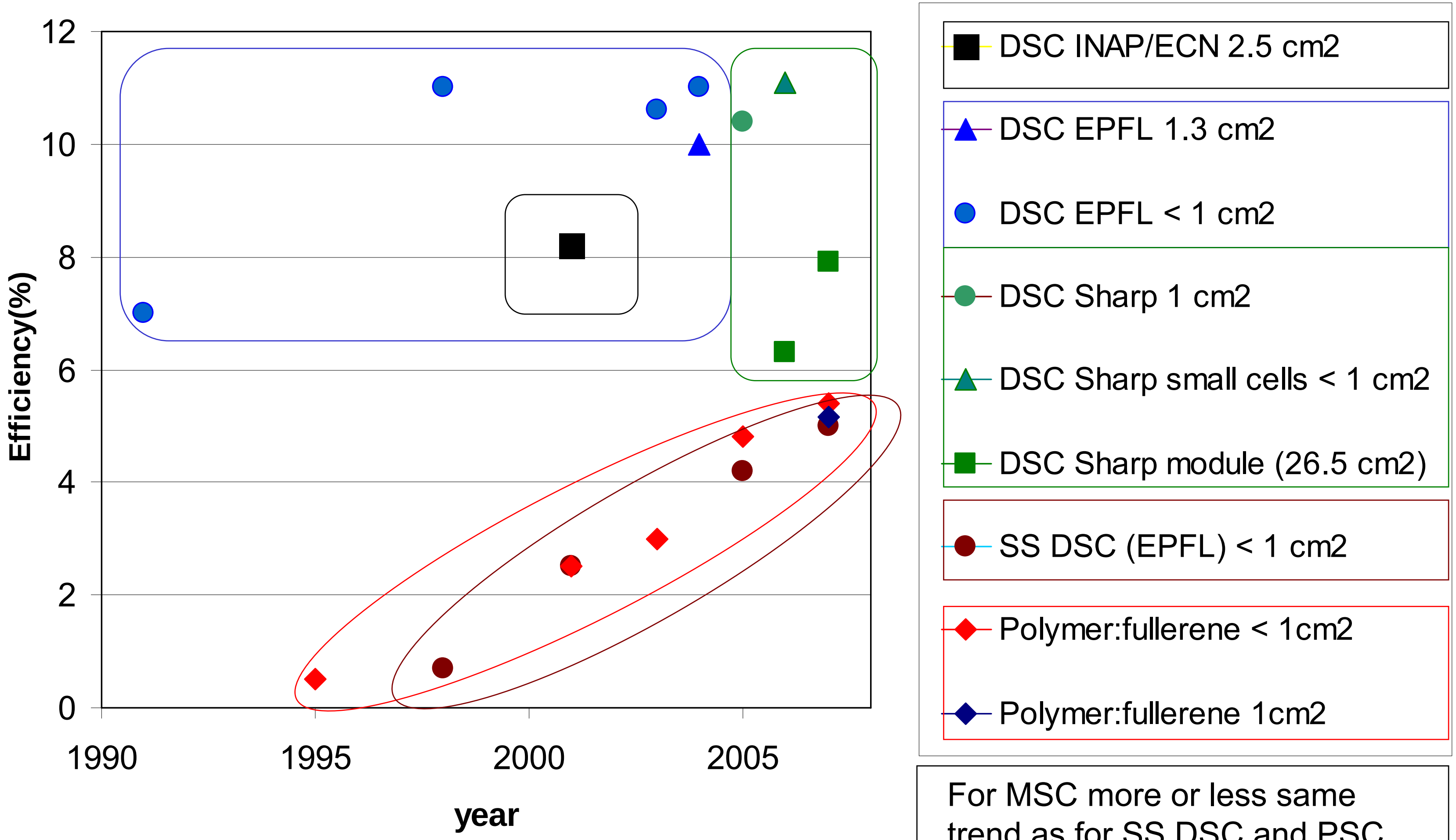
Table III. 'Notable exceptions': top ten confirmed cell and module results, not class records (Global AM1·5 spectrum, 1000 Wm^{-2}, 25°C)

Photoelectrochemical	11·1 ± 0·3	0·219 (ap)	0·736	20·9	72·2	AIST (3/06)	Sharp, dye sensitised[23]
Organic	**5·4 ± 0·3[d]**	**0·096 (ap)**	**0·856**	**9·70**	**65·3**	**NREL (7/07)**	**Plextronics[11]**

Overview maximum efficiencies for OBPV

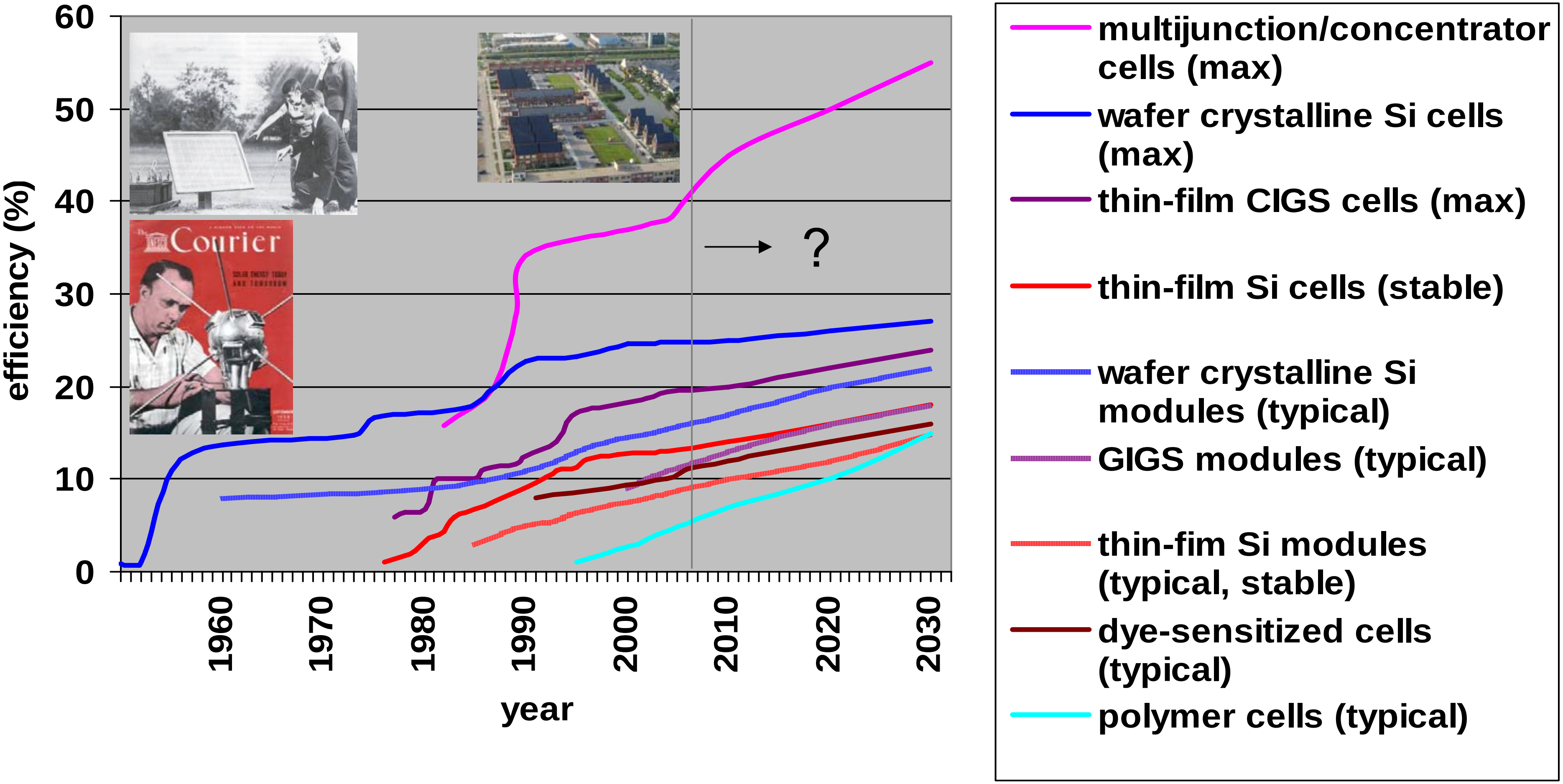
Type	η (%) AM1.5 (maximum)	Who?
Dye Sensitized Oxide (liquid)	**10.4 (1 cm^2)** **11.1 (0.2 cm^2)** **7.9 (26.5 cm^2): module** ***Confirmed by AIST***	Sharp
Dye Sensitized Oxide (solid)	**5 (< 1 cm^2)** ***not confirmed***	EPFL
Molecular solar cells **(single junctions + tandems)**	**5-6 (< 0.1 cm^2)** ***not confirmed***	Princeton
Polymer: fullerene	**5.15 (1 cm^2)** **5.4 (0.1 cm^2)** ***Confirmed by NREL***	Konarka Plextronics
	~ 6 (< 1 cm^2): tandem ***not confirmed***	UCSB
Polymer: Polymer	**1.5-2.0 (0.1-1 cm^2)** ***not confirmed***	Potsdam, ECN Cambridge
Hybrids (Polymer + inorganic SC)	**2-3 (< 1 cm^2)** ***not confirmed***	Cambridge Berkeley

Efficiency development DSC and polymer: fullerene cells



For MSC more or less same trend as for SS DSC and PSC

PV development: selected cell (max) & module (typical) efficiencies

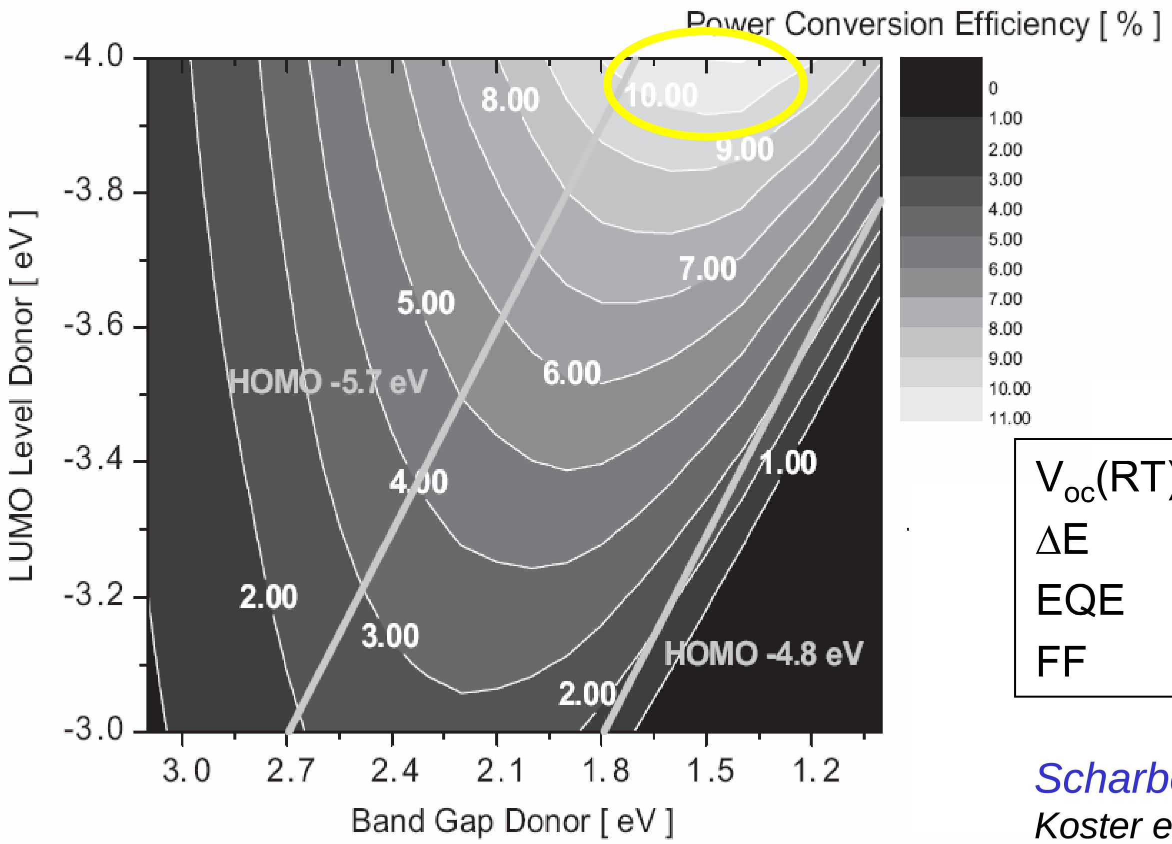


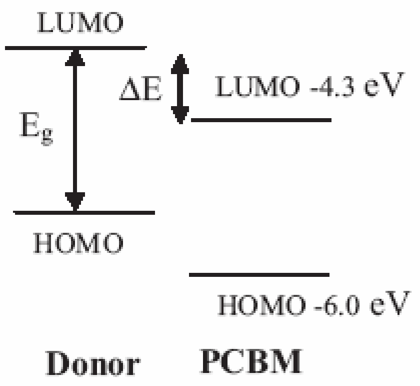
General strategies to increase effciency

- Materials development
    - better spectrum utilization
    - Improve charge carrier mobilities
    - control of energy levels
    - morphology control
- Interfacial engineering to reduce recombination
- Novel cell concepts
    - Light management strategies (scattering, plasmons)
    - Multi-junction approaches
- Characterization and modeling

Polymer:fullerene Solar Cells

Practical efficiency limits and design rules for single junctions





$V_{oc}(RT) = 1/e(E_D^{HOMO} - E_A^{LUMO}) - 0.3$ V

$\Delta E = 0.3$ V

EQE = 0.65

FF = 0.65

Scharber et al., Adv. Mat. 2006, 18, 789

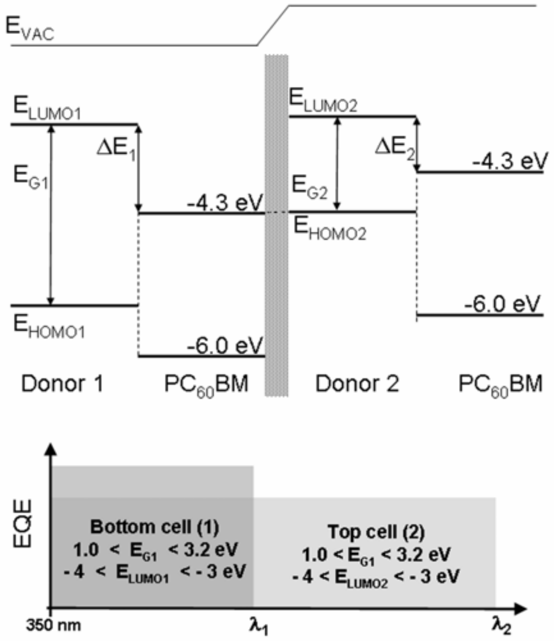
Koster et al., APL, 2006, 88, 093511

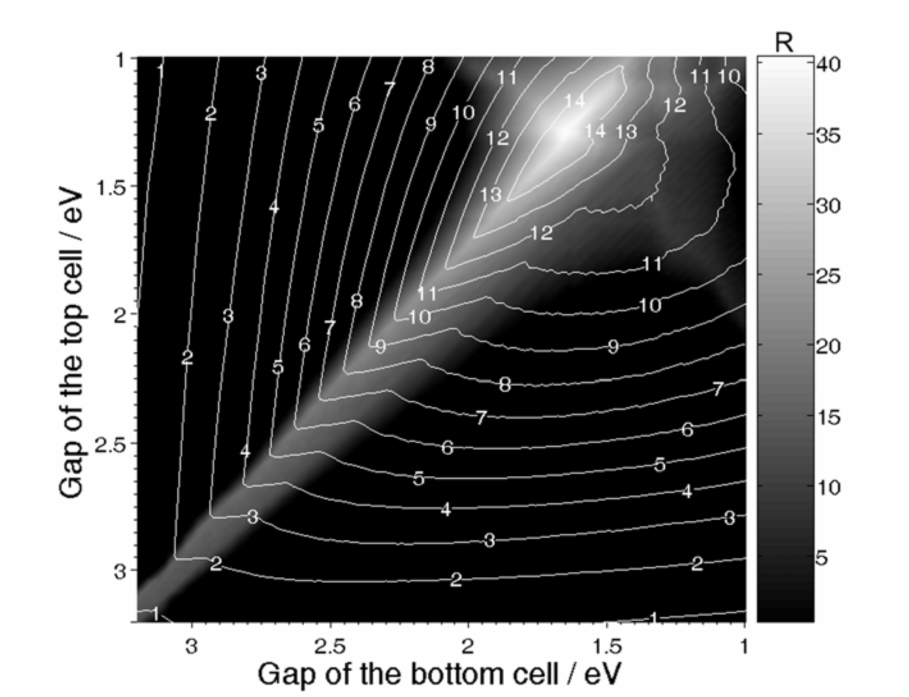
Minneart et al., PIP, 2007, 15, 741

Gregg; Forrest, MRS bulletin, 2005 (MSC)

Polymer:fullerene Solar Cells

Practical efficiency limits and design rules for multi-junctions

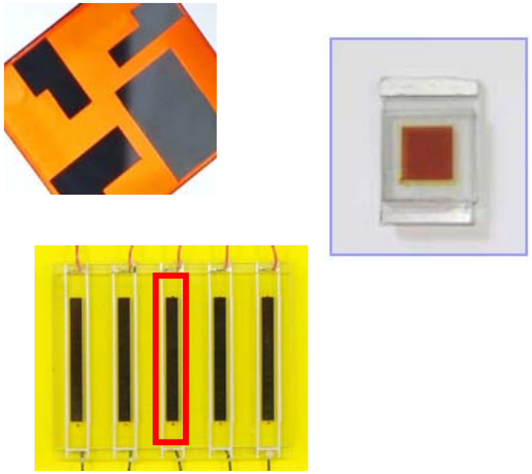


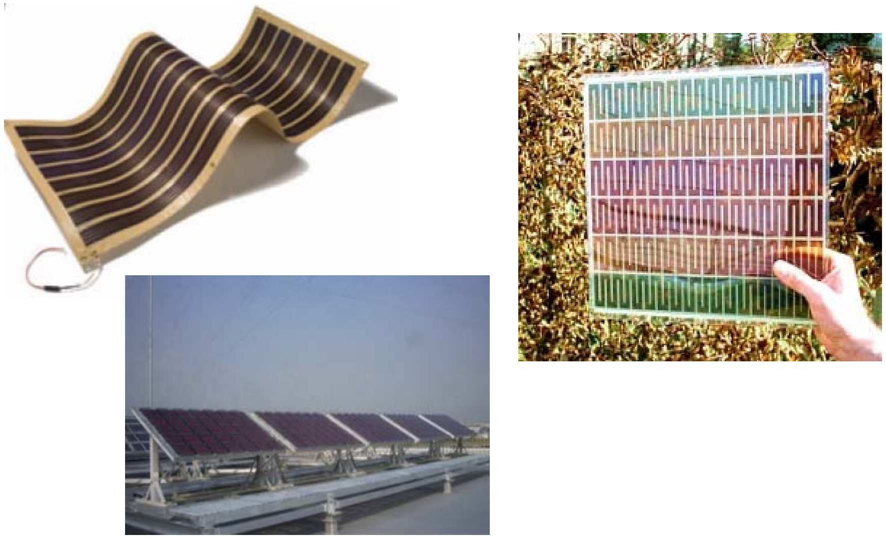


Tandem cells with efficiencies up to 15 % are technically feasible given the availability of an optimized donor couple.

Dennler et al., AM, 2008, in press

From hero lab cell to large area module efficiencies





Several modules designs possible, depending on application field

Loss in total area efficiency is expected due to:

- Ratio [active area/total area] < 1→ J_{sc} <
- Upscaling leads to increase R_{series} → FF <
- Search for cost effective, robust and environmentally friendly solutions

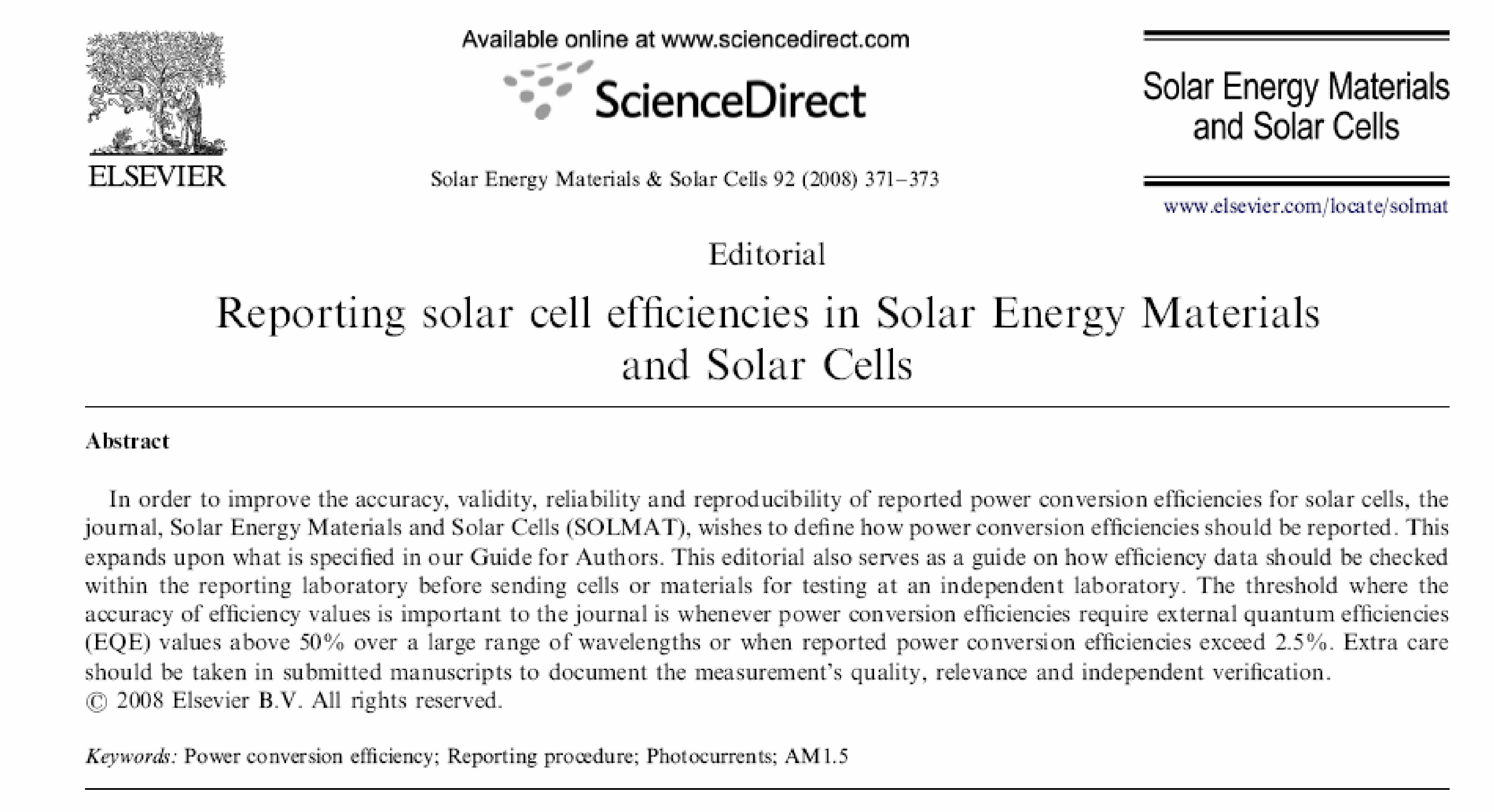
Future outlook

Success of OBPV in penetrating existing and new PV markets will not only depend on lowest €/Wp

- low light performance for indoor consumer PV
- costs in €/Wp as well as €/m^2 of product (aesthetics)
- power availability (kWh/W$_p$/annum): importance of diffuse light
- technical and environmental profile
- added value for the consumer and architects
- ease of production and scale at which production plant becomes economically feasible

Conclusion and recommendations

- Since efficiencies for OPV are increasing, accurate measurement of efficiency are getting more important:
  not only for single cells but also for multijunctions
- Accurate measurement is not straightforward and requires:
  - Calibrated reference cell with known AM1.5 current and SR(A/W)
  - Regularly measured spectral distribution of a solar simulator
  - SR, IV following standard (or adapted) procedures
- Final aim:
  the organic solar cell community should adopt (modified) standards
  - ➢Organization of round trials to get uniformity in efficiency results
  - ➢Send high efficiency cells to independent/certification labs
  - ➢Instructions to editors of journals to appoint qualified referees to check if right procedures are applied when record efficiencies are claimed



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Solar Energy Materials
and Solar Cells

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Editorial

Reporting solar cell efficiencies in Solar Energy Materials and Solar Cells

Abstract

In order to improve the accuracy, validity, reliability and reproducibility of reported power conversion efficiencies for solar cells, the journal, Solar Energy Materials and Solar Cells (SOLMAT), wishes to define how power conversion efficiencies should be reported. This expands upon what is specified in our Guide for Authors. This editorial also serves as a guide on how efficiency data should be checked within the reporting laboratory before sending cells or materials for testing at an independent laboratory. The threshold where the accuracy of efficiency values is important to the journal is whenever power conversion efficiencies require external quantum efficiencies (EQE) values above 50% over a large range of wavelengths or when reported power conversion efficiencies exceed 2.5%. Extra care should be taken in submitted manuscripts to document the measurement's quality, relevance and independent verification.

Keywords: Power conversion efficiency; Reporting procedure; Photocurrents; AM1.5

GP Smestad, FC Krebs et al.

Thank you for attention !

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