Concentrated photovoltaics: ultra-high efficiency and some ideas for unique applications

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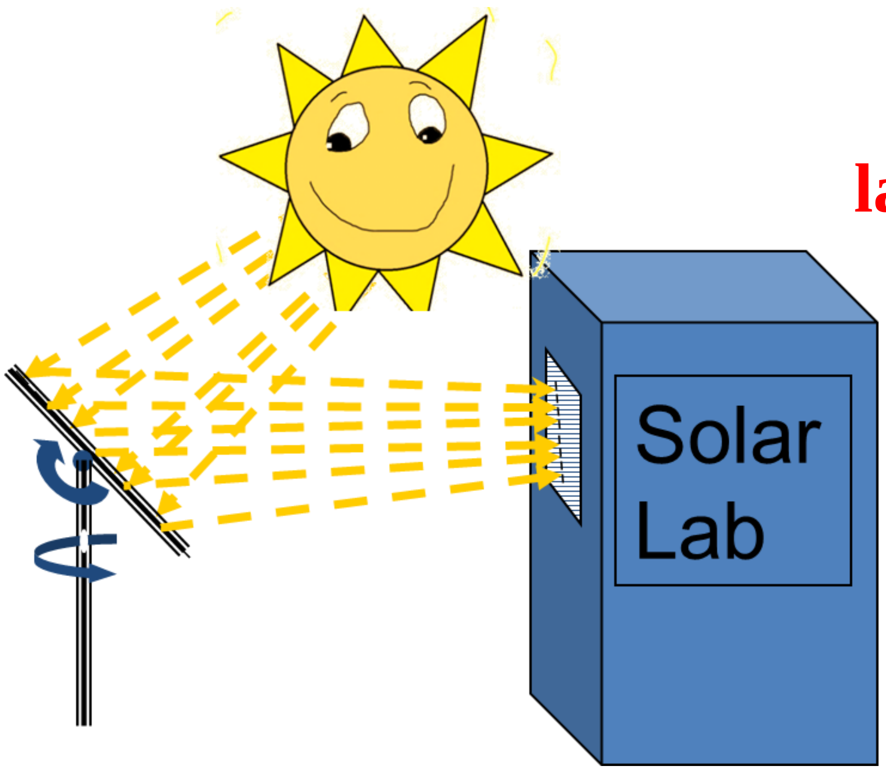
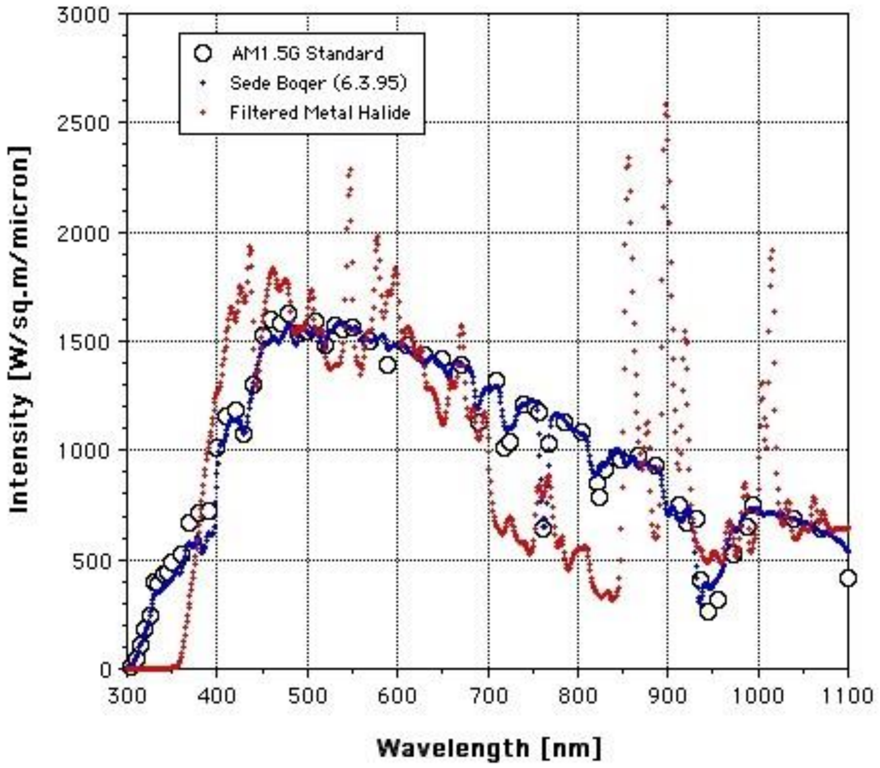
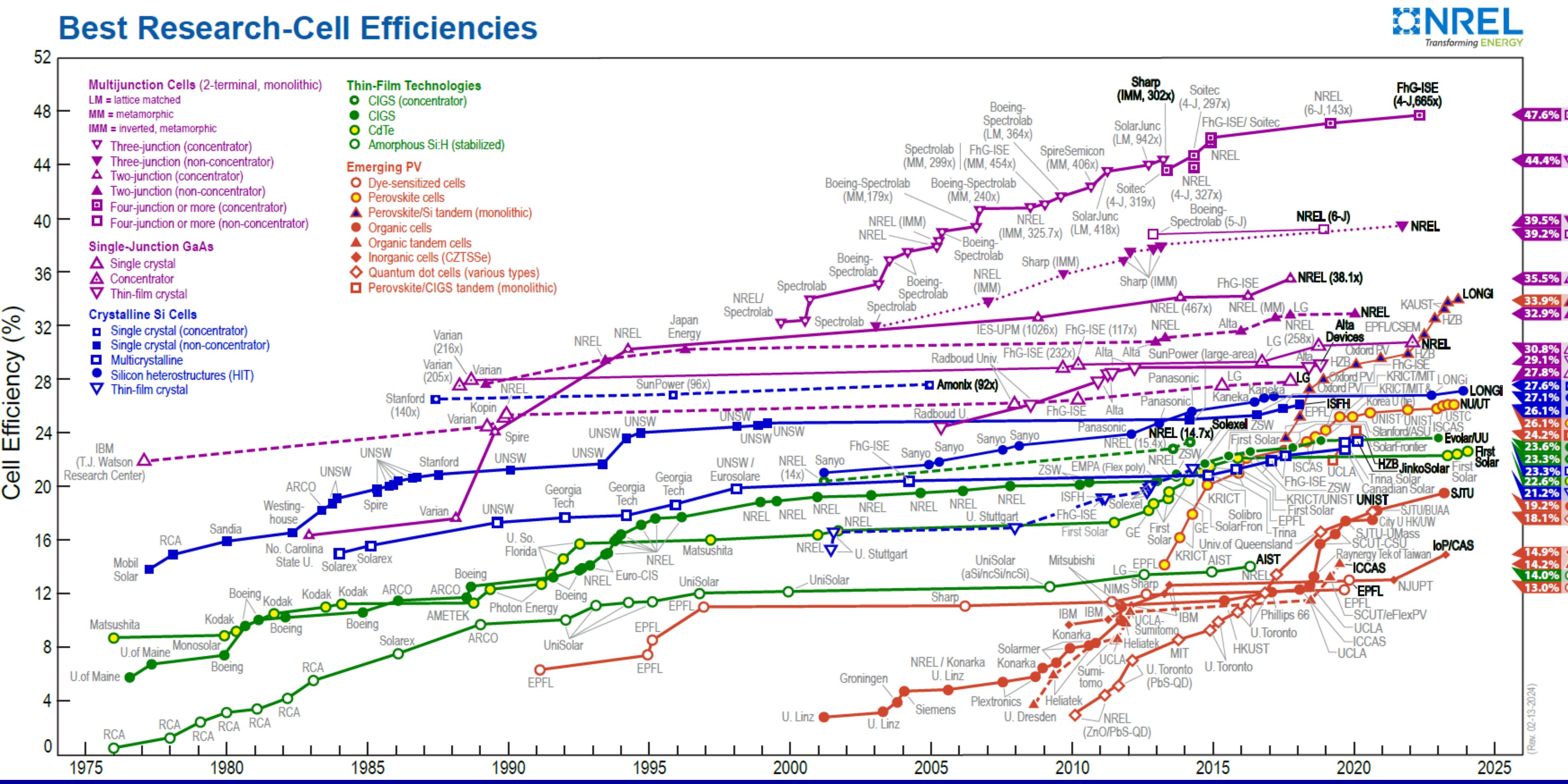
Solar spectrum in Sede Boker (in the Negev Desert, Israel, lat. 30.8N, lon. 34.8E, alt. 475 m)

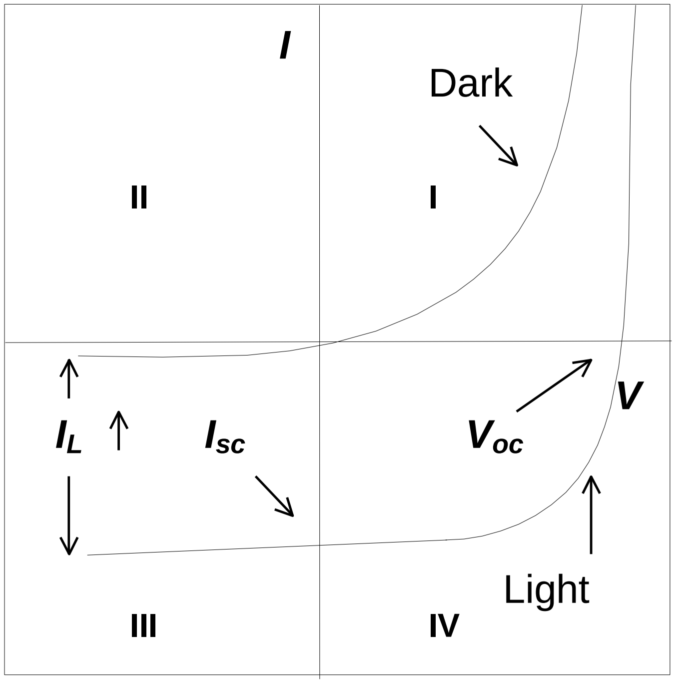




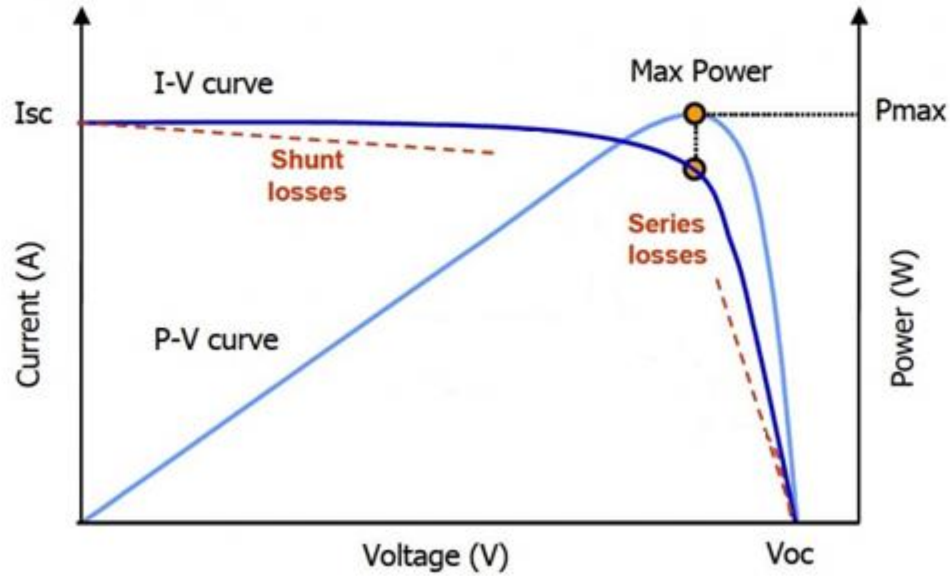
Noontime spectrum on cloudless days is always extremely close to the standard AM 1.5G spectrum when compared to any solar simulator

Best Research-Cell Efficiencies





a



$$I_d = I_0\left[\exp\left(\frac{q(V+IR_s)}{nkT}\right)-1\right]+\frac{V+IR_s}{R_{sh}}$$

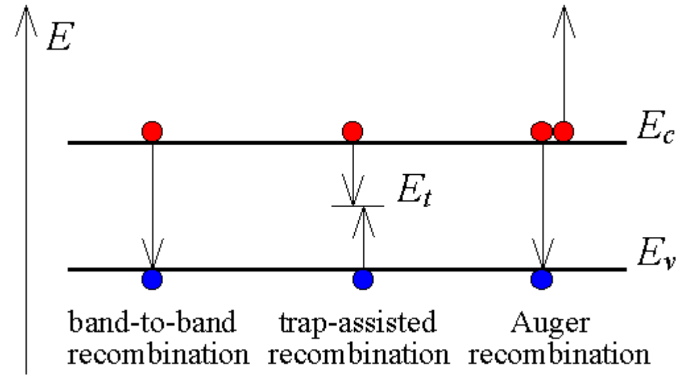
$$I_L = I_0\left[\exp\left(\frac{q(V+IR_s)}{nkT}\right)-1\right]+\frac{V+IR_s}{R_{sh}}-I_p$$

$$FF = \frac{I_{\max}\times V_{\max}}{V_{oc}\times I_{sc}}$$

$$\eta = \frac{I_{\max}\times V_{\max}}{P_{in}} = FF\,\frac{V_{oc}\times I_{sc}}{P_{in}}$$

$$V_{oc} = \frac{n\kappa T}{q} \ln\left(\frac{I_{sc}}{I_o} + 1\right)$$

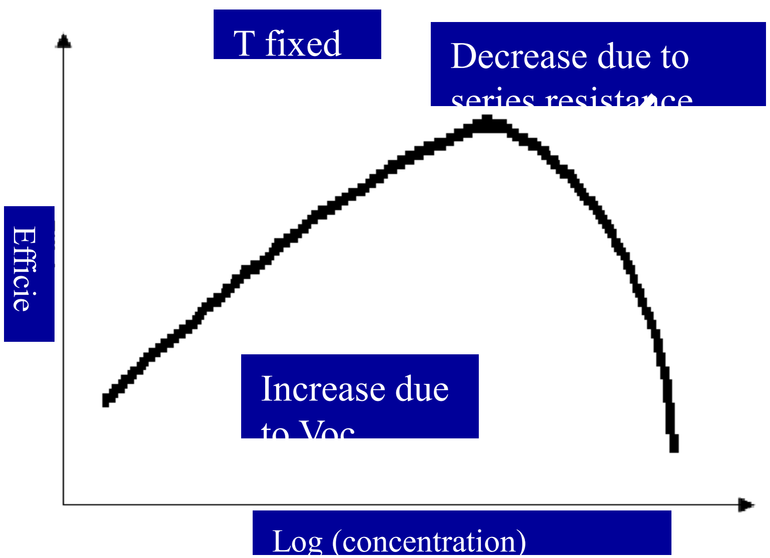
$$\frac{dn}{dt} = G - k_1 n - k_2 n^2 - k_3 n^3$$



n = 2 for monomolecular recombination

n = 1 for bimolecular recombination

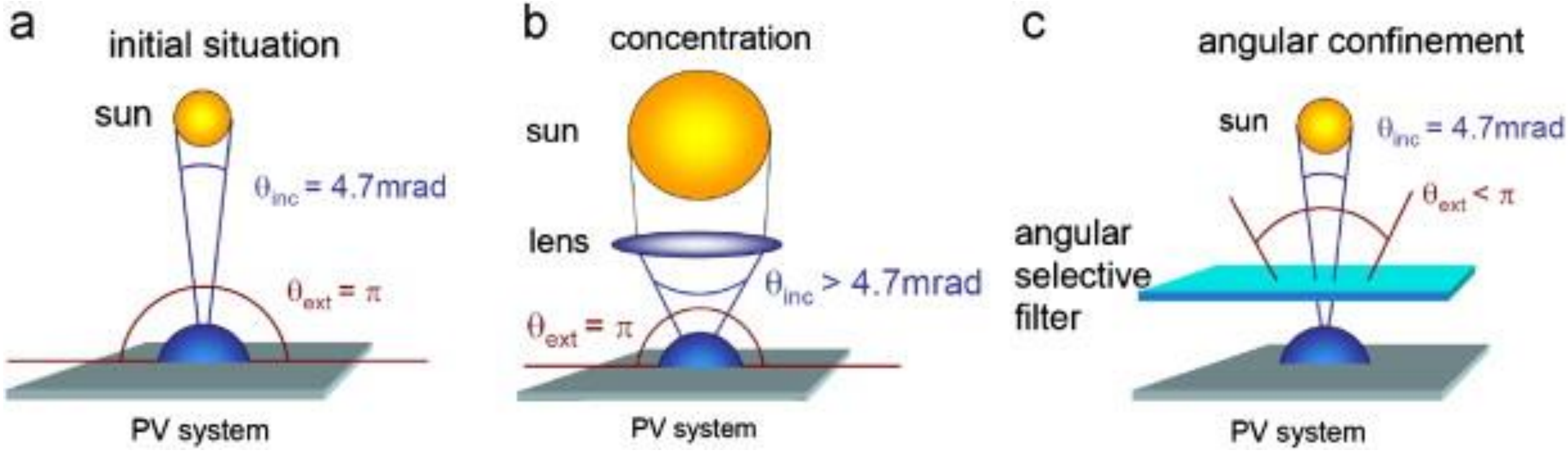
$$I_o = qN_v N_c \left[\exp\left(-E_g / \kappa T\right)\right] \cdot \left(\frac{L_n}{n_n \tau_n} + \frac{L_p}{p_p \tau_p}\right)$$



$$I_L = I_0 \left[\exp\left(\frac{q(V + IR_s)}{nkT}\right) - 1\right] + \frac{V + IR_s}{R_{sh}} - I_p$$

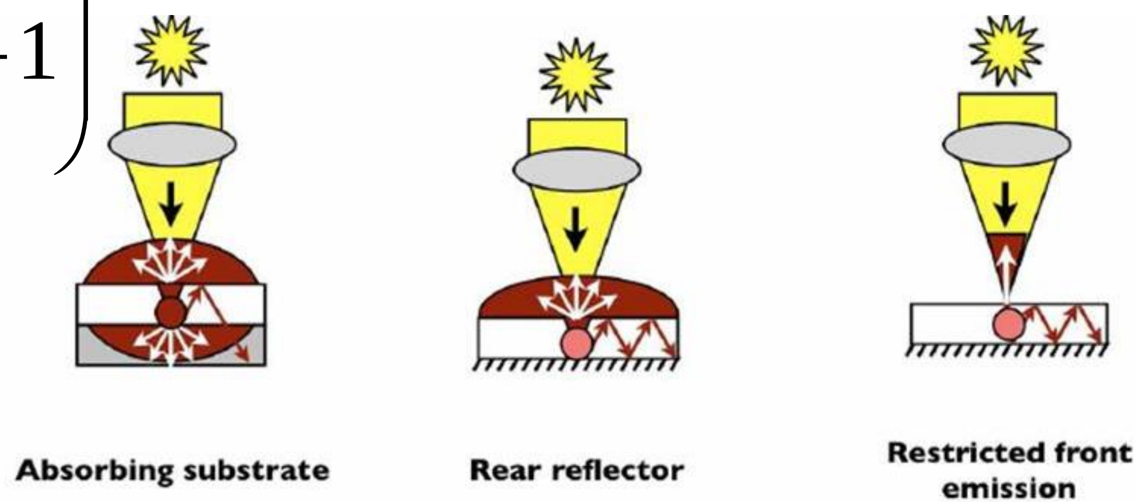
$$\eta = \frac{I_{max} \times V_{max}}{P_{in}} = FF \frac{V_{oc} \times I_{sc}}{P_{in}}$$

New concept of ultra-efficient PV: concentration *vs* angular restriction of emission



$$V_{oc} = \frac{n\kappa T}{q} \ln\left(\frac{I_{sc}}{I_o} + 1\right)$$

$$qV_{oc} = E_g\left(1 - \frac{T}{T_{sun}}\right) - kT\left[\ln\left(\frac{\Omega_{emit}}{\Omega_{sun}}\right) + \ln\left(\frac{4n^2}{I}\right) - \ln(QE)\right]$$



33% 36% 41%

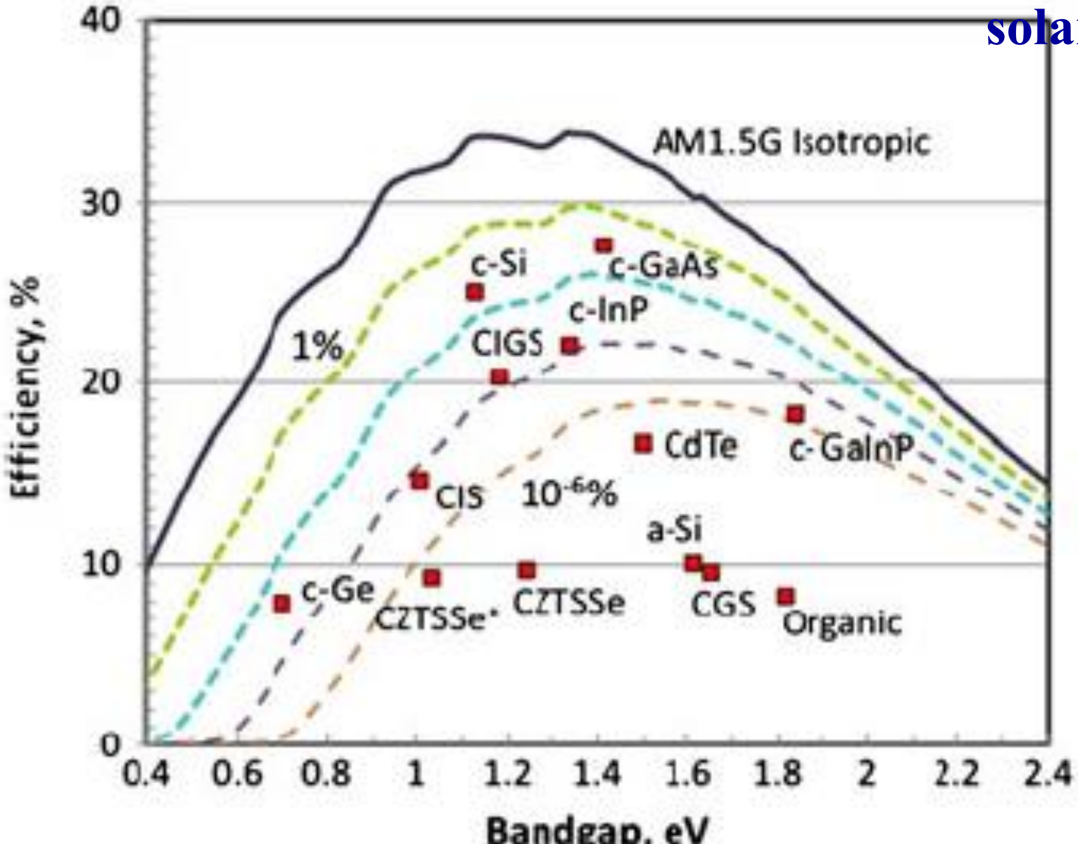
Shockley–Queisser limits:

(1) external radiative recombination efficiency $Q_e = I_{o,rad}/I_o=1$;

(2) $\eta_{e\text{-}h} = 0$ for $h\nu < E_g$

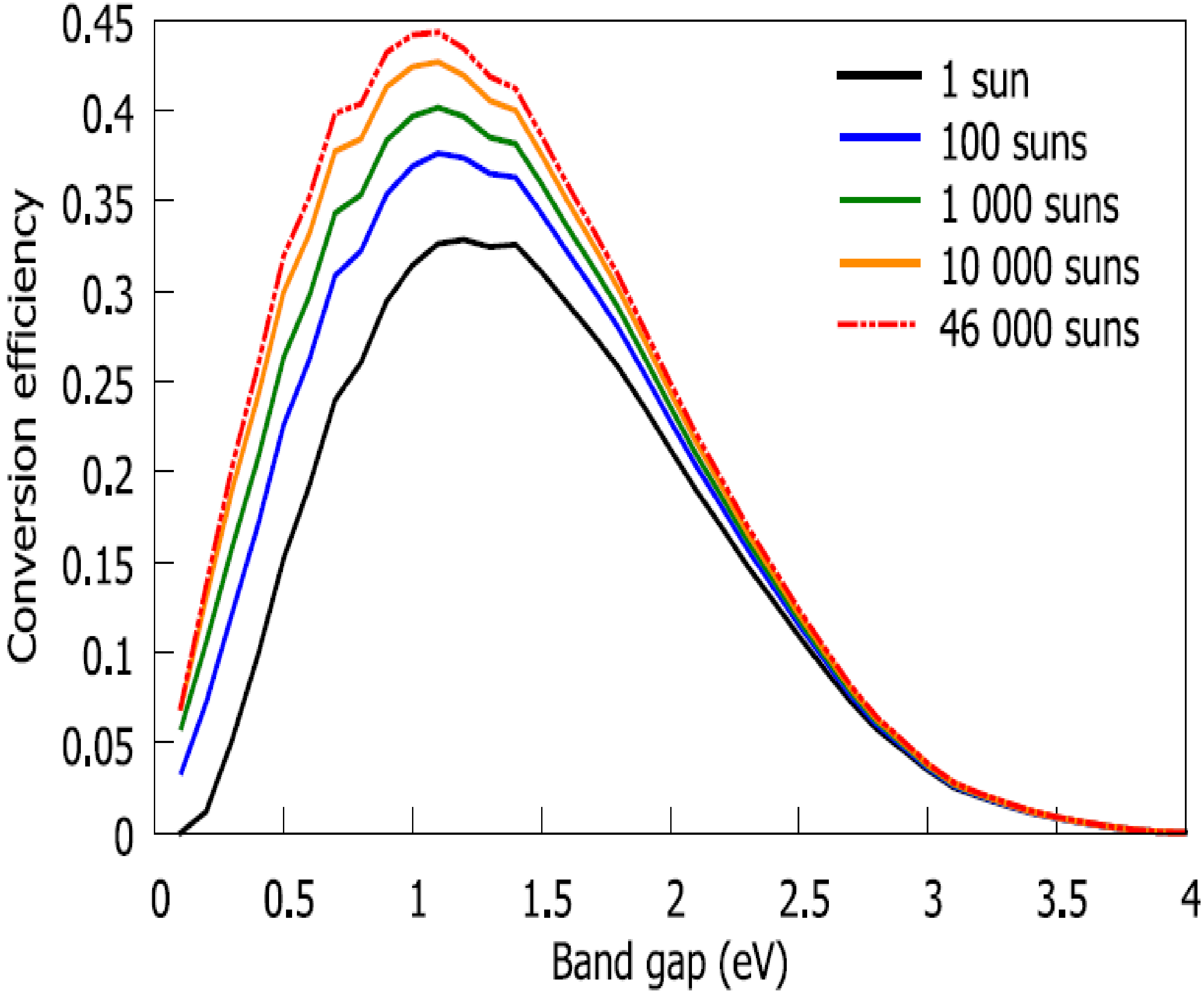
(3) $\eta_{e\text{-}h} = 1$ for $h\nu > E_g$

W. Shockley, H.J. Queisser, "Detailed balance limit of efficiency of p-n junction solar cells", *J. Appl. Phys.* 32, 510-519 (1961).



For 1 sun – 33.5 %;
For maximum sunlight concentration – 41%

Shockley–Queisser limits on the efficiency of single-junction cells as well as limits for cells of Q_e = 1%, 0.01%, 0.0001% and 0.000001%. The best confirmed experimental results are also shown.


0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Conversion efficiency
0
0.5
1
1.5
2
2.5
3
3.5
4
Band gap (eV)
1 sun
100 suns
1 000 suns
10 000 suns
46 000 suns

2. Concentrated photovoltaics: lessons with real sunlight

Motivation for high concentration:
(1) Economics

- 1 football field of ~ 17% solar cells at 1-sun ~ 500 kW.
- By using MJ cells (35%) at concentration of 500 suns, same power is produced from smaller semiconductor area (or the football field produce 500 MW).

Combination of high efficiency & 500X concentration boosts output per semiconductor area by a factor of 1000.

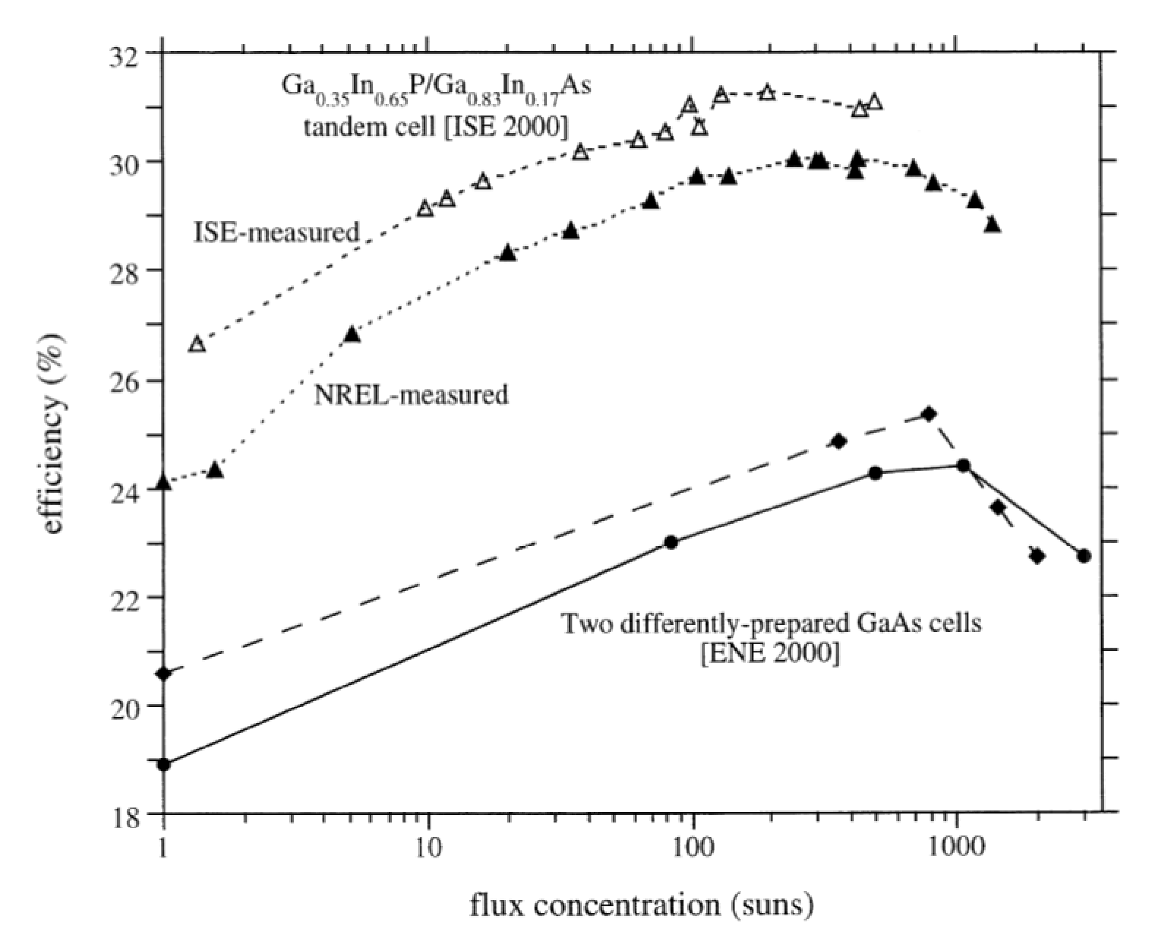
MJ cells are replaced by less expensive optics and common materials.

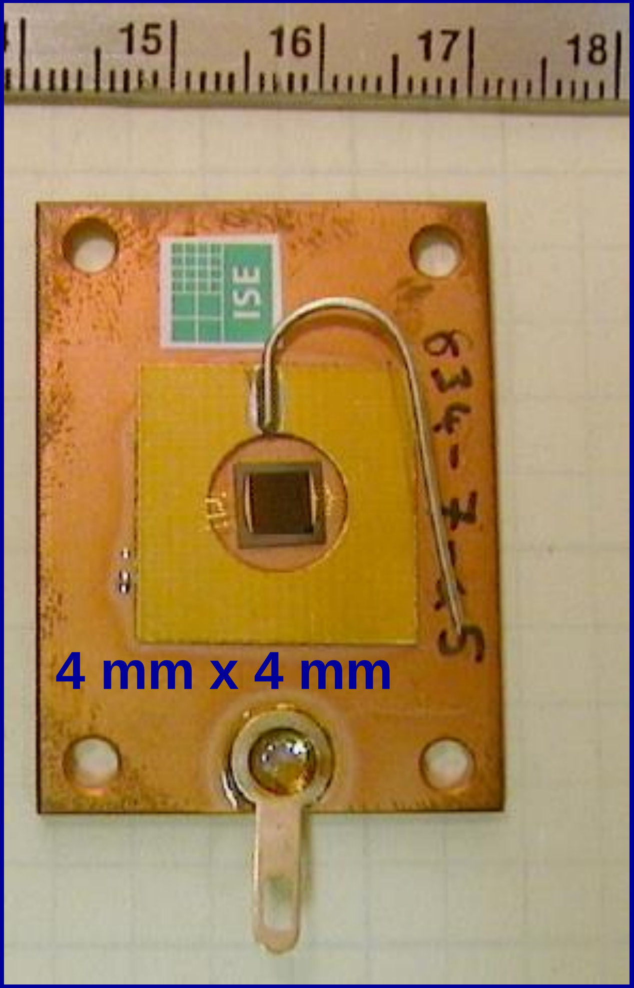
Leads to reduced cost of energy despite paying extra for tracking & cooling.

Courtesy of Spectrolab, Inc.

Motivation for high concentration:
(1) Economic;
(2) Achievable increase in efficiency with flux

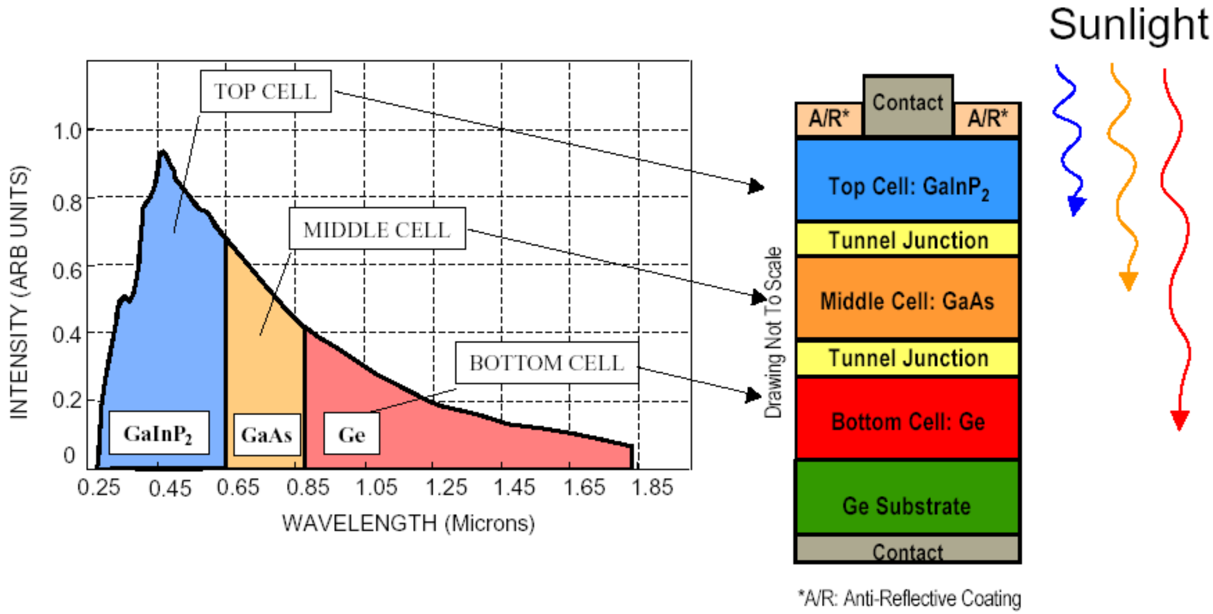
Tandem $Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As$ solar cells





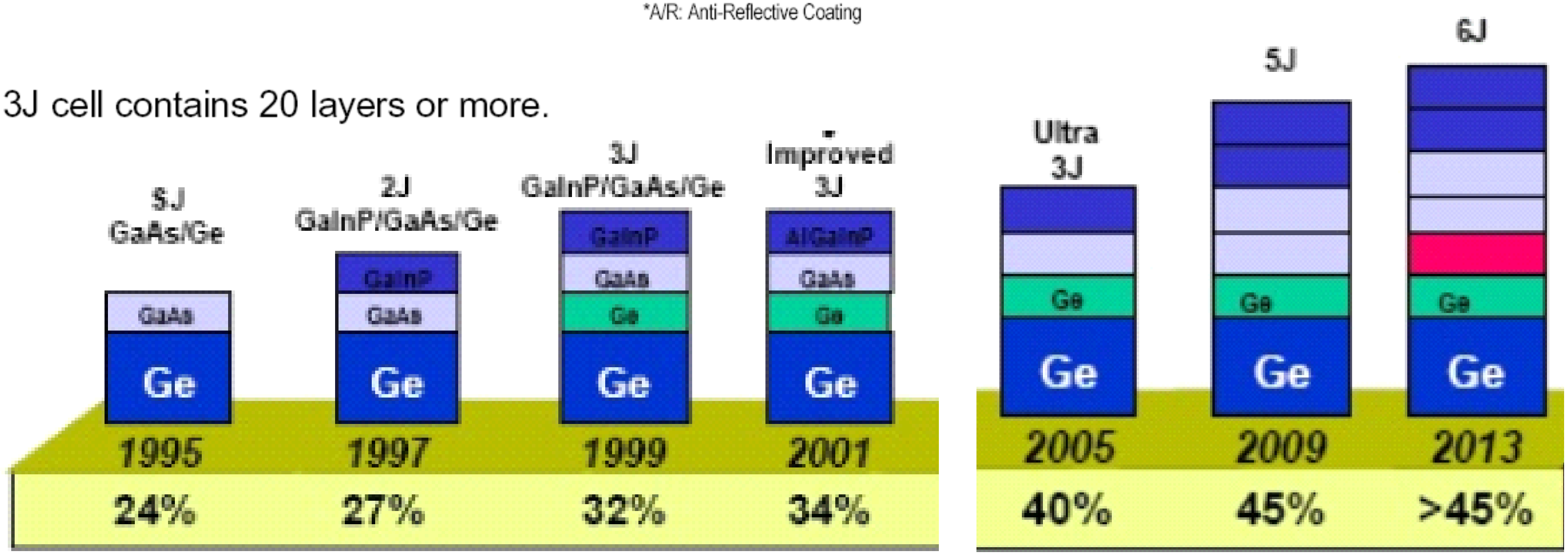
F. Dimroth, et. al., Progress in Photovoltaics 9, 165 (2001)

"3J cells: high efficiency at high concentrations

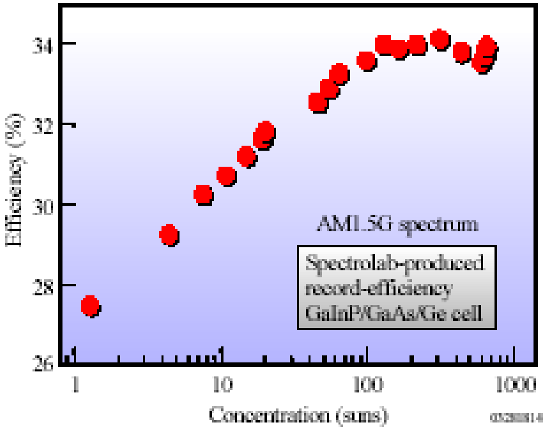


World record > 47%

- Typical 3J cell contains 20 layers or more.



Courtesy of Spectrolab, Inc.



1 cm^2 3-j cell – max at 350 suns

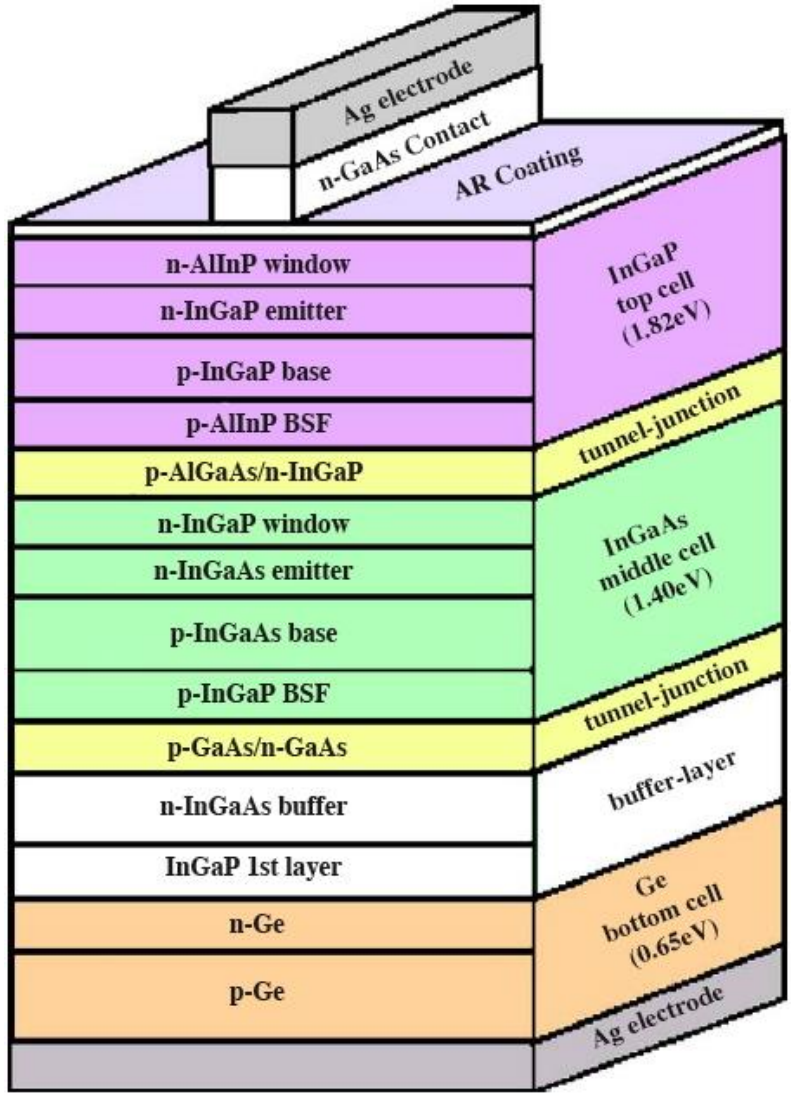
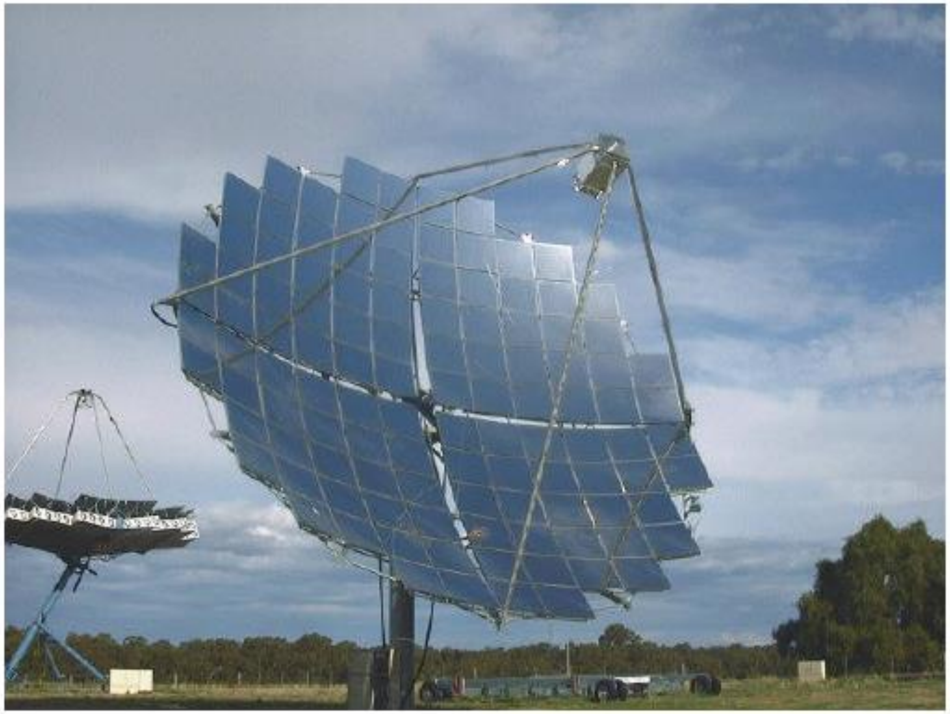


Fig. 1. Schematic of an InGaP/InGaAs/Ge triple-junction solar cell.



- ❑ Big reflective dish
- ❑ Central receiver
- ❑ Active cooling

- Systems located in central Australia,
- Each system produces 20 kW using Si cells

Modules of III-V 3-j cells

SolarSystems

“Big dish” in Sede Boker

GaAs Monolithic Interconnected Modules (MIM) with integrated Bypass diodes, ISE

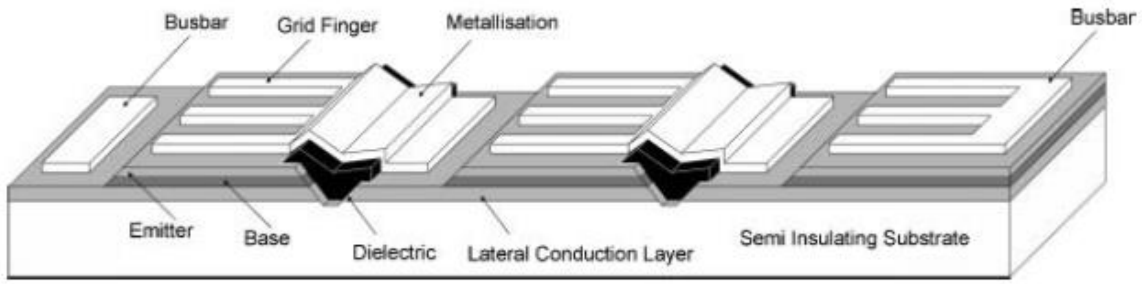
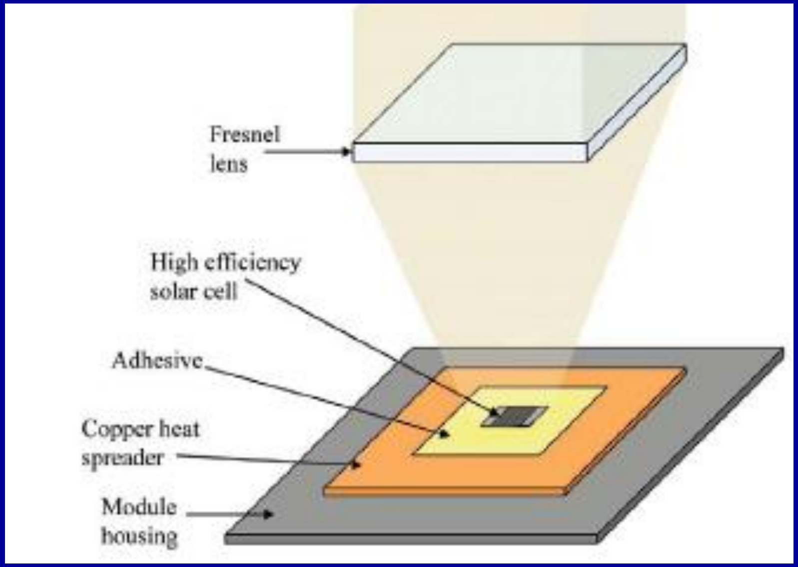


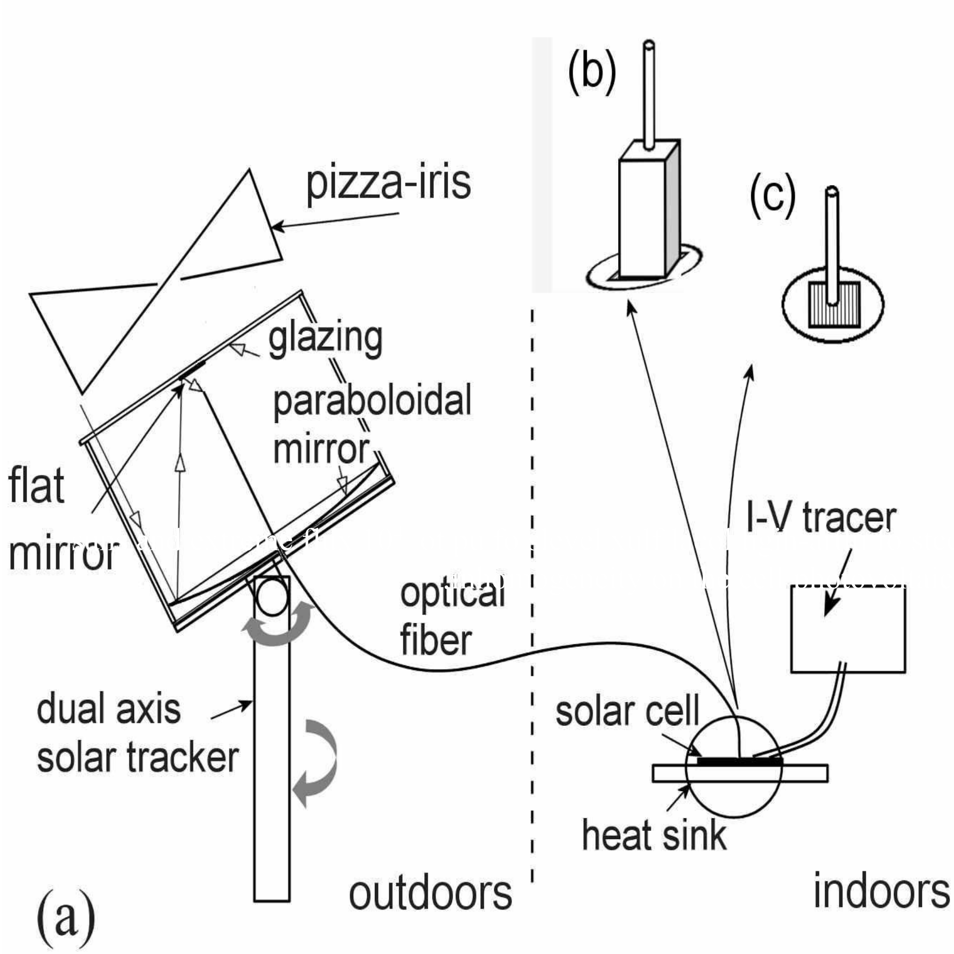
Figure 2. Sketch of a simple, 3 segment MIM

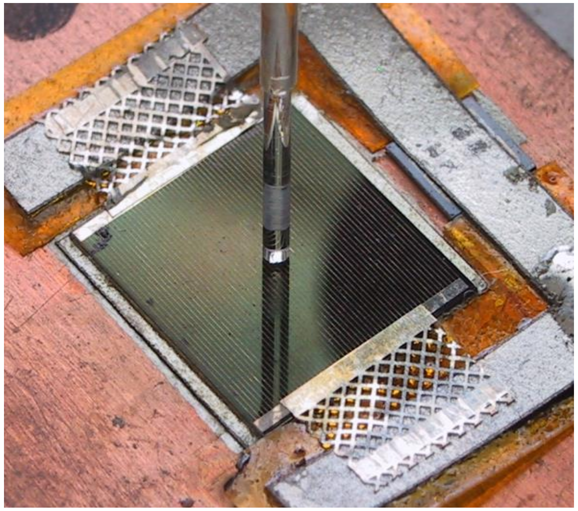
Flatcon concentrator,

ISE, Concetrix



Our solar fiber-optic mini-dish concentrator indoor test facility for ultra-high flux PV characterization





(d)

Solar radiation is concentrated outdoors by a minidish mounted on a dual-axis solar tracker. A small flat mirror re-images the sun to the tip of an optical fiber which guides the concentrated sunlight to an indoor laboratory. Radiation on the cell was varied by a pizza-slice iris.

Flux uniformity is achieved with a square cross-section kaleidoscope (b), while direct fiber/cell contact is used for localized irradiation probe (c, d).

Localized irradiation probing

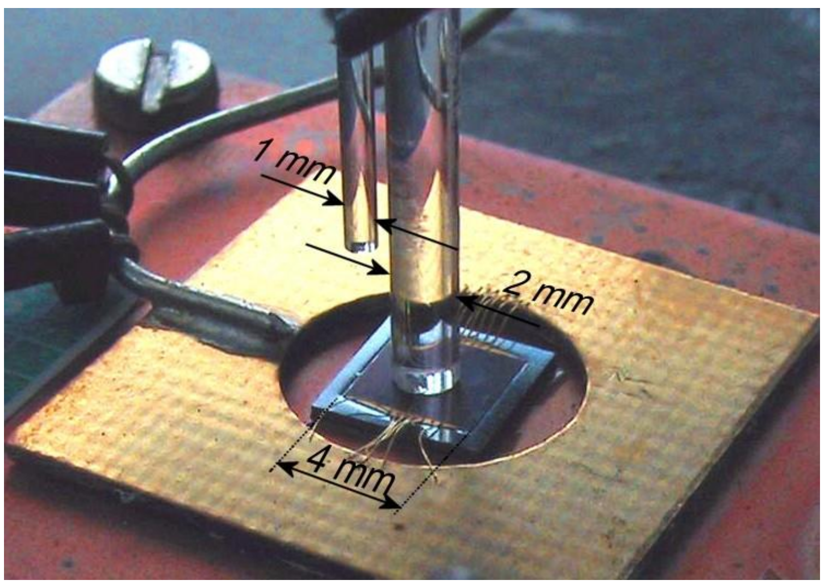
permits investigating effects of:

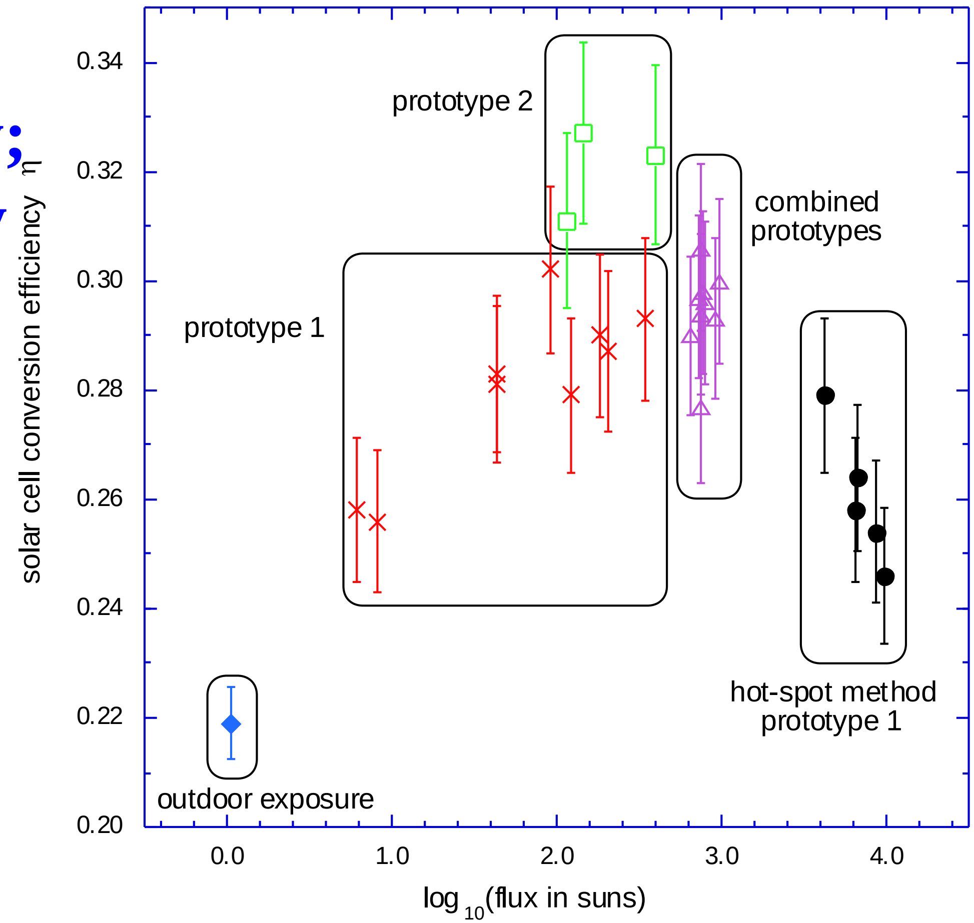
(1) ultra-high local flux levels (up to 10^4 suns);

(2) extreme flux inhomogeneity;

(3) PV performance uniformity over cell surface.

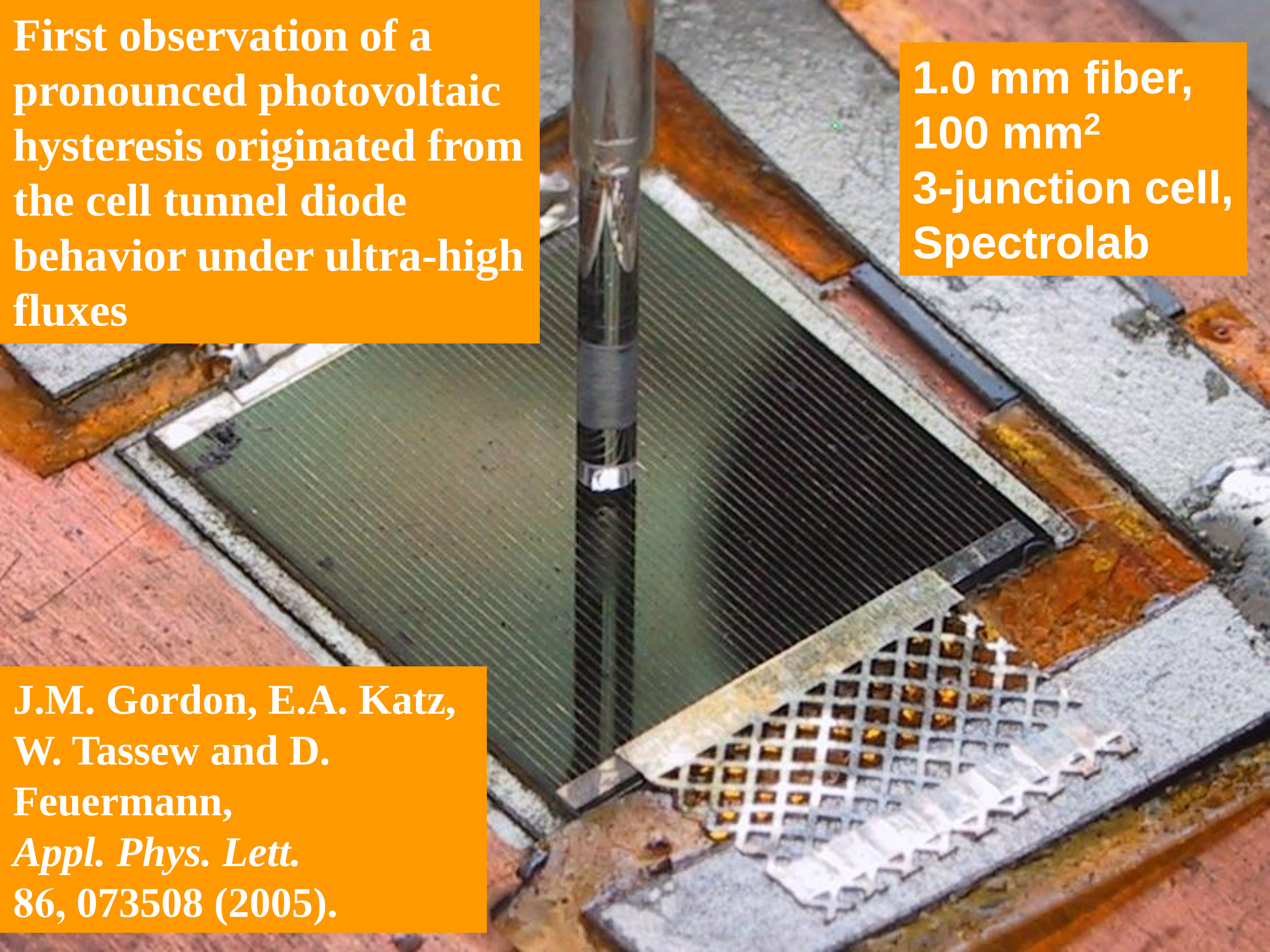
J.M. Gordon, E.A. Katz, D. Feuermann and M. Huleihil, *Appl. Phys. Lett.* 84, 3642 (2004).





$Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As$ 2-j cells

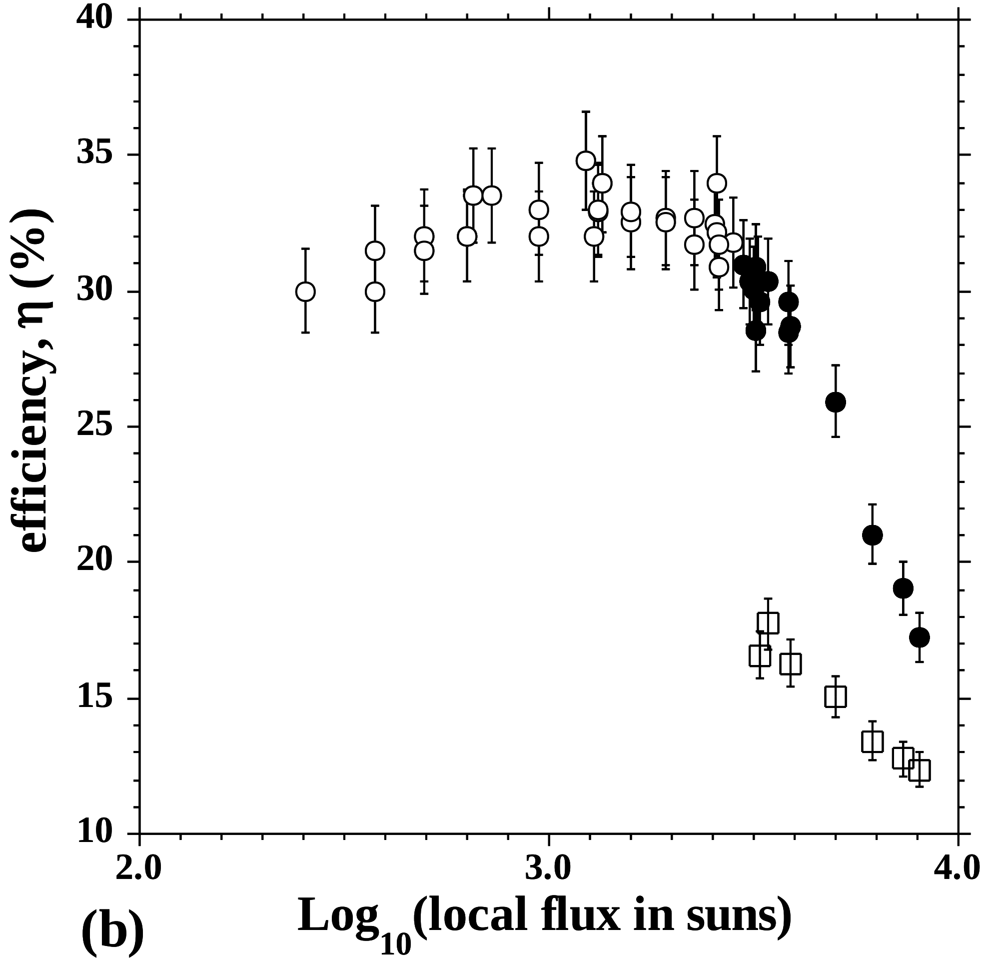
First observation of a pronounced photovoltaic hysteresis originated from the cell tunnel diode behavior under ultra-high fluxes



1.0 mm fiber,
$100\ mm^2$
3-junction cell,
Spectrolab

J.M. Gordon, E.A. Katz, W. Tassew and D. Feuermann,
Appl. Phys. Lett.
86, 073508 (2005).

Cell efficiency as a function of local optical concentration

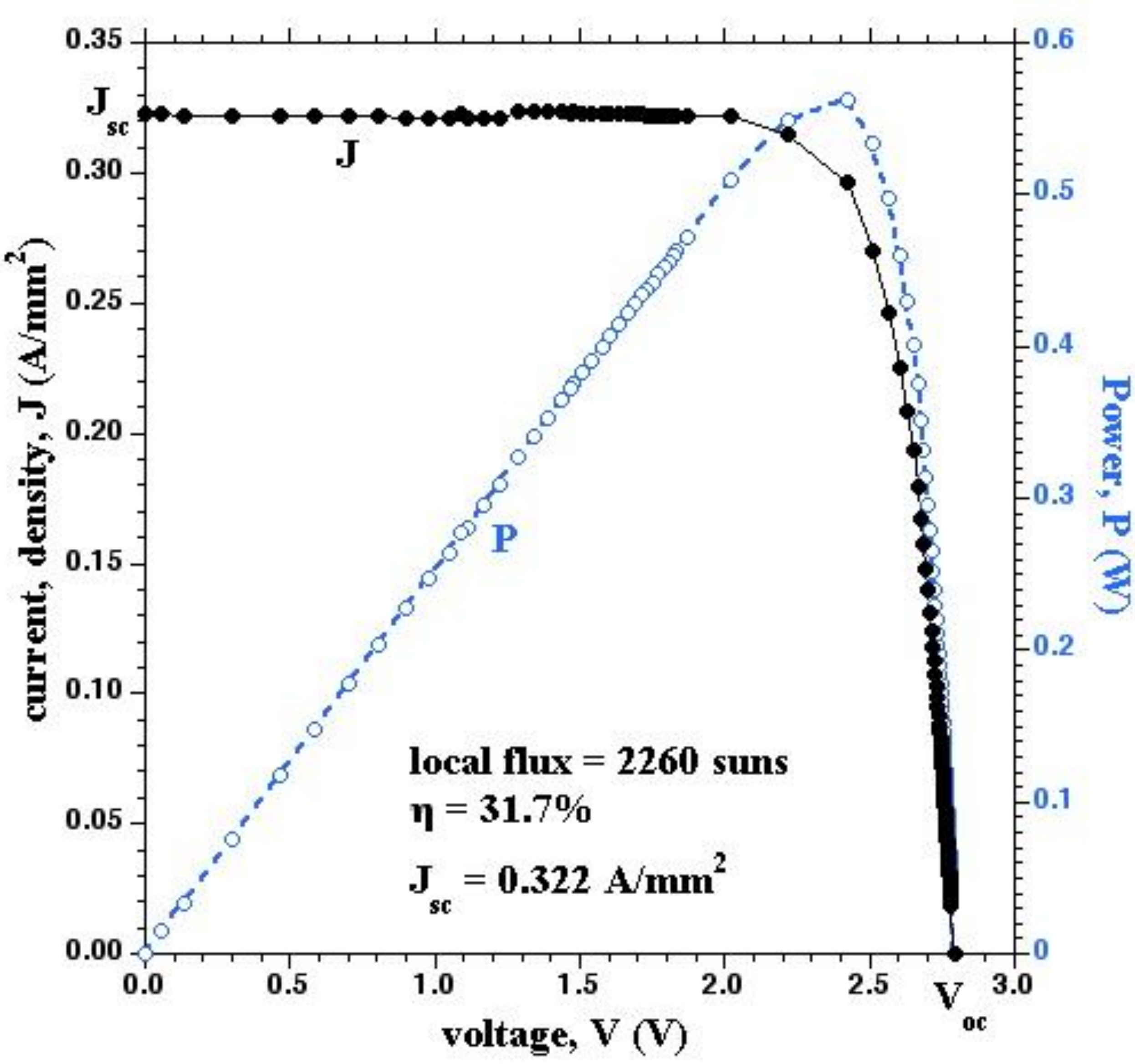


(b)

○ below threshold
● above threshold, increasing current
□ above threshold, decreasing current

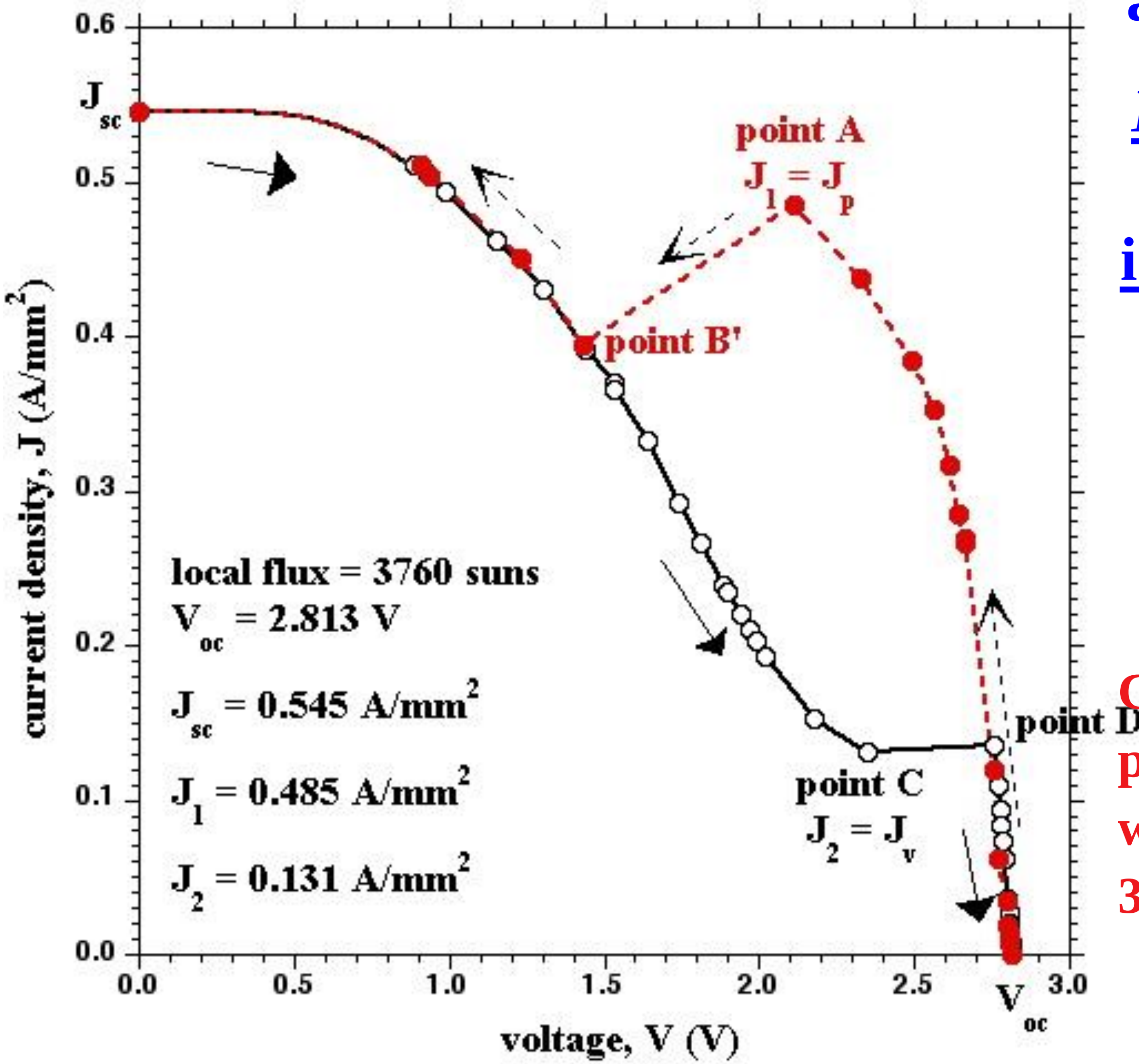
Data points below the 3200-sun threshold are independent of *I-V* trace direction.

Local flux values < 3200 suns



I-V **curves are independent of measurement direction (open-to short-circuit or vice versa).**

Local flux values > 3200 suns



I-V trace from open- to short-circuit:

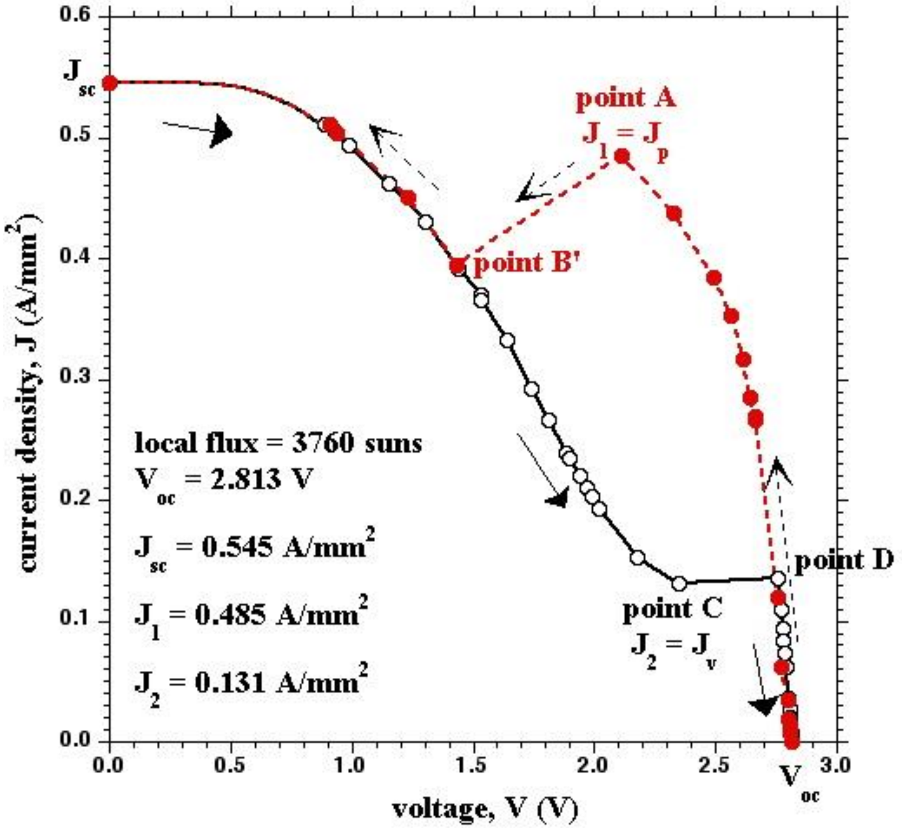
a discontinuity $J = J_1$.

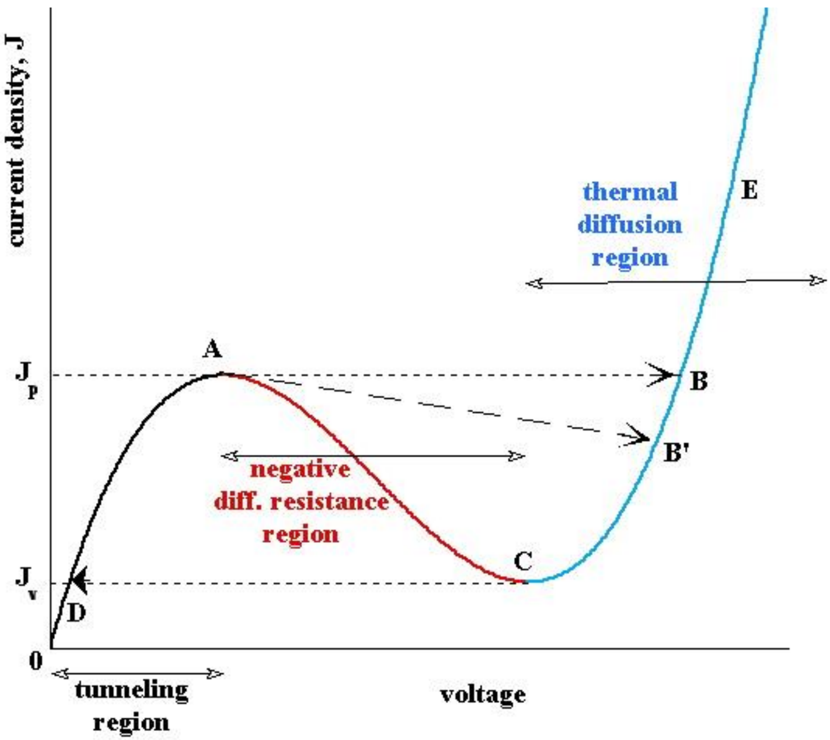
I-V trace from short- to open- circuit at identical flux values :

The transition (voltage jump) occurred at considerably lower current density J_2.

Completely reversible phenomenon, when flux was again lowered below 3200 suns

A consequence of the impact of a tunnel diode on photovoltaic performance





$J_{sc} < J_p \Rightarrow$ **no hysteresis, normal photovoltaic *J-V* curves**

When the cell's current density exceeds the lowest J_p value of the cell's tunnel diodes, an instability is triggered: the electron tunneling that allows efficient low-resistance photovoltaic performance switches to the thermal-diffusion (high-resistance) regime.

Application:

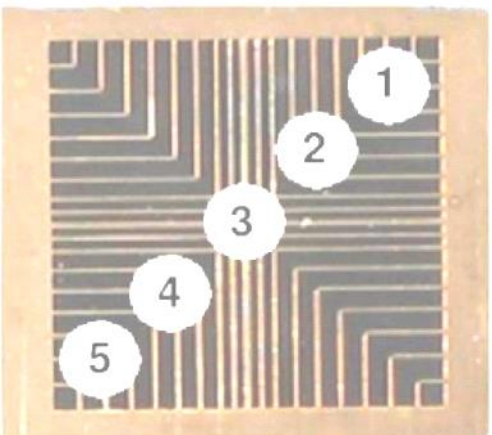
non-destructive *in situ* determination of the tunnel diode's valley and peak (threshold) current densities;

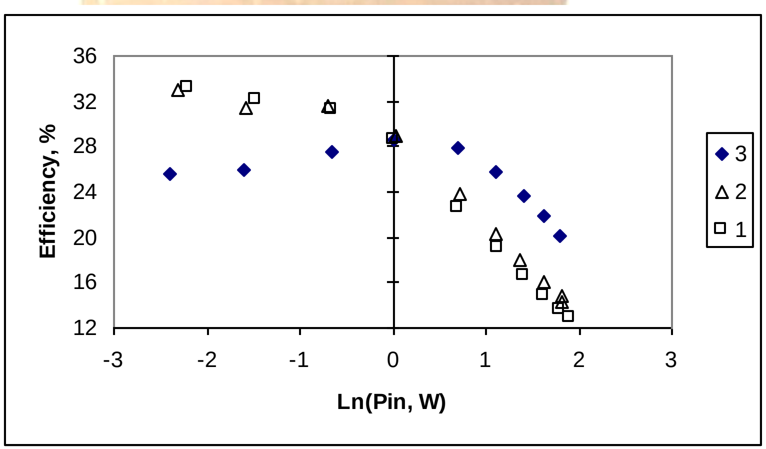
mapping J_p and J_v values over the cell area.

Other applications of our method:

1) examination how PV current-voltage (*I* -*V*) curves change with localized irradiation

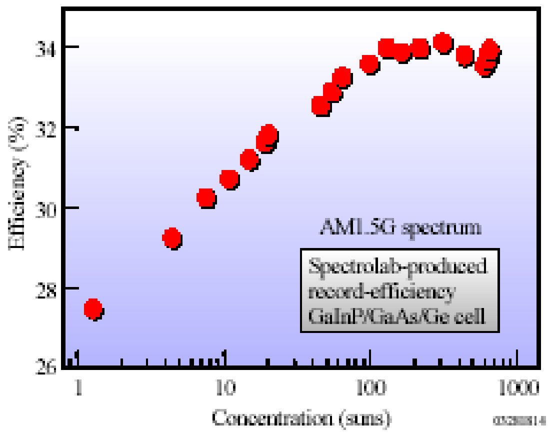
2) Mapping of PV performance of concentrated solar cells





E.A. Katz, J.M. Gordon, W. Tassew and D. Feuermann, *J. Appl. Phys. 100*, 044514 (2006).

E. A. Katz, J. M. Gordon and D. Feuermann, *Progress in Photovoltaics*, 14, 298 (2006).



O. Korech, B. Hirsch, E. A. Katz and J. M. Gordon. *Appl. Phys. Lett.* 91, 064101 (2007).

1 cm^2 3-j cell – max at 350 suns

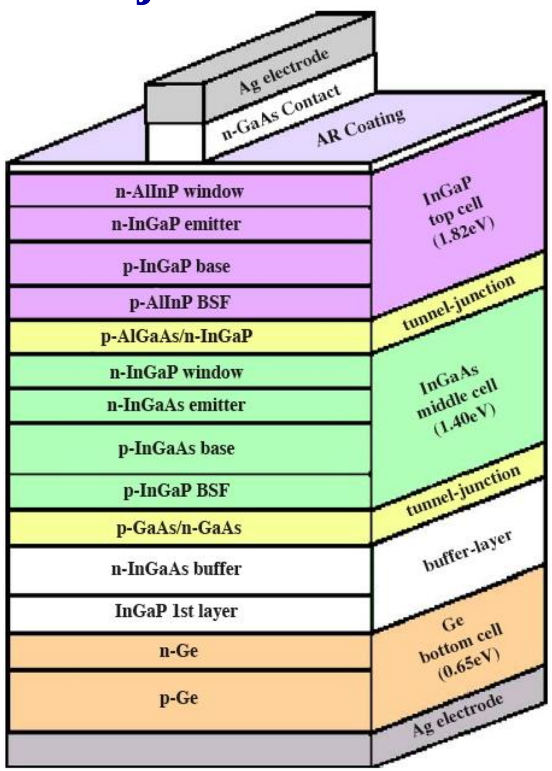
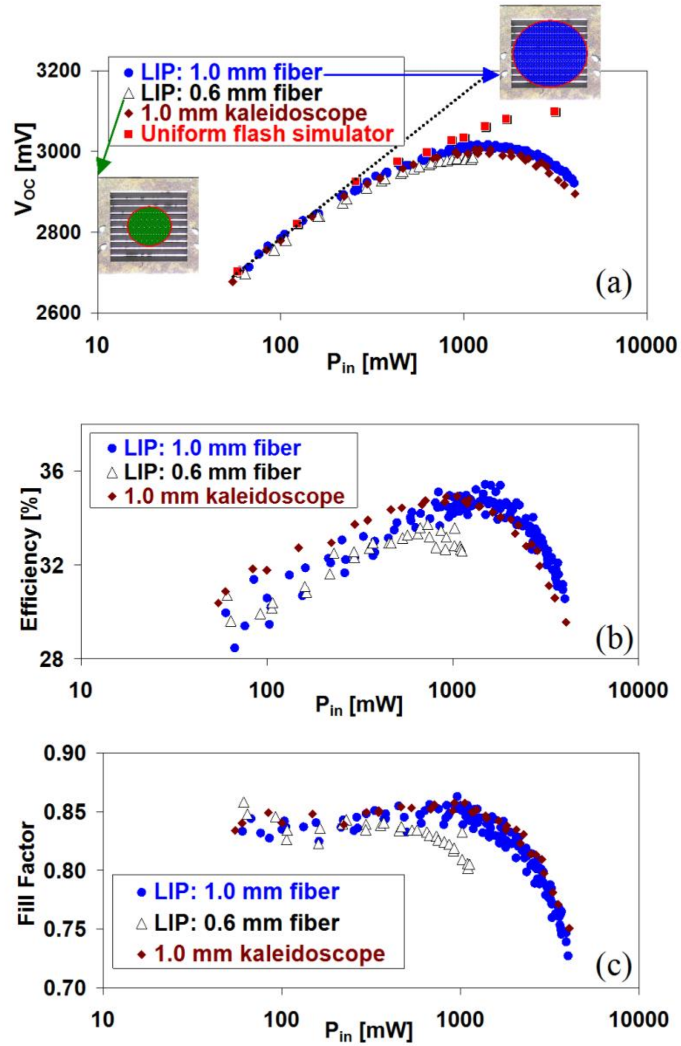


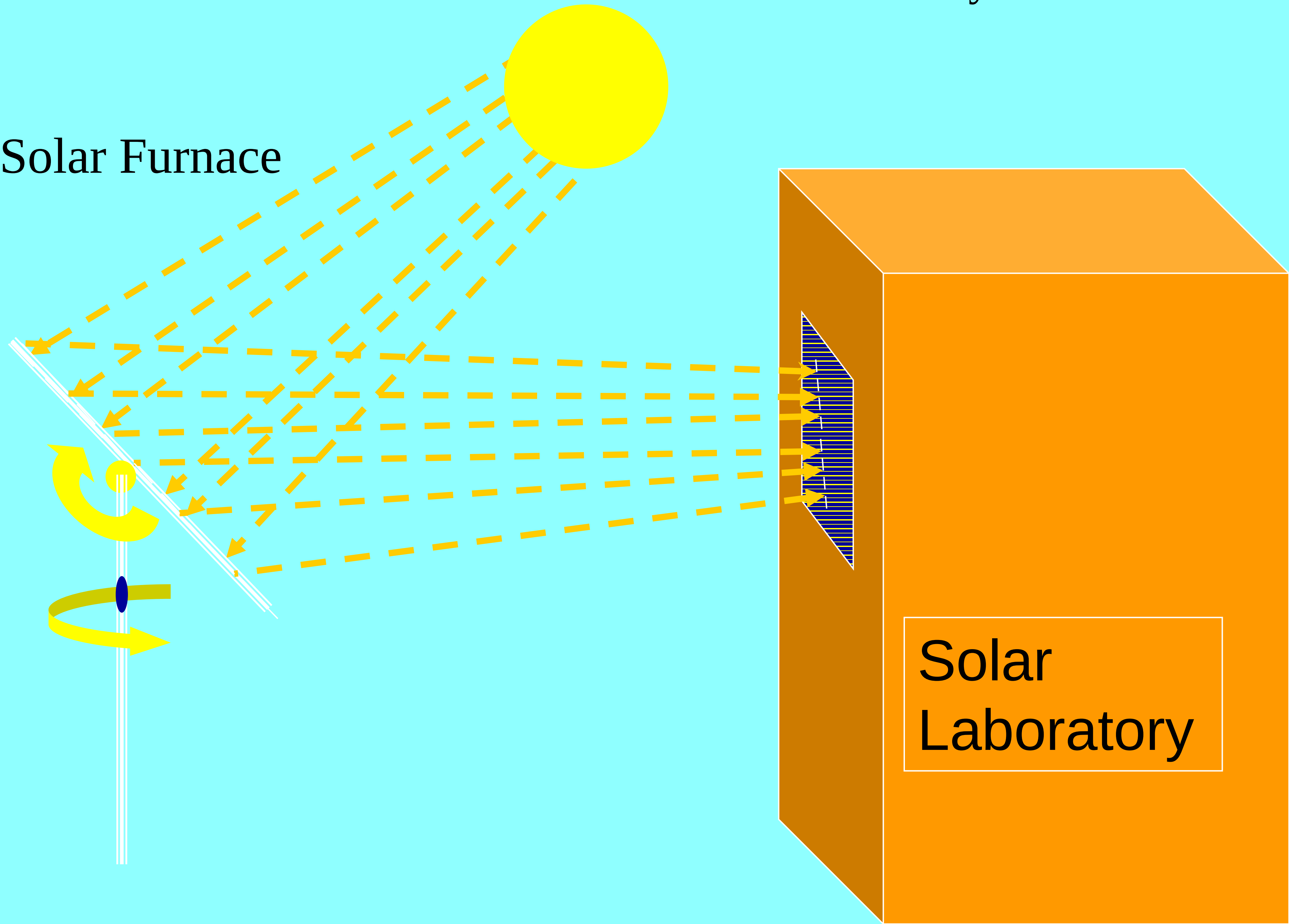
Fig. 1. Schematic of an InGaP/InGaAs/Ge triple-junction solar cell.



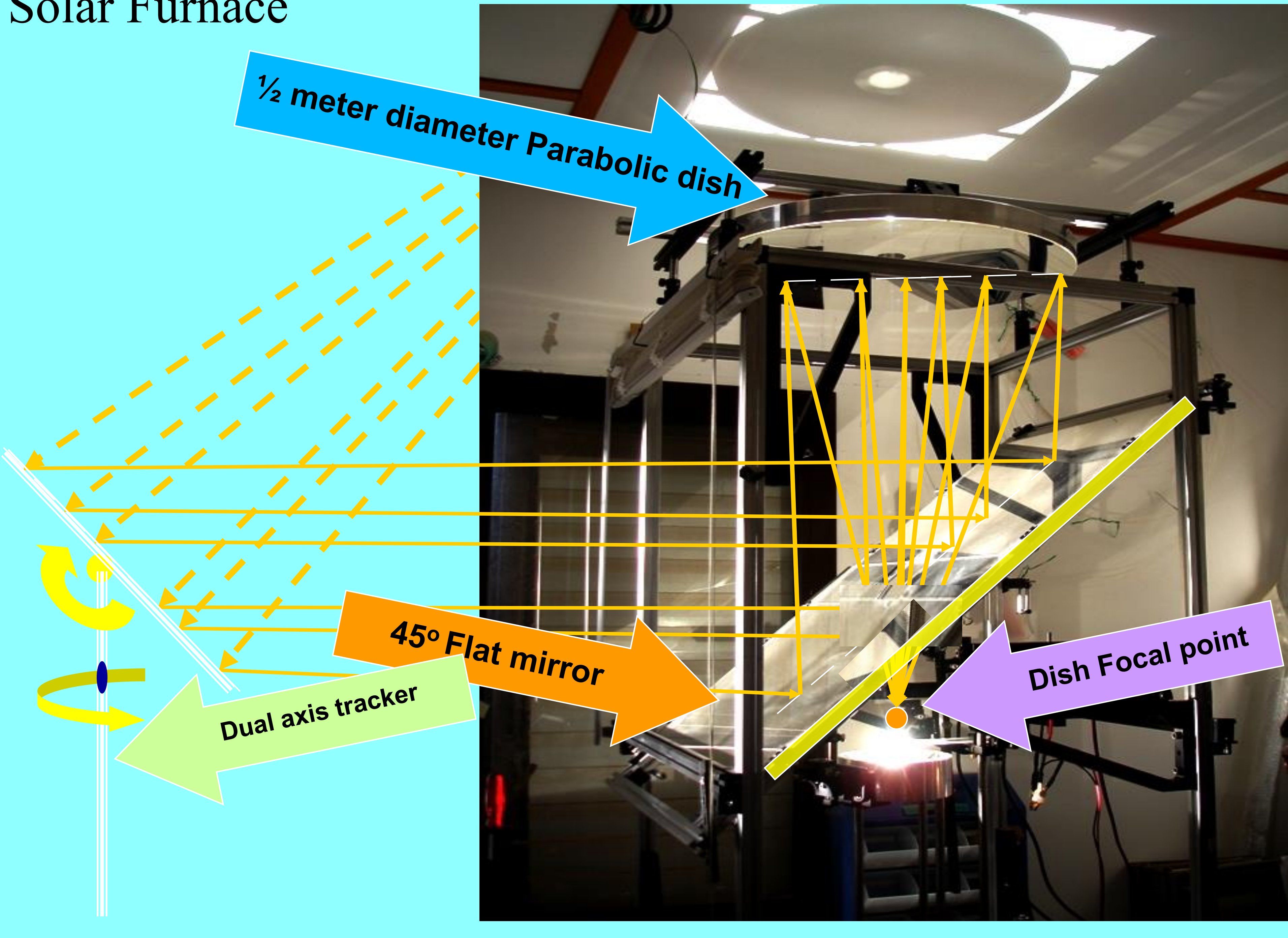
1 mm^2 3-j cell – max efficiency at 1000 suns

Slide courtesy: D. Feuermann

Solar Furnace



Solar Furnace



Temperature dependence of V_{oc} and *eff*

$$V_{oc} = \frac{n\kappa T}{q}\ln\left(\frac{I_{sc}}{I_o}+1\right)$$

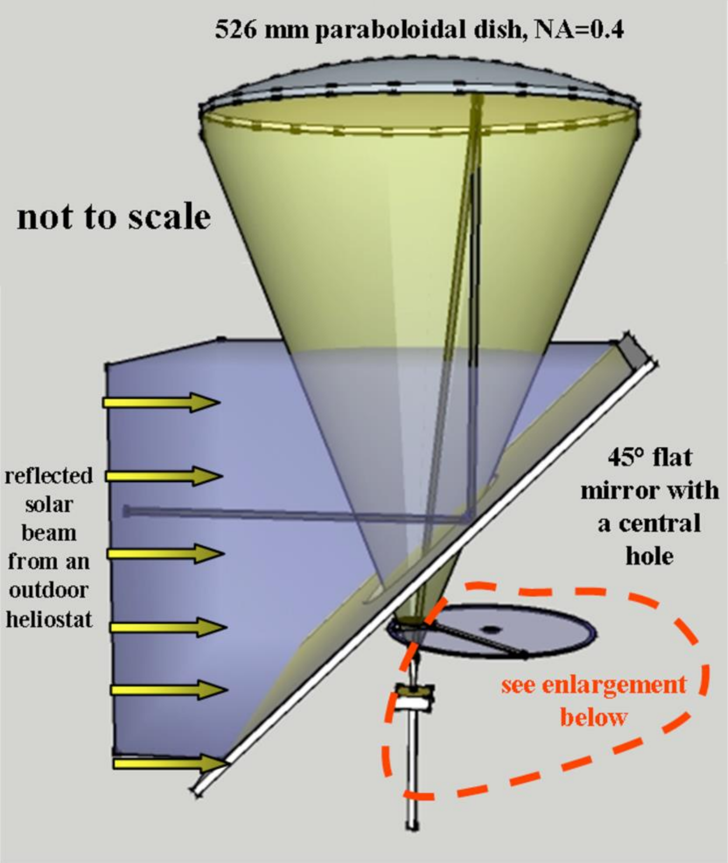
$$I_o = qN_v N_c\left[\exp\left(-E_g/\kappa T\right)\right]\cdot\left(\frac{L_n}{n_n\tau_n}+\frac{L_p}{p_p\tau_p}\right)$$

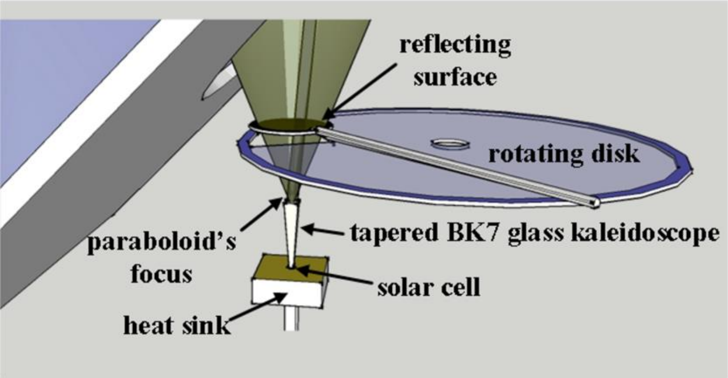
$$V_{oc} = \frac{nE_g}{q} - \frac{n\kappa T}{q}\cdot\ln\left[\frac{1}{I_{sc}}\cdot qN_v N_c\right]\left(\frac{L_n}{n_n\tau_n}+\frac{L_p}{p_p\tau_p}\right) = a - bT$$

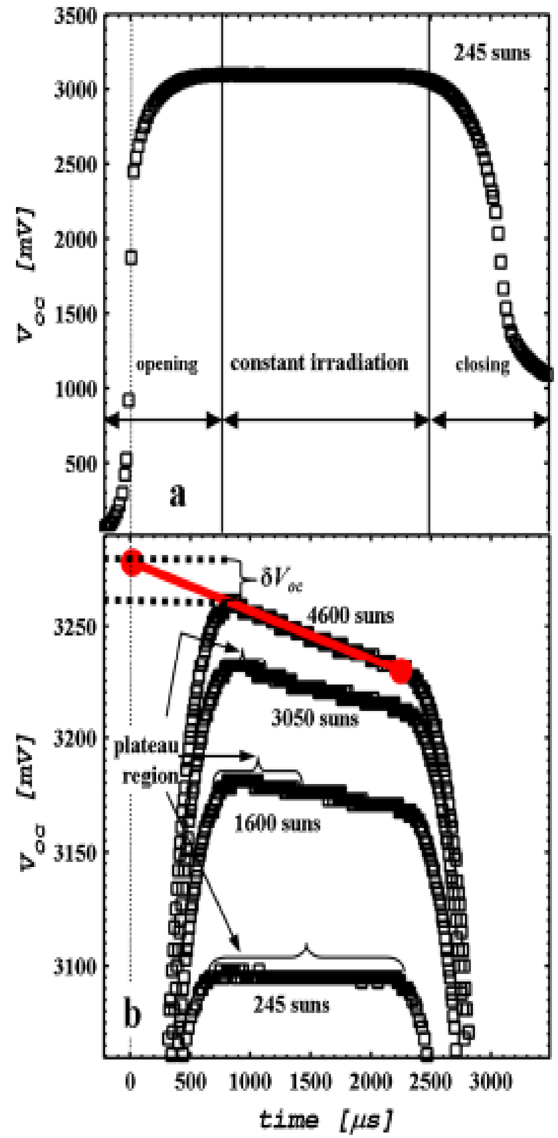
$$a = V_{oc}(0K) = \frac{nE_g}{q}$$

$$b = -dV_{oc}/dT = \frac{n\kappa}{q}\ln\left[\frac{1}{I_{sc}}\cdot qN_v N_c\right]\left(\frac{L_n}{n_n\tau_n}+\frac{L_p}{p_p\tau_p}\right)$$

"Solar furnace"







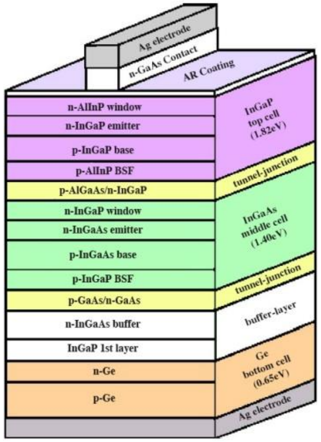
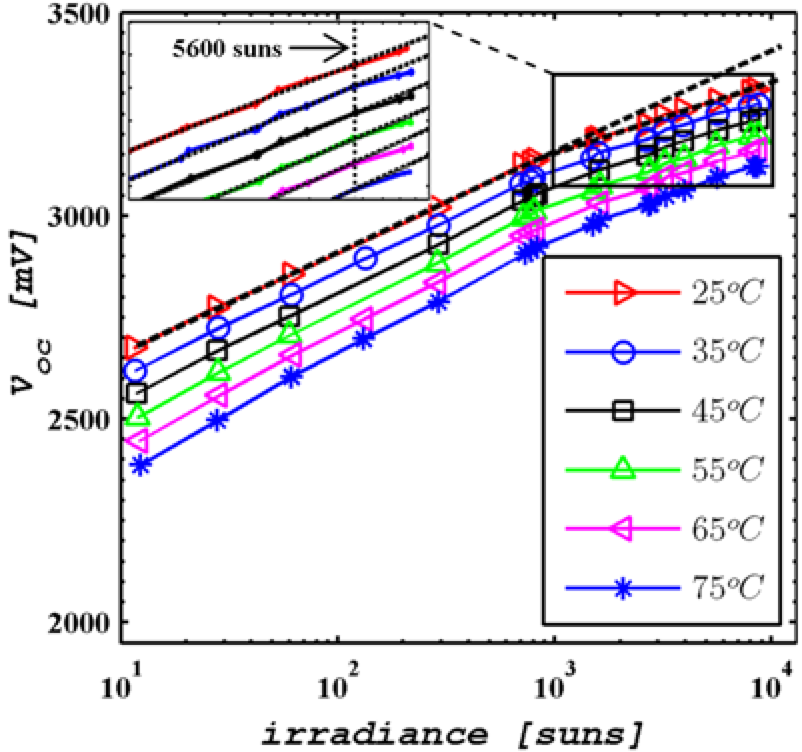
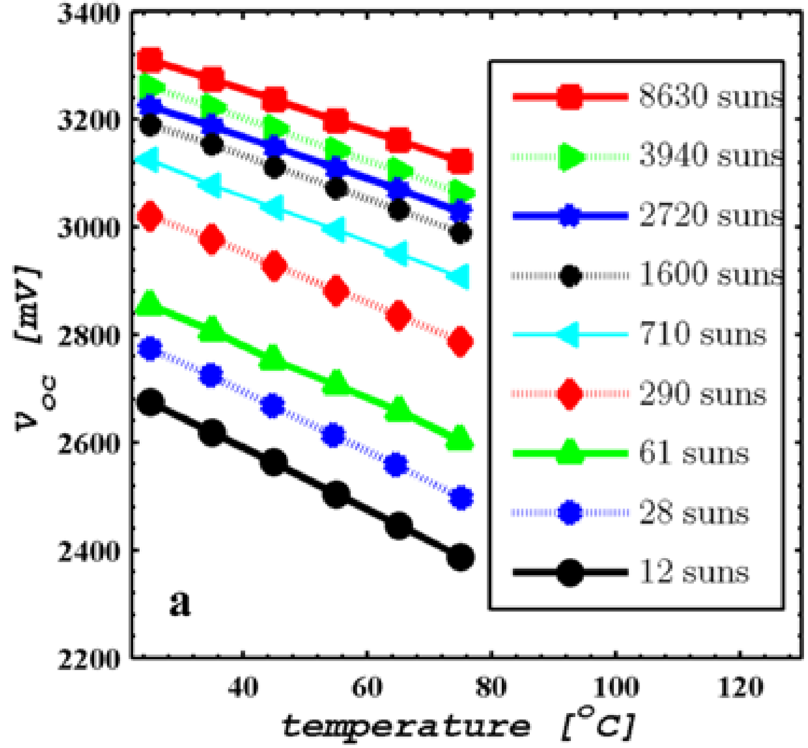
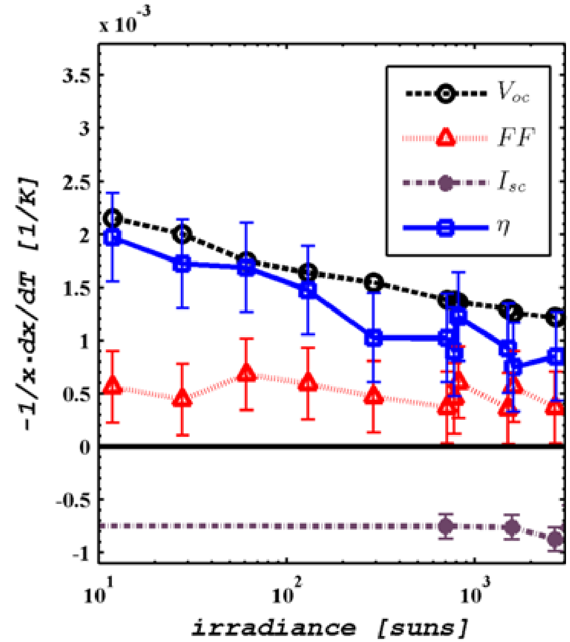


Fig. 1. Schematic of an InGaP/InGaAs/Ge triple-junction solar cell.

A. Braun, B. Hirsch, A. Vossier, E.A. Katz, and J.M. Gordon, *Prog. Photovoltaics*, 21, 202 (2013).







A. Braun, B. Hirsch, A. Vossier, E.A. Katz, and J.M. Gordon, *Prog. Photovoltaics*, 21, 202 (2013).

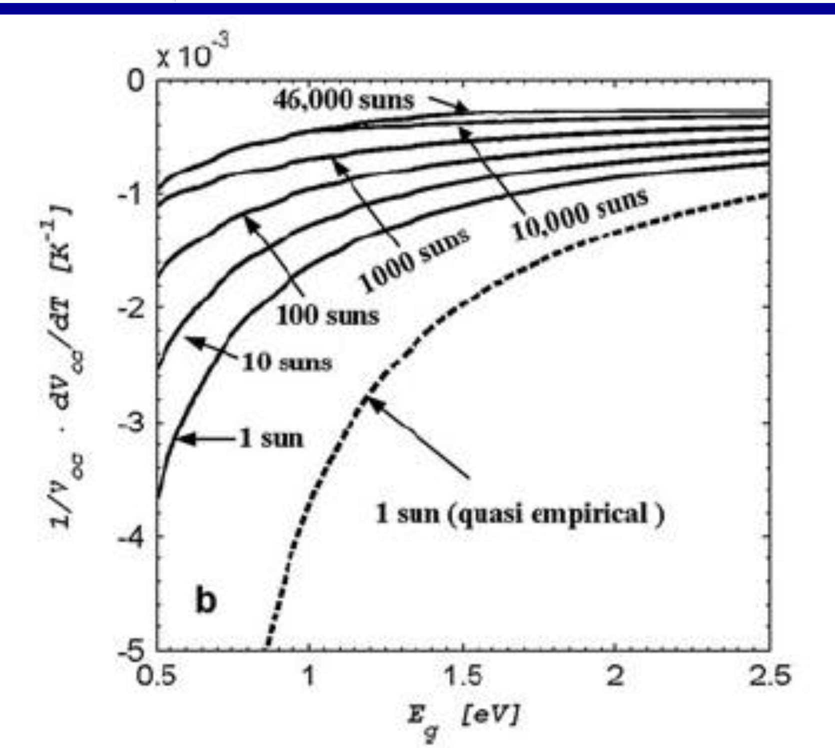
Progress in PHOTOVOLTAICS

PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. 2013; **21**:1087–1094
Published online 9 May 2012 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.2210

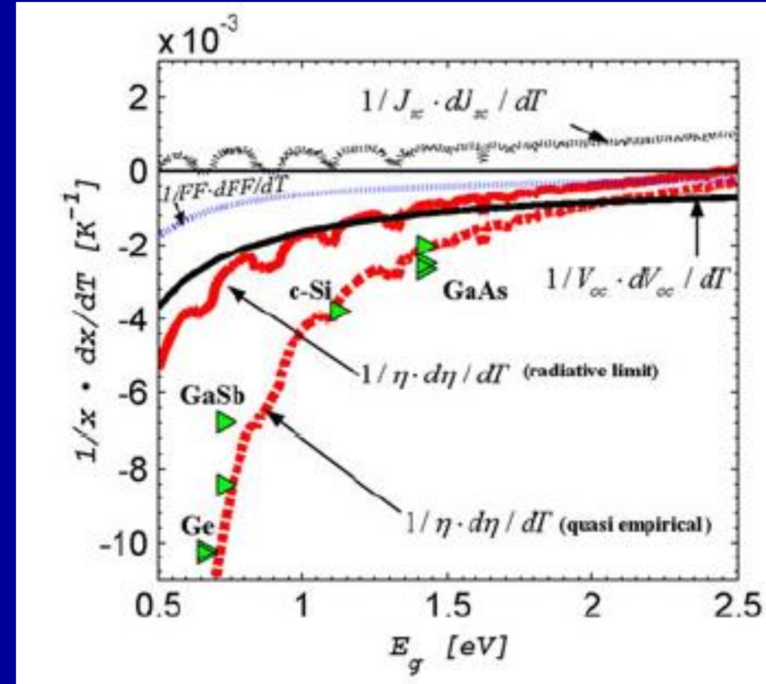
RESEARCH ARTICLE

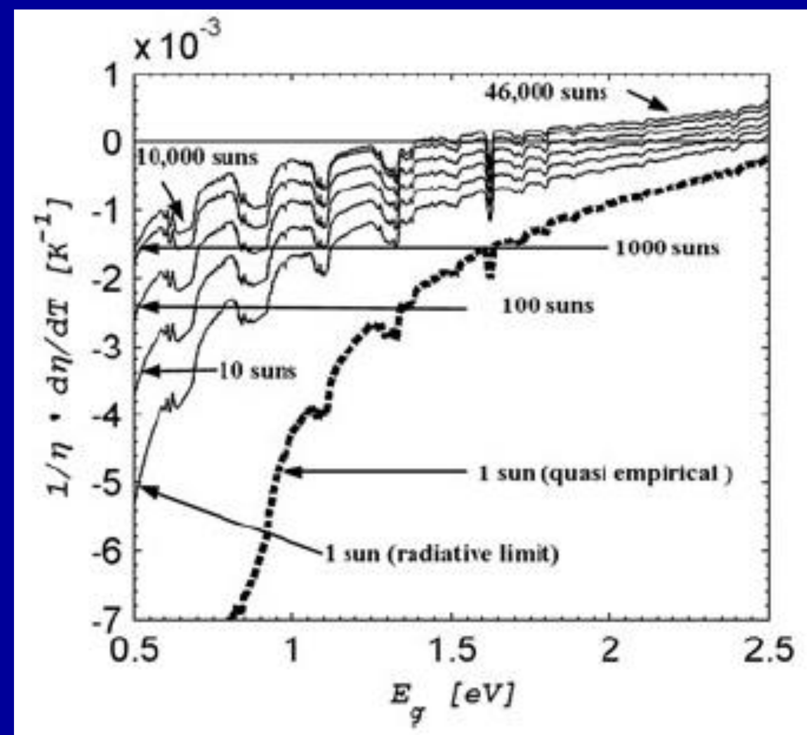
Basic aspects of the temperature coefficients of concentrator solar cell performance parameters

Avi Braun[1], Eugene A. Katz[1,2] and Jeffrey M. Gordon[1,3]*



1 sun →





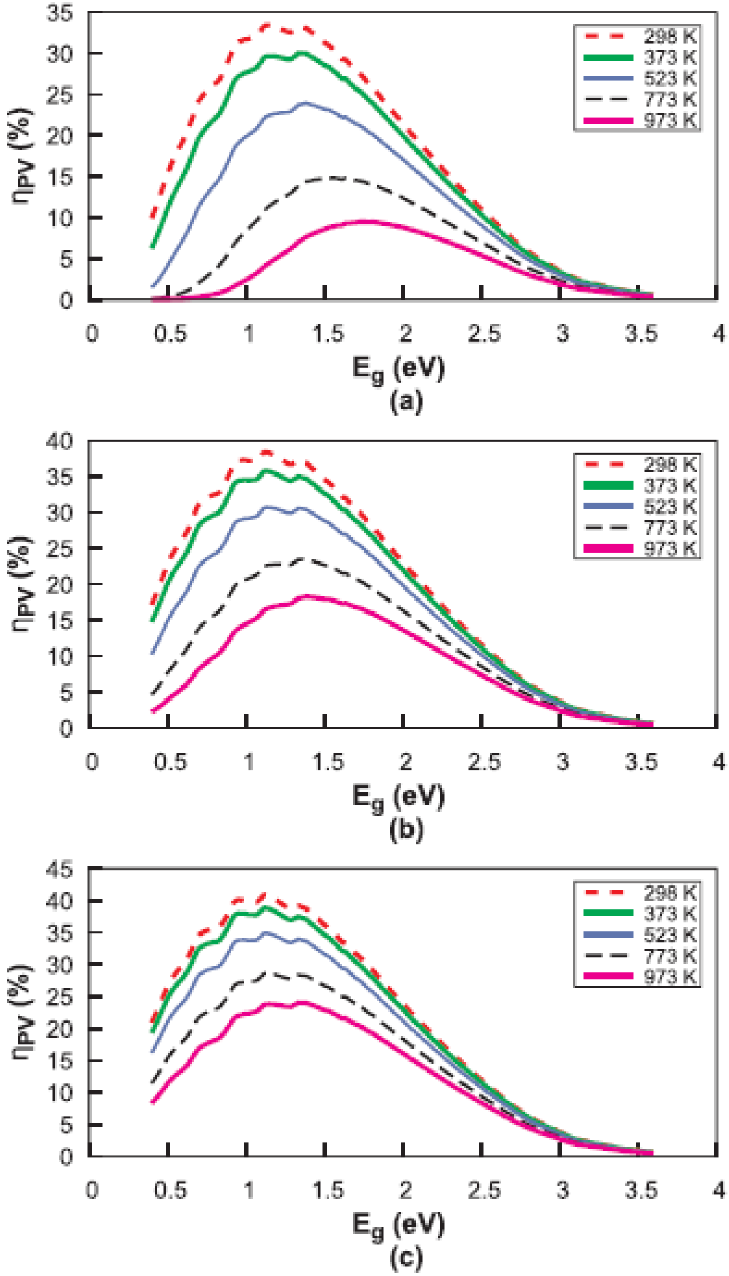


Fig. 1. PV efficiency achievable with a 1-junction cell as a function of E_g, for T = 298–973 K, and for C = 1 (a), 100 (b), and 1000 (c).

J. Zeitouny, N. Lalau, J. M. Gordon, E. A. Katz, G. Flamant, A. Dollet, A. Vossier, Sol. Energy Mater. Sol. Cells, 182, 61, 2018

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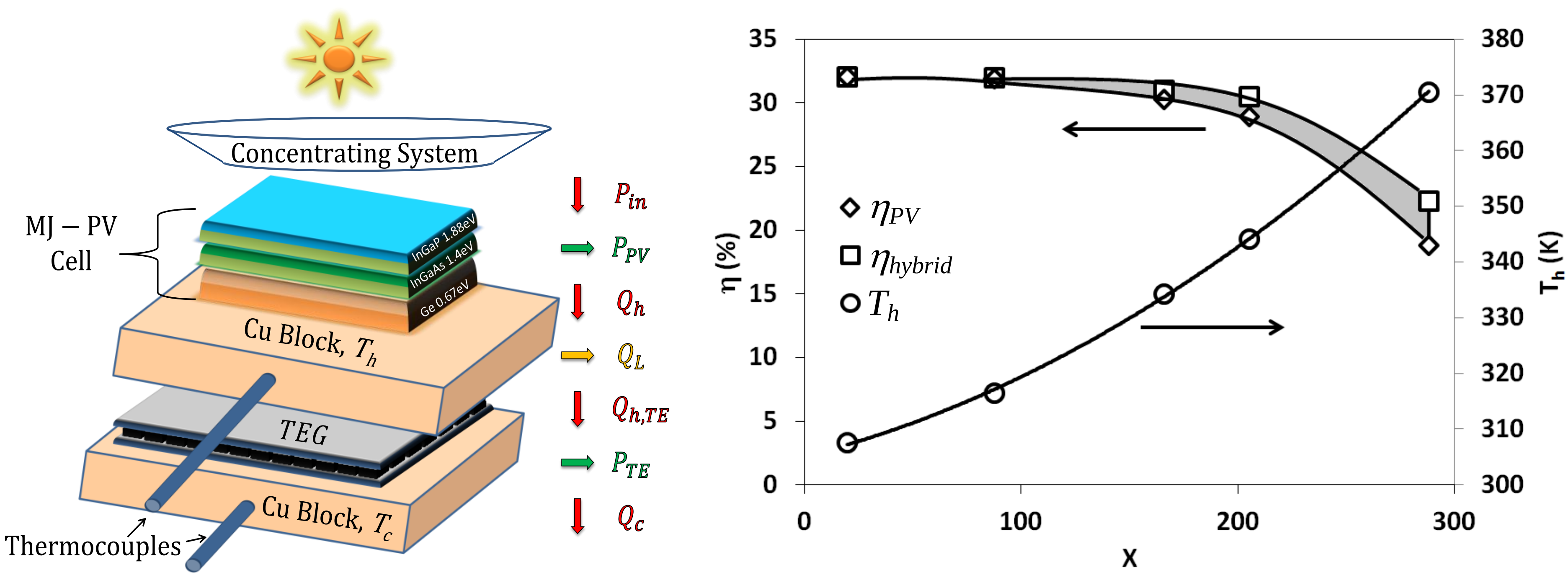
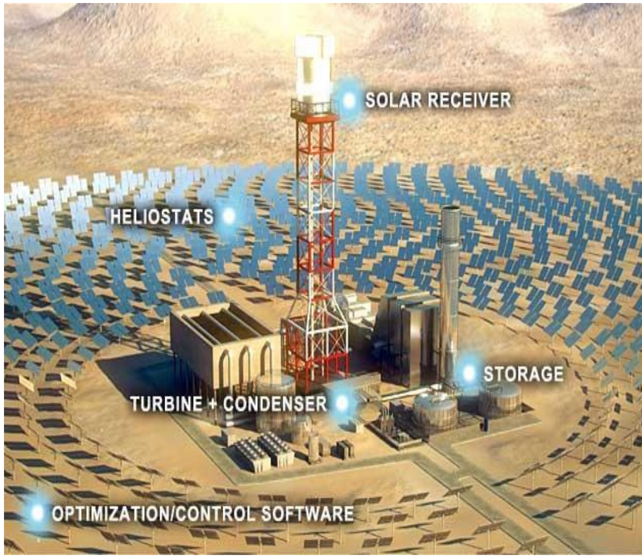
Hybrid photovoltaic-thermoelectric system for concentrated solar energy conversion: Experimental realization and modeling

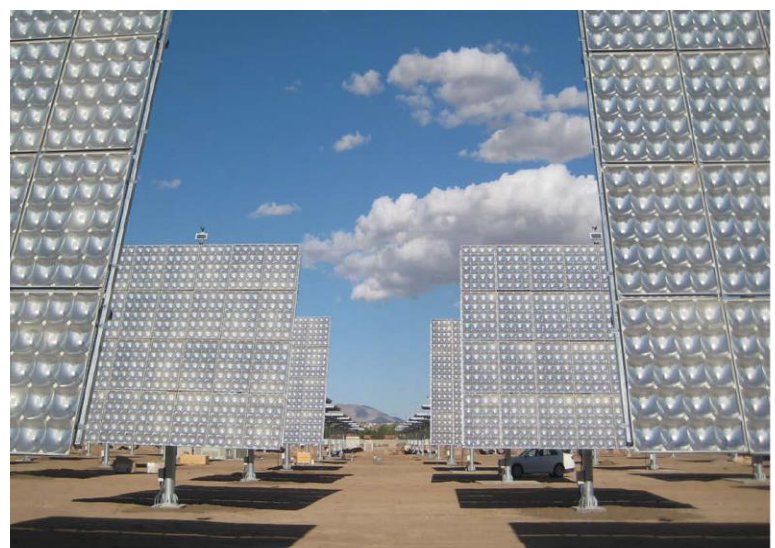
Ofer Beeri,[1,a)] Oded Rotem,[2] Eden Hazan,[1] Eugene A. Katz,[3,4] Avi Braun,[3,b)] and Yaniv Gelbstein[1,2]



Exploit the options of solar thermal for *dispatchability* via:
(a) gas backup heating, and/or (b) multi-hour thermal storage



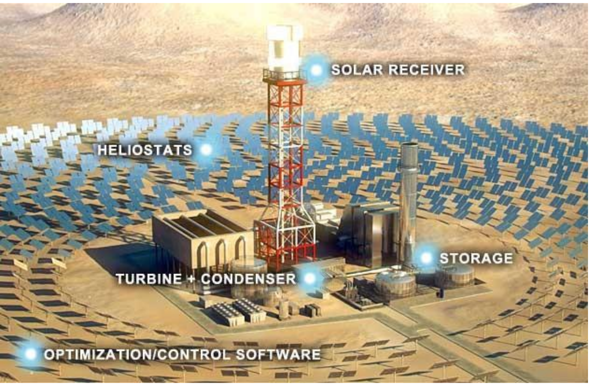
combined with the substantially higher efficiency of PV, in particular concentrator PV (CPV).

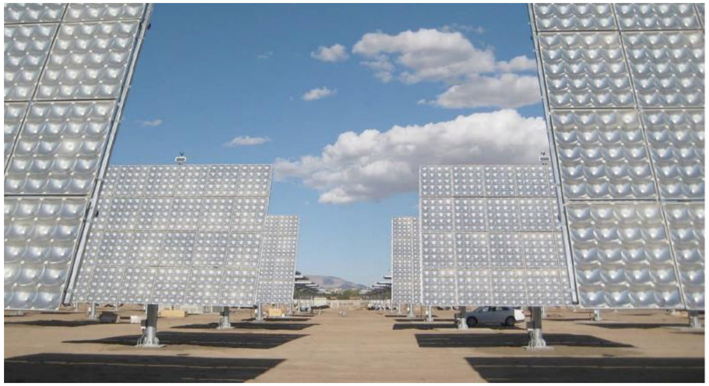


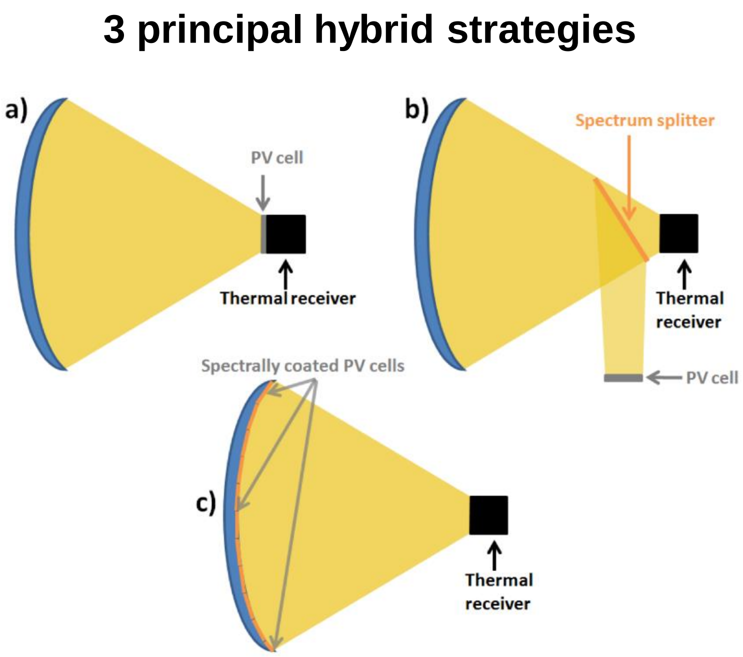
But how?

A. Vossier, J. Zeitouny, E.A. Katz, A. Dollet, G. Flamant, J. M. Gordon,
Sustainable & Energy Fuels, 2018, 2, 2060

High-temperature hybrid photovoltaic-solar thermal plants for dispatchable and high-efficiency electricity generation







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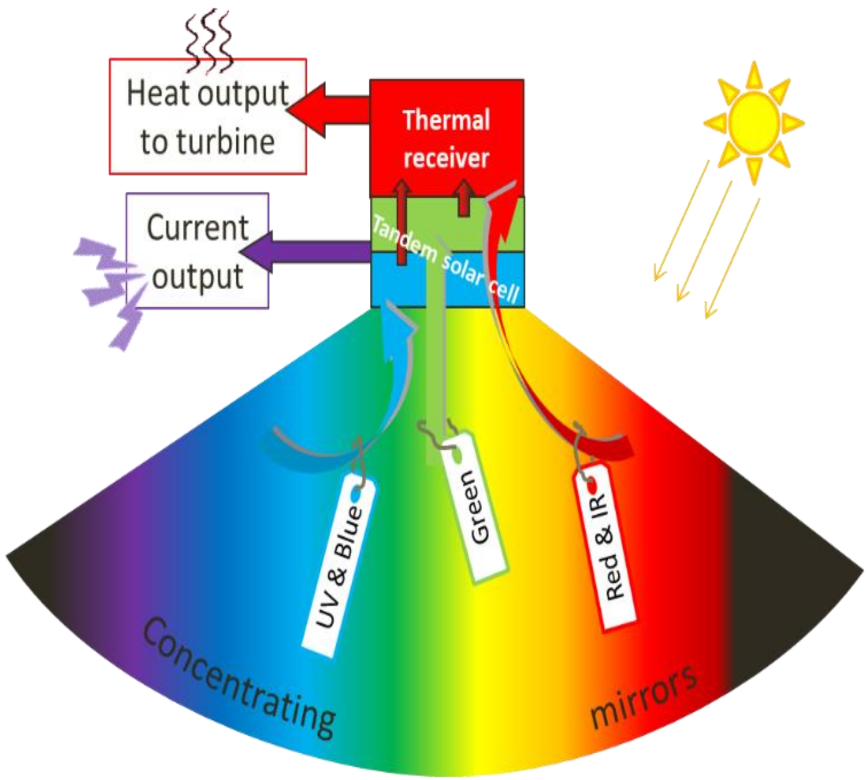
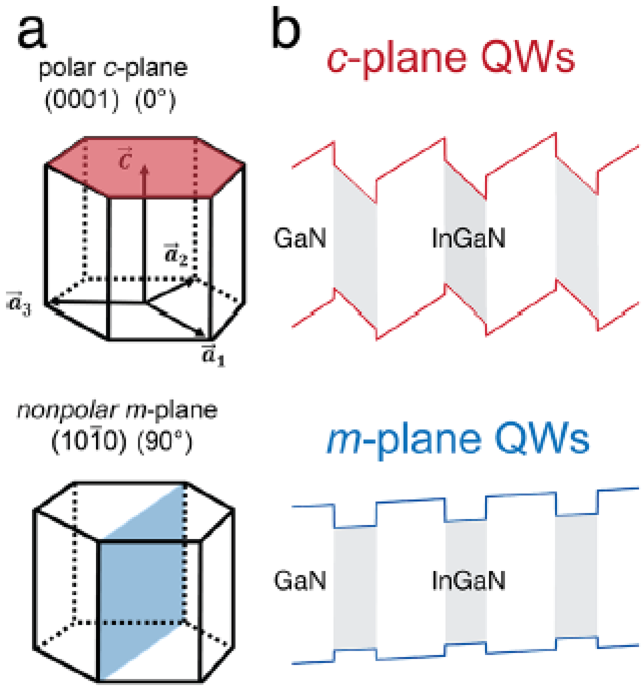
RESEARCH ARTICLE

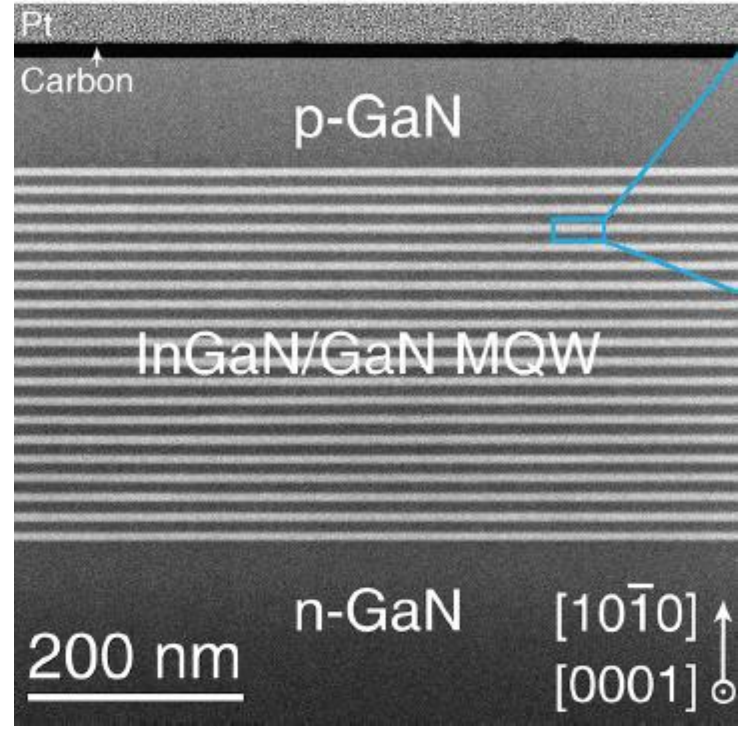
PROGRESS IN PHOTOVOLTAICS WILEY

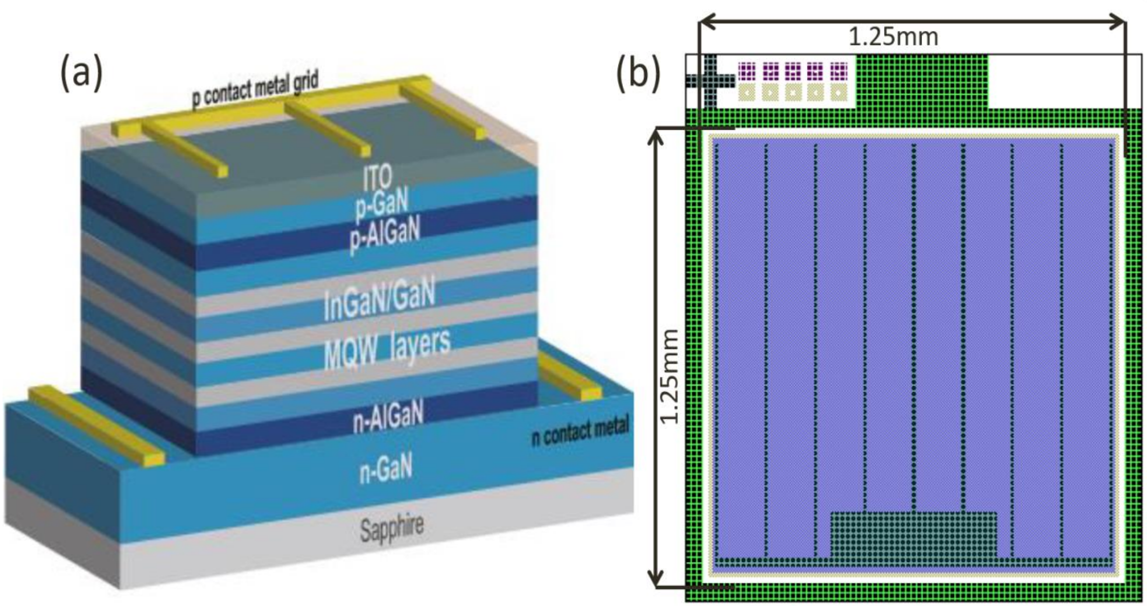
InGaN/GaN multi-quantum-well solar cells under high solar concentration and elevated temperatures for hybrid solar thermal-photovoltaic power plants

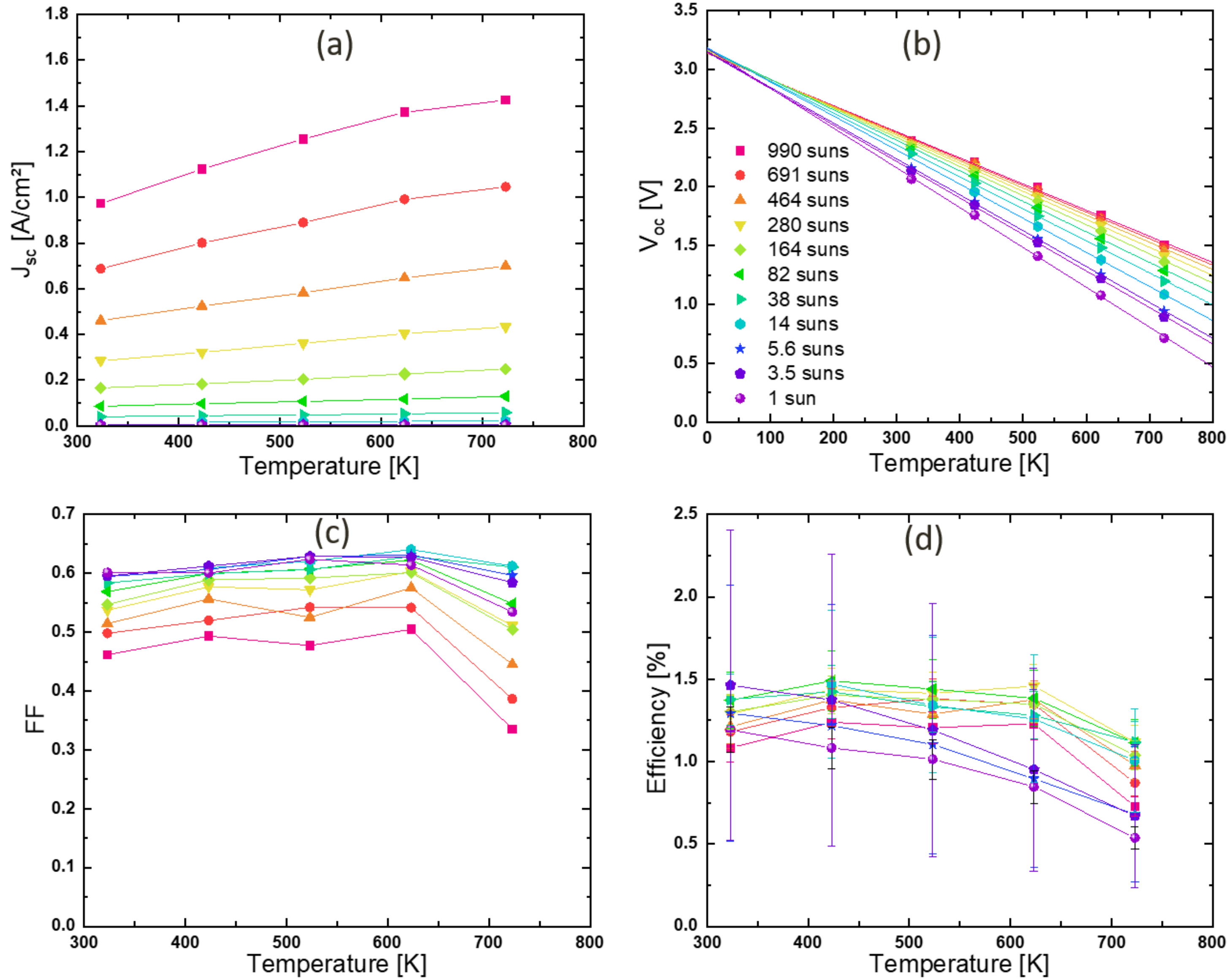
Gilad Moses[1,2] | Xuanqi Huang[3] | Yuji Zhao[3] | Matthias Auf der Maur[4] |
Eugene A. Katz[1,5] | Jeffrey M. Gordon[1]



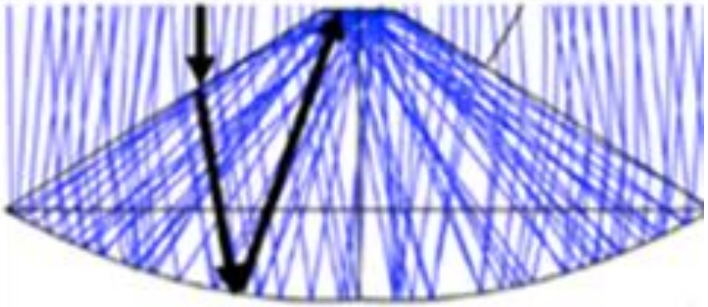

a
polar c-plane
(0001) (0°)
nonpolar m-plane
(10$\bar{1}$0) (90°)
b
c-plane QWs
GaN
InGaN
m-plane QWs
GaN
InGaN

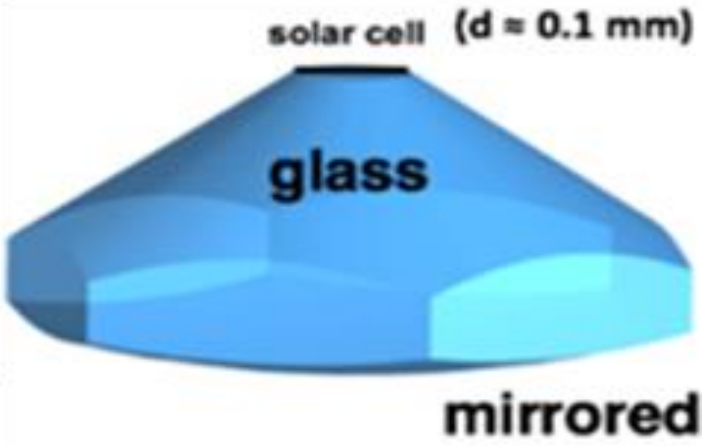

Pt
Carbon
p-GaN
InGaN/GaN MQW
n-GaN
200 nm
[10$\bar{1}$0]
[0001]

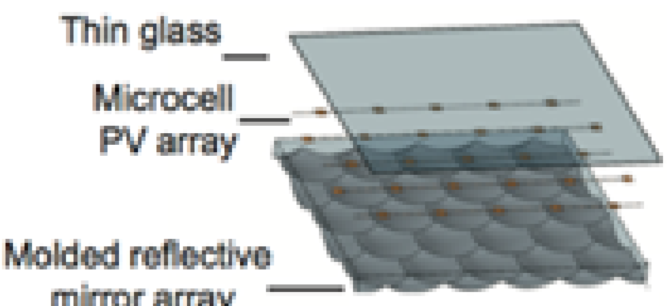

(a)
p contact metal grid
ITO
p-GaN
p-AlGaN
InGaN/GaN
MQW layers
n-AlGaN
n contact metal
n-GaN
Sapphire
(b)
1.25mm
1.25mm



G. Moses, X. Huang, Y. Zhao, M. Auf der Maur, E. A. Katz, J. M. Gordon. GaN/InGaN multi-quantum-well solar cells under high solar concentration and elevated temperatures for hybrid solar thermal-photovoltaic power plants. *Progress in Photovoltaics: Research and Applications*, 28, 1167-1174 (2020).





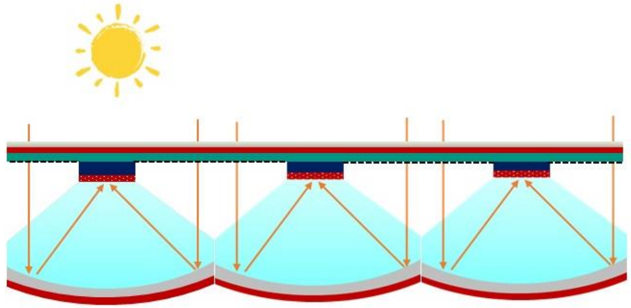


Compact MC lens for space, tested with high-efficiency III-V MJ solar cells

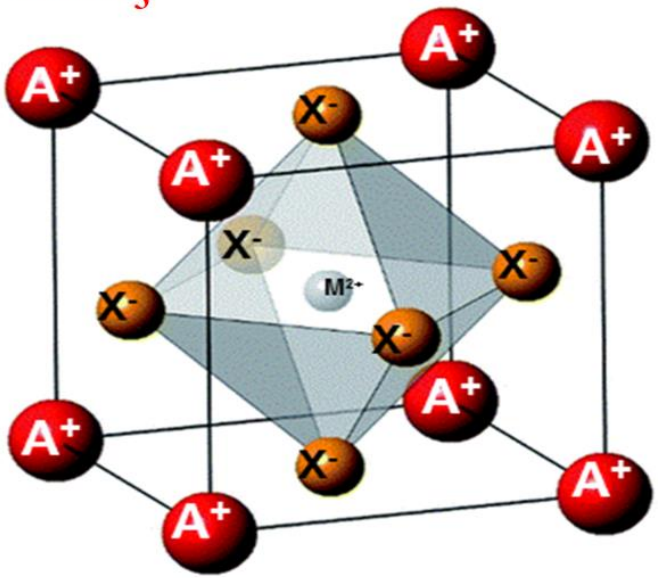
C. J. Ruud, A.J. Grede, J. K. Chang, M. P. Lumb, K. J. Schmieder, B. Fisher, J. A. Rogers, J.M. Gordon. Design and demonstration of ultra-compact microcell concentrating photovoltaics for space. *Optics Express*, 27: A1467 (2019).

C. J. Ruud, J.M. Gordon, N. C. Giebink. Microcell concentrating photovoltaics for space. *Joule*, 7: 1093 (2023).

High-efficiency perovskite μCPV prototype



AMX_3



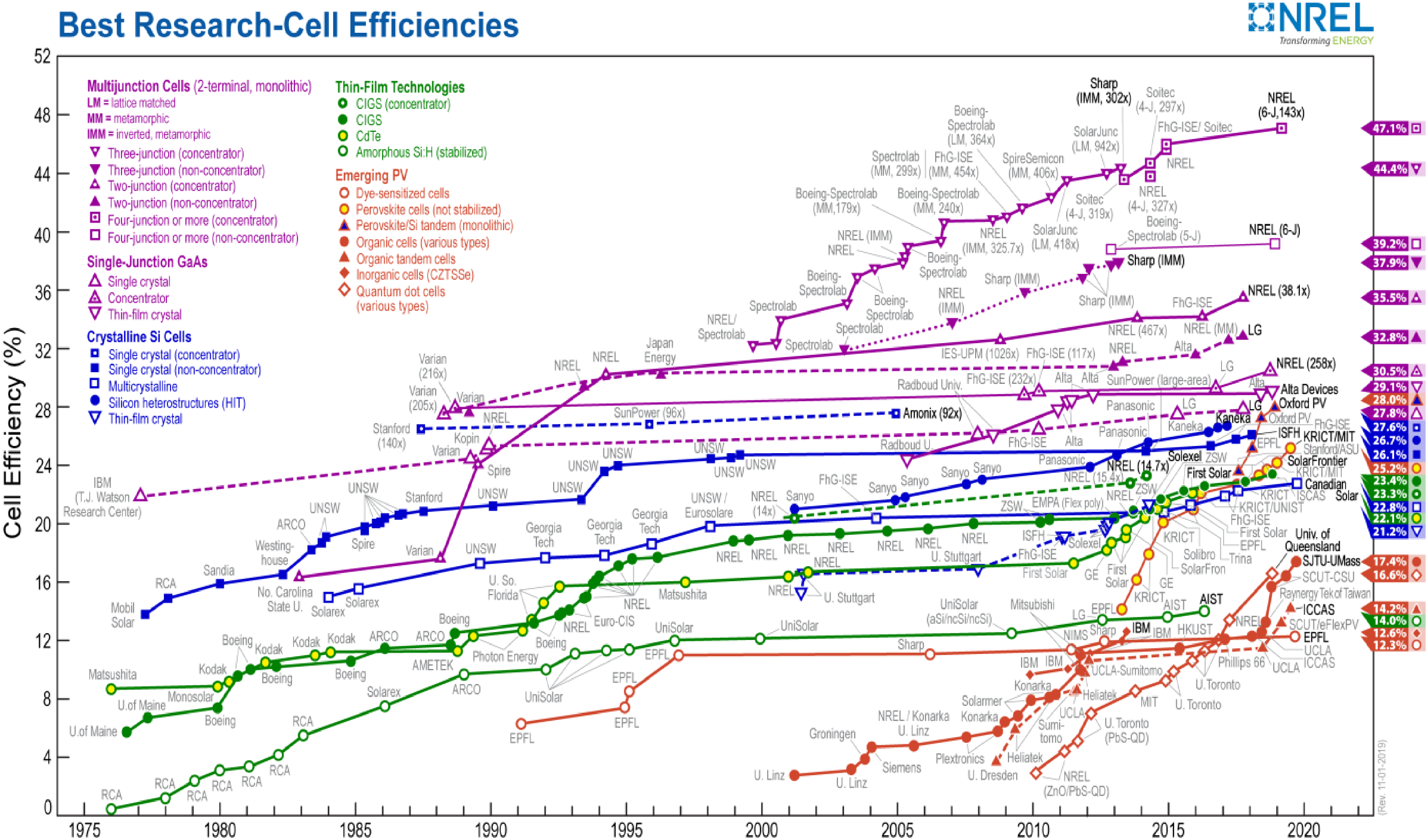
$A = Cs^+$,
$CH_3NH_3^+$ (MA),
$NH{=}CHNH_3^+$ (FA);

M = Pb, Sn;

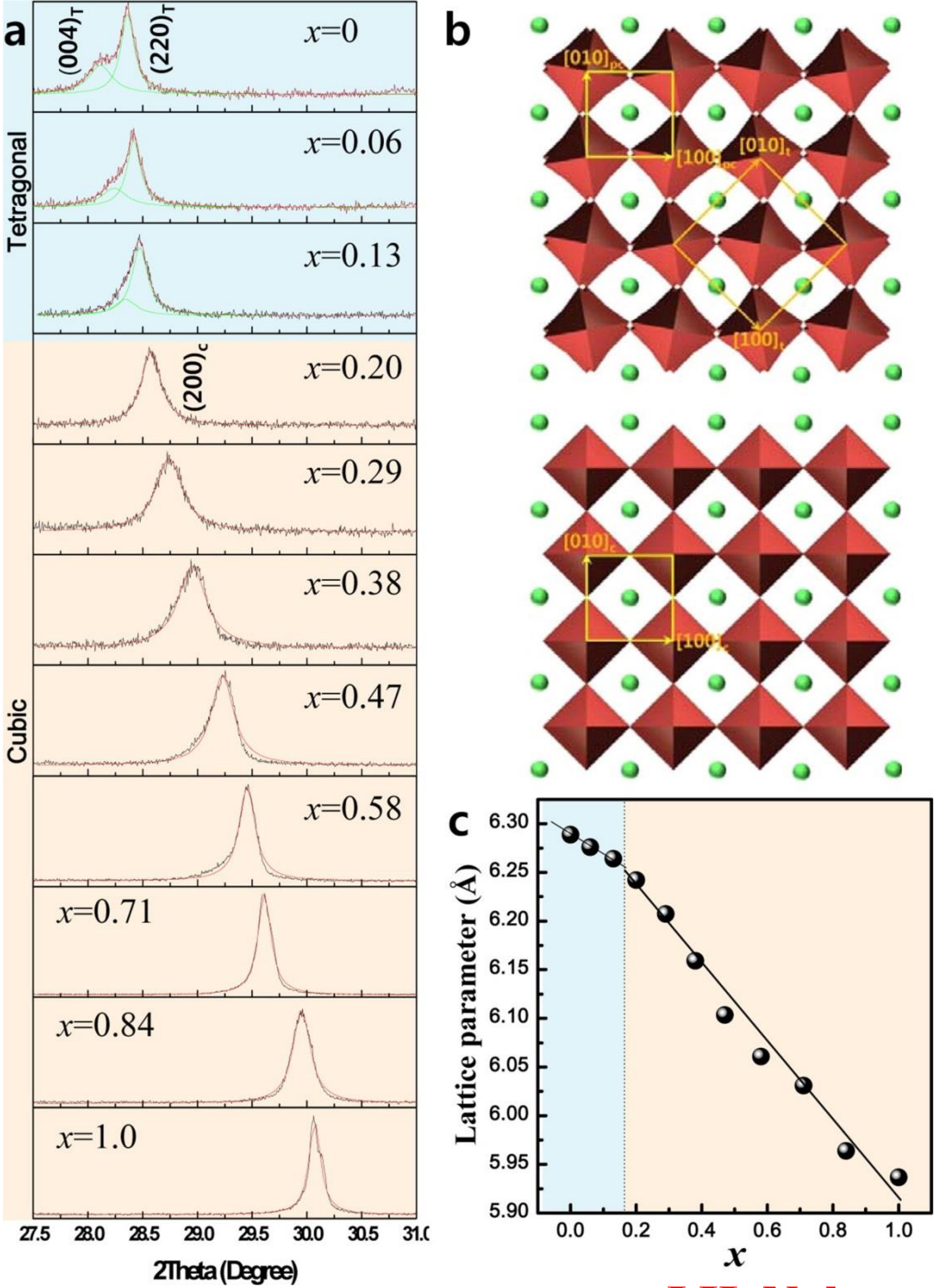
X = I, Br, Cl

$CH_3NH_3PbX_3$

Unit cell of metal halide perovskite.
Here, A is an organic or inorganic cation, M is a divalent metal cation, and X is a halide anion.

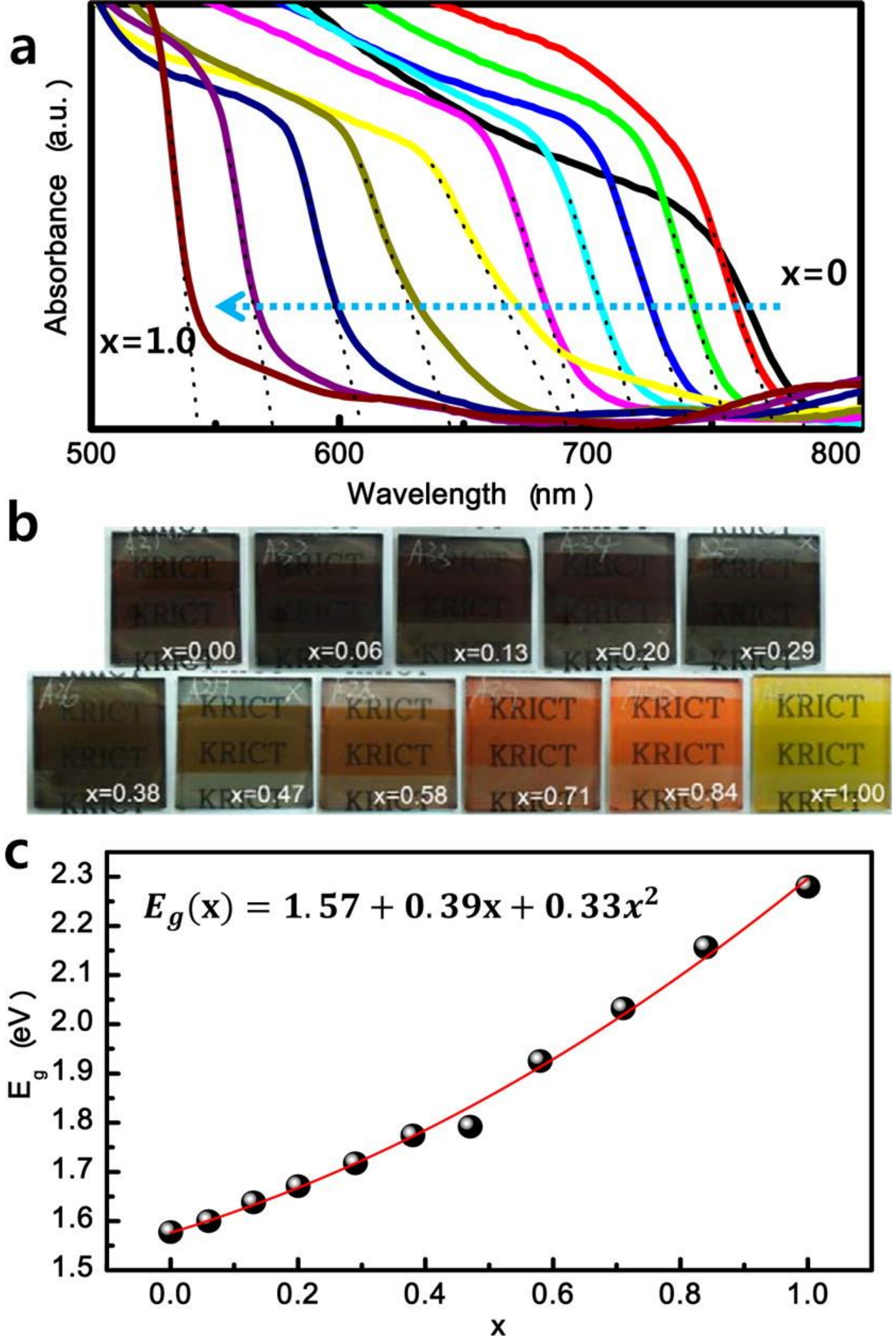


Record laboratory efficiencies of solar cells



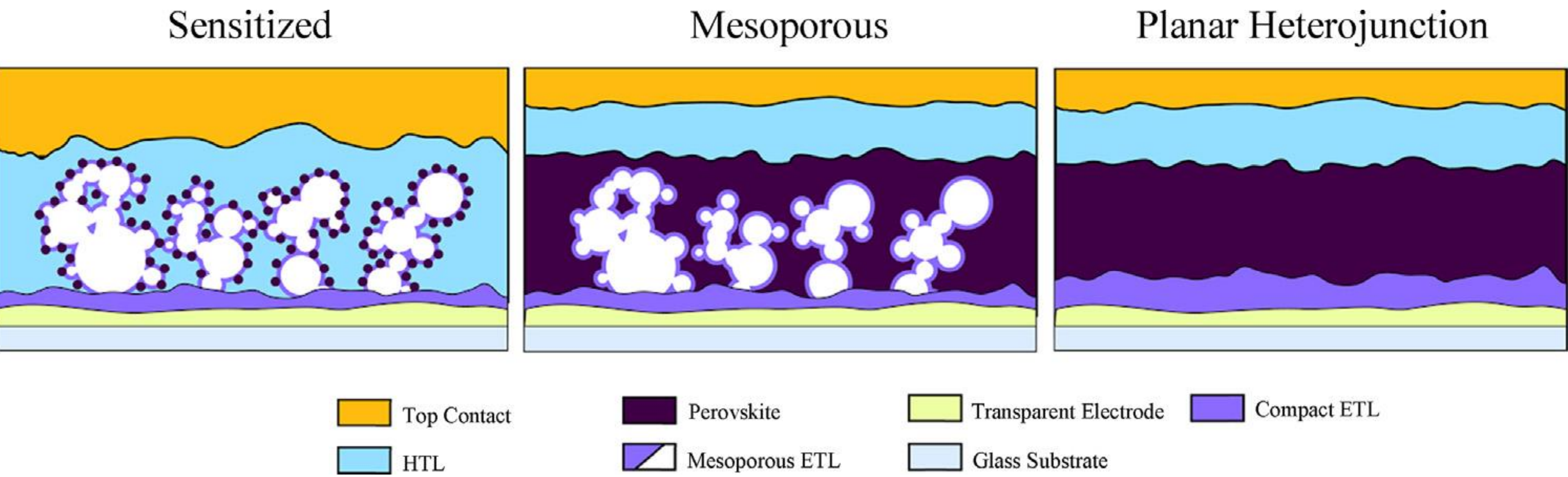
X-ray diffraction analysis of the $MAPb(I_{1-x}Br_x)_3$. (a) XRD patterns of $MAPb(I_{1-x}Br_x)_3$ (x = 0, 0.06, 0.13, 0.20, 0.29, 0.38, 0.47, 0.58, 0.71, 0.84, 1.0), magnified in the region of the tetragonal (004)T and (220)T and cubic (200)C peaks (2θ = 27.5–31.0°). (b) Crystal structures and unit lattice vectors on the (00l) plane of the tetragonal (I4/mcm) (top) and cubic ($Pm\bar{3}m$) (bottom) phases are represented. The tetragonal lattice can be taken by the pseudocubic (pc) lattice. (c) Lattice parameters of pseudocubic or cubic $MAPb(I_{1-x}Br_x)_3$ as a function of Br composition (x).

J.H. Noh, et al, *Nano Letters*. 13, 1764-1769.



Photographs and UV–vis absorption spectra of $MAPb(I_{1-x}Br_x)_3$. (a) UV–vis absorption spectra of FTO/bl-TiO_2/mp-TiO_2/ $MAPb(I_{1-x}Br_x)_3$/Au cells measured using an integral sphere. (b) Photographs of 3D TiO_2/$MAPb(I_{1-x}Br_x)_3$ bilayer nanocomposites on FTO glass substrates. (c) A quadratic relationship of the band-gaps of $MAPb(I_{1-x}Br_x)_3$ as a function of Br composition (x).

J.H. Noh, et al, *Nano Letters*. 13, 1764-1769.



Three major groups of perovskite solar cells categorized based on the deposition sequence.

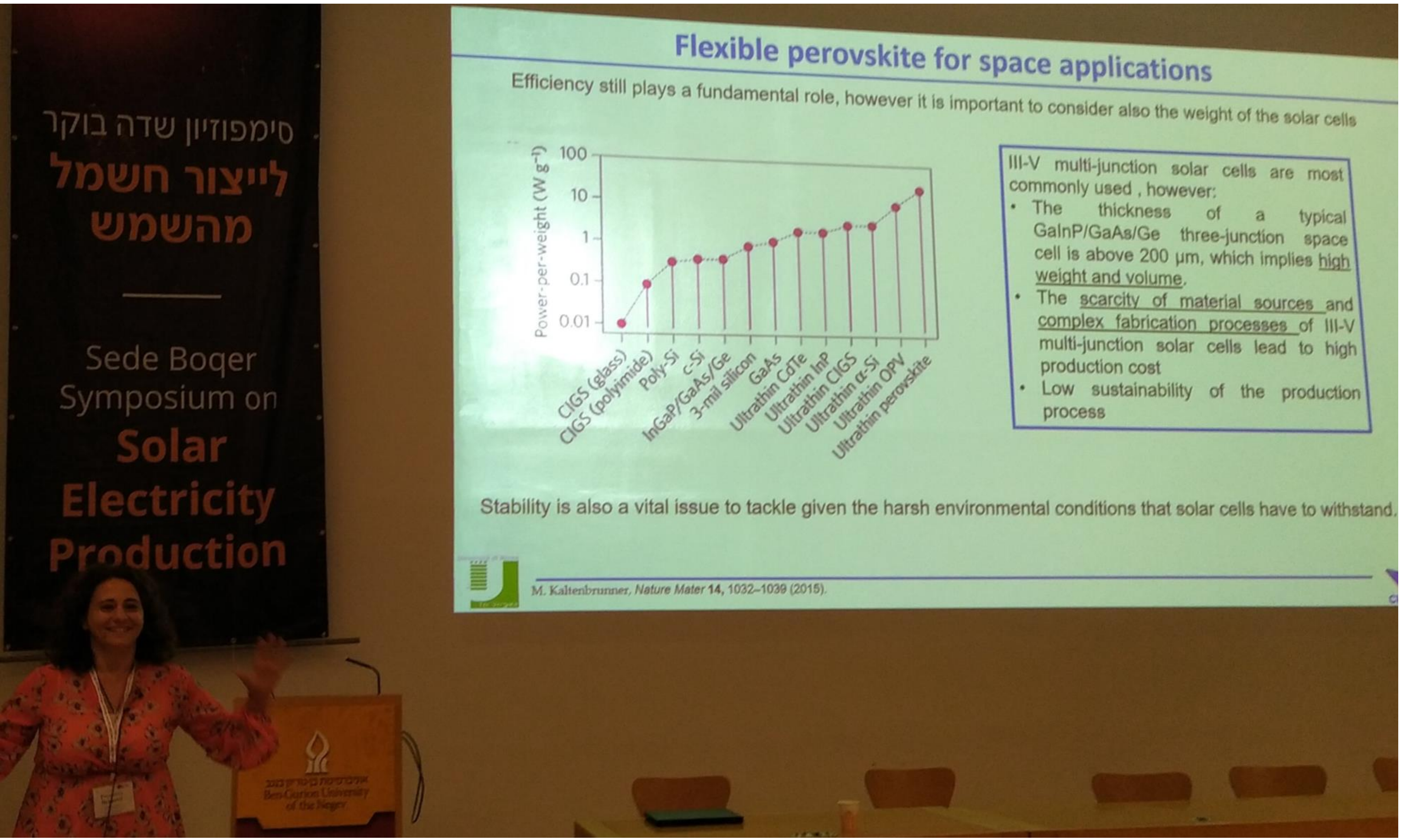
Three intriguing features of metal-halide perovskites

Defect tolerance

Self healing

Resistance to cosmic radiation

due to the softness of the perovskite lattice (?)



Francesca Brunetti, University of Rome Tor Vergata

M. Kaltenbrunner, et al, Nature Mater. 14, 1032, 2015.

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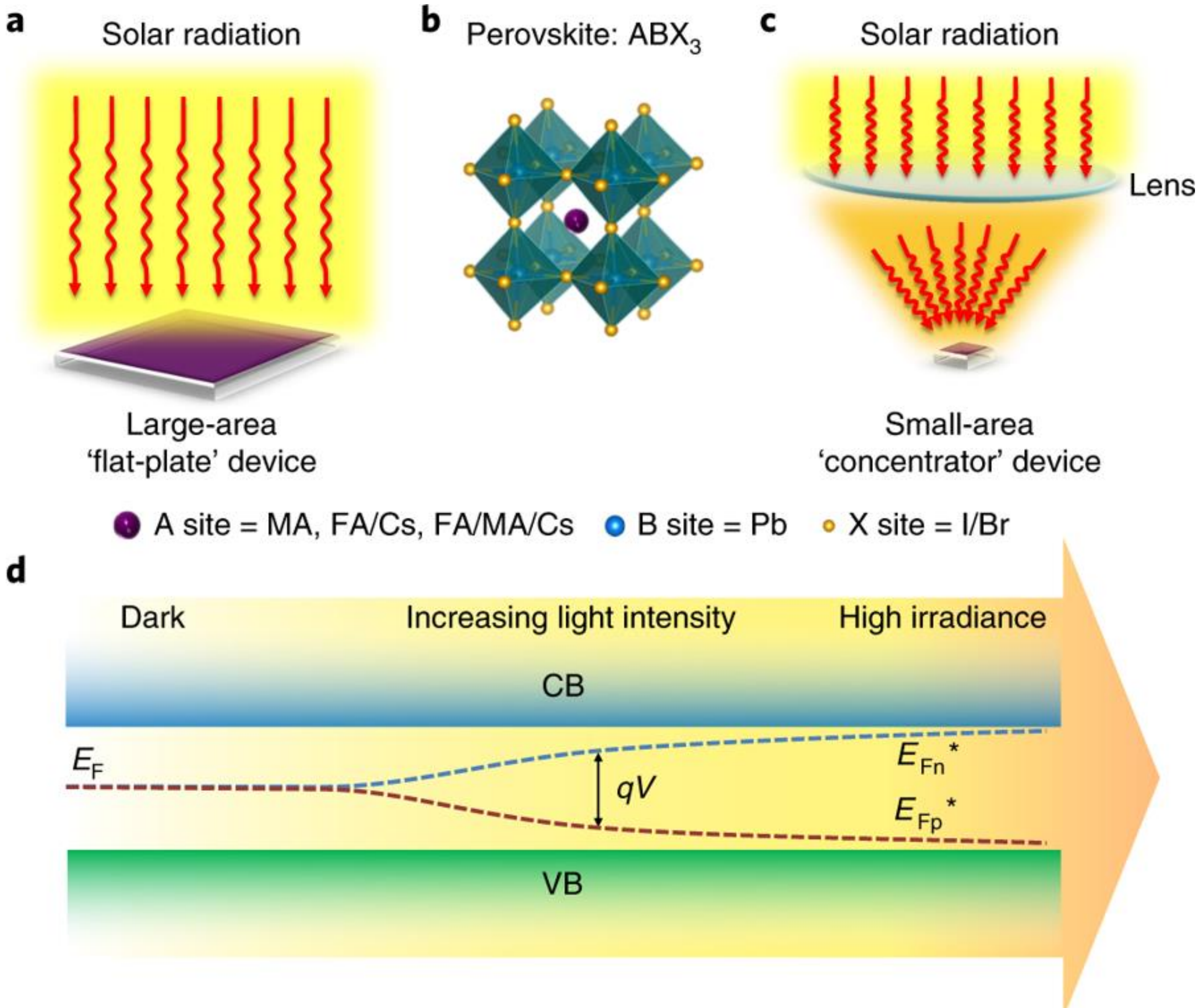
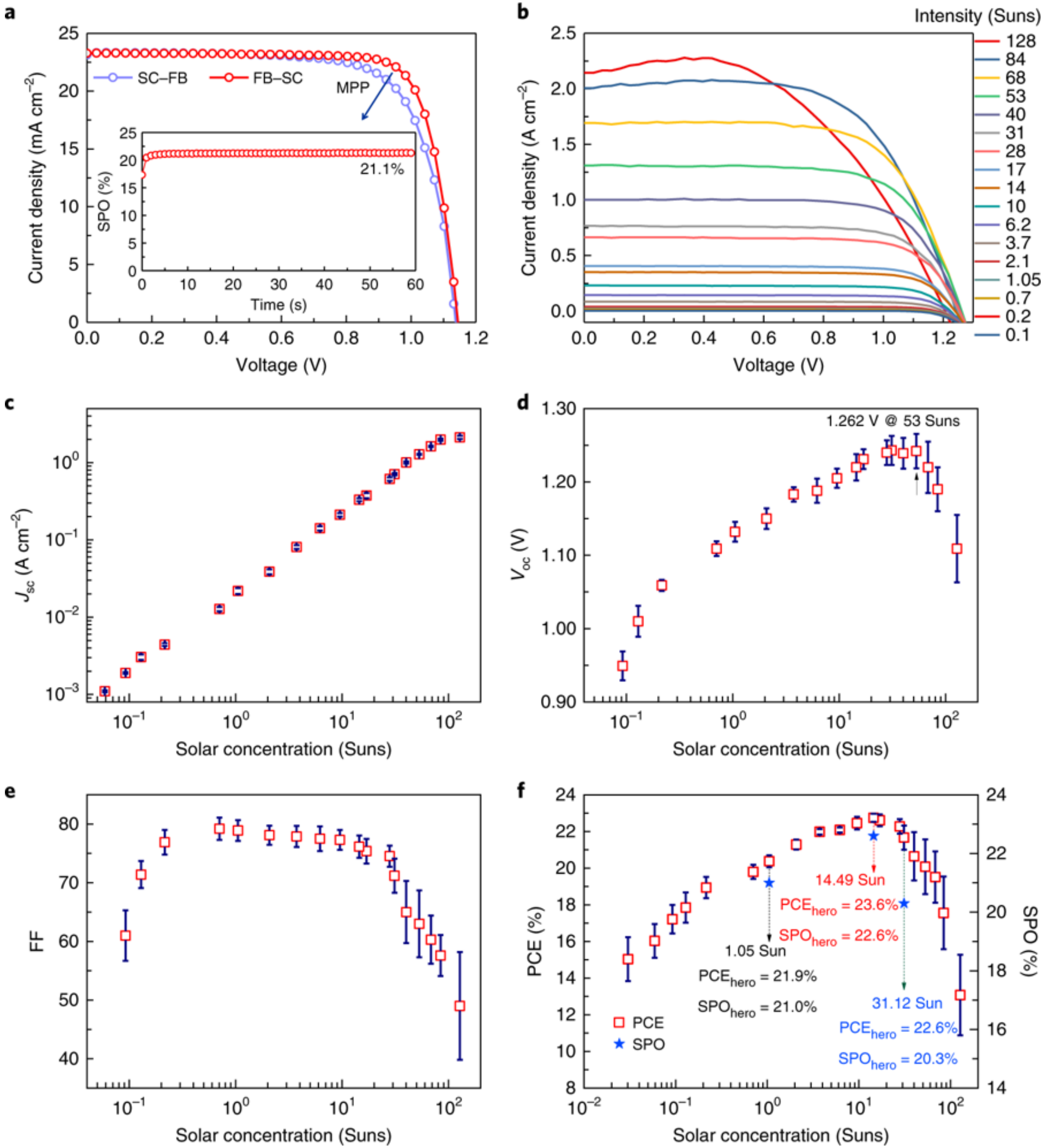
https://doi.org/10.1038/s41560-018-0220-2

Corrected: Publisher Correction

High irradiance performance of metal halide perovskites for concentrator photovoltaics

Zhiping Wang[1,2], Qianqian Lin[1,2], Bernard Wenger[1], M. Greyson Christoforo[1], Yen-Hung Lin[1], Matthew T. Klug[1], Michael B. Johnston[1], Laura M. Herz[1] and Henry J. Snaith[1*]


a
Solar radiation
Large-area
'flat-plate' device
b
Perovskite: ABX3
c
Solar radiation
Lens
Small-area
'concentrator' device
A site = MA, FA/Cs, FA/MA/Cs
B site = Pb
X site = I/Br
d
Dark
Increasing light intensity
High irradiance
CB
EF
qV
EFn*
EFp*
VB



a
SC–FB
FB–SC
MPP
21.1%
SPO (%)
Time (s)
Current density (mA cm^{-2})
Voltage (V)
b
Intensity (Suns)
128
84
68
53
40
31
28
17
14
10
6.2
3.7
2.1
1.05
0.7
0.2
0.1
Current density (A cm^{-2})
Voltage (V)
c
J_{sc} (A cm^{-2})
Solar concentration (Suns)
d
1.262 V @ 53 Suns
V_{oc} (V)
Solar concentration (Suns)
e
FF
Solar concentration (Suns)
f
14.49 Sun
PCE$_{hero}$ = 23.6%
SPO$_{hero}$ = 22.6%
1.05 Sun
PCE$_{hero}$ = 21.9%
SPO$_{hero}$ = 21.0%
31.12 Sun
PCE$_{hero}$ = 22.6%
SPO$_{hero}$ = 20.3%
PCE
SPO
PCE (%)
SPO (%)
Solar concentration (Suns)

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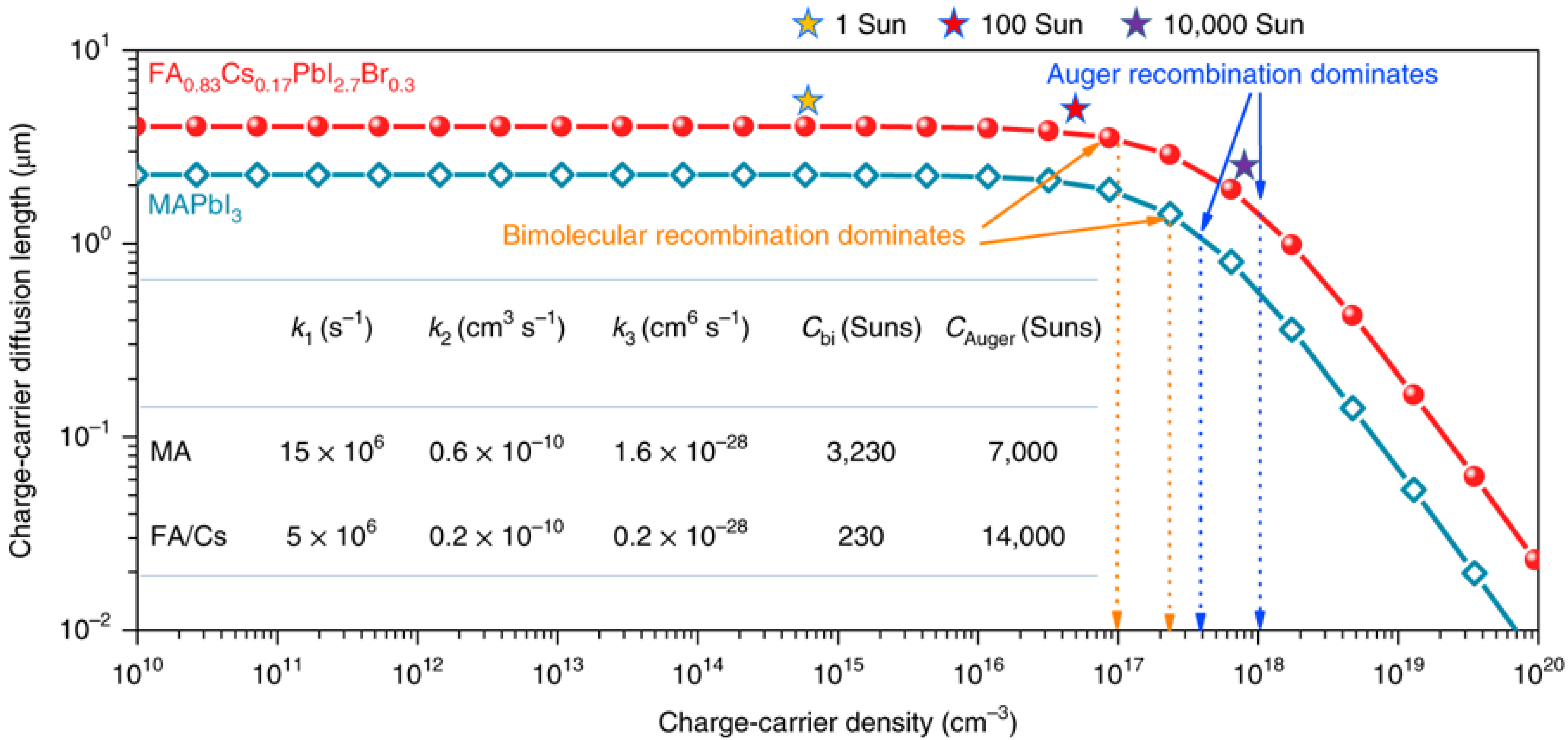

	k_1 (s^{-1})	k_2 ($cm^3 s^{-1}$)	k_3 ($cm^6 s^{-1}$)	C_{bi} (Suns)	C_{Auger} (Suns)
MA	15×10^6	0.6×10^{-10}	1.6×10^{-28}	3,230	7,000
FA/Cs	5×10^6	0.2×10^{-10}	0.2×10^{-28}	230	14,000

Take home messages

Concentrator photovoltaics (CPV) provides possibilities for:

- ultra-high efficiency;
- high tolerance to the cell heating;
- hybrid technologies: CPV-thermoelectricity, CPV-thermosolar (CSP) – prospect for thermal storage;
- CPV (microcells) with ultra-high specific power and high tolerance to cosmic radiation (perovskites)

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