# Concentrating & Splitting Optics Toolkit

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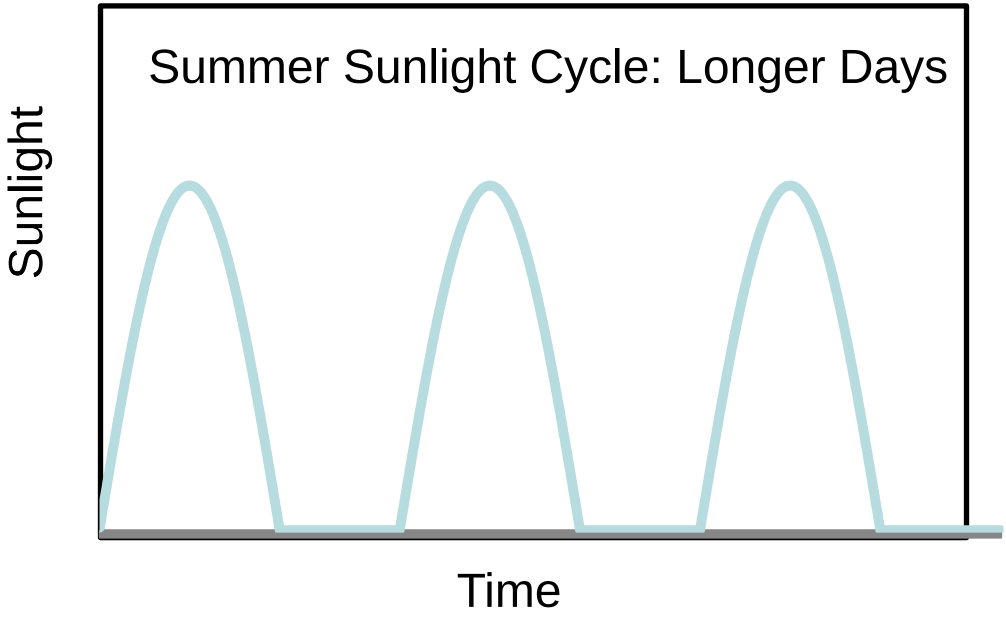
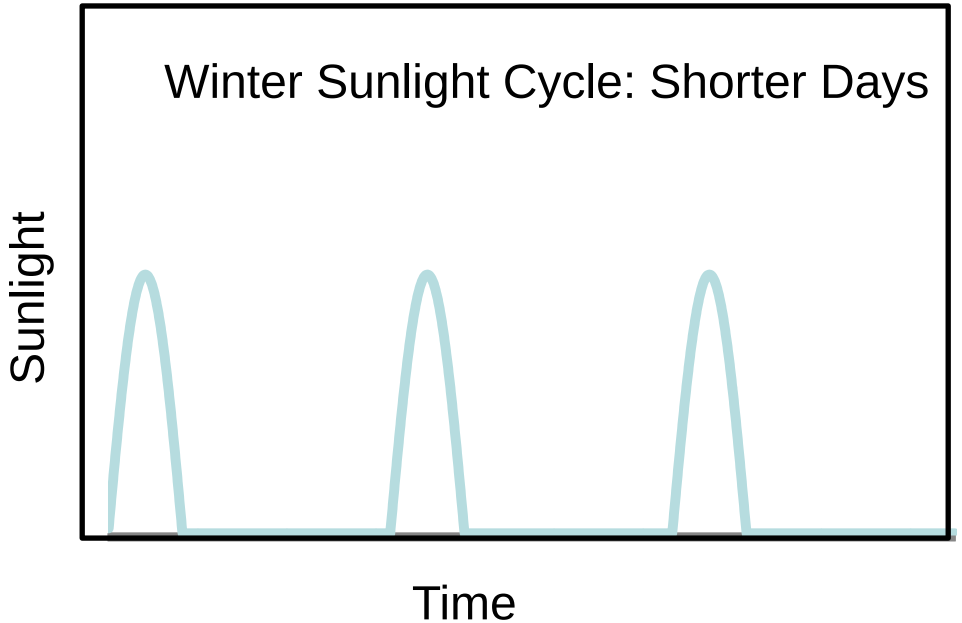
Boulder, CO
April 11, 2013

# Need for seasonal, long term energy storage.

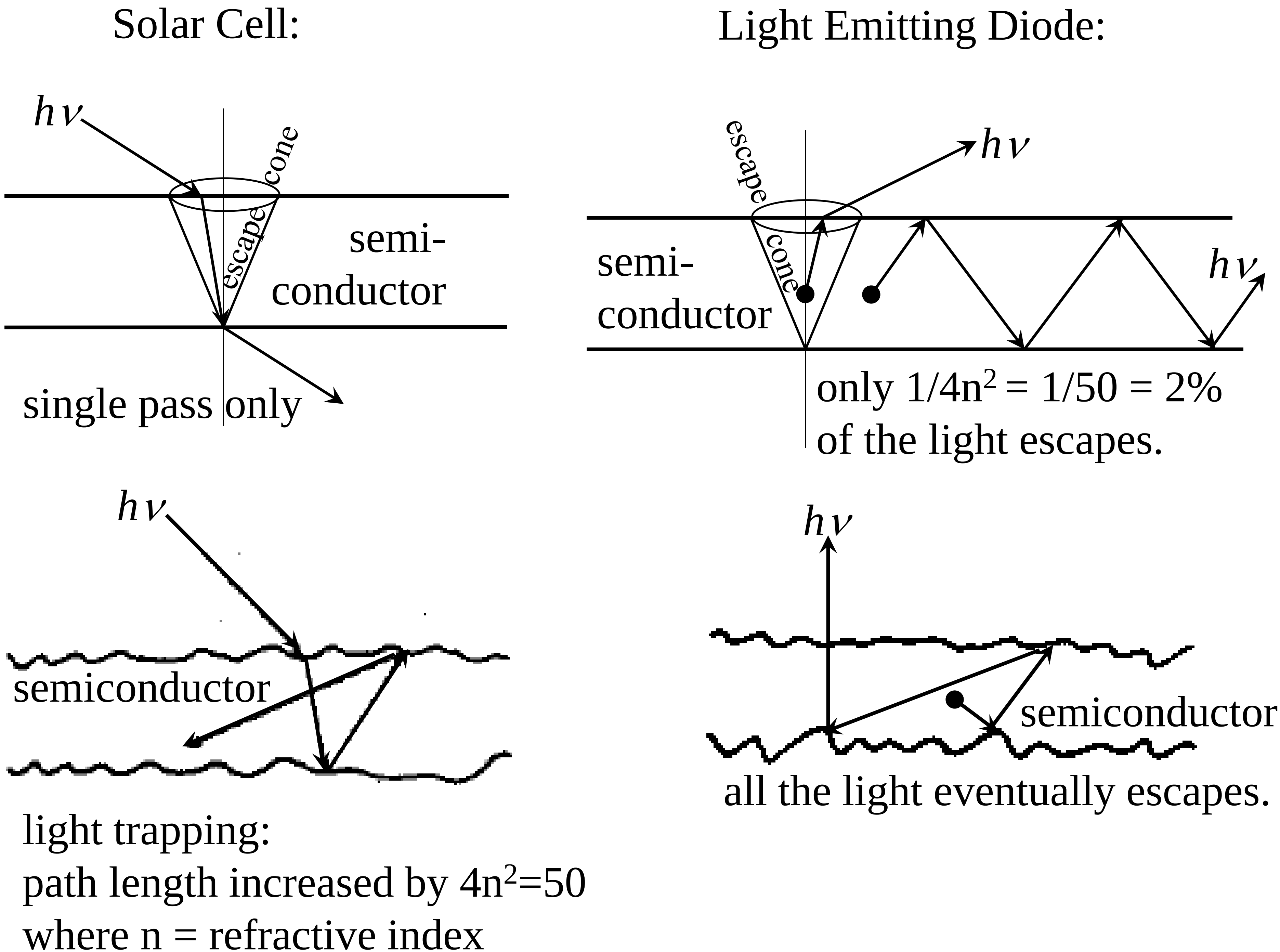



-Summer: More hours of daylight.
Sun is higher in the sky




-Winter: Shorter days, increased cloudiness, and sun is lower.

Therefore storable fuel,
not batteries
are needed.


Solar Cell:
Light Emitting Diode:
hν
escape cone
semi-
conductor
single pass only
hν
escape cone
semi-
conductor
hν
hν
only 1/4n² = 1/50 = 2%
of the light escapes.
hν
semiconductor
light trapping:
path length increased by 4n²=50
where n = refractive index
hν
semiconductor
all the light eventually escapes.

$$\text{Density of Optical Modes per Unit Volume in air} = \frac{8\pi\,\nu^2}{c^3}$$

$$\text{Density of Optical Modes per Unit Volume in semiconductor} = \frac{8\pi\,n^2\,\nu^2}{c^3}$$

What is the ratio? …… $n^2$

There is a factor 2 from double pass

and

There is a factor 2 from $\cos\theta$ averaging

The net benefit is $4n^2$

**Light Trapping Requirement:**

1. Either the high index material has to be textured, or the photon recycling should be very efficient.

**The Benefit:**

a. $4n^2$ ~50 times thinner layer can be sufficient to absorb the sunlight saving semiconductor cost.
b. In a thinner cell, there is less series resistance, and a higher Fill Factor
c. The operating point voltage, (not just $V_{oc}$), increases by $kT \ln\{4n^2\} \sim 0.1$Volts.

Total Internal Reflection is completely compatible with an Anti-Reflection Coating.

What is the ideal voltage $V_{oc}$ to expect, i.e. the Quasi-Fermi Level separation, chemical potential, or Free Energy?

$$\exp\left\{\frac{\text{Free Energy}}{\text{kT}}\right\} = \left\{\frac{\textit{excited state population in the light}}{\textit{excited state population in the dark}}\right\}$$

Boltzmann Factor

In molecules and quantum dots:

$$qV_{oc} = \text{Free energy} = kT \ln\left\{\frac{\text{excited state population in the light}}{\text{excited state population in the dark}}\right\}$$

In semiconductors with mobile electrons & holes:

$$\text{Free energy} = E_{Fc} - E_{Fv} = 2kT \ln\left\{\frac{\text{electron density in the light}}{\text{electron density in the dark}}\right\}$$

What is the voltage to expect, i.e. the Quasi-Fermi Level separation, chemical potential, or Free Energy?

Shockley-Queisser Limit (1961):

$$qV_{oc} = kT \ln\left\{\frac{\text{external Luminescent emission}}{\text{band – to – band emission in the dark}}\right\}$$

But in quasi-equilibrium:

$$qV_{oc} = kT \ln\left\{\frac{\text{incoming sunlight}}{\text{band – to – band emission in the dark}}\right\}$$

# Yes photons have entropy, S

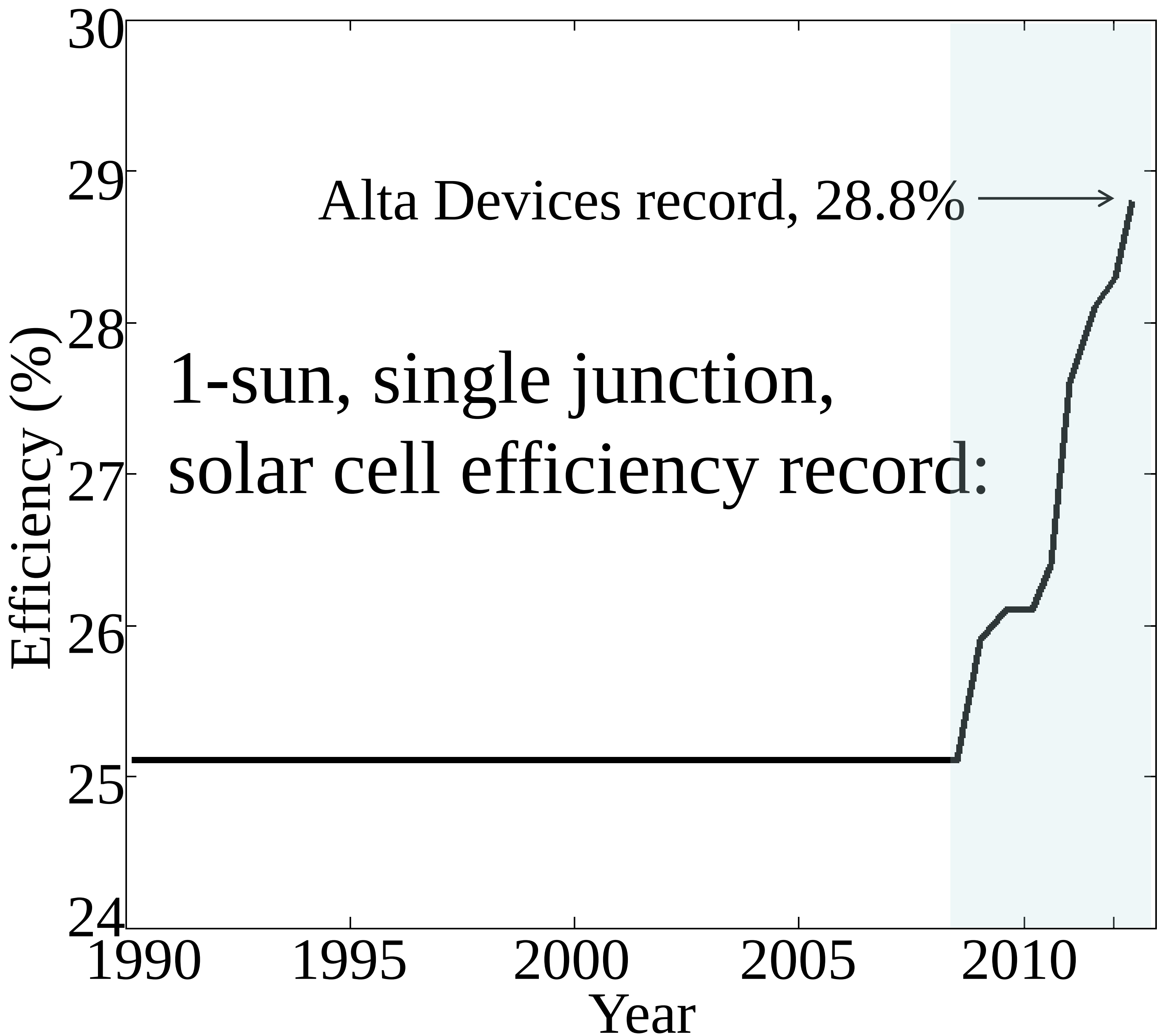
## Photon Free Energy = hν - TS
## Photon Free Energy = hν - kT lnW

$qV_{\mathbf{operating\ point}} =$

$$E_g - kT\{\underbrace{\overbrace{\ln(\pi/\Omega_s)}^{-0.28eV}}_{\text{Entropy due to loss of directivity information}} + \underbrace{\overbrace{\ln(4n^2)}^{-0.1eV}}_{\text{Entropy due to incomplete light trapping}} + \underbrace{\overbrace{\ln(qV_{op}/kT)}^{-0.1eV}}_{\text{Free energy loss due to power-point optimization}} - \underbrace{\overbrace{\ln(\eta)}^{0.0\rightarrow -0.3eV}}_{\text{Free energy loss due to poor } \eta \equiv \text{ Quantum Efficiency}} \overbrace{- \underbrace{\ln\left(\frac{1.4T_s}{T} e^{-\frac{E_g}{kT_s}}\right)}_{\text{correction for Planck emission-bandwidth}}}^{+0.02eV}\}$$

where $\Omega_s$ is the solid angle subtended by the sun

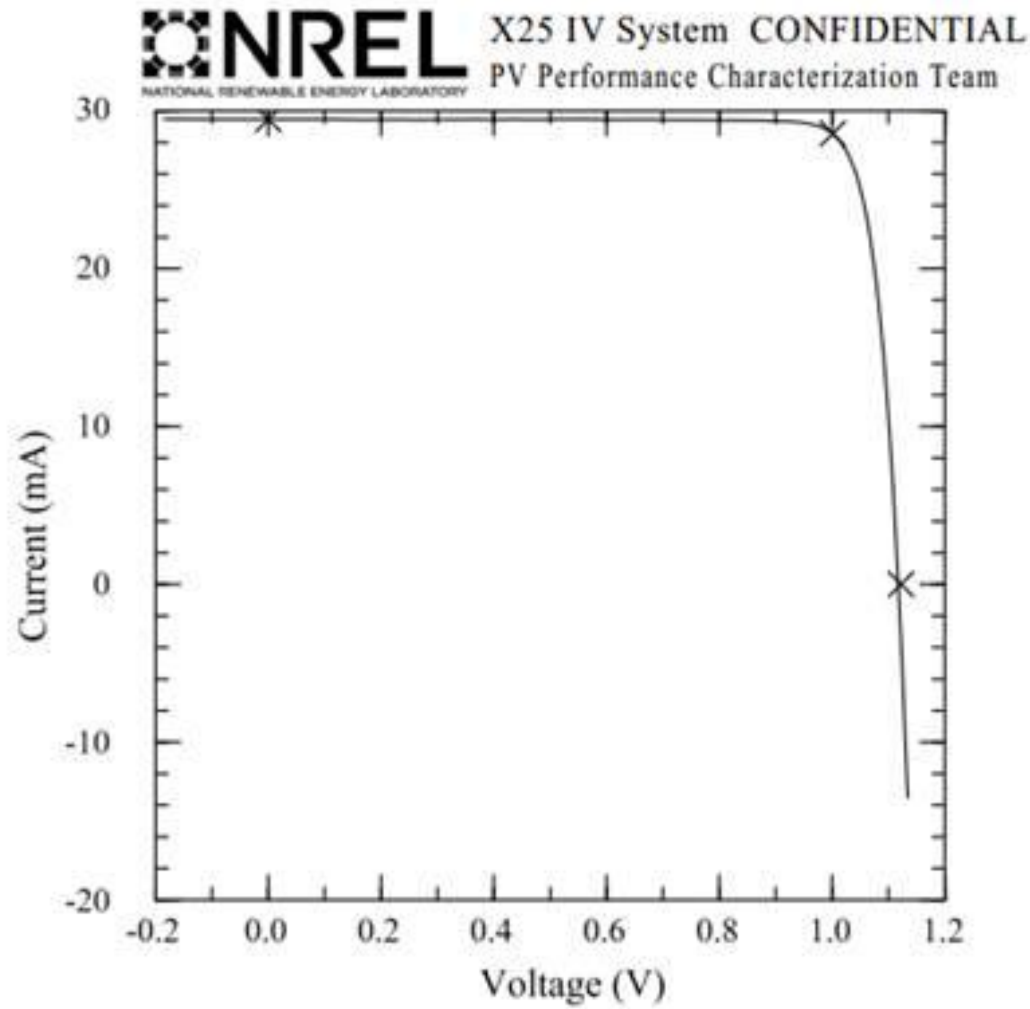
nicest treatment:
R.T.Ross "Some Thermodynamics of PhotoChemical Systems", J. Chem. Phys. 46, 44590 (1967)



Alta Devices record, 28.8%
1-sun, single junction,
solar cell efficiency record:
Efficiency (%)
30
29
28
27
26
25
24
1990
1995
2000
2005
2010
Year

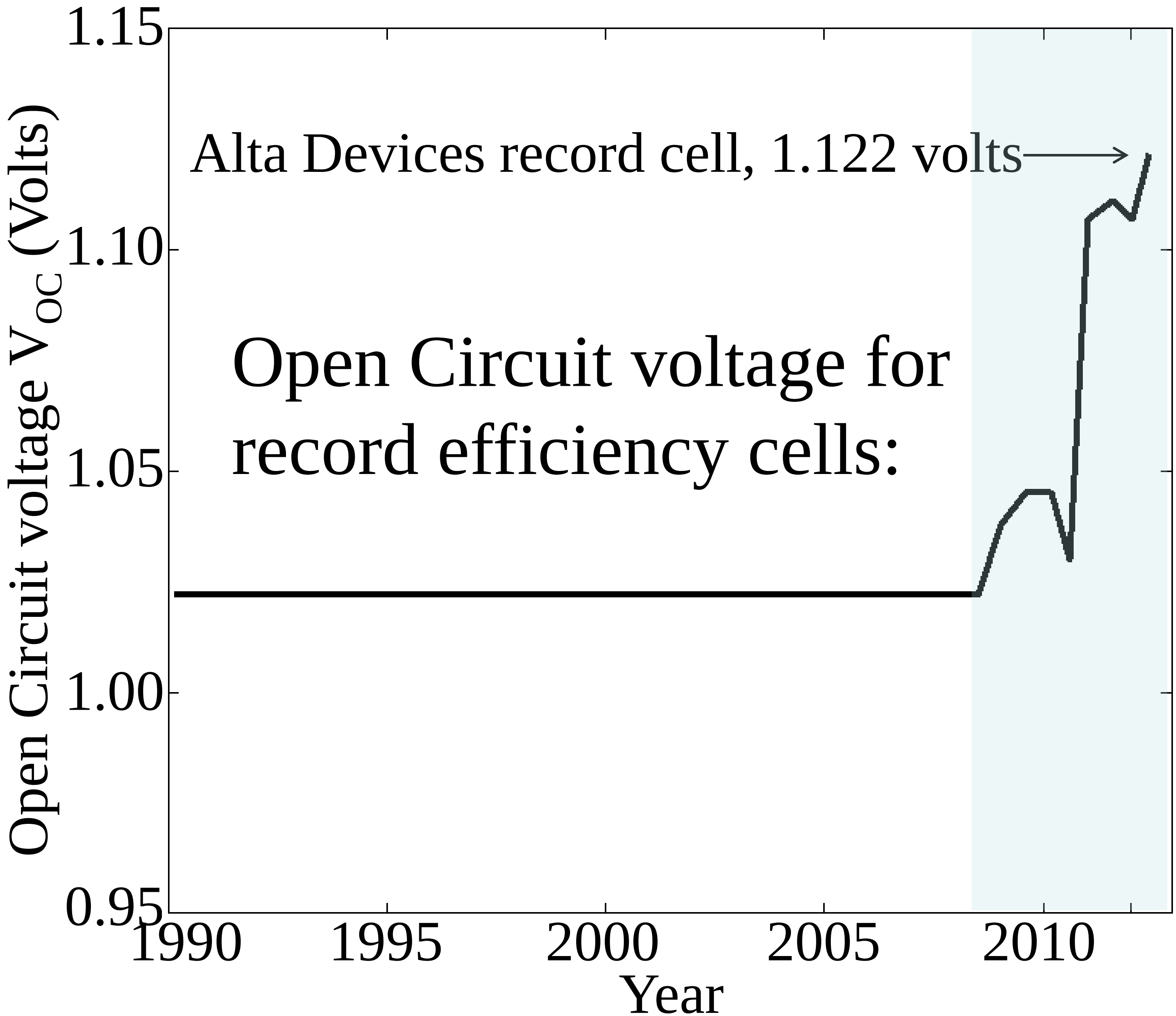
Latest 1 sun single-junction results from Alta Devices, Inc.

Expected to reach 34% dual junction, eventually.




$V_{oc}$ = 1.1220 V
$I_{sc}$ = 29.461 mA
$J_{sc}$ = 29.677 mA/cm$^2$
Fill Factor = 86.50 %

$I_{max}$ = 28.557 mA
$V_{max}$ = 1.0013 V
$P_{max}$ = 28.593 mW
Efficiency = 28.80 %



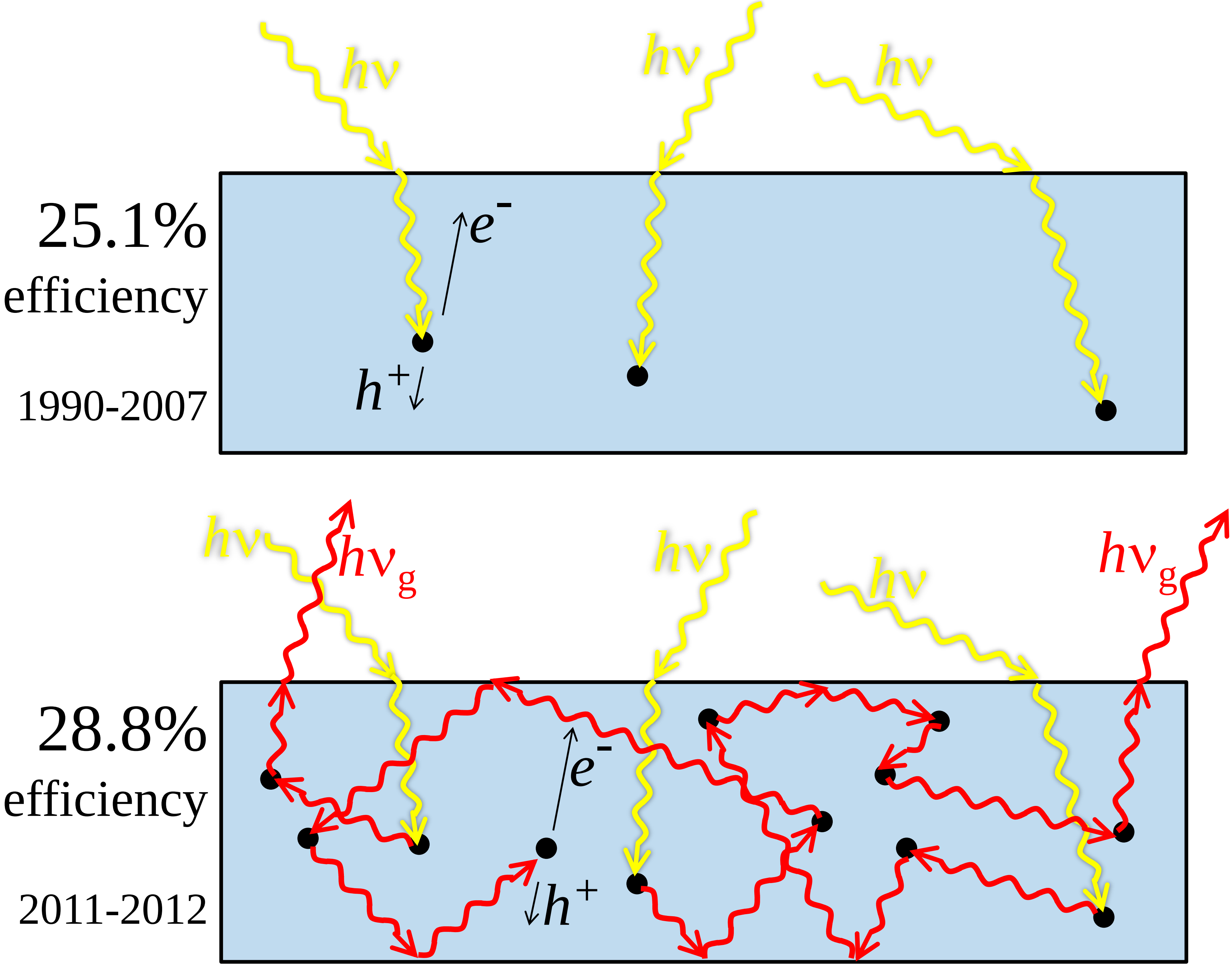
Alta Devices record cell, 1.122 volts
Open Circuit voltage for
record efficiency cells:
Open Circuit voltage $V_{OC}$ (Volts)
1.15
1.10
1.05
1.00
0.95
1990
1995
2000
2005
2010
Year

What if the material is not ideal, and the electrons and holes are lost to heat before they can luminesce?

$$qV_{oc} = qV_{oc\text{-}ideal} - kT|\ln\{\eta_{ext}\}|$$

The external fluorescence yield $\eta_{ext}$ is what matters!

Only external Luminescence can balance the incoming radiation.



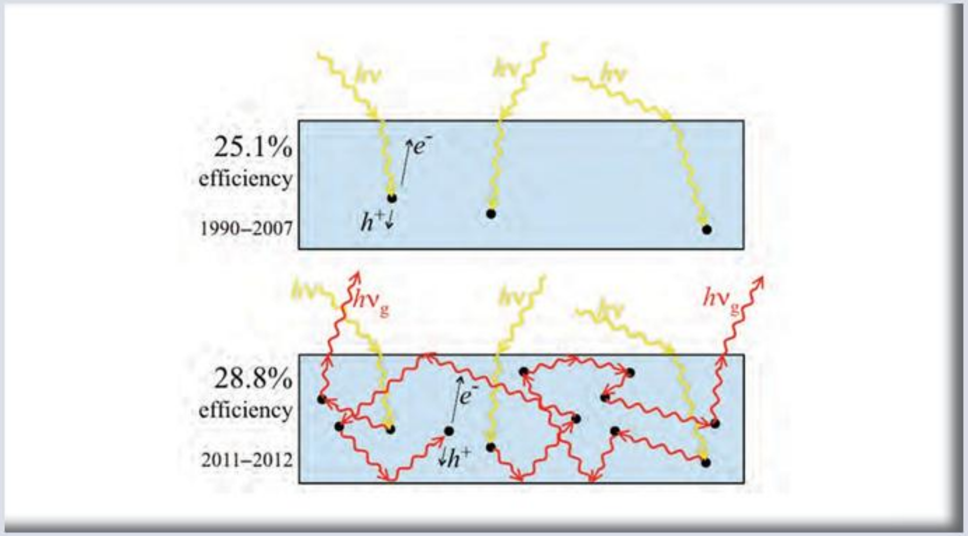
25.1%
efficiency
1990-2007
$h\nu$
$e^-$
$h^+$
28.8%
efficiency
2011-2012
$h\nu_g$

February 2013
Vol. 27, No. 1
www.PhotonicsSociety.org

IEEE photonics SOCIETY NEWS

## The Opto-Electronics of Solar Cells

## Recent Advances in Colloidal Quantum Dot Photovoltaics




### Also Inside:

- IEEE Photonics Society 2013 Fellows
- 2013–15 Elected Members of Board of Governors

IEEE

For solar cells at 25%,
good electron-hole transport is already a given.

Further improvements of efficiency above 25% are all about the photon management!

A good solar cell has to be a good LED!

Counter-intuitively, the solar cell performs best when there is
maximum external fluorescence yield $\eta_{ext}$.

Miller et al, IEEE J. Photovoltaics, vol. 2, pp. 303-311 (2012)

Paradox: Why is external luminescence is good for solar cell efficiency?
Reason #5; Luminescence IS Voltage:

External luminescence is sometimes used as a type of **contactless voltmeter**, indicating the separation of quasi-Fermi levels in the solar material.

$$\text{Luminescence} = \mathrm{B}np = \mathrm{B}n_i^2\, exp\{qV/kT\}$$

(This is sometimes employed as a contactless, quality-control-metric, in solar cell manufacturing plants. )

This viewpoint is tautological:
Good external luminescence actually is good voltage, and therefore good efficiency.

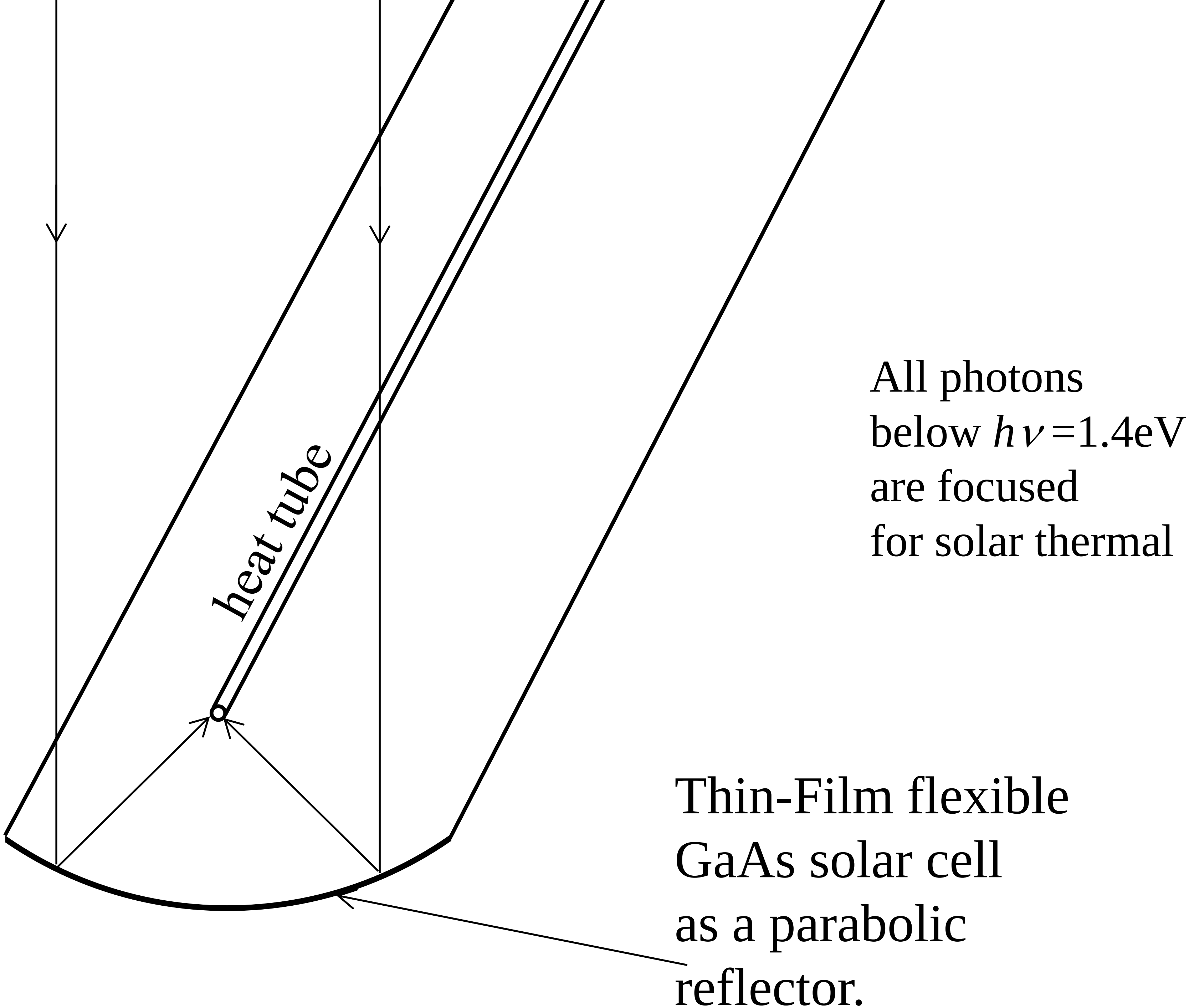
Diffuse Light has lots of entropy:

$S=k\,ln(\pi/\Omega_s) \approx 12k$

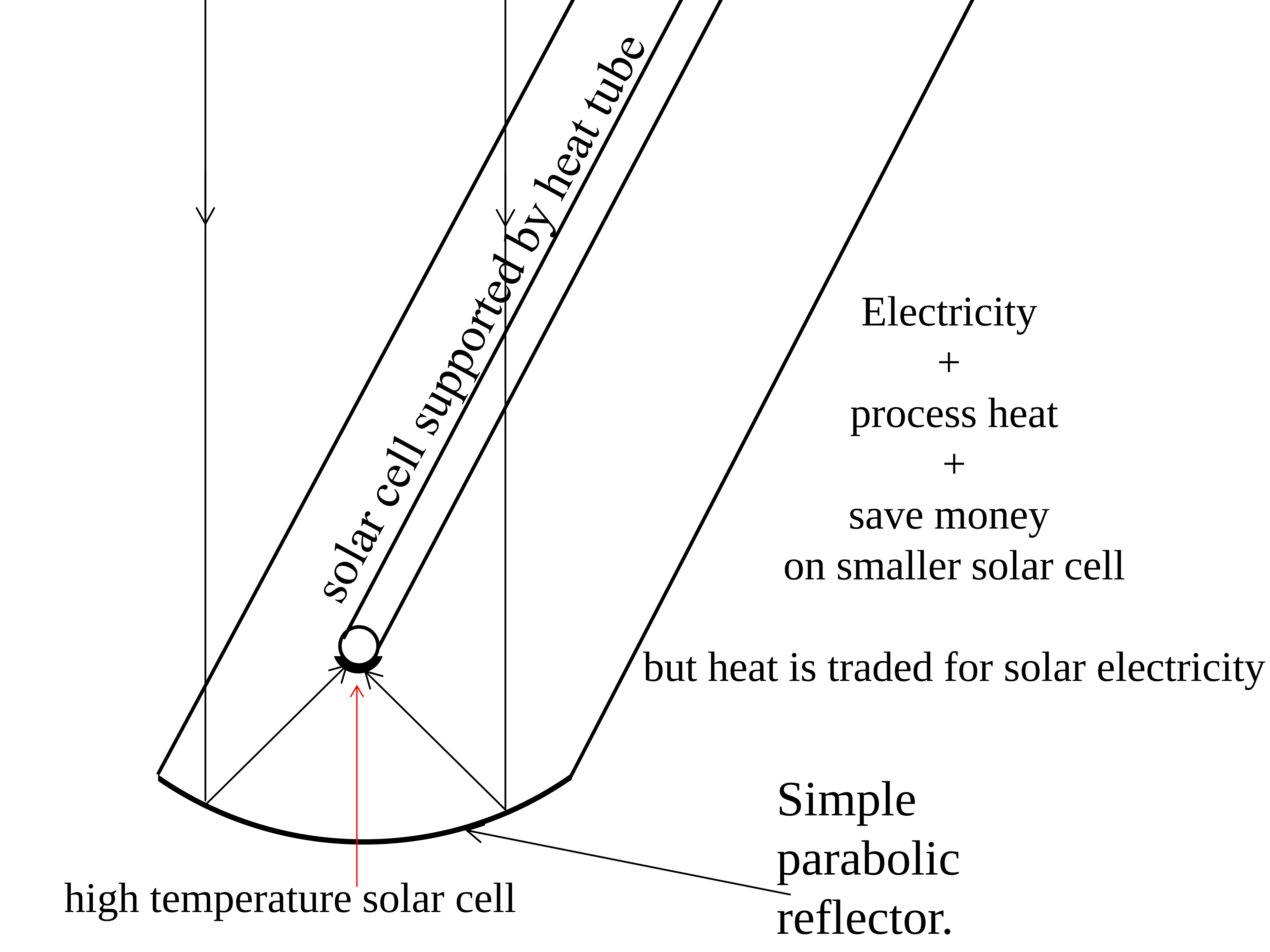
It cannot be focused in a concentrator

A Flat plate cell exploits diffuse light.

Direct rays from the sun have little entropy,
and are easy to focus


heat tube
All photons
below $h\nu$=1.4eV
are focused
for solar thermal
Thin-Film flexible
GaAs solar cell
as a parabolic
reflector.

GaAs
Courtesy of
Alta Devices,
Inc.


solar cell supported by heat tube
Electricity
+
process heat
+
save money
on smaller solar cell
but heat is traded for solar electricity
Simple
parabolic
reflector.
high temperature solar cell

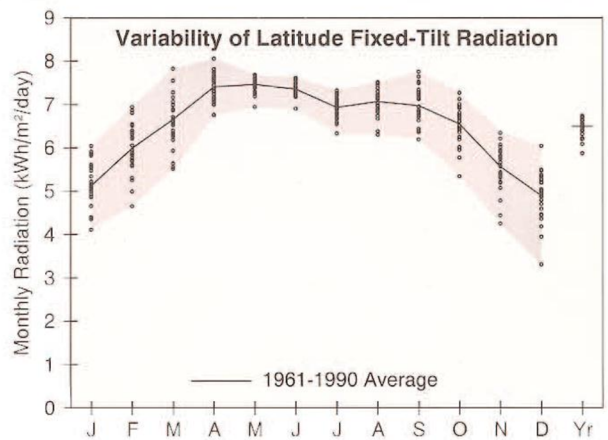
# The Problem with Concentrators:

**Phoenix, AZ**

**WBAN NO. 23183**

LATITUDE: 33.43° N
LONGITUDE: 112.02° W
ELEVATION: 339 meters
MEAN PRESSURE: 974 millibars

STATION TYPE: Primary




**Solar Radiation for 1-Axis Tracking Flat-Plate Collectors with a North-South Axis ($kWh/m^2/day$), Uncertainty ±9%**

| Axis Tilt (°) | | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | Average | 4.7 | 6.2 | 7.8 | 9.9 | 11.0 | 11.4 | 10.0 | 9.6 | 8.6 | 7.1 | 5.3 | 4.4 | 8.0 |
| | Min/Max | 3.8/5.6 | 4.6/7.3 | 6.2/9.5 | 8.9/11.4 | 9.9/11.8 | 10.3/12.2 | 8.8/11.1 | 8.0/10.5 | 7.4/9.9 | 5.6/8.1 | 4.0/6.2 | 2.9/5.5 | 7.1/8.4 |
| Latitude -15 | Average | 5.6 | 7.1 | 8.5 | 10.3 | 11.1 | 11.3 | 10.0 | 9.8 | 9.2 | 8.0 | 6.3 | 5.3 | 8.5 |
| | Min/Max | 4.4/6.7 | 5.2/8.3 | 6.7/10.3 | 9.2/11.9 | 9.9/11.8 | 10.2/12.1 | 8.8/11.1 | 8.2/10.8 | 7.9/10.5 | 6.2/9.1 | 4.6/7.3 | 3.4/6.7 | 7.6/8.9 |
| Latitude | Average | 6.2 | 7.5 | 8.7 | 10.3 | 10.7 | 10.8 | 9.6 | 9.6 | 9.3 | 8.4 | 6.8 | 5.8 | 8.6 |
| | Min/Max | 4.8/7.4 | 5.5/8.9 | 6.8/10.6 | 9.1/11.8 | 9.6/11.5 | 9.8/11.6 | 8.4/10.7 | 8.1/10.6 | 8.0/10.7 | 6.5/9.5 | 4.9/8.0 | 3.8/7.4 | 7.6/9.0 |
| Latitude +15 | Average | 6.5 | 7.7 | 8.6 | 9.9 | 10.1 | 10.1 | 9.0 | 9.2 | 9.1 | 8.5 | 7.1 | 6.2 | 8.5 |
| | Min/Max | 5.0/7.8 | 5.6/9.1 | 6.8/10.5 | 8.8/11.4 | 9.1/10.8 | 9.1/10.8 | 7.9/10.0 | 7.7/10.1 | 7.8/10.5 | 6.6/9.7 | 5.1/8.3 | 4.0/7.9 | 7.5/8.9 |

**Direct Beam Solar Radiation for Concentrating Collectors ($kWh/m^2/day$), Uncertainty ±8%**

| Tracker | | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1-Axis, E-W Horiz Axis | Average | 4.2 | 4.6 | 4.8 | 5.7 | 6.4 | 6.8 | 5.6 | 5.3 | 5.2 | 5.0 | 4.5 | 4.1 | 5.2 |
| | Min/Max | 3.0/5.4 | 3.0/5.9 | 3.4/6.3 | 4.8/7.1 | 5.2/7.1 | 6.0/7.5 | 4.5/6.7 | 4.4/6.3 | 4.1/6.3 | 3.5/6.0 | 2.6/5.8 | 2.5/5.8 | 4.5/5.6 |
| 1-Axis, N-S Horiz Axis | Average | 3.4 | 4.6 | 5.8 | 7.6 | 8.5 | 8.9 | 7.2 | 7.0 | 6.5 | 5.4 | 4.0 | 3.2 | 6.0 |
| | Min/Max | 2.4/4.5 | 2.8/5.9 | 4.0/7.7 | 6.5/9.8 | 7.0/9.7 | 7.9/10.0 | 5.7/8.8 | 5.6/8.4 | 5.1/8.1 | 3.6/6.6 | 2.2/5.1 | 1.8/4.5 | 5.2/6.5 |
| 1-Axis, N-S Tilt=Latitude | Average | 4.7 | 5.7 | 6.5 | 7.8 | 8.2 | 8.3 | 6.8 | 7.0 | 7.1 | 6.5 | 5.2 | 4.5 | 6.5 |
| | Min/Max | 3.3/6.1 | 3.6/7.3 | 4.5/8.6 | 6.6/10.1 | 6.7/9.4 | 7.3/9.3 | 5.4/8.3 | 5.6/8.4 | 5.5/8.7 | 4.4/7.8 | 3.0/6.7 | 2.6/6.3 | 5.6/7.1 |
| 2-Axis | Average | 5.0 | 5.8 | 6.5 | 8.0 | 8.7 | 9.1 | 7.3 | 7.2 | 7.1 | 6.5 | 5.5 | 4.8 | 6.8 |
| | Min/Max | 3.5/6.5 | 3.7/7.5 | 4.5/8.6 | 6.7/10.3 | 7.1/9.9 | 8.0/10.1 | 5.8/9.0 | 5.7/8.6 | 5.5/8.7 | 4.4/7.9 | 3.1/7.1 | 2.8/6.8 | 5.8/7.4 |

Percentage Direct SunLight:

| | |
|---|---|
| Phoenix | 76% |
| Los Angeles | 65% |
| Houston | 62% |
| New York | 59% |

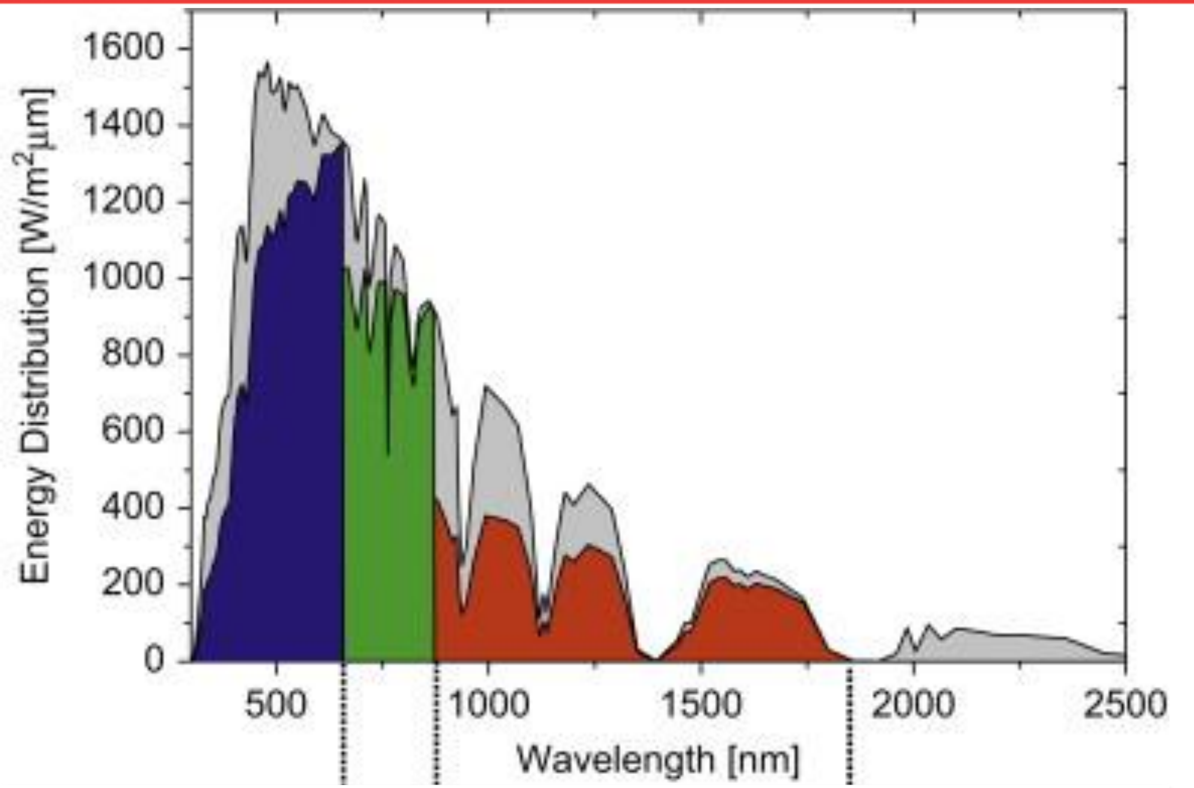
(1-axis tracking)

Partly compensated by Voltage Boost:

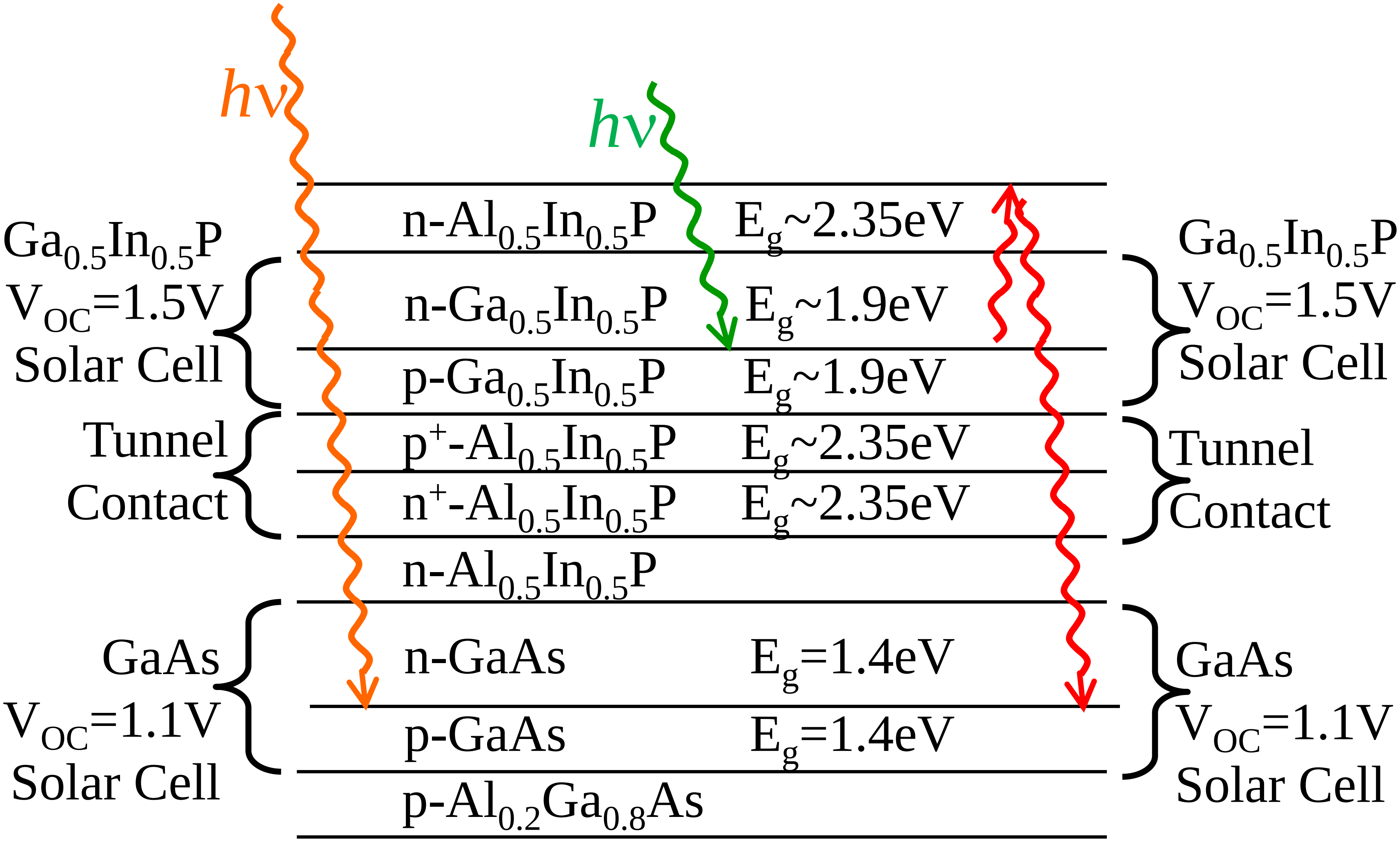
$$(kT/q)\times ln\{\text{Concentration Ratio}\}$$

# The Next Step: Split the Solar Spectrum for efficiencies >30%

Splitting:



# >30%, dual Junction Series-Connected Tandem Solar Cell




All Lattice-Matched η~34% efficiency should be possible.

Latest 1 sun dual-junction results from Alta Devices, Inc.

Expected to reach 34% dual junction, eventually.

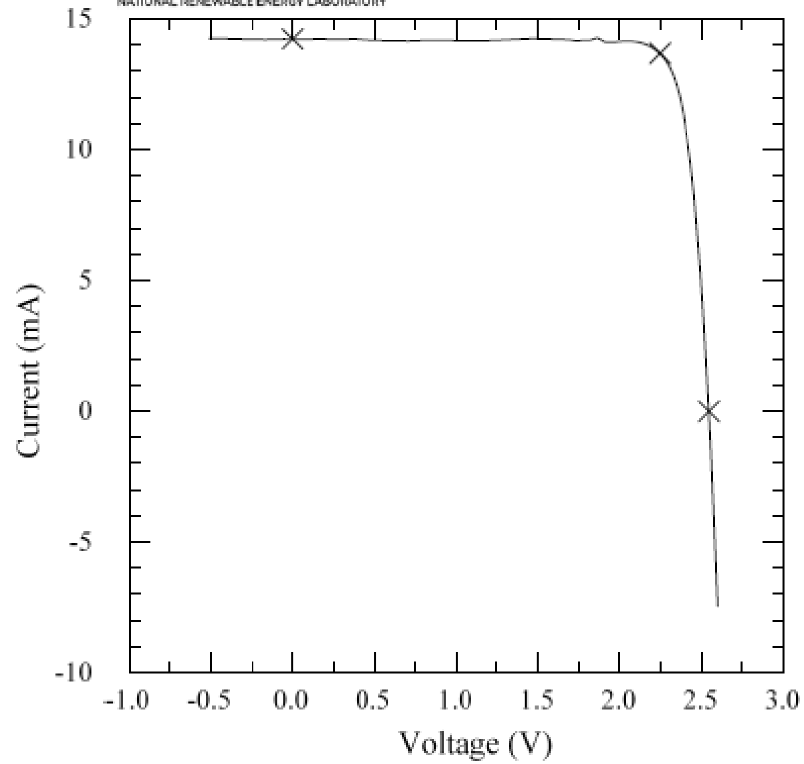
**Alta Devices**

**GaInP/GaAs Tandem Cell**

| | |
|---|---|
| Device ID: AD13609-F-G2 | Device temperature: 25.0 ± 1.0 °C |
| 4:41 PM 2/1/2013 | Device area: 0.999 $cm^2$ |
| Spectrum: ASTM G173 global | Irradiance: 1000.0 $W/m^2$ |

NREL NATIONAL RENEWABLE ENERGY LABORATORY

OSMSS IV System CONFIDENTIAL
PV Performance Characterization Team

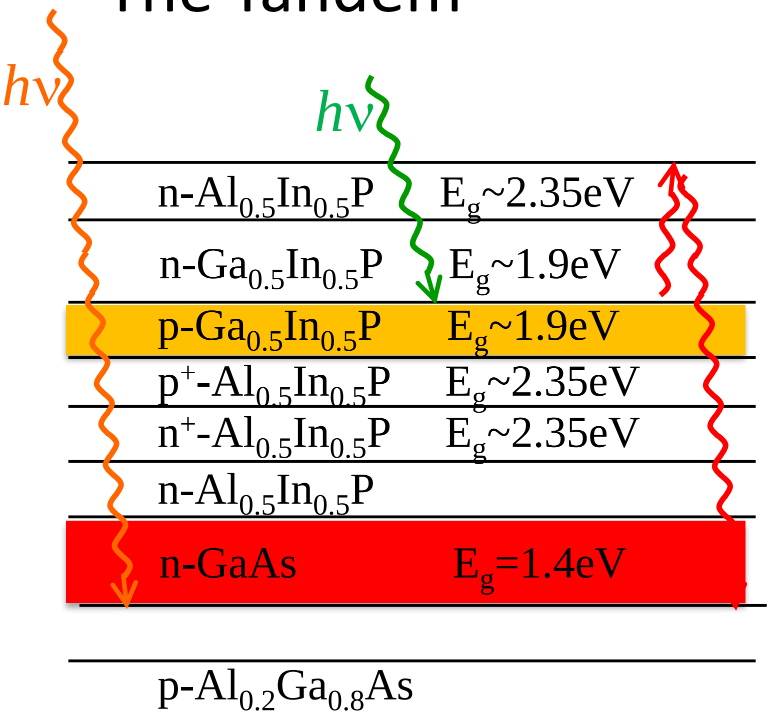



| | |
|---|---|
| $V_{oc}$ = 2.5468 V | $I_{max}$ = 13.681 mA |
| $I_{sc}$ = 14.247 mA | $V_{max}$ = 2.2477 V |
| $J_{sc}$ = 14.255 $mA/cm^2$ | $P_{max}$ = 30.752 mW |
| Fill Factor = 84.7 % | Efficiency = 30.77 % |

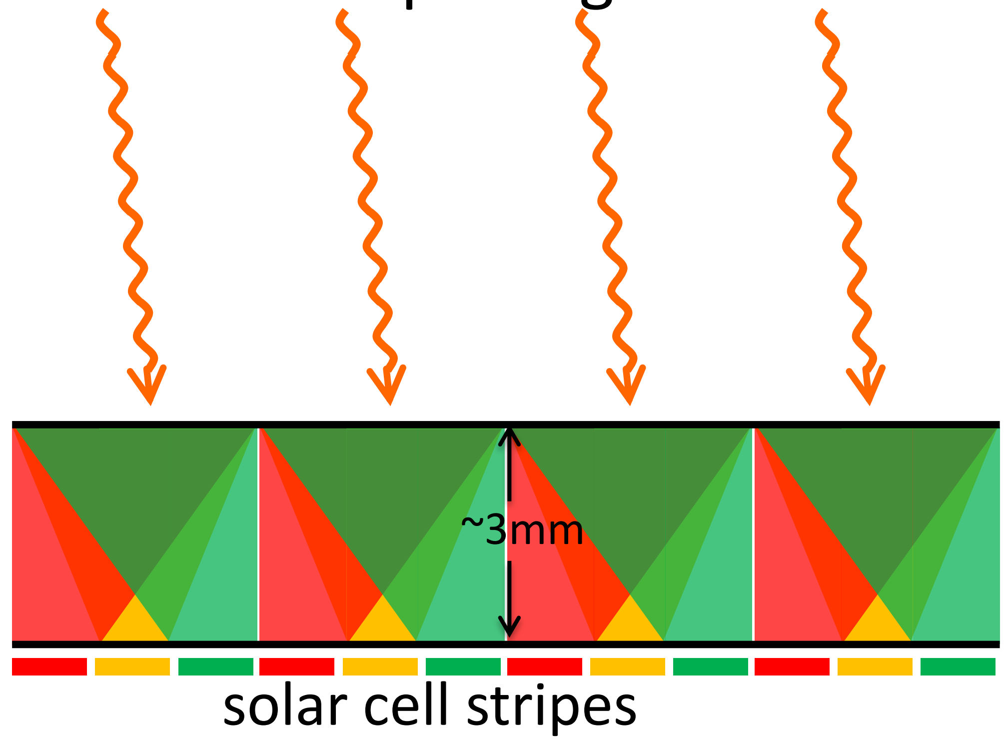
Luminescent coupling corrected bottom QE

# The Next Step: How to Split the Solar Spectrum for efficiencies >30%

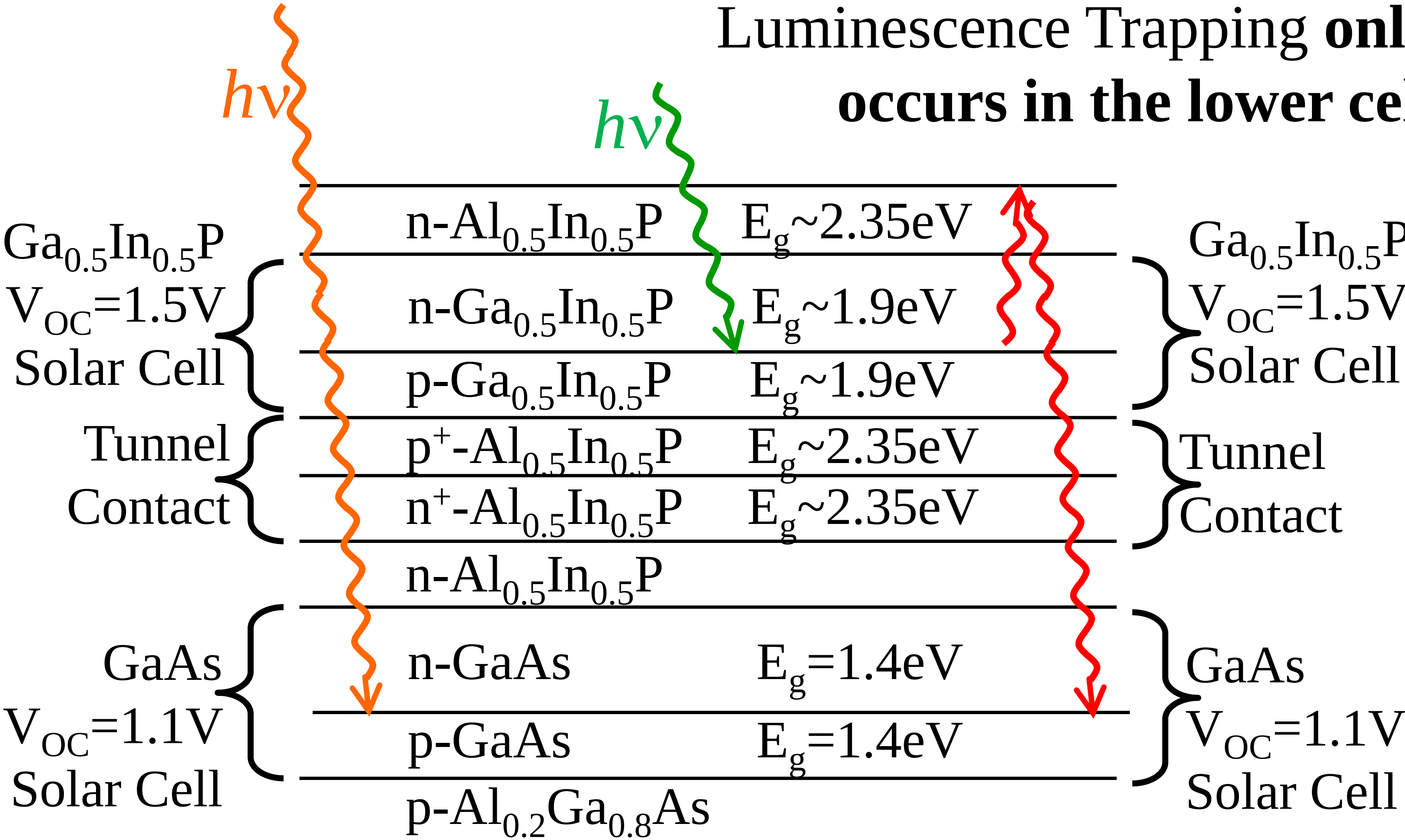
## Serial Splitting: The Tandem




## Lateral Splitting:



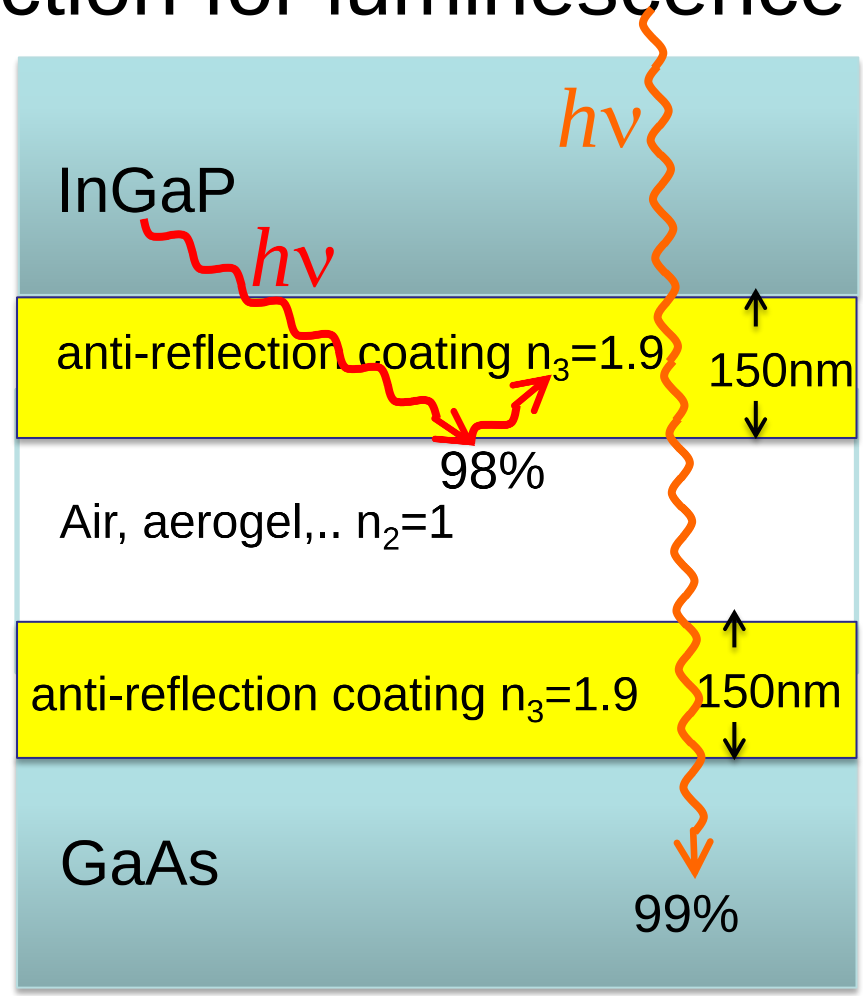
# The Voltage Boost due to Luminescence Trapping **only occurs in the lower cell**




All Lattice-Matched  η~34% efficiency should be possible.

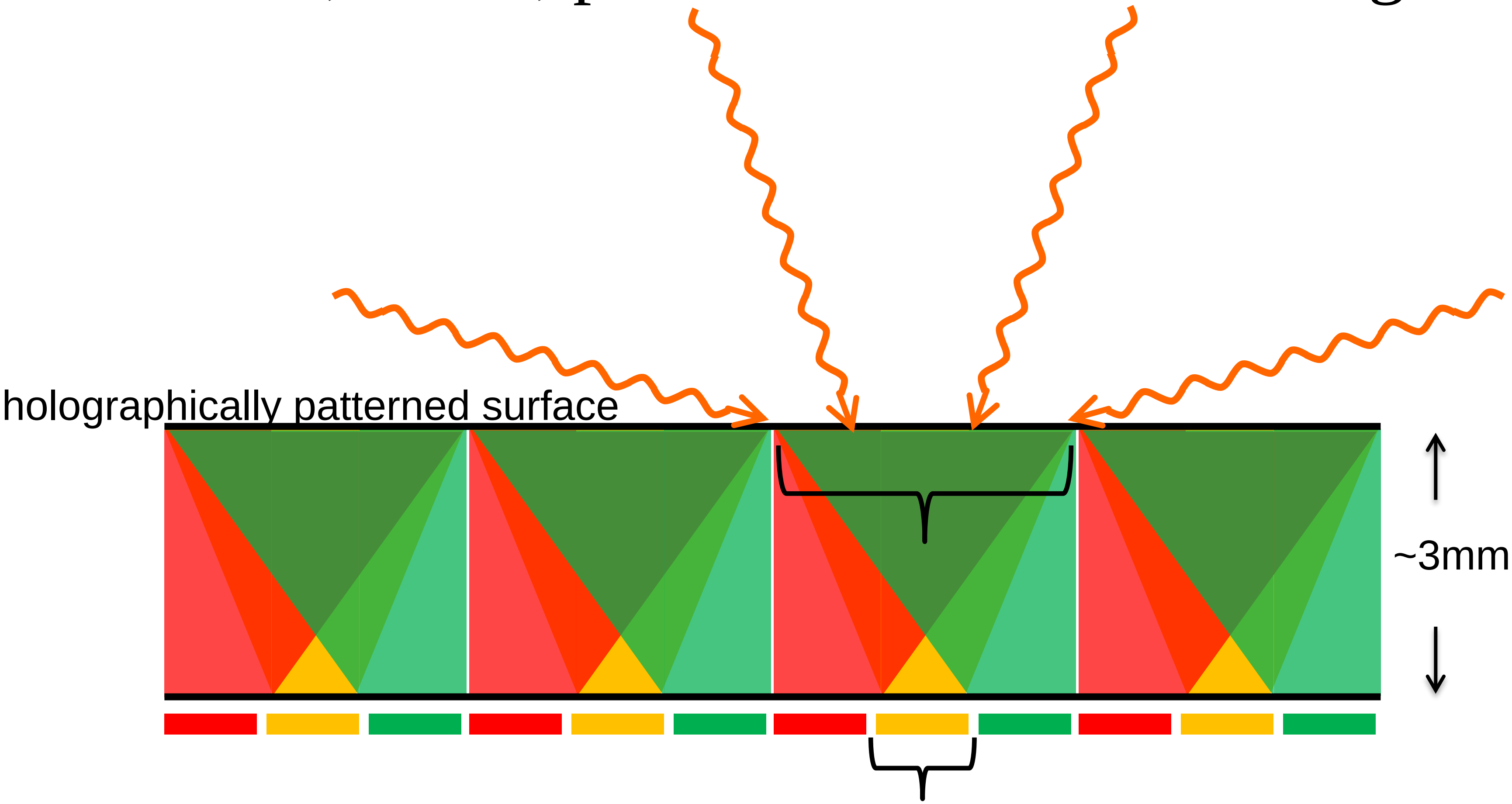
# Challenge: Achieve maximum transmission for incident sunlight, and maximum total internal reflection for luminescence

- An air-gap provides 98% total-internal-reflection of luminescence, based on angular selectivity rather than spectral selectivity.
- The anti-reflection coating provides 99% transmission of band-edge radiation.



# Lateral Splitting requires mild concentration

# Glass index, n=1.5, provides sufficient focusing.

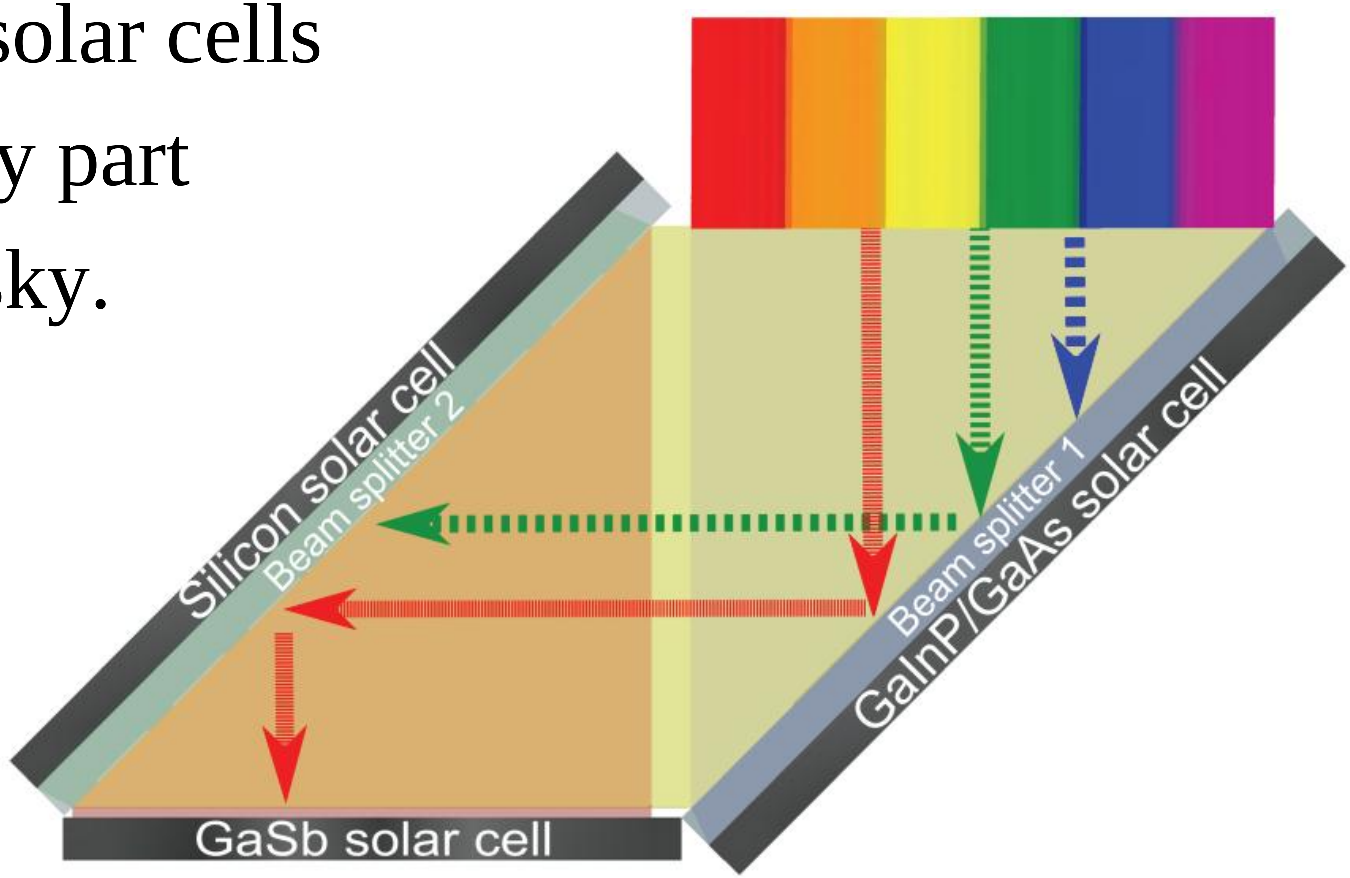


directivity entropy problem:

These solar cells

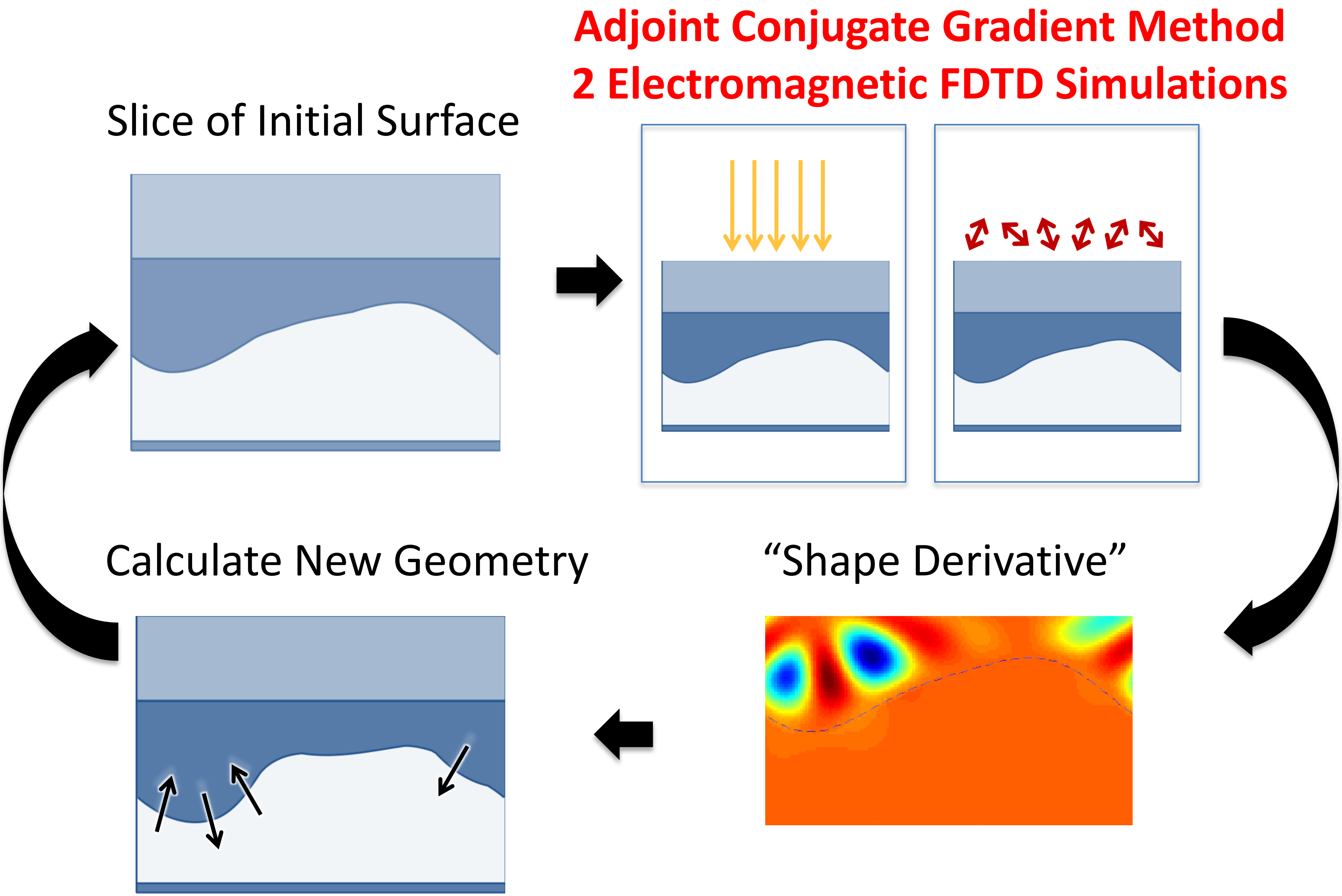
see only part

of the sky.

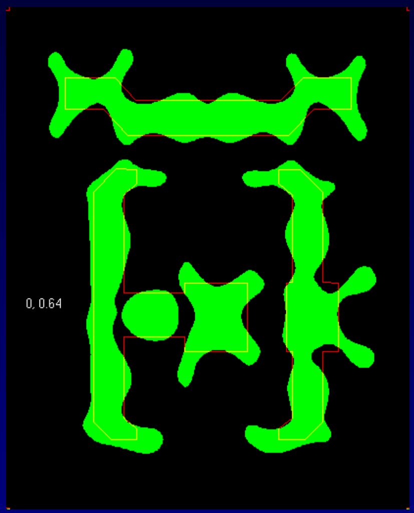


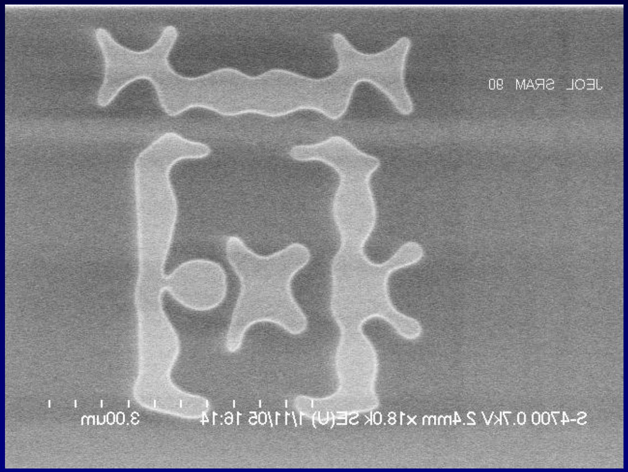

24th European Photovoltaic Solar Energy Conference, 21-25 September 2009
B. Groß, G. Peharz, G. Siefer, M. Peters, J.C. Goldschmidt, M. Steiner, W. Guter, V. Klinger, B. George, and F. Dimroth, Fraunhofer Institute for Solar Energy Systems

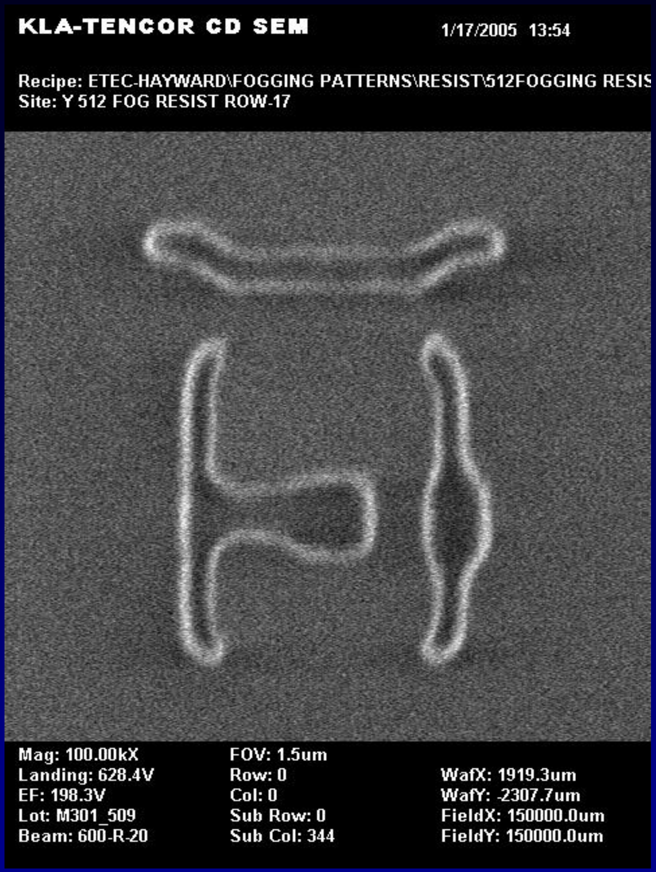
# Shape Calculus for Inverse Design



# SRAM 90nm Wafer

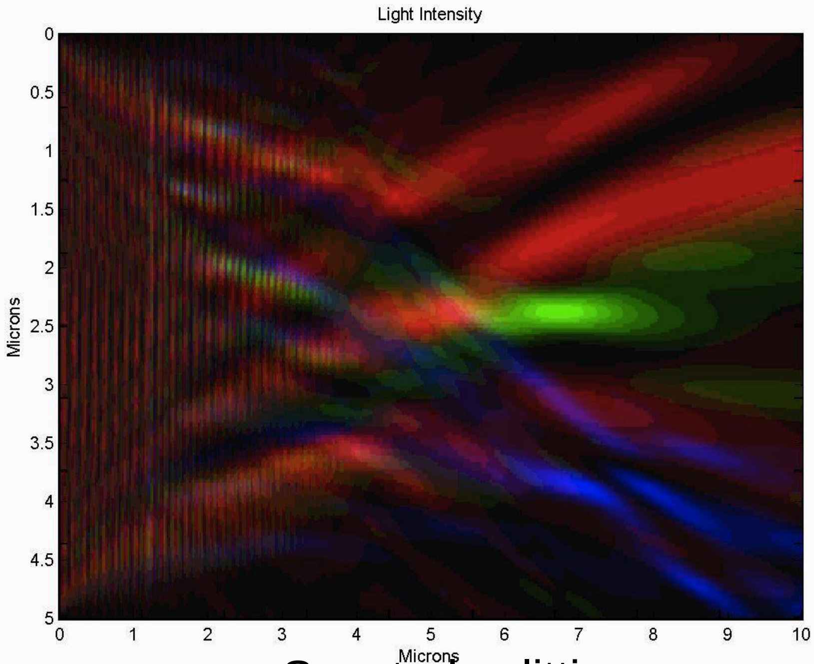


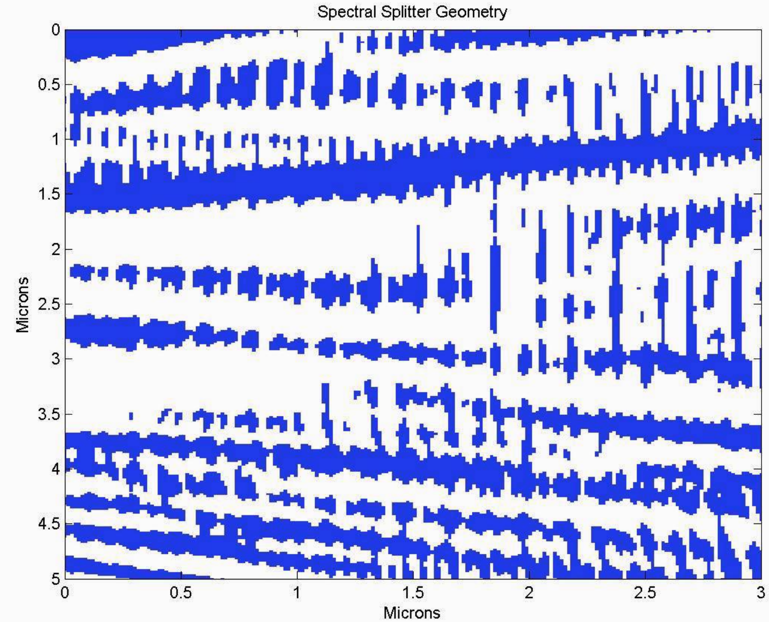



**the mathematical solution is rather non-intuitive!**

Image Courtesy of Luminescent Technologies, Inc.




Spectral splitting




holographic pattern

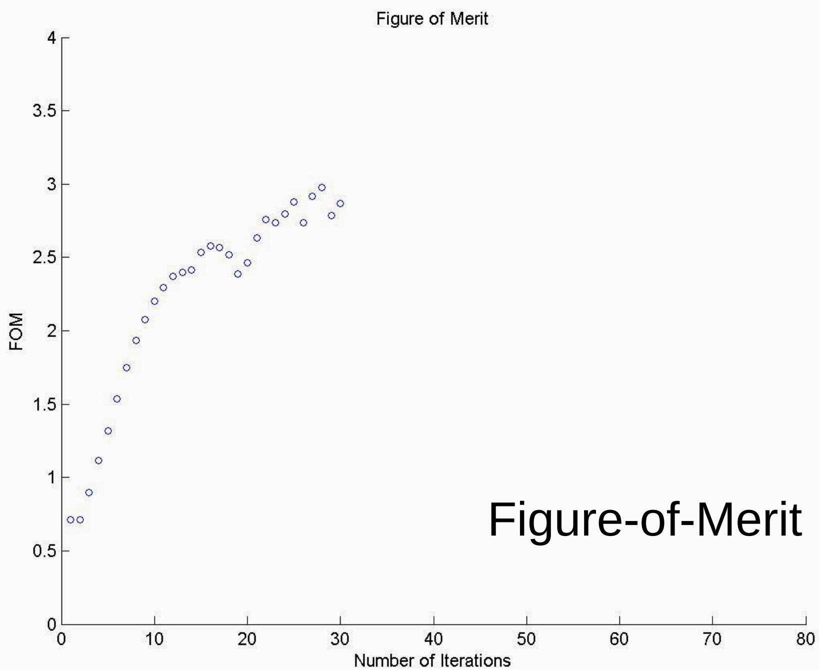



Figure-of-Merit

Gases to Liquid Fuels Fischer-Tropsch; Runs 24 hours a day is already economic.

Qatar Oryx GTL Plant from Sasol

$$\underset{\text{syngas}}{8CO + 17H_2} \xrightarrow[\text{reaction}]{\text{actual}} C_8H_{18} + 8H_2O$$

Pearl Gas to Liquids (GTL) Plant from Shell – Largest GTL Plant in the world Qatar

But Electrolyzer runs only 6 hours/day.

# Summary

1. Use mathematical “Inverse Design”--

   One-time design of the spectral-splitting holographic pattern.—

   Reproduce the hologram by stamping, indefinitely.

2. 30%-50% efficiency solar cell efficiency, at low cost, will eventually be the norm.

3. Seasonal as well Nightly storage will be needed.

4. For seasonal storage, high-value fuels will be needed.

   The petrochemical industry is poised for the conversion of solar electricity to fuel.