In High Efficiency Cells, >25%, Optical Simulation is More Important than Electronic Simulation

Challenges in PV Science, Technology, and Manufacturing:
Workshop on the Role of Theory, Modeling, And Simulation

Purdue University, West Lafayette, Indiana
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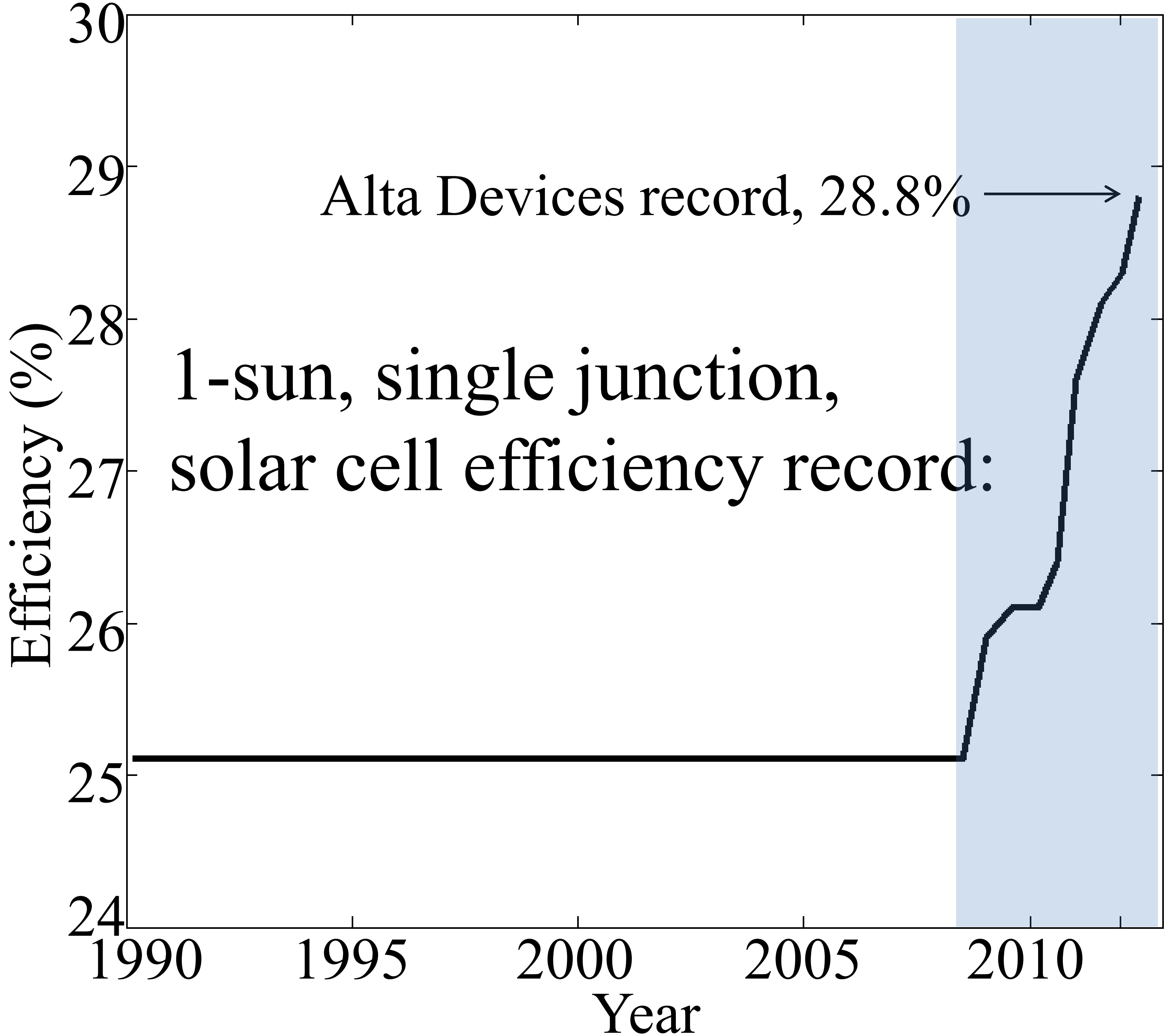
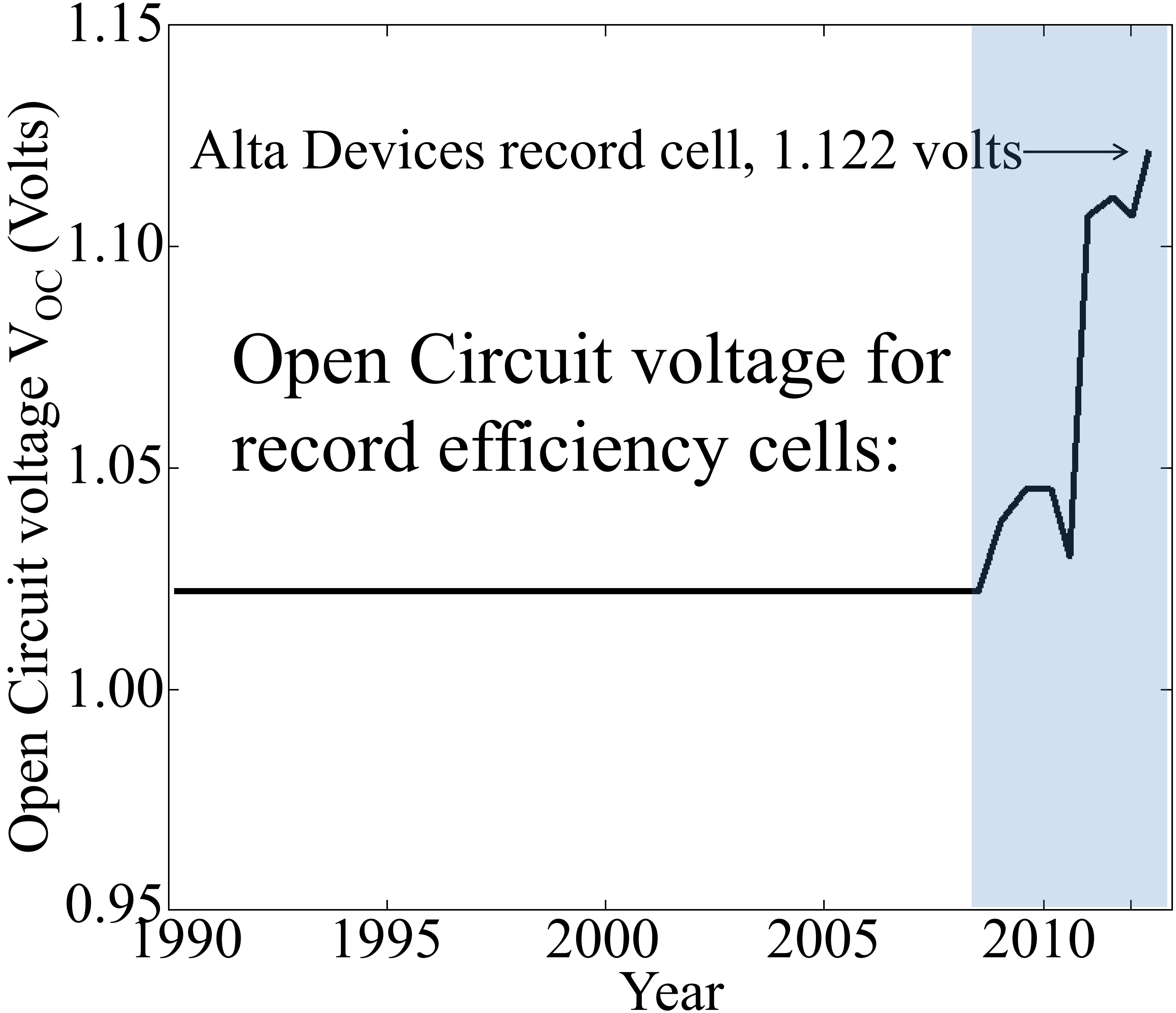
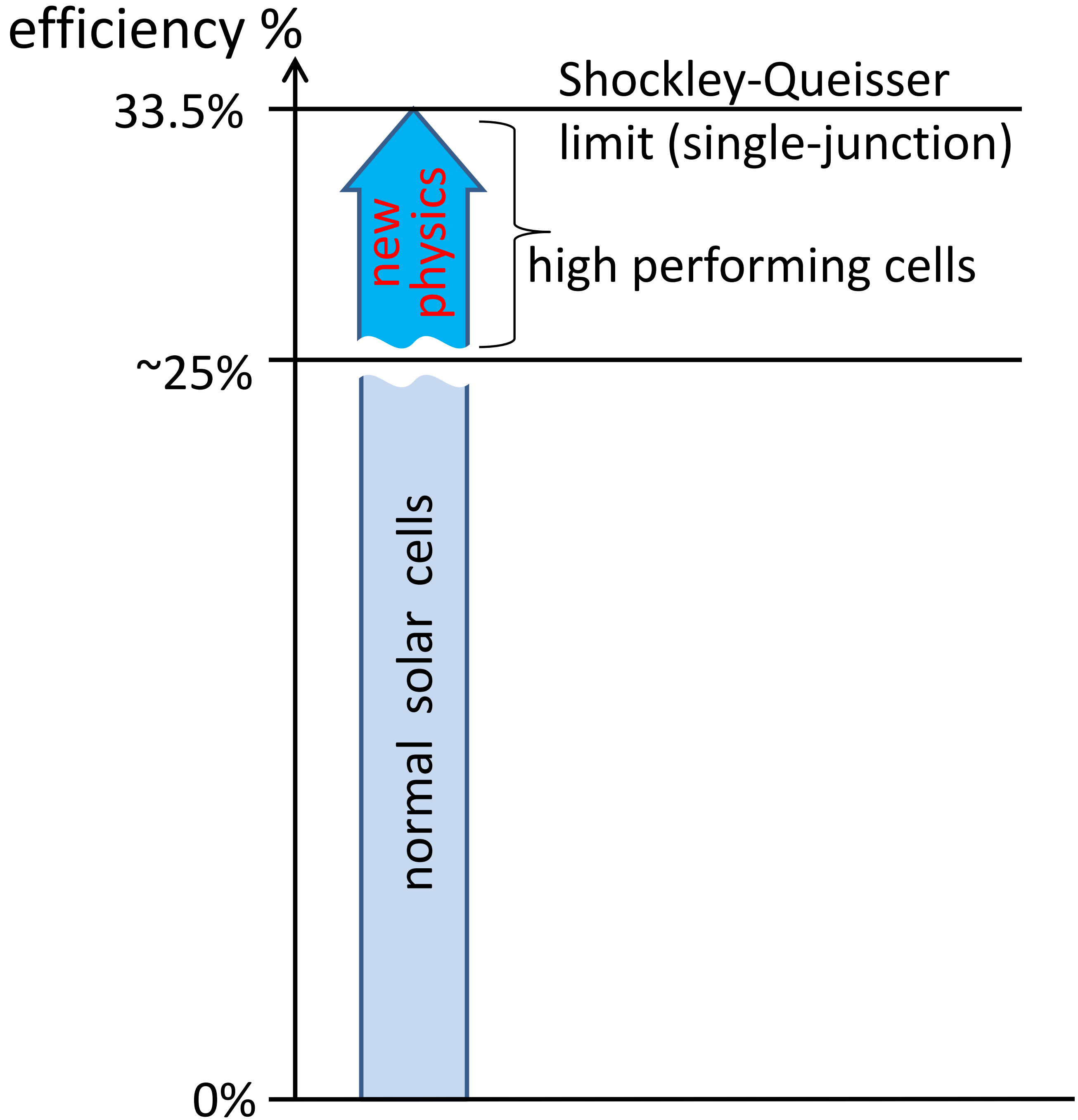
Miller et al, IEEE J. Photovoltaics, vol. 2, pp. 303-311 (2012)


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

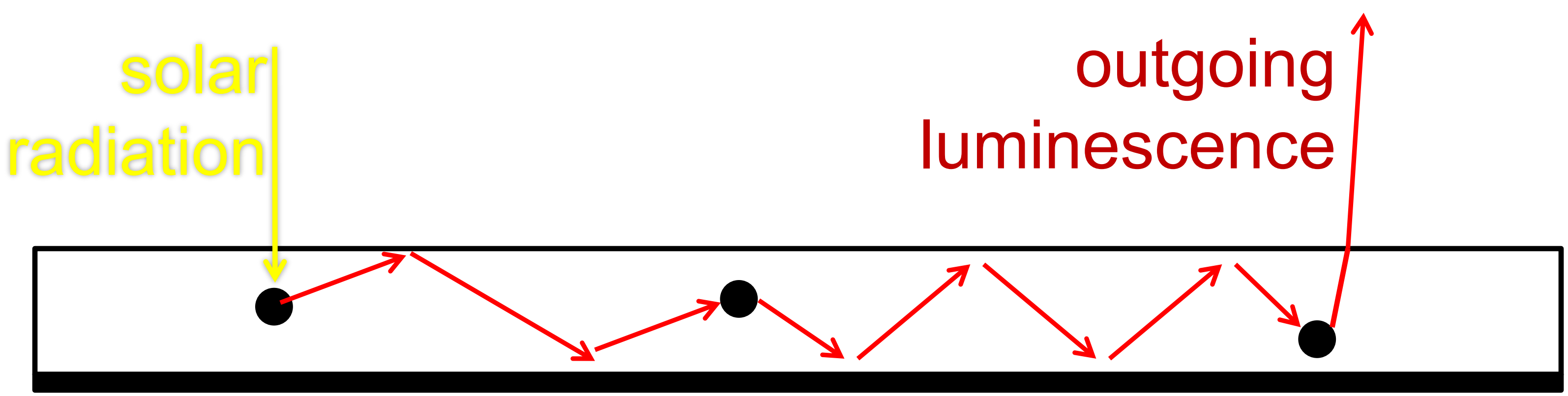


Open Circuit voltage V_{OC} (Volts)
1.15
1.10
1.05
1.00
0.95
1990
1995
2000
2005
2010
Year
Alta Devices record cell, 1.122 volts
Open Circuit voltage for record efficiency cells:

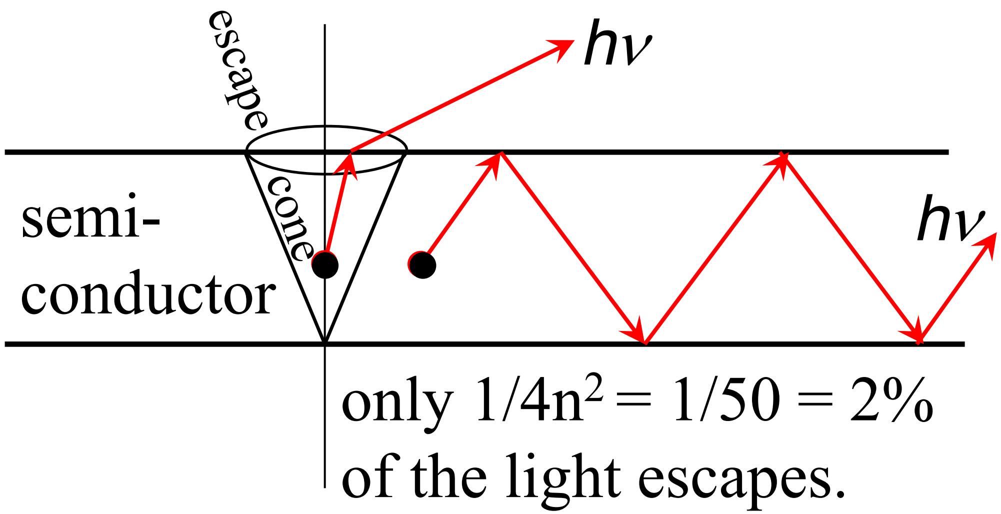

efficiency %
33.5%
Shockley-Queisser
limit (single-junction)
new
physics
high performing cells
~25%
normal solar cells
0%

What did Shockley-Queisser say?
Any absorber also has to be an emitter!

At the open-circuit condition the electrons & holes have no place to go.
They build up, and ideally they are lost only to luminescence.



In an ideal solar cell, at open-circuit,
the outgoing luminescence will equal the incoming solar radiation

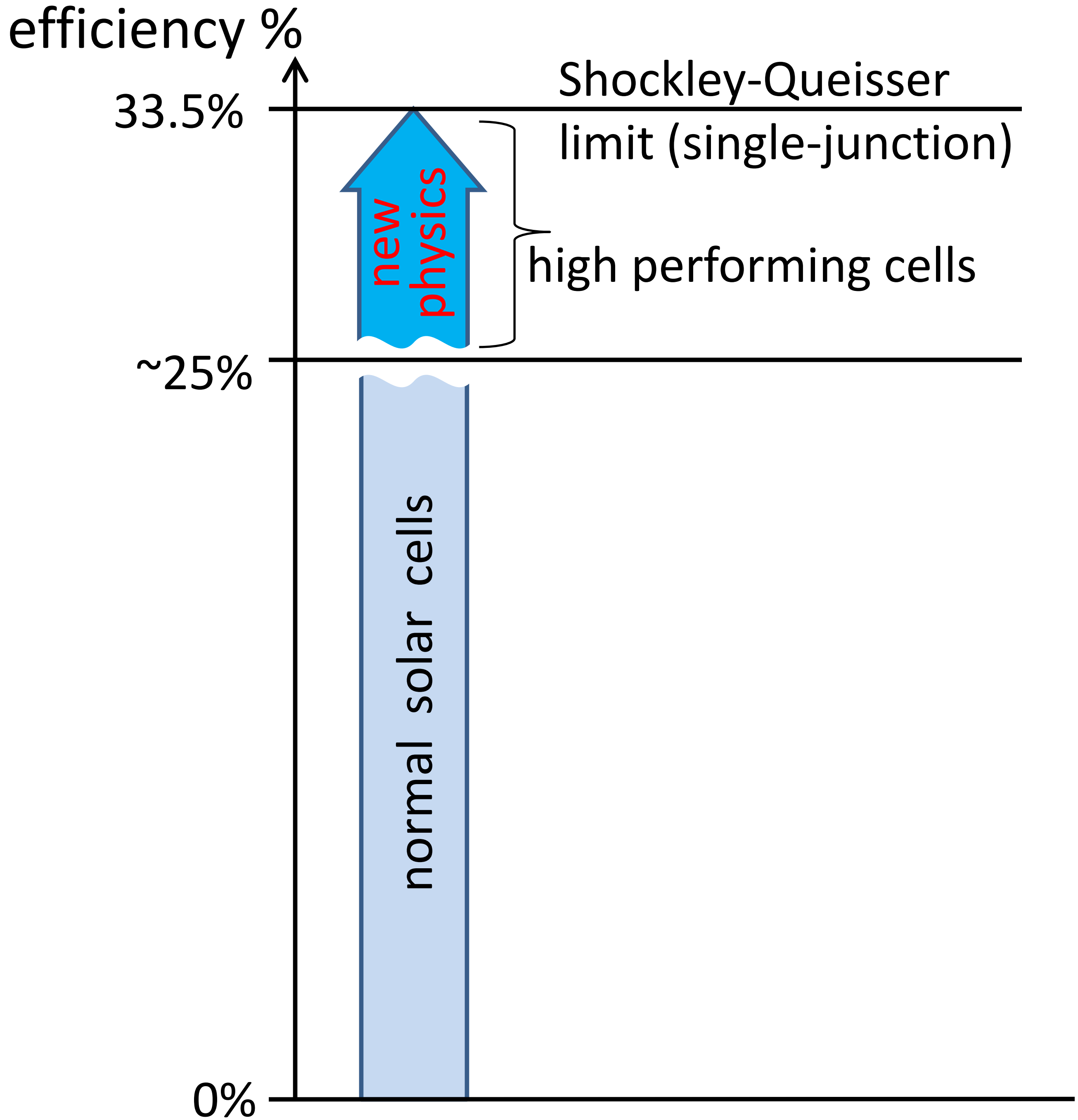

escape
cone
semi-
conductor
hν
hν
only 1/4n² = 1/50 = 2%
of the light escapes.

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 η_{ext} is what matters!

Only external Luminescence can balance the incoming radiation.



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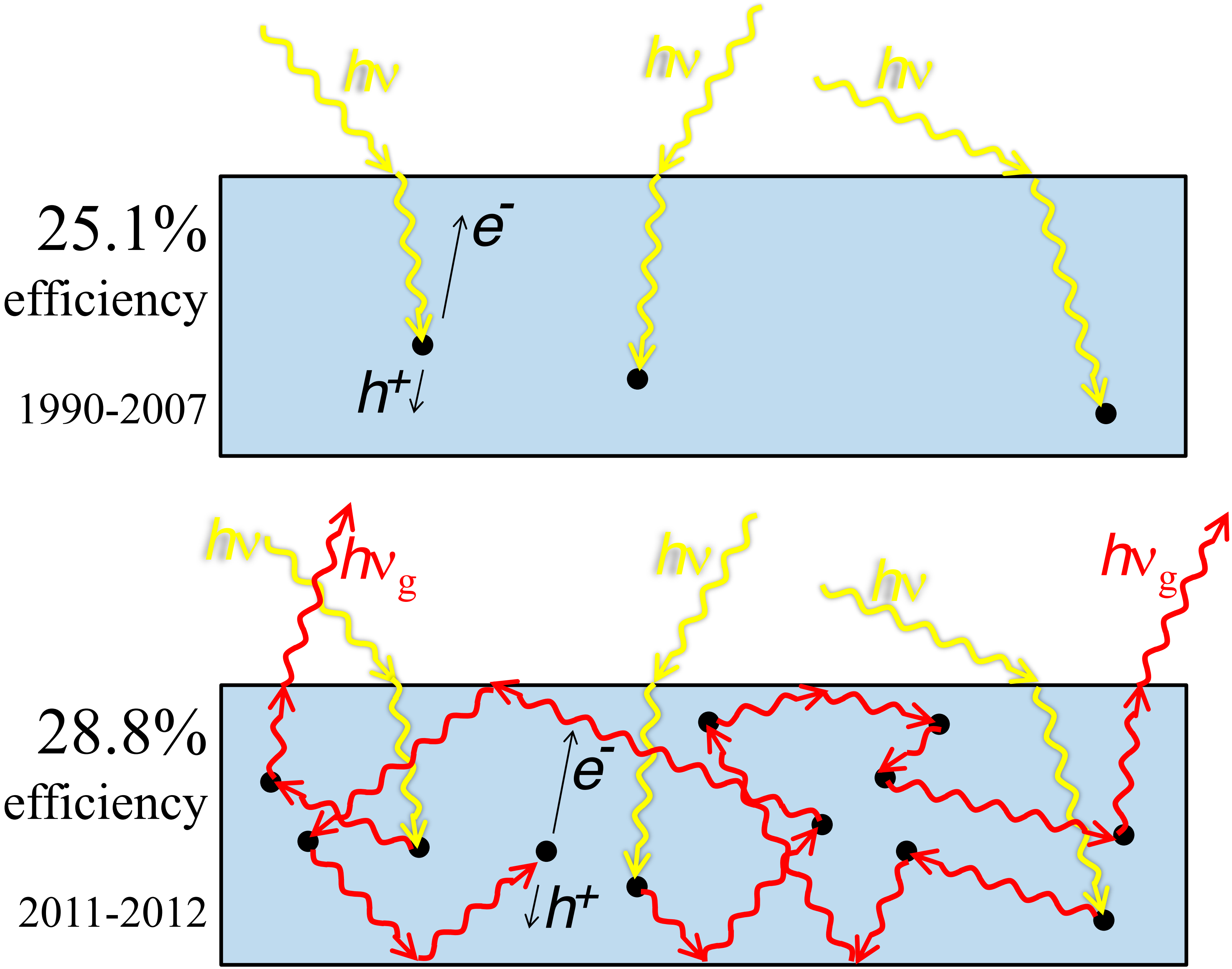
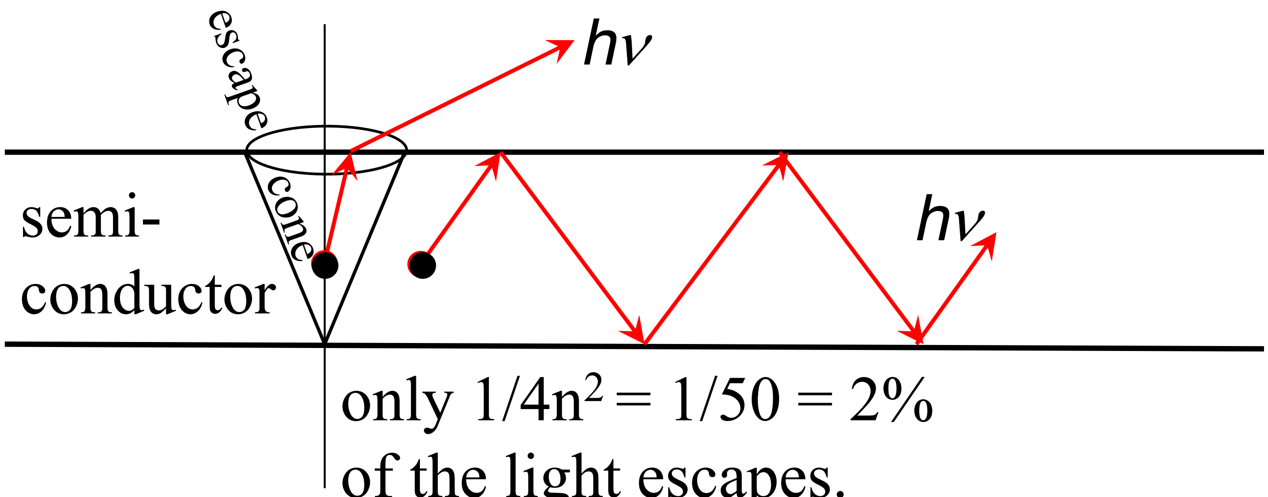
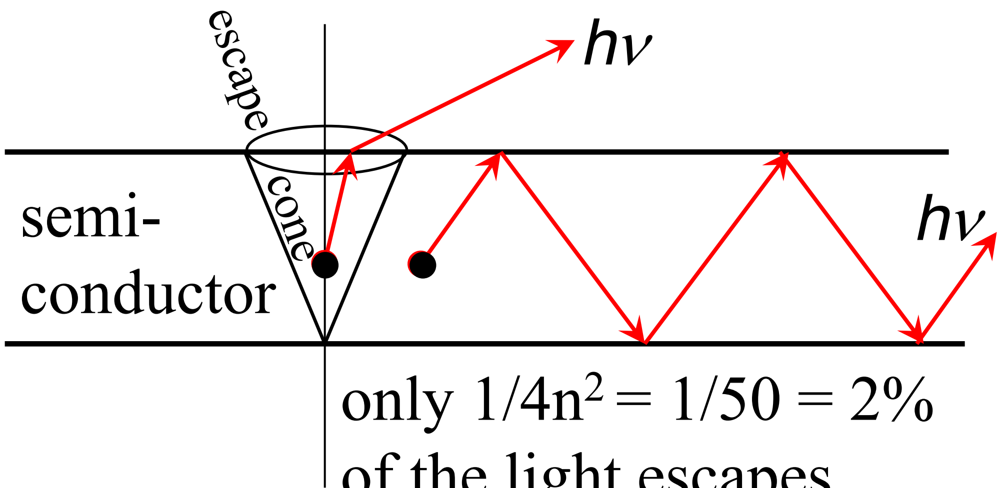


25.1%
efficiency
1990-2007
hν
hν
hν
e^-
h^+
28.8%
efficiency
2011-2012
hν
$hν_g$
hν
hν
$hν_g$
e^-
h^+



You may need an internal efficiency of η_{int}=99% just to get an external efficiency of η_{ext}=50%

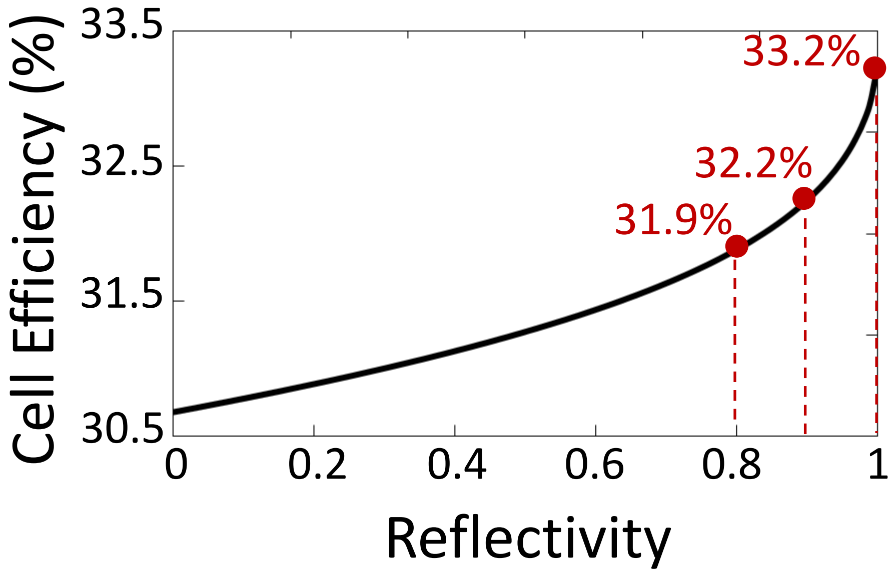


But this is really hard to do:

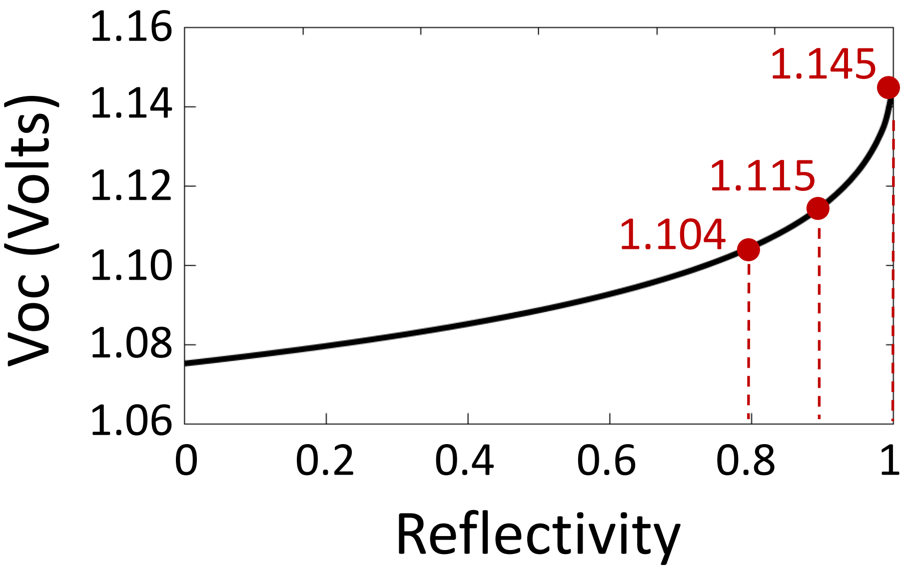
You may need an internal efficiency of η_{int}=99%

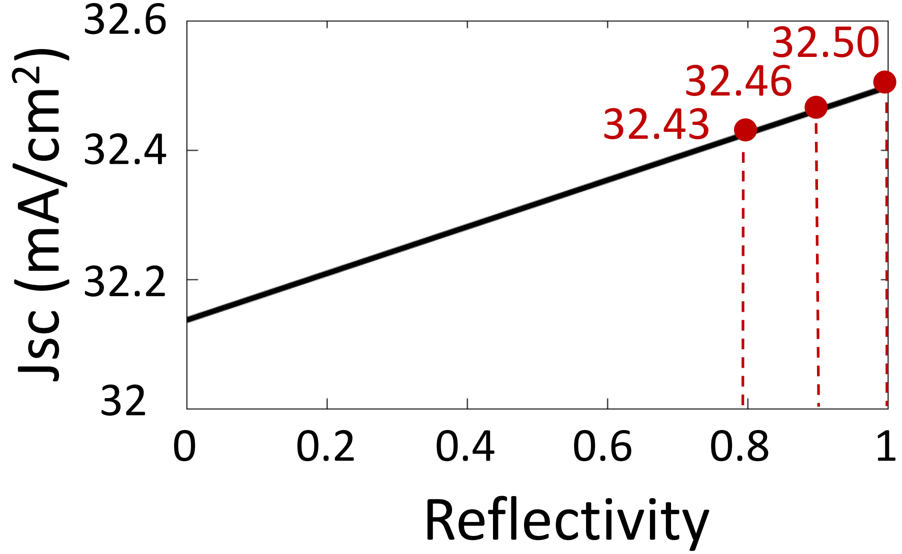
just to get an external efficiency of η_{ext}=50%

Efficiency vs. Rear Reflectivity, GaAs 3μm

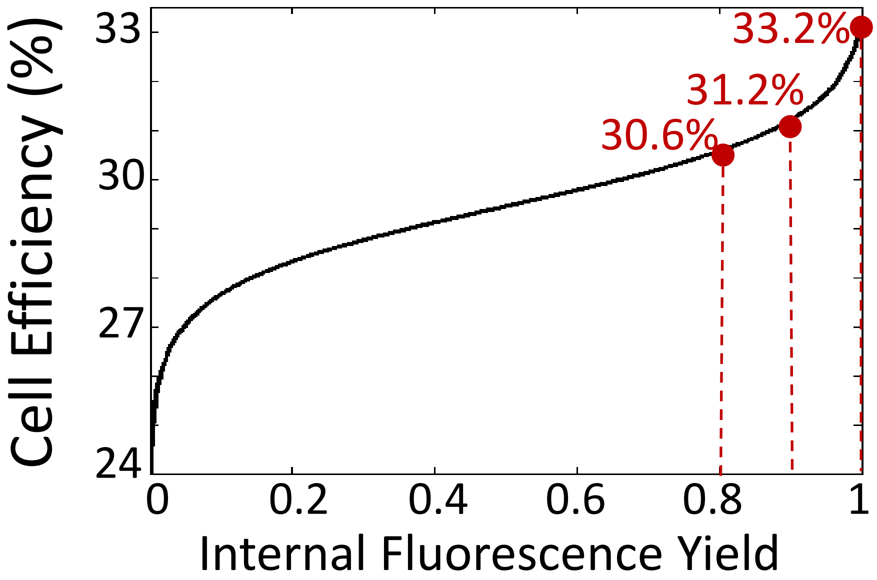


90% Rear Reflectivity Is Not Enough!

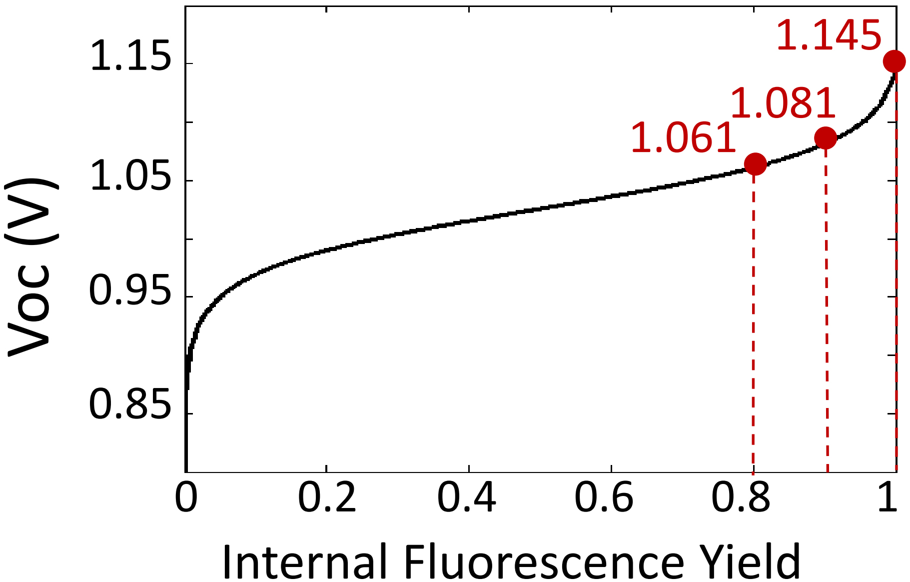


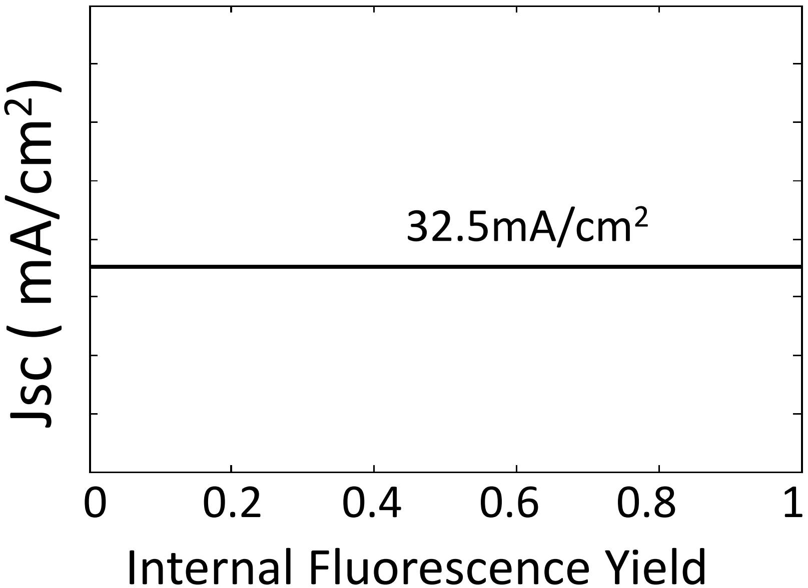


Efficiency vs. Internal Fluorescence Yield, GaAs 3μm

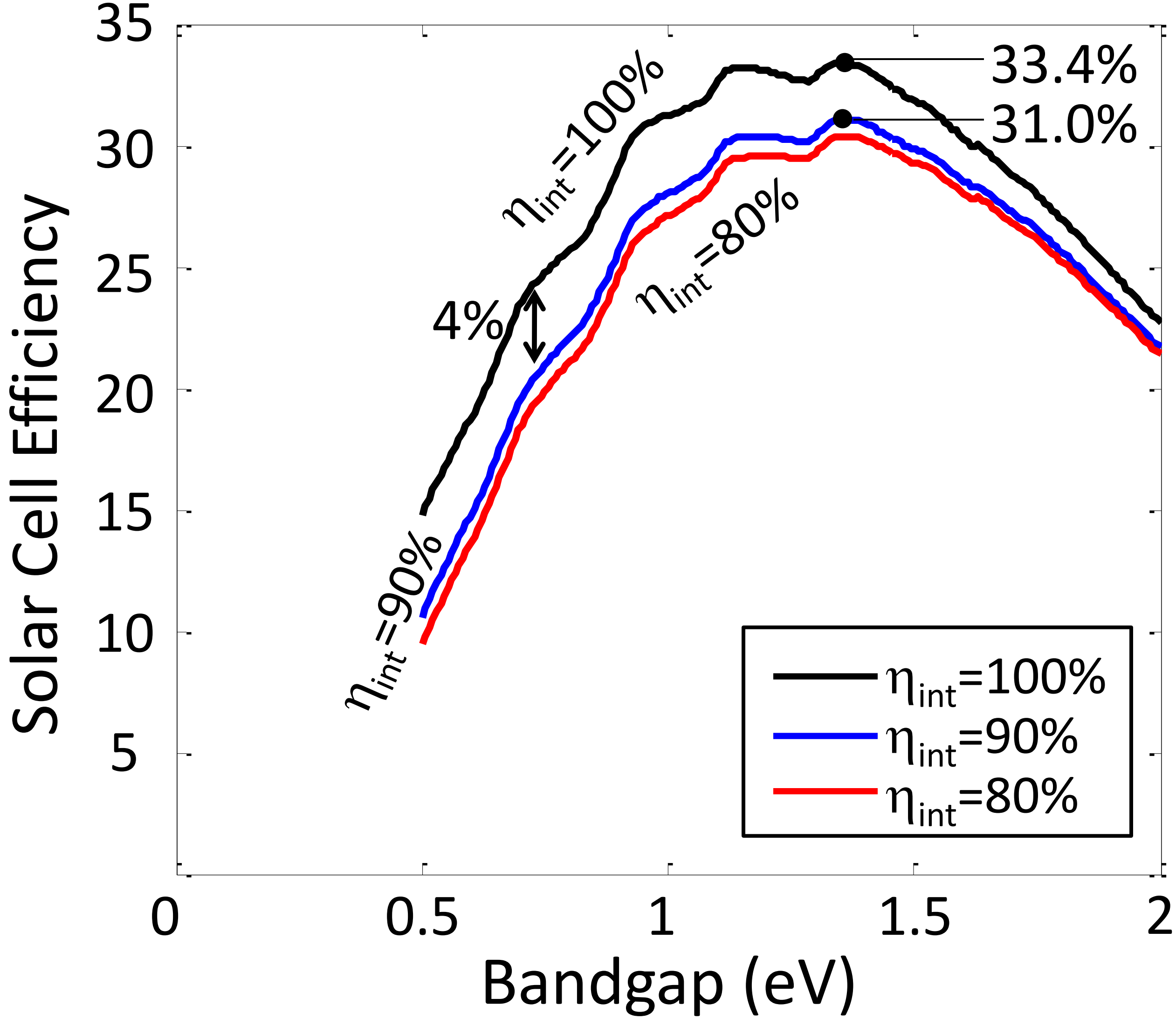


90% Internal Fluorescence Yield Is Not Enough!



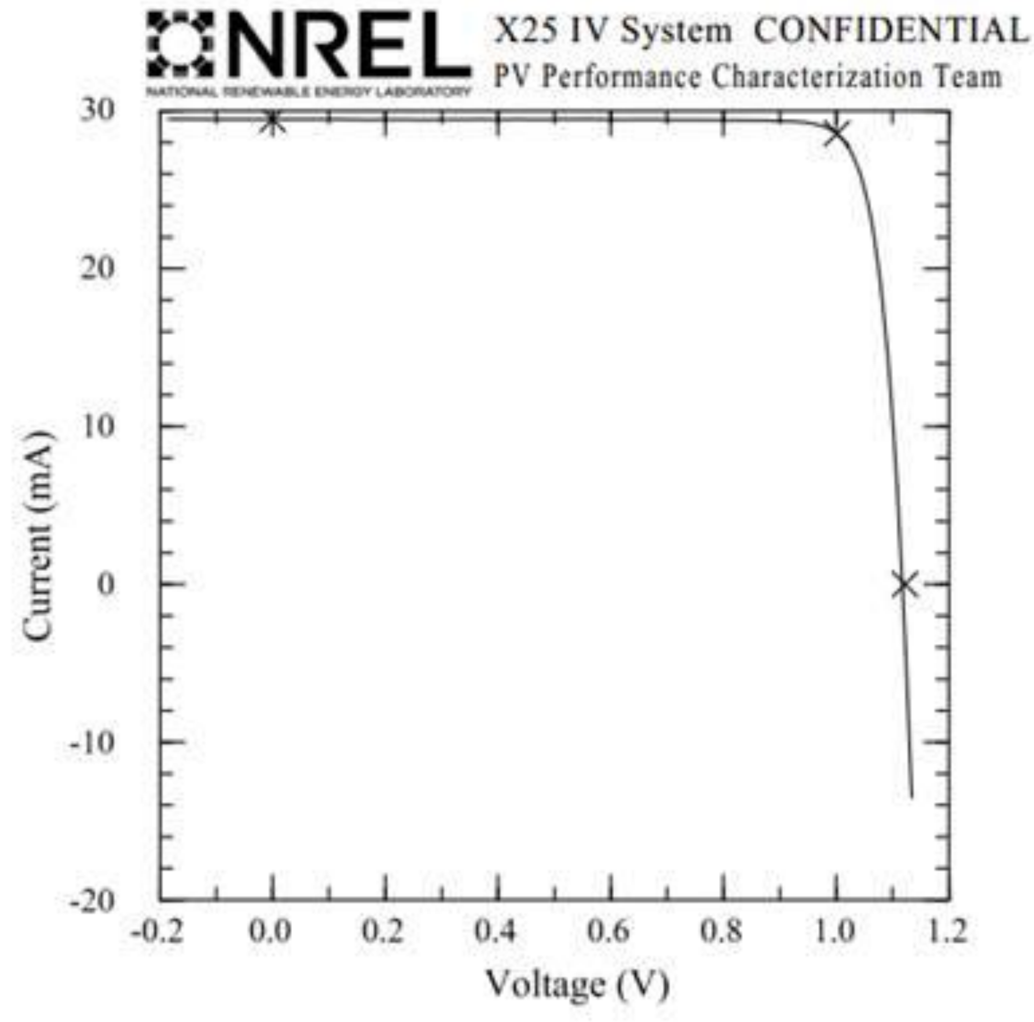


Solar Cell Efficiency Limits for $\eta_{int} < 1$



Latest 1 sun results from Alta Devices, Inc.

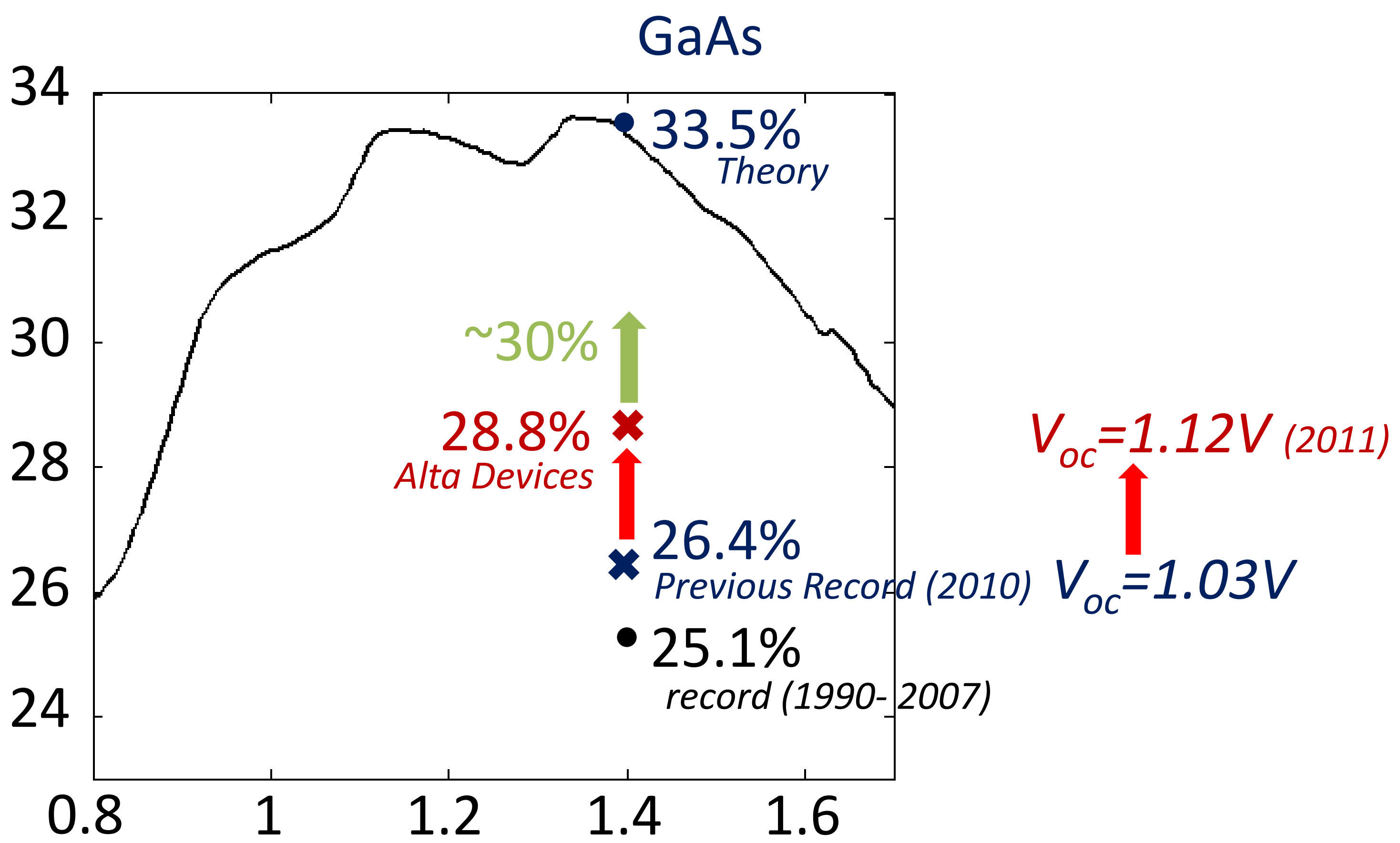
Expected to reach 29.5% single junction shortly, and 34% dual junction, eventually.

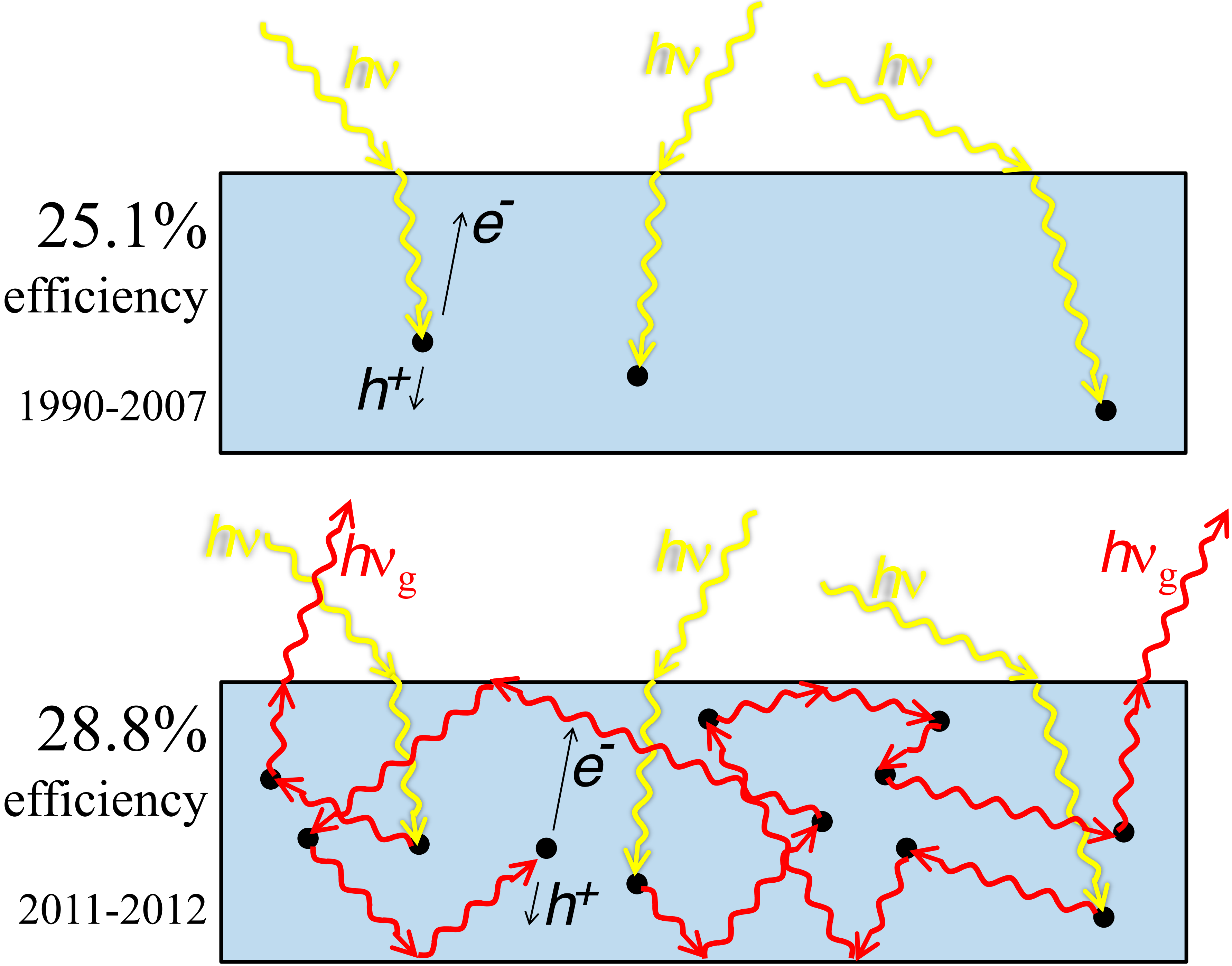


V_{oc} = 1.1220 V
I_{sc} = 29.461 mA
J_{sc} = 29.677 mA/cm^2
Fill Factor = 86.50 %

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

GaAs, theory & expt.





hν
hν
hν
25.1%
efficiency
e-
h+
1990-2007
hν
hνg
hν
hν
hνg
28.8%
efficiency
e-
h+
2011-2012

Counter-Intuitively, to approach the Shockley-Queisser Limit, you need to have good external fluorescence yield η_{ext} !!

Internal Fluorescence Yield η_{int} >> 90%
Rear reflectivity >> 90%

} Both needed for good η_{ext}

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

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

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?

In molecules and quantum dots:

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

But this can also be written:

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

The external Luminescence intensity is a "<u>Volt-meter</u>" into the solar cell.

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 η_{ext}.

Owen D. Miller, Yablonovitch, Sarah Kurtz
IEEE J. Photovoltaics vol. 2, No. 3, page 303-311, (July 2012)

Paradox:

Why is external luminescence is good for solar cell efficiency?

Reason #1; Non-radiative Recombination:

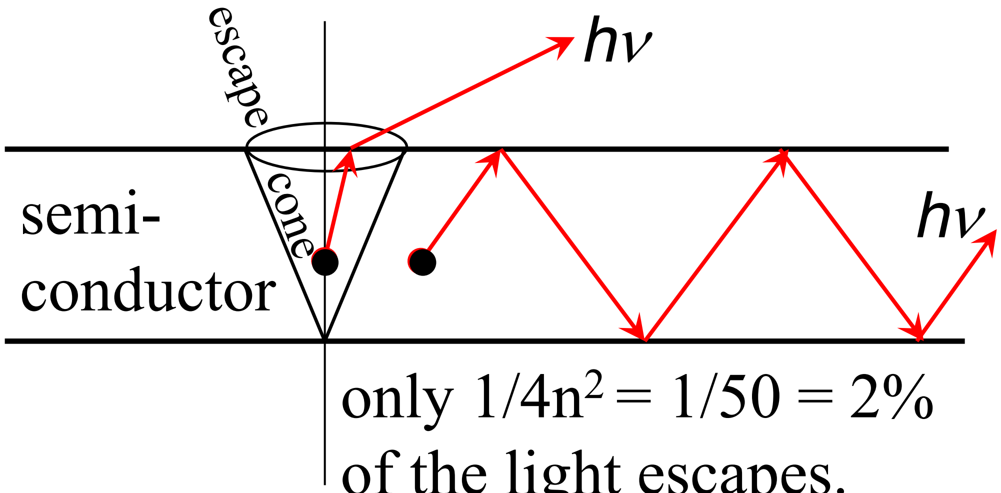
Good external luminescence is a gauge of low internal non-radiative recombination processes.

Non-radiative recombination would certainly impair the solar cell efficiency.

Paradox:

Why is external luminescence is good for solar cell efficiency?

Reason #2; (for plane parallel cells):



Another way to look at this,

1. the recycled photons are not lost,
2. the carrier lifetime increases,
3. increasing carrier density
4. Increasing V_{oc}

Paradox: Why is external luminescence is good for solar cell efficiency?
Reason #3; 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.

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 η_{ext} is what matters!

Only external Luminescence can balance the incoming radiation.

Alta Devices uses photon transport modeling **only**, to project record solar cell efficiencies.

Electronic modeling is used only for the grid resistance, and internal resistance.

Conclusion: Solar cell modeling has to become photon transport modeling, as in LED extraction efficiency.