The Opto-Electronic Physics Which Just Broke the Efficiency Record in Solar Cells

Green Photonics Symposium at Technion
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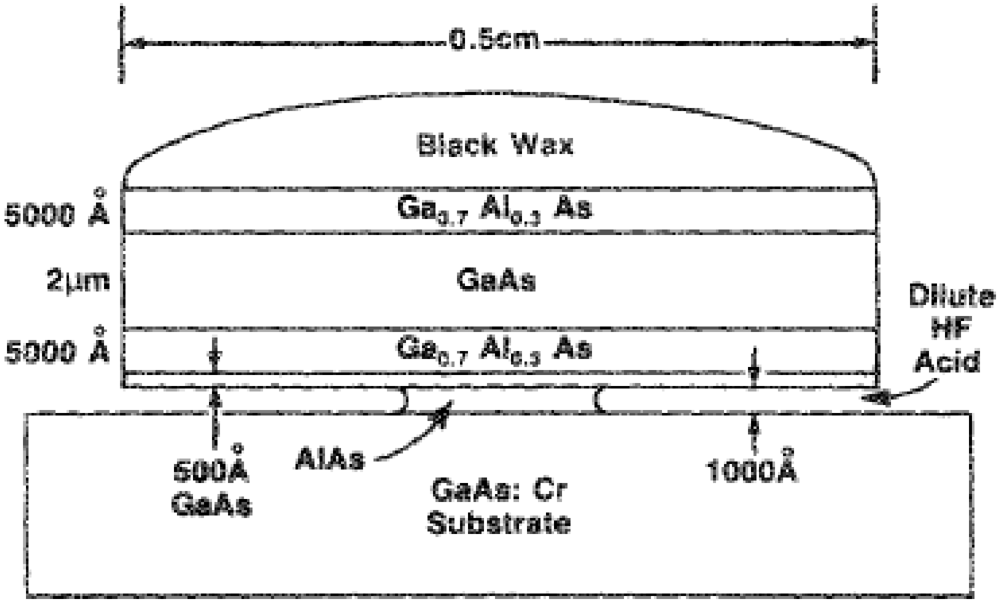
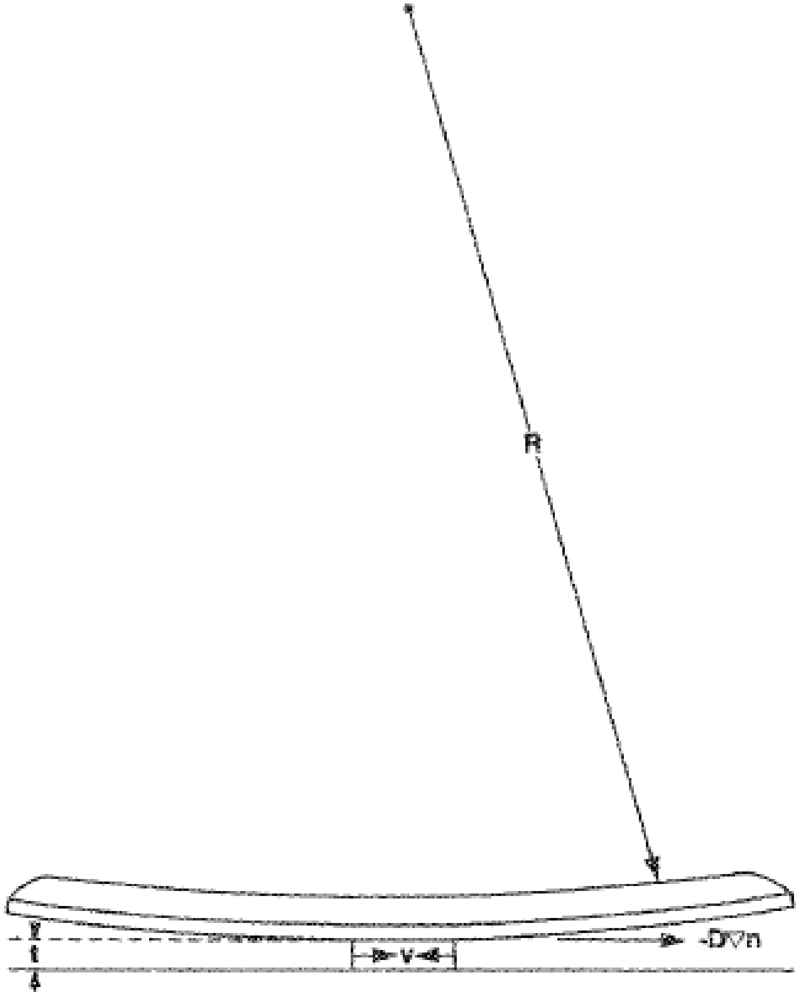
Miller et al, IEEE J. Photovoltaics, vol. 2, pp. 303-311 (2012)

GaAs solar cells are the preferred technology, where cost is no objection: Space

Courtesy of JAXA

The Epitaxial Liftoff Process:





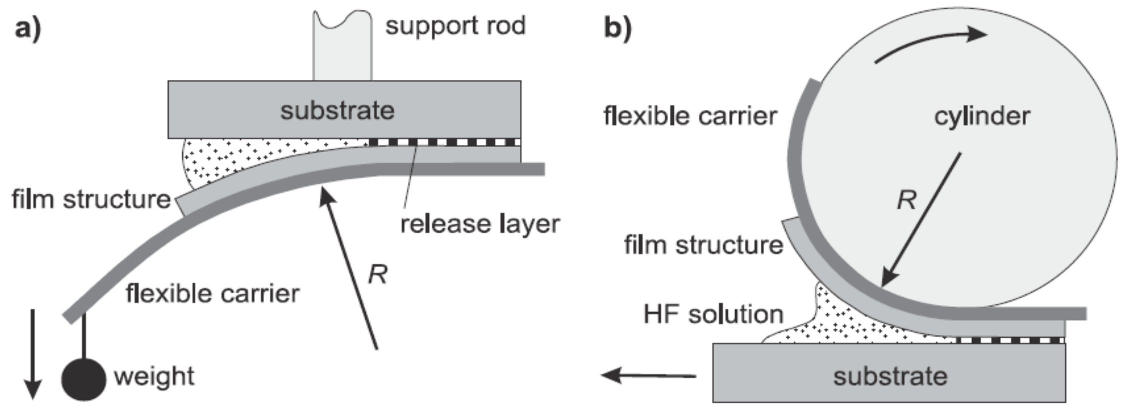


Fig. 1 Schematic representation of the ELO process. a) The weight induced ELO process, b) ELO with a stabilized radius of curvature by guiding the temporary flexible carrier over a cylinder surface.

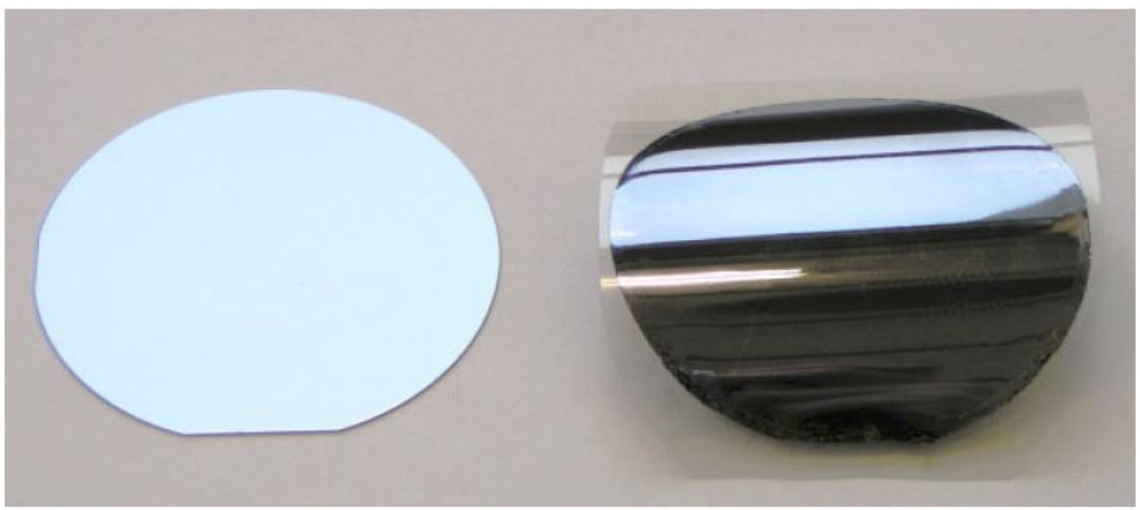
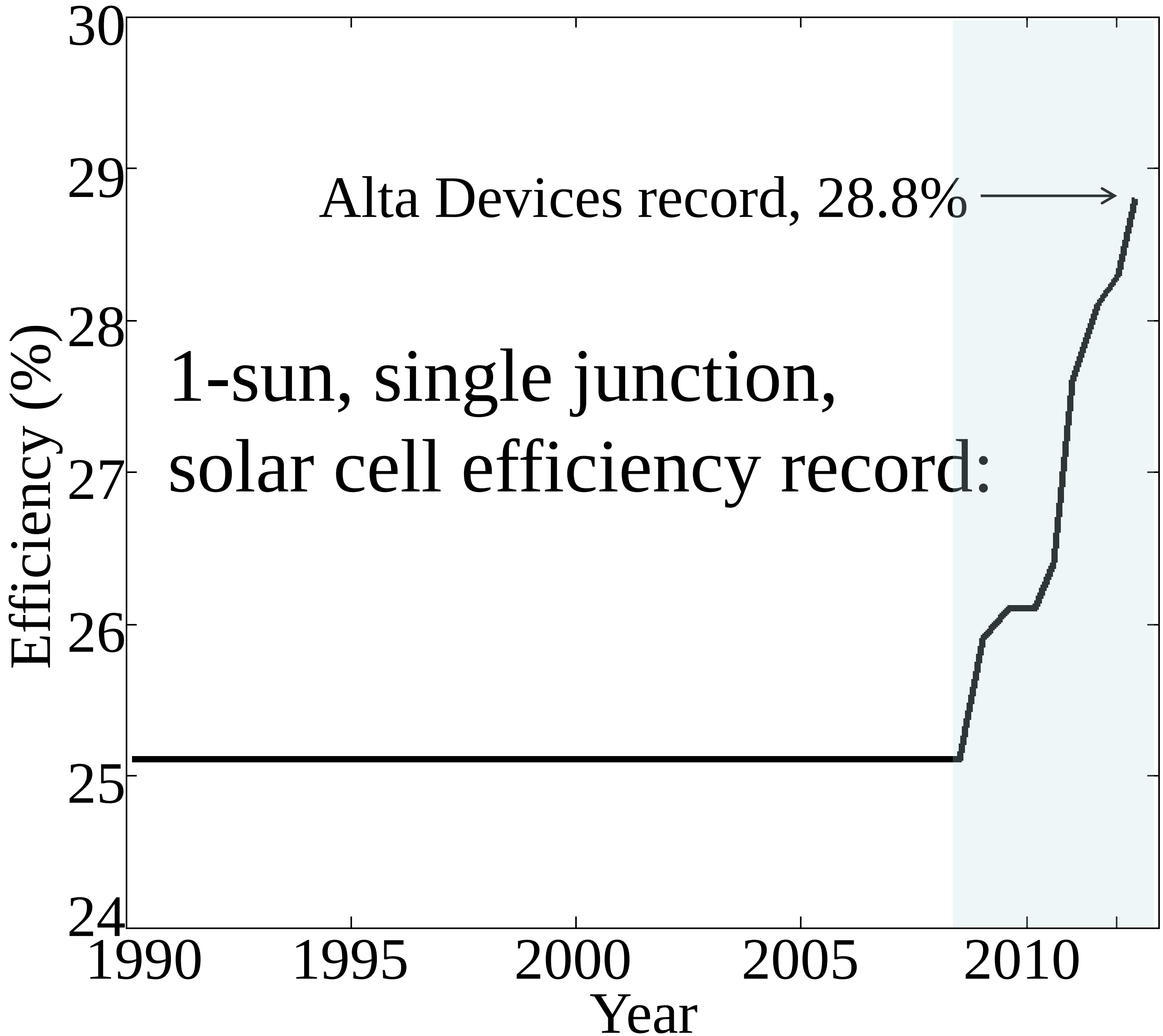
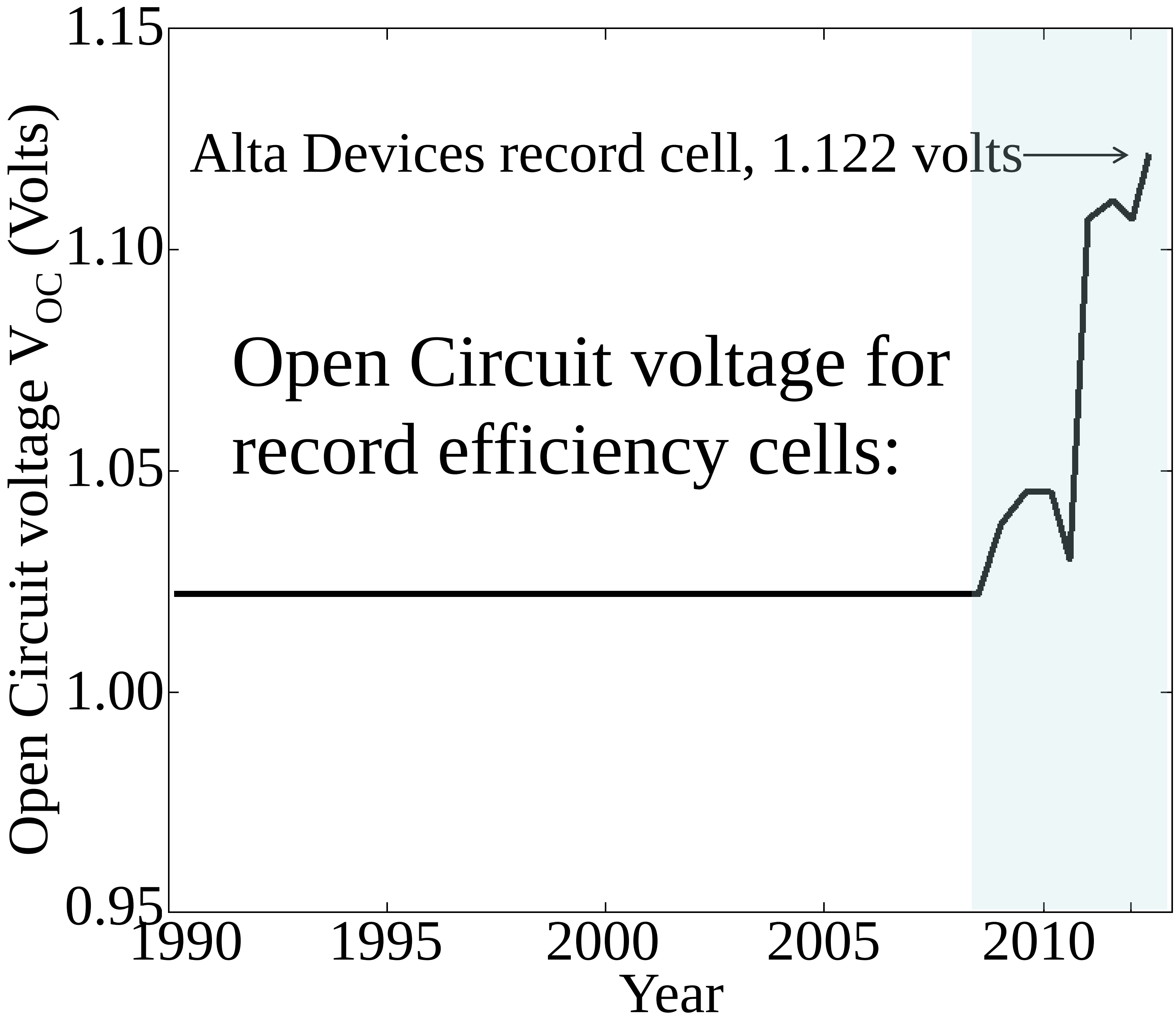


Fig. 2 (online colour at: www.pss-a.com) 1 µm thick GaAs film of 2 inch in diameter on a flexible plastic carrier (right hand side) after epitaxial lift-off from its substrate (left hand side).

GaAs
Courtesy of Alta Devices, Inc.


Alta Devices BOD Meeting
(General & Technical)


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


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 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?

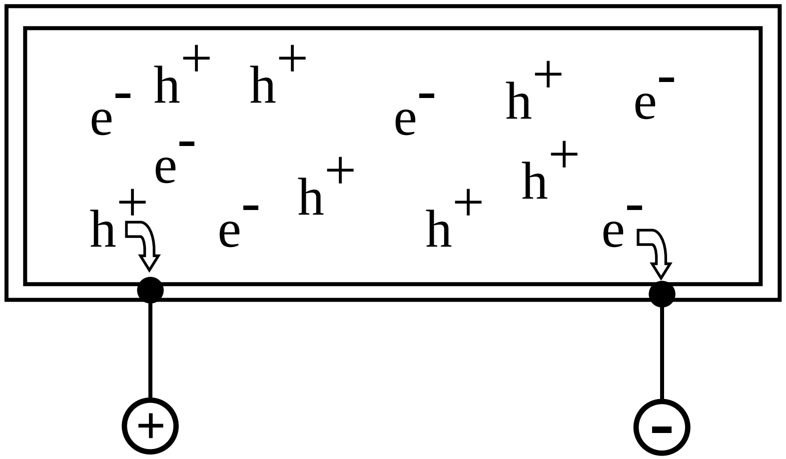
Shockley-Queisser Limit (1961):

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

But in quasi-equilibrium:

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

What is the operating voltage?



To extract current, voltage at contacts must be slightly lower than Voc

But, operating voltage linked directly to Voc

$$V_{OP} \approx V_{OC} - \frac{kT}{q} \ln\left(\frac{qV_{OC}}{kT}\right)$$

We only need to understand the open-circuit voltage

Yes photons have entropy, S

Photon Free Energy = hν - TS

Photon Free Energy = hν - kT lnW

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

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

where Ω_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)

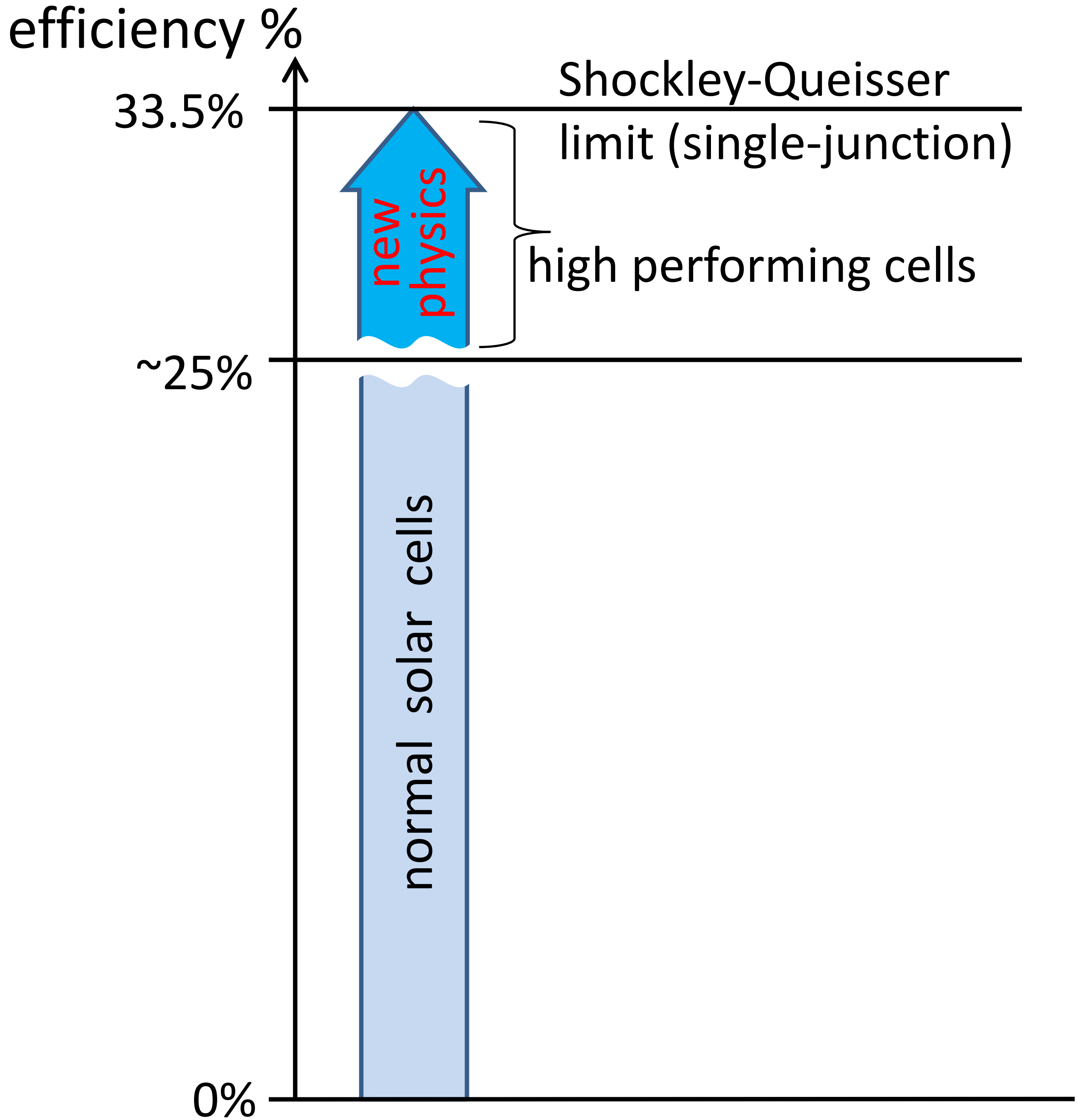
Small bandgaps are particularly vulnerable to entropy:

After you subtract off all the entropy terms, you don't have much Free Energy left.

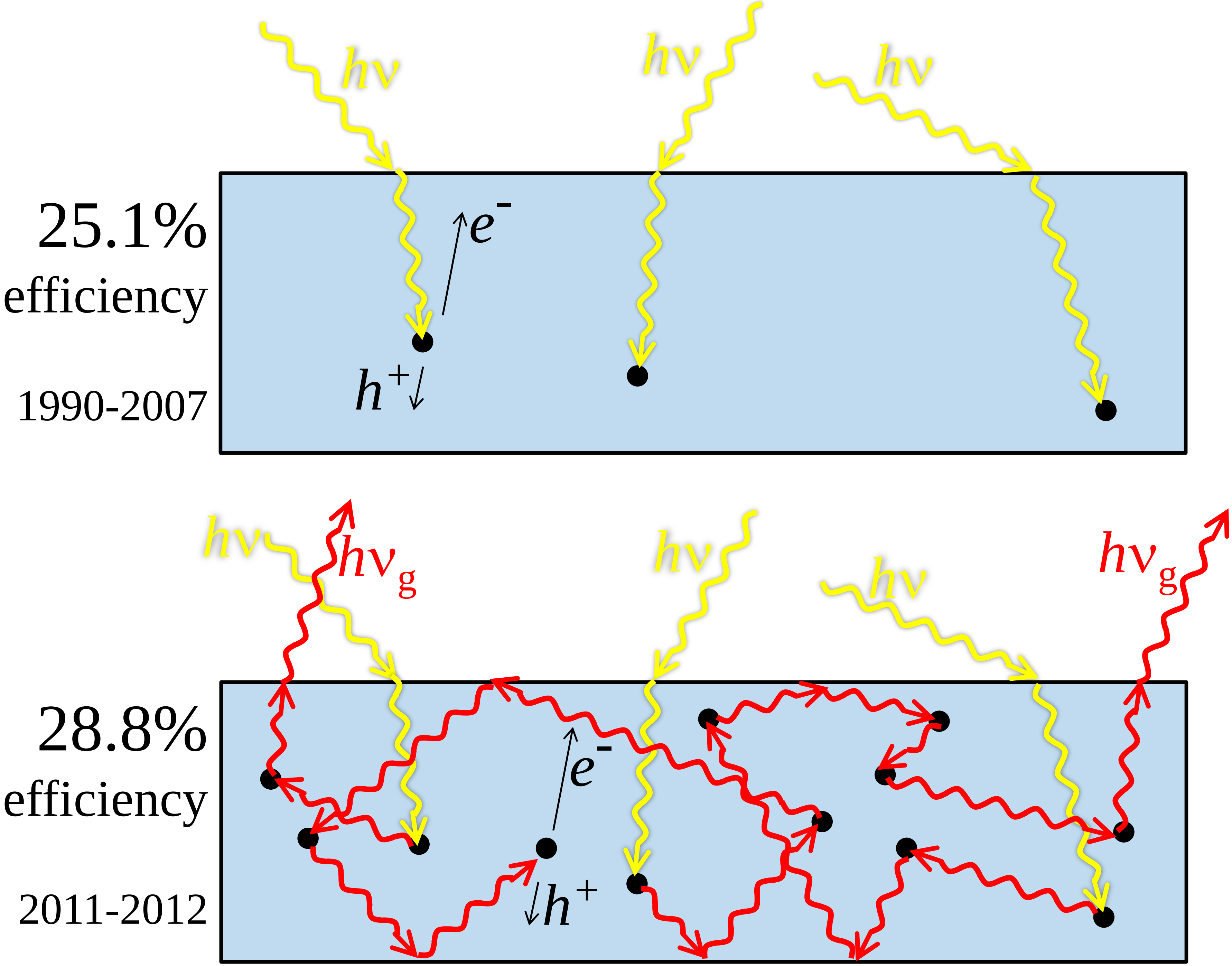
$qV_{\textbf{operating point}} = 1.1\text{eV} - 0.8\text{eV} = 0.3\text{eV}$

A lousy 0.3eV from all those big photons

In general we cannot afford to compromise with regard to quantum efficiency.



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



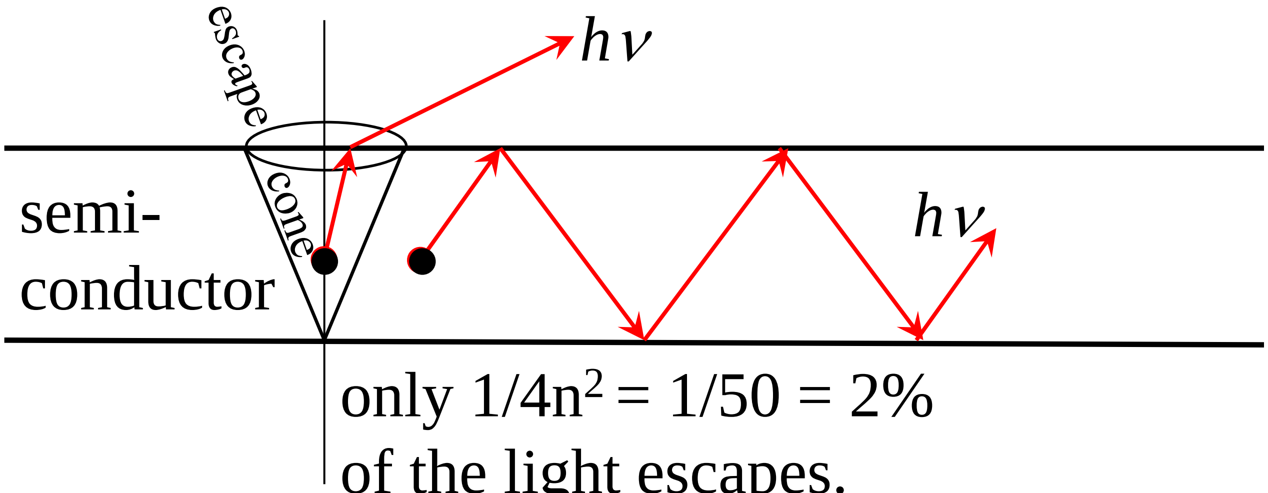
$h\nu$
$h\nu$
$h\nu$
25.1%
efficiency
1990-2007
e^-
h^+
$h\nu$
$h\nu_g$
$h\nu$
$h\nu$
$h\nu_g$
28.8%
efficiency
2011-2012
e^-
h^+

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

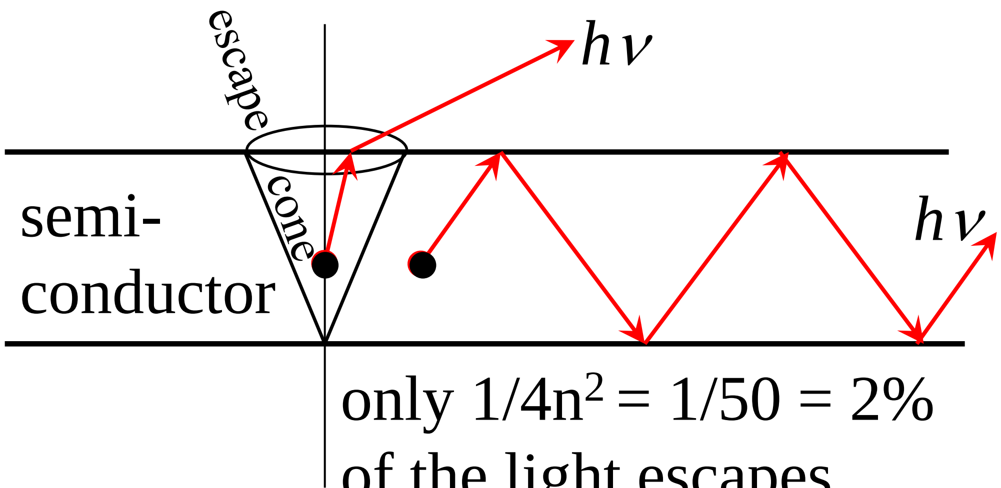
$$qV_{oc} = qV_{oc\text{-ideal}} - kT|\ln\{\eta_{ext}\}|$$

The external fluorescence yield η_{ext} is what matters!

Only external Luminescence can balance the incoming radiation.



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

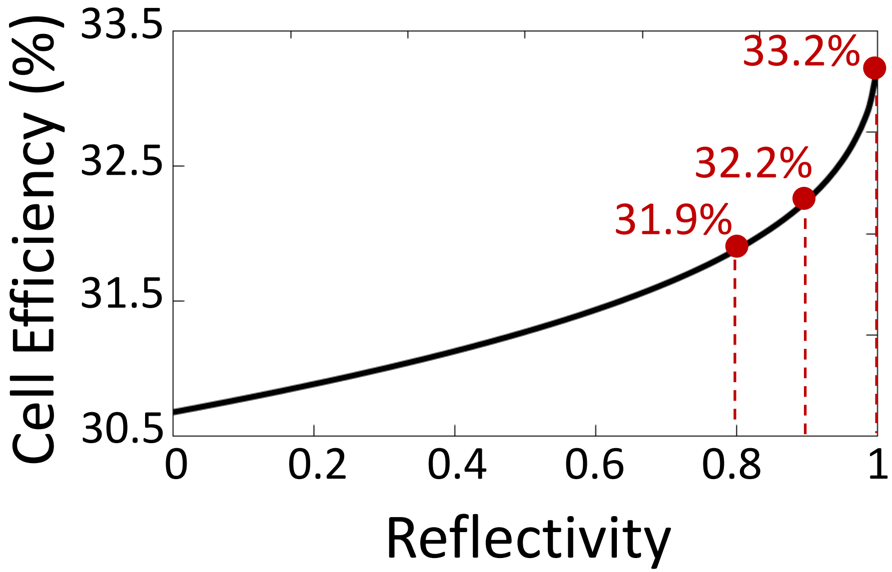


But this is really hard to do:

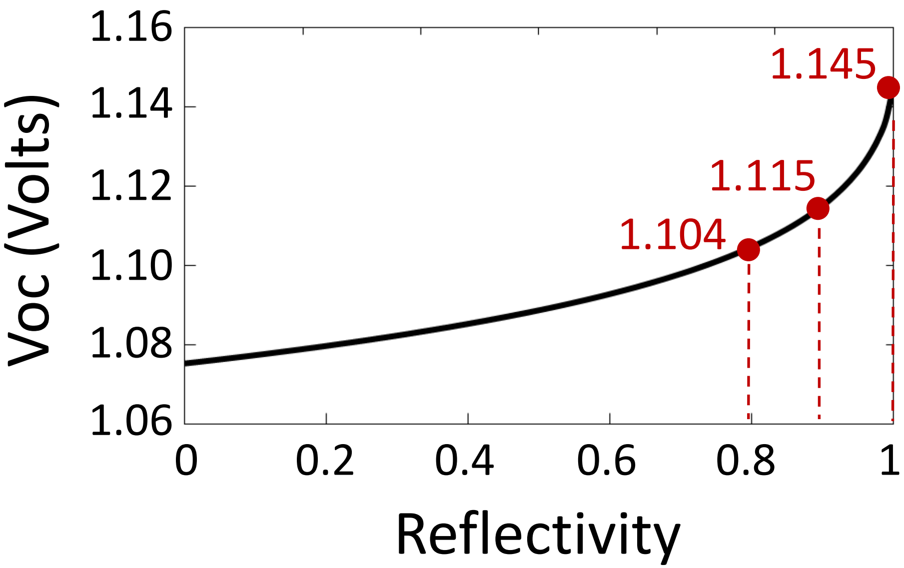
You may need an internal efficiency of η_{int}=99%

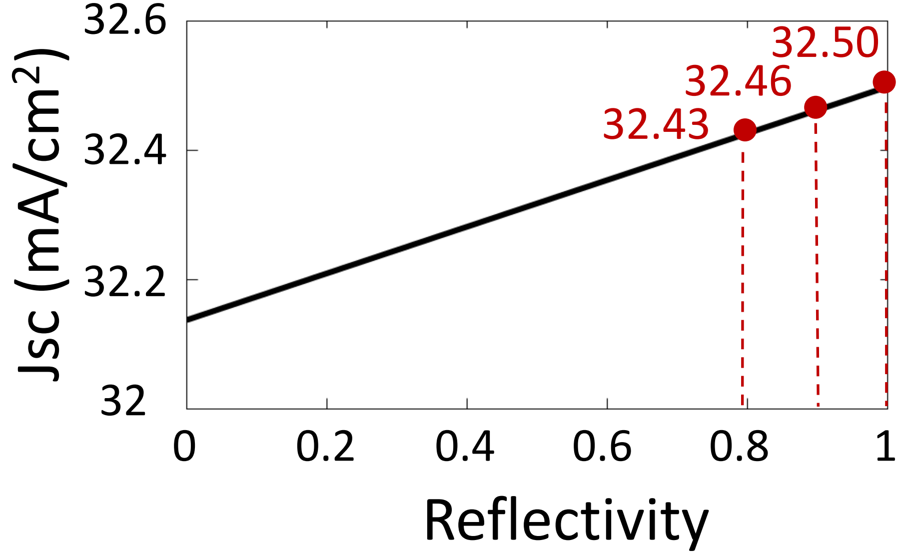
just to get an external efficiency of η_{ext}=50%

Efficiency vs. Rear Reflectivity, GaAs 3μm



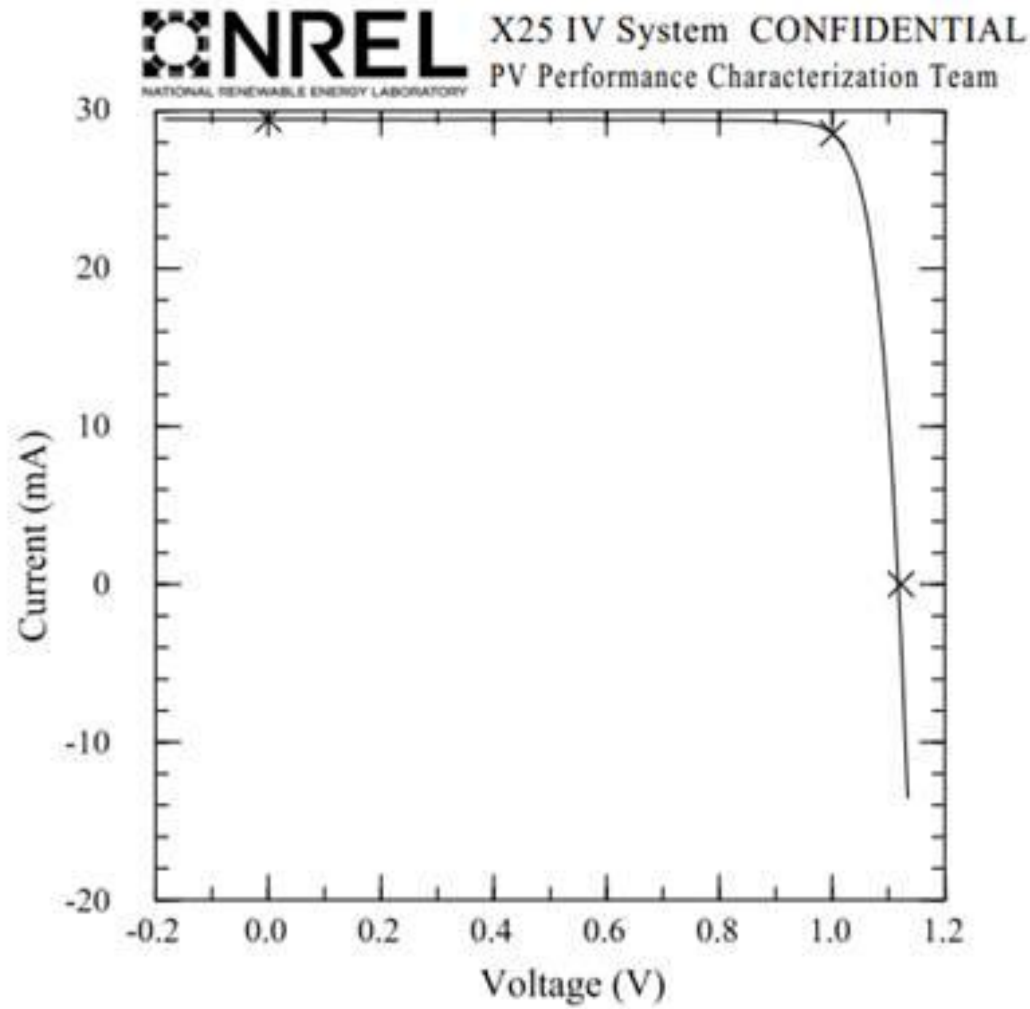
90%
Rear
Reflectivity
Is Not
Enough!





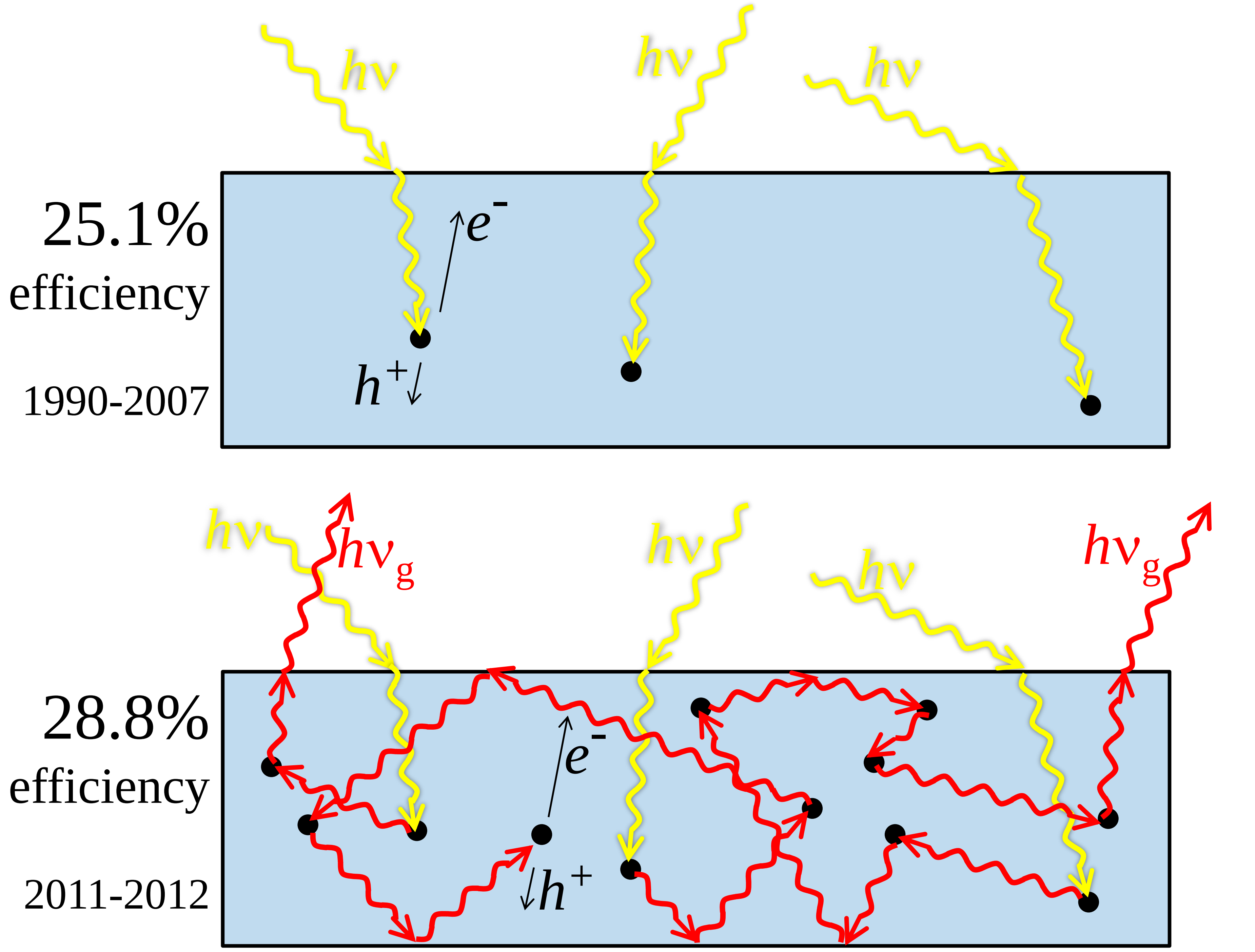
Latest 1 sun single-junction results from Alta Devices, Inc.

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 %



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

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}

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!

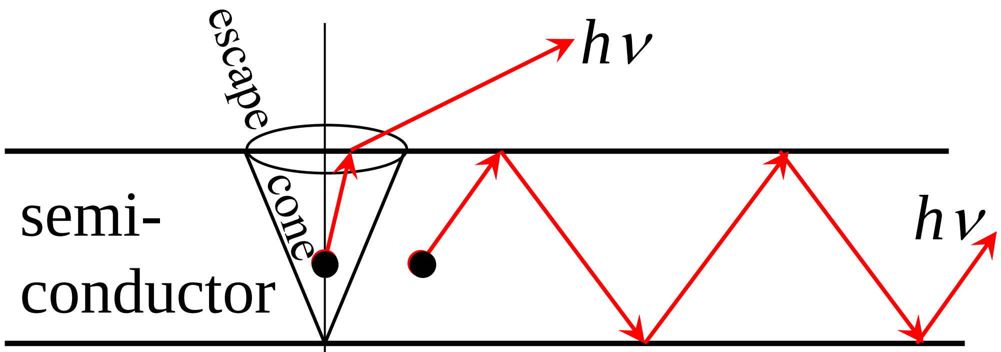
A good solar cell has to be a good LED!

Counter-intuitively:

1. Thin-film cells are more efficient than the best wafer cells.
2. Solar cells perform best when there is maximum external fluorescence yield η_{ext}.

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

Why the record-setting Voltage?



only $1/4n^2 = 1/50 = 2\%$ of the light escapes.

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}

This Photon-Recycling explanation is incomplete!
Good external luminescence can be achieved with texturing and no-photon-recycling.

Paradox: Why is external luminescence is good for solar cell efficiency?

Reason #4; Luminescence <u>IS</u> Voltage:

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

At quasi-equilibrium:

$$\text{Luminescence} = (\text{Black Body}) \times exp\{qV/kT\}$$

(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.

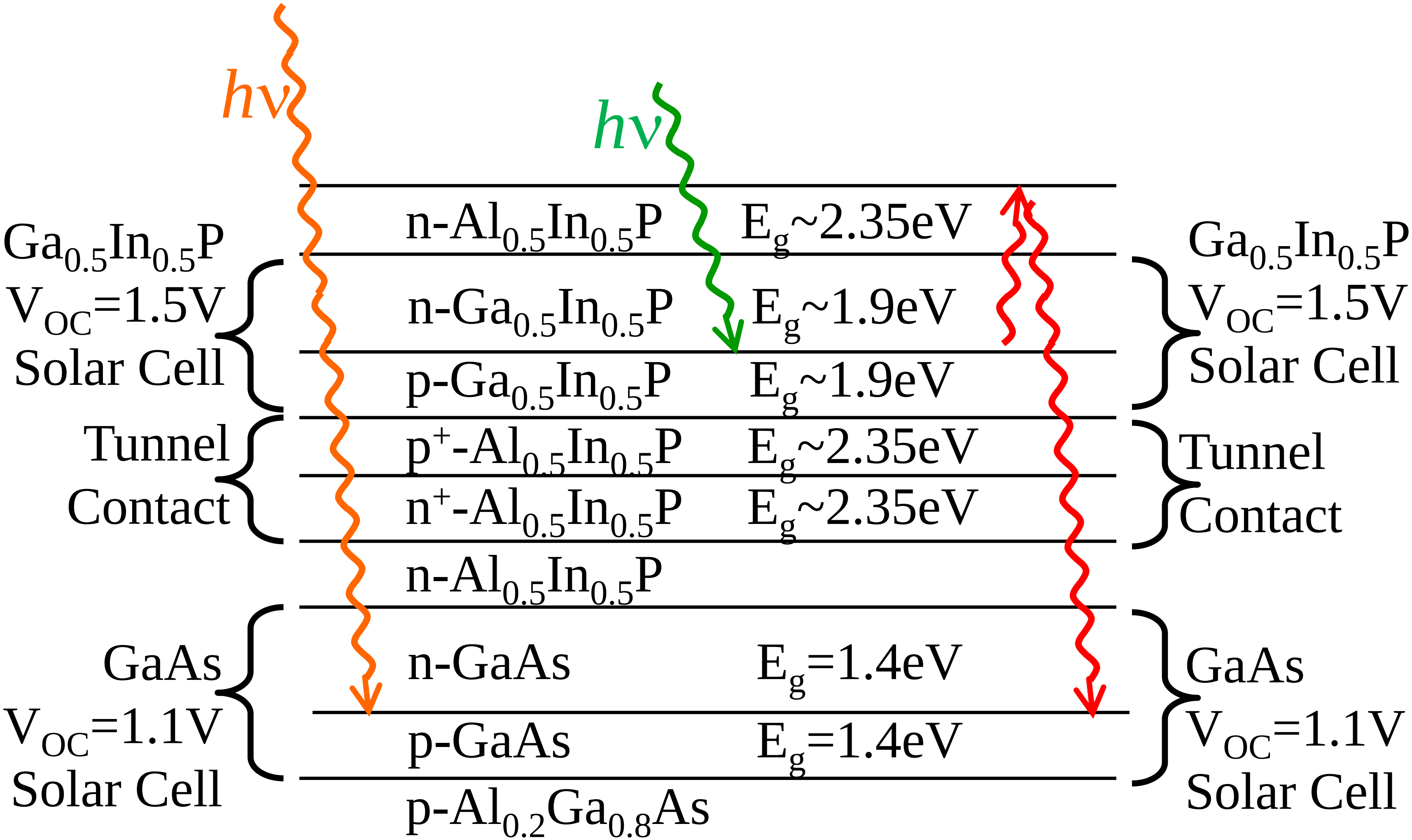
What if the material is not ideal, and the electrons and holes are lost to heat before they can luminesce?

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

The external fluorescence yield η_{ext} is what matters!

Only external Luminescence can balance the incoming radiation.

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.

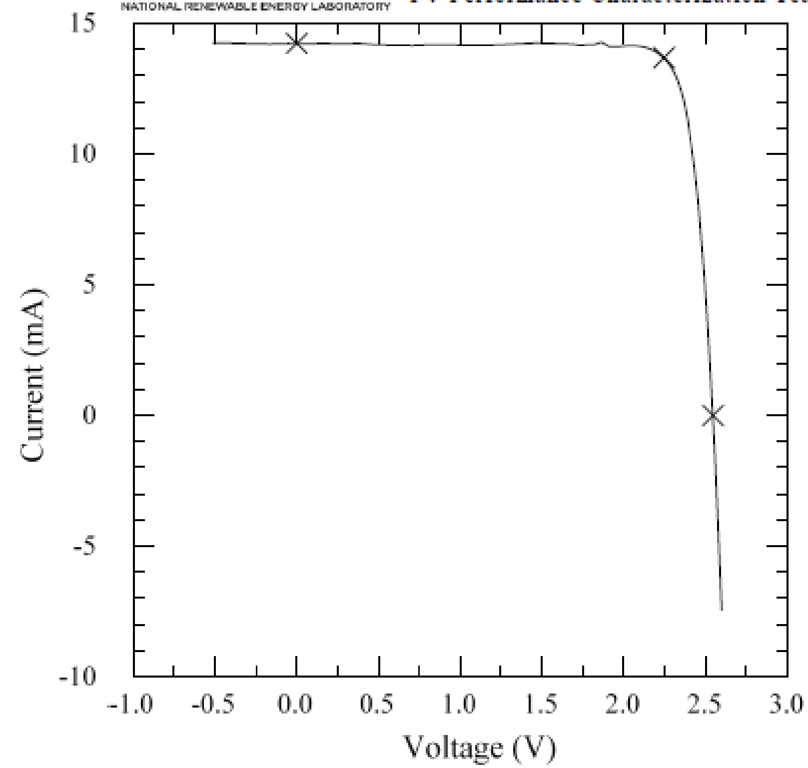
Expected to reach 34% dual junction, eventually.

Alta Devices
GaInP/GaAs Tandem Cell

Device ID: AD13609-F-G2
4:41 PM 2/1/2013
Spectrum: ASTM G173 global

Device temperature: 25.0 ± 1.0 °C
Device area: 0.999 cm^2
Irradiance: 1000.0 W/m^2

NATIONAL RENEWABLE ENERGY LABORATORY
OSMSS IV System CONFIDENTIAL
PV Performance Characterization Team



V_{oc} = 2.5468 V
I_{sc} = 14.247 mA
J_{sc} = 14.255 mA/cm^2
Fill Factor = 84.7 %

I_{max} = 13.681 mA
V_{max} = 2.2477 V
P_{max} = 30.752 mW
Efficiency = 30.77 %

Luminescent coupling corrected bottom QE

Conclusions:

1. Thin-Film GaAs of ~28% efficiency is in the process of scale-up for solar panels.

2. Opto-electronics can provide the motive power for automobiles.

3. The automotive power market is 10× bigger than the panel electricity market.