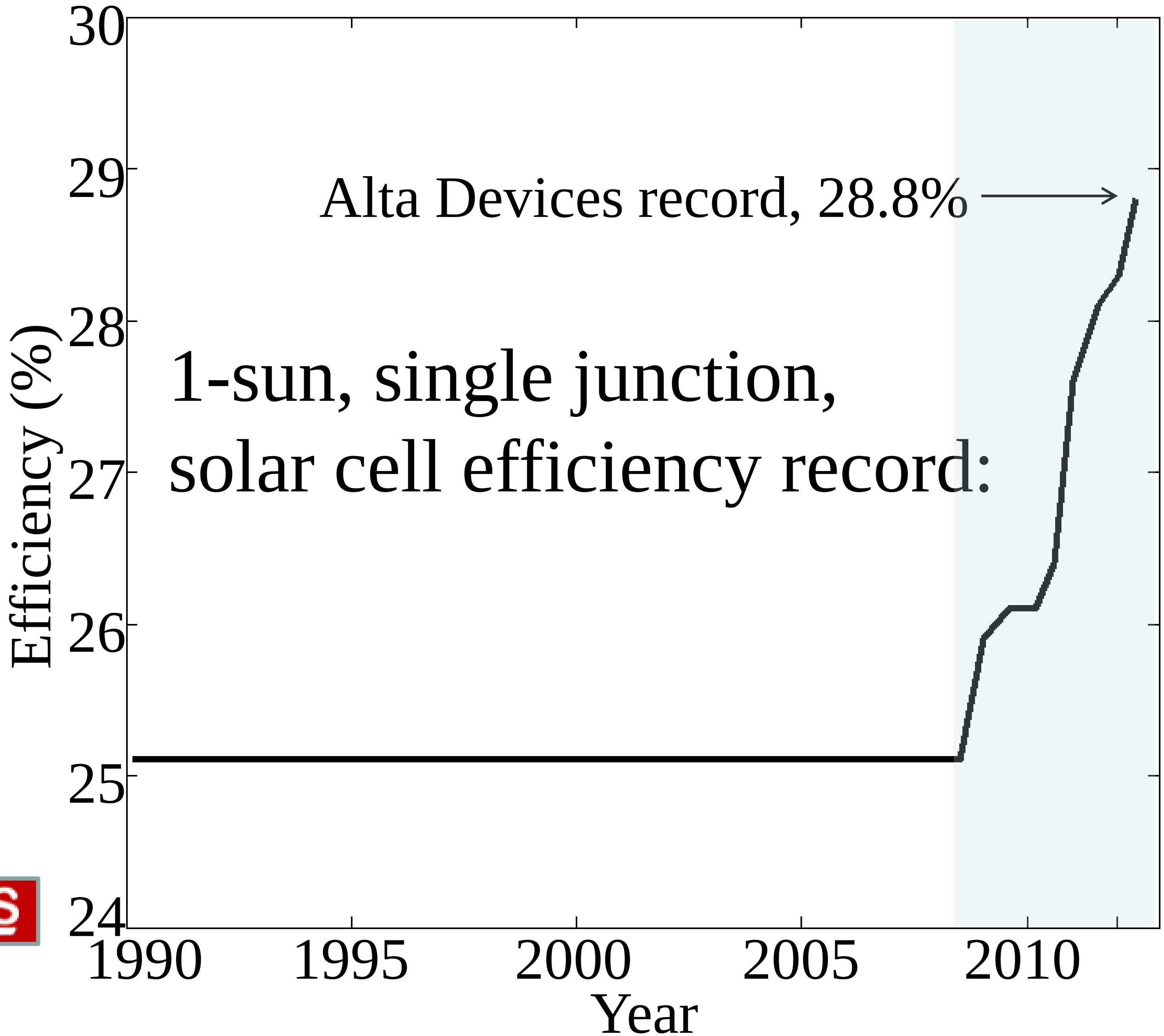
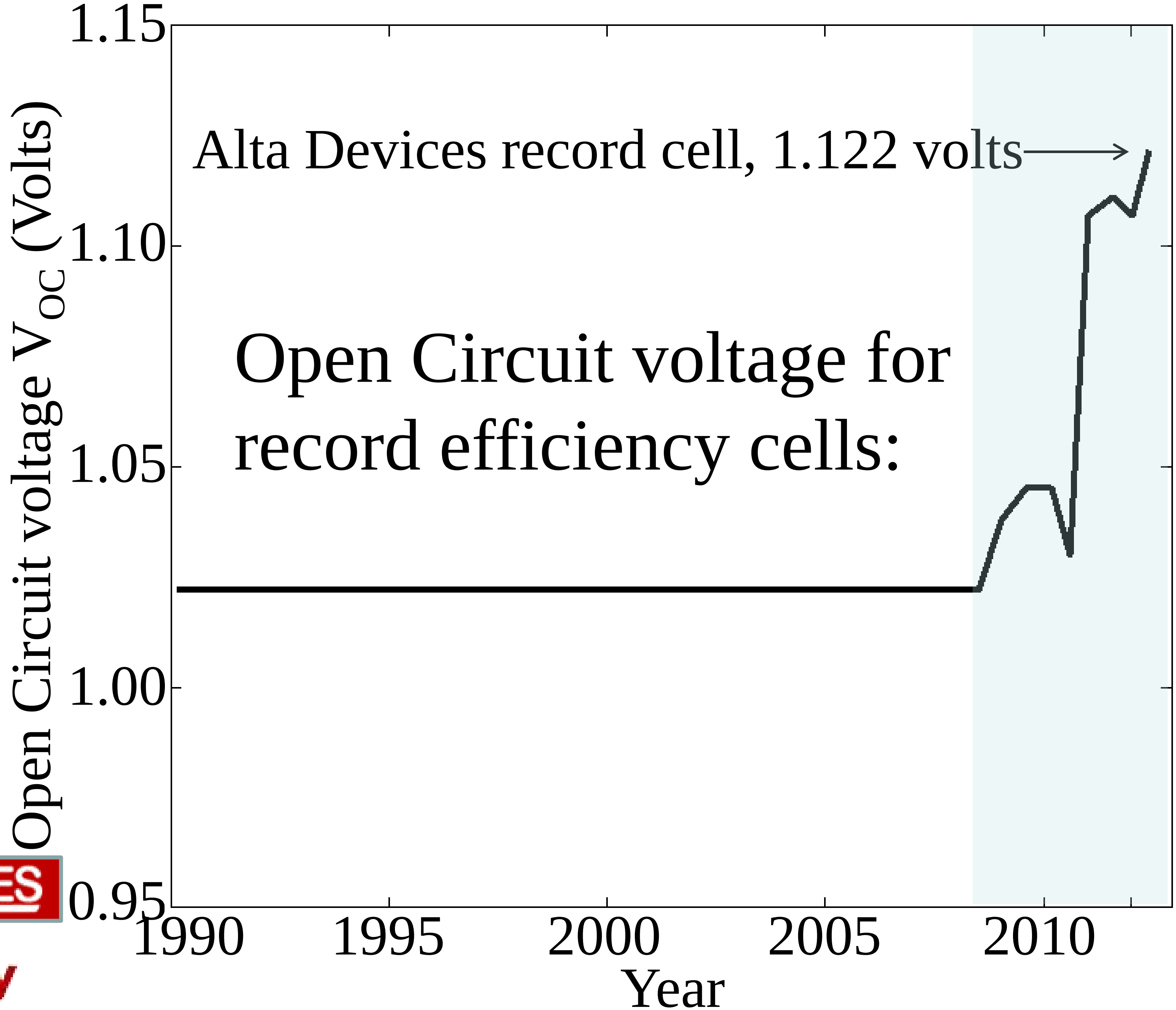
“A Great Solar Cell Has To Be a Great LED”; So What’s Wrong With Subsidized Solar Panels?

MIT Energy Initiative IHS Seminar,
Cambridge Mass.
5PM, Wednesday Feb. 8, 2017

Eli Yablonovitch, Vidya Ganapati, Patrick Xiao
Electrical Engineering and Computer Sciences Dept.,
Univ. of California, & Lawrence Berkeley Laboratory

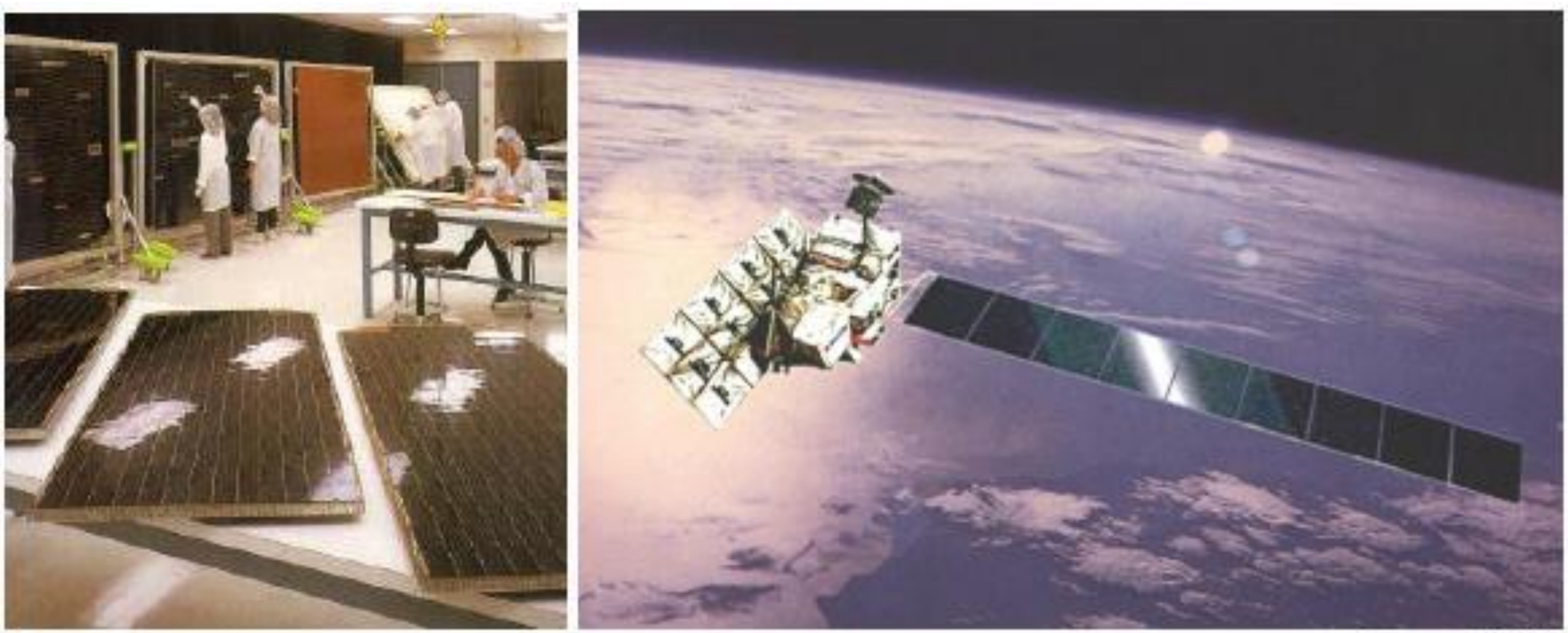


ALTA DEVICES
A Hanergy Company



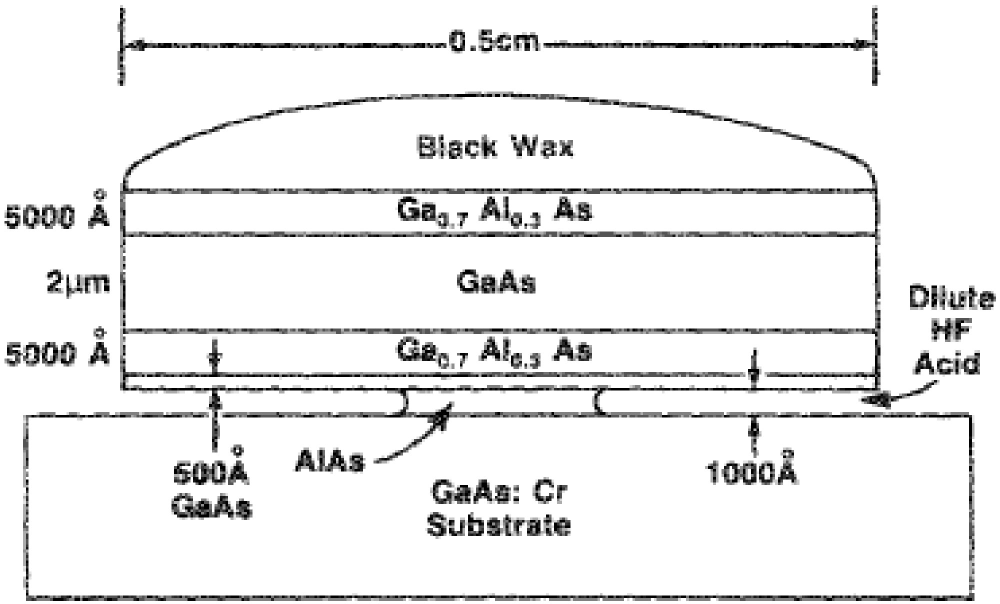
ALTA DEVICES
A
Hanergy
Company

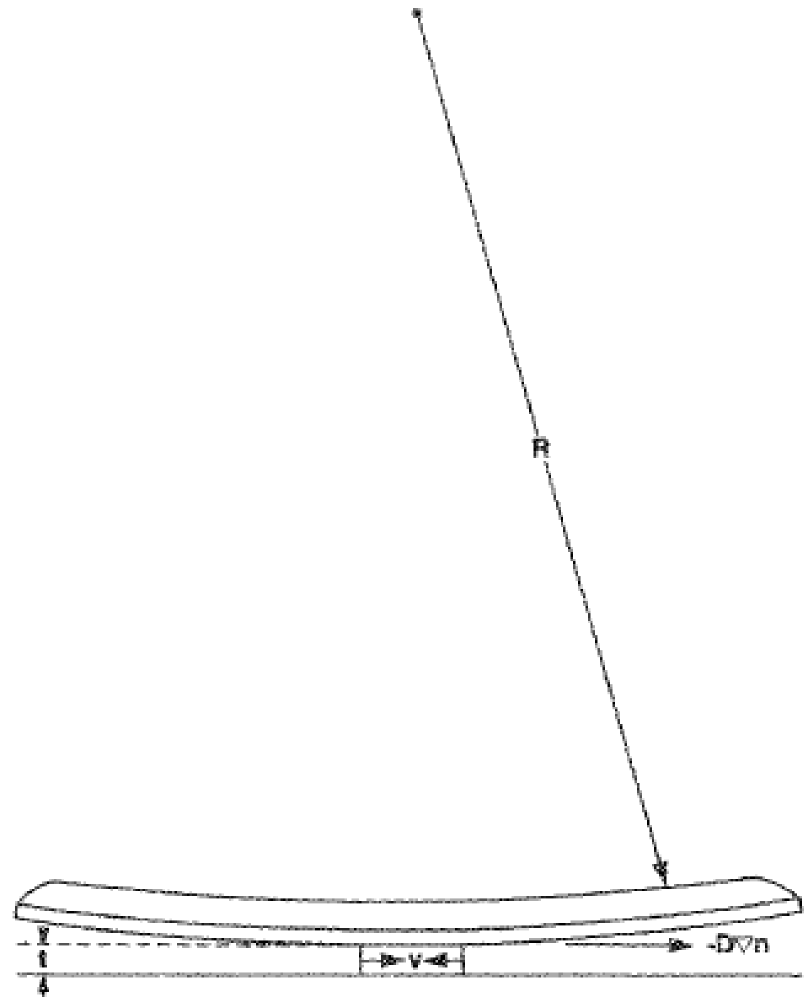
GaAs solar cells are the preferred technology, where cost is no objection: Space



Courtesy of JAXA

The Epitaxial Liftoff Process:





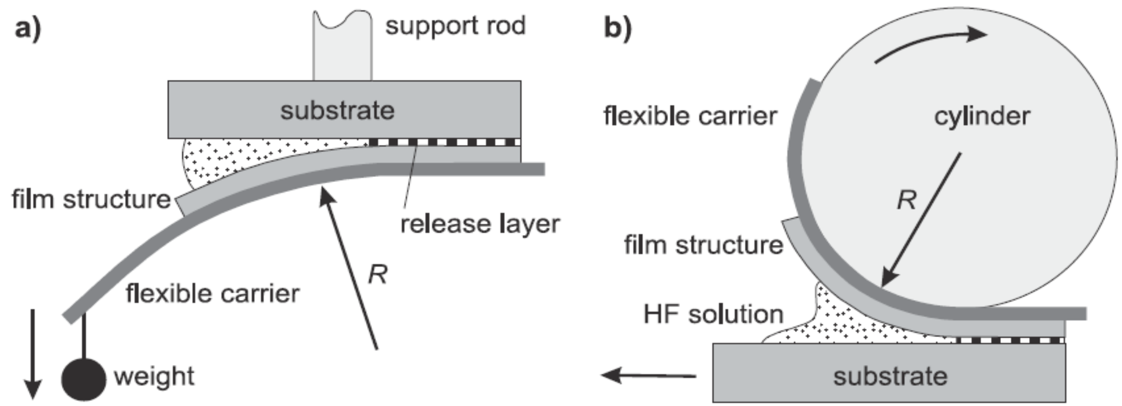


Fig. 1 Schematic representation of the ELO process. a) The weight induced ELO process, b) ELO with a stabilized radius of curvature by guiding the temporary flexible carrier over a cylinder surface.

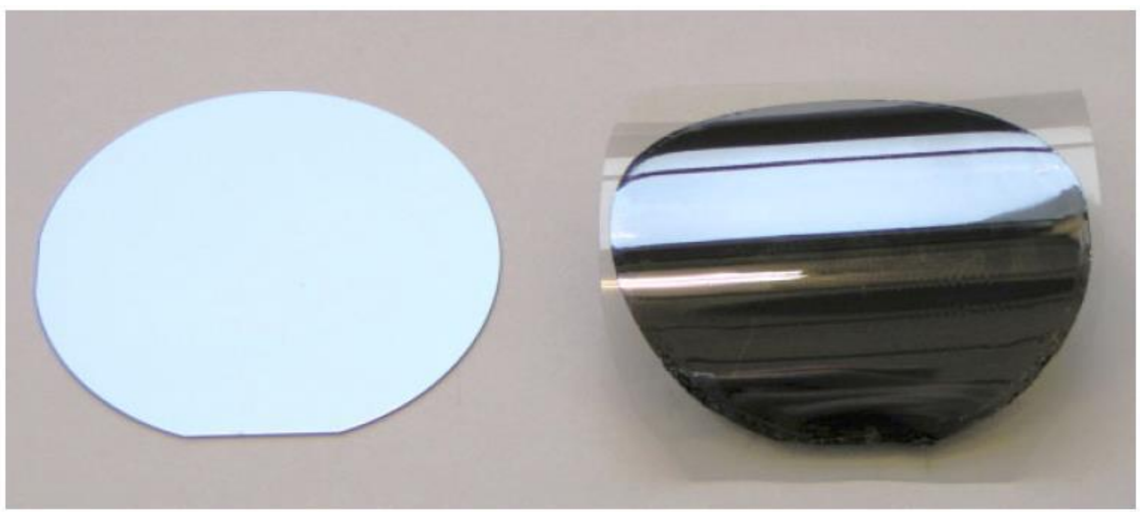


Fig. 2 (online colour at: www.pss-a.com) 1 µm thick GaAs film of 2 inch in diameter on a flexible plastic carrier (right hand side) after epitaxial lift-off from its substrate (left hand side).

Courtesy of
Alta Devices, Inc.

ALTADEVICES
A
Hanergy
Company

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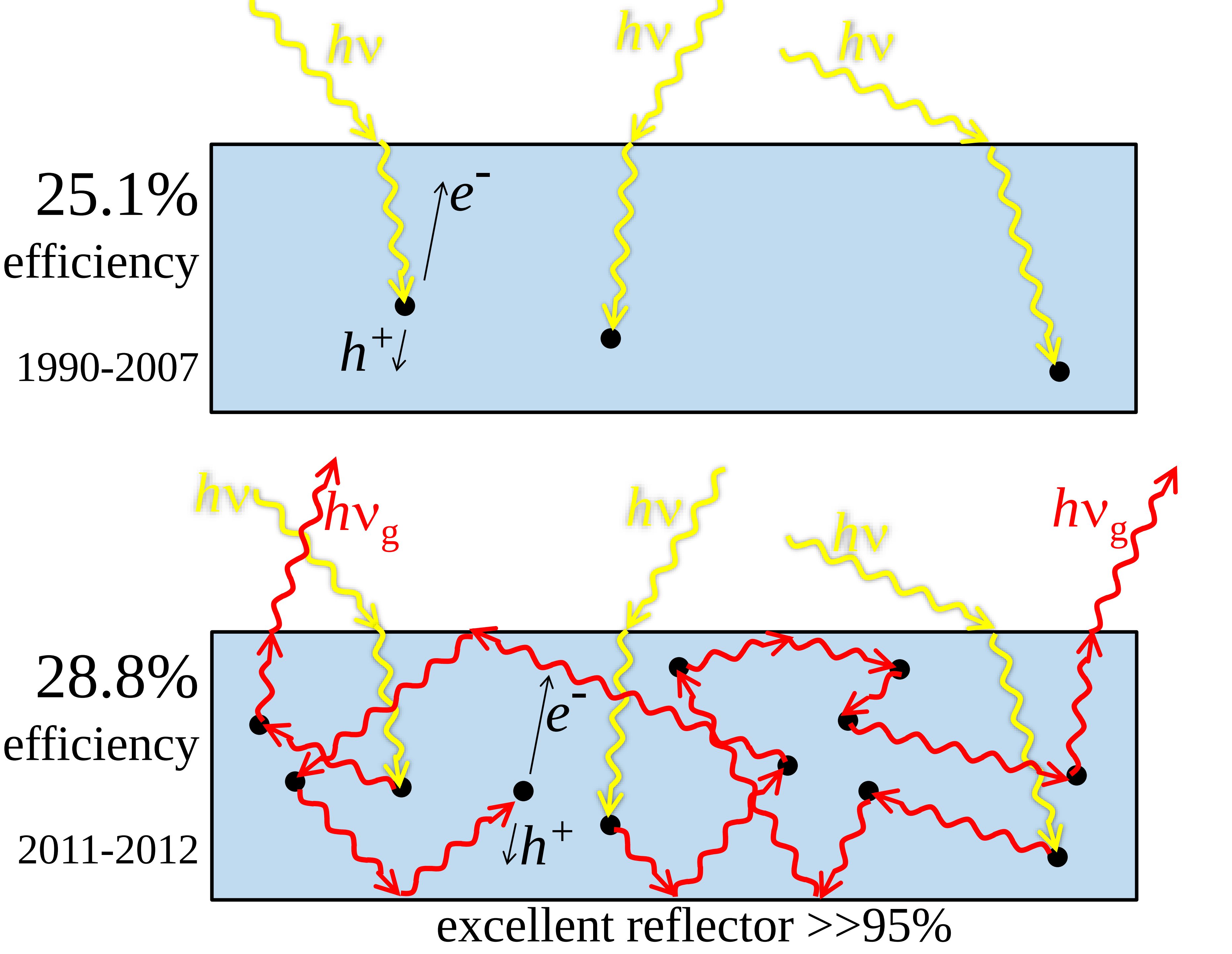
Li Hejun


hν
hν
hν
25.1%
efficiency
1990-2007
e-
h+
hν
hνg
hν
hν
hνg
28.8%
efficiency
2011-2012
e-
h+
excellent reflector >>95%

Shockley told us to generate the maximum possible external luminescence:

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

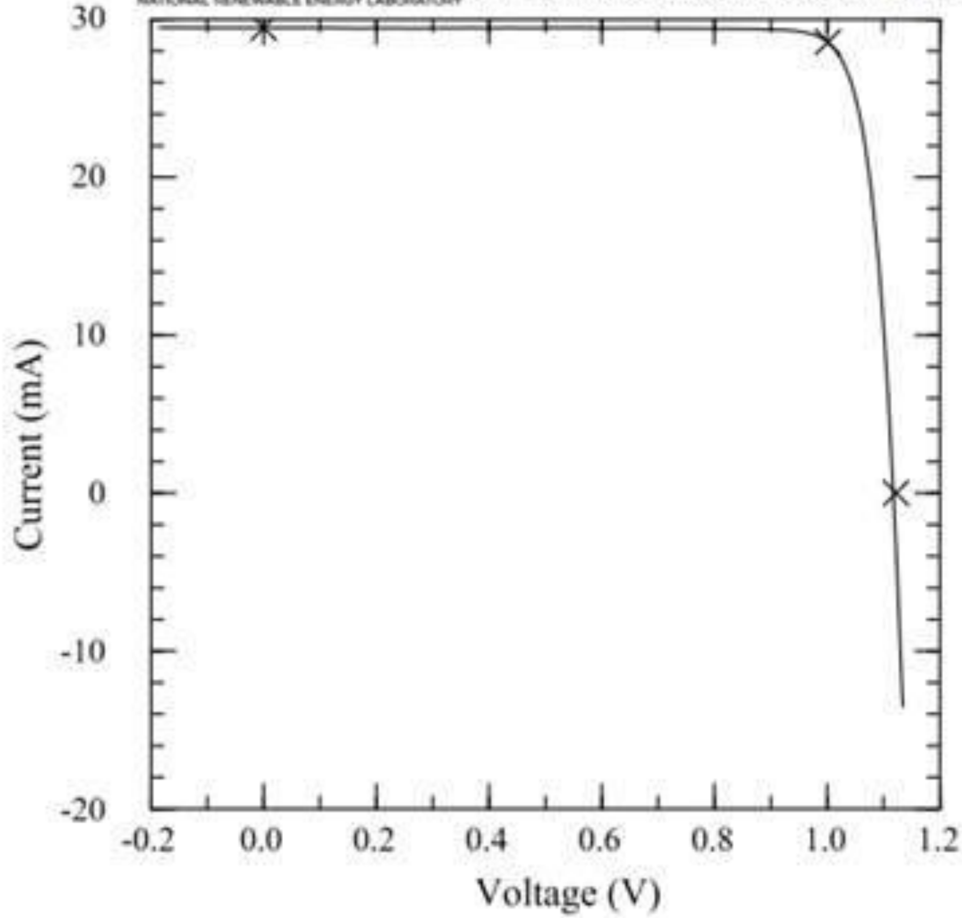
The external luminescence yield η_{ext} is what matters!

Only external Luminescence can balance the incoming radiation.

1 sun results from Alta Devices, Inc.

Expected to reach 29.8% single junction

NREL X25 IV System CONFIDENTIAL
PV Performance Characterization Team



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
A Hanergy Company

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!

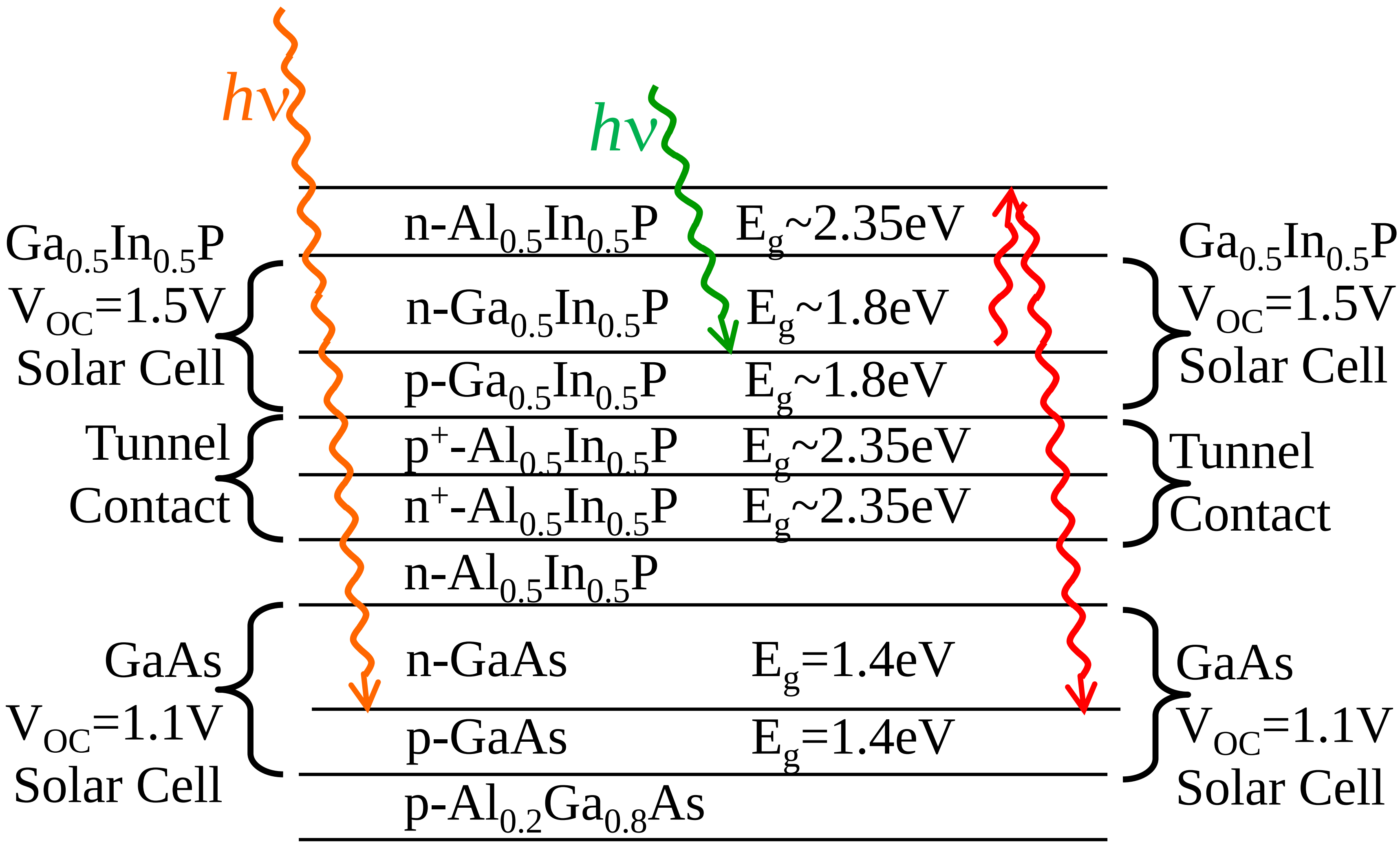
A great solar cell needs be a great LED!

Counter-intuitively:

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)

Dual Junction Series-Connected Tandem Solar Cell



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

Dual-junction 1 sun results from Alta Devices, Inc.

ALTADEVICES

A Hanergy Company

ALTA has demonstrated >31.5% efficiency in the same system.

Expected to reach 34% dual junction, eventually.

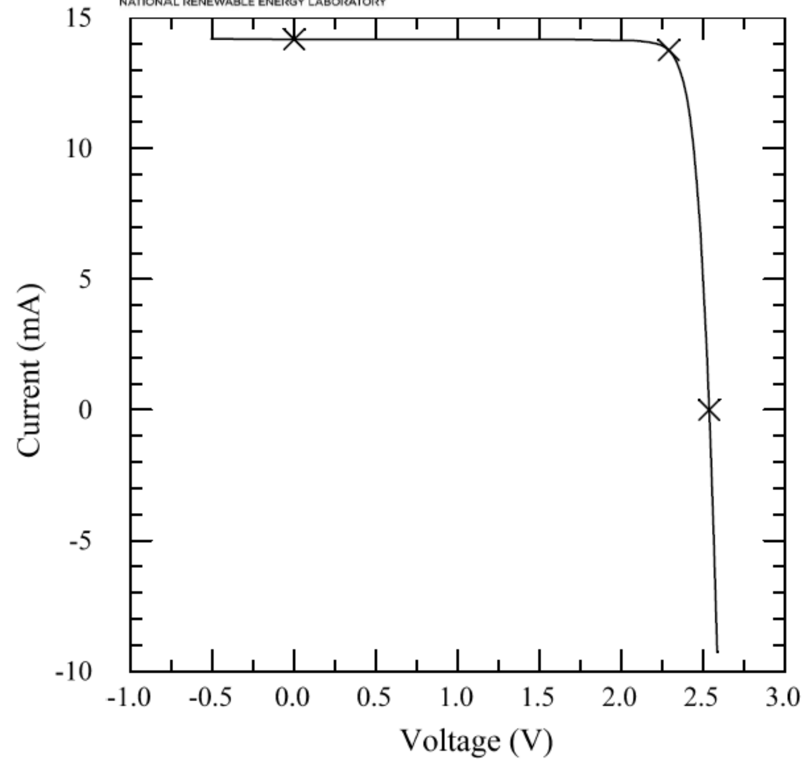
Alta Devices

GaInP/GaAs Tandem Cell

Device ID: AD33551-I-3	Device temperature: 25.0 ± 1.0 °C
5:14 PM 1/5/2016	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

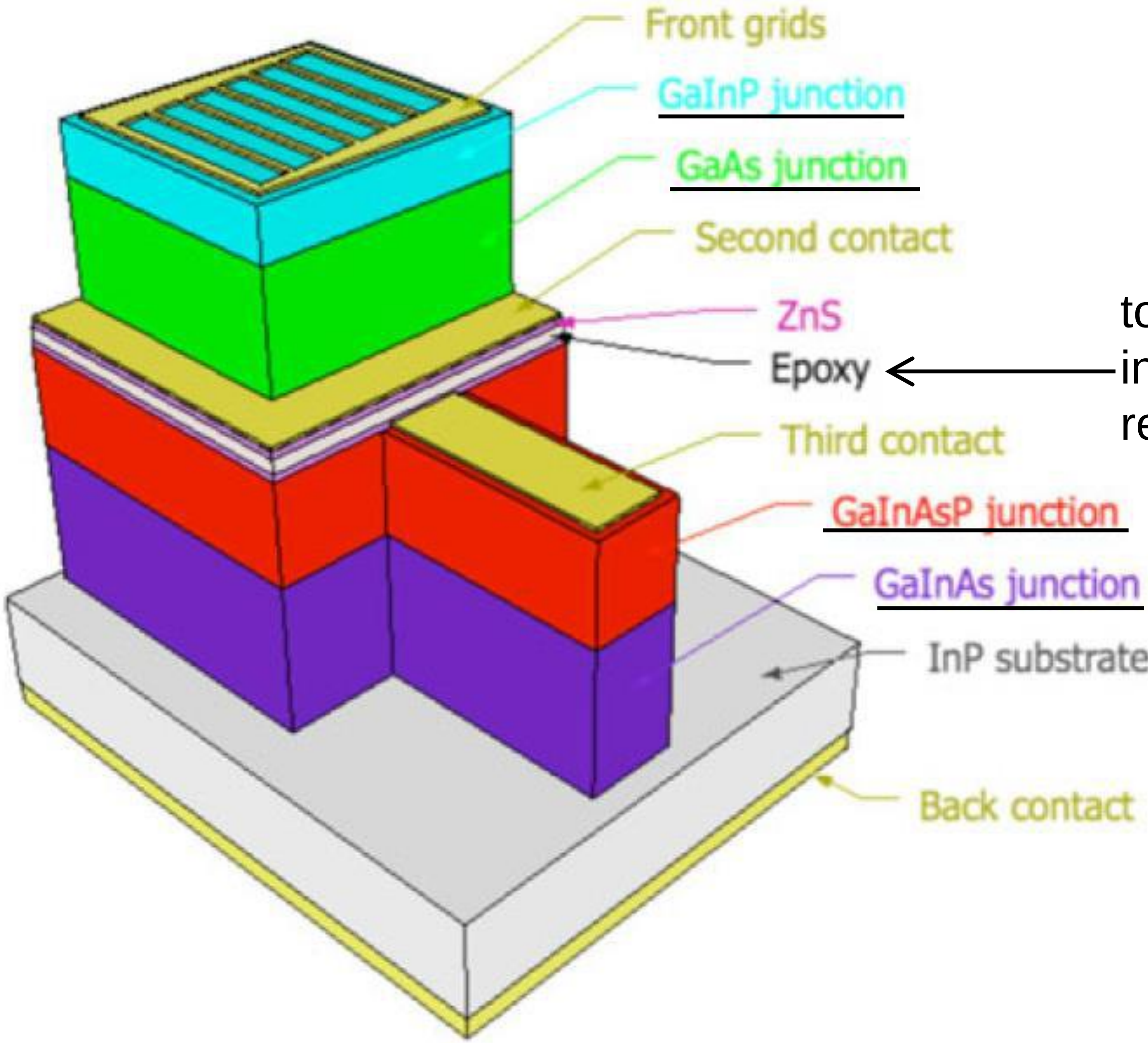


V_{oc} = 2.5381 V	I_{max} = 13.754 mA
I_{sc} = 14.164 mA	V_{max} = 2.2906 V
J_{sc} = 14.184 mA/cm^2	P_{max} = 31.505 mW
Fill Factor = 87.7 %	Efficiency = 31.55 %

Ref Cell: N40

38.8% Efficient--all time champion solar cell
Quadruple-junction 1-sun cell captures diffuse & direct light

designed for Luminesce-Extraction & Photon-Recycling



total internal reflection

IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 6, p.358 (JANUARY 2016)
Myles A. Steiner, Sarah R. Kurtz, et al, NREL USA

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 happening in the solar economy?

c-Si η ~ 15%-23% in production

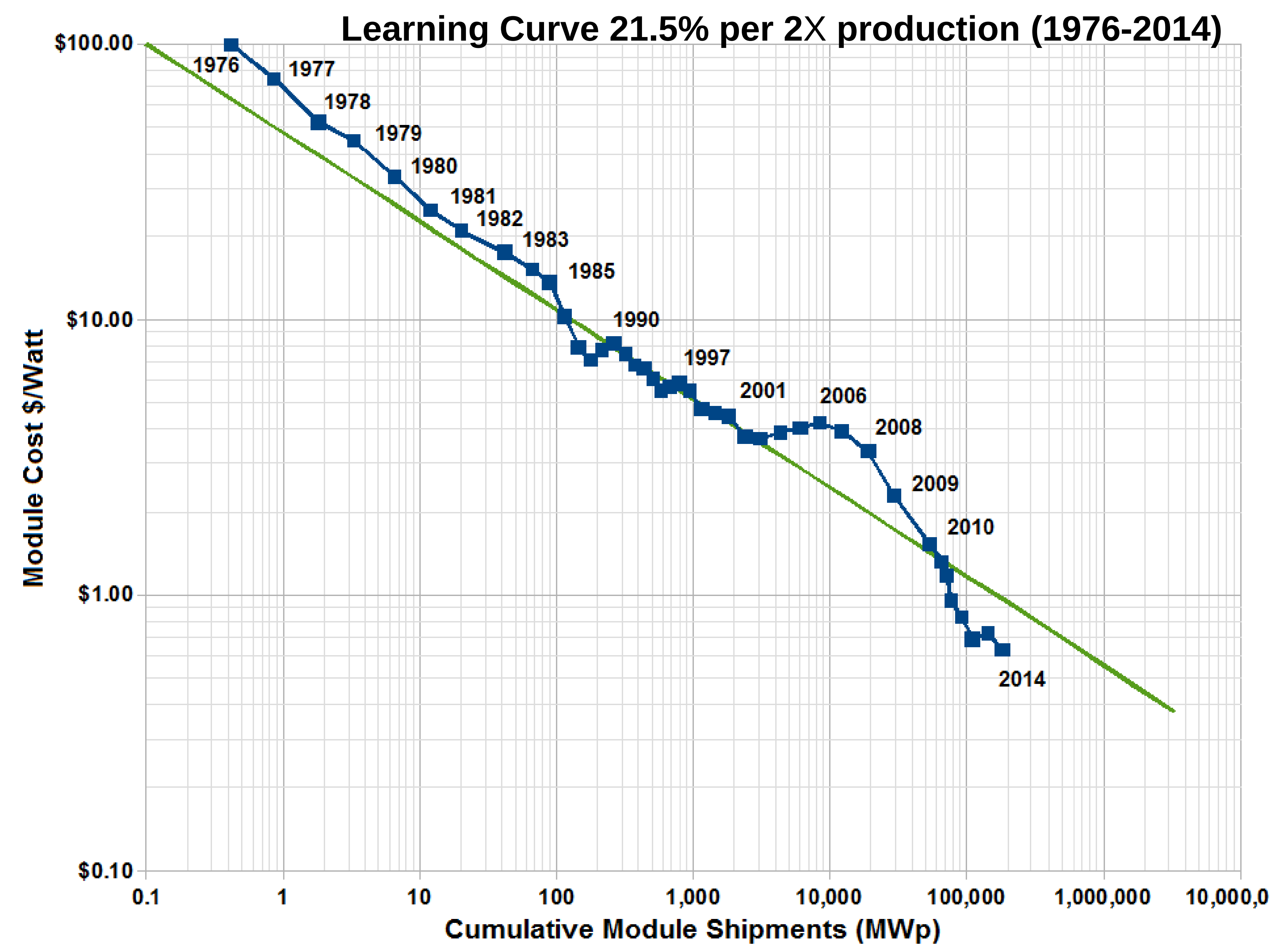
90% market share

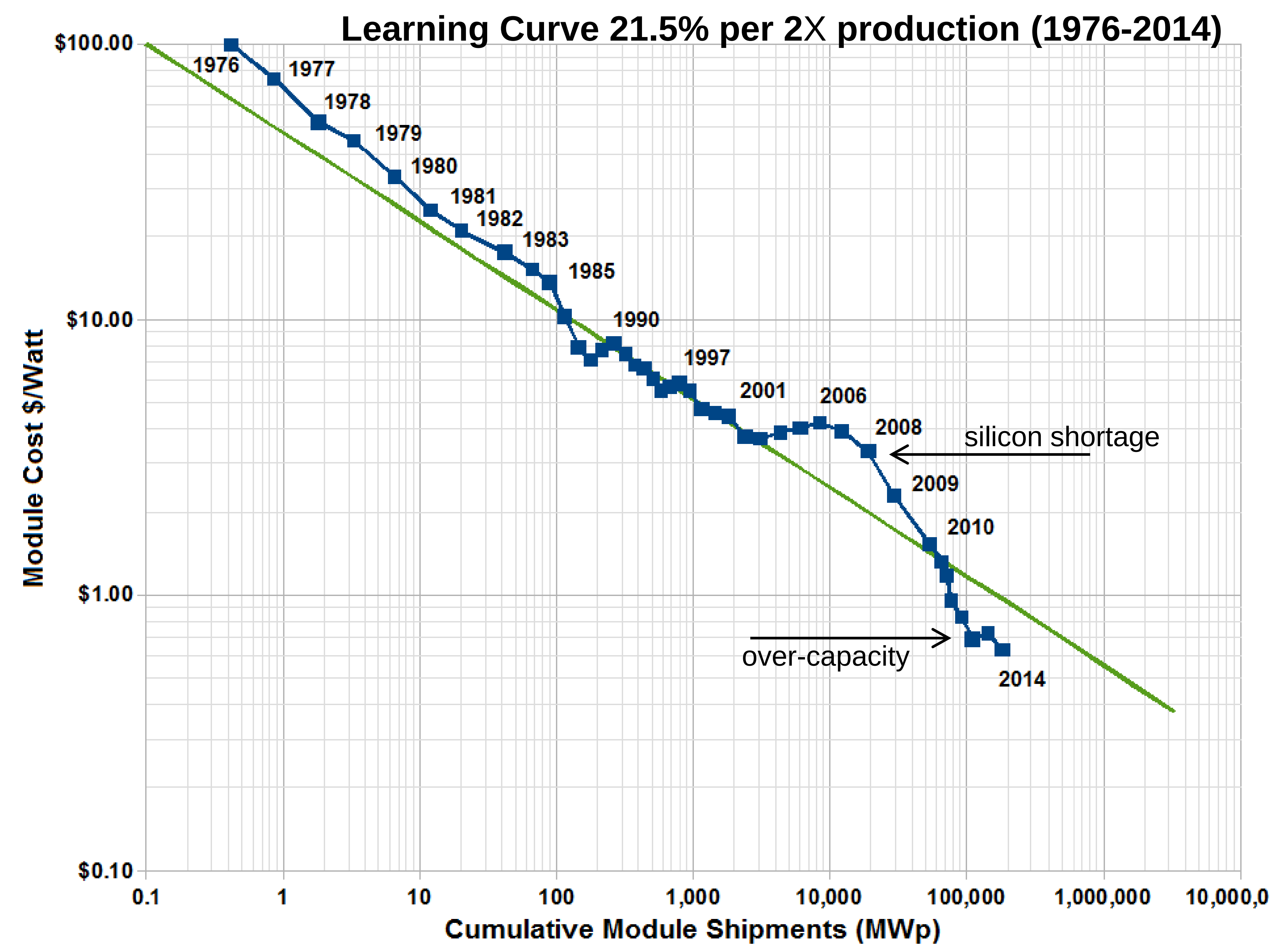
75GW/year annual world-wide production capacity

World-wide demand ~60GW/year

Oversupply!

The current world price has settled at $0.40-0.50/Watt


Learning Curve 21.5% per 2X production (1976-2014)
Module Cost $/Watt
$100.00
$10.00
$1.00
$0.10
0.1
1
10
100
1,000
10,000
100,000
1,000,000
10,000,0
Cumulative Module Shipments (MWp)
1976
1977
1978
1979
1980
1981
1982
1983
1985
1990
1997
2001
2006
2008
2009
2010
2014



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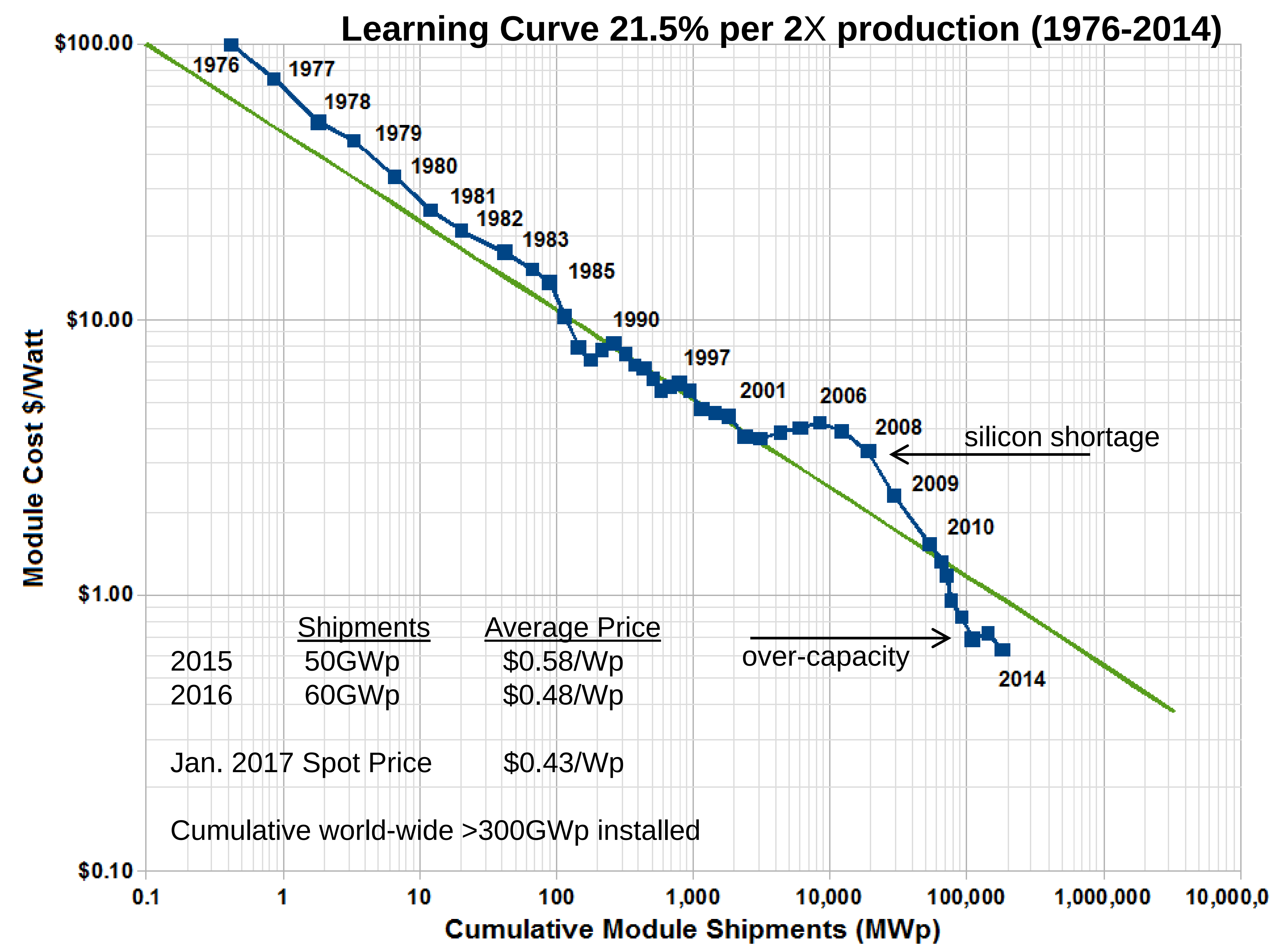
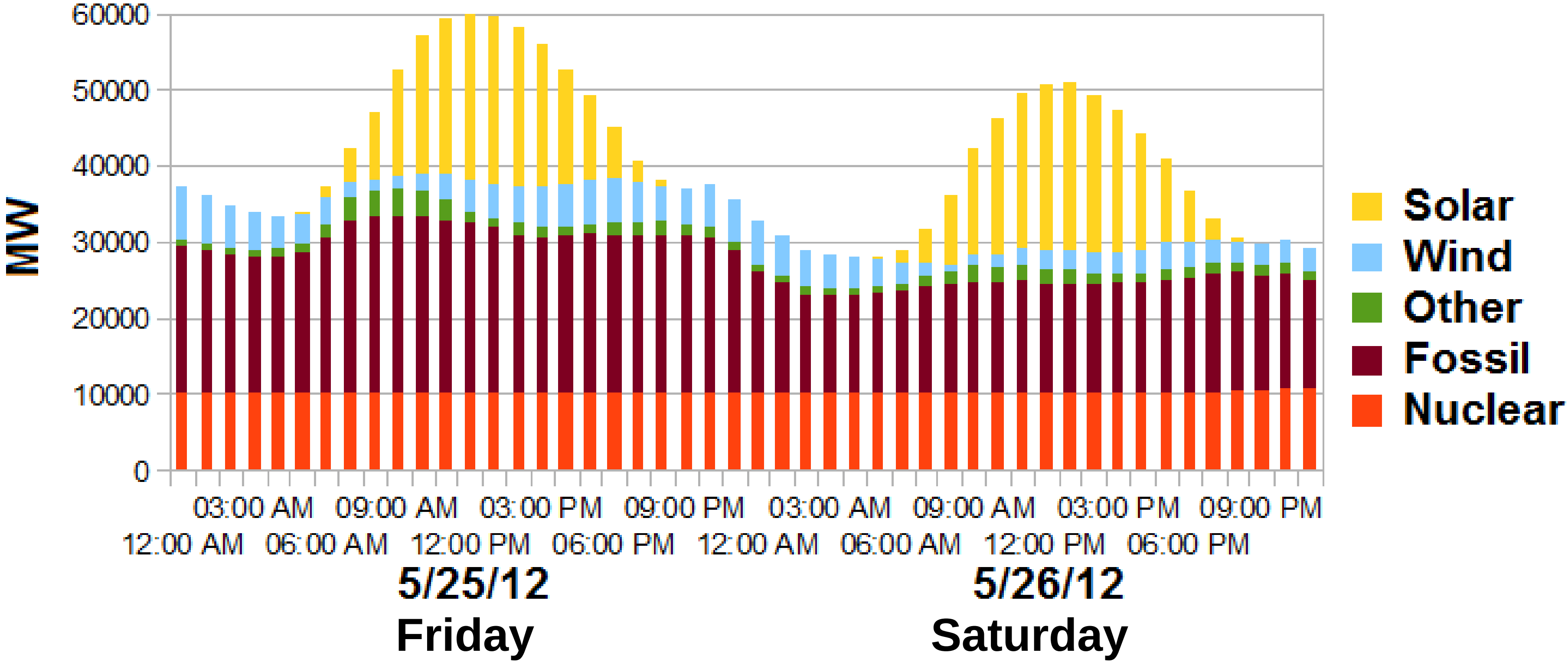
Module Cost $/Watt
Cumulative Module Shipments (MWp)
$100.00
$10.00
$1.00
$0.10
0.1
1
10
100
1,000
10,000
100,000
1,000,000
1976
1977
1978
1979
1980
1981
1982
1983
1985
1990
1997
2001
2006
2008
2009
2010
2014
silicon shortage
over-capacity



Learning Curve 21.5% per 2X production (1976-2014)
$100.00
$10.00
$1.00
$0.10
Module Cost $/Watt
0.1
1
10
100
1,000
10,000
100,000
1,000,000
10,000,0
Cumulative Module Shipments (MWp)
1976
1977
1978
1979
1980
1981
1982
1983
1985
1990
1997
2001
2006
2008
2009
2010
2014
silicon shortage
over-capacity
Shipments
Average Price
2015
50GWp
$0.58/Wp
2016
60GWp
$0.48/Wp
Jan. 2017 Spot Price
$0.43/Wp
Cumulative world-wide >300GWp installed

Germany Electricity Generation



After spending ~10^{11}Euros,
Germany has installed 40GW of panels,
but receives only 7% of its electricity from solar

What is happening in the solar economy?

c-Si η ~ 15%-23% in production

90% market share

75GW/year annual world-wide production capacity

World-wide demand ~60GW/year

Oversupply!

The current world price is diving to $0.40-0.50/Watt

but cost is > $0.60-0.70/Watt

Two TeraWatts can be built out in 30 years,

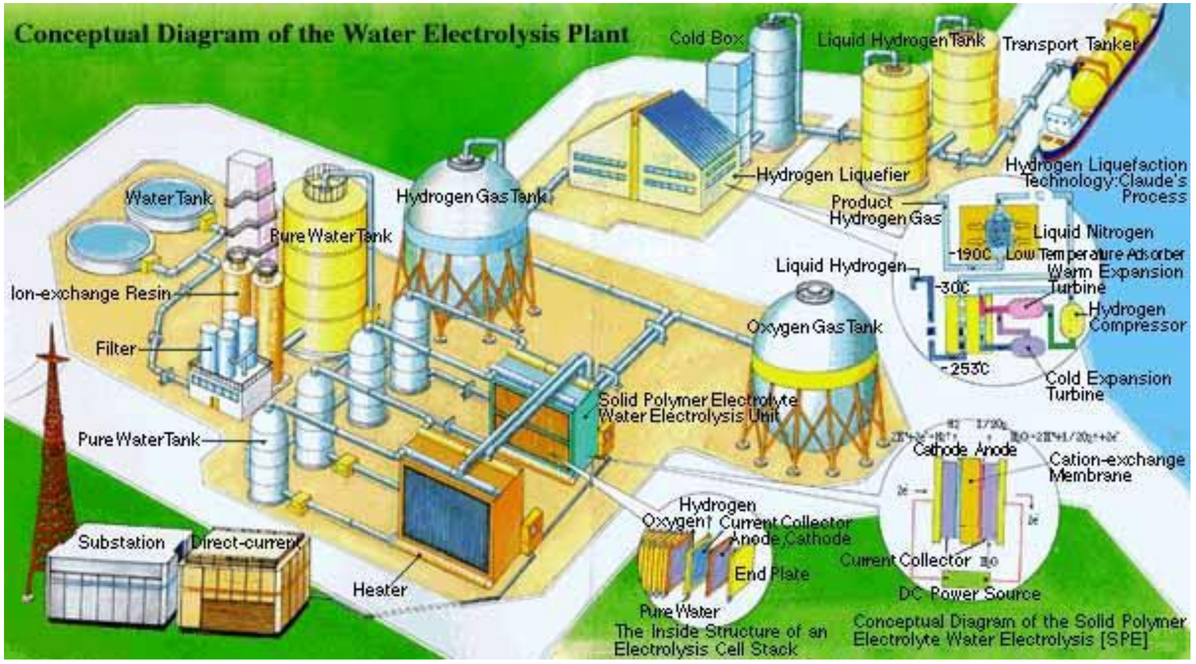
requiring no additional capacity.

To justify additional production capacity

New and different application markets are needed.

For Photovoltaics to make a further impact,
new applications and markets are needed; bigger than the 10% impact on the electric utility industry.

1. Pumped water for Reverse Osmosis desalination.
2. Solar Fuels:

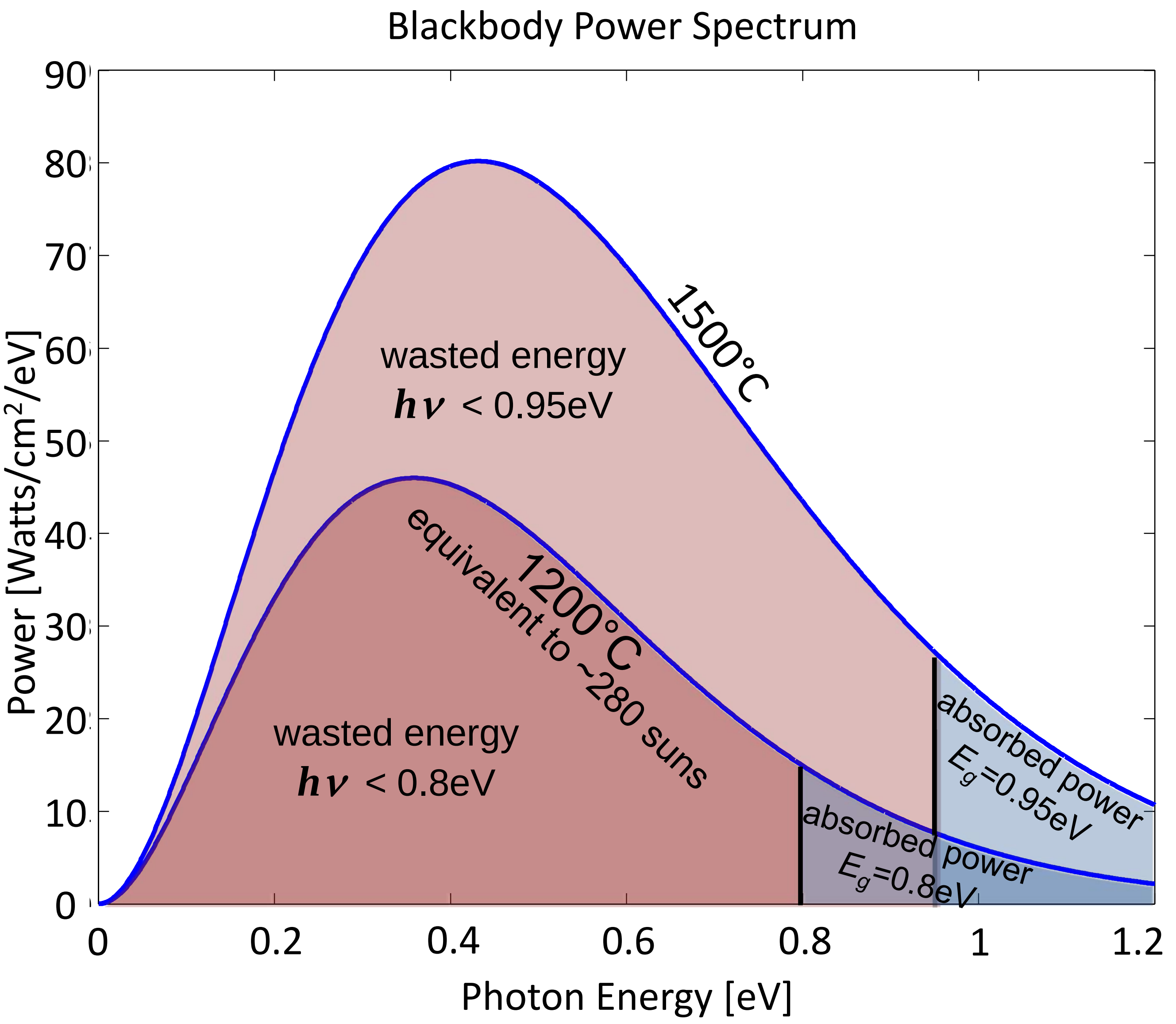


3. Thermo-PhotoVoltaics
4. Electro-Luminescent Refrigeration & Heat Engines

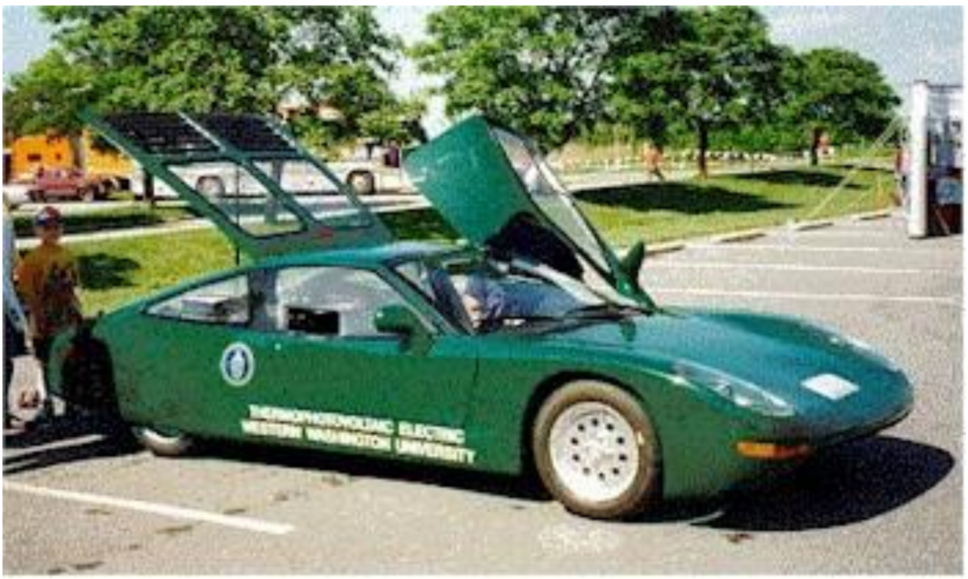
Since we are for the first time making really efficient photovoltaic cells (also LED's),
some new ideas become very timely

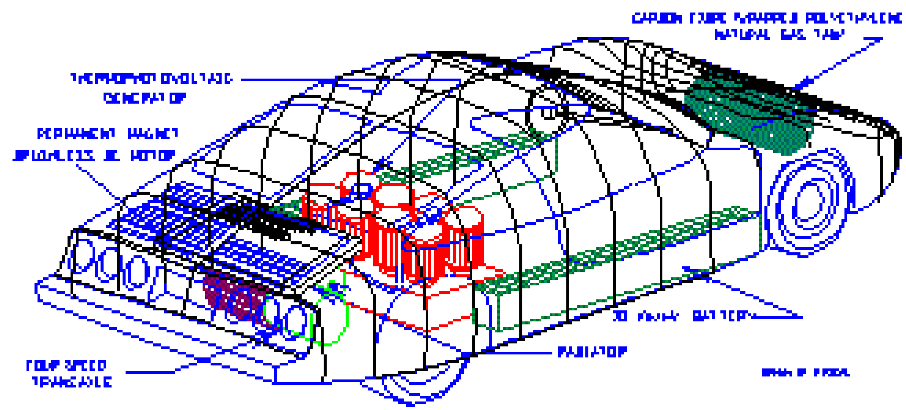
What is Thermo-PhotoVoltaics?

What is Thermo-PhotoVoltaics?



Thermo-PhotoVoltaic Hybrid Car:



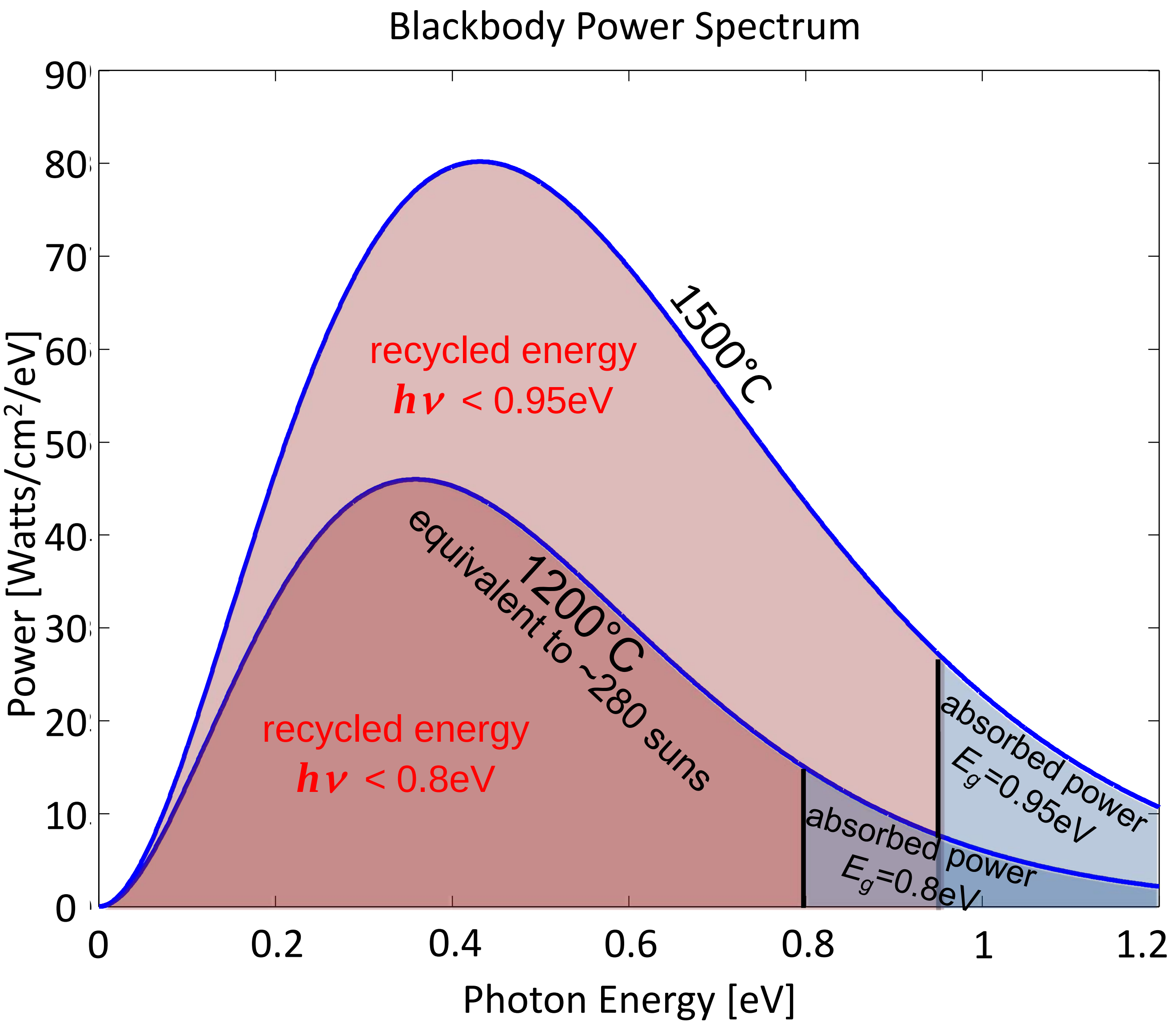


1997

Only ~20% efficiency

Proceedings Future Transportation Technology Conference, Christ, S. and Seal, M., "Viking 29 - A Thermophotovoltaic Hybrid Vehicle Designed and Built at Western Washington University," SAE Technical Paper 972650, 1997, doi:10.4271/972650.

Superb Rear Reflector; Recycle the Infrared Photons:



Default Solution:
engineer the emissivity spectrum to preferentially produce big photons, $h\nu > E_g$

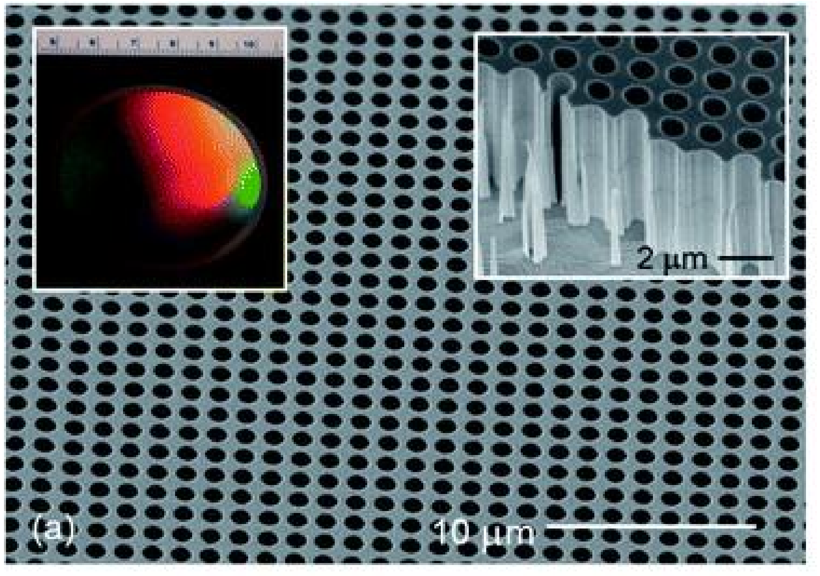
~50 years of research

Recent developments in high-temperature photonic crystals for energy conversion

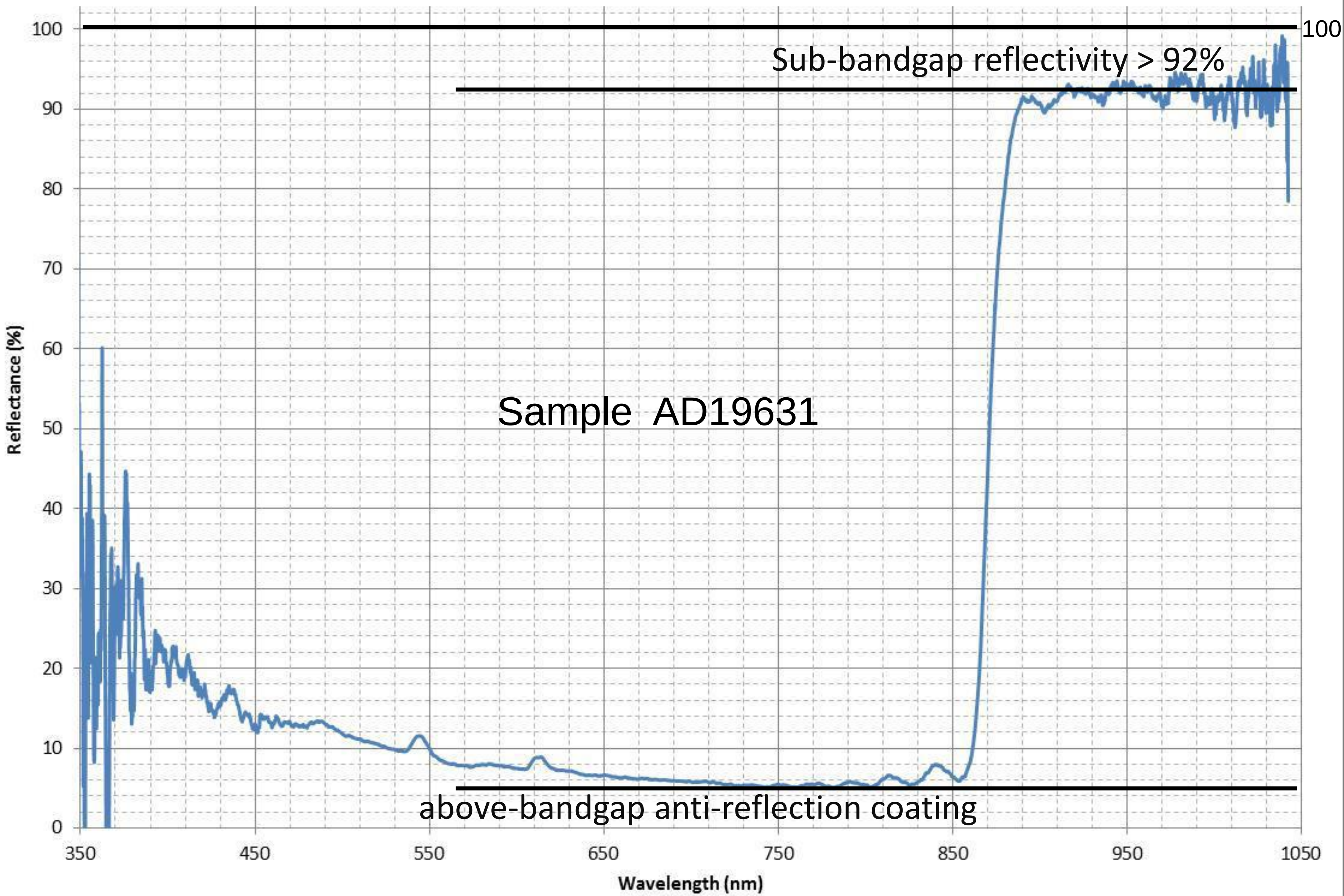
Veronika Rinnerbauer *[a], Sidy Ndao [bc], Yi Xiang Yeng [ab], Walker R. Chan [ab], Jay J. Senkevich [b], John D. Joannopoulos [ab], Marin Soljačić [ab] and Ivan Celanovic [b]

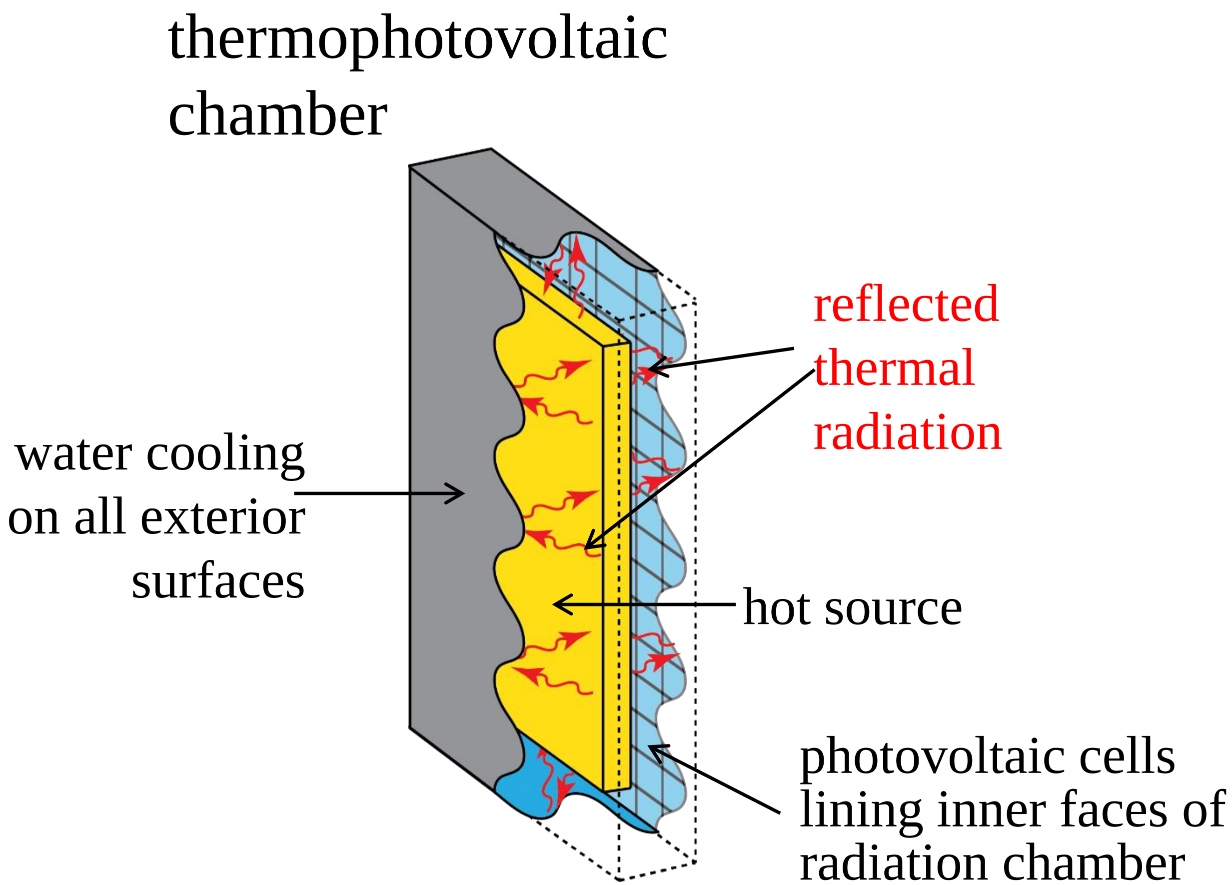
[a]*Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA*

Energy Environ. Sci., (2012), **5**, 8815-8823



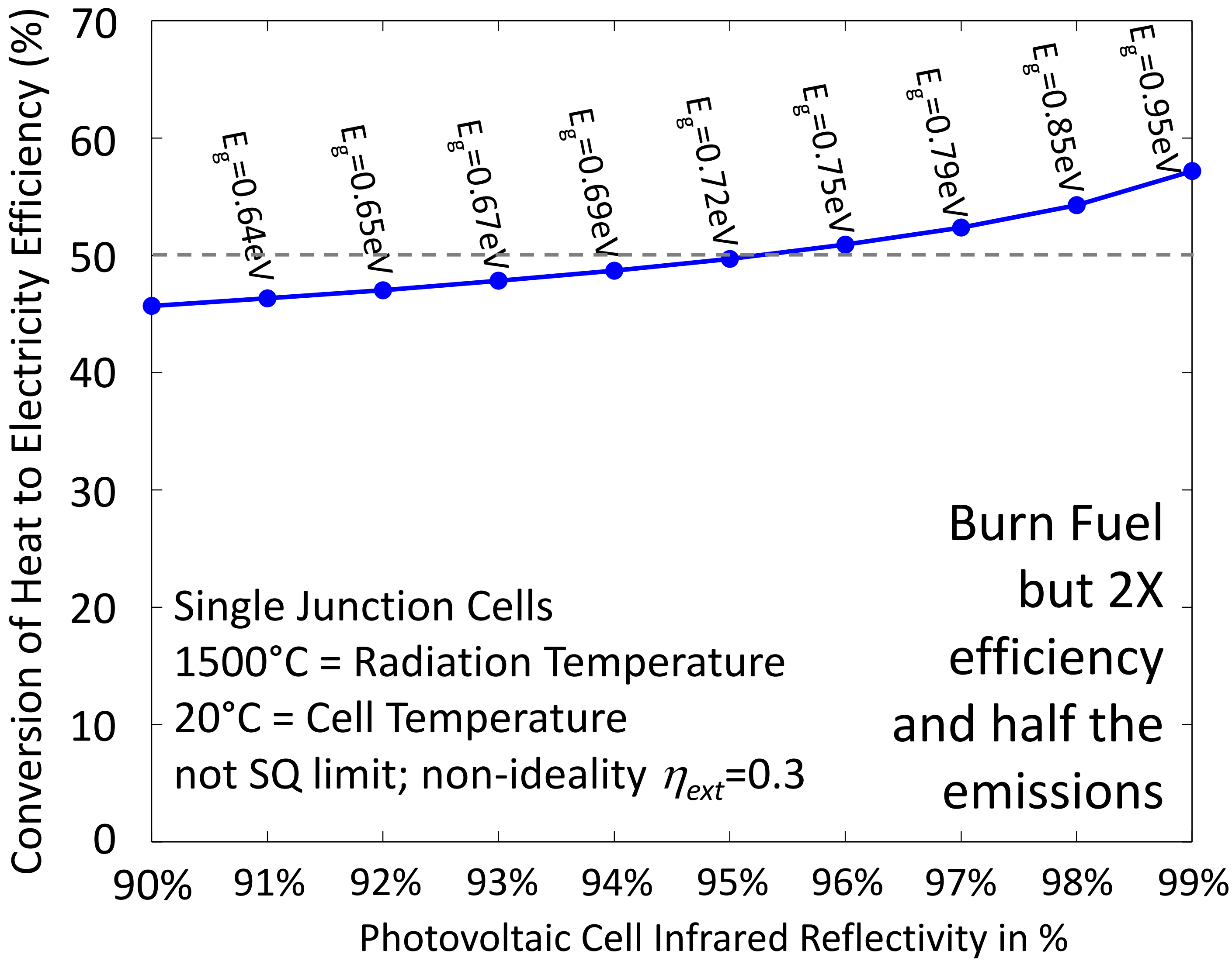
Thin-Film GaAs Solar Cell: Reflectivity Above and Below BandGap



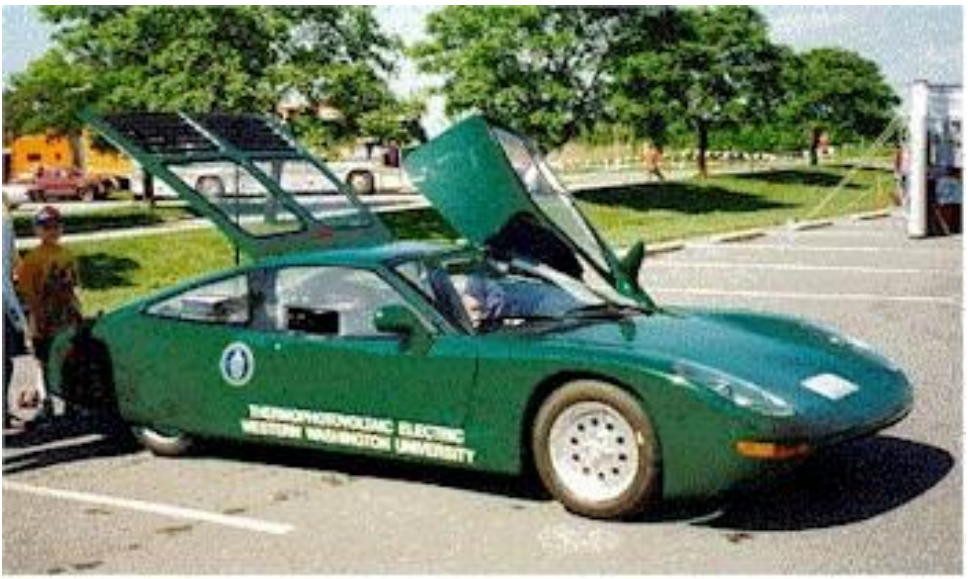


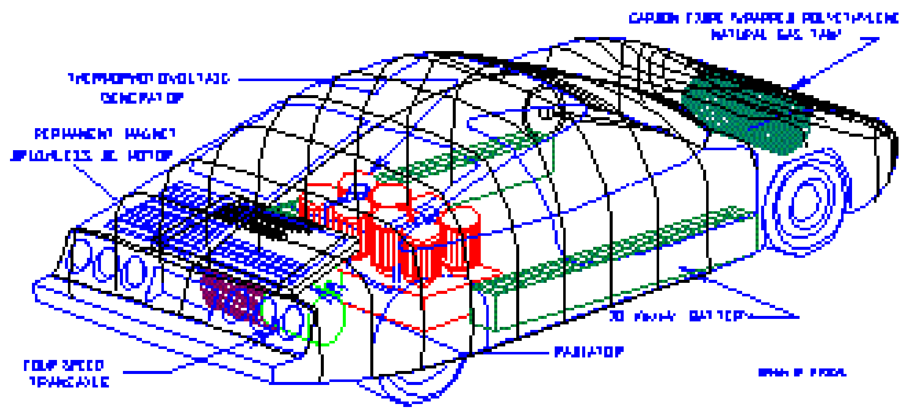
280 suns bouncing around internally!
Small area photovoltaic cell is adequate.

Convert Heat to Electricity with >50% Efficiency



Thermo-PhotoVoltaic Hybrid Car:

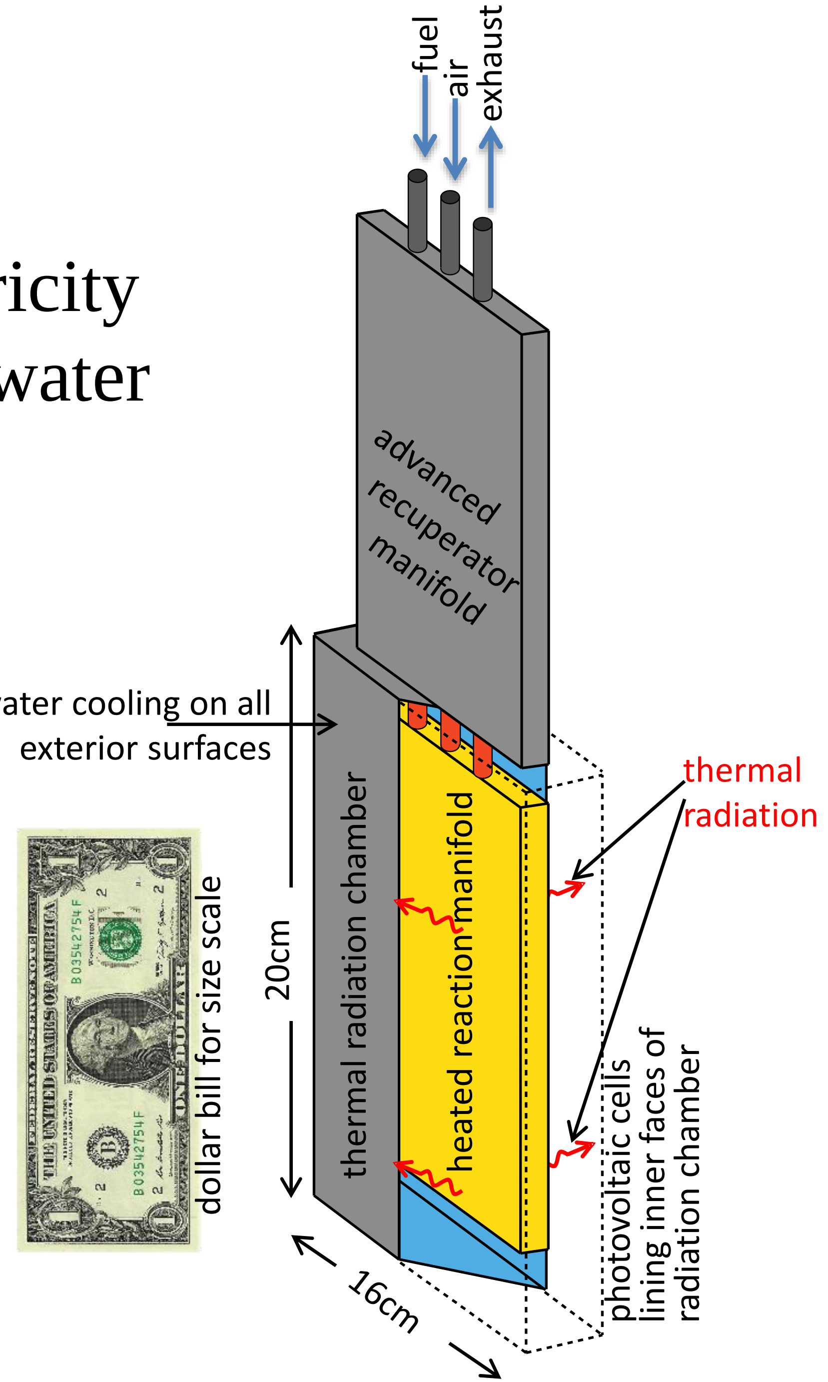




50kWatt—70cm × 70cm

1200°C is equivalent to 100suns to 500suns

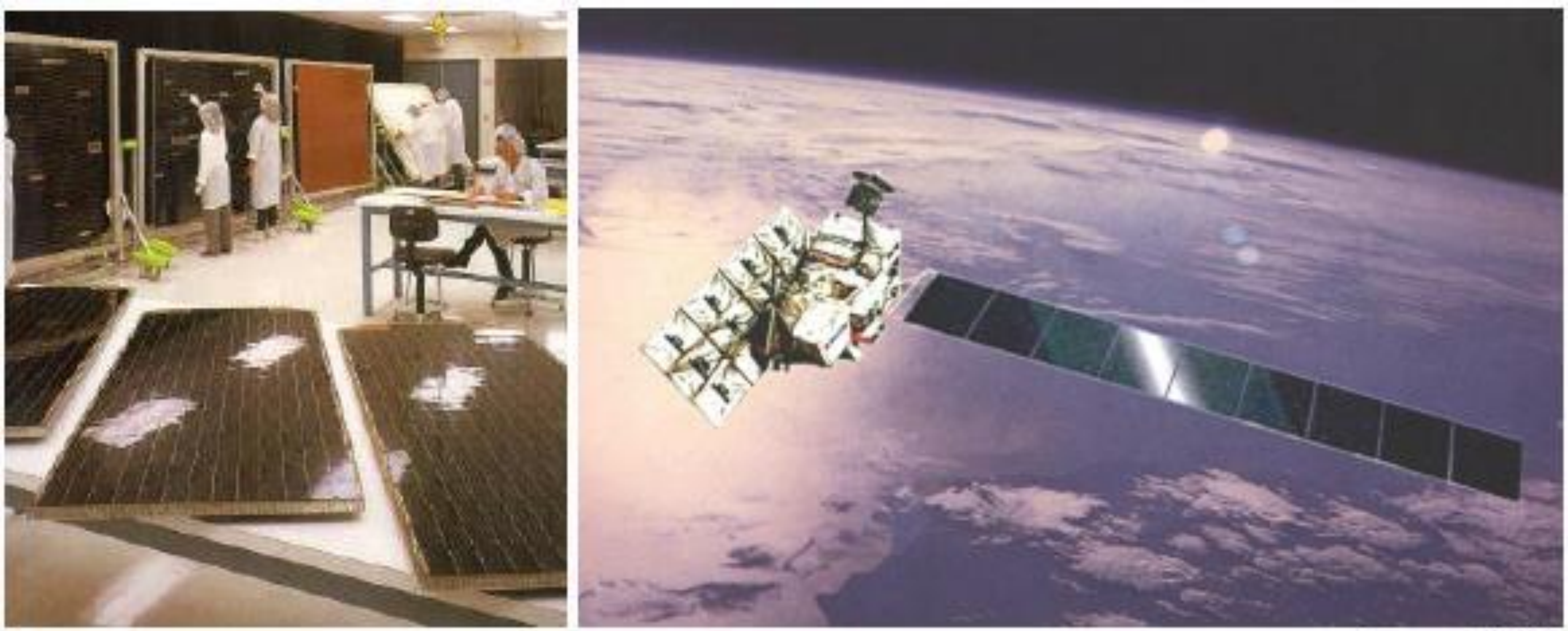
For home use:
1000 Watt electricity
1056 Watts hot water



Quad-Copters for
civilian & military use:
:
Duration depends on energy density
Lithium battery lasts 20 minutes.

Liquid fuel has 50× times higher
energy density, would last 16 hours.

For Deep Space use, heat Source can be nuclear,
SiC pellets at 1500°C.



Courtesy of JAXA

But there is competition from Fuel Cell vehicles; $2H_2+O_2 \rightarrow 2H_2O$

requires H_2 storage;

(but new H_2 storage technologies are being invented)

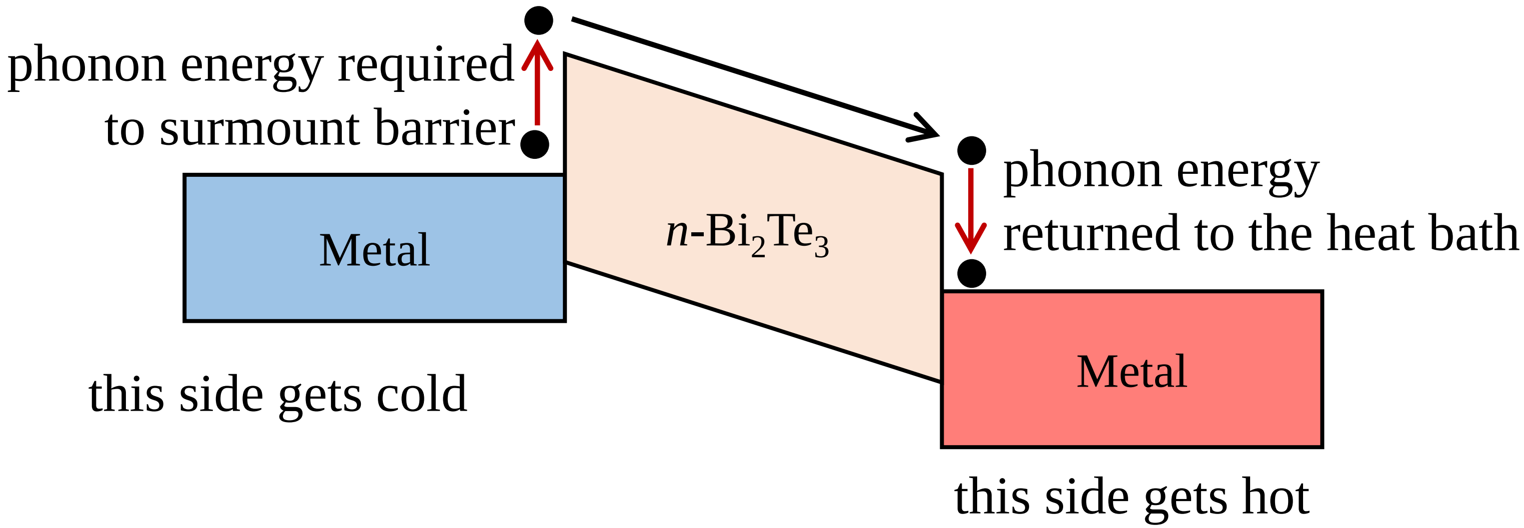
Since we are for the first time making really efficient photovoltaic cells (also LED's),
some new ideas become very timely

Electro-luminescent refrigeration
(thermophotonic cooling)

My student Patrick Xiao

Traditional Thermoelectric cooler/generator

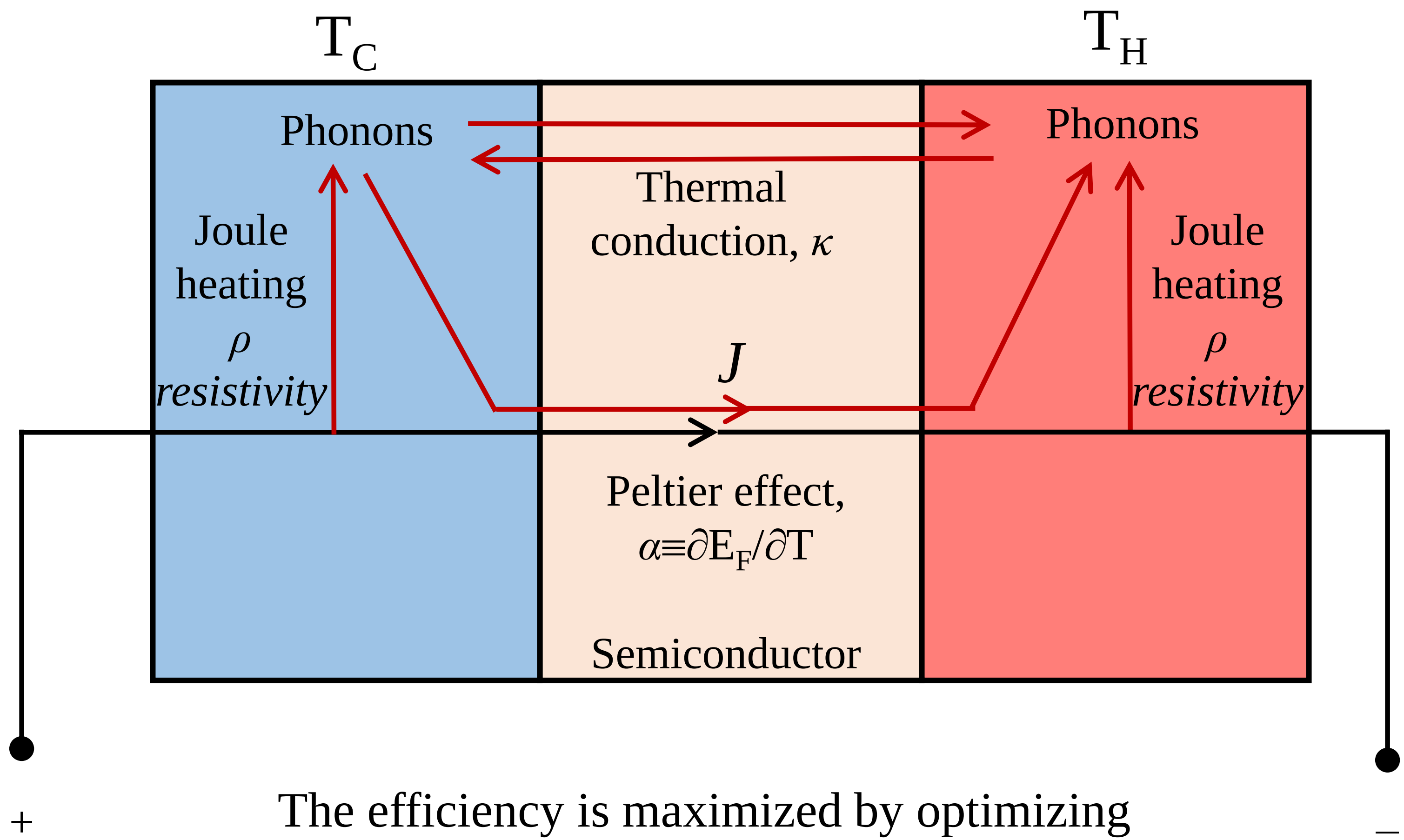
electric current carries heat



electric current drags entropy → from left to right

Also works to generate electricity
The hot side sends out more electrons than the cold side

Thermoelectric cooler

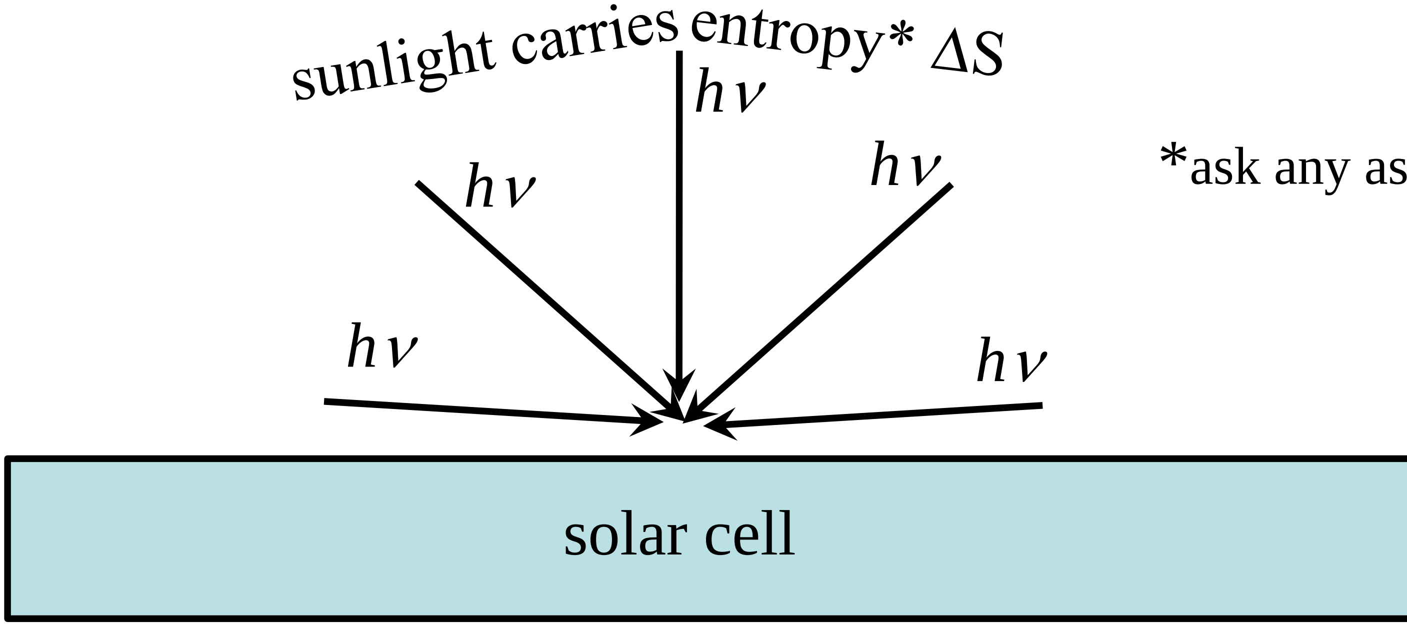


The efficiency is maximized by optimizing

$$Z = \frac{\alpha^2}{\rho\kappa}$$

State of the art: $ZT = 1$, (T = 300K)

→ ~10% of Carnot limit



*ask any astrophysicist

$$\text{Free Energy} = h\nu - T\Delta S$$

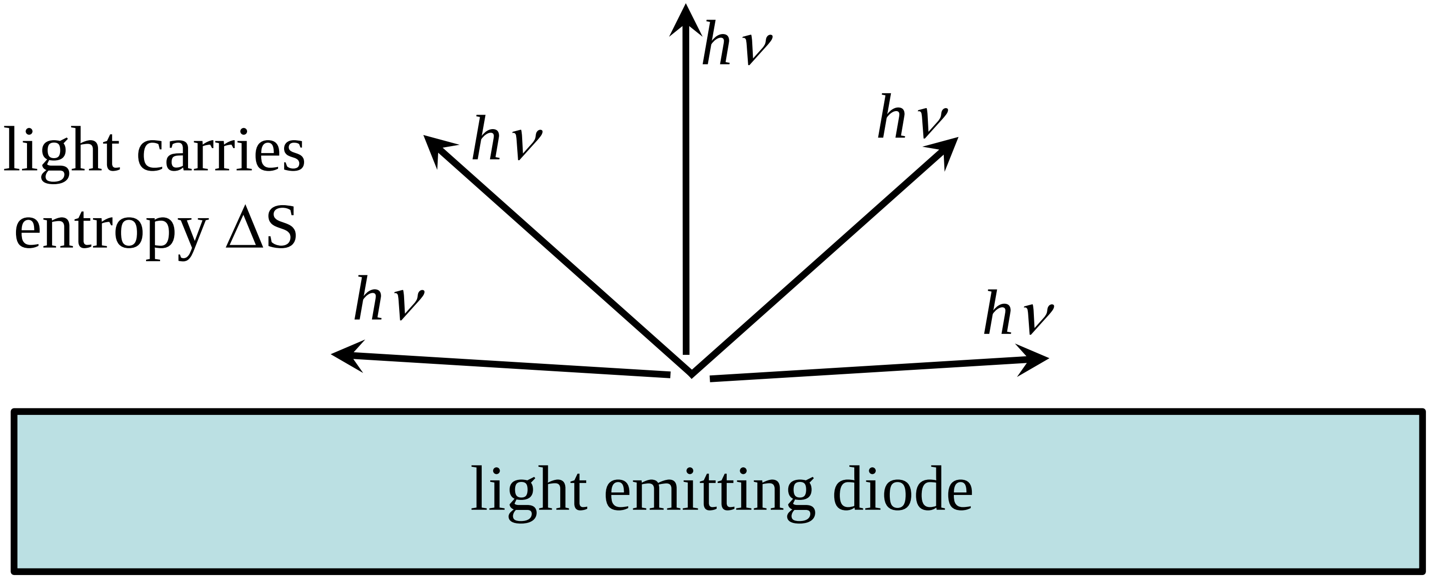
$$qV_{oc} = E_g - T\Delta S$$

For GaAs E_g is 1.4eV
But the record V_{oc}=1.12Volts

Most of the entropy is due to loss of directionality information.

Now reverse everything

LED light carries away entropy ΔS



input 1.12 Volts

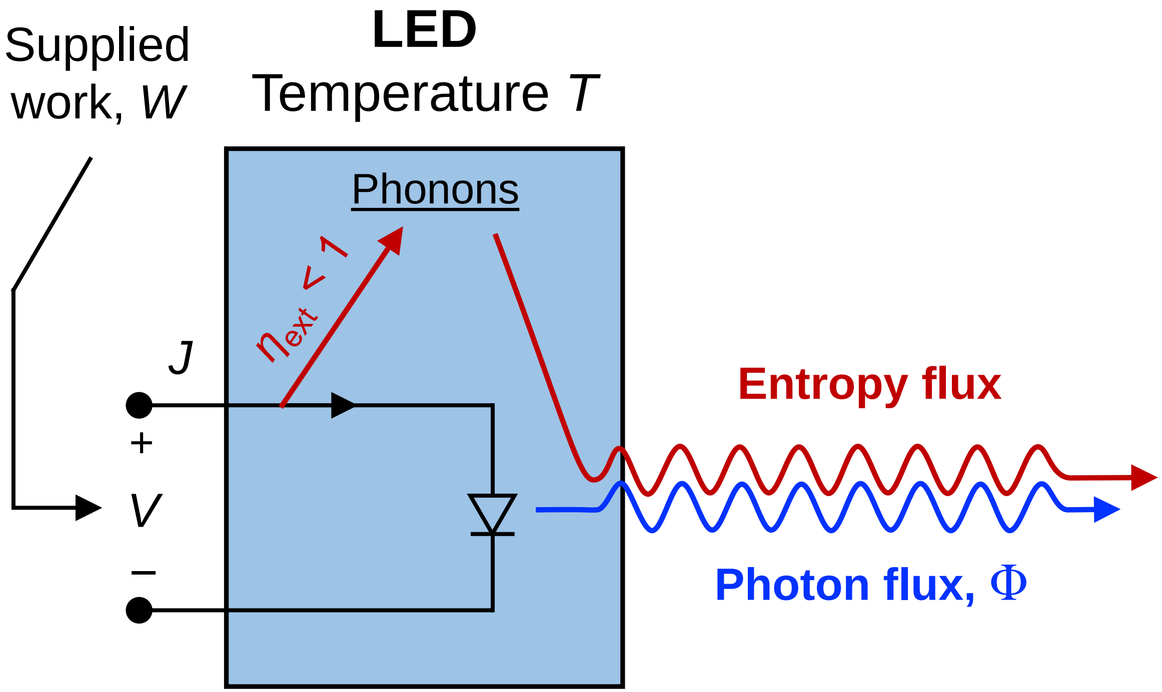
get out $E_g = h\nu = 1.4\text{eV}$

Where does the extra 0.28eV come from?

obviously heat from the lattice.

Most of the LED light entropy is due to loss of directionality information.

Electro-luminescence pumps out 0.3eV of heat/photon



$$qV = \hbar\omega - TS$$

$$S = \frac{\hbar\omega - qV}{T}$$

Entropy carried per photon

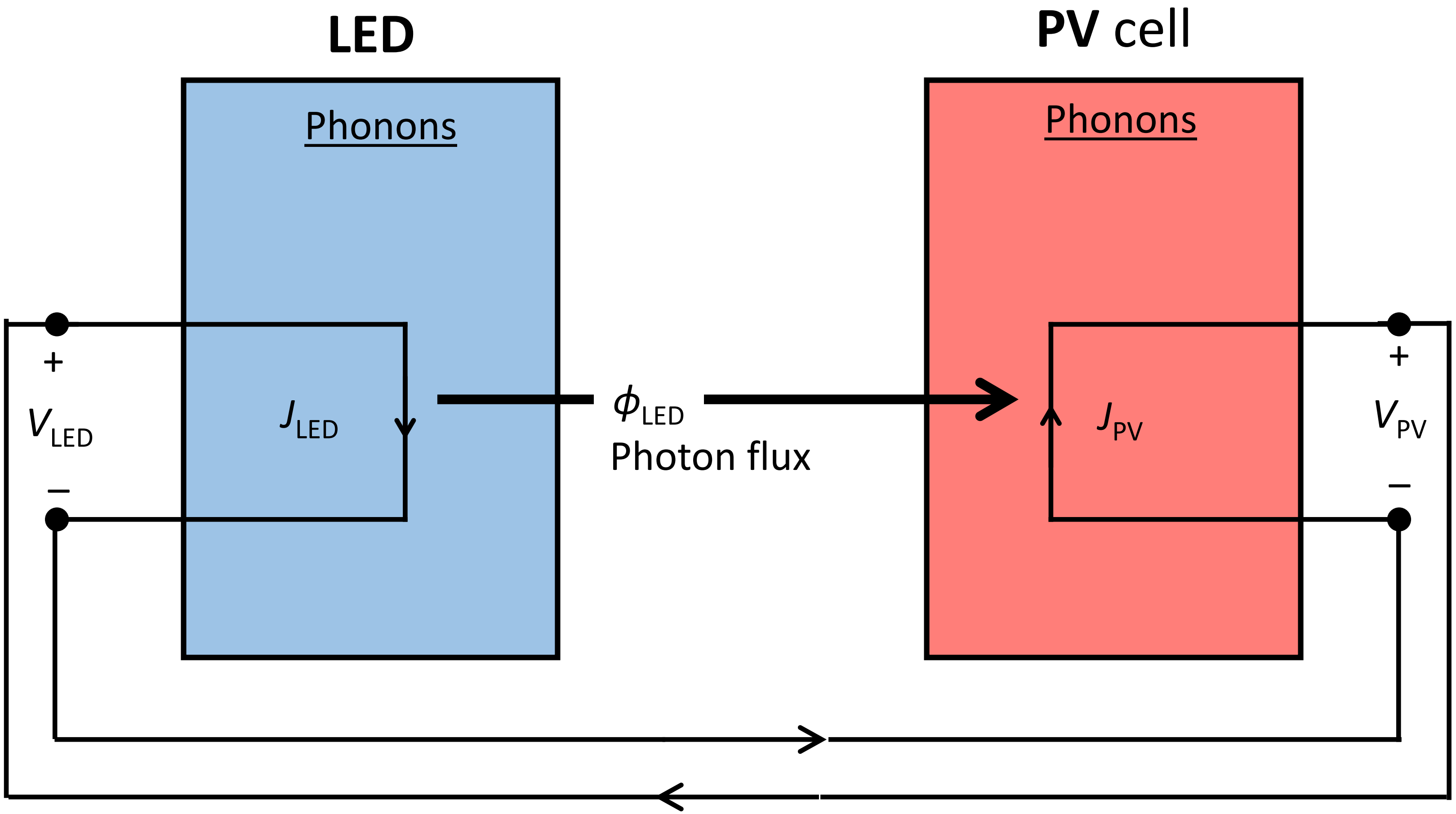
Heat pumped out of LED $= \Phi\left(TS - \frac{1-\eta_{ext}}{\eta_{ext}} \cdot qV\right) > 0$

Heat pumped per emitted photon, **0.3 eV**

Heat generated per failed luminescence, **1.1 eV**

This means: we need at least $\eta_{\text{ext}} > 80\%$!
Or much higher for good performance

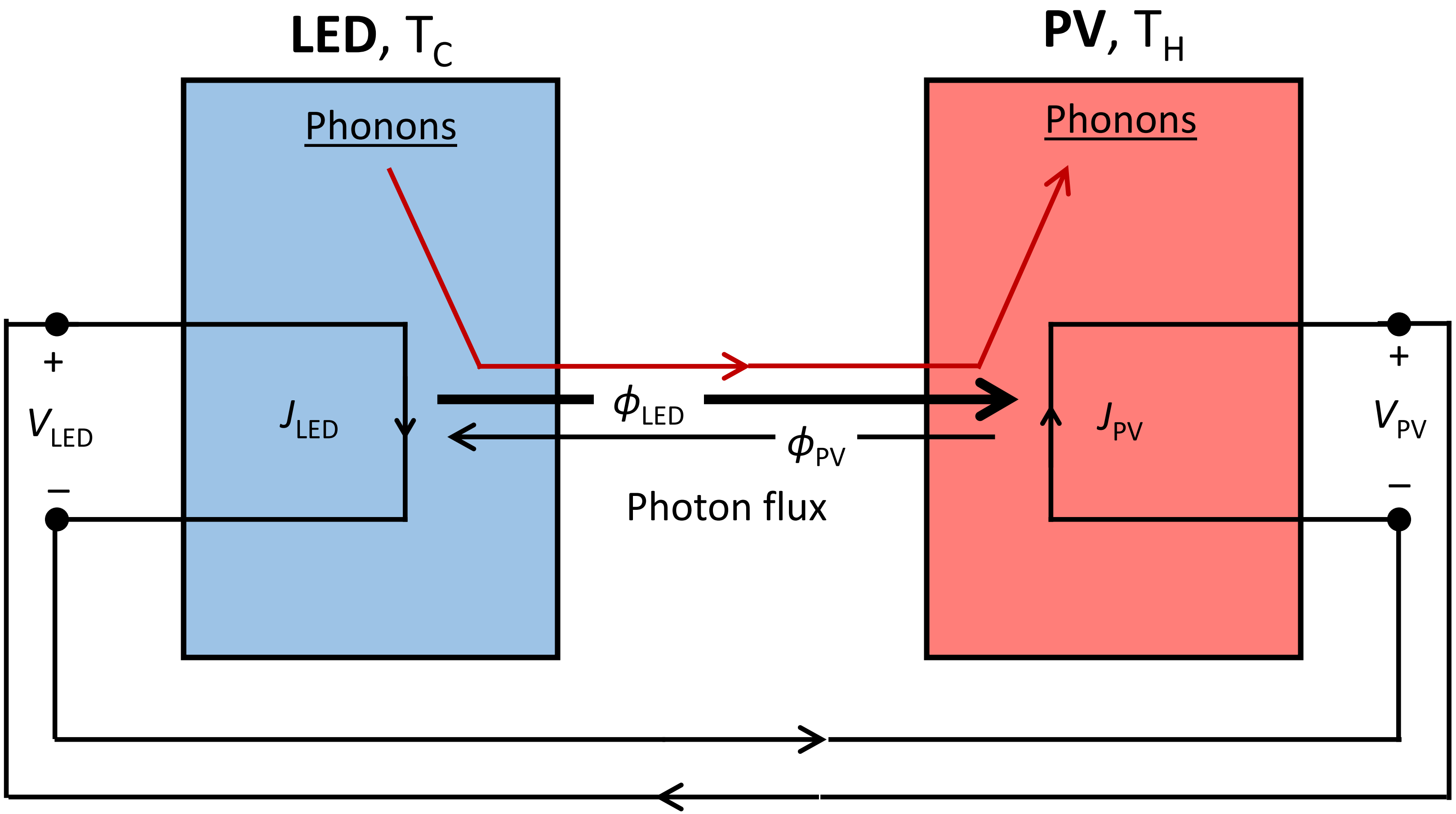
Shockley's perpetual motion machine, circa ~1955



"Thermal Energy Taken from Surroundings in the…Radiation from a p-n Junction
Jan Tauc, Czechoslovak J. Phys. 7, 275 (1957)

Electro-Luminescent Heat Engine: $T_C \neq T_H$

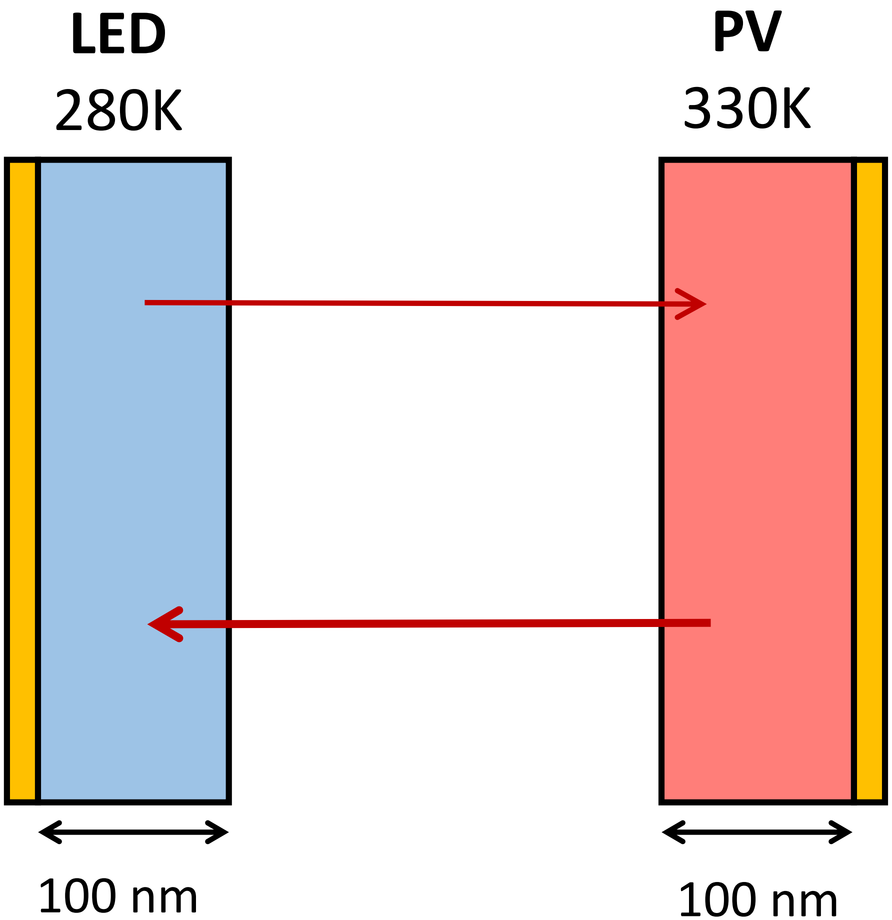
Convert heat to electricity, or electricity to refrigeration

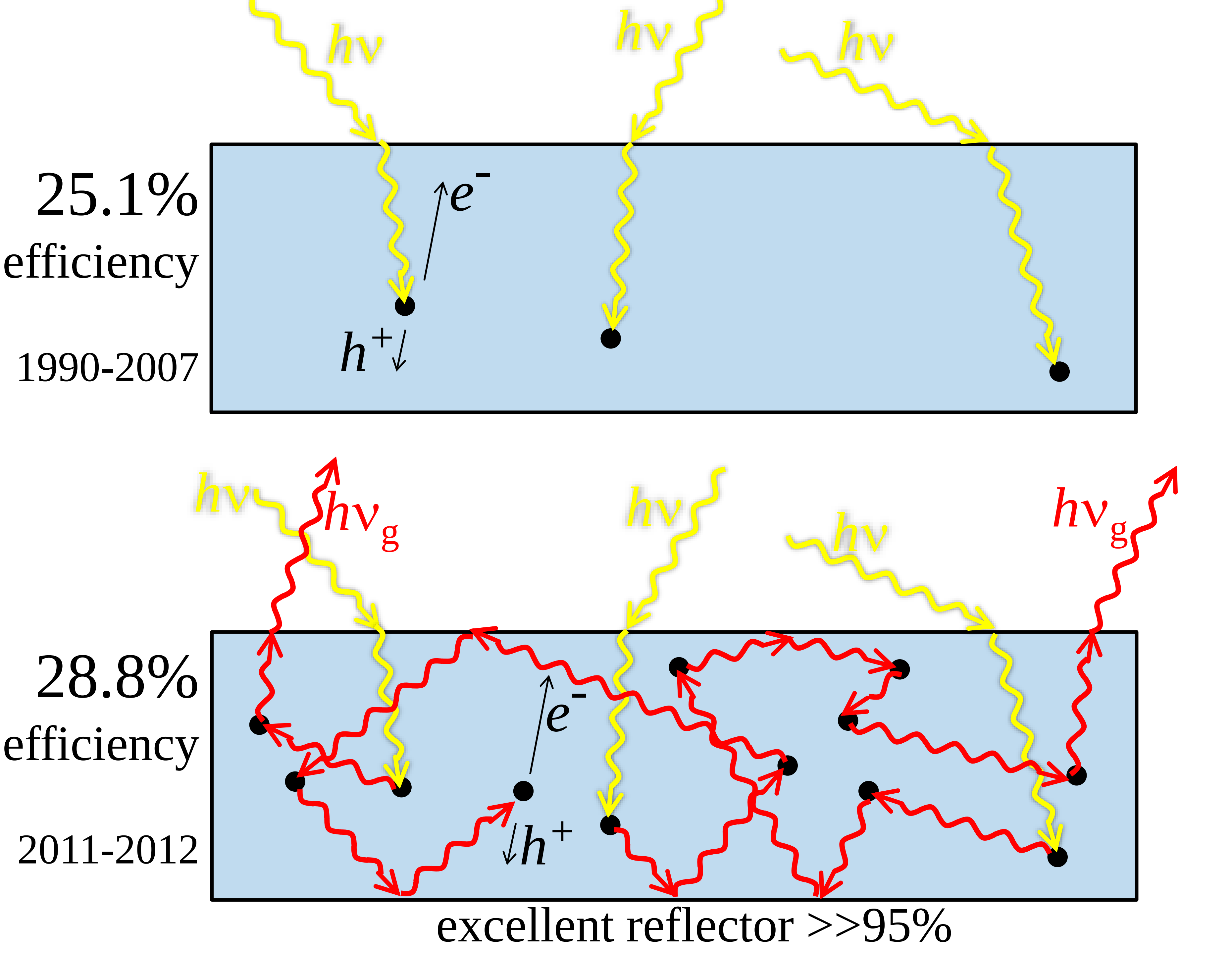


$$J_{LED} = J_{PV} = q(\phi_{LED} - \phi_{PV})$$

$$COP = \frac{Q_C}{W} = \frac{\left(\frac{\langle h\nu \rangle}{q} - V_{LED}\right) \cdot J_{LED}}{V_{LED} \cdot J_{LED} - V_{PV} \cdot J_{PV}}$$

The LED and the PhotoVoltaic Cell are really the same device.

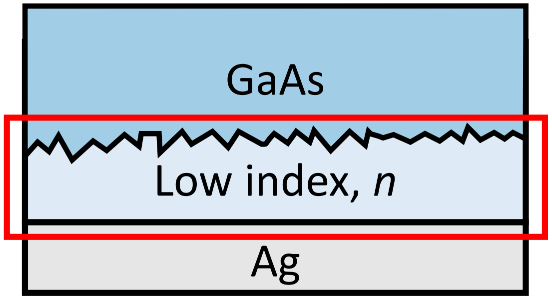



hν
hν
hν
25.1%
efficiency
e-
h+
1990-2007
hν
hνg
hν
hν
hνg
28.8%
efficiency
e-
h+
2011-2012
excellent reflector >>95%

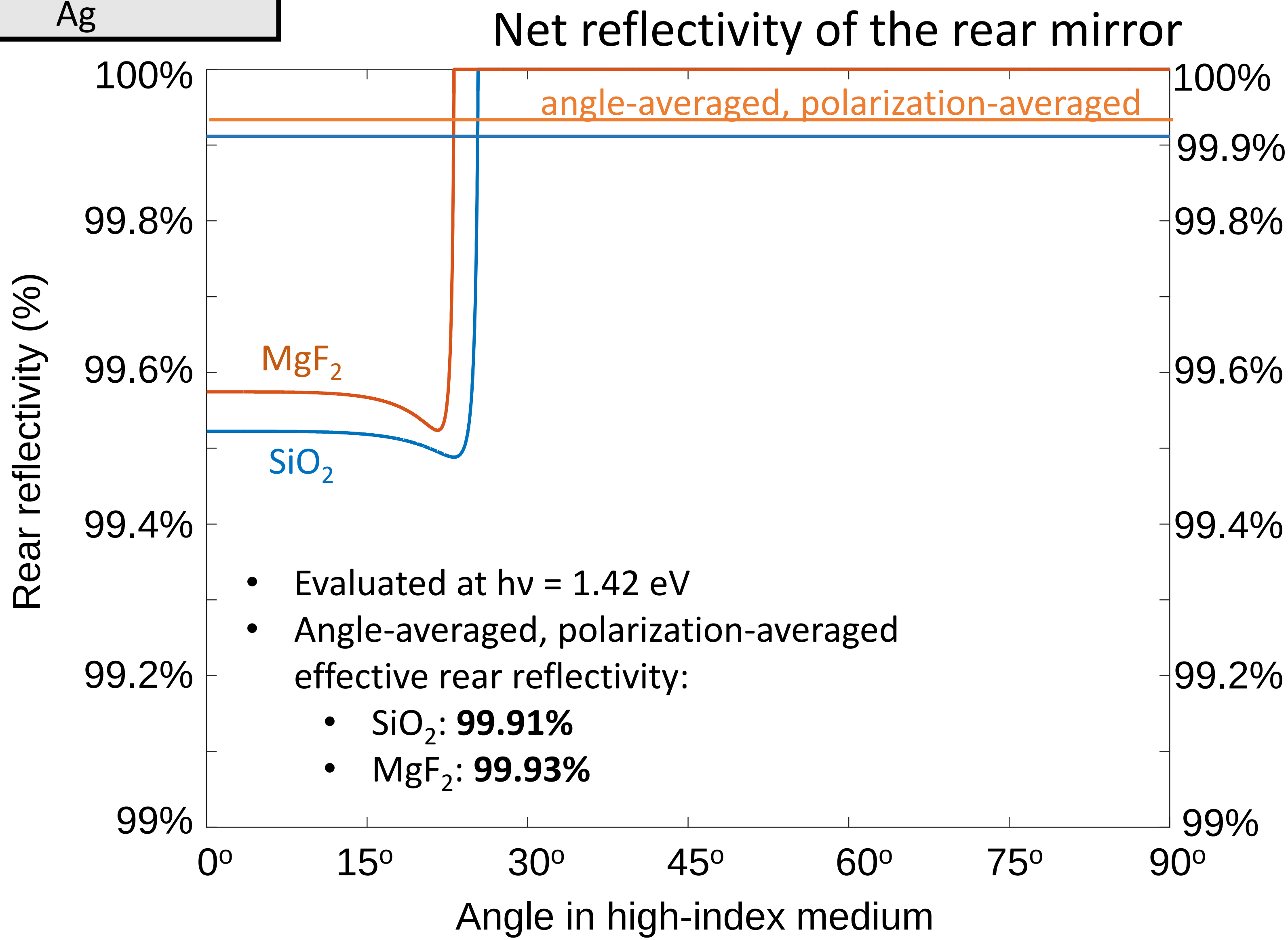
This all works because GaAs is the most efficient fluorescent material that can be electrically pumped.

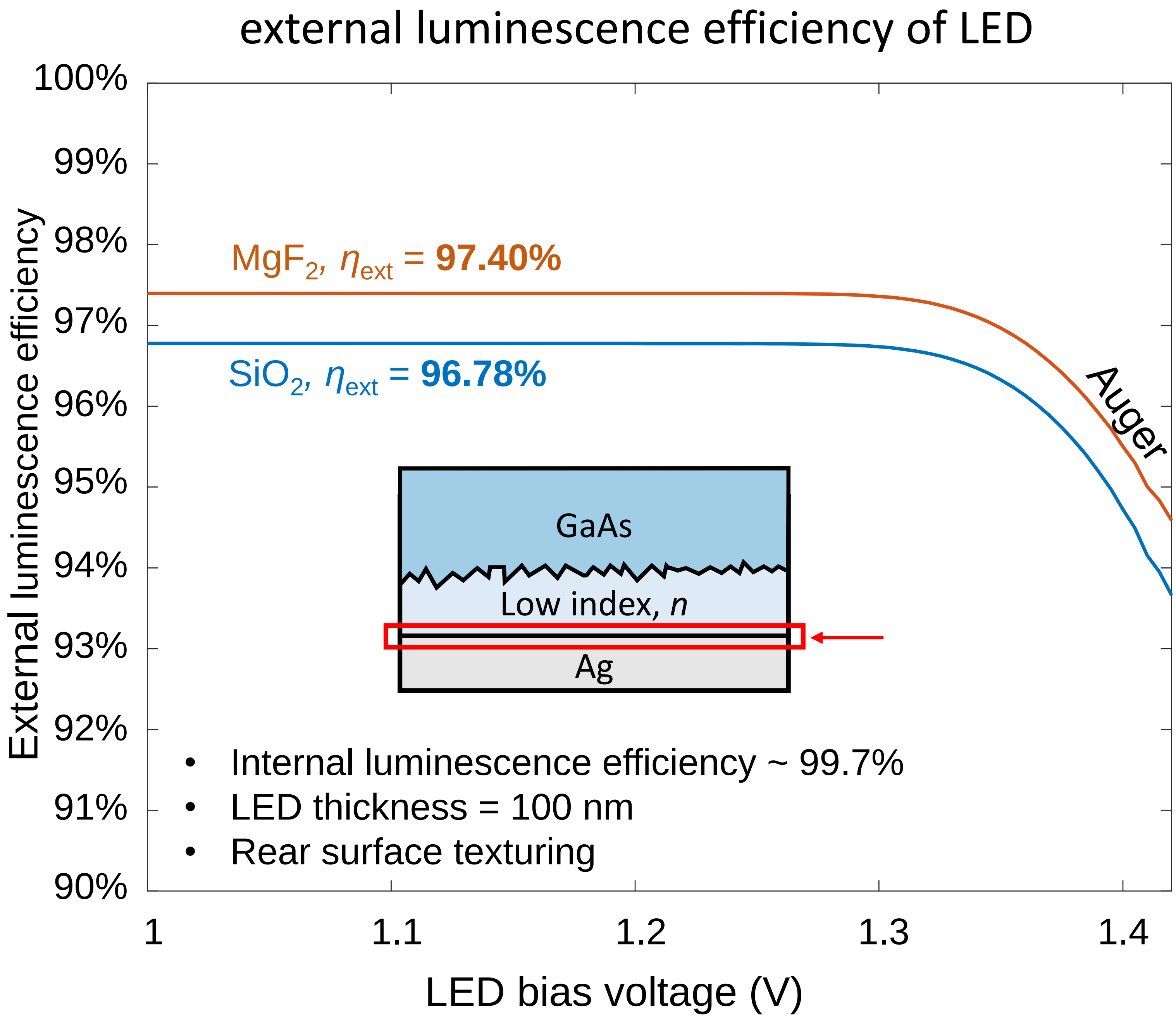
99.7% internal luminescent efficiency has been documented.

For Yb:YLF, Ytterbium in Yttrium Lithium Fluoride, 99.9% luminescent efficiency is known.



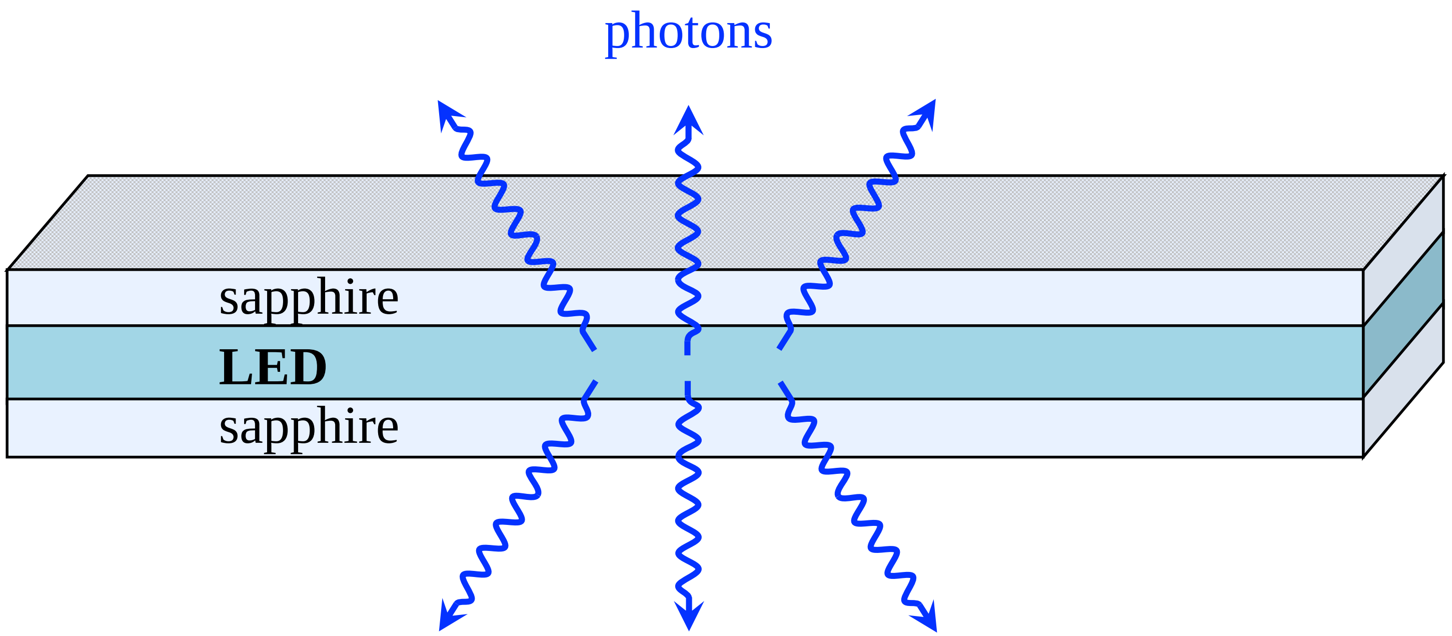
LED light extraction design controls performance



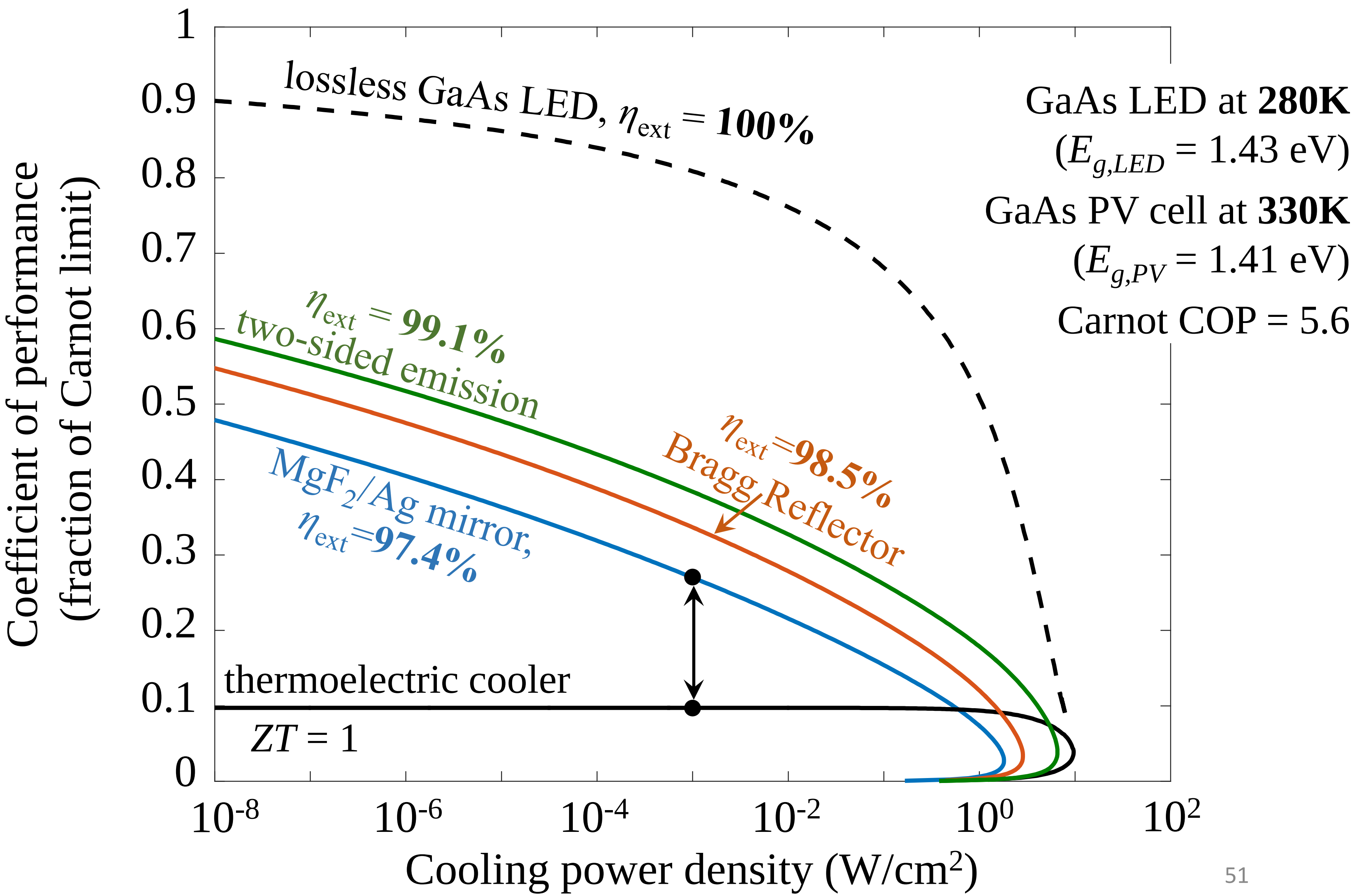


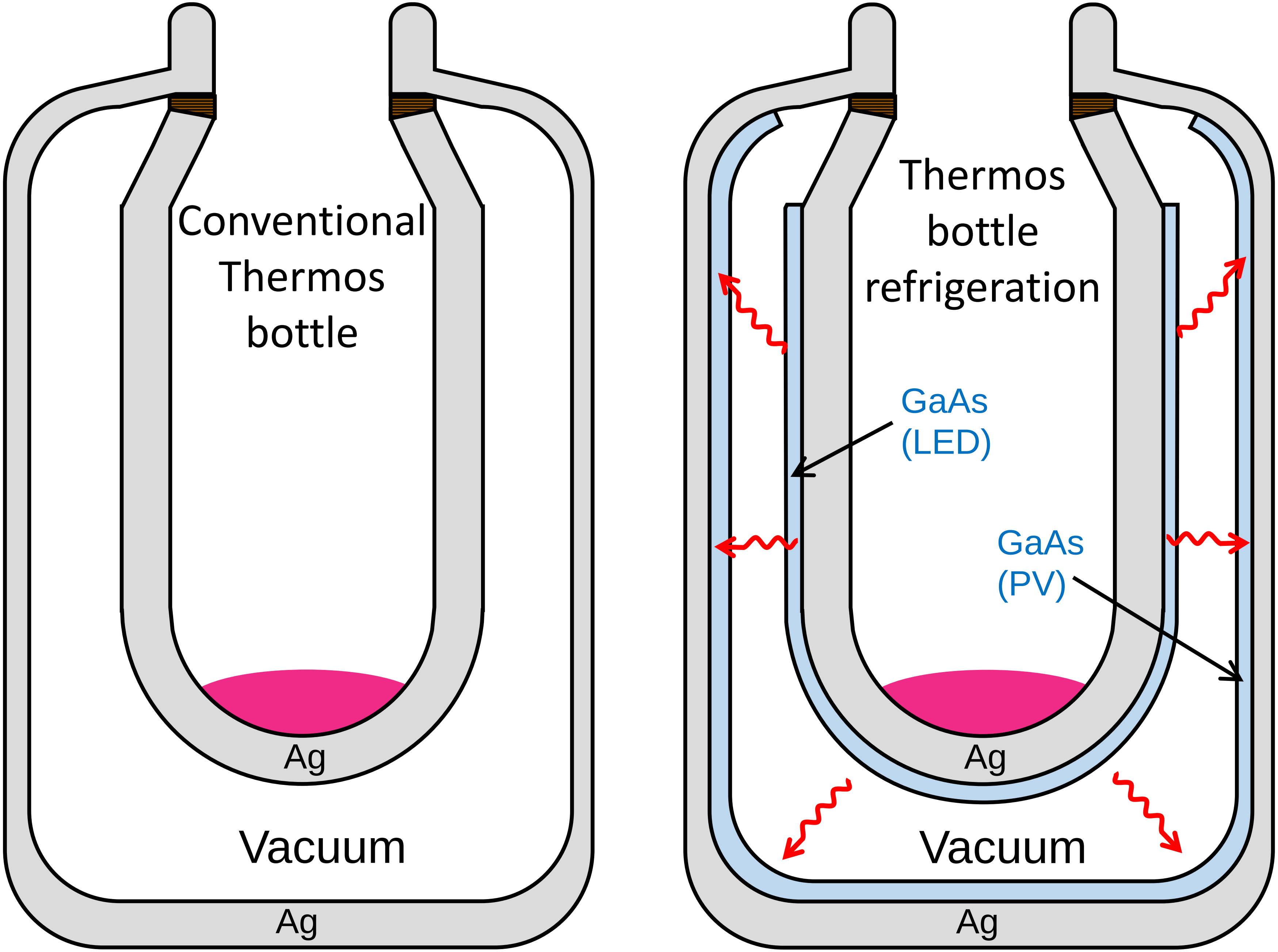
external luminescence efficiency of LED
100%
99%
98%
97%
96%
95%
94%
93%
92%
91%
90%
External luminescence efficiency
MgF2, ηext = 97.40%
SiO2, ηext = 96.78%
Auger
GaAs
Low index, n
Ag
• Internal luminescence efficiency ~ 99.7%
• LED thickness = 100 nm
• Rear surface texturing
1
1.1
1.2
1.3
1.4
LED bias voltage (V)

We can actually do better than a perfect rear mirror: ideal transparent windows on both sides



~3× better than commercial thermo-electric coolers



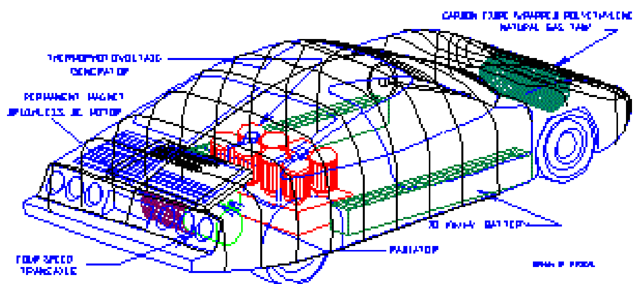

Conventional
Thermos
bottle
Ag
Vacuum
Ag
Thermos
bottle
refrigeration
GaAs
(LED)
GaAs
(PV)
Ag
Vacuum
Ag

Conclusions:

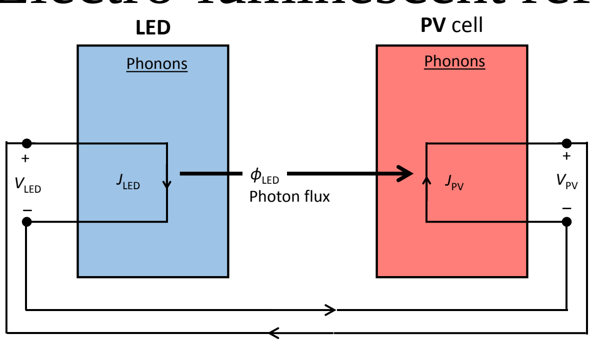
Since we are for the first time making really efficient photovoltaic cells (also LED's), some new ideas become very timely

Beyond Solar

- High temperature Thermo-PhotoVoltaics, for cars and other vehicles



- Electro-luminescent refrigeration (thermophotonic cooling) and electro-luminescent heat engines.



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