Mass Production of Thin-Film Single-Crystal GaAs Solar Cells

22nd Symposium on Solar Electricity Production
Sede Boqer
Sept. 25, 2019

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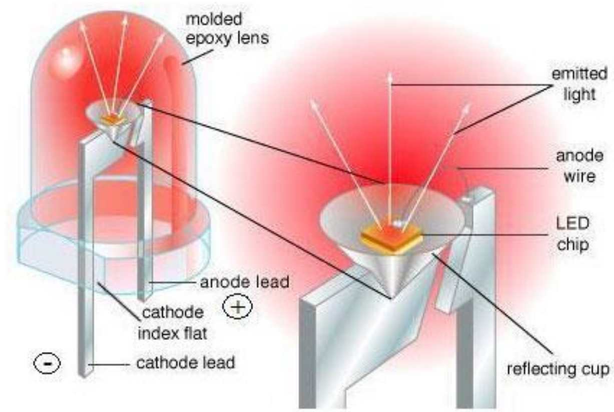
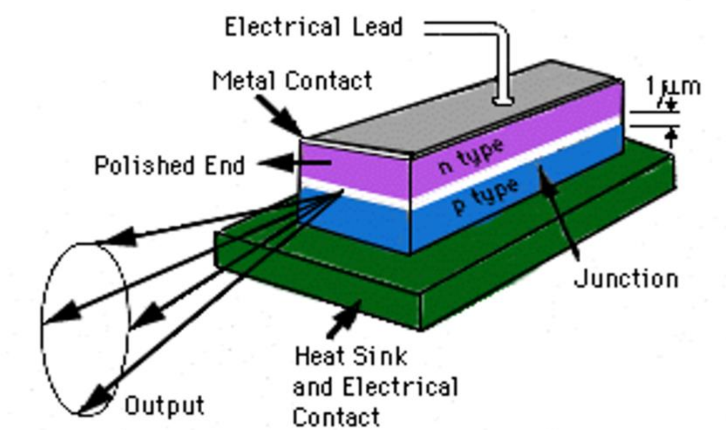
Univ. of California, Berkeley

The Solar Cell, the LED, the semiconductor laser,----are all the same device:

The Solar Cell

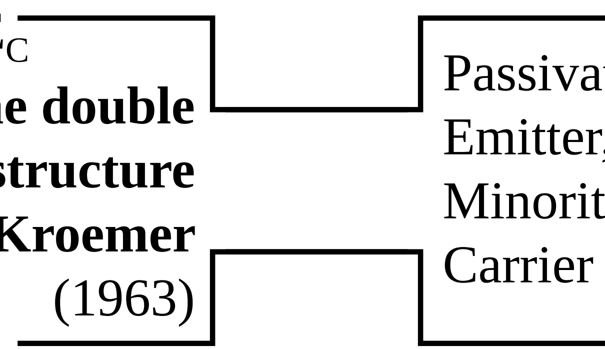


The LED



The Semiconductor Laser

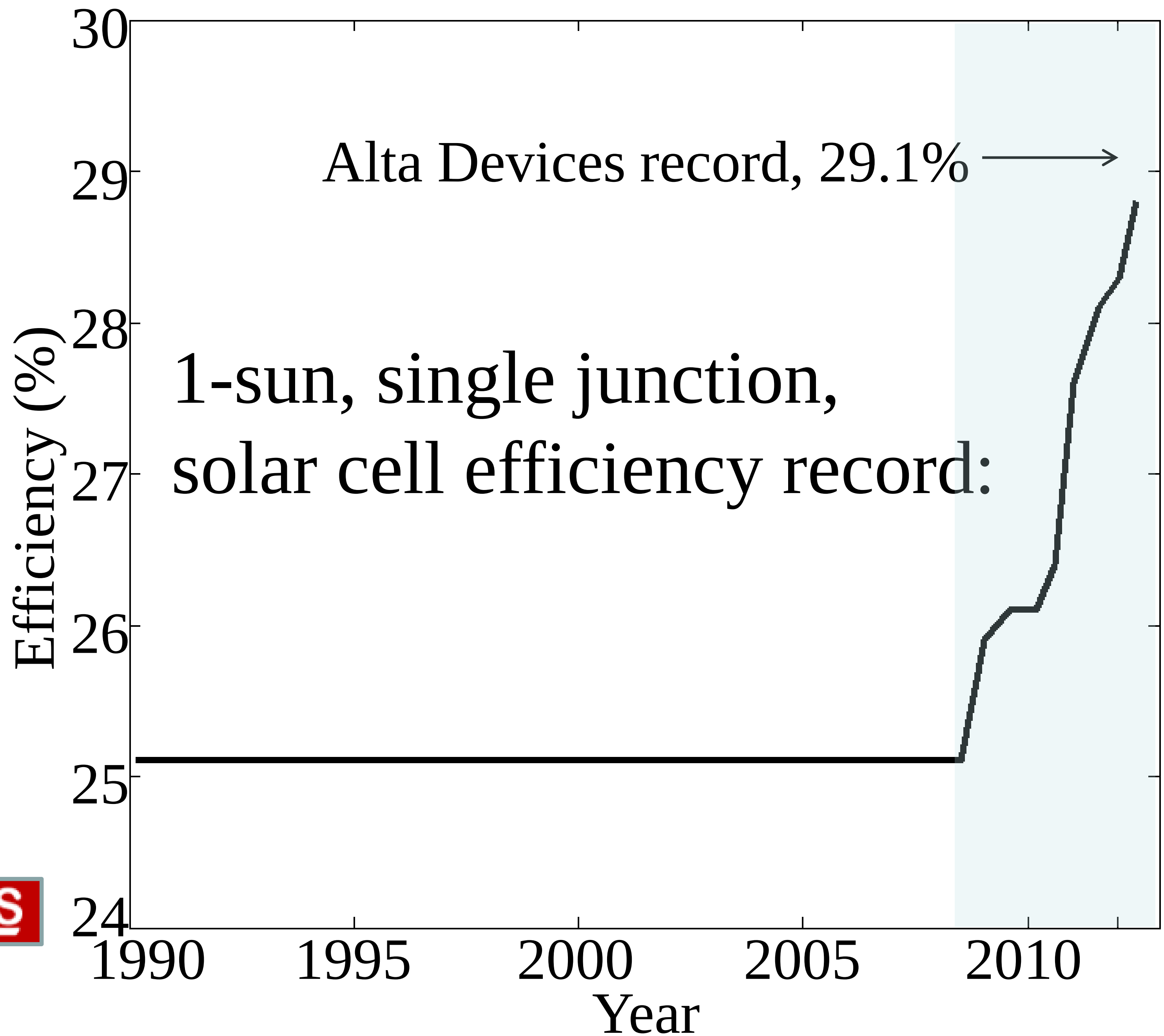
E_C



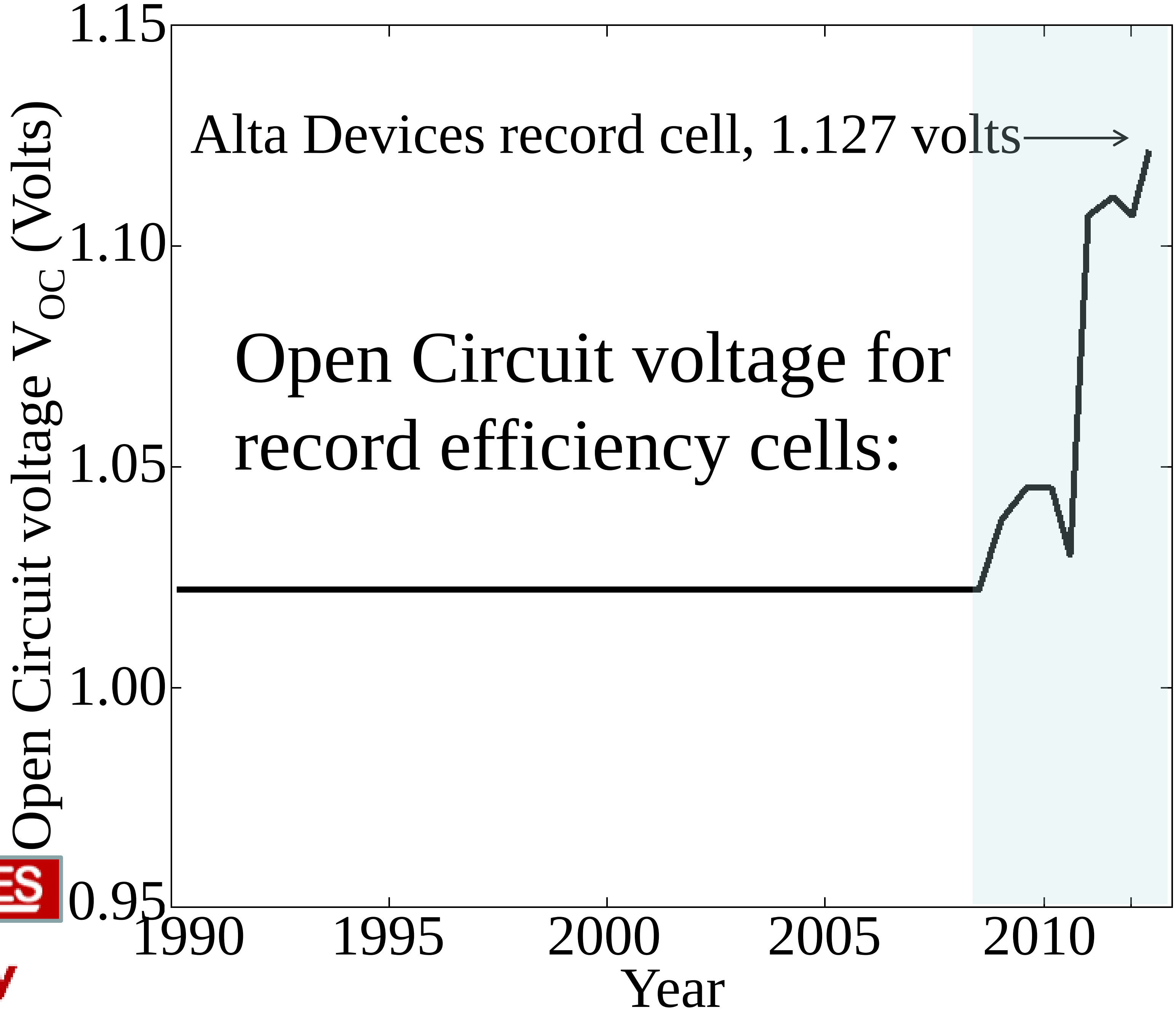
E_V

The double hetero-structure Herb Kroemer (1963)

Passivated Emitter, or; Minority Carrier Mirror



ALTA DEVICES
A
Hanergy
Company



ALTA DEVICES
A
Hanergy
Company

Courtesy of
Alta Devices,
Inc.

ALTA DEVICES
A
Hanergy
Company

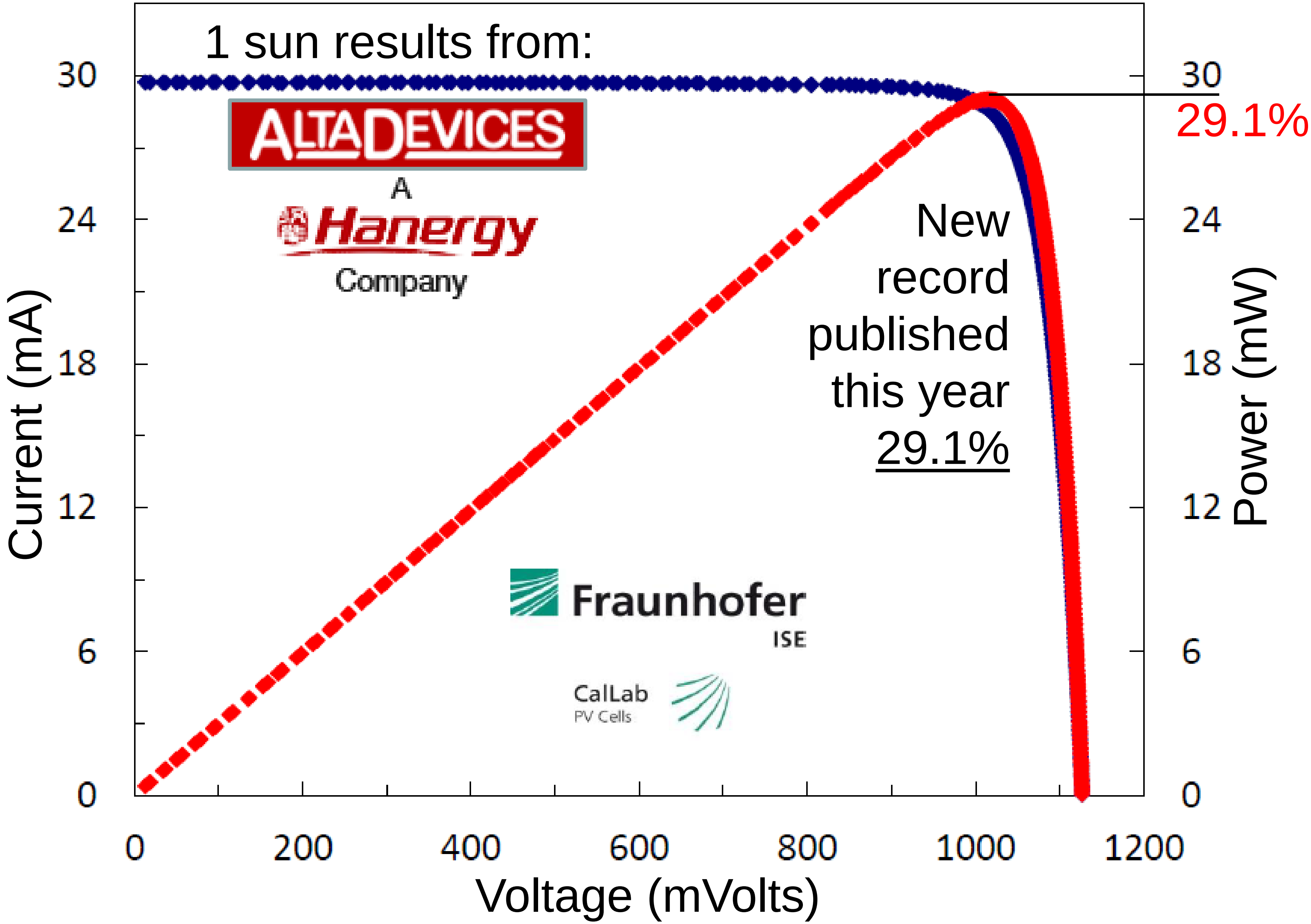
ALTADEVICES

A

Hanergy

Company

Li Hejun



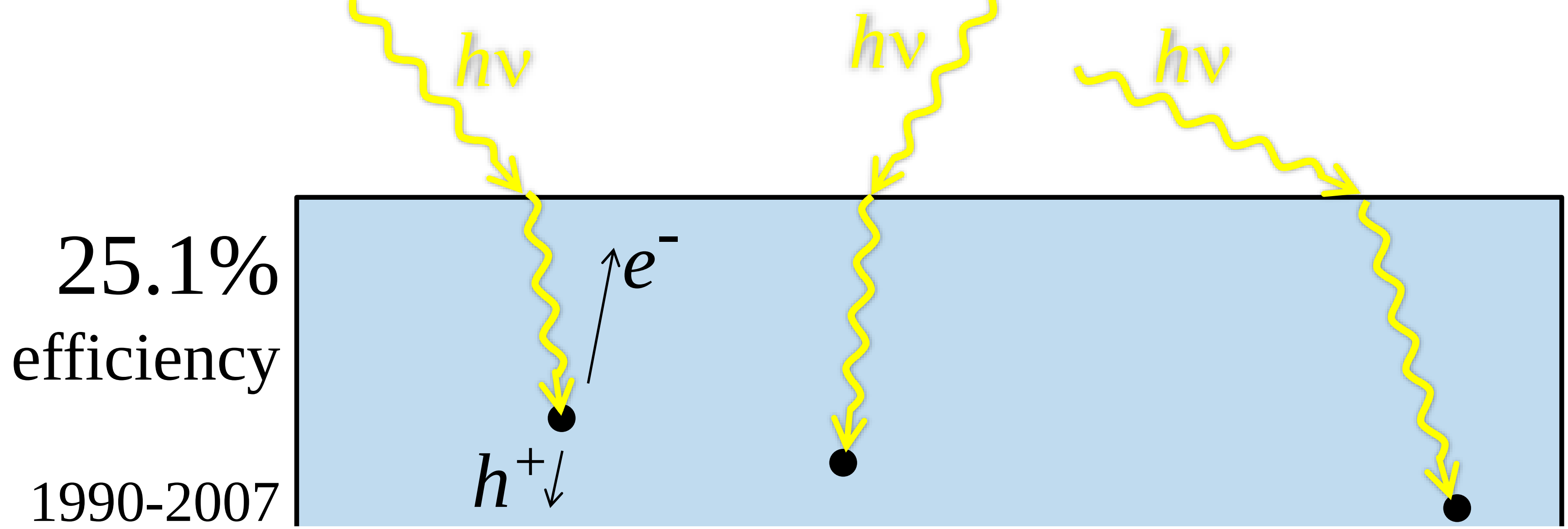
V_{oc} =1.1272Volts J_{sc} =29.78mA/cm^2 Fill Factor =0.867

Shockley told us to generate the maximum possible external luminescence:

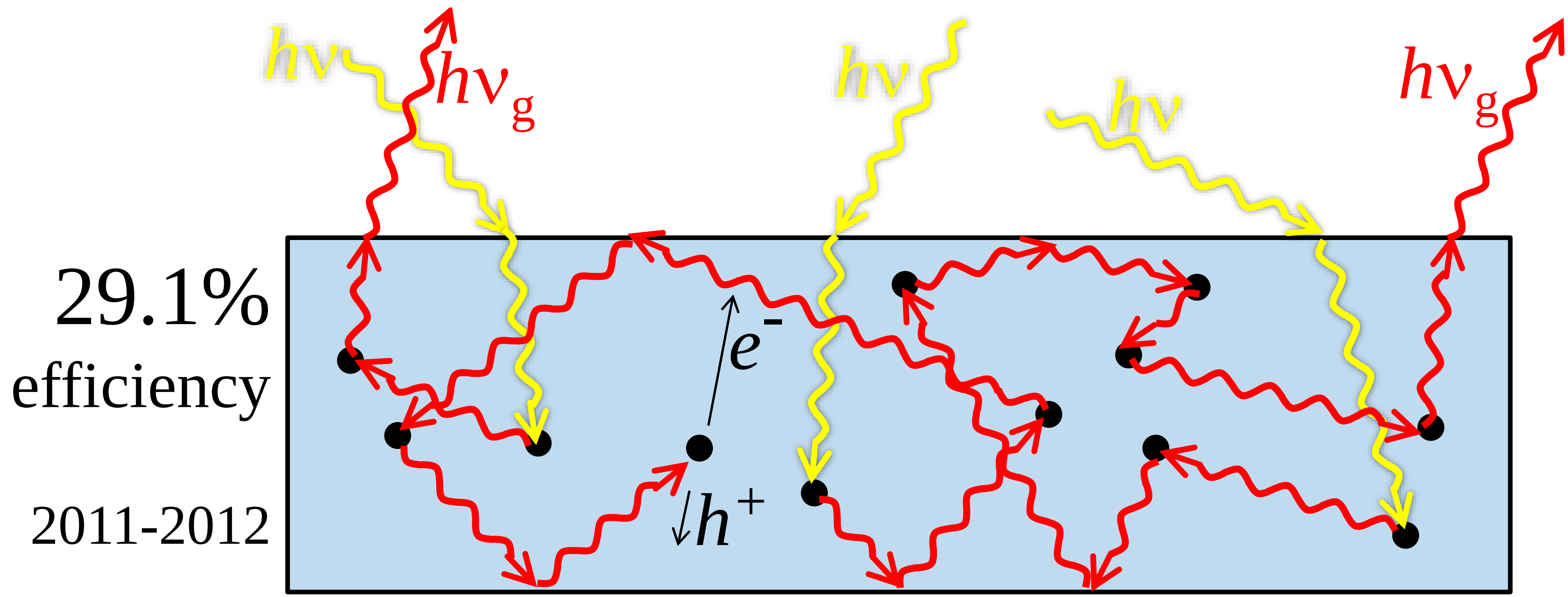
$$qV_{oc} = qV_{oc\text{-}ideal} - kT|\ln\{\eta_{ext}\}|$$

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

Only external Luminescence can balance the incoming radiation.



The benefit is ~100mVolts at the operating point.



excellent reflector >>95%

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)

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}

sunlight carries entropy* ΔS

*ask any astrophysicist

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

$$\text{Free Energy} = h\nu - \overbrace{kT\,|\ln\{\pi/\Omega_s\}|}^{-0.3\text{eV}} - \overbrace{kT\,|\ln\{0.1\}|}^{-0.1\text{eV}}$$

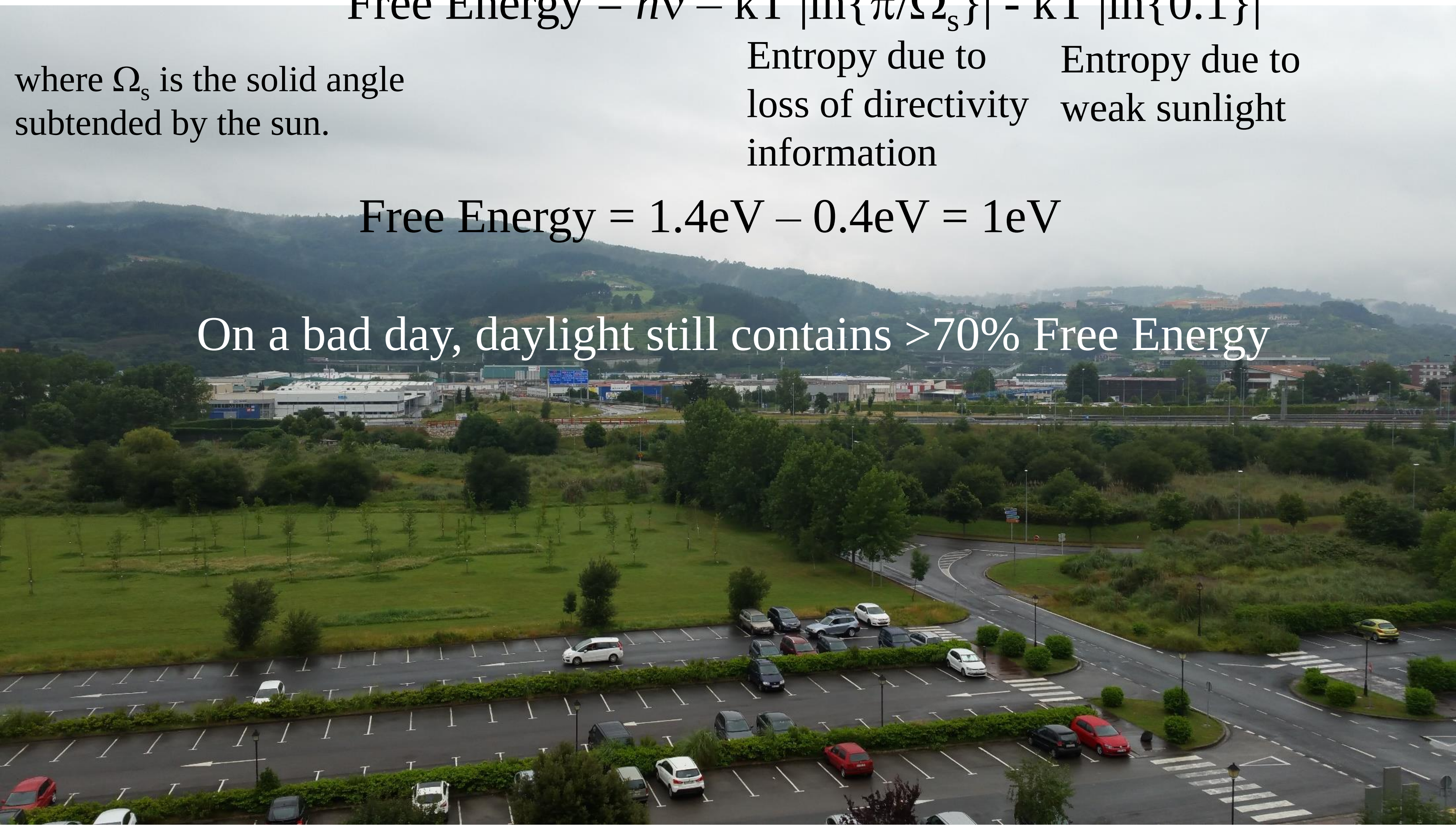
Entropy due to loss of directivity information

Entropy due to weak sunlight

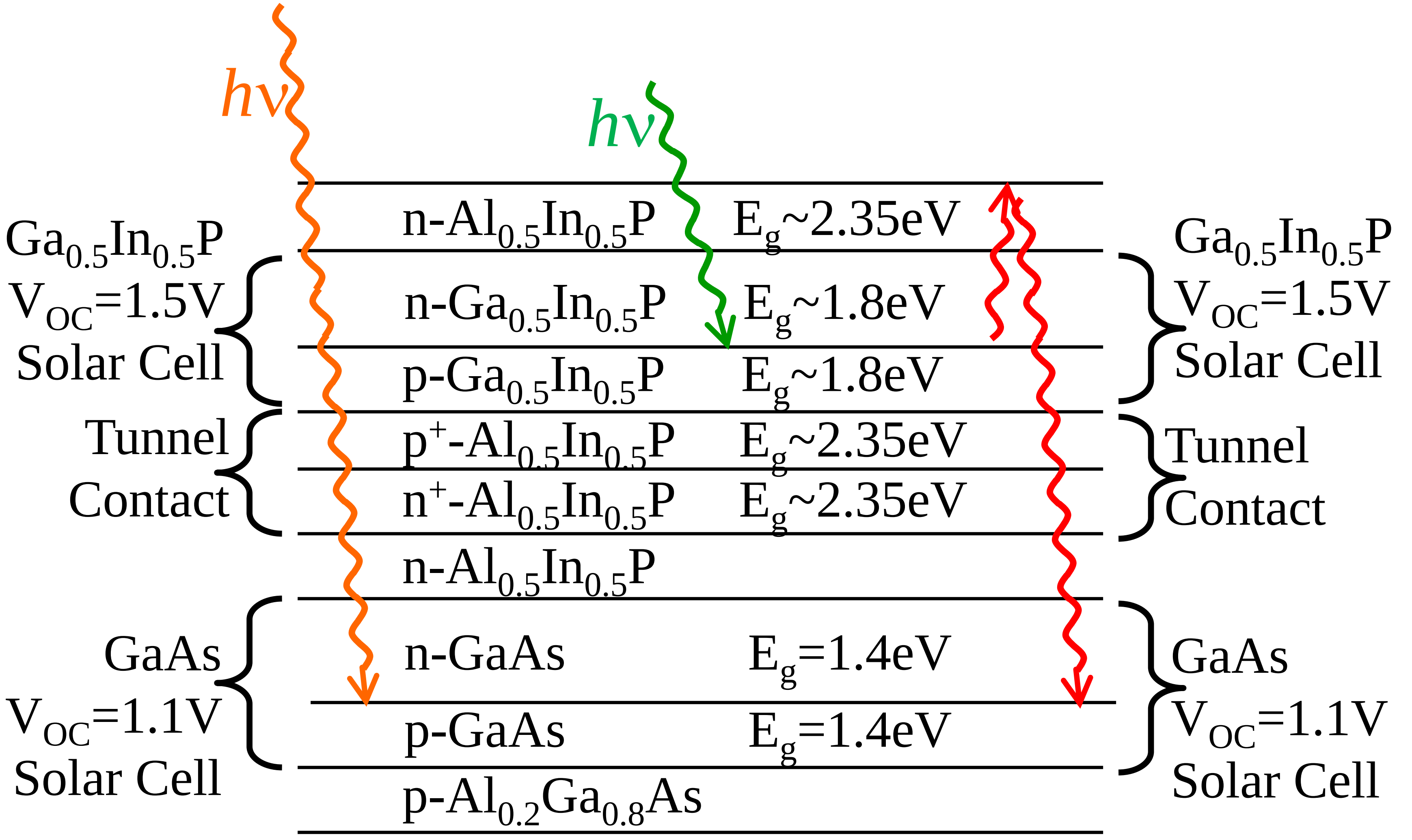
where Ω_s is the solid angle subtended by the sun.

$$\text{Free Energy} = 1.4\text{eV} - 0.4\text{eV} = 1\text{eV}$$

On a bad day, daylight still contains >70% Free Energy



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.

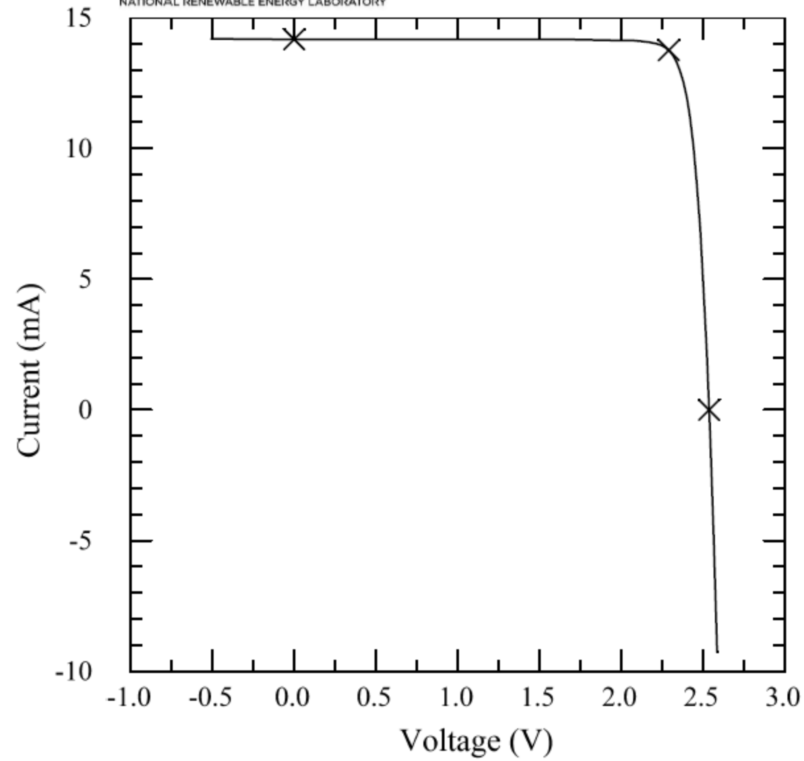
Alta Devices

GaInP/GaAs Tandem Cell

Device ID: AD33551-I-3
5:14 PM 1/5/2016
Spectrum: ASTM G173 global

Device temperature: 25.0 ± 1.0 °C
Device area: 0.999 cm^2
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_{sc} = 14.164 mA
J_{sc} = 14.184 mA/cm^2
Fill Factor = 87.7 %

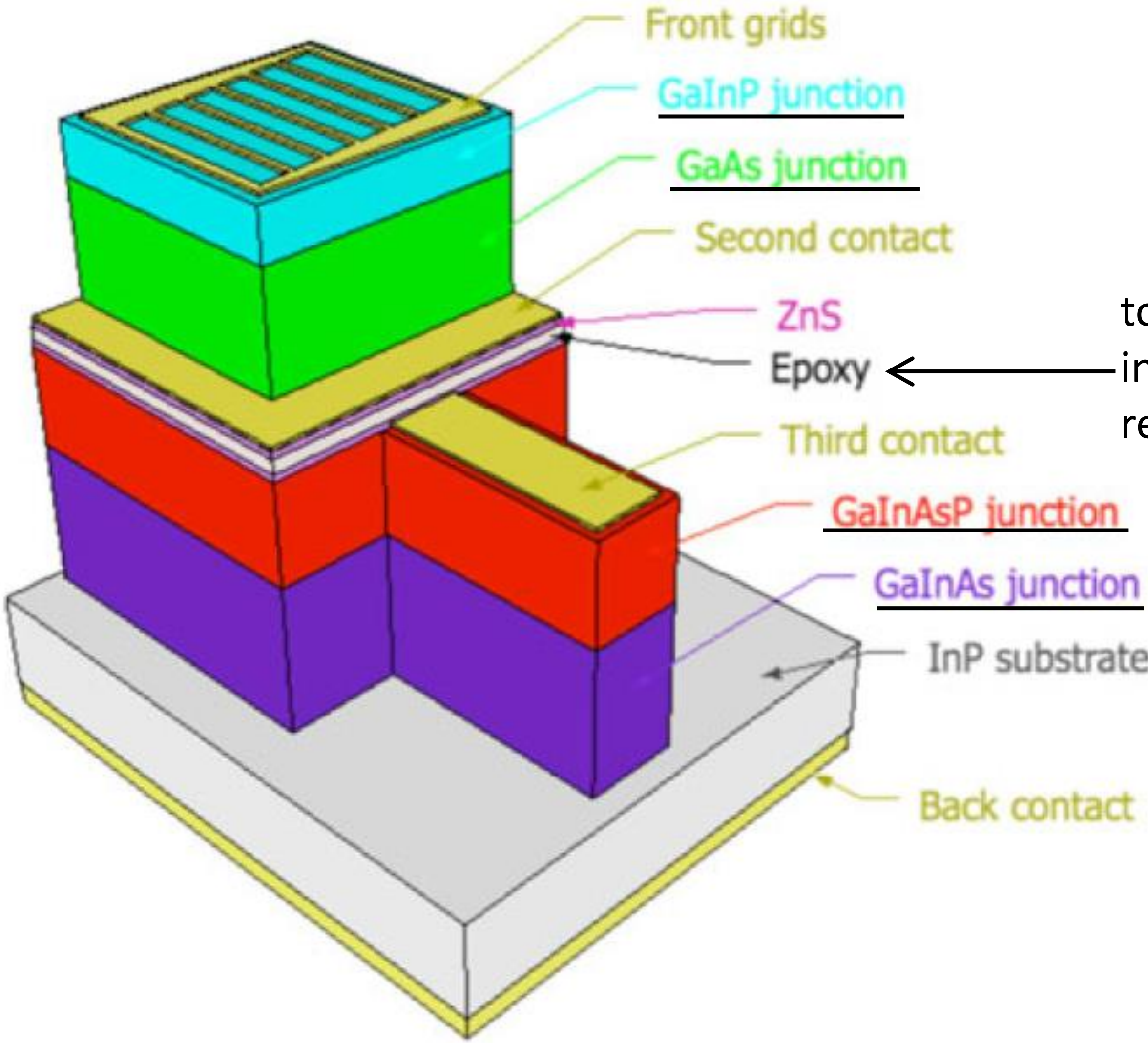
I_{max} = 13.754 mA
V_{max} = 2.2906 V
P_{max} = 31.505 mW
Efficiency = 31.55 %

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

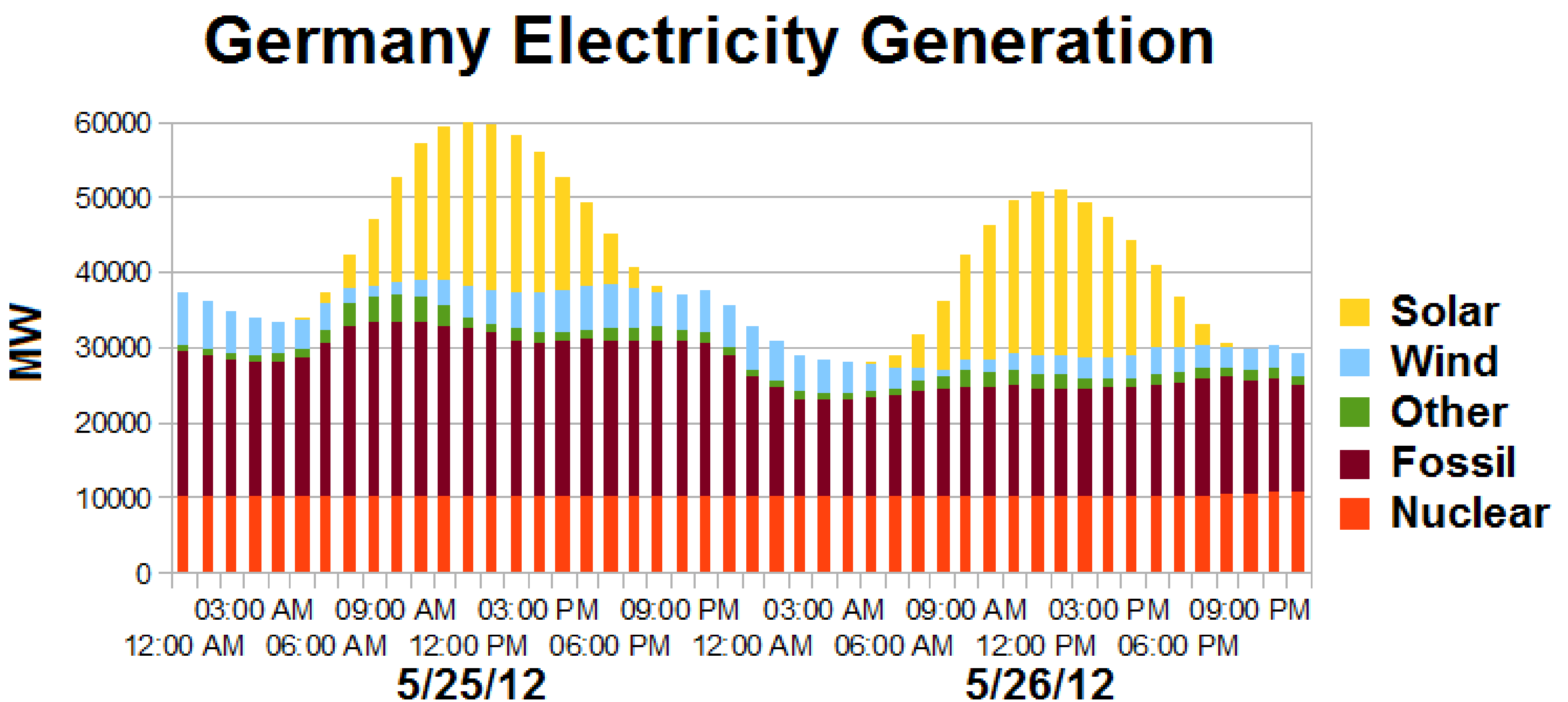


total internal reflection

IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 6, p.358 (JANUARY 2016)

Myles A. Steiner, Sarah R. Kurtz, et al, NREL USA

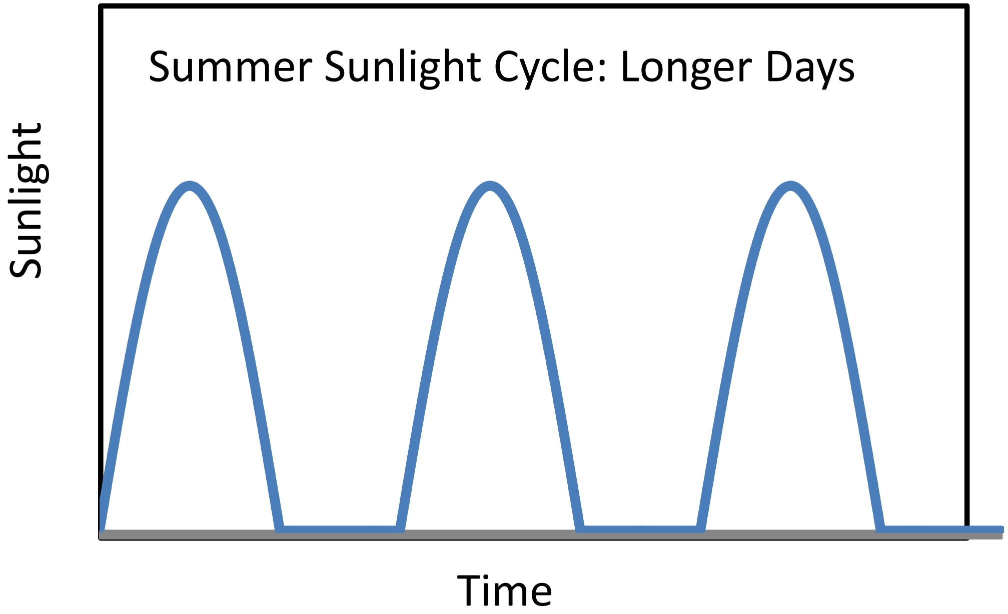
The need for Seasonal Storage:



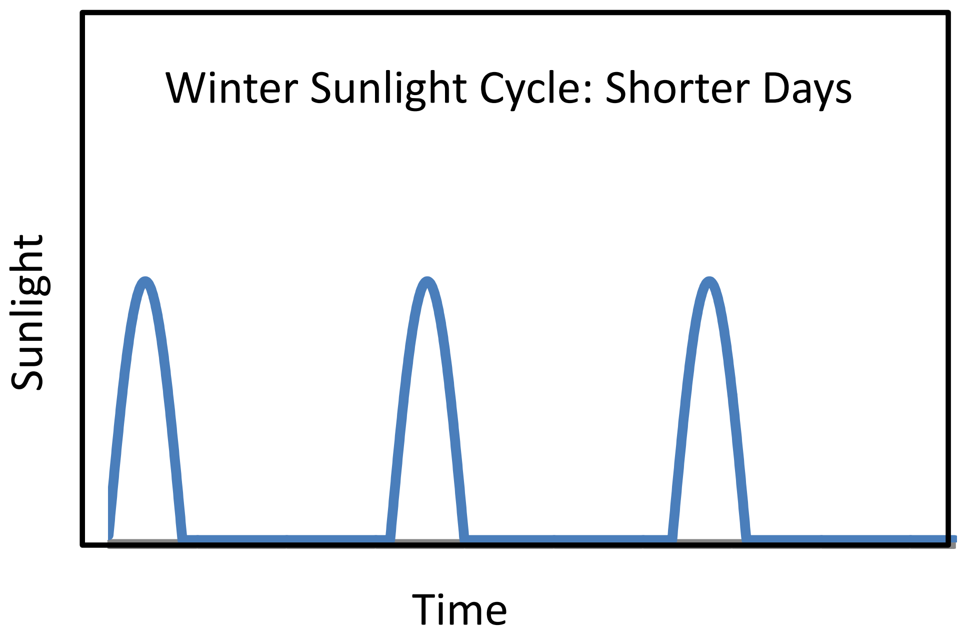
Friday **Saturday**

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

Need for seasonal, long term energy storage.



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

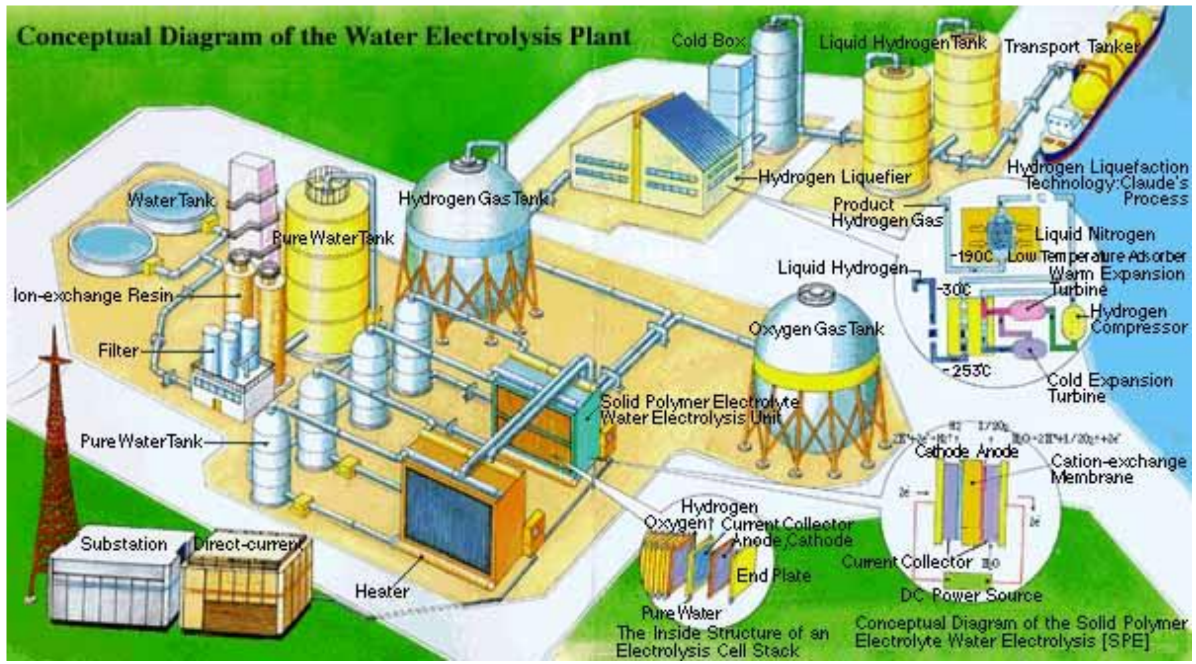


-Winter: Shorter days, increased cloudiness, and sun is lower.

Therefore storable fuel, not batteries are needed.

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:



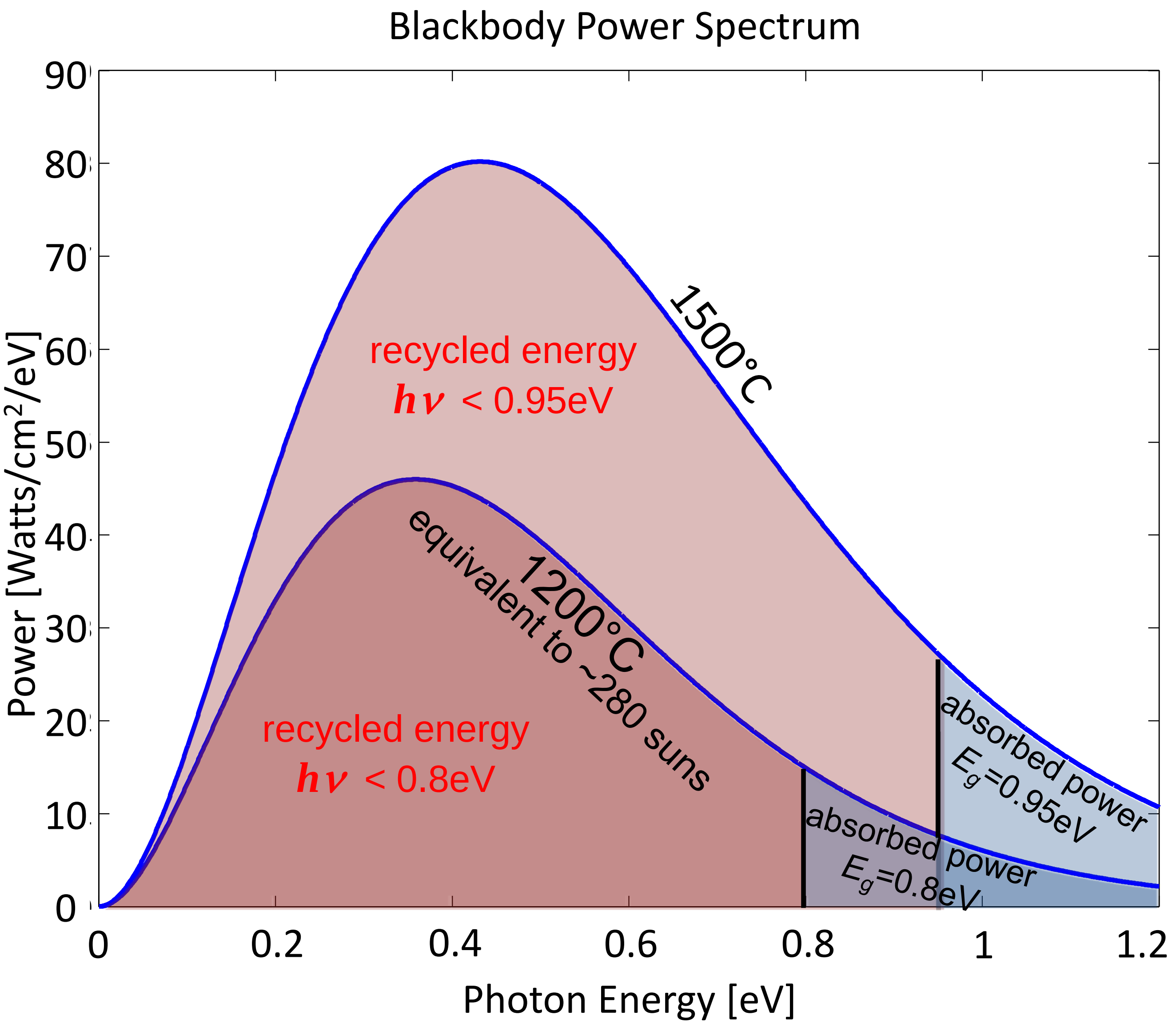
3. Thermo-PhotoVoltaics
4. Electro-Luminescent Refrigeration & Heat Engines

Opto-Electronics, Is There Anything it Cannot Do?

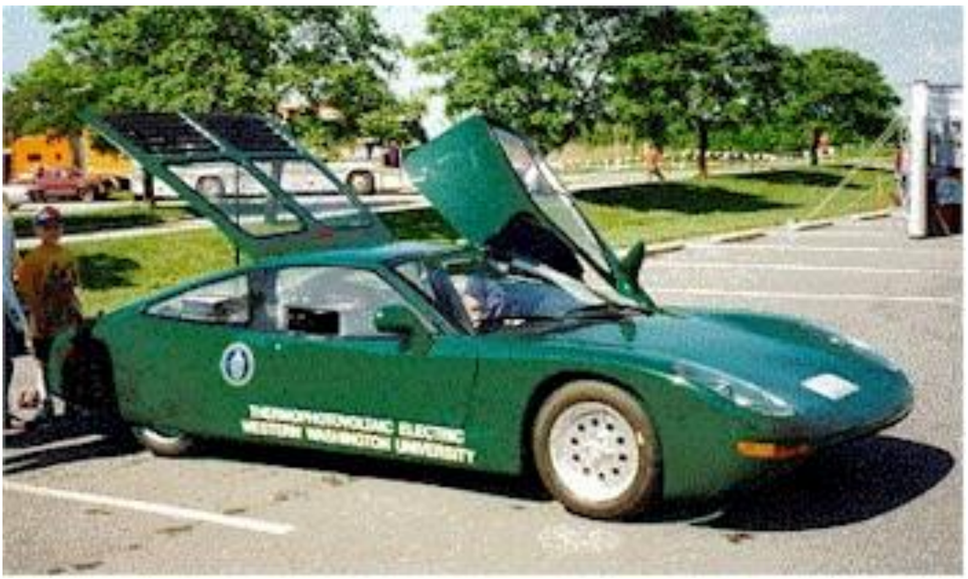
Application	**Required Internal Luminescence Efficiency**
1. Internet Communication	~90%
2. GaN Lighting	~90%
3. Electricity Generation by Solar Panels	~99% (to break records)
4. Automobile Engine	~90%
5. Refrigeration	~99.9%

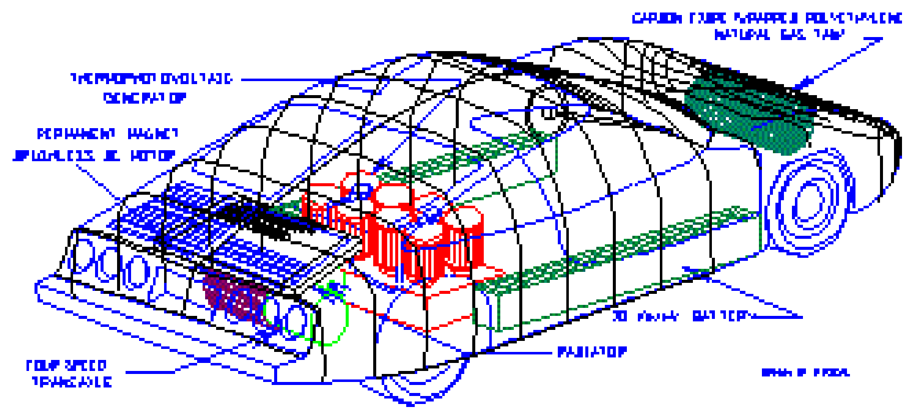
Thermo-PhotoVoltaics TPV

Superb Rear Reflector; Recycle the Long-Wave Infrared Photons:



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.

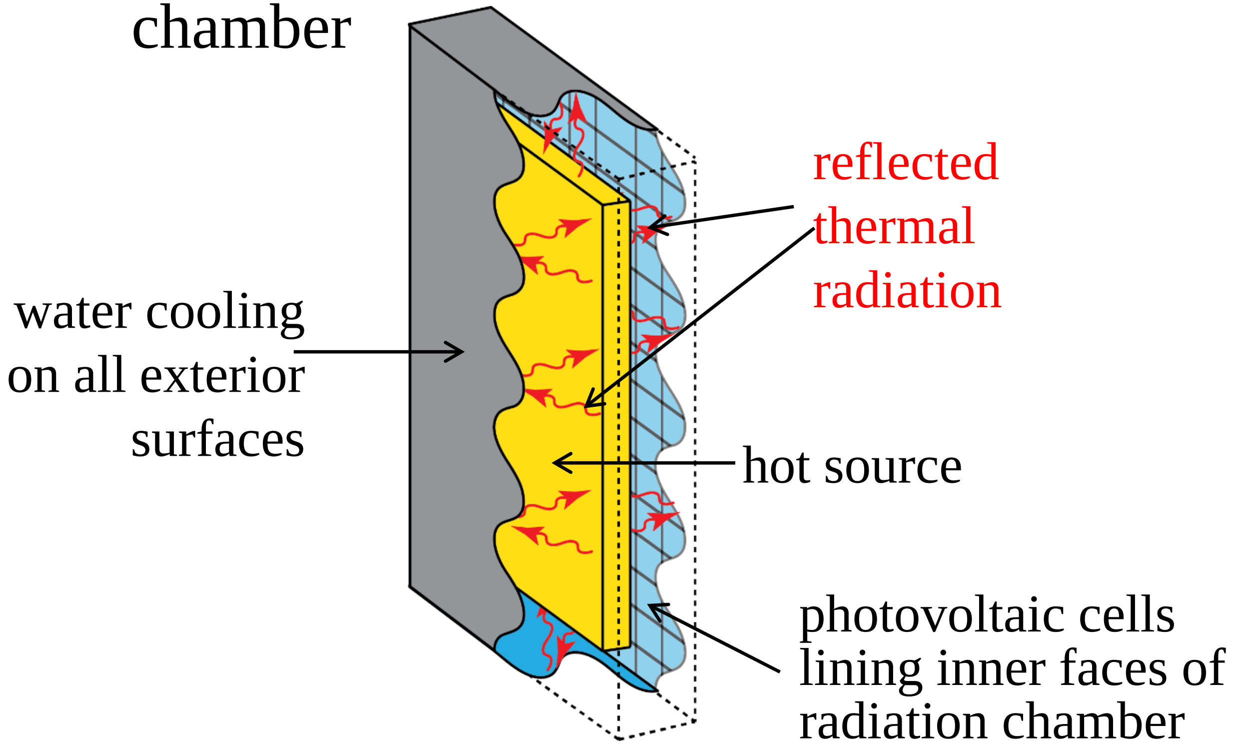
At 1200C, there are 280 suns bouncing around internally!

semiconductor bandgap itself is the ideal spectral filter.

spectrally selective emissivity not needed.

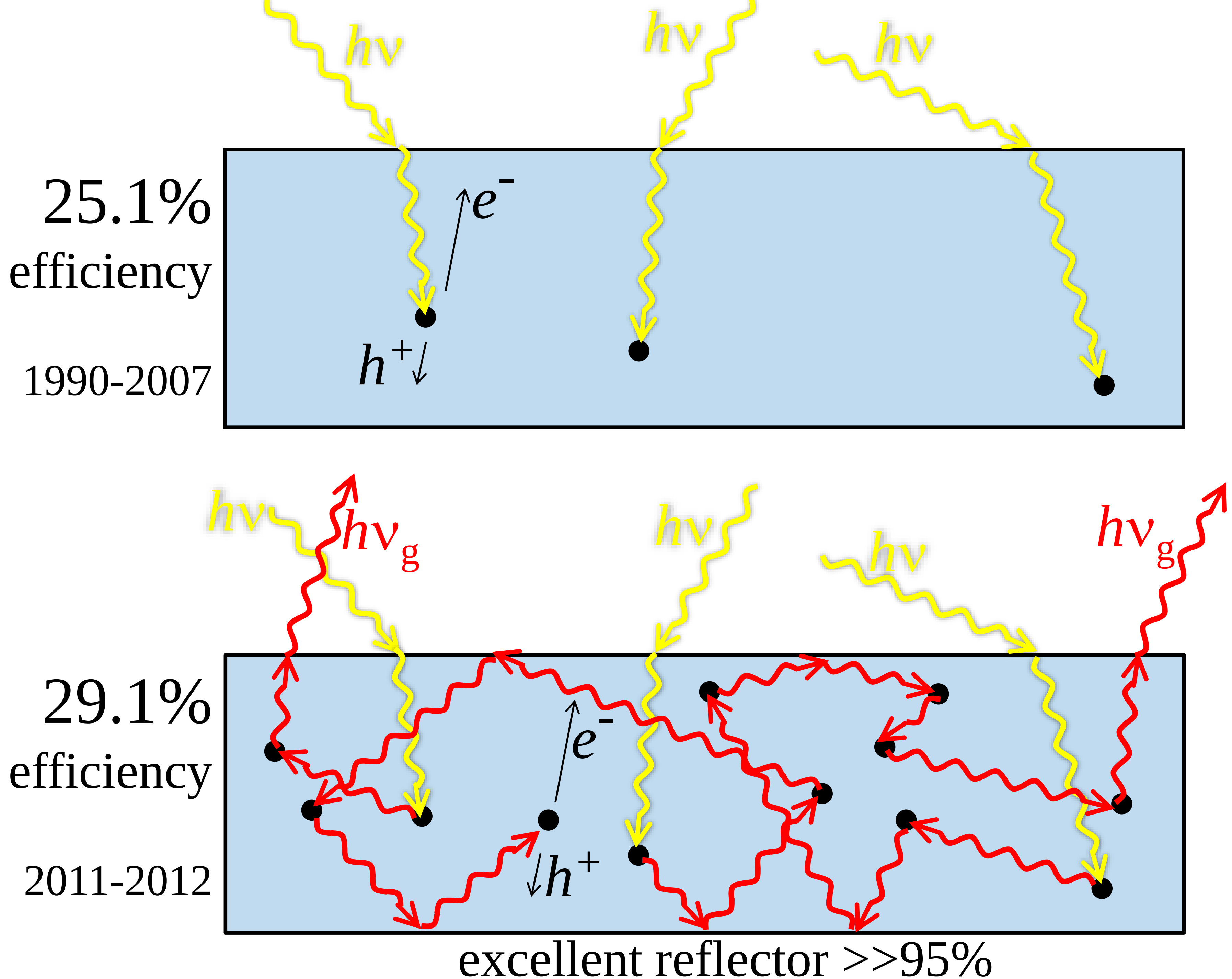
>50% efficiency is possible

thermophotovoltaic chamber

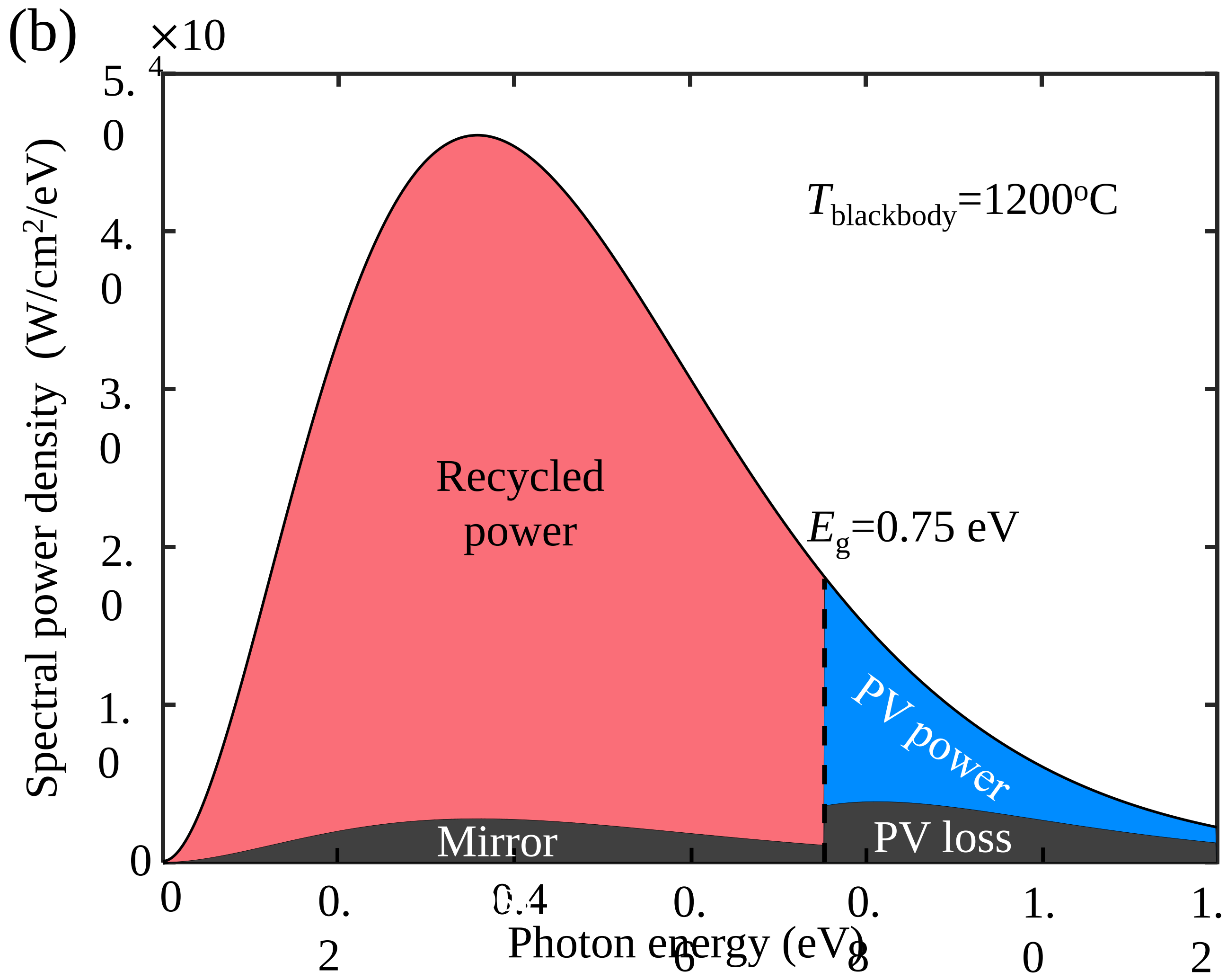


280 suns bouncing around internally!

70cm×70cm is adequate for hybrid car.



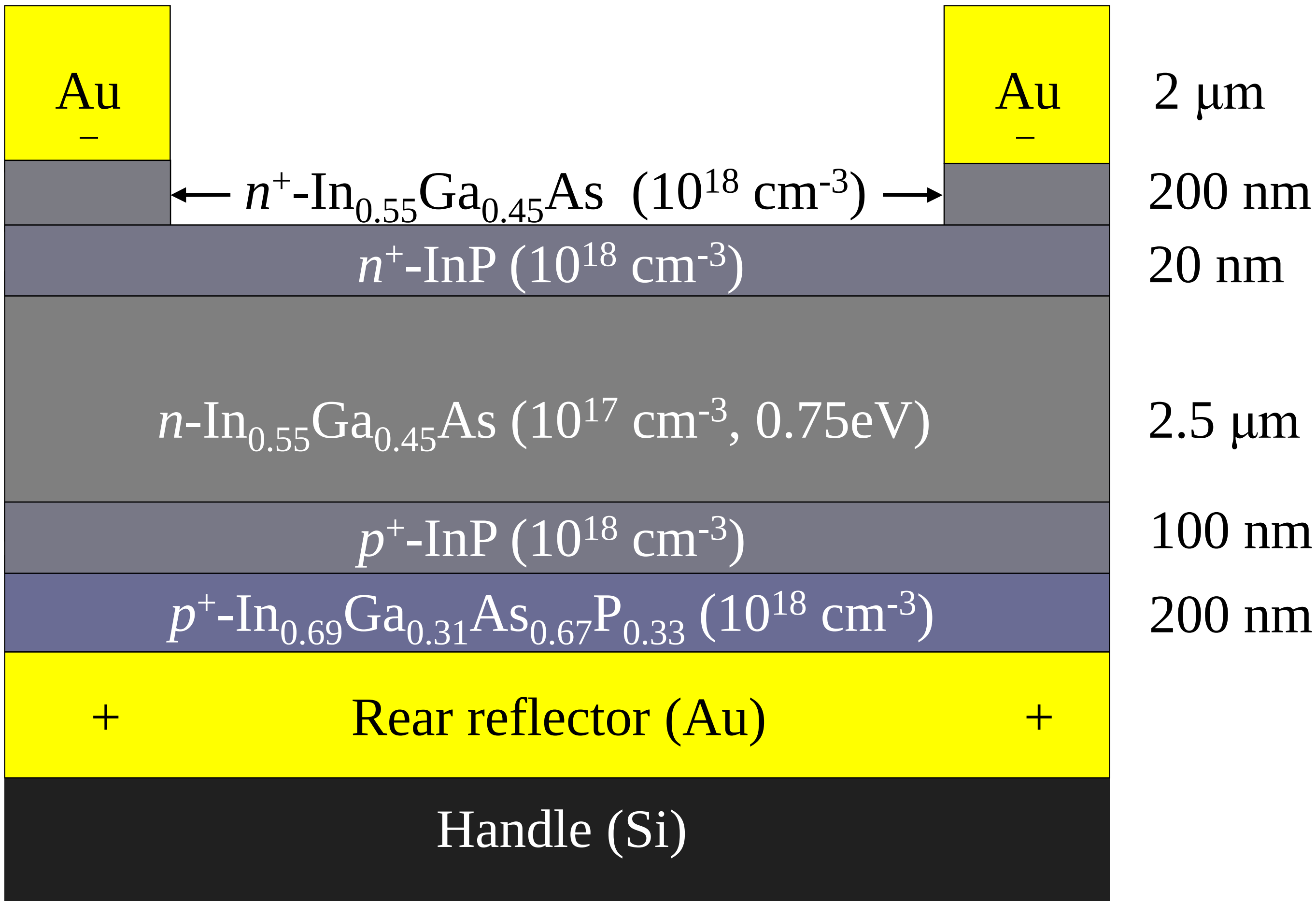
hv
hv
hv
25.1%
efficiency
1990-2007
e-
h+
hv
hvg
hv
hv
hvg
29.1%
efficiency
2011-2012
e-
h+
excellent reflector >>95%



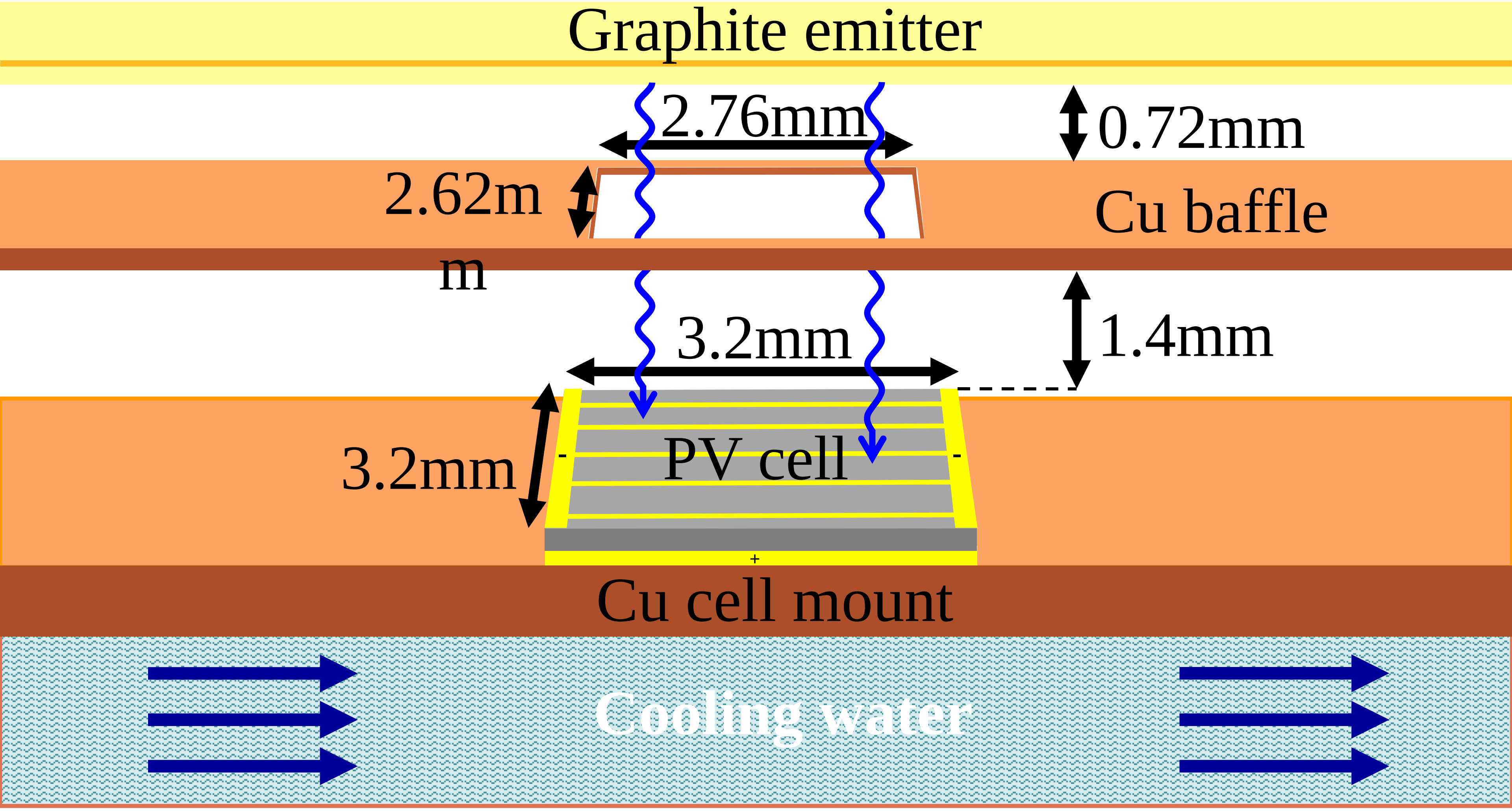
(b)
×10
4
5.
0
4.
0
3.
0
2.
0
1.
0
0
Spectral power density (W/cm^2/eV)
$T_{blackbody}$=1200^{o}C
Recycled
power
E_g=0.75 eV
PV power
Mirror
PV loss
0
0.
2
0.4
0.
6
0.
8
1.
0
1.
2
Photon energy (eV)

Myles Steiner Cell Design:

(b)

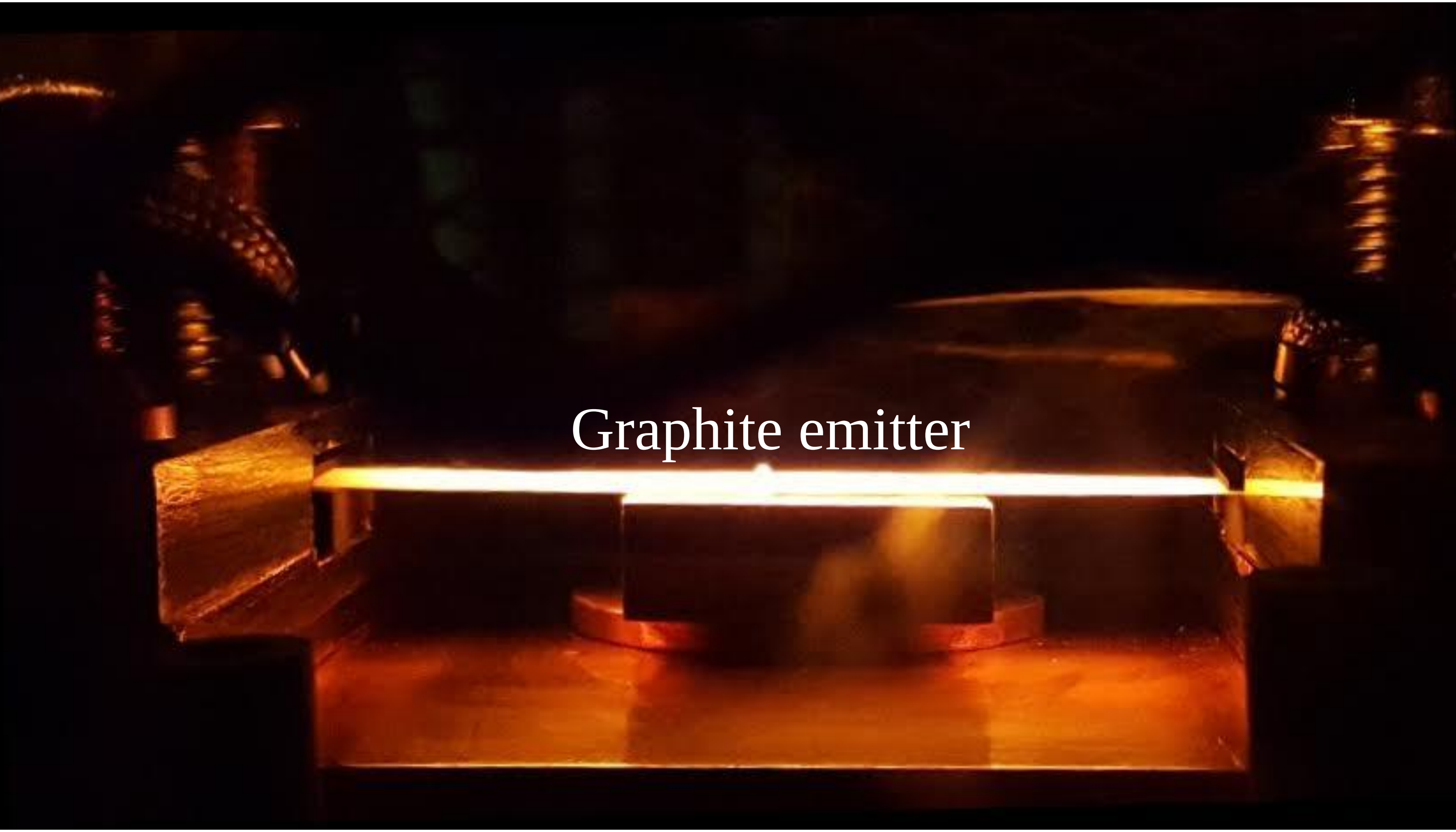


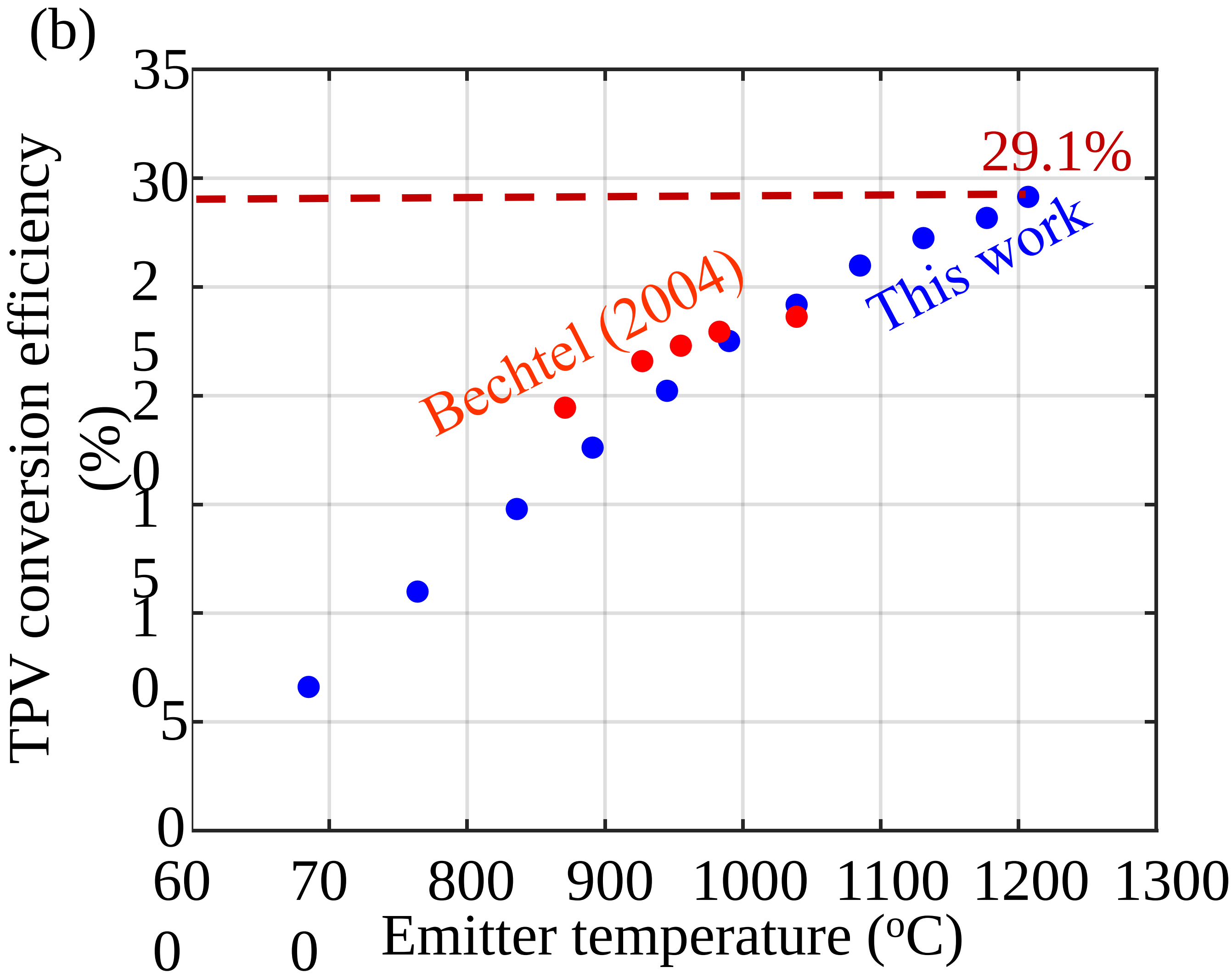
(a)



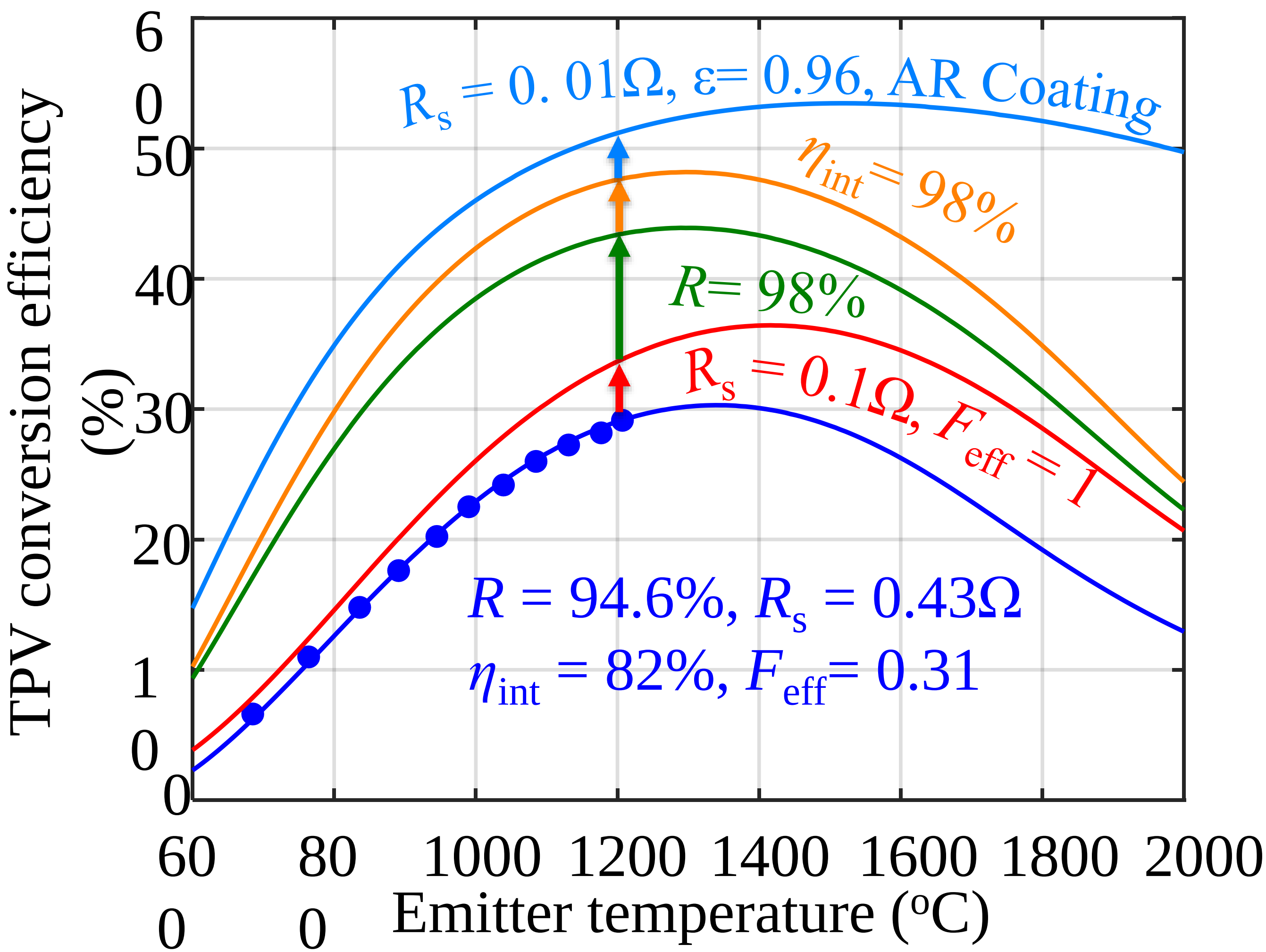
Graphite emitter
2.76mm
0.72mm
2.62m
m
Cu baffle
3.2mm
1.4mm
3.2mm
PV cell
-
-
+
Cu cell mount
Cooling water

Emitter at 1200°C

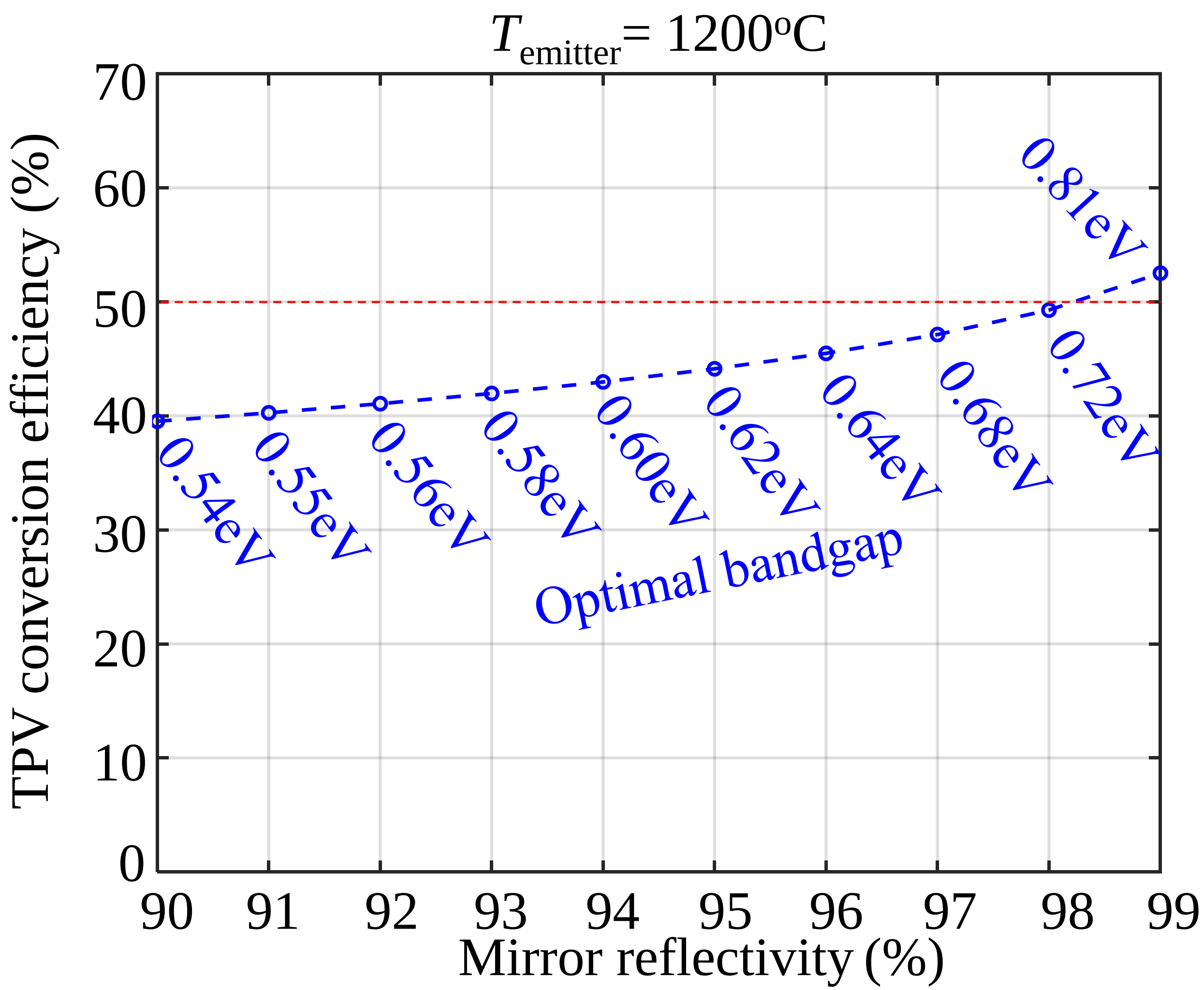




(b)
29.1%
Bechtel (2004)
This work
TPV conversion efficiency (%)
Emitter temperature (ºC)



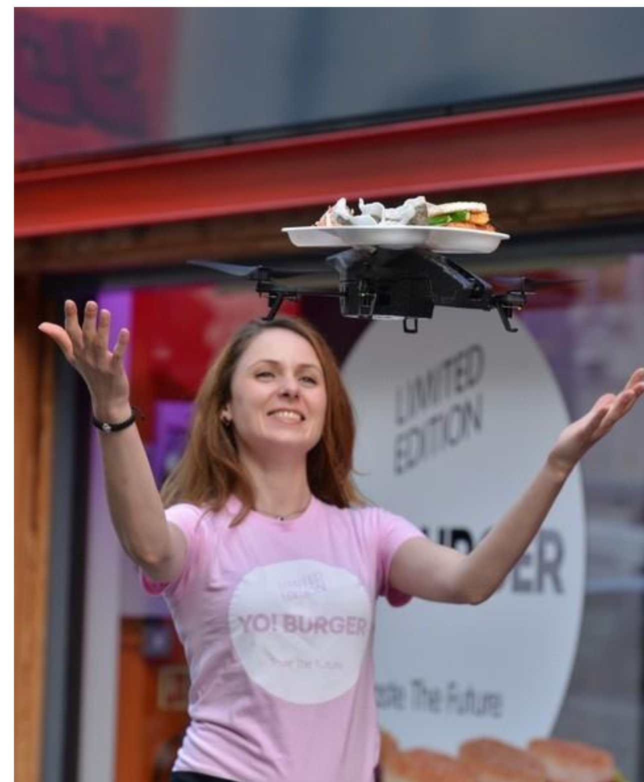
TPV conversion efficiency (%)
60
50
40
30
20
10
0
600
800
1000
1200
1400
1600
1800
2000
Emitter temperature (°C)
Rs = 0. 01Ω, ε= 0.96, AR Coating
ηint= 98%
R= 98%
Rs = 0.1Ω, Feff = 1
R = 94.6%, Rs = 0.43Ω
ηint = 82%, Feff= 0.31



$T_{emitter}$= 1200°C
TPV conversion efficiency (%)
Mirror reflectivity (%)
0
10
20
30
40
50
60
70
90
91
92
93
94
95
96
97
98
99
0.54eV
0.55eV
0.56eV
0.58eV
0.60eV
0.62eV
0.64eV
0.68eV
0.72eV
0.81eV
Optimal bandgap

Quad-Copters for
civilian & military use:
:
Duration depends on energy density
Lithium battery lasts a short period.

Liquid fuel has 50× times higher
energy density, would last >40 hours.



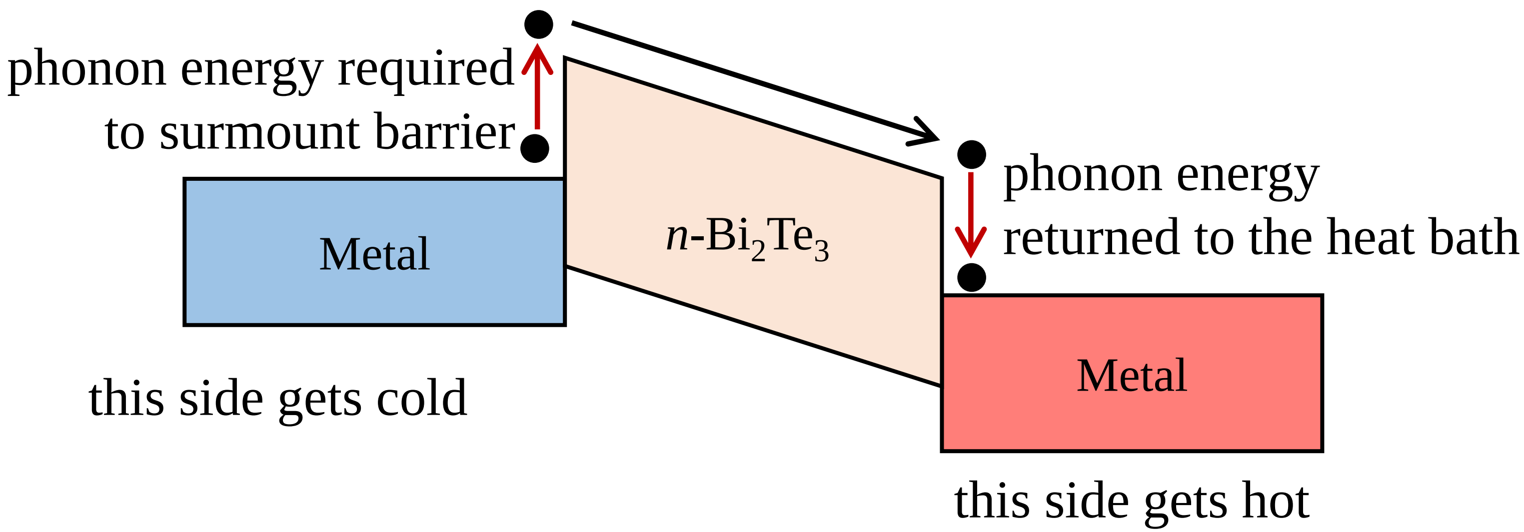
But there is competition from Fuel Cell vehicles; $2H_2+O_2 \rightarrow 2H_2O$

requires H_2 storage;

(but new H_2 storage technologies are being invented)

Traditional Thermoelectric cooler/generator

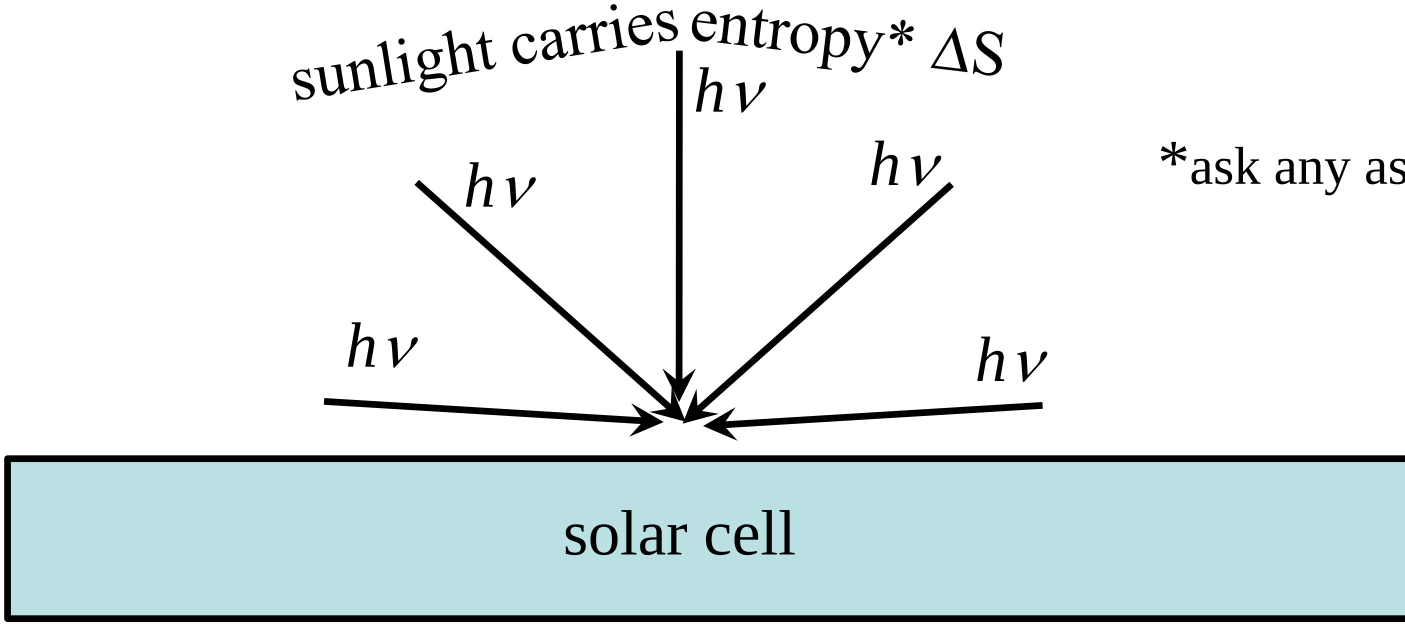
electric current carries heat



electric current drags entropy → from left to right

Also works to generate electricity

The hot side sends out more electrons than the cold side



*ask any astrophysicist

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

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

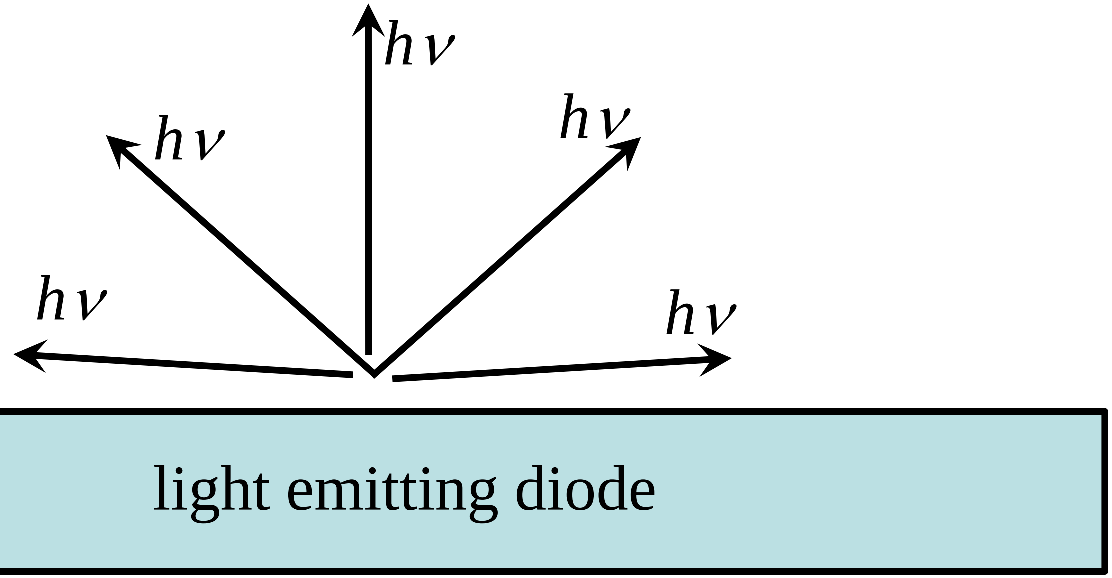
For GaAs E_g is 1.4eV

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

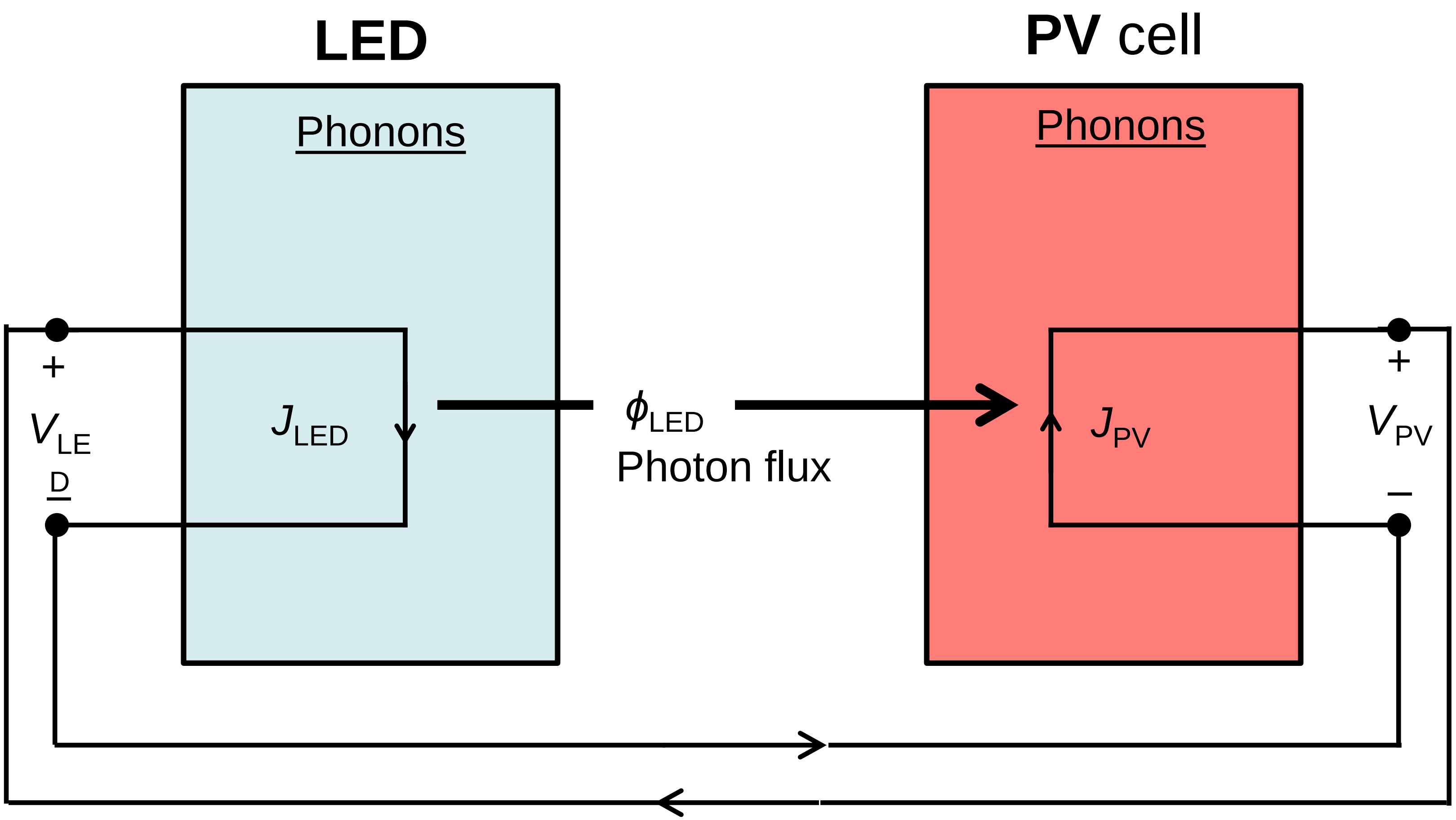
get out $E_g = h\nu = 1.4\text{eV}$

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.

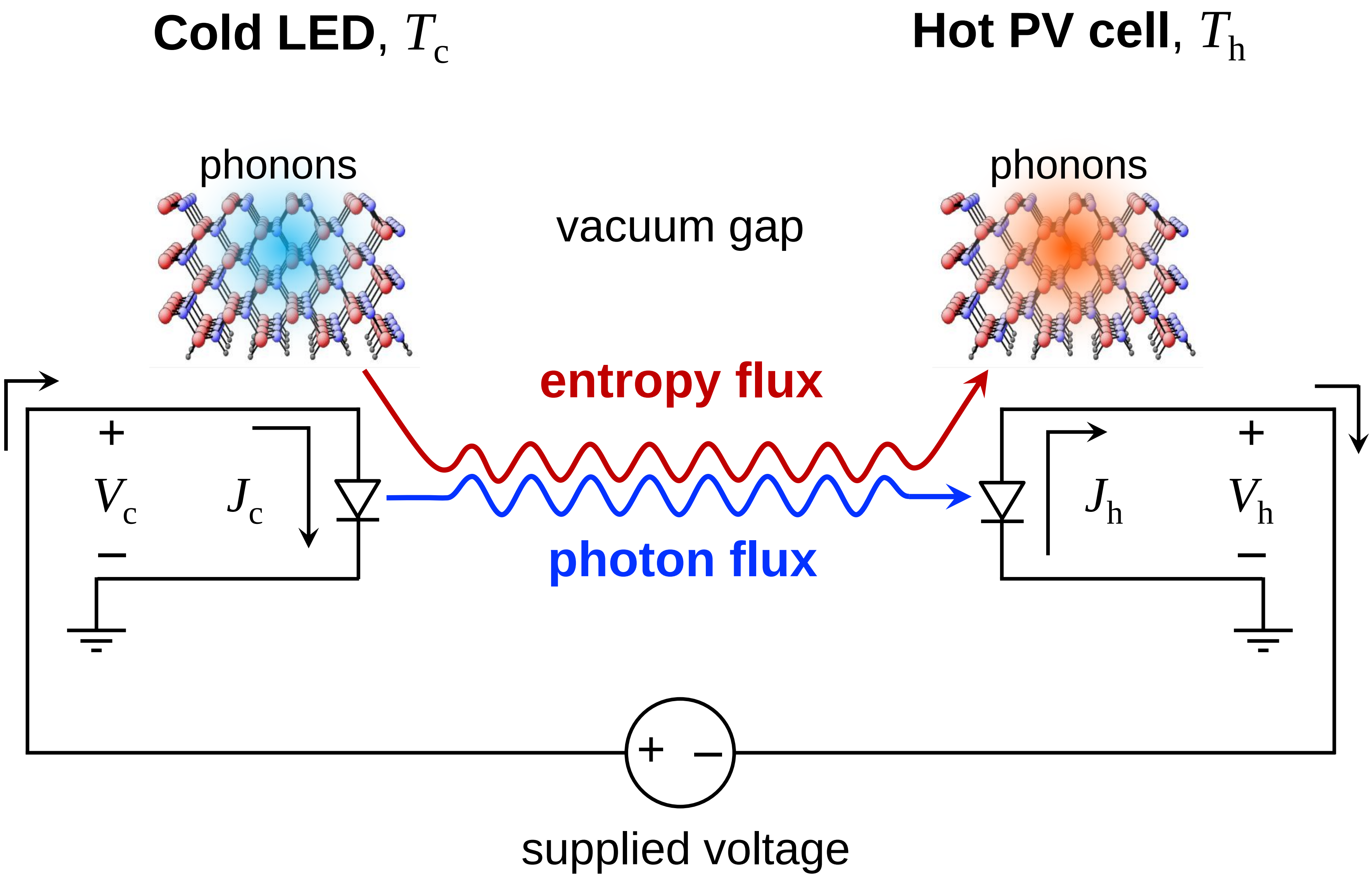
Shockley's perpetual motion machine, circa ~1955



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

"Thermo-Photonics" N. P. Harder & M. A. Green,
Semicond. Sci. Tech. **18,** S270 (2003)

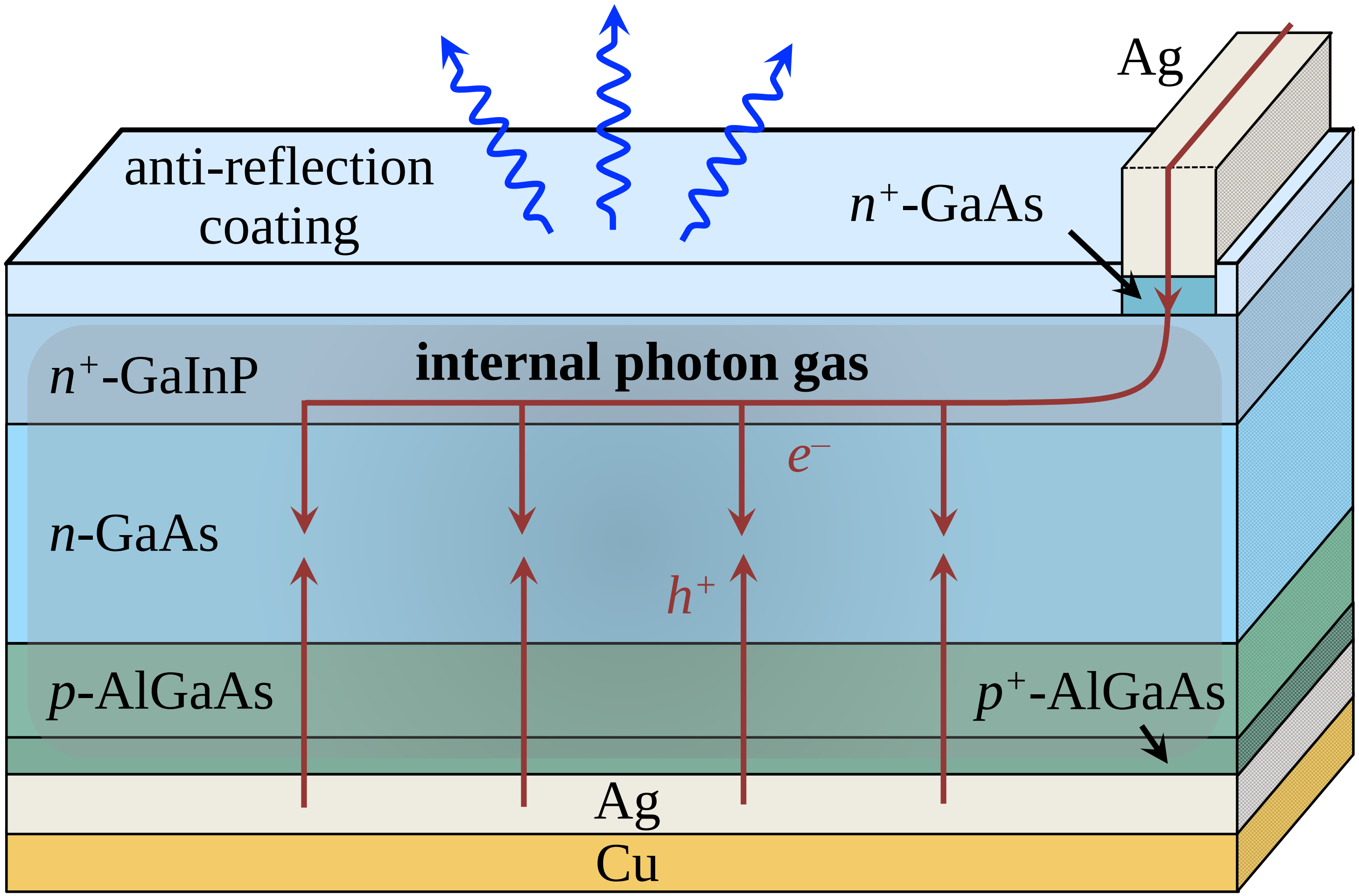
Electroluminescent refrigeration



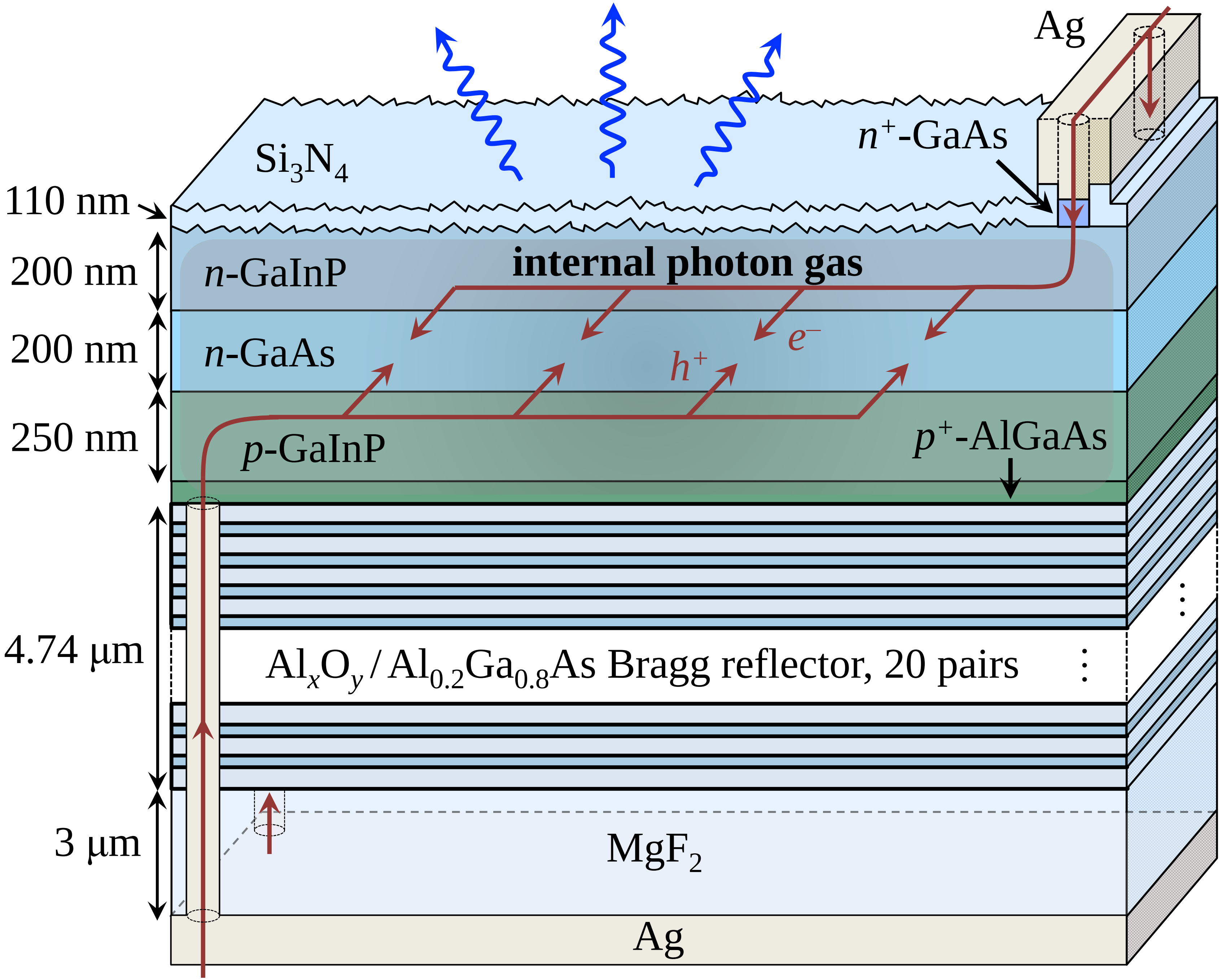
This all works because GaAs is the most efficient fluorescent material.

GaAs Luminescent Efficiency:
99.9% internal at 300K
99.99% internal at 130K

For Yb:YLF,
Ytterbium in Yttrium Lithium Fluoride,
99.9% luminescent efficiency is known.
For $CH_3NH_3PbI_3$ >99%



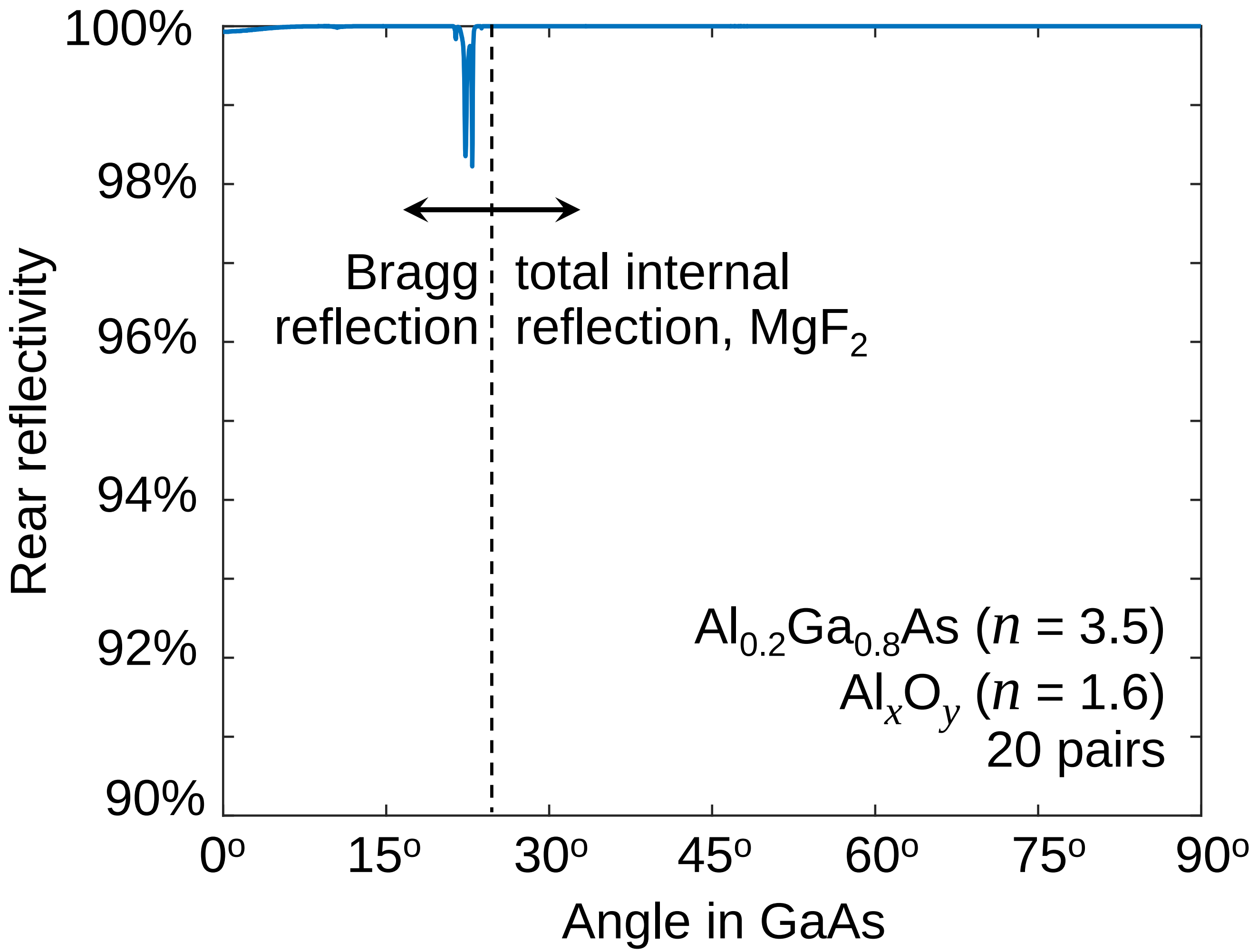
Record-Breaking ALTA Devices Solar Cell,
~35% external electro-luminescence Efficiency



Super LED, >98% external electro-luminescence Efficiency

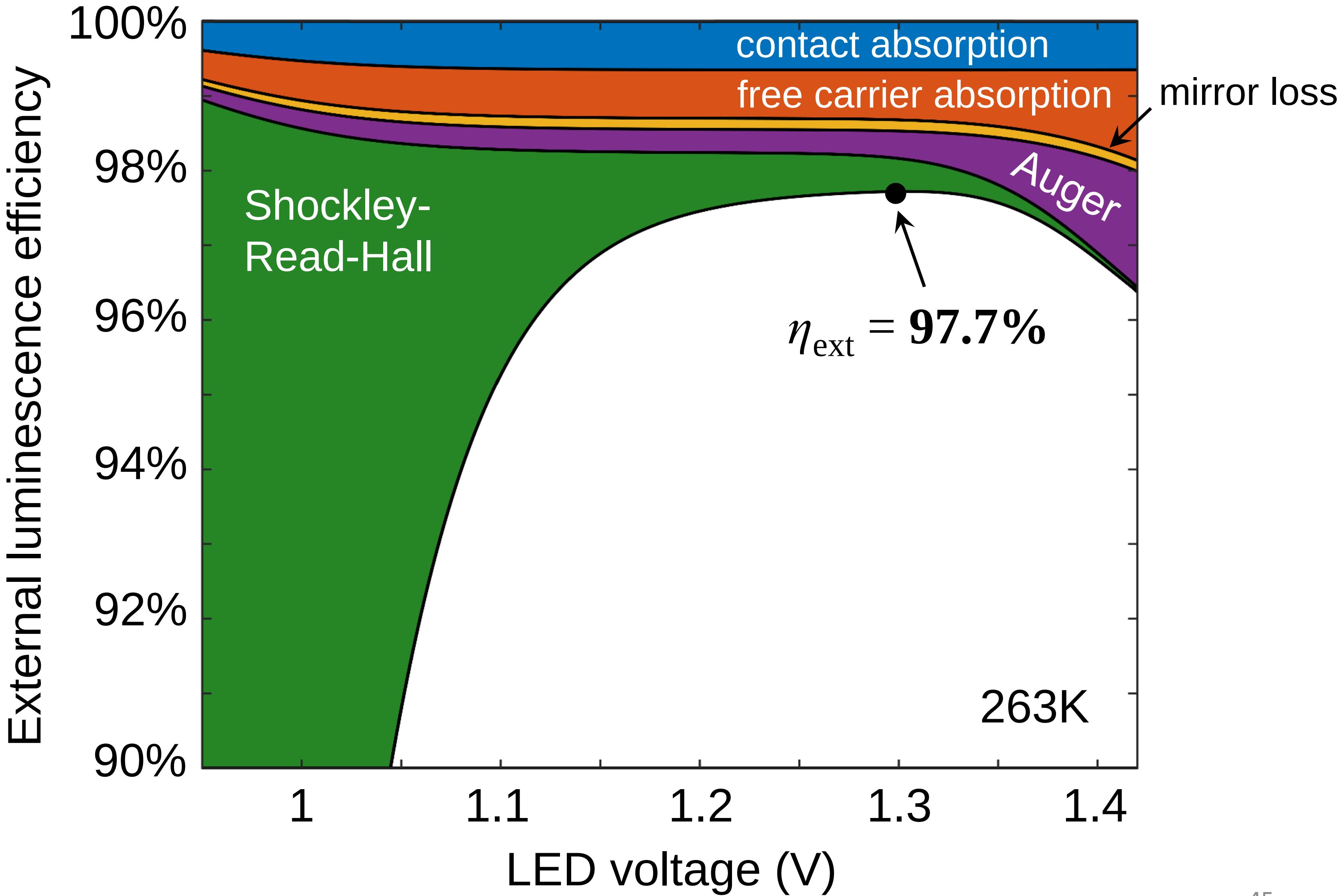
Composite rear reflector:
99.99% reflectivity

(angle-, energy-, polarization-averaged)

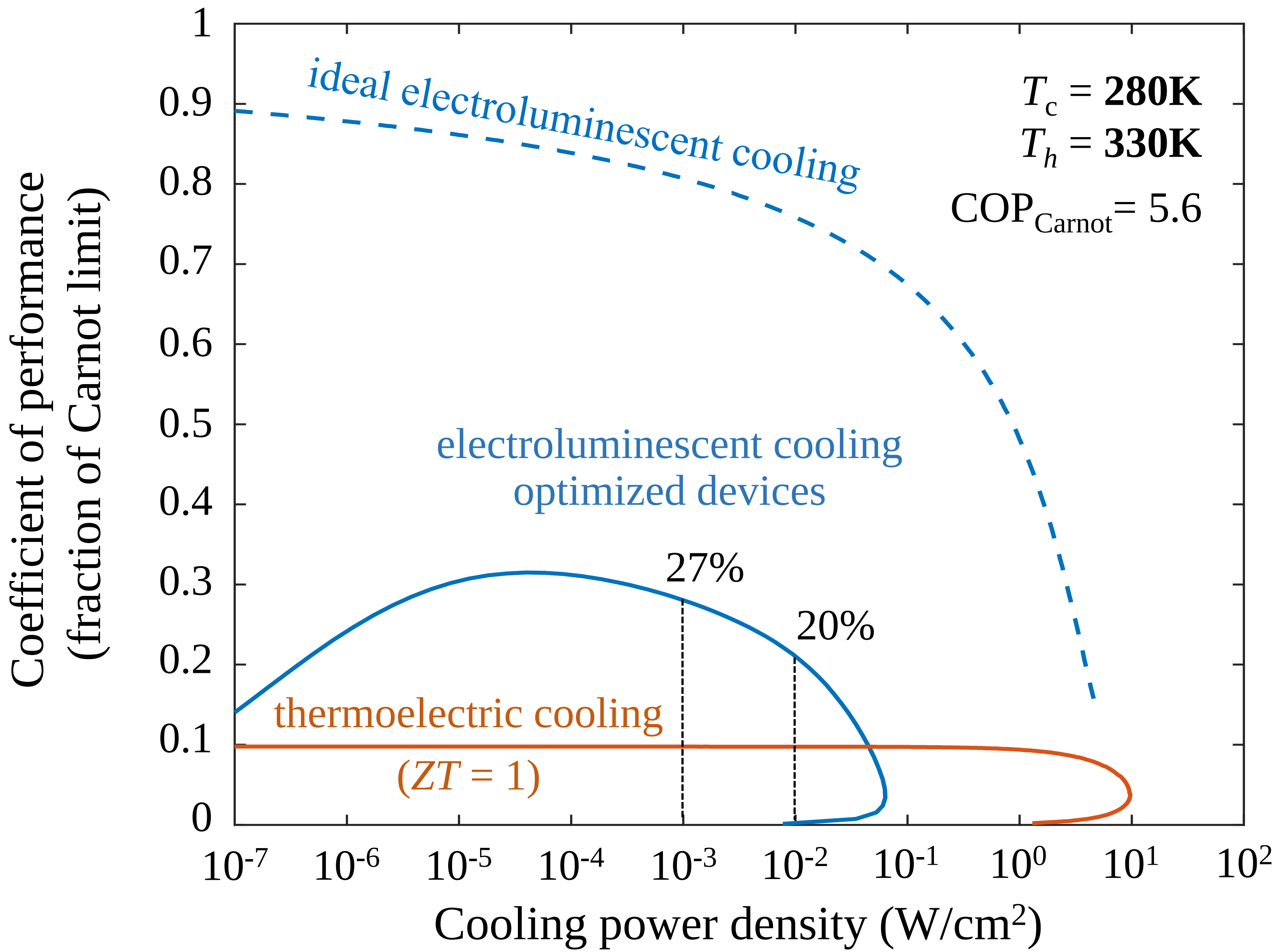


External luminescence efficiency

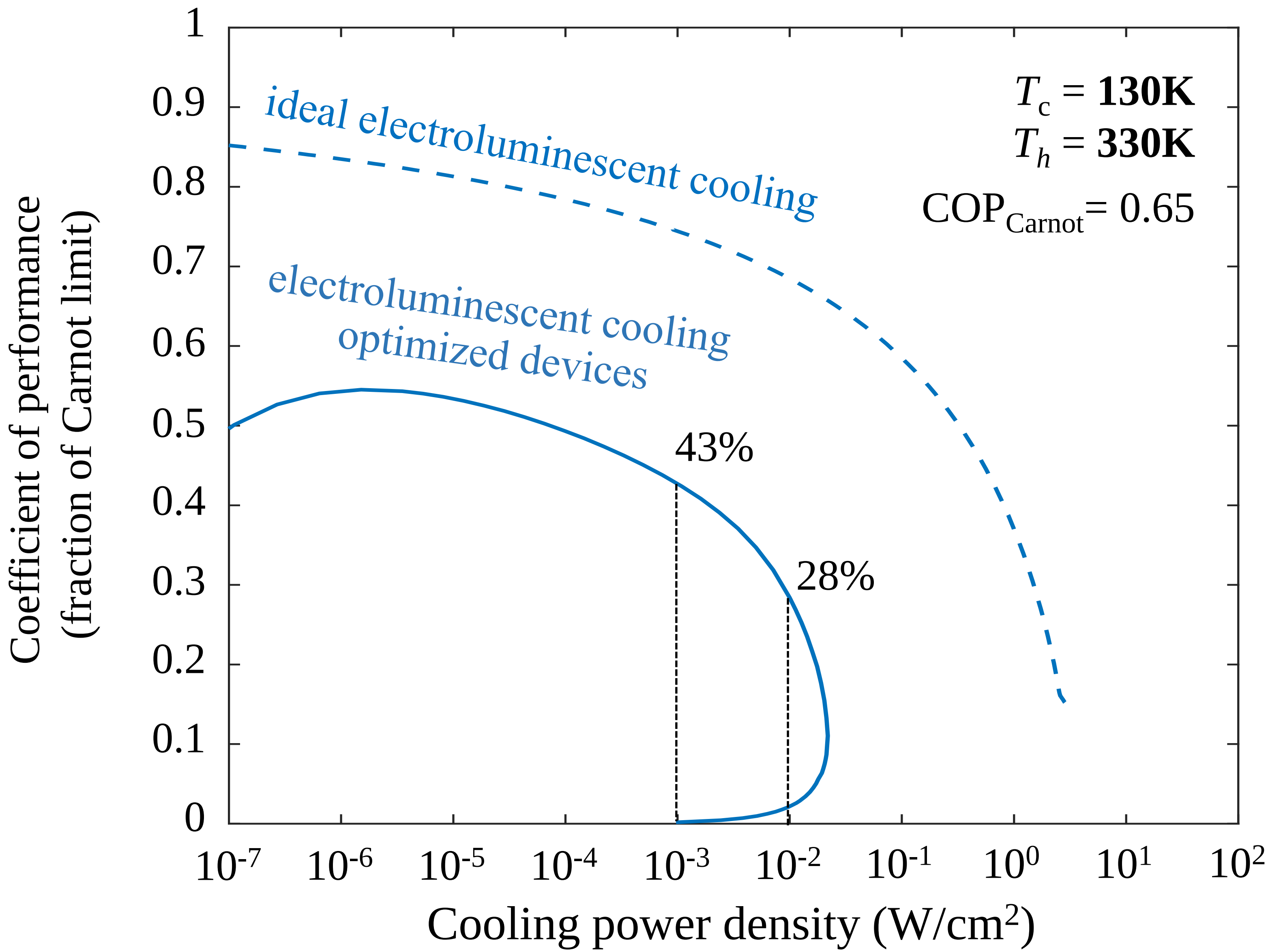
based on longest observed SRH lifetime, τ_{srh} = 21 μs

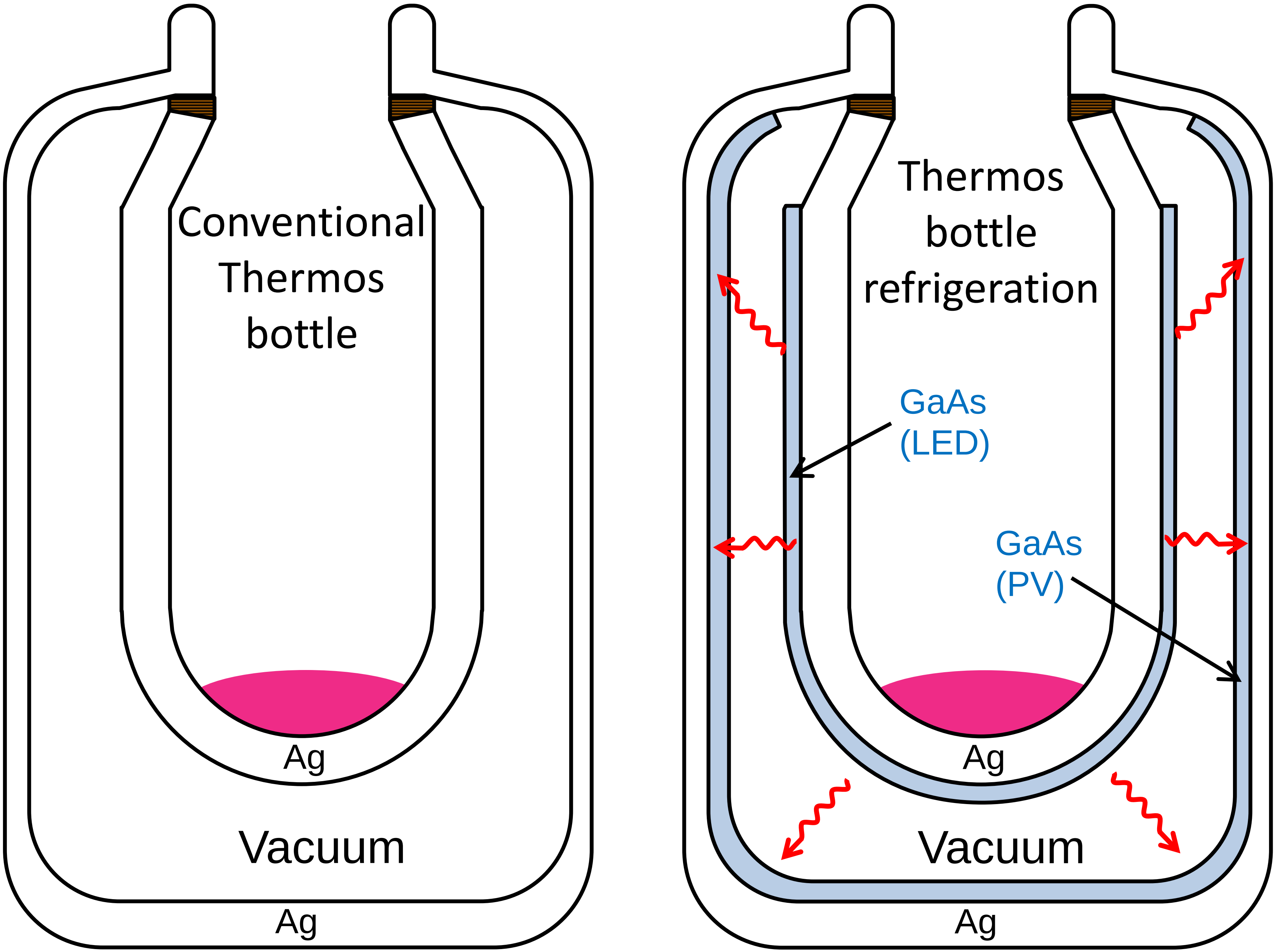


At room temperature, 2-3× more efficient than thermoelectrics



Improved cooling efficiency for cryogenic applications



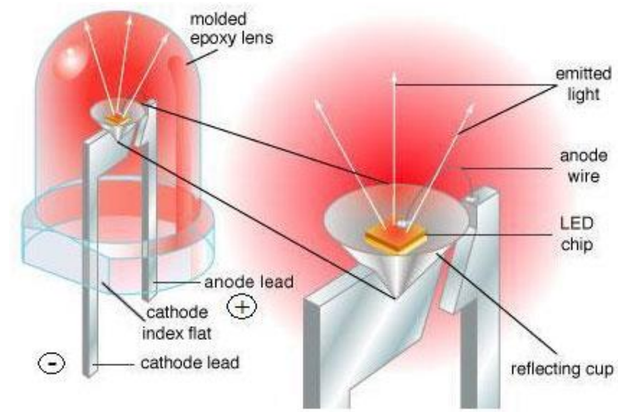


Conventional Thermos bottle
Ag
Vacuum
Ag
Thermos bottle refrigeration
GaAs (LED)
GaAs (PV)
Ag
Vacuum
Ag

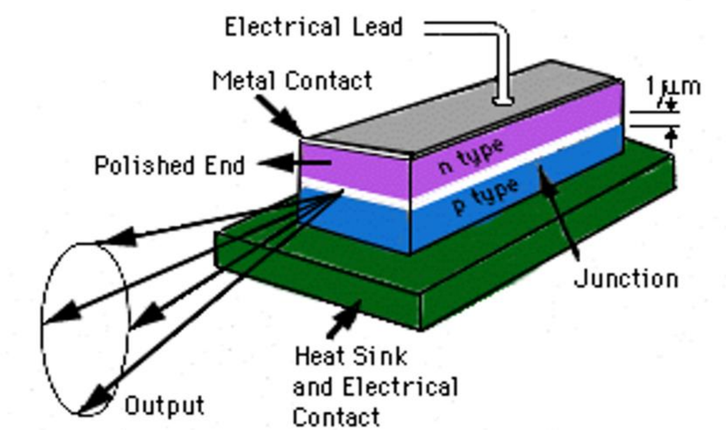
OPTO-ELECTRONICS

The Solar Cell,
the LED,
the semiconductor laser,----are all the same device:

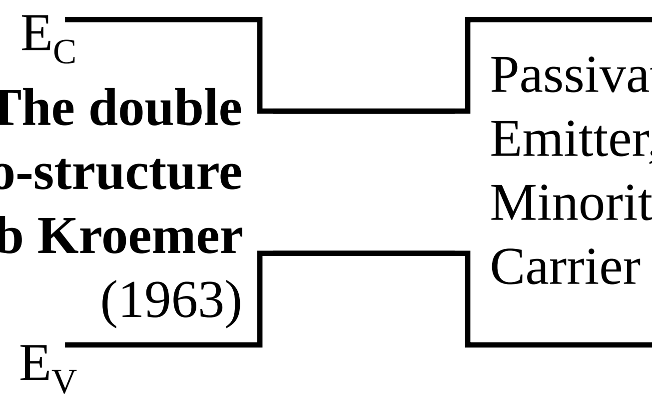
The Solar Cell



The LED



The Semiconductor Laser



The double hetero-structure Herb Kroemer (1963)

Passivated Emitter, or; Minority Carrier Mirror

Opto-Electronics, Is There Anything it Cannot Do?

<u>Application</u>	**<u>Required Internal Luminescence Efficiency</u>**
1. Internet Communication	~90%
2. GaN Lighting	~90%
3. Electricity Generation by Solar Panels	~99% (to break records)
4. Automobile Engine	~90%
5. Refrigeration	~99.9%