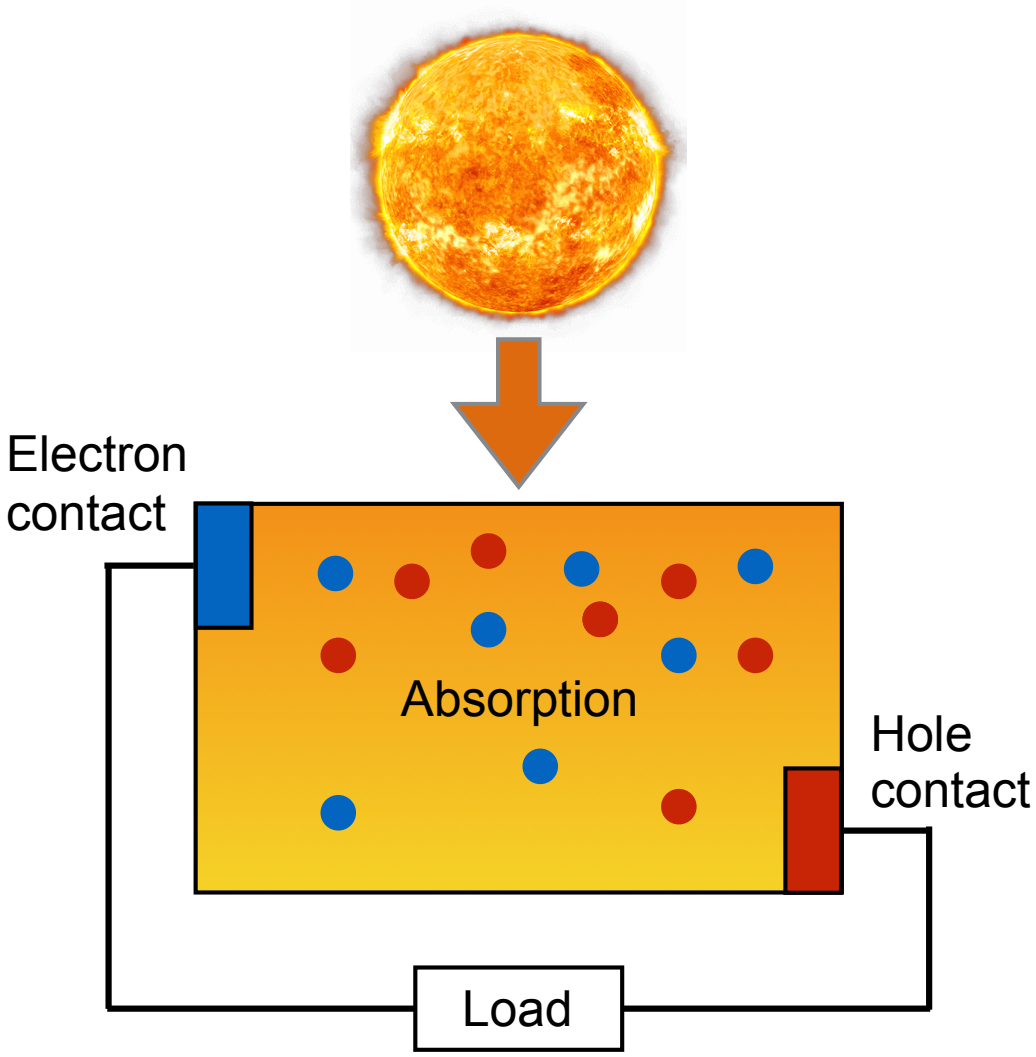
FFFF01 / FFFF05 vt 2019

Photovoltaics

Martin Magnusson
Solid State Physics

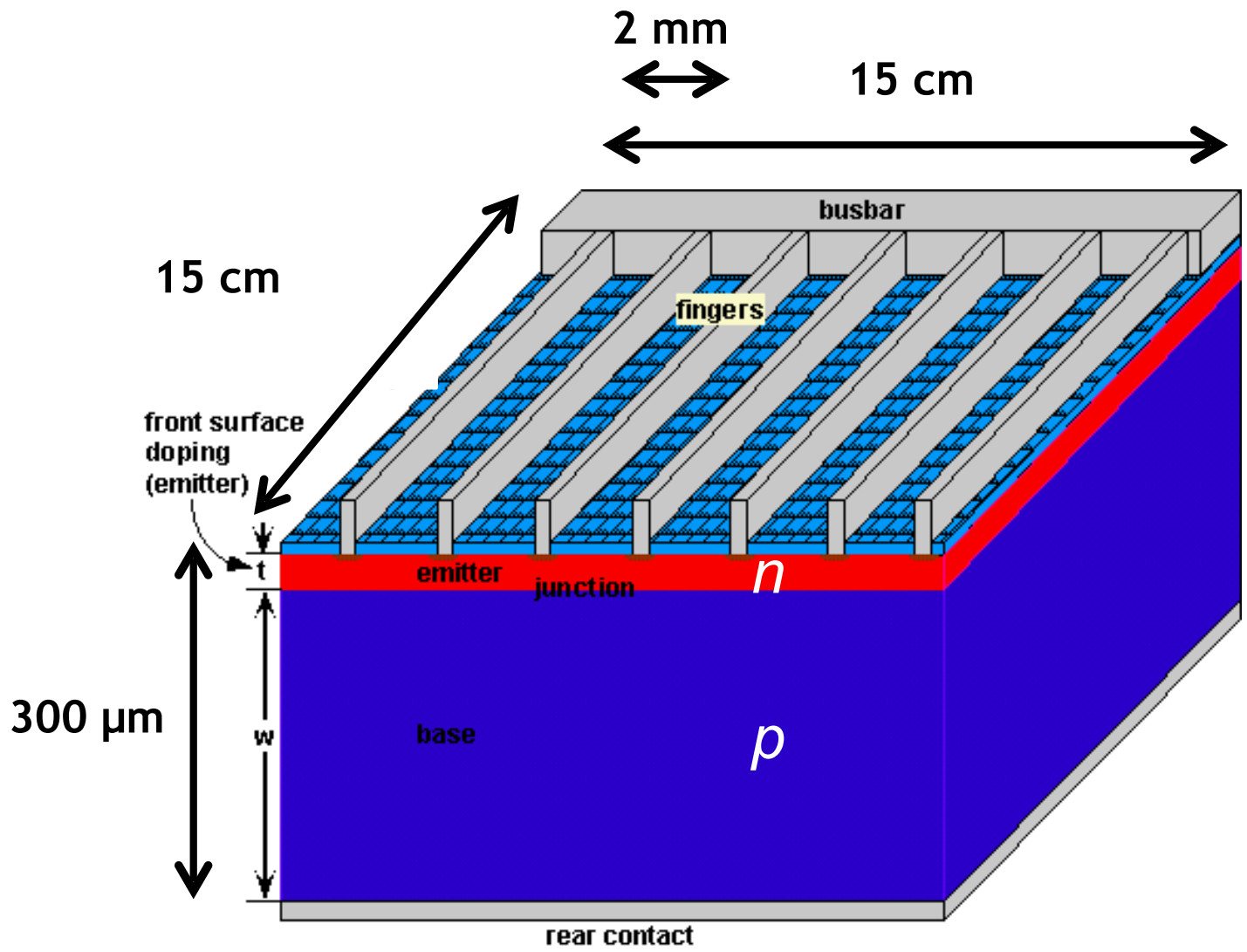
What is a solar cell, fundamentally?

- A material that can absorb light and form electrons and holes
  - –Semiconductor
- Selective contacts
  - –*p*- and *n*-doping
- Yields a potential
  - –Connected to a load

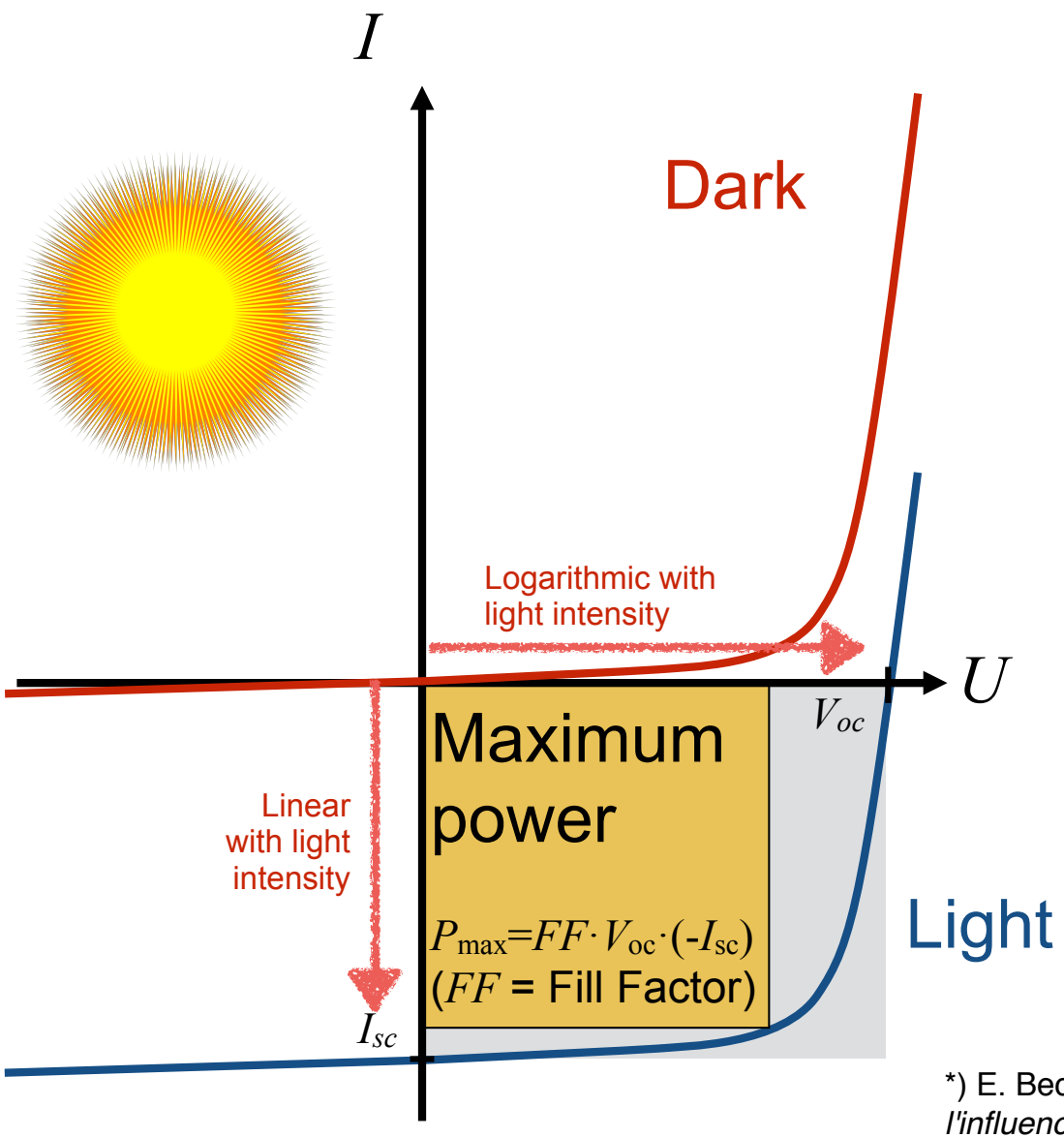


Typical Si solar cell

- Realized as a ***pn*-junction**
- We call the region above the junction **emitter**
- Region below junction is the **base**



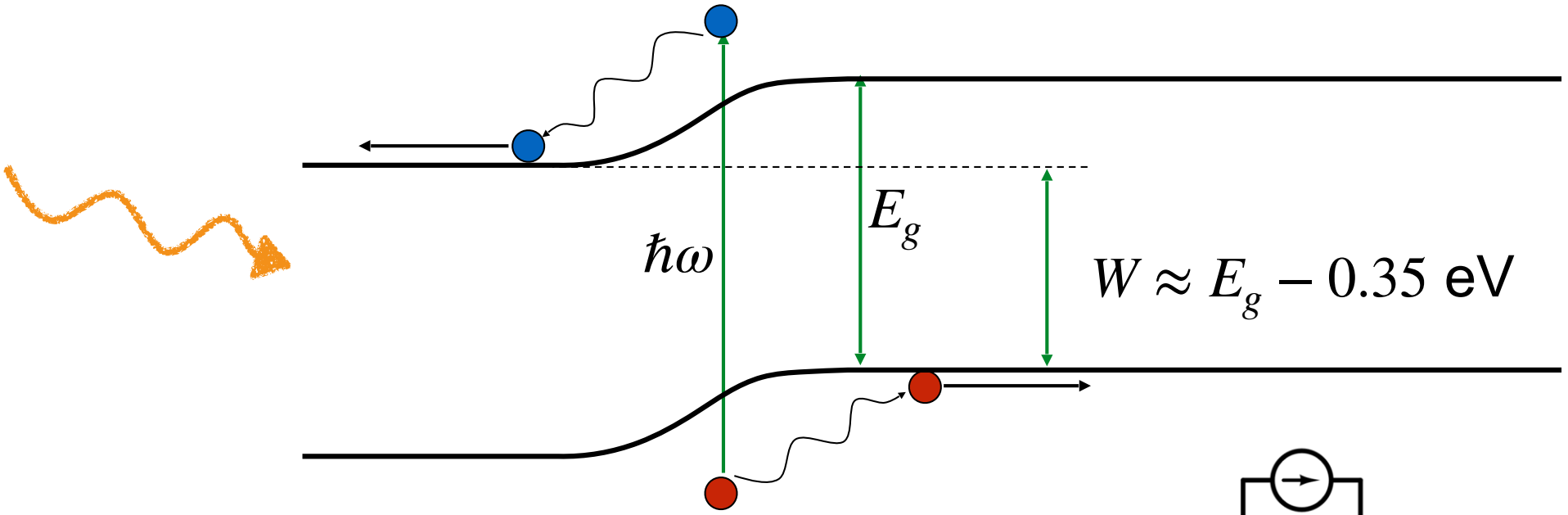
Solar cell principle



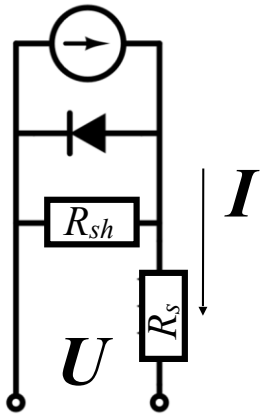
- Photogalvanic effect discovered by Becquerel in 1839*
- The modern silicon solar cell was developed by Bell Labs in 1954 to power remote phone exchanges
- The first application of Si PV was in 1958 to power satellites in orbit (Hoffman Electronics)

*) E. Becquerel, *"Mémoire sur les effets électriques produits sous l'influence des rayons solaires"*, Comptes Rendus **9**: 561–567 (1839)

Single junction



Equivalent circuit



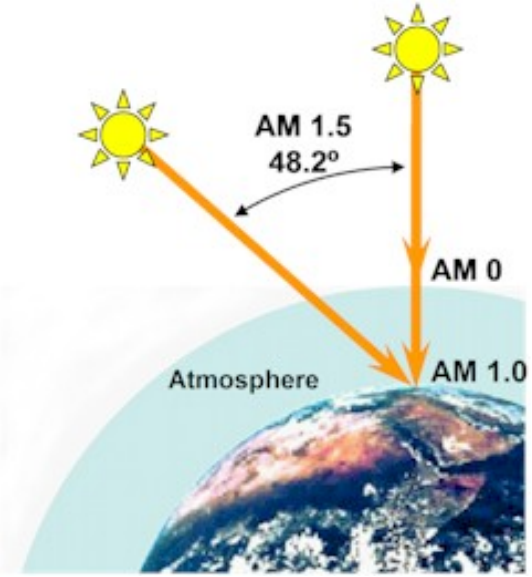
What makes a good solar cell?

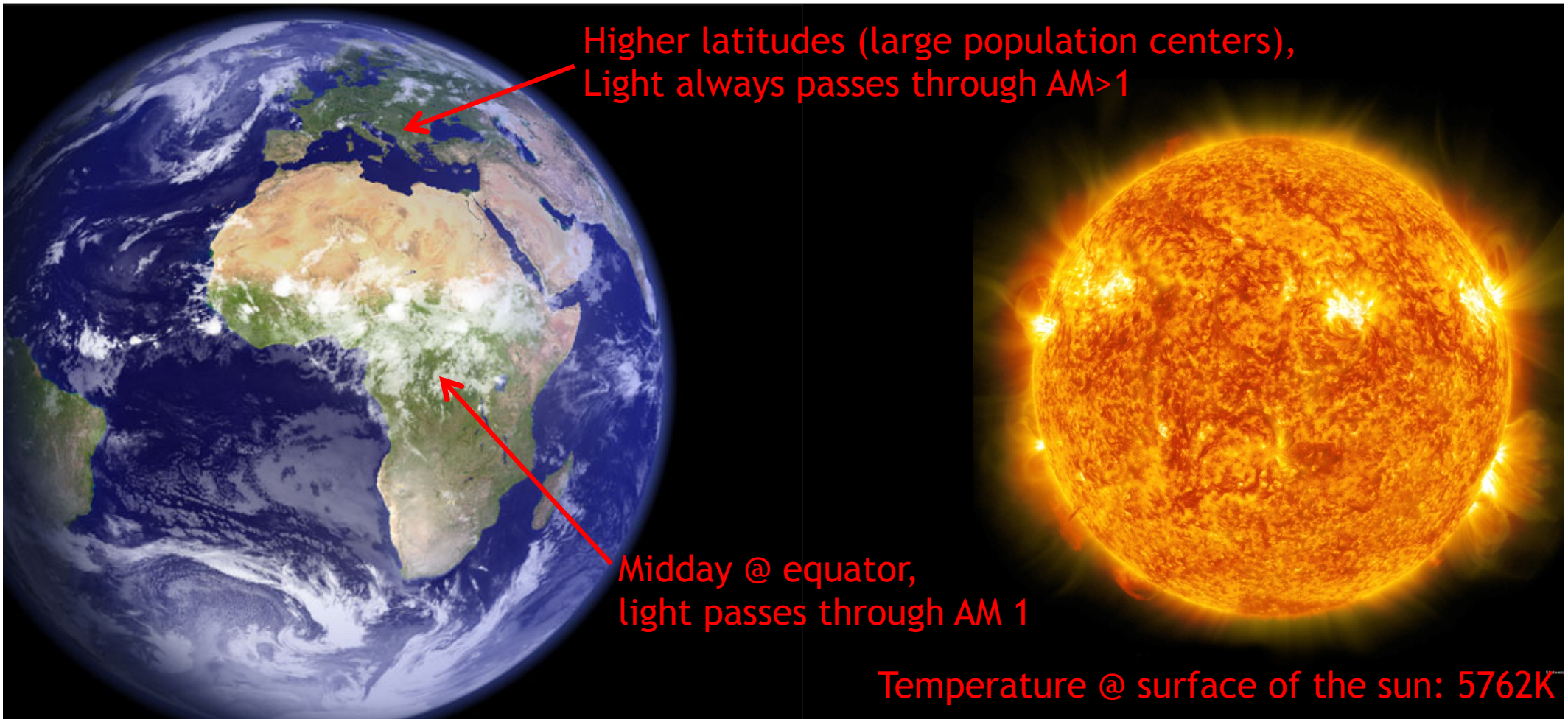
- High absorption
  - Small and direct bandgap
- Low optical losses
  - Reflection
  - Contact shadowing
- Low carrier losses
  - Bulk recombination
  - Surface recombination

- High voltage
  - Large bandgap
- Low electrical losses
  - Series resistance
  - Shunt resistance
- COMPROMISE!

Sunlight

- Solar spectrum: 5762 K black body radiation
- Power density in space, Air Mass 0 (AM0)
  - 136 mW/cm^2
- Power density on ground, Air Mass 1.5 (AM1.5)
  - 100 mW/cm^2, 1000 W/m^2

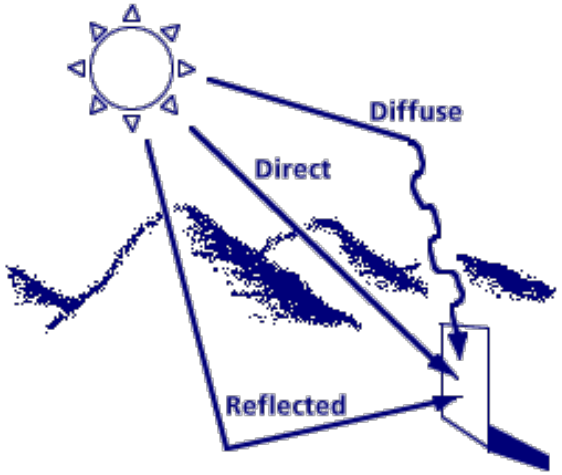


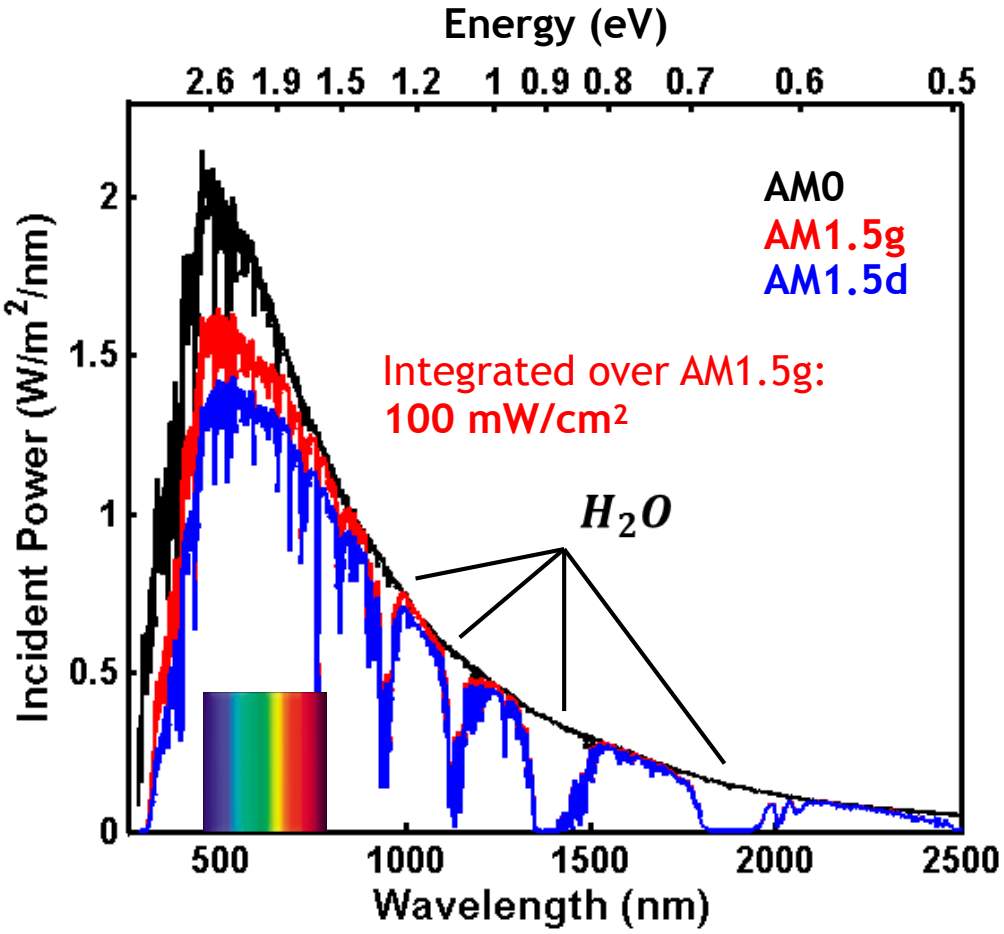


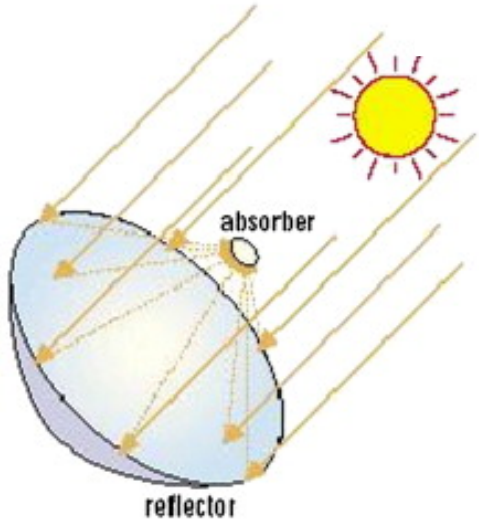
The solar spectrum

AM0: No atm. abs.
relevant for satellites
AM1.5g (global): Direct+diffuse light
Relevant for solar cells without concentrator
AM1.5d (direct): Only direct light
Relevant for solar cells with concentrator

Diffuse light
Part of the light comes from scattering in atmosphere

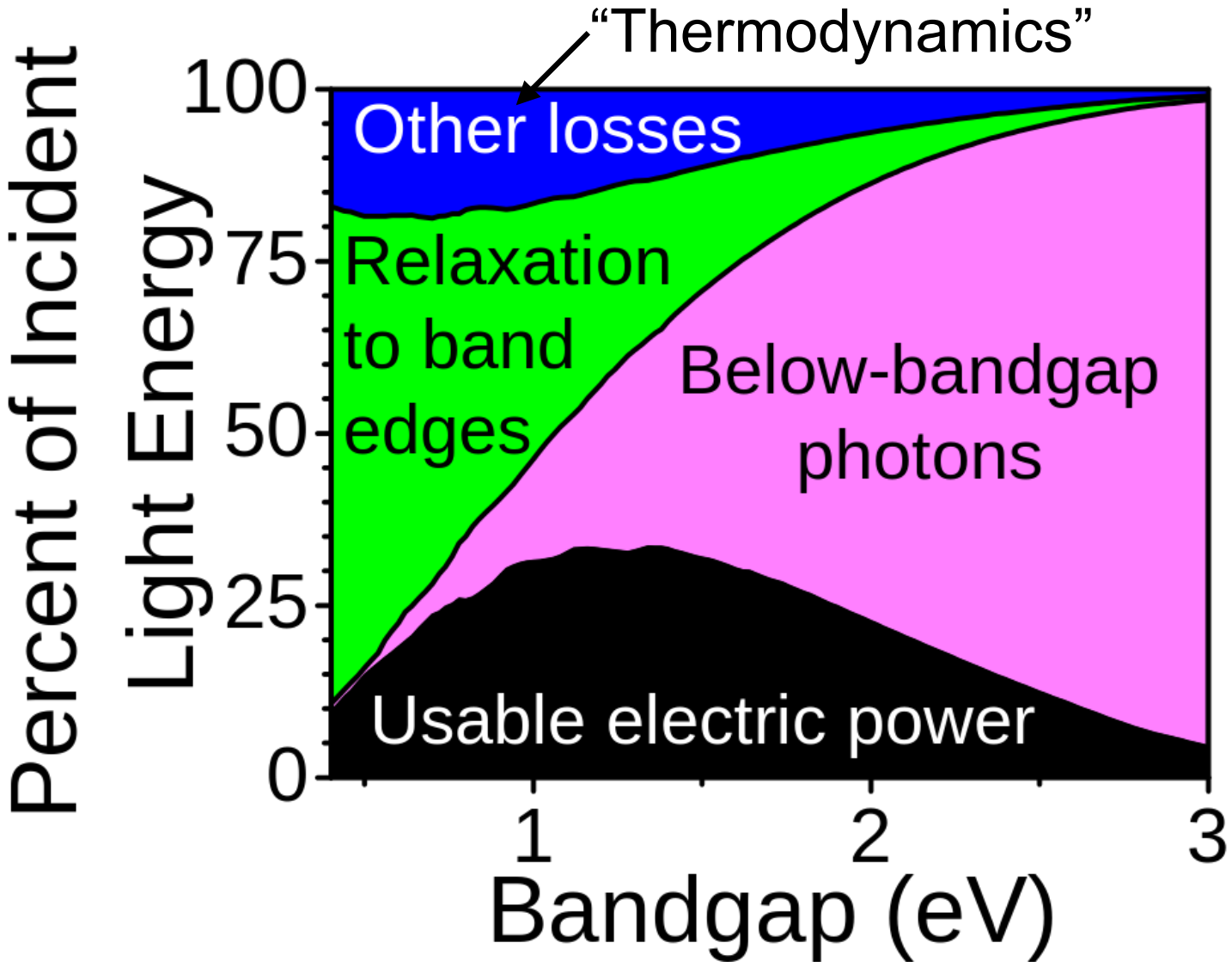






But it is only *direct light* that you can concentrate

Shockley–Queisser limit



W. Shockley and H. J. Queisser, "*Detailed Balance Limit of Efficiency of p-n Junction Solar Cells*", J Appl Phys **32**, 510 (1961)

JV curve for diode under illumination

$$J' = J_0(e^{qV/kT} - 1) - J_L$$

Consumed Power = $I \cdot V$

Generated Power = $-I \cdot V$

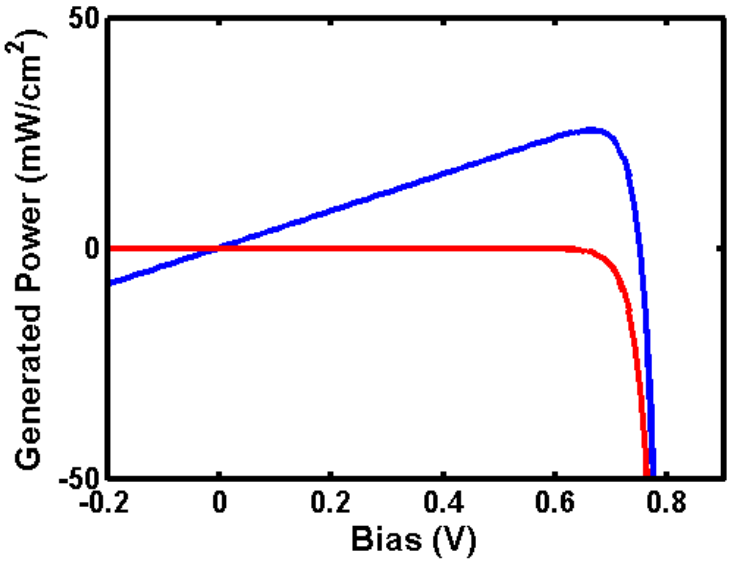
In the dark:

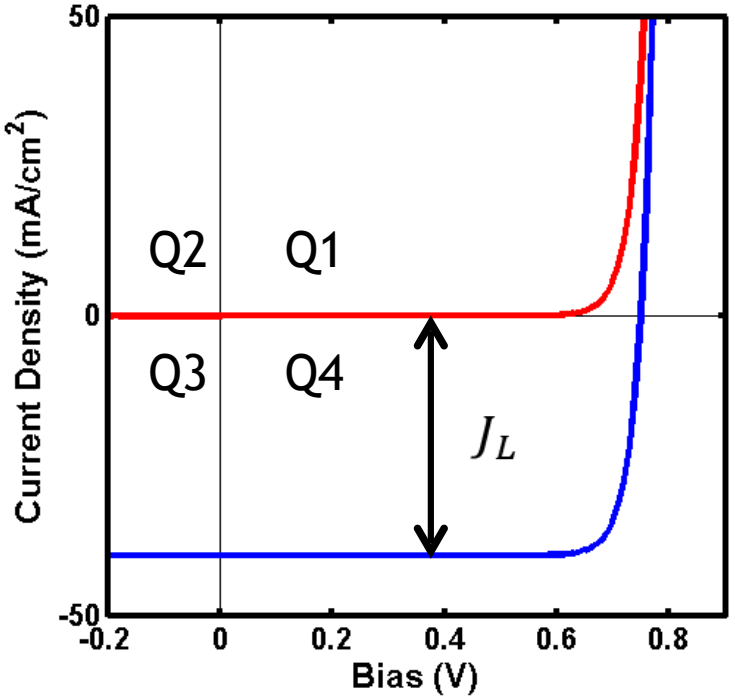
Power is never generated

Under illumination:

Power can only be generated in quadrant 4

From now on let's focus on this





JV curve for diode under illumination

Under illumination:

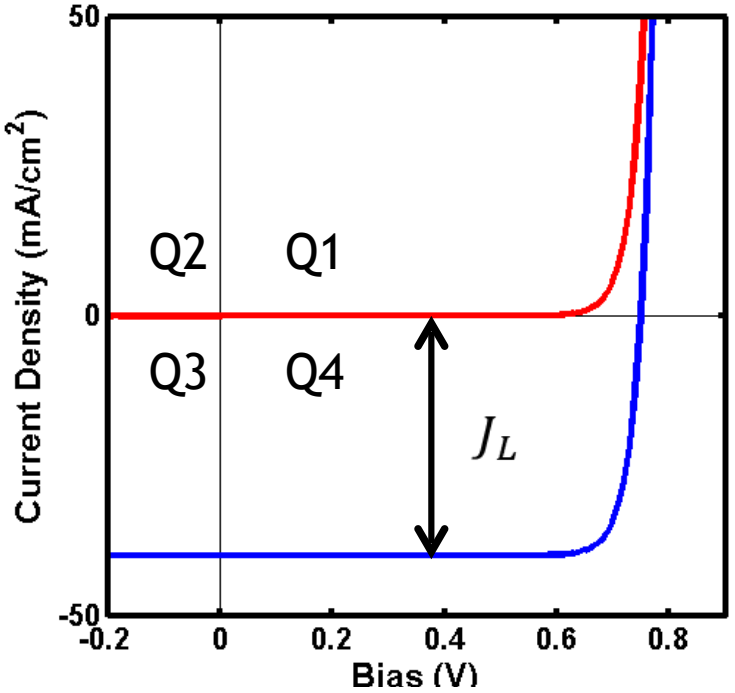
Power can only be generated in quadrant 4

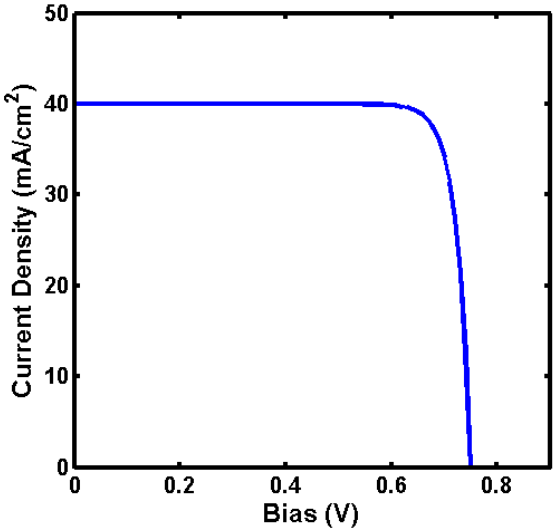
From now on let's focus on this

$$J' = J_0(e^{qV/kT} - 1) - J_L$$

Also, let's define the reverse current as positive

$$J = J_L - J_0(e^{qV/kT} - 1)$$





JV curve under illumination: Characteristics

Efficiency:

Maximum output power / Input power

$$\eta = \frac{J_{mp} V_{mp}}{P_{in}}$$

Under 1 sun illumination:

$$\eta = \frac{J_{mp} V_{mp}}{100\ \mathrm{mW/cm^2}}$$

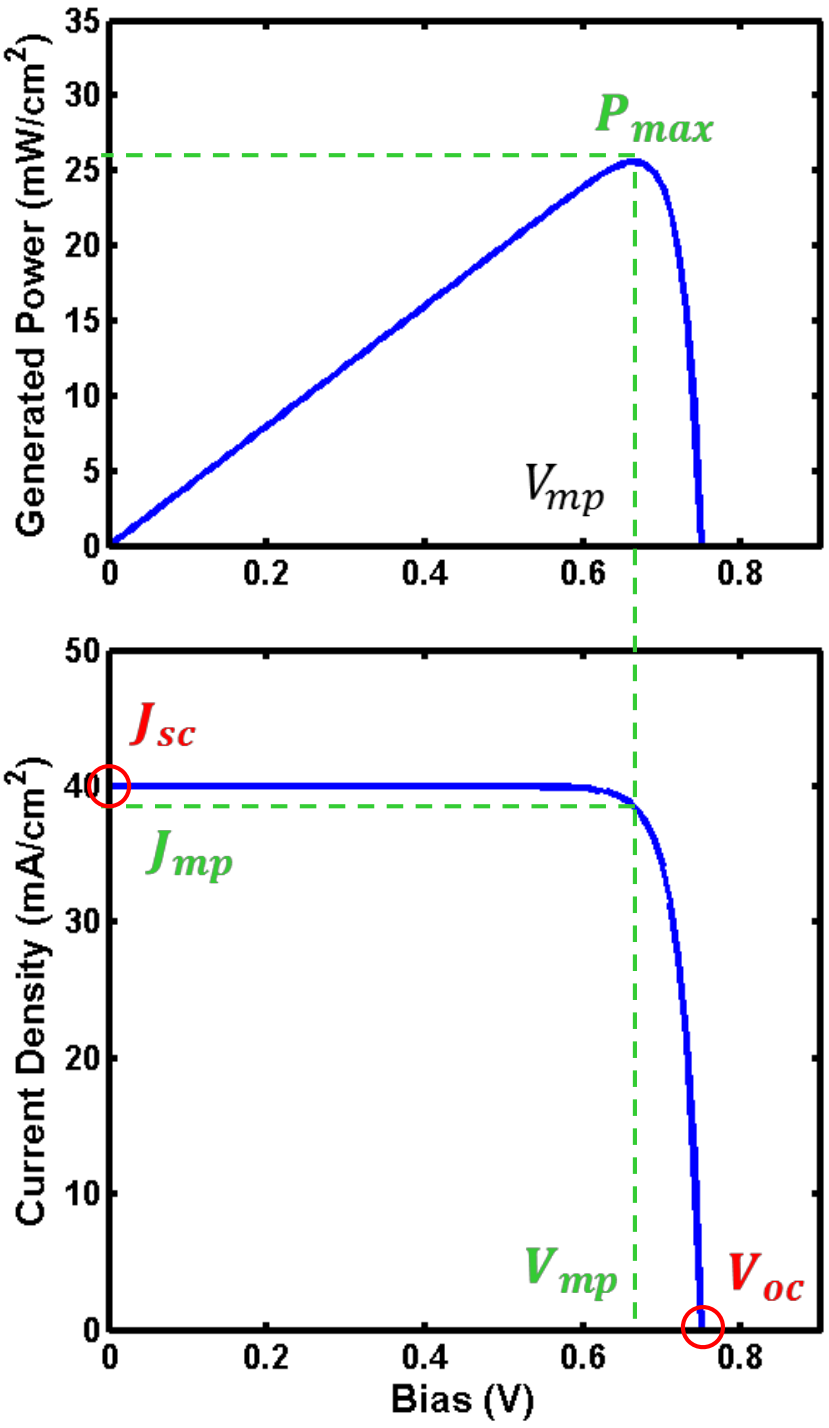
Input power must be measured accurately

Measurements at 25 °C for fair comparison

A solar cell with η = 20% gives

20 mW/cm² = 200 W/m²

1 Sun illumination



Power comparisons

- Toaster
  - (1 kW)

$$\frac{10^3\ \mathrm{W}}{0.020\ \mathrm{W/cm^2}} = 50\ 000\ \mathrm{cm^2} = 5\ \mathrm{m^2}$$

- Cell phone
  - (full sun, 1 h)

$$\frac{3000\ \mathrm{mAh} \cdot 4\ \mathrm{V}}{20\ \mathrm{mW/cm^2} \cdot\ 1\ \mathrm{h}} = 600\ \mathrm{cm^2} = 6\ \mathrm{dm^2}$$

  - (indoor)

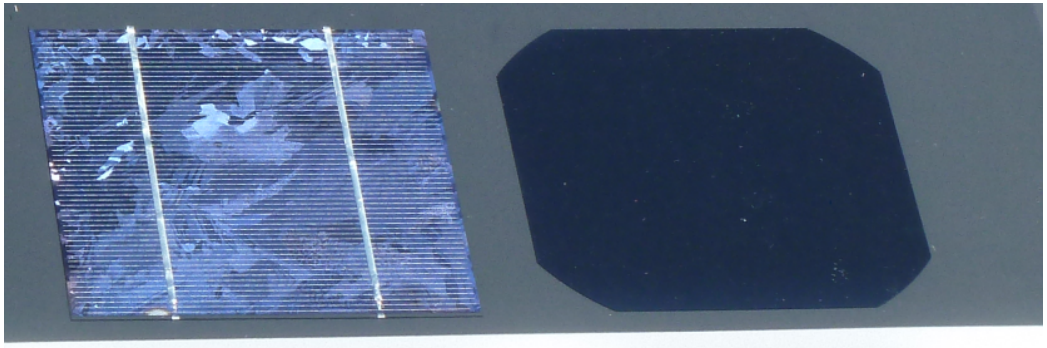
$$\frac{120\ 000\ \mathrm{lux}}{500\ \mathrm{lux}} = 240\ \mathrm{times\ longer} = 10\ \mathrm{days!}$$

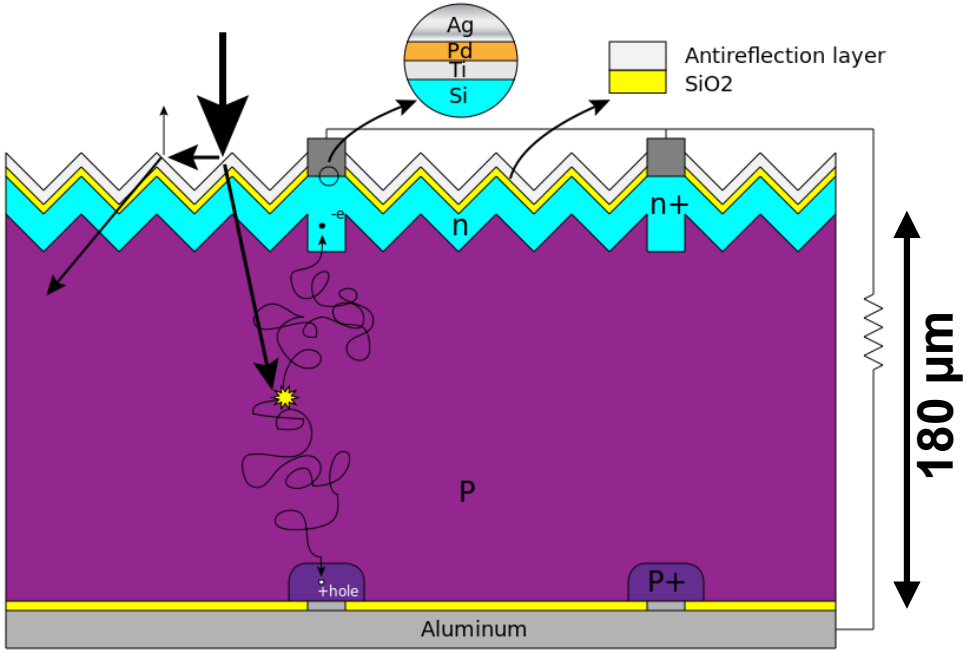
- Car
  - (100 hp)

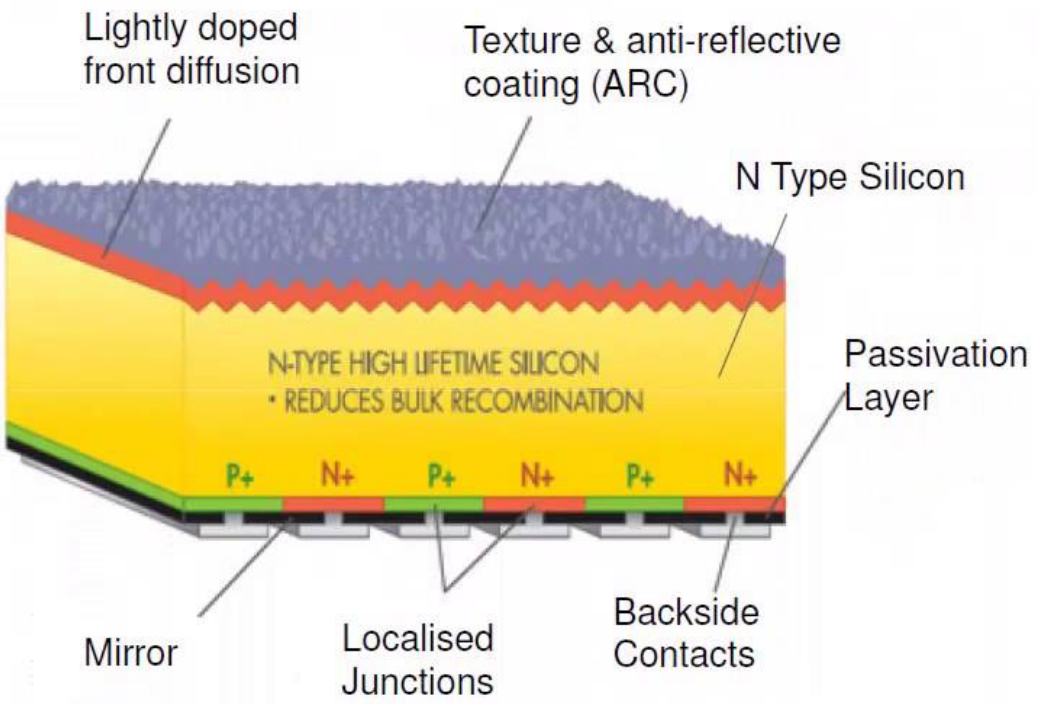
$$\frac{100 \cdot 735\ \mathrm{W}}{0.020\ \mathrm{W/cm^2}} = 3.7 \cdot 10^6\ \mathrm{cm^2} = 370\ \mathrm{m^2}$$

Si solar cells

Poly-Si High end

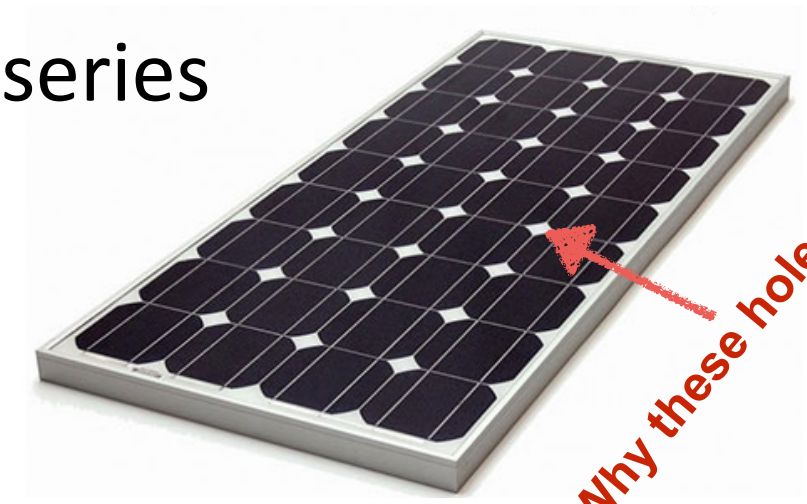






Solar modules

- Cells connected in series
  - –Raise voltage, reduce current
    - Reduce resistive losses in cables
  - –What happens if a bird shades one of the cells?
    - Risk of damage as the shaded cell is driven in reverse
    - Use protection diodes

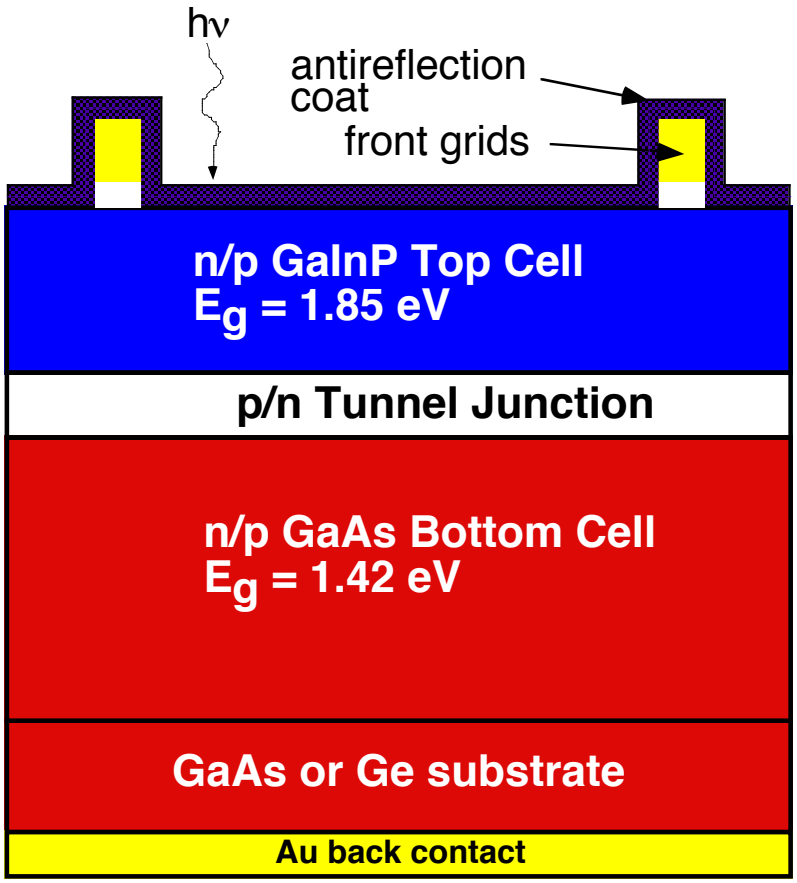


Mono-crystalline

Poly-crystalline

GaInP/GaAs/Ge multi-junction solar cell

- Invented at NREL 1984
- Used in space
  - Mars rovers Spirit and Opportunity
  - 80 % of new satellites
- Highest efficiency on the market today
- Also used in concentrators



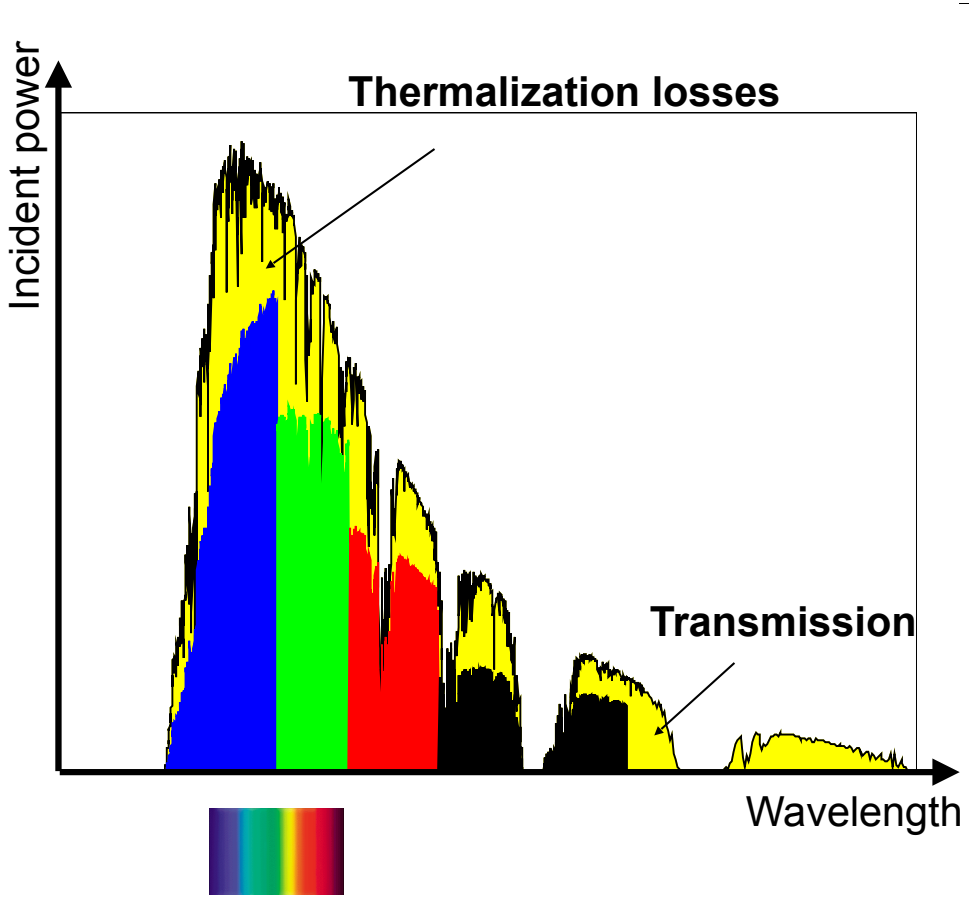
Concentrators

- Multijunction solar cells are expensive!
  - To get your money's worth use concentrator
- Up to 1000 Suns (but normally 300–500)
- Can only collect the direct component of the light
  - You need to track the sun with a motorized stage
- Efficiency increases with increasing power since you saturate non radiative recombination centres
  - At some point it decreases again due to heating

Single- and multi-junction solar cells

- Theoretical best cases

- Example: silicon *pn*-junction
  - up to 31 % efficiency at 1 sun
- Example: four junctions
  - 49 % efficiency
- Concentration
  - 59 % at 1000 suns
  - Current increases linearly with light intensity
  - $U(C) = U(1\ \text{sun}) + kT/\text{e} \cdot \ln(C)$
    $C = 1000$ gives $\Delta U = +0.18$ V
    (for each sub-diode!)
- 36 junctions gives 72 % efficiency

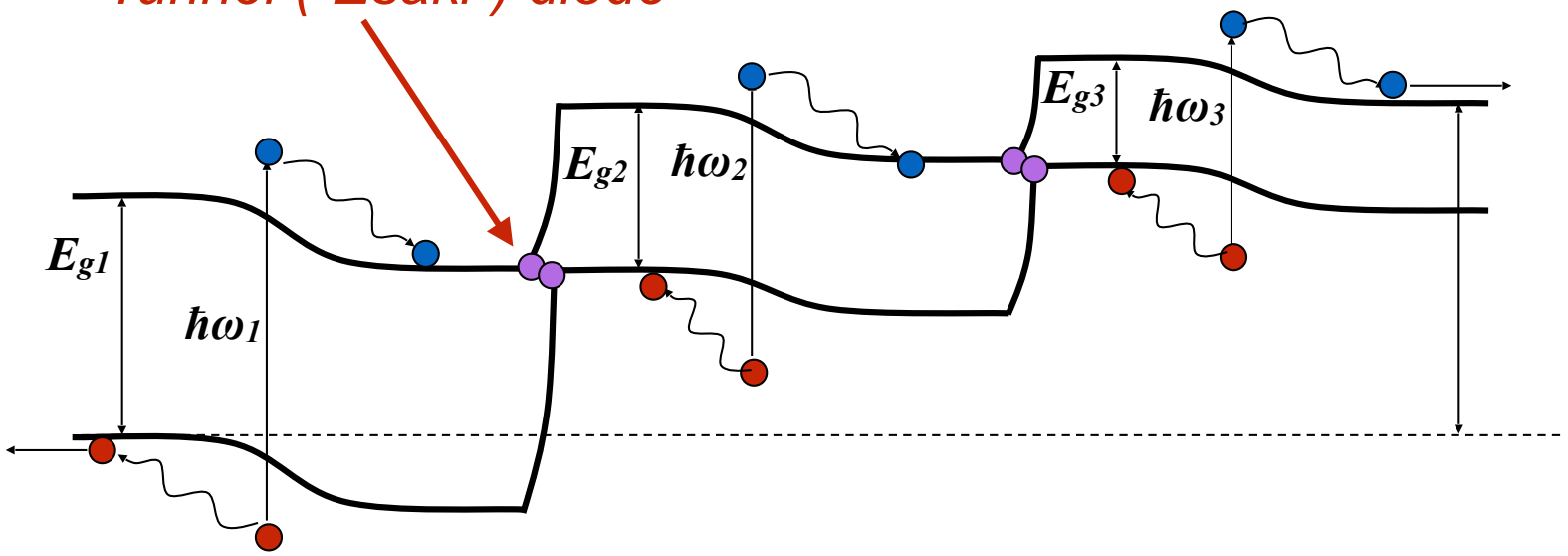


C. H. Henry, "*Limiting efficiencies of ideal single and multiple energy gap terrestrial solar cells*", J Appl Phys **51**, 4491 (1980)

Triple junction

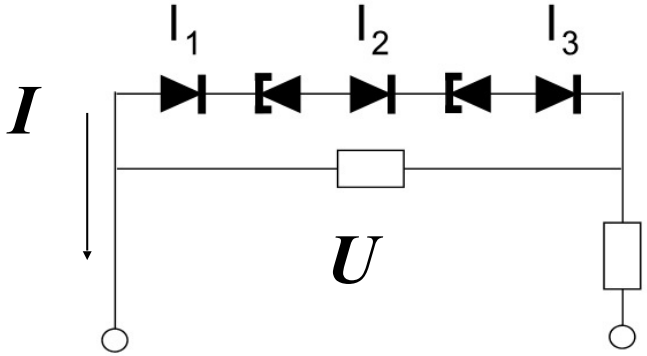
Voltage addition, current reduction

$$W \approx \sum E_g - 3 \cdot 0.35 \text{ eV}$$

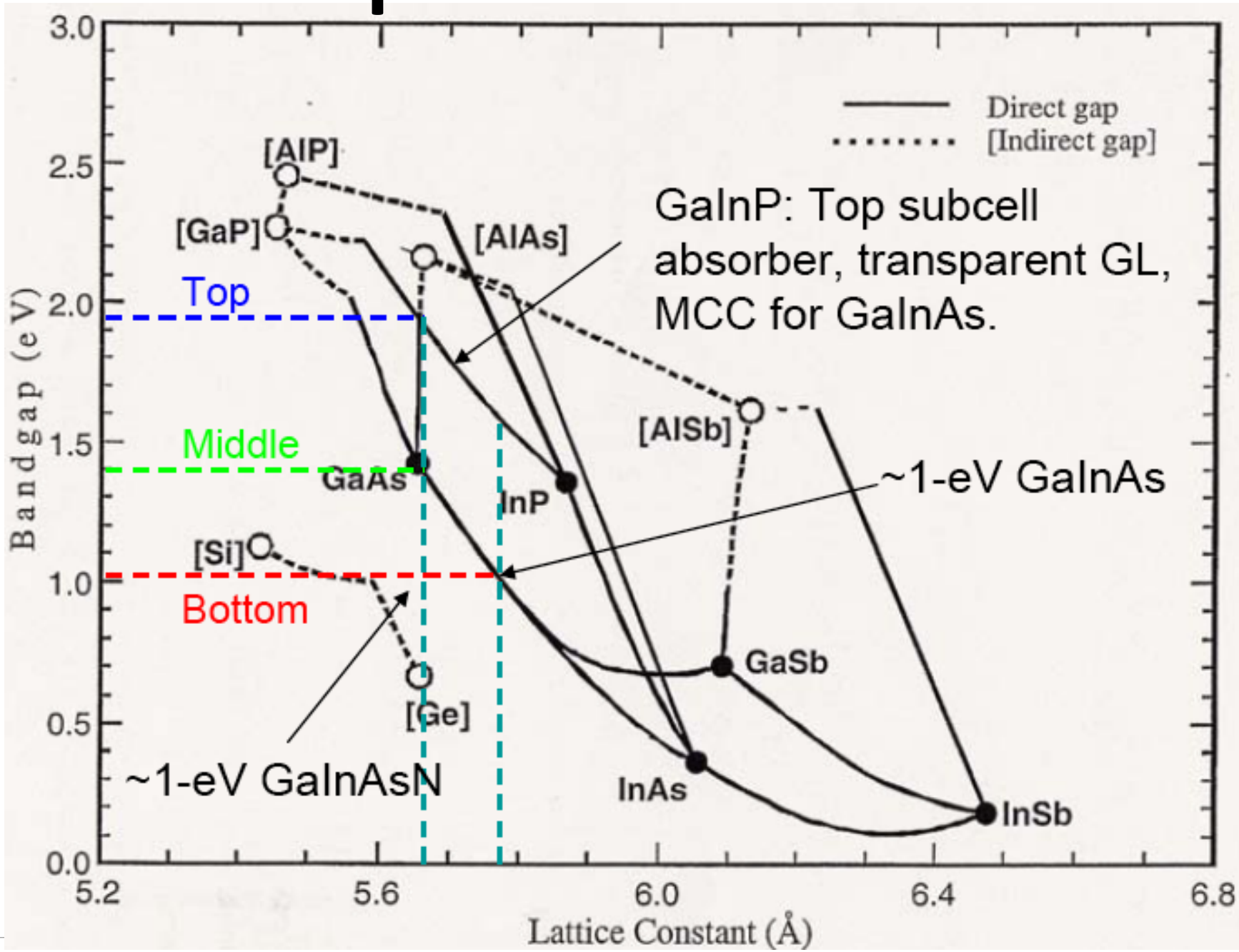


Equivalent circuit

Current matching!

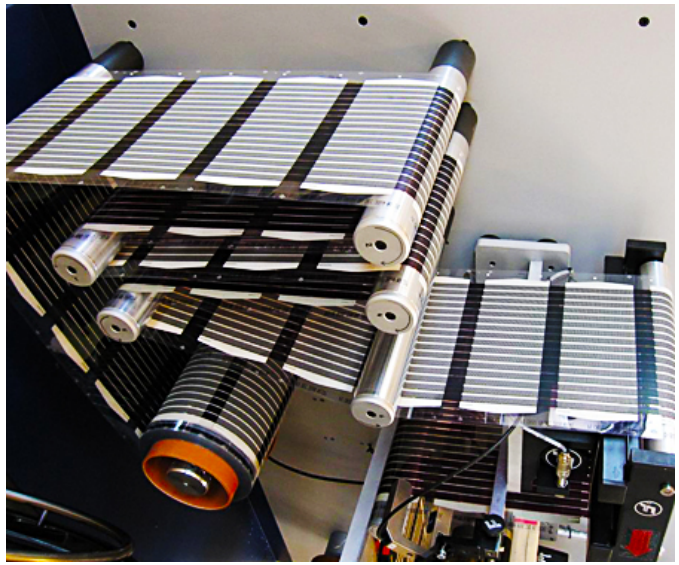


Triple cell materials



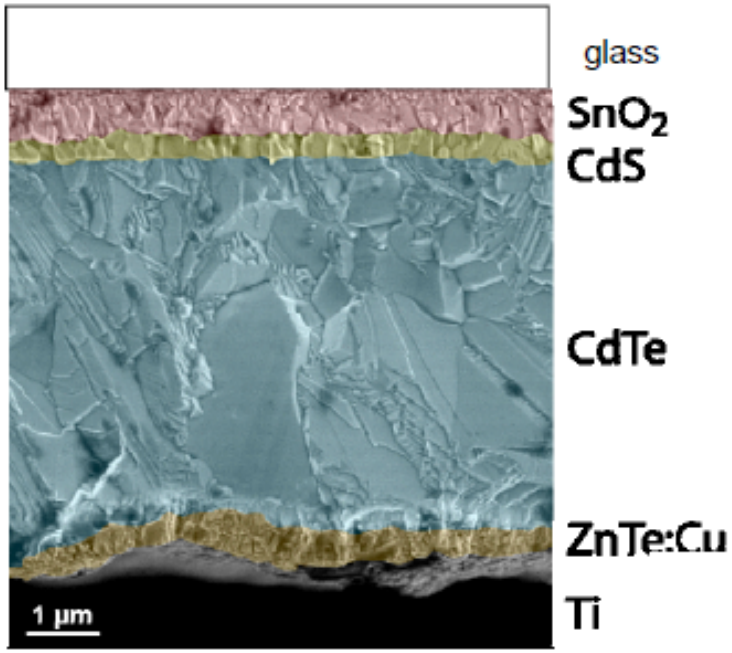
Thin film solar cells: evaporated/ sputtered material

- A thin film of (direct bandgap) semiconductor material is deposited by low-cost methods
- Evaporate or sputter at room *T*
  - Polycrystalline but still ok η
- Less material is used (a few μm instead of 100s of μm thick)
- Can be flexible
  - Roll-to-roll production possible
  - Easy integration onto roofing material



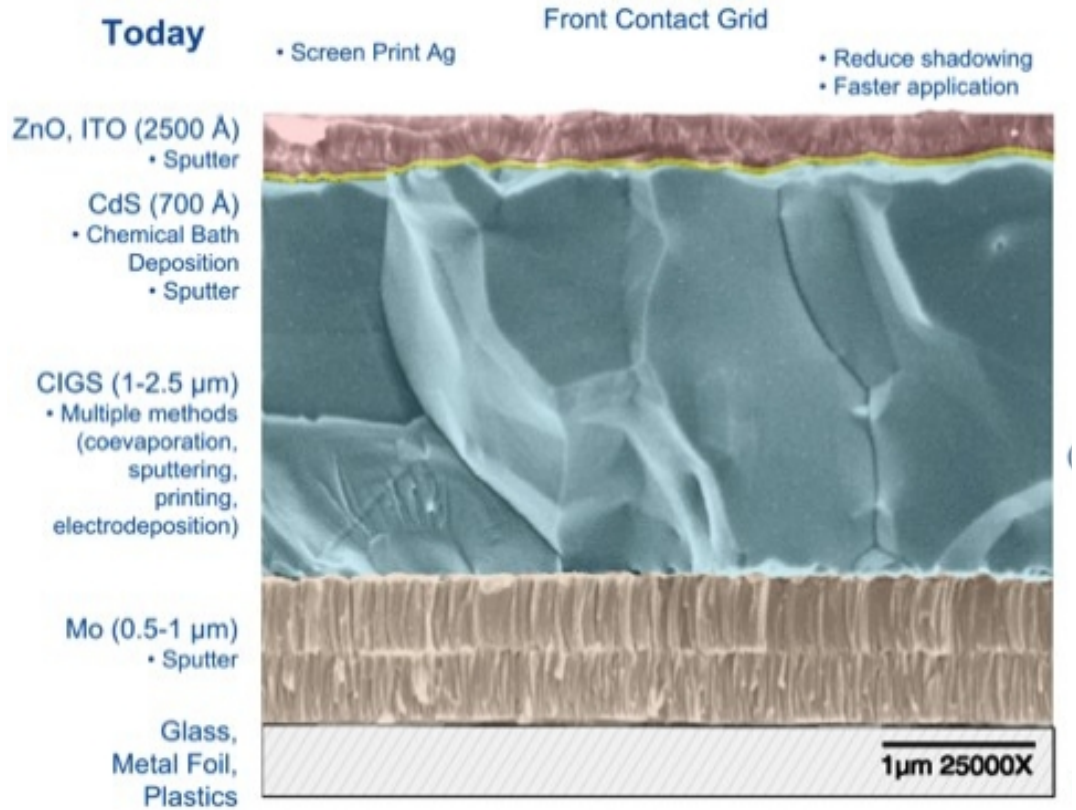
Thin film solar cells: evaporated/ sputtered material

Cadmium Telluride
- Direct bandgap, 1.45 eV
- Good efficiency (Record: 18.5 %)
- Long term stability (20 years)

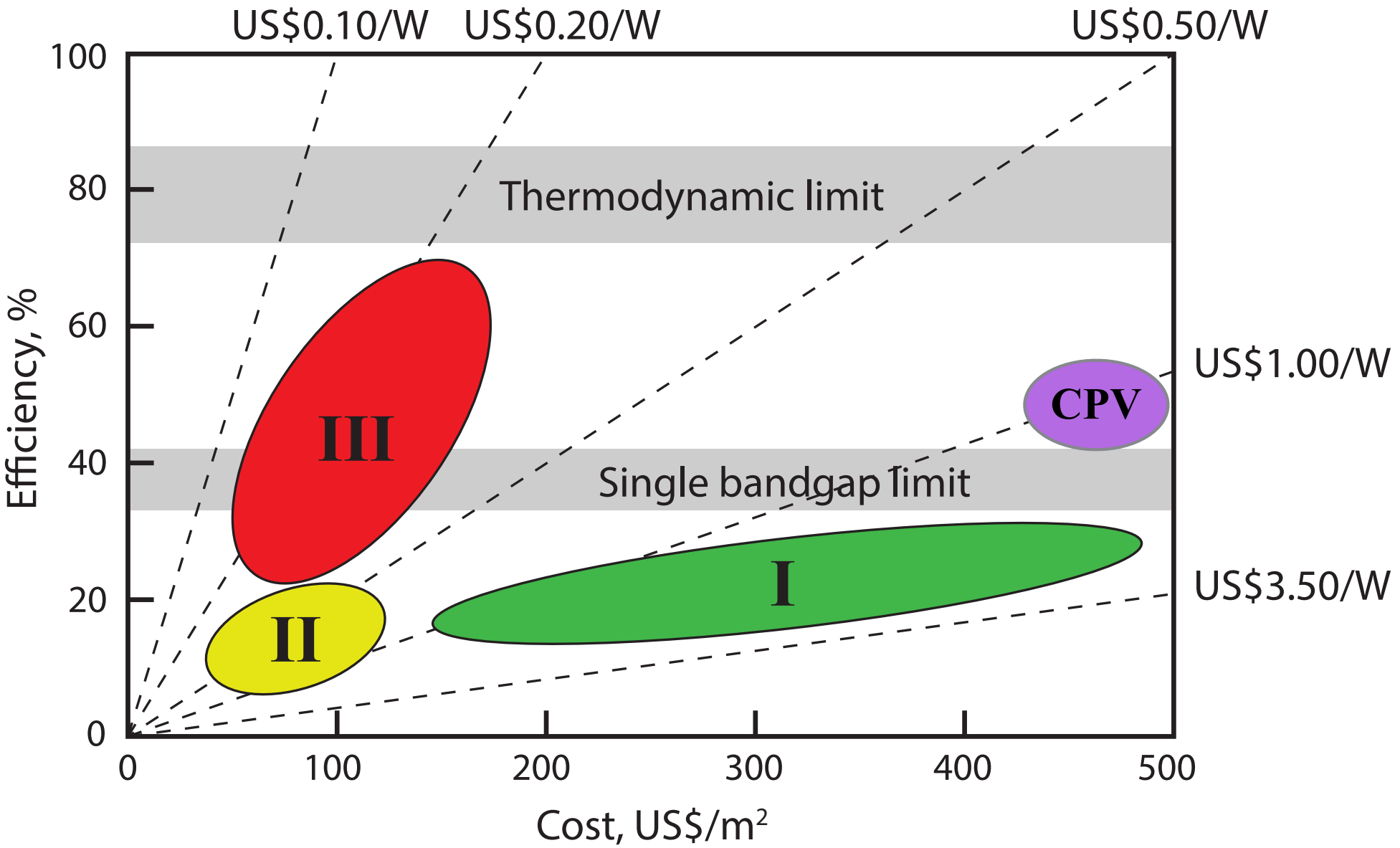


CdS/CdTe

Copper Indium Gallium Selenide (CIGS)
- Direct bandgap, 1.02-1.65 eV
- Good efficiency (Record 21.7%)
- Stability issues



PV technology generations



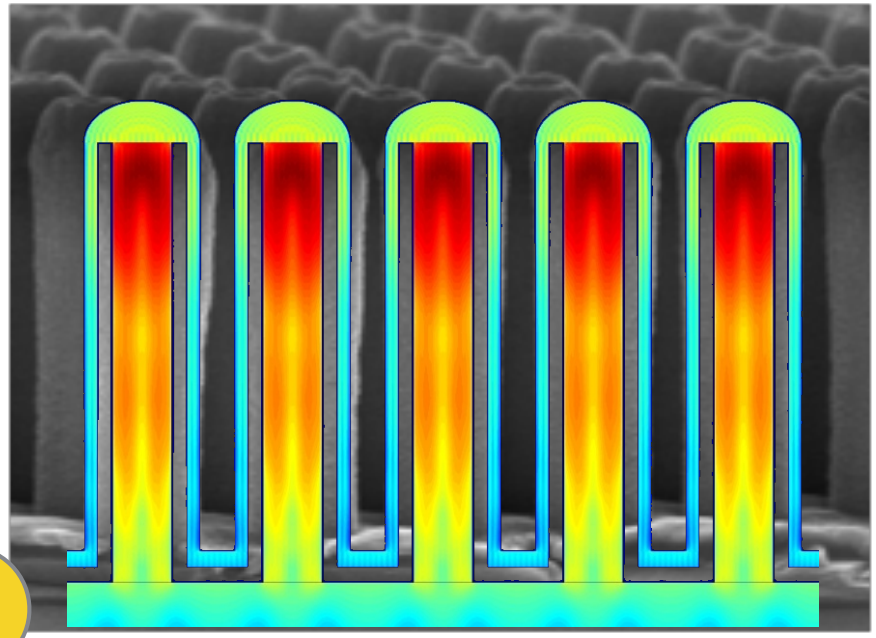
Top competing technologies

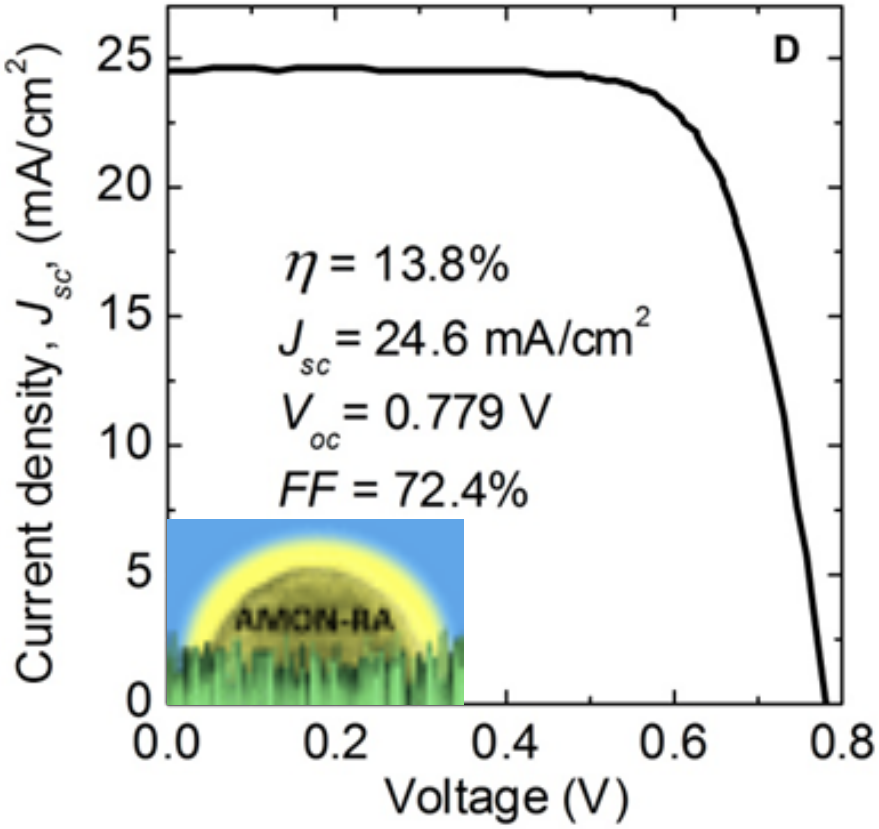
Technology	Lab efficiency	Module efficiency	Approximate market share	Important player
Polycrystalline Si	21.9 %	11 – 16 %	70 %	“China”
Single crystalline Si	25.0 %	14 – 18 %	16 %	Sharp
High-end Si	26.7 %	21 %	8 %	SunPower
Poly-CdTe	21.0 %	16 %	4 %	First Solar
Poly-CuInGaSe	21.7 %	13 %	2 %	Nanosolar
Concentrator III–V tandem	46 %	38.9 %	0.1 %	Soitec
Lift-off thin film GaAs	28.8 %	?	-	Alta Devices
Nanowire III–V	15.3 %	?	-	Sol Voltaics

Nanowire solar cells

Wires capture light efficiently
- 12 % surface coverage
- 83 % of the current from a planar cell

Minimal materials use
- ~ 1 g/m²
- 1000 × less than a Si cell
- 20 × less than a planar III–V cell





J. Wallentin *et al.*, "InP Nanowire Array Solar Cells Achieving 13.8% Efficiency by Exceeding the Ray Optics Limit", Science **339**, 1057 (2013)

I Åberg *et al.*, "A GaAs Nanowire Array Solar Cell With 15.3% Efficiency at 1 Sun" IEEE J Photovolt **6** 185 (2016)

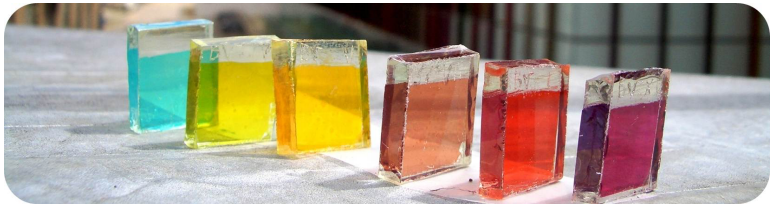
II

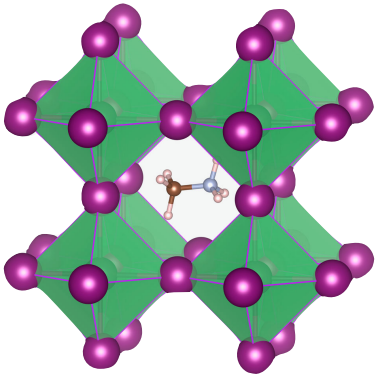
VINNOVA

SOLVOLTAICS®

Other low-cost concepts

- Organic solar cells (e.g. Olle Inganäs, LiU)
  - –Very low cost, low efficiency, low durability
  - –Indoor, clothing…
- Dye-sensitized solar cells (Grätzel cells)
  - –TiO_2 particles + organic dye molecules
  - –Colourful transparent panels
- Perovskites (e.g. Eva Unger, LU)
  - –Organic–inorganic hybrid material
  - –High efficiency, but so far unstable in air
  - –Potential for multijunction





Other Shockley–Queisser beating concepts

- Photon upconversion
  - –Addition of two or more low energy photons to emit one high-energy photon
- Intermediate bands
  - –Similar to upconversion, but with energy band in middle of bandgap
- Photon downconversion (heat or fluorescence)
  - –Convert all light to heat, then use energy filtering to control mission of thermal energy, coupled to optimal IR PV cell
  - –Or, convert one high-energy photon to several low-energy ones
- Hot carrier collection
  - –Try to collect carriers before they thermalize, e.g. via quantum dots