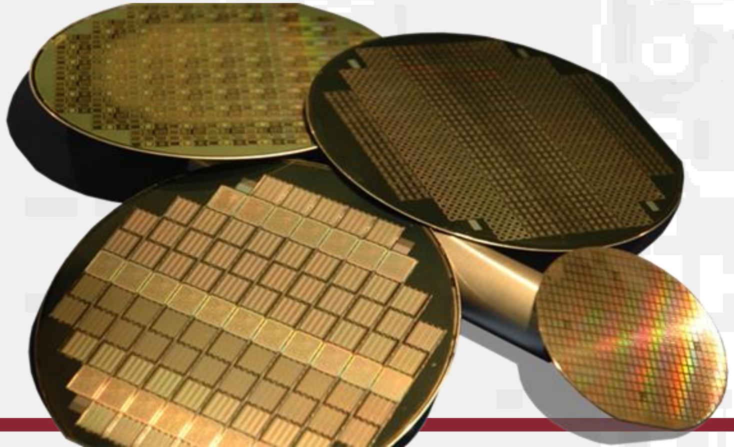
Budapest University of Technology and Economics
Department of Electron Devices

Solar cell working principles



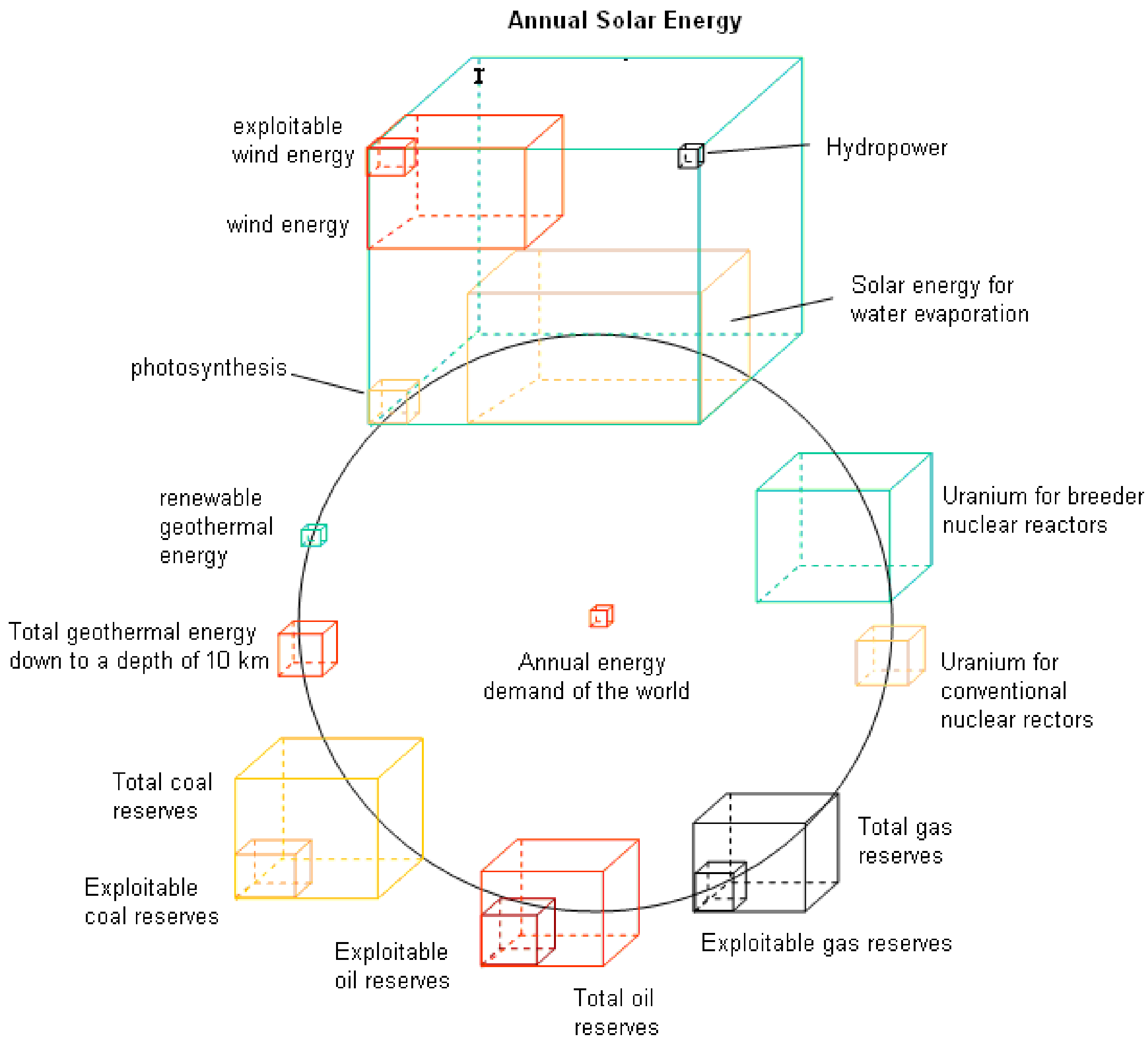
Balázs Plesz

http://www.eet.bme.hu

Motto

"One day, a person would no more think about buying a house without solar than they would a house without plumbing."

– Bob Clearman, Dow Chemical


Annual Solar Energy
exploitable wind energy
wind energy
Hydropower
Solar energy for water evaporation
photosynthesis
renewable geothermal energy
Uranium for breeder nuclear reactors
Total geothermal energy down to a depth of 10 km
Annual energy demand of the world
Uranium for conventional nuclear rectors
Total coal reserves
Exploitable coal reserves
Total gas reserves
Exploitable gas reserves
Exploitable oil reserves
Total oil reserves

Photovoltaic systems

- Stand alone or grid connected systems?
  - Reliability
  - Reconsideration of the tasks of the grid
  - A single plant for every user?
- Tracking or fixed Installation?
  - Higher energy gain with tracking
  - Higher costs
  - Shading
  - Higher maintenance

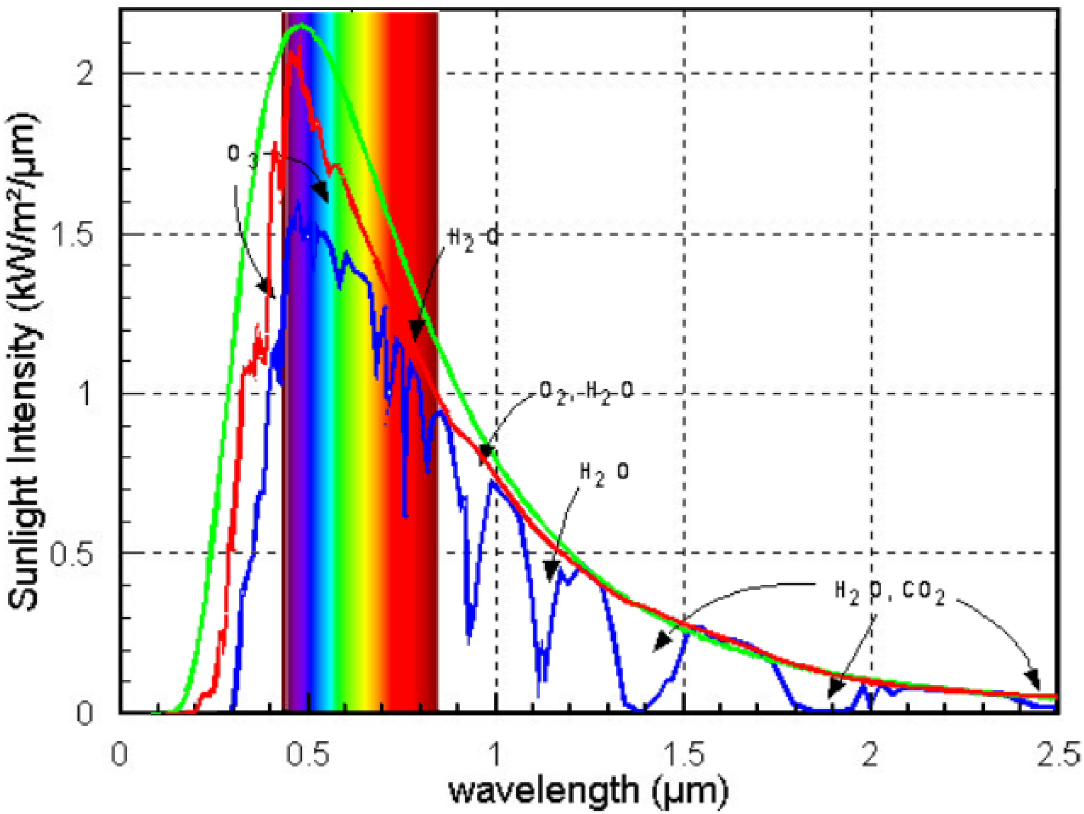
Dilemma of solar cell usage

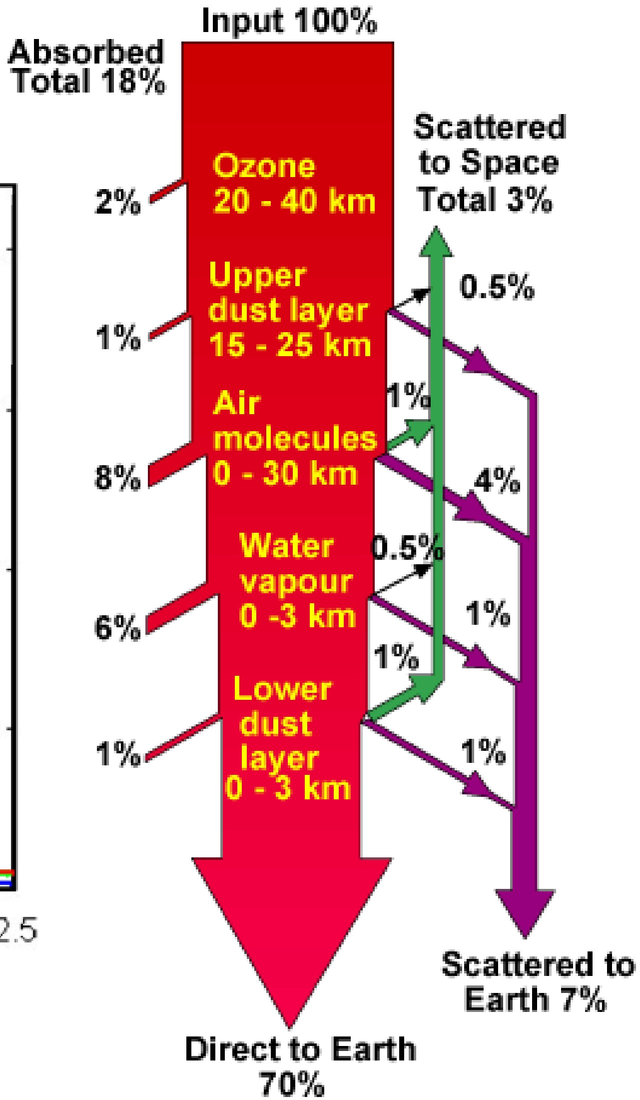
High efficiency solar cells with concentrators

Large arrays of low cost solar cells

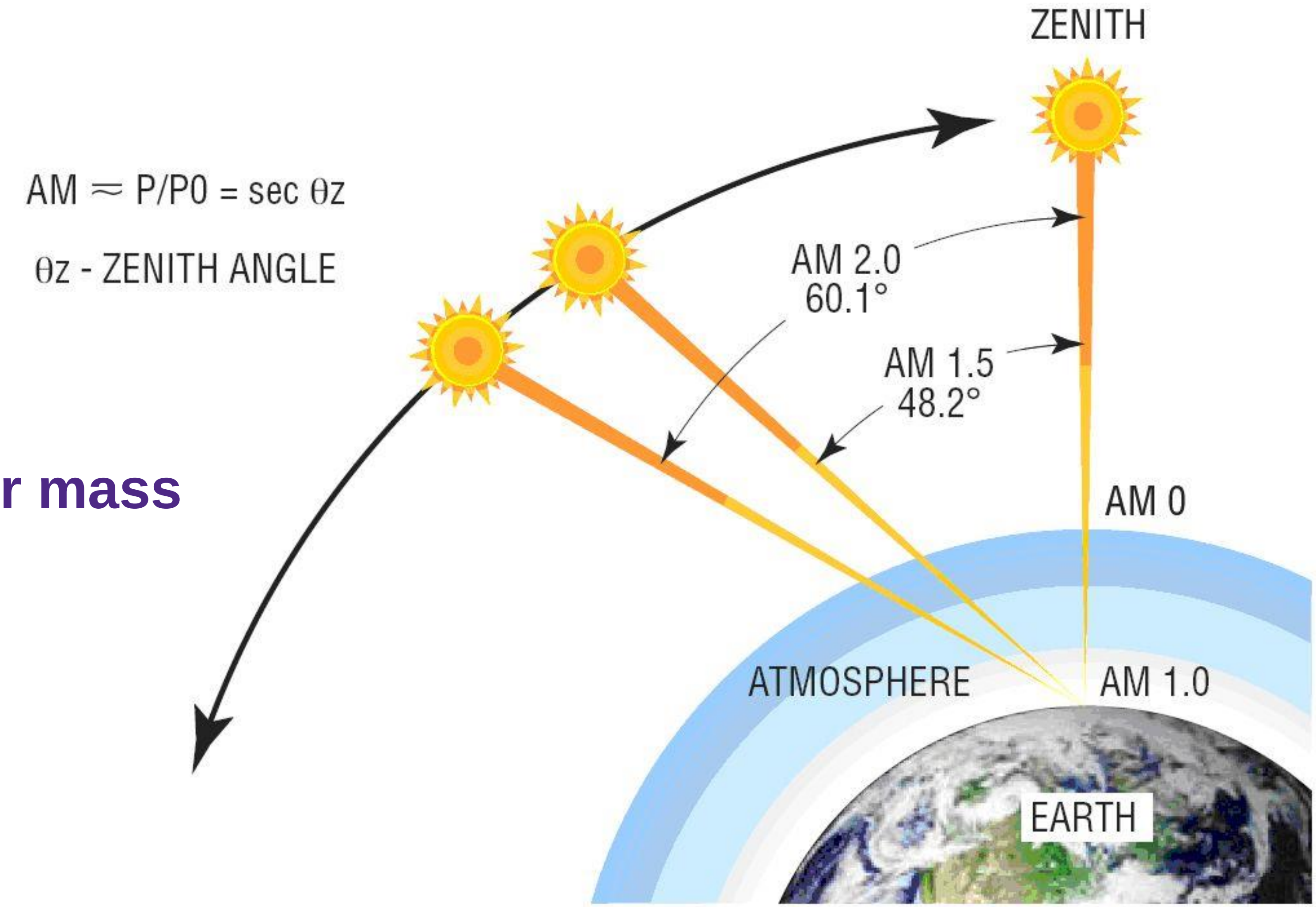
?

Solar energy properties





Solar radiation on the surface of Earth



AM - air mass

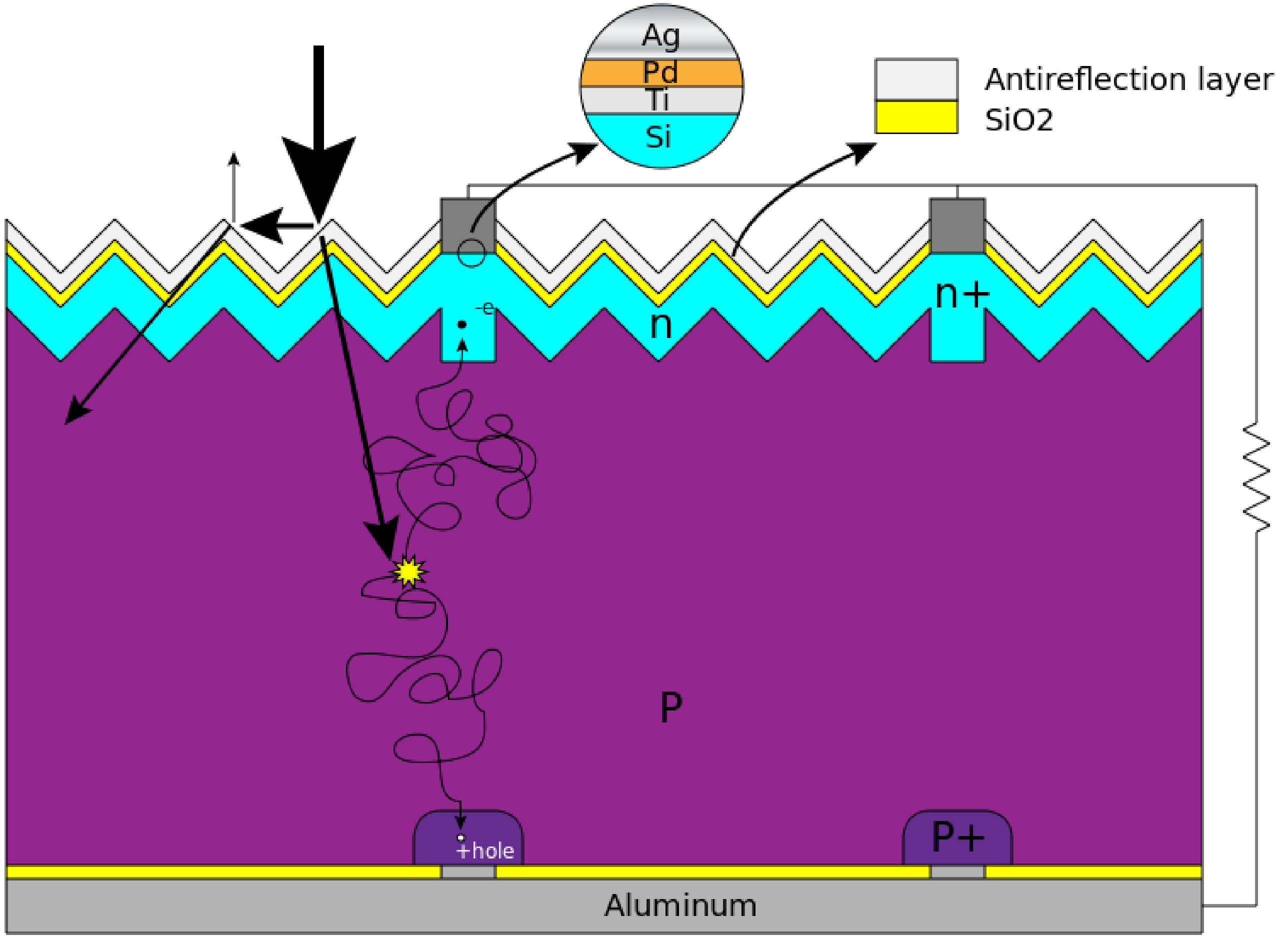
HOW DO SOLAR CELLS WORK?

What is a solar cell?

- Definition:
  - Solar cells are devices that use the photoelectric effect to convert solar irradiation directly to electrical energy.

- Practical implementation:
  - An illuminated semiconductor diode (p-n junction).

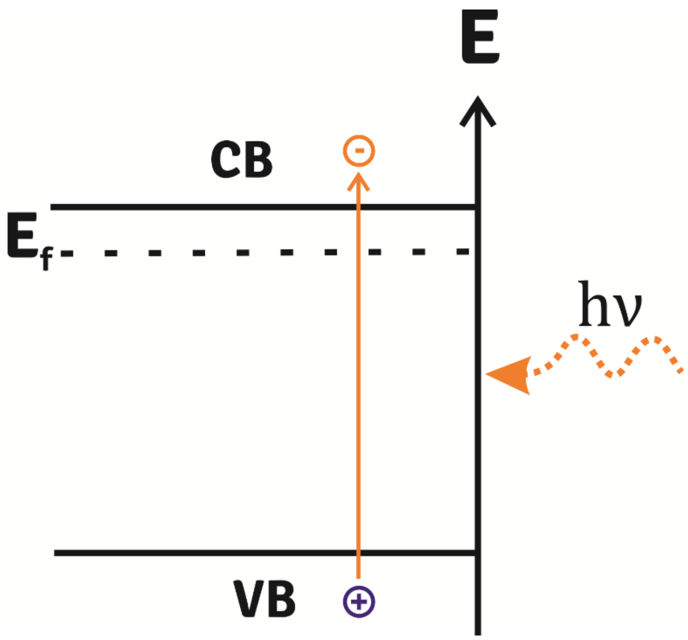
Solar cell basic structure



$$V_{pn} = \mathrm{V_T} \ln \frac{\mathrm{N_d N_a}}{\mathrm{n_i^2}}$$

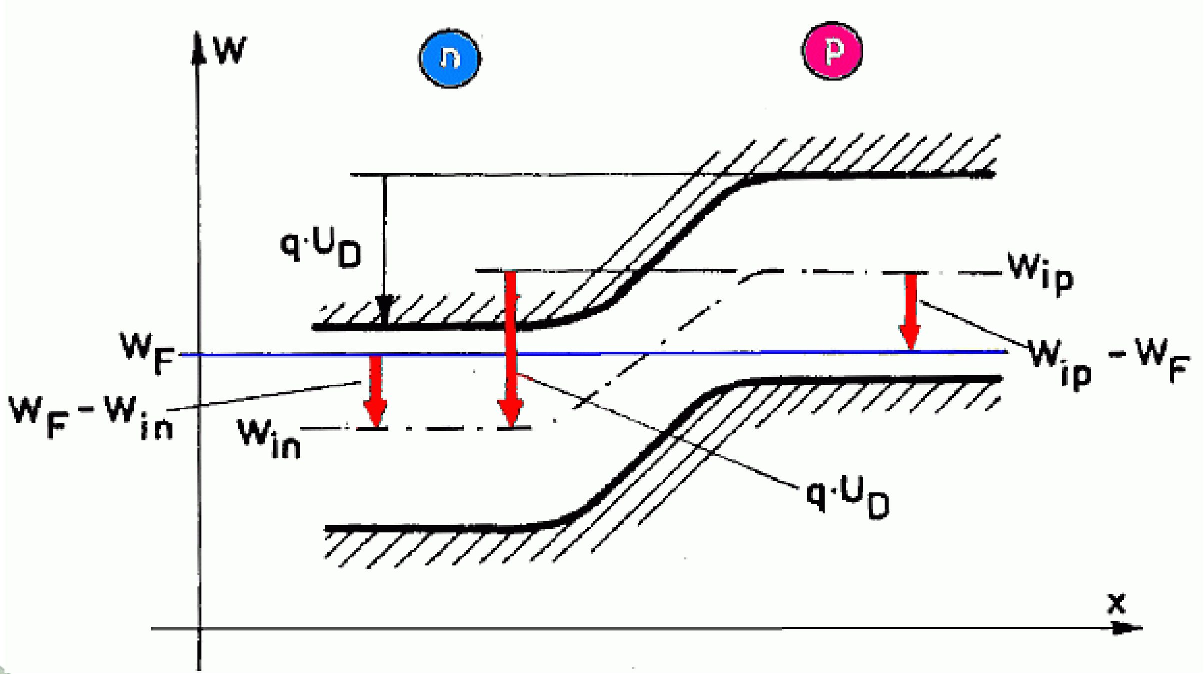
How do solar cells work?

- Photoelectric effect
  - Incoming photons excites an electron from the valence to the conduction band (photogeneration)
    This happens only if the energy of the photon is higher than the bandgap of the semiconductor ($h\nu > W_g$)



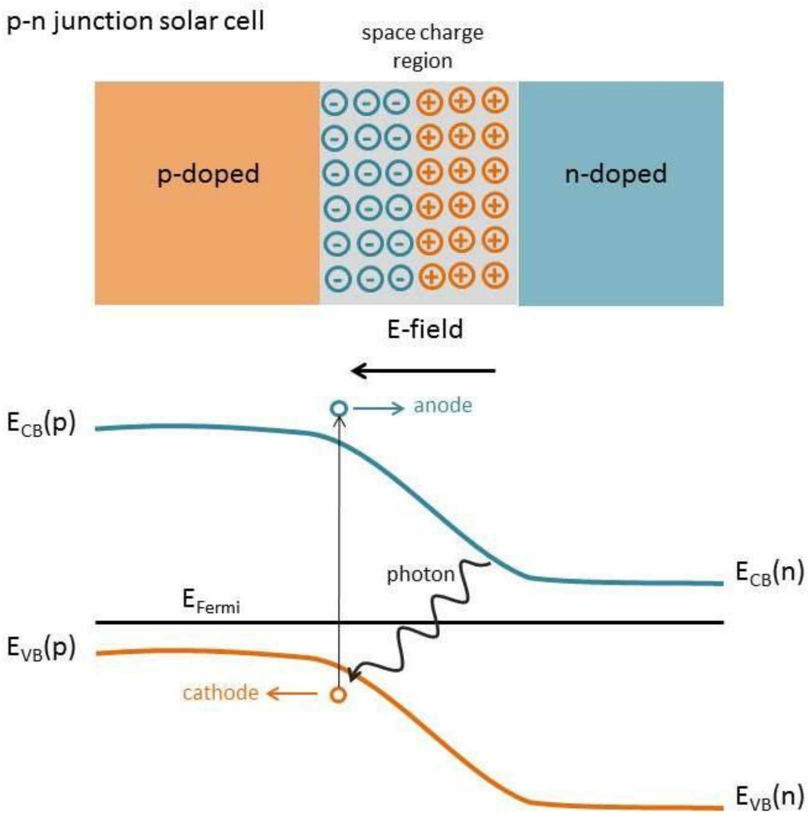
How do solar cells work?

- Built-in electric field
  - Tthe different dopings on the tow sides of the p-n junction result in an electric fielf in the depleted region .



$$U_D = U_T \ln \frac{N_d N_a}{n_i^2}$$

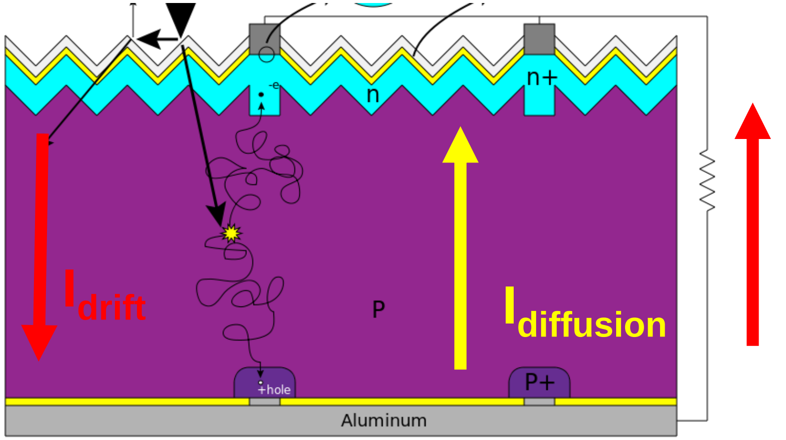
How do solar cells work?



Photon with higher energy than the bandgap excite electron-hole pairs.The built-in potential of the p-n jubction seprates the charge carriers, and drives the electrons to the n-side and the holes to the p-side (drift current). Thus negative charge accumulates on the n-side and a positive on the p-side.

How do solar cells work?

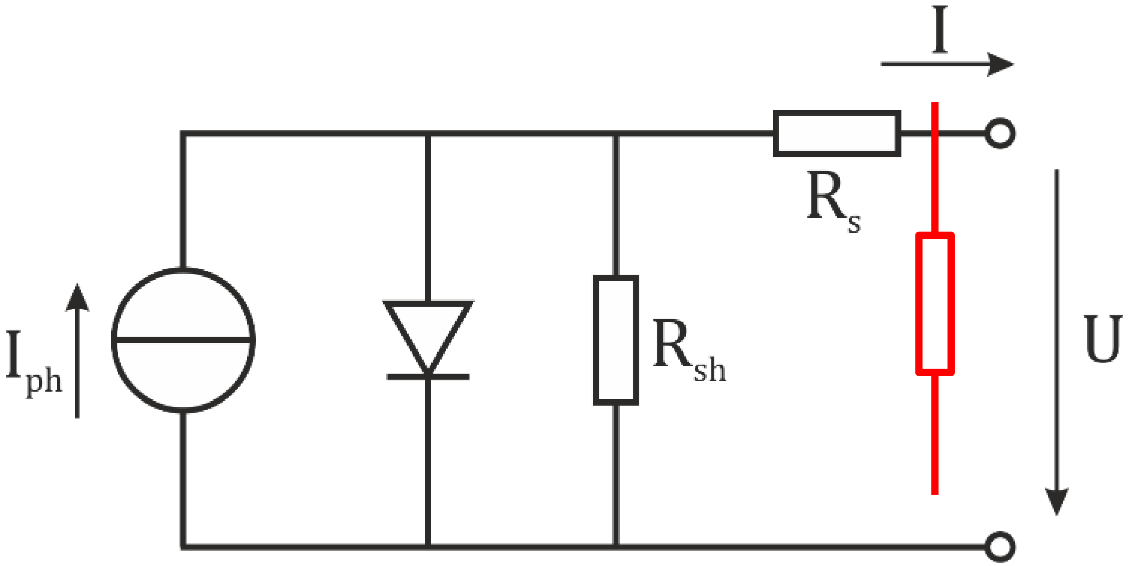
- If we put an external resistor between the n-side and the p-side a current will start to flow on this external resistor, and we can extract electrical power.
- If there is no external resistor, the voltage will rise until the so called open circuit voltage, and due to the diffusion potential of the charge carriers a diffusion current will start to flow in the opposite direction to the drift current.



EQUIVALENT CIRCUIT AND I-V CURVE

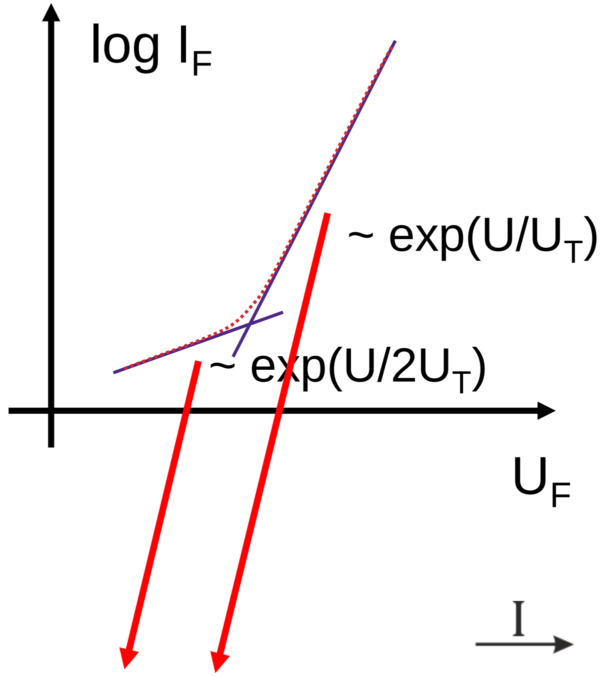
Equivalent circuit of a solar cell

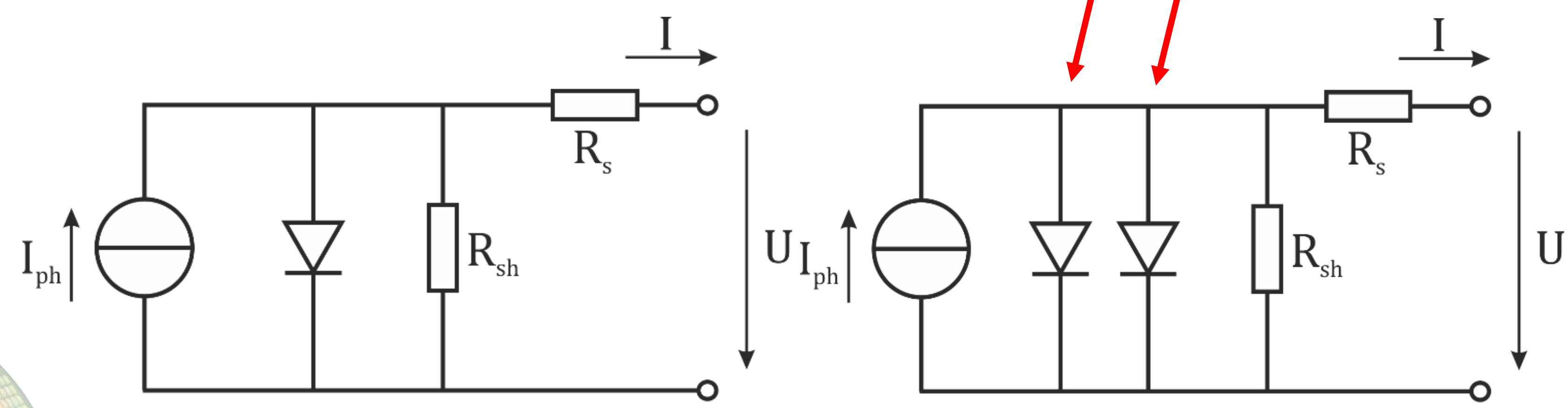
- Current source:drift current from the photogenerated cherge cerriers
- Diode: p-n junction, its current depends on the diffusion potential (forward current = diffusion current)
- The diffusion potential of the diode is determined by the load resistance and the parasitic esistances



Single diode or two diode model

- Recombination current can be taken into account with a two diode model
- It is neglectible compared to the photo current

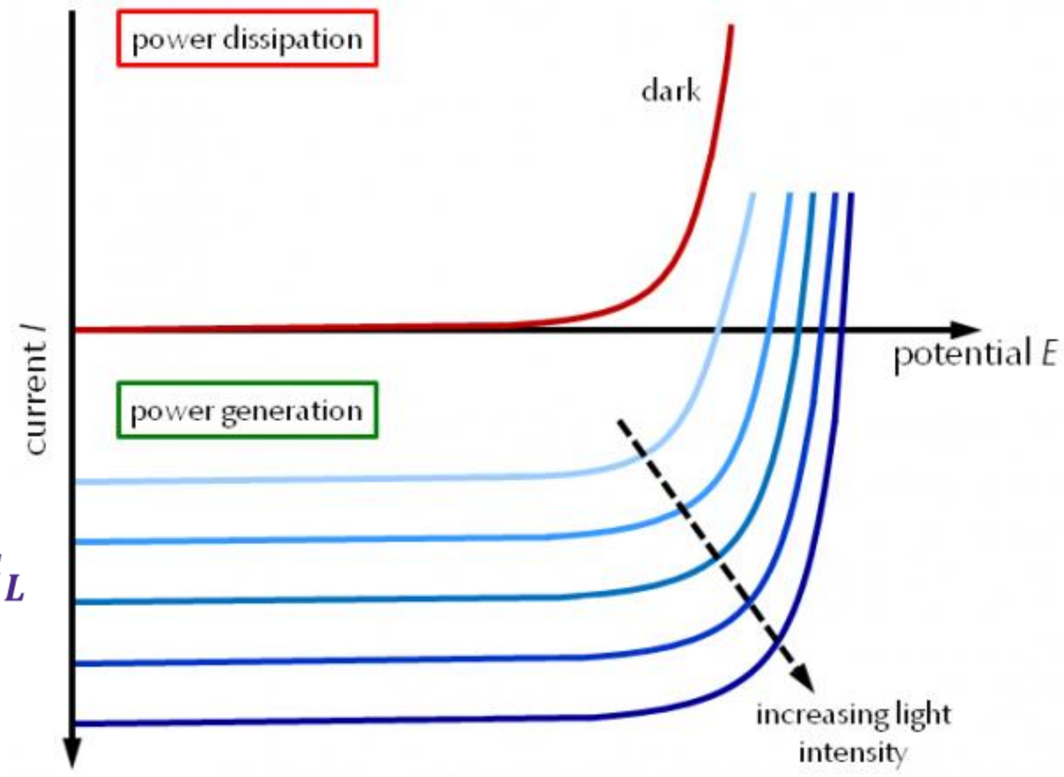




I-V curve of a solar cell

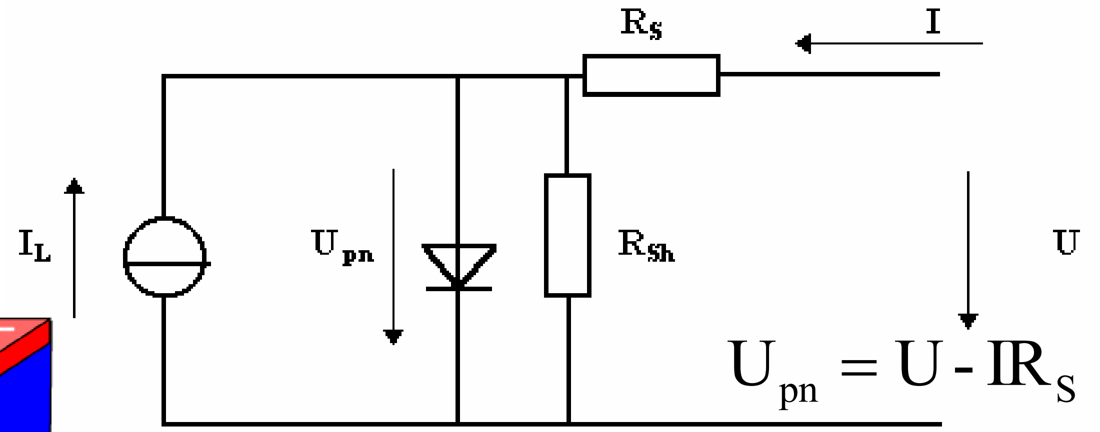
- *Ideal solar cell*
- $I = I_0\left(e^{\frac{U}{\eta U_T}} - 1\right)$
- *Non-ideal solar cell*
- $I = I_{ph} - I_0\left(e^{\frac{U+I\cdot R_S}{nU_T}} - 1\right) - \frac{U+I\cdot R_S}{R_{sh}}$

$I_{ph} = k \cdot G_L$

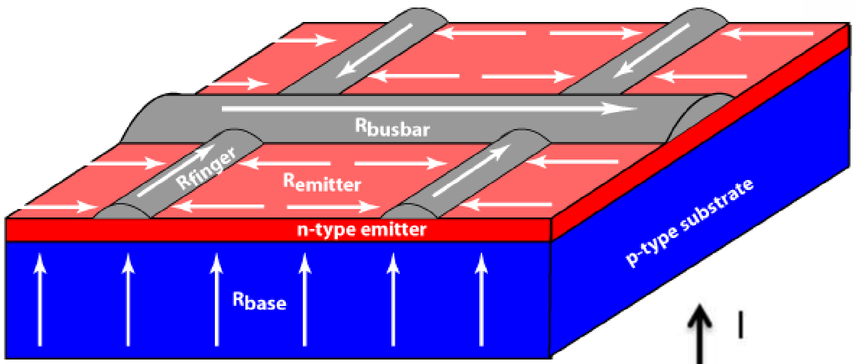


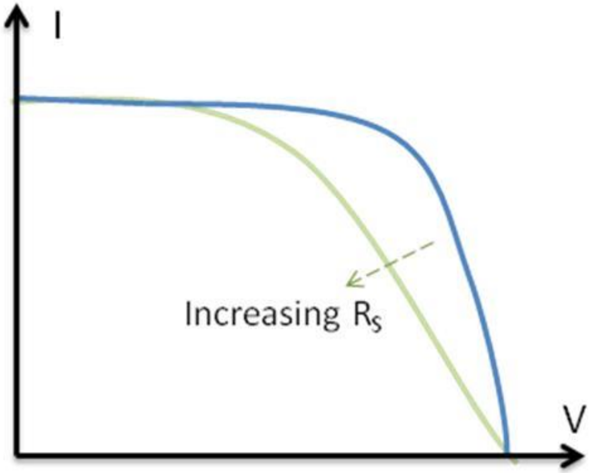
Effect of parasitic resistances

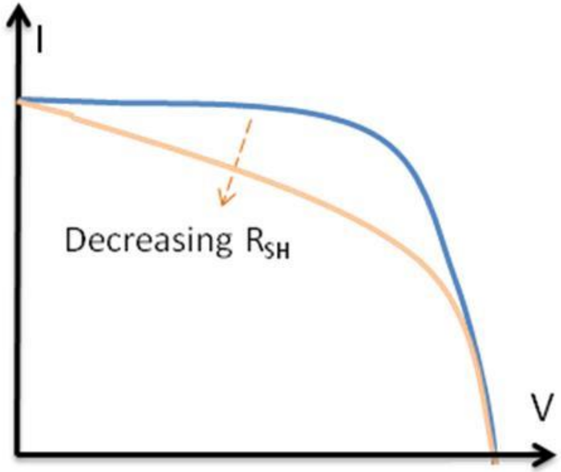
- R_S – series resistance
- R_{sh} – shunt resistance
- I_L – photocurrent



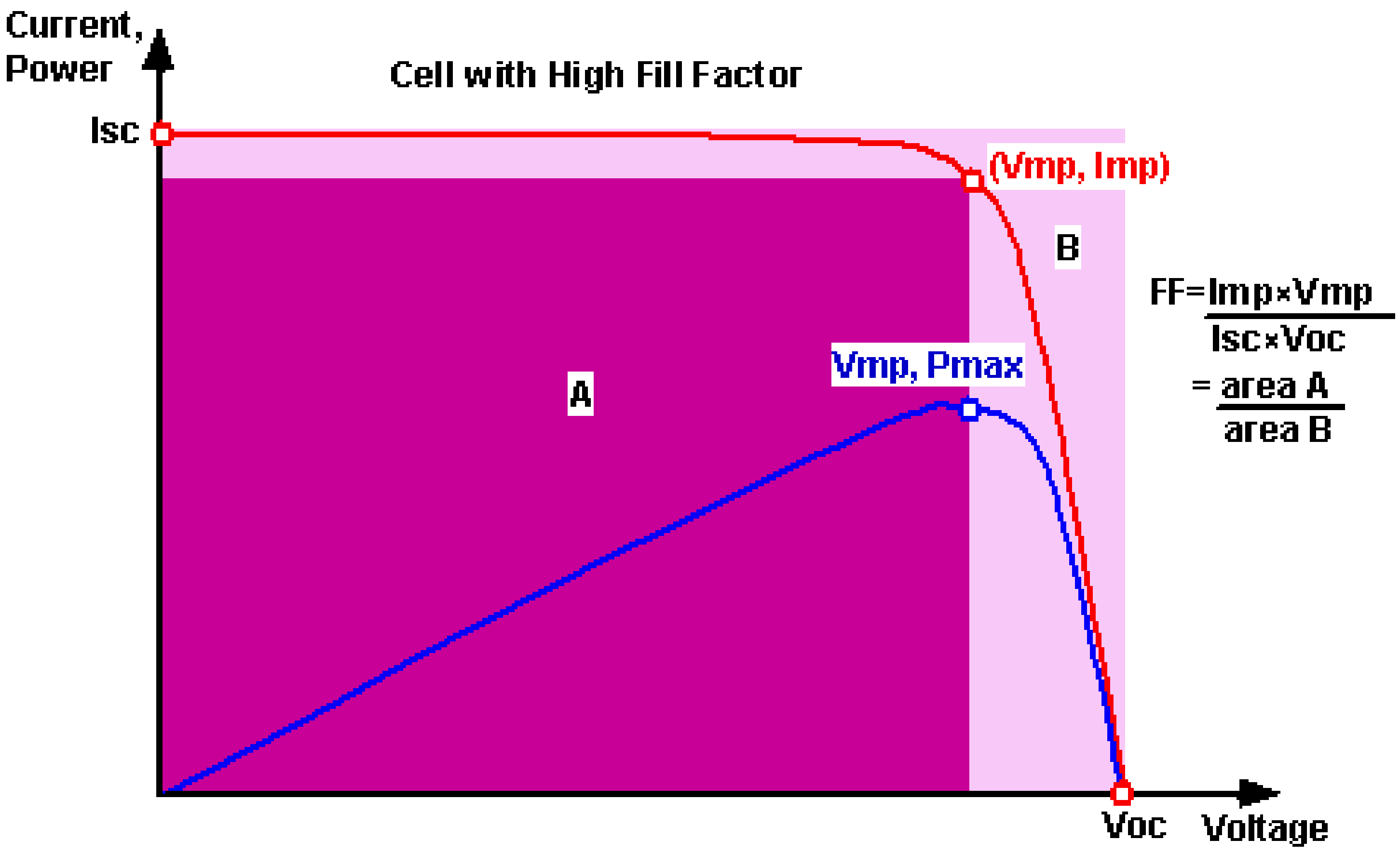
$$U_{pn} = U - IR_S$$







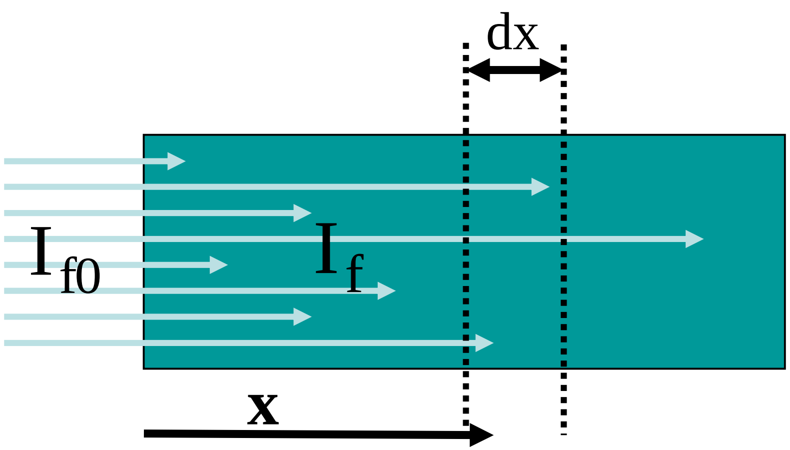
Ideal solar cell characteristics



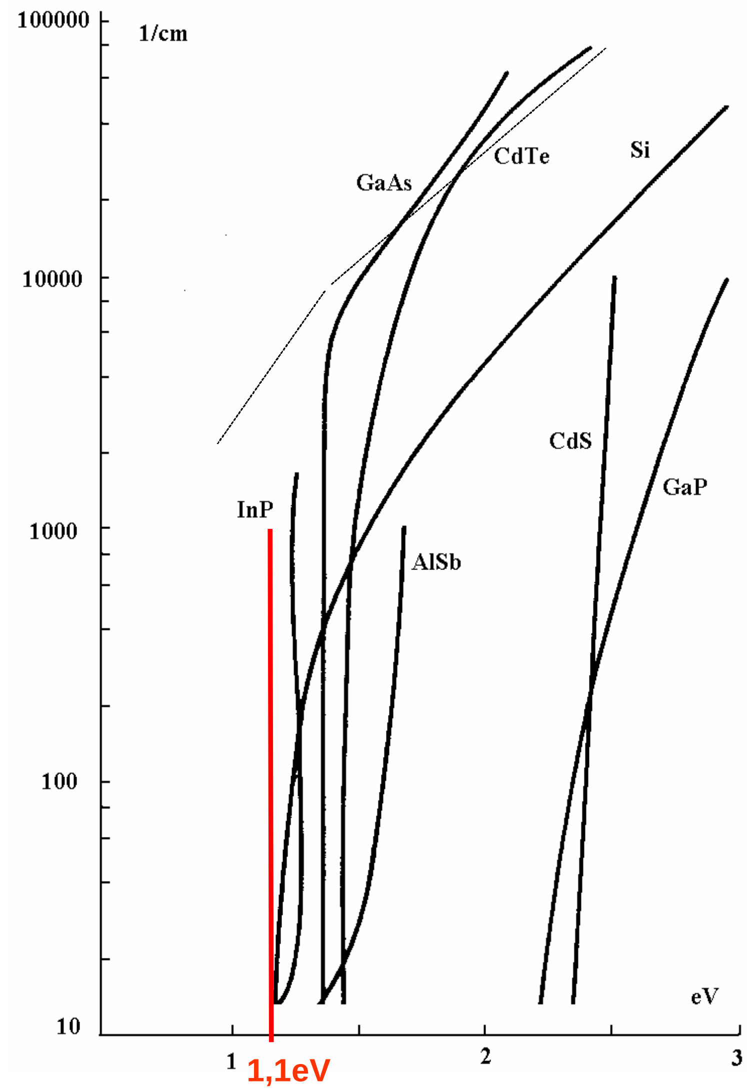
SPECTRAL RESPONSE

Light and semiconductor interaction

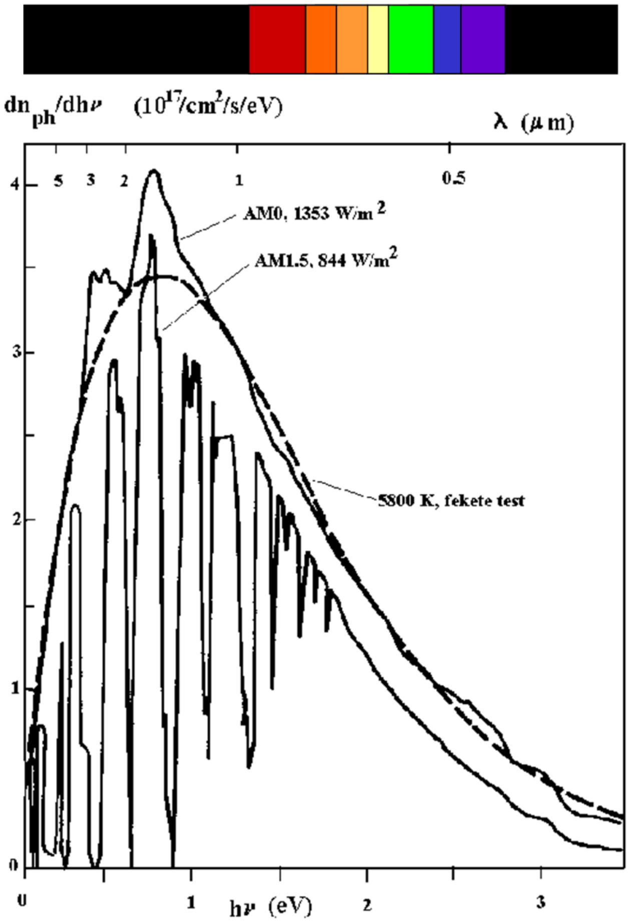
$$dI_f = -\alpha \cdot I_f \cdot dx$$

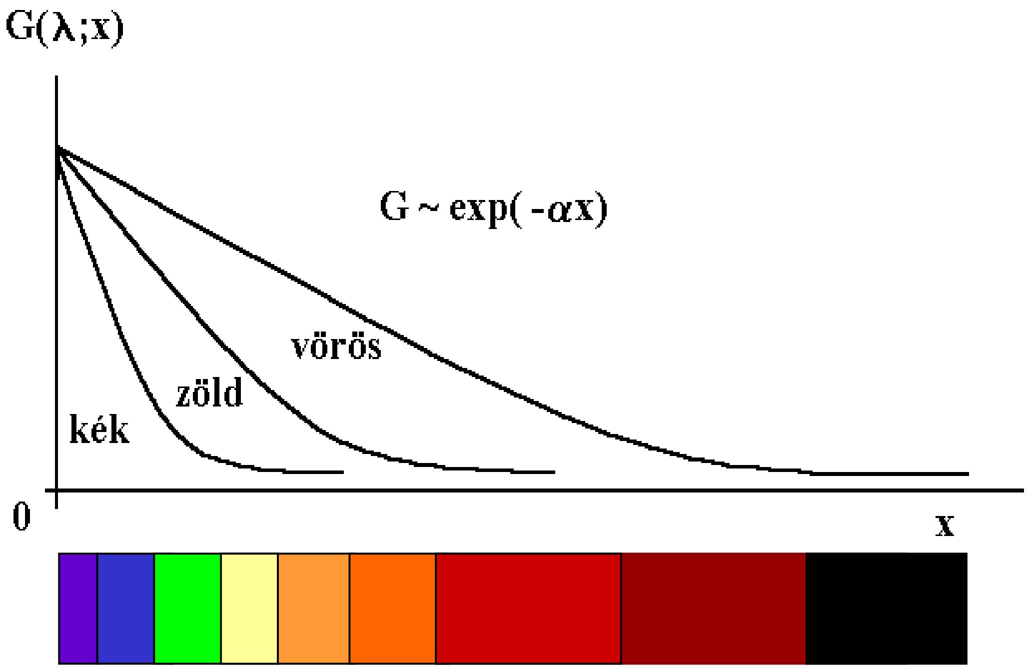


$$I_f = I_{f0} \exp(-\alpha \cdot x)$$



Generation rate

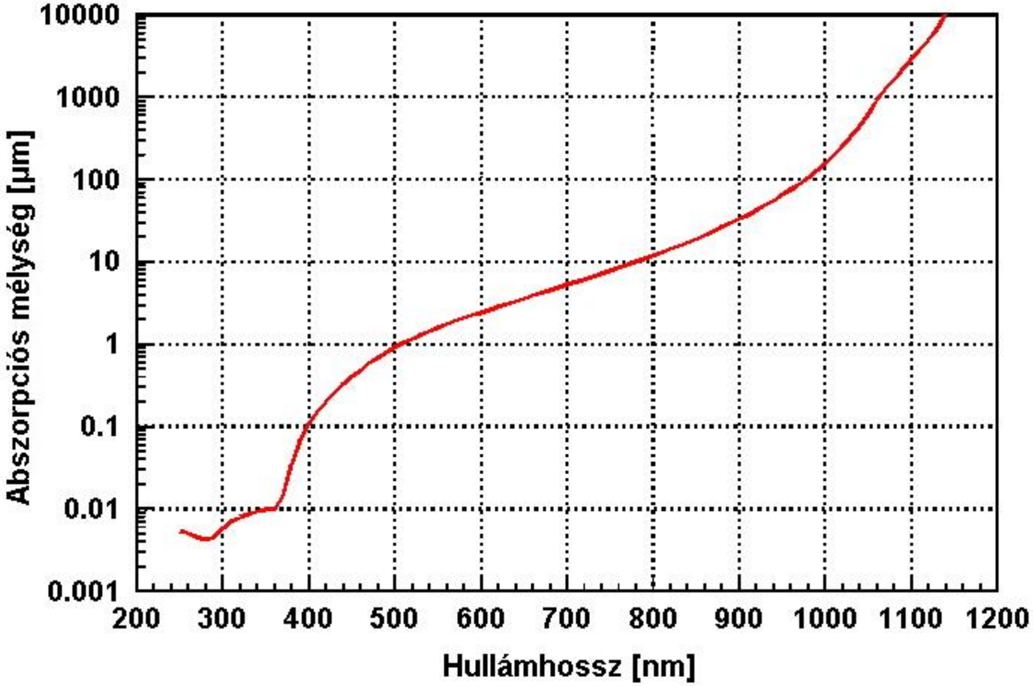


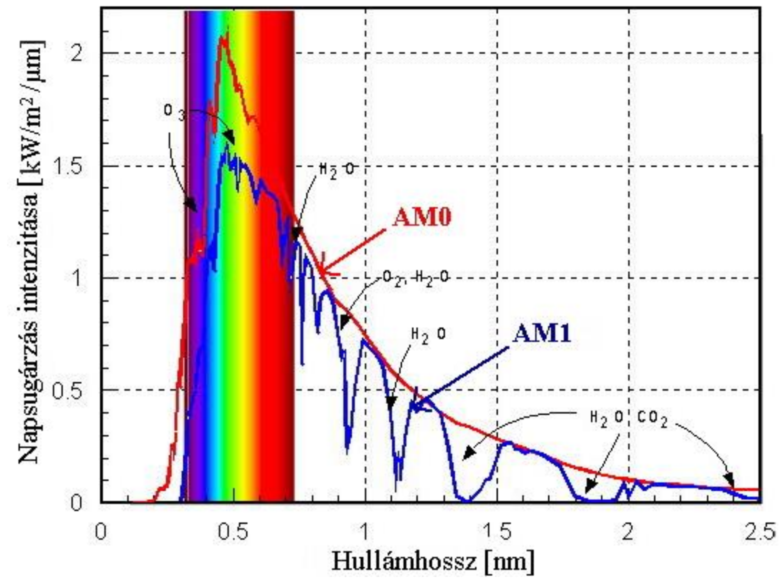


Calculation of the generation rate:

$$G(\lambda,x)=\alpha(\lambda)\cdot F(\lambda)\cdot[1-R(\lambda)]\cdot \exp(-\alpha(\lambda)\cdot x)$$

Absorption depth

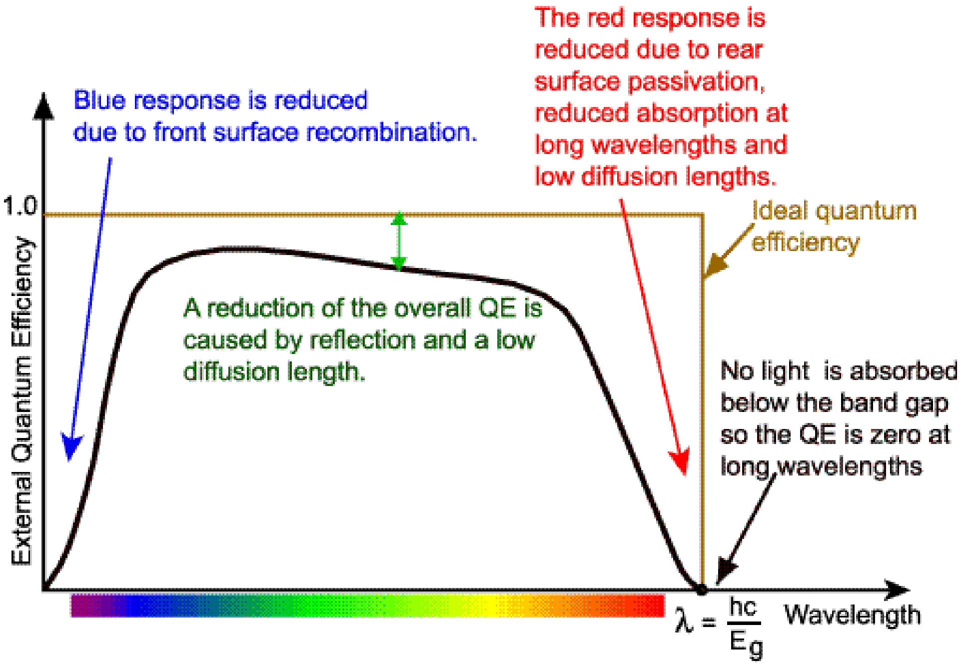




- UV and blue light have a high absorption coefficient → absorbed at the surface
- NIR wavelentghs have a lower absorption coefficient → absorbed in the depth of the material

Quantum efficiency

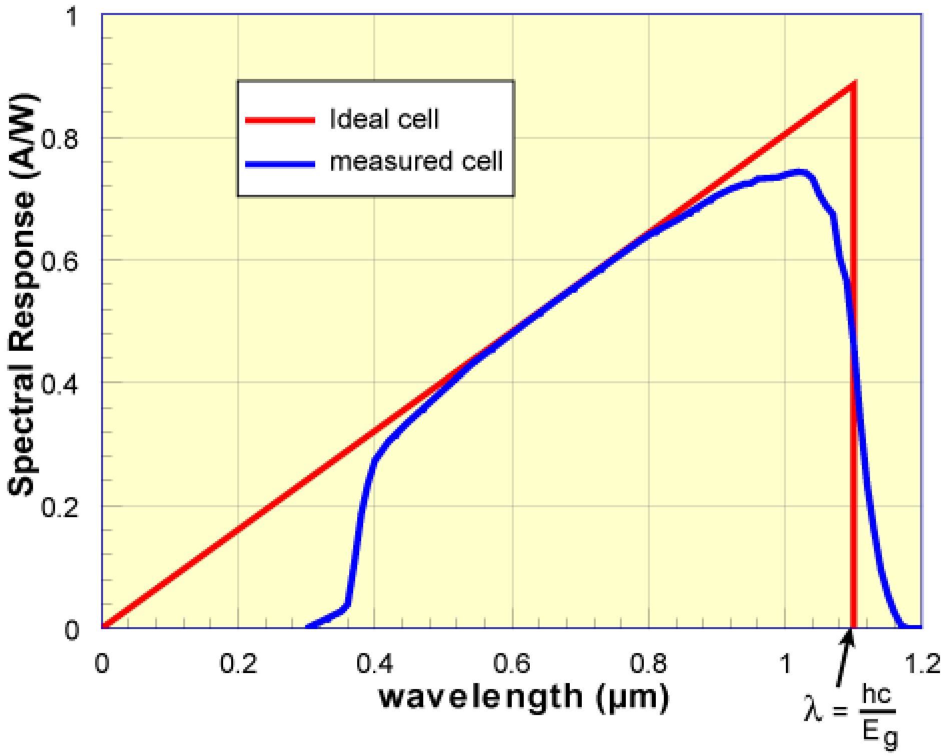
- The ration of the number of extracted electrons and the number of irradiated photons
- Due to reflexion there is a difference between external (EQE)and internal (IQE) quantum efficiency
- The sum of all the extracted electrons is the short circuit current that almost equals the photocurrent
- It is complicated to measure the number of photons



$$I_L = q\int_{(\lambda)} F(\lambda)\cdot[1-R(\lambda)]\cdot IQE(\lambda)\, d\lambda$$

Spectral response

- A generált fotoáram és az adott hullámhosszú fény teljesítményének hányadosa, adott felületen
- A napelem rétegszerkezetének vizsgálatára alkalmas
- Technológia ismeretében az esetleges hibák kideríthetők (rossz felületi passziváls, BSF réteg)



$$SR = \frac{J_z}{P_{fény}} = \frac{I_z}{A \cdot P_{fény}}$$

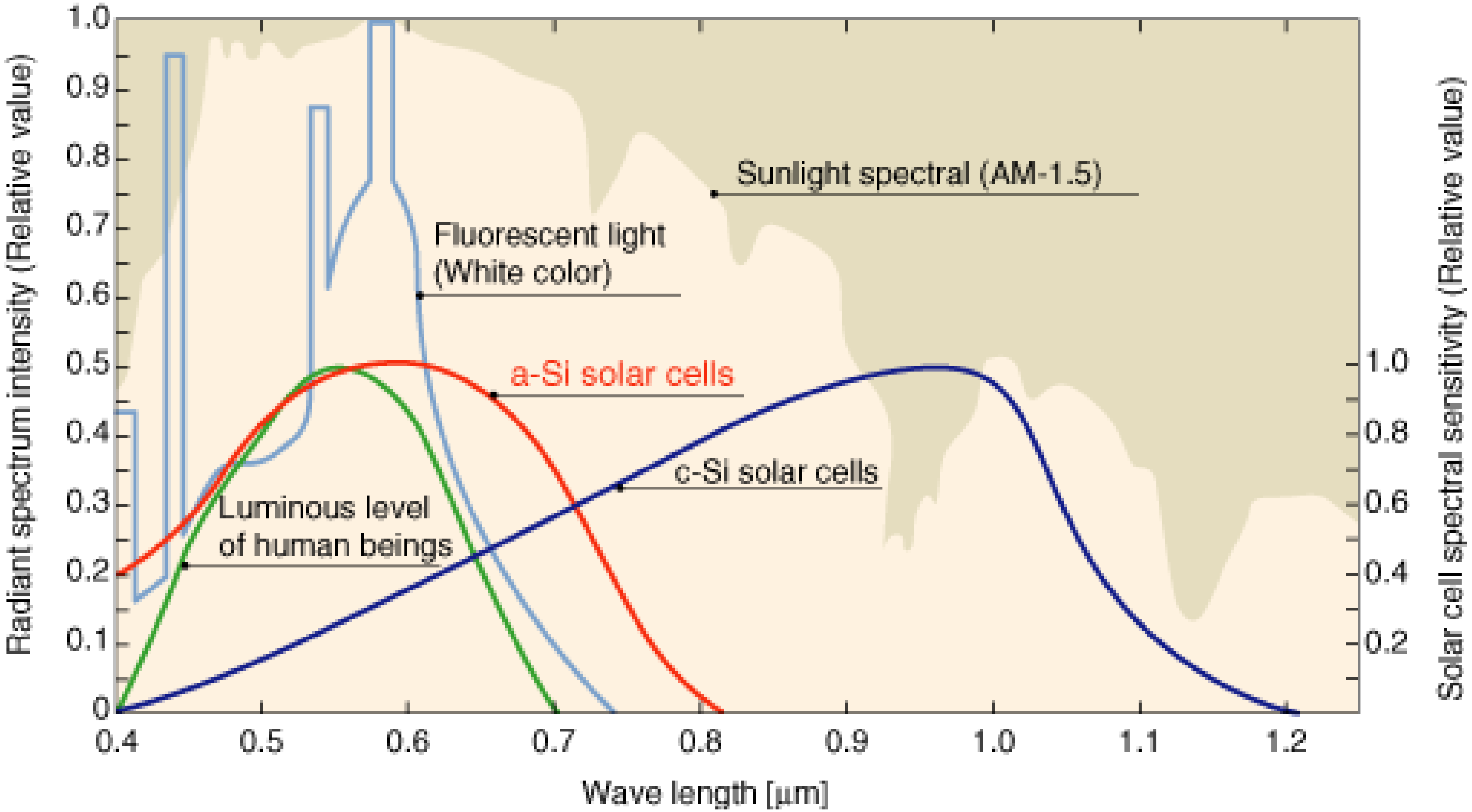
$$SR(\lambda) = \frac{q \cdot \lambda}{h \cdot c} \cdot QE(\lambda) = 0{,}808 \cdot \lambda \cdot QE(\lambda)$$

Spectral response – what is it for?

1. It is a „footprint" of the technology! (It shows the nature and location of the problems.)
2. If the spectral response is known, than the response for a given light source can be calculated:

$$J_L = q\int_0^{\lambda_m} F(\lambda)\left[1 - R(\lambda)\right] SR(\lambda)\, d\lambda$$

Spectral response



EFFICIENCY LIMITS AND OPERATIONAL CONDITIONS

Loss factors

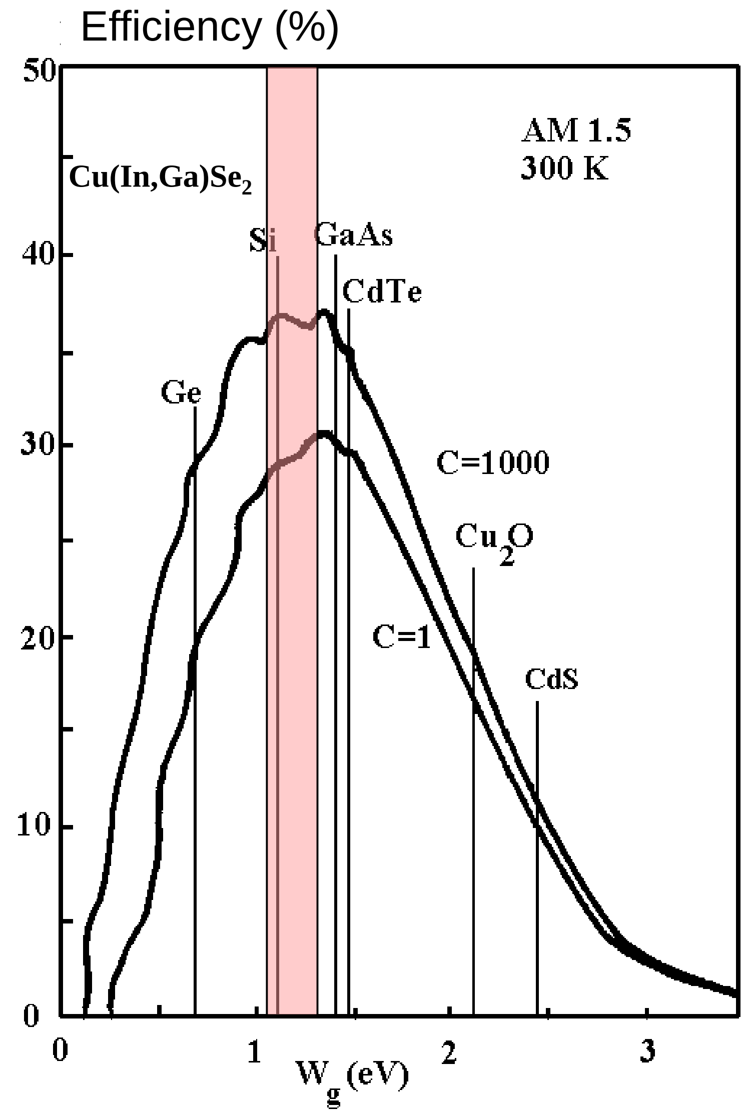
- Photons with lower energy than the band gap
- Above bandgap photon energy
- Broad solar spectrum
- Voltage reduction: due to its structure a solar cell can not produce an open circuit voltage of 1,12 V as its band gap would suggest, but only ca. 0,6-0,7 V
- Fill Factor: the I-V curve is not „square”, thus we have losses due to the exponential characterisic of the p-n juncion: the diode is partially open at the maximum power point.

$$\eta_{max} = 29\,\%\ (for\ silicon, AM\ 1,5\ solar\ spectrum)$$

Choosing the semiconductor material

Optimal material

- AM1.5 Earth conditions
- Without concentration,
- 1000x concentration
- Theoretical limit for the conversion efficiency as function of the energy gap (Schockley-Queisser Limit)



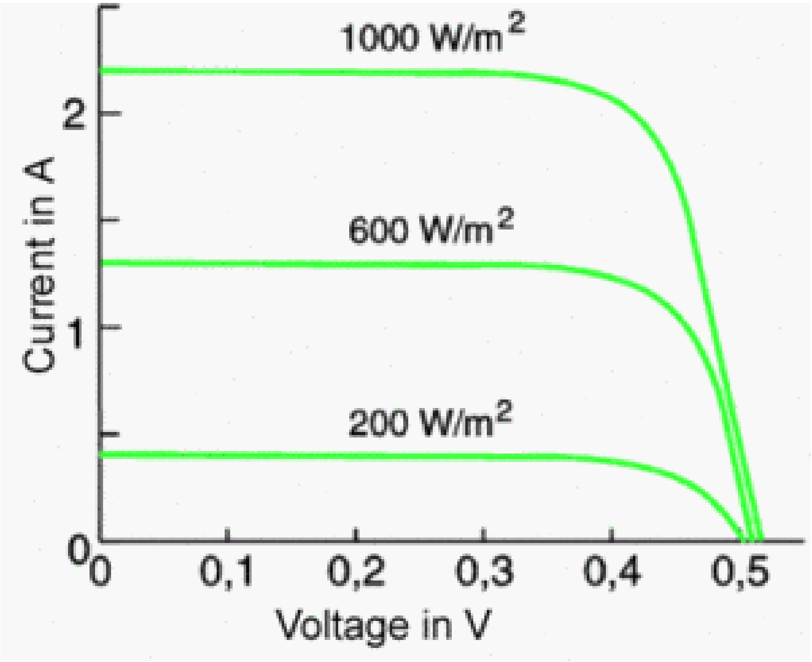
Effect of illumination

Open-circuit condition (I=0)

$$U_0 = U_T \ln\left(1+\frac{I_L}{I_S}\right) \cong U_T \ln\frac{I_L}{I_S} = U_T \ln\frac{kI_{f0}}{I_S}$$

10x-higher intensity:

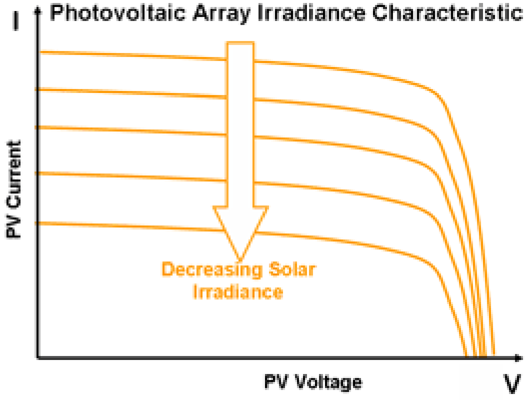
$$\Delta U = U_T \ln 10 = 60\text{mv}$$



Short-circuit condition (U=0)

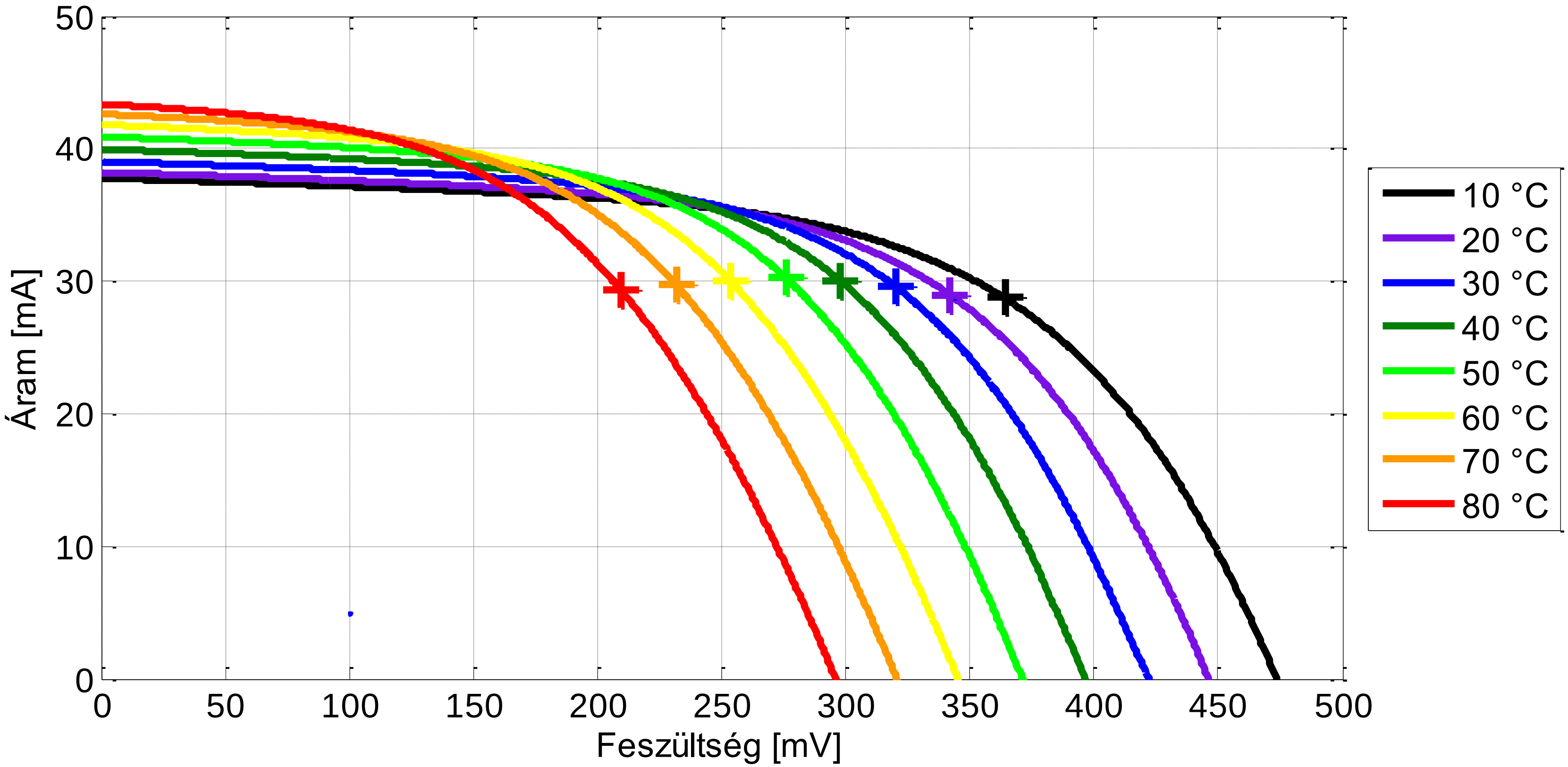
$$I_{sc} = -I_L = kI_{f0}$$

10x- higher intensity: $I_{sc,10} = 10 \cdot I_{sc}$



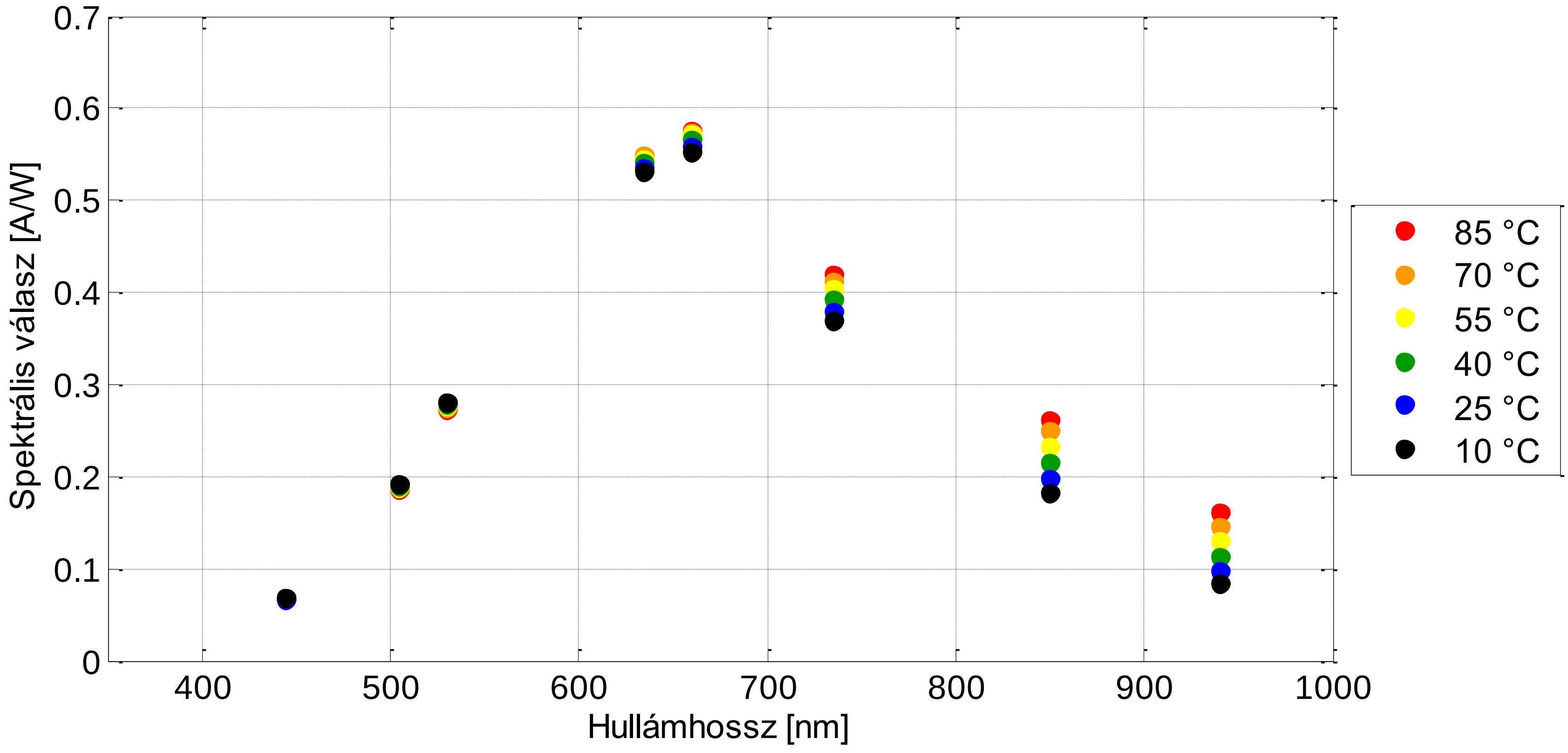
I_{f0} – photon flux (incoming photons/ sec)

Effect of temperature



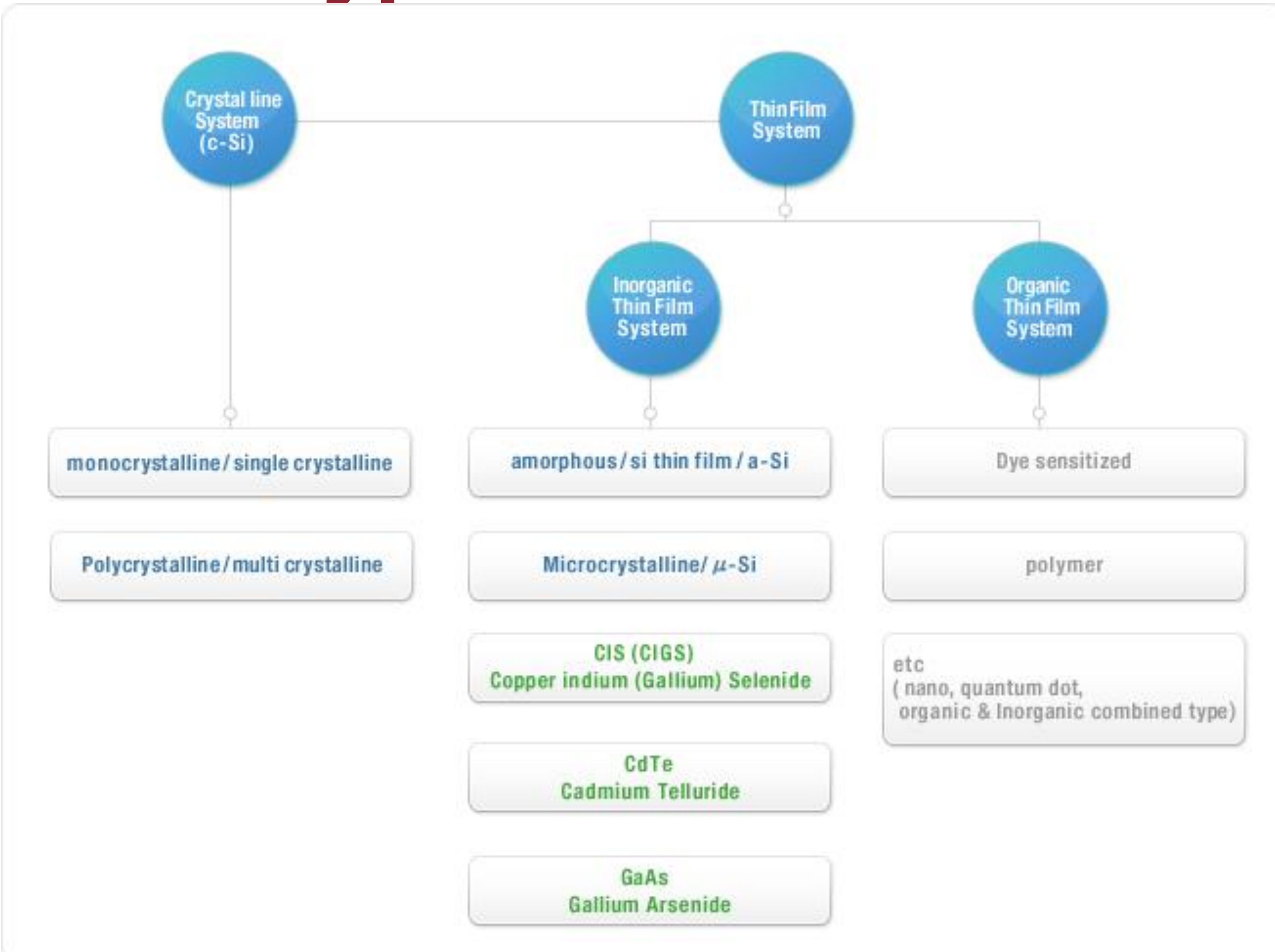
$$\frac{dI_{SC}}{dT} \approx 0,1..0,2\ \%/°C \qquad \frac{dU_{OC}}{dT} \approx 2\ mV/°C$$

Effect of temperature on the spectral response



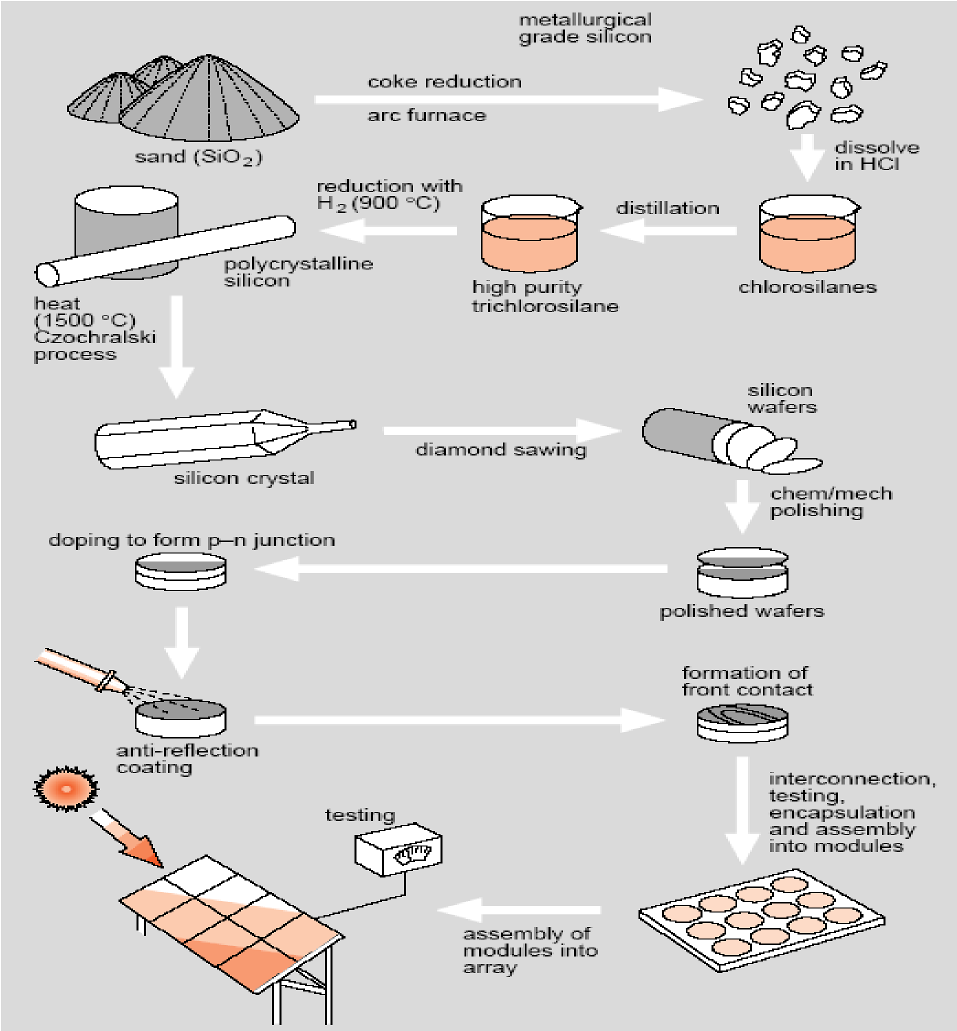
TYPES OF SOLAR CELLS

Solar cell types

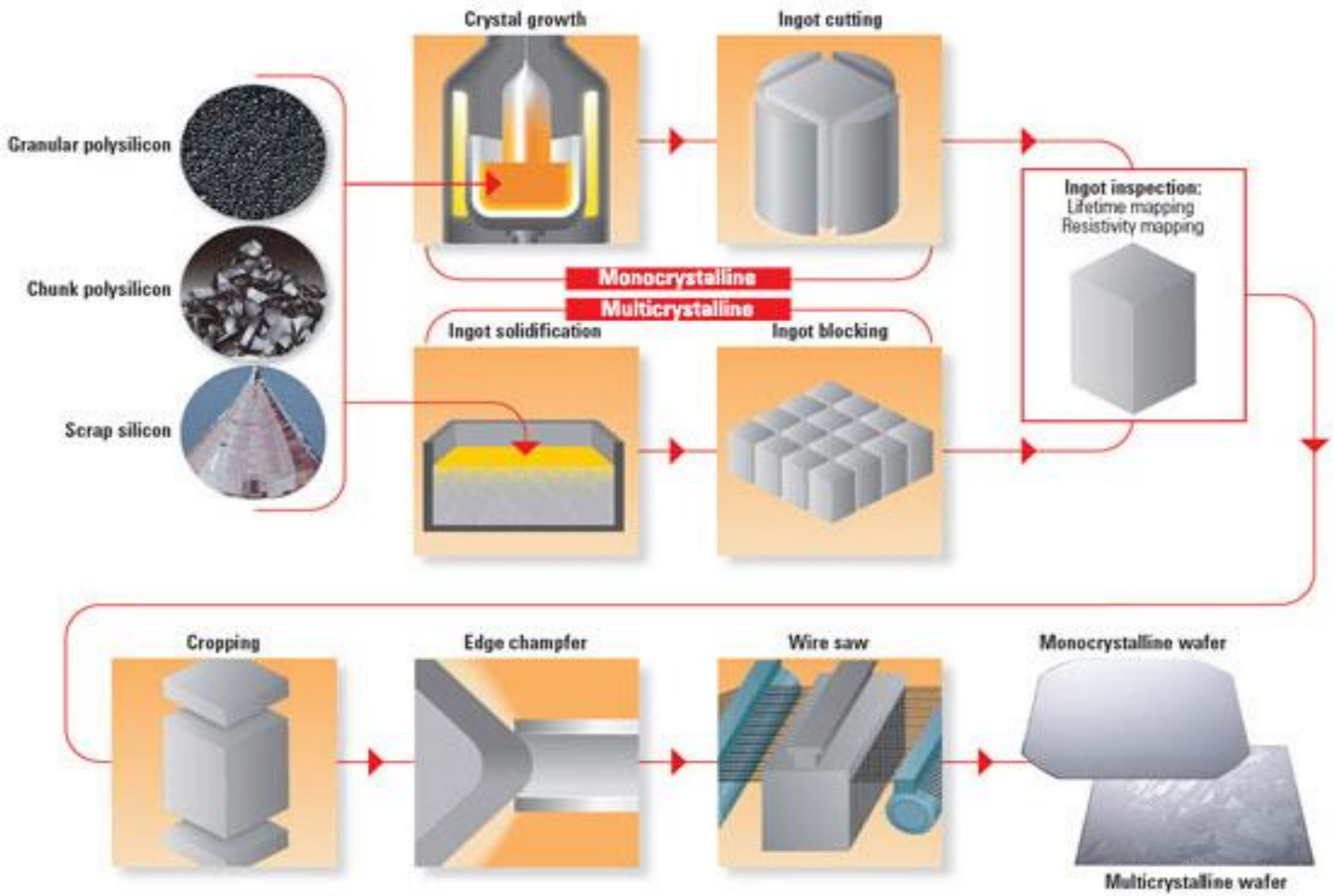


Process steps of monocrystalline solar cells

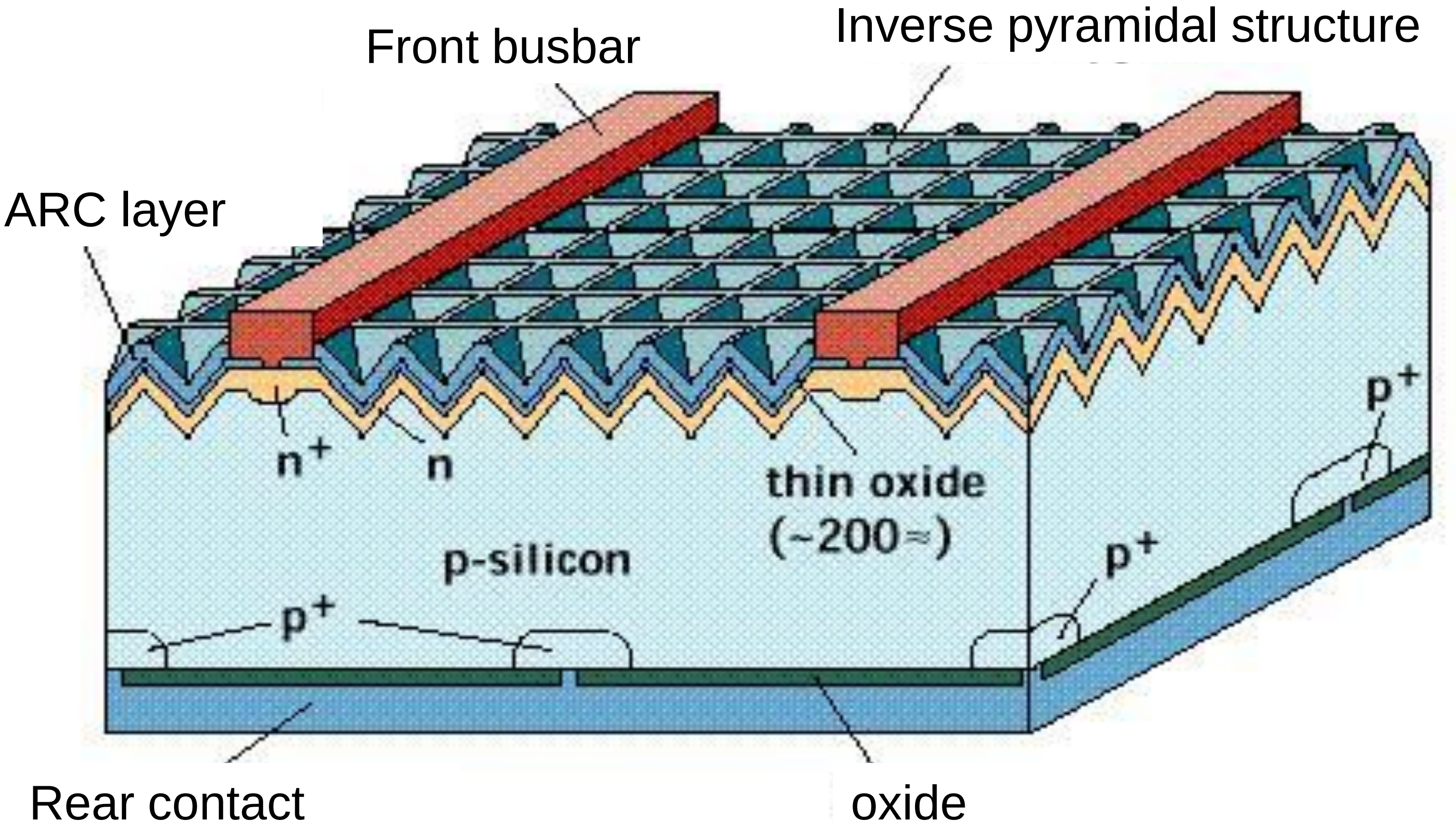
- Sand (SiO_2)
- Metallurgic Si
- Chlorsilanes (for example $SiHCl_3$)
- High purity chlorsilan
- Polycristalline Si bulk
- Single crystal growth
- Slicing of the bulk (diamond saw)
- Ploishing of the surface
- Adalékolás
- ARC layer
- Contact layer
- Modul assembly and testing



Crystalline wafer production

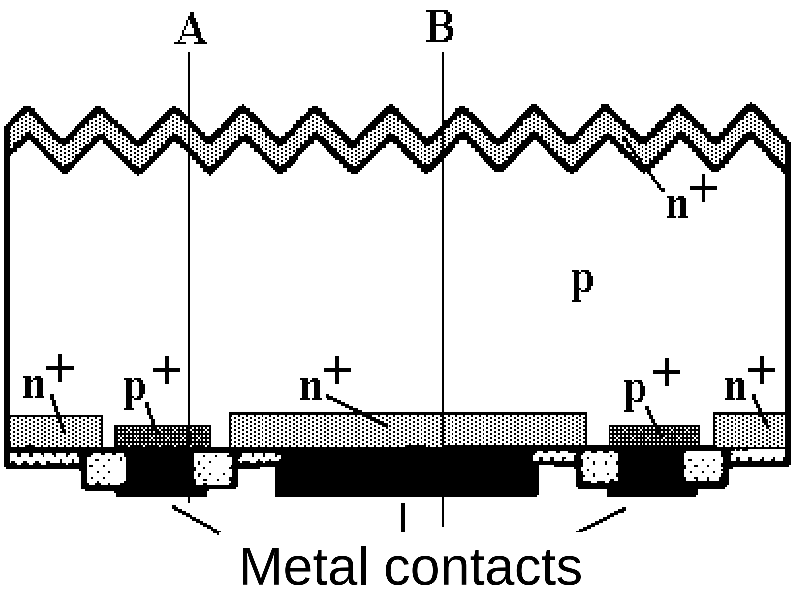


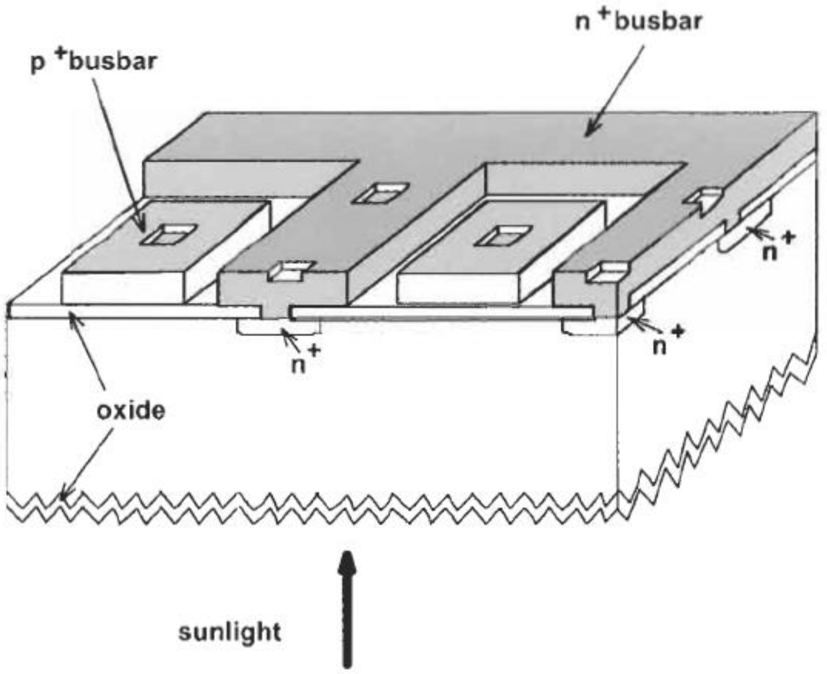
PEARL (passivated emitter and rear locally) cella



24% efficiency

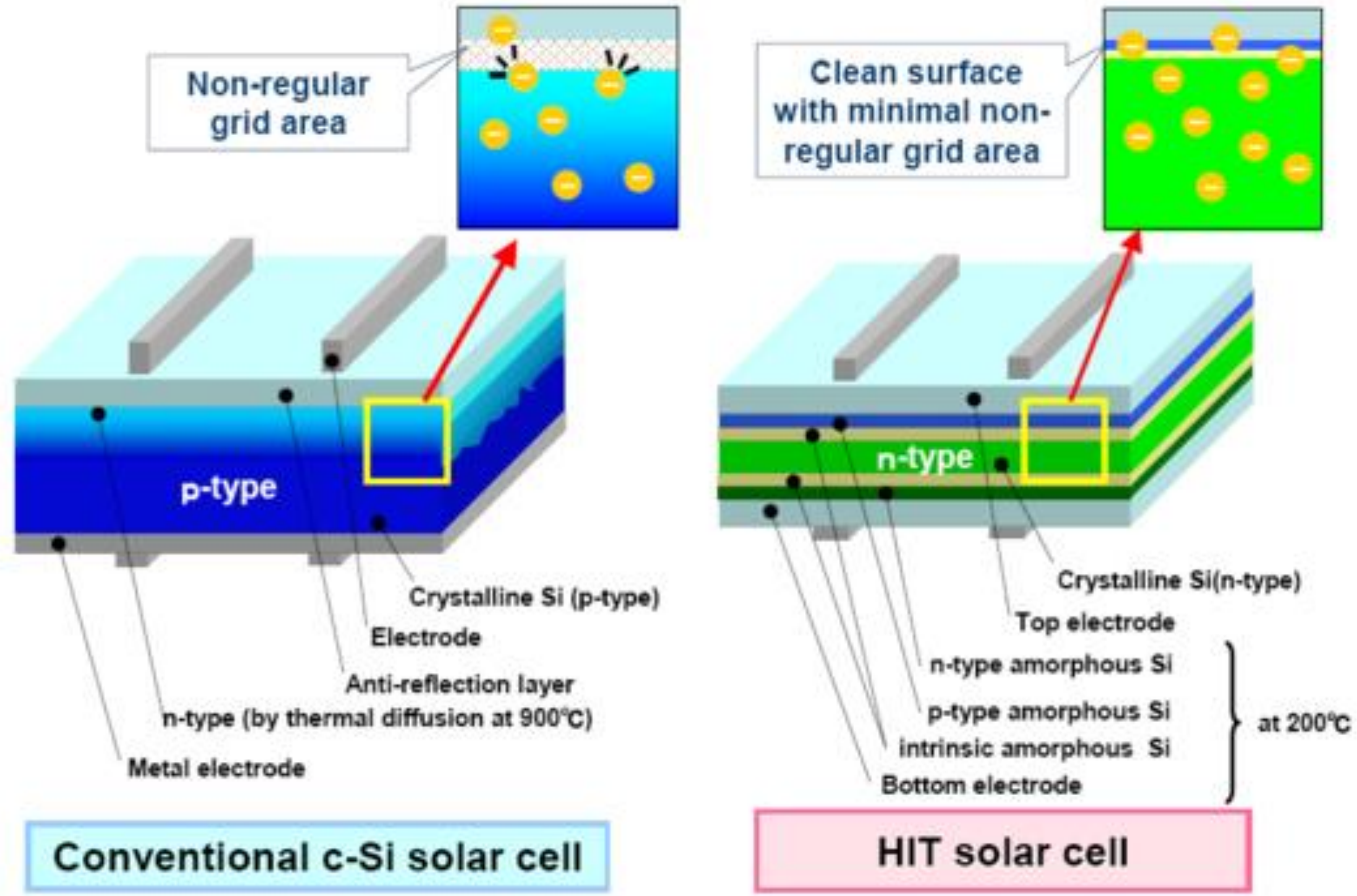
Interdigitated Back contact cells



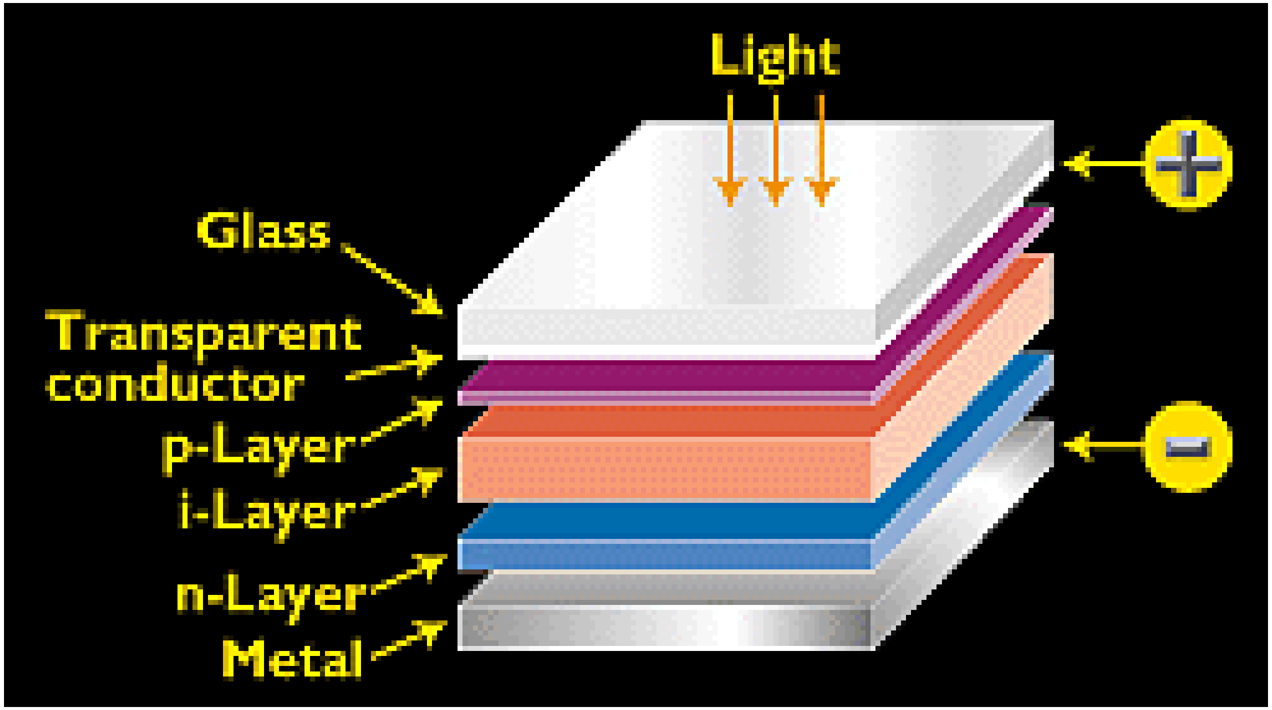


24% efficiency

HIT cella (Sanyo)

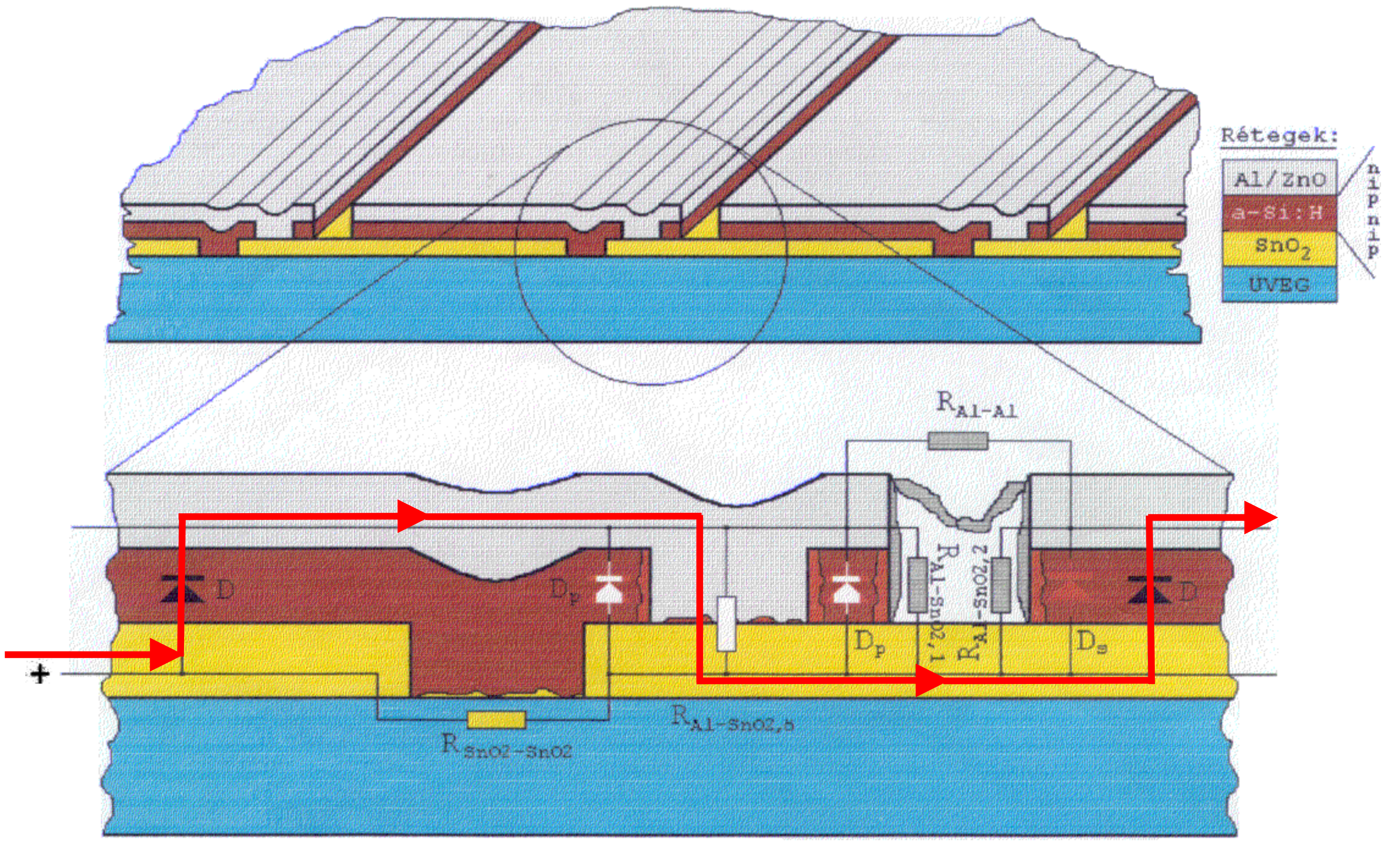


Amorphous Si solar cell (a-Si)

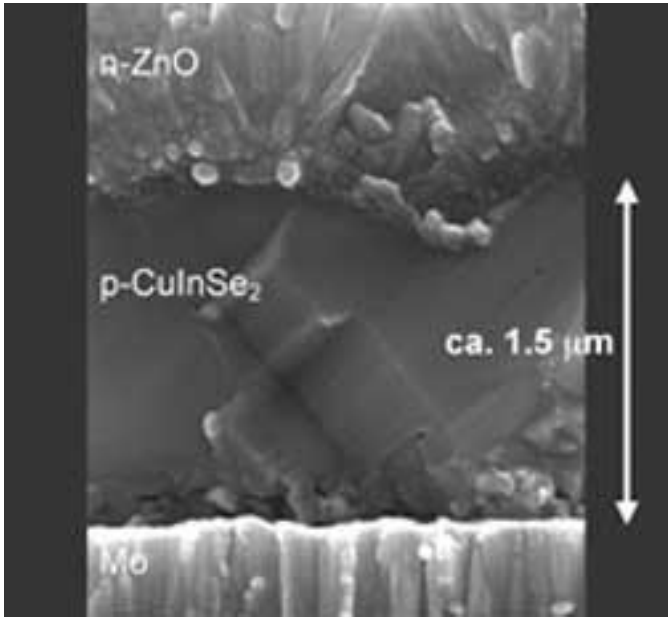


- ultra thin (0,008 μm) p^+ layer
- intrinsic layer (0,5 – 1 μm)
- thin (0,02 μm) n^+ layer

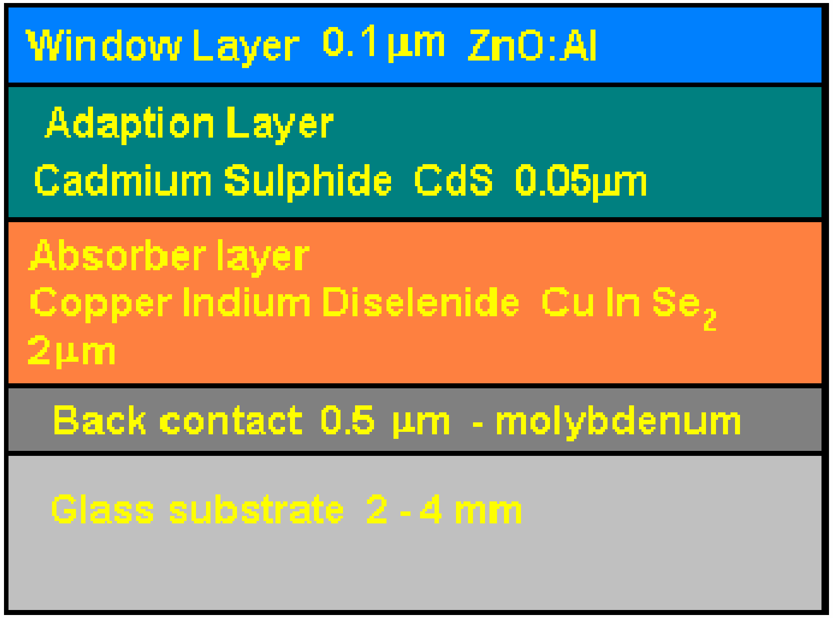
Amorphous Si solar cell (a-Si)



CIS (copper indium diselenid)

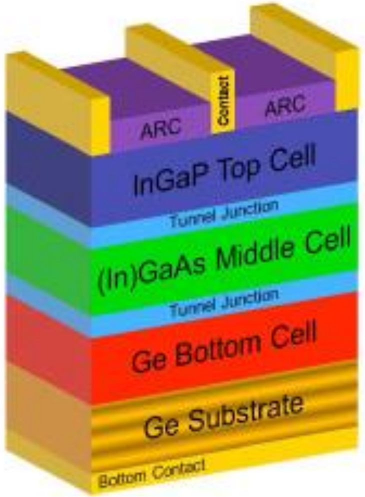


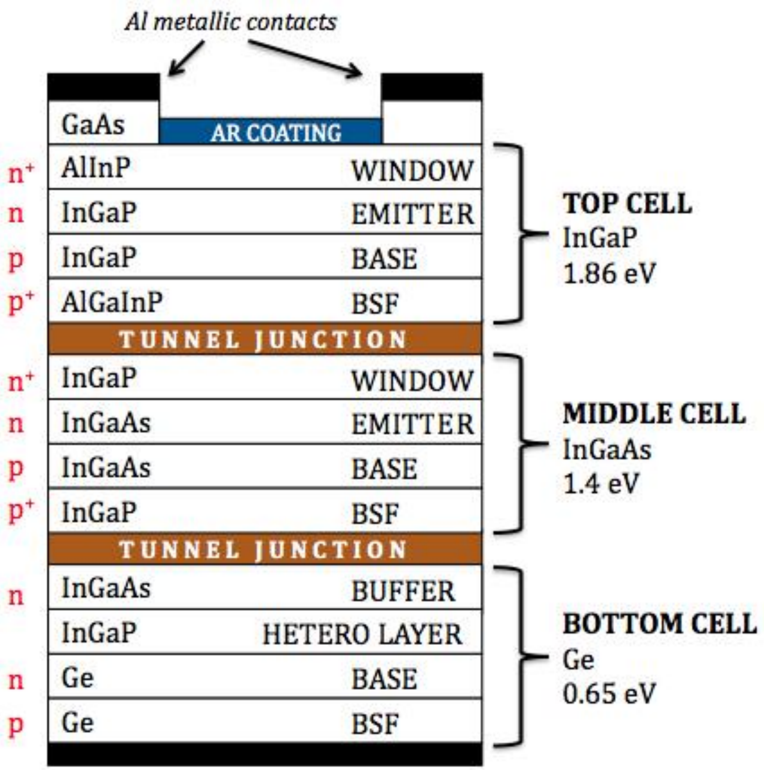
Cella cross-sectional view



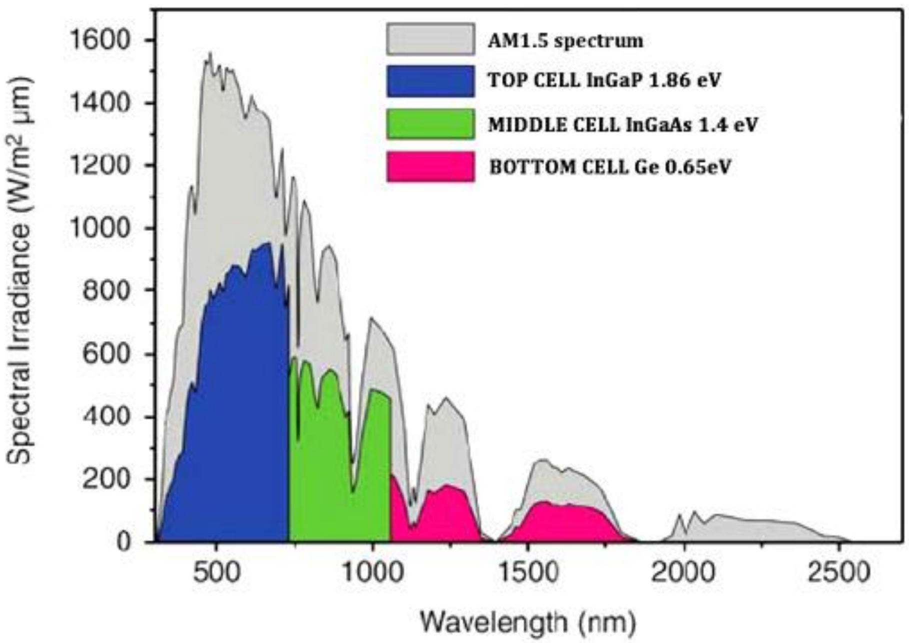
CIS stucture

Multijunction solar cells



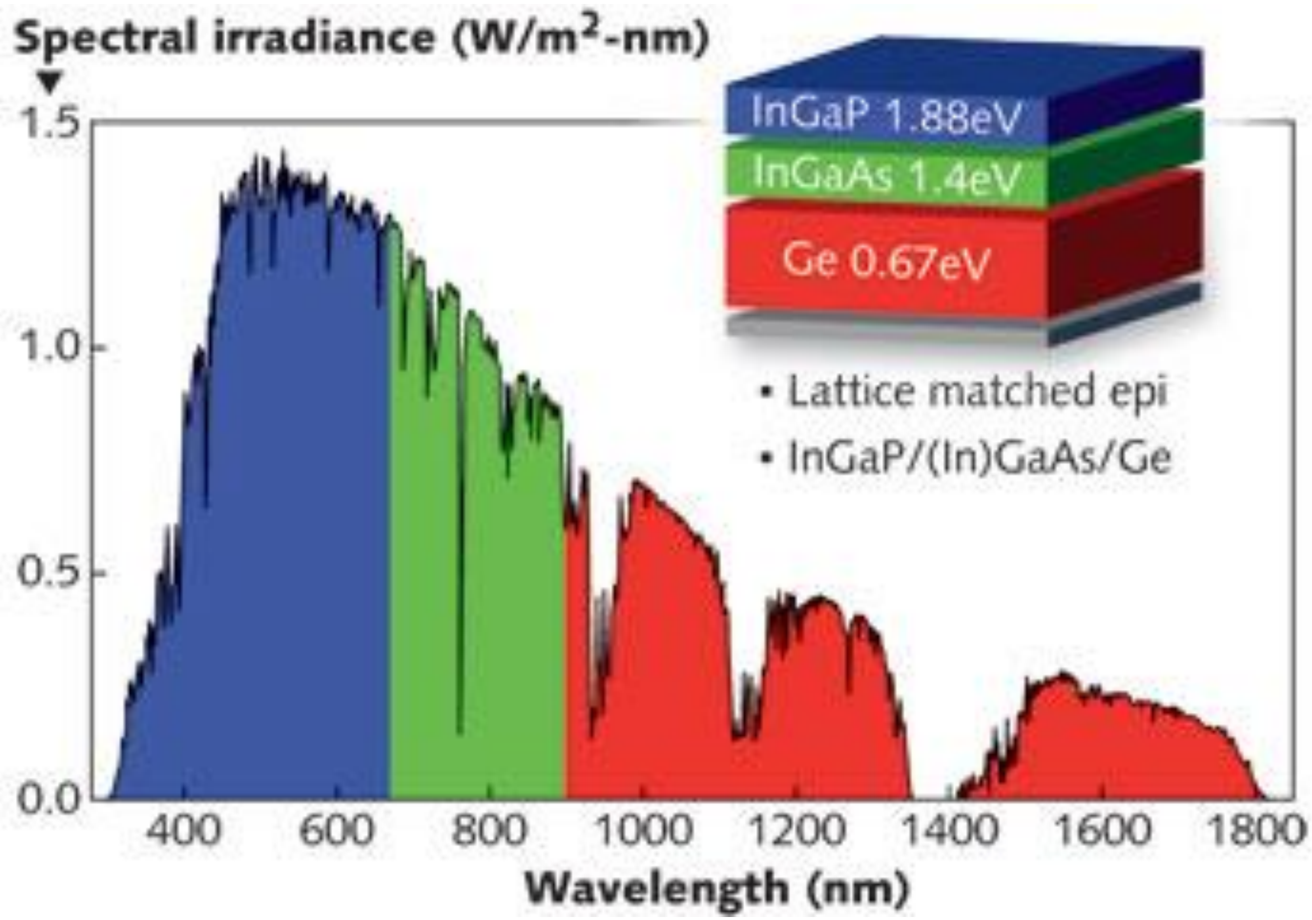


(a)

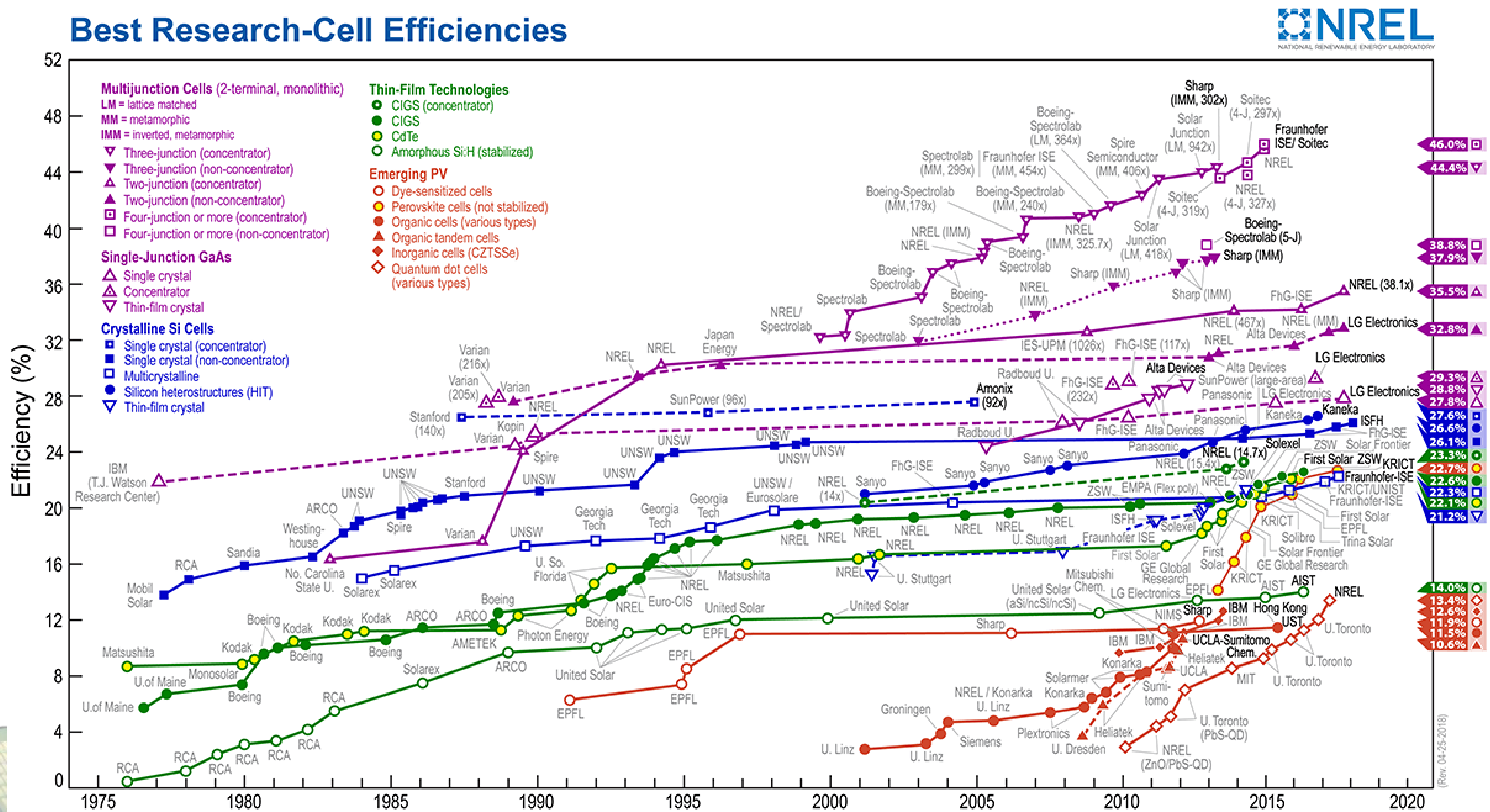


(b)

Multijunction solar cells



NREL efficiency chart



If you want to know more…

- Course: Solar Cells and Renewable Energy sources
  - 4 credits
  - 2 lectures (90 min) a week
  - BME VIEEAV99
  - https://portal.vik.bme.hu/kepzes/targyak/VIEEAV99/en/