F.-J. Haug

Photovoltaics and solar cells

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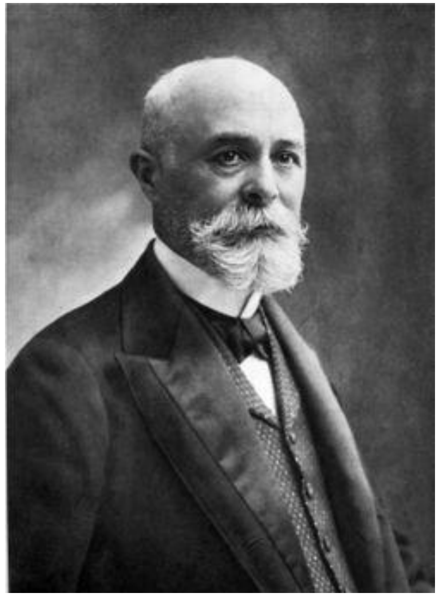
Photovoltaic effect

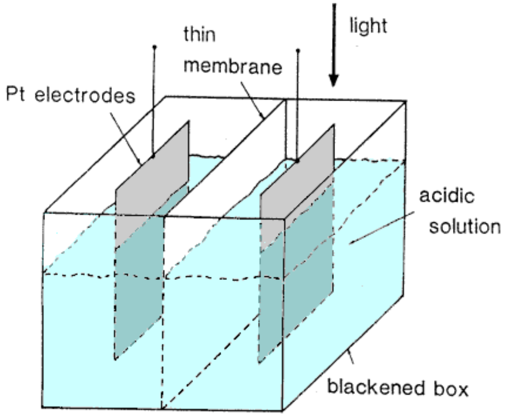
Discovered by Edmund Becquerel (son of Antoine César Becquerel) in 1839, at the age of 19

Experiment with electrolytic cell

Conductivity increased when exposed to light.

E. Becquerel, 'On electron effects under the influence of solar radiation.' Comptes Rendus 9, 561.





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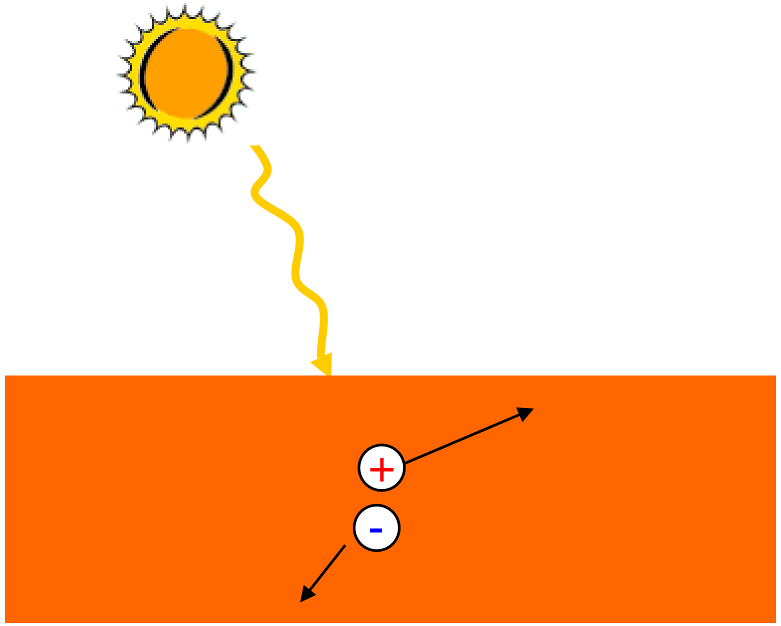
PV device - Physical principle

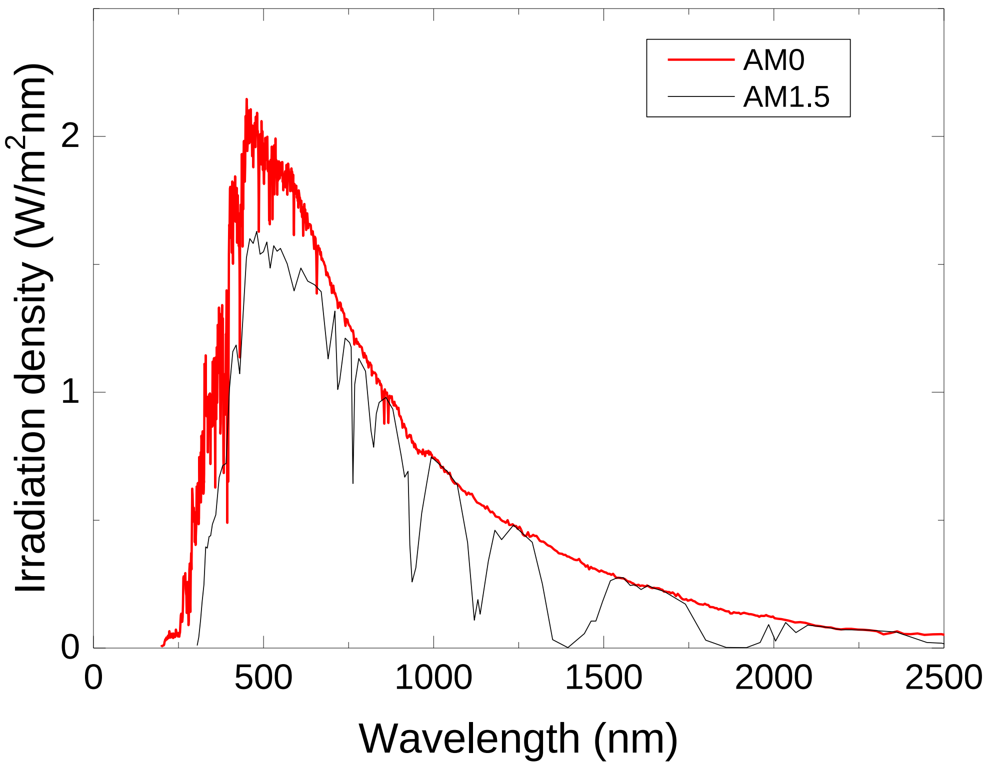


2 step process :

1) Absorption of a photon in a **semiconductor** to create an electron-hole pair

2) Separation of the electron-hole pair by an internal electric field or a diffusion gradient towards selective contacts, usually p-type and n-type regions of a diode (but not necessarily)

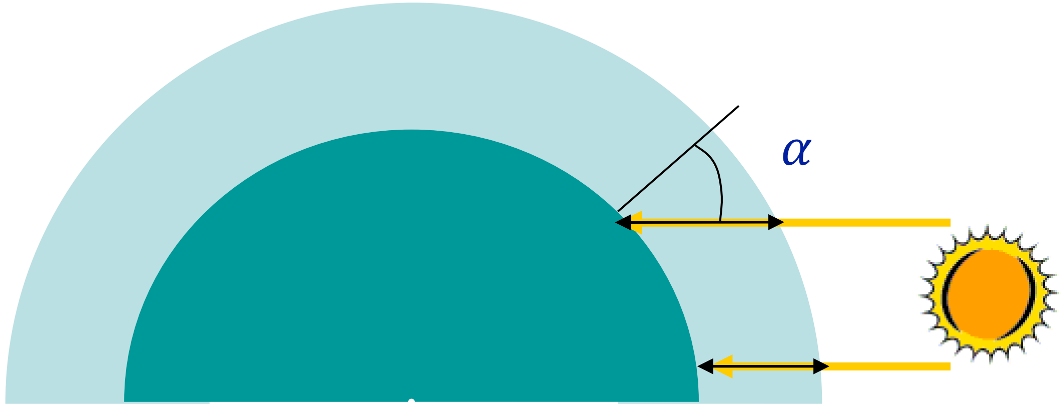
Solar spectra



$AM0$: resembles black body at 6500 K (Fraunhofer lines by photosphere)

$AM1.5$: standard for solar cells (approx. Central Europe or North America)

Air mass



- **Air Mass** : Attenuation (through the atmosphere)

$$AM = 1/\cos\alpha$$

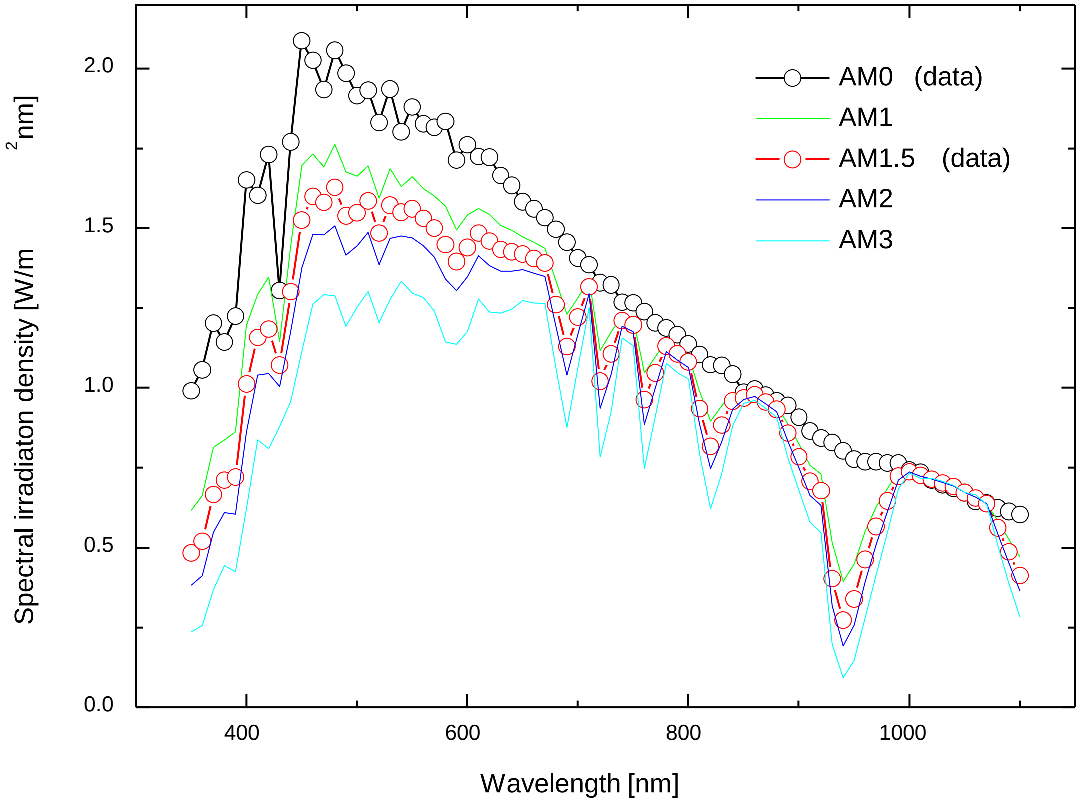
α : angle between sun and vertical

  - $AM0$: solar spectrum (outside of the atmosphere)
  - $AM1$: solar spectrum at equator with sun vertically above
  - $AM1.5$: sun at an angle of $\approx$ 48° with respect to the vertical direction.
  - AMx: defines both the **spectrum and the radiation intensity**. $AM1.5 \rightarrow$ 100 mW/cm^2

- Efficiencies of PV systems are usually calibrated for $AM1.5$

Spectral change of illumination

Daily (and seasonal) changes of spectral irradiation density



$AM0$: space

$AM1$: equator

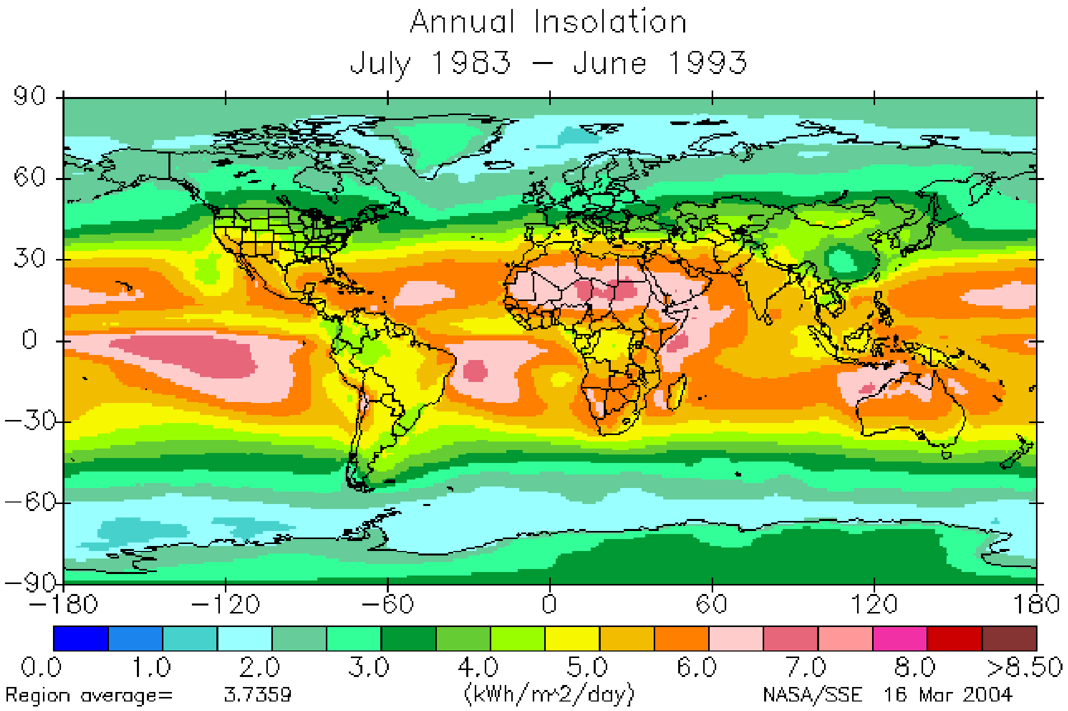
$AM1.5$: (central Europe, equinox, noon, 48° above horizon)

$AM2$: 30° above horizon

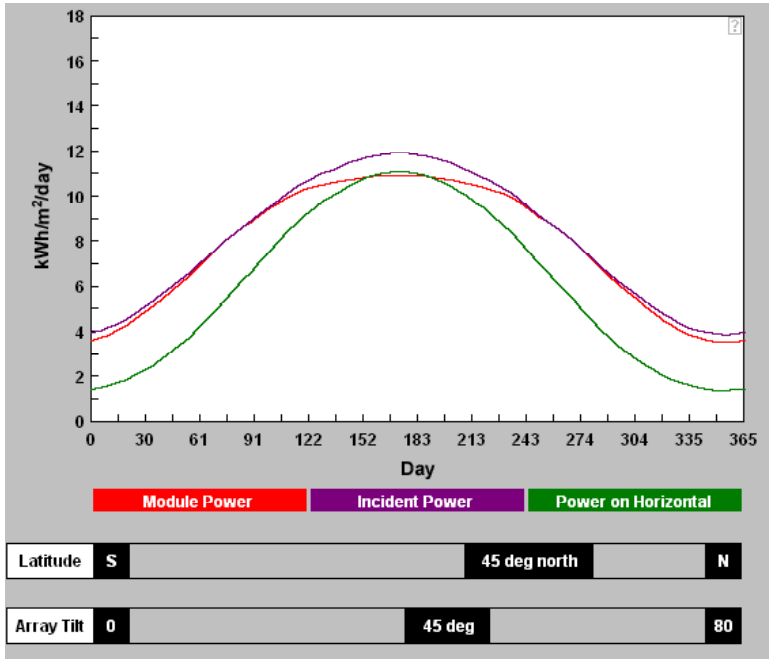
$AM3$: 20° above horizon

Changes are expected mostly in the visible part of the spectrum

Irradiation



- Yearly incident energy on solar panels (with a fixed orientation), weakly orientation dependent.
  - Irradiation (normal surface): 1 kW/m^2
  - Switzerland: 800-1200 kWh/m^2/year



Hourly variation of the insolation

- oriented twds. sun (purple)
- horizontal (green)

Module output (red)

(reduced at noon, high module temperature)

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Absorption process

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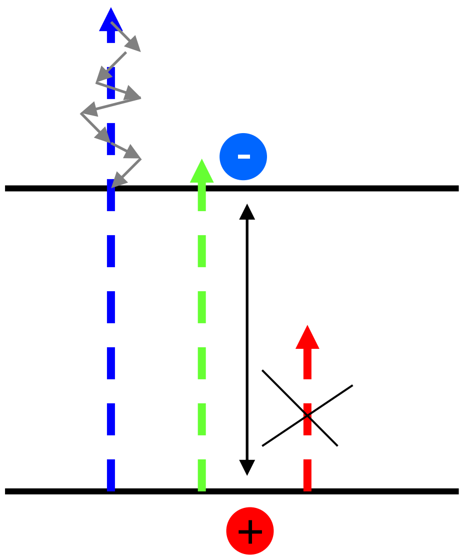
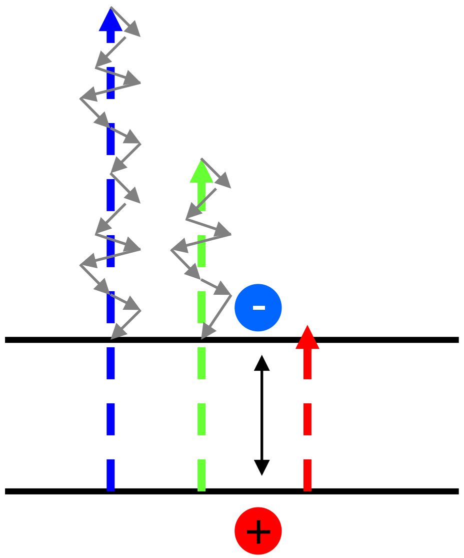
High band gap (e.g. a-Si)



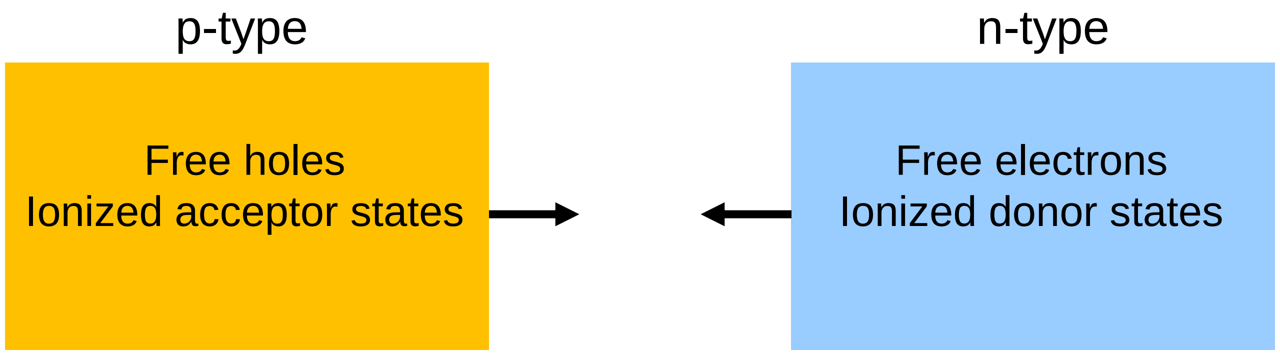
Low band gap (e.g. μc-Si)

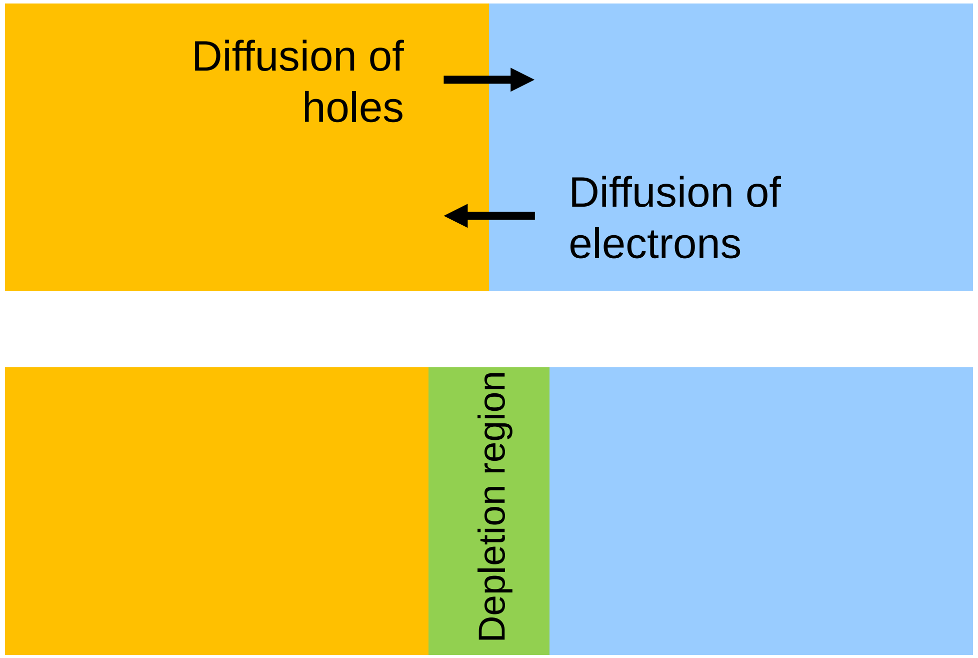


Photons with energy less than the band gap are not absorbed

Photon energy in excess of band gap is lost to thermalization

p-n junction formation

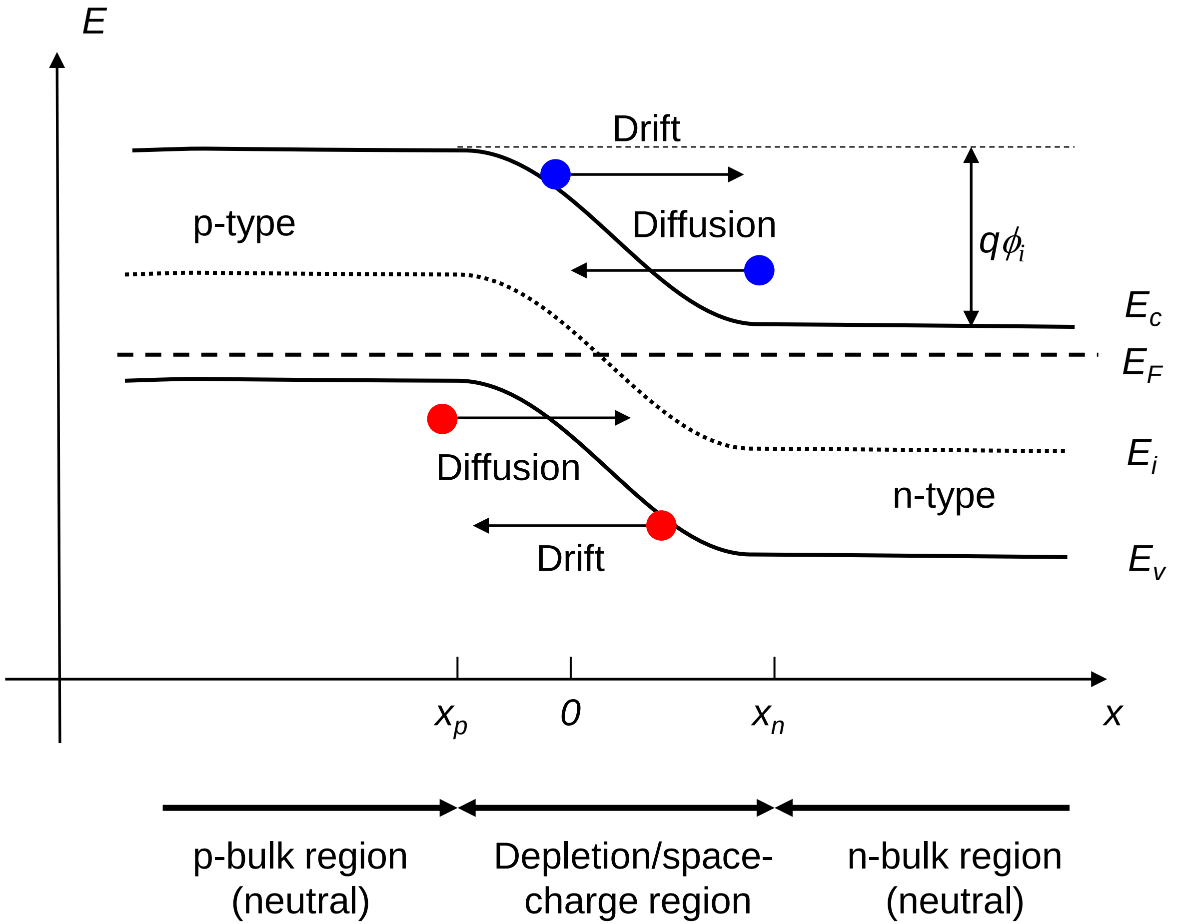




Depletion region =
Space charge region

In the depletion region :
Diffusion current = drift current

Thermal equilibrium diagram



Solar cell configurations

ideal p-n diode

(collection by diffusion in neutral region)

→ crystalline solar cells

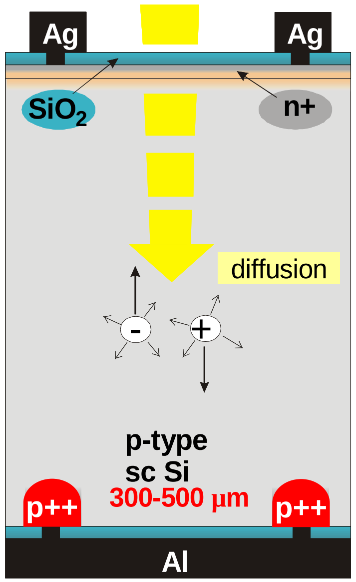
p-i-n structure

(collection by drift in field over i-region)

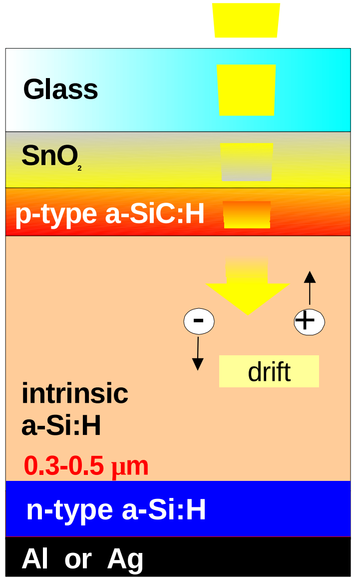
→ amorphous solar cells

→ photodetectors (crystalline or amorphous)

Crystalline Si solar cell



a-Si:H *p-i-n* solar cell



M. Zeman,
Delft University

Band diagram, internal field (dark, equilibrium)

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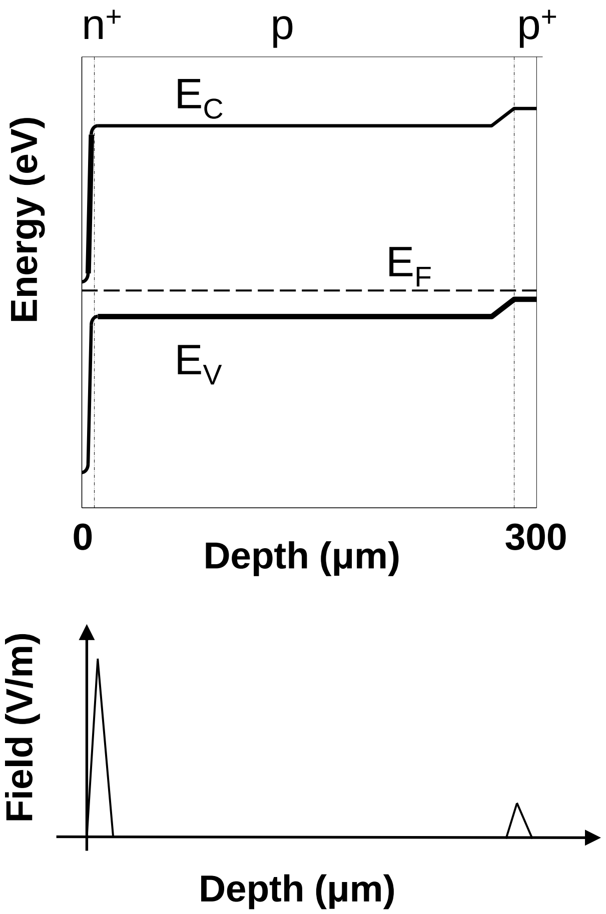
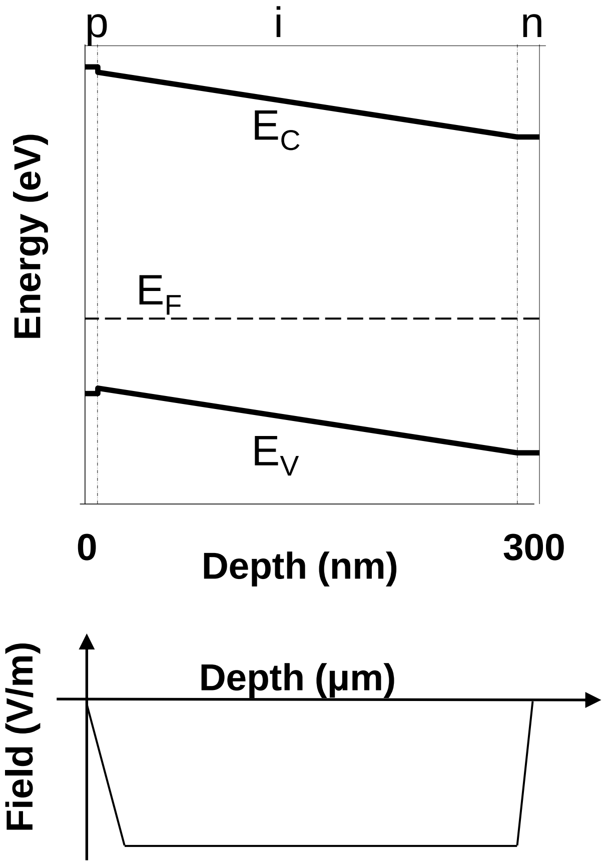
Crystalline Si solar cell



Narrow field region close to contacts

a-Si:H *p-i-n* solar cell



Field region extends throughout the device

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Deviation from equilibrium: forward / reverse bias

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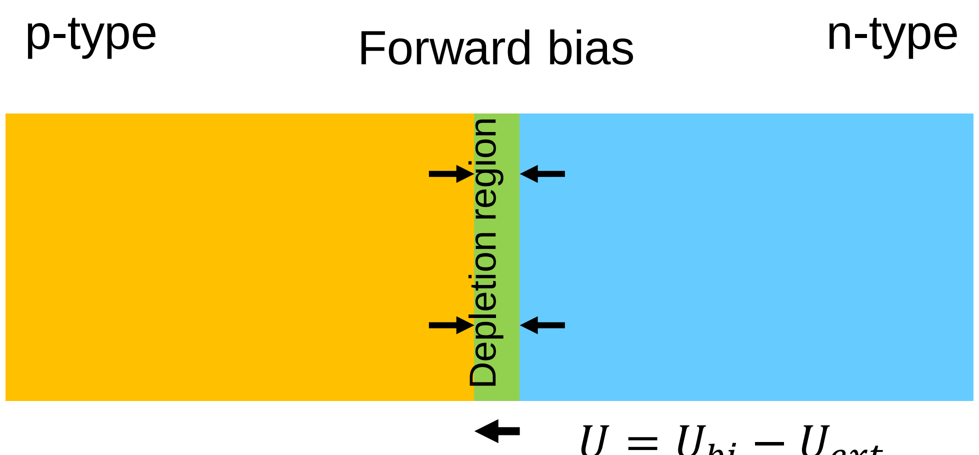
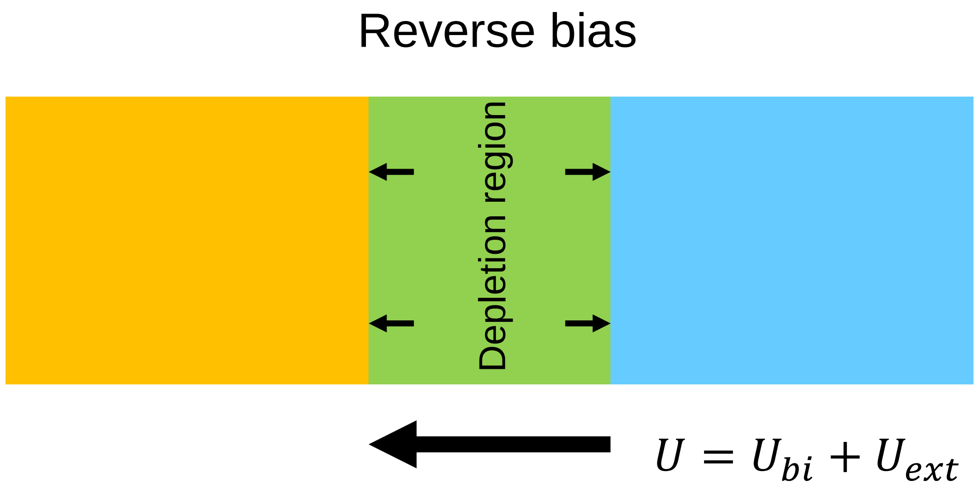


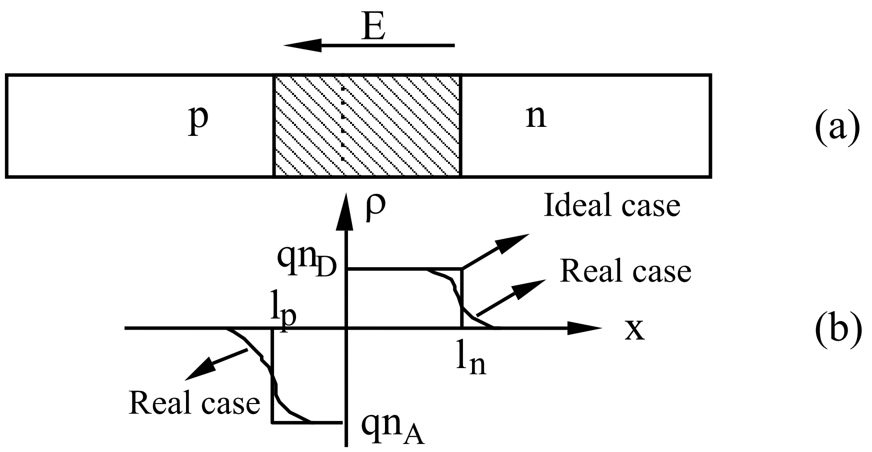
$$U = U_{bi} - U_{ext}$$



$$U = U_{bi} + U_{ext}$$

How to derive a j-V characteristics (p-n diode)?

Five approximations:



a) Abrupt p-n junction (transition between n and p region over a very short distance; $n_A > n_D$.

b) Distribution of the space charge

1. Depletion approximation: the p-n cell is divided in two types of regions:
   a) Two quasi-neutral regions ("bulk")
   b) A depletion zone (space charge region) no majority carriers, only charge of dopants (and minority carriers)

   → allows the determination of the charge distribution $\rho(x)$, the electric field $E(x)$ and the potential $\Phi(x)$ in the depletion zone.

2. in the depletion zone: $j_{drift} \approx j_{diff}$

   approximation is valid in open circuit condition ($j_{tot} = 0$) and holds approximately for small j_{tot}.
   → allows linking the concentrations $n(x)$ and $p(x)$ to the potential $\Phi(x)$

3. In the “bulk":
   - in the n-region: $n \gg p$
   - in the p-region: $p \ll n$

   (not valid for p-i-n cells, e.g. thin-film cells)

4. In the “bulk", minority carriers move by diffusion (drift is negligible for minority carriers).

   (not valid for p-i-n cells , e.g. thin-film cells)

5. Carrier recombination and generation is negligible in the depletion zone (which is very thin in p-n cells) → j_n and j_p are constant in this zone

   (not valid for p-i-n cells , e.g. thin-film cells).

Injection of carriers across SCR

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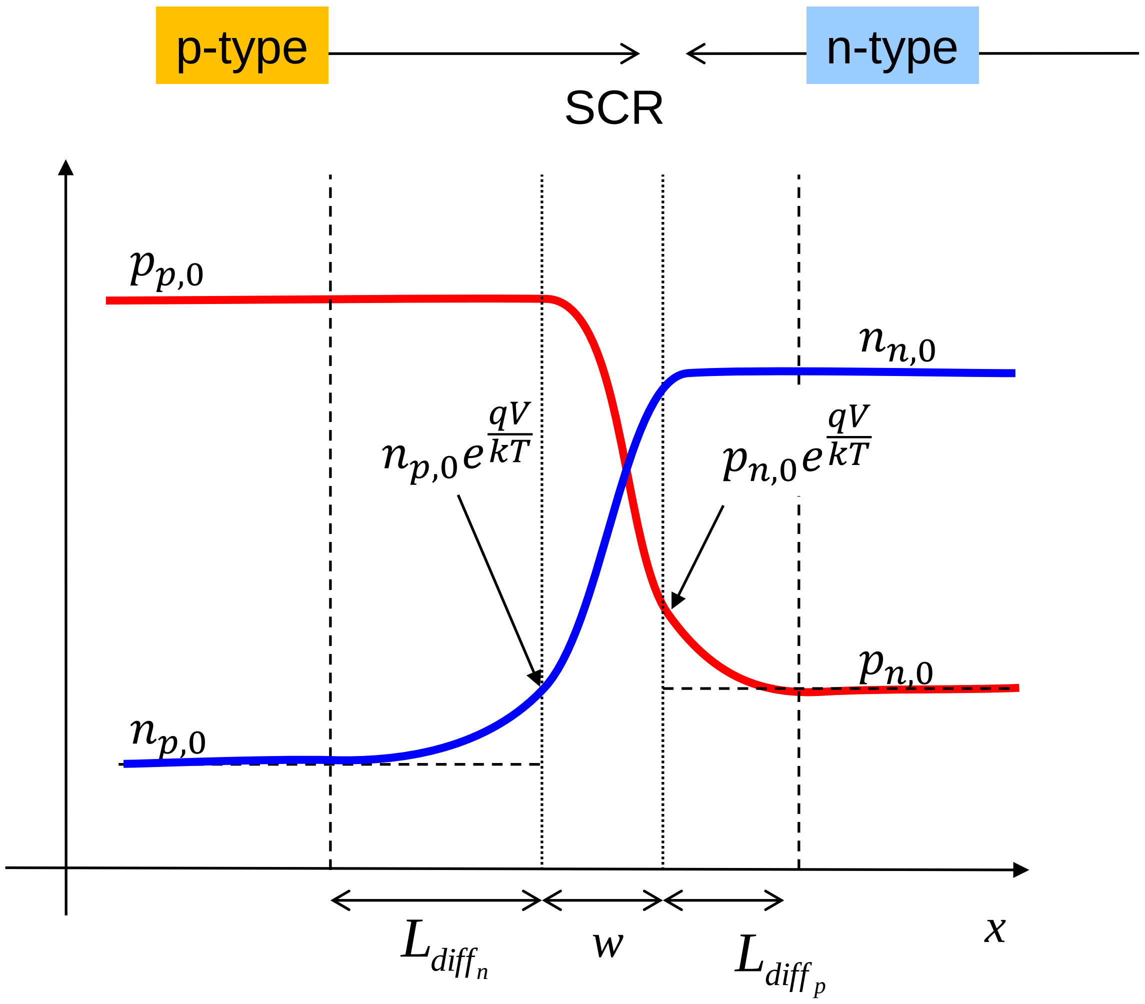
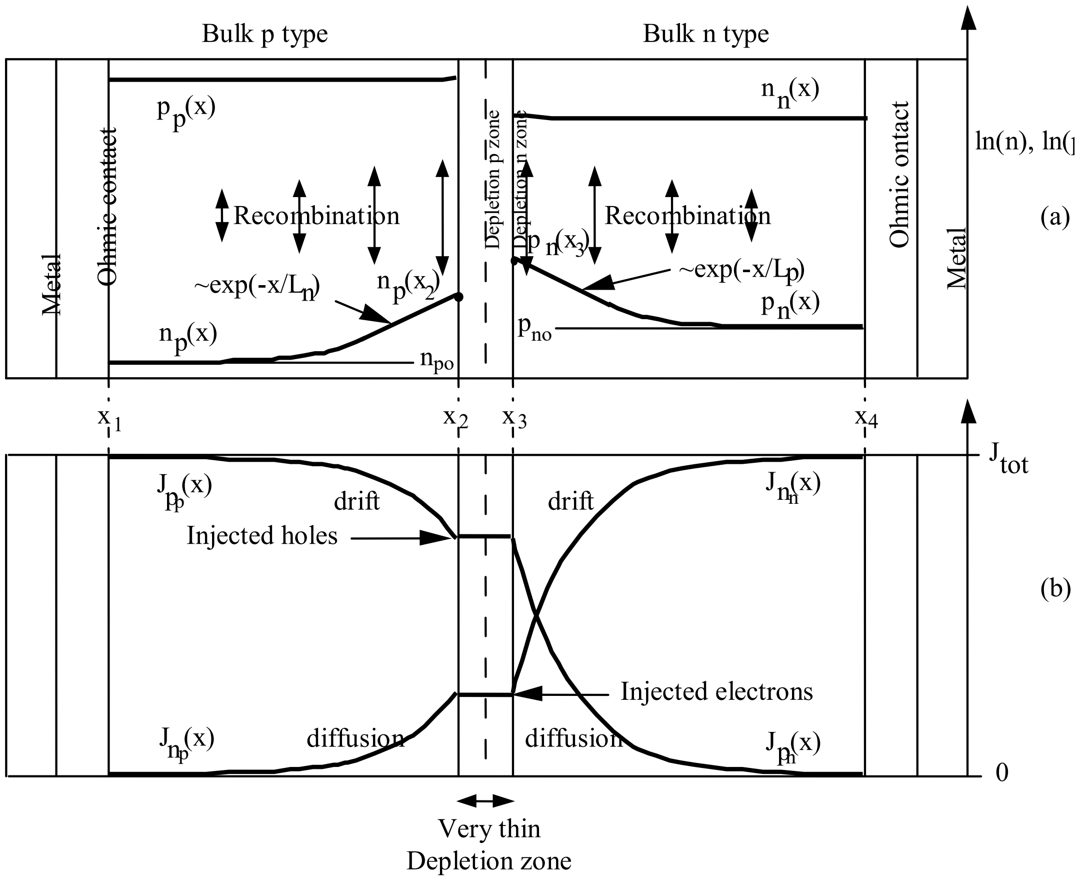


1. Take majority on one side, e.g. $p_{p,0}$
2. Calculate minority on other side, far away from SCR, e.g. $p_{n,0}$
3. Calculate enhancement due to bias voltage, at edge of SCR => $p_{n,0}e^{\frac{qV}{kT}}$
4. Solve drift-diffusion eqn. for $p_n(x)$
5. Calculate current

Diode in forward (in the dark)



(a) Free carrier distribution
(b) Current distribution in the junction

- Inject majority carriers twds. junction (e.g. holes from p-region)
- Once the junction is crossed, those carriers become minority carriers
  - → their concentrations at the edge of the junction are higher than the equilibrium concentrations
  - → they diffuse into the neutral regions
  - → they recombine within ca. one diffusion length

Diode equation (Shockley)

Ideal I(V) characteristics in the dark (diffusion model)

- Solving the transport, continuity and Poisson equations (with the 5 approximations):

$$j_{dark} = I/A = j_0 \left[\exp\left(\frac{qV}{kT}\right) - 1\right]$$

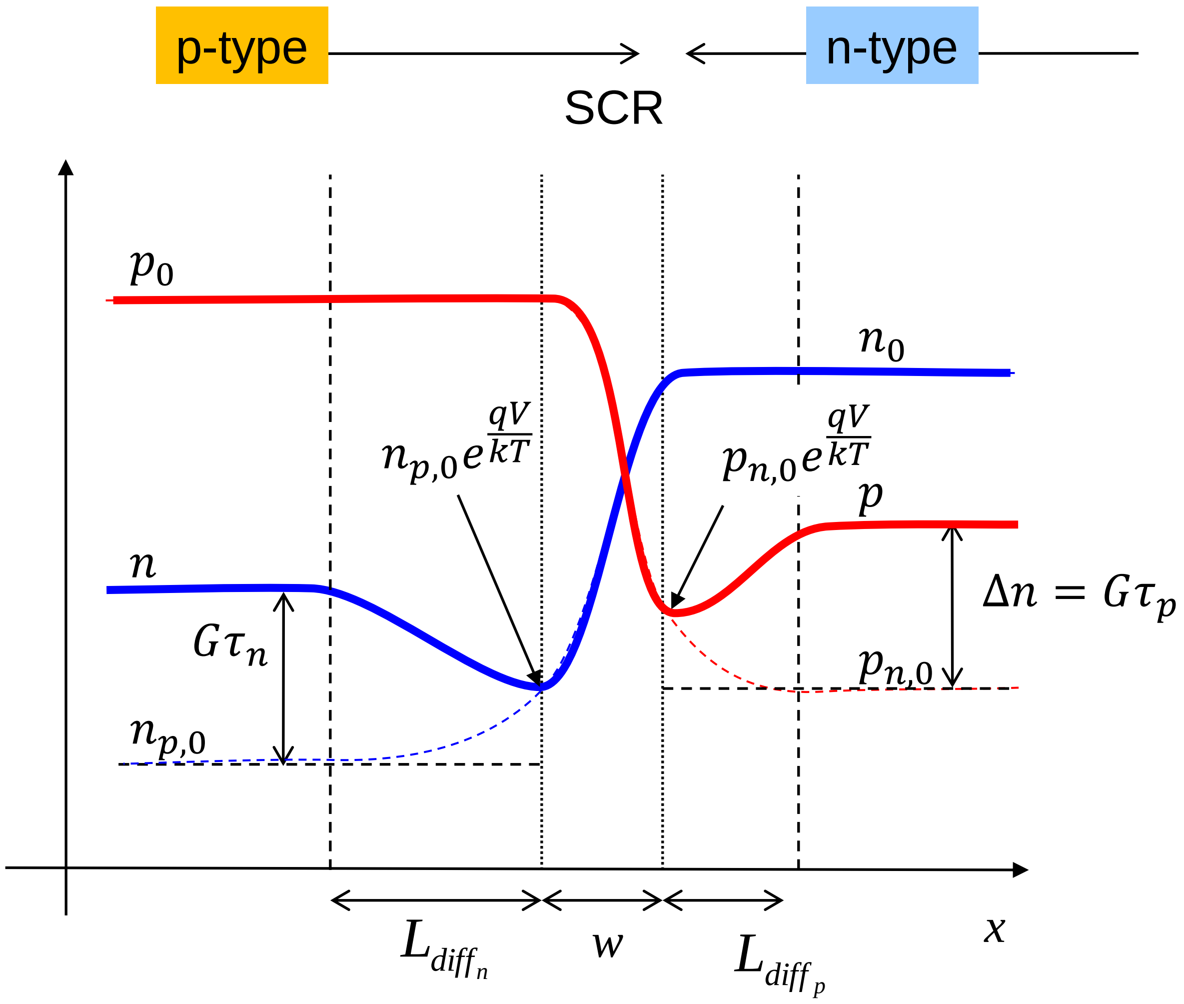
with

$$j_0 = \left[\frac{qD_n n_i^2}{L_n N_A} + \frac{qD_p n_i^2}{L_p N_D}\right]$$

where

k : the Boltzmann constant
q: the elementary charge
T: the absolute temperature
A: the junction area
N_A, N_D: the dopant densities
n_i: intrinsic carrier density
D_p, D_n: diffusion constants of the minority carriers in the p, resp, n region
L_p, L_n: diffusion length of the minority carriers in the n, resp, p region

I-V characteristics under illumination



1. Take majority on one side, e.g. $p_{p,0}$
2. Calculate minority on other side, far away from SCR, e.g. $p_{n,0} + \Delta n$
3. Calculate enhancement due to bias voltage, at edge of SCR => $p_{n,0}e^{\frac{qV}{kT}}$
4. Solve drift-diffusion eqn. for $p_n(x)$
5. Calculate current

I-V characteristics under illumination

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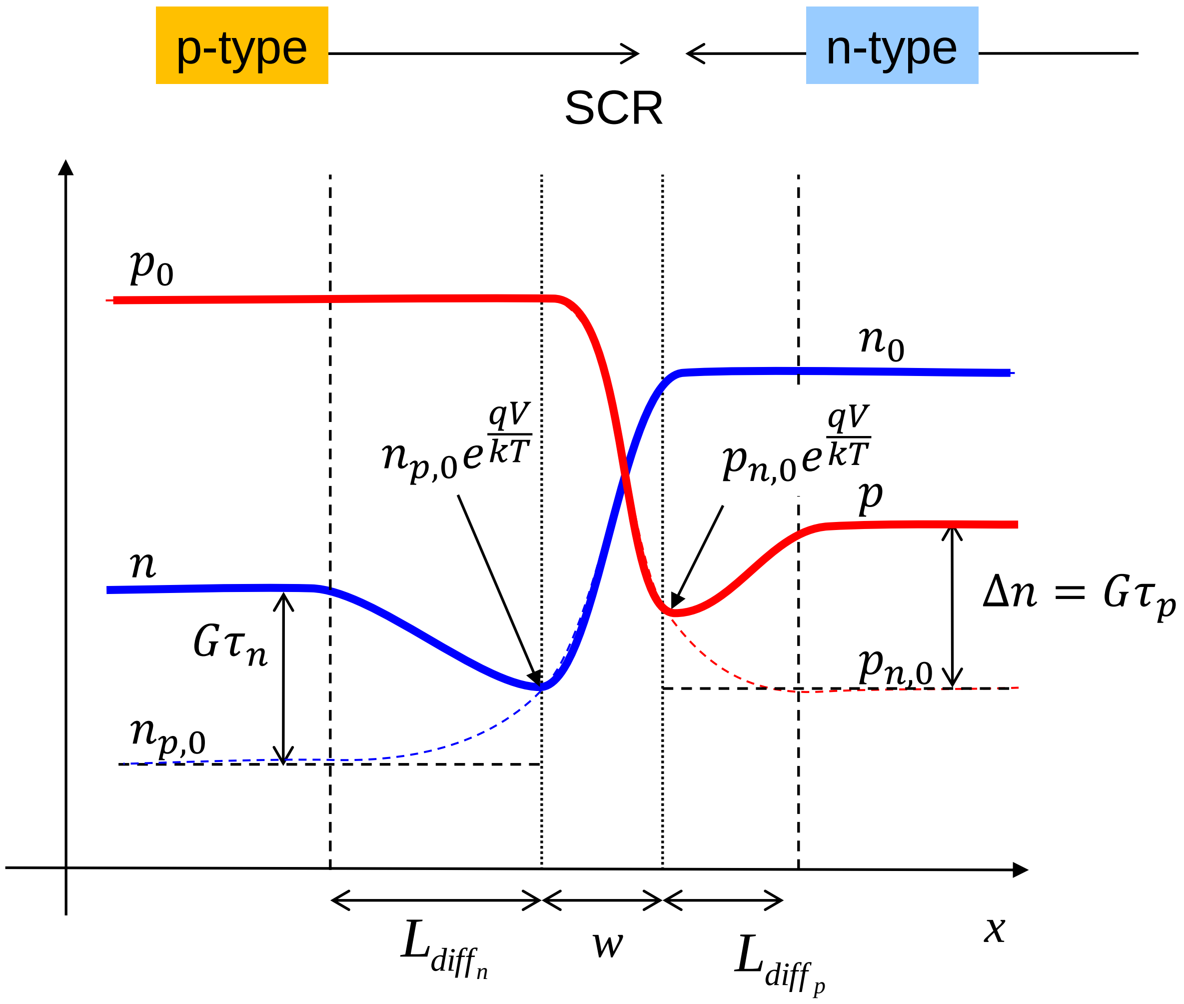


- The four first approximations are still valid under illumination
- Taking into account the generation rate:

$$j = J_0\left[\exp\left(\frac{qV}{kT}\right) - 1\right] - j_L$$

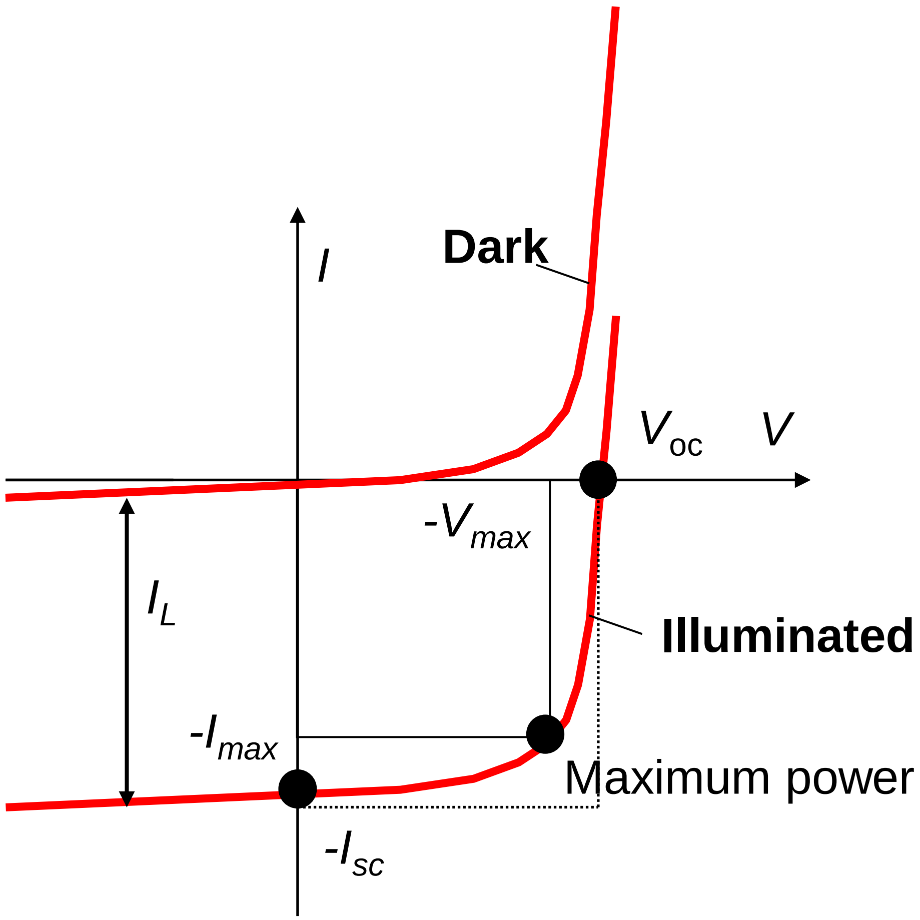
with

$$j_L = qG(L_n + w + L_p)$$

where

- G: a uniform generation rate
- j_0: diode saturation current density
- j_L: current density given by the photo carriers in the depletion region and in a region given by the diffusion length of the minority carriers (on both side of the depletion region)

Superposition principle



"Superposition" principle of the photogenerated current j_L

$$j(V) = j_{dark} - j_L$$

Principle valid for a p-n diode in ideal conditions (in general not valid for a-Si:H diodes)

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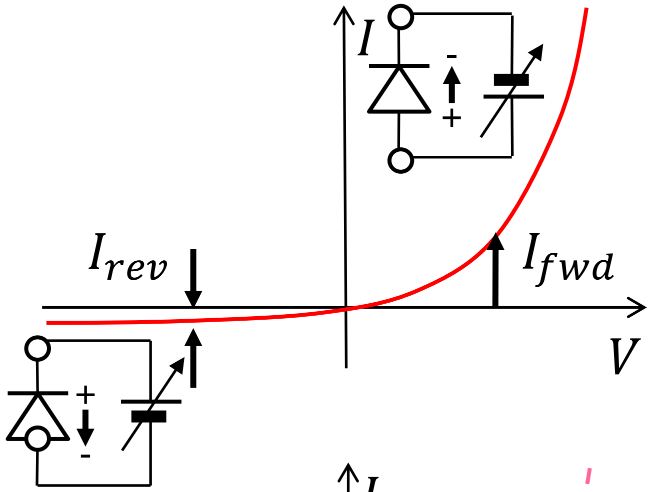
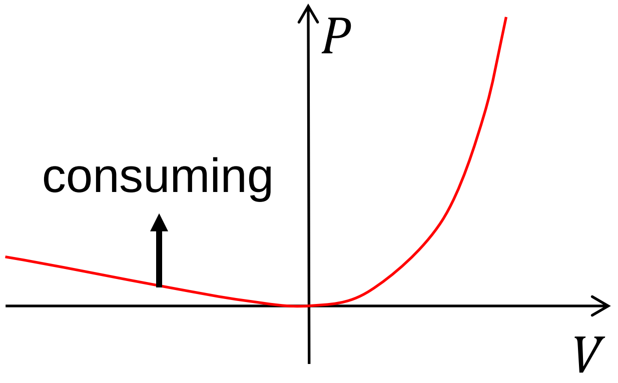
Sign convention

dark

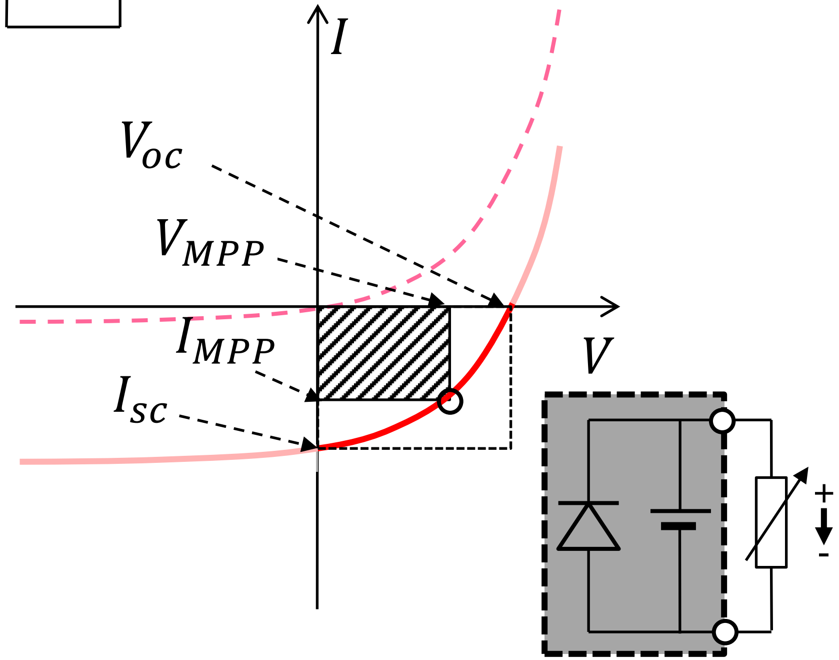
$$j = J_0\left[\exp\left(\frac{qV}{kT}\right) - 1\right]$$

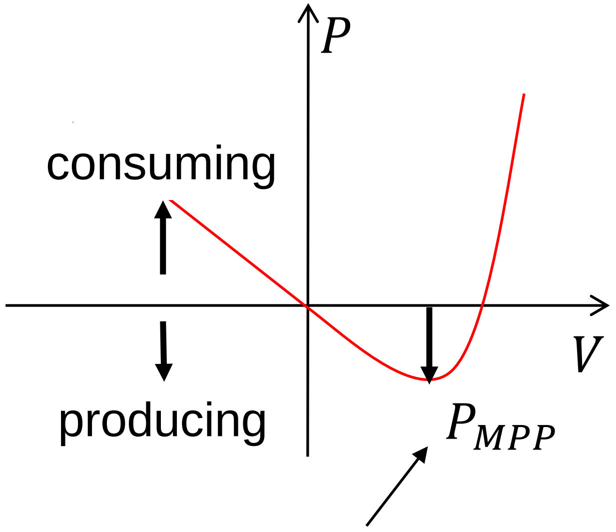




light

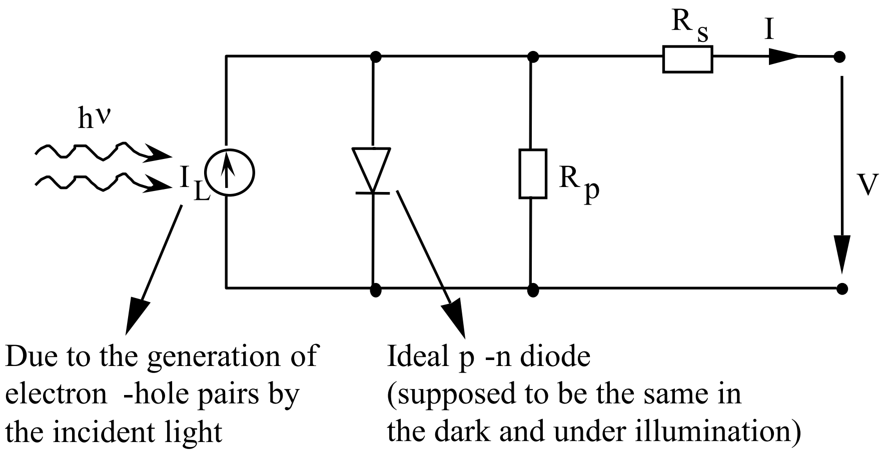
$$j = J_0\left[\exp\left(\frac{qV}{kT}\right) - 1\right] - j_L$$

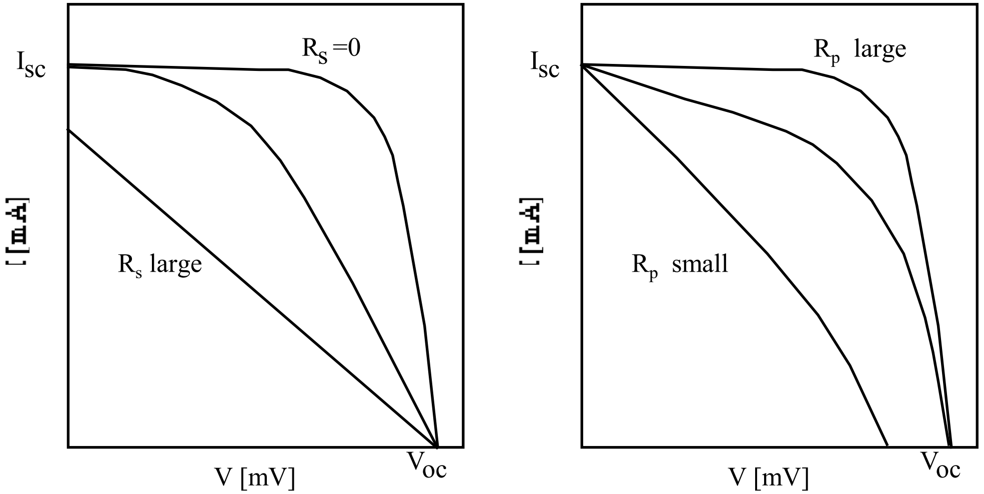




Power can be delivered to a load !

Equivalent circuit of a p-n solar cell





Empiric addition to account for current transport contacts:

series resistance R_s:

- the resistance of the metallic connections
- the resistance of the metal-semiconductor interfaces (ohmic contacts);
- the resistance of the semiconducting layers.

Empiric addition to account for imperfections

parallel resistance (or shunt) R_p:

- the leakage currents at the junction periphery
- impurities in the junctions
- additional recombination (with respect to the ideal diode)

(Note: $j(V)$ flipped into first quadrant is often found in literature)

Solar cell with two-diode model

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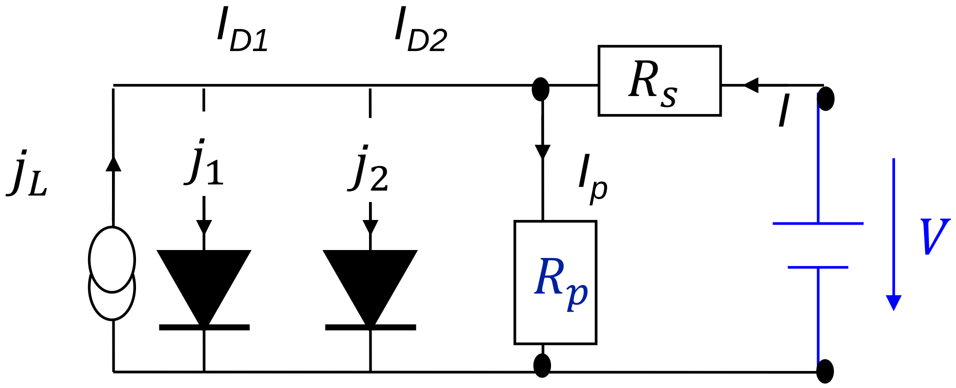
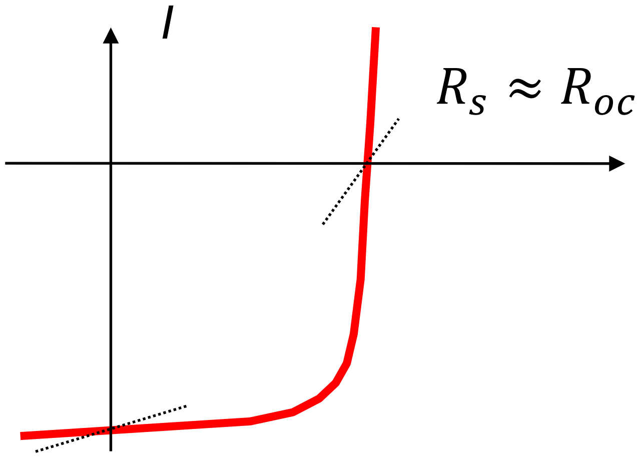
For **crystalline Si** the so-called
2 diode model is often used





$$R_s \approx R_{oc} = \left.\frac{dV}{dj}\right|_{V_{oc}}$$

$$R_p \approx R_{sc} = \left.\frac{dV}{dj}\right|_{V=0}$$

R_s series resistance (must be small)
R_p parallel resistance (must be high)

$$j(V) = j_{0,1}\left(\exp\left(\frac{qV - jR_s}{n_1 kT}\right) - 1\right) + j_{0,2}\left(\exp\left(\frac{qV - jR_s}{n_2 kT}\right) - 1\right) + \frac{V - jR_s}{R_p} - j_L$$

Equation of the two diodes circuit

Empirical expression

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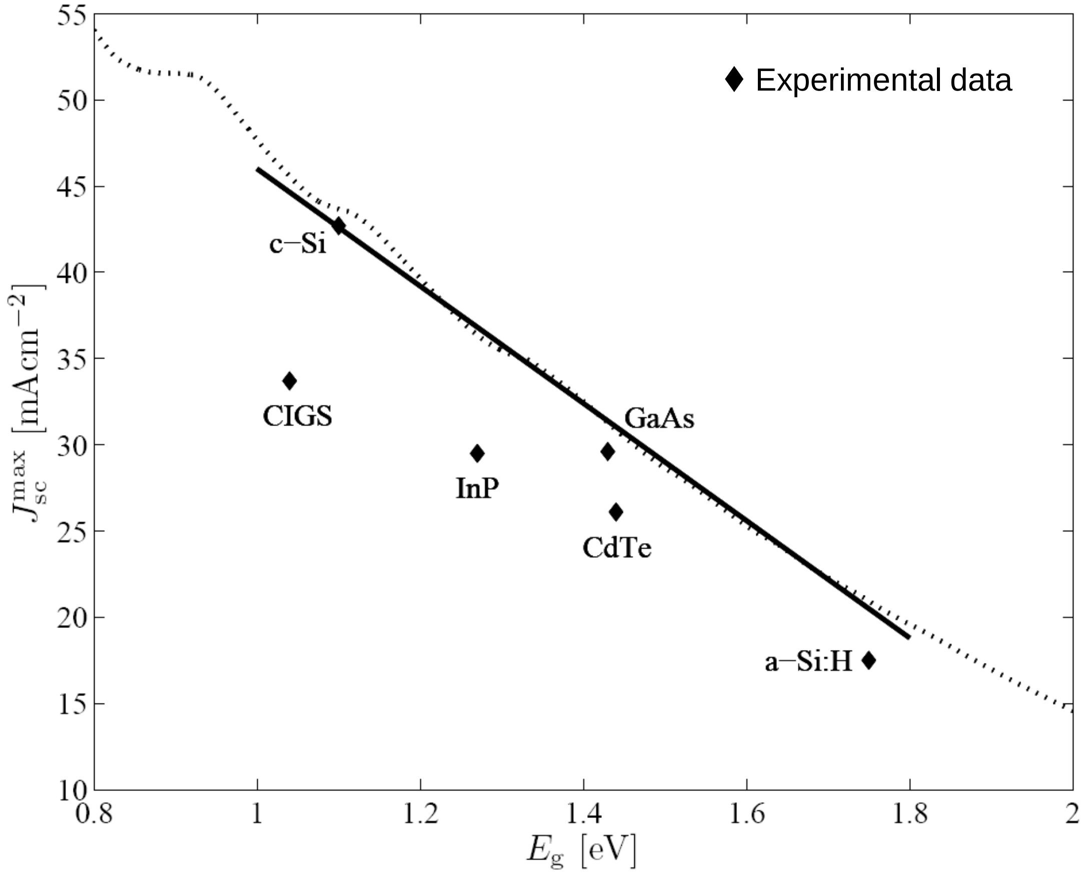
- The expressions $j_{0,n}$ and $j_{0,p}$ comprise parameters that have to be determined experimentally (not always possible)

- They can be replaced by a more simple empirical expression for the saturation current j_0:

$$j = \underbrace{j_{00} \exp\left(-\frac{E_g}{kT}\right)}_{j_0} \cdot \exp\left(\frac{qV}{nkT}\right) - j_L$$

- j_0: empiric dependence on bandgap (expressing only n_i^2, ignoring τ, D, etc.)
- n: diode quality factor

Limiting efficiency: short-circuit current I_{sc}



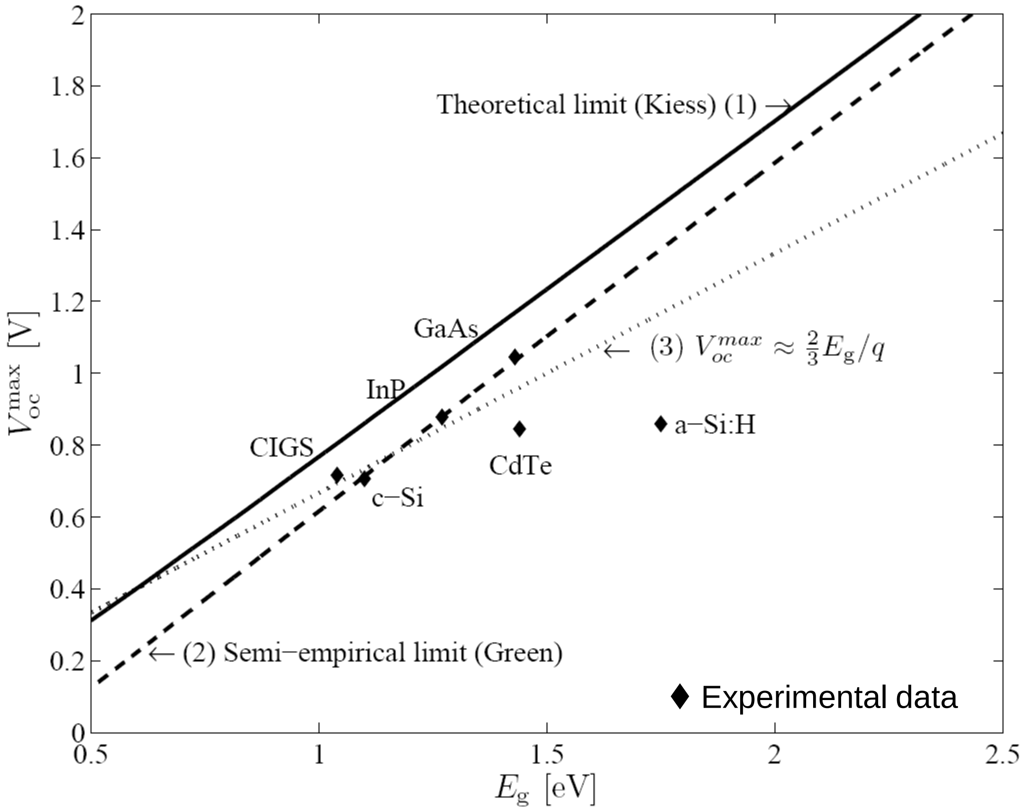
Theoretical maximum short-circuit current under AM1.5 illumination

- Assuming $R_s = 0$ et $R_p = \infty$
- Ideal illuminated diode in short-circuit condition

$$I_{sc}=I_L$$

- Theoretical maximum of I_{sc} given by :
  - solar spectrum
  - semiconductor gap: $I_{sc}= \phi q$, with
    - ϕ: number of photogenerated "electron-hole" pairs per unit time
    - q: elementary charge
- Hypothesis for this limit:
  - cell thickness sufficient for absorbing all useful light
  - total collection of the carriers
  - no recombination.
- Effect of the temperature:
  - I_{sc} only very weakly temperature dependent (E_g decreases when the temperature increases).

Limiting efficiency: open-circuit voltage V_{oc}



Open-circuit voltage Voc as a function of the gap for a AM1.5 illumination with the approximations: (1) $V_{oc} \approx \frac{2}{3}\frac{E_g}{q}$

(2) $V_{oc} \approx \frac{k_B T}{q} ln\left(\frac{1}{1,5\ 10^8}\frac{I_L}{[mA/cm^2]}\right) + \frac{E_g}{q}$

where the values I_L are obtained from the Fig. 7.26, (3) theoretical limit of Kiess [Kiess, 1995]

- The voltage supplied by a cell directly depends on gap E_g
- Ideal open-circuit voltage V_{oc} given by:

$$I = I_L - I_0\left[\exp\left(\frac{qV_{oc}}{k_B T}\right) - 1\right] = 0$$

$$\Rightarrow \quad V_{oc} = \frac{k_B T}{q}\ln\left(\frac{I_L}{I_0} + 1\right)$$

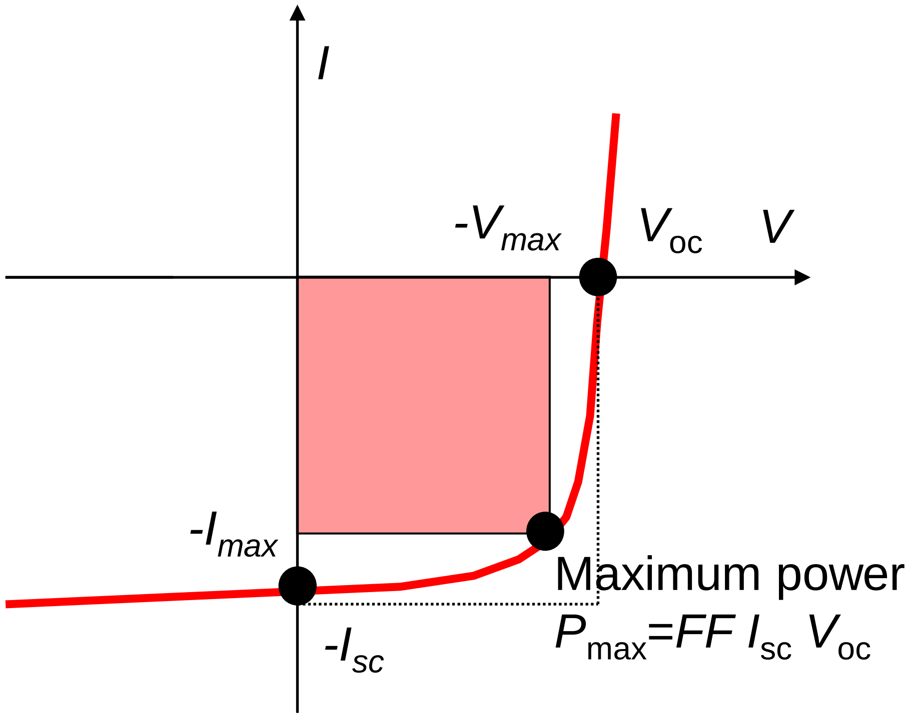
Formula does not explicitly contain E_g

- From the empirical expression of the ideal p-n diode $V_{oc} \approx \frac{k_B T}{q} ln\left(\frac{1}{1,5\ 10^8}\frac{I_L}{[mA/cm^2]}\right) + \frac{E_g}{q}$

V_{oc} is a quasi linear function of the gap

- Limits
  - E_g/q is an upper bound for V_{oc}: $V_{oc} \approx \frac{2}{3}\frac{E_g}{q}$
  - V_{oc} increases if I_L increases → advantage of cells working with light concentration (higher efficiencies).
- Temperature effect
  - V_{oc} decreases almost linearly when the temperature increases (0,4% per degree Celsius for c-Si).

Fill-factor and cell power



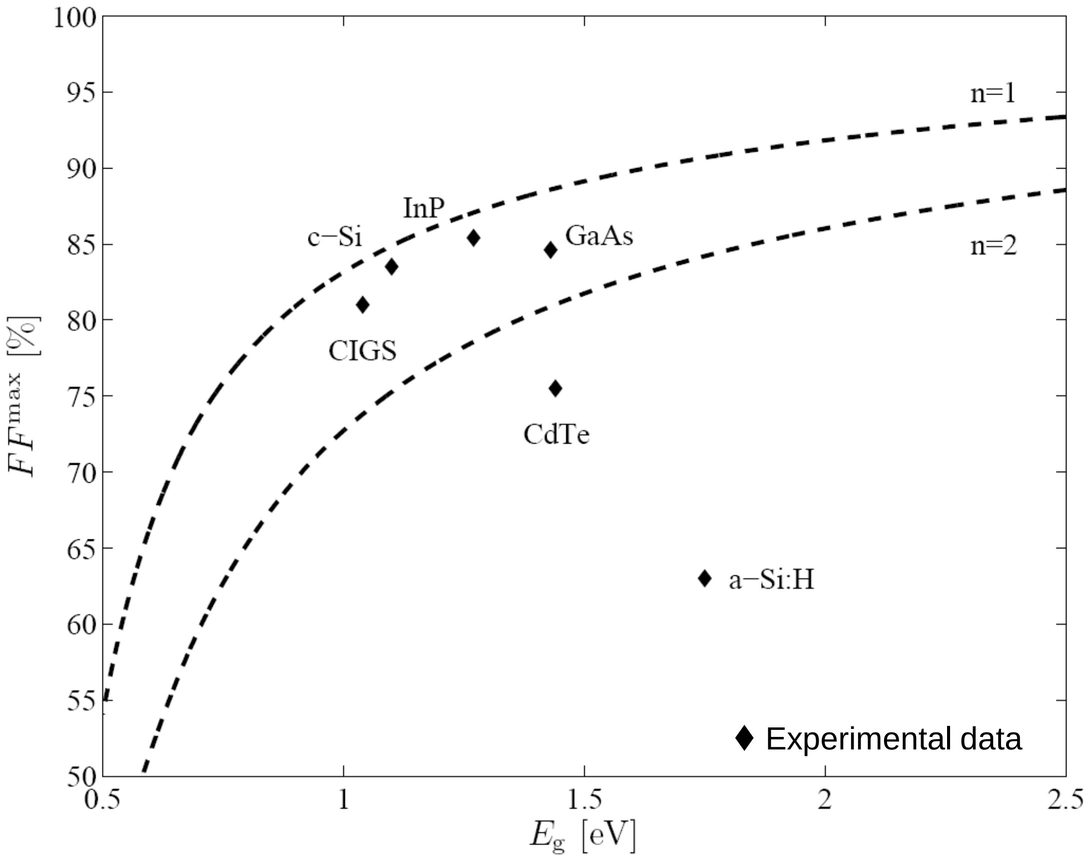
- Fill- factor FF defined as

$$FF = \frac{I_{\max}V_{\max}}{I_{sc}V_{oc}} = \frac{P_{\max}}{I_{sc}V_{oc}}$$

where I_m, V_m are the current and voltage when the cell output power is maximum (maximum power point)

- For a quality solar cell:
  - 0.7 < FF < 0.8 (a-Si:H)
  - 0.8 < FF < 0.85 (c-Si)

Fill-factor FF



semi-empirical value of Fill-factor FF as a function of the gap for two values of the ideality factor n and for an AM1.5 illumination.

- ideally, FF is a function of the open-circuit voltage V_{oc}

$$FF = \frac{v_{oc} - \ln(v_{oc} + 0.72V)}{v_{oc} + 1}$$

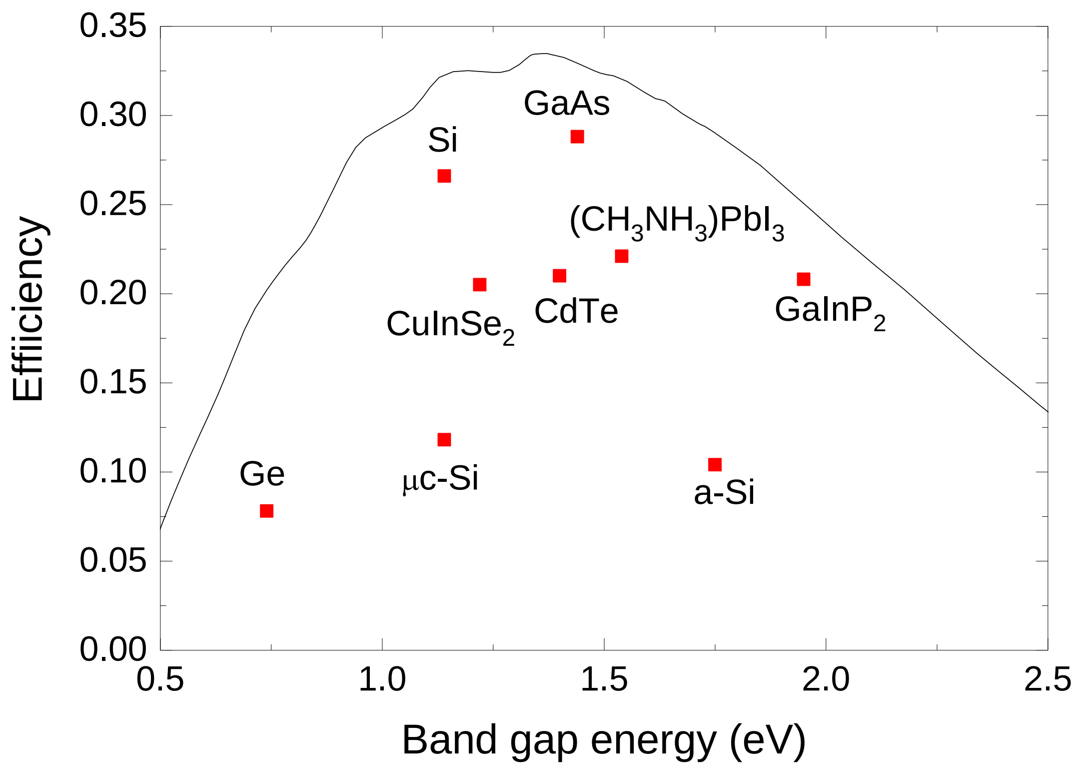
with $$v_{oc} = \frac{V_{oc}}{nk_B T / q}$$

valid for v_{oc} >10, n: ideality factor

- FF is a very sensitive indication of the solar cell quality!

- Temperature effect:
  FF decreases with increasing T
  - decrease of V_{oc}
  - increase of Rs

Efficiency



maximum "theoretical" limit η as a function of gap E_g under AM1.5 illumination

- The efficiency η is defined as:

$$\eta = P_{\max} / P_{inc}$$

with $P_{max} = I_m V_m = FF\, I_{sc} V_{oc}$

- The total solar cell efficiency is given by:

$$\eta = \eta_{p/n} . \eta_s$$

$\eta_{p/n}$ being the efficiency of the carrier separation (second step)

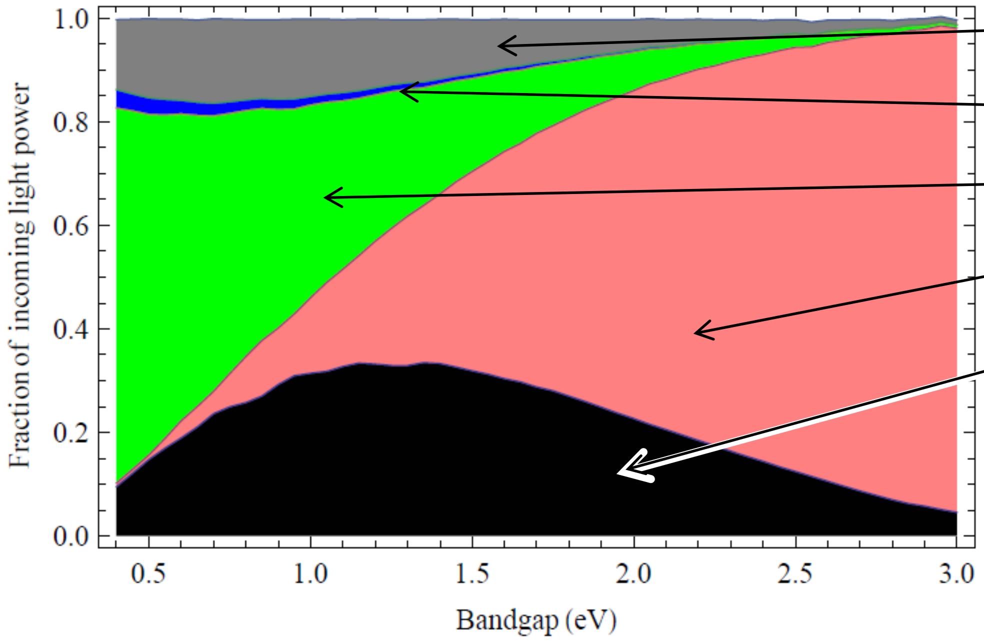
$$\eta_{p/n} = FF \left(\frac{V_{oc}}{E_g / q} \right)$$

and η_s the spectral conversion efficiency.

- Practically

$\eta = I_{sc}$ [mA/cm²] V_{oc} [V] FF / 100 [mW/cm²]

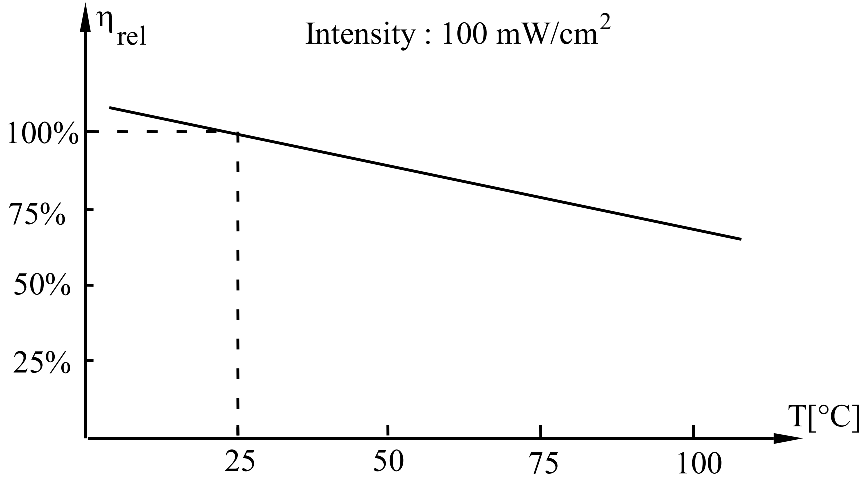
Shockley-Queisser limit: efficiency vs. bandpgap

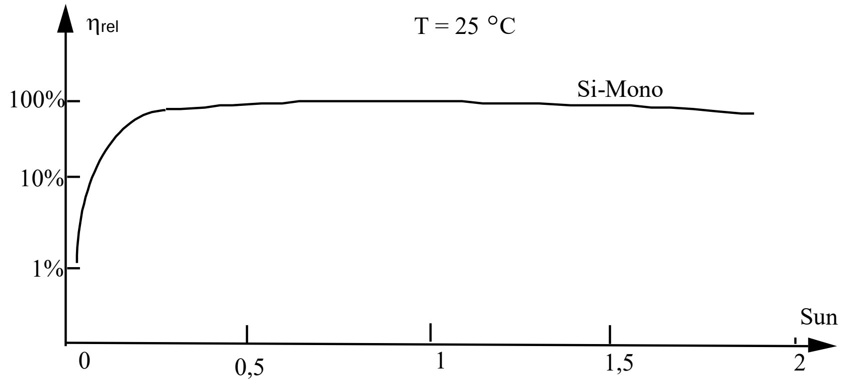


- Voltage less than bandgap
- Radiative recombination
- E-h relaxation to band edges
- Below-gap photons
- **Useful electricity**

Hirst, Prog. in PV (2011)

Efficiency dependences





- Effect of temperature
  - For c-Si : η decreases by 0.4-0.5 %/˚C
  - For a-Si : η decreases by 0.2-0.3 %/˚C
  - Decrease is less important for high bandgap materials.
- Effect of the light intensity
  - normally: η increases with intensity (Voc depends on injection level)
  - η may decrease at low intensity (loss in R_p)
  - η may decreases at high intensity (loss in R_s, increase of the temperature, diffusion model no more valid; use diode model with high injection).

Practical losses

- Recombination loss
  - not only BB radiation, but defects (SRH) and Auger recombination (important in Si)

- Dead zones
  - high surface recombination (needs surface passivation, "window layer")
  - Doped layers in a-Si:H and µc-Si:H cells

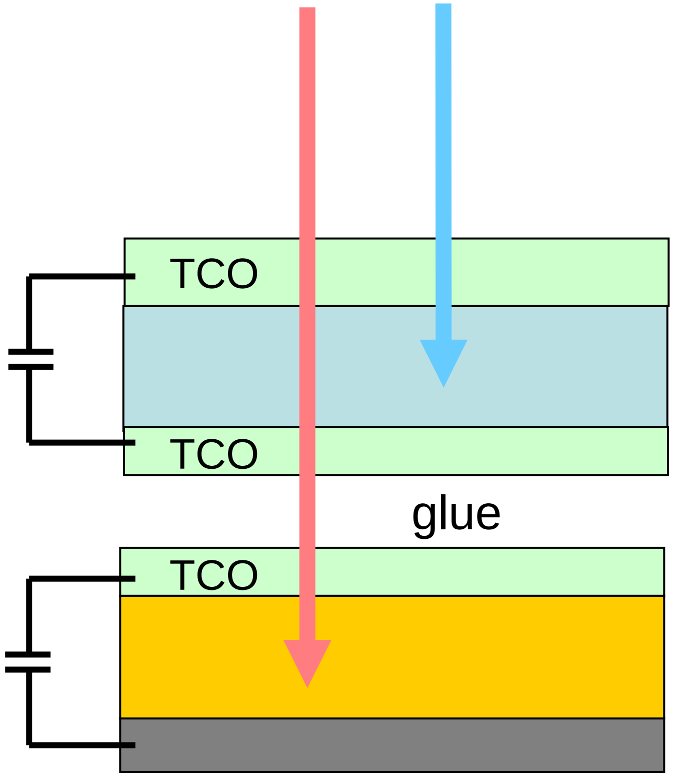
- Reflection loss
  - Without AR coating: R ≈ 30% (refractive index n ≈3.5)
  - Reflection at air-glass interface as well as other interfaces

- Too thin semiconductor active layer
  - thin layers for strong field (a-Si)
  - reduced material consumption (c-Si: interest to go towards 100 µm wafers)

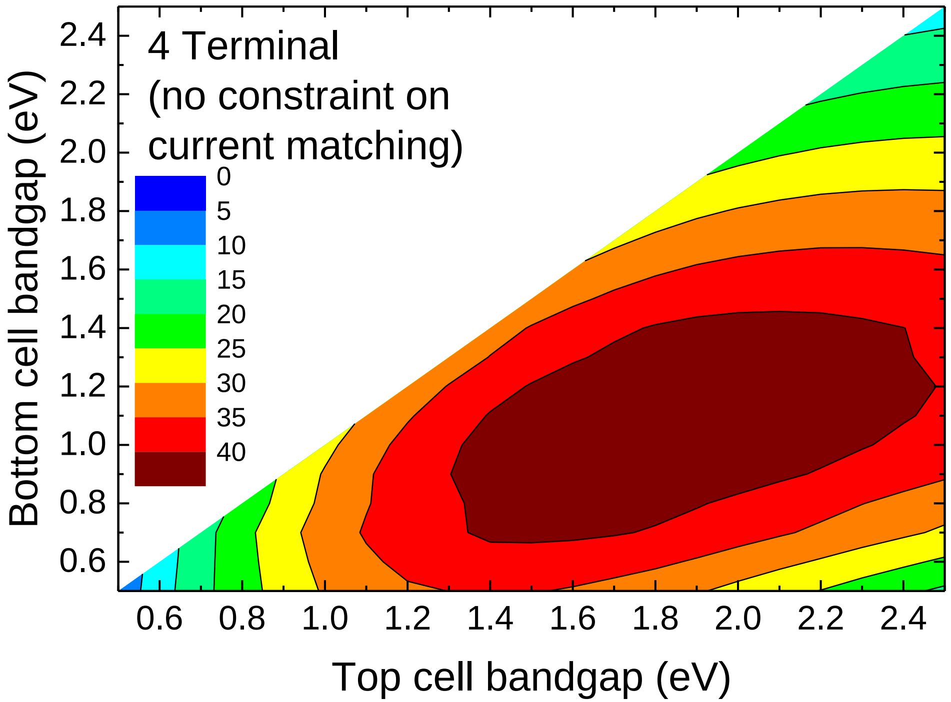
- Non transparent electrodes

Beyond the SQ limit: multijunction solar cells

Mechanically stacked tandem



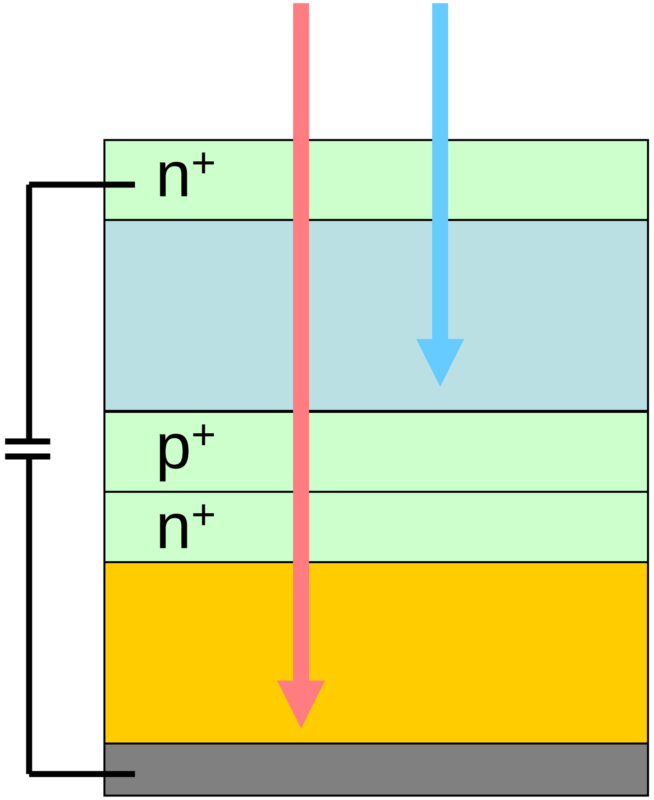
Map of max. efficiency (AM1.5)



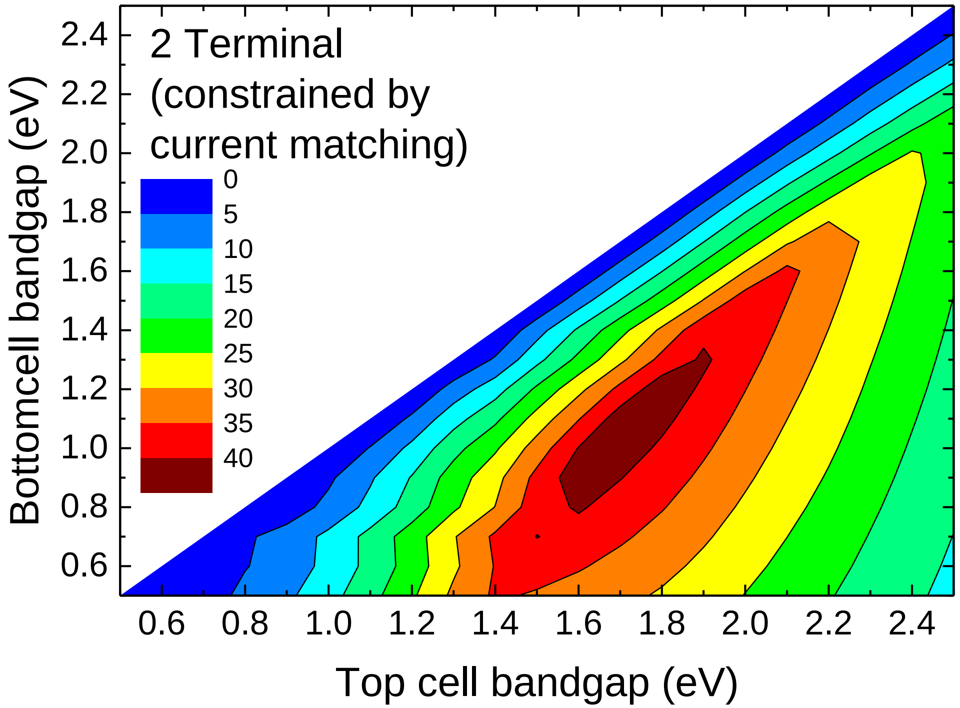
Four terminal device, no current matching necessary!

Beyond the SQ limit: multijunction solar cells

Monolithic tandem

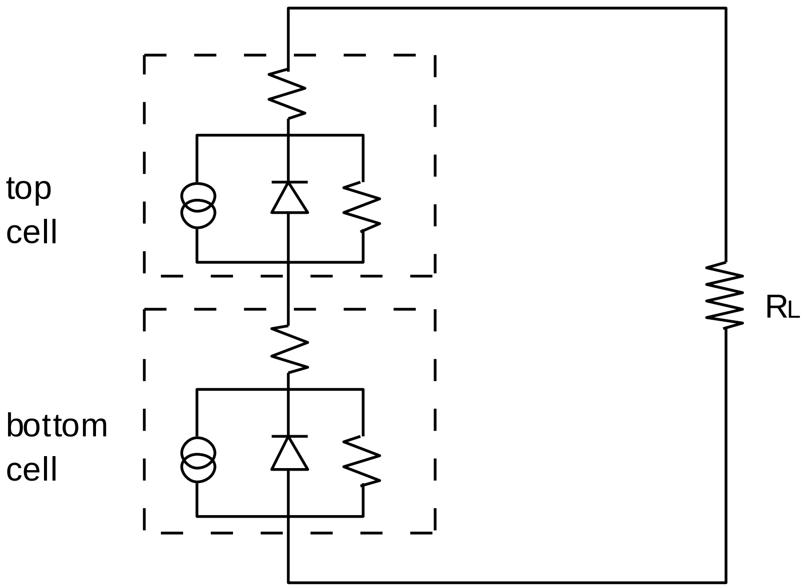


Map of max. efficiency (AM1.5)

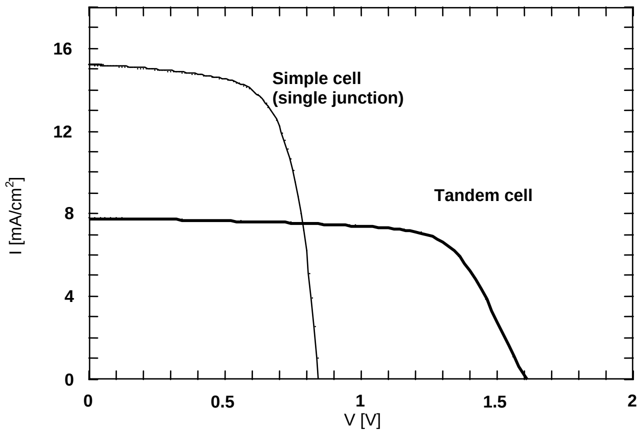


Two terminal device
Current matching required, narrower region of high efficiency

Tandem equivalent circuit



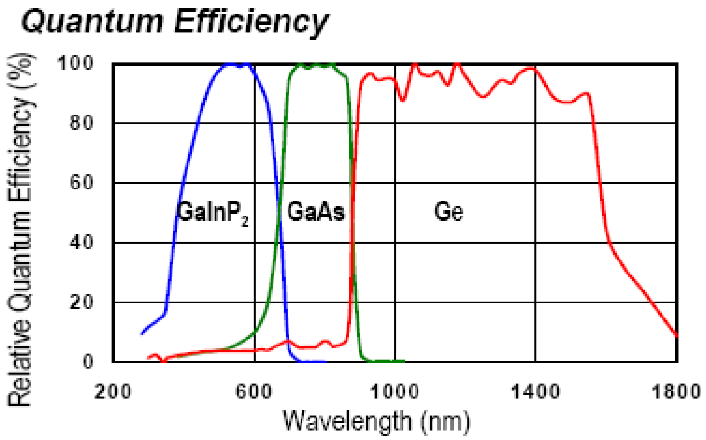
- “Top” cell: $I_{top} = I_{top}(V_{top})$
- “Bottom” cell: $I_{bot} = I_{bot}(V_{bot})$
- Tandem cell:
  - $I = I_{top} = I_{bot}$
  - $V(I) = V_{top}(I) + V_{bot}(I)$
  - I_{sc} @ min $(I_{sc,top}, I_{sc,bot})$
  - $V_{oc} = V_{oc,top} + V_{oc,bot}$

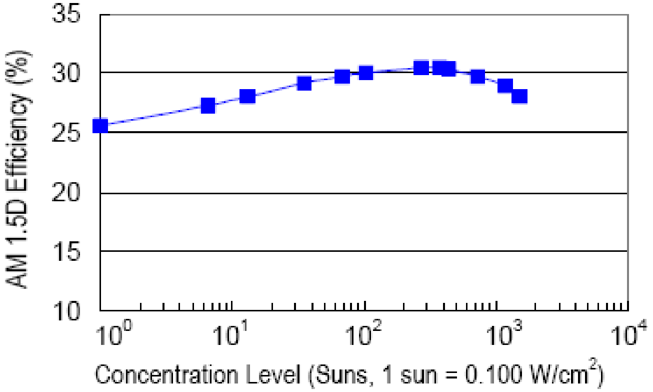


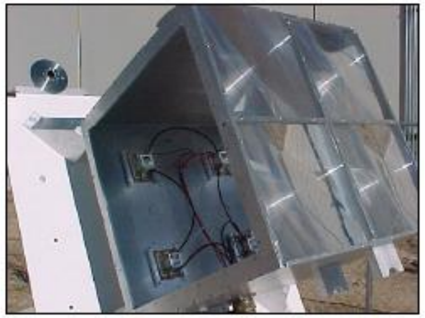
typical I(V) curves of a single-junction and tandem a-Si:H cells

Concentrator / space cells

III-V materials: for concentrator and space applications







On-Sun testing at EMCORE Photovoltaics at 520 Suns

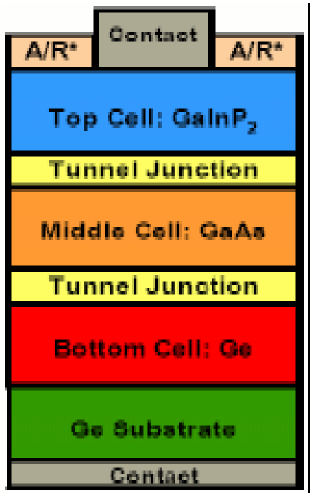
Multijunction record efficiencies (AM1.5):

- 38.8% (5j, Spectrolab)
- 37.9% (3j, Sharp)

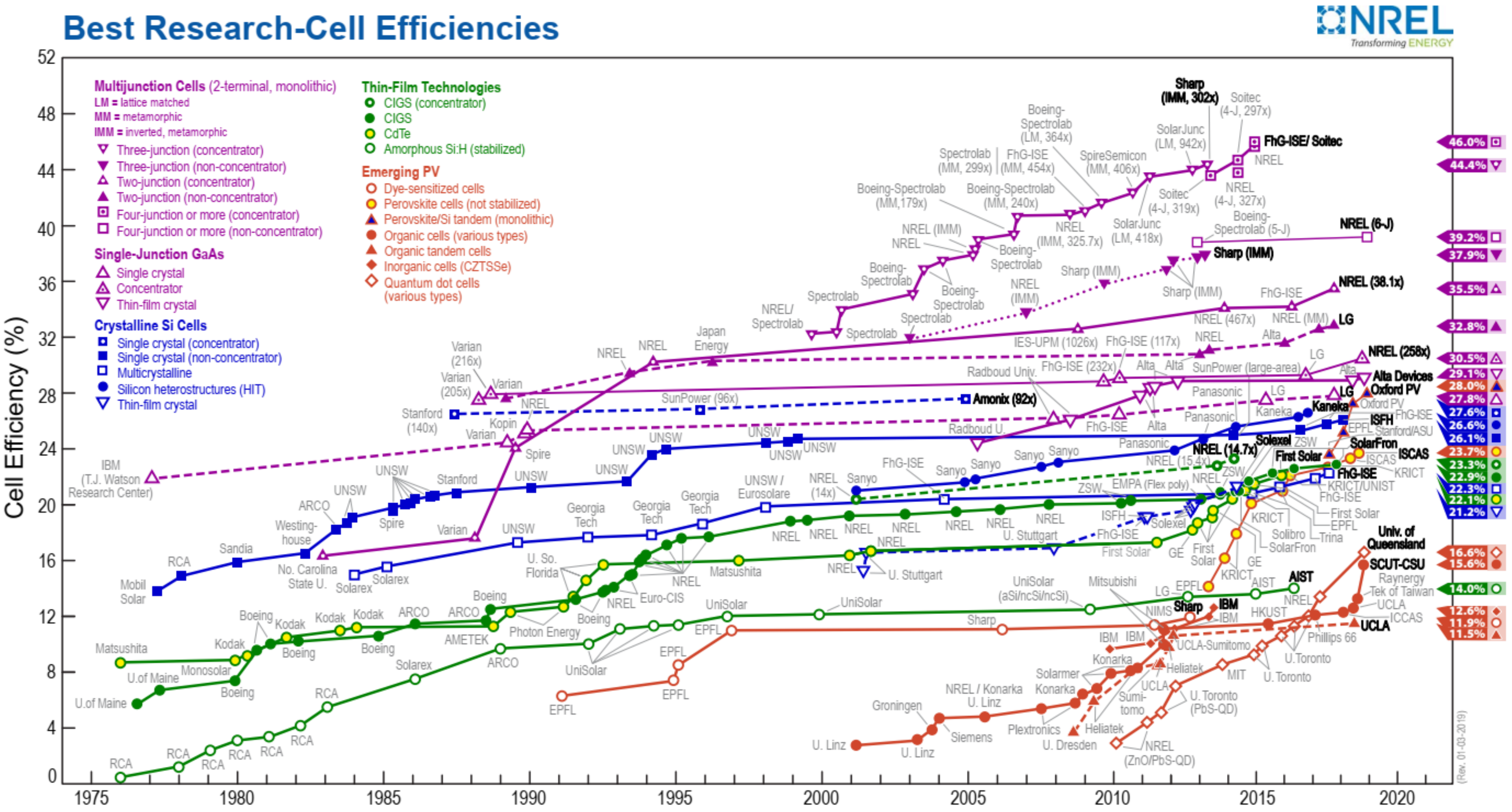
Concentrator cells:

- 47.7% at 258 suns (6j metamorphic, NREL)
- 46.0% at 508 suns (4j bonded, Soitec)

www.spectrolab.com
www.emcore.com
www.rwe.com
www.sj-solar.com



Conversion efficiency vs. time



https://www.nrel.gov/pv/cell-efficiency.html

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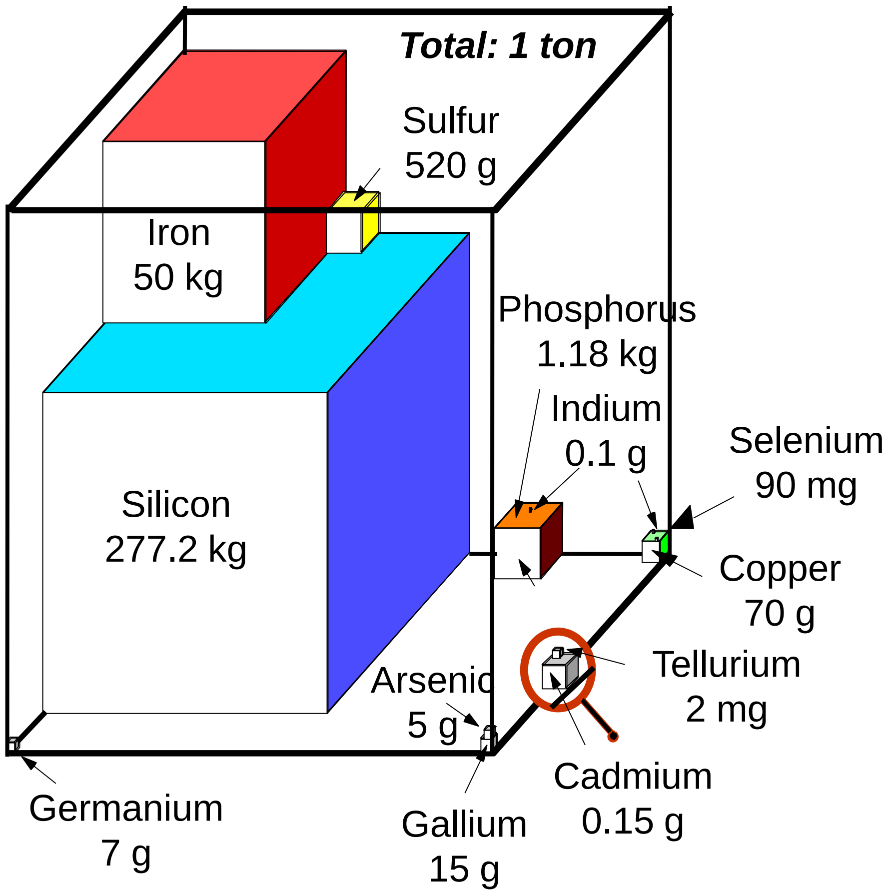
“Ideal technology”

Requirements:

- Semiconductor with suitable gap for illumination spectrum
- Doping possible
- Large availability
- Non toxic
- No pollution during extraction, processing or recycling
- Low cost (raw material extraction and preparation)
- Low energy usage for processing
- High light absorption (esp. for thin film cells)

Availability of various materials for PV



Availability of various materials in 1 ton of earth crust

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  - Silicon Solar Cells: Advanced Principles and Practice, *M.A. Green*, University of New South Wales
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  - https://www.pveducation.org
  - Solar Cell Efficiency Tables : https://onlinelibrary.wiley.com/doi/abs/10.1002/pip.3102
  - https://en.wikipedia.org/wiki/Solar_cell

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