Photovoltaic cell and module physics and technology

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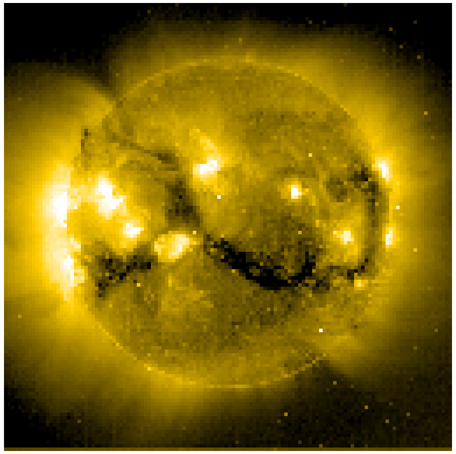
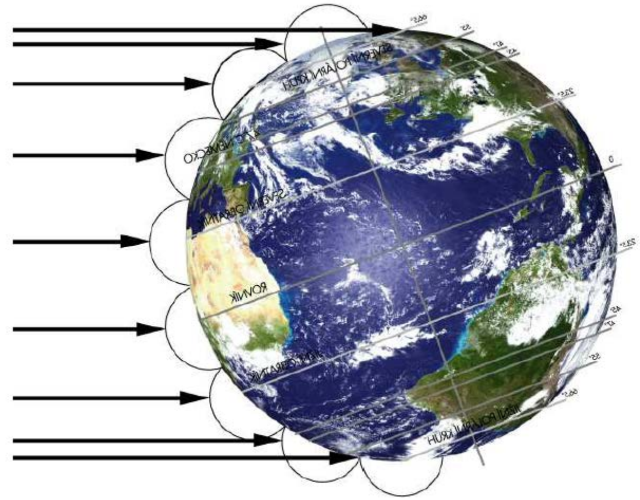
Outlines

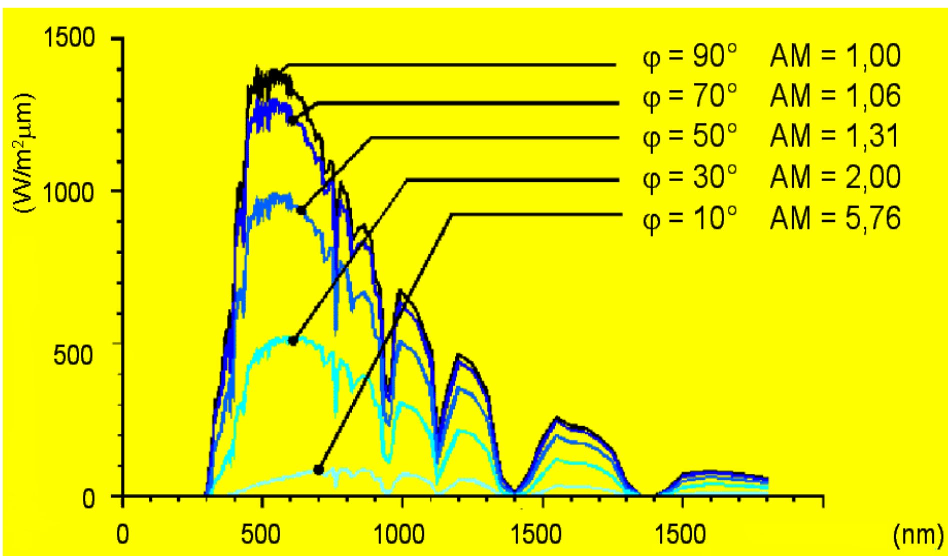
- Photovoltaic Effect
- Photovoltaic cell structure and characteristics
- Photovoltaic cell construction and technology
- PV modules – construction and technology
- Summary

Solar energy



170 000 TW





Photovoltaics

Direct transformation energy of solar irradiation into electricity

1. Light absorption in materials and excess carrier generation

Photon energy $h\nu = hc/\lambda$ (h is the Planck constant)
photon momentum ≈ *0*

Light is absorbed in the material.

$\Phi(x)$ is the light intensity

$$\Phi(x) = \Phi_0 \exp(-\alpha x) = \Phi_0 \exp\left(-\frac{x}{x_L}\right)$$

$\alpha = \alpha(\lambda)$ is the absorption coefficient

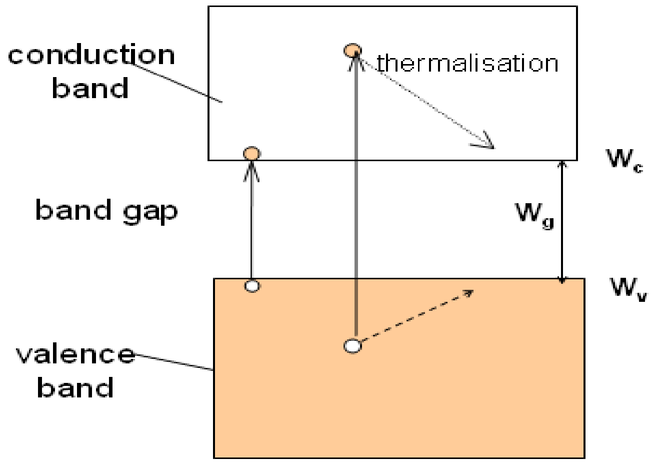
$x_L = \frac{1}{\alpha}$ is the so-called **absorption length**

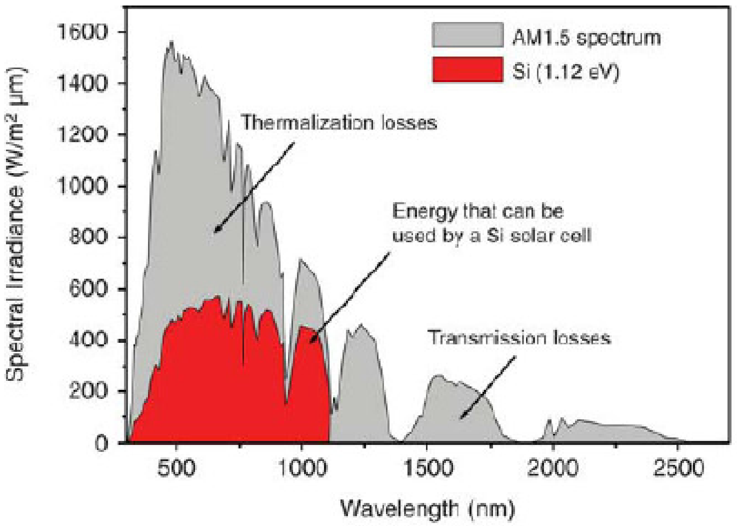
$$\int_0^{x_L} \Phi(x)dx = 0.68\int_0^{\infty} \Phi(x)dx$$

Absorption is due to interactions with material particles (electrons and nucleus).
If particle energy before interaction was W_1, after photon absorption is $W_1 + h\nu$

- **interactions with the lattice –results in an increase of temperature**
- **interactions with free electrons - results also in temperature increase**
- **interactions with bonded electrons- the incident light may generate some excess carriers (electron/hole pairs)**

At interaction with photons of energy $h\nu \geq W_g$ electron-hole pairs are generated and carrier generation increases





$$G(\lambda;x) = \left(\frac{d\Delta n}{dt}\right)_{gen} = \alpha(\lambda)\beta(\lambda)\Phi_0(\lambda)\exp\left(-\alpha(\lambda)x\right)$$

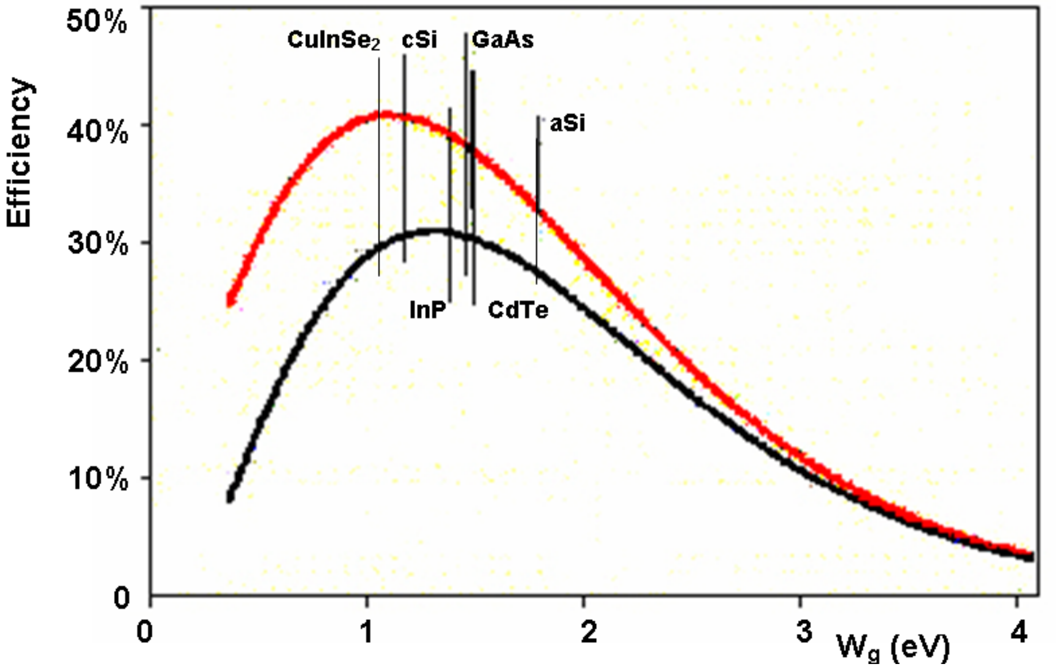
$$n = n_0 + \Delta n\,, \qquad p = p_0 + \Delta p$$

Excess carriers recombine with the recombination rate
τ is so called carrier lifetime

$$R = \left(\frac{d\Delta n}{dt}\right)_{rec} = -\frac{\Delta n}{\tau}$$

In dynamic equilibrium $\boldsymbol{\Delta n = \Delta p = \tau G}$

Efficiency of excess carrier generation by solar energy depens on the semiconductor band gap



Suitable materials

Silicon

GaAs

$CuInSe_2$

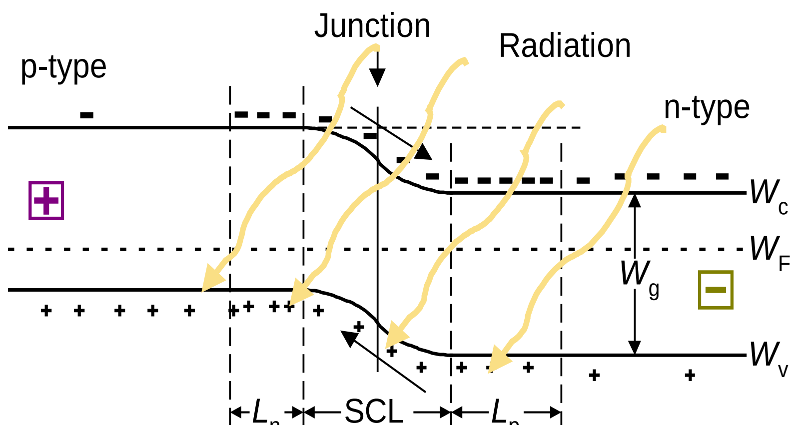
amorphous SiGe

CdTe/CdS

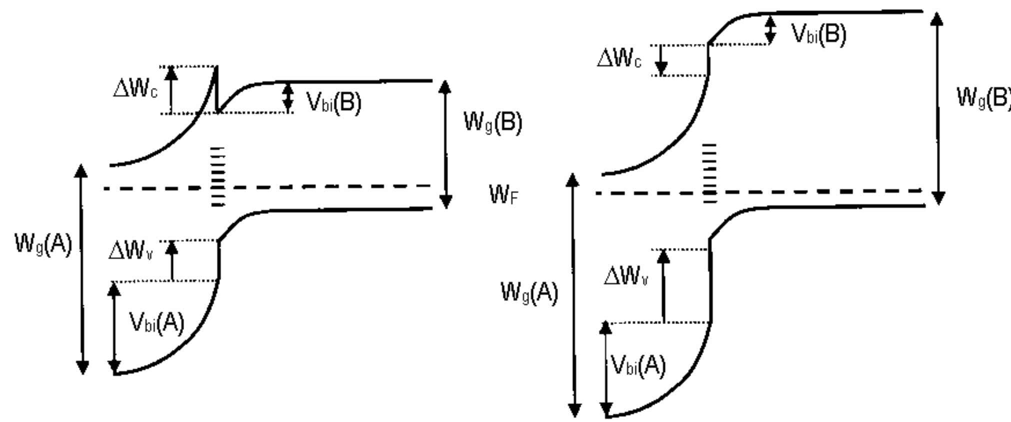
To obtain a potential difference that may be used as a source of electrical energy, an inhomogeneous structure with internal electric field is necessary.

Suitable structures with built-in electric field:

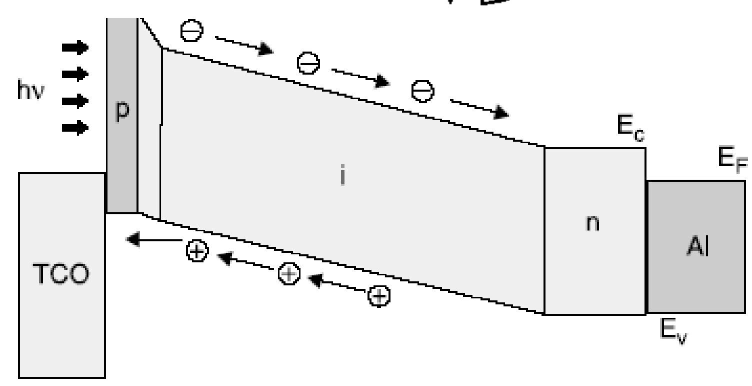
- PN junction



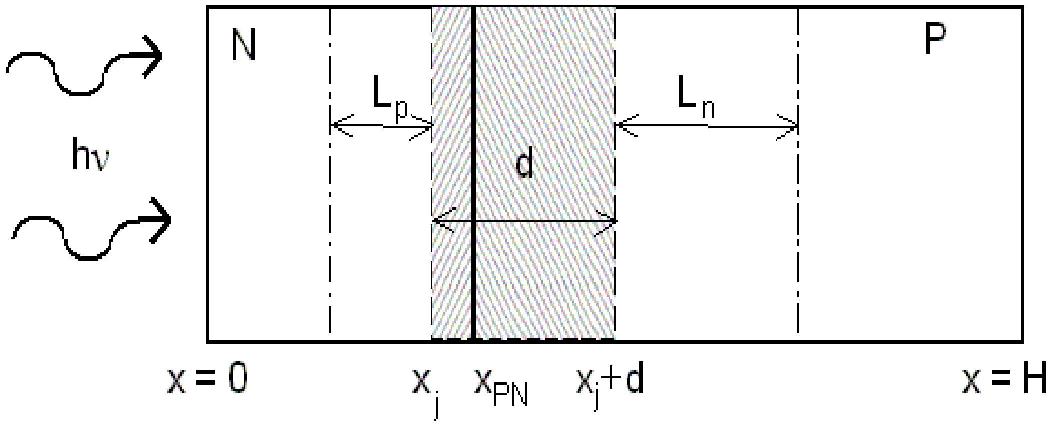
- heterojunction (contact of different materials).



- PIN structures



Principles of solar cell function



In the illuminated area generated excess carriers diffuse towards the PN junction. The density J_{PV} is created by carriers collected by the built-in electric field region

$$J_{PV}(\lambda) = q\int_0^H G(\lambda; x)dx - q\int_0^H \frac{\Delta n}{\tau}dx - J_{sr}(0) - J_{sr}(H)$$

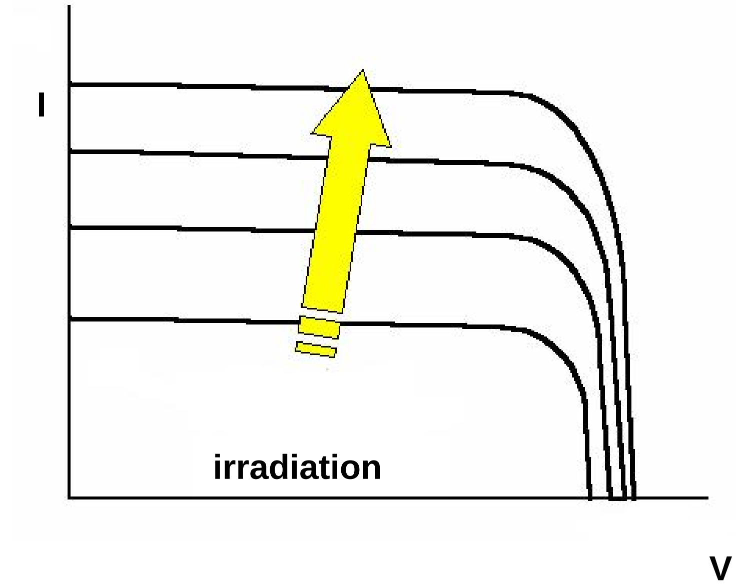
J_{sr} is surface recombination

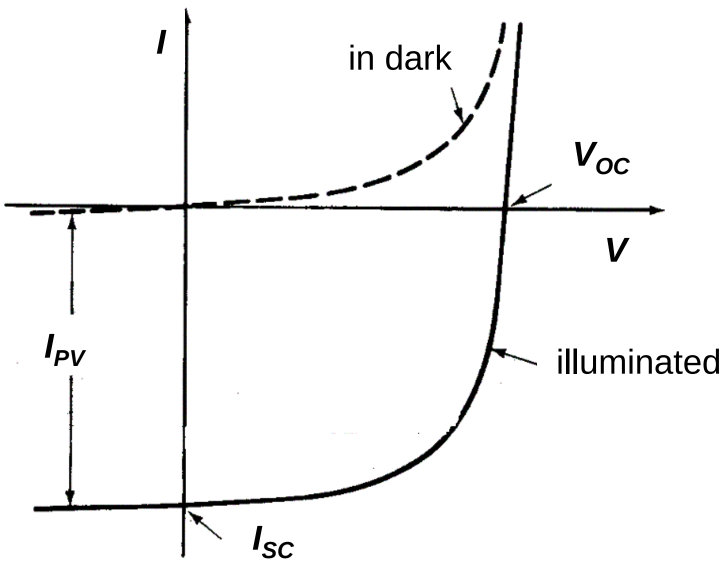
Total generated current density

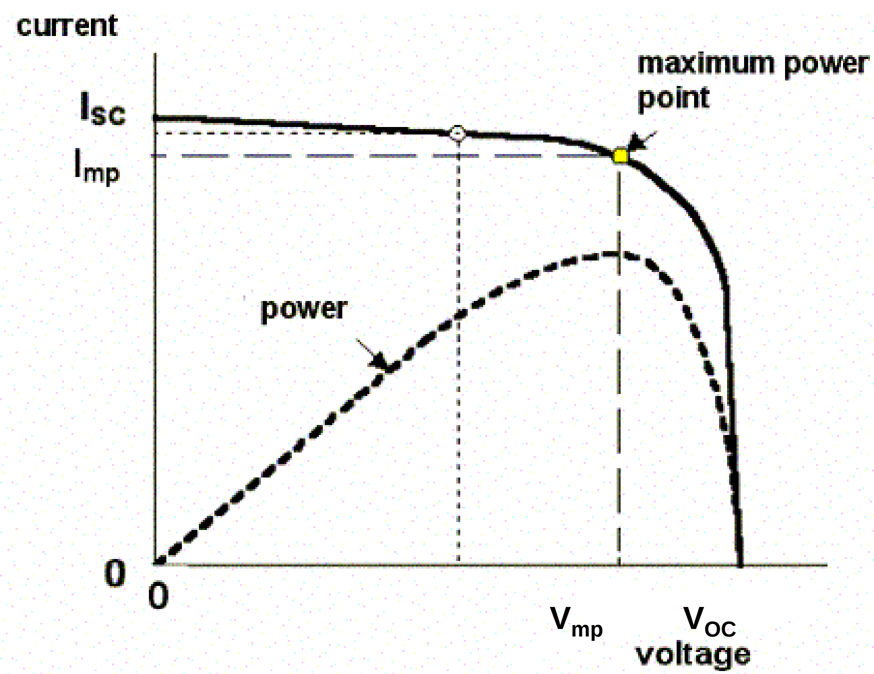
$$J_{PV} = \int J_{PV}(\lambda)d\lambda$$

Illuminated PN junction: supperposition of photo-generated current and PN junction (dark) I-V characteristic

A

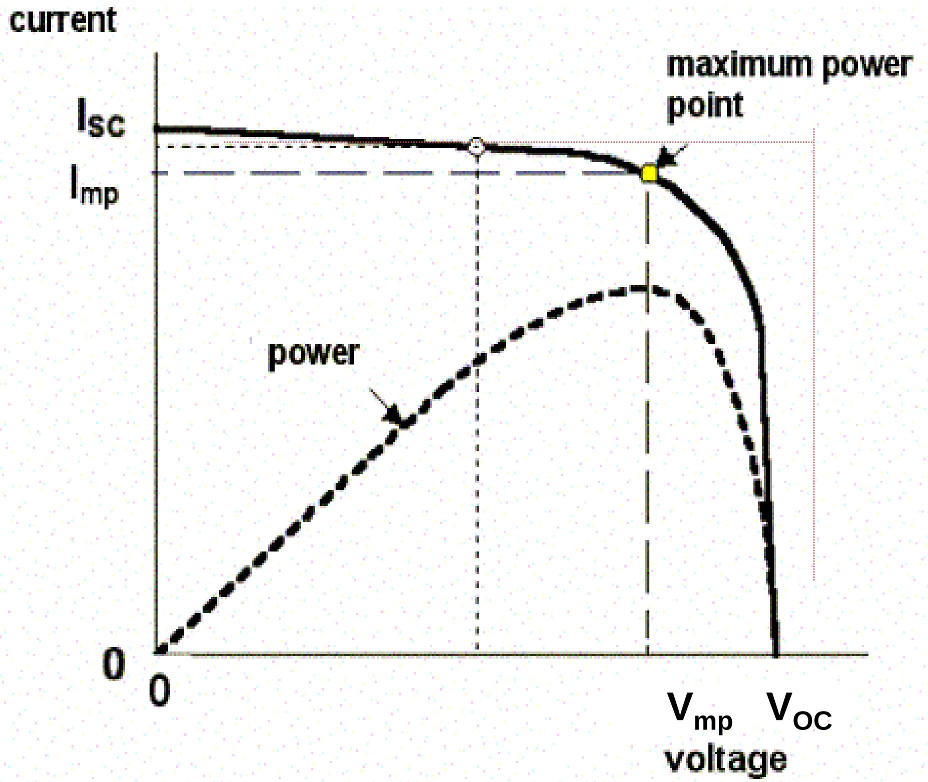






Solar cell I-V chacteristic and its importan points

Important solar cell electrical parameters

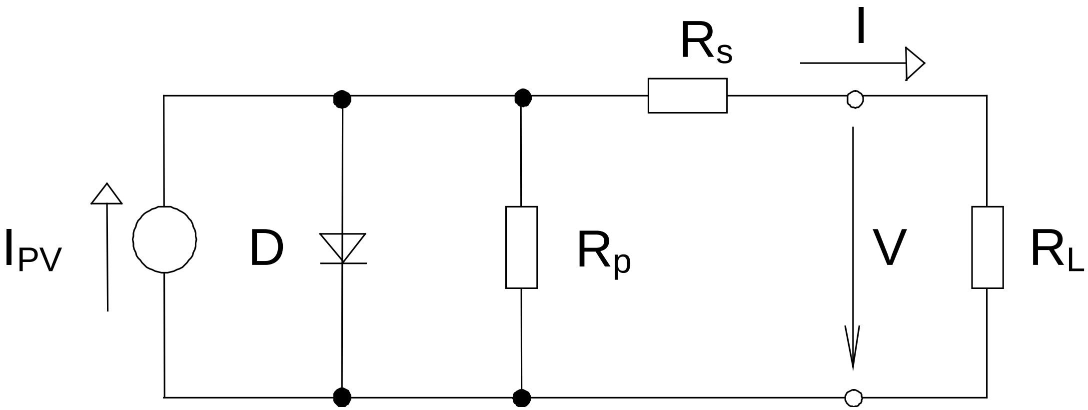


- open circuit voltage $\boldsymbol{V_{OC}}$,
- short circuit current $\boldsymbol{I_{SC}}$
- maximum output power $\boldsymbol{V_{mp}I_{mp}}$
- fill factor $FF = \dfrac{V_{mp}I_{mp}}{V_{OC}I_{SC}}$
- efficiency $\eta = \dfrac{V_{mp}I_{mp}}{P_{in}} = \dfrac{V_{OC}I_{SC}FF}{P_{in}}$

All parameters V_{OC}, I_{SC}, V_{mp}, I_{mp}, FF and η are usually given for standard testing conditions (STC):

- **spectrum AM 1.5**
- **radiation power 1000 W/m^2**
- **cell temperature 25°C.**

Modelling I-V characteristics of a solar cell



Parallel resistance R_p

Series resistance R_S

PN junction I-V characteristics

$$J = J_{01}\left[\exp\left(\frac{qV_j}{\varsigma_1 kT}\right)-1\right]+ J_{02}\left[\exp\left(\frac{qV_j}{\varsigma_2 kT}\right)-1\right]$$

$$J_{01} = n_i^2 q\left(\frac{D_n}{L_n}\frac{1}{p_{p0}}+\frac{D_p}{L_p}\frac{1}{n_{n0}}\right) \qquad J_{02} = \frac{qn_i d}{\tau_{sc}} \qquad 1 \le \varsigma_1 \le 2 \qquad 2 \le \varsigma_2$$

Output cell voltage $\boldsymbol{V = V_j - R_s I}$

A - total cell area A_{ill} – illuminated cell area

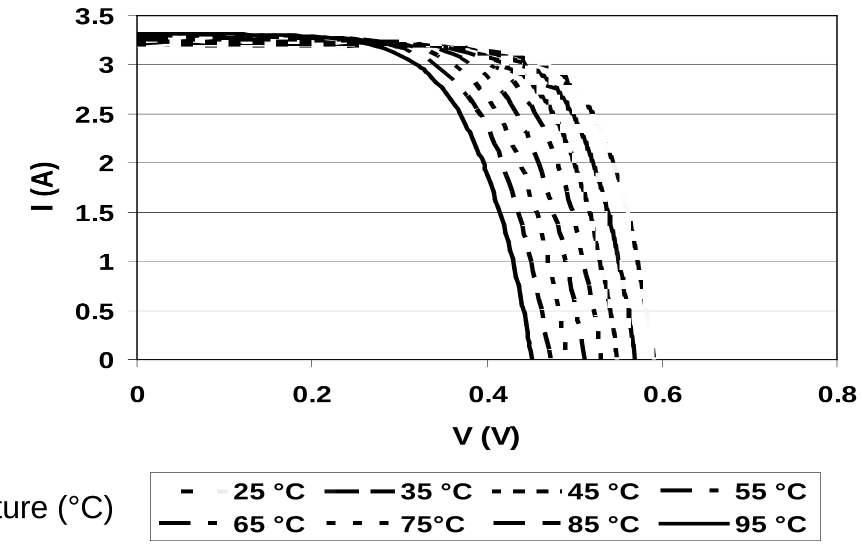
$$I = A_{ill} J_{PV} - AJ_{01}\left[\exp\left(q\frac{V+R_s I}{\varsigma_1 kT}\right)-1\right] - AJ_{02}\left[\exp\left(q\frac{V+R_s I}{\varsigma_2 kT}\right)-1\right] - \frac{V+R_s I}{R_p}$$

Influence of temperature

For a high R_p $$V_{OC} \approx \frac{kT}{q} \ln \frac{I_{PV}}{I_{01}}$$

$$I_{01} \sim \quad n_i^{\,2} = BT^3 \exp\left(\frac{-W_g}{kT}\right)$$

Consequently $$\frac{\partial V_{OC}}{\partial T} < 0$$



For silicon cells the decrease of V_{OC} is about 0.4%/K

R_s increases with increasing temperature

R_p decreases with increasing temperature

Both fill factor and efficiency decrease with temperature

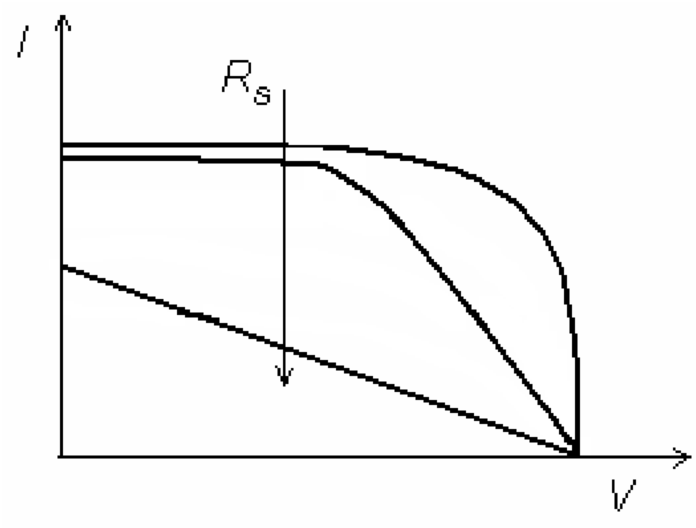
$$\frac{\partial FF}{\partial T} < 0 \qquad \frac{\partial \eta}{\partial T} < 0$$

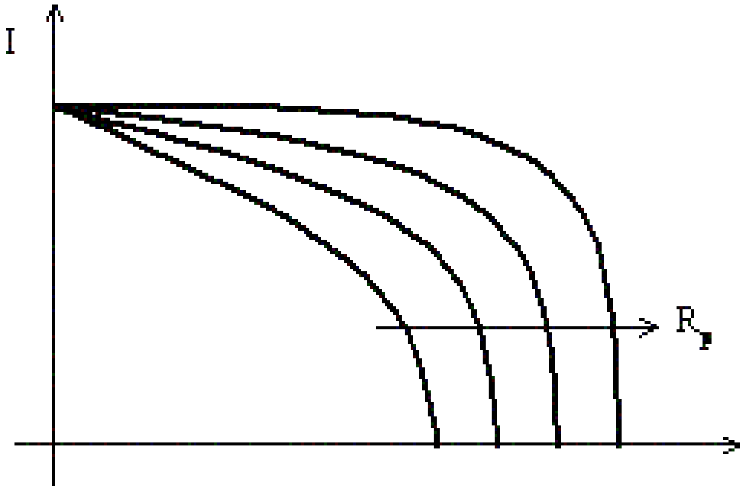
At silicon cells $\frac{1}{\eta}\frac{\partial \eta}{\partial T} \approx 0.5\% K^{-1}$

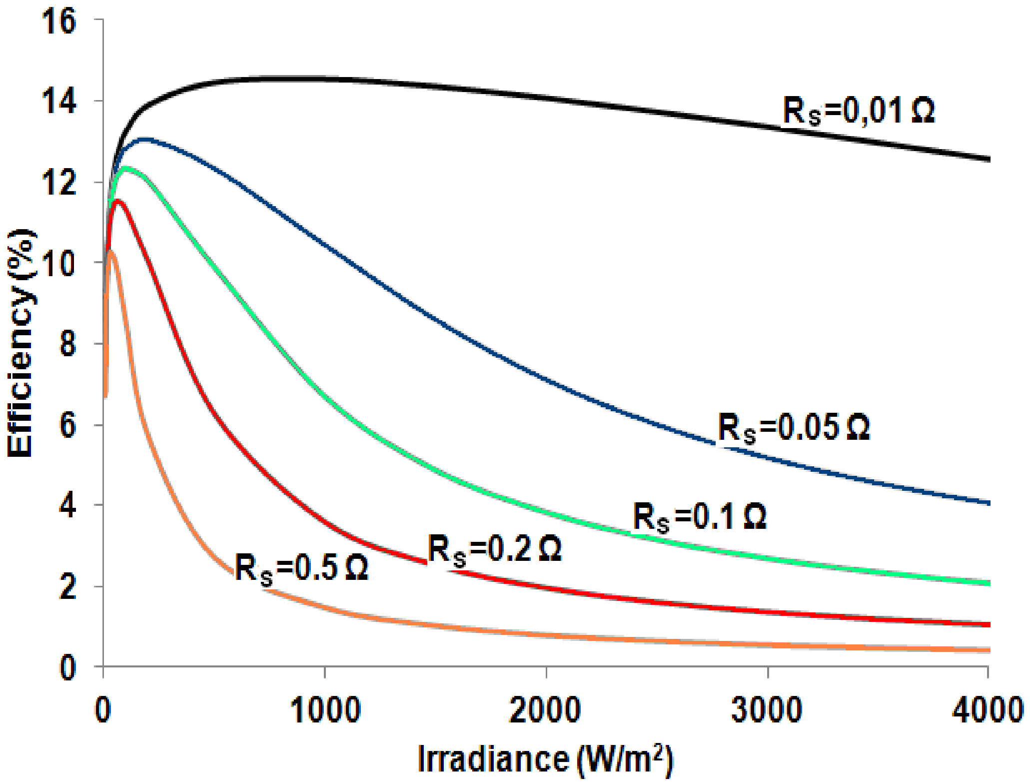
Cell type	η (28°C)	$(1/\eta)(d\eta/dT)$ [$\times 10^{-3}$/°C]
Si	0.148	−4.60
Ge	0.090	−10.1
GaAs/Ge	0.174	−1.60
InP	0.195	−1.59
a-Si	0.066	−1.11 (nonlinear)
$CuInSe_2$	0.087	−6.52

The resistances R_s and R_p influences the cell efficiency

At a constant irradiance

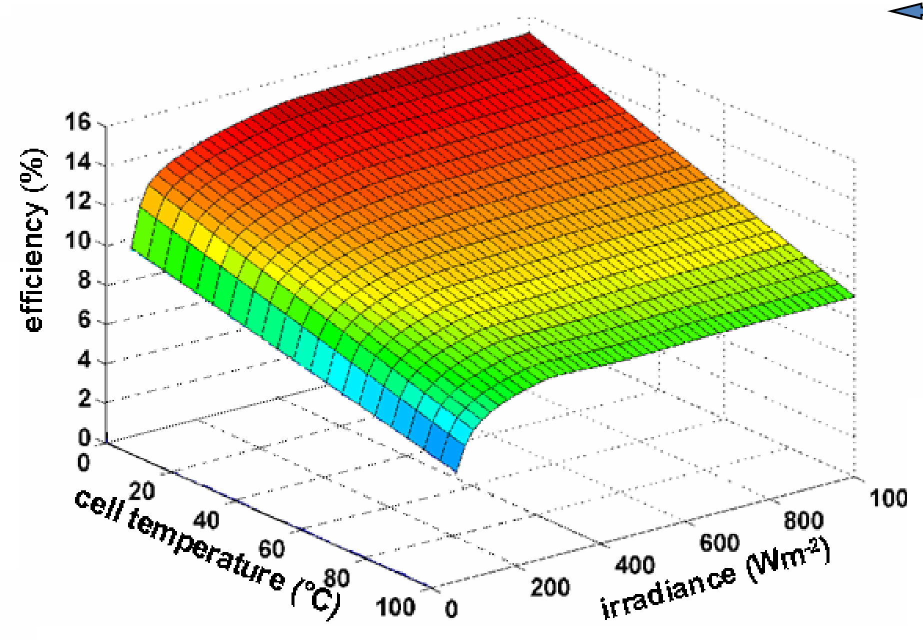






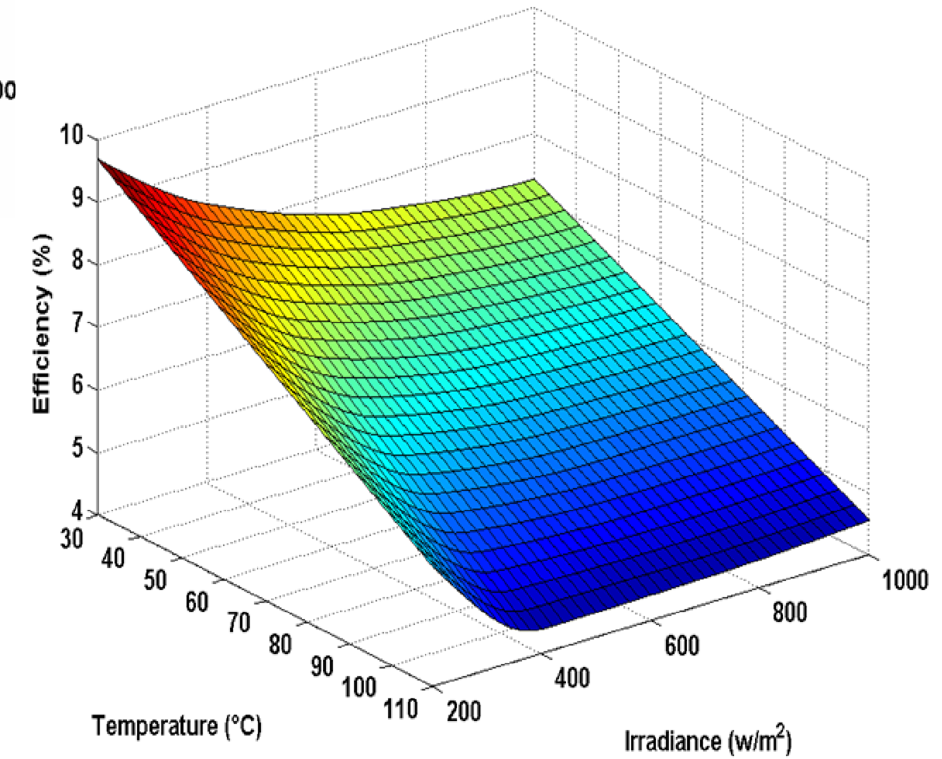
PV cell (module) with a low R_s

the efficiency increases with irradiance



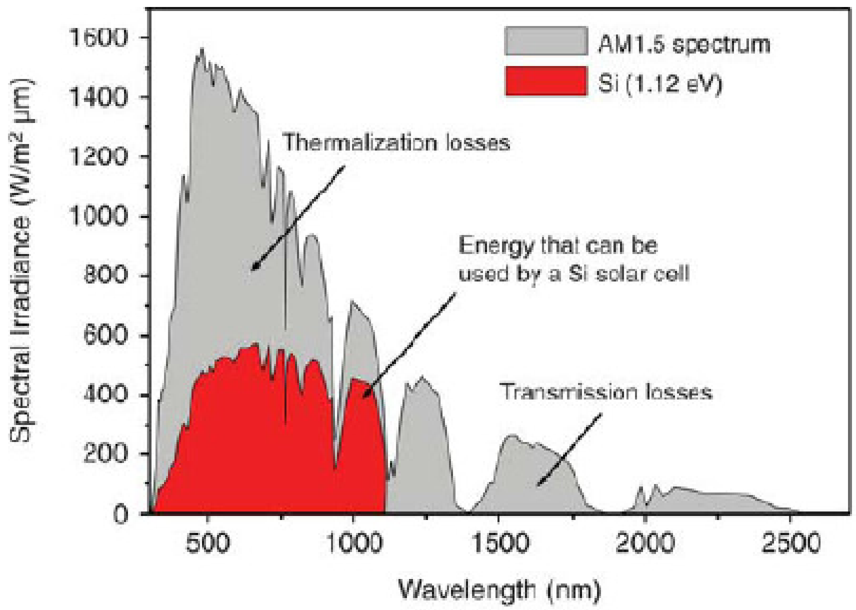
PV cell (module) with a high R_s

The efficiency decreases with increasing irradiance



To maximise current density J_{PV} it is necessary

- maximise generation rate G
- minimise losses



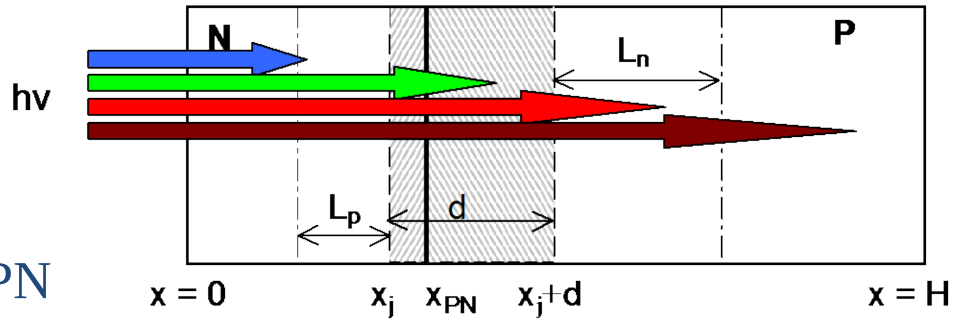
losses

optical
- reflection
- shadowing
- not absorbed radiation

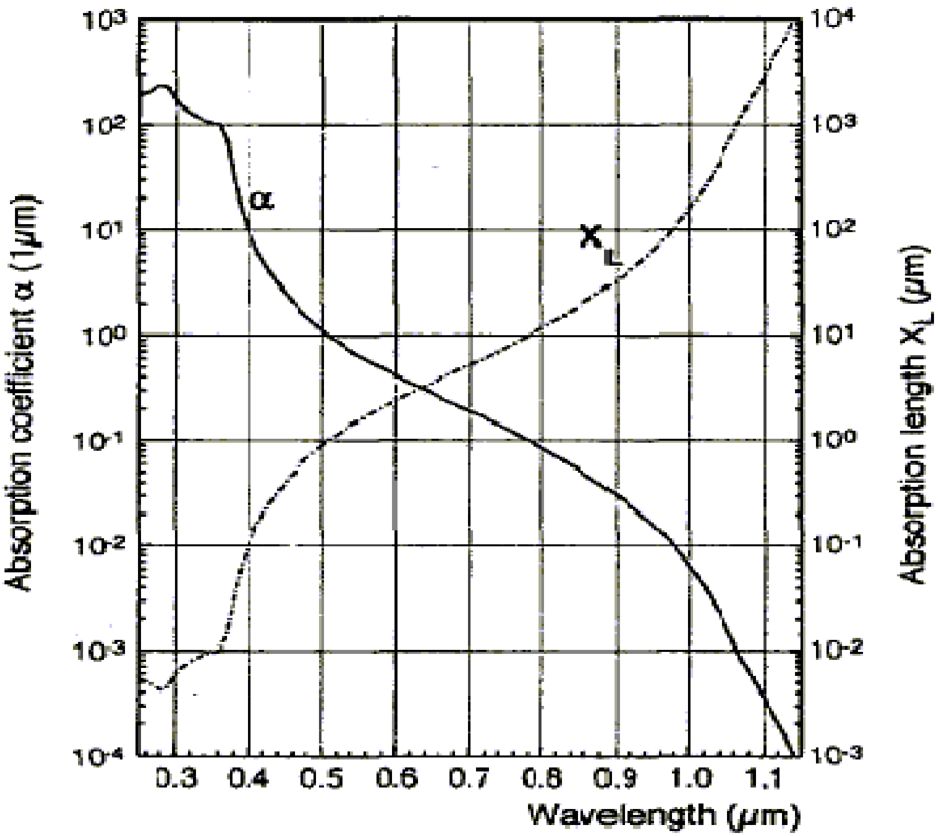
recombination
- emitter region
- base region
- surface

electrical
- series resistance
- parallel resistance

Optimising cell thickness and PN junction depth



The photo-current density J_{PV} consists from carriers collected by the electric field in the space charge region of the PN junction, i.e. from carriers generated in a distance of about diffusion length from the PN junction.



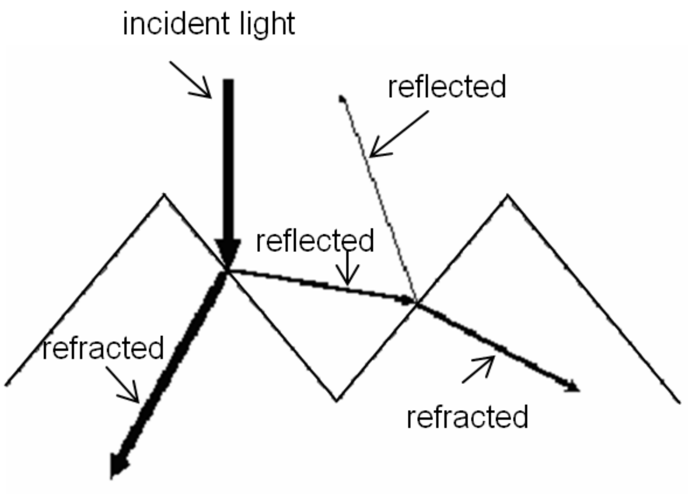
The PN junction depth x_j should be less than 0.5 μm (0.2 μm is desirable).

To decrease recombination, defects should be passivated

Optical losses

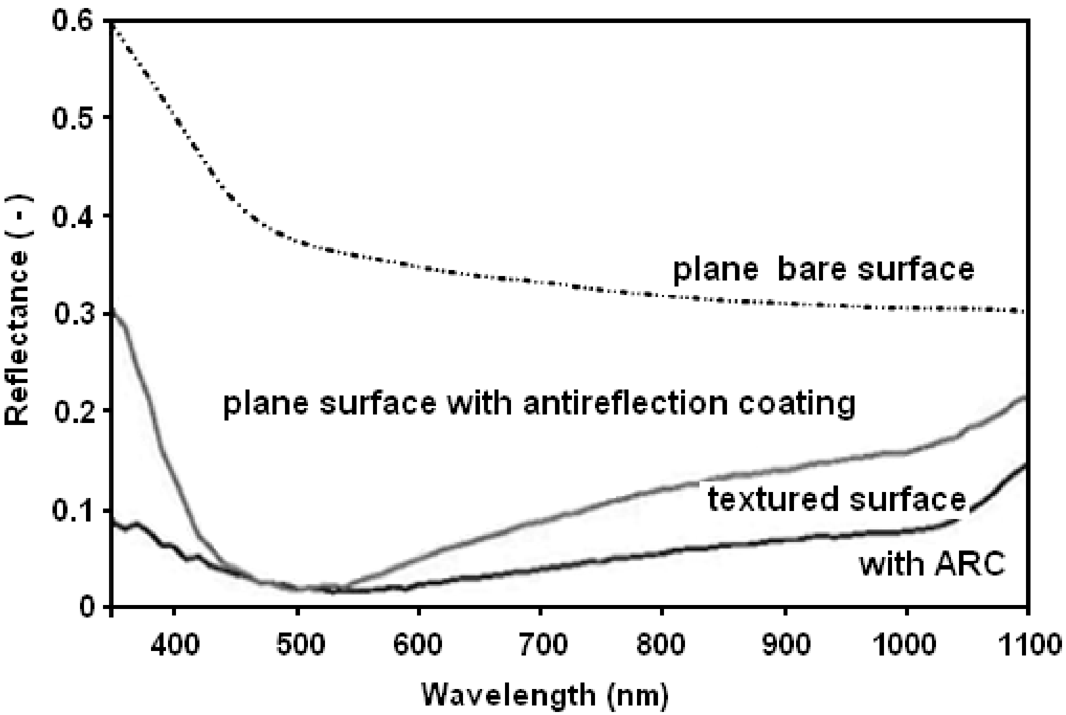
Surface texturing

If the surface has a pyramidal structure it is possible to decrease reflection on about one third of that on a plane surface



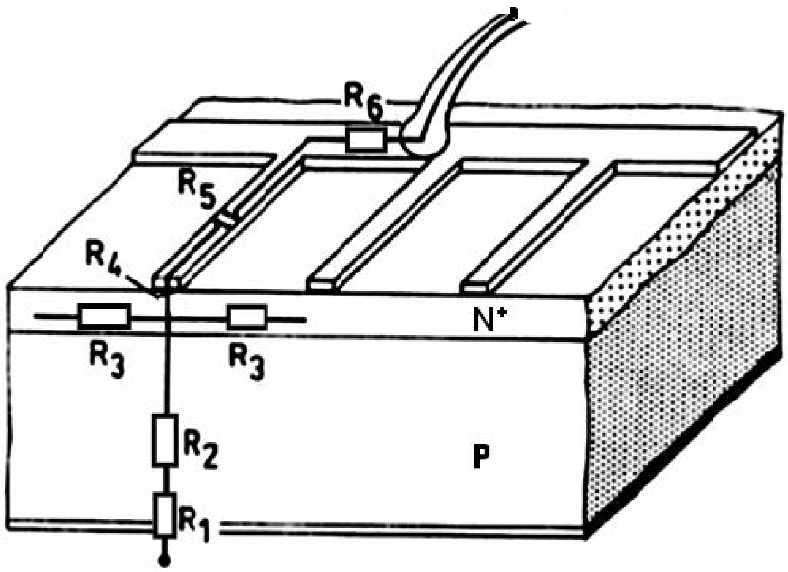
Antireflection coating

Both principles (surface texturing and antireflection coating) can be combined to minimise losses by surface reflection



Electrical losses

Series resistance R_s influences strongly solar cells efficiency



Series resistance R_s consists of:

- R_1 – contact metal-semiconductor on the back surface
- R_2 – base semiconductor material
- R_3 – lateral emitter resistance between two contact grid fingers
- R_4 – contact metal-semiconductor on the grid fingers
- R_5 – resistance of the grid finger
- R_6 – resistance of the collector bus

$$R_2 = \rho_{Si} H / A$$

$$R_3 \sim \frac{\rho_N d}{x_j}$$

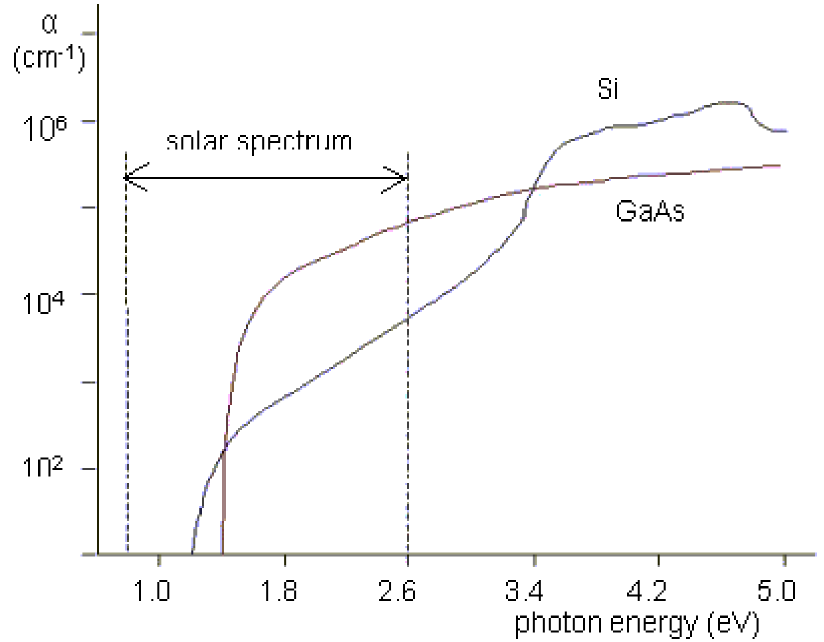
$$R_5 = \frac{\rho_M l}{3bh}$$

$$R_6 \sim \frac{\rho_M l_B}{h b_B}$$

Two types of band structure

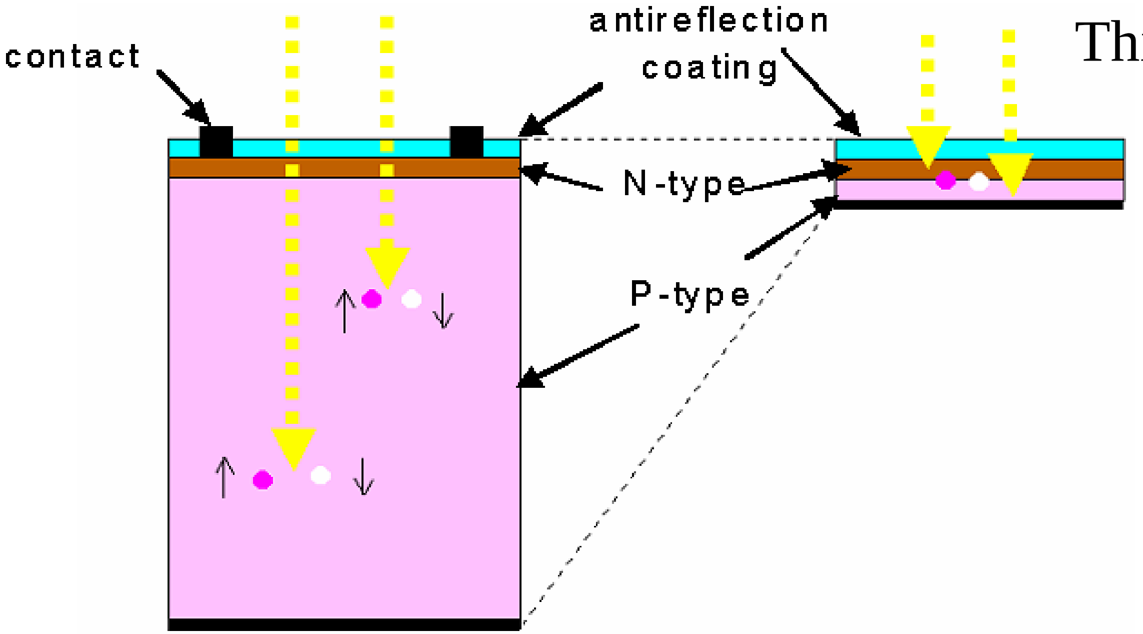
-direct (GaAs like)

-undirect (Si like)



Basic types of solar cells:

Crystalline silicon cells



Thin film cells

Suitable materials

$CuInSe_2$

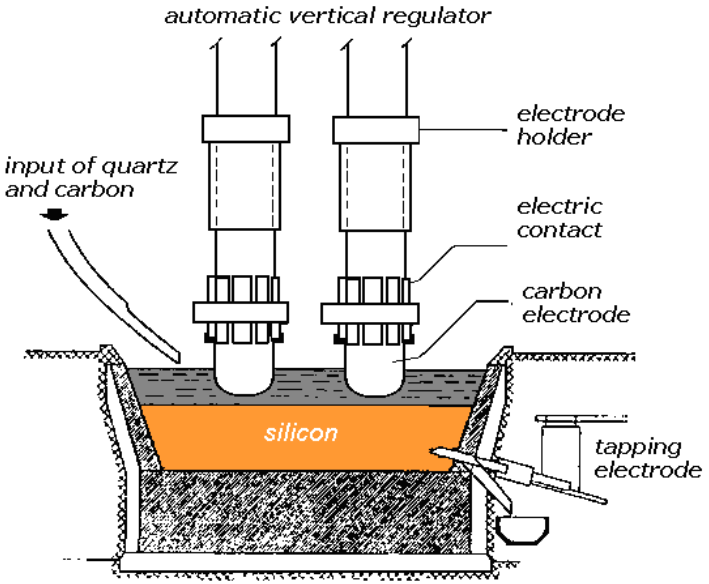
amorphous silicon

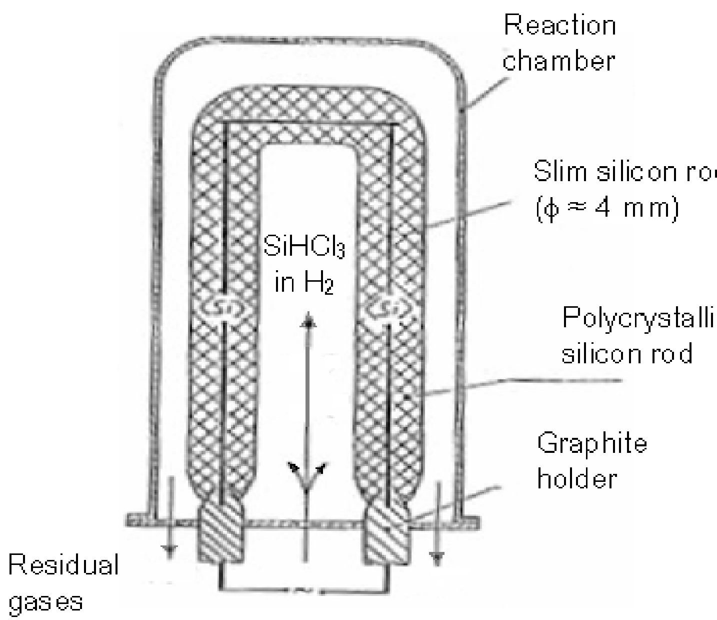
amorphous SiGe

CdTe/CdS

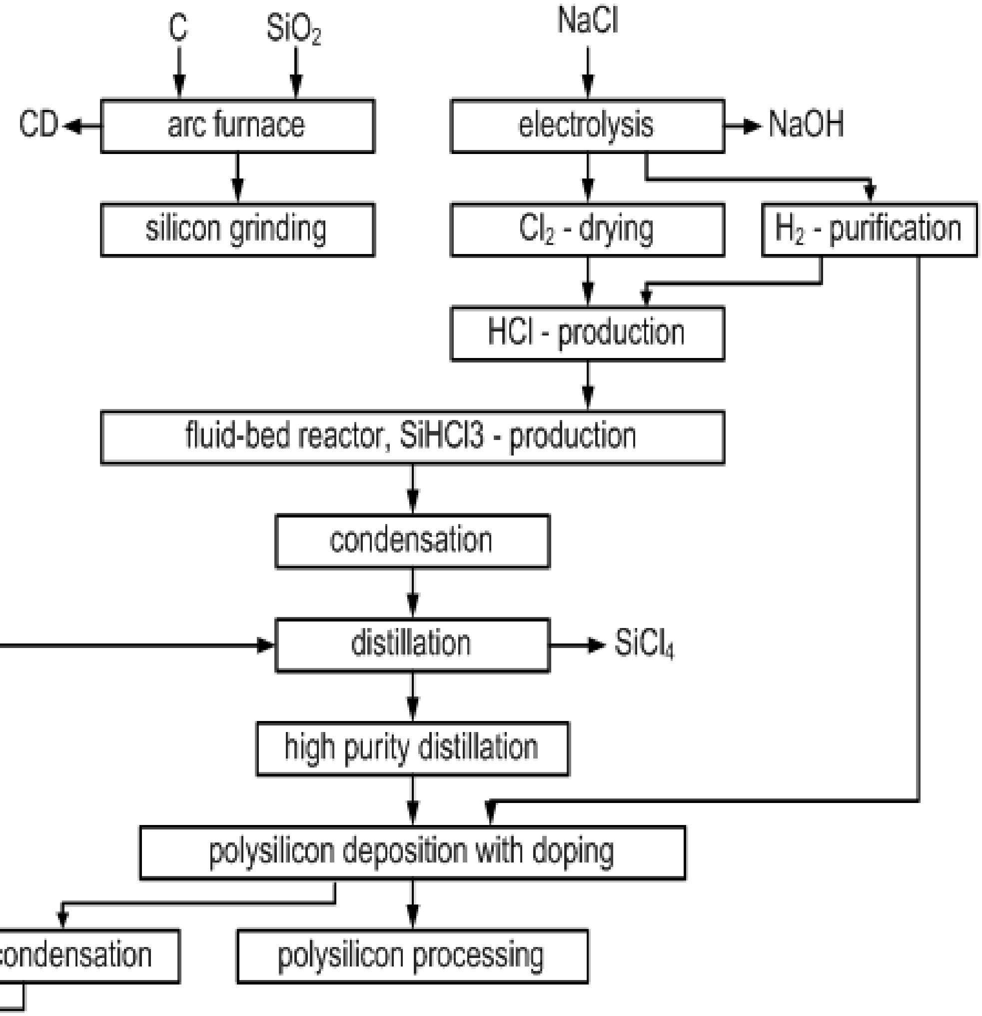
Preparing semicondutor silicon

$SiO_2 + C \rightarrow Si + CO_2$





$Si(s) + 3HCl = HSiCl_3 + H_2$

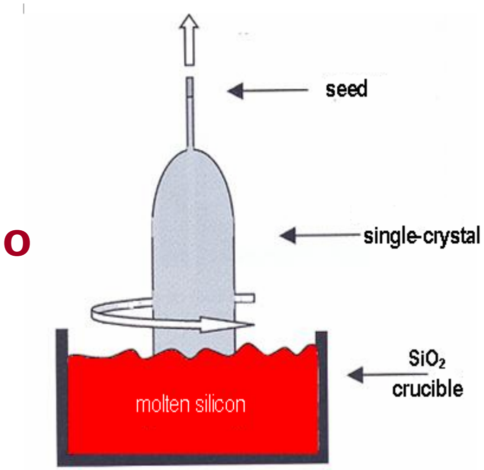


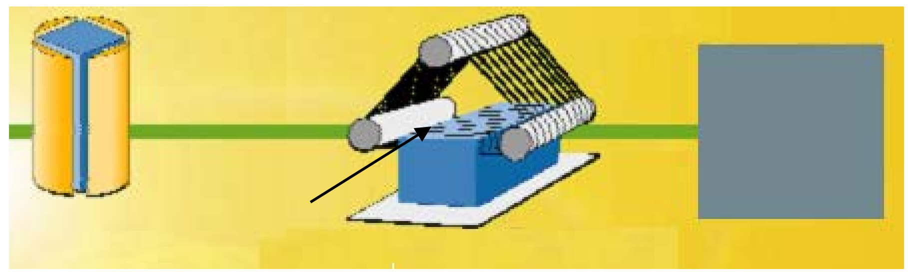
$HSiCl_3 + H_2 = Si(s) + 3HCl$

PV cells and modules from crystalline silicon (c-Si)

PV cells are realised from crystalline silicon wafers of thickness 0,15 – 0,25 mm and sides of 100 - 200 mm

c-Si mono

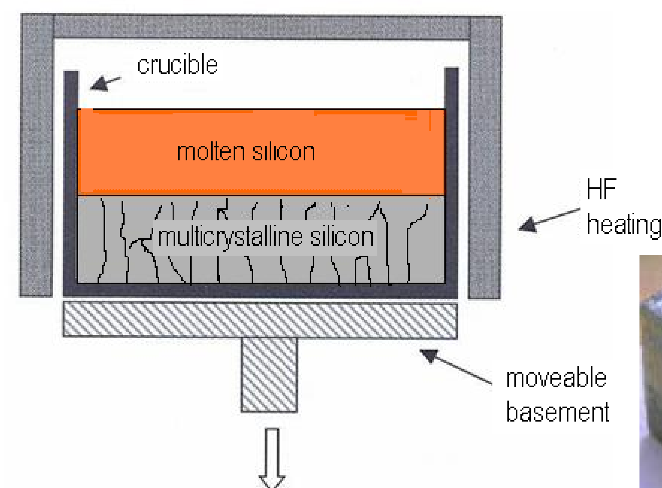




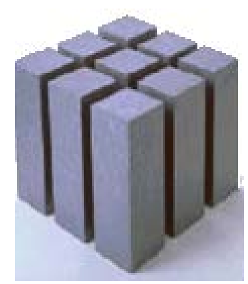
(37 %)

Kerfs losses about 40%

c-Si multi

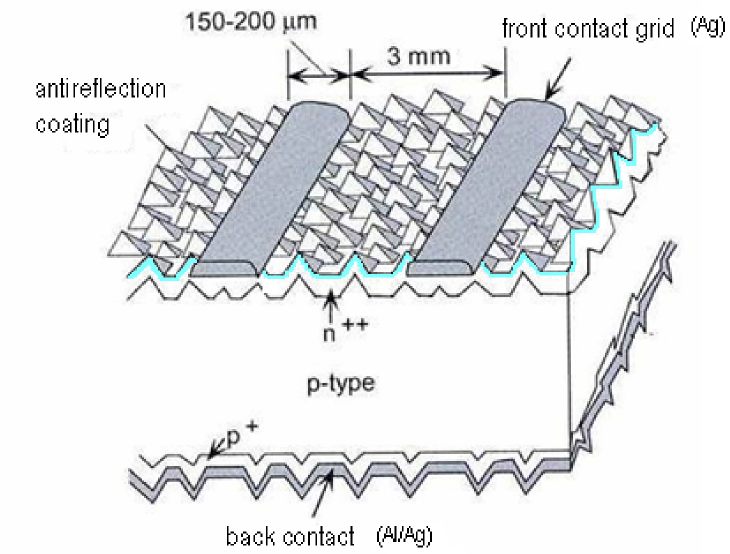


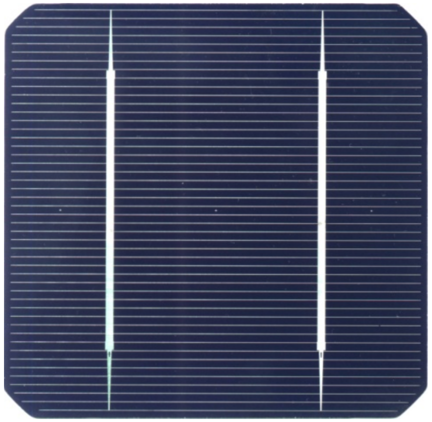
(50 %)

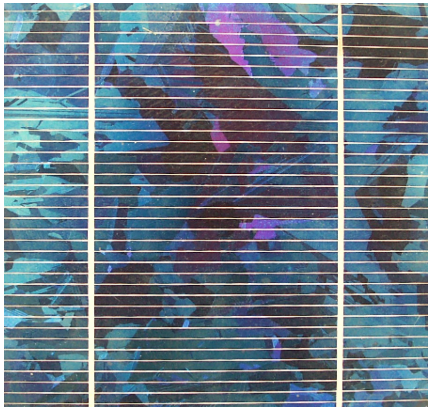


Standard mass production (c-Si cells)

- starting P-type wafers
- chemical surface texturing
- phosphorous diffusion
- SiN(H) antireflection surface coating and passivation
- contact grid realised by the screen print technique
- contact firing
- edge grinding
- cell measuring and sorting







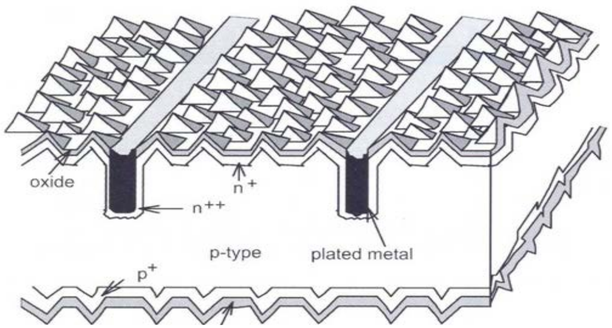
multi-crystalline $\eta \approx 16\%$

mono-crystalline $\eta \approx 17\%$

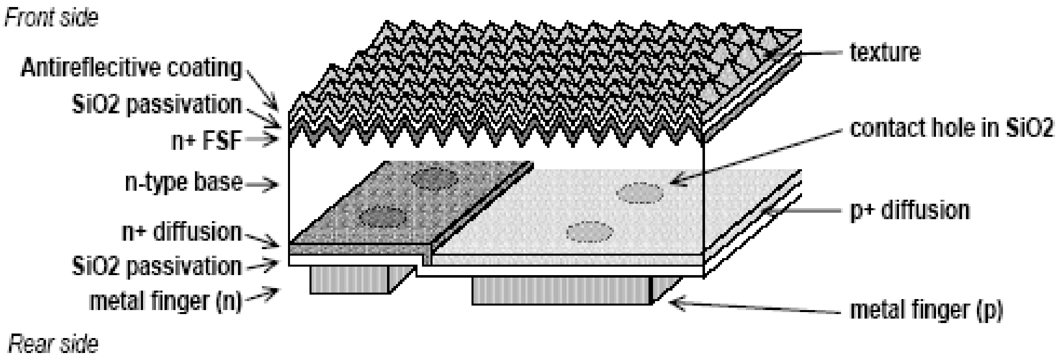
The technology limit is $\boldsymbol{\eta \approx 19\%}$

Increasing cell efficiency

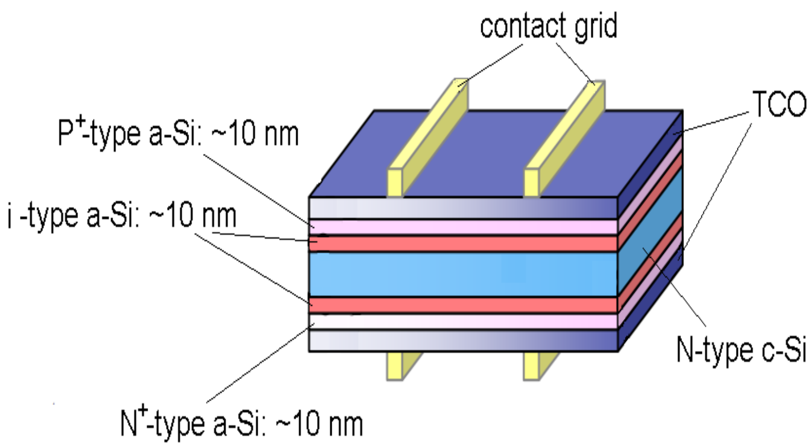
Selective emitter



Back contact cells

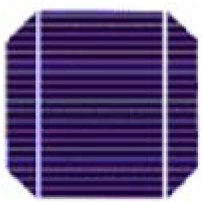


Hetero junction cells (HIT)

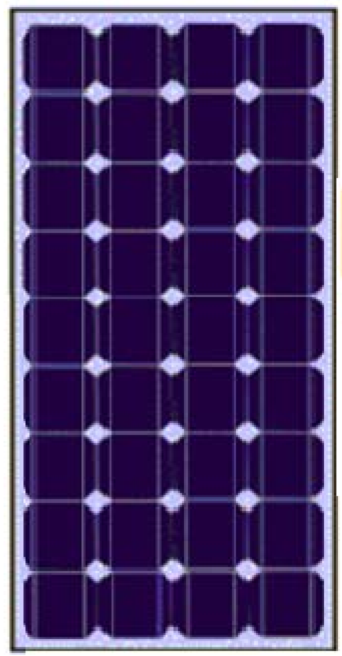


A single solar cell……~0.5 V, about 30 mA/cm^2

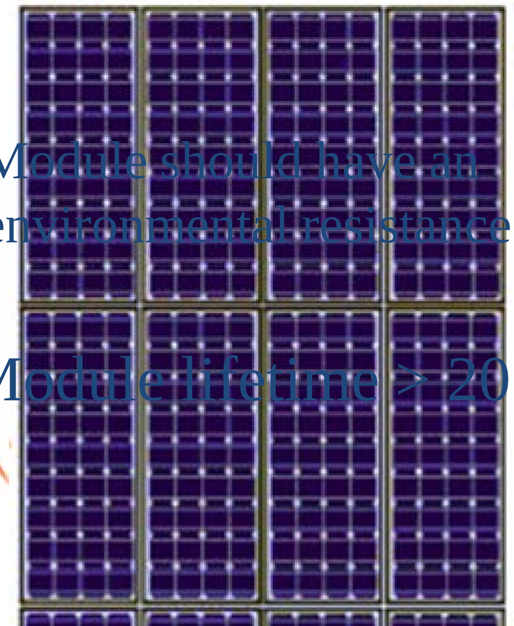
For practical use it is necessary connect cells in series to obtain a source of higher voltage and in parallel to obtain a higher current



Solar cell

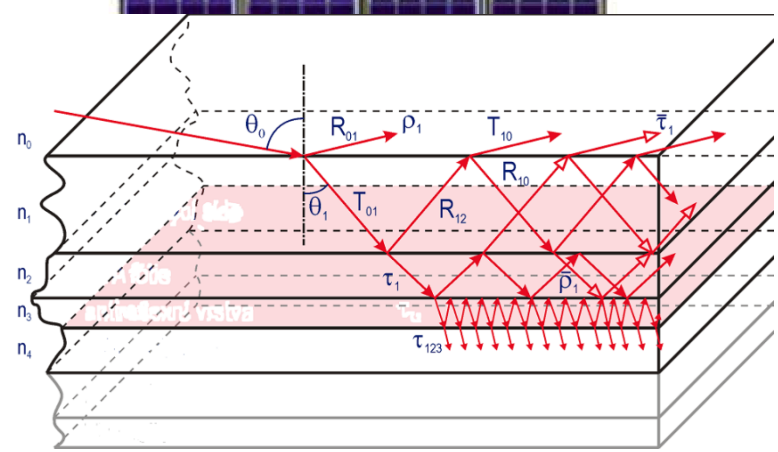


PV module



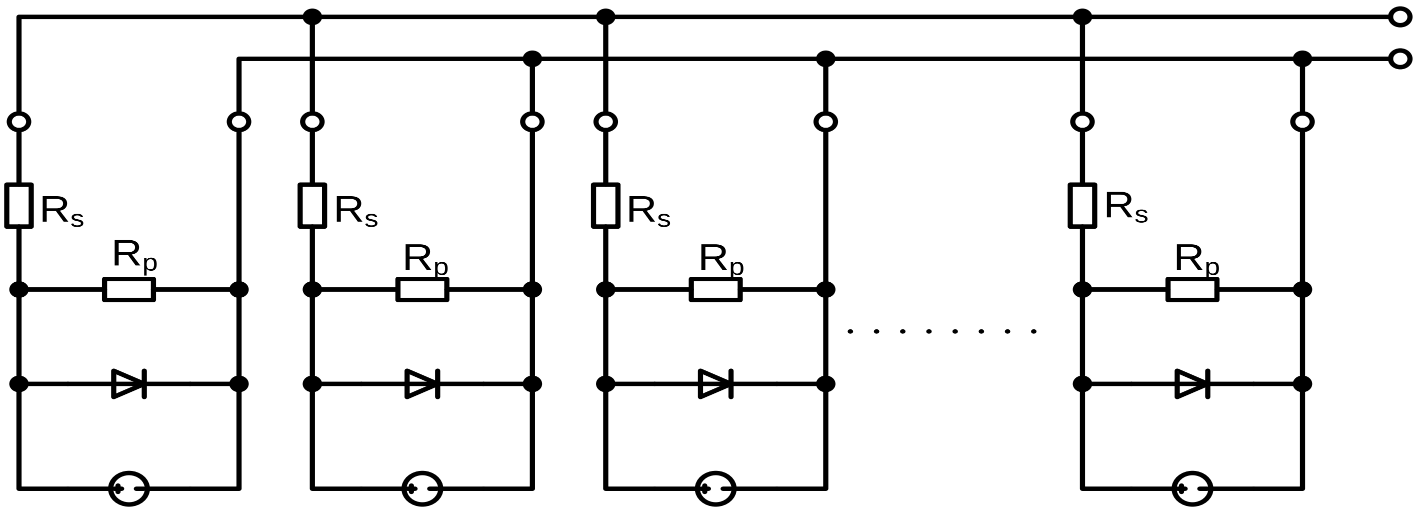
Module should have an environmental resistance

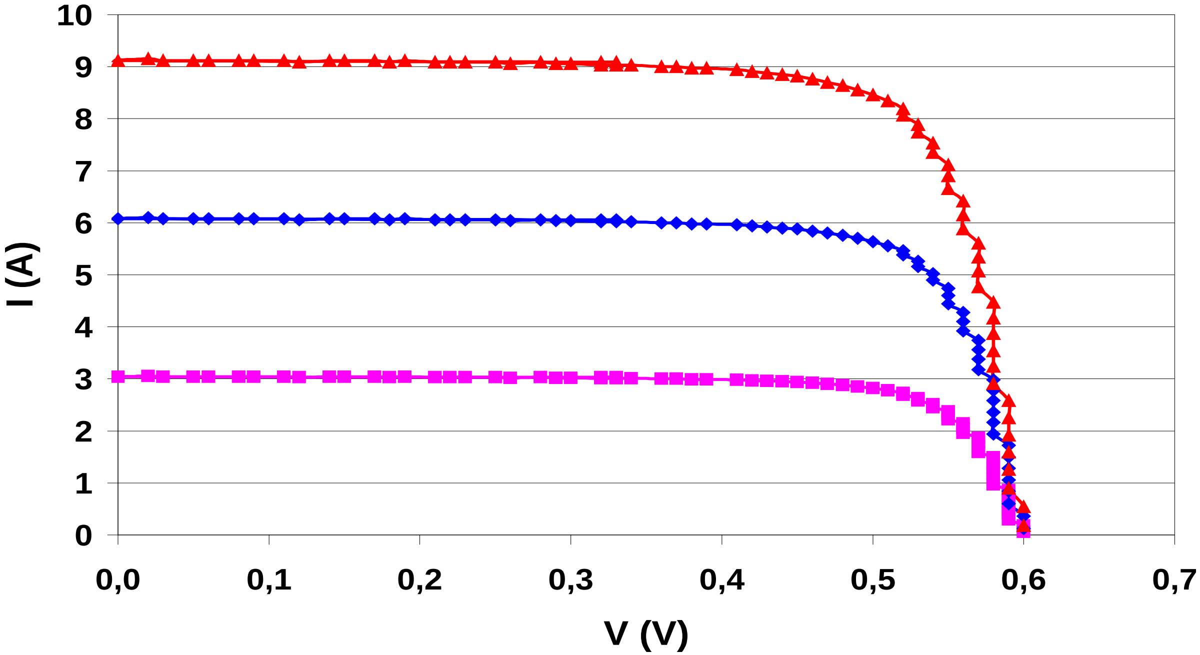
Module lifetime > 20 years



Minimising optical losses

Cell connection in parallel

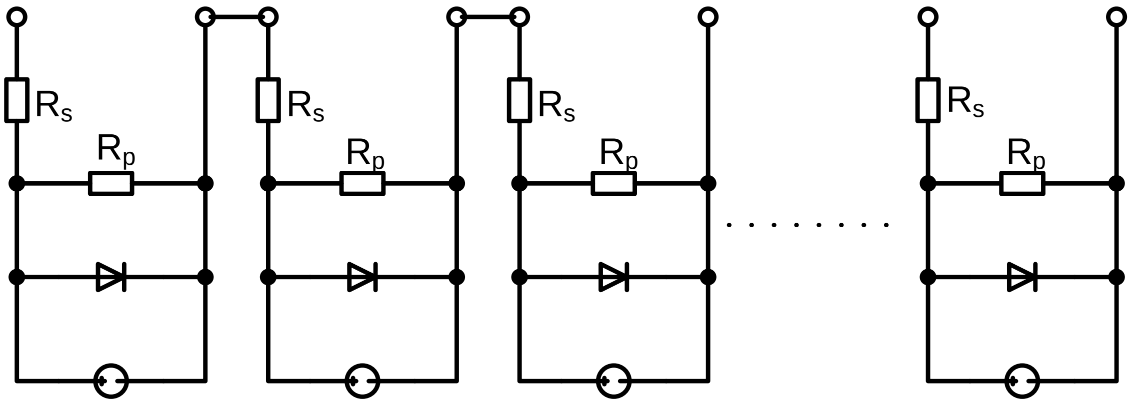


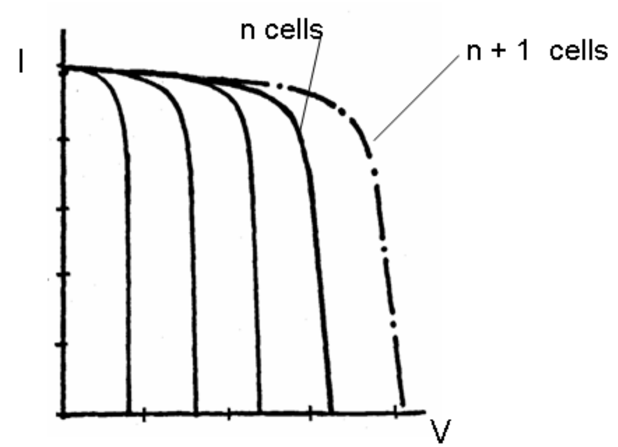


Optimum situation: all cells have the same V_{MP}

If characteristics of individual cells in parallel differ, efficiency decreases

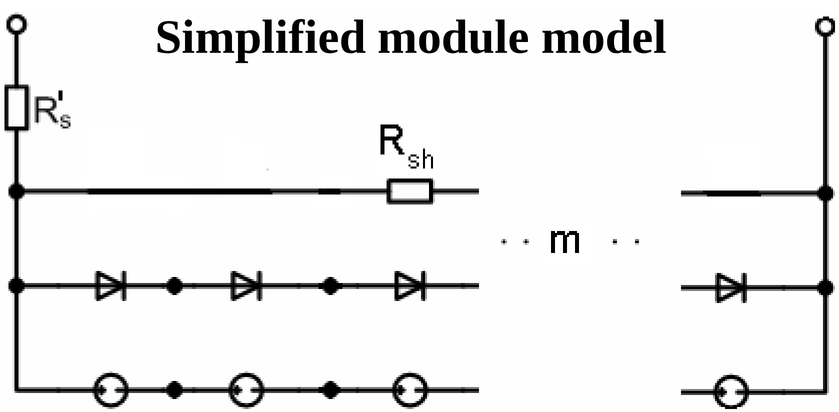
Cells in series….. the same current flows through all cells
voltage does sums





Optimum situation: **all cells have the same I_{MP}**

Simplified module model

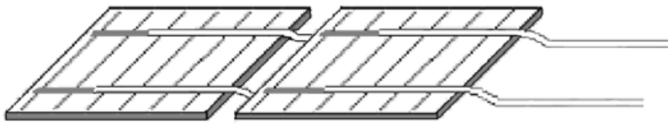


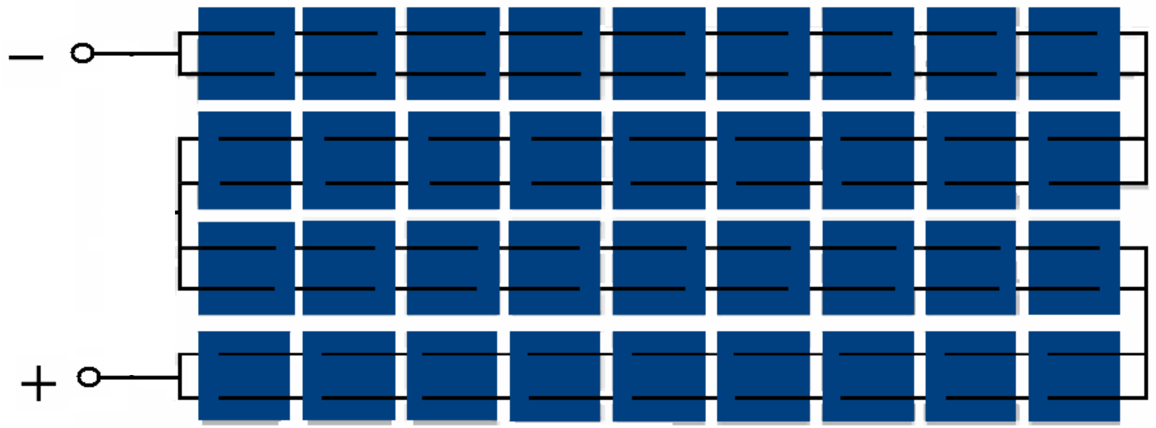
If characteristics of individual cells in series differ, efficiency decreases

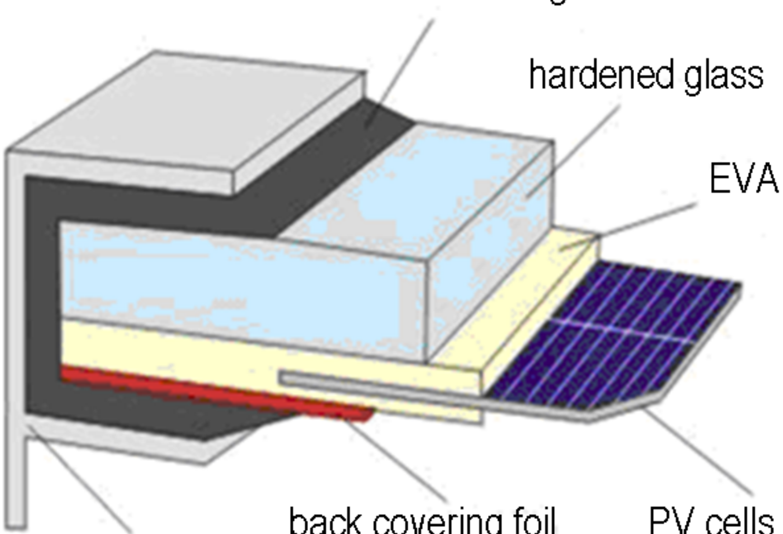
$$I = I_{PV} - I_{01}\left[\exp\left(q\frac{V + R_s^{'}I}{m\varsigma_1 kT}\right) - 1\right] - I_{02}\left[\exp\left(q\frac{V + R_s^{'}I}{m\varsigma_2 kT}\right) - 1\right] - \frac{V + R_s^{'}I}{R_{sh}}$$

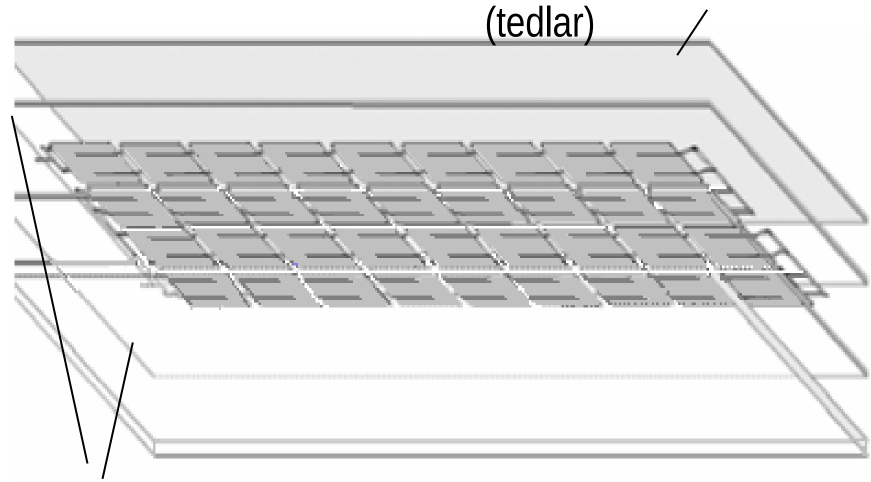
PV c-Si module technology

soldering

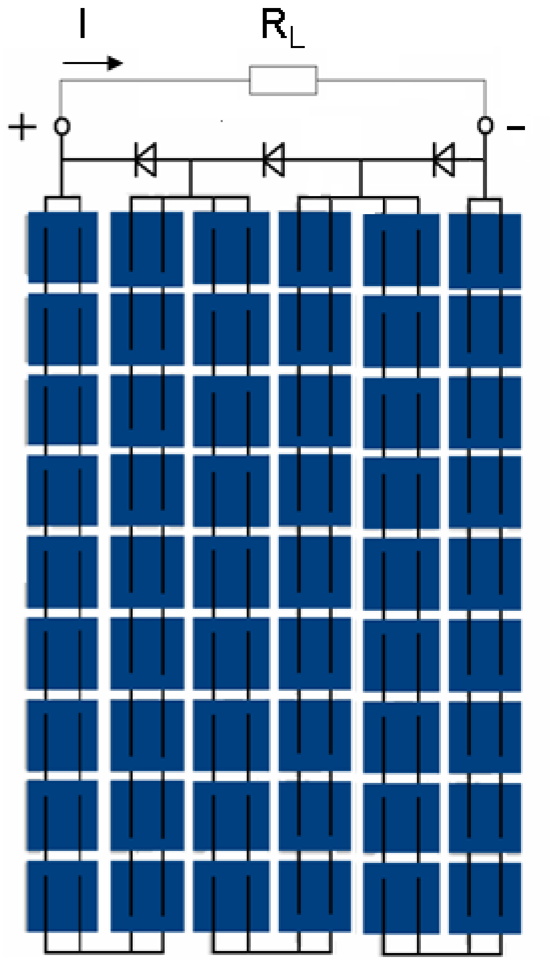


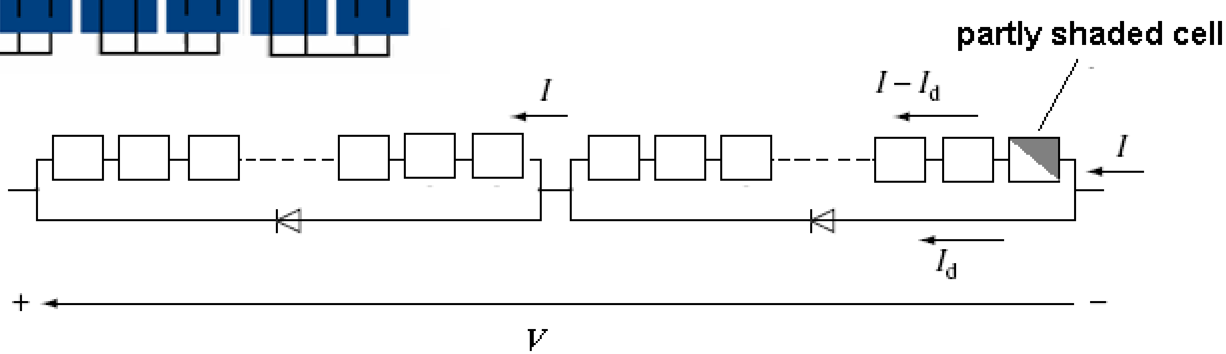






Bypass diodes





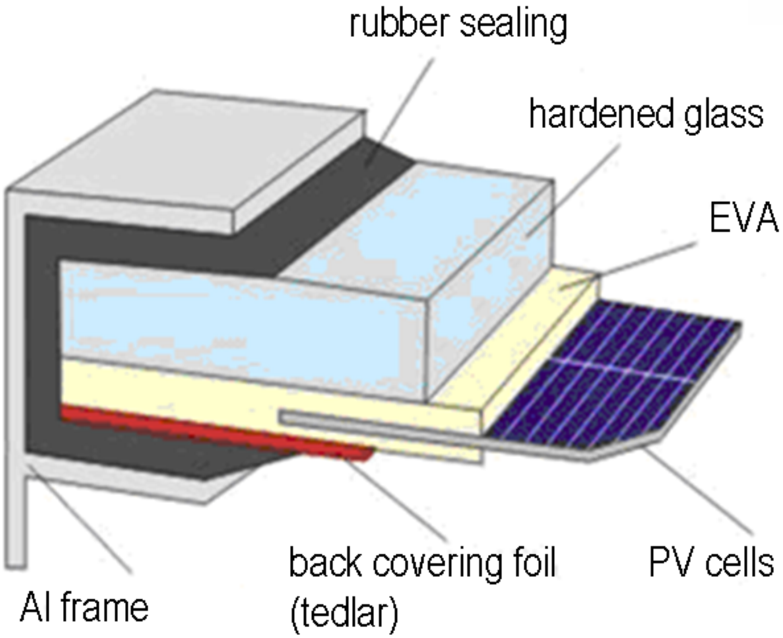
Module parameters

- open circuit voltage $\boldsymbol{V_{OC}}$,
- short circuit current $\boldsymbol{I_{SC}}$
- maximum output power $\boldsymbol{V_{mp}I_{mp}}$

- fill factor $$FF = \frac{V_{mp} I_{mp}}{V_{OC} I_{SC}}$$

- efficiency $$\eta = \frac{V_{mp} I_{mp}}{P_{in}} = \frac{V_{OC} I_{SC} FF}{P_{in}}$$

STC (25°C, 1kW/m^2, AM 1,5)



Real operating temperature

$$T_c = T_a + r_{thca} G_{ab}$$

$$r_{\mathrm{thca}} = \frac{r_{\mathrm{thcaf}} r_{\mathrm{thcab}}}{r_{\mathrm{thcaf}} + r_{\mathrm{thcab}}} \qquad r_{thcab} = \frac{d_b}{\lambda_b} + \frac{1}{h_b} \qquad r_{thcaf} = \frac{d_f}{\lambda_f} + \frac{1}{h_f}$$

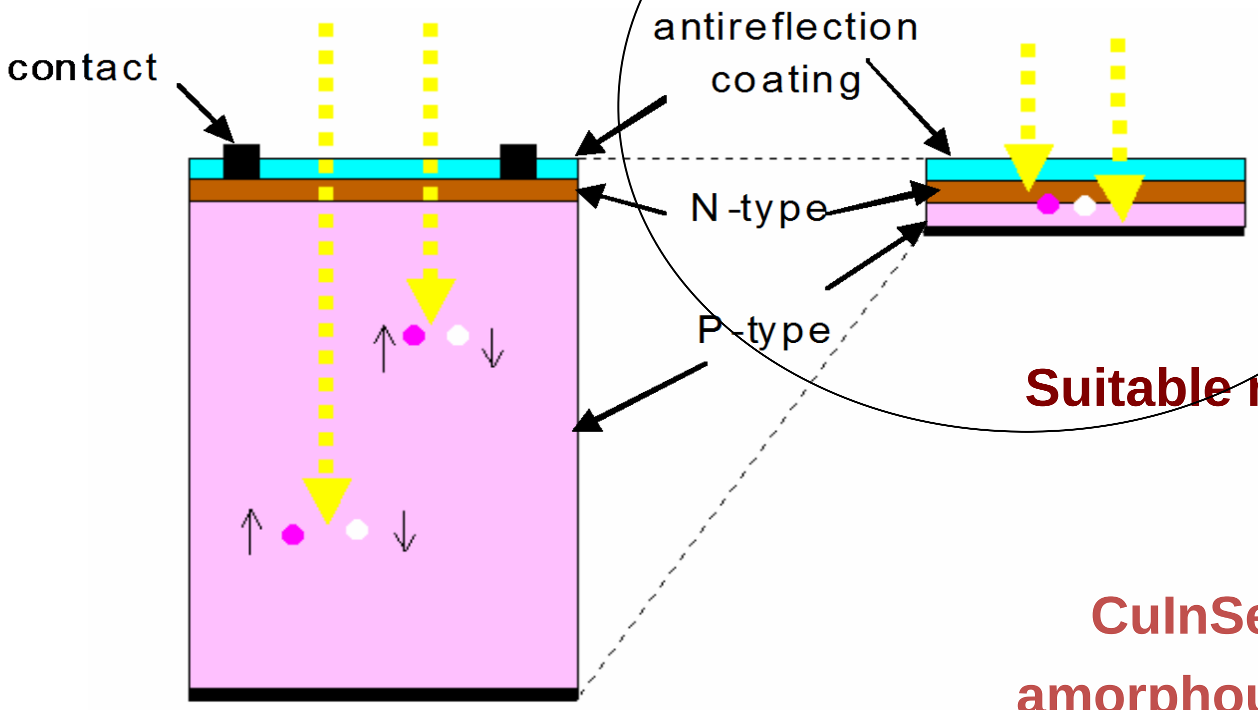
NOCT (Nominal Operating Conditions Temperature)

Ambient temperature 20°C, 800 W/m^2, wind 1 m/s

Basic types of solar cells:

Crystalline silicon cells

Thin film cells



Suitable materials

$CuInSe_2/CdS$

amorphous silicon

amorphous SiGe

CdTe/CdS

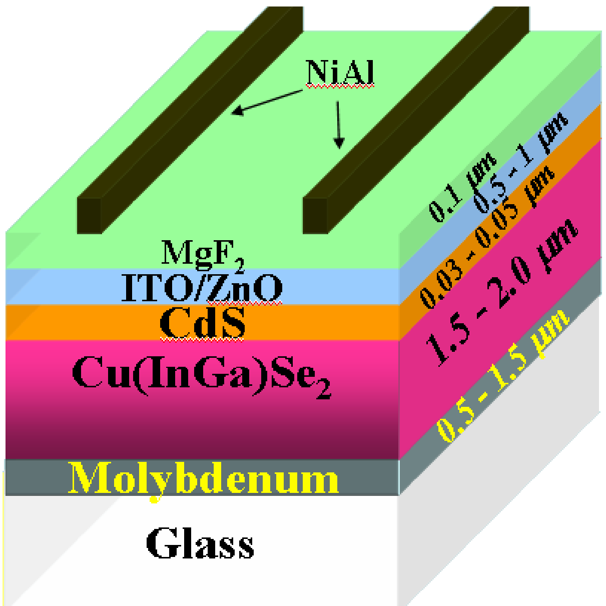
Basic problem: cost…...

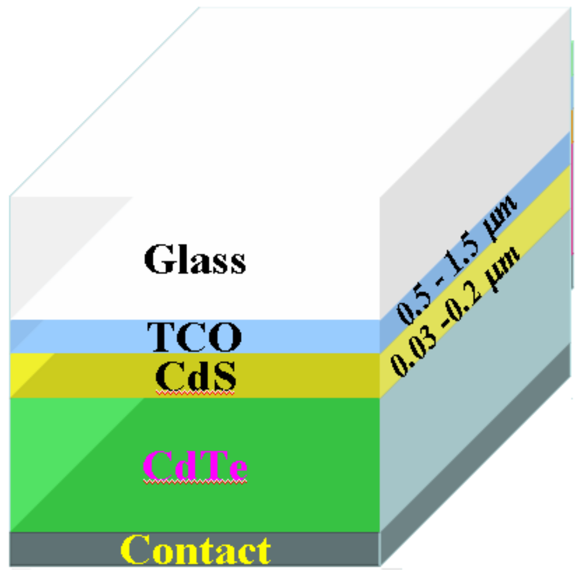
Thin film solar cells

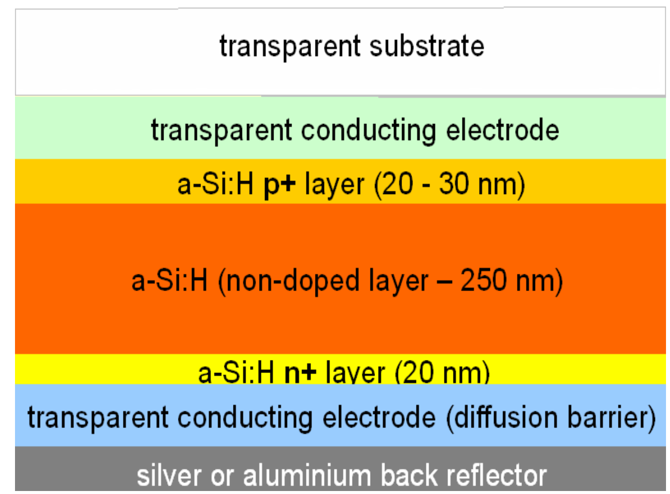
CIS

CdTe/CdS

Amorphous Si







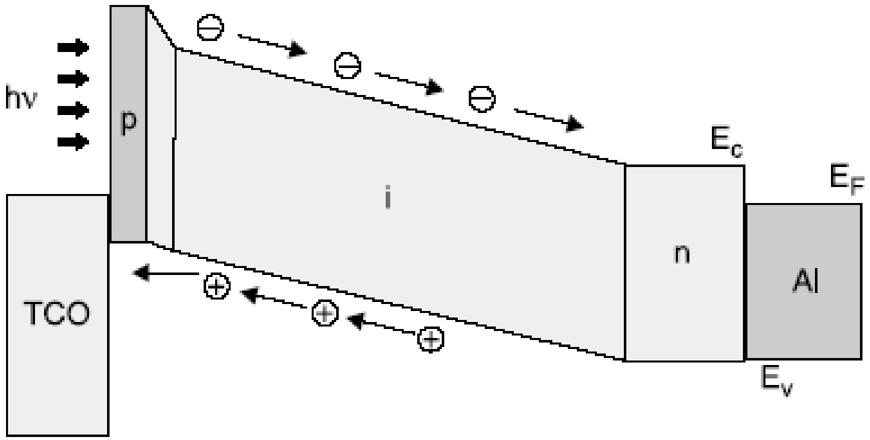
Market share:

1.5%

5.7%

4.7%

Amorphous silicon solar cells

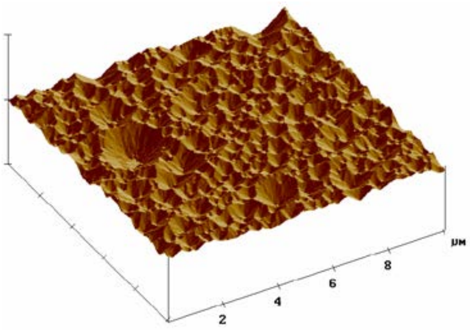


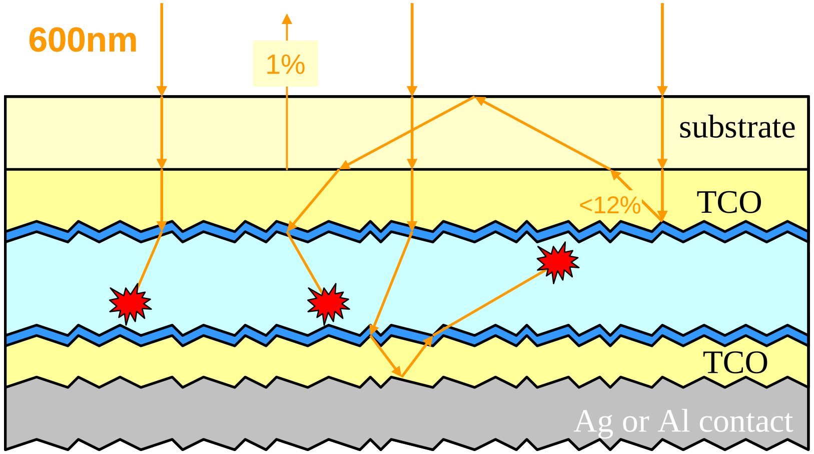
TCO:

SnO_2

ITO (indium-tin oxide)

ZnO

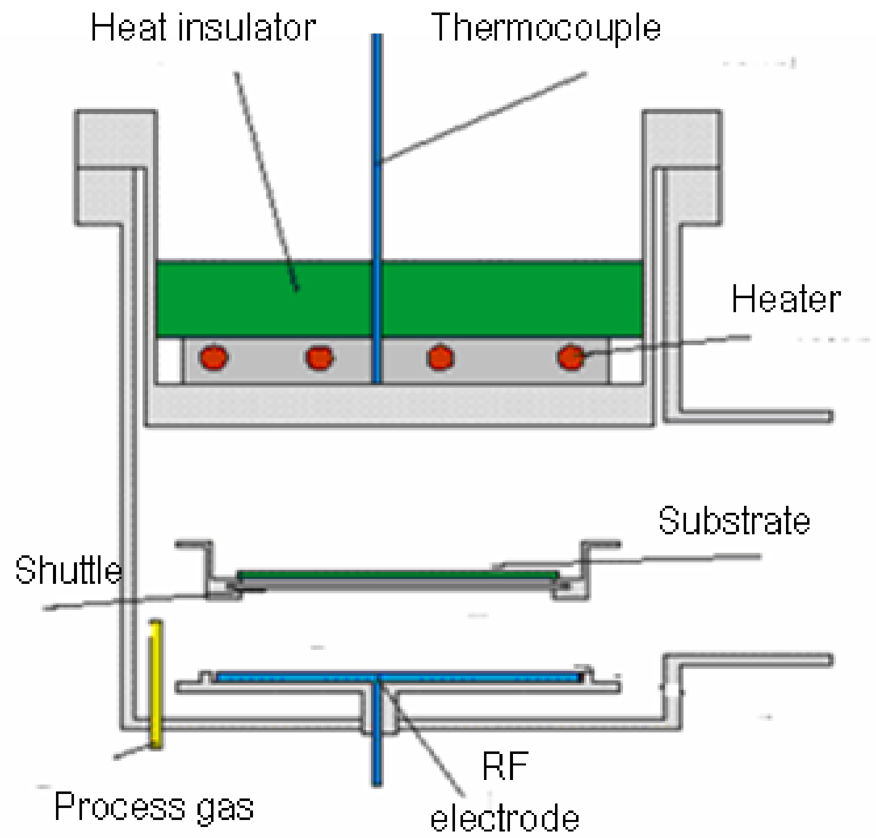




Light trapping

Plasma enhanced CVD (PECVD)

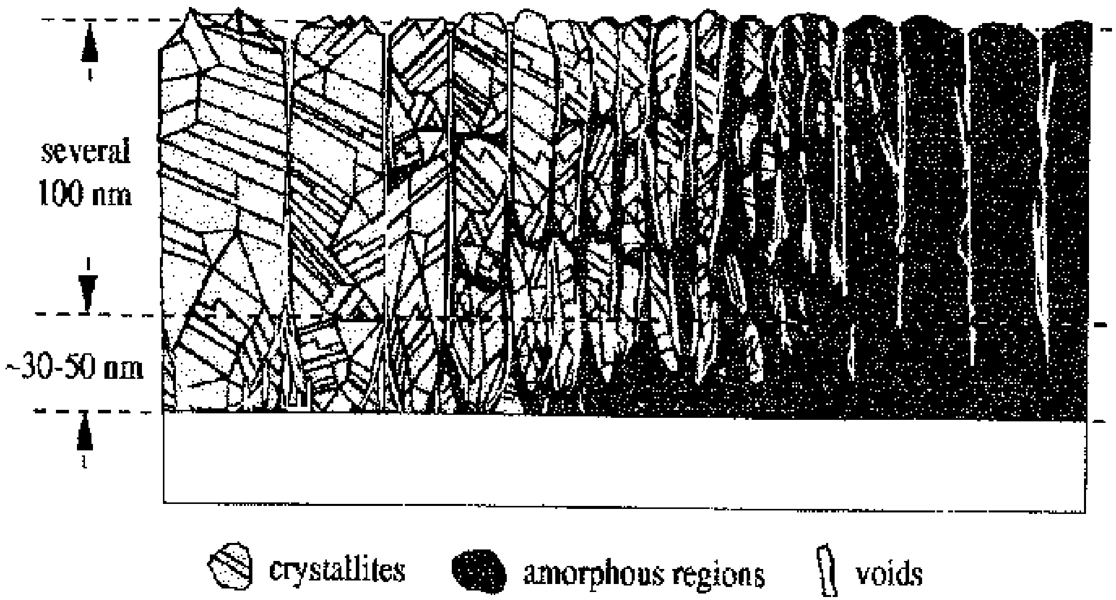
RF electrode and substrate create the capacitor structure.
In this space the plasma and incorporated deposition of material on substrate takes place



deposition of silicon nitride **$3SiH_4 + 3NH_3 \rightarrow Si_3N_4 + 12H_2$**
deposition polysilicon layers **$SiH_4 \rightarrow Si + 2H_2$.**

The deposited layer structure depends on the gas composition and substrate temperature

150 – 350°C



dilution ratio

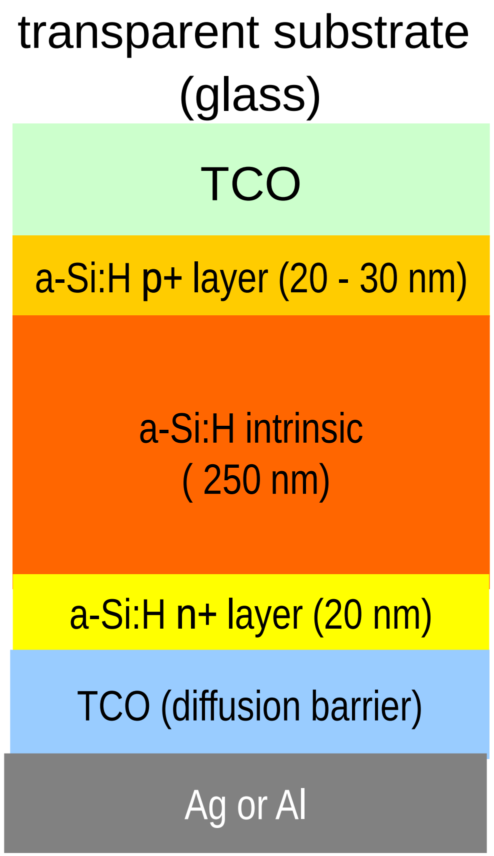
$rH = ([H2] + [SiH4])/[SiH4]$.

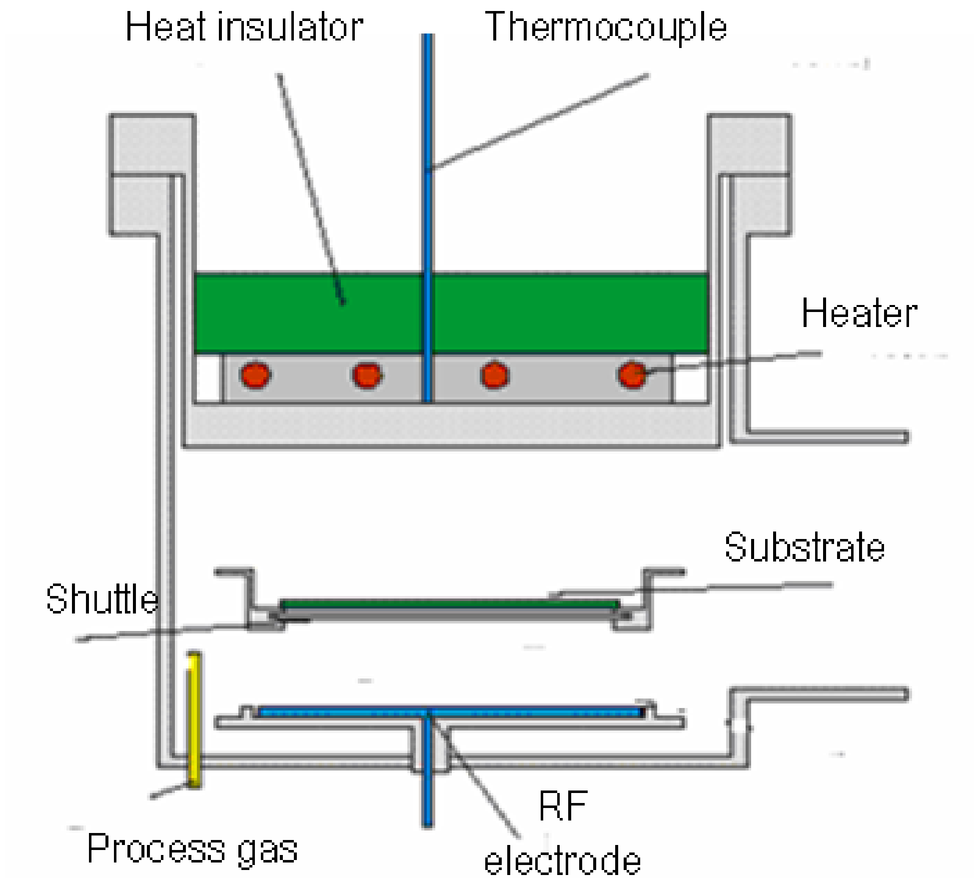
rH < 30, amorphous silicon growth

rH > 45, crystalline layers are formed

Thin film solar cell technology

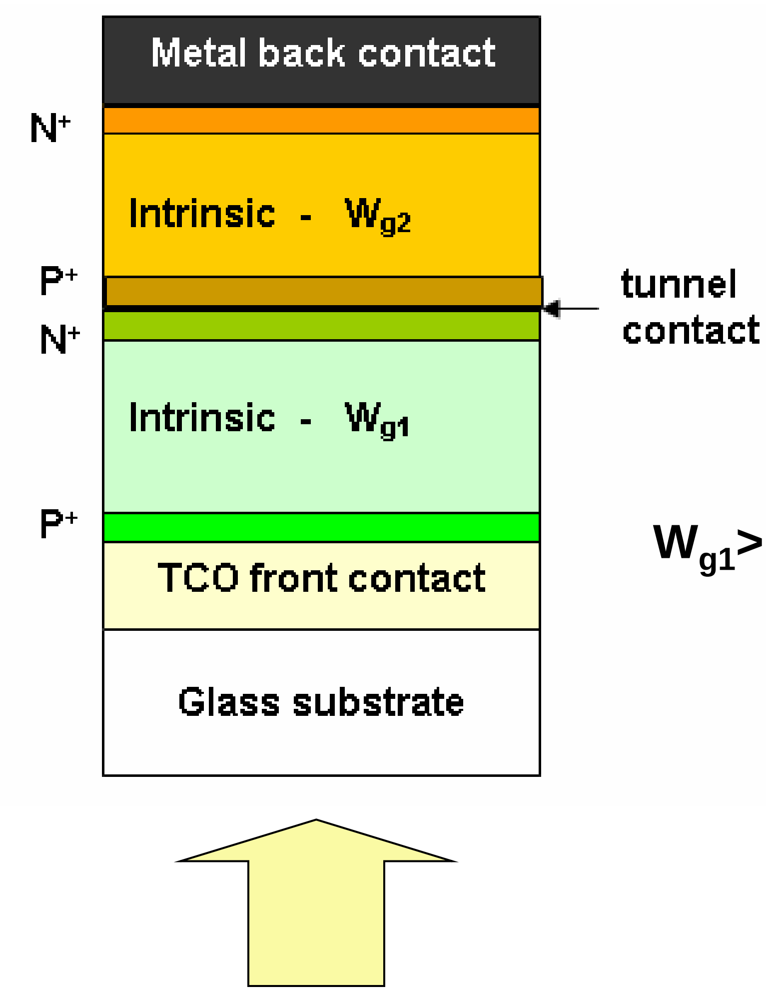
Amorphous (microcrystalline) silicon solar cells





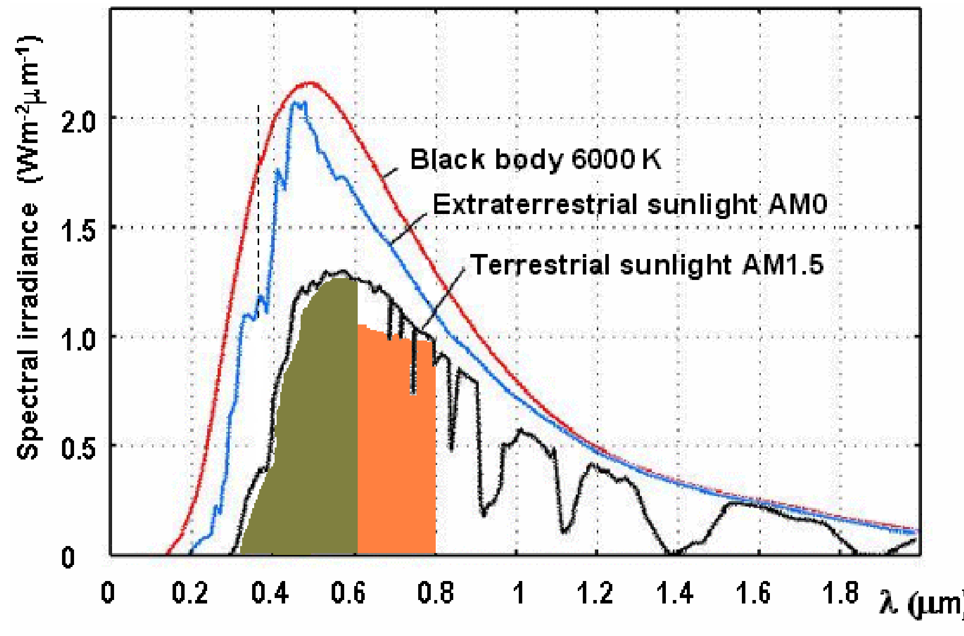
SiH_4, H_2, B_2H_6, PH_3, GeH_4, etc

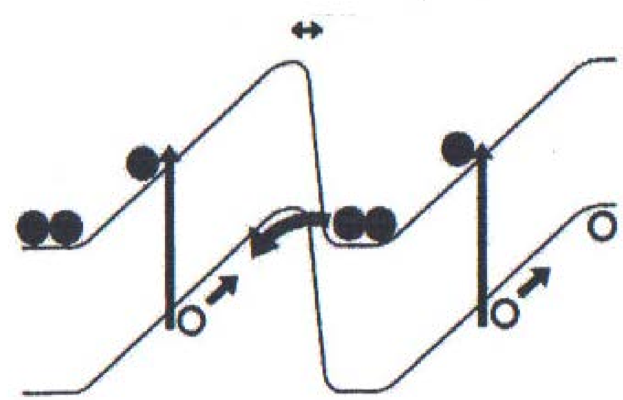
Tandem cells



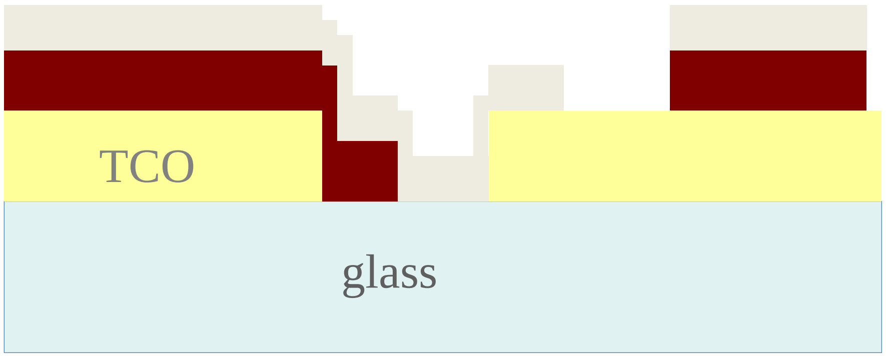
$W_{g1} > W_{g2}$

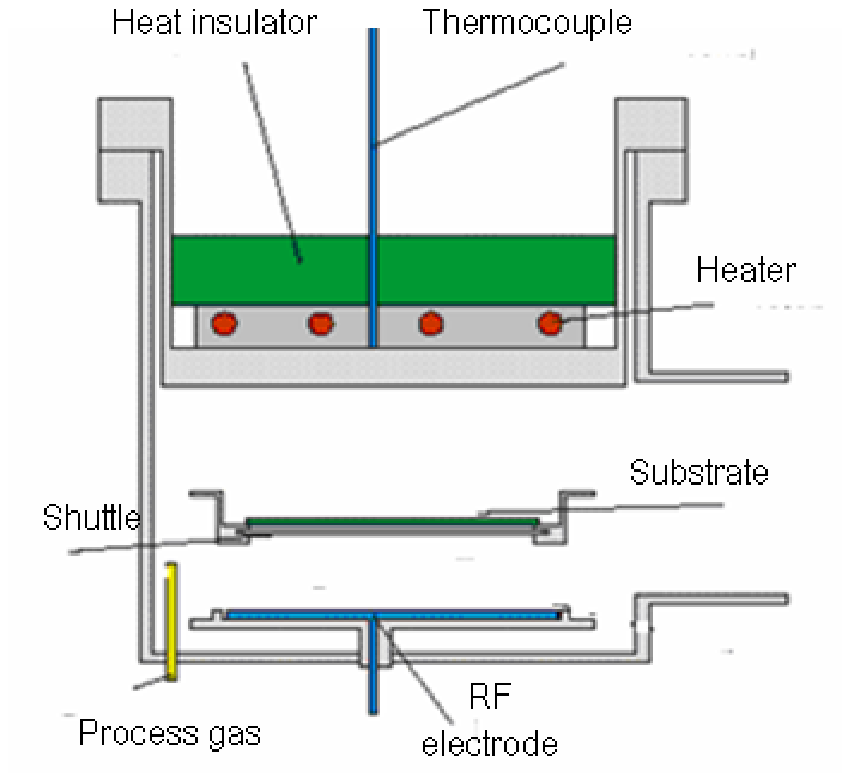
irradiation

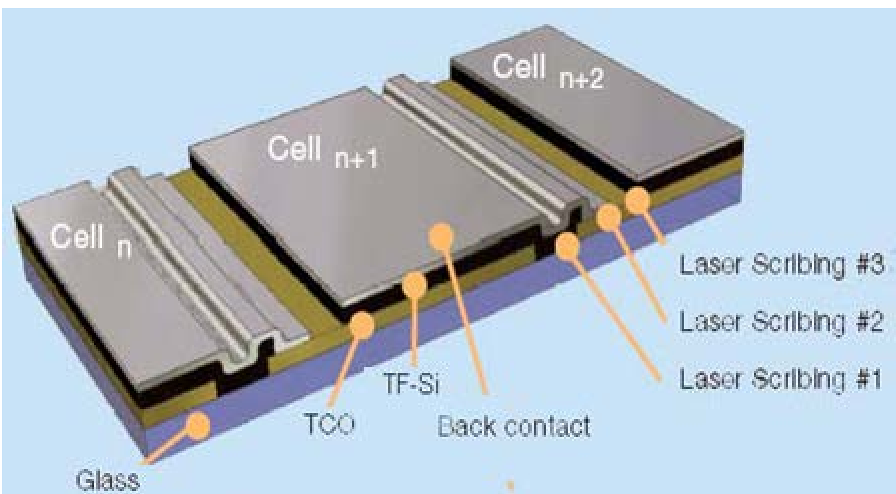


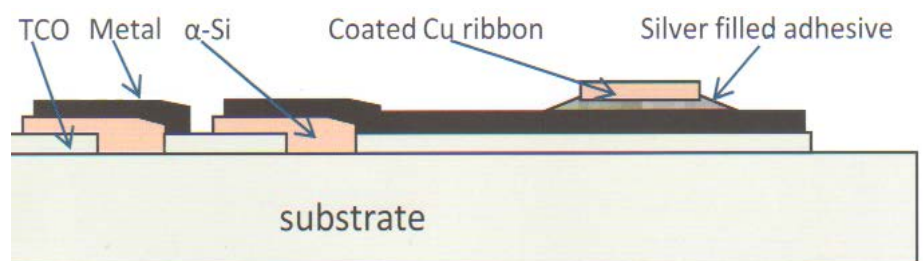


Thin-film modules on glass substrates



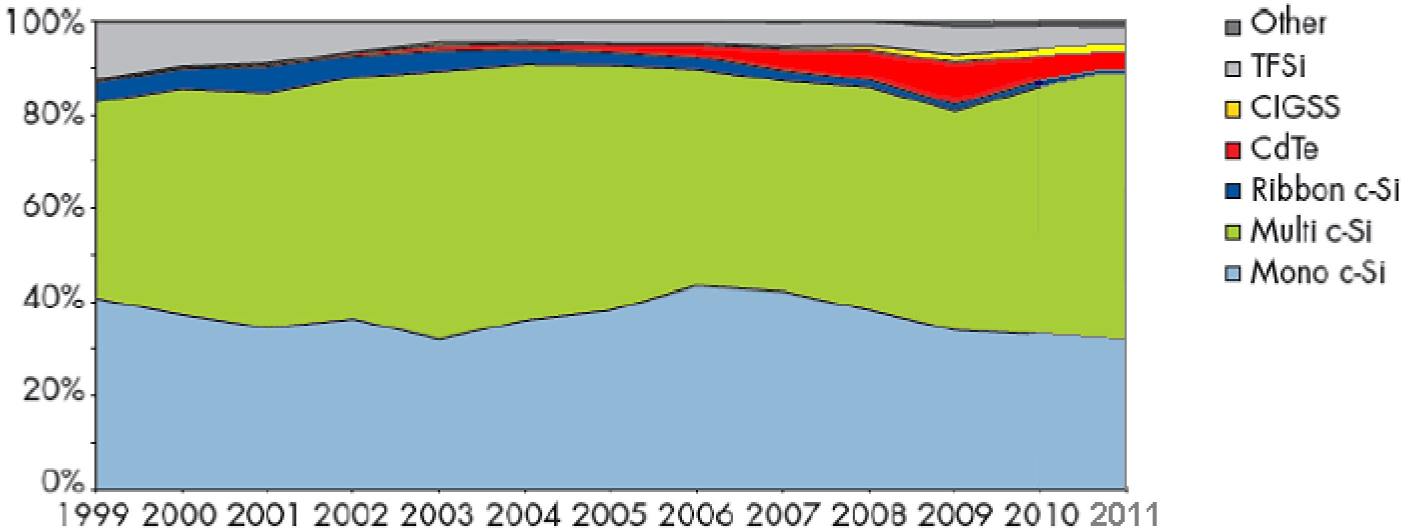




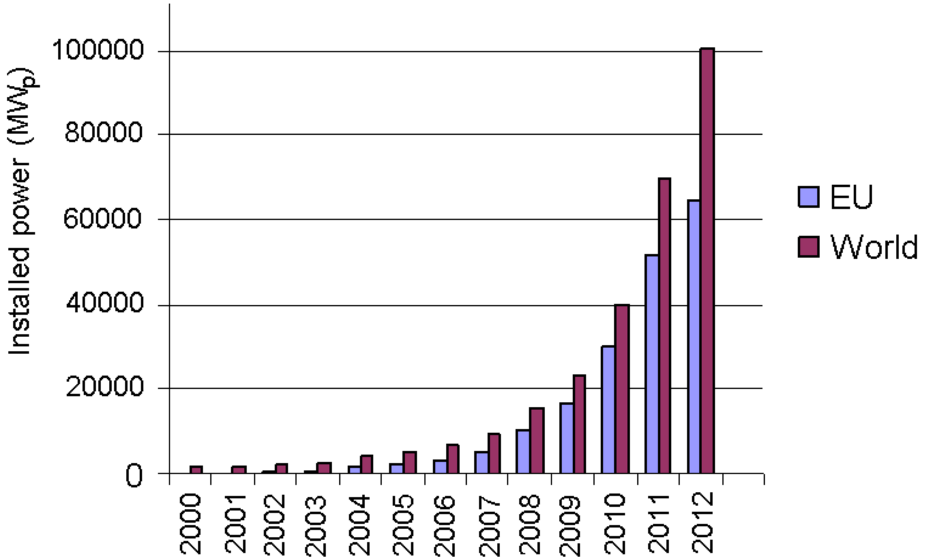


Back surface is laminated with EVA and suitable covering sheet (glass, tedlar)

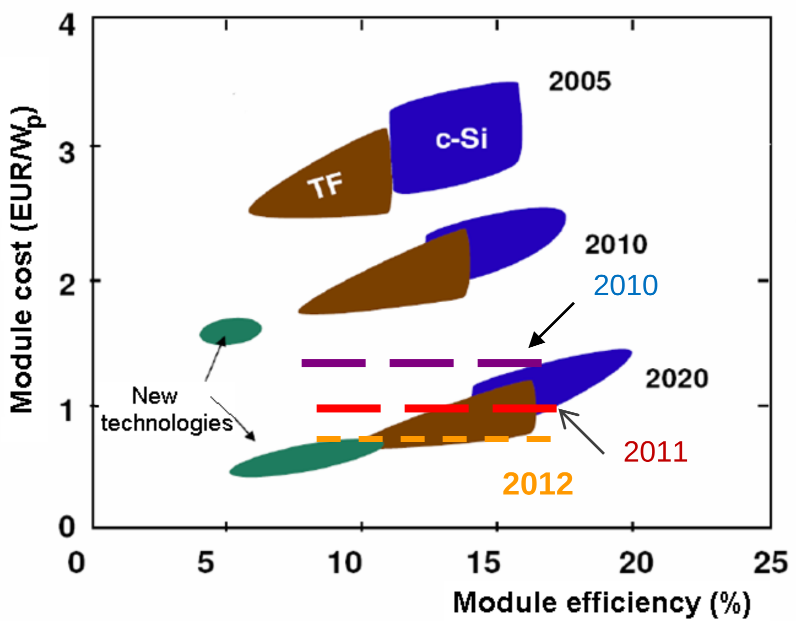
Market share development



	2010	2011	2012
Crystalline silicon	84,4%	87%	87%
Thin Film	14,8%	12%	12%
Others	0,9%	1%	1%



PV module cost development



Reduction of silicon cost

2008…… 500 USD/kg

2010………55 USD/kg

2012 …….. 22 USD/kg

Reduction of C-Si module cost

Thin-film modules are not cheaper than modules from crystalline silicon (yet)