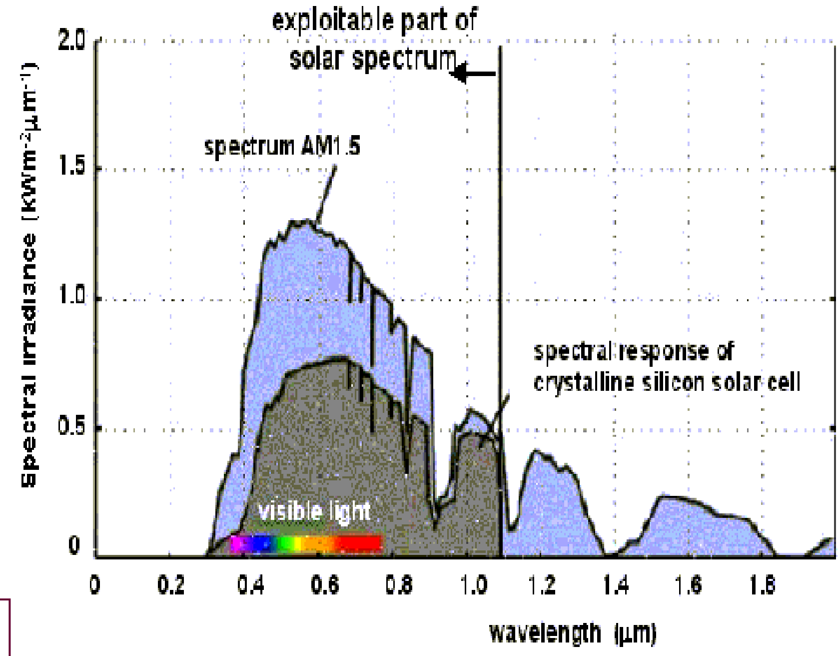
Crytalline silicon cell and module construction and technology

To maximise current density J_{PV} it is necessary

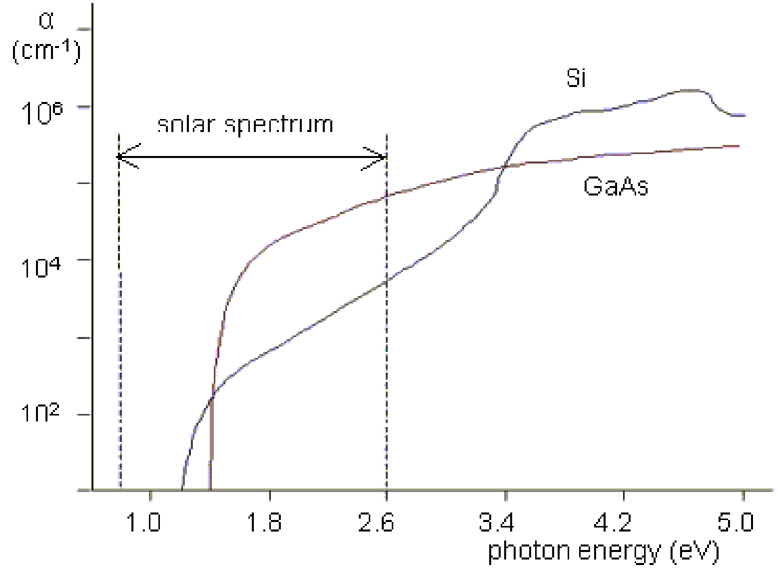
- **maximise generation rate G**
- **minimise losses**



losses

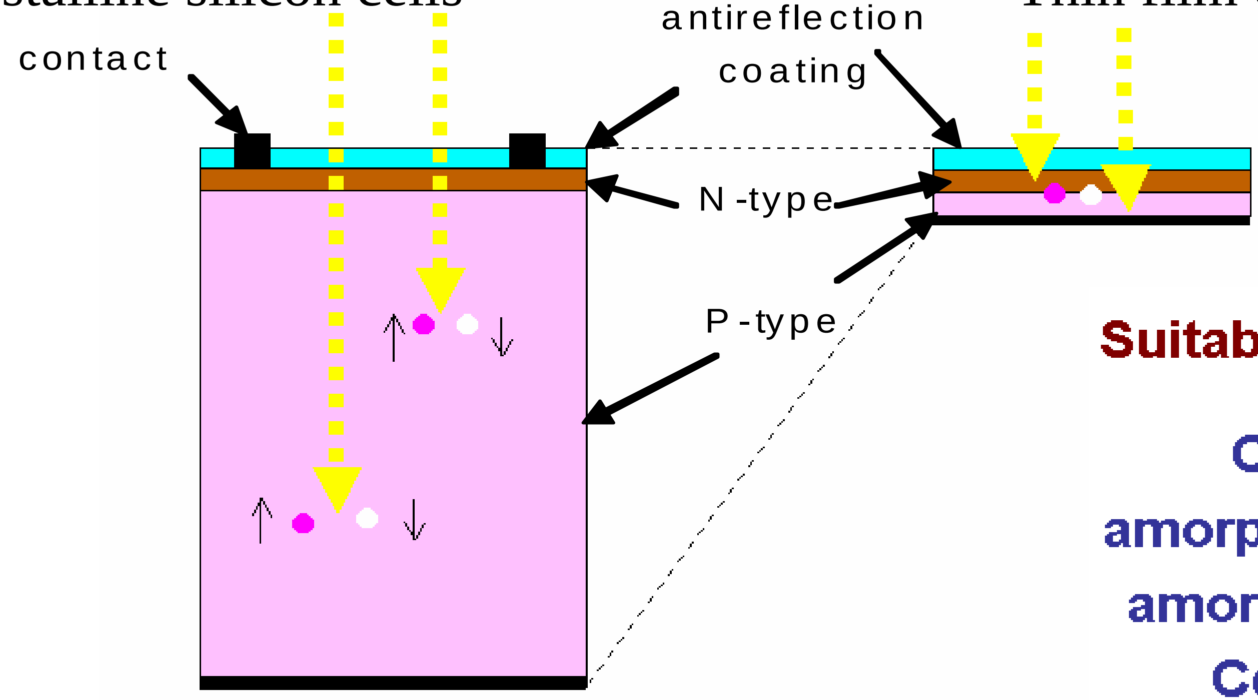
- **optical**
  - reflection
  - shadowing
  - not absorbed radiation
- **recombination**
  - emitter region
  - base region
  - surface
- **electrical**
  - series resistance
  - parallel resistance

Basic types of solar cells:



Crystalline silicon cells

Thin film cells



Suitable materials

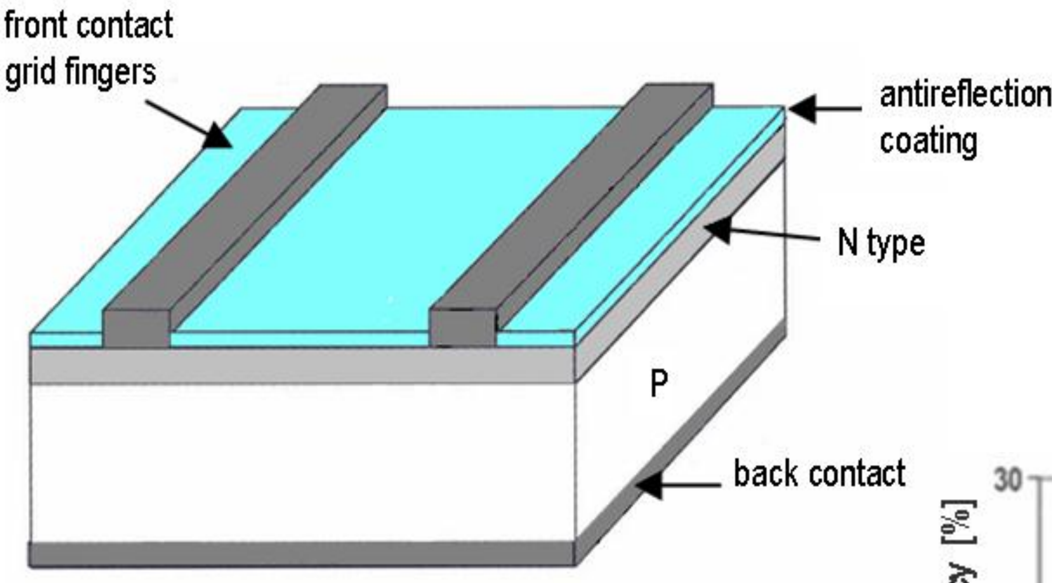
$CuInSe_2$

amorphous silicon

amorphous SiGe

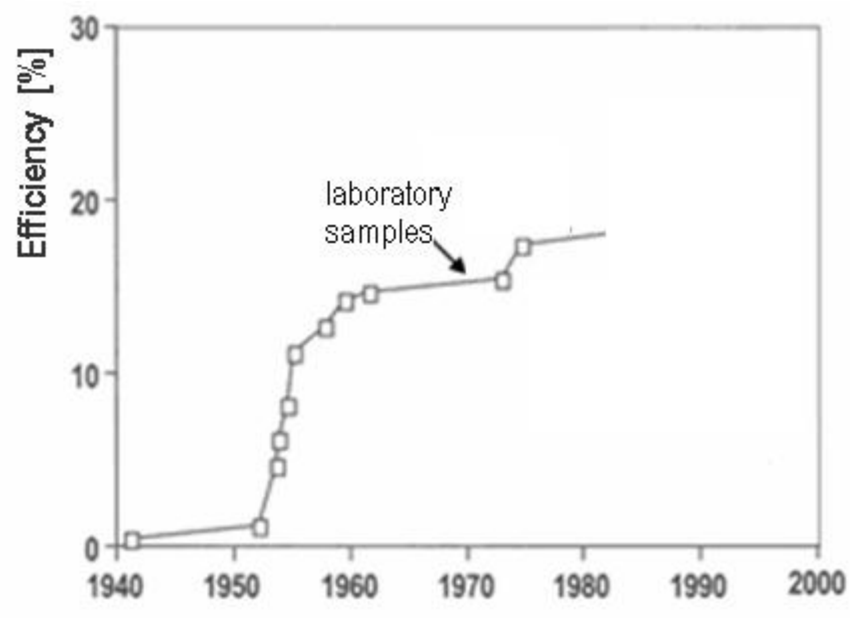
CdTe/CdS

Crystalline silicon solar cell and modules



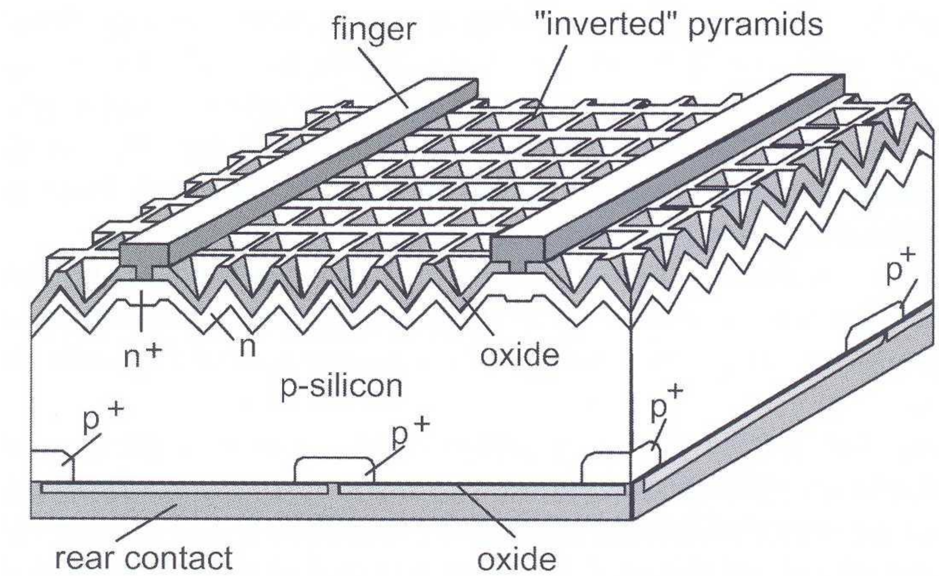
1960 -1980

- ***plane surface***
- ***SiO_2 (TiO_2) antireflection layer***
- ***photolithography***
- ***vacuum contact deposition***

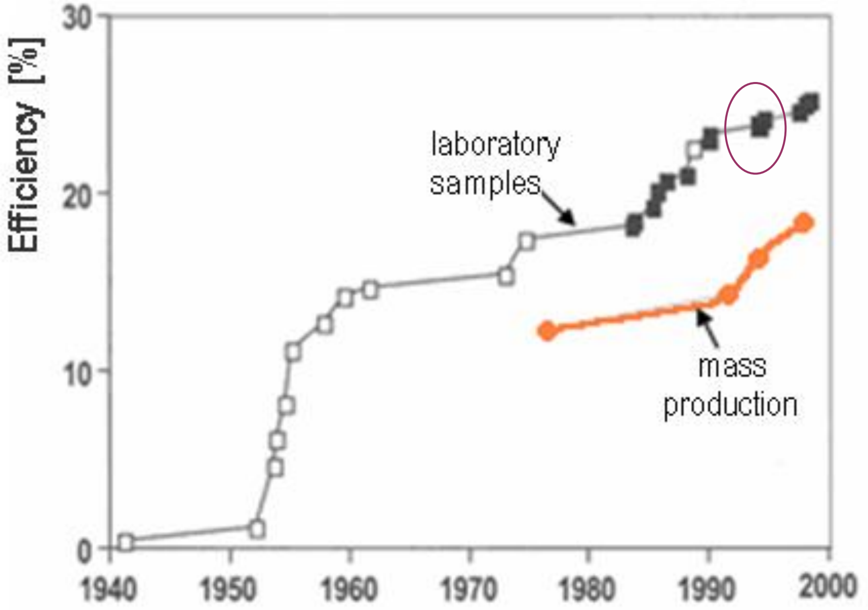


New construction principles

PEARL structure (1994)



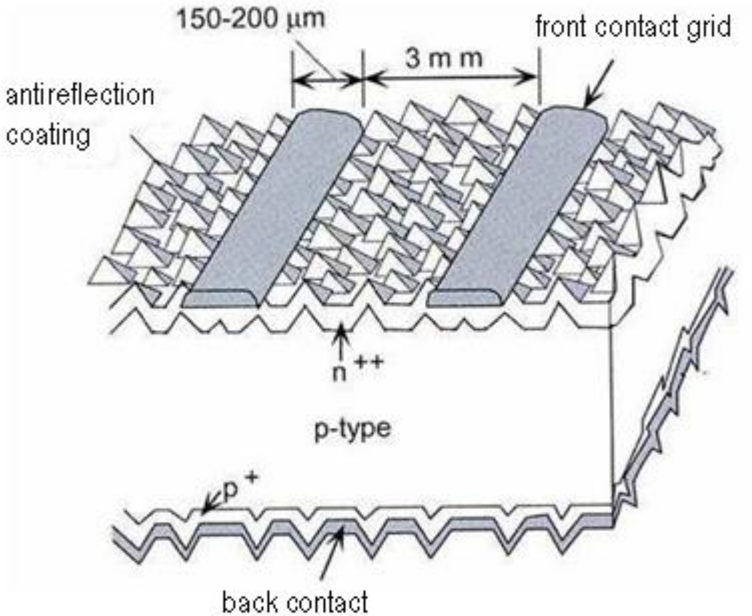
microelectronics technology with several photolithographic processes



- **antireflection coating improvement**
- **high contact quality**
- **high quality starting (FZ) Si**
- **minimising the structure thickness**

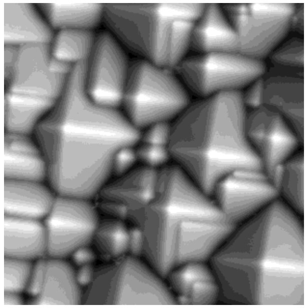
principles of construction and technology were simplified for mass production

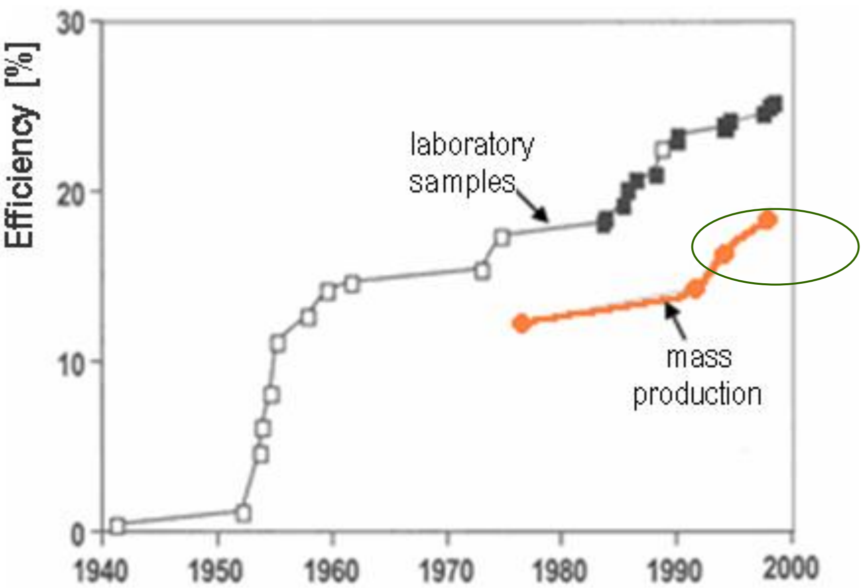
Present construction used in mass production



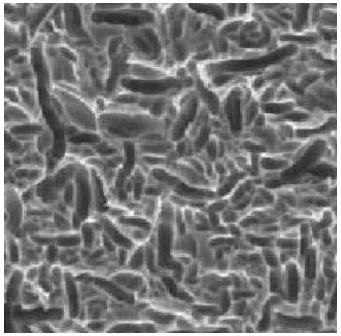
-Surface texturing without photolithography

- etching monocrystalline (1,0,0) Si in KOH



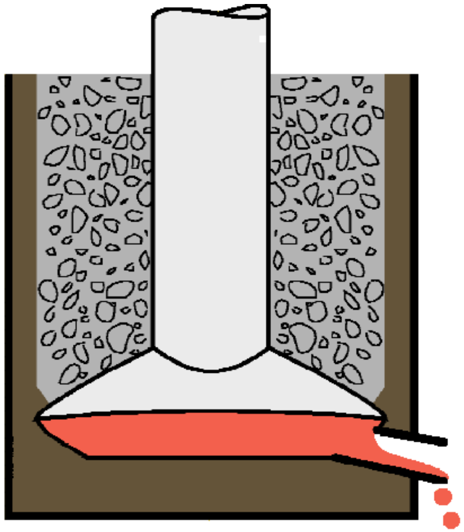


- acid etching in the case of other crystallographic orientation of Si



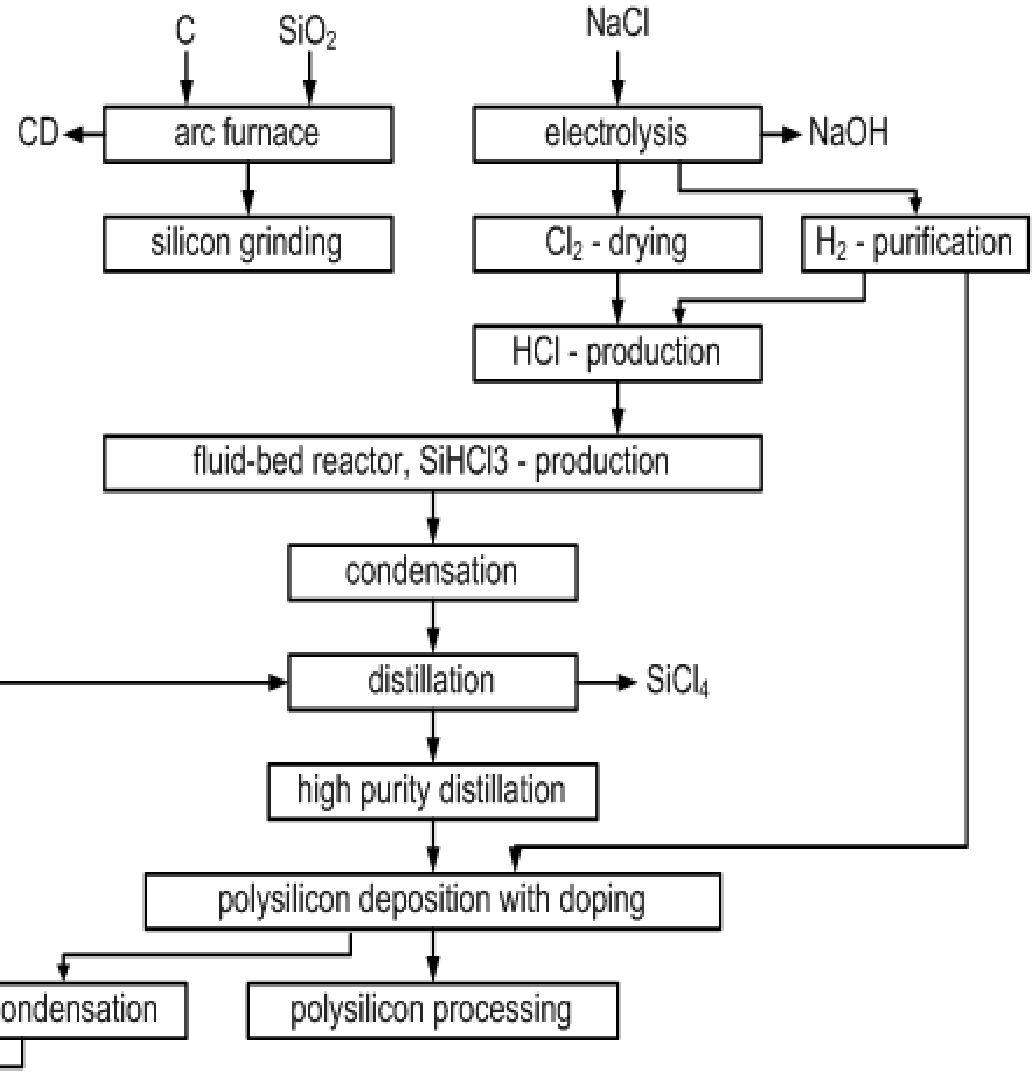
Preparing semicondutor silicon

$SiO_2 + C \rightarrow Si + CO_2$



99%

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



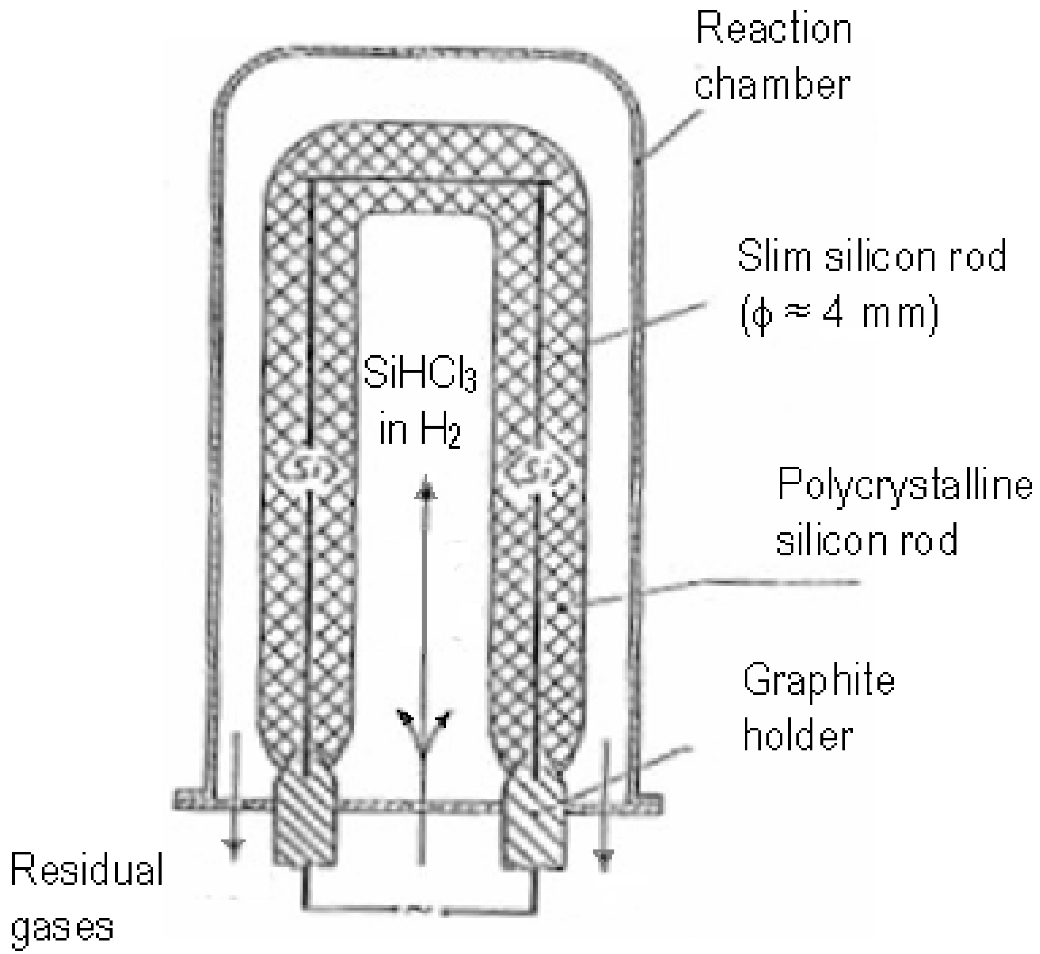
Polycrystalline silicon fabrication

(Siemens process)

$SiHCl_3 + H_2 \rightarrow Si + 3HCl$

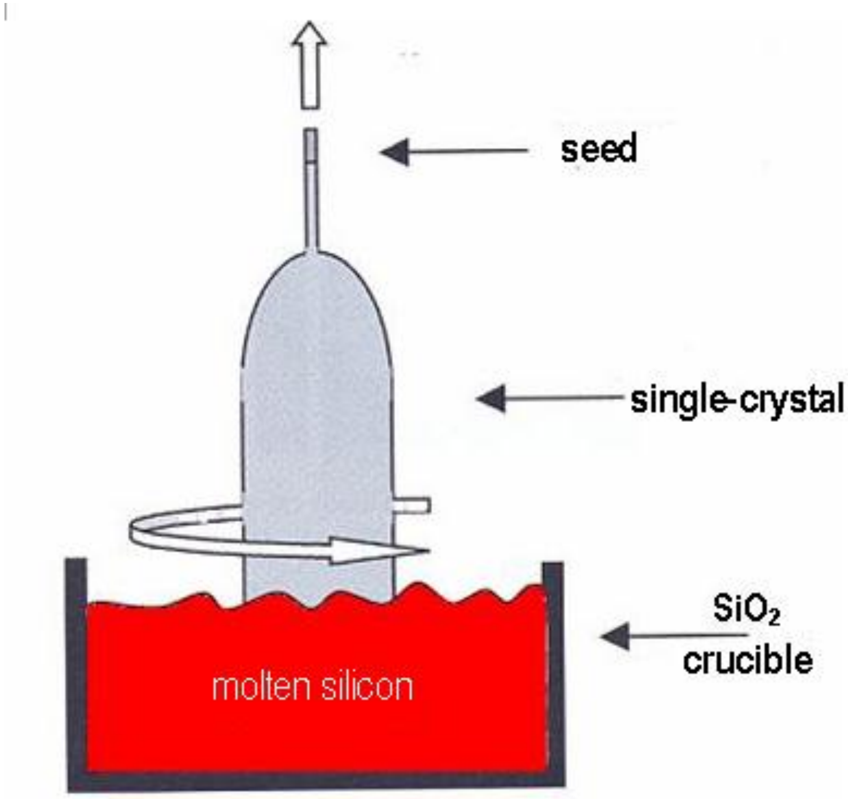
$HCl + HSiCl_3 \rightarrow SiCl_4 + H_2$

Solar grade Si
99,999%



Single-crystal fabrication

Czochralski method



- Diameter up to 450 mm
- Weight up to 300 kg

Single-crystal fabrication

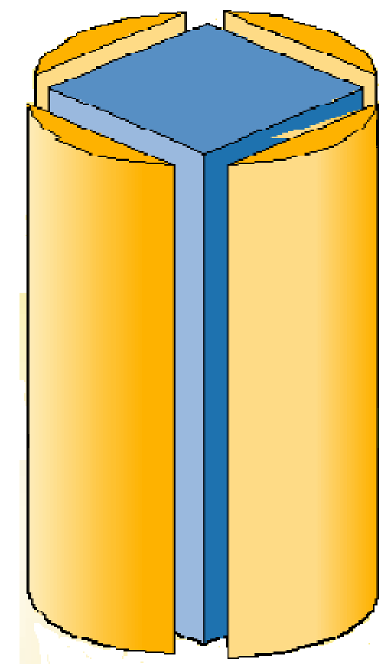
polycrystalline silicon processing

FZ-pulling

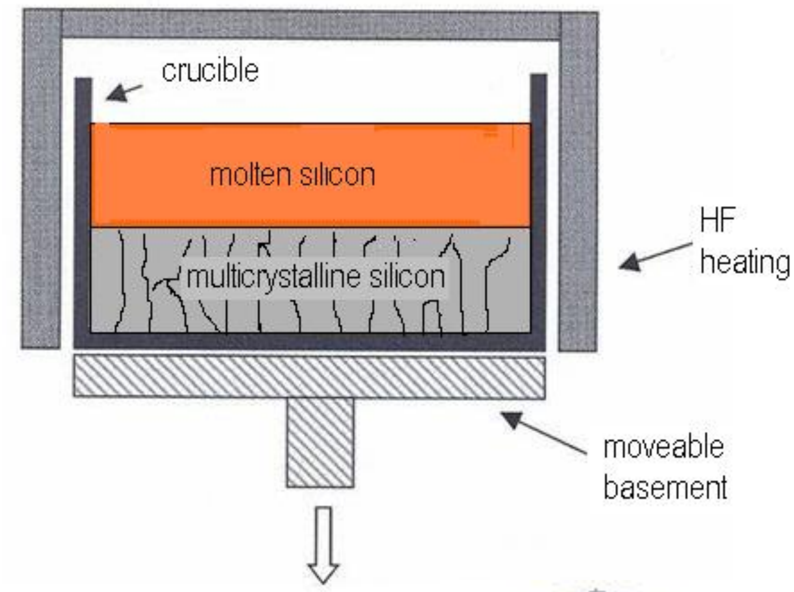
CZ-pulling

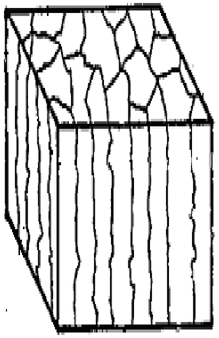
slim-rod pulling

single crystal rod shaping



Multicrystalline rod fabrication





Wafer fabrication

crystalline silicon shaped rod

↓

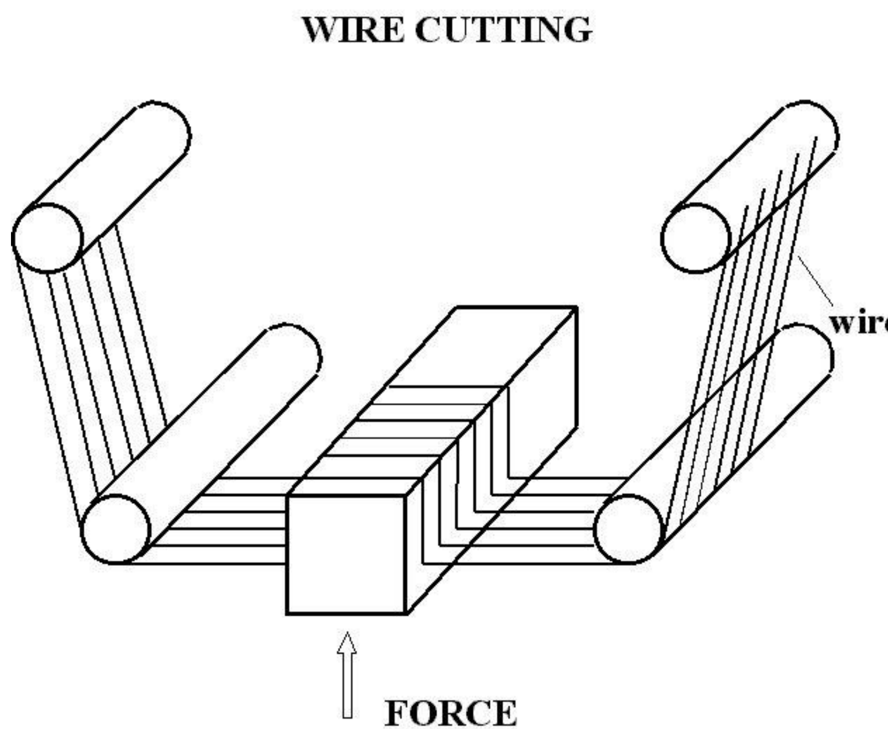
sawing

↓

etching and cleaning

↓

solar cell grade quality wafer



~40% of material is lost during crystalline rod cutting (sawing)

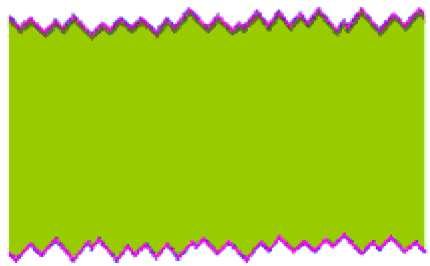
Fabrication of c-Si solar cells

a) Starting silicon wafer, wire cut, without grinding (crystal orientation 1,0,0, P-type)

b) Silicon wafer after isotropic etching, surface damaged layer (about 30 μm) etched-off

c) Silicon wafer after surface texturing by anisotropic etching in KOH (NaOH)

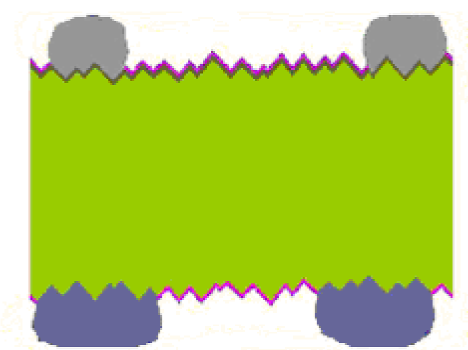
d) Silicon wafer after one-side phosphorous difussion, diffusion depth about 0.5 μm



e) Antireflection coating with silicon nitride layer of thickness about 75 μm, both sides

f) Print-screening Al + Ag paste on back surface of the cell (a layer 30-50 μm thick)

g) Print-screening Ag paste on front surface of the cell (a layer about 30-50 μm thick)



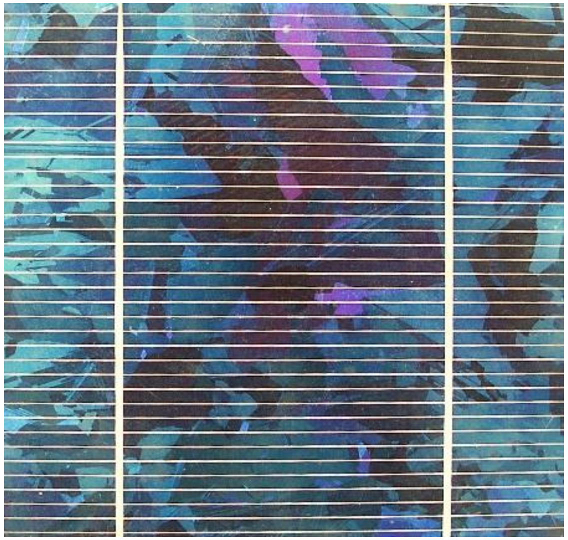
h) Contact sintering at temperature about 800°C, realisation ohmic contacts, edge grinding.

Crystalline Si solar cells

mono-crystalline

$\eta \leq 17\%$

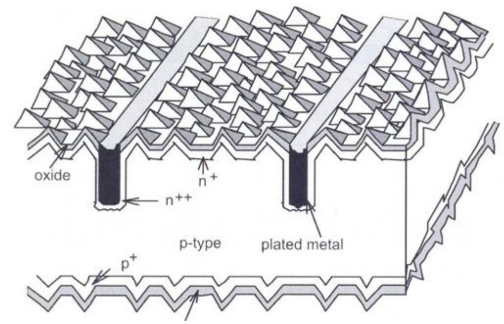
multi-crystalline



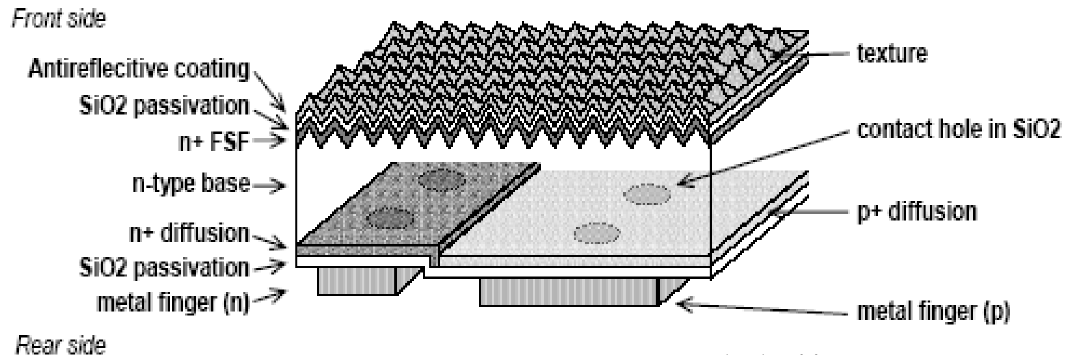
$\eta \leq 16\%$

Increasing cell efficiency

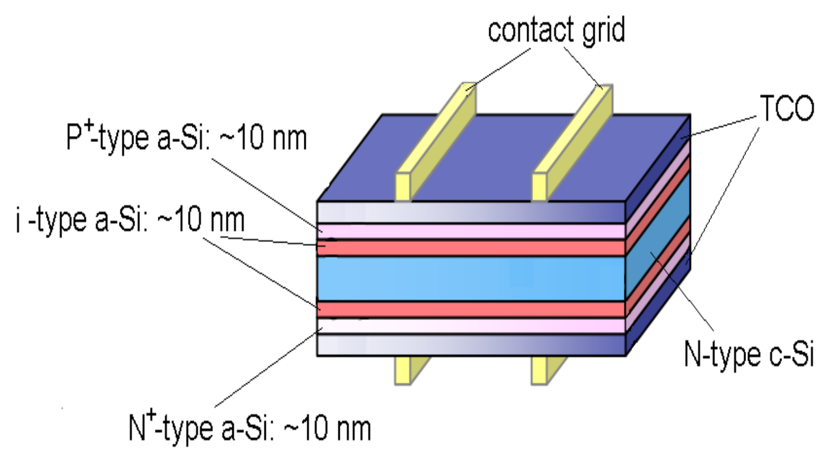
Selective emitter



Back contact cells

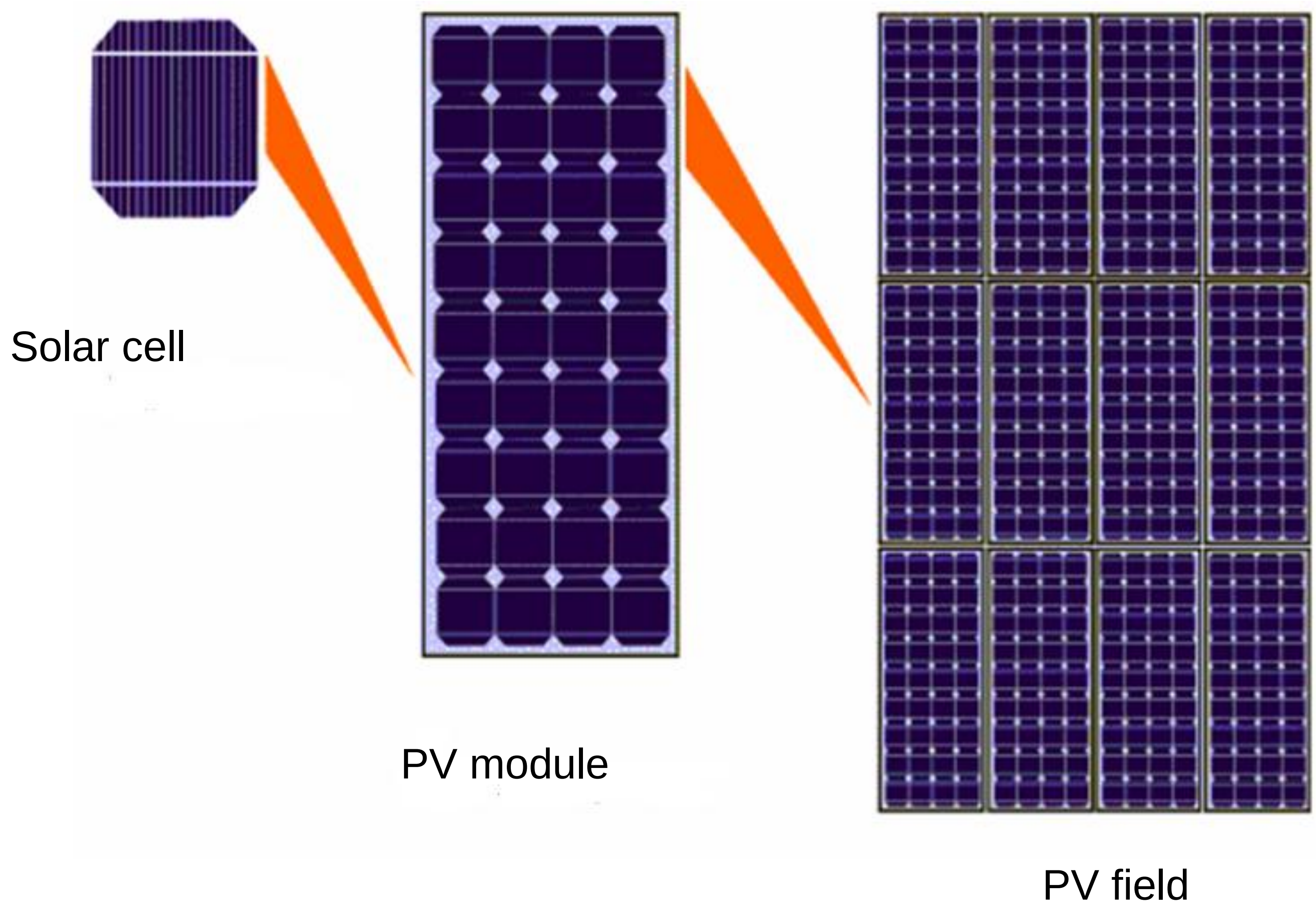


Hetero junction cells

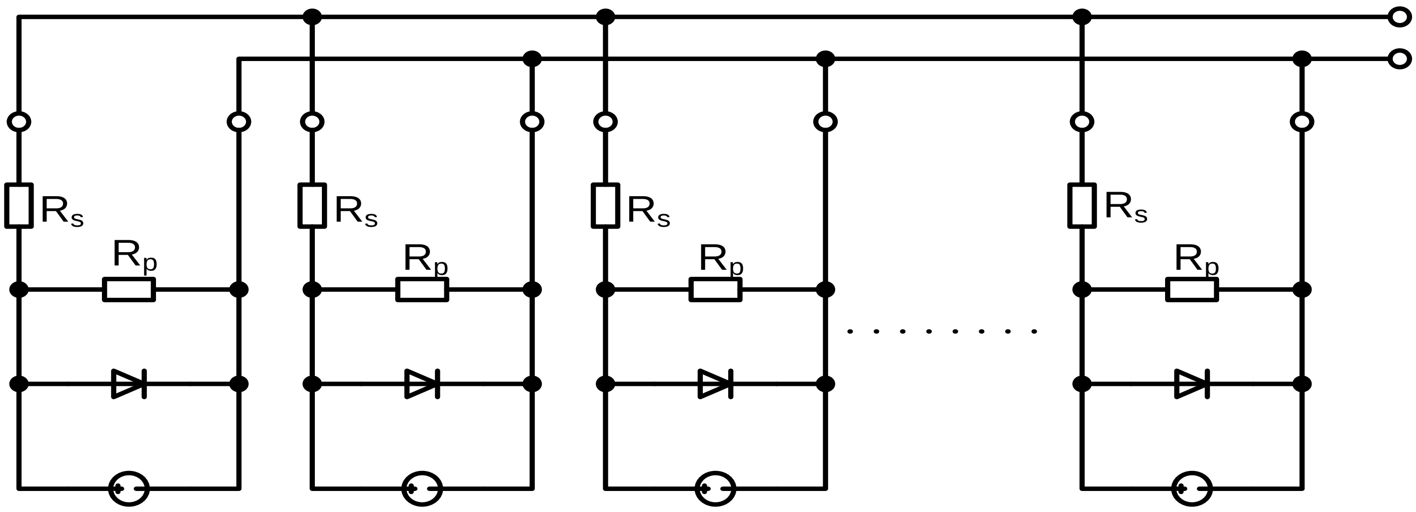


A single solar cell……~0.5 V, about 30 mA/cm^2

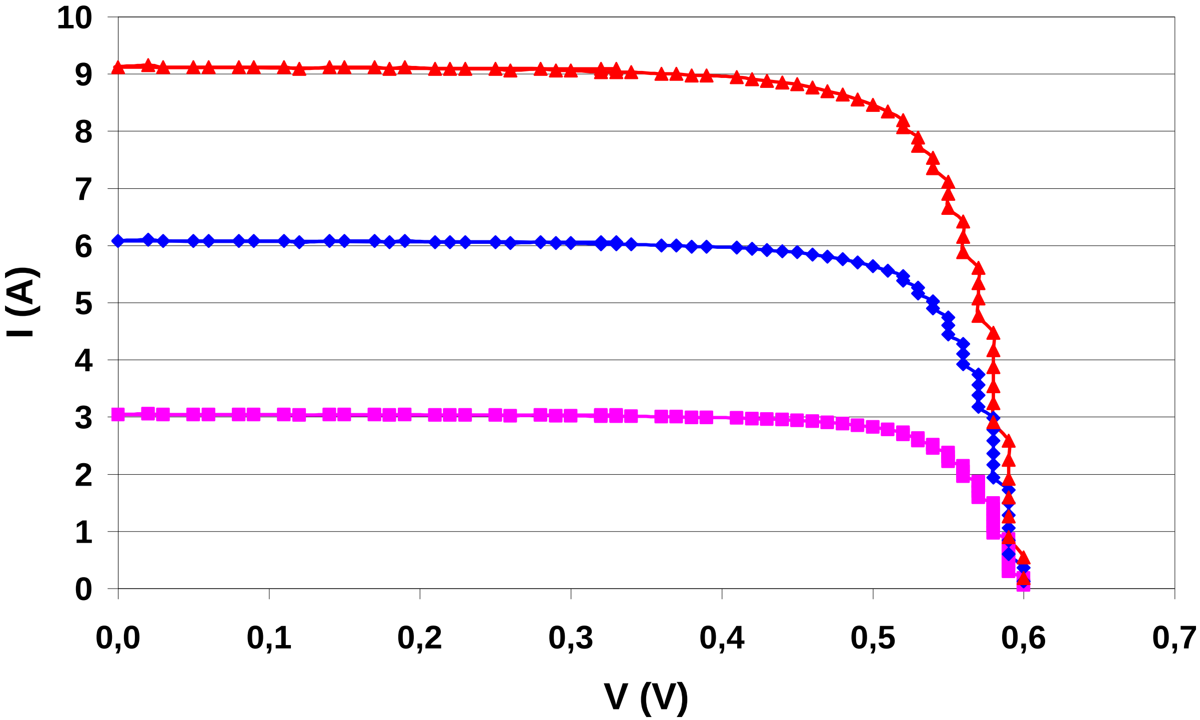
For practical use it is necessary connect cells in series to obtain a source of higher voltage and in parallel to obtain a higher current



Cell connection in parallel



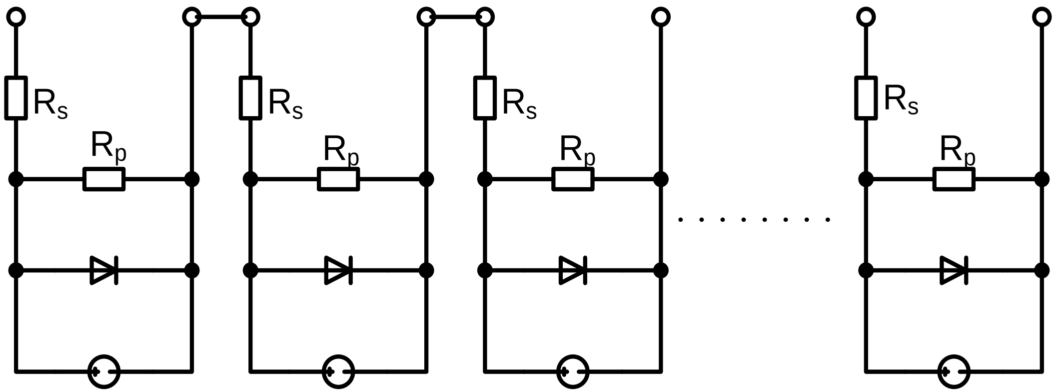
Optimum situation: all cells have the same V_{MP}

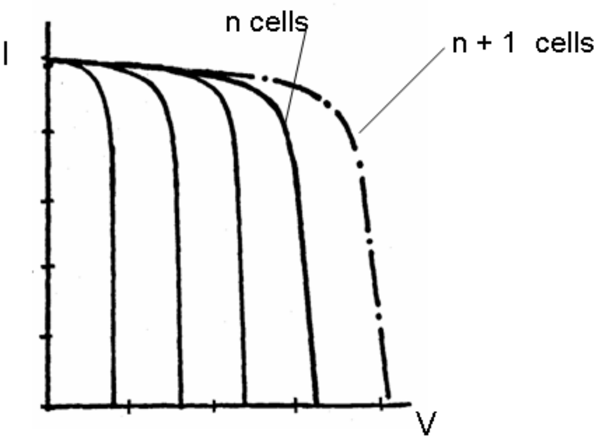


If characteristics of individual cells in parallel differ, efficiency decreases

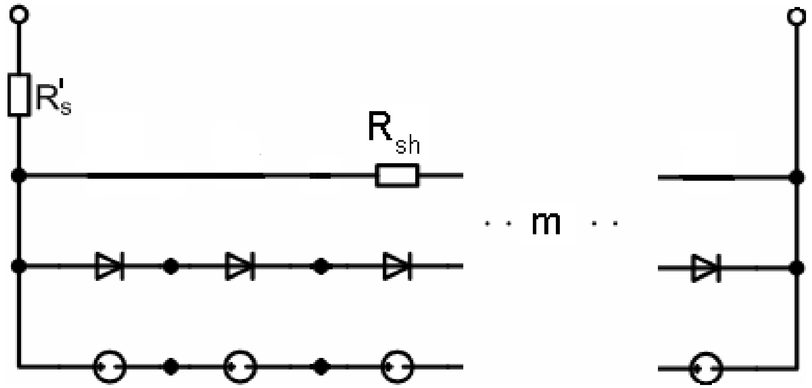
Cells in series

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





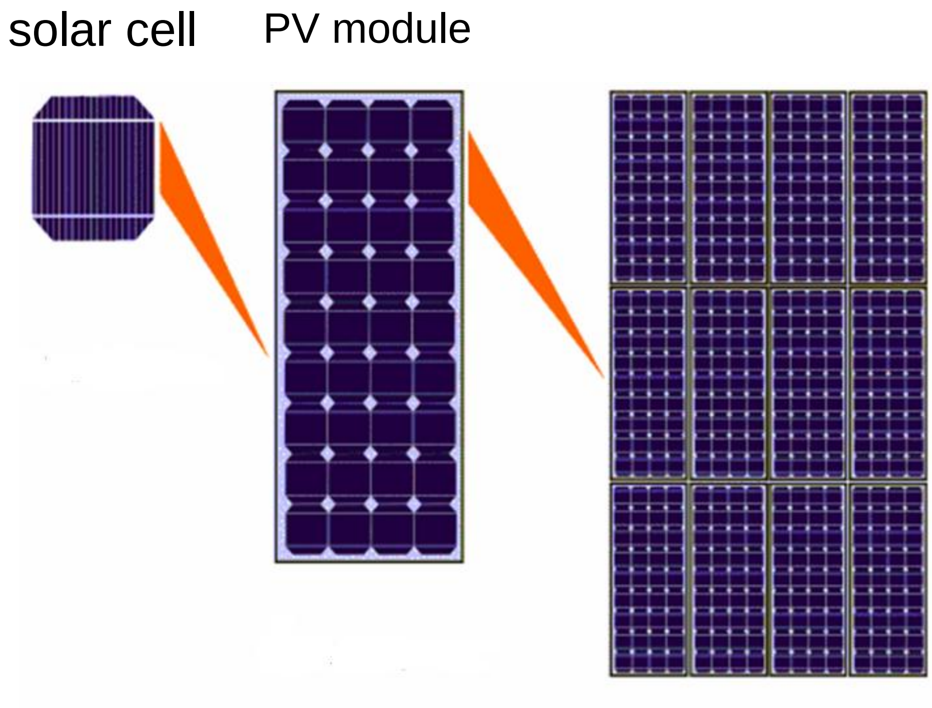
Optimum situation: all cells have the same I_{MP}



If characteristics of individual cells in series differ, efficiency decreases

$$I = I_{PV} - I_{01}\left[\exp\left(q\frac{V + R_s' I}{mn_1 kT}\right) - 1\right] - I_{02}\left[\exp\left(q\frac{V + R_s' I}{mn_2 kT}\right) - 1\right] - \frac{V + R_s' I}{R_{sh}}$$

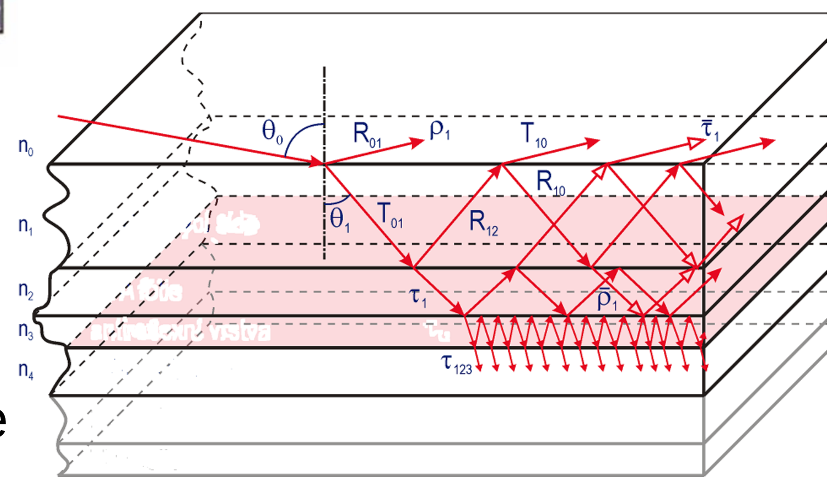
PV module technology



Module should have an environmental resistance

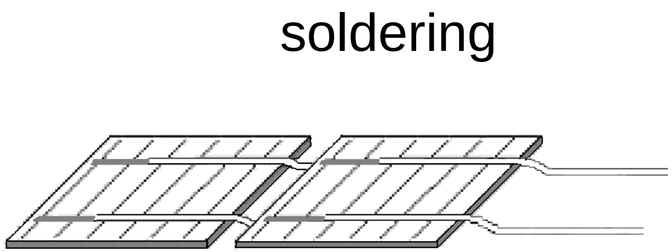
Module lifetime > 20 years

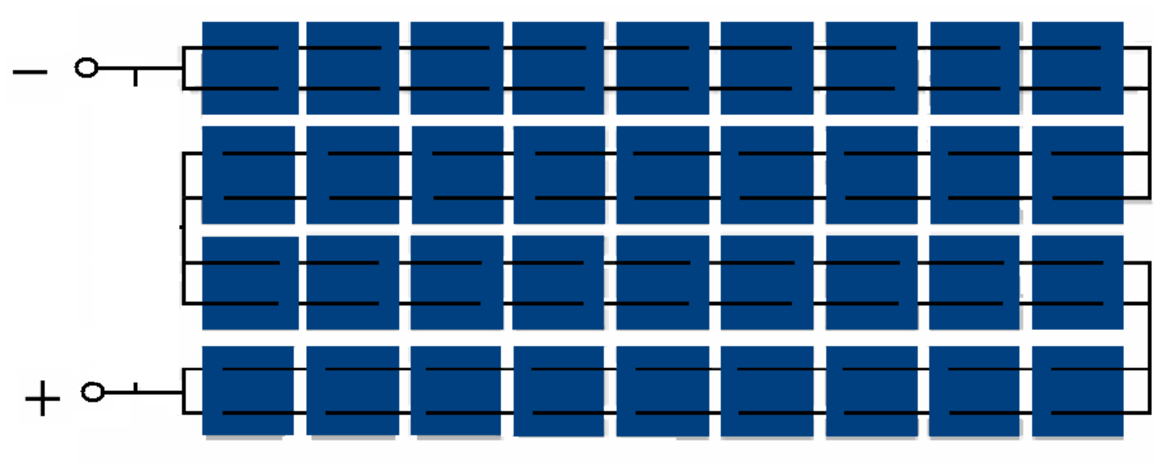
Minimising optical losses

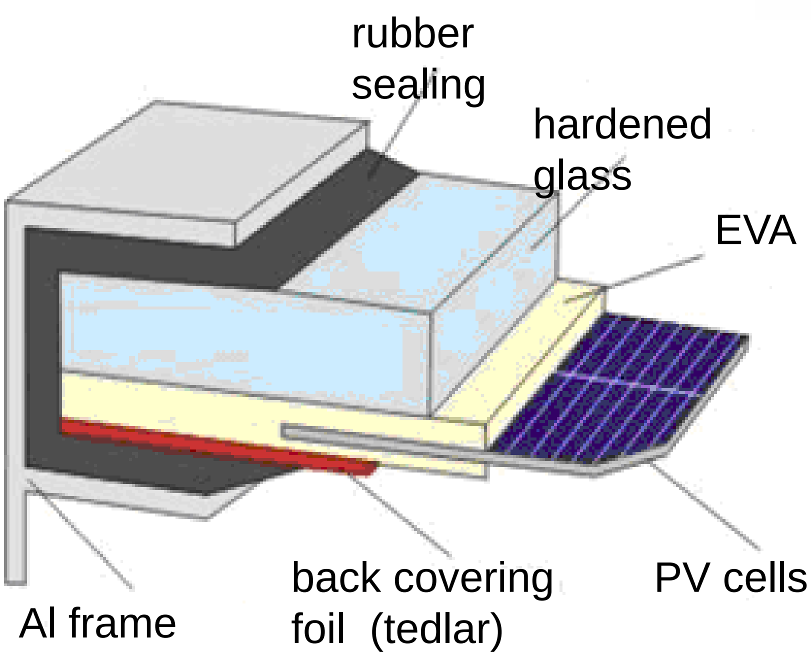


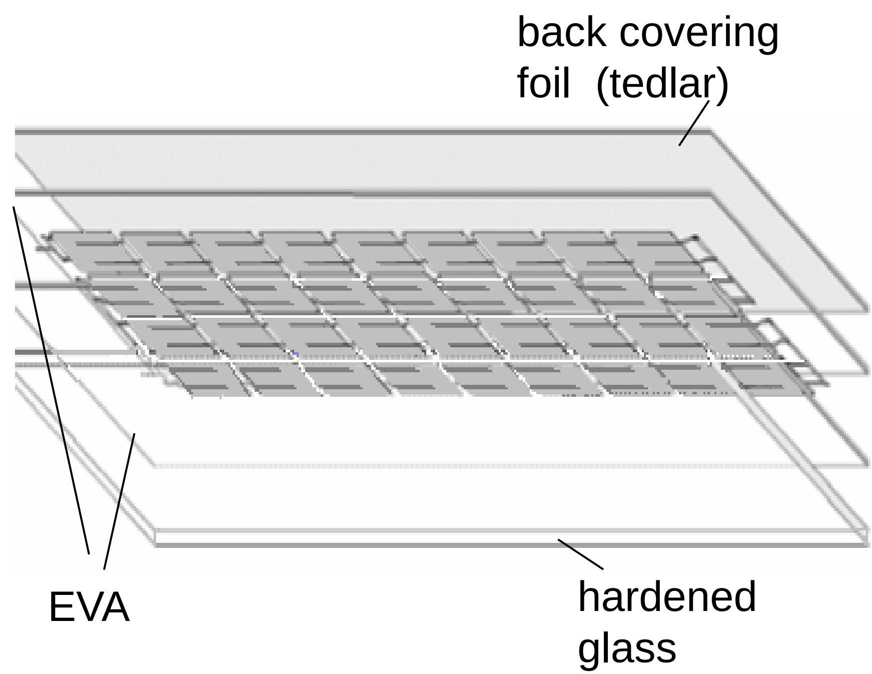
EVA = has the same refraction index like glass

PV c-Si module technology

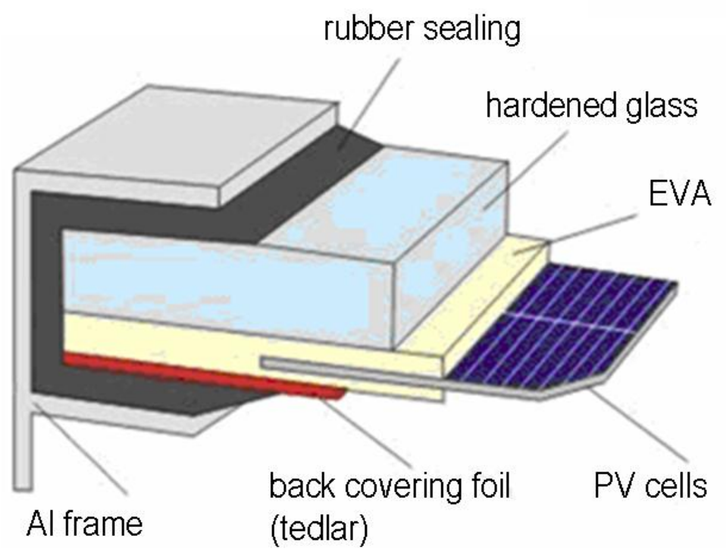








Operating cell temperature



Operating temperature of cells in the module depends on the ambient temperature and the module construction (thermal resistance R_{th}).

NOCT (Nominal Operating Cell Temperature) is the cell temperature T_c at the ambient temperature $T_a' = 20°C$, irradiance $G = 0.8\ kWm^{-2}$ and the wind speed $1\ ms^{-1}$.

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

$$r_{thcab} = \frac{d_b}{\lambda_b} + \frac{1}{h_b}$$

$$r_{thcaf} = \frac{d_f}{\lambda_f} + \frac{1}{h_f}$$

$$r_{\mathrm{thca}} = \frac{r_{\mathrm{thcaf}} r_{\mathrm{thcab}}}{r_{\mathrm{thcaf}} + r_{\mathrm{thcab}}}$$

If the module temperature T_{mod} is measured at the back module surface

$$T_c = T_{\mathrm{mod}} + \Delta T \frac{G}{G_{SCT}}$$

Effect of partial shading – one cell

(a decrease of illuminated area A_{ill})

$$I = A_{ill} J_{PV} - I_{01}\left[\exp\left(q\frac{V + R_s I}{kT}\right) - 1\right] - I_{02}\left[\exp\left(q\frac{V + R_s I}{2kT}\right) - 1\right] - \frac{V + R_s I}{R_p}$$

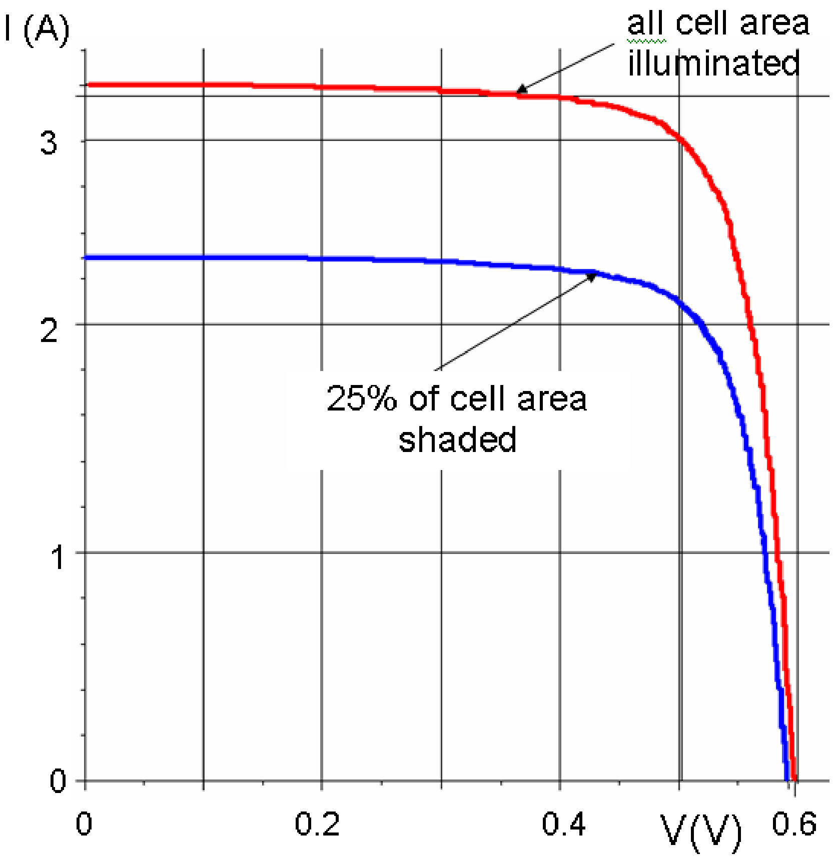
$$V_{OC} = \frac{2kT}{q}\ln\left(\frac{-I_{02} + \sqrt{I_{02}^{2} + 4I_{01}(I_{02} + I_{01} + A_{ill} J_{PV})}}{2I_{01}}\right)$$

In the case of one cell

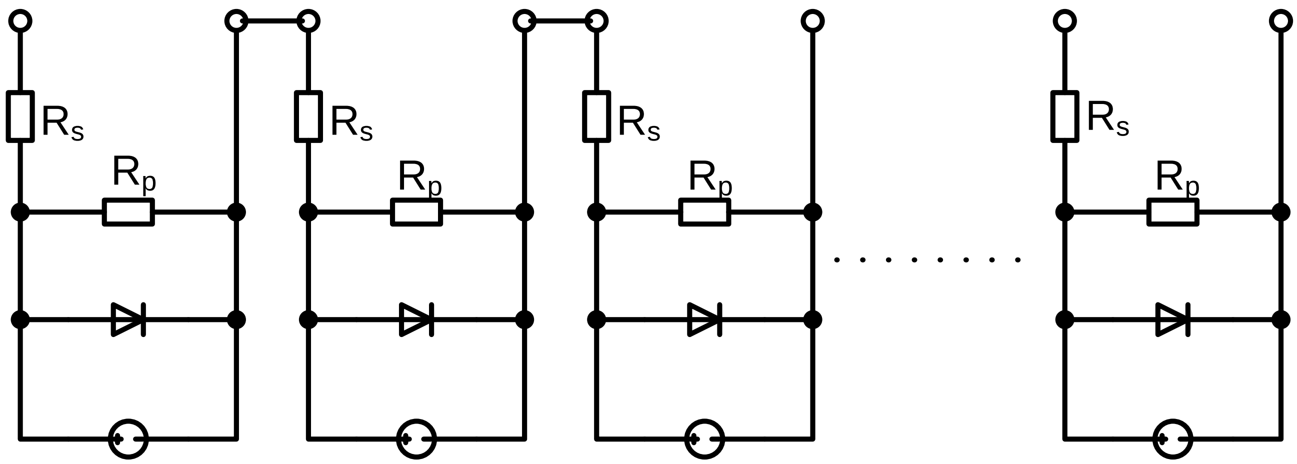
• a decrease of the output current (proportional to area illuminated)

• a decrease of the output voltage

• a decrease of the output power

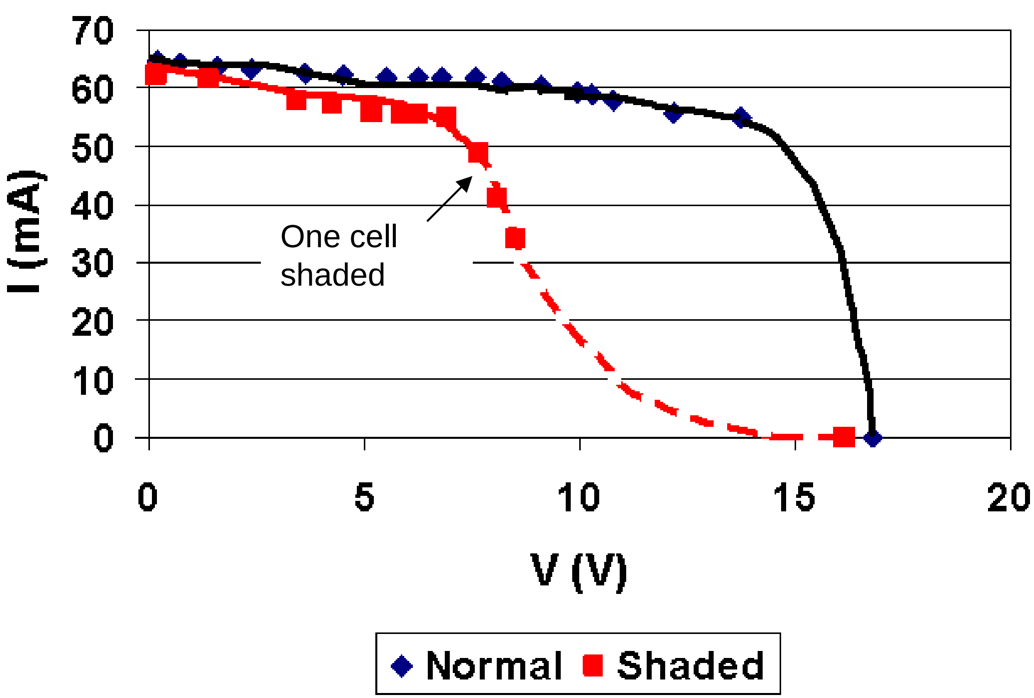


Effect of partial shading – cells in series

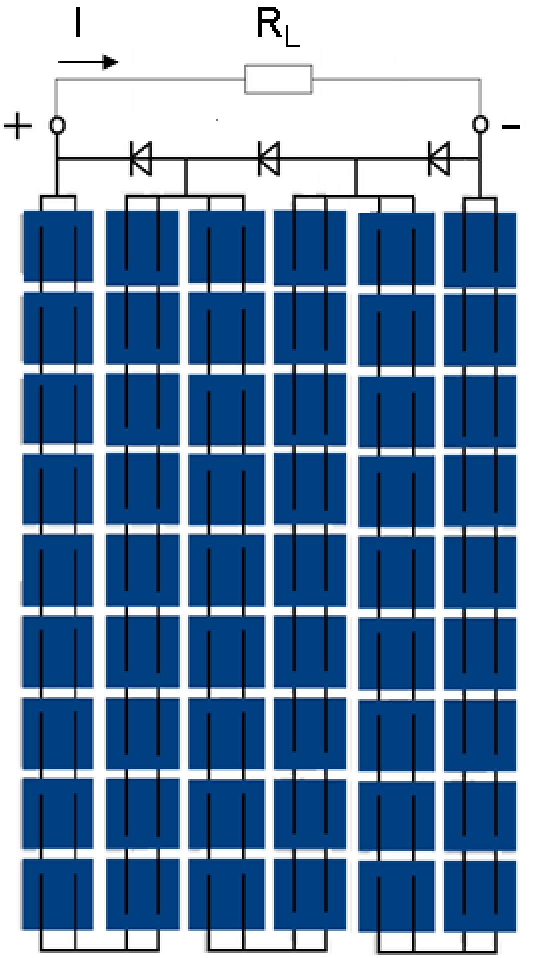


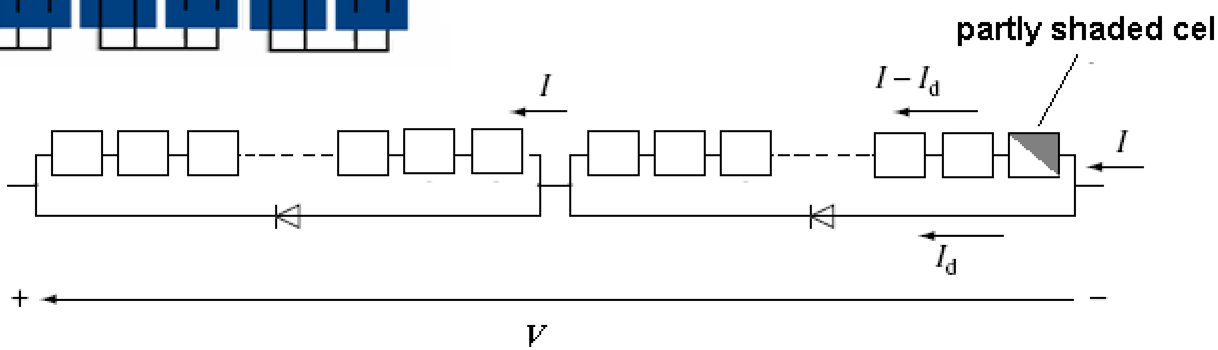
In the case of cells in series increases series resistance

- a decrease of the output current
- a decrease of the output voltage
- a considerable decrease of the output power



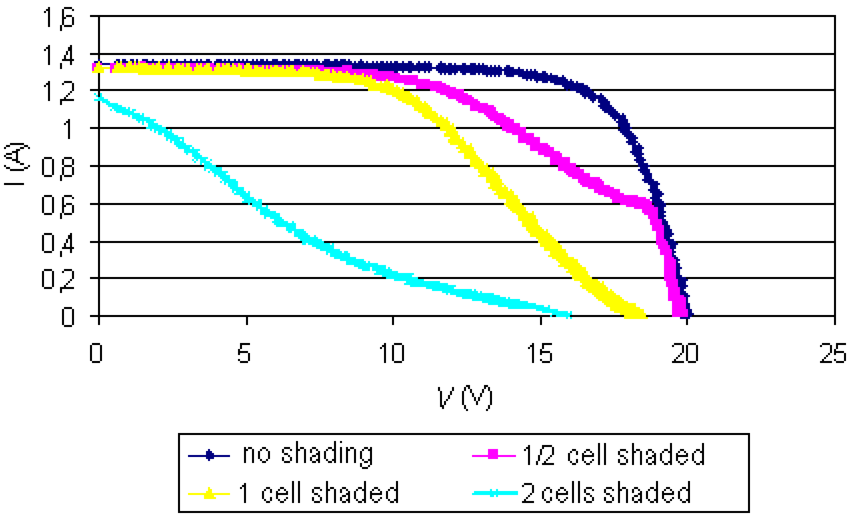
Bypass diodes

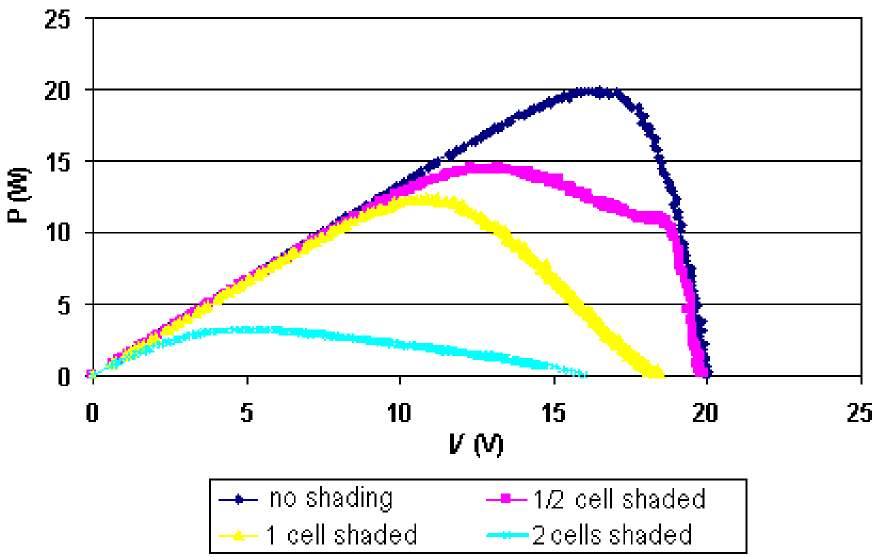




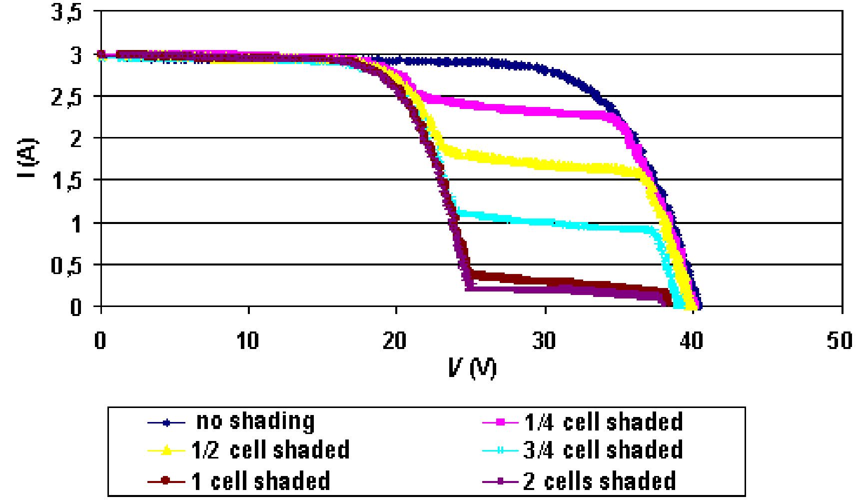
Vliv překlenovacích diod

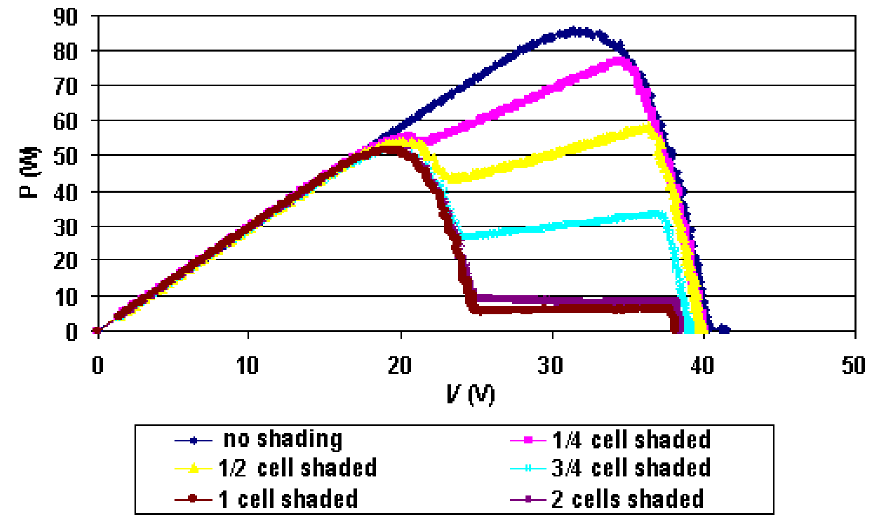
Without diodes

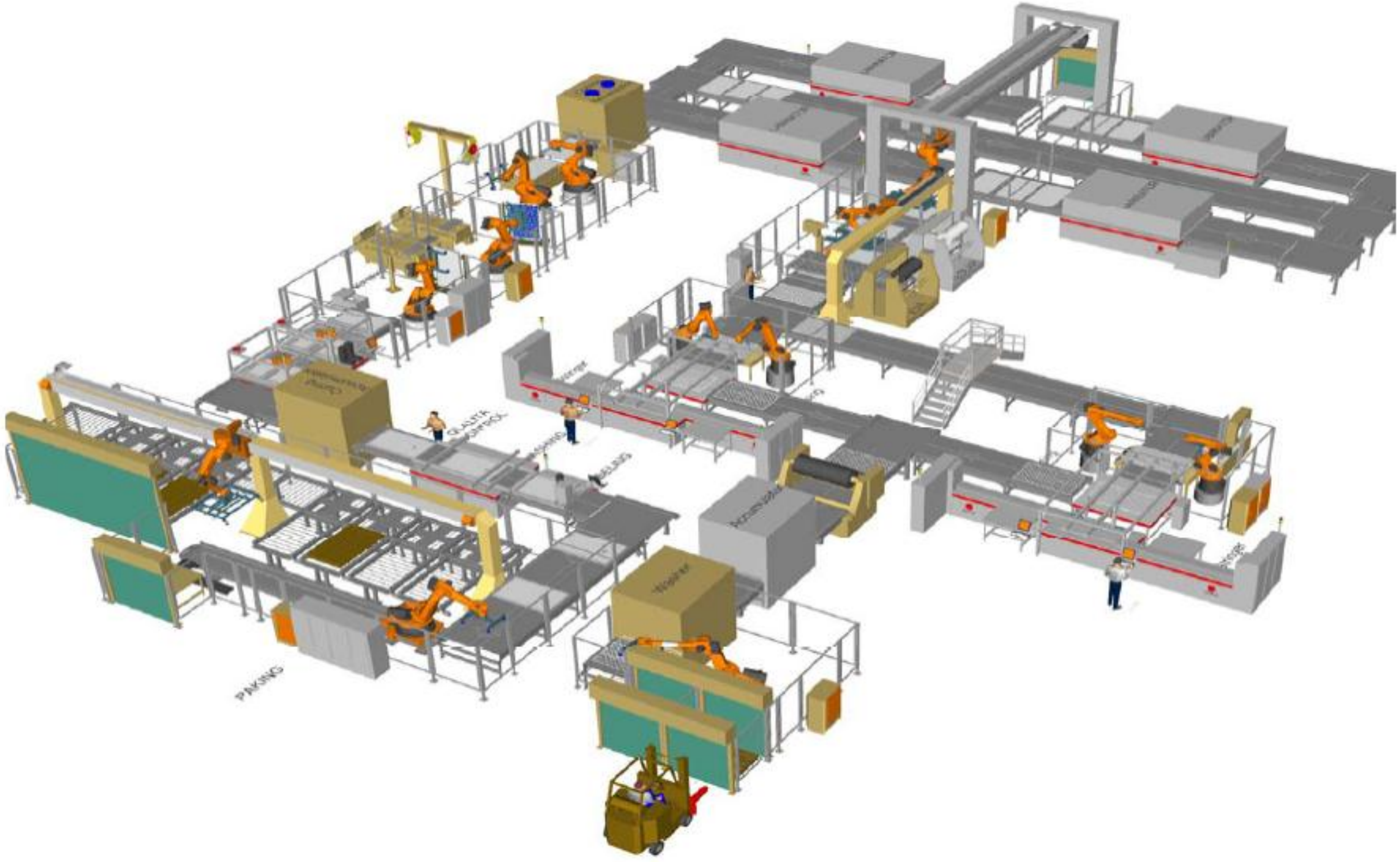




With bypass diodes







In 2012 about 28 GW_p of c-Si modules were installed (90% of total)

The installed modules have area about 225 km^2