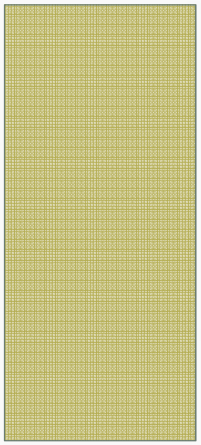
OPTIMIZE SOLAR CELL PERFORMANCE

DRAGICA VASILESKA



MINIMIZE LOSSES IN SOLAR CELLS

➢ Optical loss

- Concentration of light
- Minimize Shadowing

- Trapping of light:

✓ AR coatings
✓ Mirrors (metallization rear surface or growing active layers on top of a Bragg stack)
✓ textured surface

- Photon recycling

reabsorption of photons emitted by radiative recombination inside the cell

➢ Electrical Loss

- Surface passivation
- Resistive loss

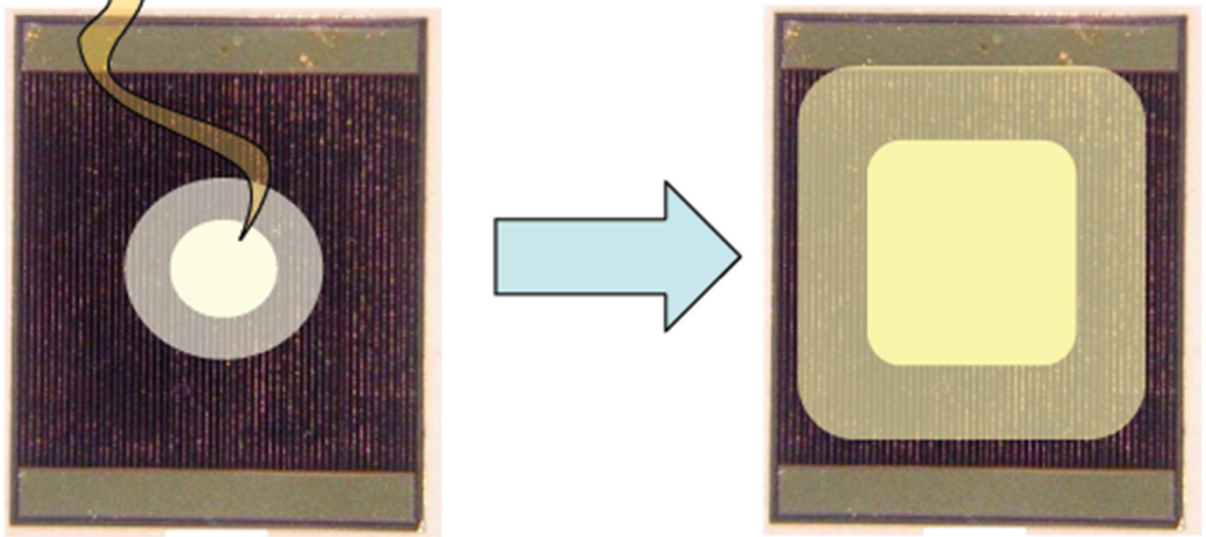
……

OPTICAL LOSS

CONCENTRATION OF LIGHT

Integration in Solar Concentration

- Multi-junction cells become more efficient with high concentration (1000x)
- But above very high local concentration efficiency drops and cell can be damaged
- Illuminate evenly, spread out light



Possible solutions: Kaleidoscopic prism

Kaleidoscopic prism is not ideal for low cost mass manufacturability:

- Alignment and holding is considered complex
- High concentration on the prism entrance may be problematic
- Difficult to make for small size cells

Possible solutions:

- Rely on manufacturing errors…?
- Defocus Fresnel lens…?
- Add diffusion to produce scattering…?
- Adding refractive or reflective micro-optics on one surface…?

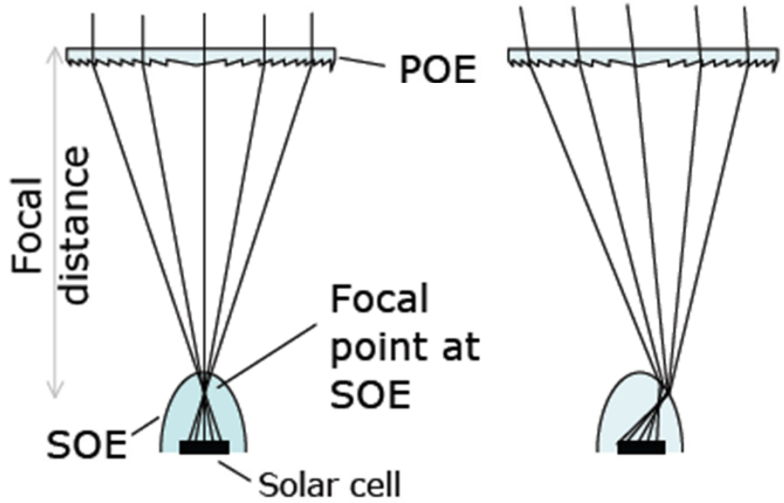
All these options reduce the acceptance angle!

On the contrary, Köhler integration

…can solve the uniformity issues with only a slight reduction of acceptance angle

First Integrator in Solar: (Sandia Labs. 1990)

- SOE is located at focal plane of POE
- SOE images POE onto solar cell
- Good uniformity
- But very deep, low acceptance at high C

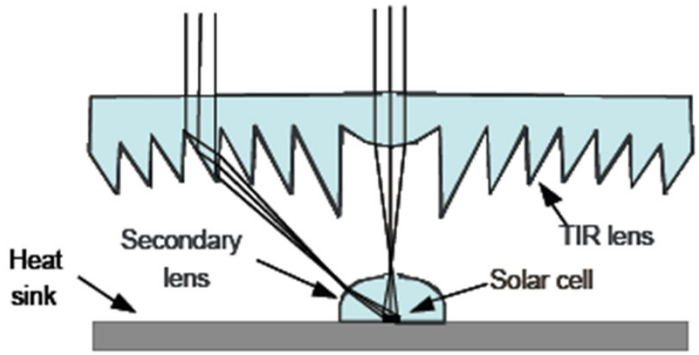


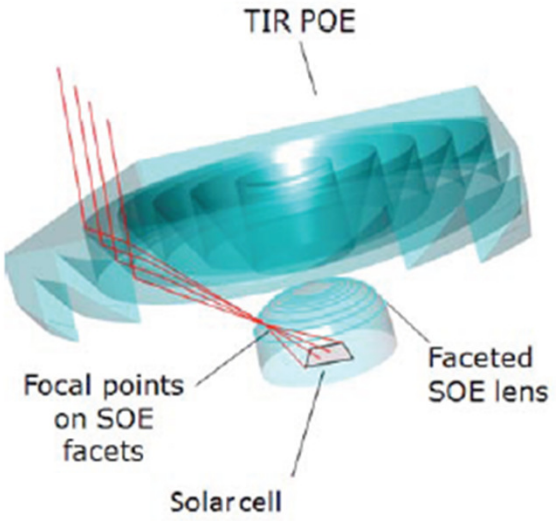
Radial Integration

- 1d-integration
- Limited uniformity
- Adjust integration zone to acceptance

TIR-R Concentrator

- Radial Kohler concepts, 1d-integration.
- Good uniformity (0.7), compact
- Integration between TIR teeth and toroidal rings on SOE
- Good CAP

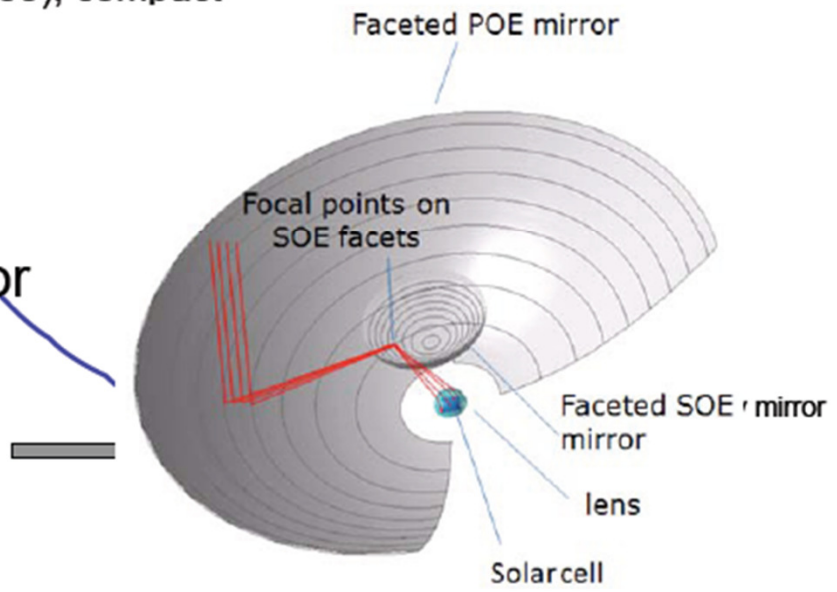




XX Concentrator

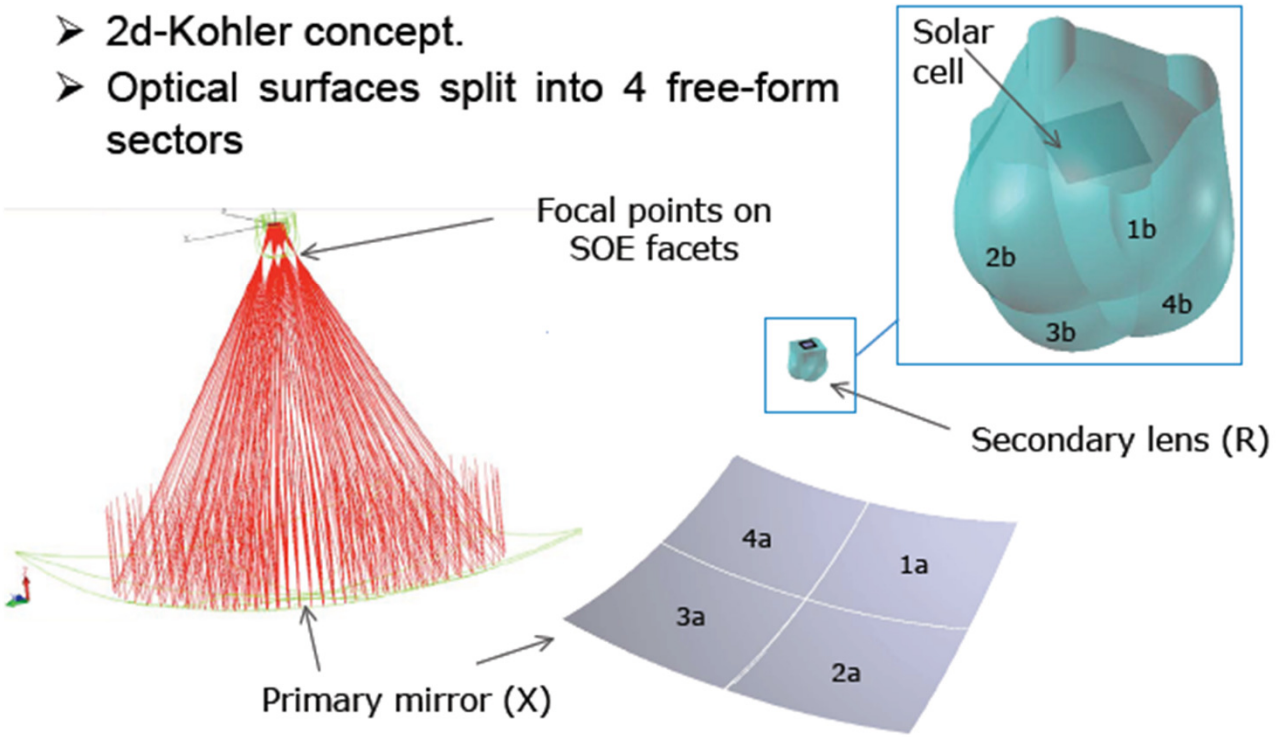
- Radial Kohler concept, 1d-integration
- Good uniformity (0.55), compact
- good CAP

XX Kohler integrator
(Benitez et al, 2006)



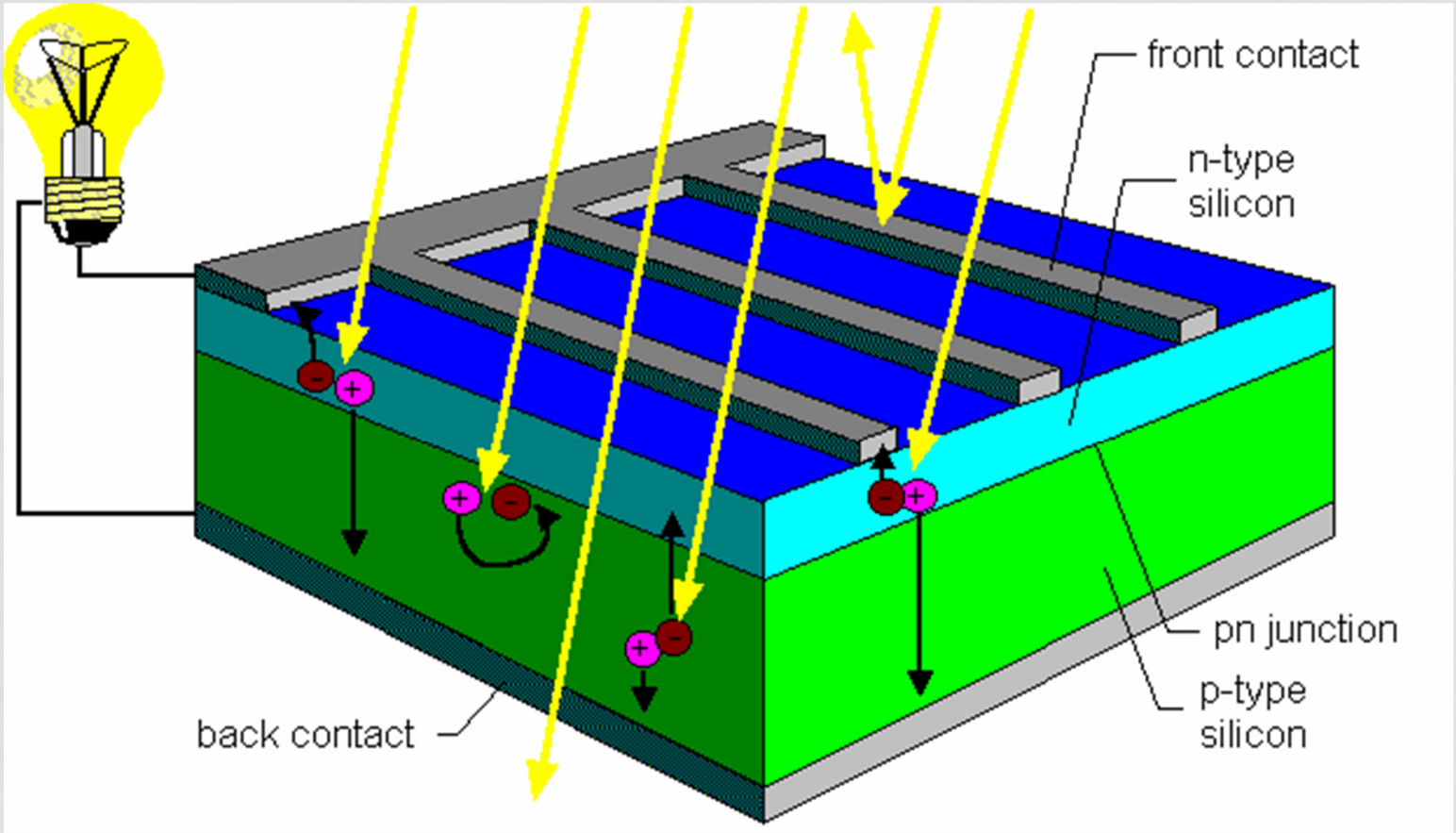
Free-form XR

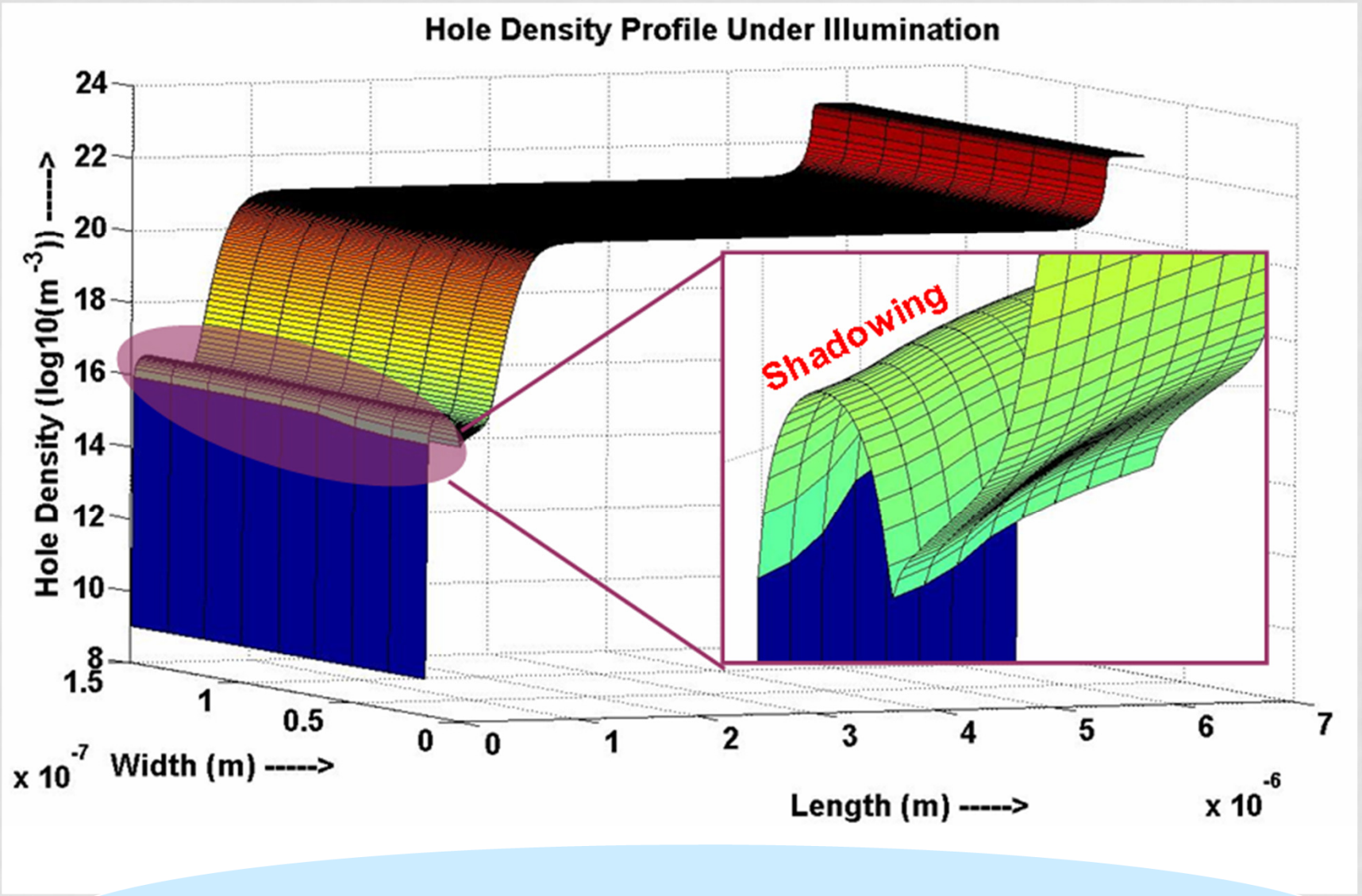
- 2d-Kohler concept.
- Optical surfaces split into 4 free-form sectors



MINIMIZE SHADOWING

- Light enters through the window normal to the top surface defined by the metal contact.
- No carriers are generated by the light under the metal contact as it is reflected back.
- Carriers generated by light entering through the window diffuse to the region below the metal contact due to density gradient. These carriers generated near the space charge region contribute to the current produced by the solar cell.
- Surface recombination takes place on the surface of the window which reduces the efficiency of the solar cell.


front contact
n-type
silicon
pn junction
p-type
silicon
back contact



Carrier Density profile in n+-p-p+ structure displaying shadowing

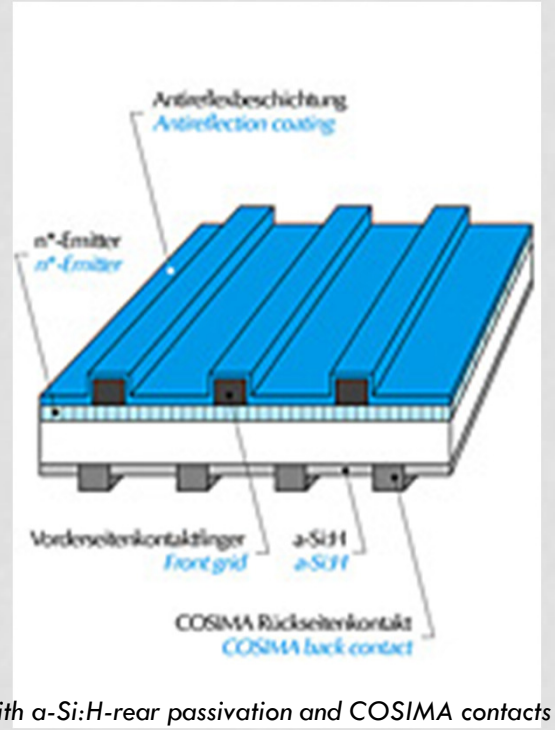
ADVANCED METALIZATION

Prevent obscuration of the solar cell or high reflection and absorption of the silver grids.

- small and high grids, which will become smaller towards the edge of the cell

<u>COSIMA (Contacts to a-Si:H passivated wafers by means of annealing):</u>

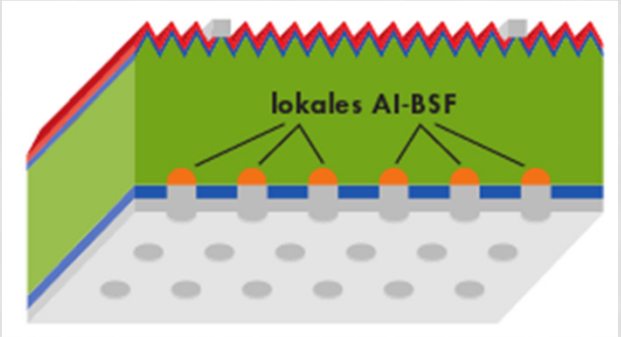
- Amorphous silicon (silane process) on mono-crystalline silicon
- Aluminium on theses layers results in contacting the monocrystalline silicon
- Process temperature ~ 200°C
- No photolithography



Solar cell with a-Si:H-rear passivation and COSIMA contacts

Advantages:

- Simplifies thin film manufacturing process
- Efficiency values about 20%



Combination with doted contacts:

- Screen printed interface layer (little holes) → good passivation
- Aluminium on the interface layer → COSIMA

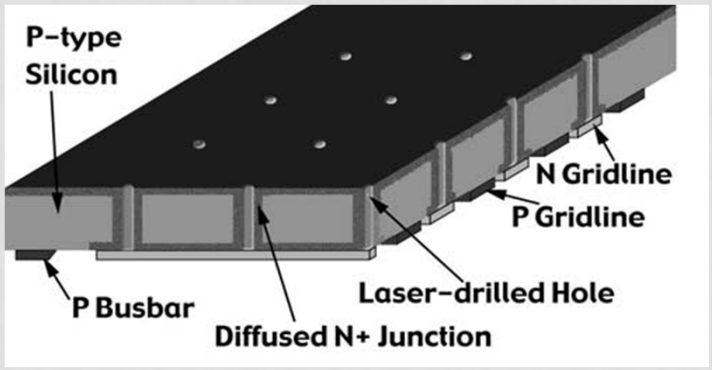
Advantages:

- Can be used on thinner wafers → no bending
- The passivation abbility of the amorphous layer will be kept after the annealing process
- The contact resistivity is 15mΩcm^2
- Increase of the quantum yield in the infrared wavelength range
- Reduces S_{eff} to 100 cm/s (4% metallization)

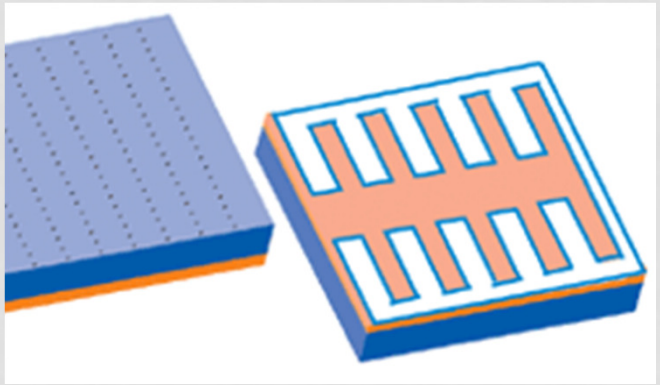
EWT/MWT

Emitter Wrap through (EWT)

- Emitter on the front surface is wraped with the rear surface by little holes
- Edges of the holes are also emitter areas, which transport emitter current
- Power-conveying busbars and the grid are moved to the rear surface
- Use double sided carrier collection (n^+pn^+) → increases the efficiency
- 100µm holes are made by laser



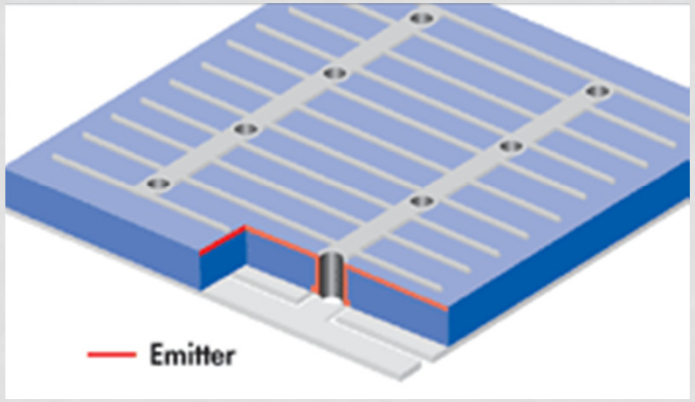
EWT- cell with n^+pn^+ - structure



Front (left) and rear (right) of a EWT-solar cell. The front contacts are brought to the rear of the solar cell by many dots.

Advantages:

- Eliminate grid obscuration → no high doping → high I_{sc} → high efficiency
- n^+pn^+- structure → use lower quality solar grade silicon
- Uniform optical appereance → improves asthetics
- Silicon solar cell < 200µm
- Efficiency around 18%
- gain in active cell area
- Diffusion length can be reduced to the half



MWT-cell

Disadvantage:

Manufacturing process is very complex

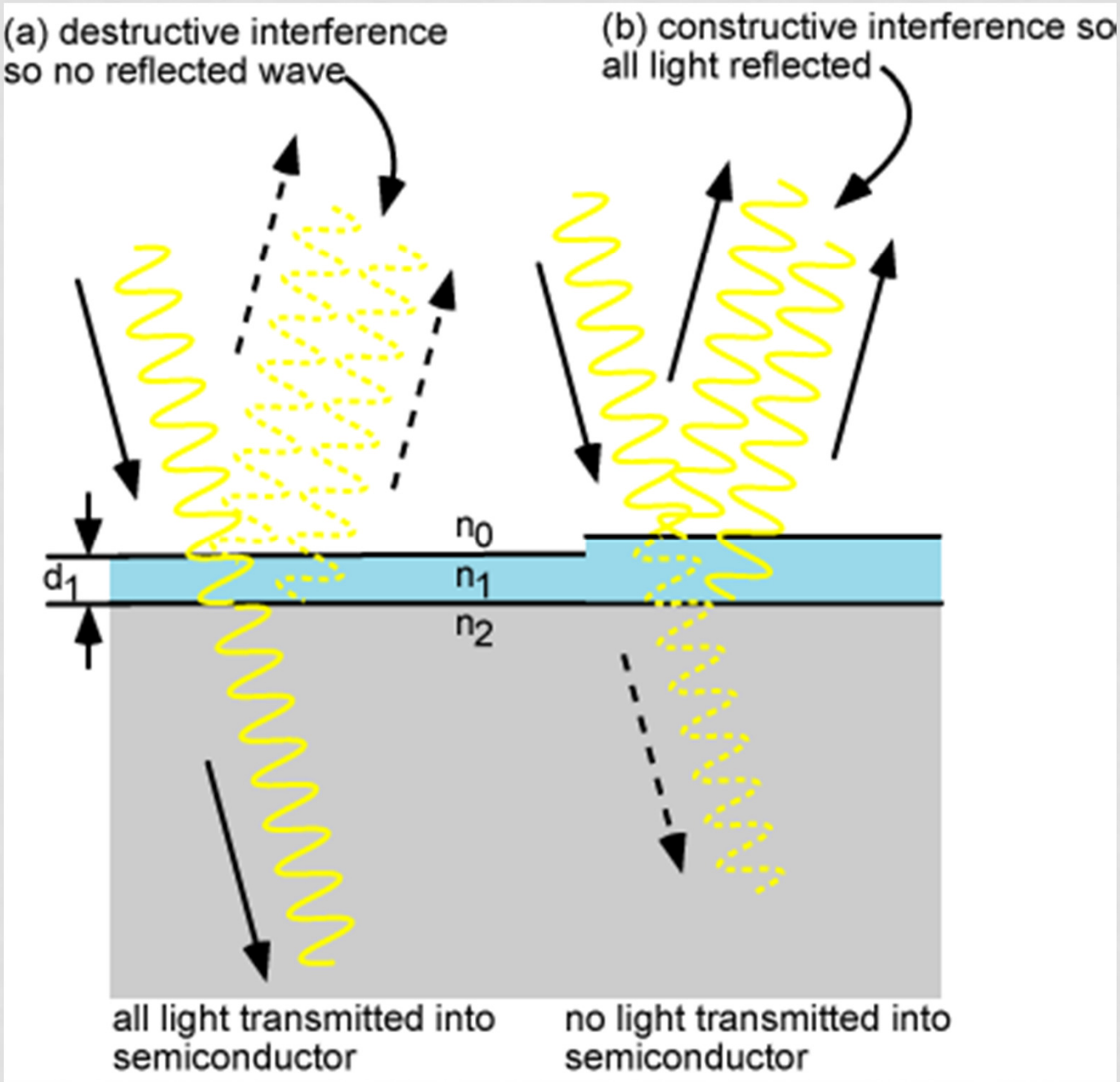
→ Metal wrap throug (MWT)

- Absence of the bus bars (on the rear side) → connection by holes
- Less serial resistance losses because of interconnection of the modules on the back
- FF ~77%; efficiency ~ 16%

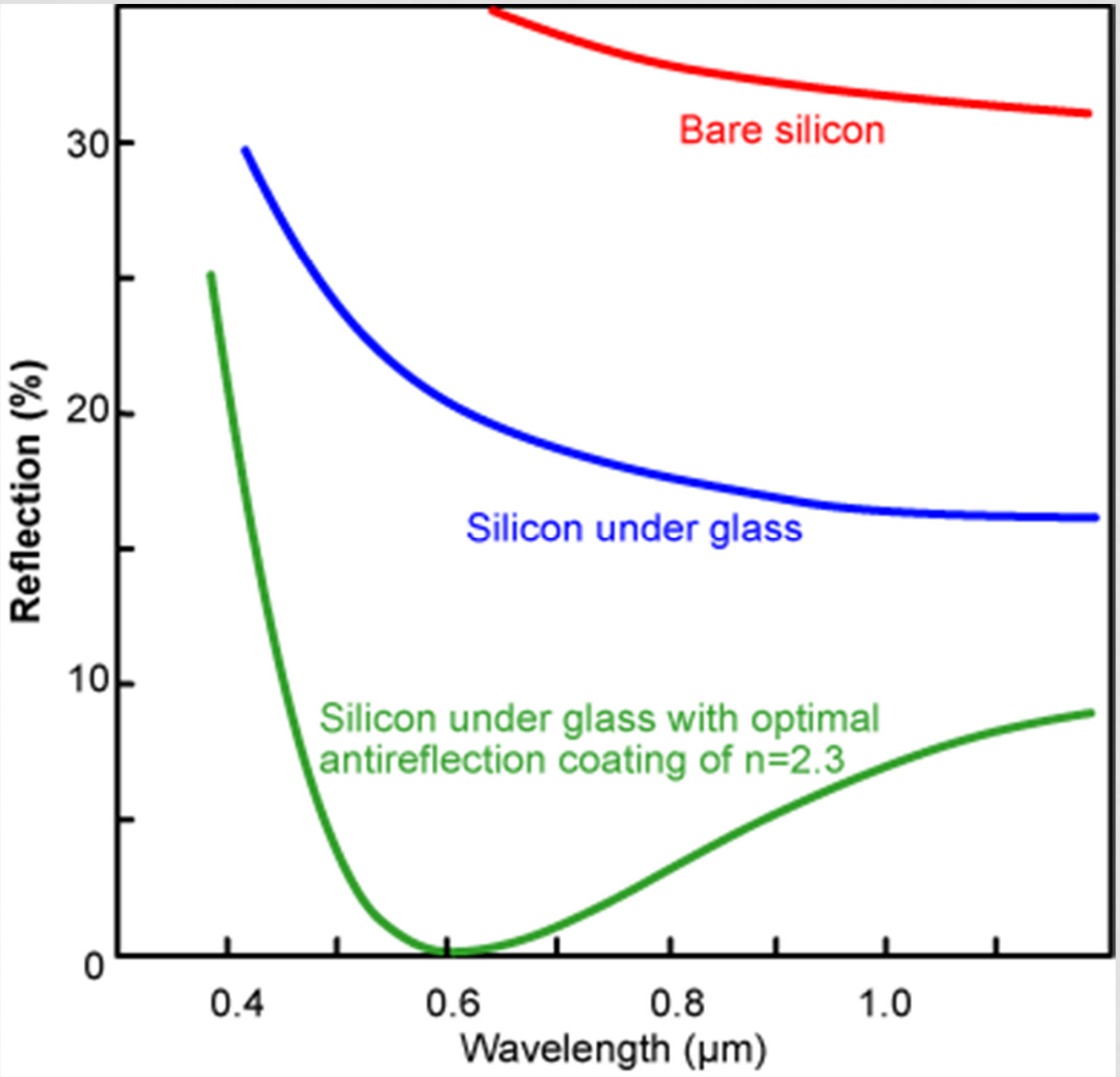
TRAPPING OF LIGHT: ANTI-REFLECTION COATINGS

- **Antireflection Coatings**

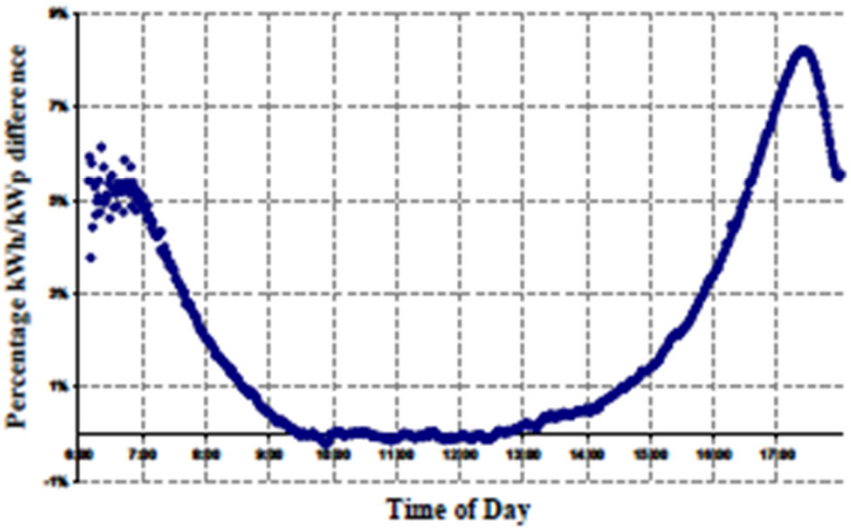
  Anti-reflection coatings on solar cells are similar to those used on other optical equipment such as camera lenses. They consist of a thin layer of dielectric material, with a specially chosen thickness so that interference effects in the coating cause the wave reflected from the anti-reflection coating top surface to be out of phase with the wave reflected from the semiconductor surfaces. These out-of-phase reflected waves destructively interfere with one another, resulting in zero net reflected energy.

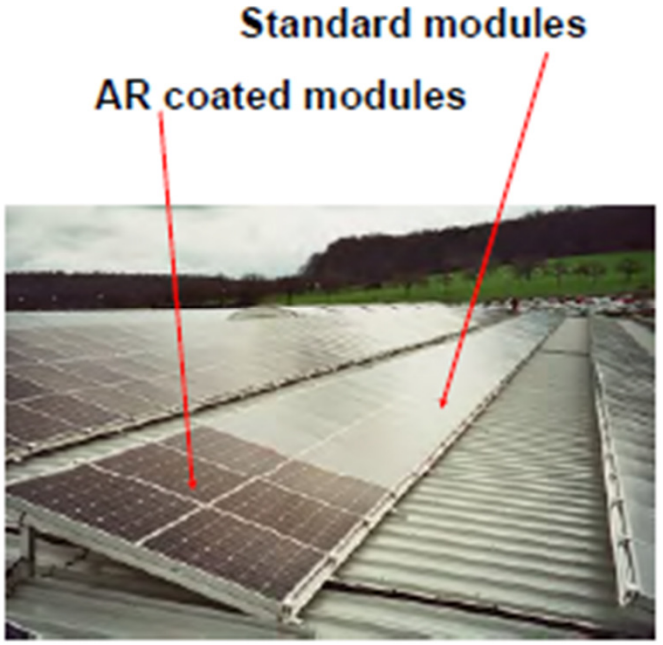


$$d_1 = \frac{\lambda_0}{4n_1}$$


Bare silicon
Silicon under glass
Silicon under glass with optimal
antireflection coating of n=2.3
Reflection (%)
30
20
10
0
0.4
0.6
0.8
1.0
Wavelength (μm)

ARC vs. standard module



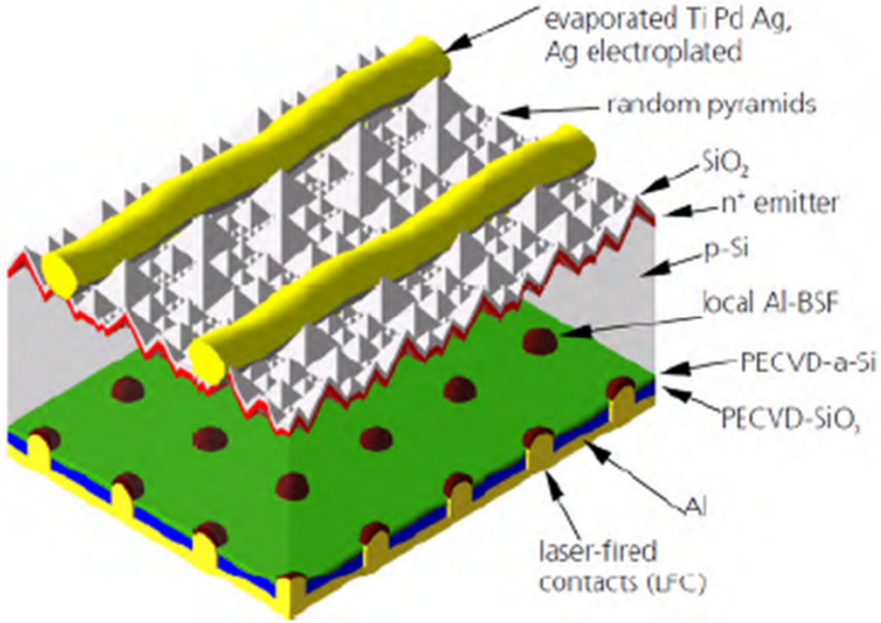


- Normalized energy generation of a day
  - 6% to 7% more energy at early and late periods of the day

TRAPPING OF LIGHT: METALLIZATION OF A REAR SURFACE

bp solar

Passivated Rear Point Contacts

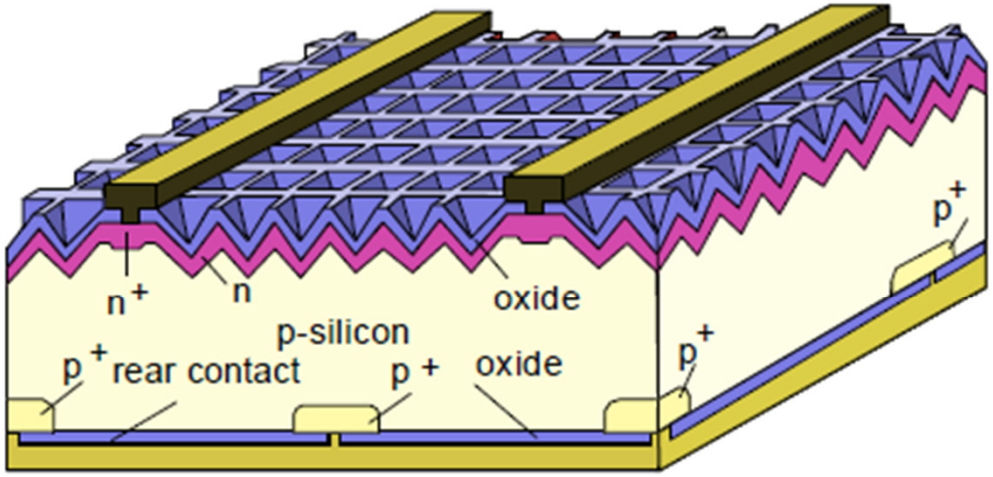


- Fraunhofer ISE has used laser firing of aluminum to fabricate high efficiency (21.7%) solar cells with passivated rear point contacts.

TRAPPING OF LIGHT: TEXTURED SURFACE

bp solar

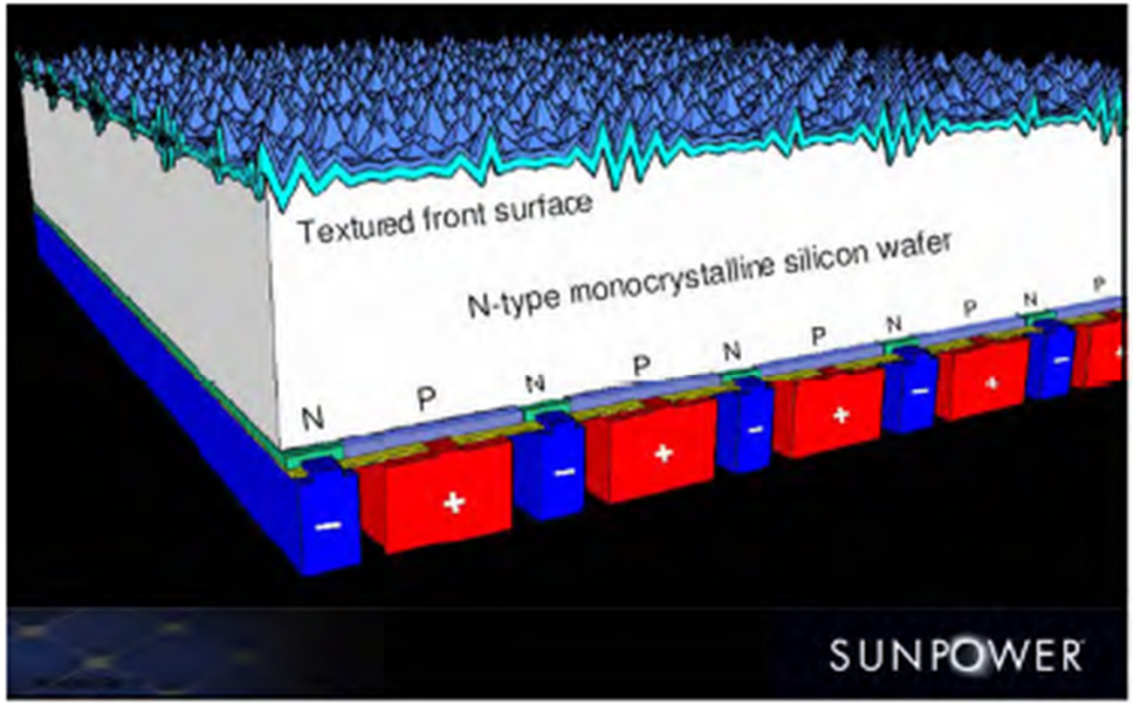
The PERL Solar Cell



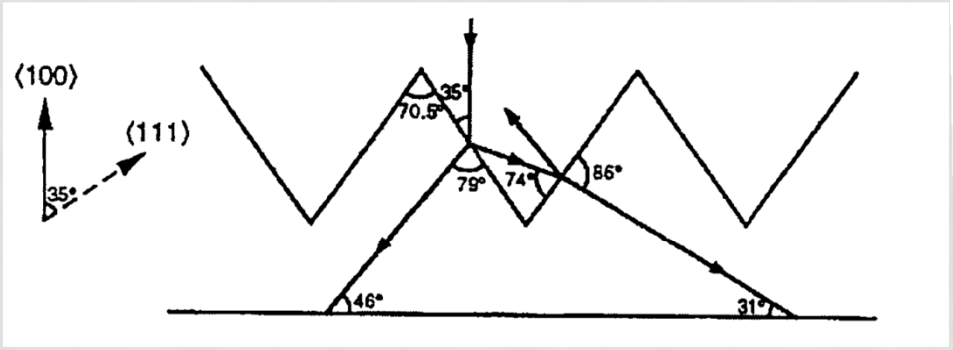
PERL Cell Structure

- The PERL solar cell has a passivated emitter with a rear locally diffused base contact, and efficiencies as high as 25% have been obtained with this structure.

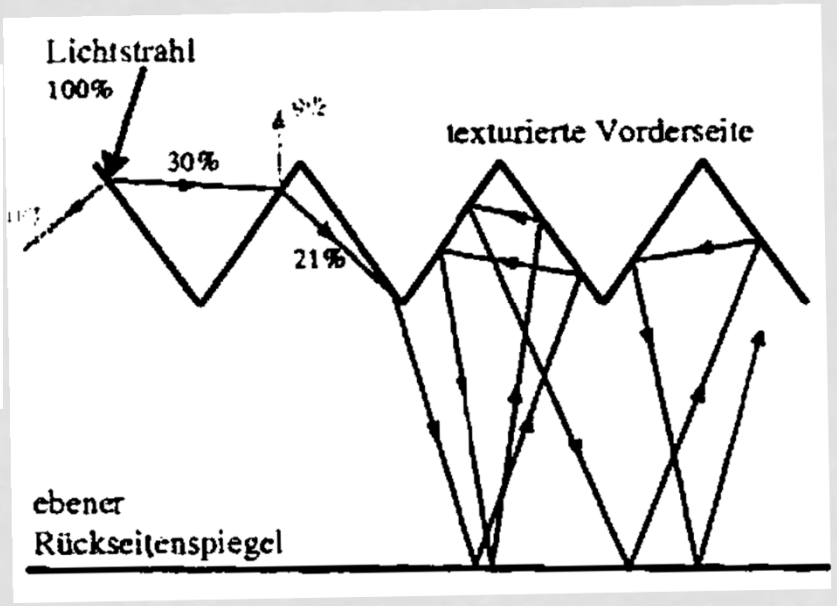
SunPower Back Contact Solar Cell



- The SunPower cell has all its electrical contacts on the rear surface of the cell.
- Production cells ~ 22.4% efficiency; new prototypes at 23.4%.
- Diffusion lengths > 3 x cell thickness (using 145 µm thick CZ-Si at end of 2008).



Examples of light trapping



→ advantages:

- At least second reflection
- The effective absorption length of the silicon layer will be reduced → the light way through the layer increases
- The area of the surface becomes bigger
- Total reflection on the inside of the front layer possible
- Reflection can be reduced about 9/10 of the former reflection

PHOTON RECYCLING

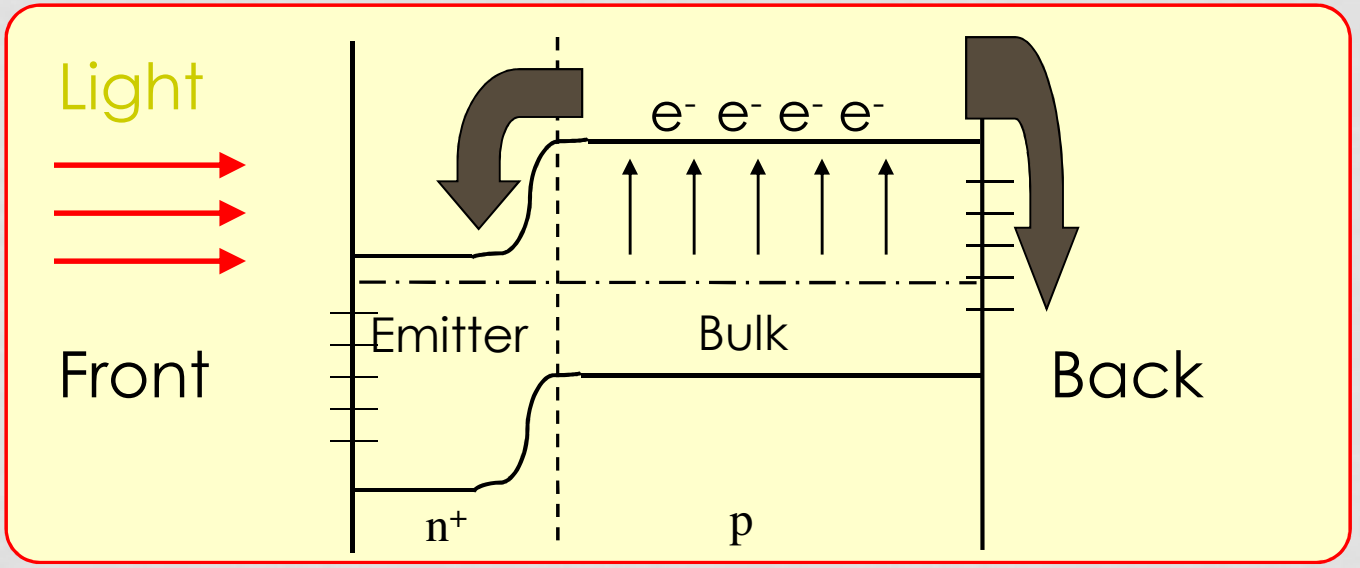
- The re-absorption of photons emitted in a semiconductor material as a consequence of radiative recombinations, a process referred to as photon recycling (PR), has been researched into for several decades because of its primary influence in increasing the minority carrier lifetime and related parameters.
- Solar cells with direct bandgap materials and high-absorption coefficients are firm candidates to show PR effects, leading to an improvement in the conversion efficiency of up to 1-2% in absolute terms for cells with conventional designs.
- However, the formal modeling of PR effects requires the inclusion of additional terms in the standard set of semiconductor equations and researchers usually tend to neglect its influence, because of the lack of available tools for an easy evaluation of this phenomenon in their particular devices.

ELECTRICAL LOSS

SURFACE PASSIVATION: MOTIVATION

- For solar cells to be able to compete with other electricity sources, $/Watt needs to be reduced:
  - Improve efficiency
  - Reduce production cost
- For high-efficiency cells, good front and back surface passivation is mandatory

INTRODUCTION



- Surface recombination velocity (SRV) is the figure of merit for passivation quality
  - Lower is better
  - Below 200 cm/s is decent

1. Thermal oxidation:

- Reduction of the density of states on the interface or surface
- Oxygen streams over the hot wafer surface and reacts with silicon to SiO_2

→ This results in an amorphous layer

- Temperature of the process ~ 1000°C
- Thickness of the layer > 35nm → efficiency decreases
- Time goes on and the velocity of the growth of the oxidic layer decreases

2. Passivation with SiN_x

- Reduction of the density of states on the interface
- Gases silane SiH_4 and methane NH_3 form a layer of Si_3N_4
- Temperature of the process ~ 350°C
- Passivation quality rises with silane amount
- S ~ 20 cm/s – 240 cm/s depending on the refraction index

→ advantages:

- lower production temperature
- Nitride seems also to work better as an anti reflection layer for solar cells

  → better passivation

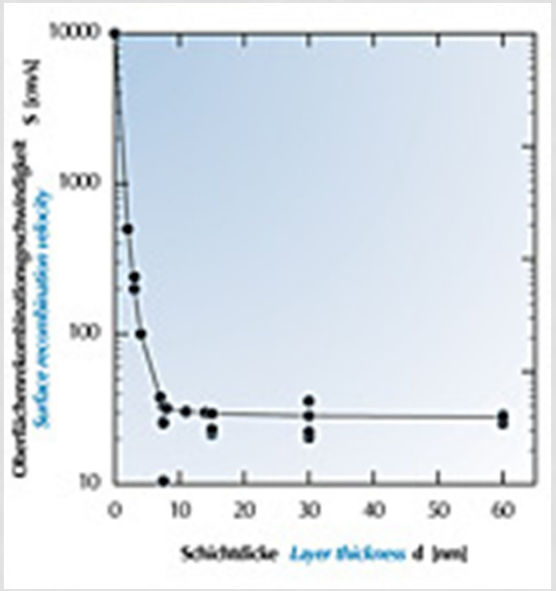
3. Passivation with only silane

- The quality of the passivation is enormous
- Passivation layer on the emitter should be very thin (10nm)

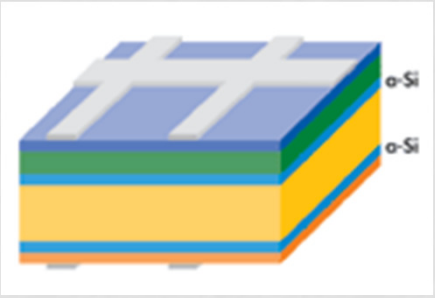
  → high absorption → prefer SiN_x-Process on the emitter
- The process temperature is ~225°C
- The passivation seems independet of contaminations of the silicon surface brought in during the manufacturing process
- An example is the HIT-Solar Cell from Sanyo

→ Layer of monocristalline silicon between amorphous silicon layers

→ Efficiency of ~ 18,5%



Passivierqualität als Funktion der a-Si:H-Schichtdicke

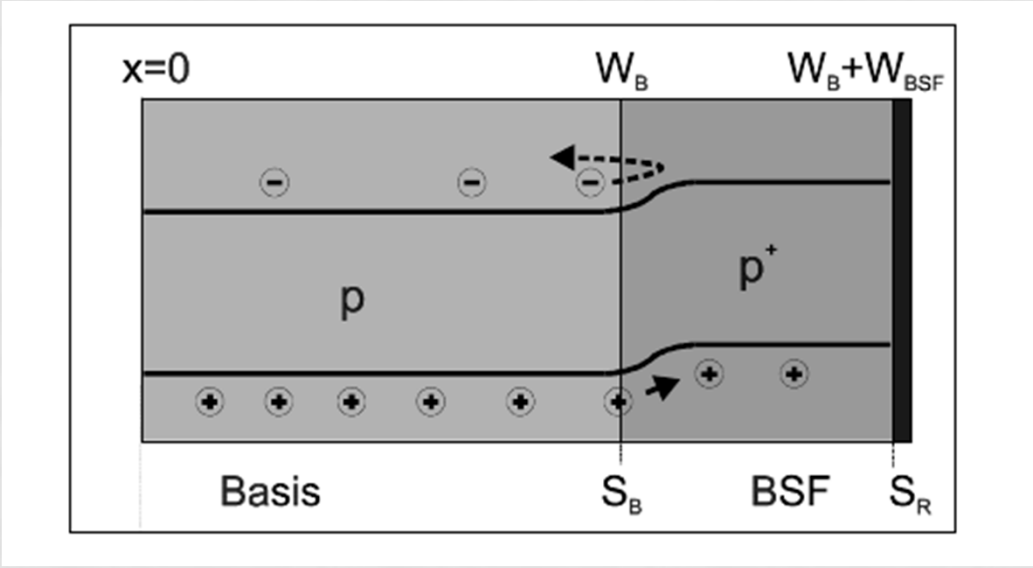


HIT solar cell

4. Back Surface Field (BSF)

A thin layer of p-doped material to prevent the minorities from moving to the back contact where they recombinate

e.g. use aluminium for a back contact, which melts (T ~ 500°C) into the silicon and creates a positive doped BSF. Besides it serves as a reflection layer.



PROCEDURE: 4 STEPS

Choose the basic passivation methods

Achieve decent quality of passivation on each of the chosen methods

Apply the methods on actual solar cells

Assess SRV

Step 1: CHOOSE THE BASIC PASSIVATION METHODS

- Three basic methods for passivation were chosen

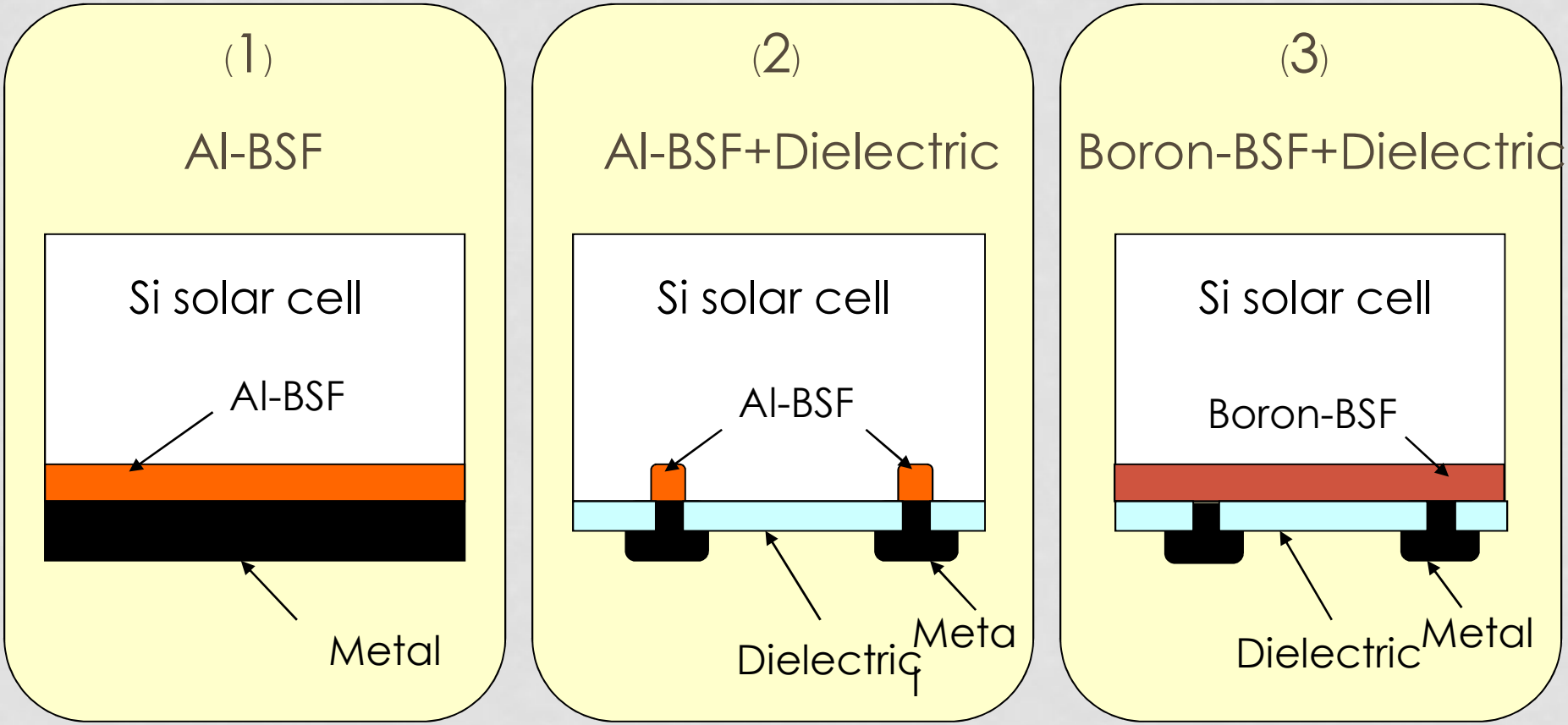
Method	Mechanism
1. Al-back surface field (Al-BSF)	Creates an electric field that pushes carriers away from the surface
2. Boron-BSF	
3. Dielectric passivation	Reduces trap levels at the surface

Step 2: ACHIEVE DECENT QUALITY OF PASSIVATION ON EACH OF THE CHOSEN METHODS

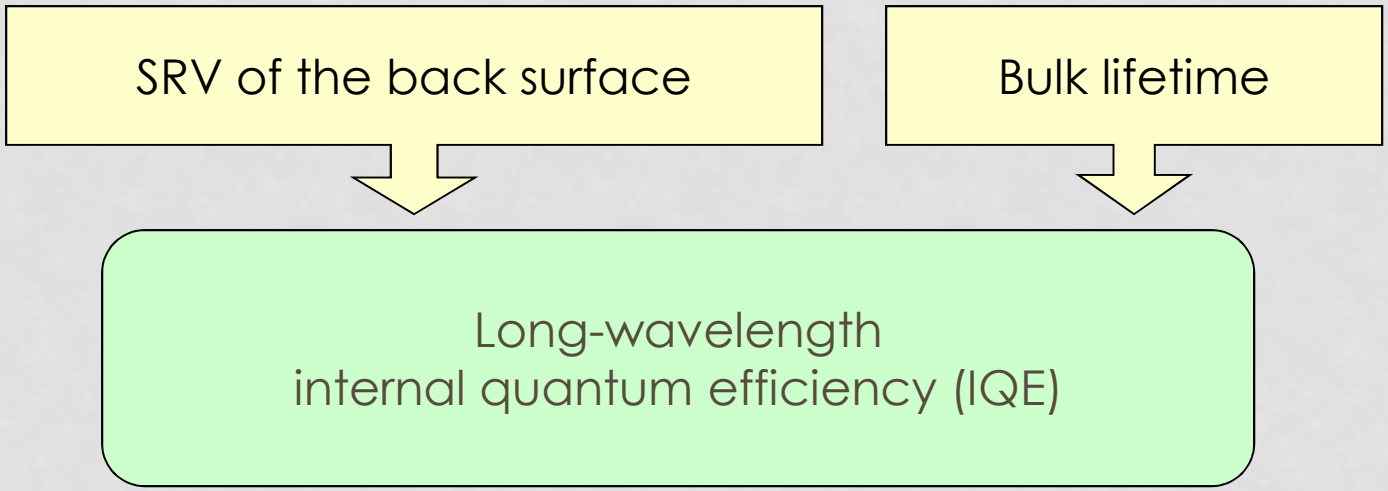
- Al-BSF
  - Method for uniform Al-BSF was established
  - SRV of 230 cm/s was obtained
- Dielectric passivation
  - RTO/LF-SiN_x provided the best passivation
  - SRV of 51 cm/s was obtained by RTO/LF-SiN_x (without electrical contacts)
- Boron-BSF
  - Results indicated promisingly low SRV

Step 3: APPLY THE METHODS ON ACTUAL SOLAR CELLS

- Three solar cells structures were proposed



STEP 4: Assess SRV

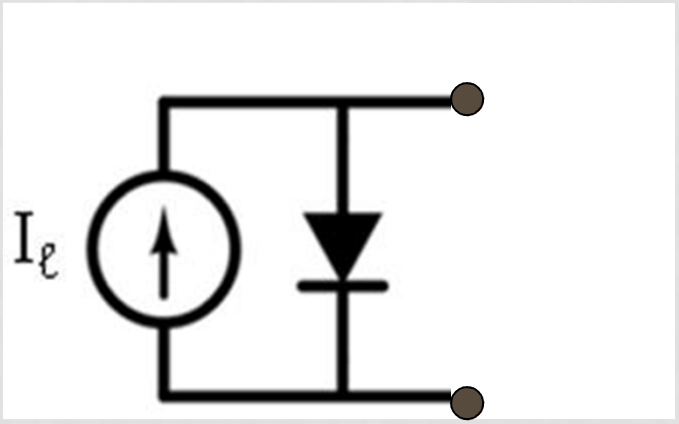


- SRV can be obtained by measuring IQE and bulk lifetime

RESISTIVE LOSS

- Equations analytical

$$I = I_{ph} - I_s\left(e^{V/V_T} - 1\right)$$



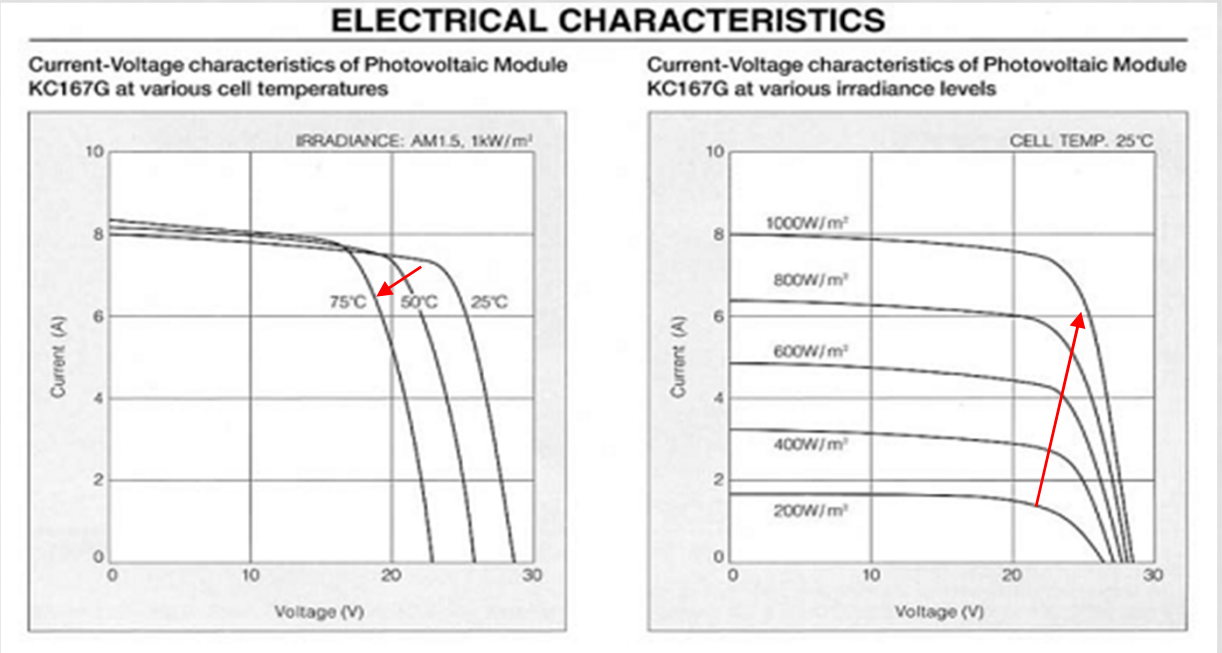
Open Circuit:
$I = 0$, $V=V_{OC}$

Short Circuit:
$V=0$, $I=I_{SC}$

Maximum power point (MMP)

depends on:

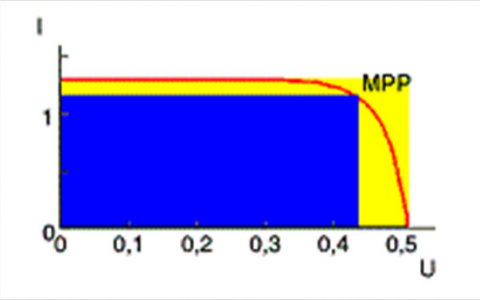
- Temperature
- Irradiance
- Solar cell characteristics



Fill factor

$$FF = \frac{P_{MPP}}{U_{OC} \cdot I_{SC}}$$

→ Performance of solar cell

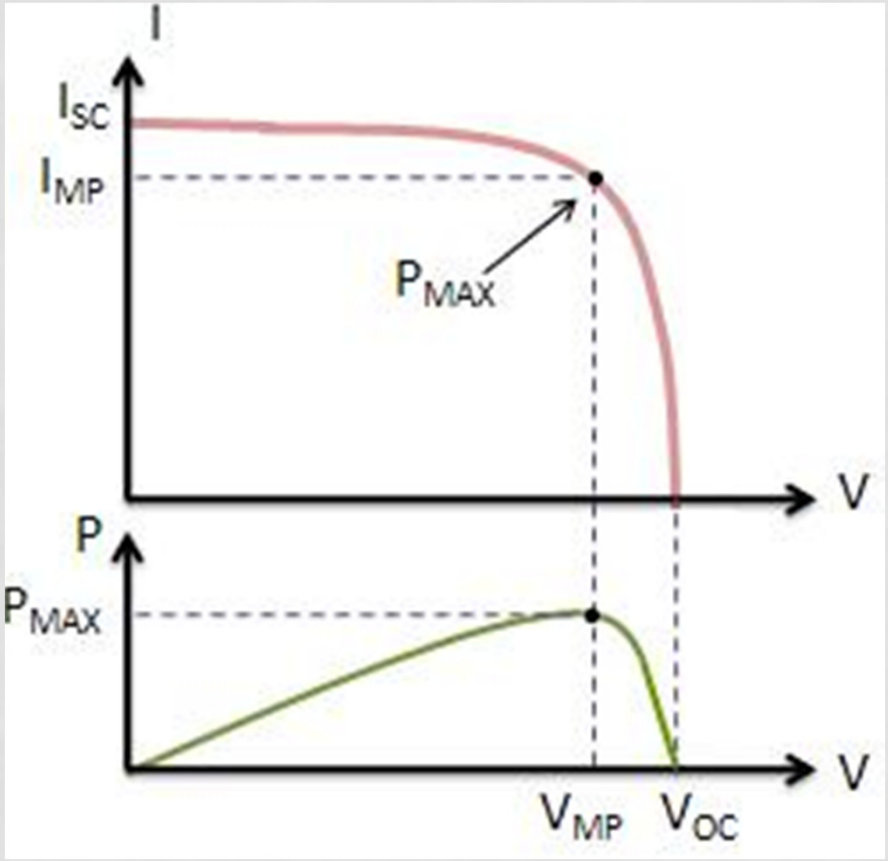


Efficency coefficent

$$\eta = \frac{P_{MPP}}{A \cdot P_{opt}}$$

Open Circuit:
$I = 0, V=V_{OC}$

Short Circuit:
$V=0, I=I_{SC}$

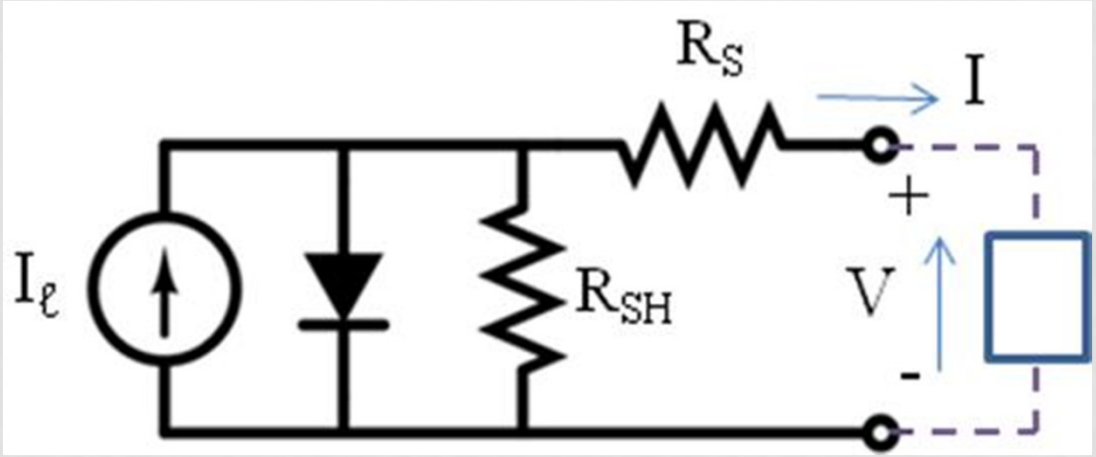


The power produced by the cell in Watts can be easily calculated along the I-V sweep by the equation $P=IV$. At the I_{SC} and V_{OC} points, the power will be zero and the maximum value for power will occur between the two. The voltage and current at this maximum power point are denoted as V_{MP} and I_{MP} respectively.

During operation, the efficiency of solar cells is reduced by the dissipation of power across internal resistances. These parasitic resistances can be modeled as a parallel shunt resistance (R_{SH}) and series resistance (R_S).

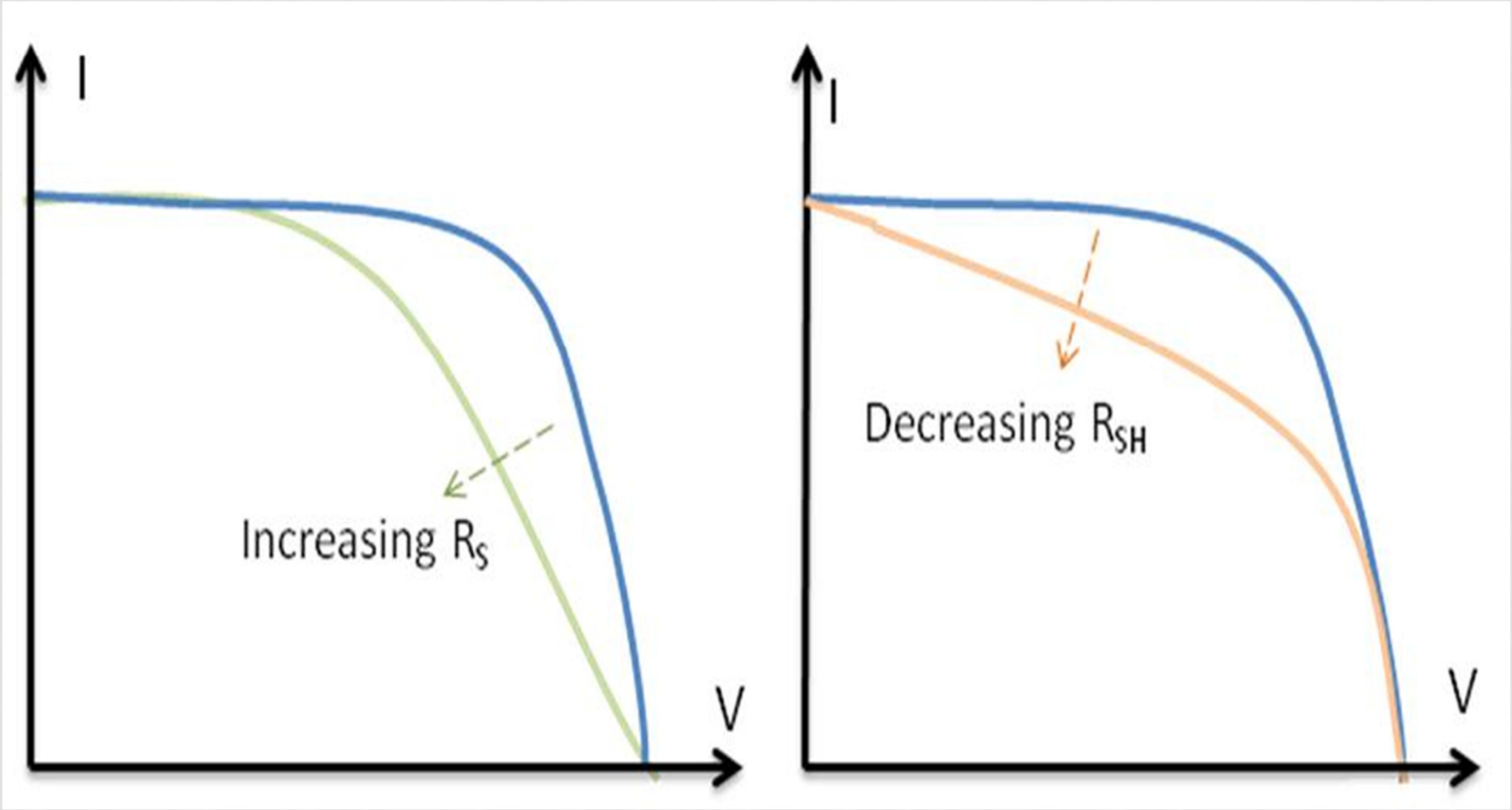
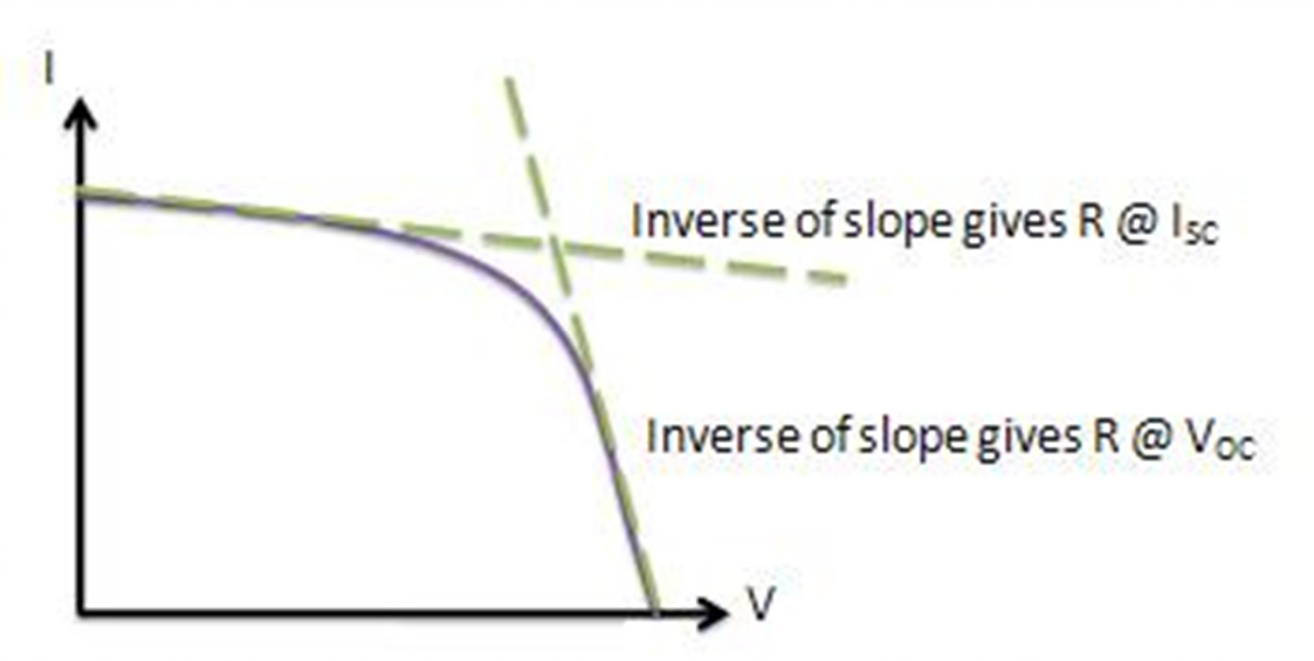
For an ideal cell, R_{SH} would be infinite and would not provide an alternate path for current to flow, while R_S would be zero, resulting in no further voltage drop before the load.

Decreasing R_{SH} and increasing R_s will decrease the fill factor (FF) and P_{MAX} as shown in the figure on the next slide. If R_{SH} is decreased too much, V_{OC} will drop, while increasing R_S excessively can cause I_{SC} to drop instead.



$$I = I_l - I_0\left(exp^{\frac{q(V+I\cdot R_S)}{n\cdot k\cdot T}} - 1\right) - \frac{V + I\cdot R_S}{R_{SH}}$$

Decrease in the FF due to R_S and R_{SH}.



It is possible to approximate the series and shunt resistances, R_S and R_{SH}, from the slopes of the I-V curve at V_{OC} and I_{SC}, respectively. The resistance at Voc, however, is at best proportional to the series resistance but it is larger than the series resistance. R_{SH} is represented by the slope at I_{SC}. Typically, the resistances at I_{SC} and at V_{OC} will be measured and noted.