PV Technology

Losses in a solar cell

- Optical losses
- Electrical losses:

  related to the cell material

  related to solar cell contacts

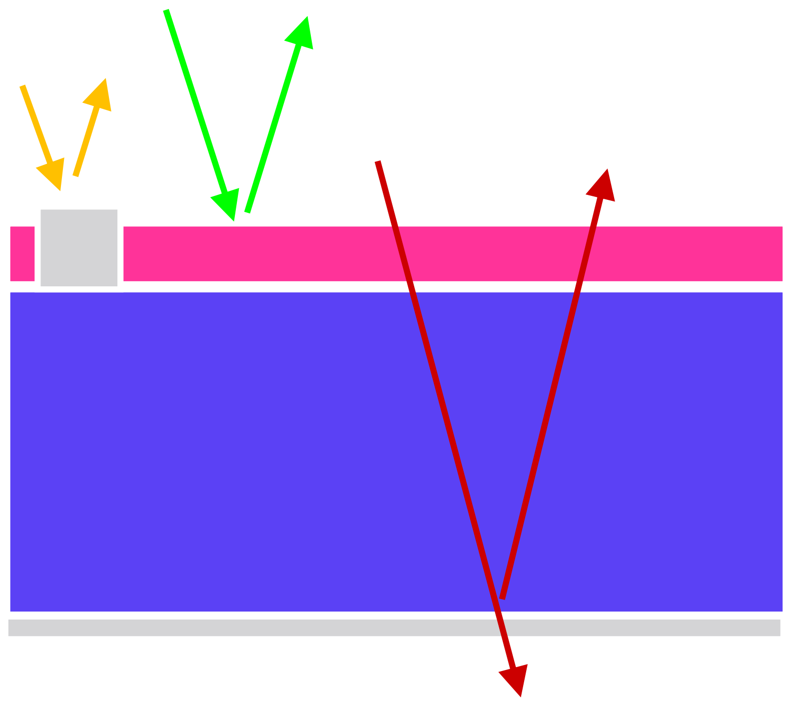
PV Technology

Losses: Optical

Front surface

Metal grid

Back of the cell



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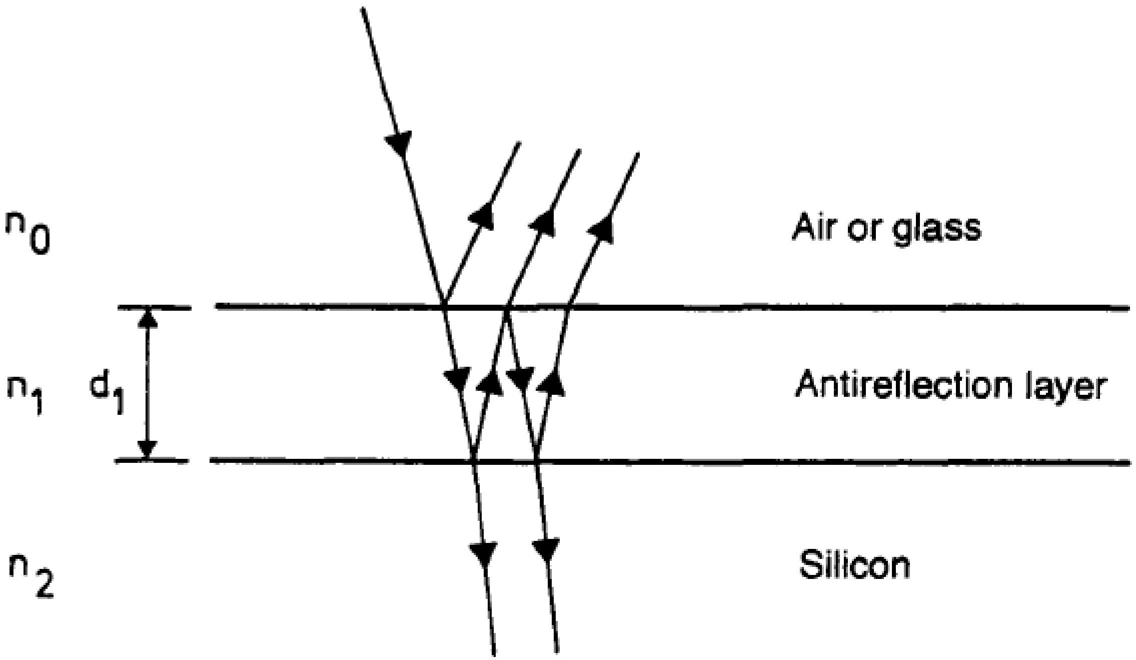
Anti-reflection coatings



$$n \cdot d = \frac{\lambda}{4}$$

PV Technology

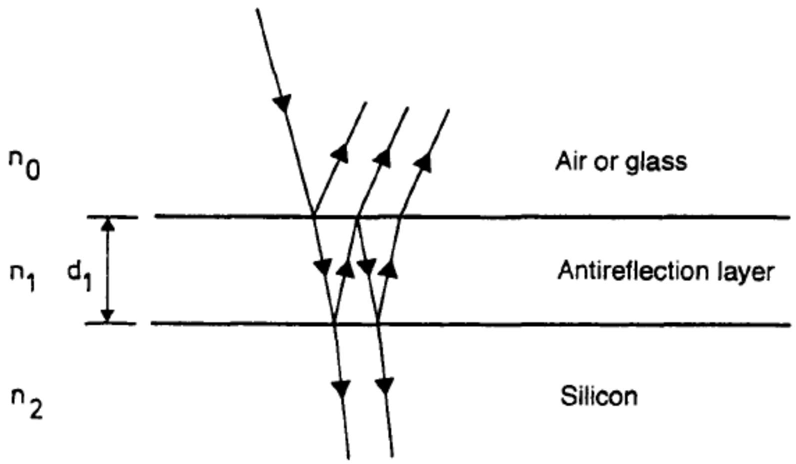
Anti-reflection coatings

$$R = \frac{r_1^2 + r_2^2 + 2 r_1 r_2 \cos 2\vartheta}{1 + r_1^2 r_2^2 + 2 r_1 r_2 \cos 2\vartheta}$$

$$r_1 = \frac{n_0 - n_1}{n_0 + n_1}$$

$$r_2 = \frac{n_1 - n_2}{n_1 + n_2}$$

$$\vartheta = \frac{2\pi n_1 d_1}{\lambda}$$



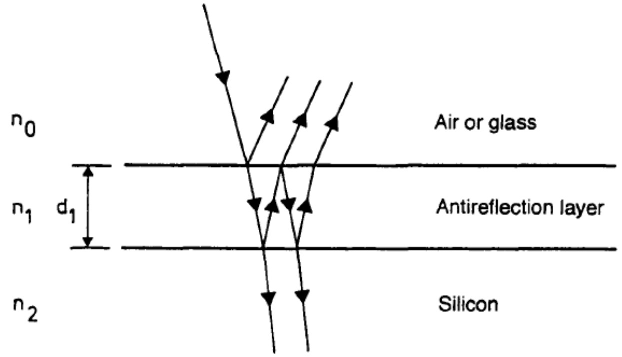
n_0 is the refractive index of the uppermost layer (air or glass),
n_1 is the refractive index of the antireflection layer, and
n_2 is the refractive index of the silicon.

PV Technology

Anti-reflection coatings

The minimum off R occurs for $n_1 d_1 = \lambda/4$

$$R_{min} = \left(\frac{n_1^2 - n_0 n_2}{n_1^2 + n_0 n_2} \right)^2$$

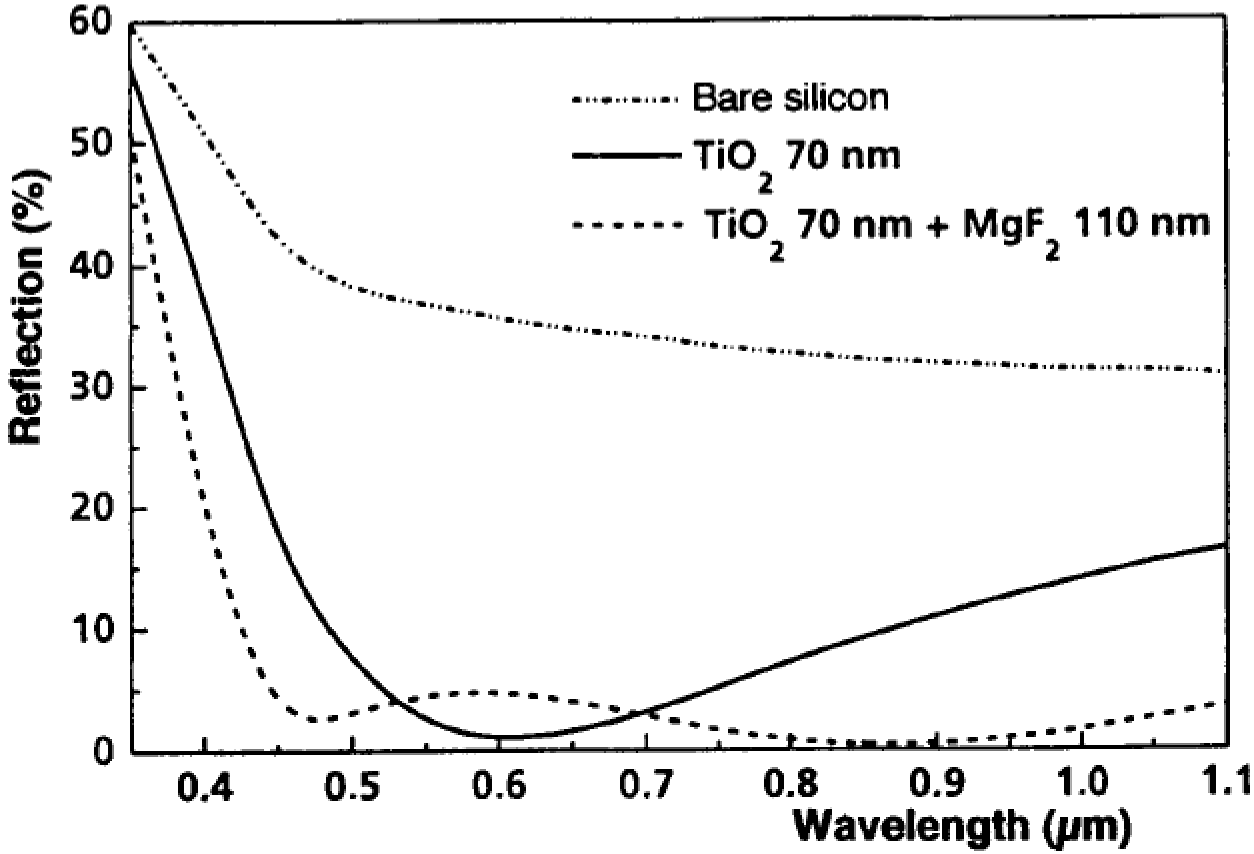


If $n_1^2 = n_0 n_2$ ⟹ Rmin=0

For that we must choose $n_1 = \sqrt{n_0 n_2}$

PV Technology

Anti-reflection coatings



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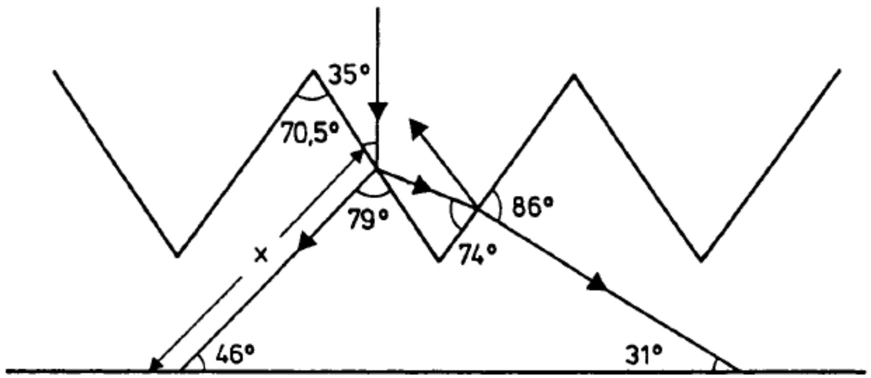
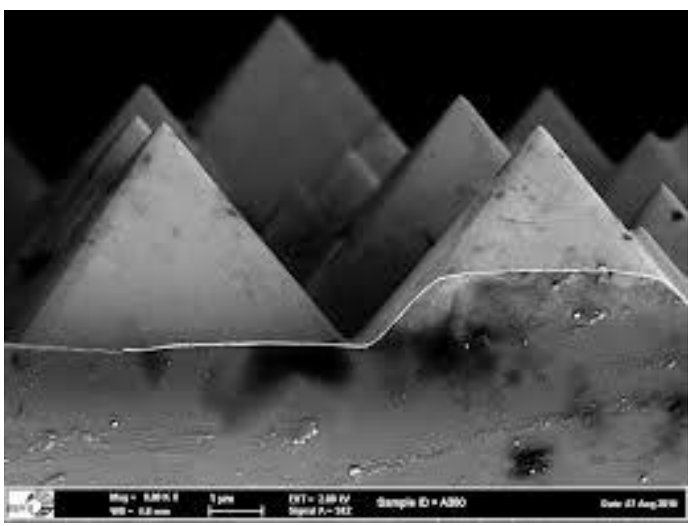
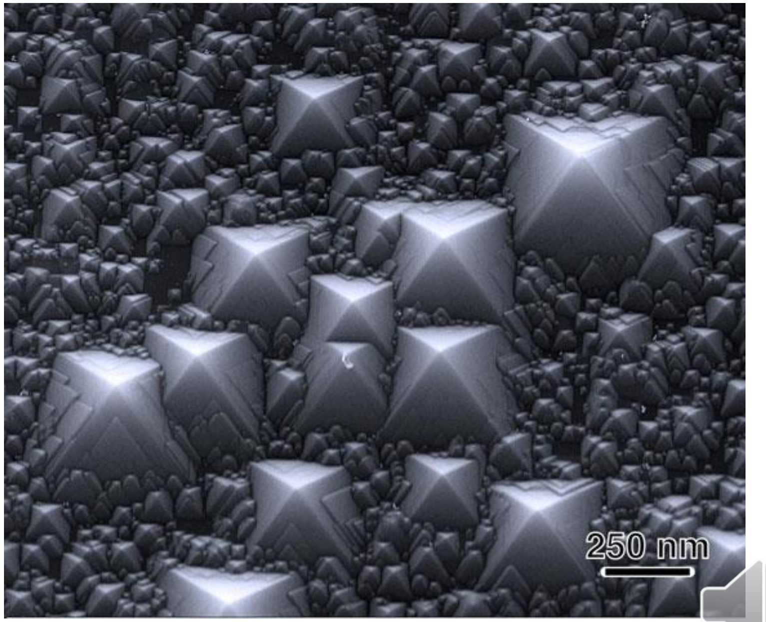
Optical losses – Surface Texturatization



Instead of 35% only 10% is reflected





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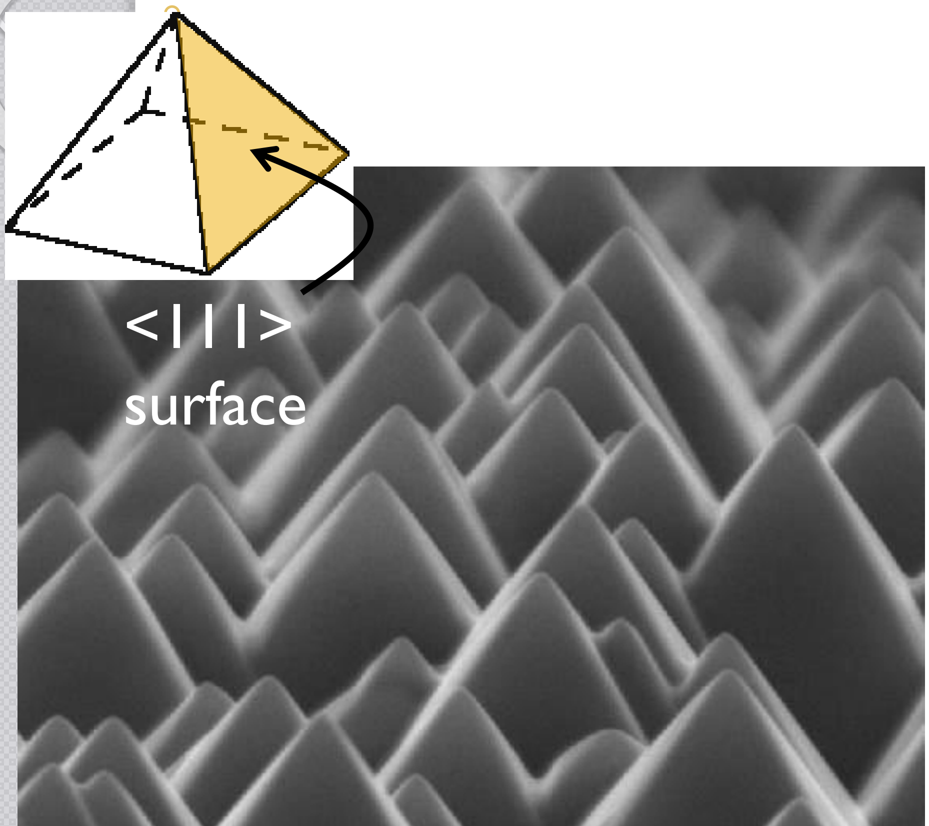
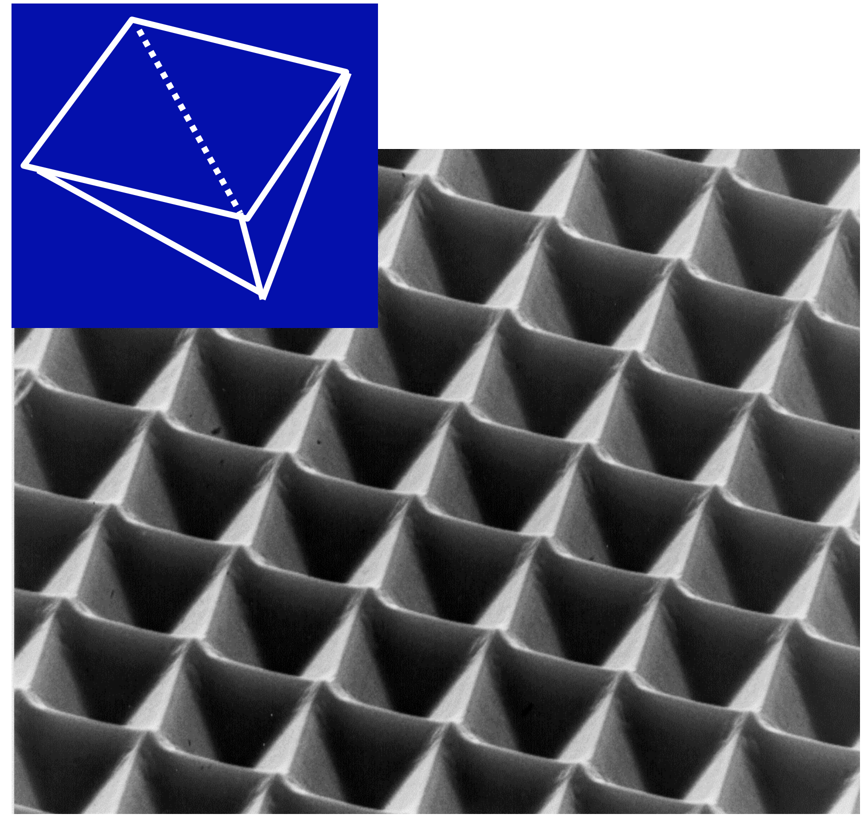
Optical losses – Surface Texturatization





SOURCE: IIT Bombay, C.S. Solanki

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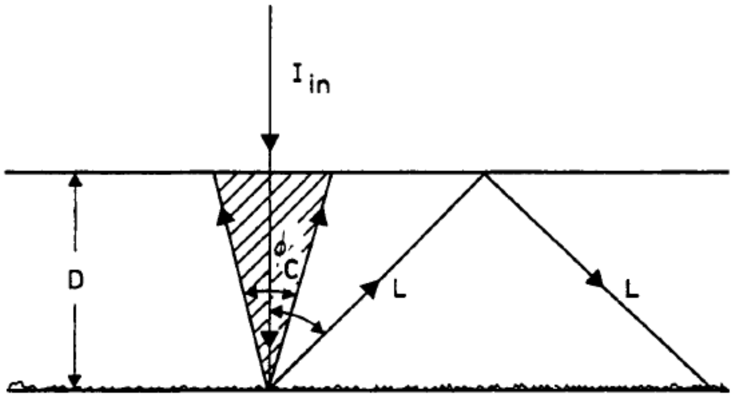
Anti-reflection coatings

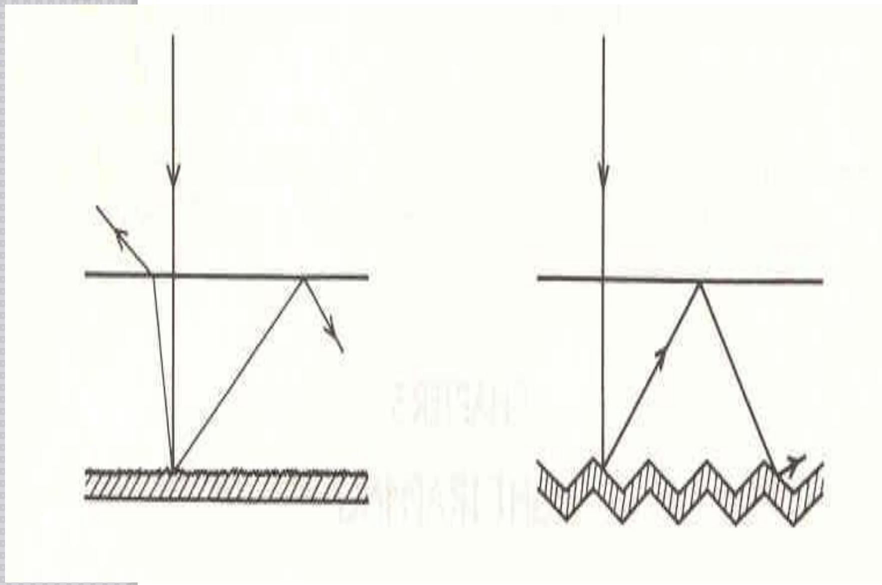


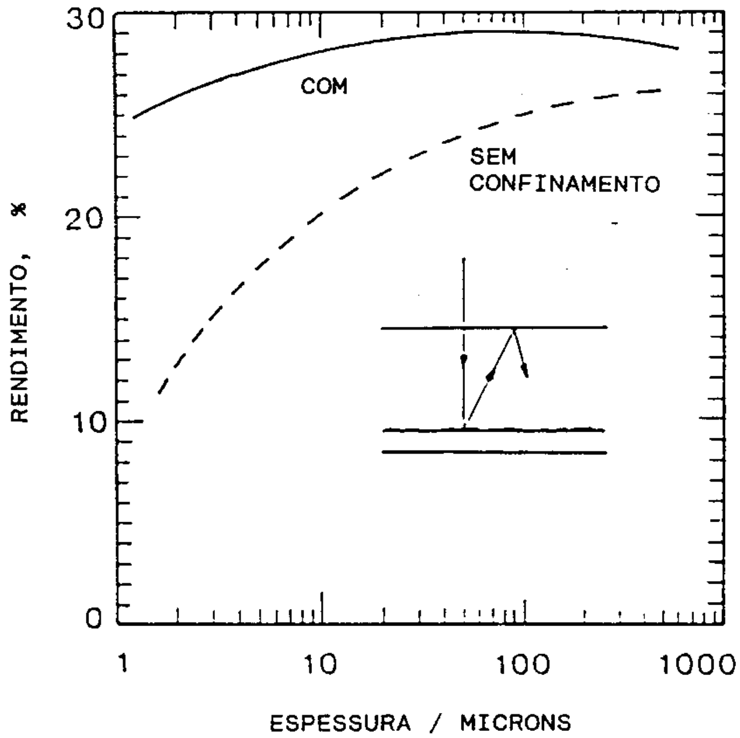
$$\sin^2\Phi_C = \frac{1}{n^2}$$

For n_{si}= 3.5 $\Phi_C = 17°$

PV Technology

Optical confinement





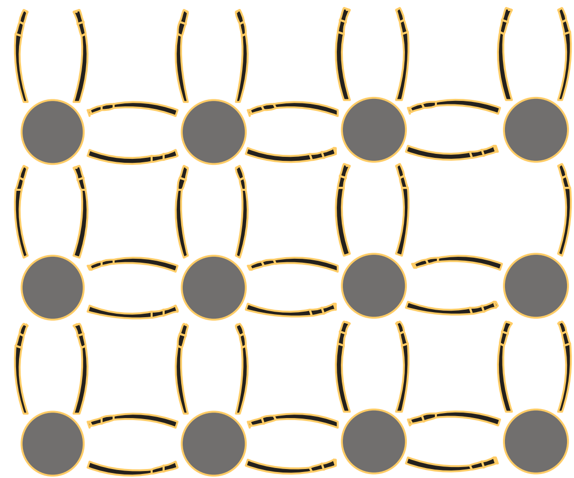
The effective path inside the cell can be strongly augmented by using the concept of light confinement

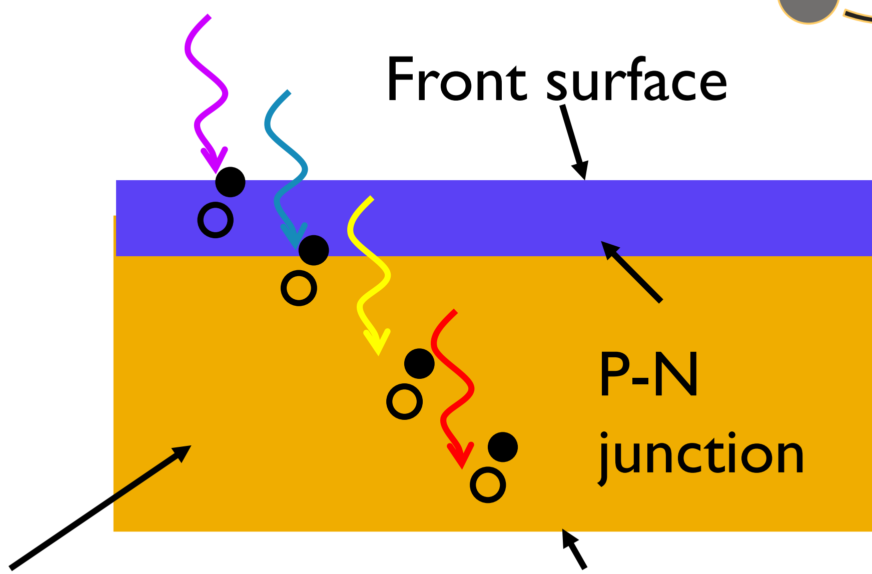
PV Technology

Losses: Recombination mechanisms

Recombination areas

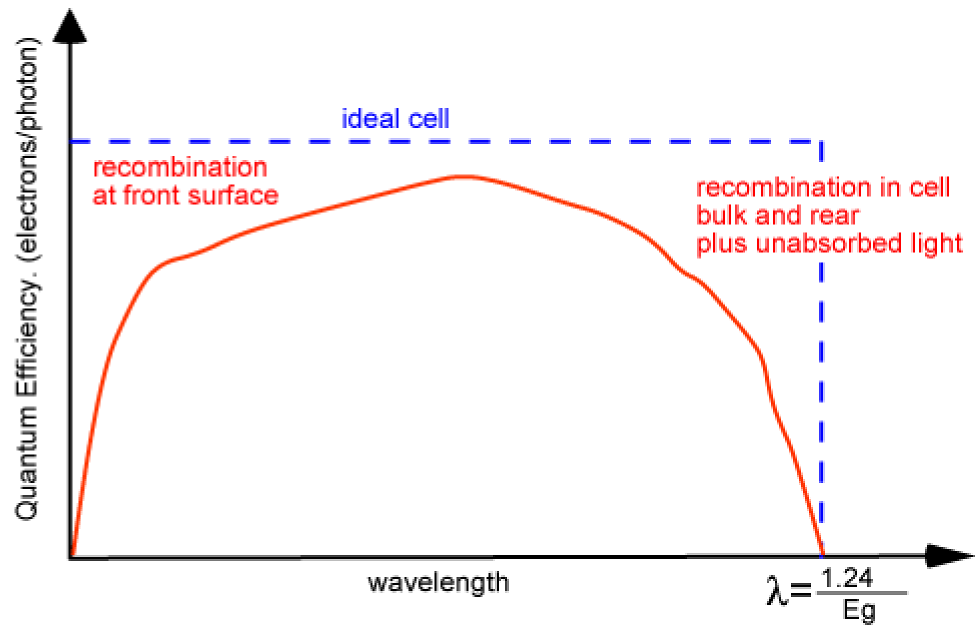
- Surface recombination
- Depletion region recombination
- Bulk recombination





PV Technology
Losses: Recombination effects

Current generation inside the cell



Generated current is reduced due to recombination

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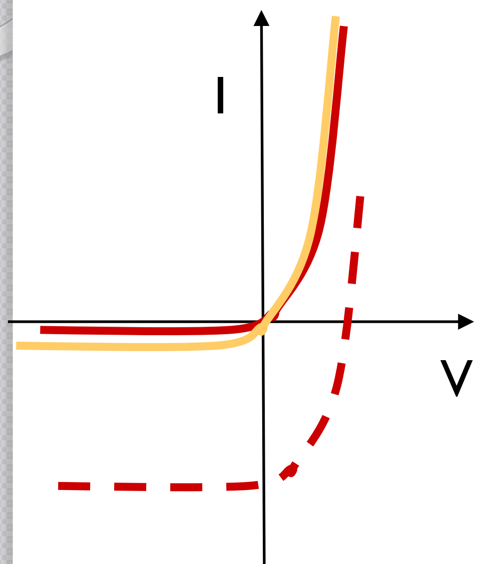
Losses: Recombination effects



$$I = I_0(e^{qV/kT} - 1) - I_L$$

$$V_{oc} = \frac{kT}{q}\ln\left(\frac{I_L}{I_0} + 1\right)$$

- V_{oc} depends on short circuit current (I_L) and saturation current (I_0)
- I_L does not vary much but I_0 can vary by several orders of magnitude → hence controls the V_{oc}

V_{oc} is a measure of recombination in a solar cell

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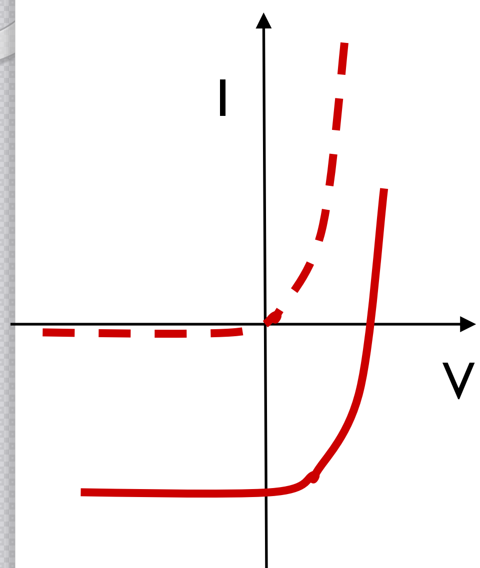
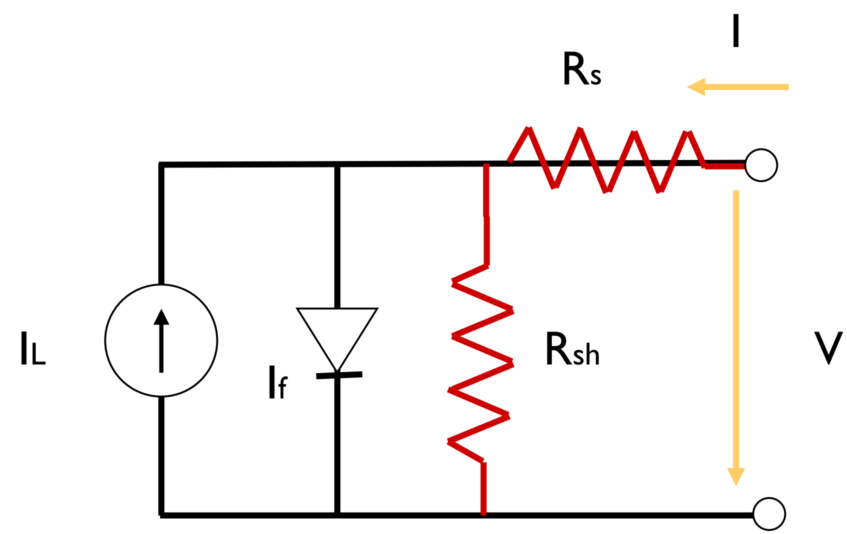
Losses: Electrical





Both R_s and R_{sh} will reduce the available cell current and so they will reduce the overall efficiency

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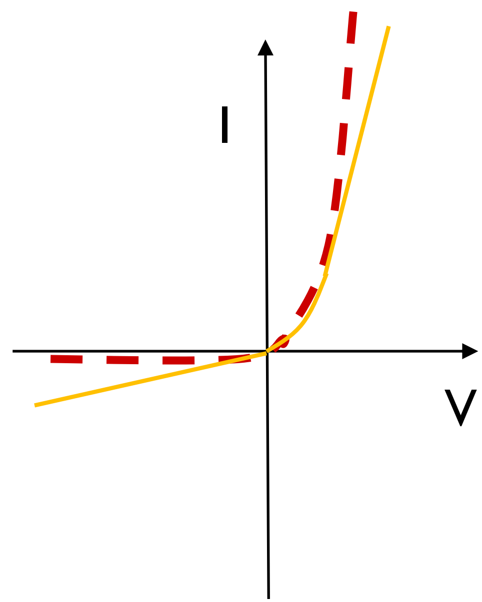
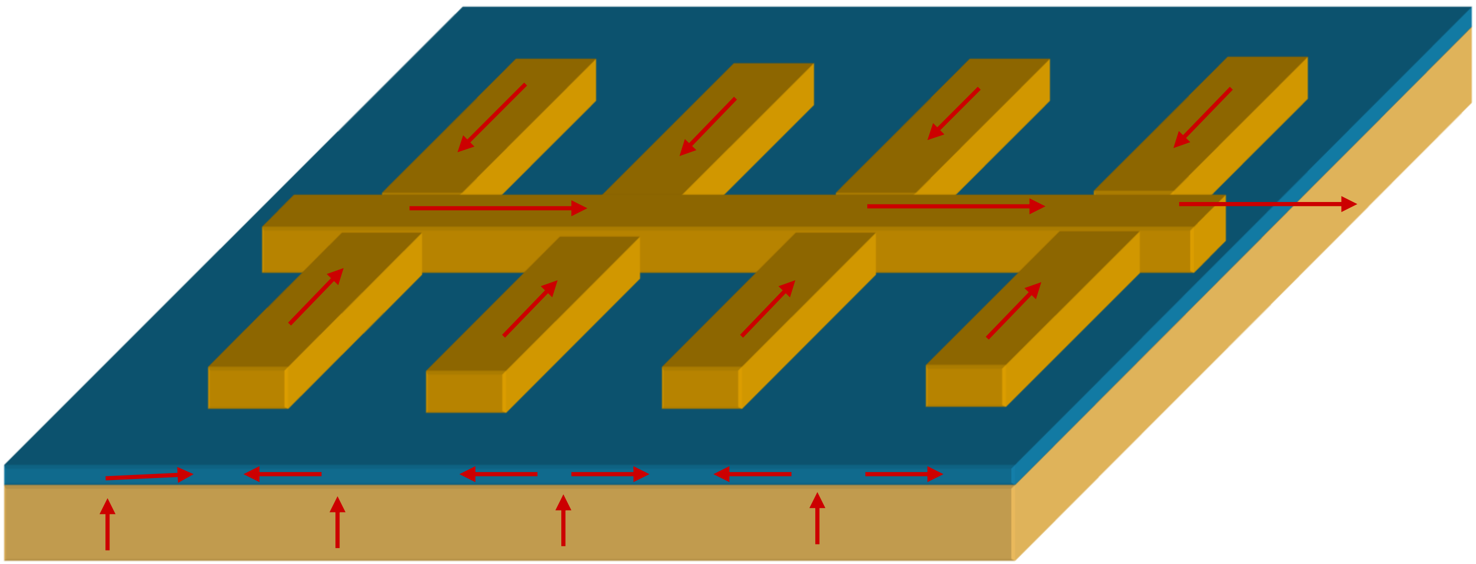
Losses: Electrical



$$I = I_L - I_0\left(\exp\frac{q(V+IR_s)}{nkT} \right) - \frac{V+IR_s}{R_{sh}}$$

PV Technology

Losses: Electrical



Componentes de R_s:

Resistência do substrato semicondutor

Resistência de contacto entre o metal e o semicondutor

Resistência da metalização

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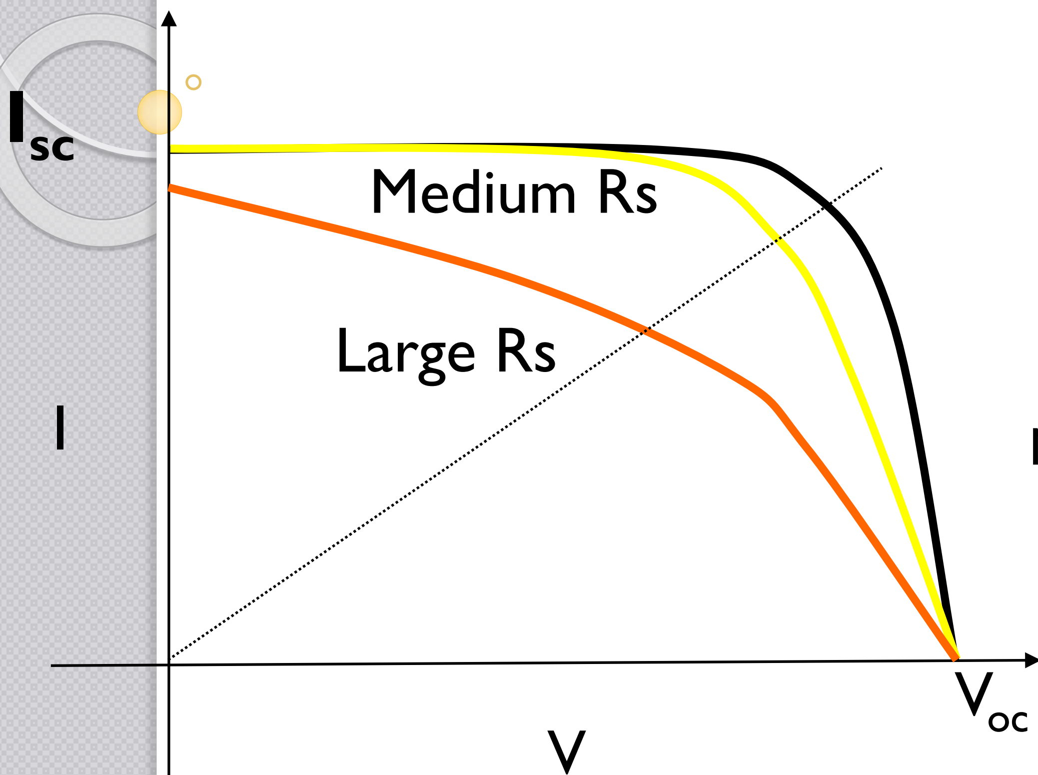
Losses: Electrical



Characteristic resistance, R_{ch}

$$R_{CH} = \frac{V_{max}}{I_{max}}$$

Normalized series resistance, r_s

$$r_s = \frac{R_s}{R_{CH}}$$

Slope of the I-V curve near V_{oc} gives indication about R_s

Effect of series resistance on the FF and maximum power

$$P_{m,s} = P_0(1 - r_s)$$

$$FF_s = FF_0(1 - r_s)$$

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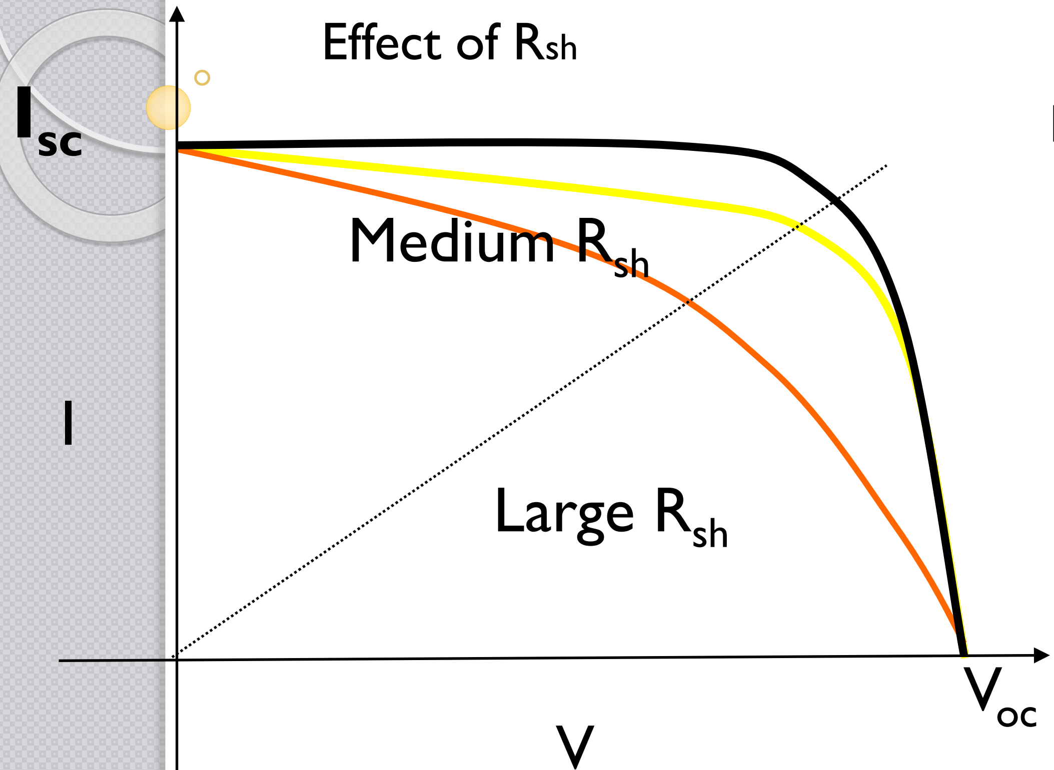
Losses: Electrical



Normalized shunt resistance, r_{sh}

$$r_{sh} = \frac{R_{sh}}{R_{CH}}$$

- Slope of the I-V curve near I_{sc} gives indication about R_{sh}
- Effect of shunt resistance on the FF and maximum power

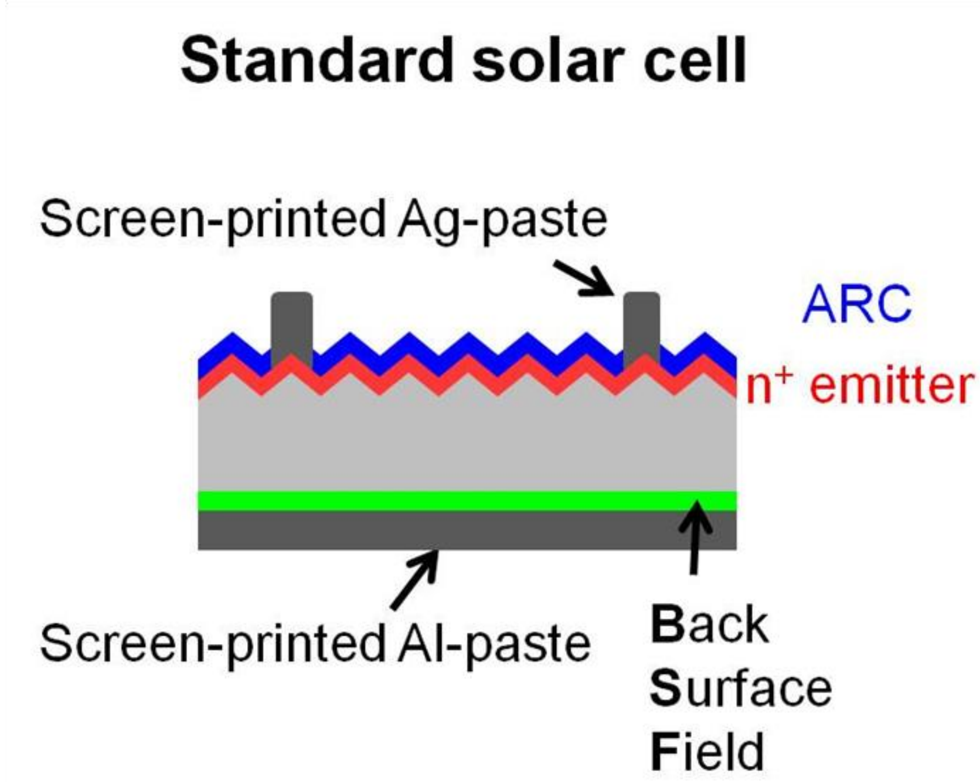
$$P_{m,sh} = P_0 \left(1 - \frac{1}{r_{sh}}\right)$$

$$FF_{sh} = FF_0 \left(1 - \frac{1}{r_{sh}}\right)$$

PV Technology

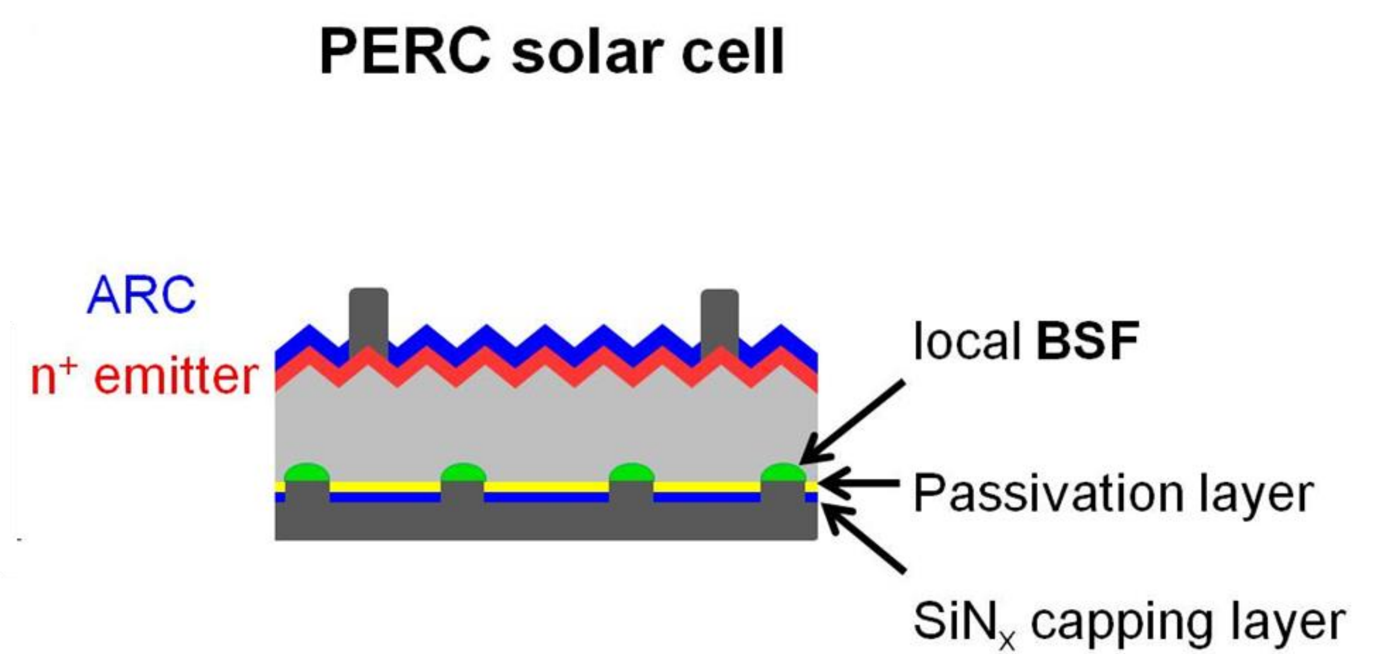
Quick Technology overview

PV Technology



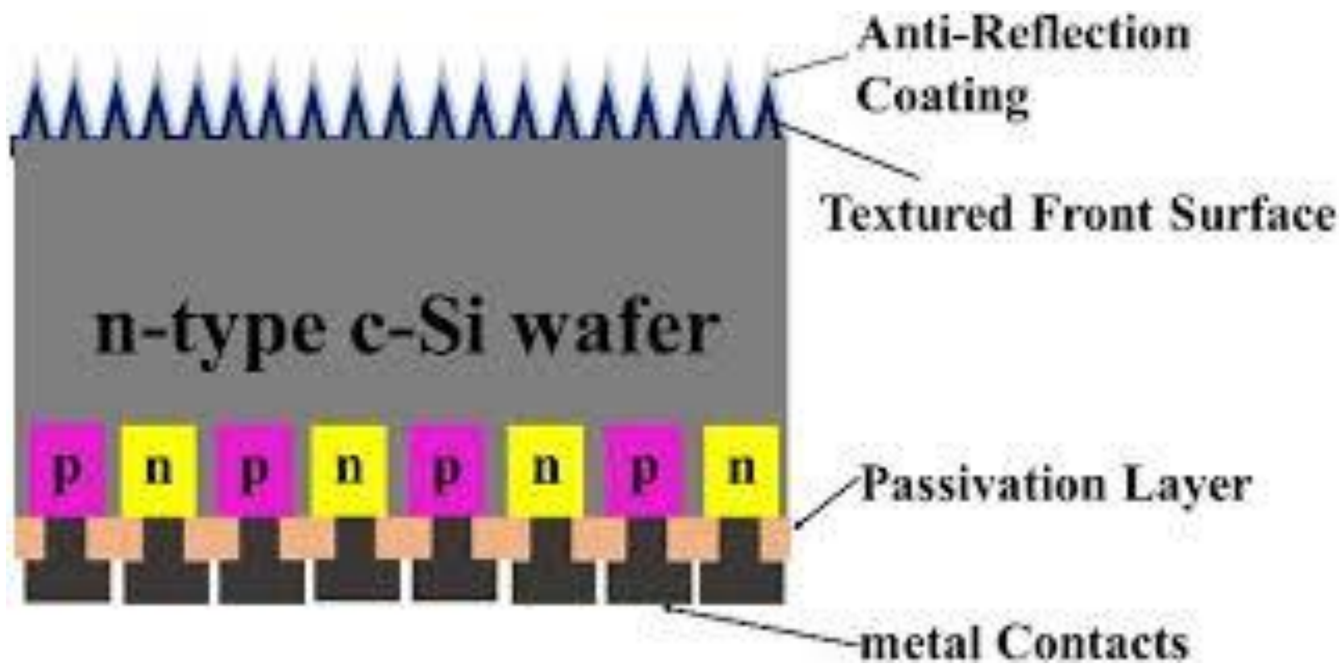
Source: Institute for Solar Energy Research Hamelin (ISFH)

PV Technology



Source: Institute for Solar Energy Research Hamelin (ISFH)

PV Technology

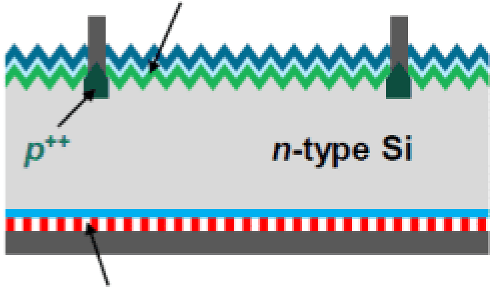


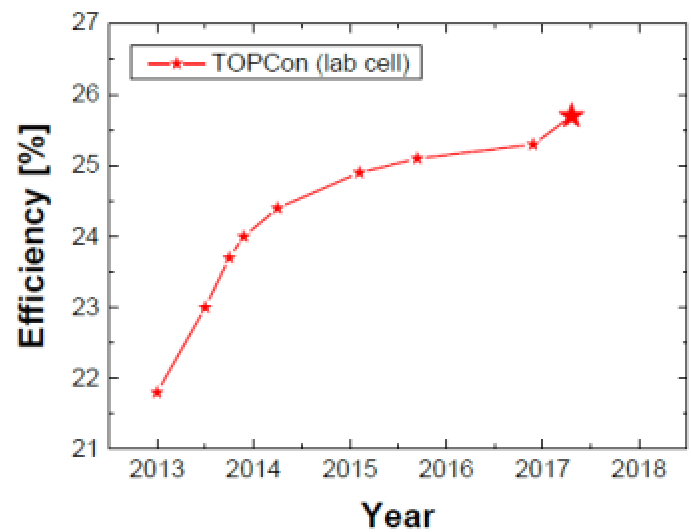
PV Technology

Passivating Contacts
Record Solar Cell

- Both-sides contacted cell with front p⁺ emitter and full-area rear contact

J_{sc} (mA/cm²)	V_{oc} (mV)	*FF* (%)	η* (%)	Area** (cm²)
42.9	724	83.1	25.8	4.0 (da)

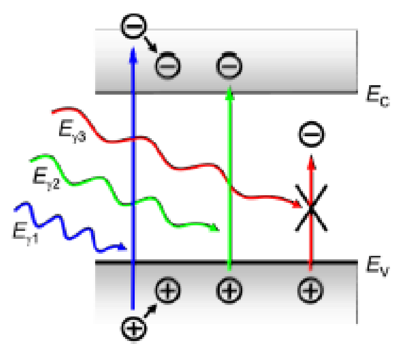


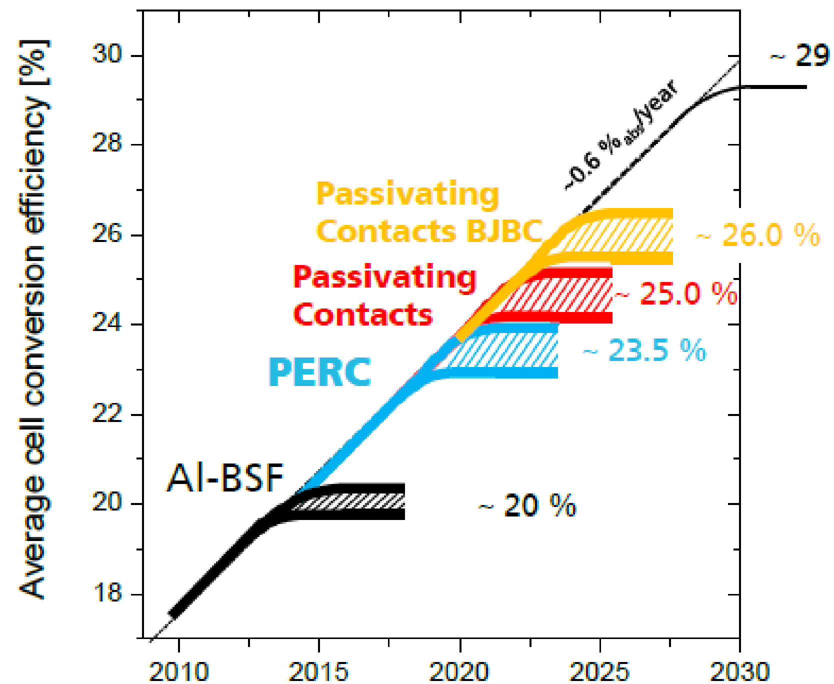


PV Technology

Future
What is the Limit of Silicon Solar Cells

- Shockley, Queisser (1961) Limit for Si 33% (AM1.5)
- Limitations by thermalization and transmission
- **Auger Limit 29.4 %**[1]





→ **End of Silicon Solar Cell Technologies?**

[1]Richter, Hermle, Glunz, *IEEE J. Photovolt.* (2013)

Fraunhofer ISE

PV Technology

You have now the needed information to perform the assignment I told you about

PVFactory

It is a virtual factory to simulate production of solar cells

I will put this assignment in fenix

PV Technology

Tandem solar cell