Solar Cell Operation

Key aim is to generate power by:

(1) **Generating a large short circuit current, I_{sc}**

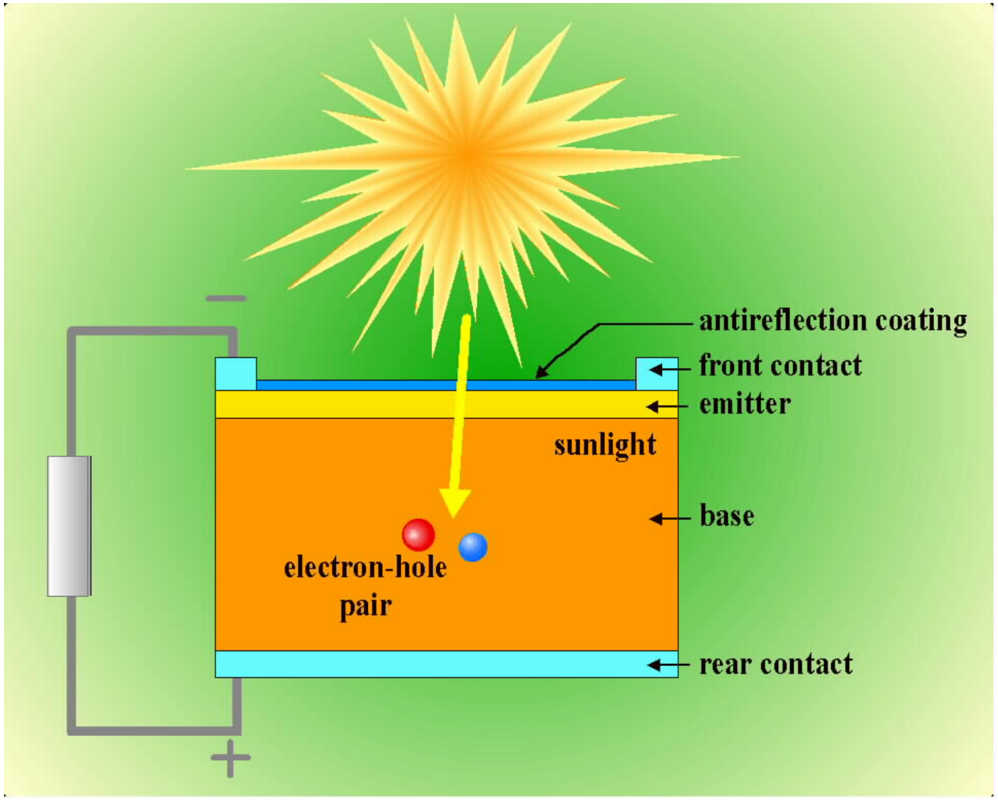
(2) **Generate a large open-circuit voltage, V_{oc}**

(3) **Minimise parasitic power loss mechanisms (particularly series and shunt resistance).**

Short Circuit Current

J_{sc} depends on:

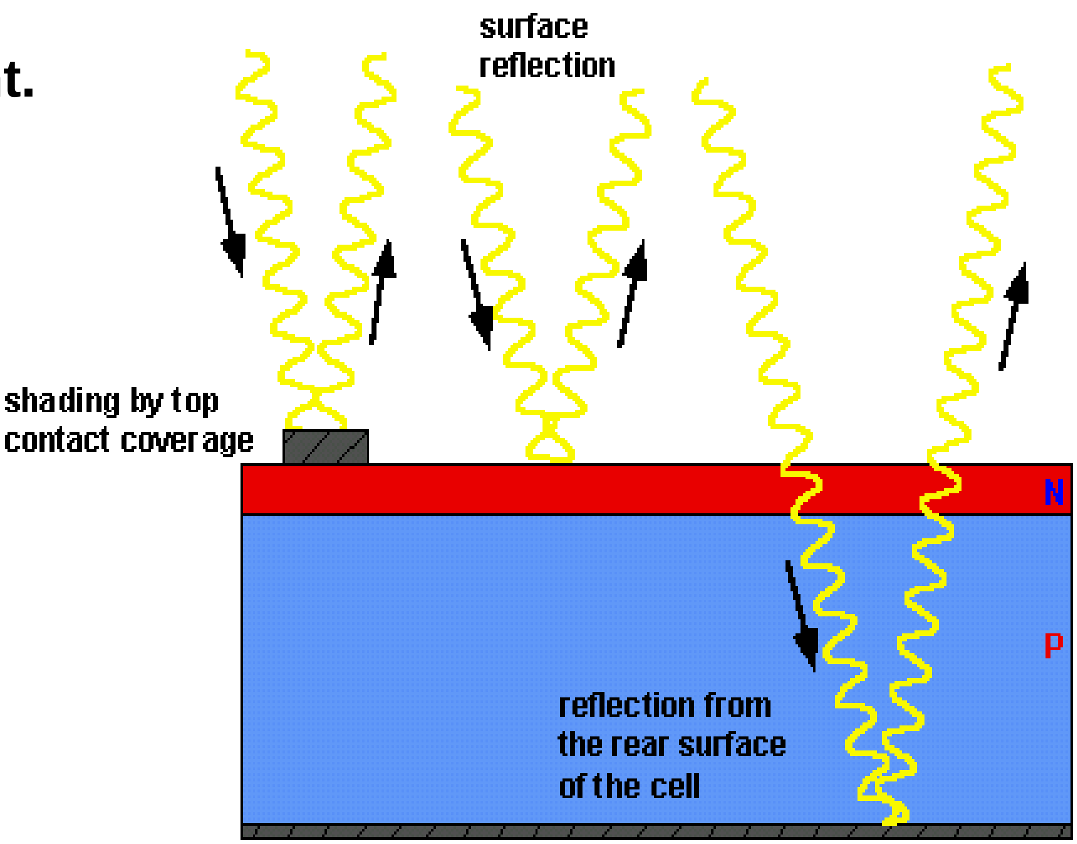
1. Generation of light-generated carries
   - Minimize reflection
   - Absorb light in semiconductor and generate carriers
   - Reflection and absorption depend on characteristics of sunlight, solar cell optical properties, E_G, and solar cell thickness
2. Collection of light generated minority carriers
   - Depends on material and device parameters



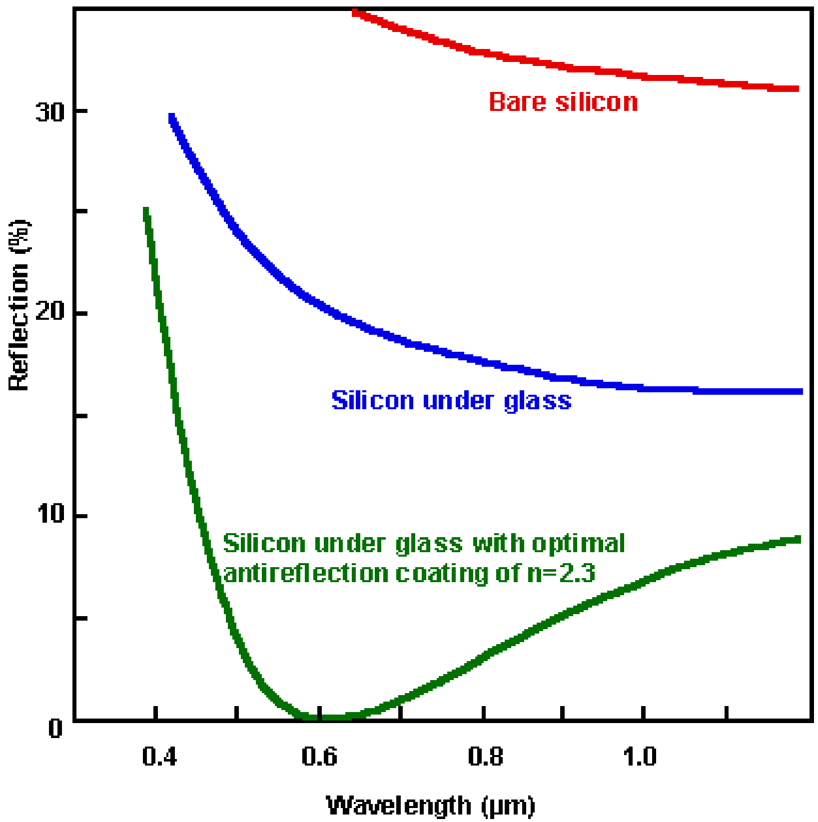
Optical Properties of Solar Cells

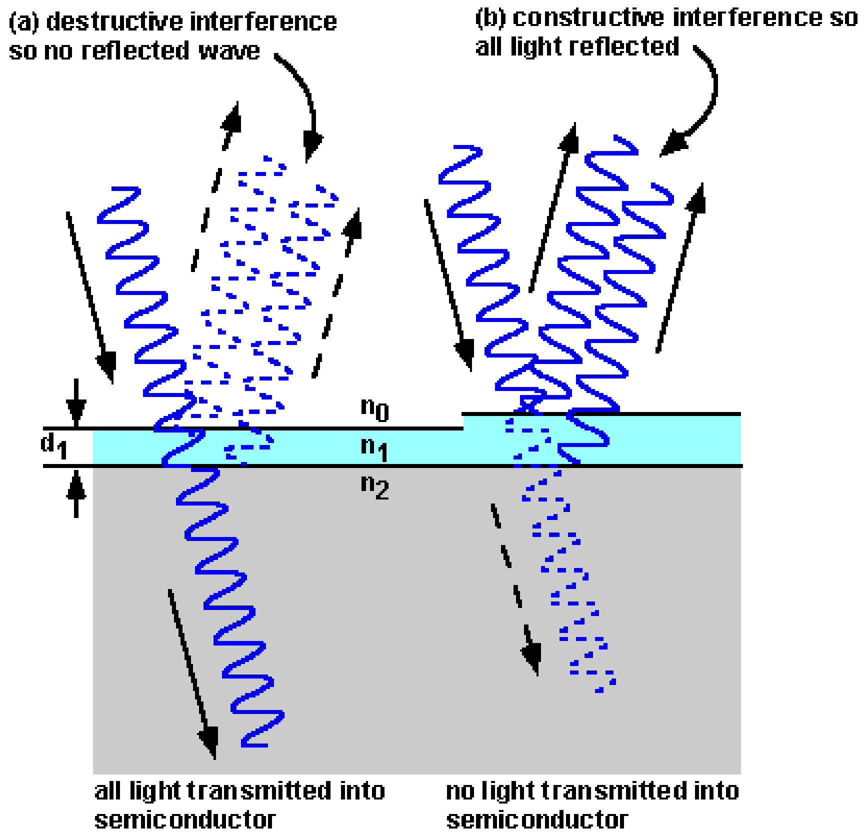
The optical properties (reflection, absorption) are key in achieving high current. To generate as many carrier as possible we need to:

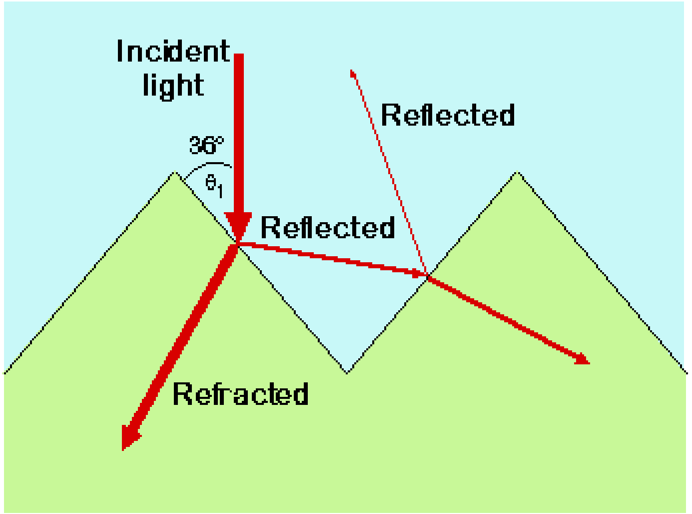
- Reduce reflection from silicon
- Reduce reflection from metal top surface.
- Increase absorption of light in semiconductor

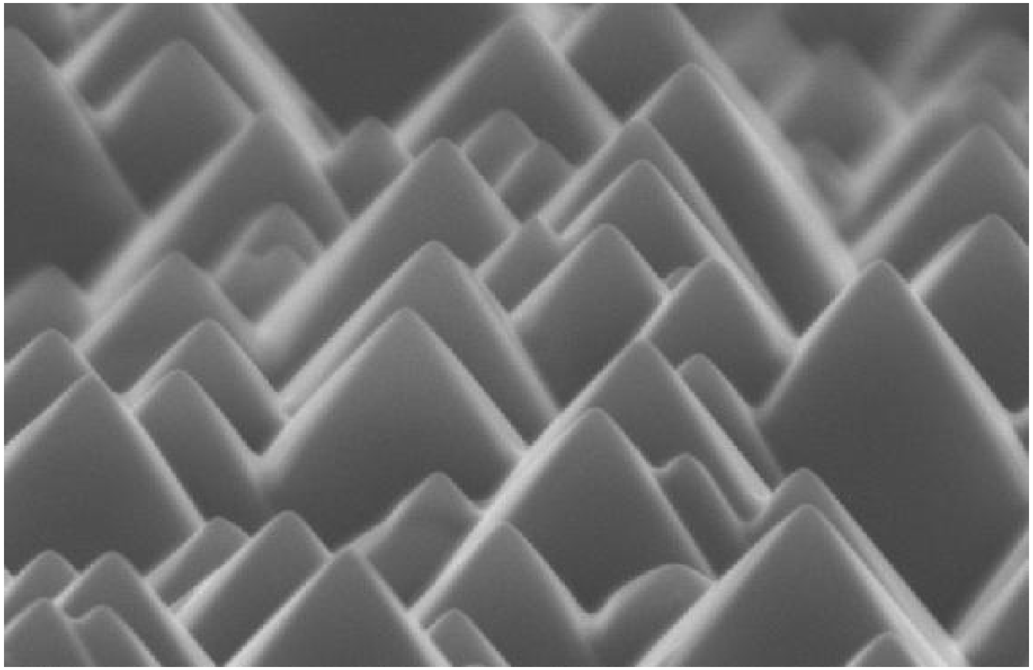


Reducing Reflection 1: AR coatings

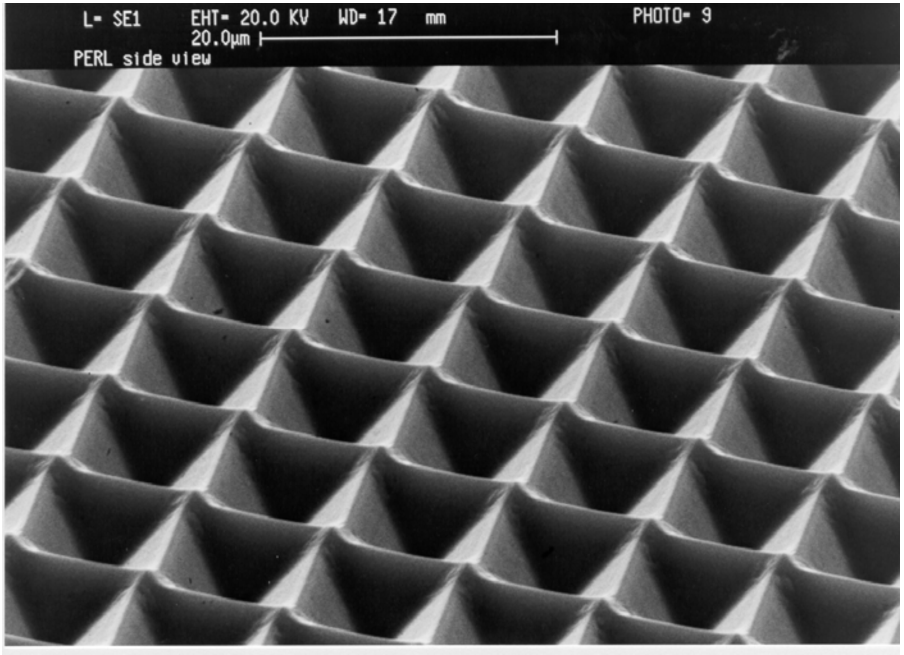


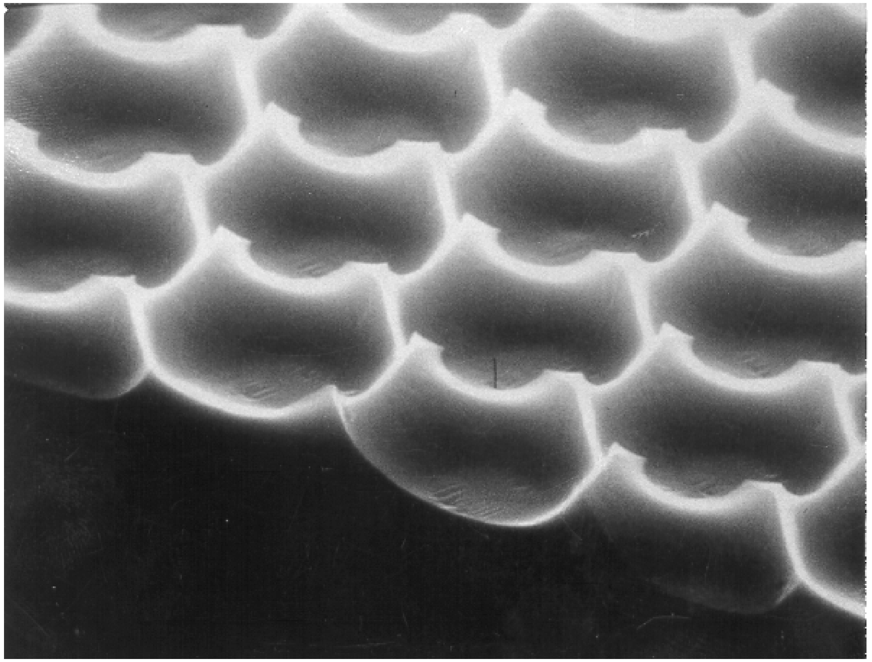



Incident light
36°
θ_1
Reflected
Reflected
Refracted



Reducing Reflection 2: Texturing



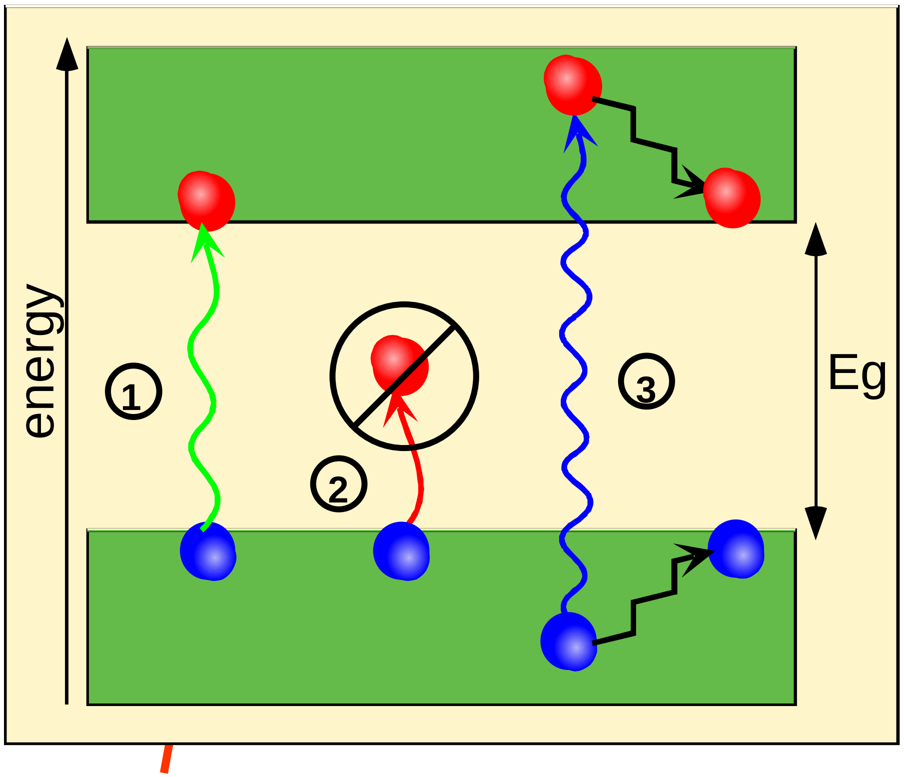


Absorption of photons: Eg

A photon in a solar cell can generate an electron-hole pair if it has an energy greater than the band gap

– Photons with $E_{ph} < E_G$ are not absorbed and are lost

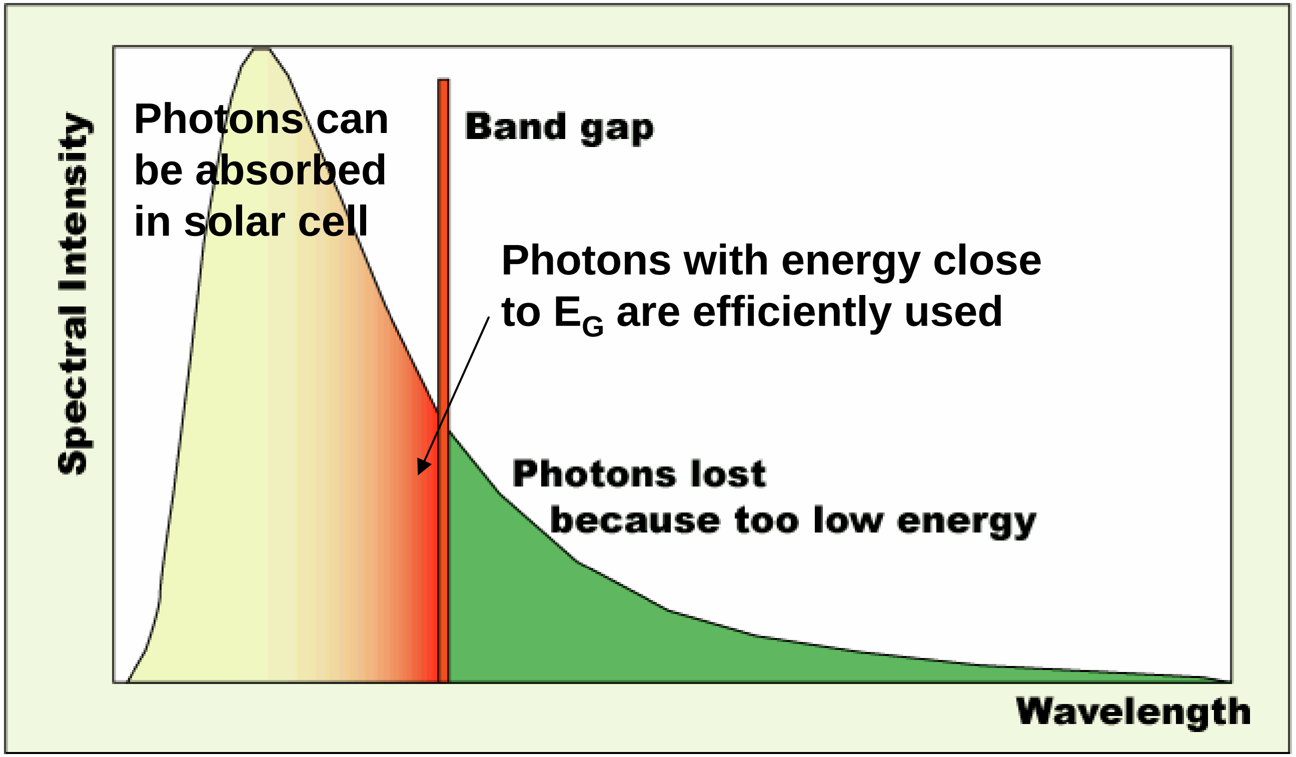
– If a photons has energy above E_G, the excess energy above E_G is lost as heat.



Absorption process

Absorption of photons: Eg

Value of band gap determines maximum possible current



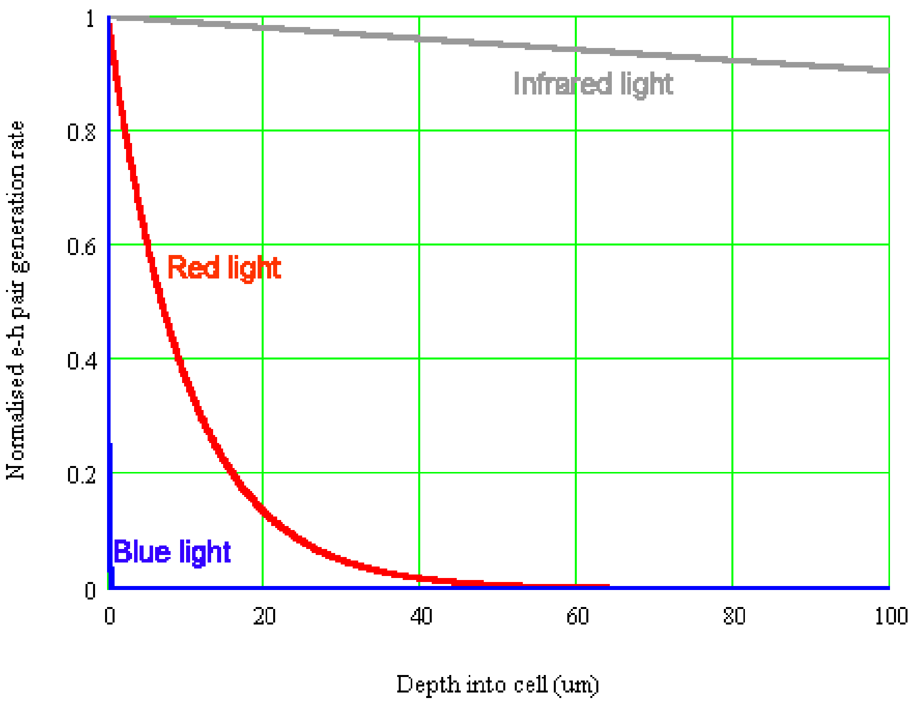
Generation of carriers

Generation, G, depends on (1) absorption coefficient of material α, (2) incident wavelength, λ, (3) thickness of material, x, and (4) number of photons.

$$N_{ph} = N_s e^{-\alpha x}$$

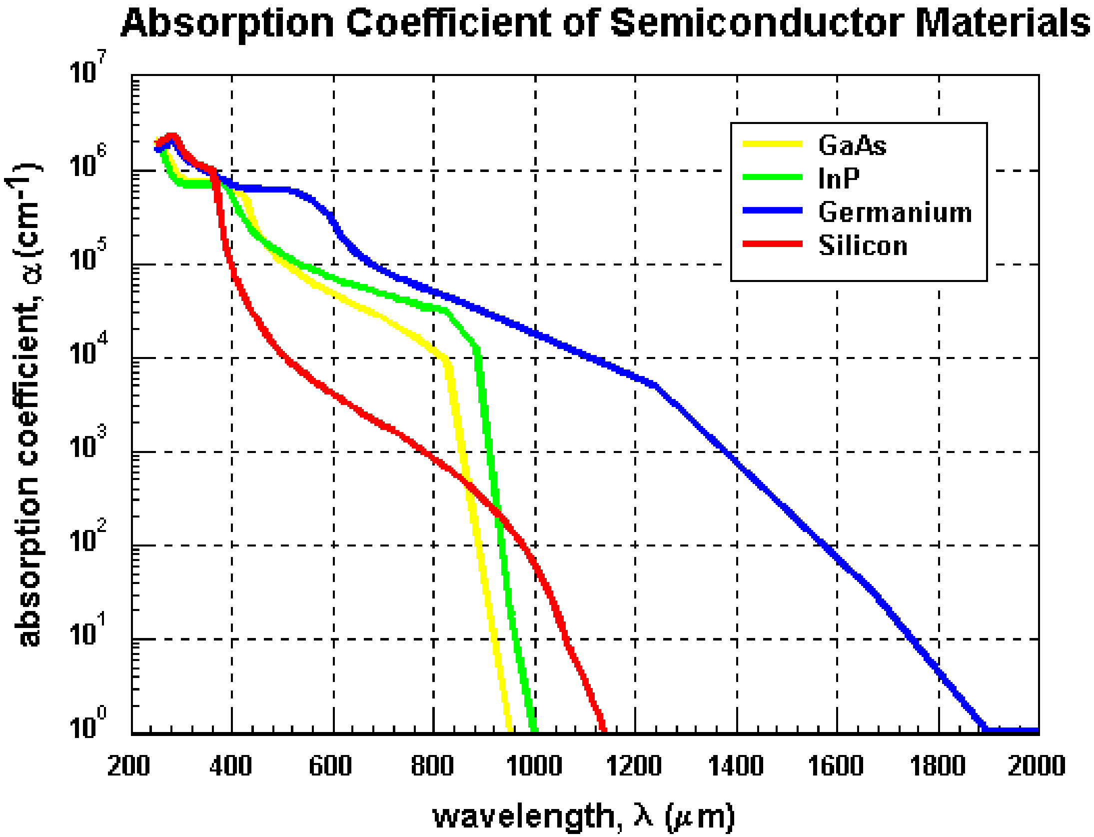
Where N_{ph} **is the number of photons**
N_s **is photons at the surface**
α **is the absorption coefficient**
x **is distance in the material**

$$G = -\frac{dN_{ph}}{dx} = \alpha N_s e^{-\alpha x}$$



Absorption coefficient, α

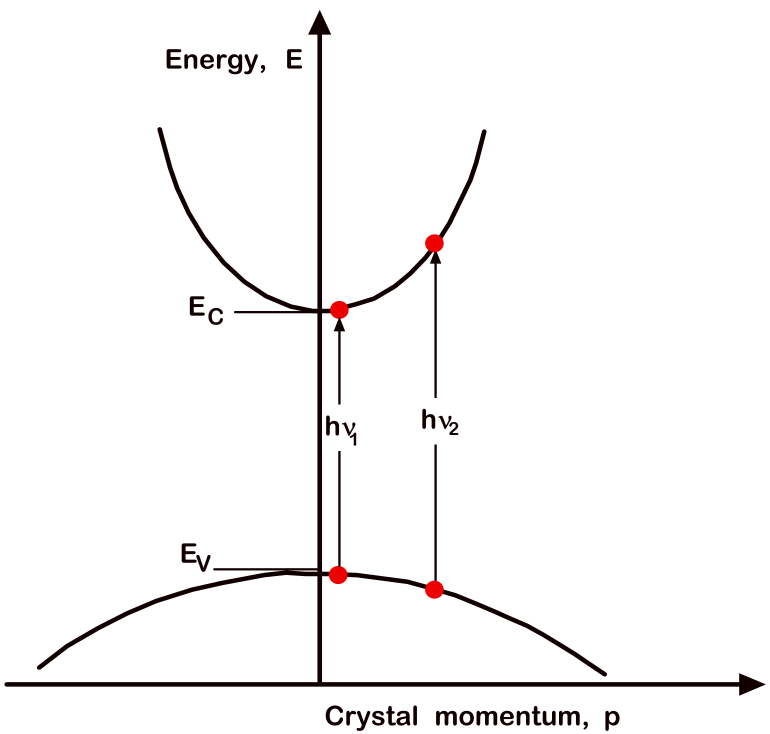
- α of a material determines generation as a function of wavelength
- α small for photons with energy below E_G – no absorption below band gap.
- For photon energies above E_G, α will determine the thickness



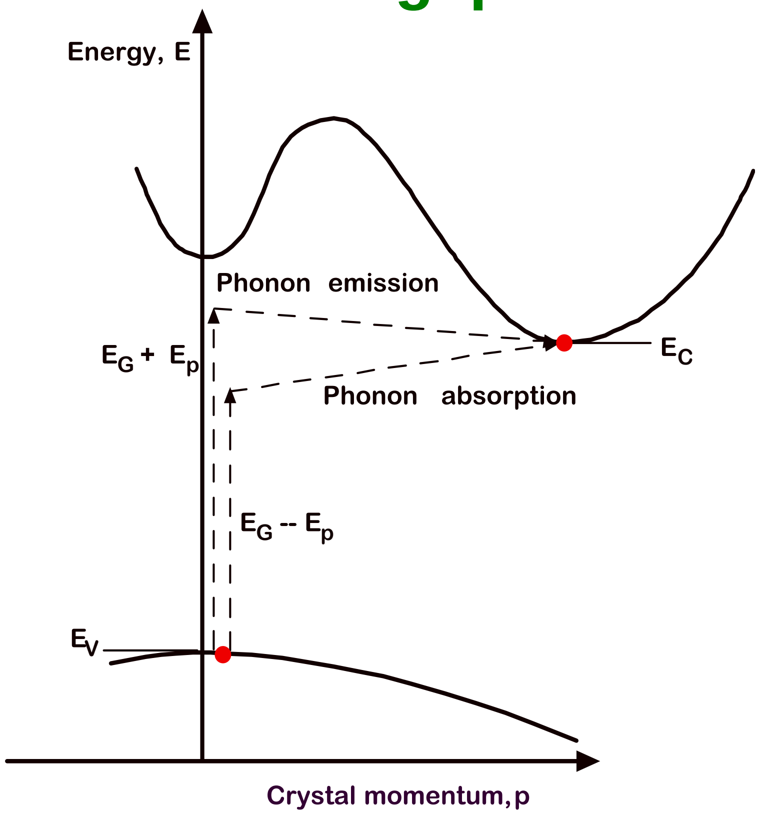
Absorption coefficient

Absorption coefficient strongly affected determined by type of band gap.

Direct band gap



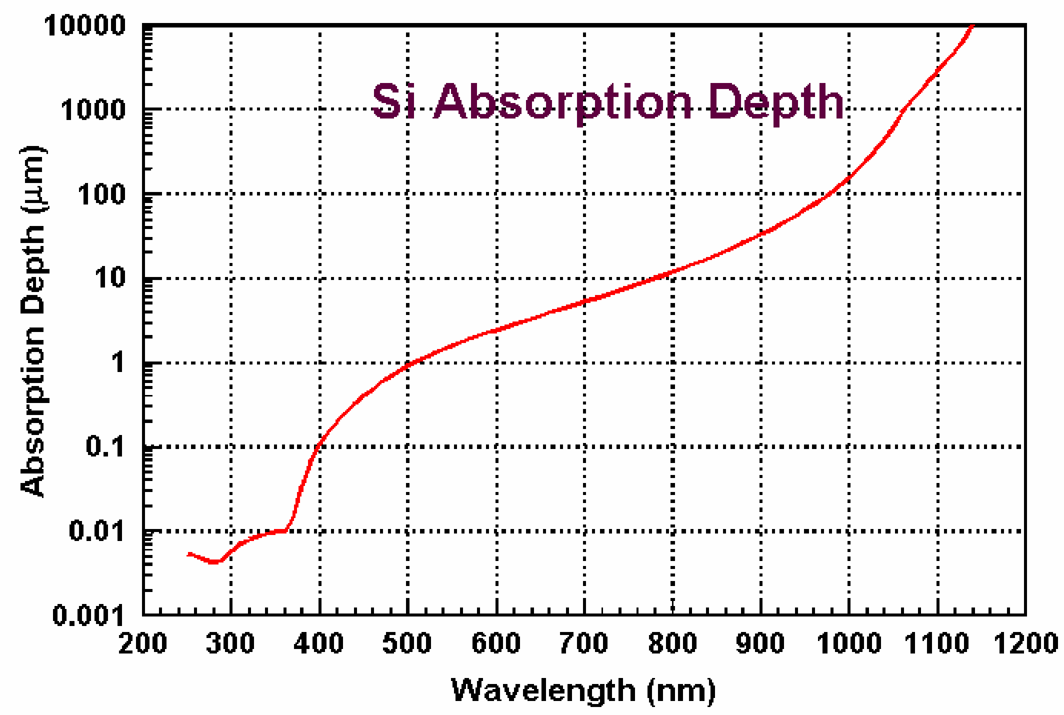
Indirect band gap



Thickness of material

The thickness of the material determines how much light is absorbed.

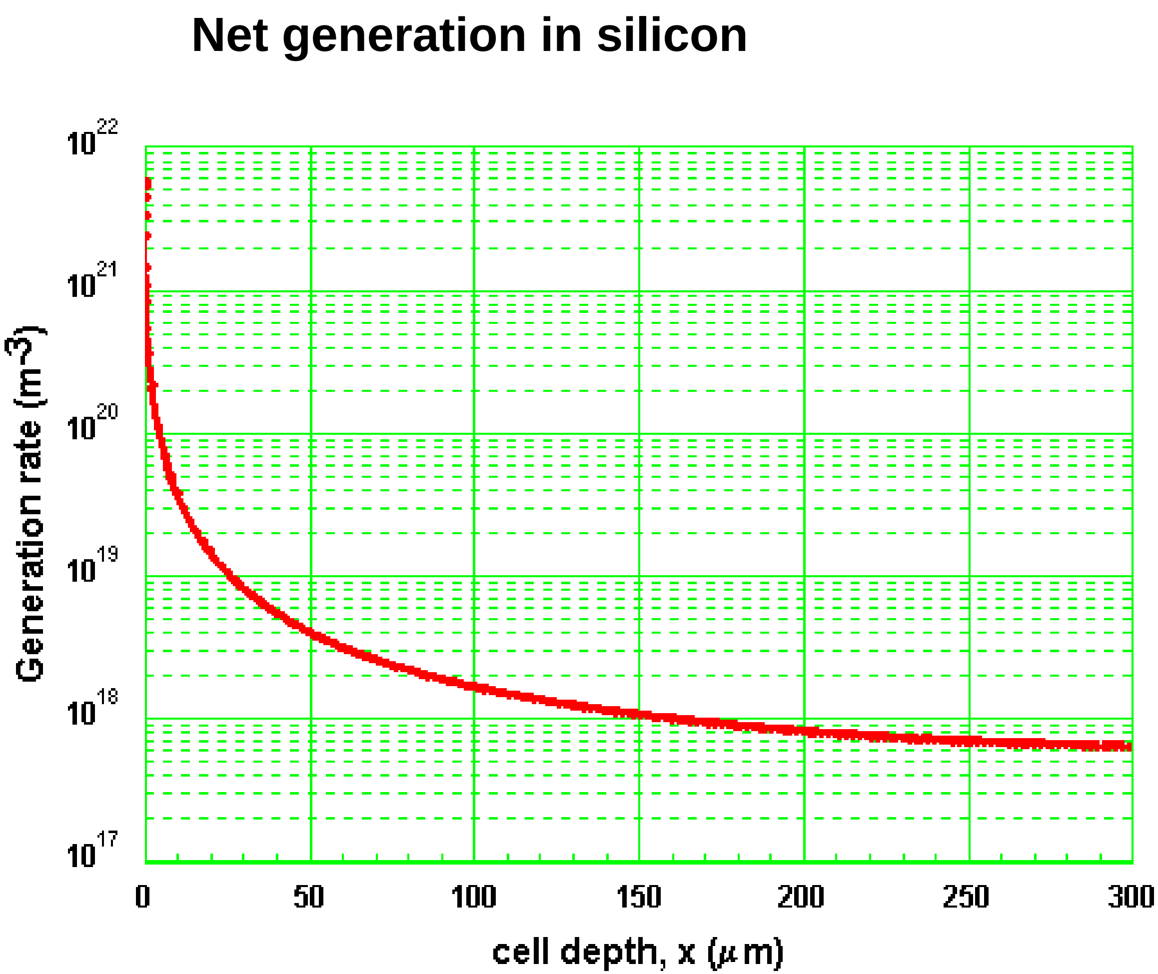
Absorption depth is thickness requires to absorb ~60% (1 – 1/e) of incident light



Net Generation Rate

Net generation rate is the integration over all wavelengths.

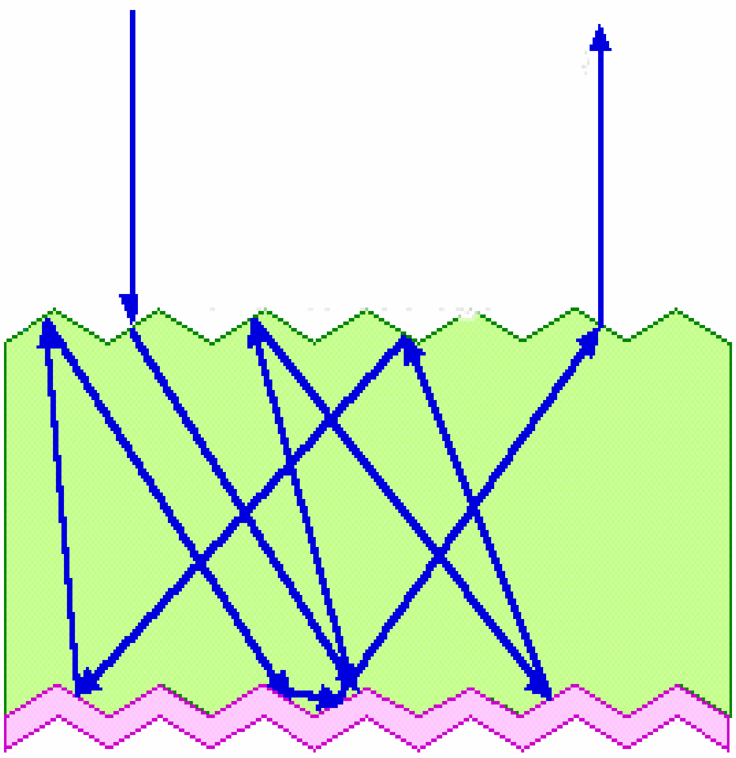
- High at surface
- In silicon, significant absorption even after 200 μm.



Increasing Absorption

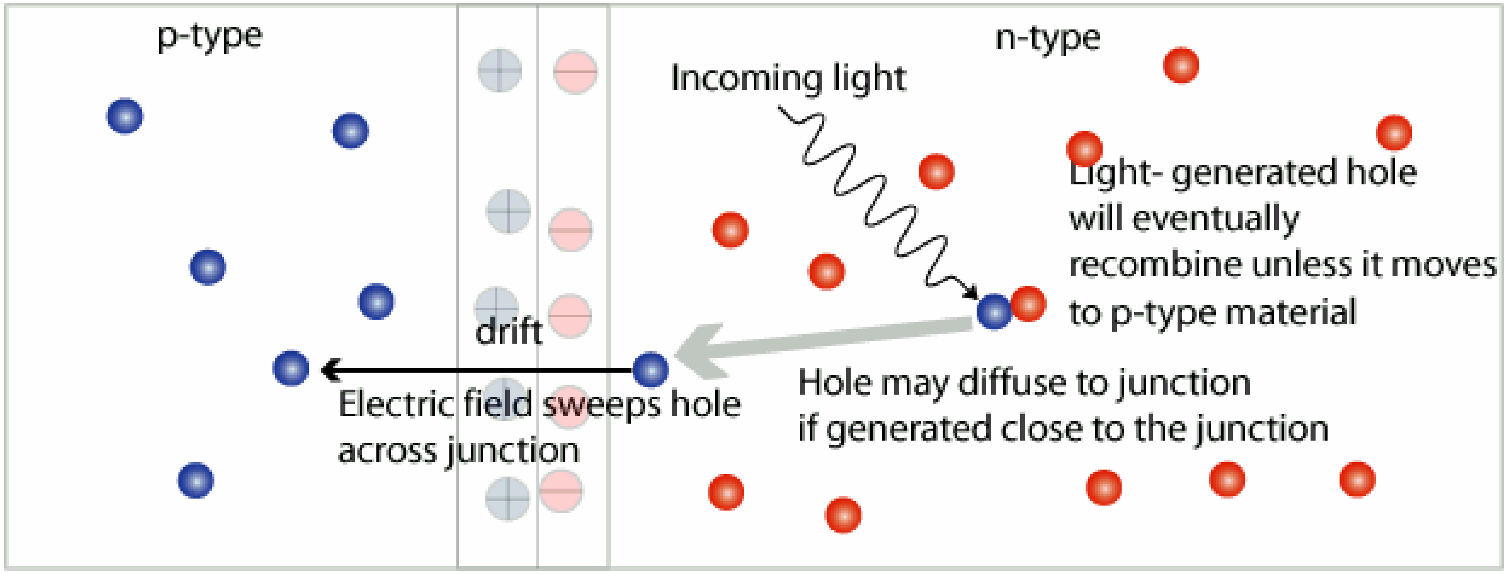
Light trapping increases the “optical thickness” of a material

- Physical thickness can remain low
- Allows carriers to be absorbed close to the junction



Collection probability

- **A light generated minority carrier can readily recombine.**
- **If it the carrier reaches the edge of the depletion region, it is swept across the junction and becomes a majority carrier. This process is collection of the light generated carriers.**
- **Once a carrier is collected, it is very unlikely to recombine.**

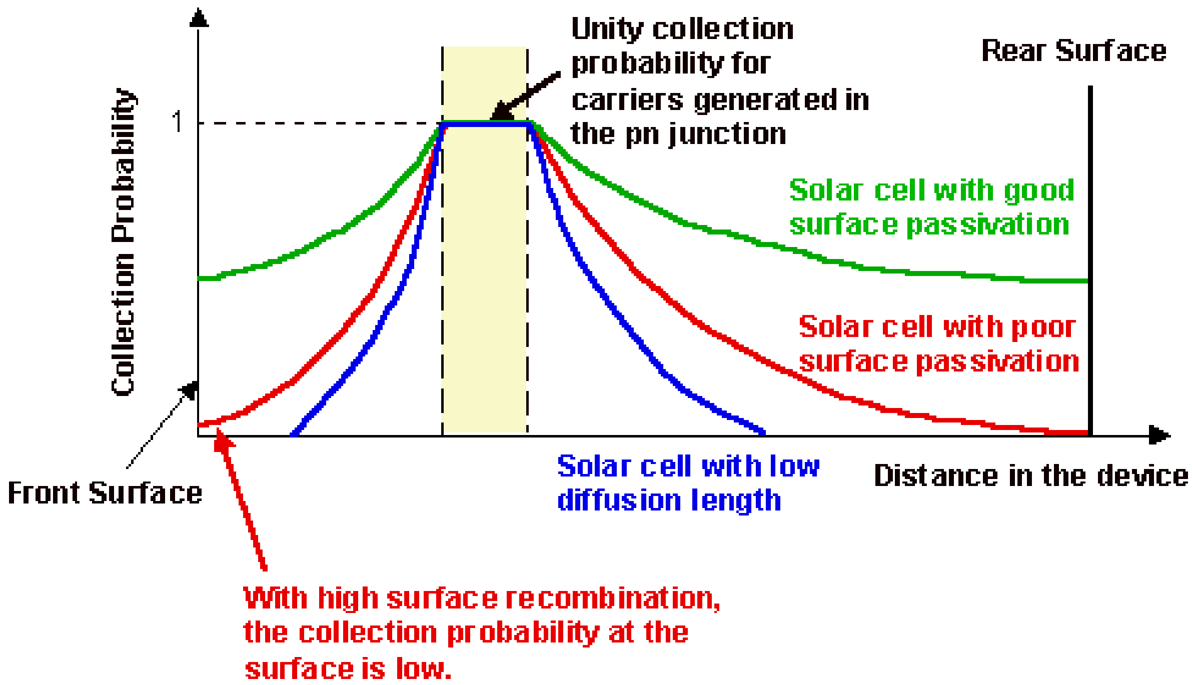


Recombination Revisited

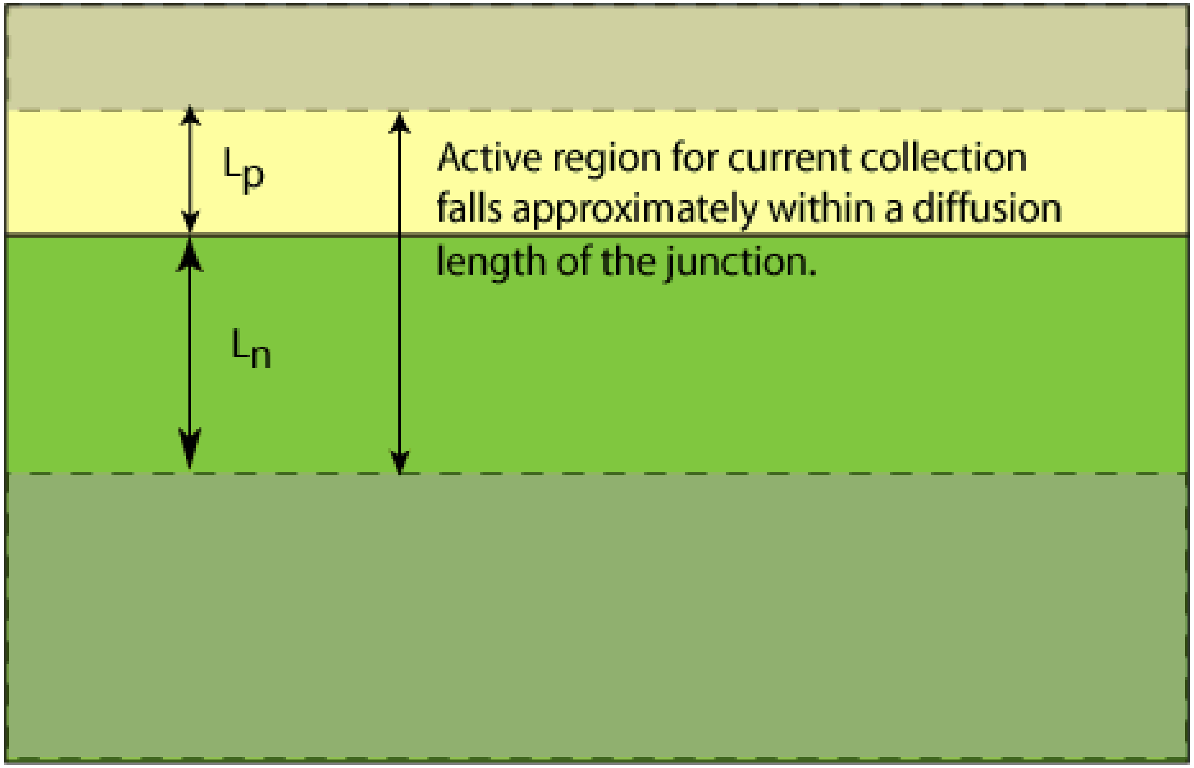
- In solar cells, two addition recombination mechanisms exist which have a large impact on the devices: Surface recombination and defect (grain boundary) recombination: Both are "surface" or localized phenomena rather than bulk phenomena.
- The physical cause of these recombination mechanisms is the interruption of the crystal lattice.
- Surface and/or interface recombination affects the entire region associated with that surface since there is a diffusion current towards the recombination site.

Collection probability

- **Collection probability is the probability that a light generated carrier will reach the depletion region and be collected.**
- **Depends on where it is generated compared to junction and other recombination mechanisms, and the diffusion length.**



Collection probability



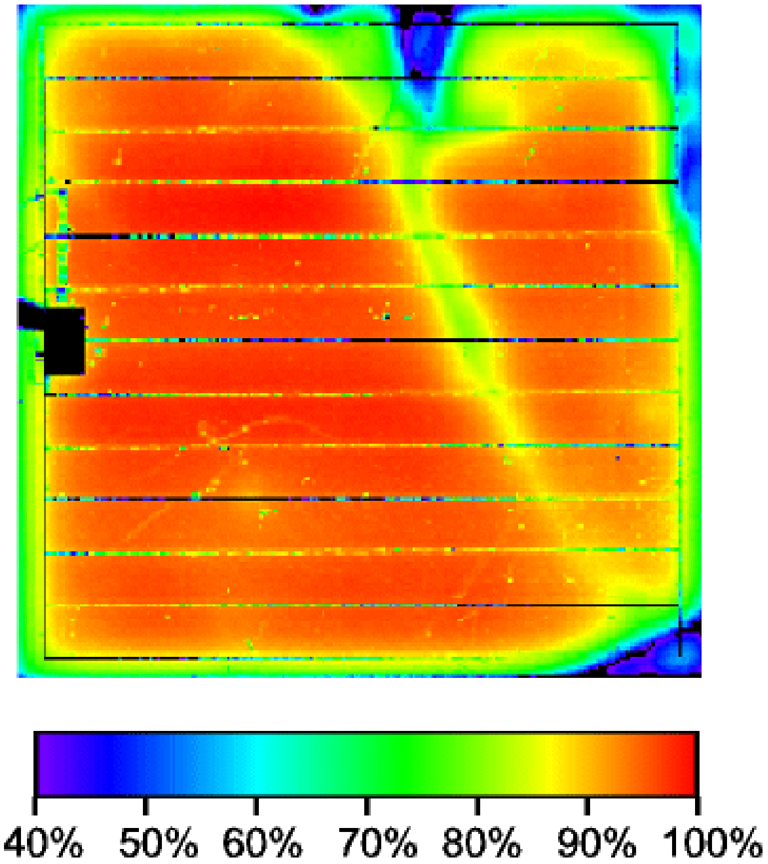
Collection probability is low further than a diffusion length away from junction

Current Collection

Need to maintain high diffusion lengths, or the collection probability is reduced.

Diffusion length strongly related to type of starting material

- **Single crystalline FZ**
- **Single crystalline CZ**
- **Multicrystalline**
- **Nanocrystalline materials**

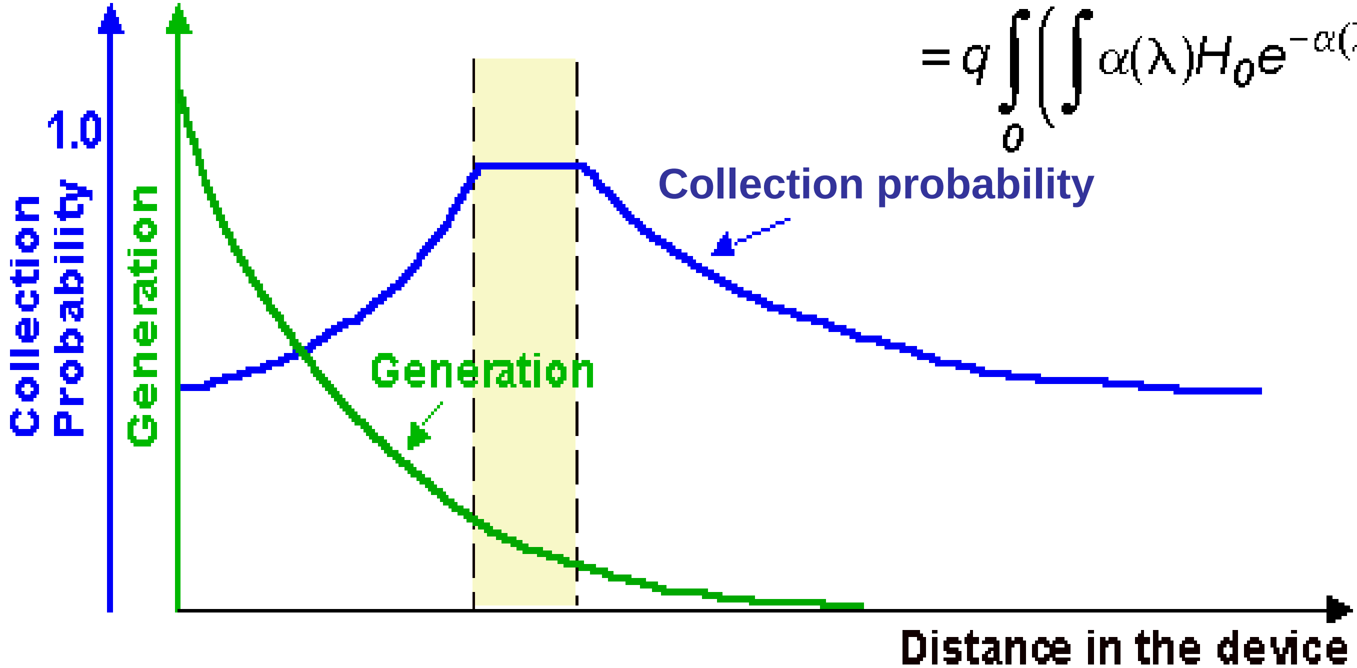


Short Circuit Current

J_{sc} determined by generation rate and collection probability

$$J_L = q\int_0^W G(x)CP(x)dx$$

$$= q\int_0^W\left(\int \alpha(\lambda)H_0 e^{-\alpha(\lambda)x}d\lambda\right)CP(x)dx$$



Collection Summary

- A carrier has a high probability of being collected if it is generated closer to the junction than to a recombination site and if it generated within a diffusion length of the junction
  - Difficult to achieve high collection near front surface (and also rear, but fewer carriers generated there).
  - Emitter junction is usually fairly thin.
- Minority carrier diffusion length (and surface recombination) are key parameters for high collection.

Short Circuit Current

- Can calculate I_{sc} using the identical approach as was used to calculate the diode equation, but setting $G \neq 0$.
- Following this approach, the differential equation to be solved is:

$$\frac{d^2 n(x)}{dx^2} = \frac{\Delta n}{\tau_n D_n} - \frac{G(x)}{D_n}$$

- The solution to this differential equation is simple only when G = constant. In this case, the carrier concentration is:

$$\Delta n(x) = A e^{-x/L_n} + B e^{x/L_n} + G \tau_n$$

Short Circuit Current

- **Applying the same boundary conditions as in the ideal diode case, differentiating to find the current, and equating the currents on the n-type and p-type sides, we get:**

$$J = \left[q \frac{D_n}{L_n} n_{p0} + q \frac{D_p}{L_p} p_{n0} \right] \left[e^{qV/kT} - 1 \right] - qG \left(L_n + L_p + W \right)$$

which is usually written as:

where:

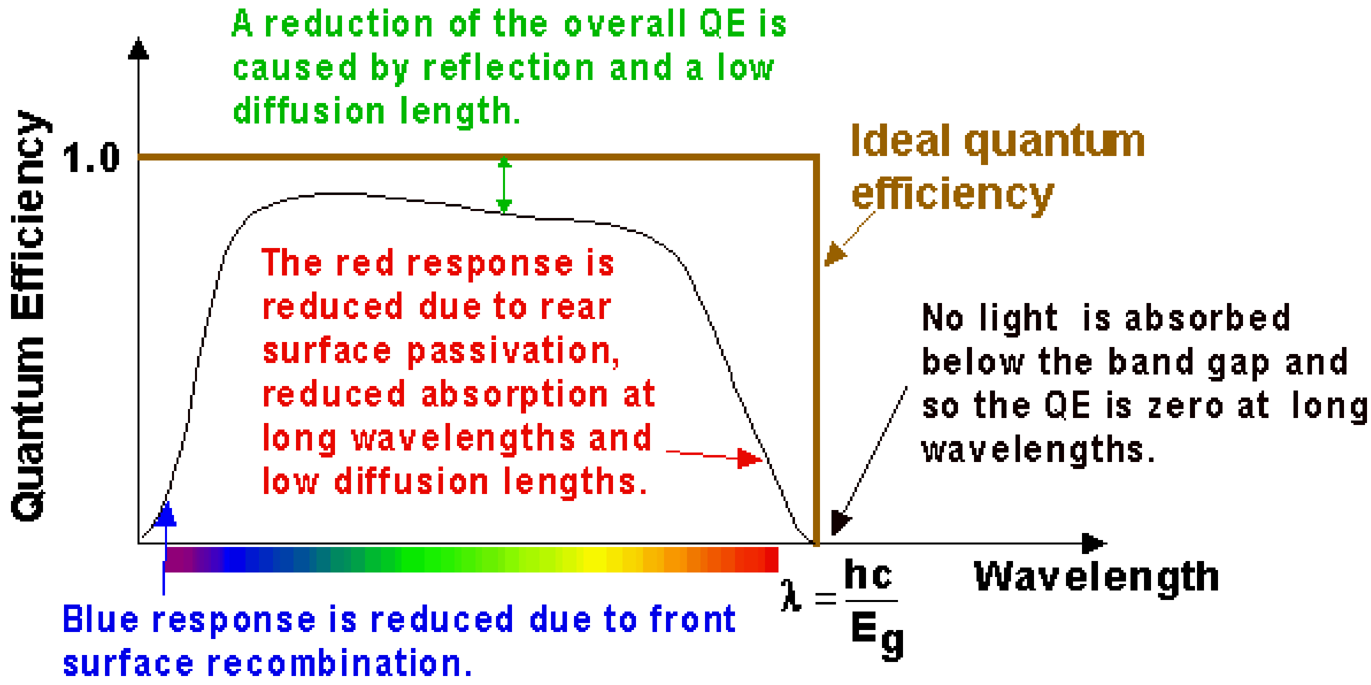
$$J = J_0 \left[e^{qV/kT} - 1 \right] - J_L$$

$$J_L = qG \left(L_n + L_p + W \right) \quad J_0 = q \left[\frac{D_n n_i^2}{L_n N_A} + \frac{D_p n_i^2}{L_p N_D} \right]$$

(same as a diode)

Quantum Efficiency

Collection probability difficult to measure, so instead use quantum efficiency, defined as ratio of photons incident to carriers collected.



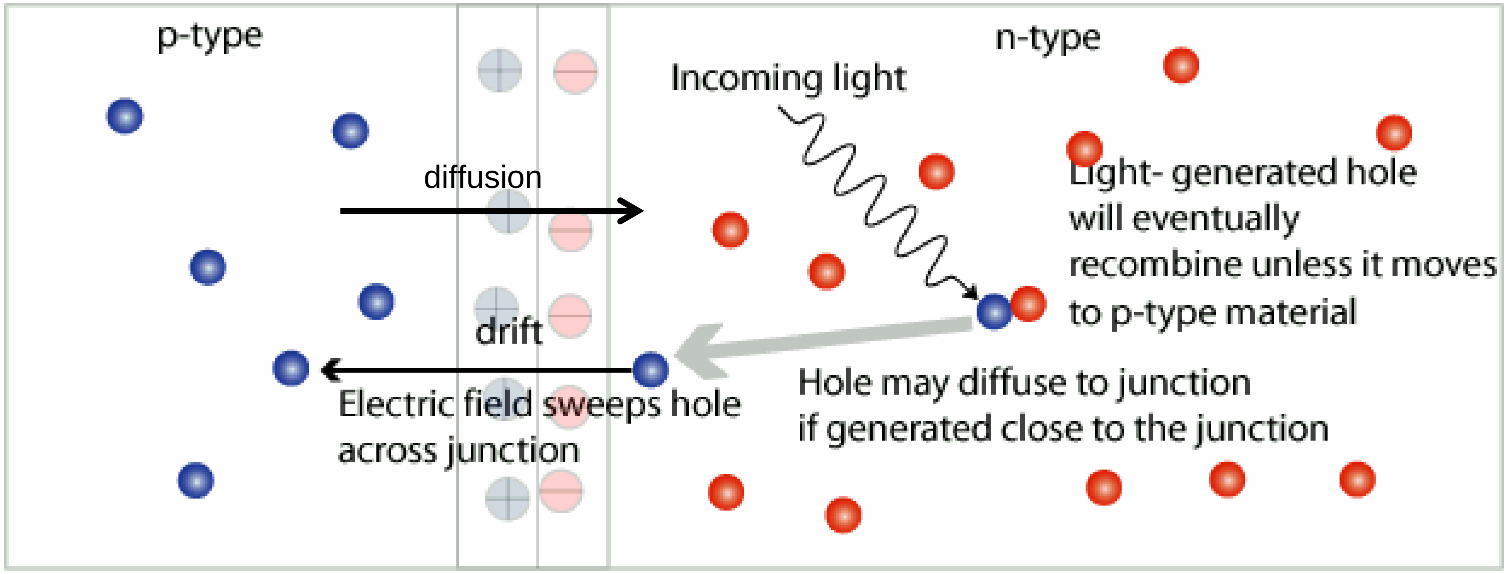
Short Circuit Current Summary

Achieve high short circuit current by:

- Low reflection by using texturing and antireflection coatings.
- Low metal coverage of the top surface.
- Light trapping or thick material (but not thicker than diffusion length).
- High diffusion length in the material.
- Junction depth optimized for absorption in emitter and base.
- Good surface passivation.

Open Circuit Voltage

- **If collected light-generated carriers are not extracted from the solar cell but instead remain, then a charge separation exists.**
- **The charge separation reduces the electric field in the depletion region, reduces the barrier to diffusion current, and causes a diffusion current to flow.**



High Open Circuit Voltage

- **For a given band gap, a high open circuit voltage arises from low recombination in the active regions within a diffusion length of the junction**

$$J = J_0\left(\exp\left(qV/nkT\right) - 1\right) - J_{sc}$$

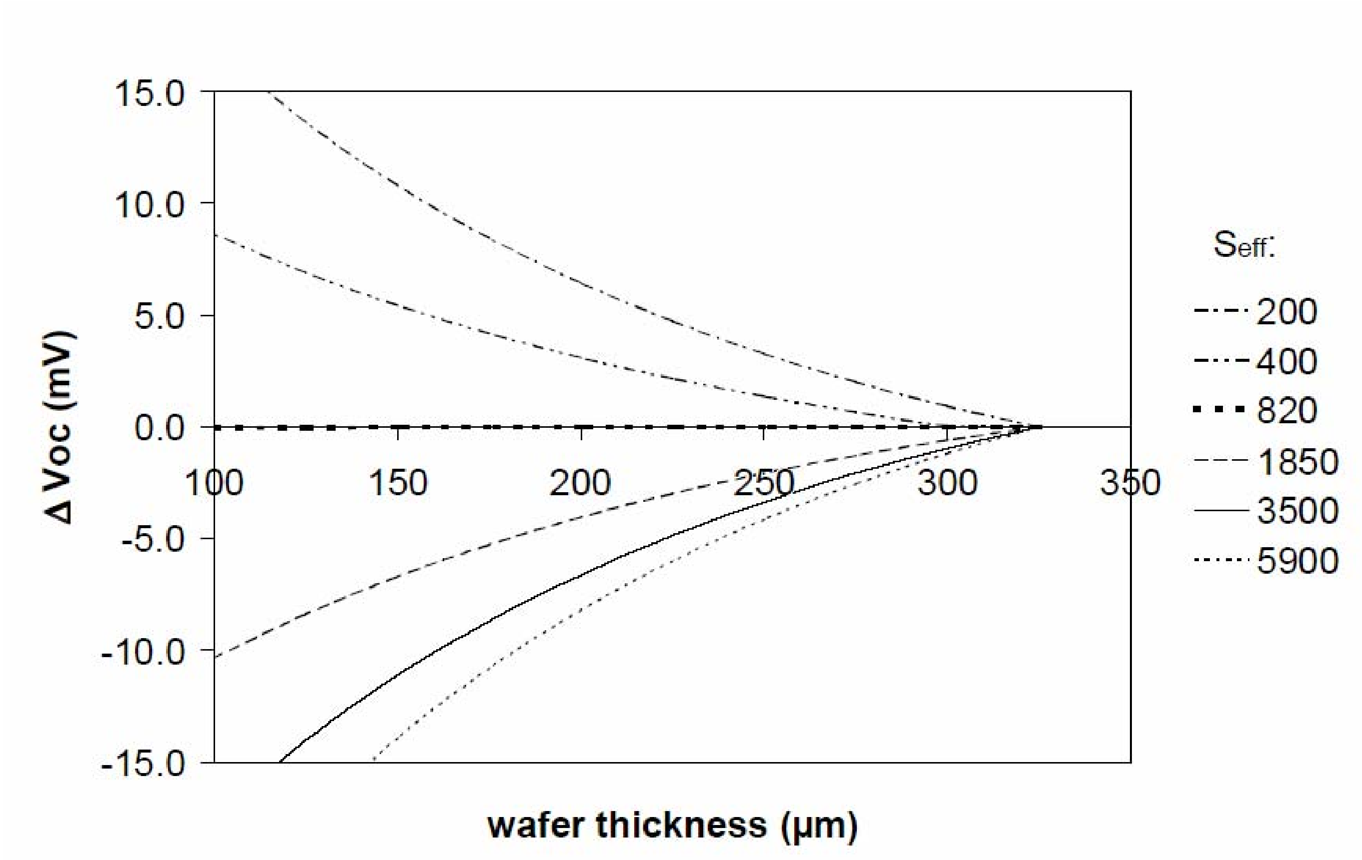
$$V_{oc} = \frac{nkT}{q}\ln\left(\frac{I_L}{I_0} + 1\right)$$

$$I_0 = A\left(\frac{qD_e n_i^2}{L_e N_A}\cdot\frac{S_h\cosh\left(W_N/L_h\right) + D_h/L_h\sinh\left(W_N/L_h\right)}{D_h/L_h\cosh\left(W_N/L_h\right) + S_h\sinh\left(W_N/L_h\right)} + \frac{qD_h n_i^2}{L_h N_D}\cdot\frac{S_e\cosh\left(W_P/L_e\right) + D_e/L_e\sinh\left(W_P/L_e\right)}{D_e/L_e\cosh\left(W_P/L_e\right) + S_e\sinh\left(W_P/L_e\right)}\right)$$

Note: J is current density A/cm^2, I is current.

Open Circuit Voltage

- **Voltage increases as devices get thinner IF the surfaces are well passivated, otherwise Voc decreases.**

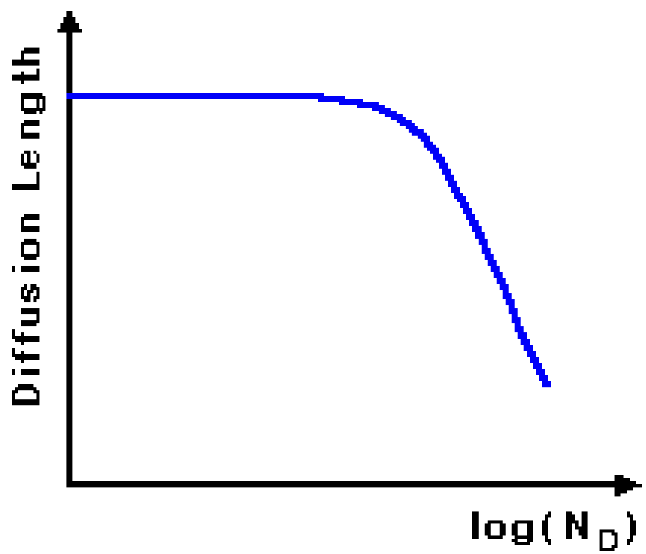


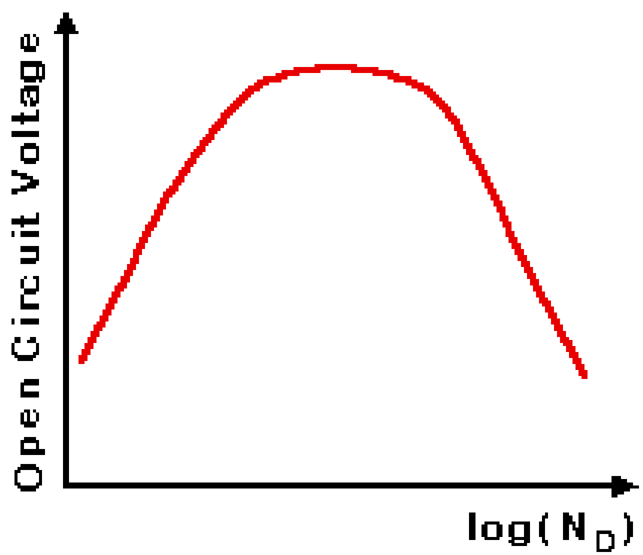
Voc and doping

For a fixed E_G, trade-off between doping and diffusion length

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

$$I_0 = qA\left(\frac{D_n n_i^2}{L_n N_A}+\frac{D_p n_i^2}{L_p N_D}\right)$$



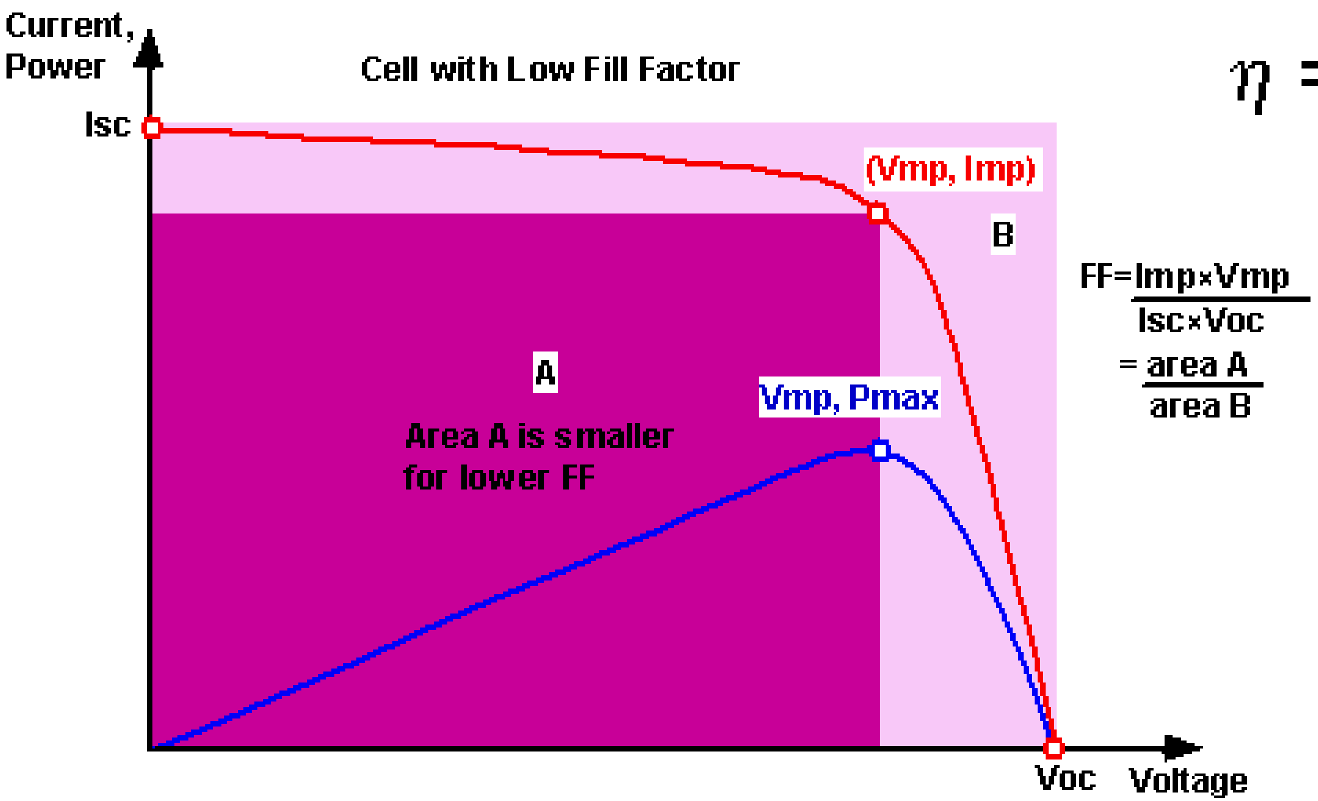


High Voc

- Must have low dark current, and hence low recombination as seen by carriers injected from edges of depletion region – not necessarily the same region where light generated carriers are, but closely related.
- Must have minority carrier diffusion length, low surface recombination, thin devices, and high doping.
- Above list are incompatible with each other or with high Jsc, so need trade-offs.

Minimizing Parasitic Losses

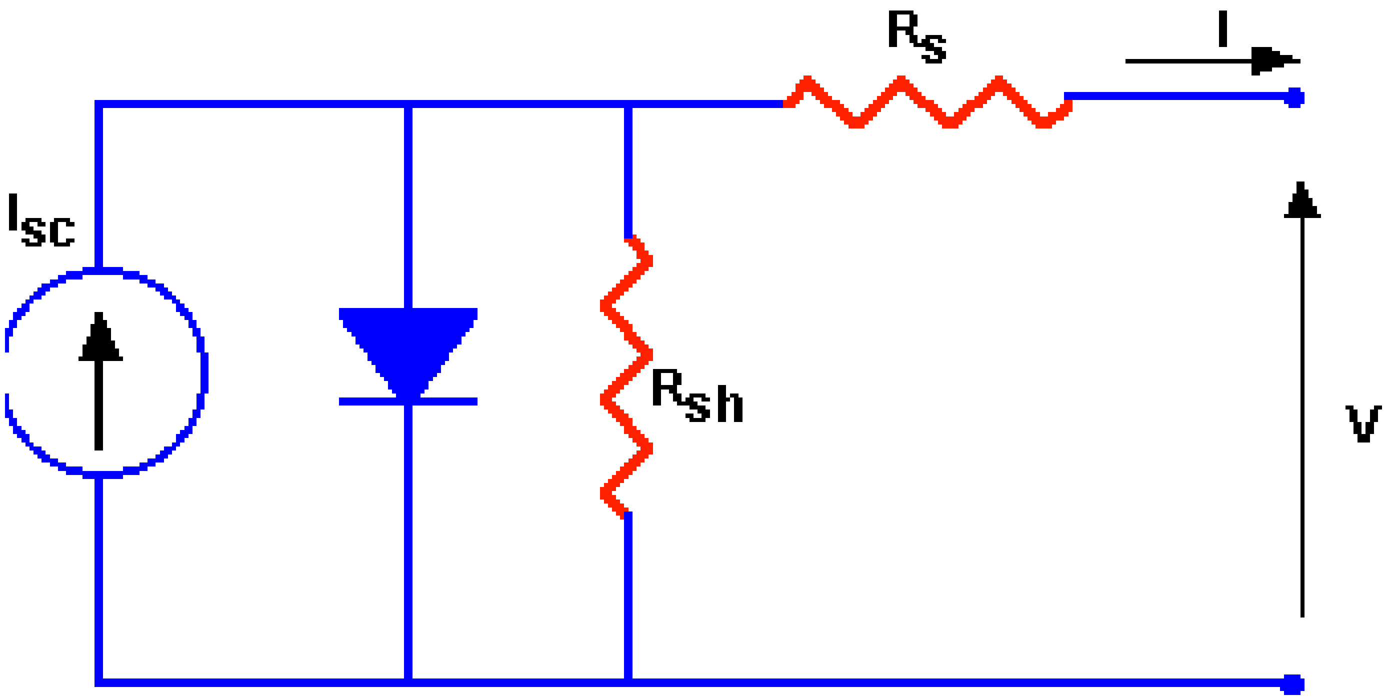
FF strongly affected by parasitic series and shunt R.



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

Solar Cell Circuit Model

Circuit model takes into account parasitic loss mechanism of series and shunt resistance

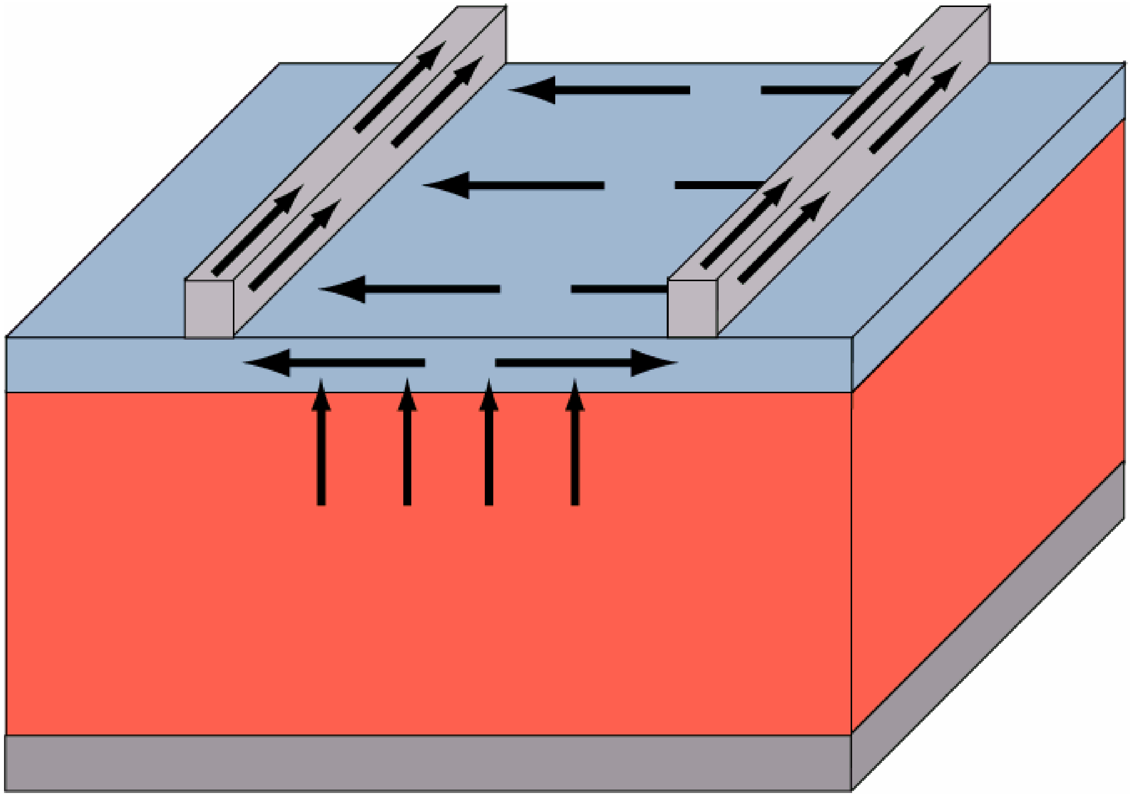


Solar Cell Circuit Model

Series resistance composed of emitter and metal grid resistance terms.

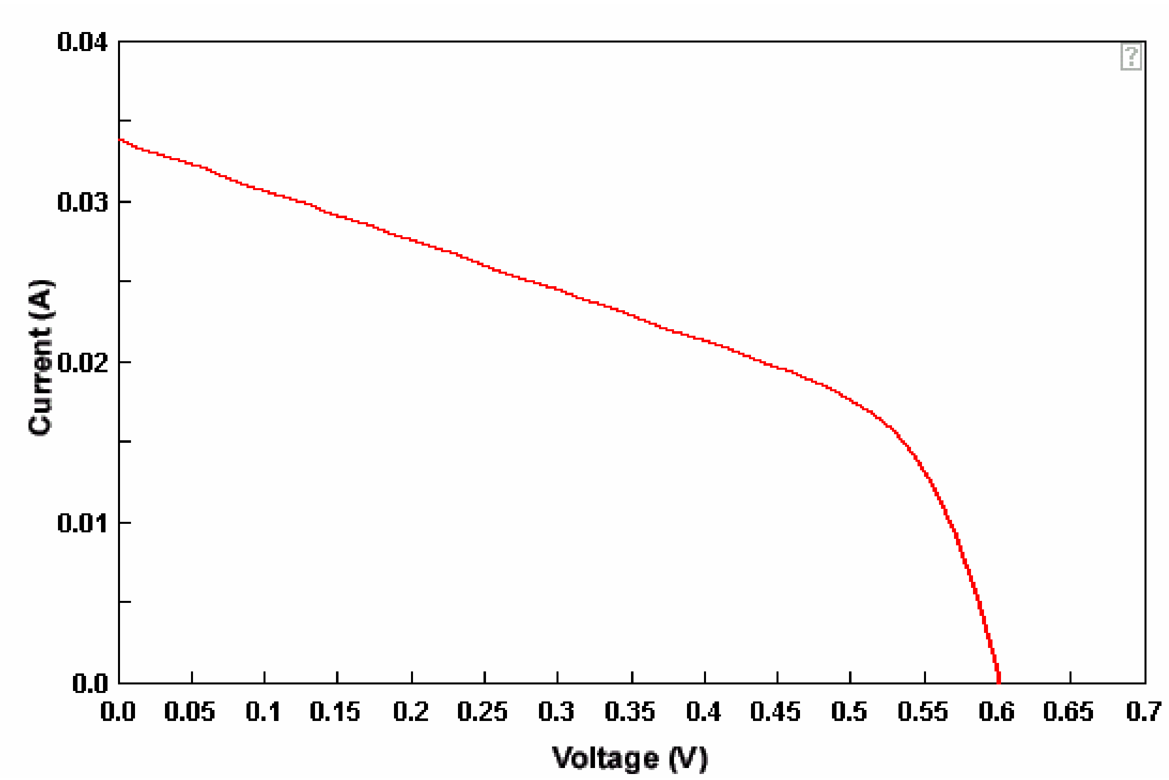
Want large cross section area of grid and emitter to reduce resistances.

$$R = \frac{\rho l}{A}$$



Effect of R_{series} and R_{shunt}

High series resistance and low shunt resistance degrade primarily FF, but in severe cases Voc and possibly Jsc.



Understanding physical processes

- Quasi-Fermi level: analog to Fermi level, but holds under steady state conditions.
  - Defined as:

$$n(x) = N_C \exp\left(-\left(E_c - E_{Fn}\right)/kT\right)$$
$$p(x) = N_V \exp\left(-\left(E_{Fp} - E_V\right)/kT\right)$$

  - Why it worlds physically:
    - Each type of carrier under steady state excitation thermalize with each other such that they approximate a Boltzman distribution

Understanding physical processes

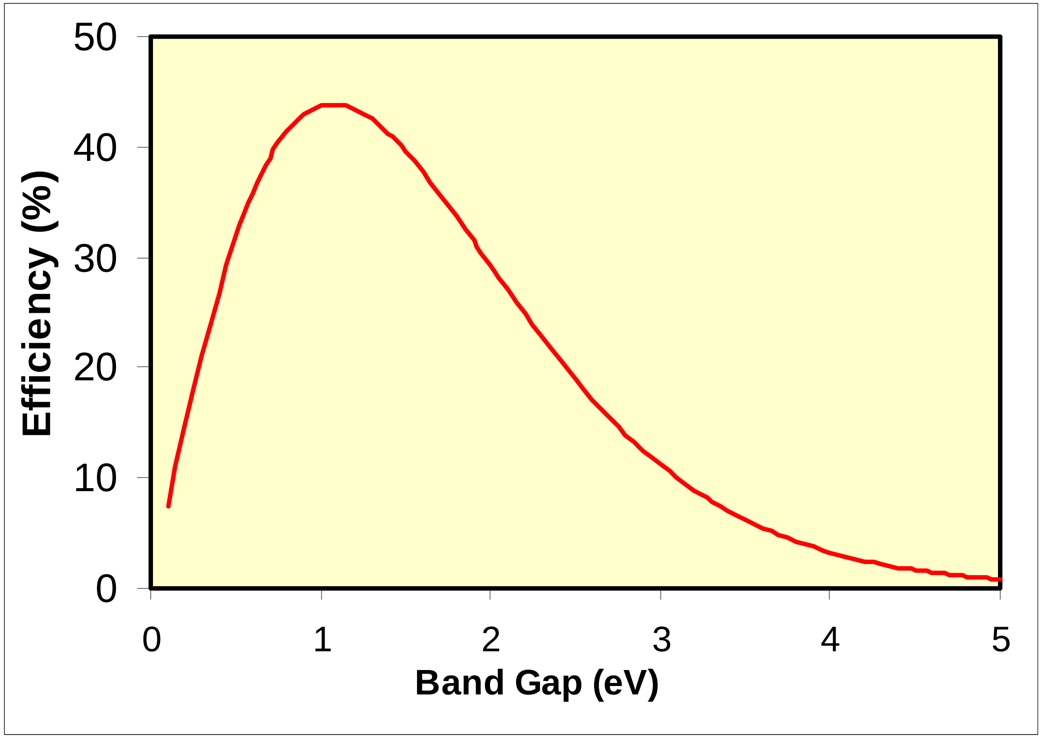
- Quasi-Fermi level & Fermi level gives the information needed about a device
  - Number of carriers
  - Recombination and generation (also need lifetime of carriers)
  - Transport
- Band diagram including quasi-Fermi levels can be used to determine:
  - Current flows
  - Bias type and conditions
  - Regions of high, low recombination

Maximizing efficiency

Band gap places a maximum value on efficiency

$$I_0 = qA\left(\frac{D_n n_i^2}{L_n N_A} + \frac{D_p n_i^2}{L_p N_D}\right)$$

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



Maximizing efficiency

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

↑ I_{sc}

- ↓ E_G
- ↓ Reflection
  - Surface
  - Metal
- ↑ L_n, L_p
- ↓ S_r
- x_j optimum

↑ V_{oc}

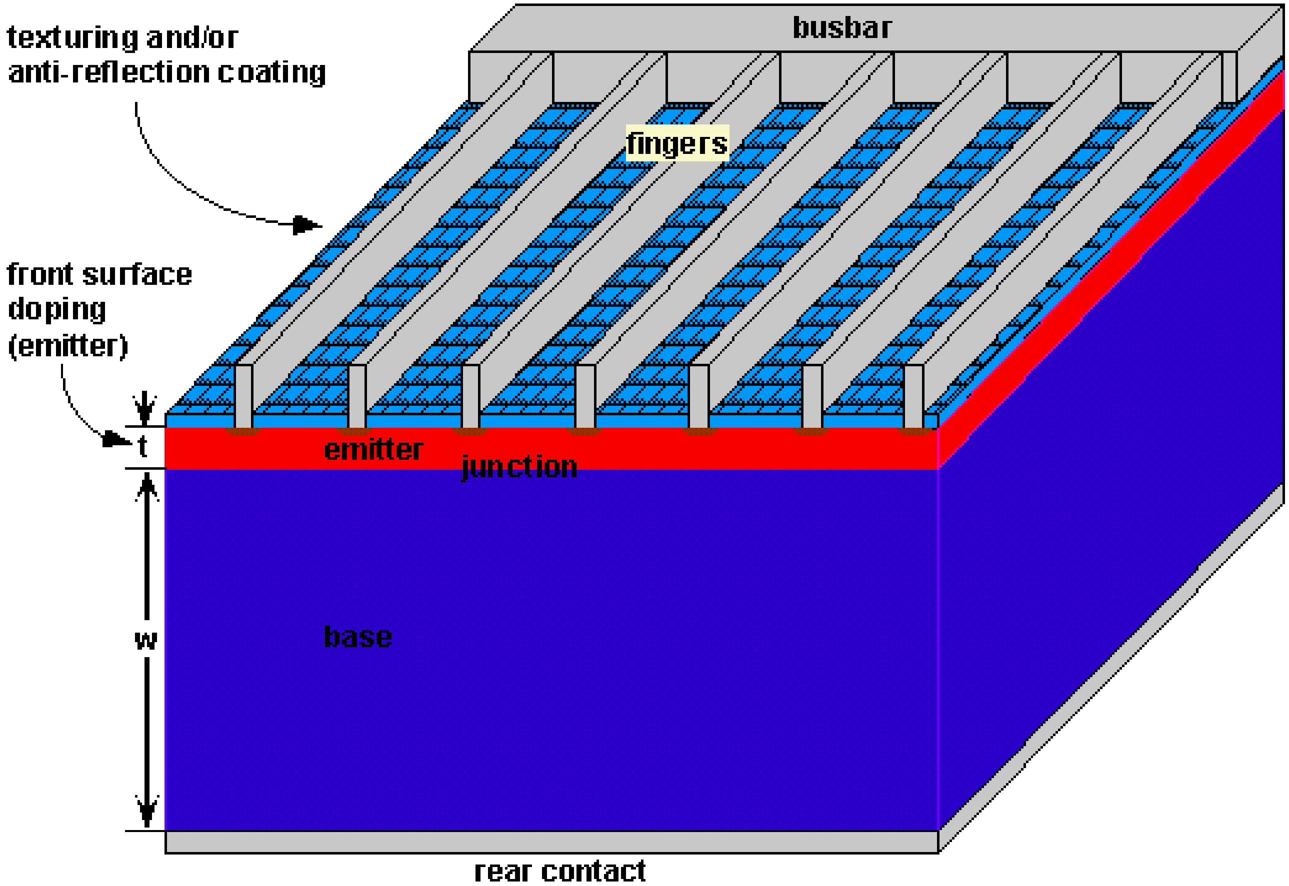
- ↑ E_G
- ↑ doping
- ↑ L_n, L_p
- ↓ S_r

Doping and diffusion length are related

↑ FF

- ↓ Series R
  - Metal
  - Emitter
    - ↑ doping
    - Thick emitter

Final Ideal Solar Cell



Solar Cell Technologies

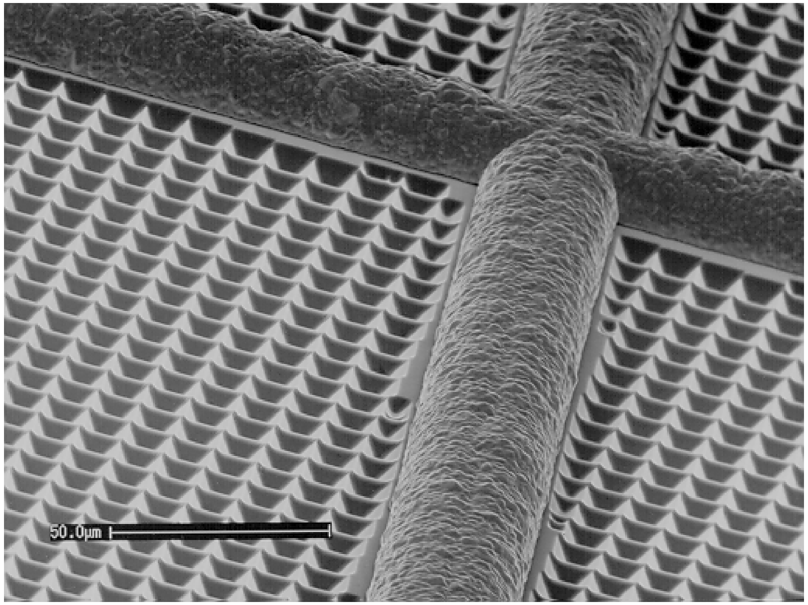
Materials for solar cells include:

- Silicon
- amorphous Si (α-Si)
- III-V solar cells
    - GaAs/AlGaAs
    - GaAs/InGaAsP
    - InP
- II-VI solar cells
    - $CuInSe_2$ (CIS)
    - $CuGaInSe_2$ (CGIS)
    - CdTe

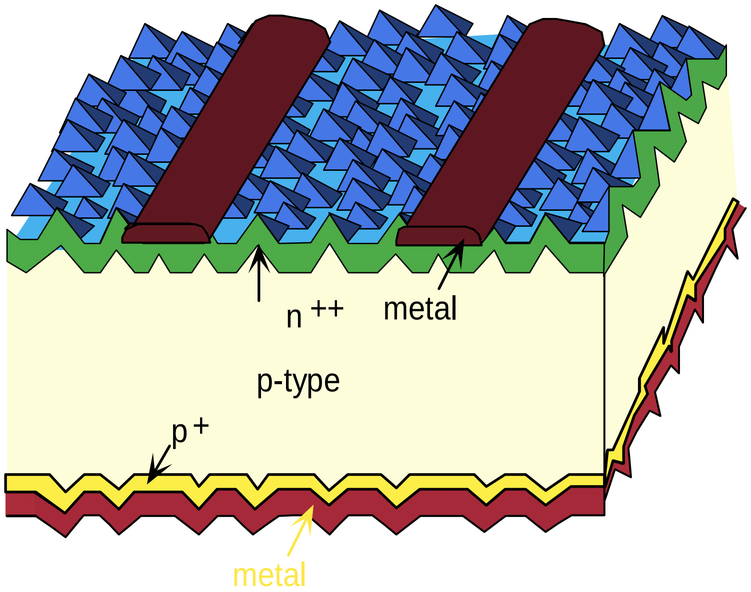
IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
							2 He 4.003
		5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.183
		13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.064	17 Cl 35.453	18 Ar 39.948
29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.922	34 Se 78.96	35 Br 79.909	36 Kr 83.80
47 Ag 107.870	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.904	54 Xe 131.30
79 Au 196.967	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.980	84 Po (210)	85 At (210)	86 Rn (222)

Silicon Solar Cell Technologies

- High efficiency solar cells made using IC processing techniques.
- Dominant commercial processing technology is screen printed.
- The buried contact (BC) technology was developed to transfer high-efficiency solar cell features into commercial production.



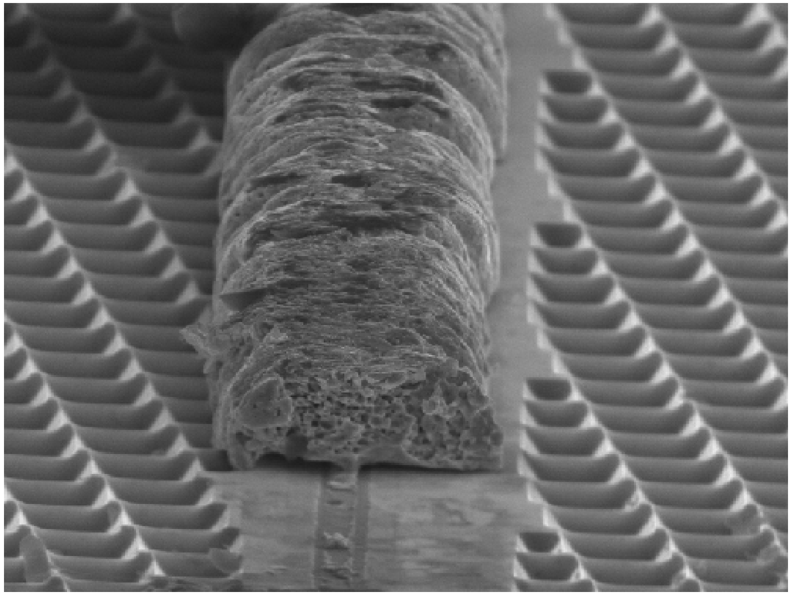
SEM of a PERL (Passivated Emitter Rear Locally diffused) solar cell.



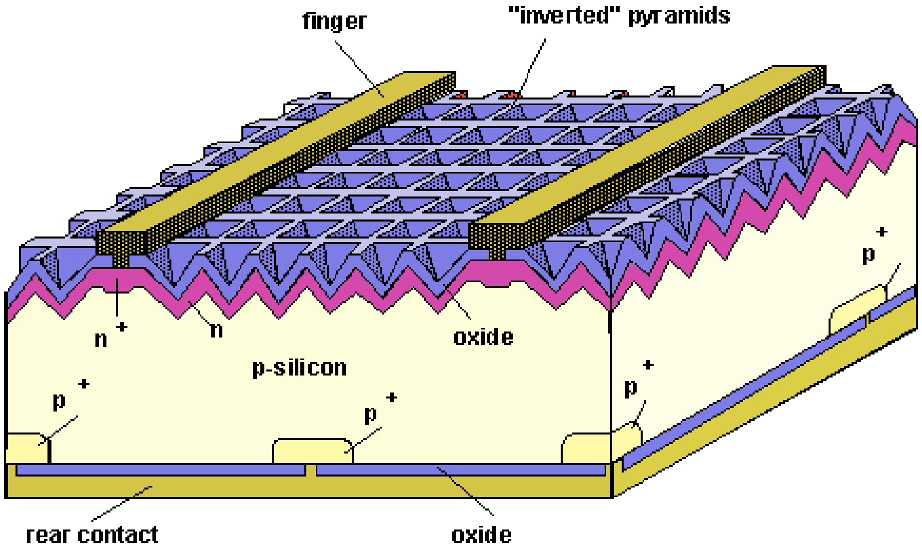
Schematic of a screen printed solar cell.

High Efficiency Silicon Solar Cells

- High efficiency silicon solar cells are made using IC technology.
- Efficiency of 24.7% at “one sun” (conventional standard illumination)
- Efficiency of 26.8% under concentration.

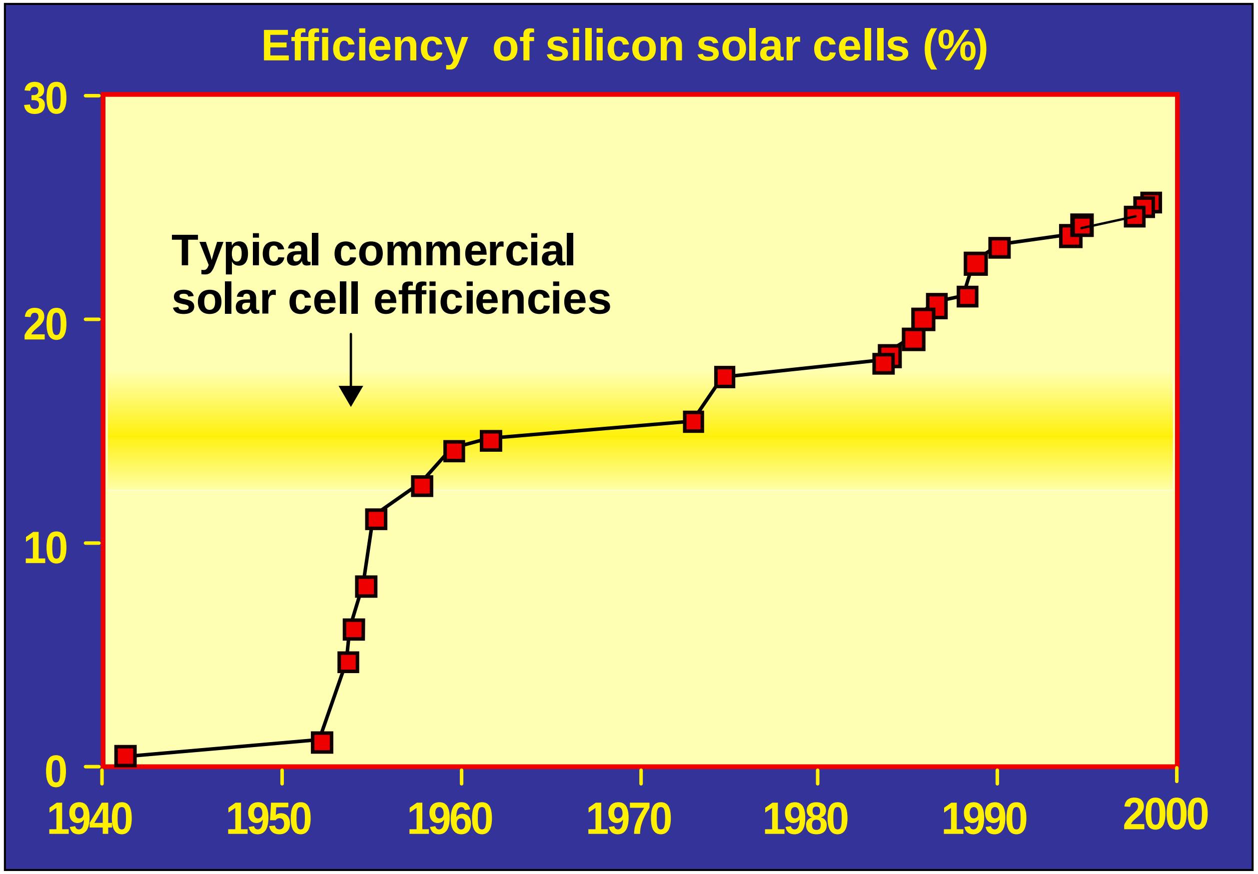


SEM of a PERL (Passivated Emitter Rear Locally diffused) solar cell.



High efficiency solar cell schematic.

Commercial Solar Cells

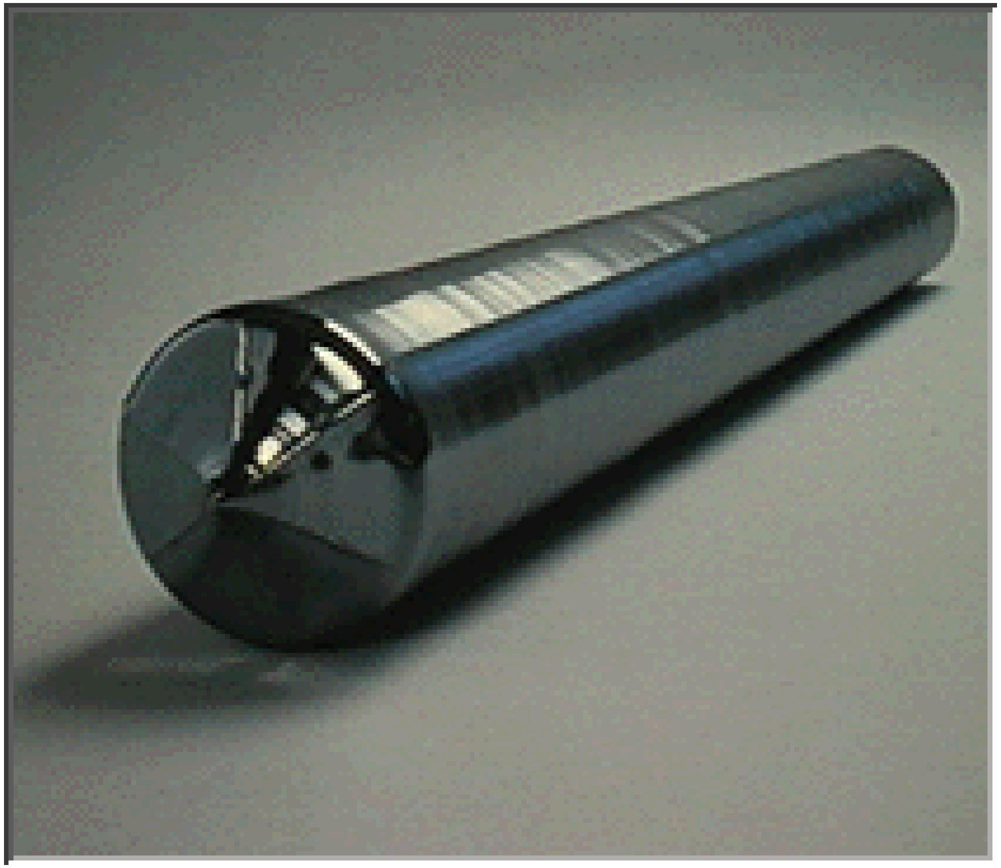


Commercial solar cells are designed to be low cost and robust.

Commercial Solar Cell Fabrication

Starting material for single crystalline solar cells (CZ material).

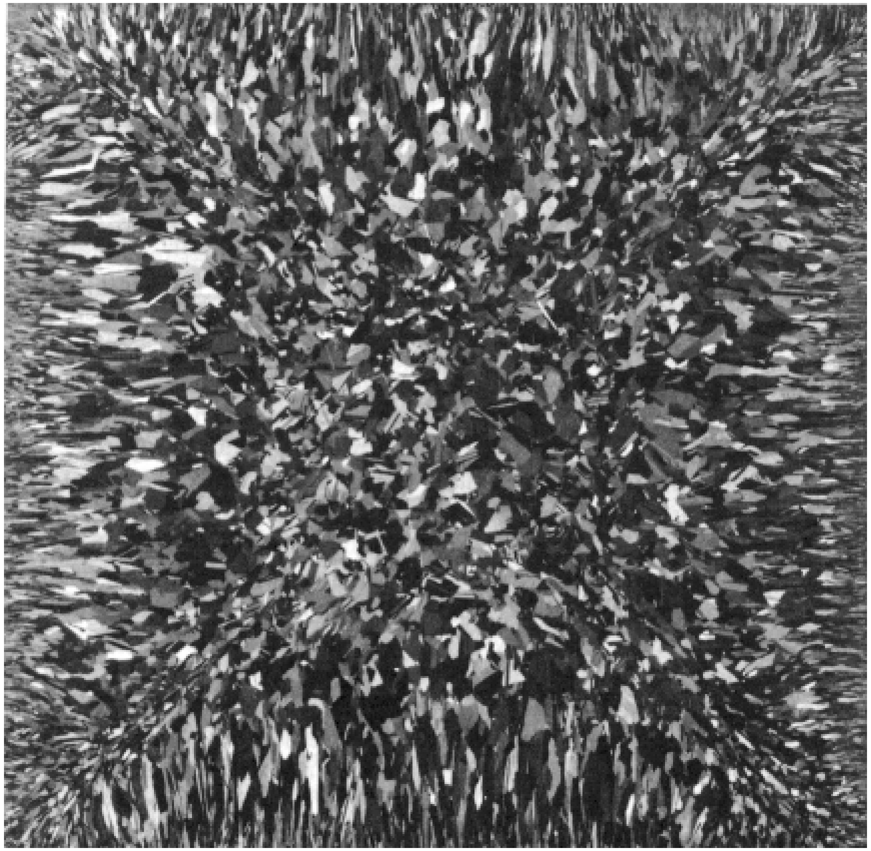
The ingot can be 30 cm in diameter and several meters long.



Commercial Solar Cell Fabrication

A silicon multicrystalline wafer.

Each change of reflectivity is a separate grain. Interfaces between grains often degrade material paramters.

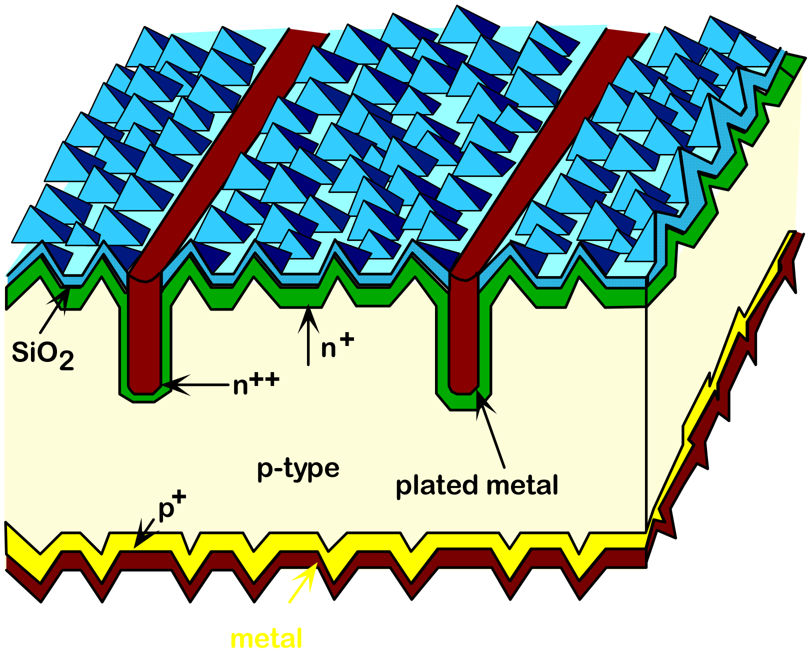


Commercial Solar Cell Fabrication

Slicing multicrystalline silicon into blocks (followed by slicing into wafers)

Silicon Solar Cell Technologies

- Metal contact formed by burying metal in groove in silicon wafer, giving low reflection, high carrier collection and low resistance.

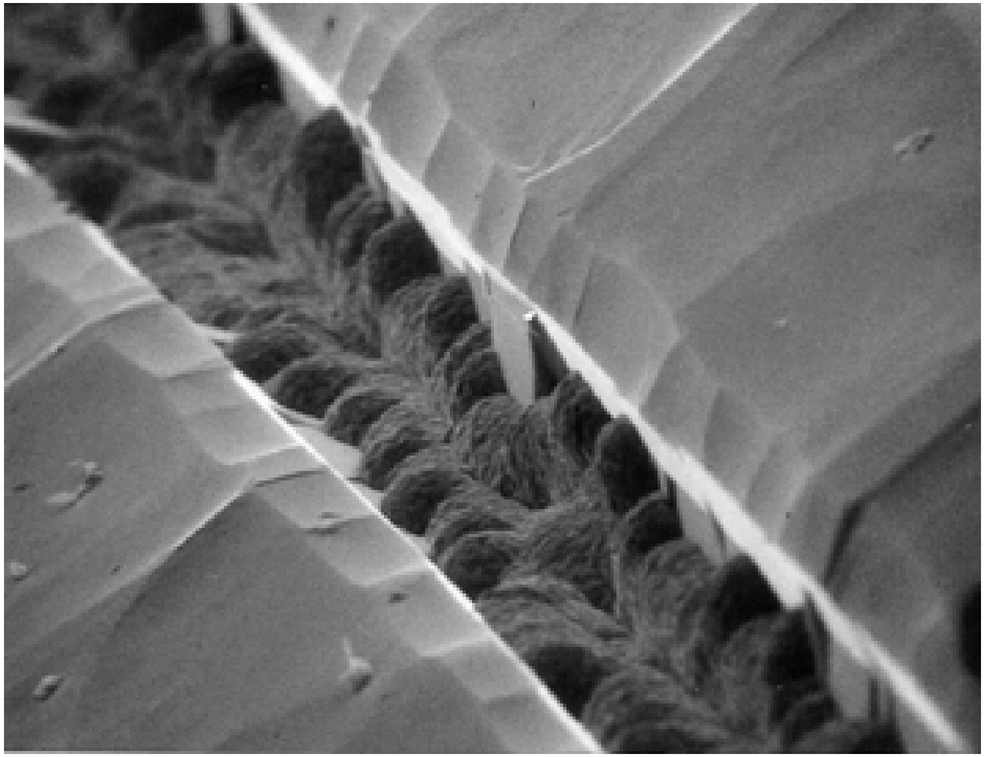


Conventional single sided buried contact solar cell.

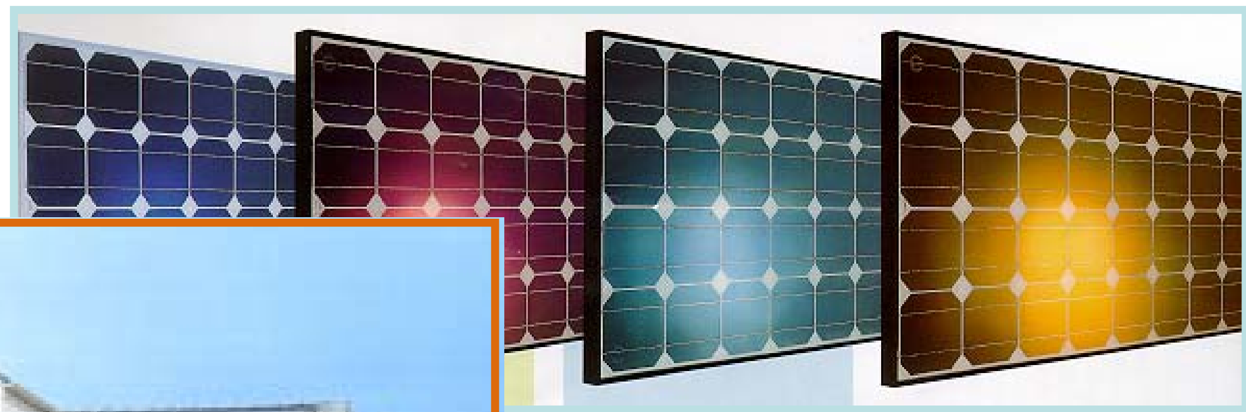
Buried contact solar cells used in building-integrated application at G8 Summit Building, England.

Buried Contact Solar Cells

Buried metal reduced reflection and also allows more flexibility in design process



Buried Contact Solar Cells



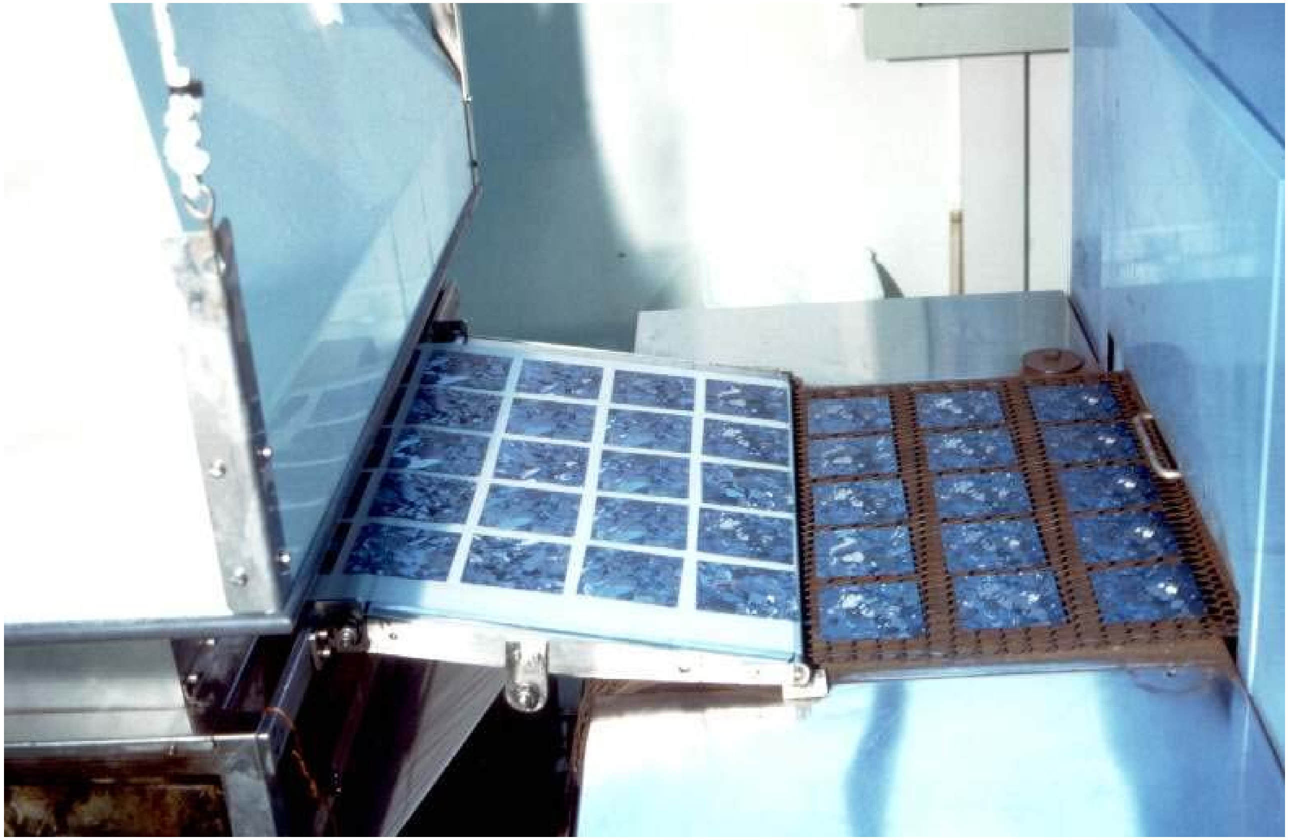
Buried contact solar cells used in Olympic Village. All houses were solar powered.

Screen Print Solar Cell Fabrication

Processing Facility at EuroSolare, Italy

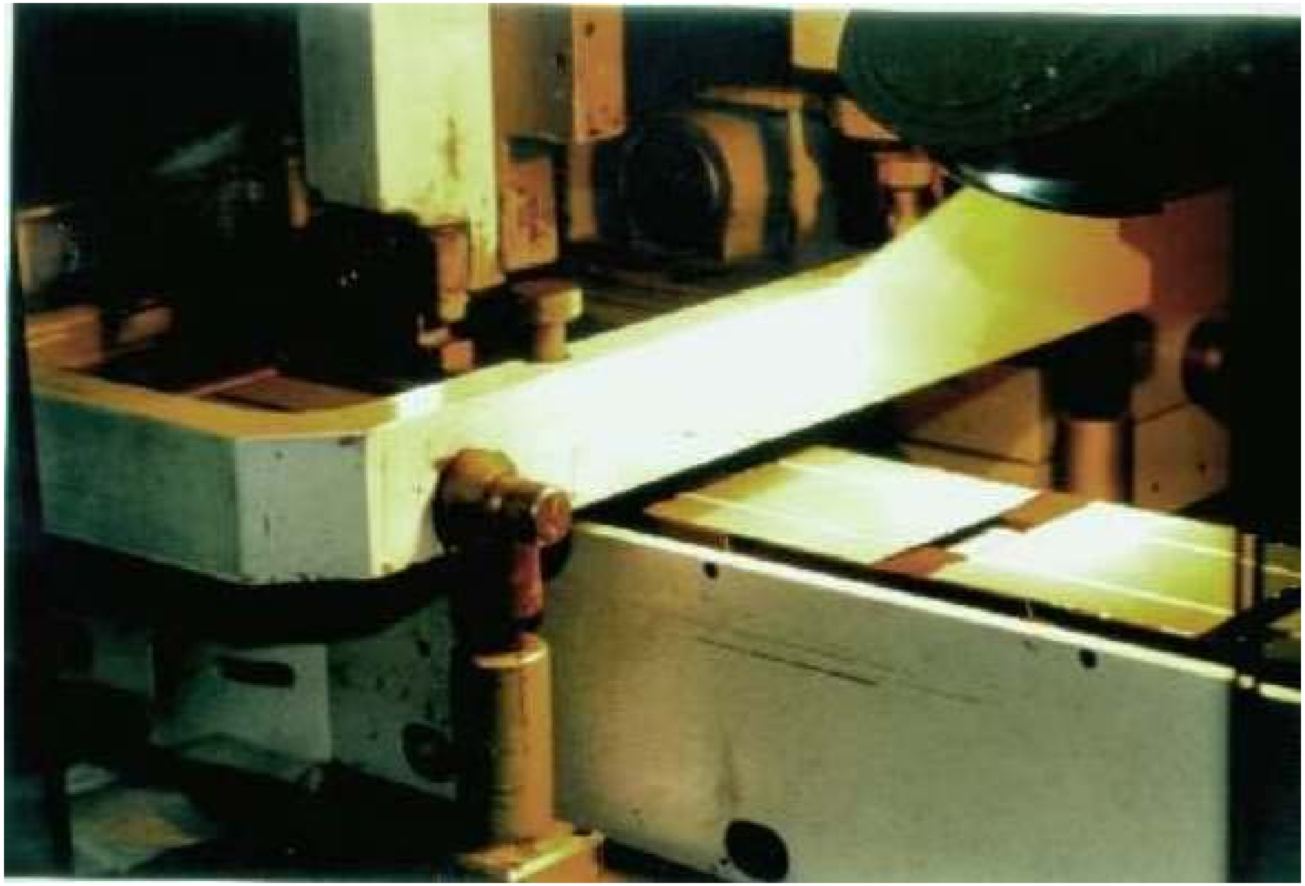
Commercial Solar Cell Fabrication

Diffusion deposition and drive-in



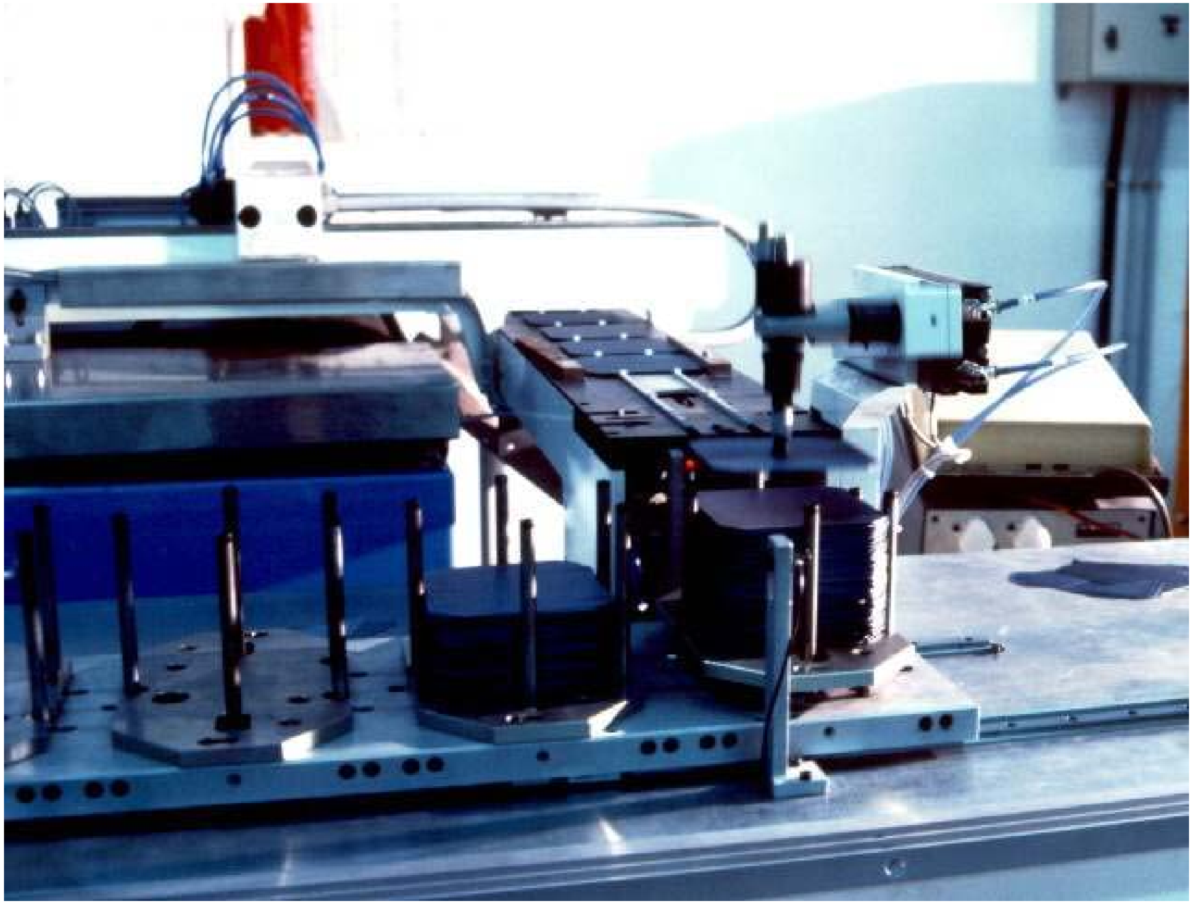
Commercial Solar Cell Fabrication

Contact Firing



Commercial Solar Cell Fabrication

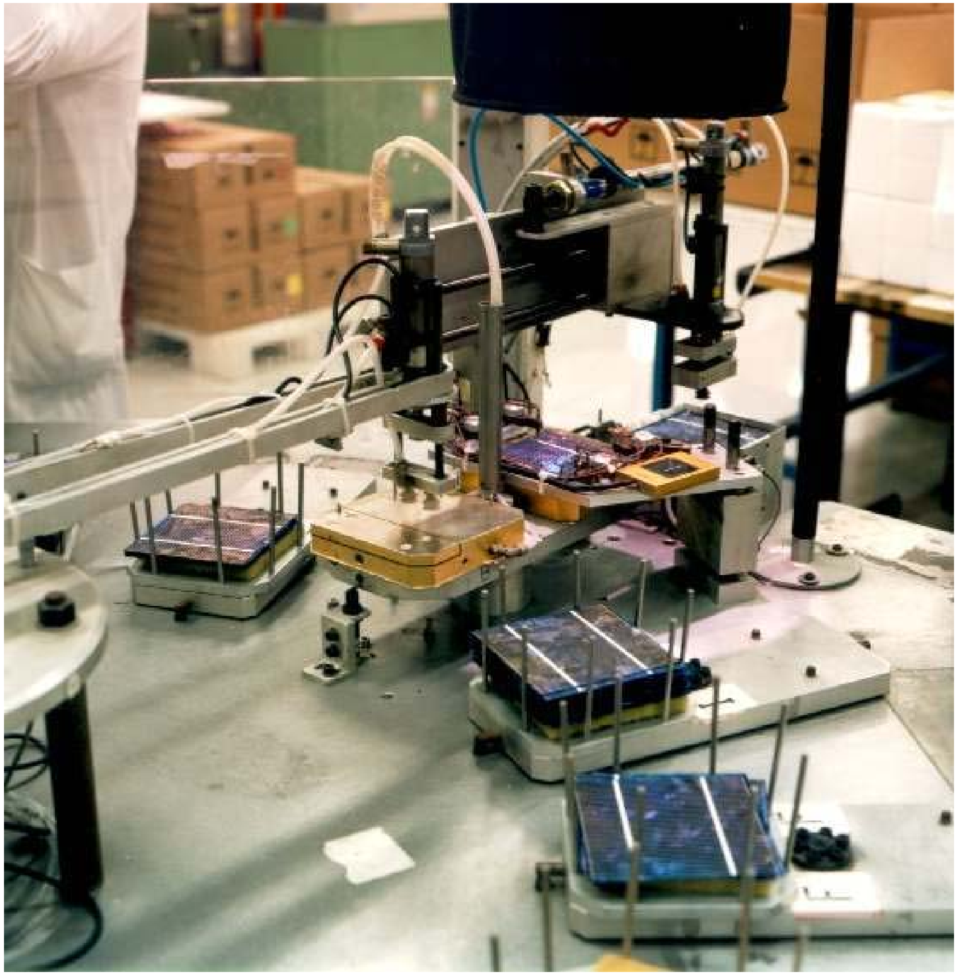
Automated cell handling



Commercial Solar Cell Fabrication

Solar Cell testing and sorting

Connection of mismatched cells reduces performance of module



Commercial Solar Cell Fabrication

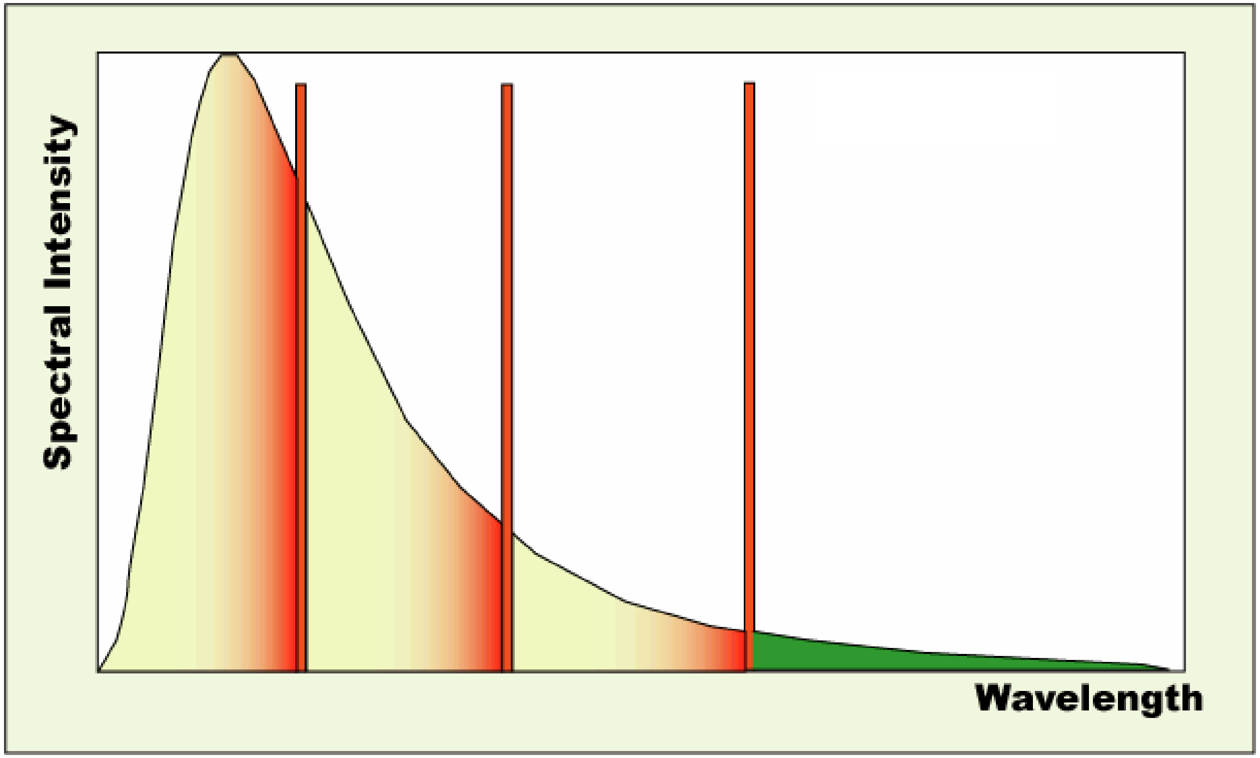
Rear view of PV module before encapsulation.

The module consists of the solar cell sandwiched between EVA (a clear polymer), with glass on the front and Tedlar on the rear.

III-V Solar Cells

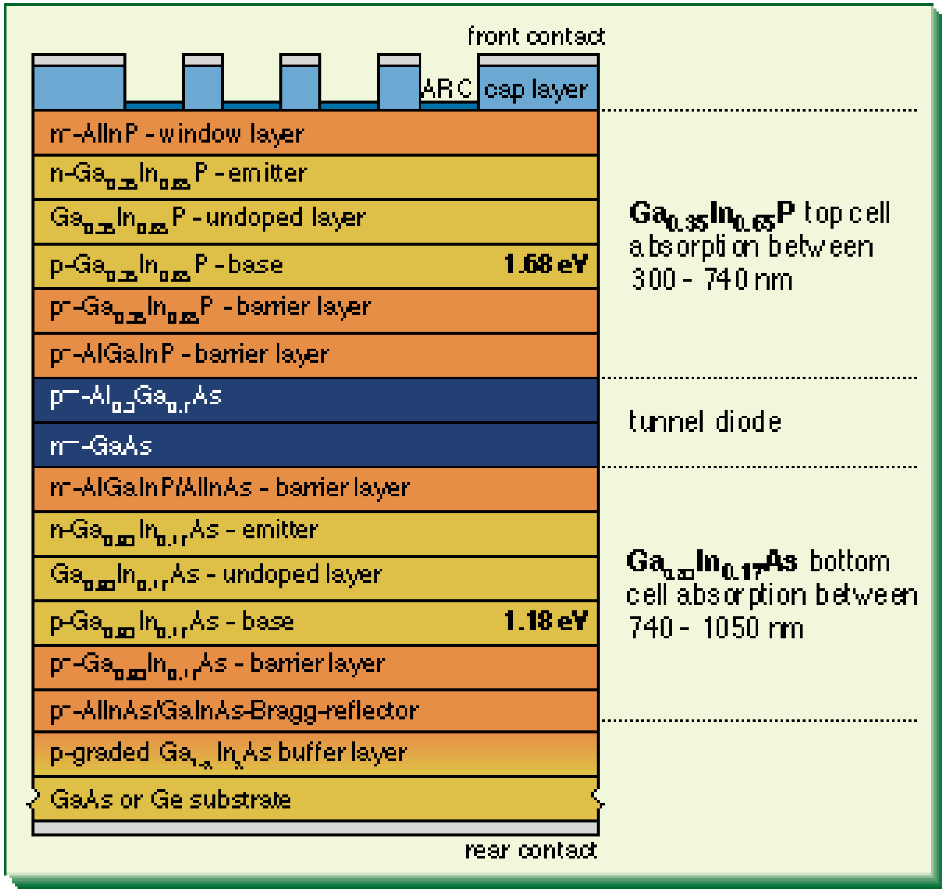
III-V solar cells have several advantages

- **Higher efficiency due to more optimum E_G.**
- **Allow tandem solar cells.**



III-V Solar Cells

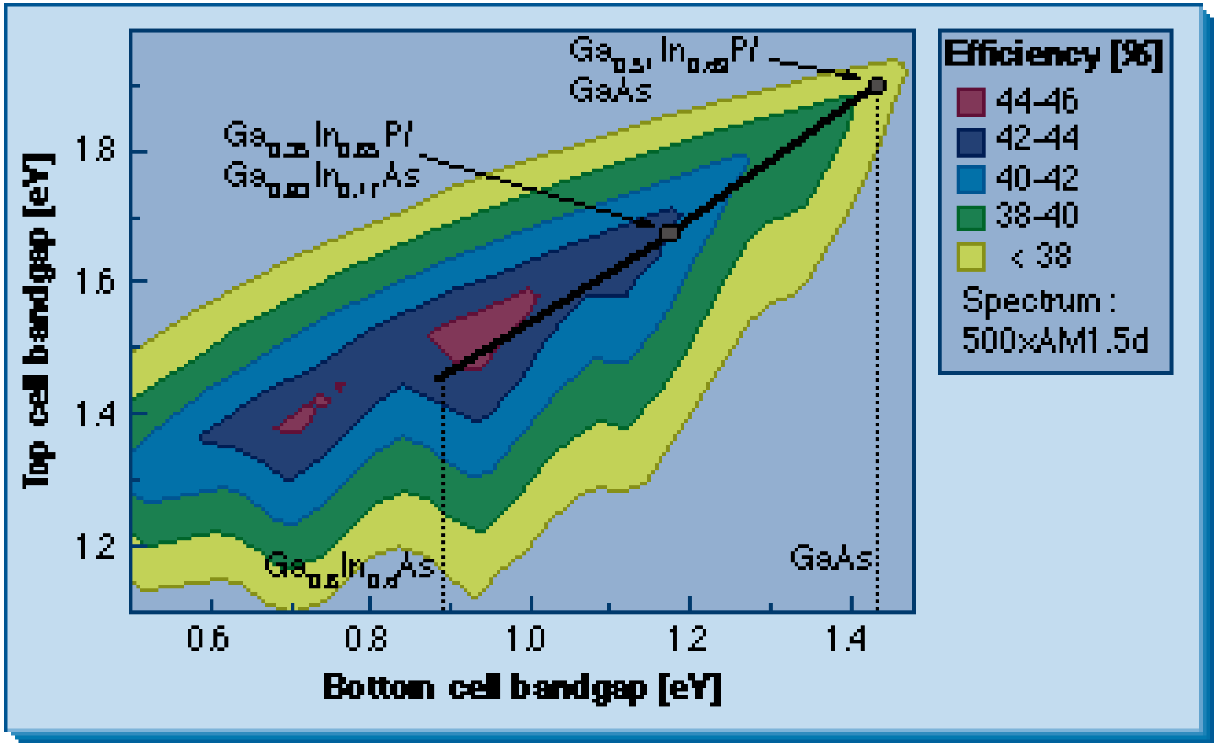
Tandem devices consist of two or more solar cells with different band gaps on top of one another



From Compound Semiconductor

III-V Solar Cells

Design of different top and rear band gap materials is a critical issue.



III-V Solar Cells

Tandem devices have reached over 33% efficiency under concentration