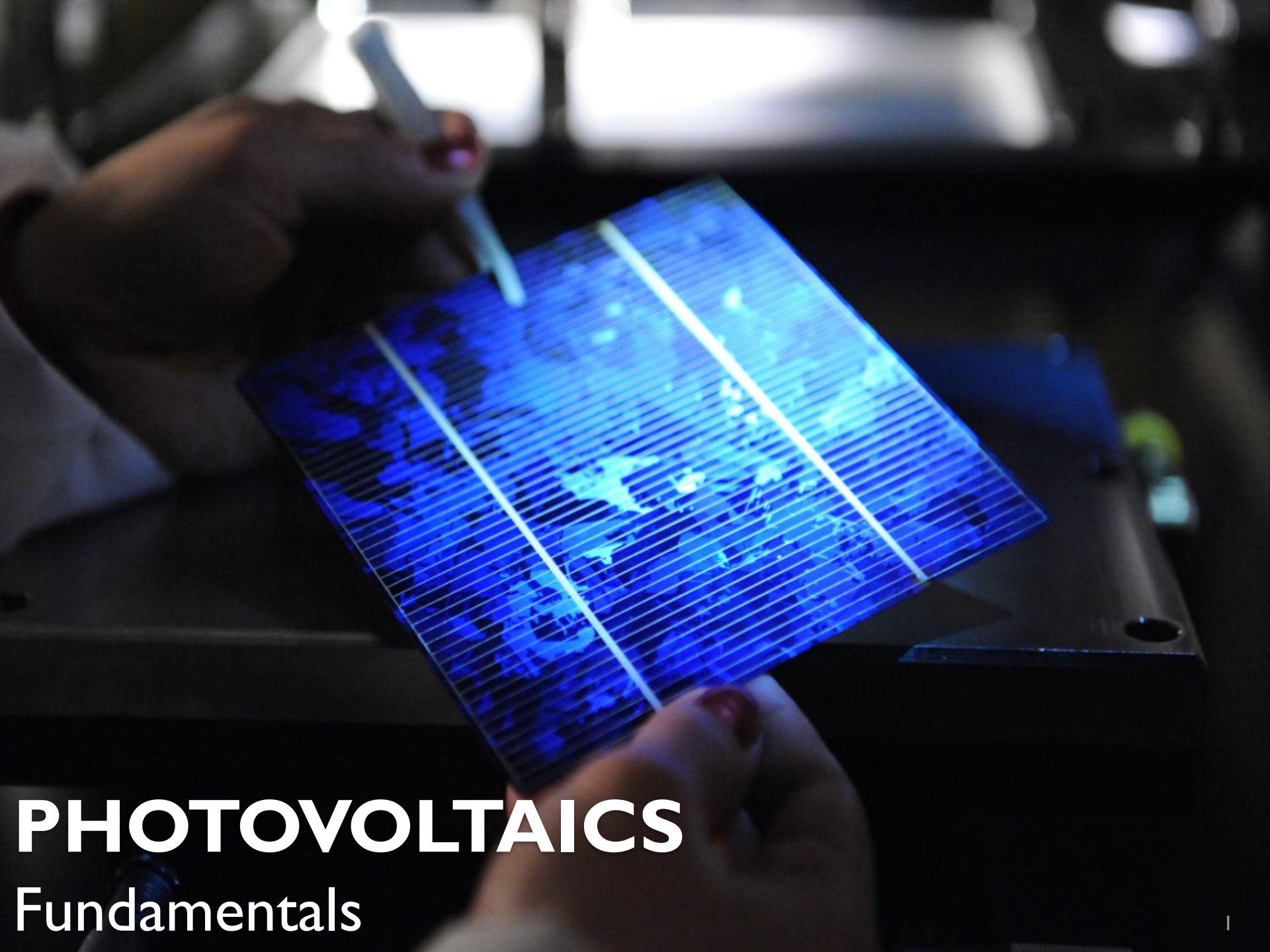


A close-up photograph of a person's hands working on a blue photovoltaic cell. The person is using a soldering iron to connect the cell to a metal base. The cell has a grid of fine lines and two thicker lines. The background is dark and out of focus, showing some industrial equipment.

PHOTOVOLTAICS

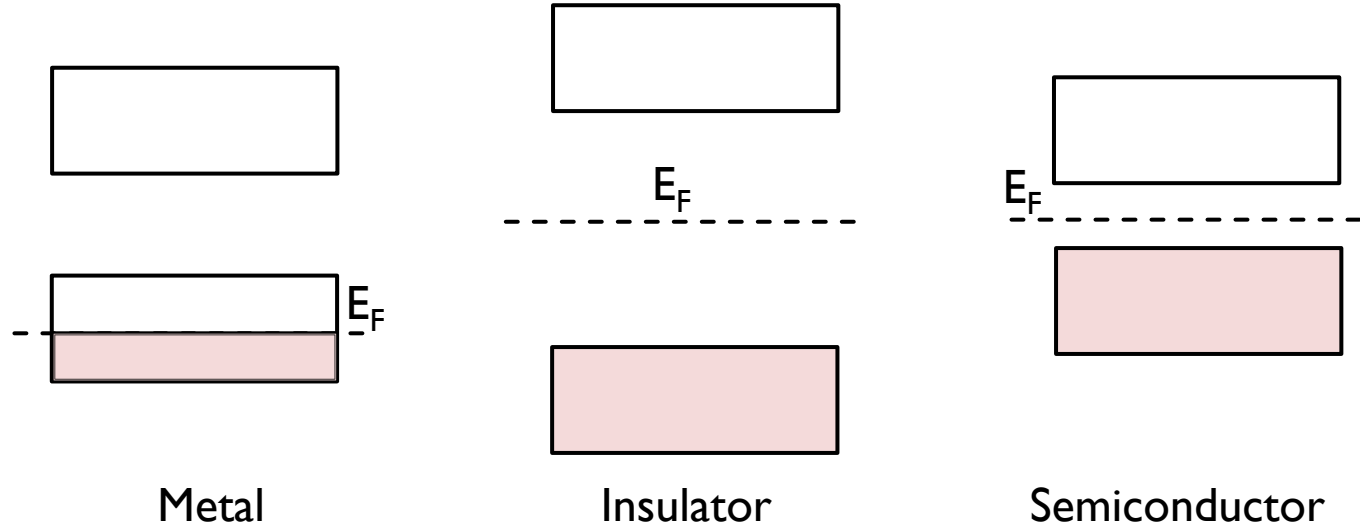
Fundamentals

PV FUNDAMENTALS

- Semiconductor basics
- pn junction
- Solar cell operation
- Design of silicon solar cell

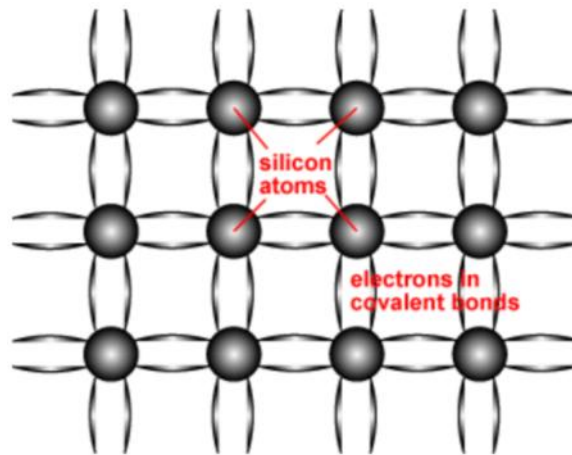
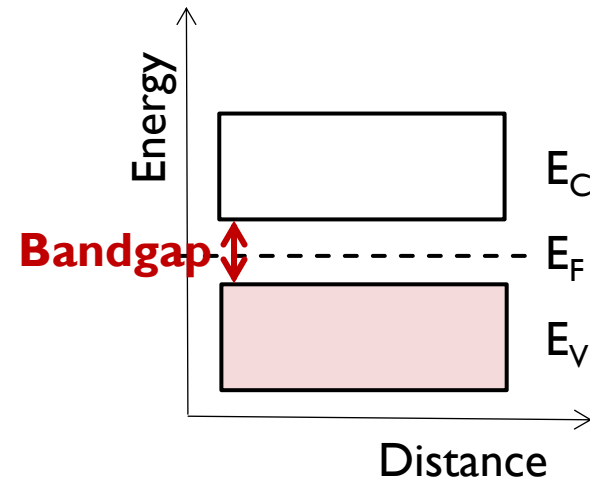
SEMICONDUCTOR BASICS

- Allowed energy bands
- Valence and conduction band
- Fermi level



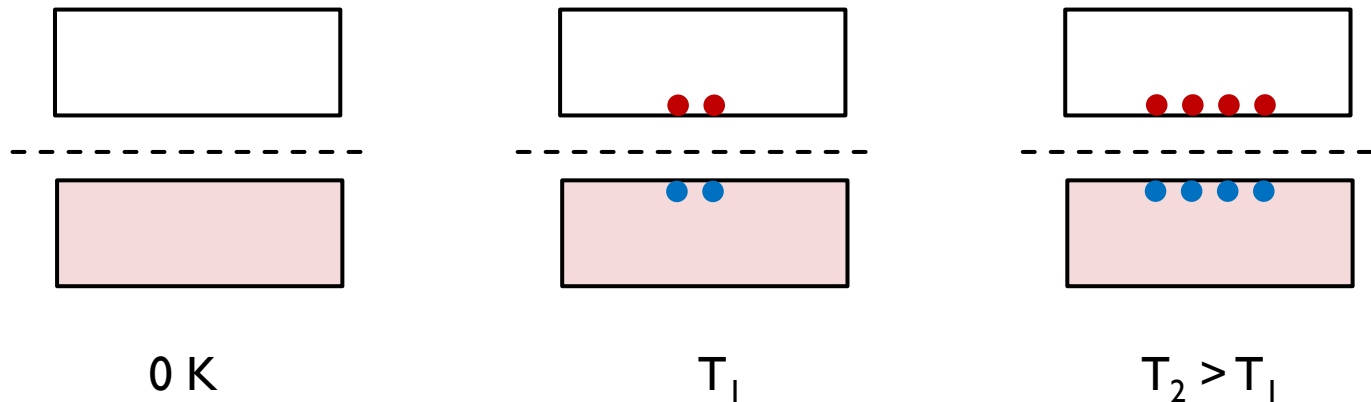
SEMICONDUCTOR BASICS

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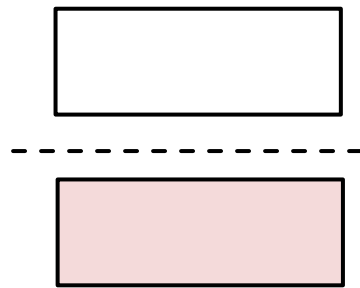
SEMICONDUCTOR BASICS

- Effect of temperature

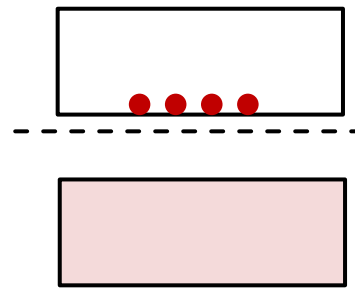


SEMICONDUCTOR BASICS

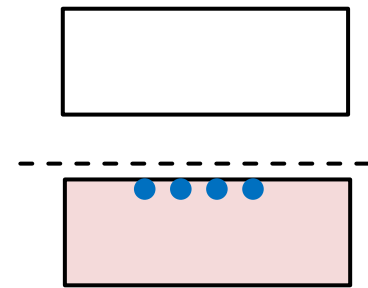
- Effect of doping



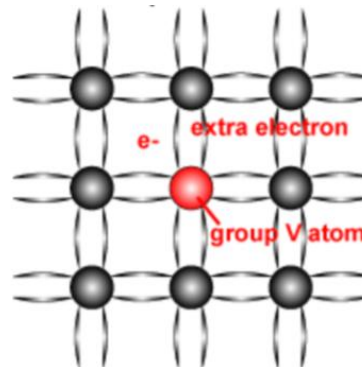
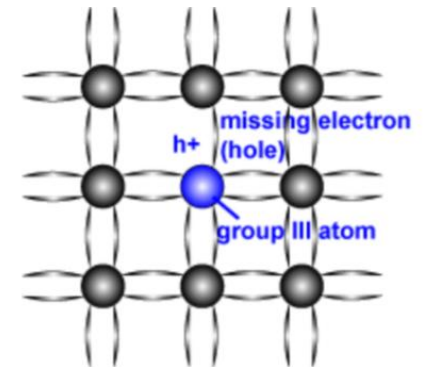
Intrinsic



N-doped

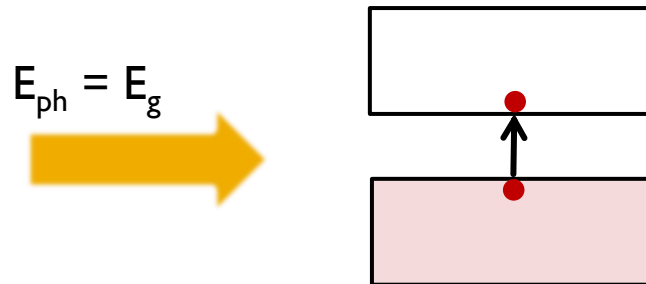


P-doped



SEMICONDUCTOR BASICS

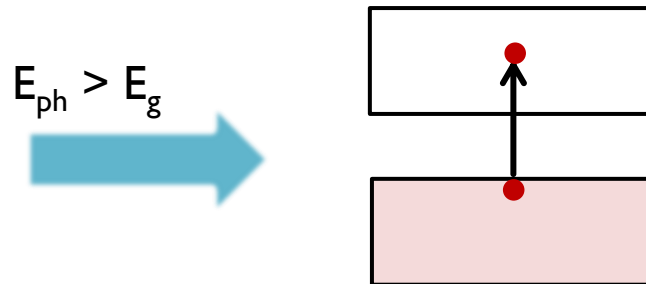
- **Absorption of light** depends on the energy of the photon (wavelength)



$$E = \frac{hc}{\lambda}$$
$$E(eV) = \frac{1.24}{\lambda(\mu m)}$$

SEMICONDUCTOR BASICS

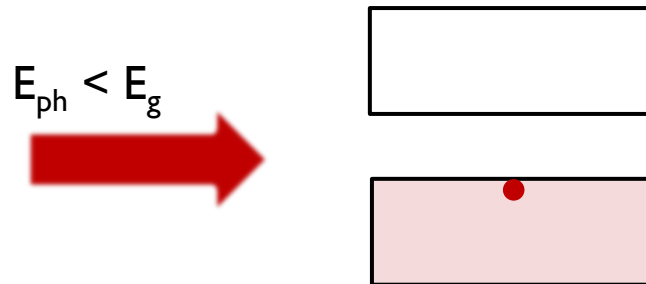
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SEMICONDUCTOR BASICS

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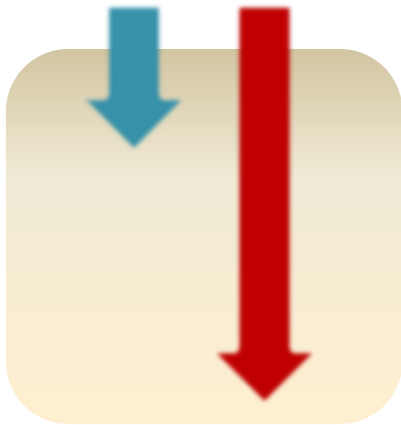


$$E = \frac{hc}{\lambda}$$
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SEMICONDUCTOR BASICS

- **Absorption coefficient** [cm^{-1}]: the distance into the material at which the light drops to about $1/e$ of its original intensity

$$I = I_0 e^{-\alpha x}$$



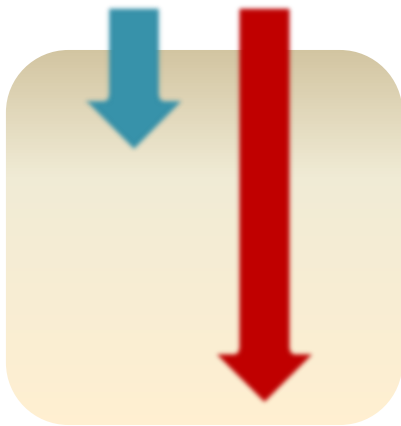
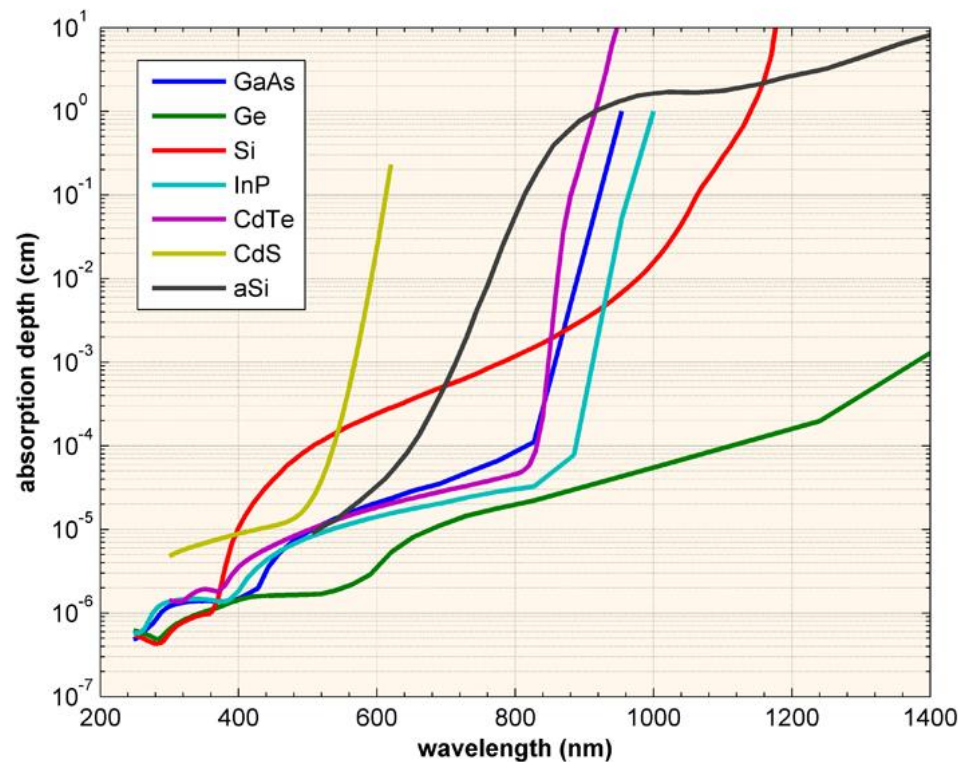
α is the absorption coefficient typically in cm^{-1}
 I_0 is the light intensity at the top surface.

$$E = \frac{hc}{\lambda}$$
$$E(\text{eV}) = \frac{1.24}{\lambda(\mu\text{m})}$$

SEMICONDUCTOR BASICS

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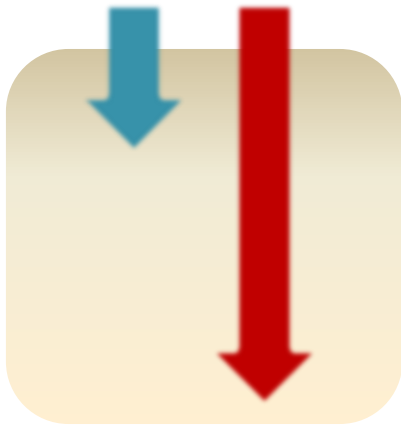
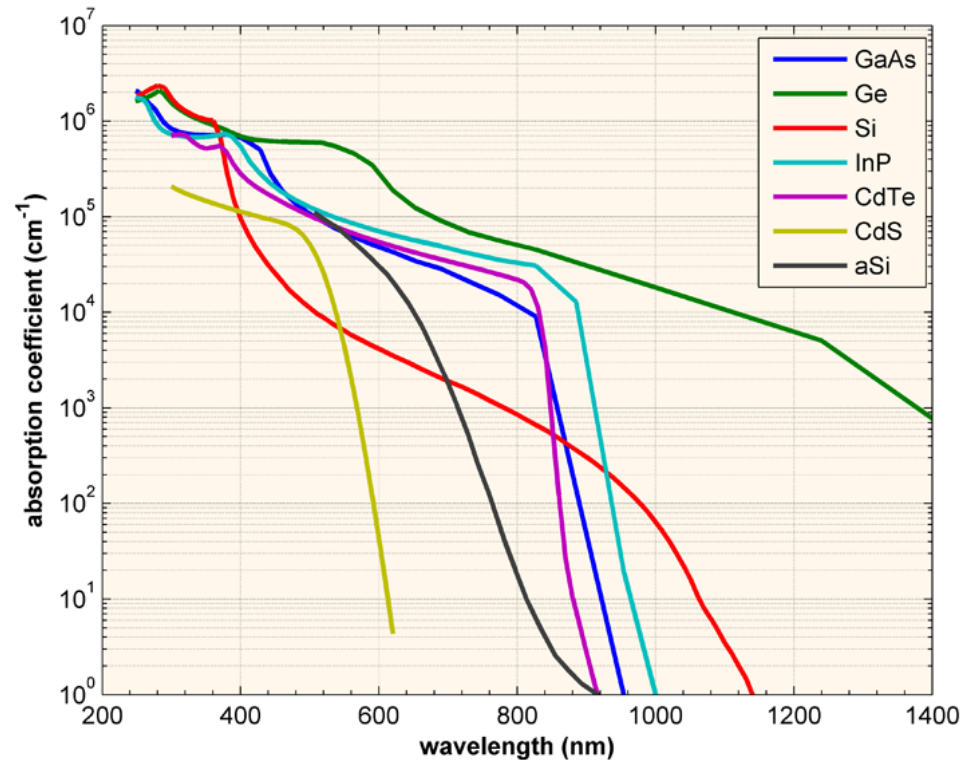


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SEMICONDUCTOR BASICS

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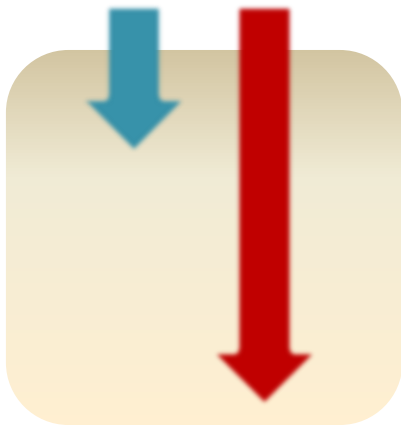
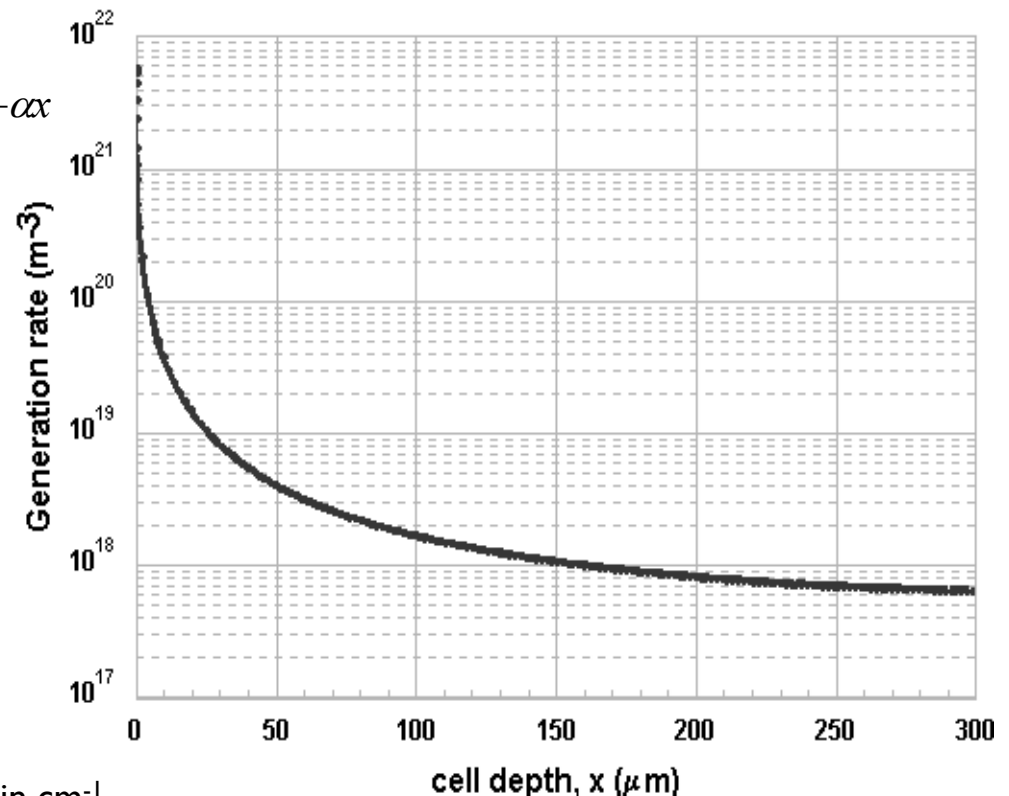


α is the absorption coefficient typically in cm^{-1}
 I_0 is the light intensity at the top surface.

PV FUNDAMENTALS

- The **generation rate** gives the number of electrons generated at each point in the device due to the absorption of photons.

$$G = \frac{dI}{dx} = \alpha N_0 e^{-\alpha x}$$



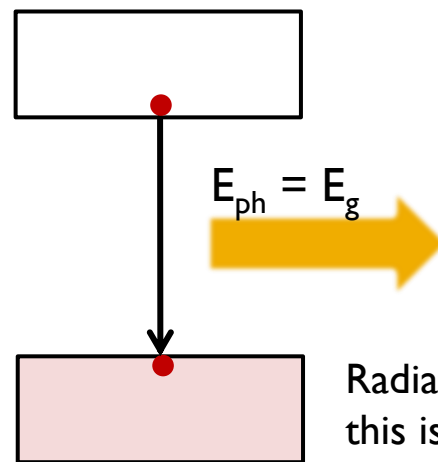
α is the absorption coefficient typically in cm^{-1}

N_0 = photon flux at the surface (photons/unit-area/sec)

PV FUNDAMENTALS

Recombination may occur through...

- **Radiative recombination** - an electron directly combines with a hole in the conduction band and releases a photon



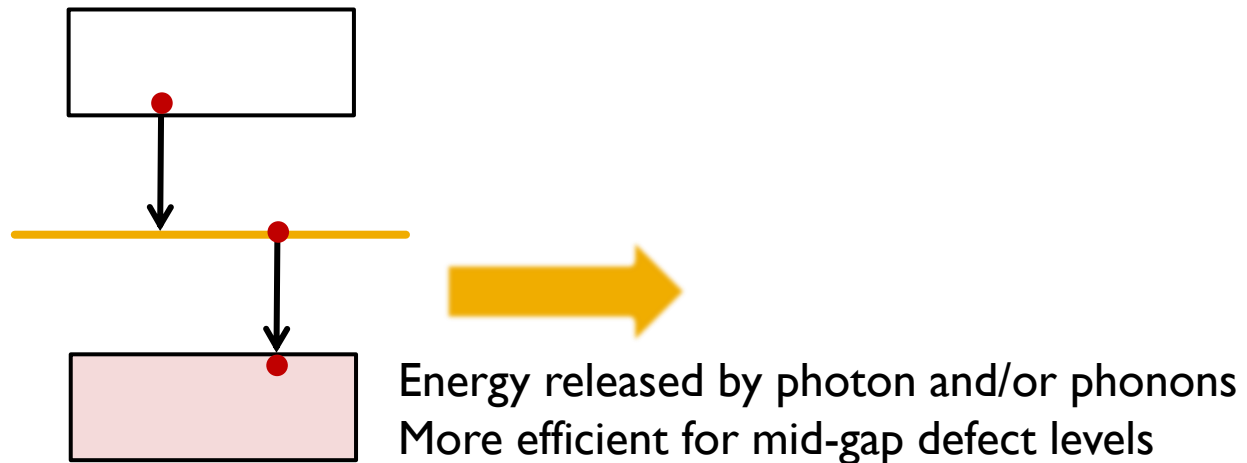
Radiated photon is weakly absorbed;
this is how LEDs work!!

Not very likely for indirect gap semiconductor like Si

SEMICONDUCTOR BASICS

Recombination may occur through...

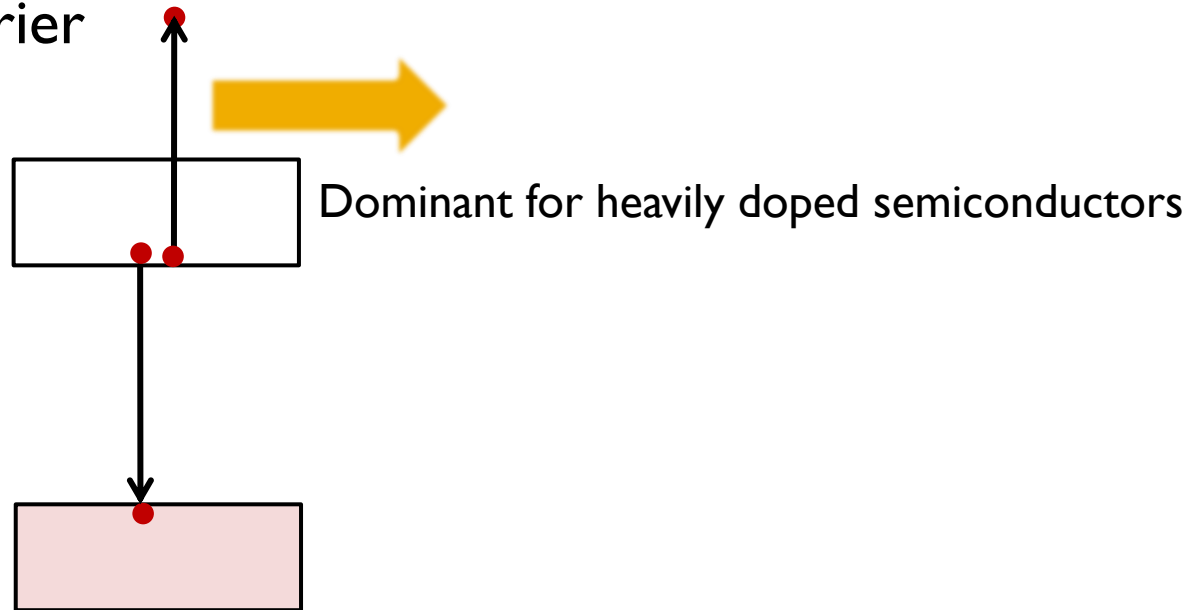
- **Shockley-Read-Hall recombination** – 2-step process: an electron is trapped in a defect level



SEMICONDUCTOR BASICS

Recombination may occur through...

- **Auger recombination** – similar to radiative recombination but energy release through a third carrier



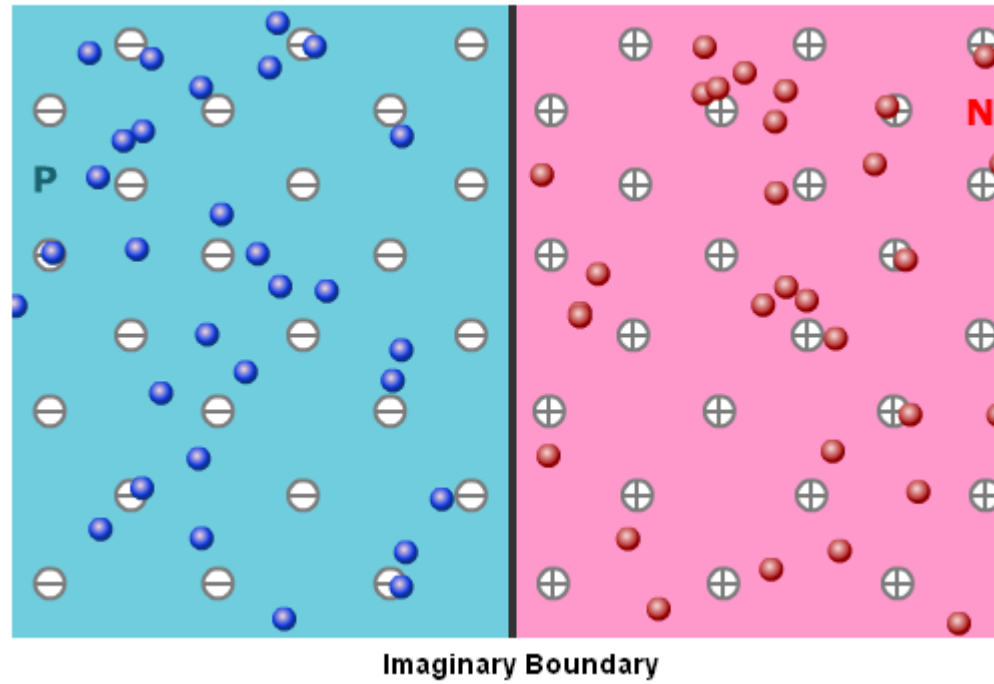
SEMICONDUCTOR BASICS

Recombination is characterized by...

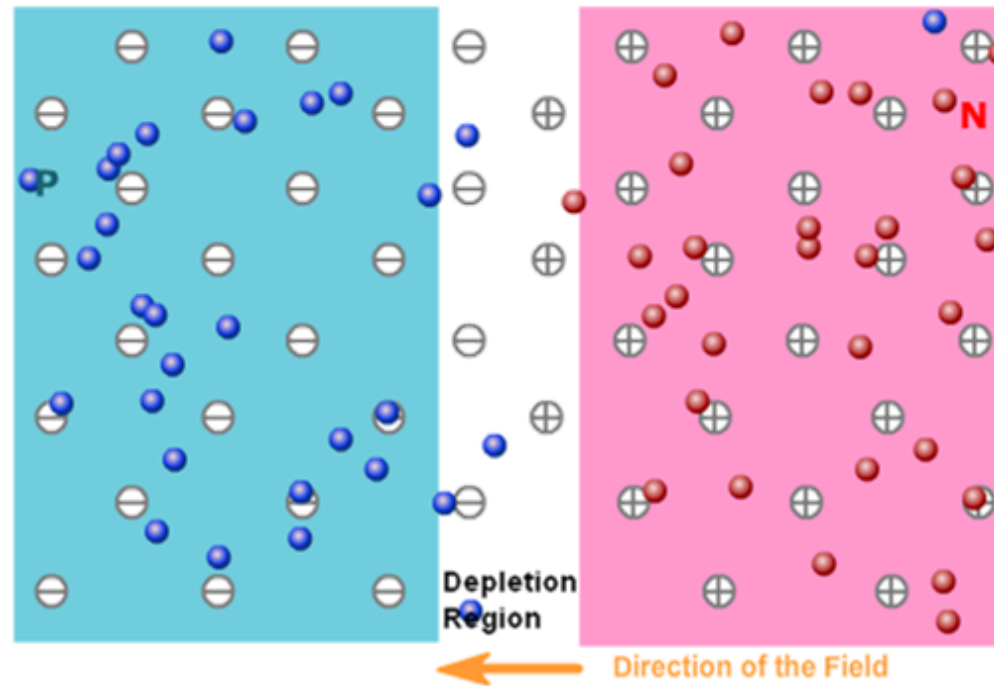
- **Recombination rate**
- Minority carrier **lifetime** – how long a carrier is likely to stay around for before recombining
- **Diffusion length** – average distance a carrier can move from point of generation until it recombines

$$\tau = \frac{\Delta n}{R} \quad L = \sqrt{D\tau}$$

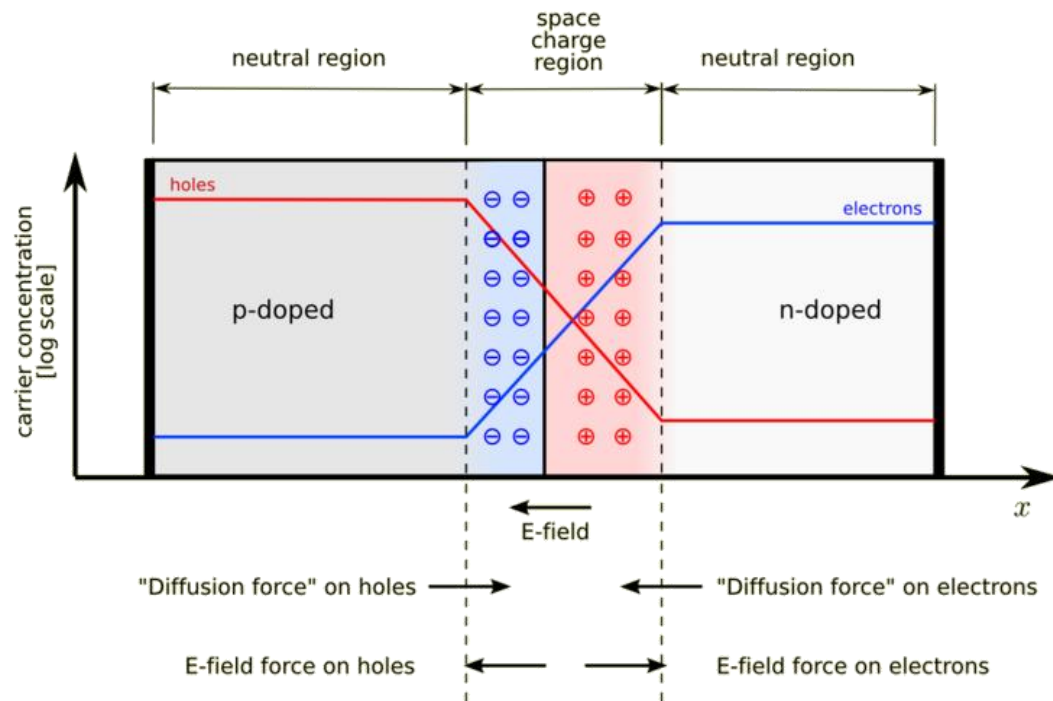
PN JUNCTION



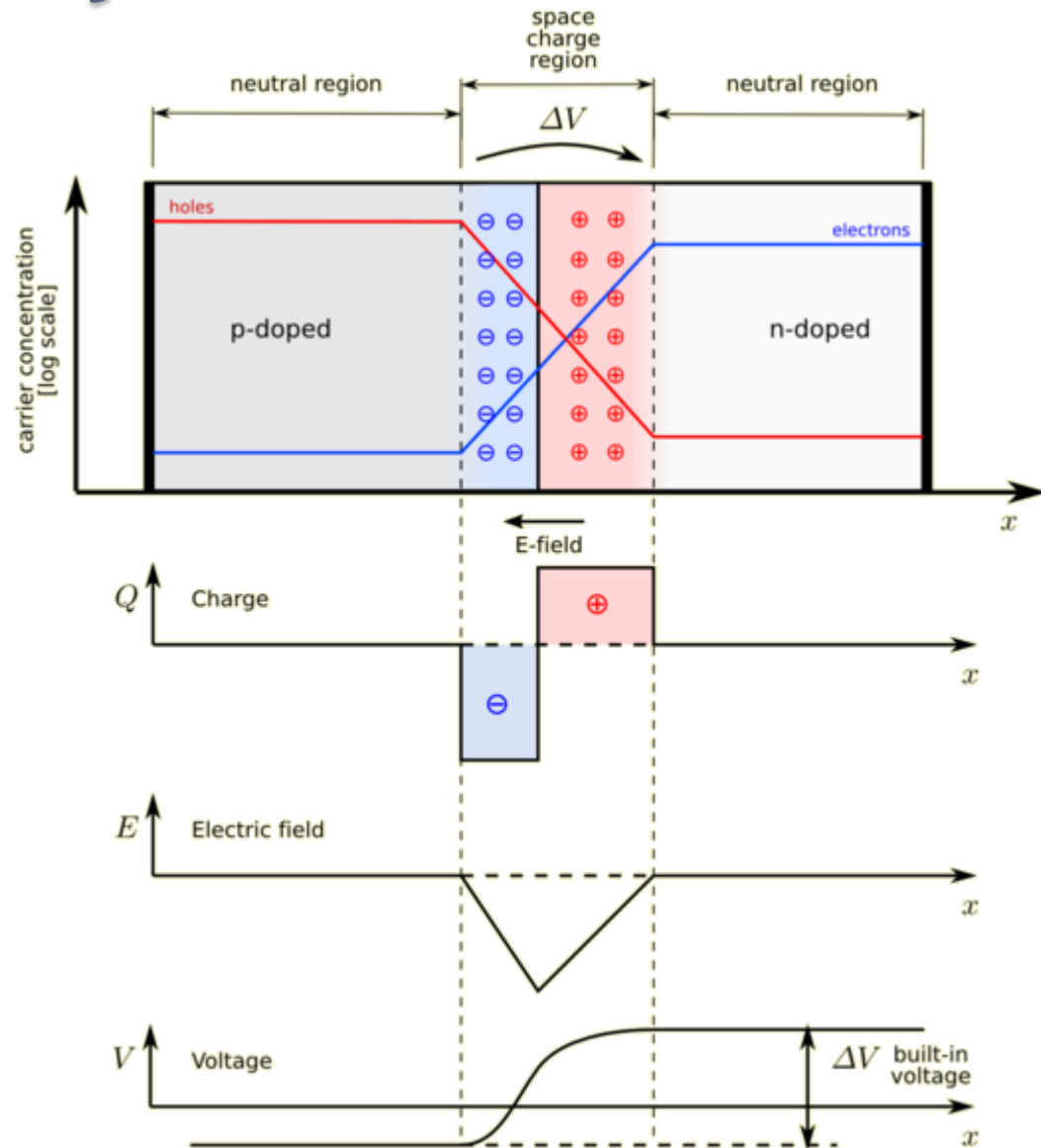
PN JUNCTION



PN JUNCTION



PN JUNCTION

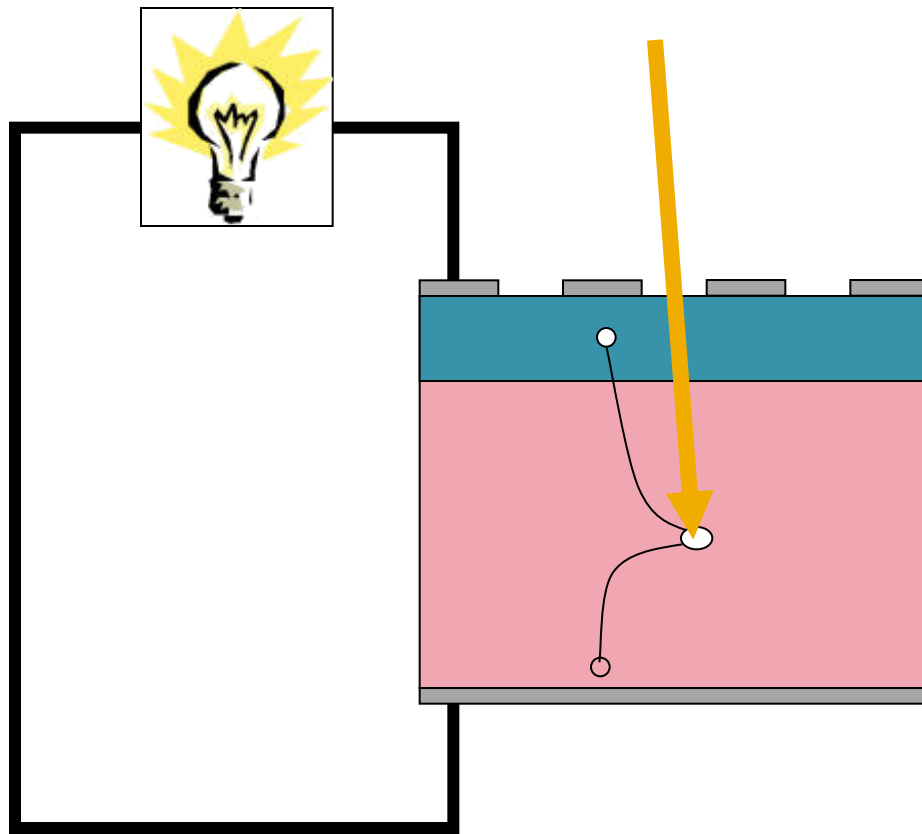


SOLAR CELL OPERATION

Basic steps:

- the **generation** of light-generated carriers;
- the **collection** of the light-generated carriers to generate a current;
- the generation of a **voltage** across the solar cell; and
- the dissipation of power in the **load** and in parasitic resistances.

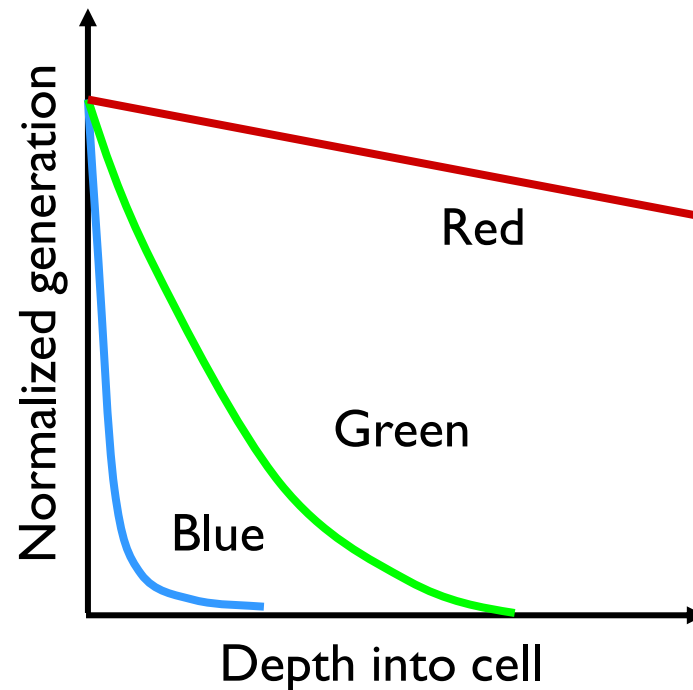
SOLAR CELL OPERATION



SOLAR CELL OPERATION

Basic steps:

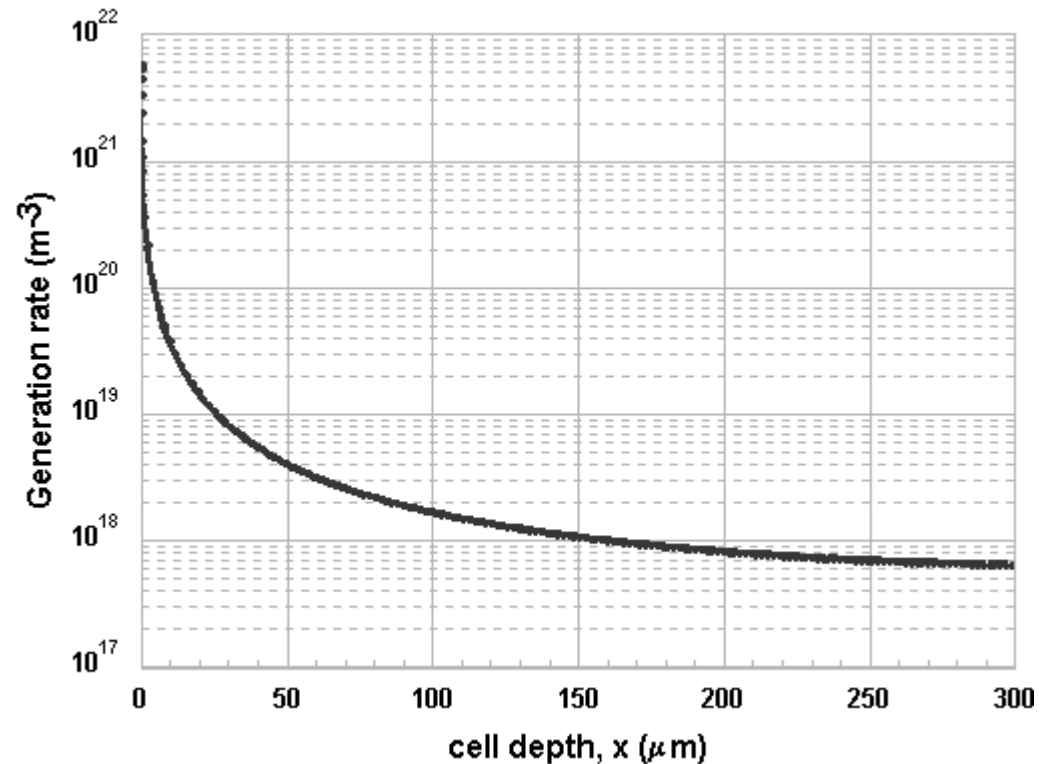
- the **generation** of light-generated carriers



SOLAR CELL OPERATION

Basic steps:

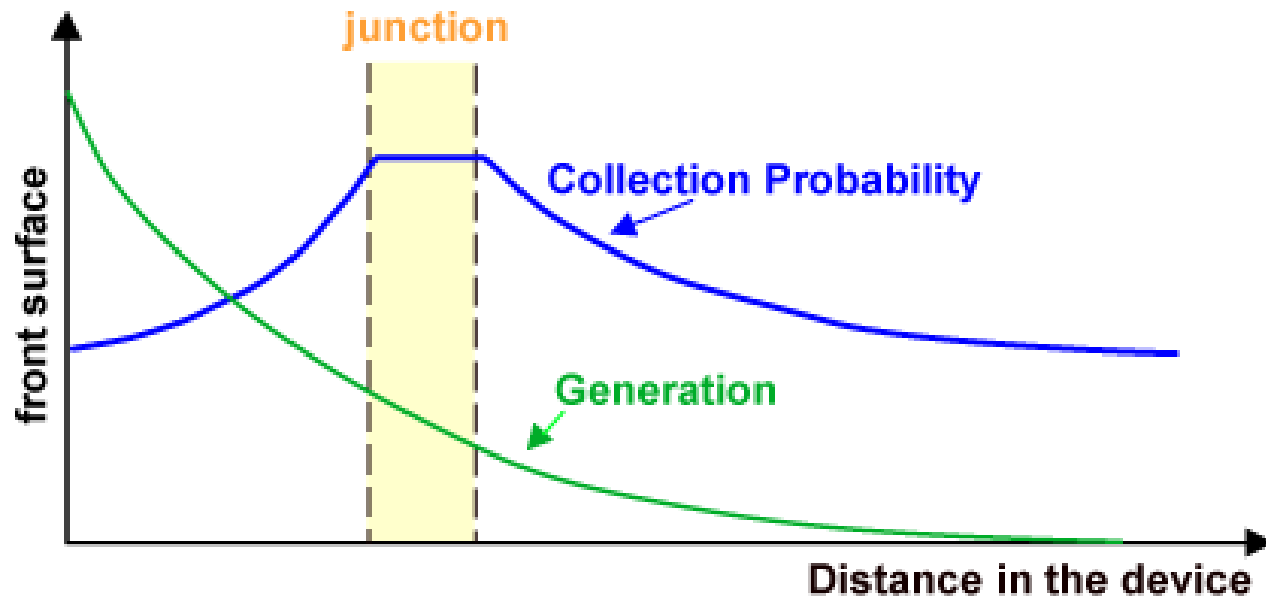
- the **generation** of light-generated carriers



SOLAR CELL OPERATION

Basic steps:

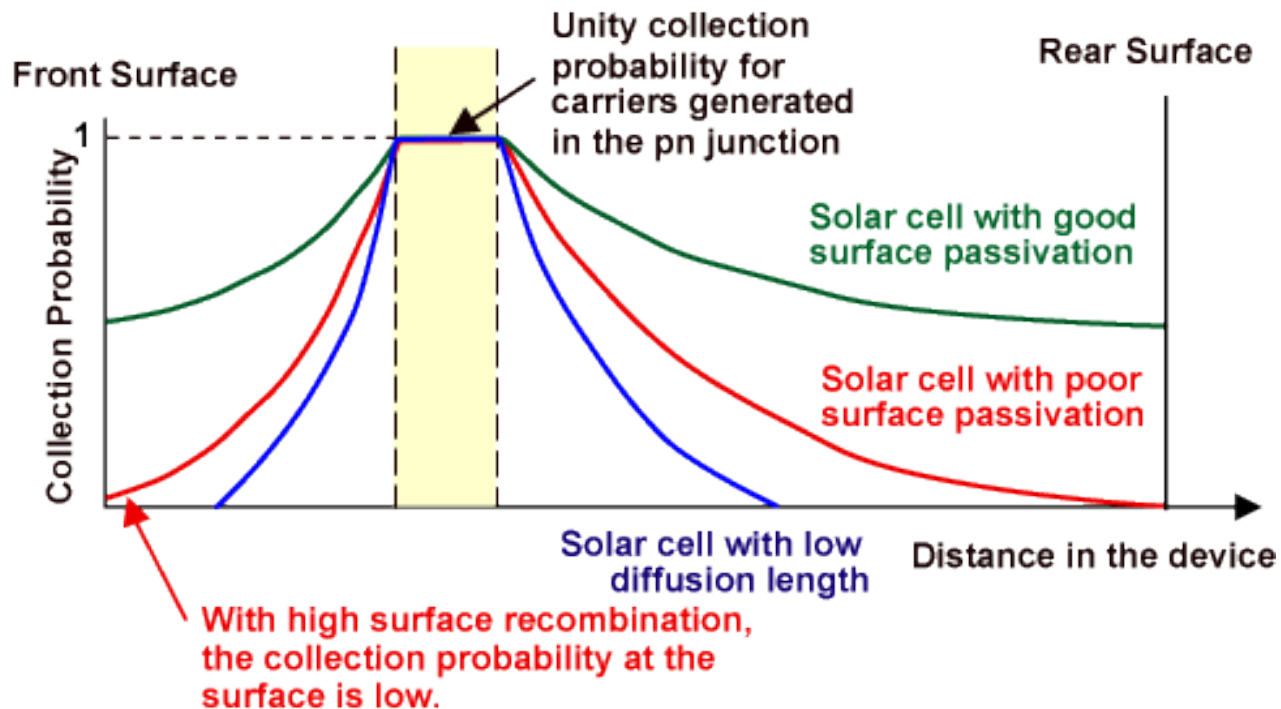
- the **collection** of the carriers



SOLAR CELL OPERATION

Basic steps:

- the collection of the carriers



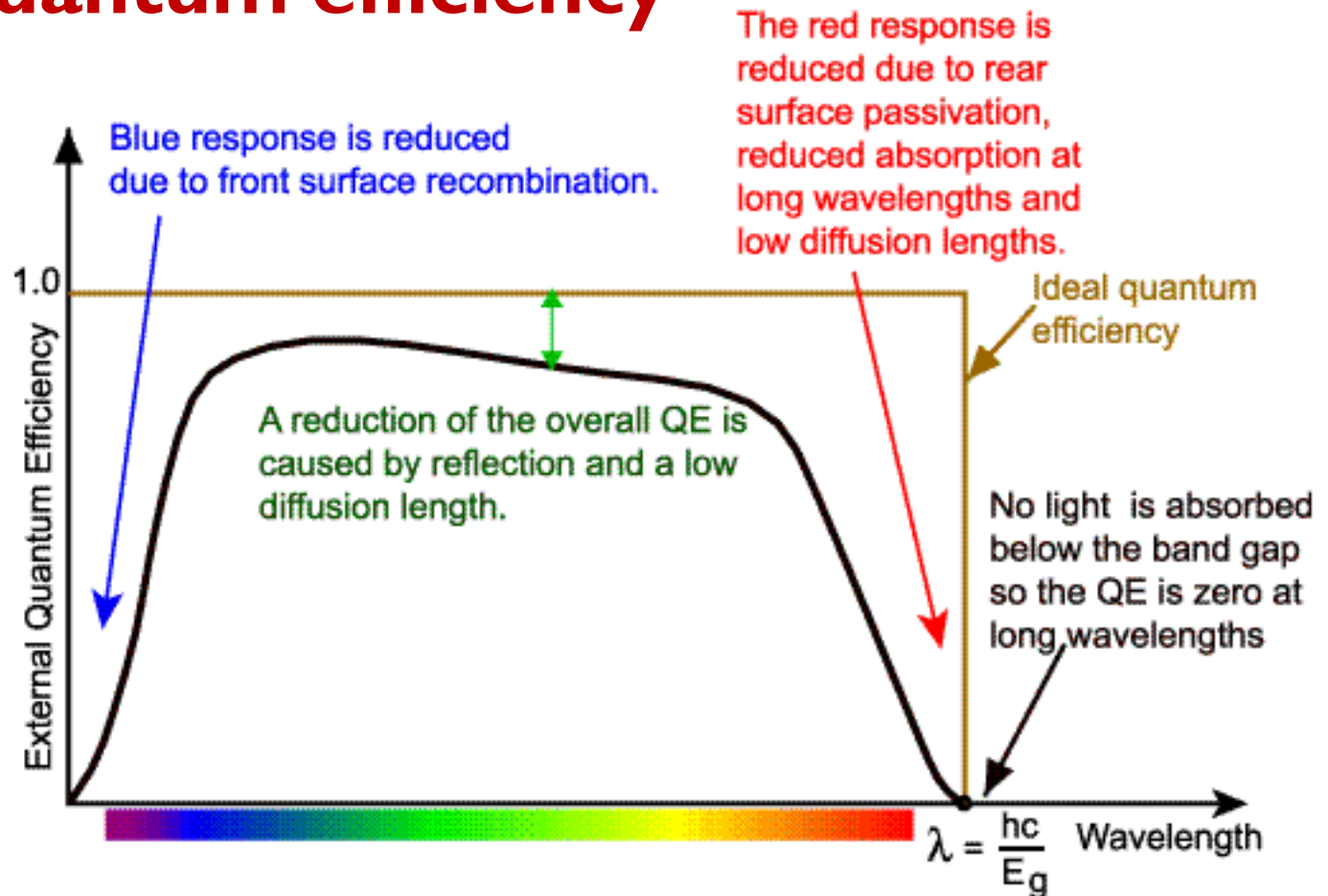
Solar cell operation

Quantum efficiency

Ratio of the number of carriers collected to the number of photons of a given energy incident

Solar cell operation

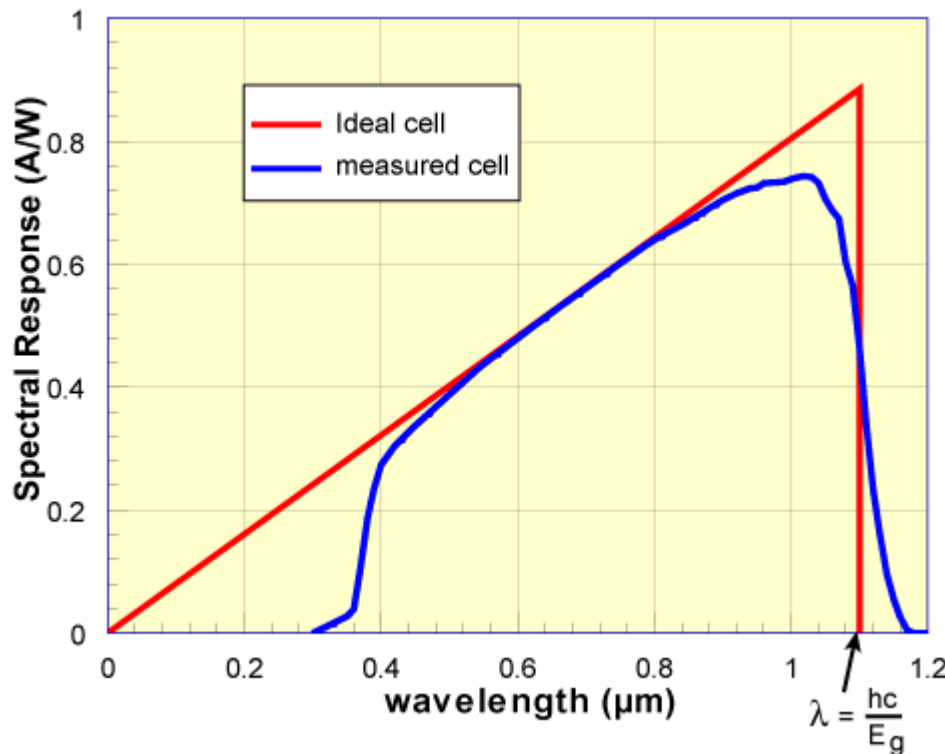
Quantum efficiency



SOLAR CELL OPERATION

Spectral response

Ratio of the **current** generated by the solar cell to the **power** incident on the solar cell



Spectral Response (SR) is measured

Quantum Efficiency (QE) is calculated from SR:

$$SR = \frac{q\lambda}{hc} QE$$

SOLAR CELL OPERATION

Solar cell parameters

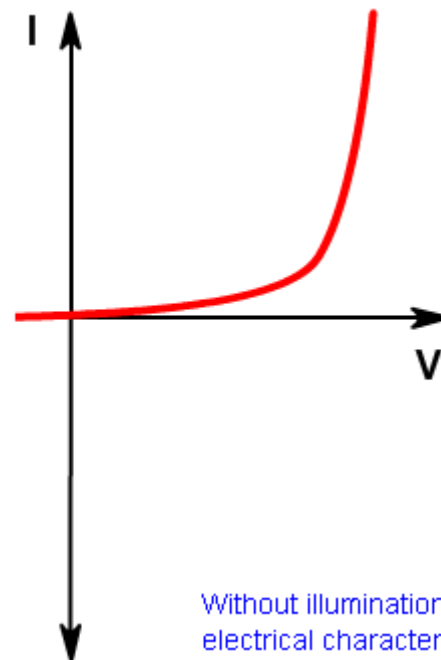
IV characteristic

= diode + light generated current

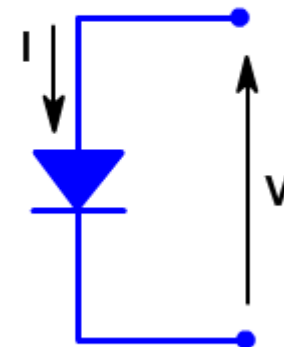
SOLAR CELL OPERATION

Solar cell parameters

IV characteristic



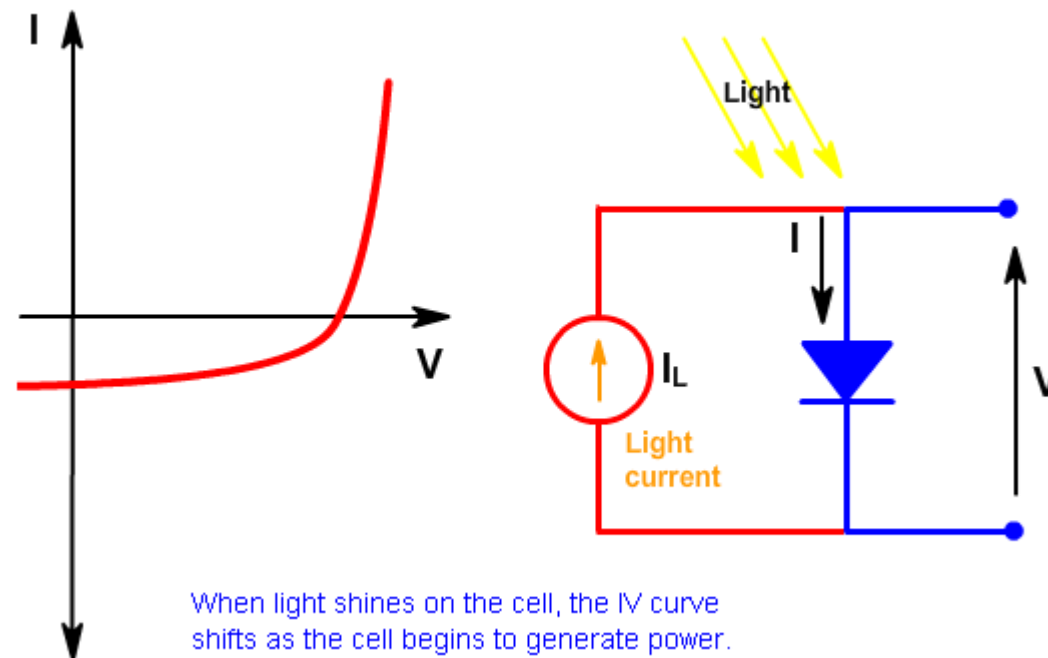
Without illumination, a solar cell has the same electrical characteristics as a large diode.



SOLAR CELL OPERATION

Solar cell parameters

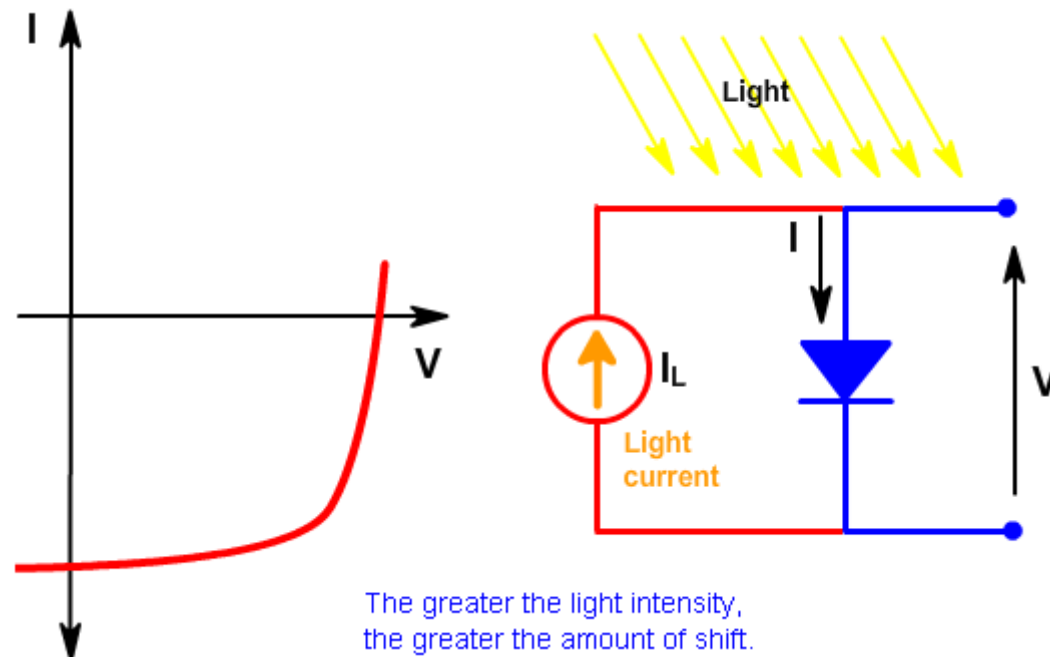
IV characteristic



SOLAR CELL OPERATION

Solar cell parameters

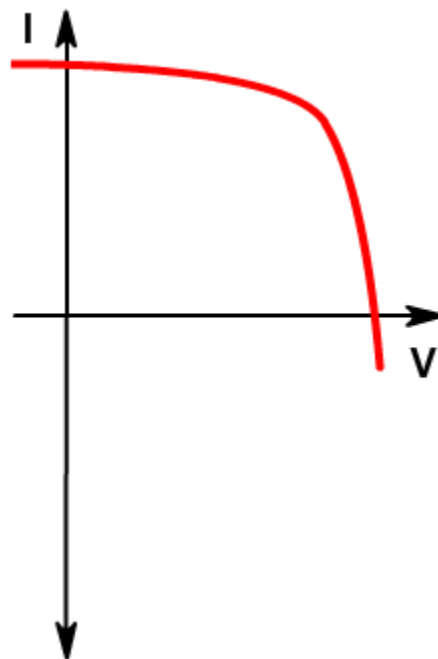
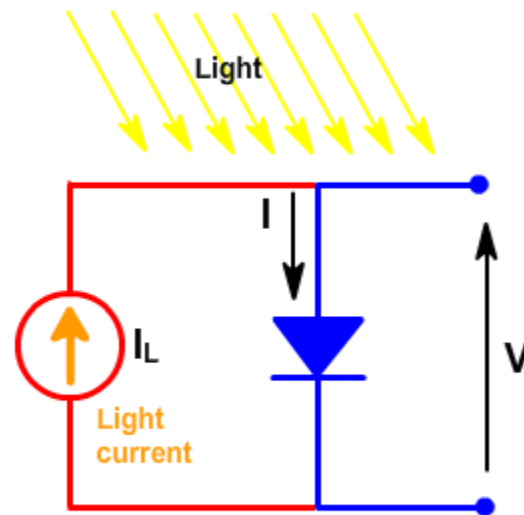
IV characteristic



SOLAR CELL OPERATION

Solar cell parameters

IV characteristic

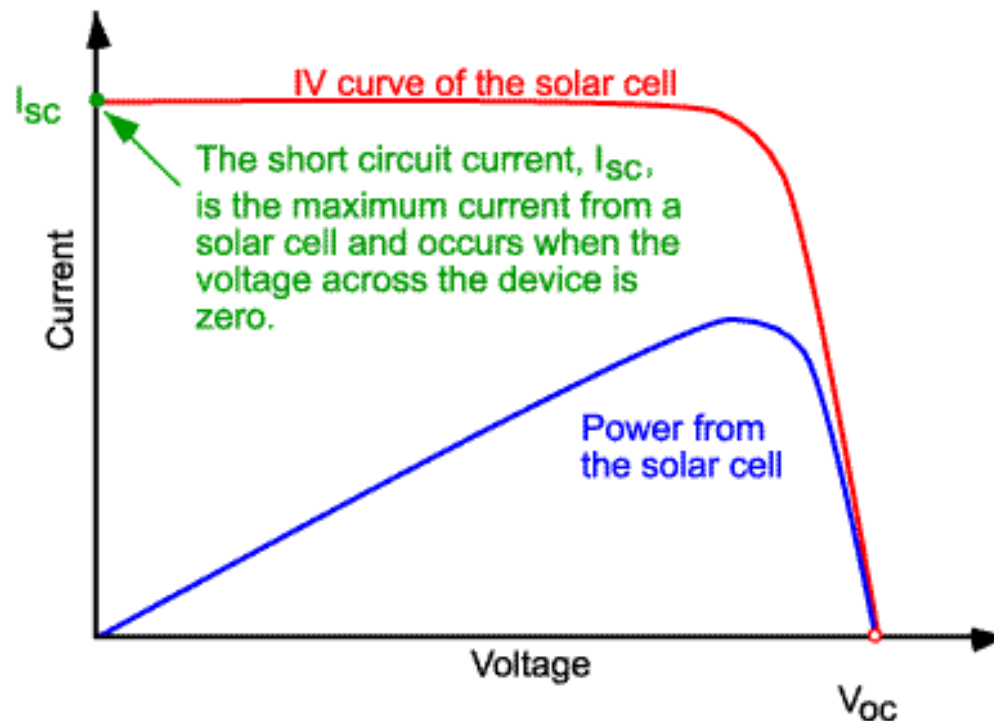


$$I = I_L - I_0 \left[\exp \left(\frac{qV}{nkT} \right) - 1 \right]$$

SOLAR CELL OPERATION

Solar cell parameters

IV characteristic: **Short Circuit Current** (I_{sc})



SOLAR CELL OPERATION

Solar cell parameters

IV characteristic: **Short Circuit Current** (I_{sc})

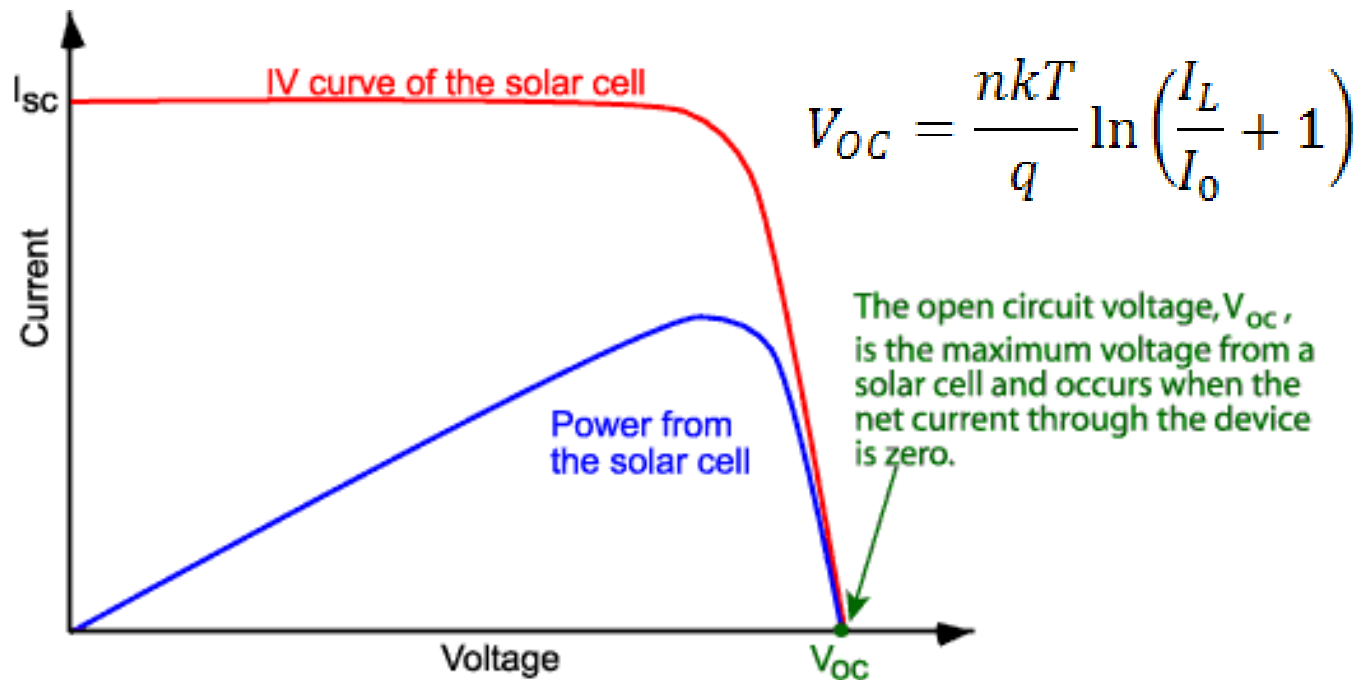
- **Area** of the solar cell (common to use J_{sc} in mA/cm²)
- Incident flux (i.e. number of **photons**)
- **Spectrum** incident light
- **Optical** properties of the solar cell
- Collection probability, e.g. **diffusion length**

$$I_{sc} = qG(L_n + L_p)$$

SOLAR CELL OPERATION

Solar cell parameters

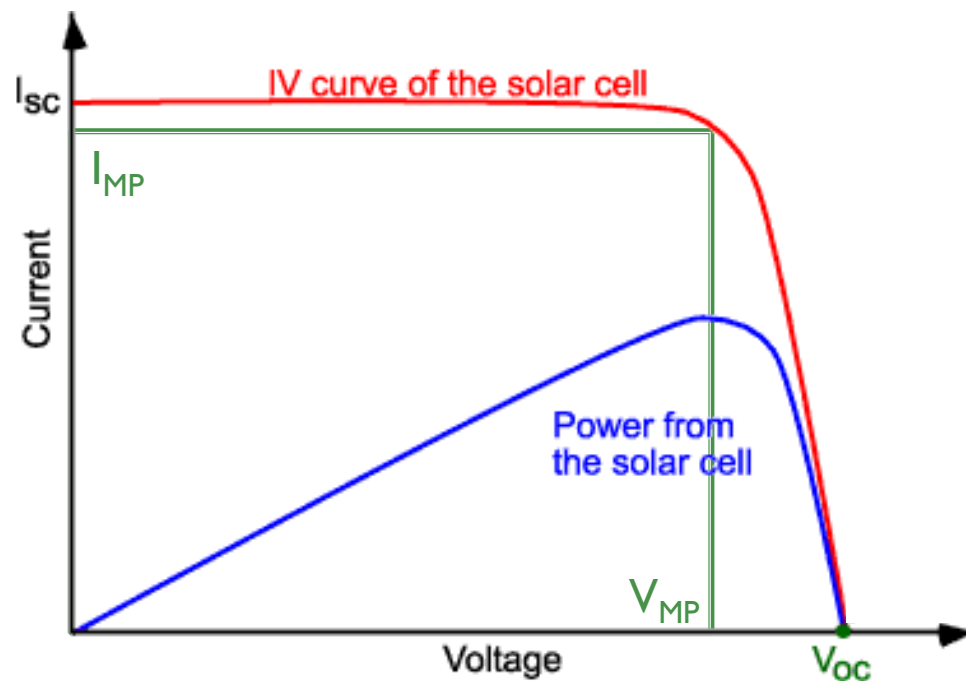
IV characteristic: **Open circuit voltage** (V_{oc})



SOLAR CELL OPERATION

Solar cell parameters

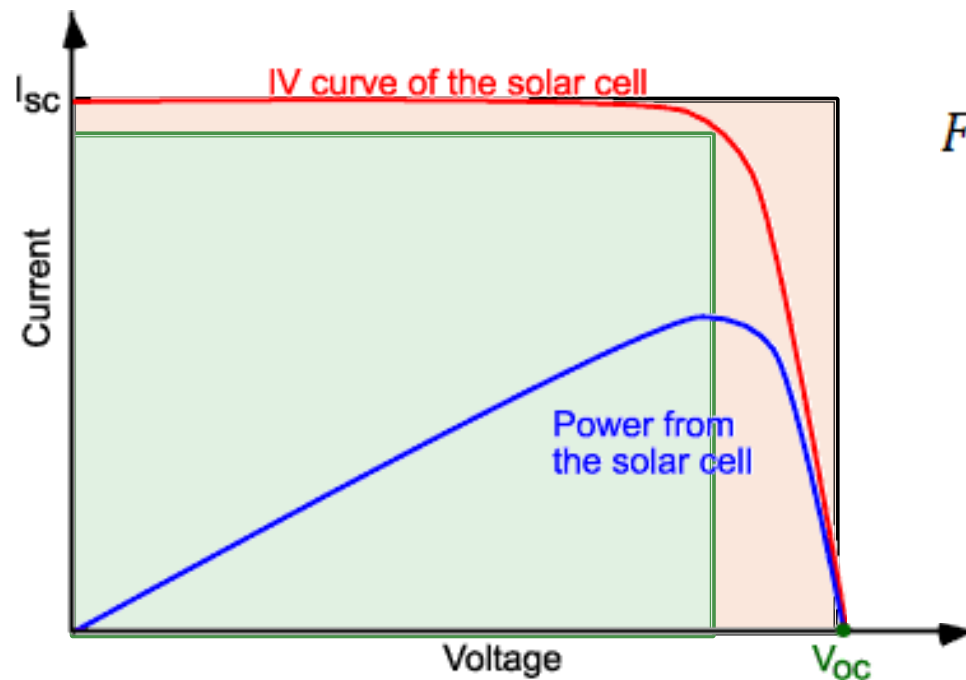
IV characteristic: **Maximum power**



SOLAR CELL OPERATION

Solar cell parameters

IV characteristic: **Fill factor** (FF)



$$FF = \frac{V_{MP} I_{MP}}{V_{OC} I_{SC}}$$

SOLAR CELL OPERATION

Solar cell parameters

Efficiency (η) is the fraction of incident power which is converted to electricity

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

SOLAR CELL OPERATION

Solar cell parameters

Resistive effects

- Characteristic resistance
- Parasitic resistance

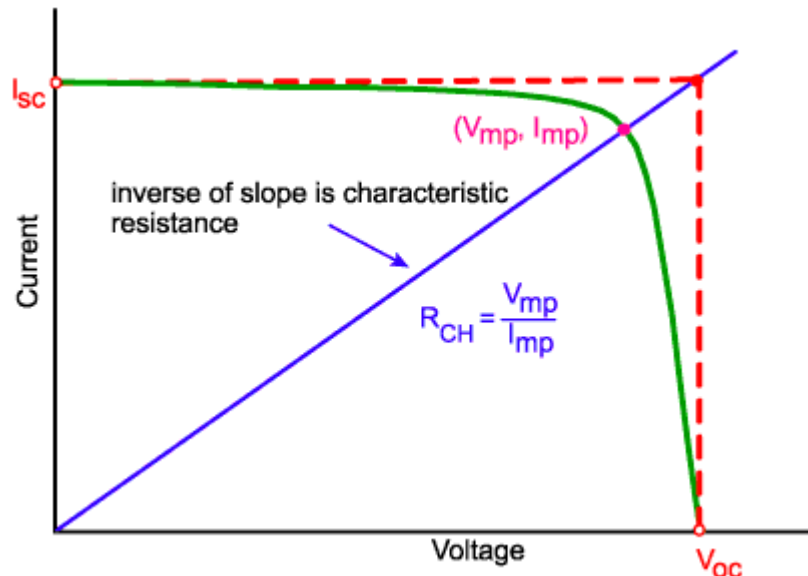
SOLAR CELL OPERATION

Solar cell parameters

Resistive effects

- Characteristic resistance

Maximum power transfer is $R_{\text{LOAD}} = R_{\text{CH}}$



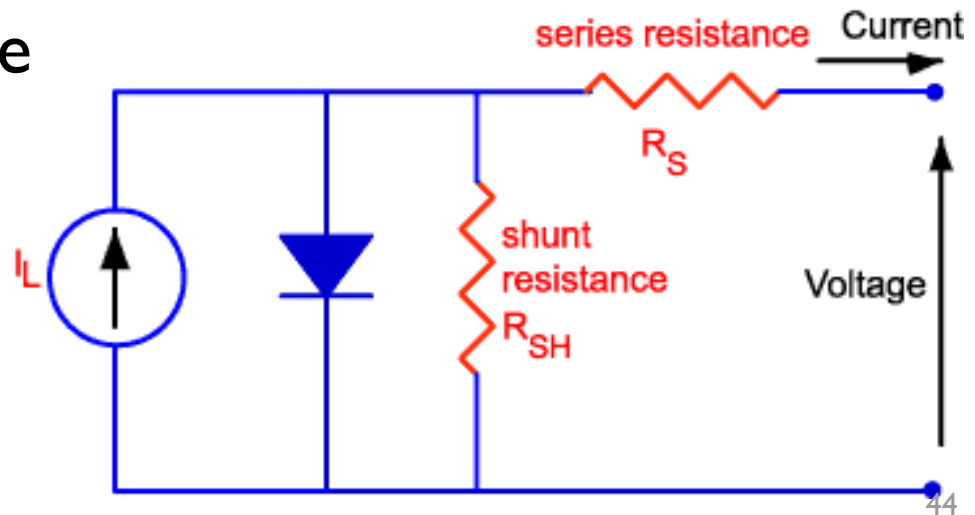
$$R_{CH} = \frac{V_{MP}}{I_{MP}} = \frac{V_{OC}}{I_{SC}}$$

SOLAR CELL OPERATION

Solar cell parameters

Resistive effects

- Characteristic resistance
- **Parasitic resistance**
 - Series resistance
 - Shunt resistance



SOLAR CELL OPERATION

Solar cell parameters

Resistive effects

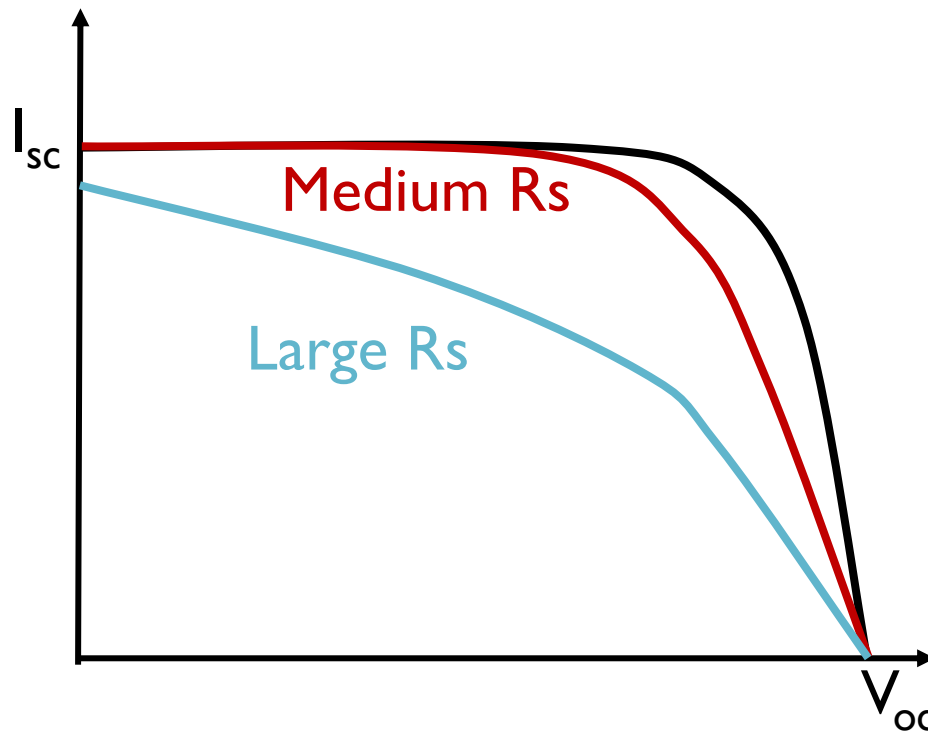
- Characteristic resistance
- Parasitic resistance
 - Series resistance
 - Shunt resistance

$$I = I_L - I_0 \exp \left[\frac{q(V - IR_S)}{nkT} \right] - \frac{V + IR_S}{R_{SH}}$$

SOLAR CELL OPERATION

Effect of the **series resistance**

$$FF' = FF(1 - r_s) \quad \text{with } r_s = \frac{R_s}{R_{CH}}$$

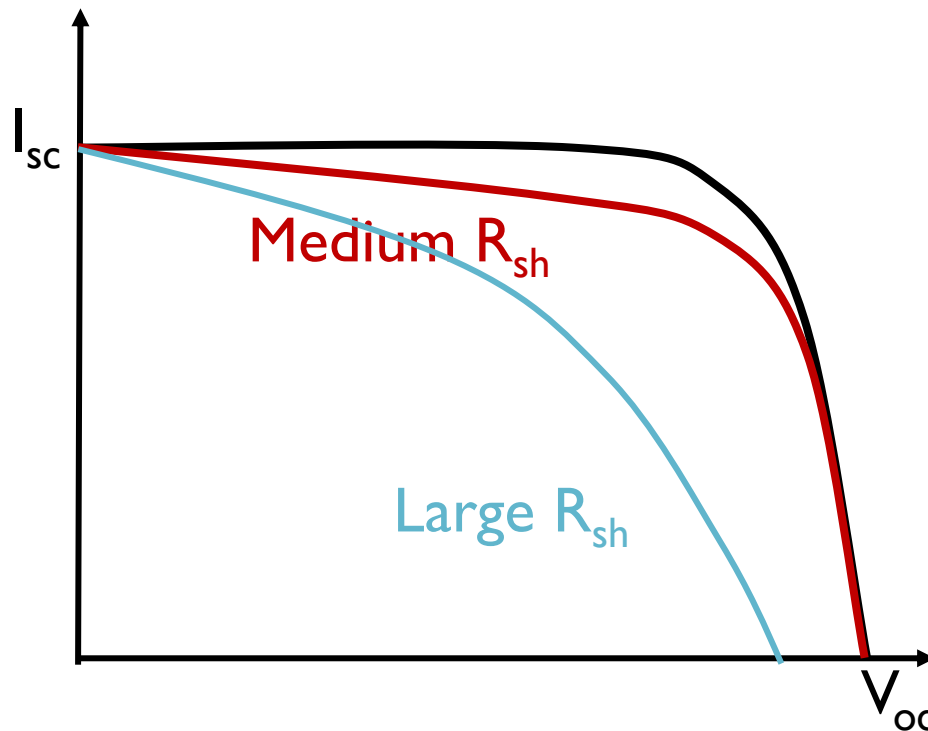


Slope of the I-V curve near V_{oc} gives indication about R_s

SOLAR CELL OPERATION

Effect of the shunt resistance

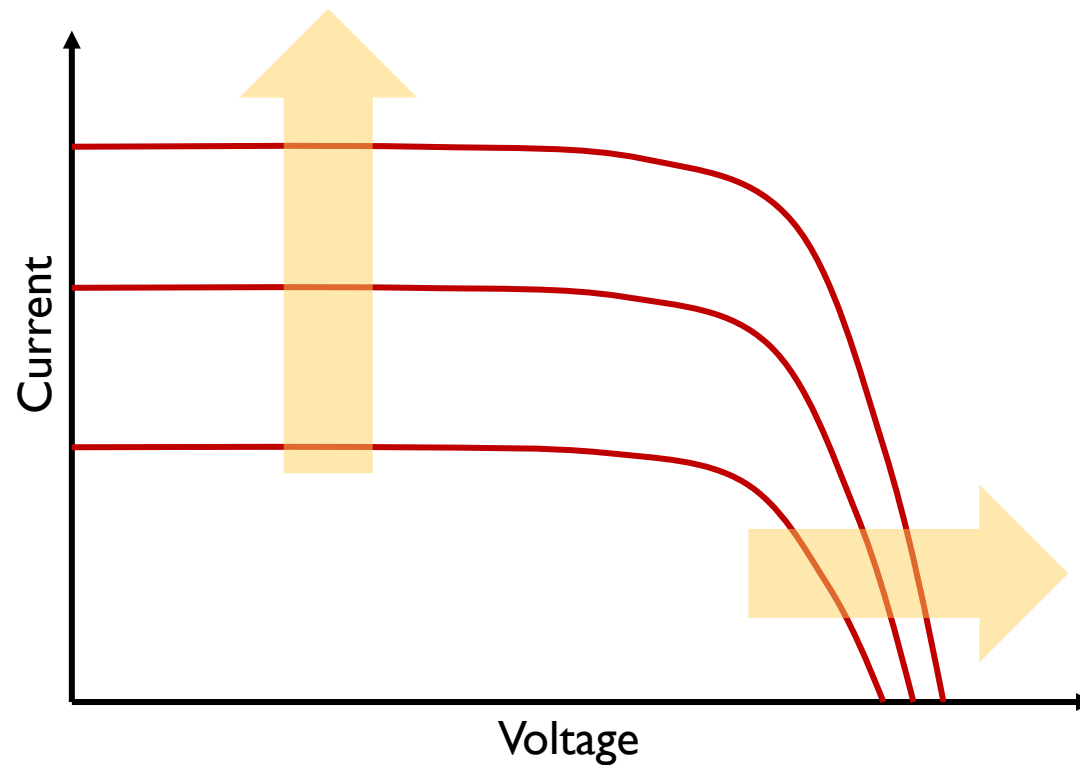
$$FF_{SH} = FF_0 \left(1 - \frac{1}{r_{SH}} \right) \quad \text{with} \quad r_{SH} = \frac{R_{SH}}{R_{CH}}$$



Slope of the I-V curve near I_{sc} gives indication about R_{sh}

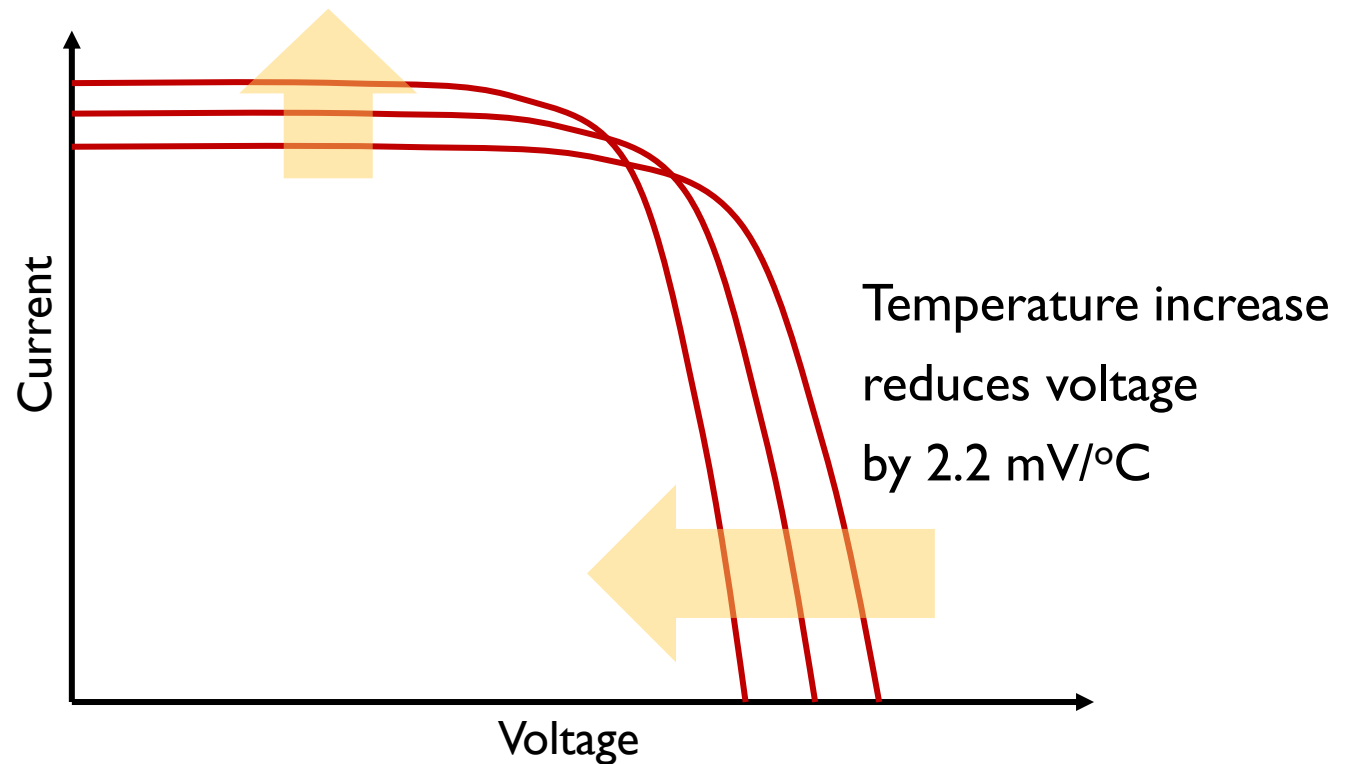
SOLAR CELL OPERATION

Effect of irradiation



SOLAR CELL OPERATION

Effect of temperature

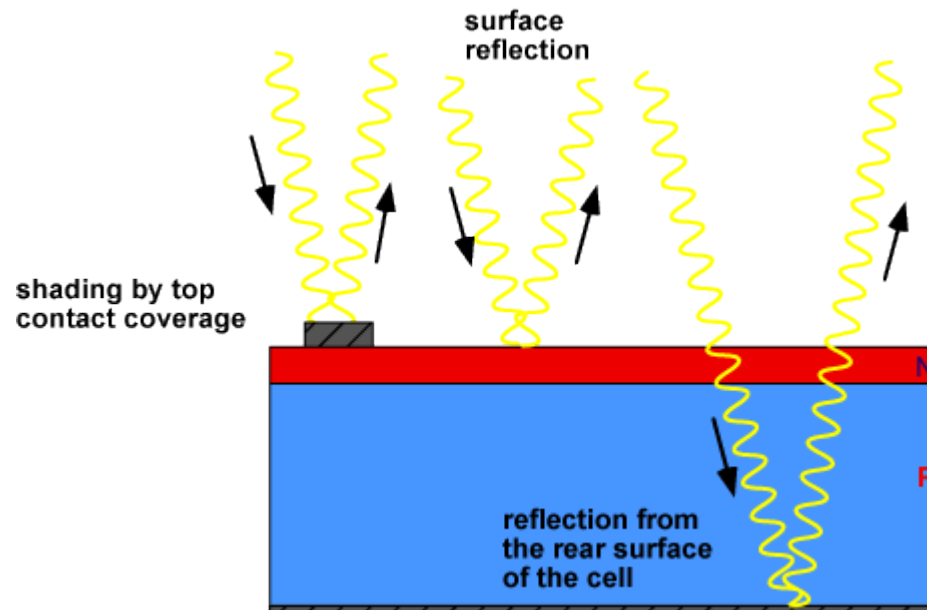


Best Research-Cell Efficiencies



DESIGN OF Si SOLAR CELL

Optical losses - light which could have generated an electron-hole pair, but does not, because the light is reflected from the front surface, or because it is not absorbed in the solar cell.



DESIGN OF Si SOLAR CELL

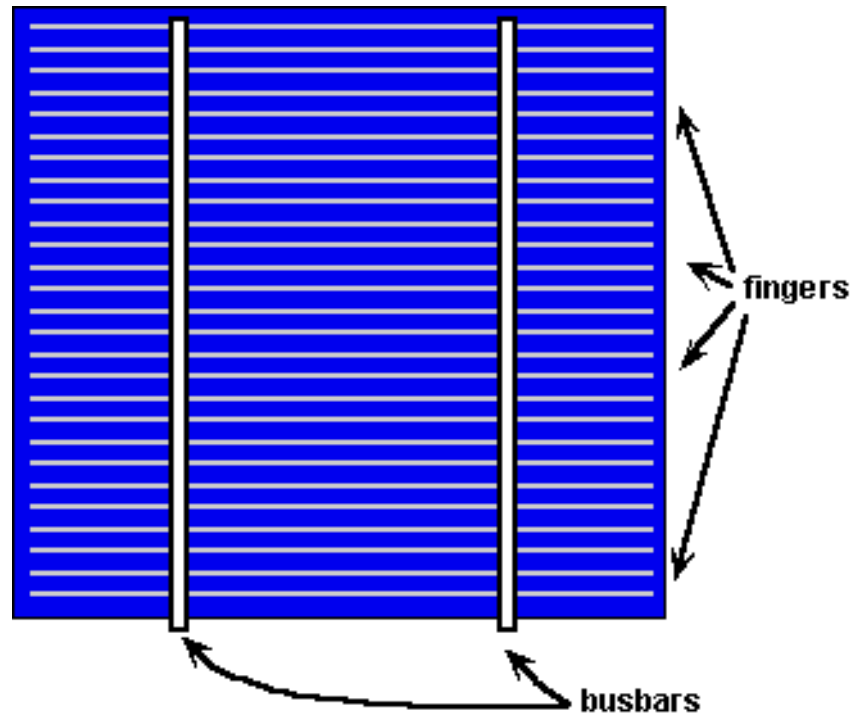
Optical losses - light which could have generated an electron-hole pair, but does not, because the light is reflected from the front surface, or because it is not absorbed in the solar cell.

- Top contact shading
- Top surface reflection
- Not enough optical path for photon absorption

DESIGN OF Si SOLAR CELL

Optical losses

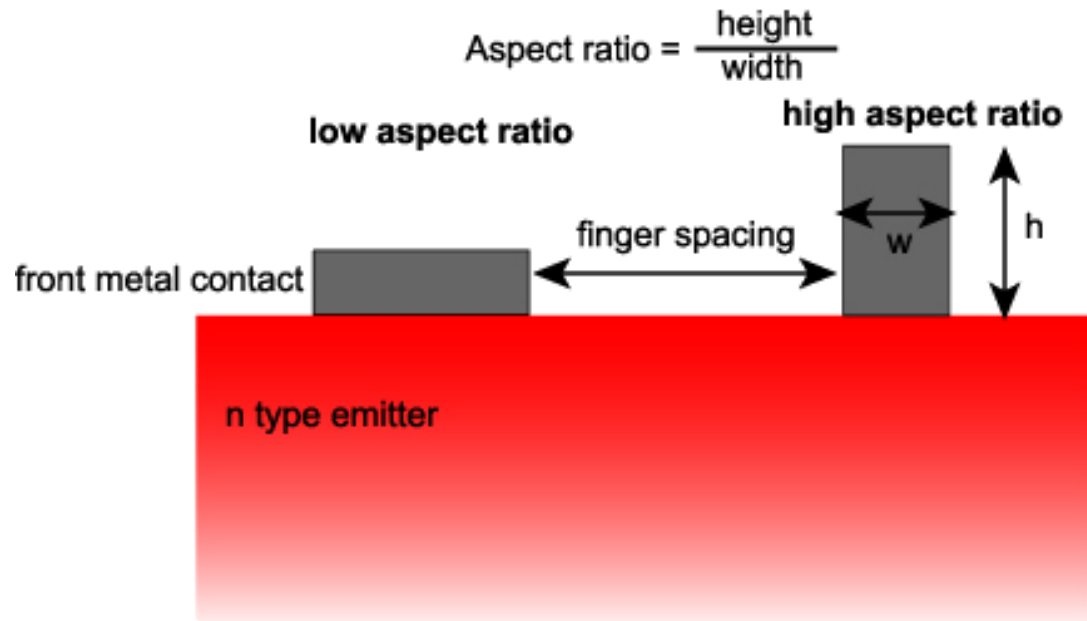
Reduce **shading** from top contacts



DESIGN OF Si SOLAR CELL

Optical losses

Reduce **shading** from top contacts



DESIGN OF Si SOLAR CELL

Optical losses

Reduce **shading** from top contacts

- May increase series resistance
- Other emitter contact concepts becoming fashionable (buried or back contacts)



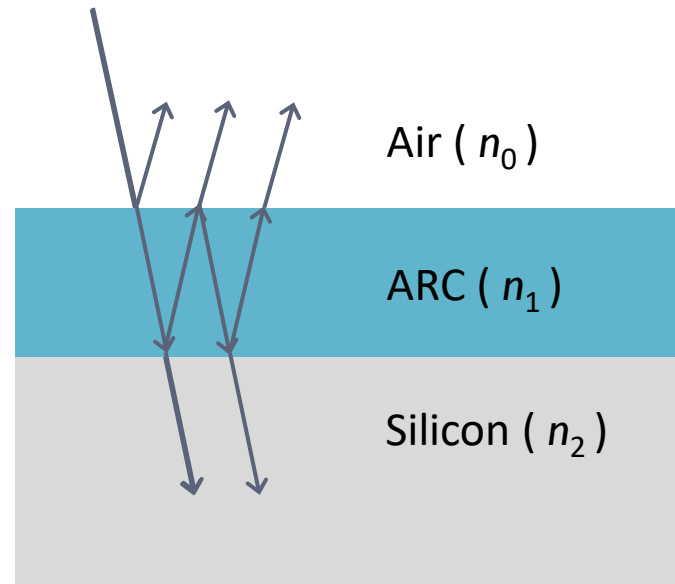
DESIGN OF Si SOLAR CELL

Optical losses

Anti-reflective coating

$$n_1 d = \frac{\lambda}{4}$$

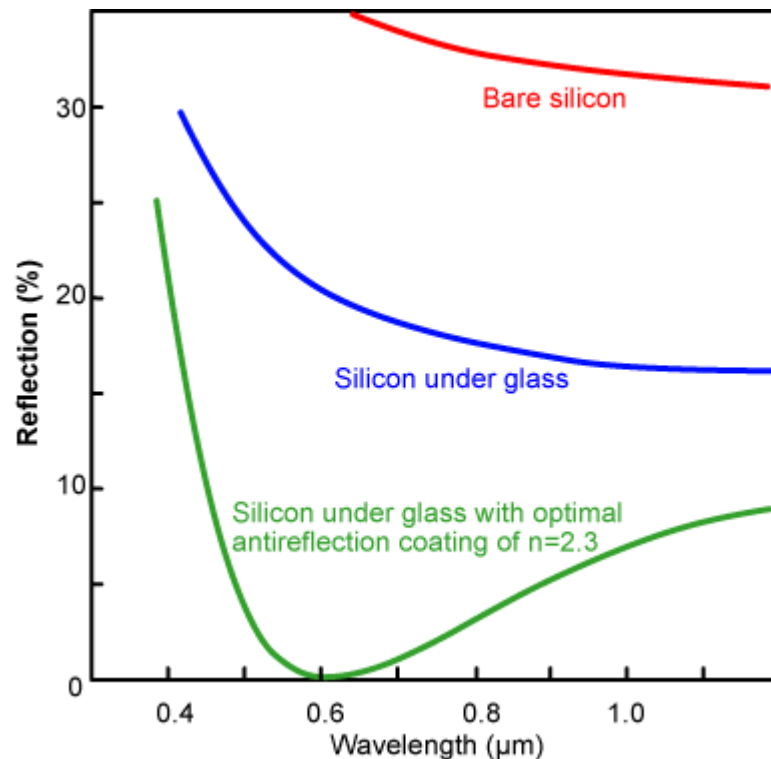
$$R = \left(\frac{n_1^2 - n_0 n_2}{n_1^2 + n_0 n_2} \right)^2$$



DESIGN OF Si SOLAR CELL

Optical losses

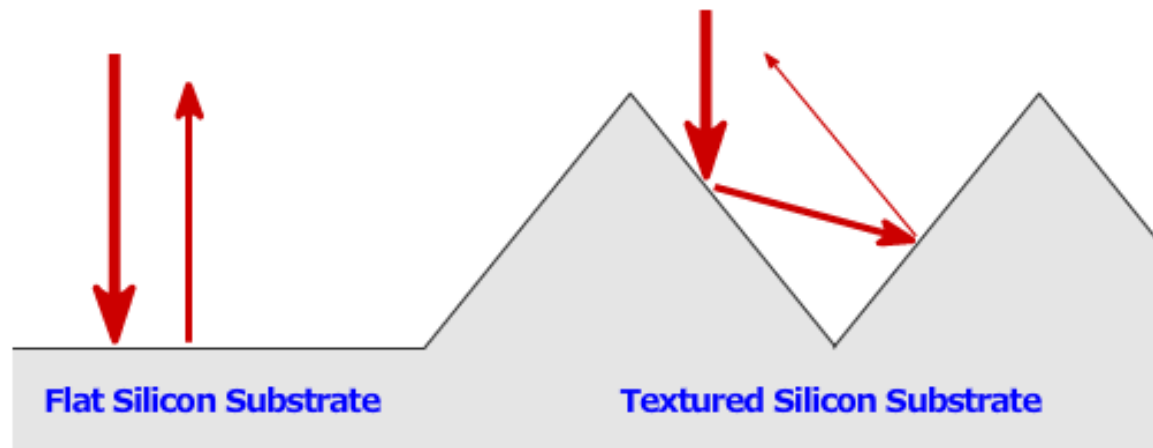
Anti-reflective coating



DESIGN OF Si SOLAR CELL

Optical losses

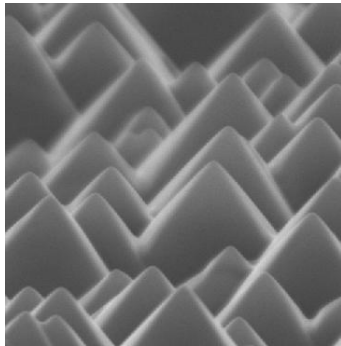
Surface **texturing**



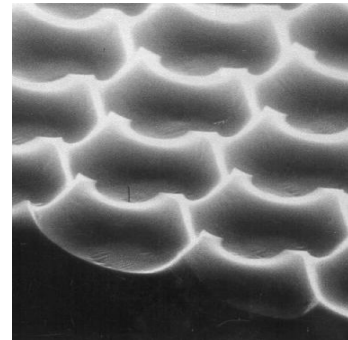
DESIGN OF Si SOLAR CELL

Optical losses

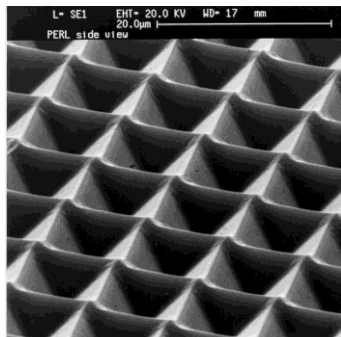
Surface **texturing**



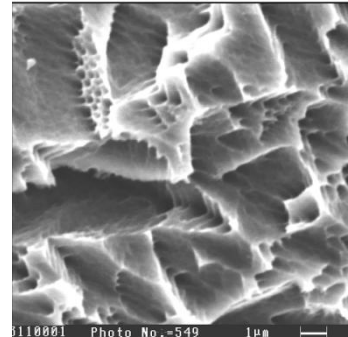
Single crystal:
Random pyramids, by
etching



Multi crystal:
texturing by
photolithography



Single crystal:
Inverted pyramids, by
etching

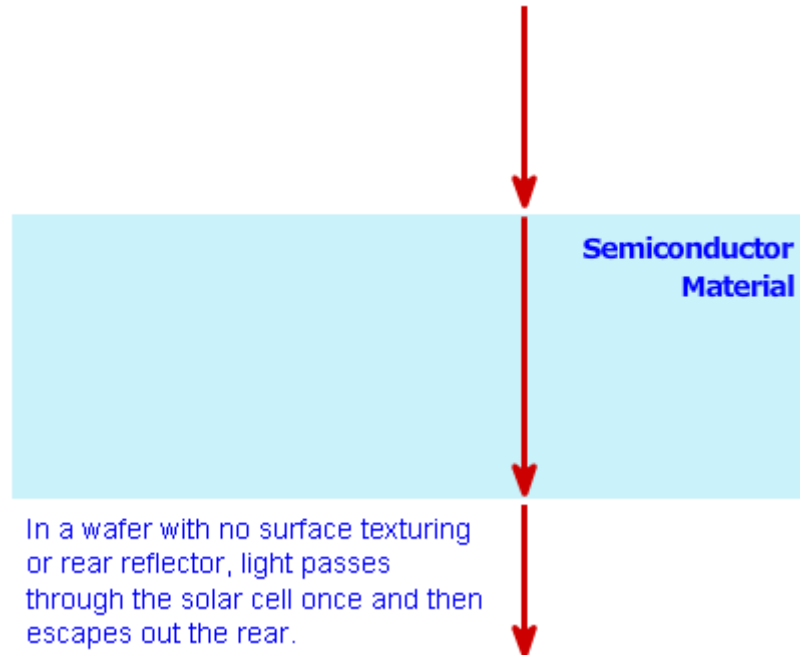


Multi crystal:
texturing by
macroporous silicon

DESIGN OF Si SOLAR CELL

Optical losses

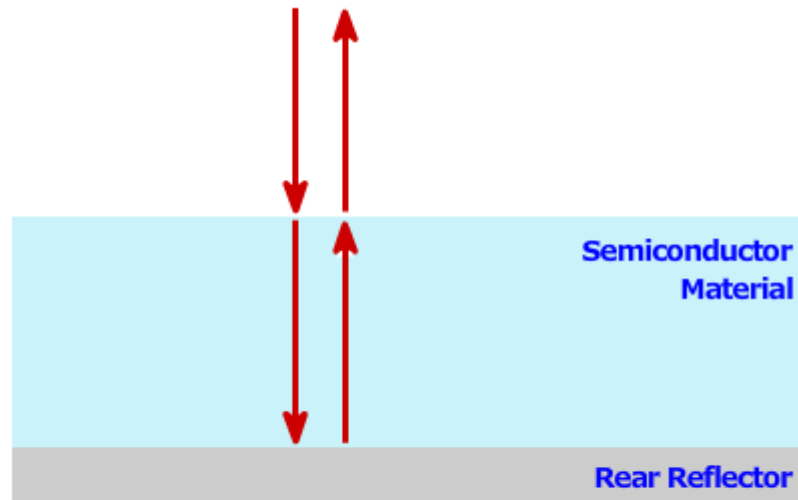
Light **trapping**: increase optical length



DESIGN OF Si SOLAR CELL

Optical losses

Light **trapping**: increase optical length

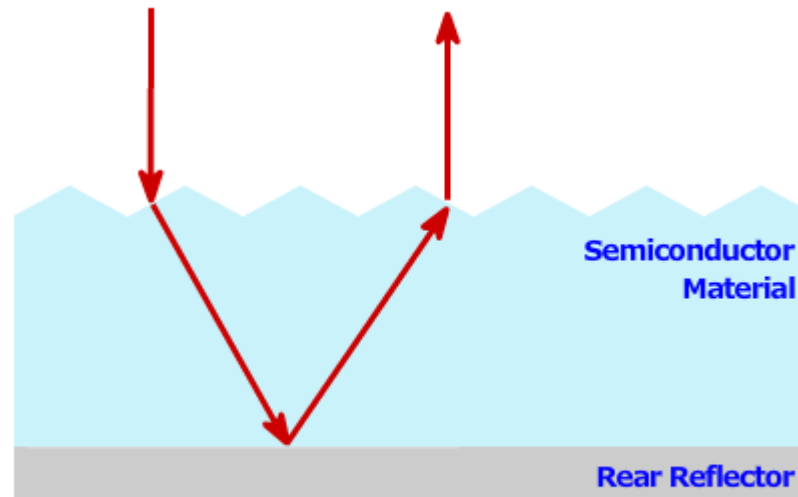


When a rear reflector is added,
the optical path length is twice
the physical device thickness.

DESIGN OF Si SOLAR CELL

Optical losses

Light **trapping**: increase optical length



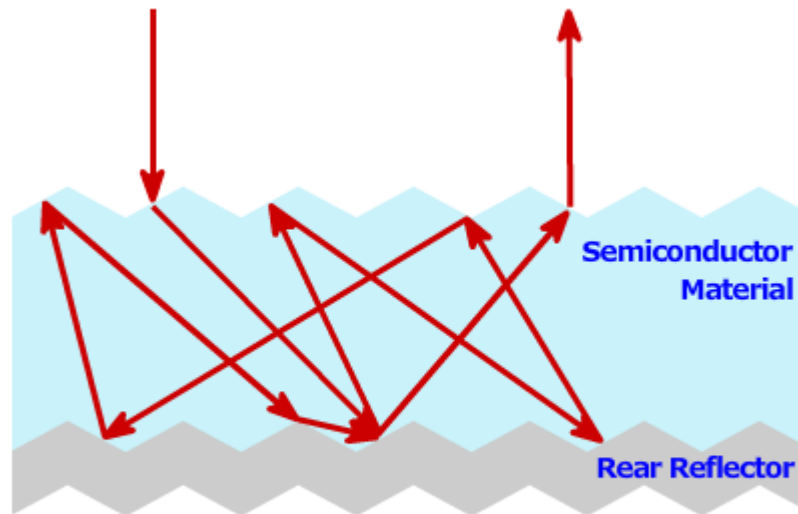
Surface texturing increases the path length but light escapes after two passes through the solar cell.

Snell's law of refraction: $n_1 \sin \theta_1 = n_2 \sin \theta_2$

DESIGN OF Si SOLAR CELL

Optical losses

Light **trapping**: increase optical length



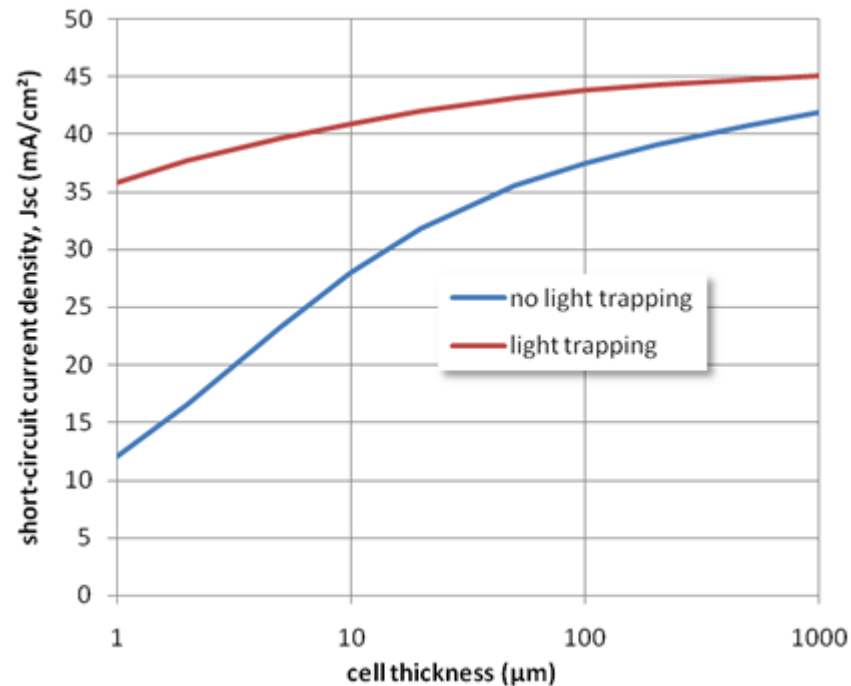
Front and rear surface texturing
can trap light for multiple passes
due to total internal reflection.

Snell's law of refraction: $n_1 \sin \theta_1 = n_2 \sin \theta_2$

DESIGN OF Si SOLAR CELL

Optical losses

Light **trapping**: increase optical length



Snell's law of refraction: $n_1 \sin \theta_1 = n_2 \sin \theta_2$

DESIGN OF Si SOLAR CELL

Optical losses

In summary:

- Reduce front contact coverage
- Anti-reflective coating
- Surface texturing
- Light trapping

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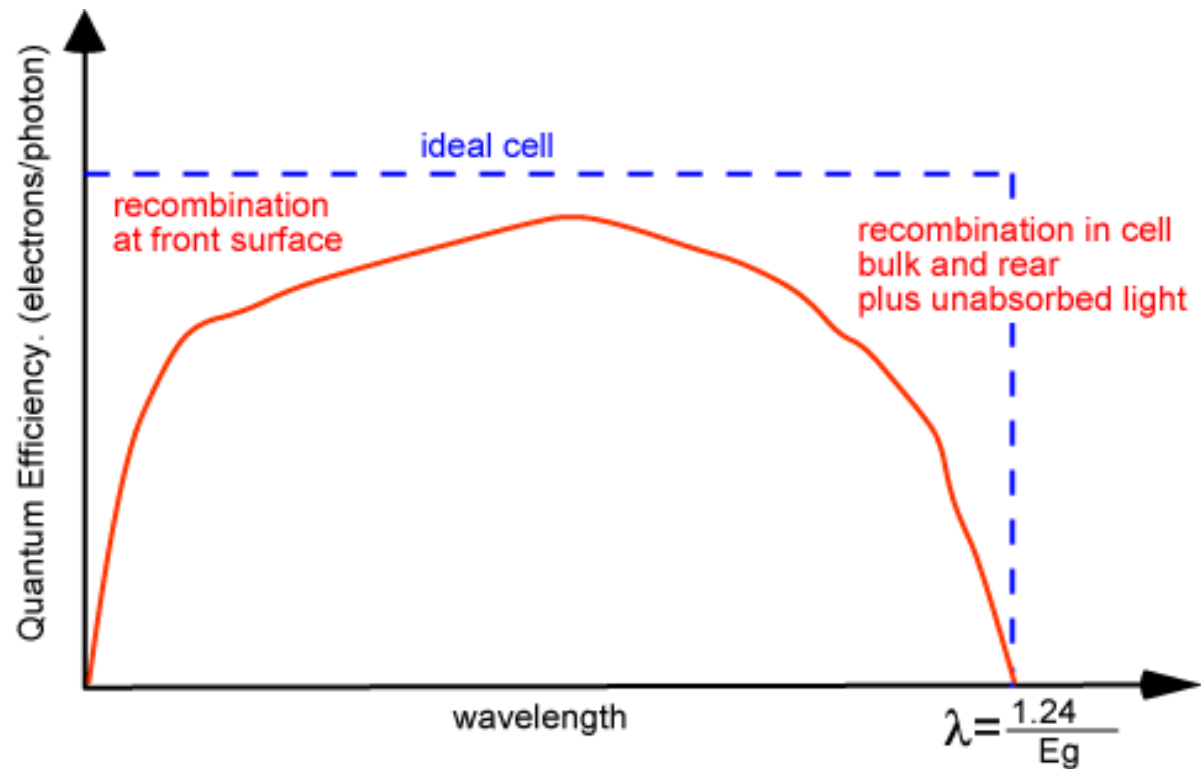
Recombination losses

Optimal conditions:

- the carrier must be generated within a **diffusion length** of the junction;
- the carrier must be generated closer to the junction than to *hazardous* recombination sites (**unpassivated** surface, grain boundary,...)

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Recombination losses

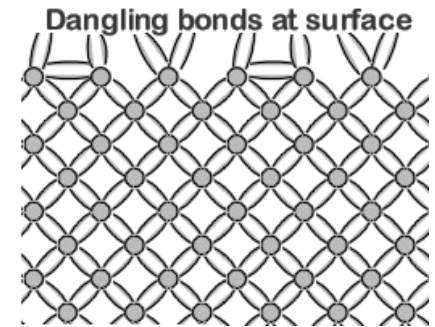


Design of silicon solar cells

Recombination losses:

Surface **passivation**

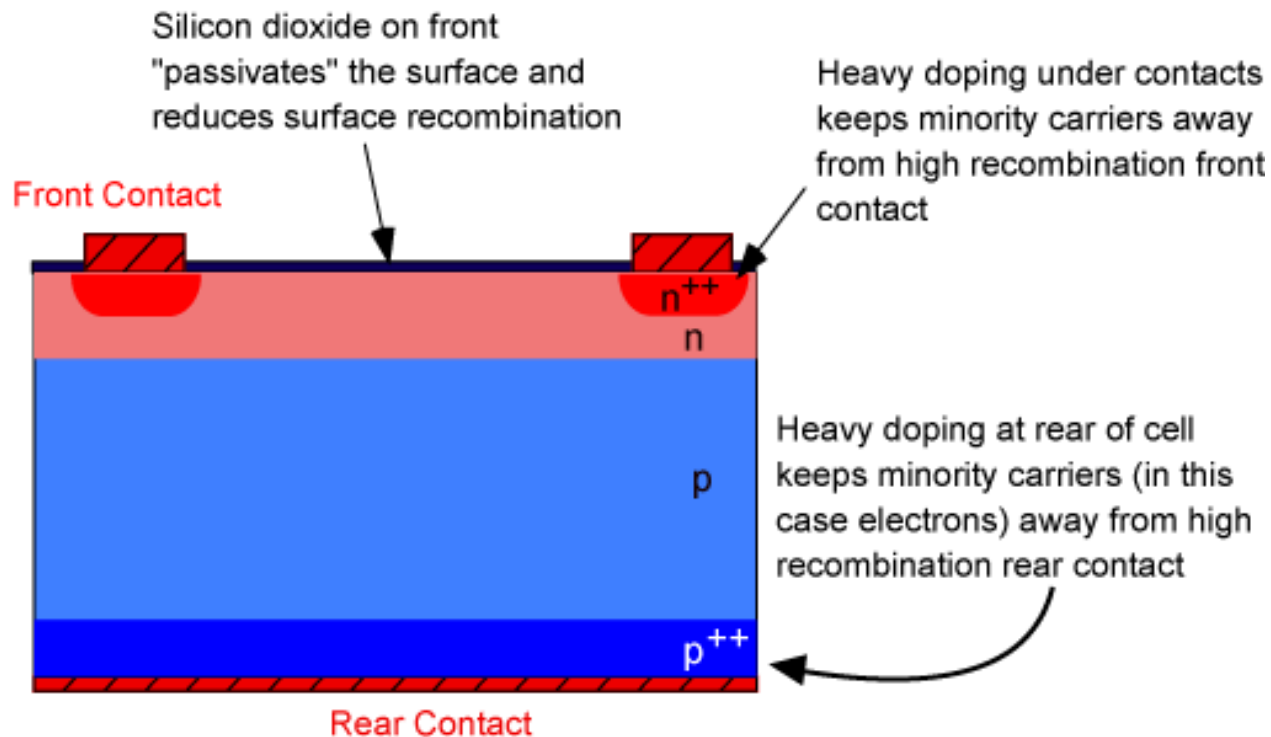
- Reducing the number of **dangling bonds** by growing a SiO_2 or SiN thin film on the surface
(also for anti-reflection coating; notice that it is an electric insulator)
- Increasing doping, creating a repelling field
(decreases diffusion length thus not suitable for charge collection region; useful closer to contacts, e.g. **Back Surface Field - BSF**)



Design of silicon solar cells

Recombination losses:

Surface **passivation**



Next class...

- How to **make** a practical photovoltaic module
- **Other** (non-silicon) technologies

And check <http://pvcdrom.pveducation.org/>