

A close-up photograph of a person's hands holding a rectangular, glowing blue photovoltaic cell. The cell has a fine grid pattern of thin lines and two prominent, thicker white busbars running diagonally across it. The background is dark and out of focus, showing some blurred lights and equipment, suggesting a laboratory or manufacturing setting.

PHOTOVOLTAICS

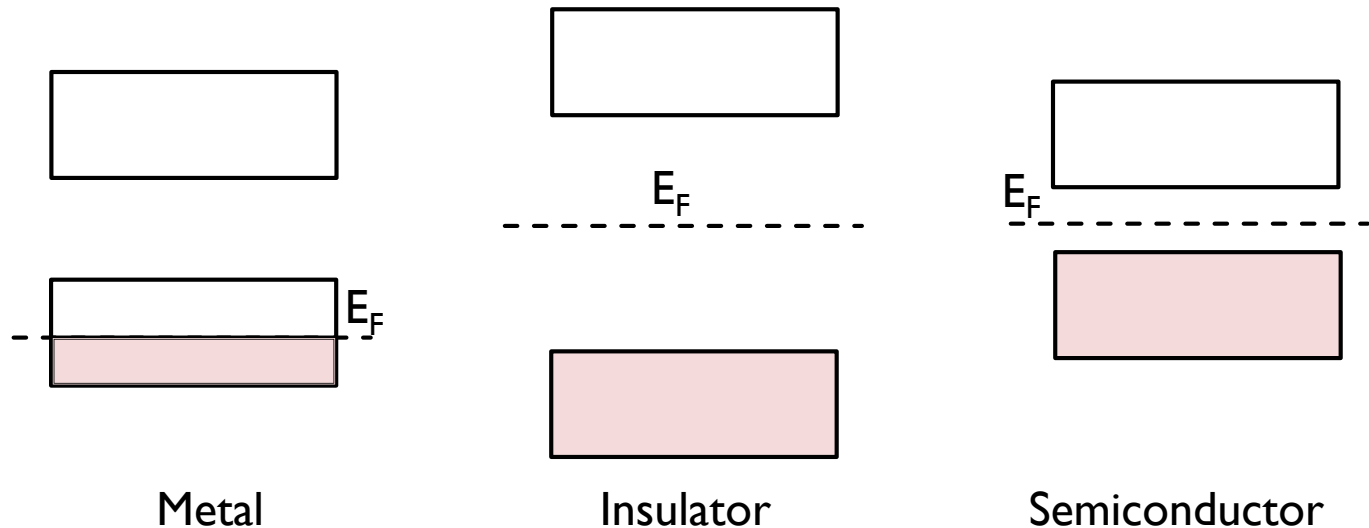
Fundamentals

PV FUNDAMENTALS

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

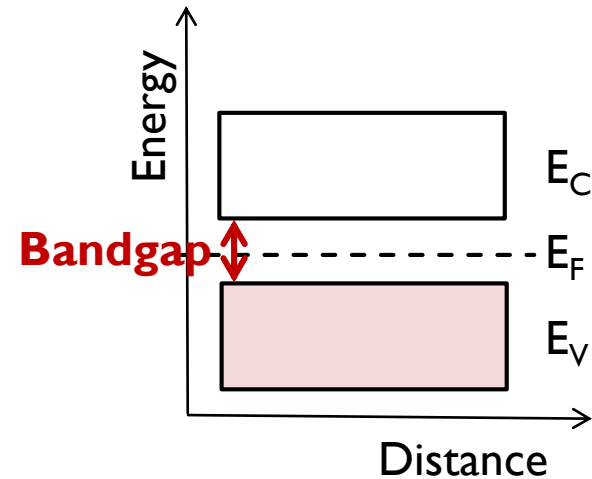
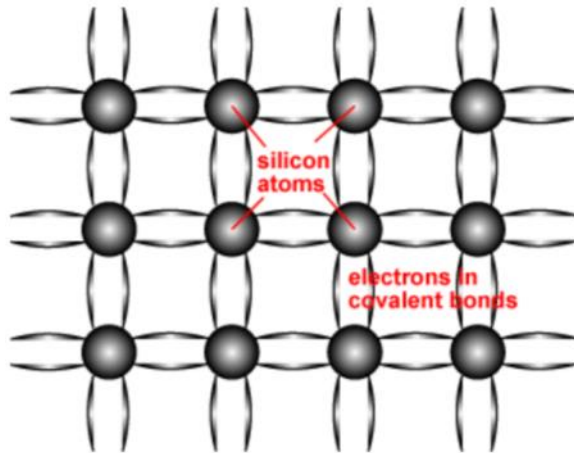
SEMICONDUCTOR BASICS

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



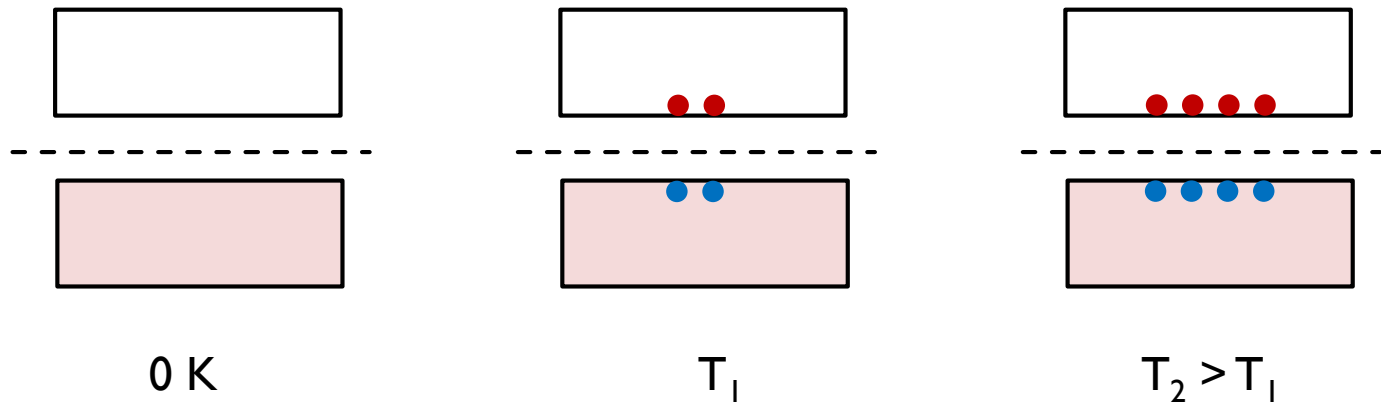
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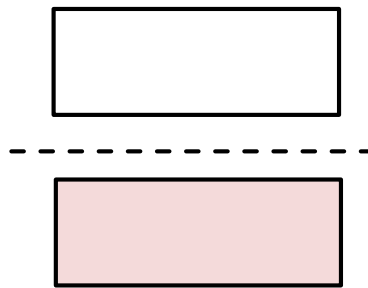
SEMICONDUCTOR BASICS

- Effect of temperature

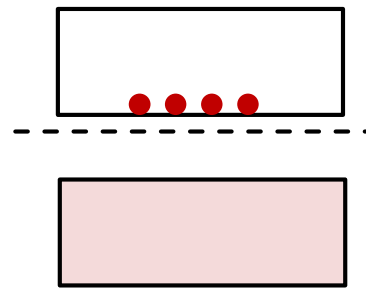


SEMICONDUCTOR BASICS

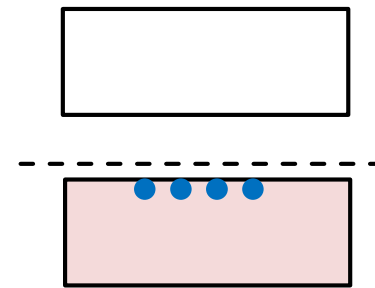
- Effect of doping



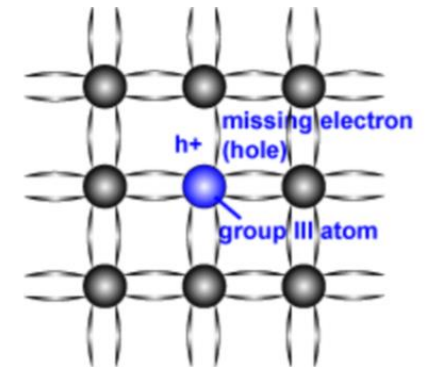
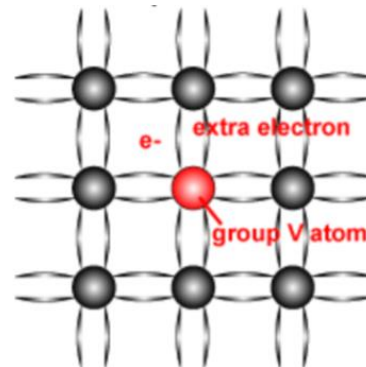
Intrinsic



N-doped

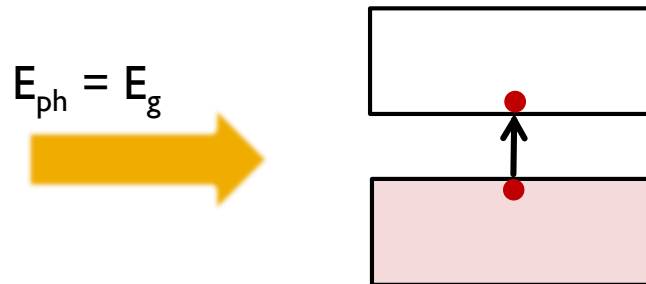


P-doped



SEMICONDUCTOR BASICS

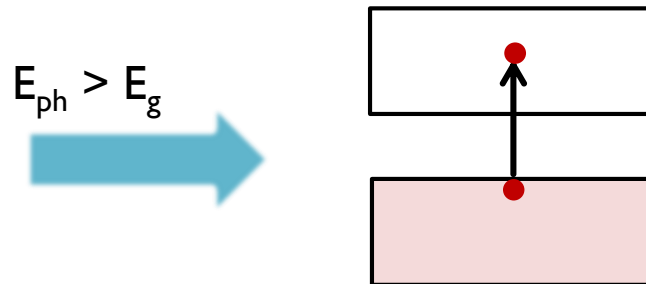
- **Absorption of light** depends on the energy of the photon (wavelength)



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

SEMICONDUCTOR BASICS

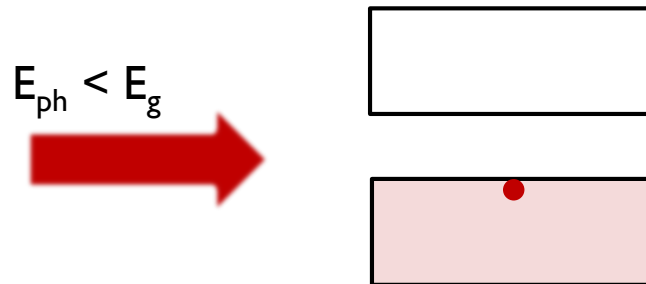
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SEMICONDUCTOR BASICS

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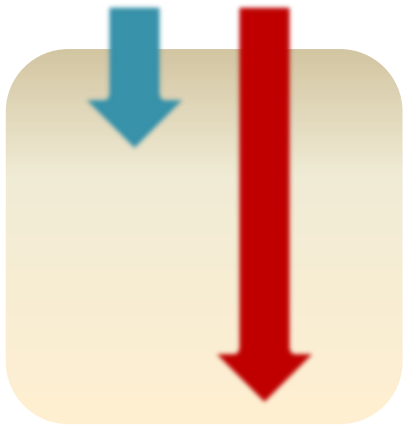


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SEMICONDUCTOR BASICS

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

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



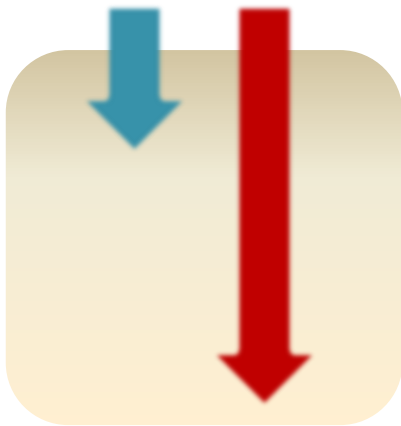
α is the absorption coefficient typically in cm^{-1}
 I_0 is the light intensity at the top surface.

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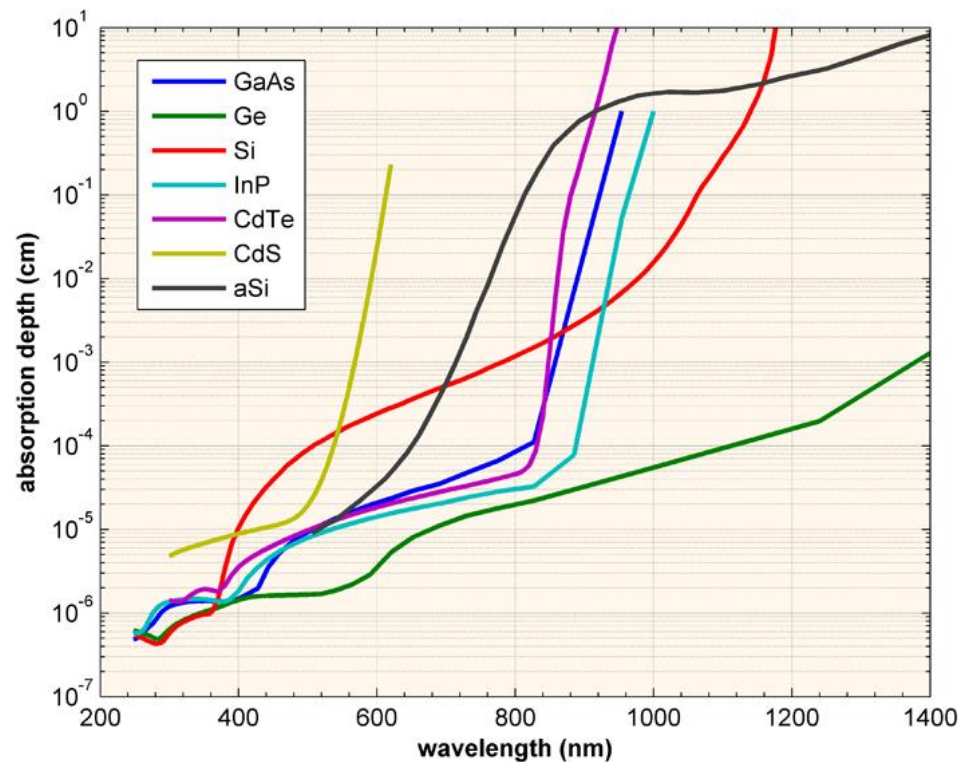
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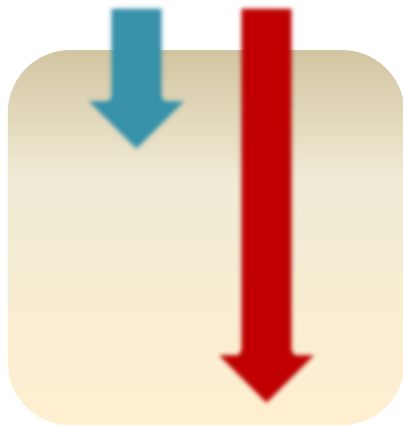
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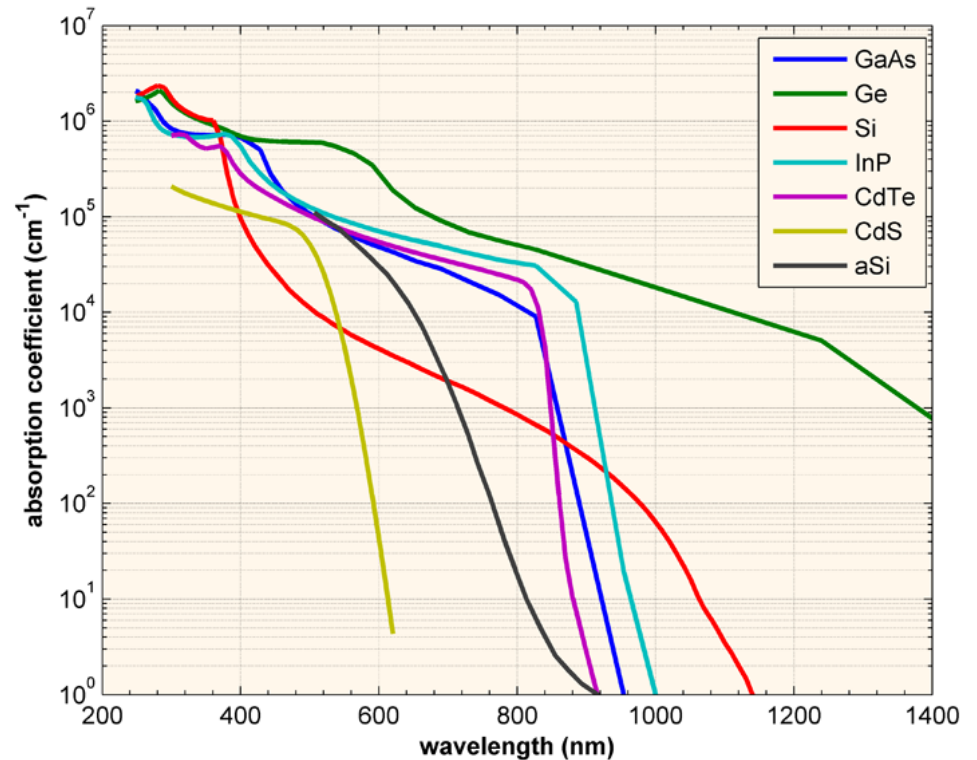
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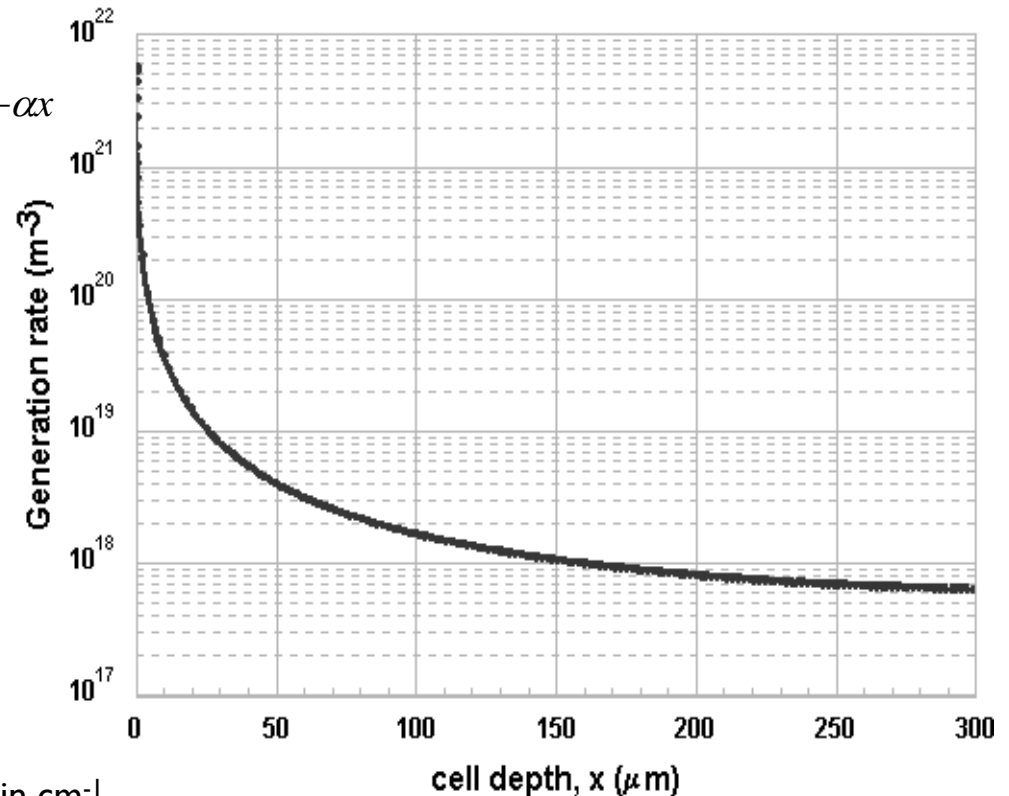
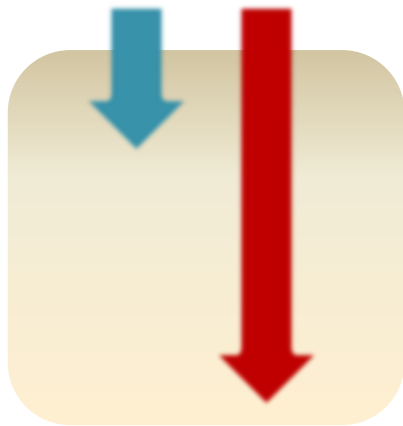
α is the absorption coefficient typically in cm^{-1}
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PV FUNDAMENTALS

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

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

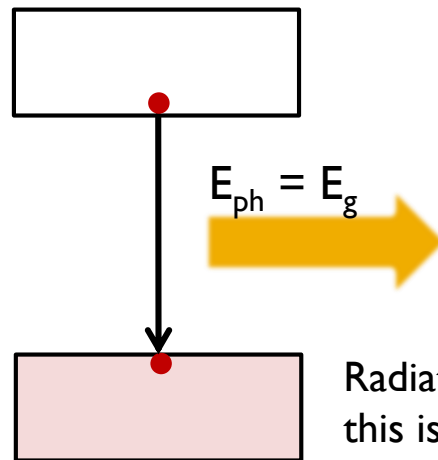


α is the absorption coefficient typically in cm^{-1}
 N_0 = photon flux at the surface (photons/unit-area/sec)

PV FUNDAMENTALS

Recombination may occur through...

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



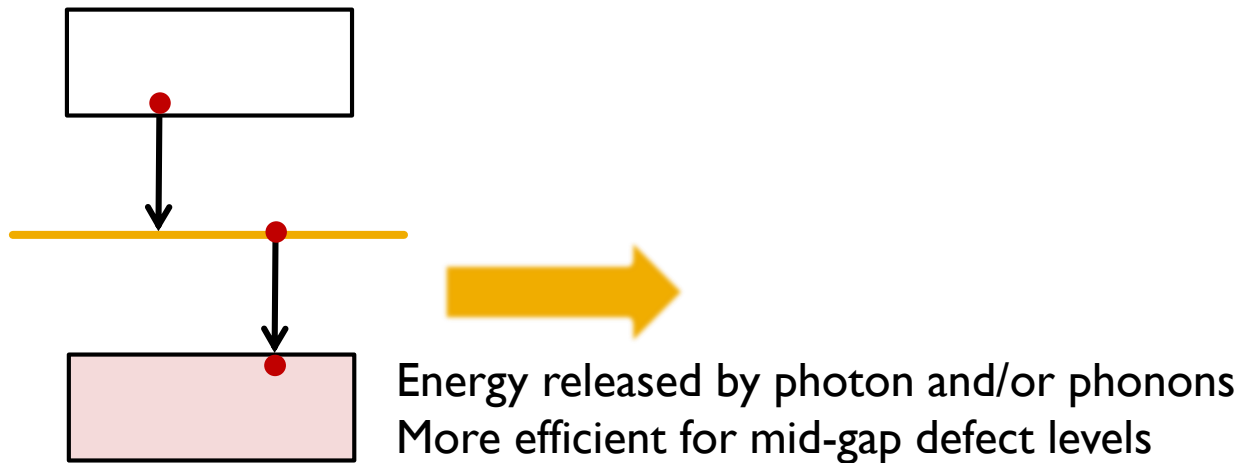
Radiated photon is weakly absorbed;
this is how LEDs work!!

Not very likely for indirect gap semiconductor like Si

SEMICONDUCTOR BASICS

Recombination may occur through...

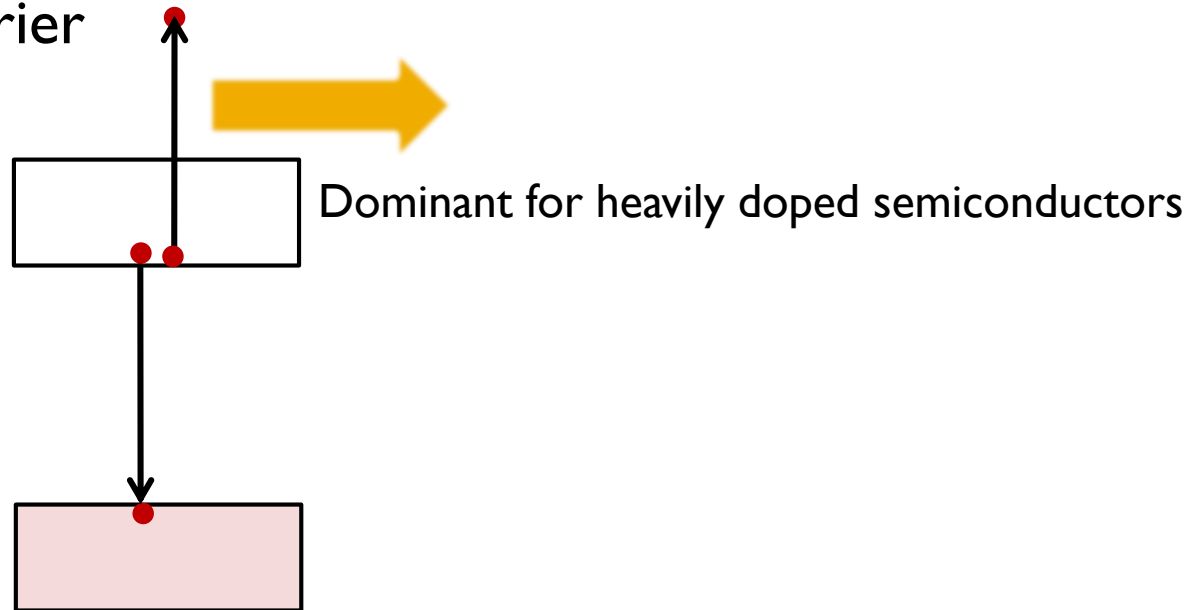
- **Shockley-Read-Hall recombination** – 2-step process: an electron is trapped in a defect level



SEMICONDUCTOR BASICS

Recombination may occur through...

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



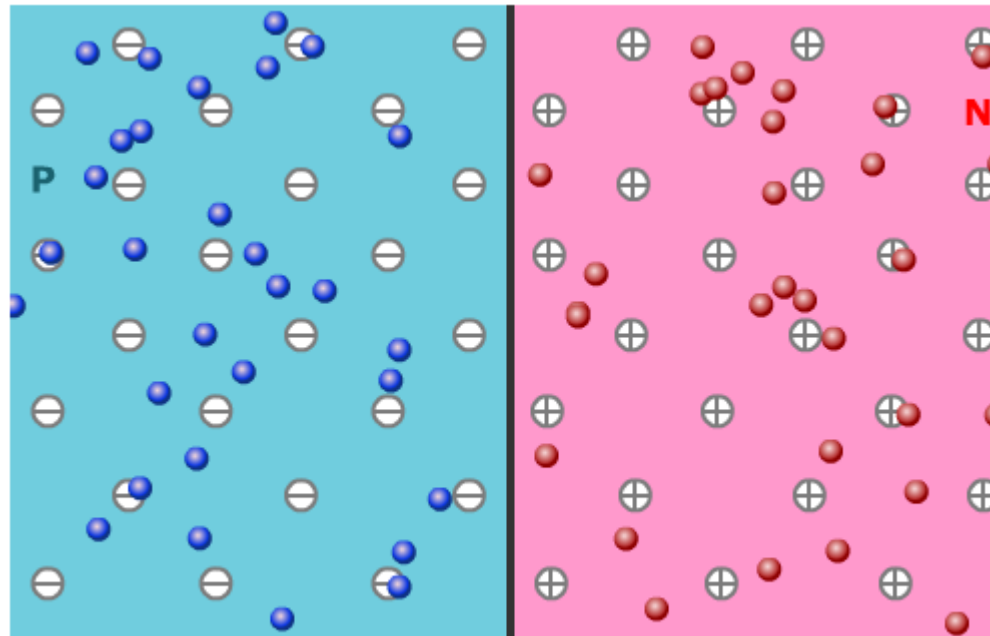
SEMICONDUCTOR BASICS

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

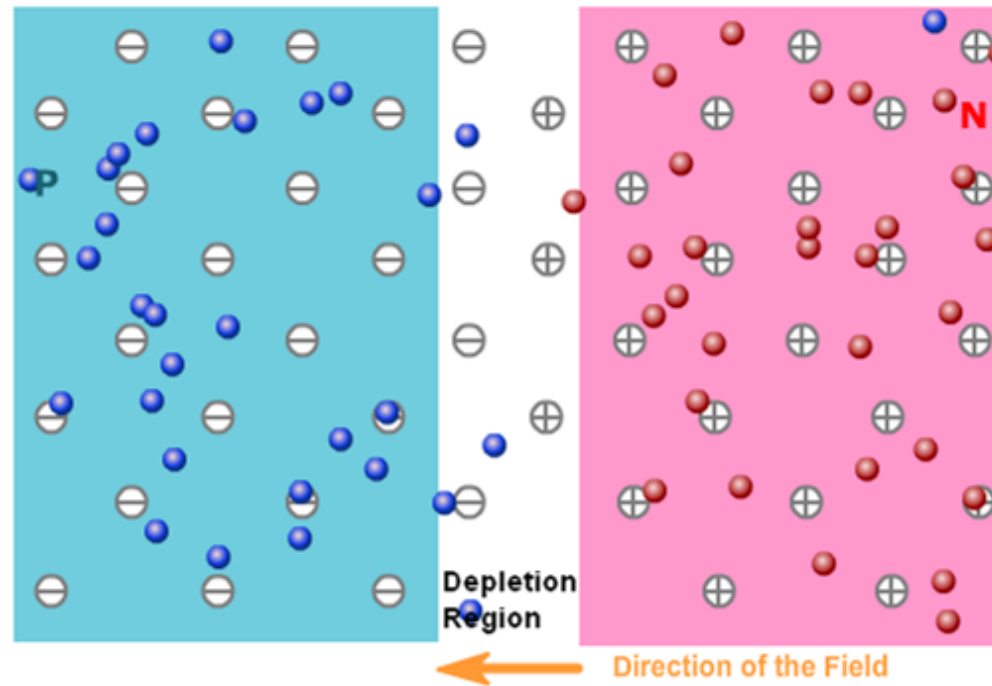
$$\tau = \frac{\Delta n}{R} \quad L = \sqrt{D\tau}$$

PN JUNCTION

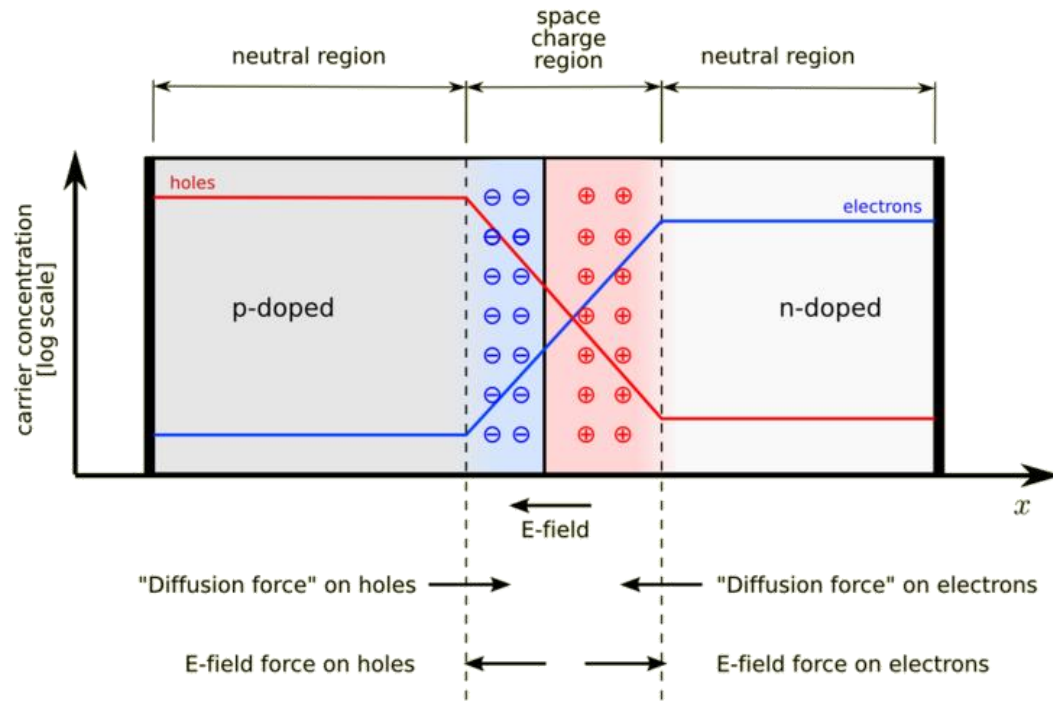


Imaginary Boundary

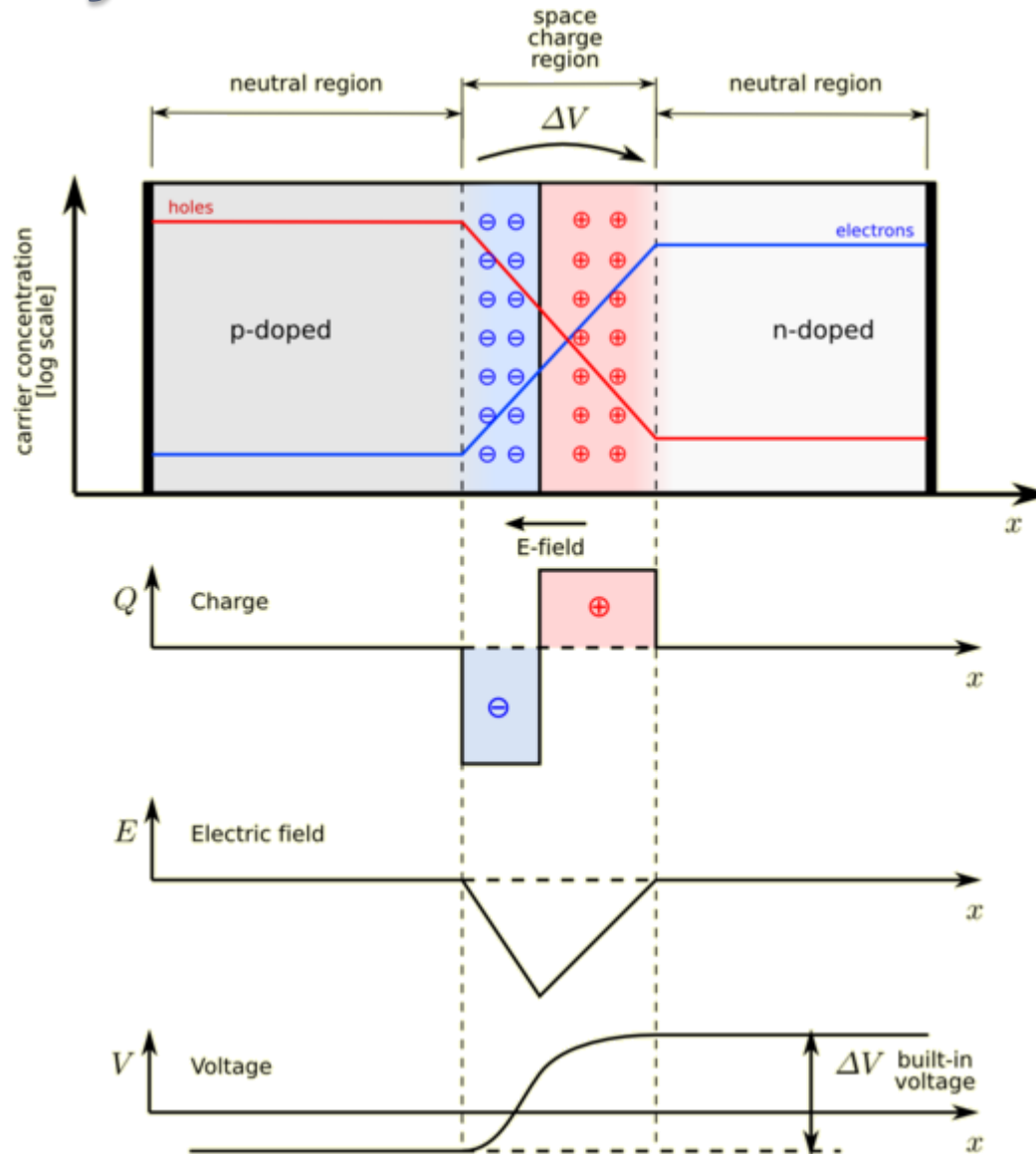
PN JUNCTION



PN JUNCTION



PN JUNCTION

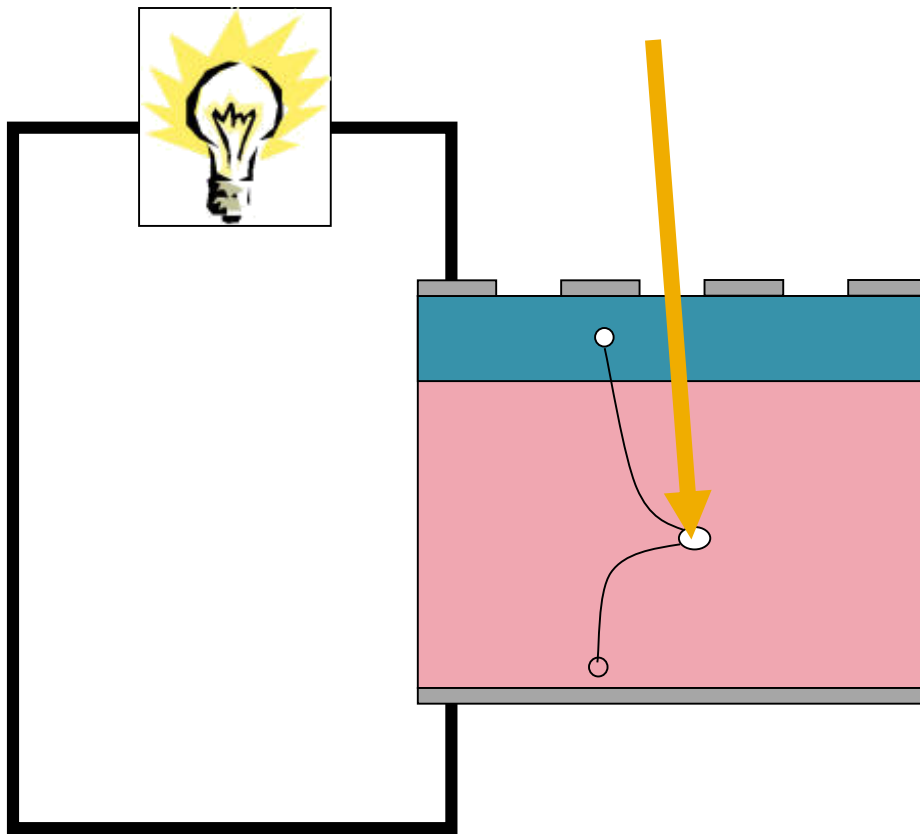


SOLAR CELL OPERATION

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.

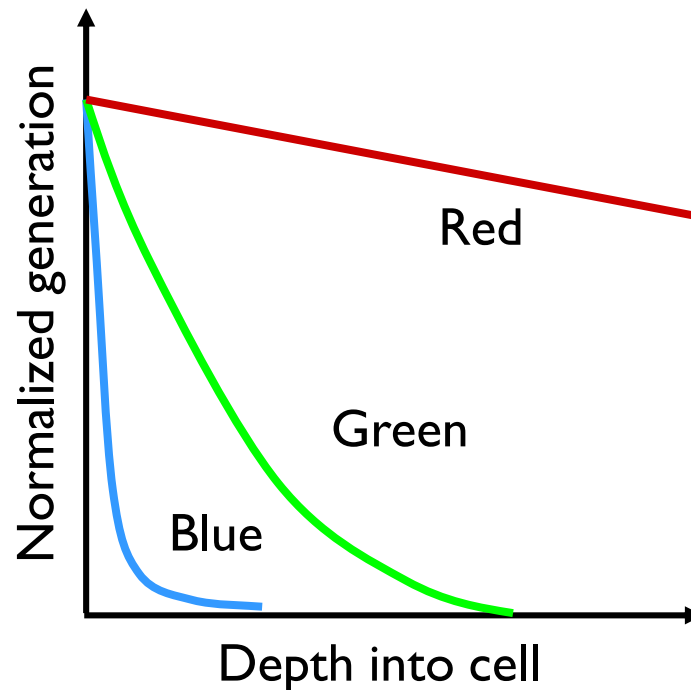
SOLAR CELL OPERATION



SOLAR CELL OPERATION

Basic steps:

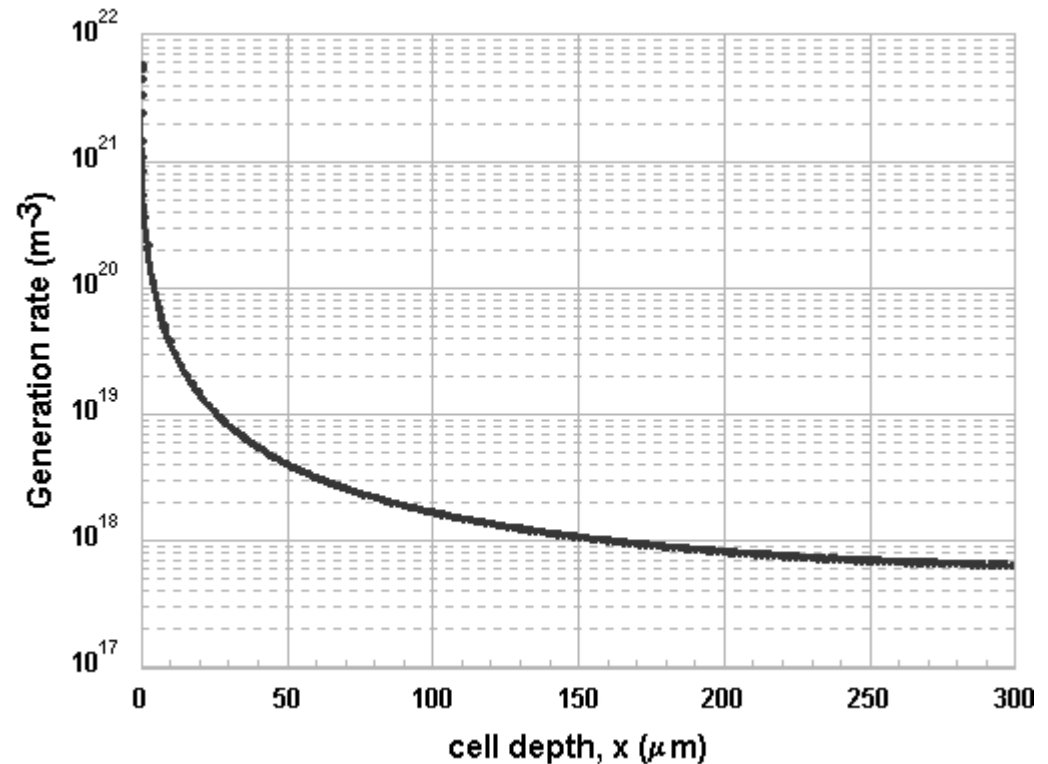
- the **generation** of light-generated carriers



SOLAR CELL OPERATION

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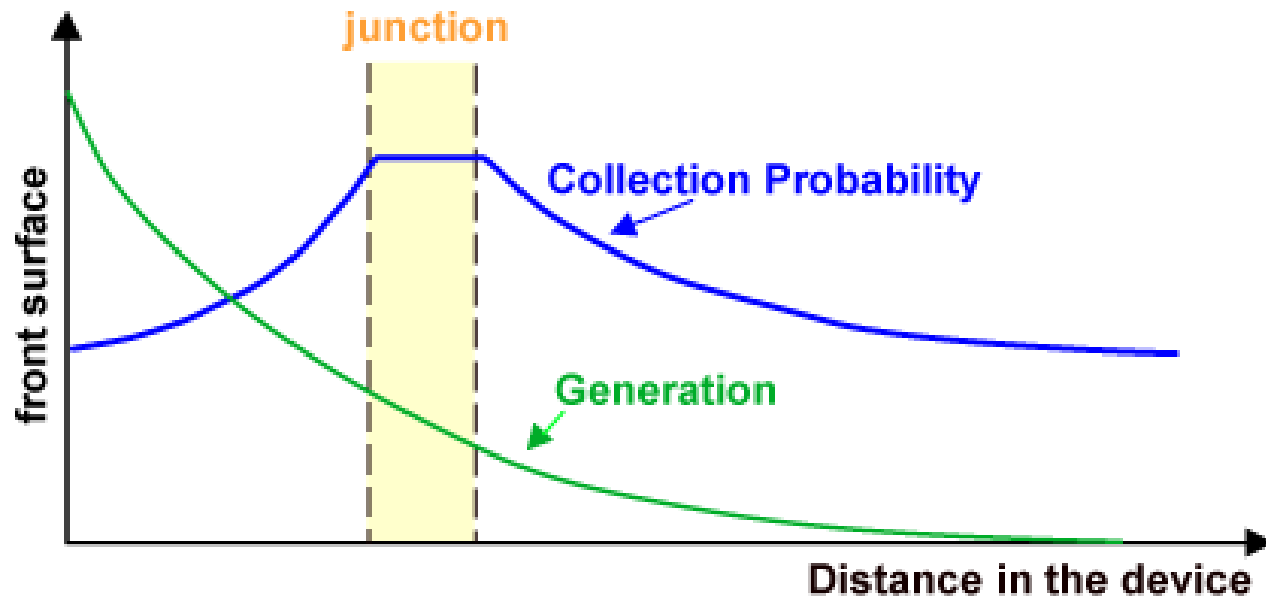
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SOLAR CELL OPERATION

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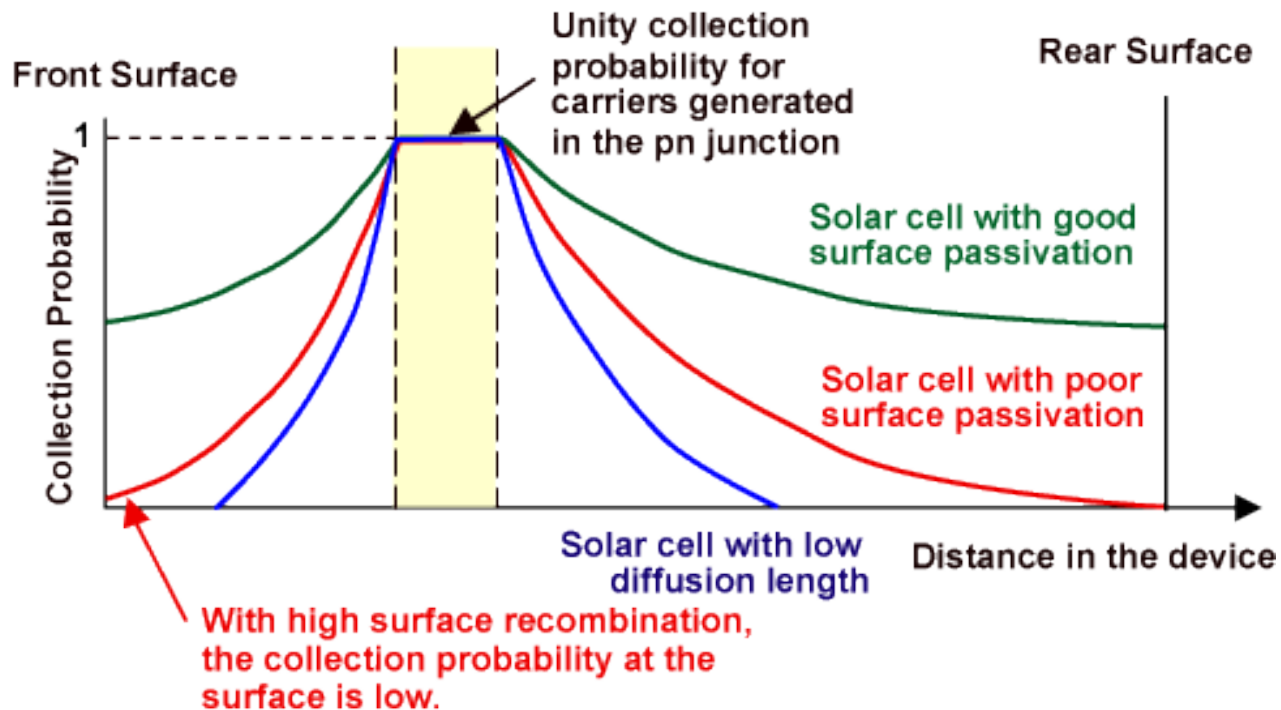
- the **collection** of the carriers



SOLAR CELL OPERATION

Basic steps:

- the **collection** of the carriers



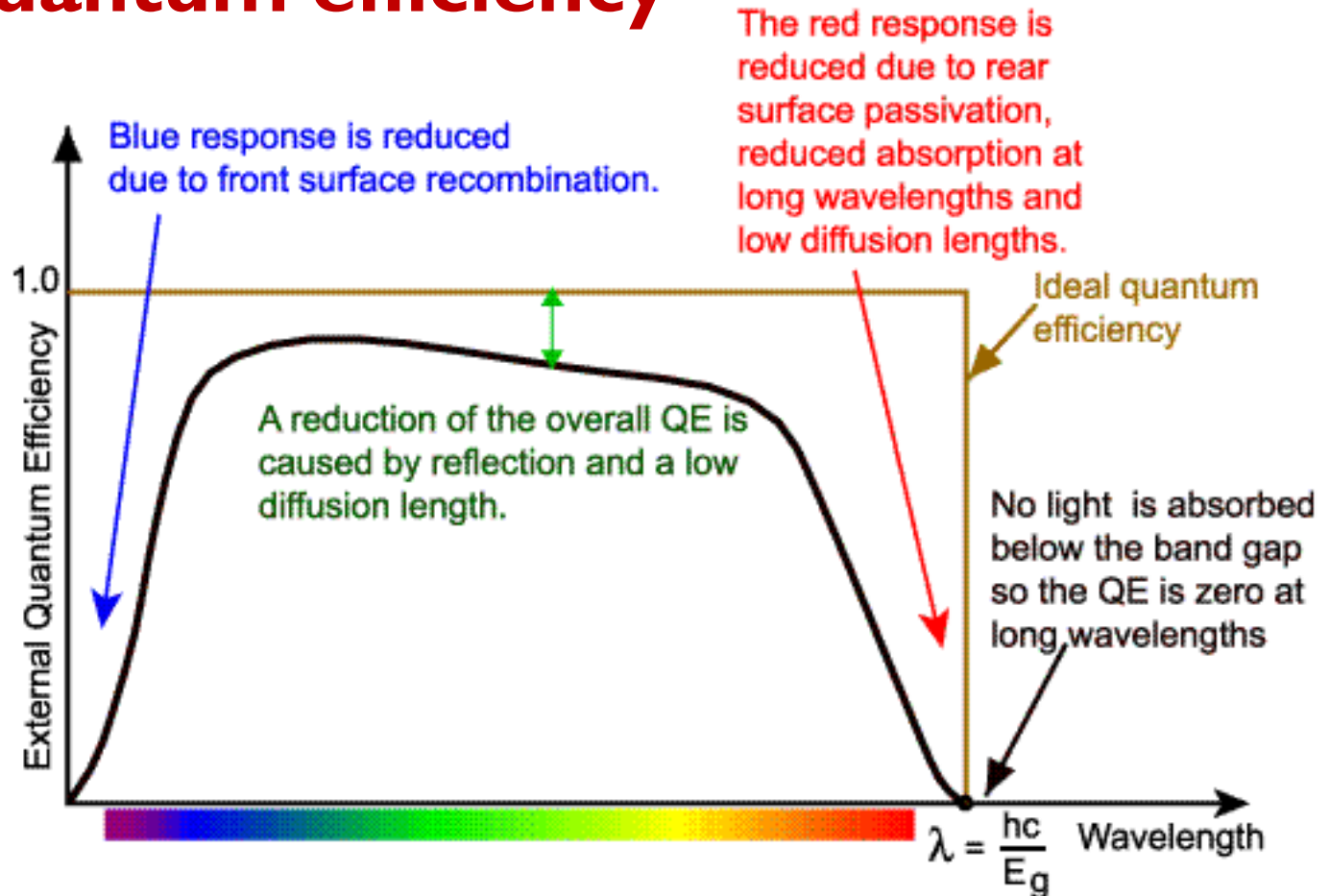
Solar cell operation

Quantum efficiency

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

Solar cell operation

Quantum efficiency

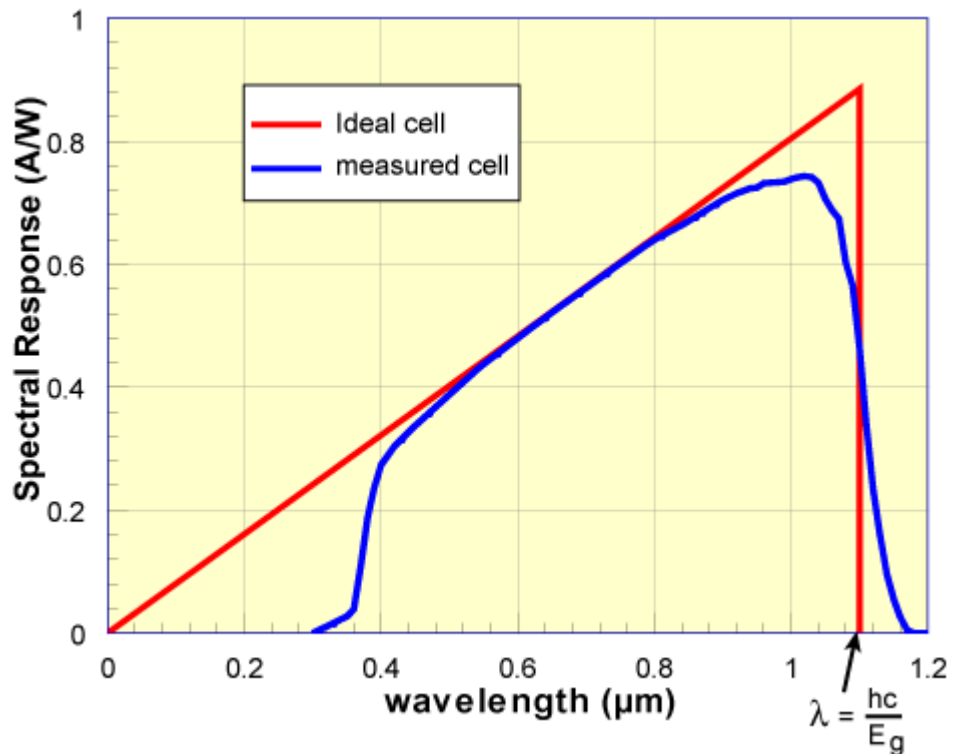


External quantum efficiency includes the effect of optical losses, e.g. reflection on the surface, ...

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

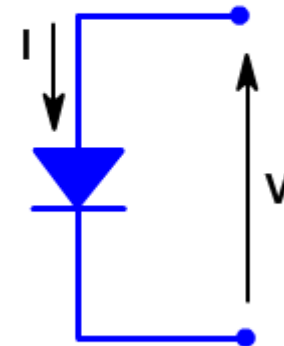
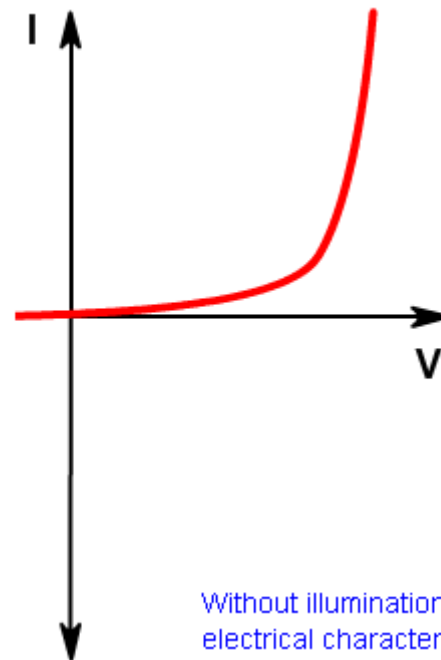
IV characteristic

= diode + light generated current

SOLAR CELL OPERATION

Solar cell parameters

IV characteristic

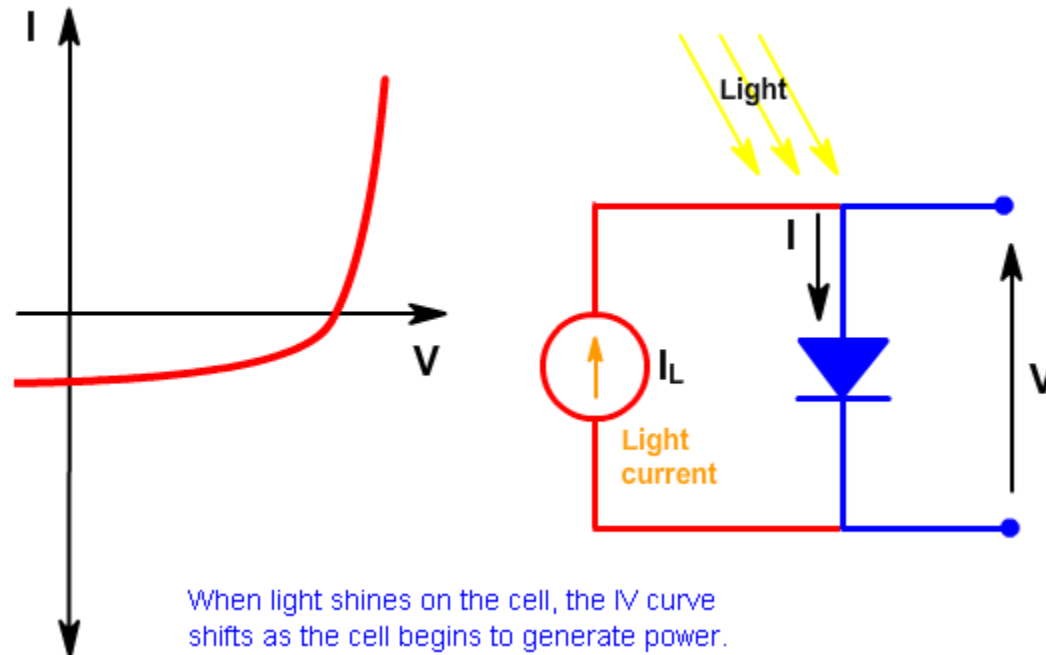


Without illumination, a solar cell has the same electrical characteristics as a large diode.

SOLAR CELL OPERATION

Solar cell parameters

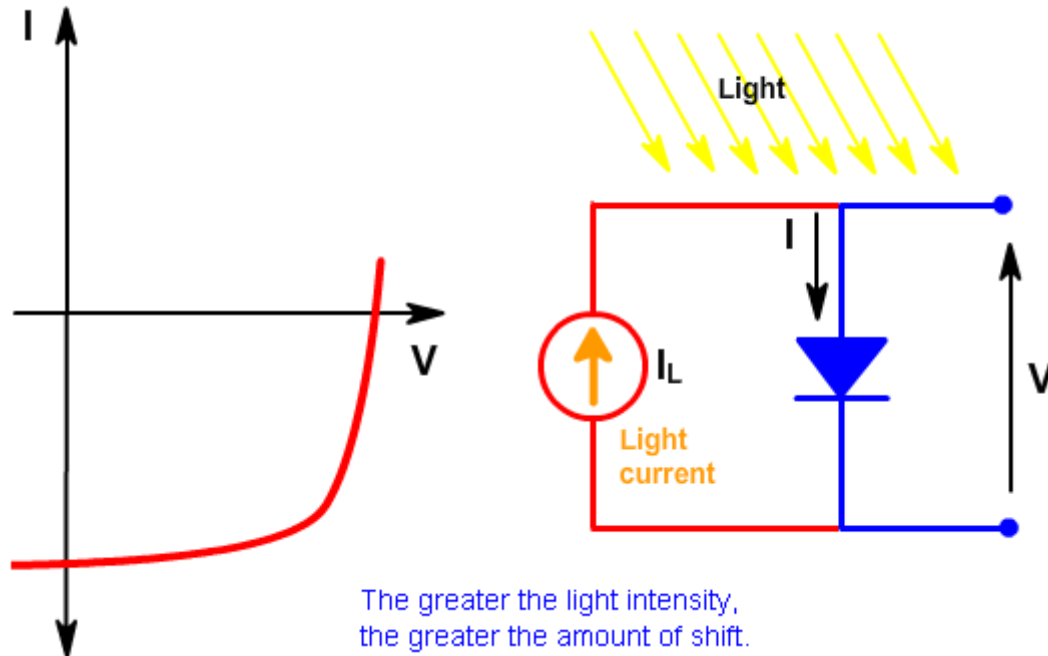
IV characteristic



SOLAR CELL OPERATION

Solar cell parameters

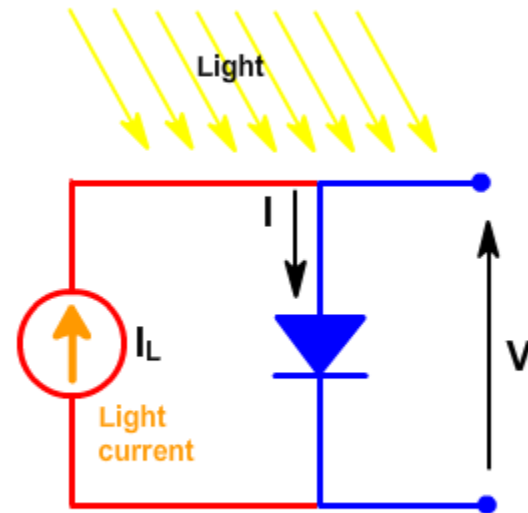
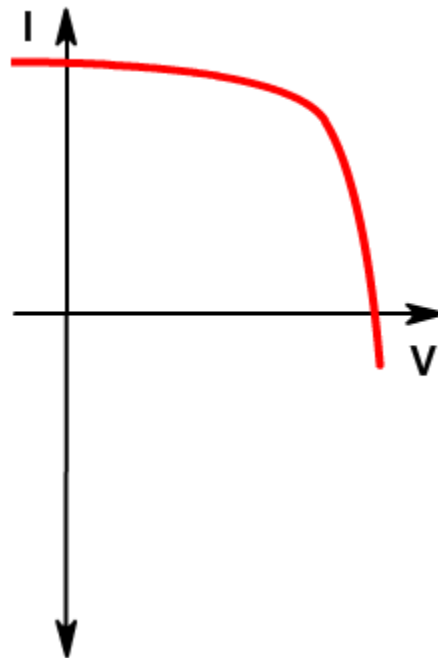
IV characteristic



SOLAR CELL OPERATION

Solar cell parameters

IV characteristic

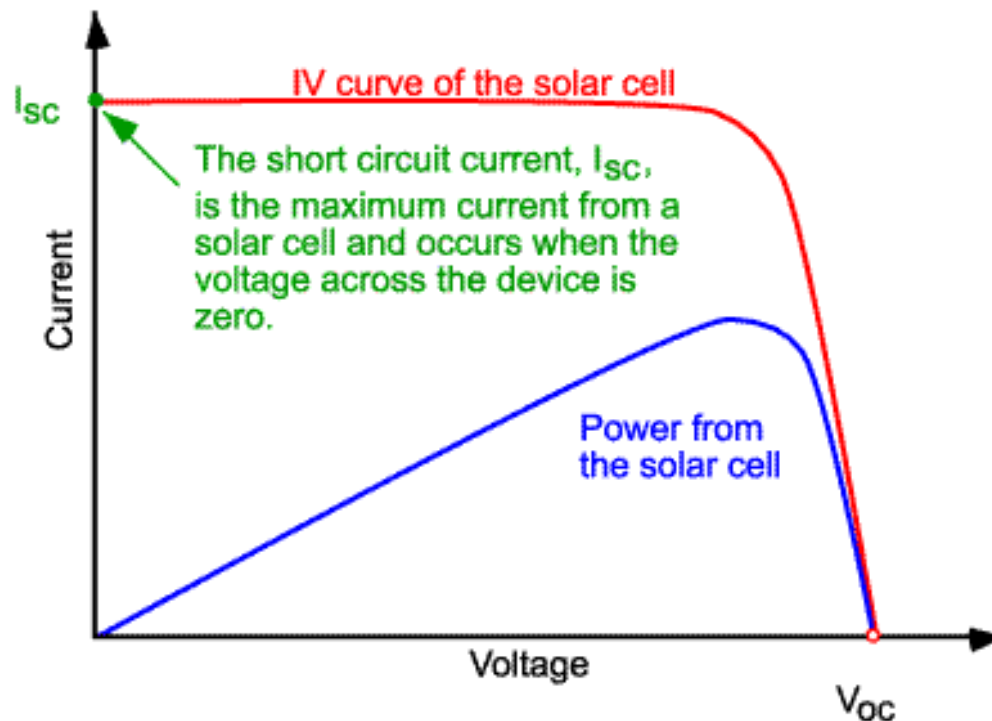


$$I = I_L - I_0 \left[\exp \left(\frac{qV}{nkT} \right) - 1 \right]$$

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})

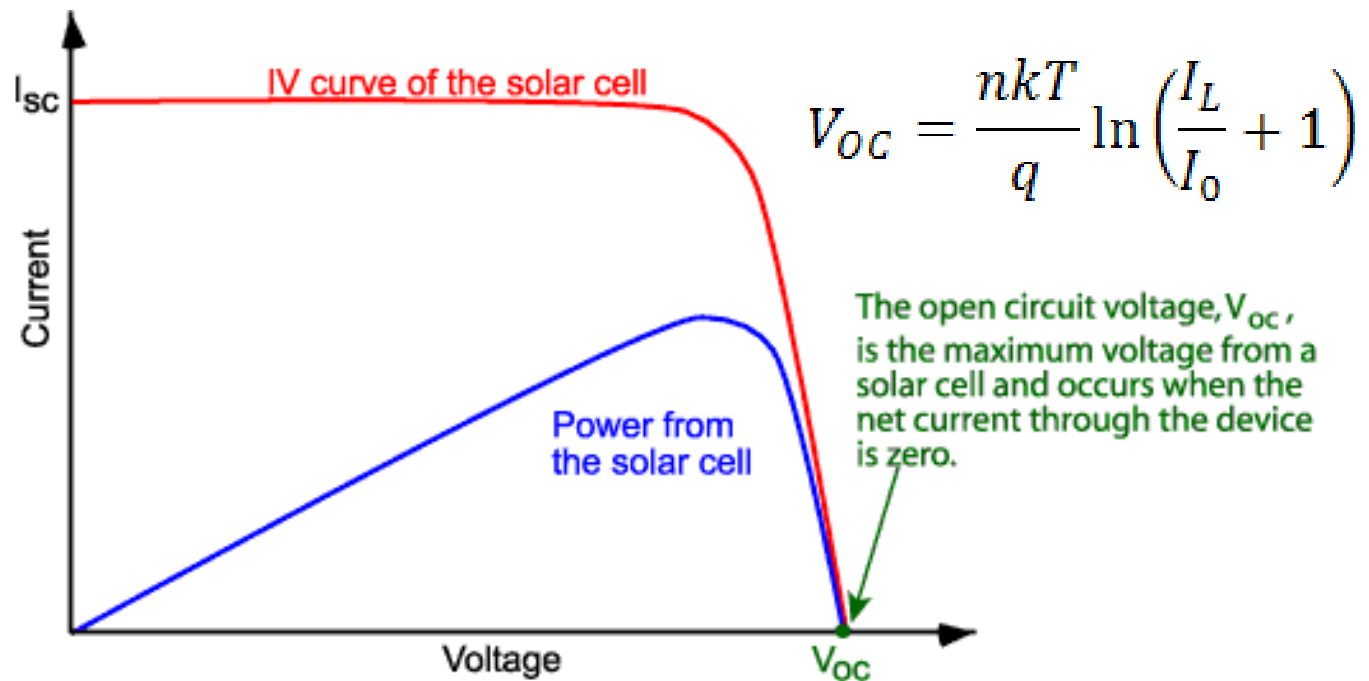
- **Area** of the solar cell (common to use J_{sc} in mA/cm²)
- Incident flux (i.e. number of **photons**)
- **Spectrum** incident light
- **Optical** properties of the solar cell
- Collection probability, e.g. **diffusion length**

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

SOLAR CELL OPERATION

Solar cell parameters

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

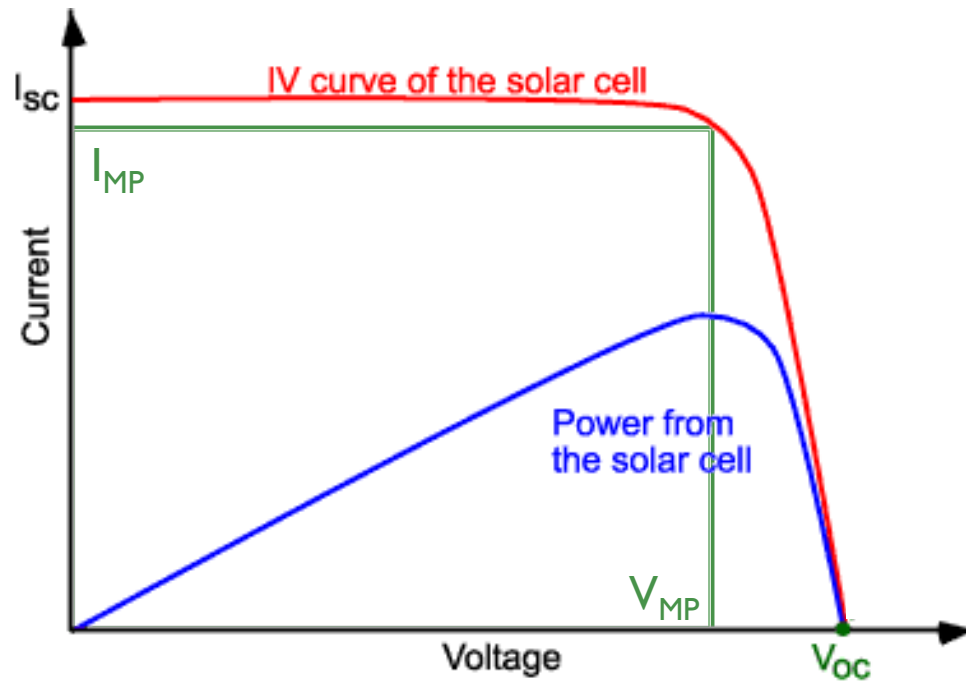


V_{oc} depends strongly on the recombination

SOLAR CELL OPERATION

Solar cell parameters

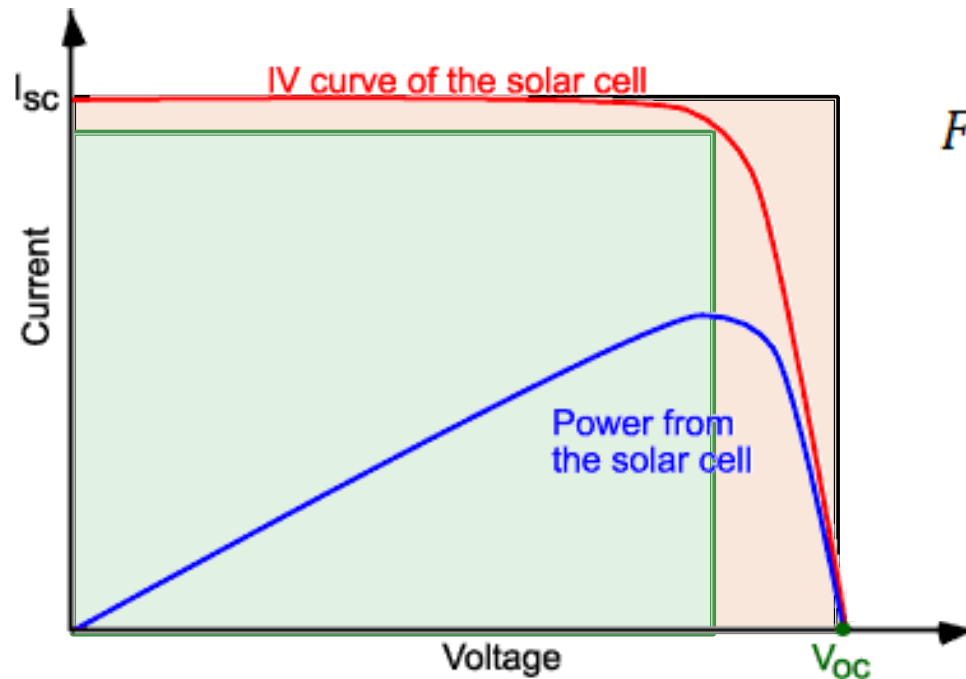
IV characteristic: **Maximum power**



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

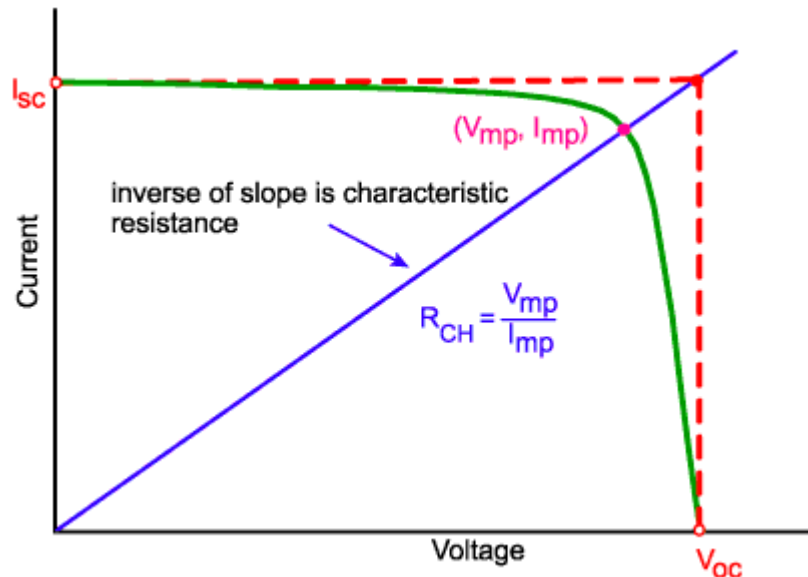
SOLAR CELL OPERATION

Solar cell parameters

Resistive effects

- Characteristic resistance

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



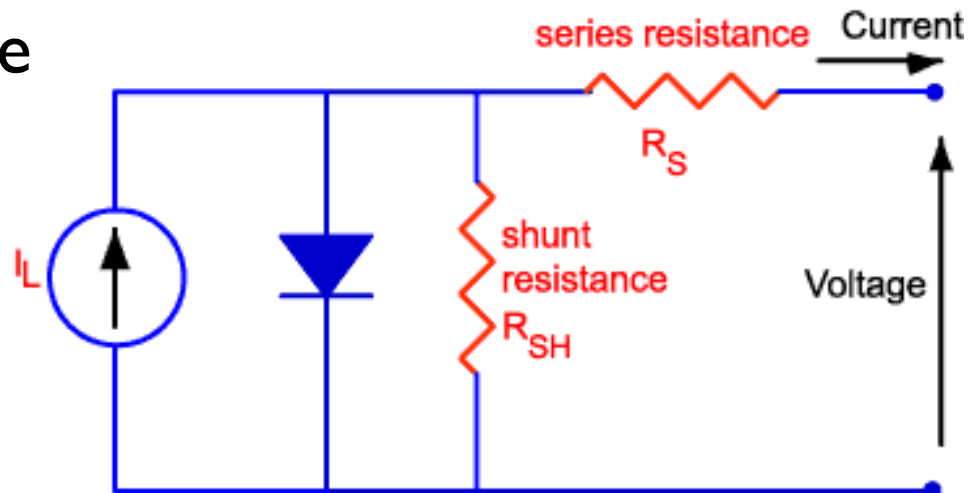
$$R_{CH} = \frac{V_{MP}}{I_{MP}} = \frac{V_{OC}}{I_{SC}}$$

SOLAR CELL OPERATION

Solar cell parameters

Resistive effects

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



SOLAR CELL OPERATION

Solar cell parameters

Resistive effects

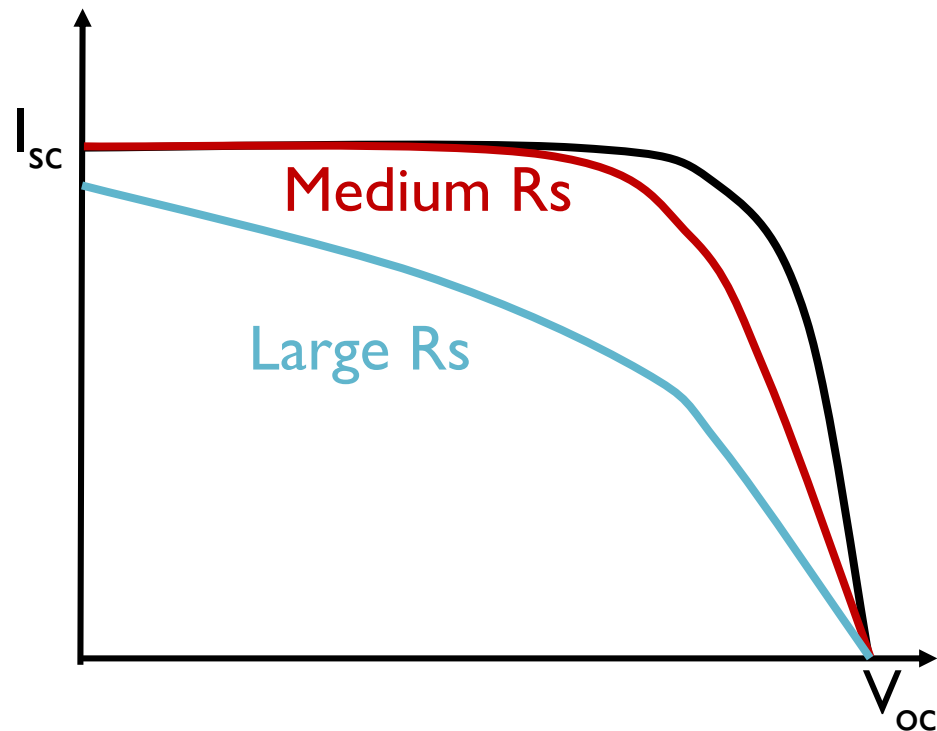
- Characteristic resistance
- Parasitic resistance
 - Series resistance
 - Shunt resistance

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

SOLAR CELL OPERATION

Effect of the **series resistance**

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

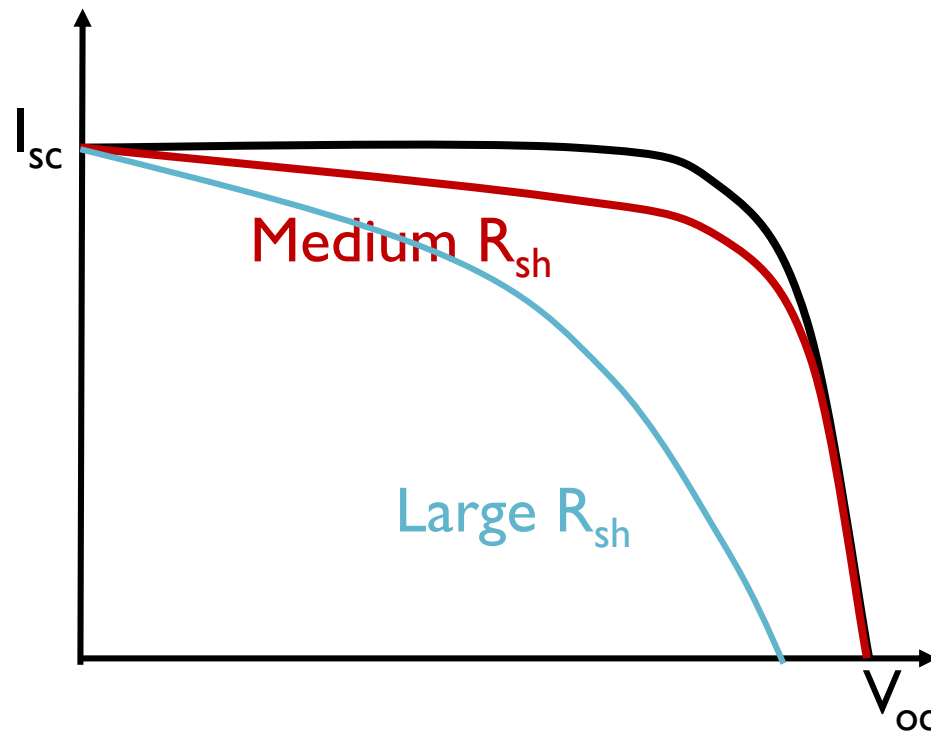


Slope of the I-V curve near V_{oc} gives indication about R_s

SOLAR CELL OPERATION

Effect of the **shunt resistance**

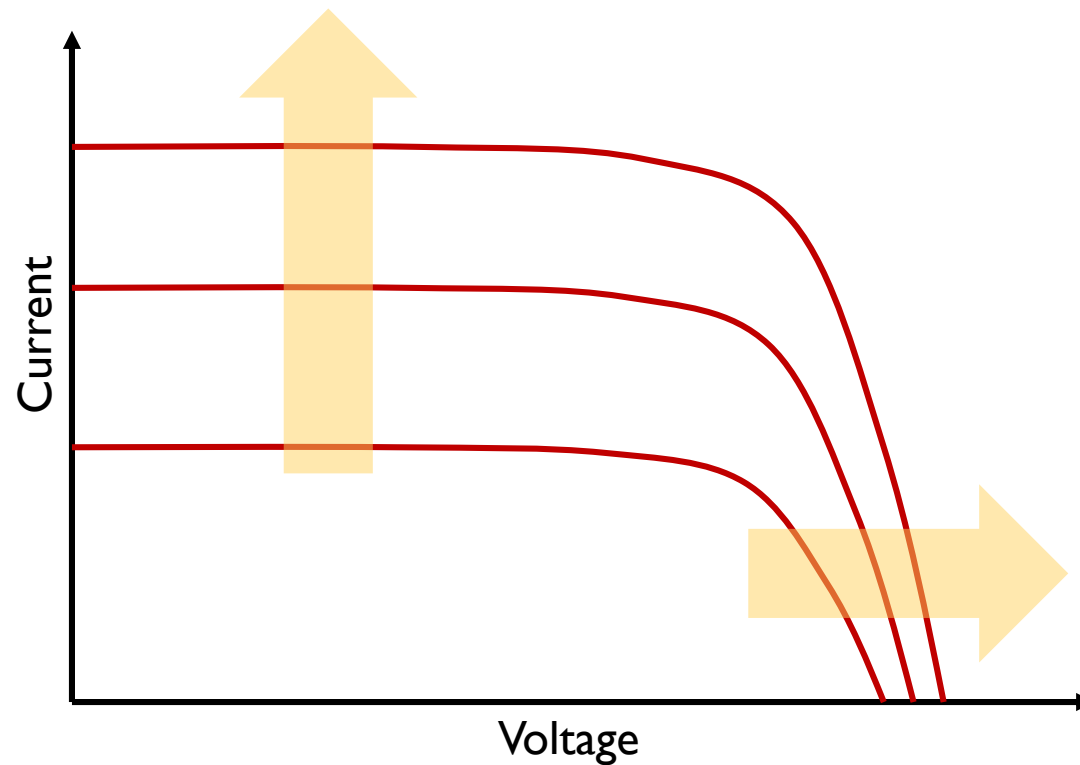
$$FF_{SH} = FF_0 \left(1 - \frac{1}{r_{SH}} \right) \quad \text{with} \quad r_{SH} = \frac{R_{SH}}{R_{CH}}$$



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

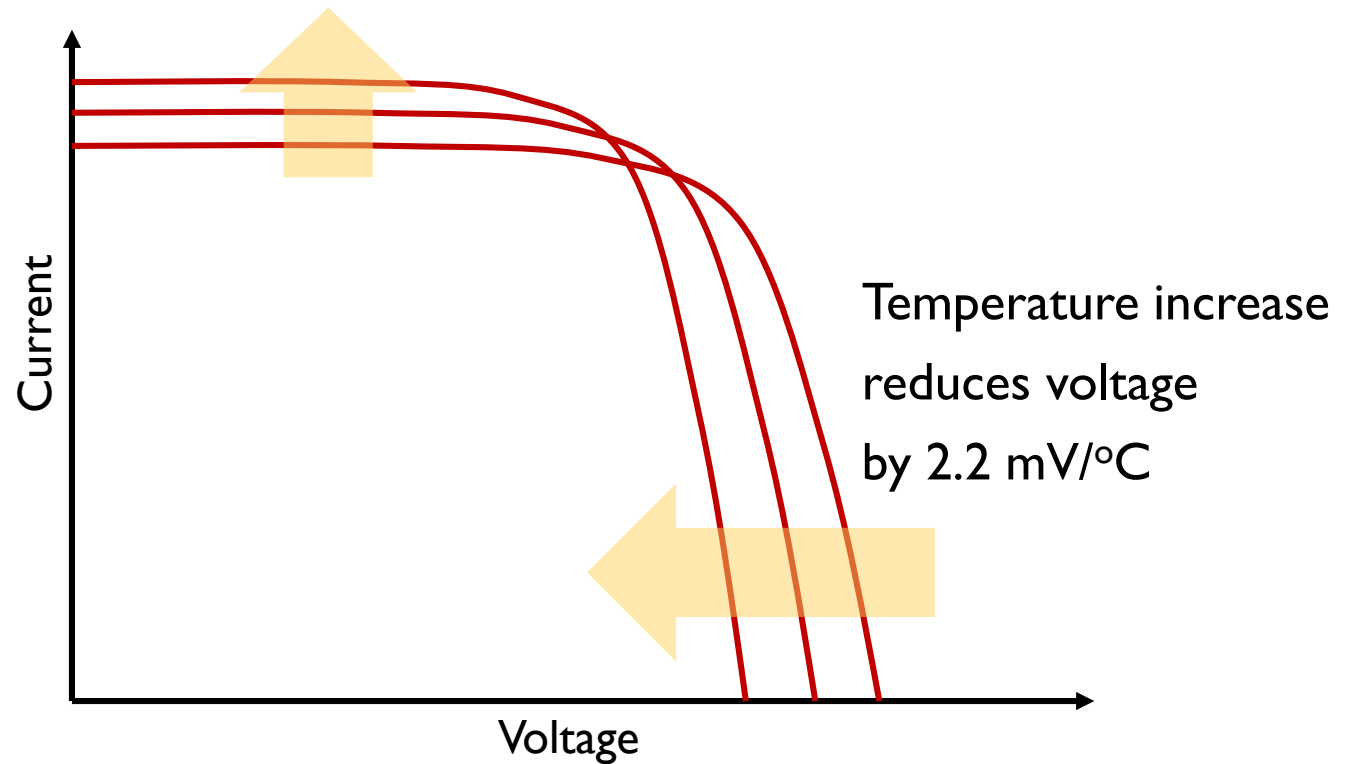
SOLAR CELL OPERATION

Effect of irradiation

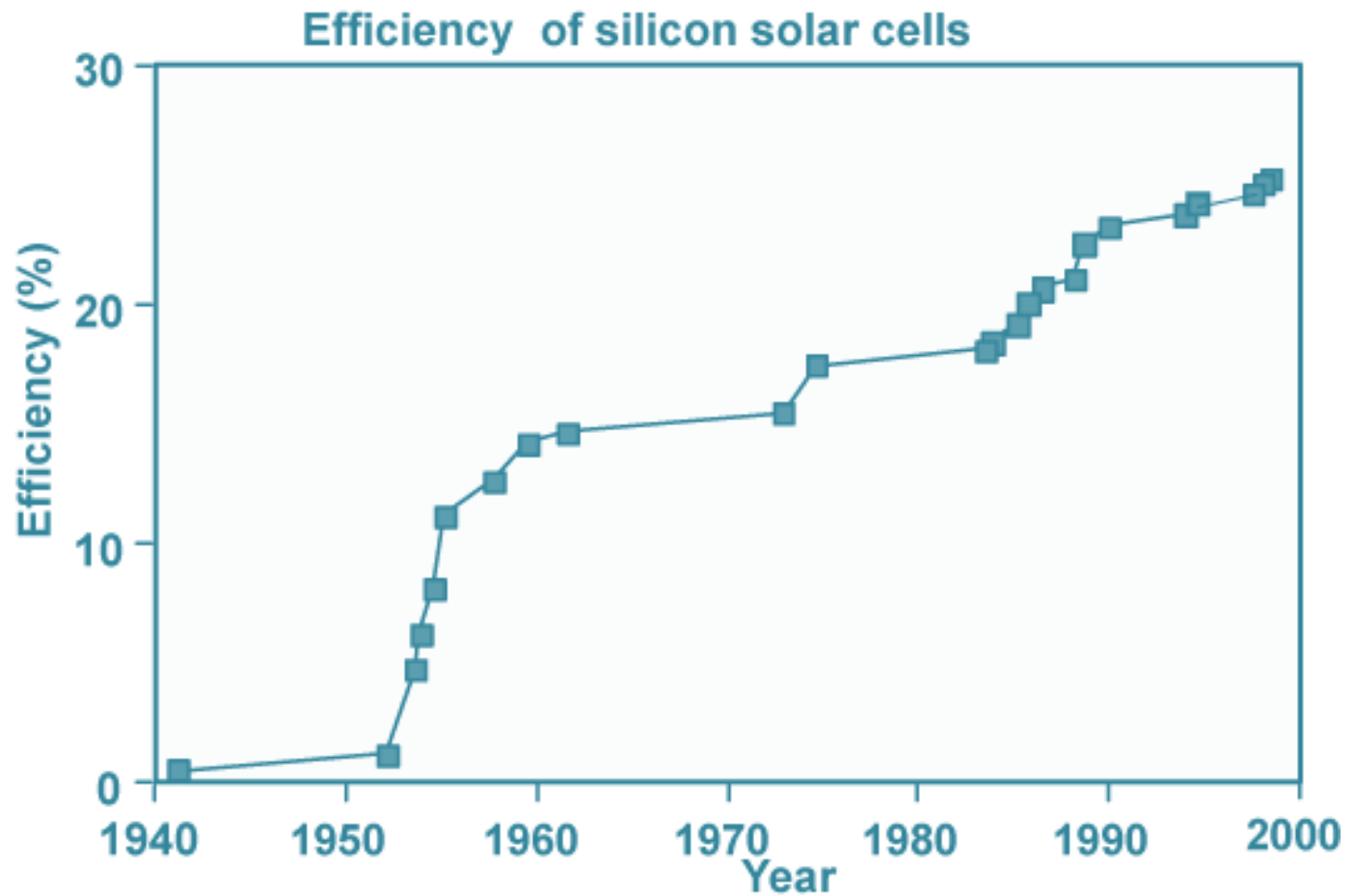


SOLAR CELL OPERATION

Effect of **temperature**

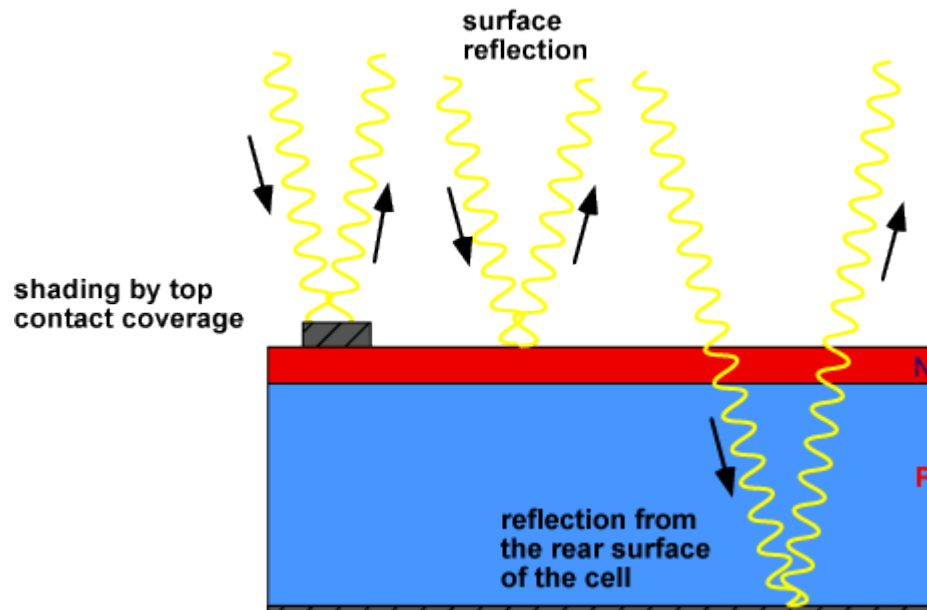


DESIGN OF Si SOLAR CELL



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.



DESIGN OF Si SOLAR CELL

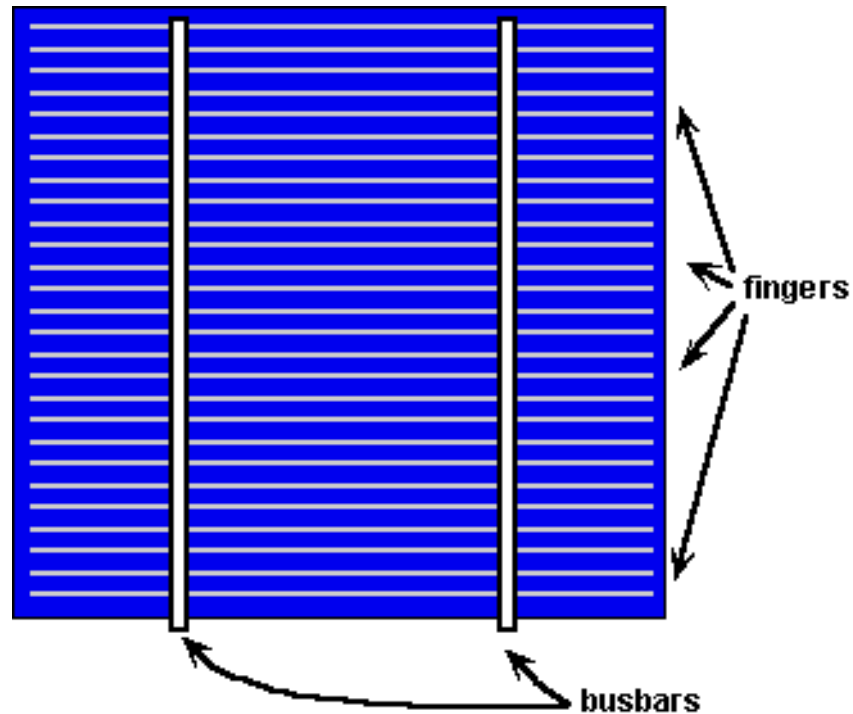
Optical losses - light which could have generated an electron-hole pair, but does not, because the light is reflected from the front surface, or because it is not absorbed in the solar cell.

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

DESIGN OF Si SOLAR CELL

Optical losses

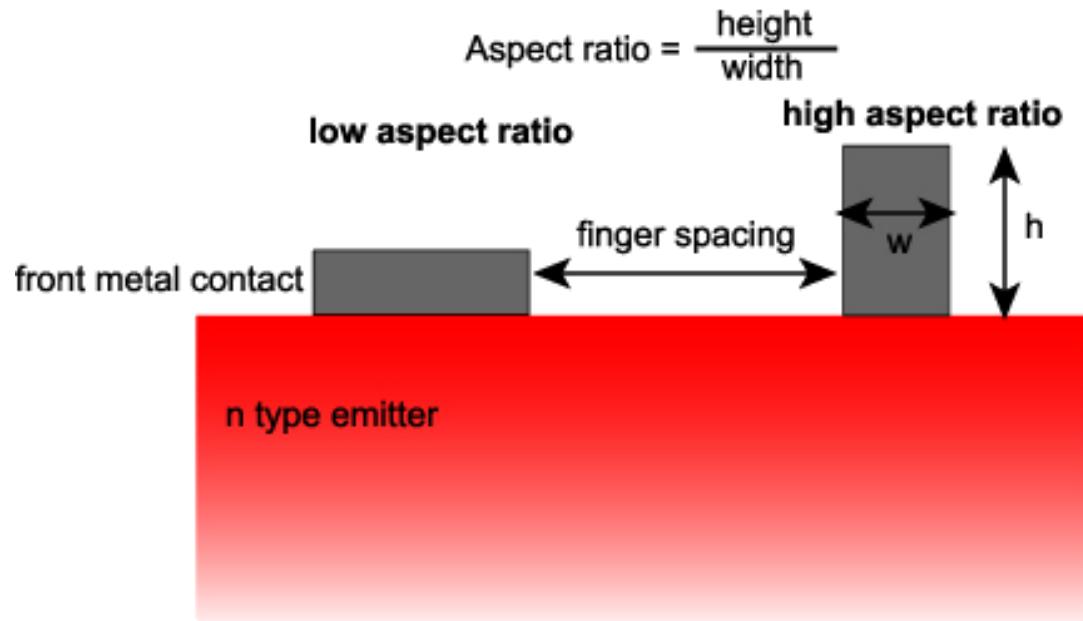
Reduce **shading** from top contacts



DESIGN OF Si SOLAR CELL

Optical losses

Reduce **shading** from top contacts

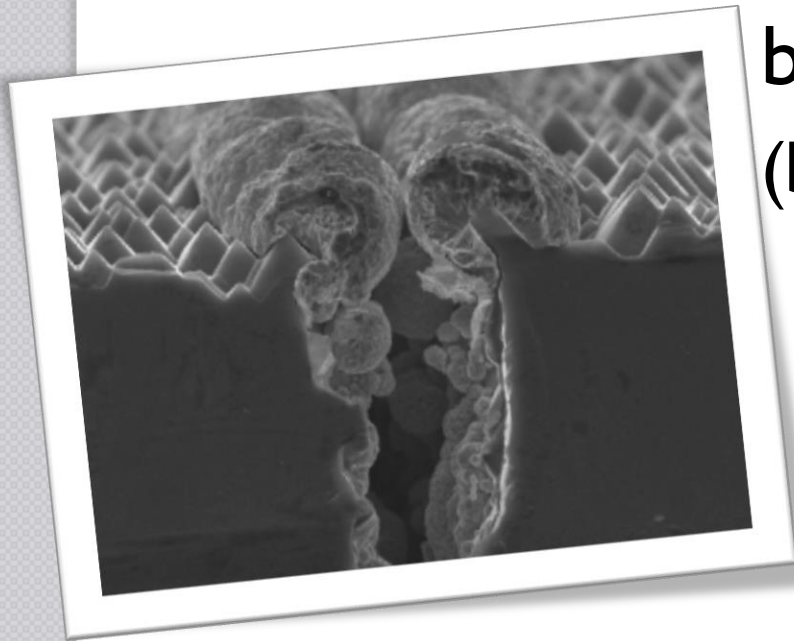


DESIGN OF Si SOLAR CELL

Optical losses

Reduce **shading** from top contacts

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



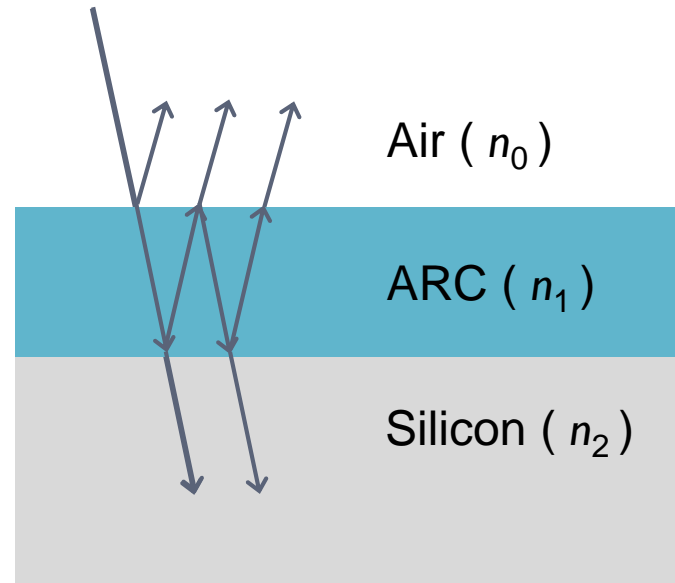
DESIGN OF Si SOLAR CELL

Optical losses

Anti-reflective coating

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

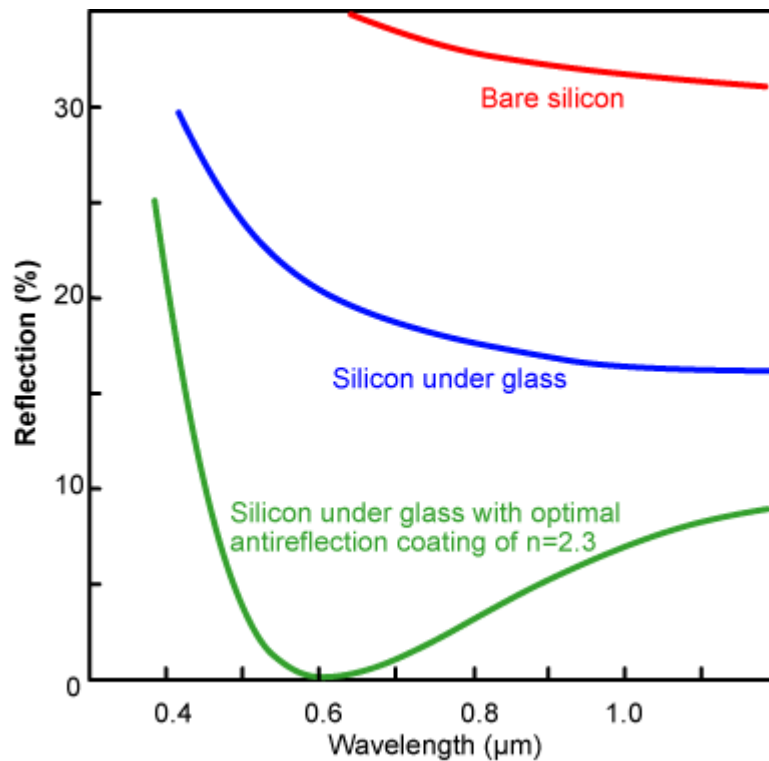
$$R = \left(\frac{n_1^2 - n_0 n_2}{n_1^2 + n_0 n_2} \right)^2$$



DESIGN OF Si SOLAR CELL

Optical losses

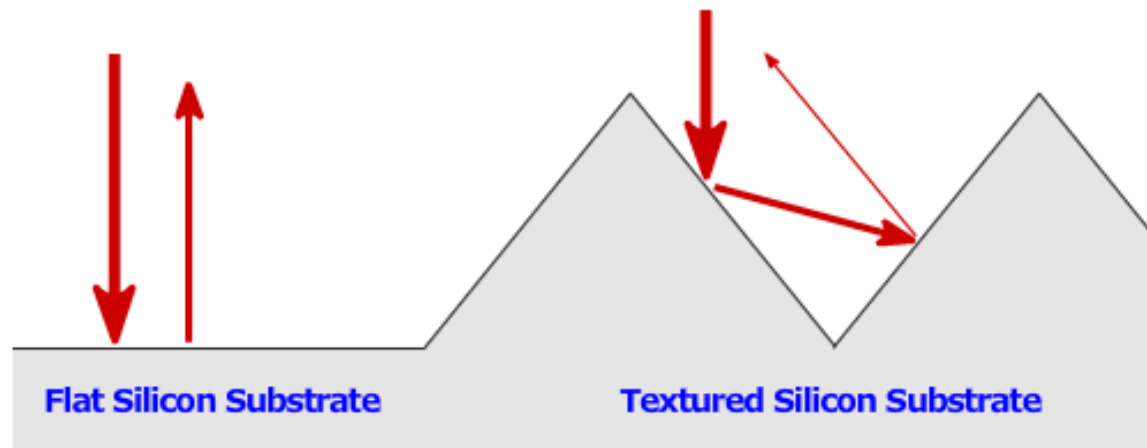
Anti-reflective coating



DESIGN OF Si SOLAR CELL

Optical losses

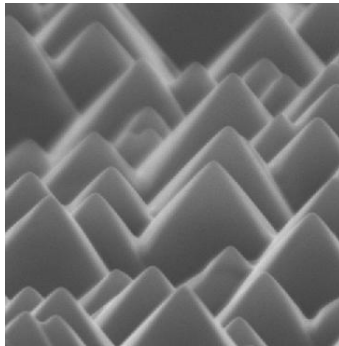
Surface **texturing**



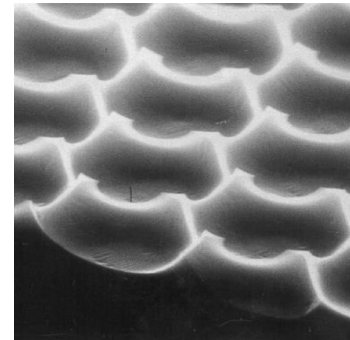
DESIGN OF Si SOLAR CELL

Optical losses

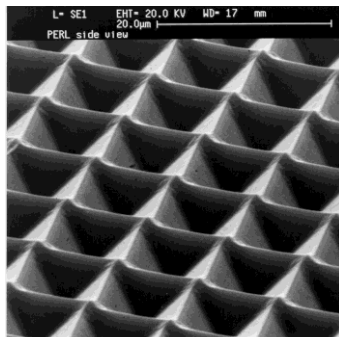
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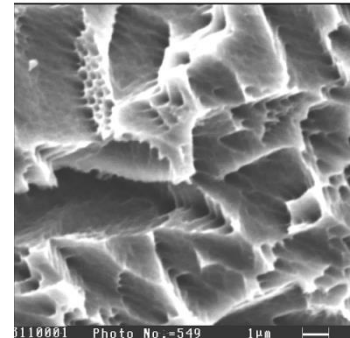
Single crystal:
Random pyramids, by
etching



Multi crystal:
texturing by
photolithography



Single crystal:
Inverted pyramids, by
etching

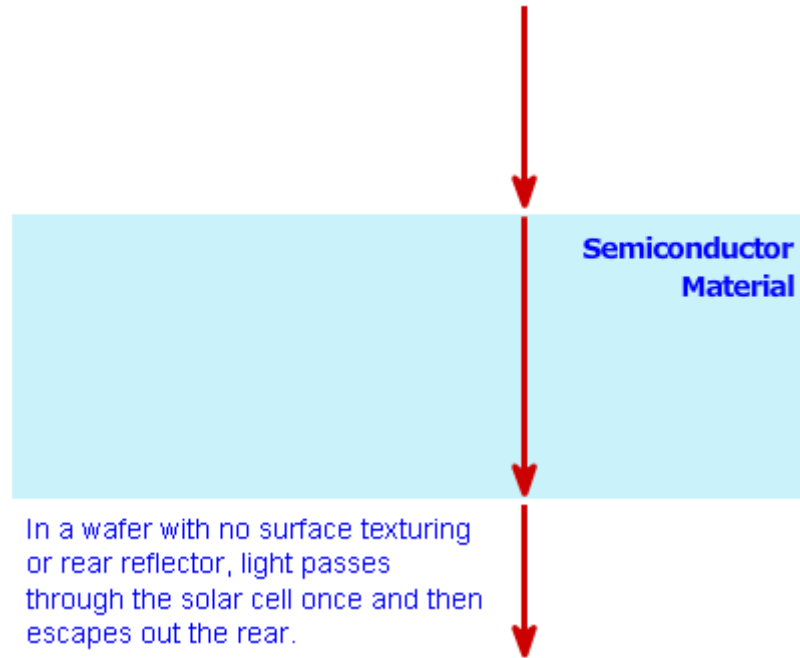


Multi crystal:
texturing by
macroporous silicon

DESIGN OF Si SOLAR CELL

Optical losses

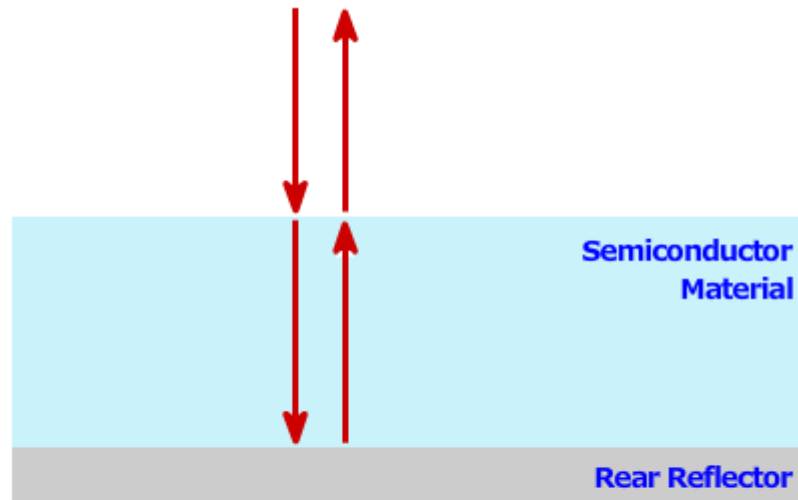
Light **trapping**: increase optical length



DESIGN OF Si SOLAR CELL

Optical losses

Light **trapping**: increase optical length

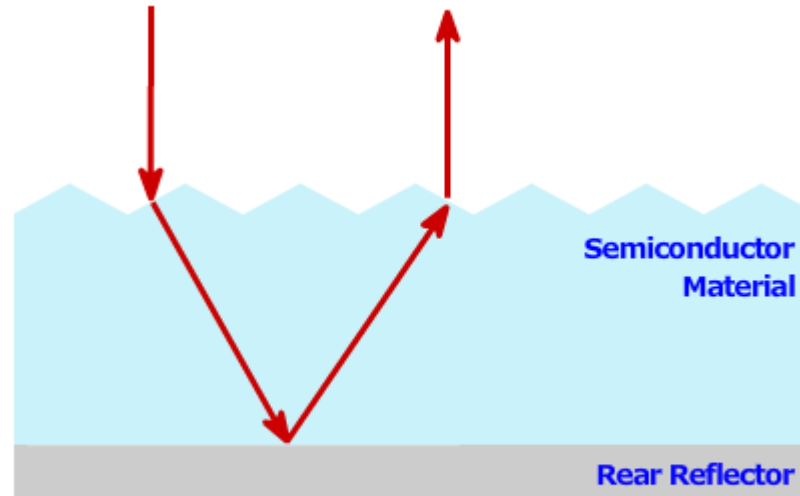


When a rear reflectors is added,
the optical path length is twice
the physical device thickness.

DESIGN OF Si SOLAR CELL

Optical losses

Light **trapping**: increase optical length



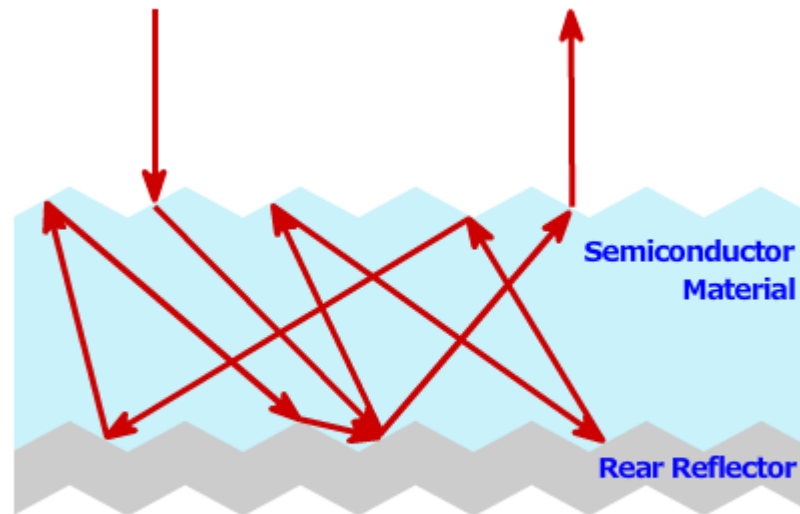
Surface texturing increases the path length but light escapes after two passes through the solar cell.

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



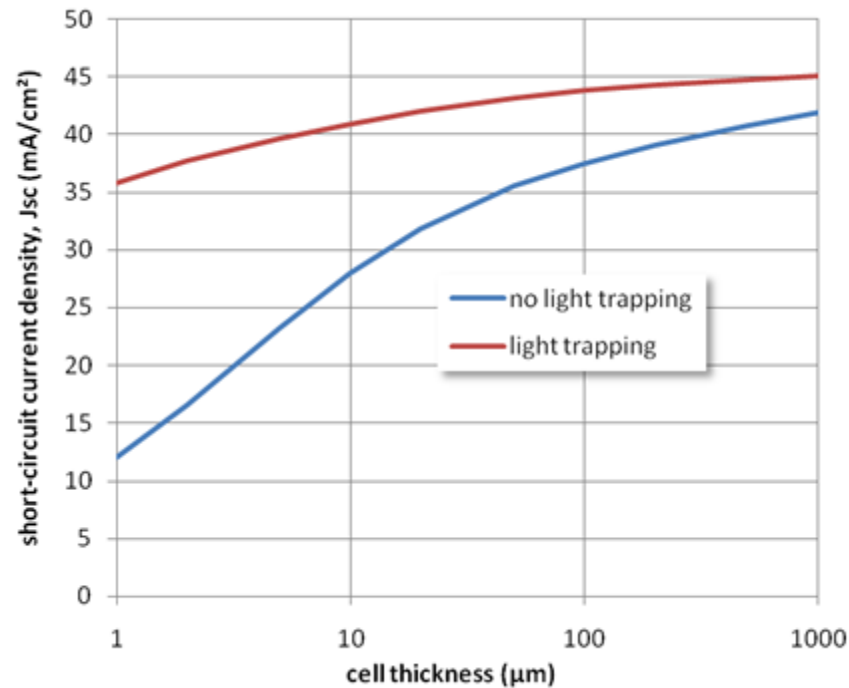
Front and rear surface texturing can trap light for multiple passes due to total internal reflection.

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

DESIGN OF Si SOLAR CELL

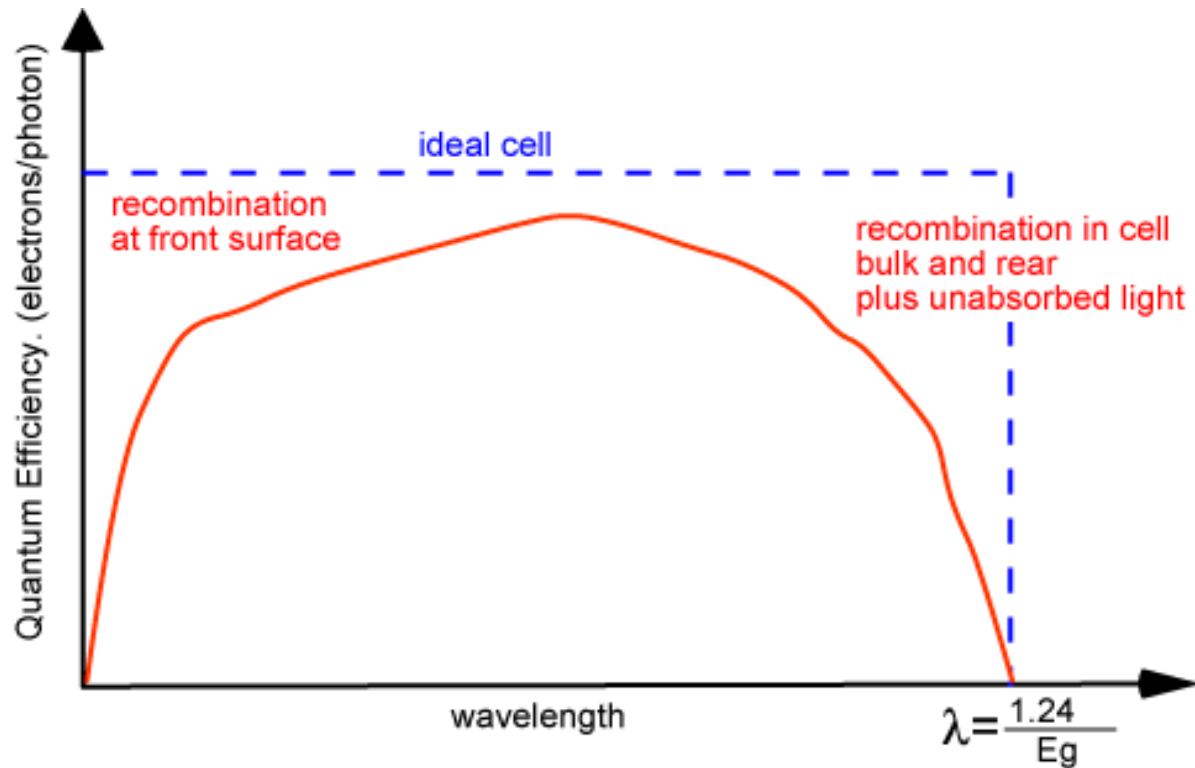
Recombination losses

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,...)

DESIGN OF Si SOLAR CELL

Recombination losses

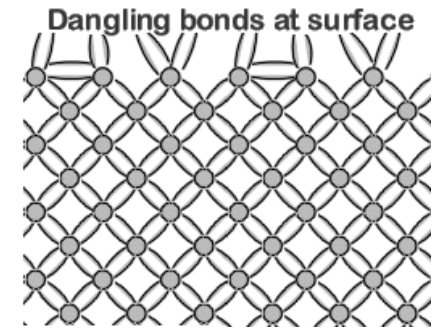


Design of silicon solar cells

Recombination losses:

Surface **passivation**

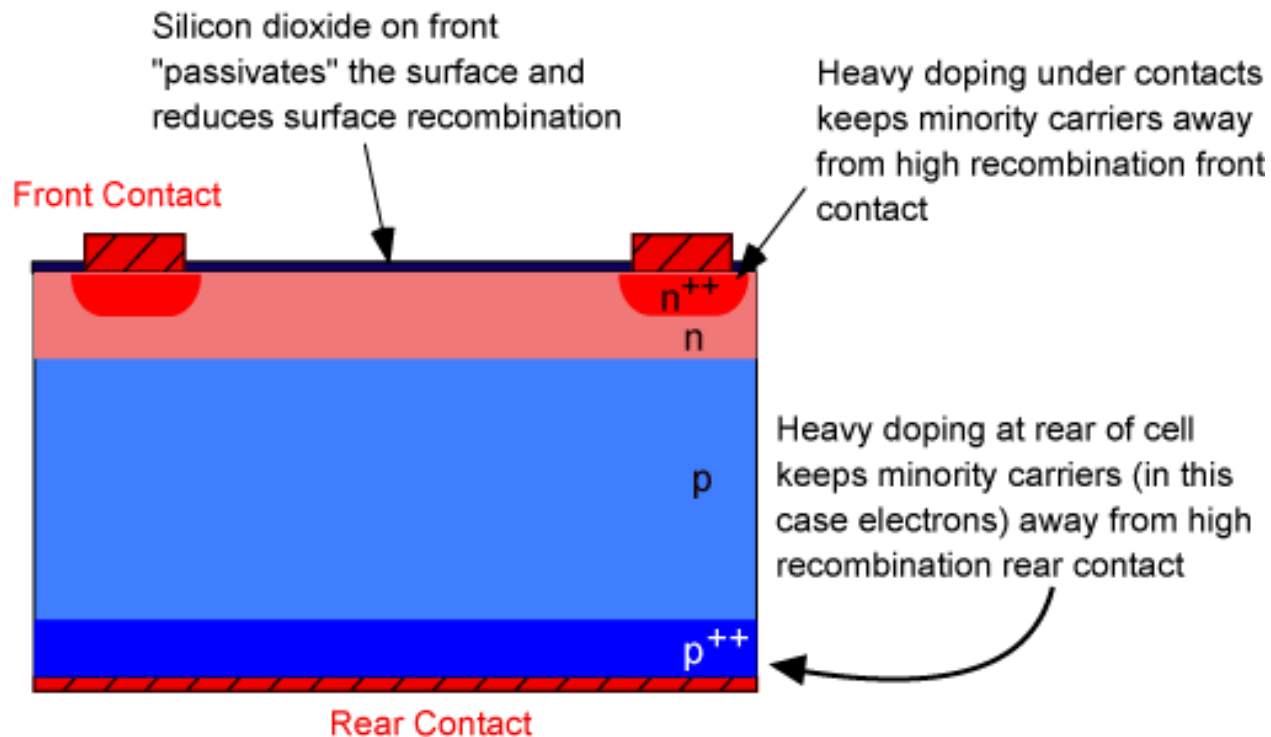
- Reducing the number of **dangling bonds** by growing a SiO_2 or SiN thin film on the surface
(also for anti-reflection coating; notice that it is an electric insulator)
- Increasing doping, creating a repelling field
(decreases diffusion length thus not suitable for charge collection region; useful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



Design of silicon solar cells

Recombination losses:

Surface **passivation**



DESIGN OF Si SOLAR CELL

Single junction silicon solar cell

- Best **lab** cell: 25%

J. Zhao *et al* Novel 19.8% efficient “honeycomb” textured multicrystalline and 24.4% monocrystalline silicon solar cells. *Applied Physics Letters* 1998; 73: 1991–1993.

- Best **module**: 23%

M. Green *et al*, *Solar Cell Efficiency Tables (Version 34)* *Prog. Photovolt: Res. Appl.* 2009; 17:320–326

- Practical cell design (for **industry!**)
requires compromises, and thus lower
efficiencies...

Check February issue of *Photon International*

Table I. Confirmed terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m²) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global)

Classification ^a	Effic ^b (%)	Area ^c (cm ²)	V _{oc} (V)	J _{sc} (mA/cm ²)	FF ^d (%)	Test centre ^e (and date)	Description
<u>Silicon</u>							
Si (crystalline)	25.0 ± 0.5	4.00 (da)	0.706	42.7	82.8	Sandia (3/99) ^f	UNSW PERL ¹¹
Si (multicrystalline)	20.4 ± 0.5	1.002 (ap)	0.664	38.0	80.9	NREL (5/04) ^f	FhG-ISE ¹²
Si (thin film transfer)	16.7 ± 0.4	4.017 (ap)	0.645	33.0	78.2	FhG-ISE (7/01) ^f	U. Stuttgart (45 μm thick) ¹³
Si (thin film submodule)	10.5 ± 0.3	94.0 (ap)	0.492 ^g	29.7 ^g	72.1	FhG-ISE (8/07) ^f	CSG Solar (1–2 μm on glass; 20 cells) ¹⁴

Table II. Confirmed terrestrial module efficiencies measured under the global AM1.5 spectrum (1000 W/m²) at a cell temperature of 25°C (IEC 60904-3: 2008, ASTM G-173-03 global)

Classification ^a	Effic. ^b (%)	Area ^c (cm ²)	V _{oc} (V)	I _{sc} (A)	FF ^d (%)	Test centre (and date)	Description
Si (crystalline)	22.9 ± 0.6	778 (da)	5.60	3.97	80.3	Sandia (9/96) ^e	UNSW/Gochermann ²⁹
Si (large crystalline)	20.3 ± 0.6	16300 (ap)	66.1	6.35	78.7	Sandia (8/07) ^e	SunPower ³⁰
Si (multicrystalline)	15.5 ± 0.4 ^f	1017 (ap)	14.6	1.37	78.6	Sandia (10/94) ^e	Sandia/HEM ³¹
Si (thin-film polycrystalline)	8.2 ± 0.2	661(ap)	25.0	0.320	68.0	Sandia (7/02) ^e	Pacific Solar (1–2 μm on glass) ³²

Table III. ‘Notable Exceptions’: ‘Top ten’ confirmed cell and module results, not class records measured under the global AM1.5 spectrum (1000 Wm⁻²) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global)

Classification ^a	Effic. ^b (%)	Area ^c (cm ²)	V _{oc} (V)	J _{sc} (mA/cm ²)	FF (%)	Test centre (and date)	Description
<u>Cells (silicon)</u>							
Si (MCZ crystalline)	24.7 ± 0.5	4.0 (da)	0.704	42.0	83.5	Sandia (7/99) ^d	UNSW PERL, SEH MCZ substrate ³⁶
Si (moderate area)	23.9 ± 0.5	22.1(da)	0.704	41.9	81.0	Sandia (8/96) ^d	UNSW PERL, FZ substrate ²⁹
Si (large crystalline)	23.0 ± 0.6	100.4(t)	0.729	39.6	80.0	AIST (2/08)	Sanyo HIT, n-type substrate⁵
Si (large crystalline)	22.0 ± 0.7	147.4(t)	0.677	40.3	80.6	FhG-ISE (3/06) ^d	Sunpower n-type substrate ³⁷
Si (large multicrystalline)	18.7 ± 0.5	217.4(t)	0.639	37.7	77.6	AIST (2/08) ^d	Mitsubishi Electric, honeycomb ³⁸

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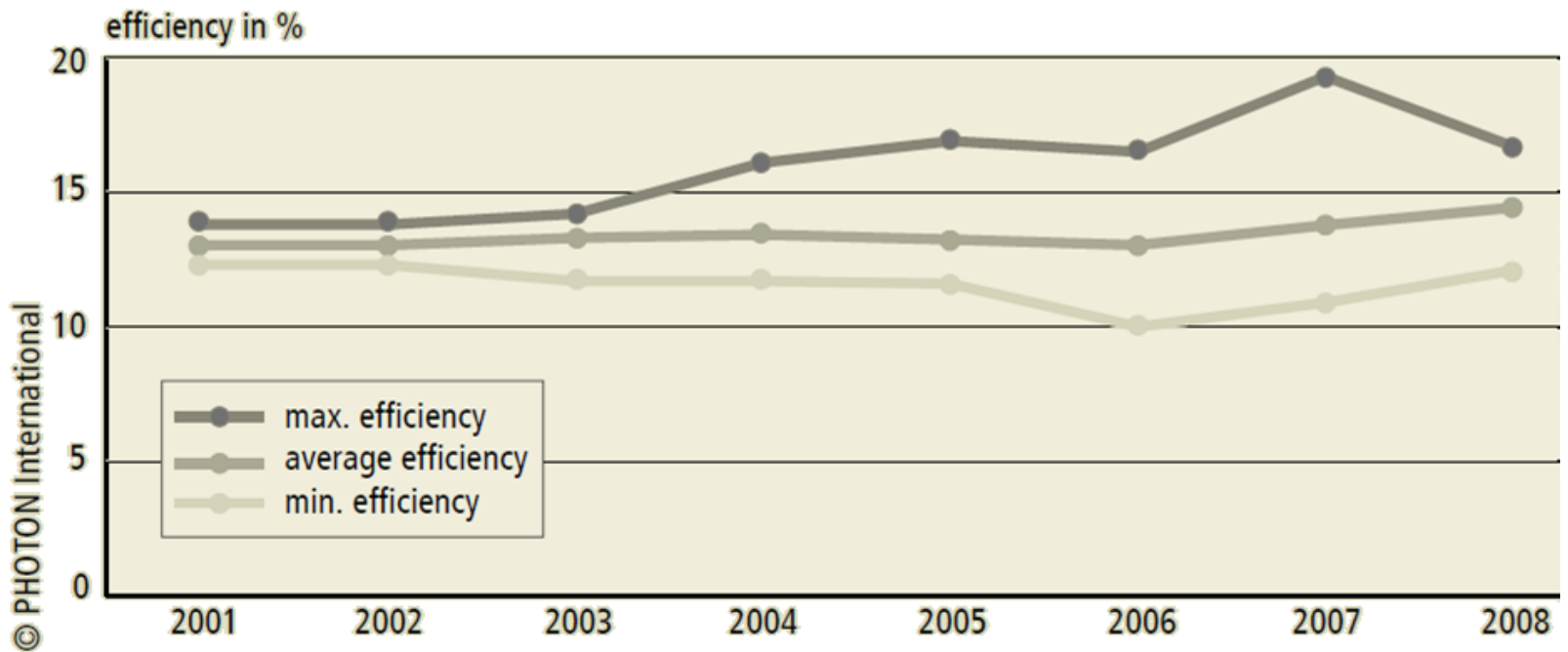
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DESIGN OF Si SOLAR CELL

- Practical cell design (for **industry!**) requires compromises, and thus lower efficiencies...



Next class...

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

A new set of **exercises**.

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