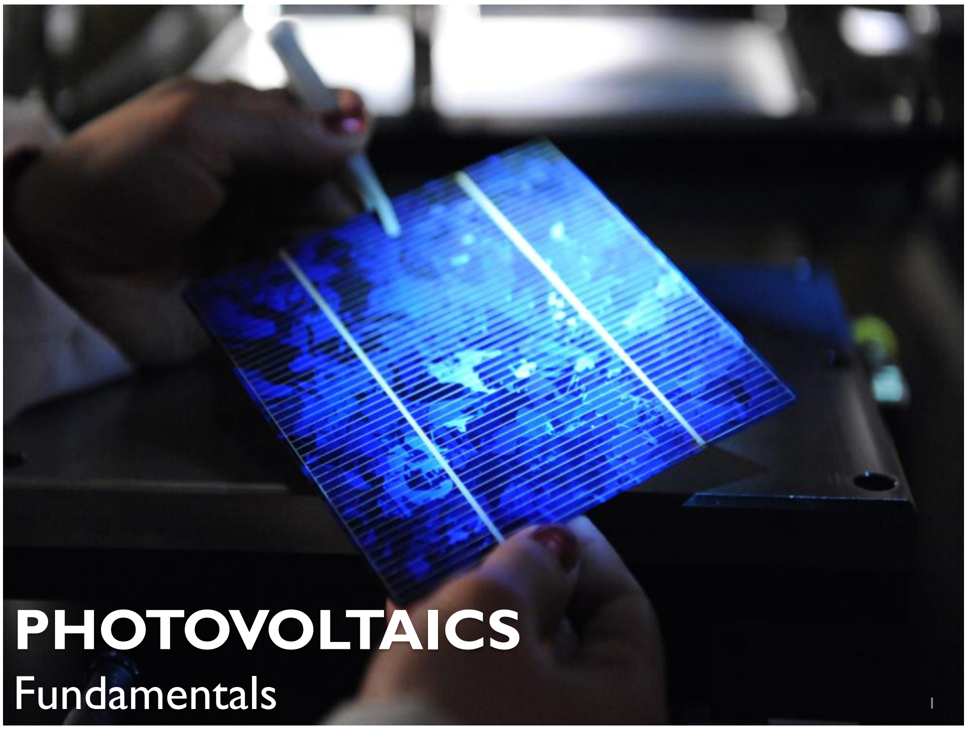


PHOTOVOLTAICS

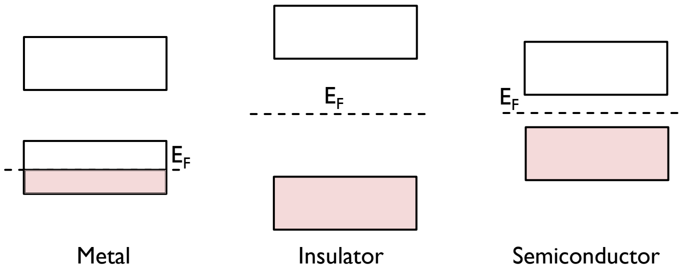
Fundamentals

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

- Allowed energy bands
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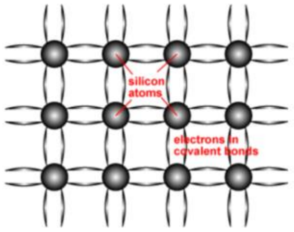
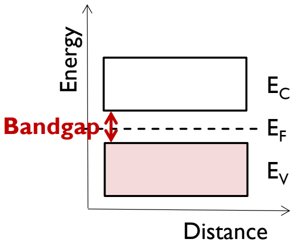
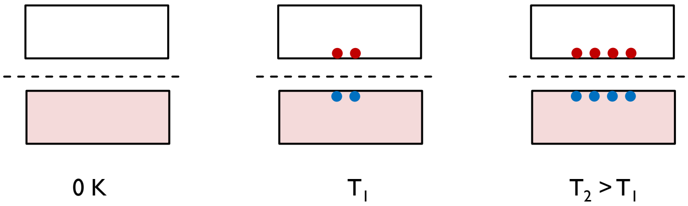




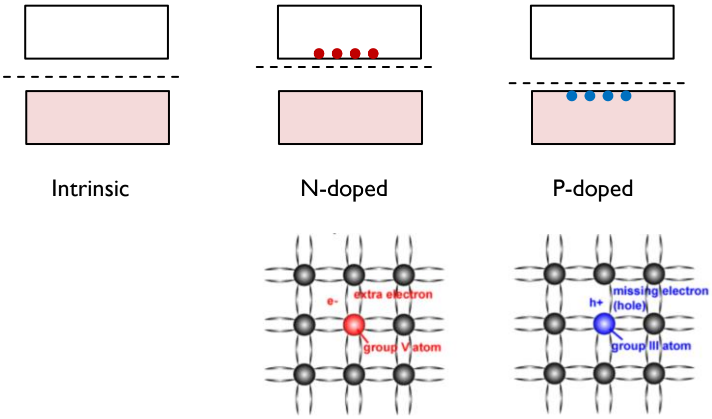
SEMICONDUCTOR BASICS

- Effect of temperature



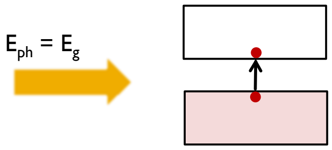
SEMICONDUCTOR BASICS

- Effect of doping



SEMICONDUCTOR BASICS

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



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

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

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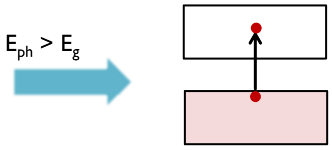

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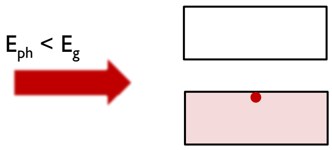

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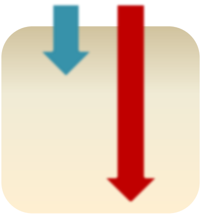
SEMICONDUCTOR BASICS

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

$$I = I_o\, e^{-\alpha x}$$



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

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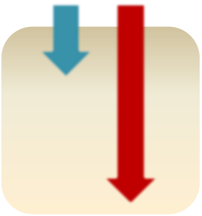

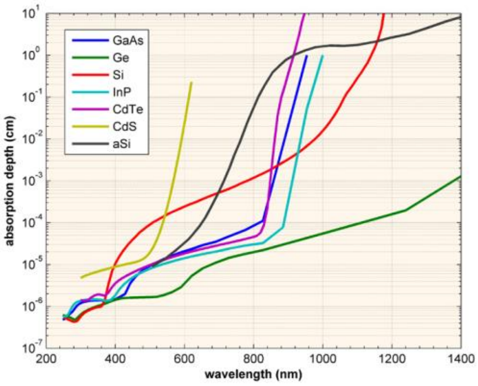

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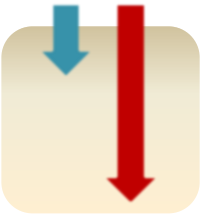
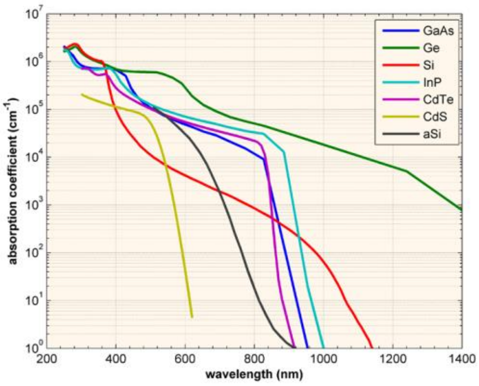


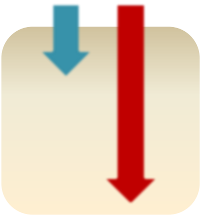


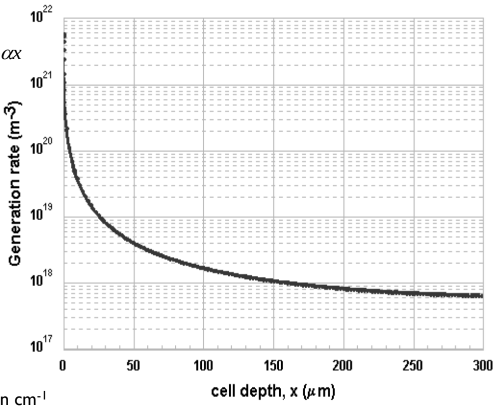
α is the absorption coefficient typically in cm^{-1}
I_0 is the light intensity at the top surface.

PV FUNDAMENTALS

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

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



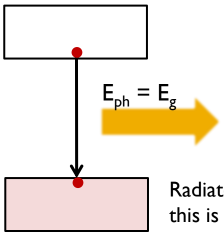


α is the absorption coefficient typically in cm^{-1}
N_0 = photon flux at the surface (photons/unit-area/sec)

PV FUNDAMENTALS

Recombination may occur through…

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

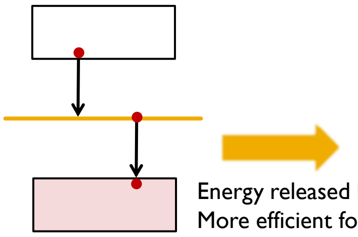


Radiated photon is weakly absorbed;
this is how LEDs work!!
Not very likely for indirect gap semiconductor like Si

SEMICONDUCTOR BASICS

Recombination may occur through…

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

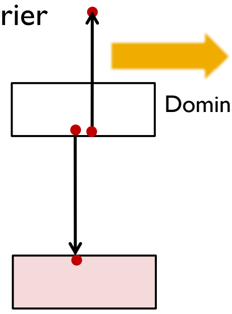


Energy released by photon and/or phonons
More efficient for mid-gap defect levels

SEMICONDUCTOR BASICS

Recombination may occur through…

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



Dominant for heavily doped semiconductors

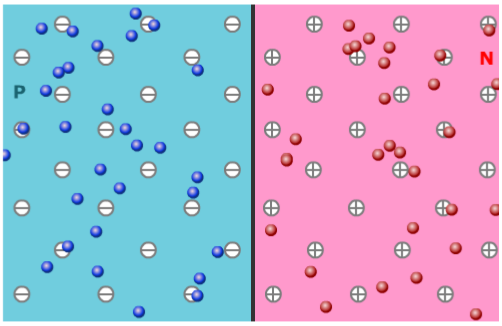
SEMICONDUCTOR BASICS

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

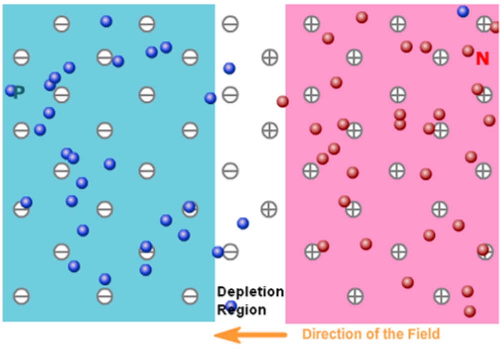
$$\tau = \frac{\Delta n}{R} \qquad L = \sqrt{D\tau}$$

PN JUNCTION



Imaginary Boundary

PN JUNCTION



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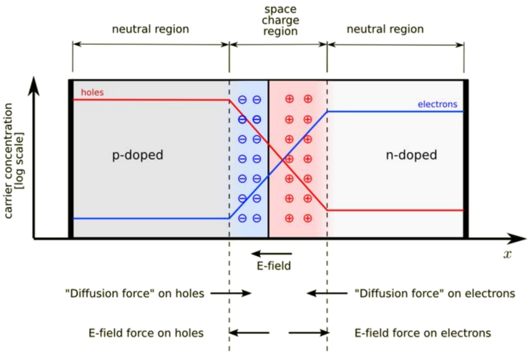

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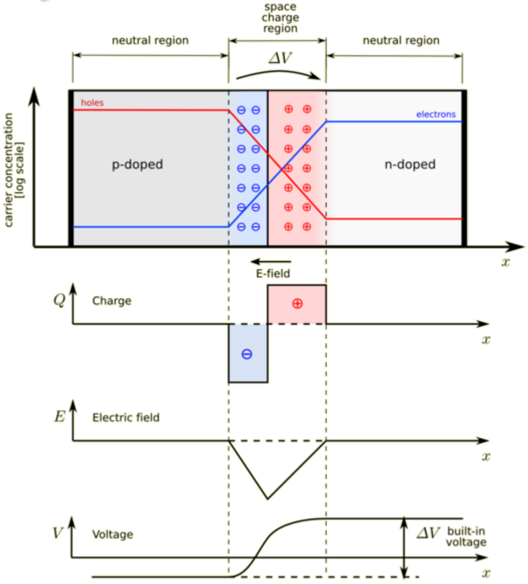
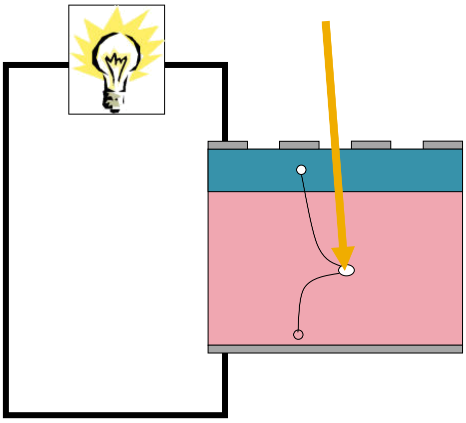


SOLAR CELL OPERATION

Basic steps:

- the generation of light-generated carriers;
- the collection of the light-generated carries 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



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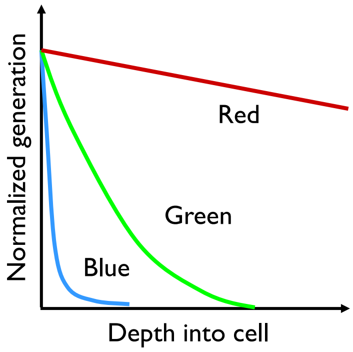

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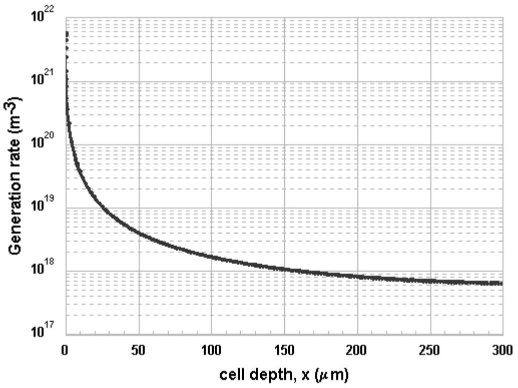
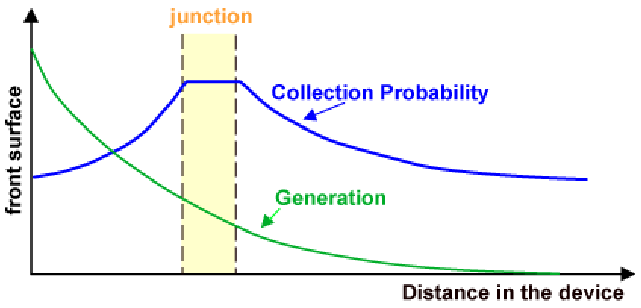


SOLAR CELL OPERATION

Basic steps:

- the collection of the carriers



SOLAR CELL OPERATION

Basic steps:

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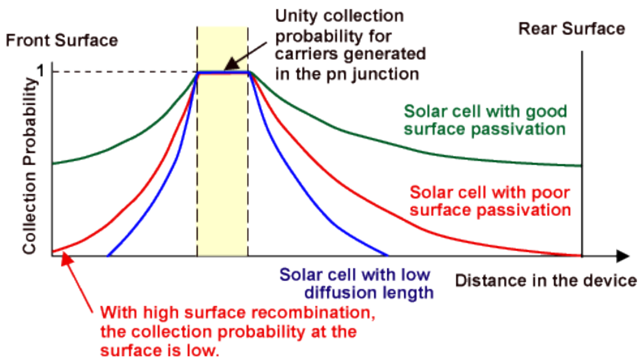


Unity collection probability for carriers generated in the pn junction

With high surface recombination, the collection probability at the surface is low.

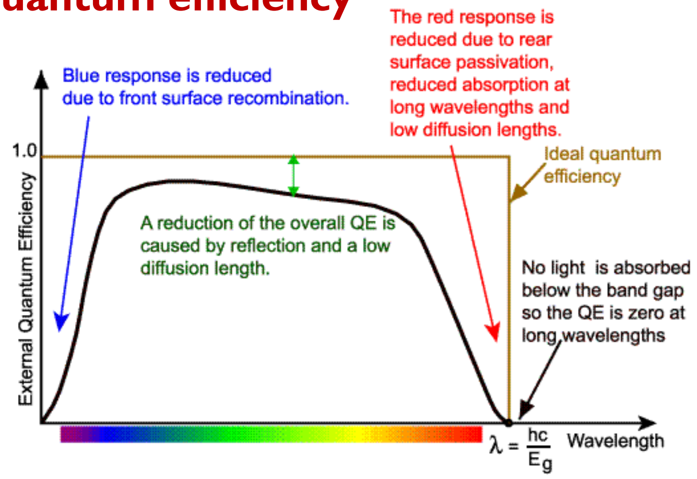
Solar cell operation

Quantum efficiency

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

Solar cell operation

Quantum efficiency



Blue response is reduced due to front surface recombination.

The red response is reduced due to rear surface passivation, reduced absorption at long wavelengths and low diffusion lengths.

Ideal quantum efficiency

A reduction of the overall QE is caused by reflection and a low diffusion length.

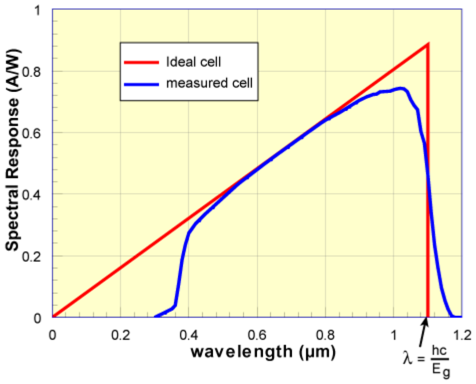
No light is absorbed below the band gap so the QE is zero at long wavelengths

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

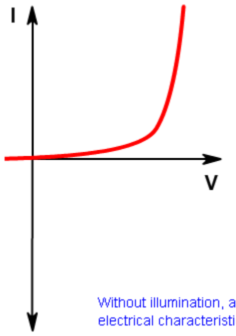
IV characteristic

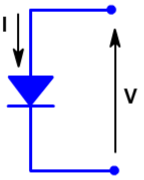
= diode + light generated current

SOLAR CELL OPERATION

Solar cell parameters

IV characteristic



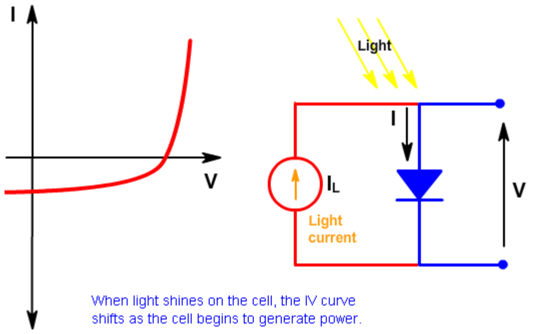


Without illumination, a solar cell has the same electrical characteristics as a large diode.

SOLAR CELL OPERATION

Solar cell parameters

IV characteristic

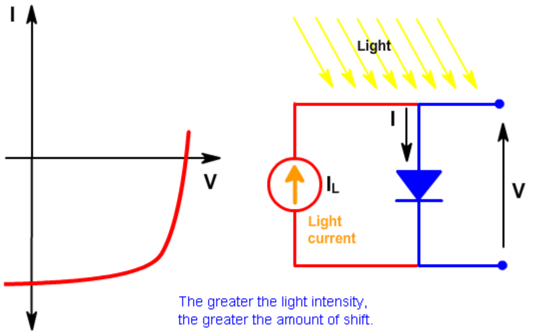


When light shines on the cell, the IV curve shifts as the cell begins to generate power.

SOLAR CELL OPERATION

Solar cell parameters

IV characteristic

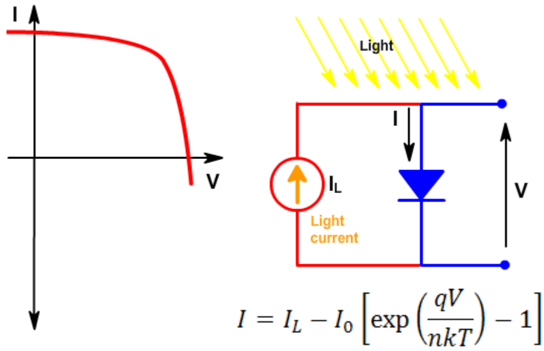


The greater the light intensity, the greater the amount of shift.

SOLAR CELL OPERATION

Solar cell parameters

IV characteristic

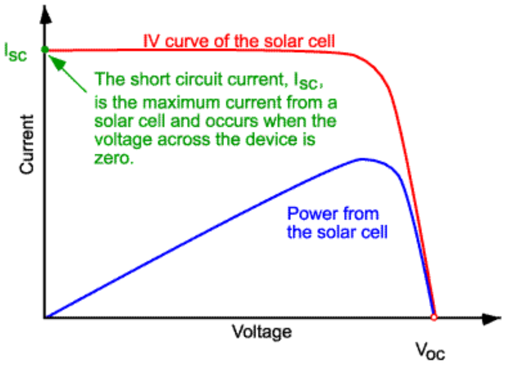


$$I = I_L - I_0\left[\exp\left(\frac{qV}{nkT}\right) - 1\right]$$

SOLAR CELL OPERATION

Solar cell parameters

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



The short circuit current, I_{SC}, is the maximum current from a solar cell and occurs when the voltage across the device is zero.

SOLAR CELL OPERATION

Solar cell parameters

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

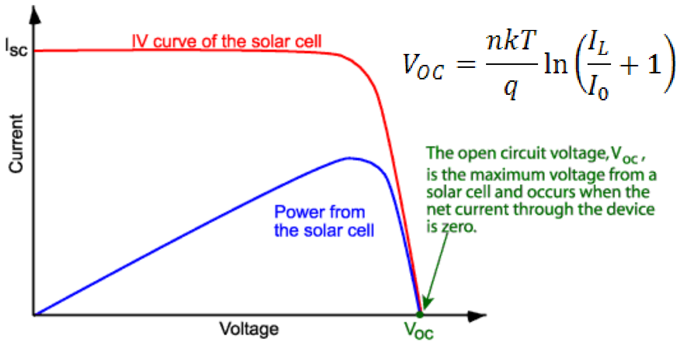
- Area of the solar cell (common to use J_{sc} in mA/cm^2)
- Incident flux (i.e. number of photons)
- Spectrum incident light
- Optical properties of the solar cell
- Collection probability, e.g. diffusion length

$$J_{SC} = qG\left(L_n + L_p\right)$$

SOLAR CELL OPERATION

Solar cell parameters

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



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

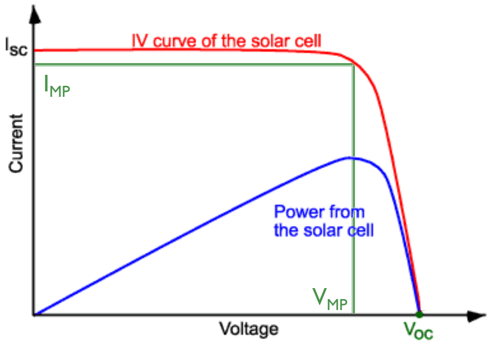
The open circuit voltage, V_{oc}, is the maximum voltage from a solar cell and occurs when the net current through the device is zero.

V_{oc} depends strongly on the recombination

SOLAR CELL OPERATION

Solar cell parameters

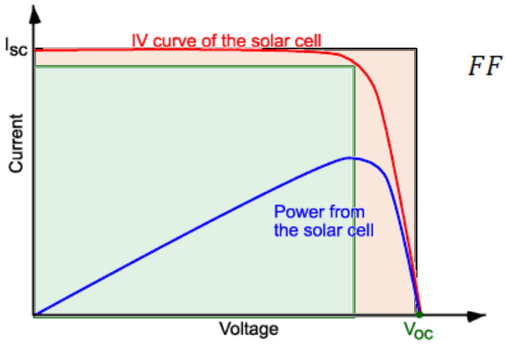
IV characteristic: Maximum power



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

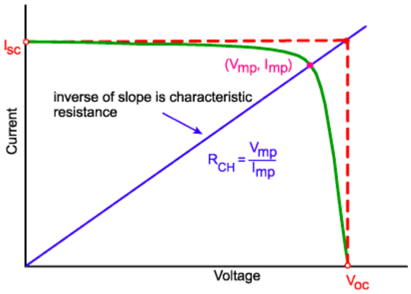
SOLAR CELL OPERATION

Solar cell parameters

Resistive effects

- Characteristic resistance

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



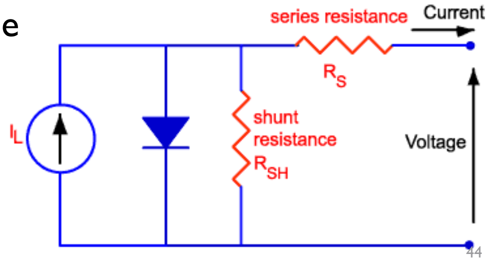
$$R_{CH} = \frac{V_{MP}}{I_{MP}} = \frac{V_{OC}}{I_{SC}}$$

SOLAR CELL OPERATION

Solar cell parameters

Resistive effects

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



SOLAR CELL OPERATION

Solar cell parameters

Resistive effects

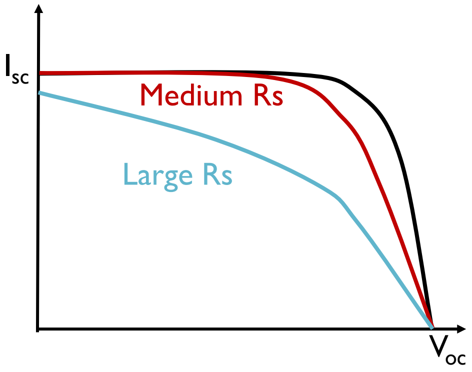
- Characteristic resistance
- Parasitic resistance
  - Series resistance
  - Shunt resistance

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

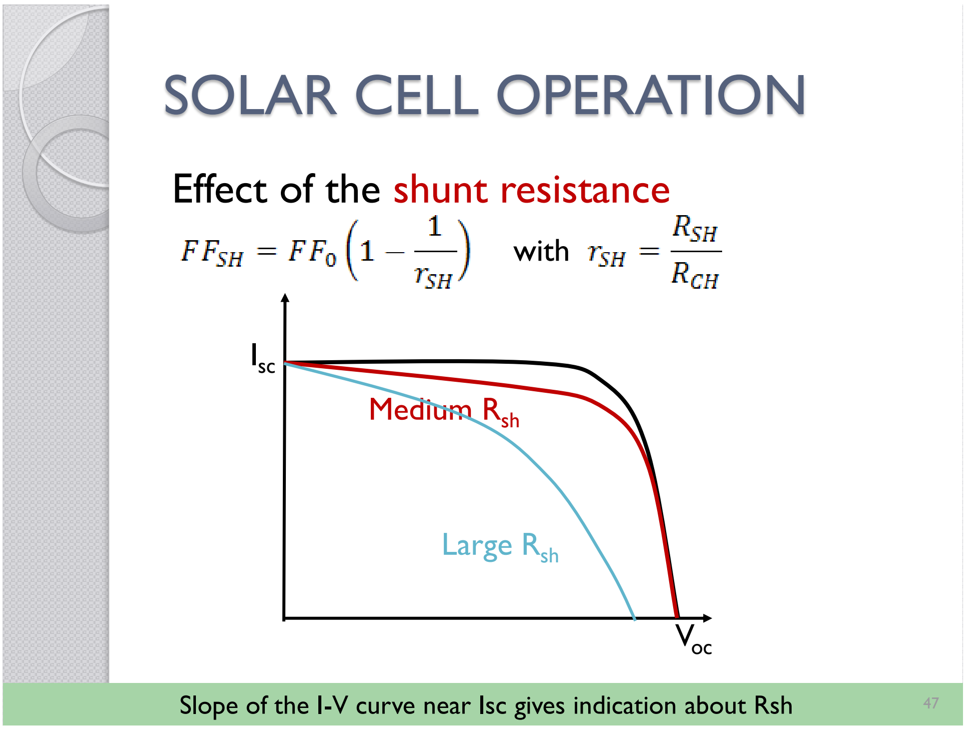
SOLAR CELL OPERATION

Effect of the series resistance

$FF' = FF(1 - r_S)$ with $r_S = \frac{R_S}{R_{CH}}$



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

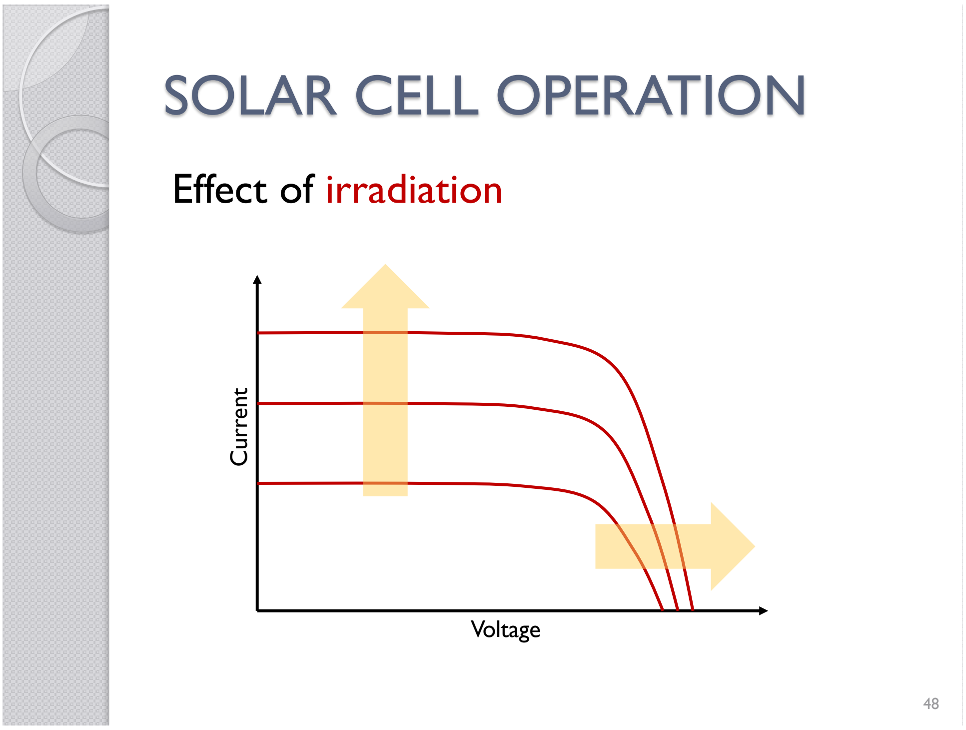


SOLAR CELL OPERATION

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 Isc gives indication about Rsh

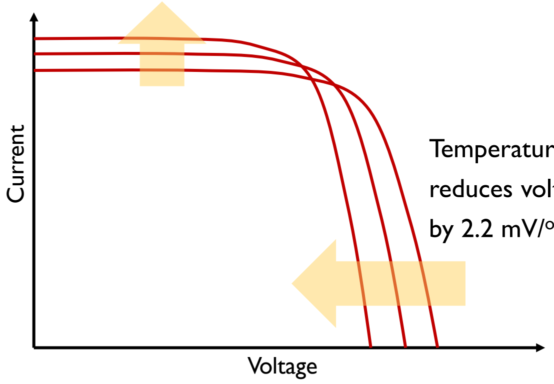


SOLAR CELL OPERATION

Effect of irradiation

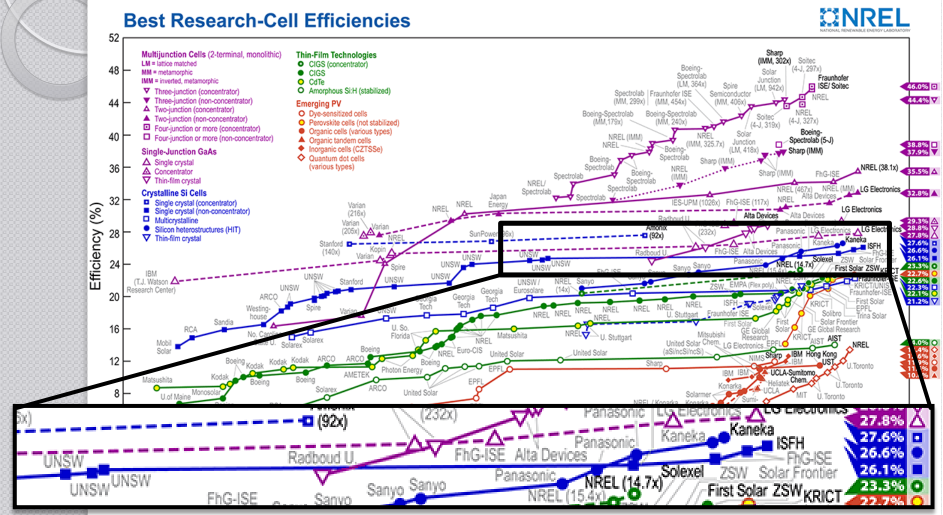
SOLAR CELL OPERATION

Effect of temperature



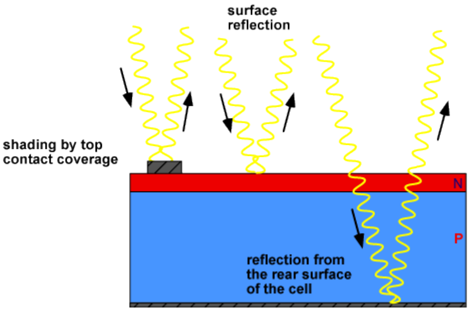
Temperature increase reduces voltage by 2.2 mV/°C

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

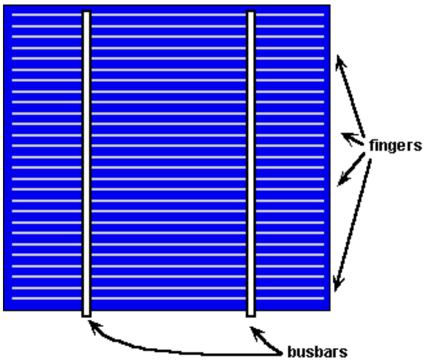
Optical losses - light which could have generated an electron-hole pair, but does not, because the light is reflected from the front surface, or because it is not absorbed in the solar cell.

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

DESIGN OF Si SOLAR CELL

Optical losses

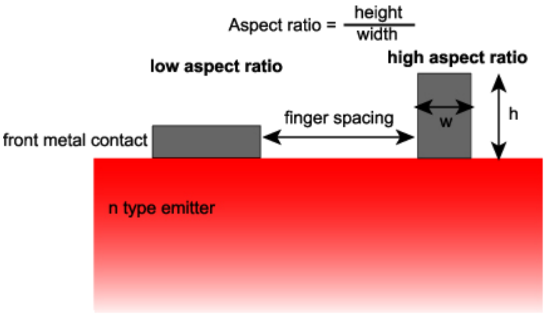
Reduce **shading** from top contacts



DESIGN OF Si SOLAR CELL

Optical losses

Reduce **shading** from top contacts

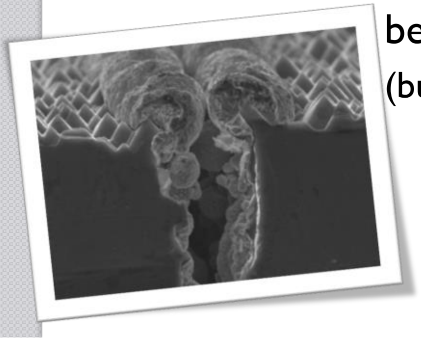


DESIGN OF Si SOLAR CELL

Optical losses

Reduce **shading** from top contacts

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



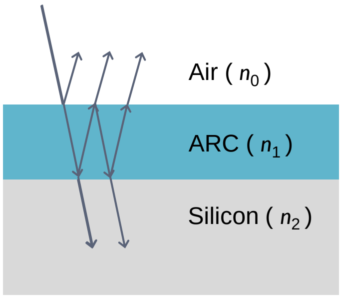
DESIGN OF Si SOLAR CELL

Optical losses

Anti-reflective coating

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

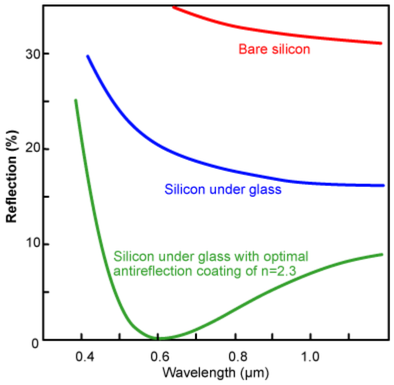
$$R = \left(\frac{n_1^2 - n_0 n_2}{n_1^2 + n_0 n_2} \right)^2$$



DESIGN OF Si SOLAR CELL

Optical losses

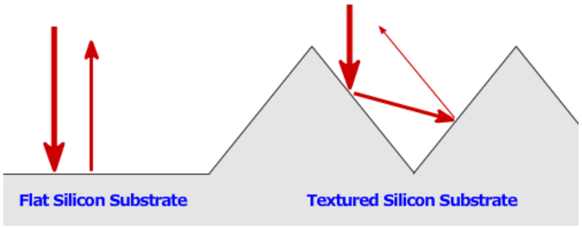
Anti-reflective coating



DESIGN OF Si SOLAR CELL

Optical losses

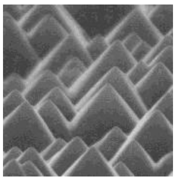
Surface **texturing**



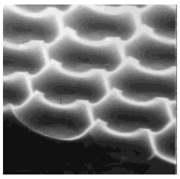
DESIGN OF Si SOLAR CELL

Optical losses

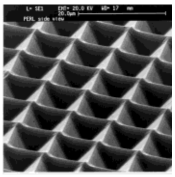
Surface **texturing**



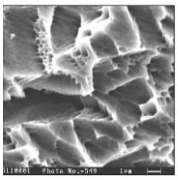
Single crystal:
Random pyramids, by etching



Multi crystal:
texturing by photolithography



Single crystal:
Inverted pyramids, by etching

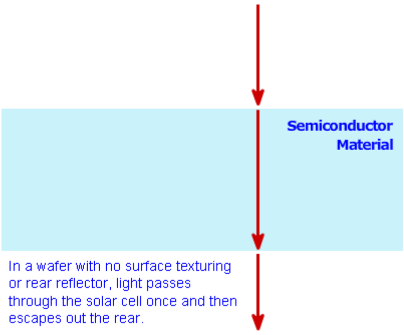


Multi crystal:
texturing by macroporous silicon

DESIGN OF Si SOLAR CELL

Optical losses

Light **trapping**: increase optical length

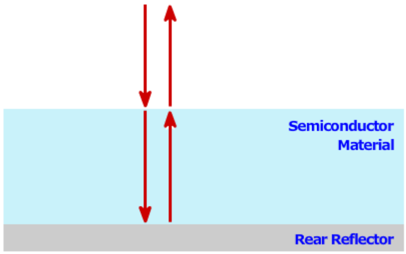


In a wafer with no surface texturing or rear reflector, light passes through the solar cell once and then escapes out the rear.

DESIGN OF Si SOLAR CELL

Optical losses

Light **trapping**: increase optical length

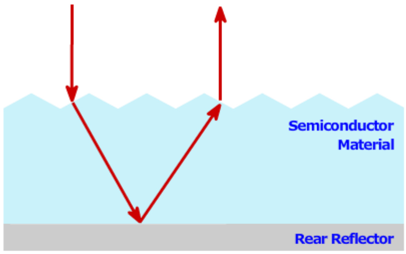


When a rear reflectors is added, the optical path length is twice the physical device thickness.

DESIGN OF Si SOLAR CELL

Optical losses

Light **trapping**: increase optical length



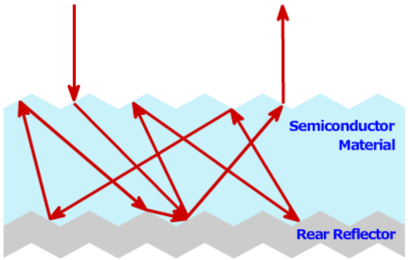
Surface texturing increases the path length but light escapes after two passes through the solar cell.

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



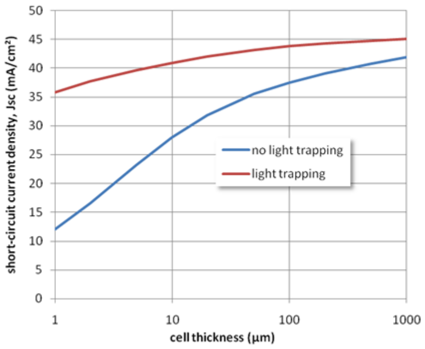
Front and rear surface texturing can trap light for multiple passes due to total internal reflection.

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

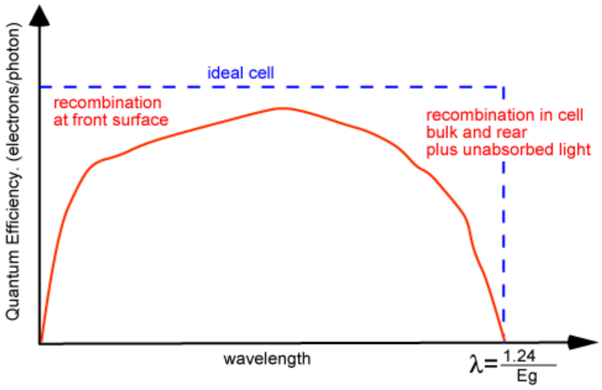
Recombination losses

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

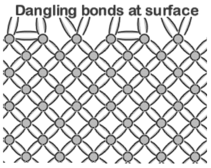
Recombination losses



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)

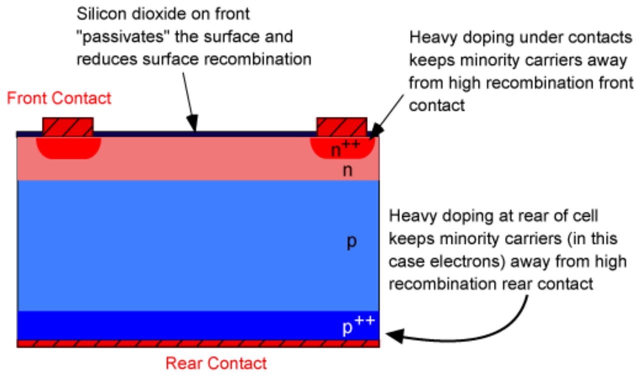
- Increasing doping, creating a repelling field

  (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**



Silicon dioxide on front "passivates" the surface and reduces surface recombination

Heavy doping under contacts keeps minority carriers away from high recombination front contact

Heavy doping at rear of cell keeps minority carriers (in this case electrons) away from high recombination rear contact

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DESIGN OF Si SOLAR CELL

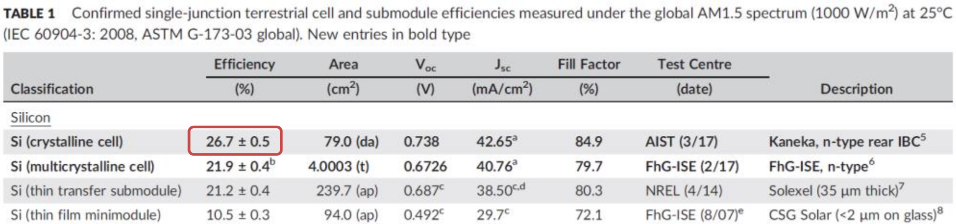


TABLE 1 Confirmed single-junction terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global). New entries in bold type

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill Factor (%)	Test Centre (date)	Description
Silicon							
Si (crystalline cell)	**26.7 ± 0.5**	**79.0 (da)**	**0.738**	**42.65**[a]	**84.9**	**AIST (3/17)**	**Kaneka, n-type rear IBC**[5]
Si (multicrystalline cell)	**21.9 ± 0.4**[b]	**4.0003 (t)**	**0.6726**	**40.76**[a]	**79.7**	**FhG-ISE (2/17)**	**FhG-ISE, n-type**[6]
Si (thin transfer submodule)	21.2 ± 0.4	239.7 (ap)	0.687[c]	38.50[c,d]	80.3	NREL (4/14)	Solexel (35 μm thick)[7]
Si (thin film minimodule)	10.5 ± 0.3	94.0 (ap)	0.492[c]	29.7[c]	72.1	FhG-ISE (8/07)[e]	CSG Solar (<2 μm on glass)[8]

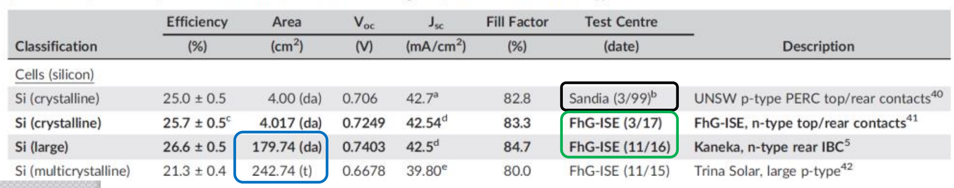


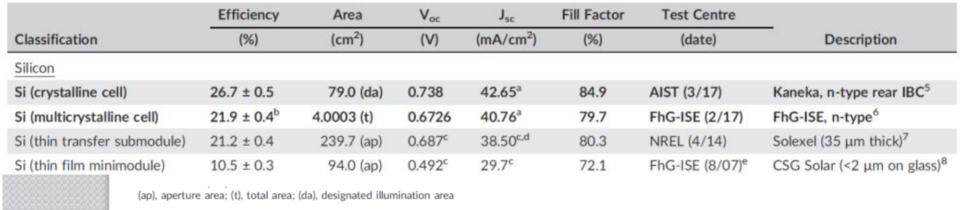
TABLE 4 "Notable exceptions": "Top dozen" confirmed cell and module results, not class records measured under the global AM1.5 spectrum (1000 Wm^{-2}) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global). New entries in bold type

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill Factor (%)	Test Centre (date)	Description
Cells (silicon)							
Si (crystalline)	25.0 ± 0.5	4.00 (da)	0.706	42.7[a]	82.8	Sandia (3/99)[b]	UNSW p-type PERC top/rear contacts[40]
Si (crystalline)	**25.7 ± 0.5**[c]	**4.017 (da)**	**0.7249**	**42.54**[d]	**83.3**	**FhG-ISE (3/17)**	**FhG-ISE, n-type top/rear contacts**[41]
Si (large)	**26.6 ± 0.5**	**179.74 (da)**	**0.7403**	**42.5**[d]	**84.7**	**FhG-ISE (11/16)**	**Kaneka, n-type rear IBC**[5]
Si (multicrystalline)	21.3 ± 0.4	242.74 (t)	0.6678	39.80[e]	80.0	FhG-ISE (11/15)	Trina Solar, large p-type[42]

(ap), aperture area; (t), total area; (da), designated illumination area

DESIGN OF Si SOLAR CELL

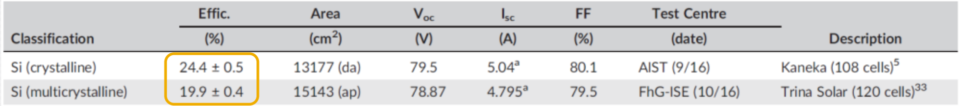
TABLE 1 Confirmed single-junction terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global). New entries in bold type



Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill Factor (%)	Test Centre (date)	Description
Silicon							
Si (crystalline cell)	**26.7 ± 0.5**	**79.0 (da)**	**0.738**	**42.65[a]**	**84.9**	**AIST (3/17)**	**Kaneka, n-type rear IBC[5]**
Si (multicrystalline cell)	**21.9 ± 0.4[b]**	**4.0003 (t)**	**0.6726**	**40.76[a]**	**79.7**	**FhG-ISE (2/17)**	**FhG-ISE, n-type[6]**
Si (thin transfer submodule)	21.2 ± 0.4	239.7 (ap)	0.687[c]	38.50[c,d]	80.3	NREL (4/14)	Solexel (35 µm thick)[7]
Si (thin film minimodule)	10.5 ± 0.3	94.0 (ap)	0.492[c]	29.7[c]	72.1	FhG-ISE (8/07)[e]	CSG Solar (<2 µm on glass)[8]

(ap), aperture area; (t), total area; (da), designated illumination area

TABLE 3 Confirmed terrestrial module efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at a cell temperature of 25°C (IEC 60904-3: 2008, ASTM G-173-03 global). New entries in bold type



Classification	Effic. (%)	Area (cm^2)	V_{oc} (V)	I_{sc} (A)	FF (%)	Test Centre (date)	Description
Si (crystalline)	24.4 ± 0.5	13177 (da)	79.5	5.04[a]	80.1	AIST (9/16)	Kaneka (108 cells)[5]
Si (multicrystalline)	19.9 ± 0.4	15143 (ap)	78.87	4.795[a]	79.5	FhG-ISE (10/16)	Trina Solar (120 cells)[33]

Solar cell efficiency tables (version 50) Martin A. Green et al

Next class…

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

A new set of exercises.

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