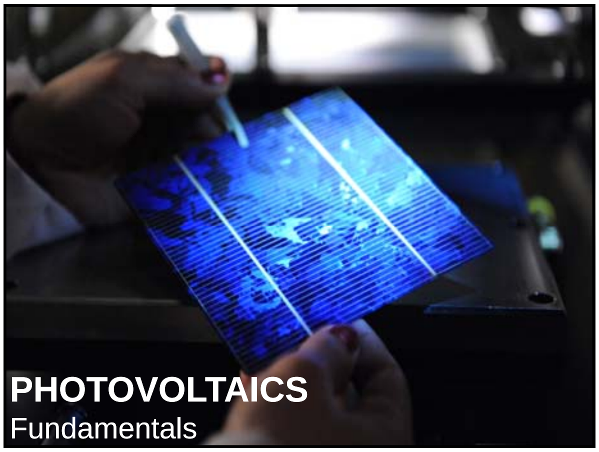
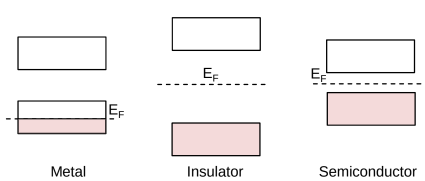


PV FUNDAMENTALS

- 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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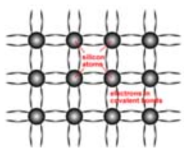
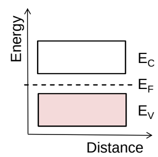
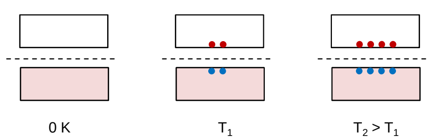




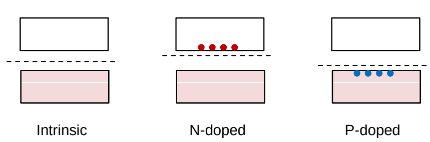
SEMICONDUCTOR BASICS

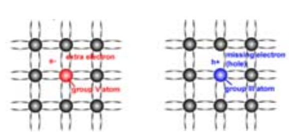
- Effect of temperature



SEMICONDUCTOR BASICS

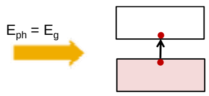
- Effect of doping





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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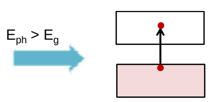

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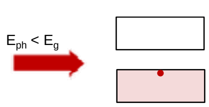


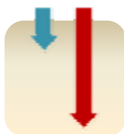
$$E = \frac{hc}{\lambda}$$

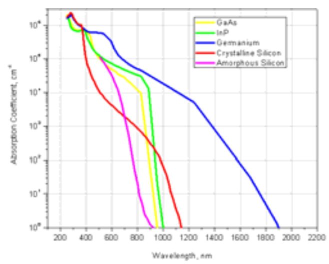
$$E(eV) = \frac{1.24}{\lambda(\mu m)}$$

SEMICONDUCTOR BASICS

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

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

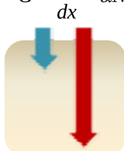


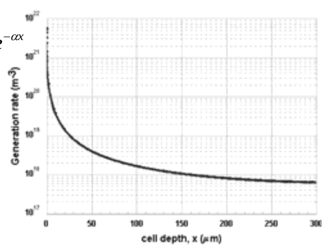


PV FUNDAMENTALS

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

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

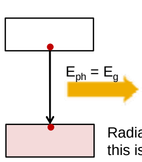




PV FUNDAMENTALS

Recombination may occur through…

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

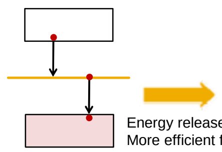


Radiated photon is weakly absorbed;
this is how LEDs work!!
Not very likely for indirect gap semiconductor like Si

SEMICONDUCTOR BASICS

Recombination may occur through…

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

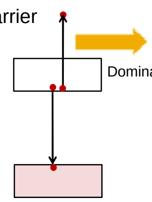


Energy released by photon and/or phonons
More efficient for mid-gap defect levels

SEMICONDUCTOR BASICS

Recombination may occur through…

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



Dominant for heavily doped semiconductors

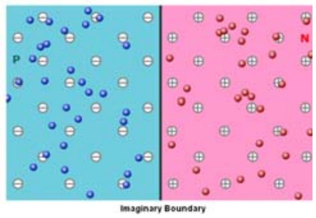
SEMICONDUCTOR BASICS

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



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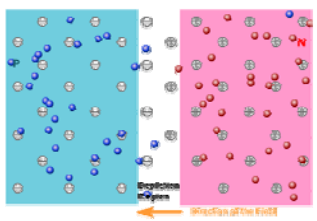

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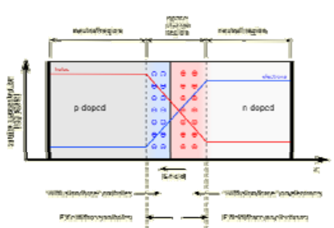

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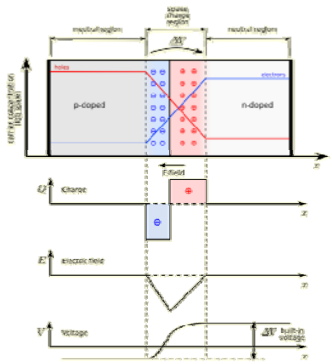
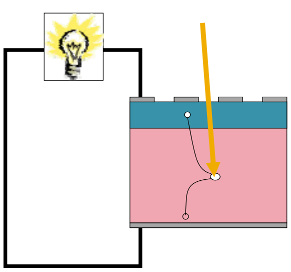


SOLAR CELL OPERATION

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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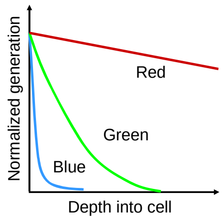

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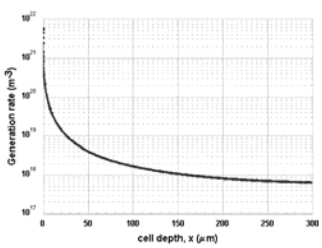
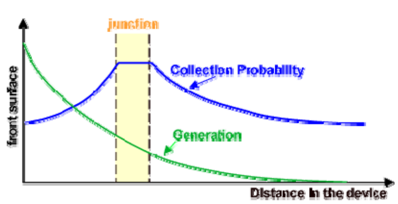


SOLAR CELL OPERATION

Basic steps:

- the collection of the carriers



SOLAR CELL OPERATION

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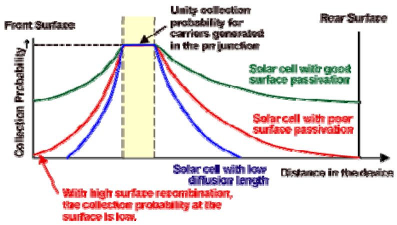


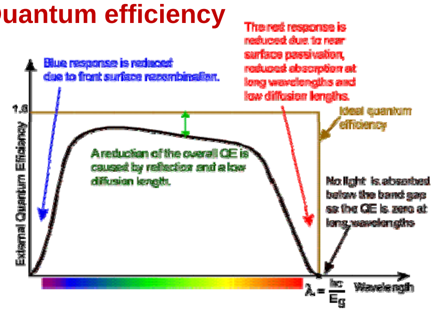
Solar cell operation

Quantum efficiency

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

Solar cell operation

Quantum efficiency

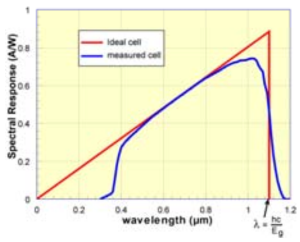


External quantum efficiency includes the effect of optical losses, e.g. reflection on the surface, ...

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

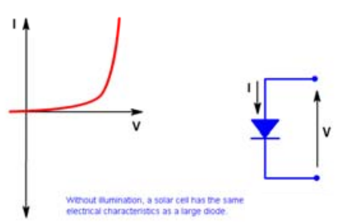
IV characteristic

= diode + light generated current

SOLAR CELL OPERATION

Solar cell parameters

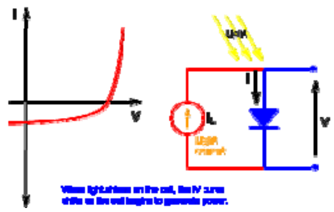
IV characteristic



SOLAR CELL OPERATION

Solar cell parameters

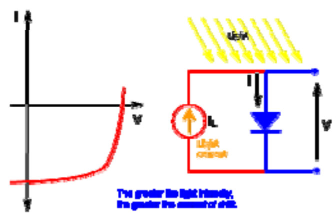
IV characteristic



SOLAR CELL OPERATION

Solar cell parameters

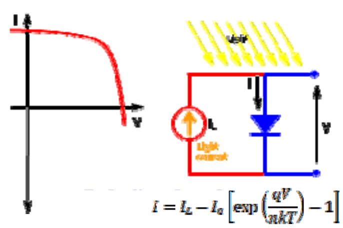
IV characteristic



SOLAR CELL OPERATION

Solar cell parameters

IV characteristic

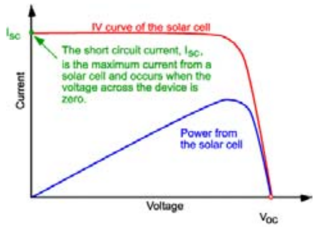


$$I = I_L - I_o\left[\exp\left(\frac{qV}{nkT}\right) - 1\right]$$

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})

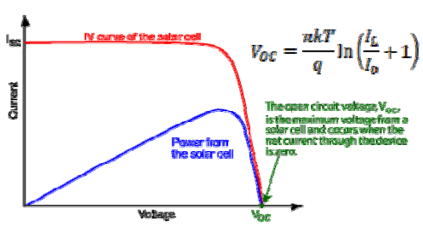
- Area of the solar cell (common to use J_{sc} in mA/cm^2)
- Incident flux (i.e. number of photons)
- Spectrum incident light
- Optical properties of the solar cell
- Collection probability, e.g. diffusion length

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

SOLAR CELL OPERATION

Solar cell parameters

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



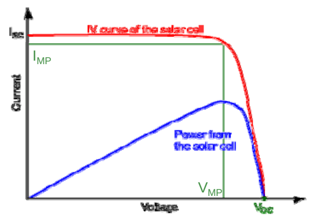
$$V_{OC} = \frac{nkT}{q}\ln\left(\frac{I_L}{I_0}+1\right)$$

V_{oc} depends strongly on the recombination

SOLAR CELL OPERATION

Solar cell parameters

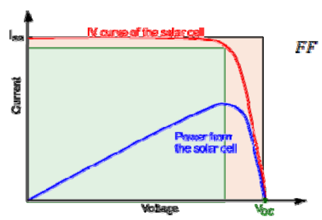
IV characteristic: Maximum power



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

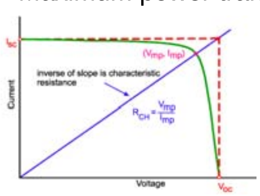
SOLAR CELL OPERATION

Solar cell parameters

Resistive effects

- Characteristic resistance

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



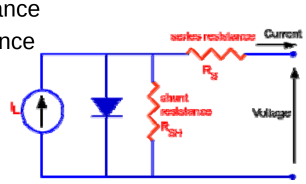
$$R_{CH} = \frac{V_{MP}}{I_{MP}} = \frac{V_{OC}}{I_{SC}}$$

SOLAR CELL OPERATION

Solar cell parameters

Resistive effects

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



SOLAR CELL OPERATION

Solar cell parameters

Resistive effects

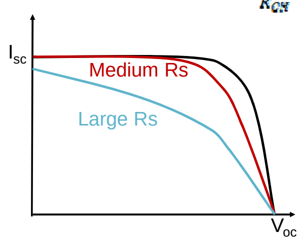
- Characteristic resistance
- Parasitic resistance
  - Series resistance
  - Shunt resistance

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

SOLAR CELL OPERATION

Effect of the series resistance

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

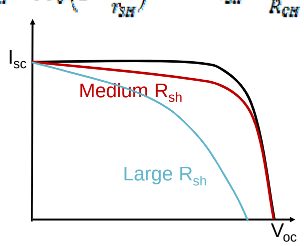


Slope of the I-V curve near V_{oc} gives indication about R_s

SOLAR CELL OPERATION

Effect of the shunt resistance

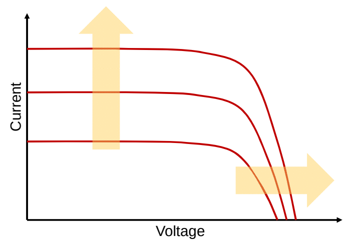
$FF_{SH} = FF_0\left(1 - \frac{1}{r_{SH}}\right)$ with $r_{SH} = \frac{R_{SH}}{R_{CH}}$



Slope of the I-V curve near Isc gives indication about Rsh

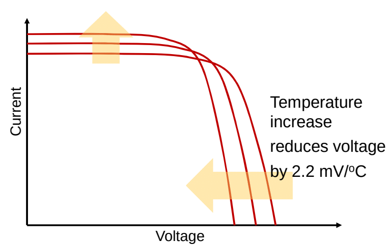
SOLAR CELL OPERATION

Effect of irradiation

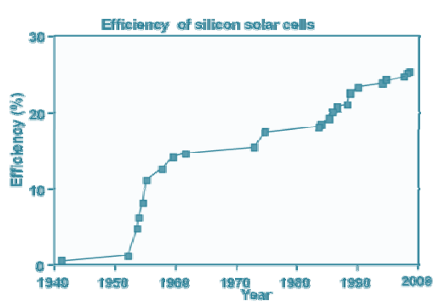


SOLAR CELL OPERATION

Effect of temperature

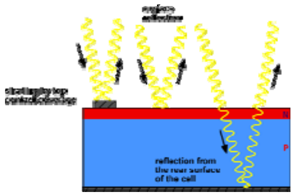


DESIGN OF Si SOLAR CELL



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

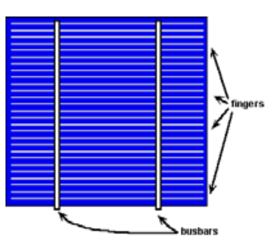
Optical losses - light which could have generated an electron-hole pair, but does not, because the light is reflected from the front surface, or because it is not absorbed in the solar cell.

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

DESIGN OF Si SOLAR CELL

Optical losses

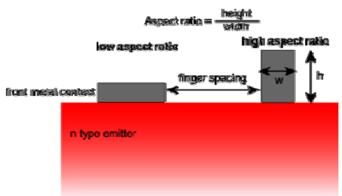
Reduce **shading** from top contacts



DESIGN OF Si SOLAR CELL

Optical losses

Reduce **shading** from top contacts

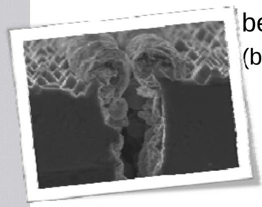


DESIGN OF Si SOLAR CELL

Optical losses

Reduce **shading** from top contacts

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



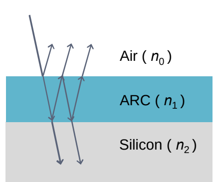
DESIGN OF Si SOLAR CELL

Optical losses

Anti-reflective coating

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

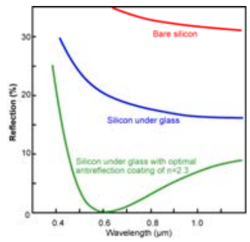
$$R = \left(\frac{n_1^2 - n_0 n_2}{n_1^2 + n_0 n_2} \right)^2$$



DESIGN OF Si SOLAR CELL

Optical losses

Anti-reflective coating



DESIGN OF Si SOLAR CELL

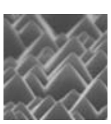
Optical losses

Surface **texturing**

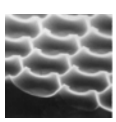
DESIGN OF Si SOLAR CELL

Optical losses

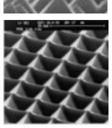
Surface **texturing**



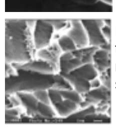
Single crystal: Random pyramids, by etching



Multi crystal: texturing by photolithography



Single crystal: Inverted pyramids, by etching



Multi crystal: texturing by macroporous silicon

DESIGN OF Si SOLAR CELL

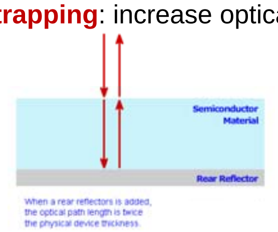
Optical losses

Light **trapping**: increase optical length

DESIGN OF Si SOLAR CELL

Optical losses

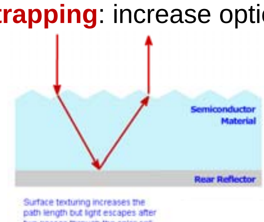
Light **trapping**: increase optical length



DESIGN OF Si SOLAR CELL

Optical losses

Light **trapping**: increase optical length

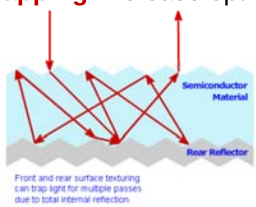


Snell's law of refraction: $n_1 \sin\theta_1 = n_2 \sin\theta_2$

DESIGN OF Si SOLAR CELL

Optical losses

Light **trapping**: increase optical length



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

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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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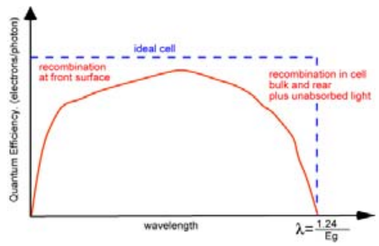
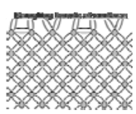
Recombination losses



Design of silicon solar cells

Recombination losses:
Surface **passivation**

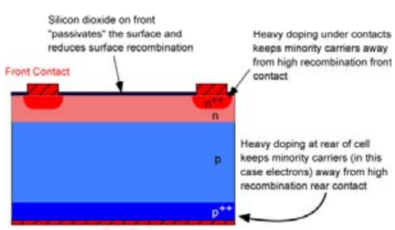
- Reducing the number of dangling bonds by growing a SiO_2 or SiN thin film on the surface (also for anti-reflection coating; notice that it is an electric insulator)



- 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**



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] (cm²)	V_{oc} (V)	J_{sc} (mA/cm²)	FF[d] (%)	Test centre[e] (and date)	Description
Silicon							
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] (cm²)	V_{oc} (V)	I_{sc} (A)	FF[d] (%)	Test centre (and date)	Description
Si (crystalline)	22·9 ± 0·5	[illegible] (da)	[illegible]	[illegible]	[illegible]	Sandia [illegible]	[illegible]
Si (large crystalline)	[illegible]	[illegible] (ap)	[illegible]	[illegible]	[illegible]	Sandia [illegible]	[illegible]
Si (multicrystalline)	[illegible]	[illegible] (ap)	[illegible]	[illegible]	[illegible]	Sandia [illegible]	[illegible]
Si (thin-film polycrystalline)	[illegible]	[illegible] (ap)	[illegible]	[illegible]	[illegible]	Sandia [illegible]	[illegible] (1–2 μm on glass)[22]

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] (cm²)	V_{oc} (V)	J_{sc} (mA/cm²)	FF (%)	Test centre (and date)	Description
Cells (silicon)							
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 substrate[5]**
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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Si (multicrystalline)	[illegible]	[illegible] (ap)	[illegible]	[illegible]	[illegible]	Sandia [illegible]	[illegible]
Si (thin-film polycrystalline)	[illegible]	[illegible] (ap)	[illegible]	[illegible]	[illegible]	Sandia [illegible]	[illegible] (1–2 μm on glass)[22]

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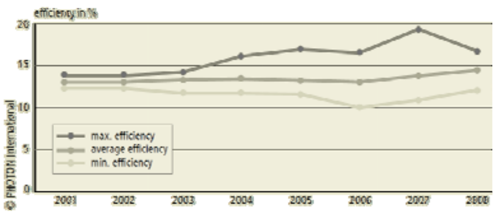
DESIGN OF Si SOLAR CELL

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



Next class…

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

And a new set of exercises…