Solar cells for energy harvesting

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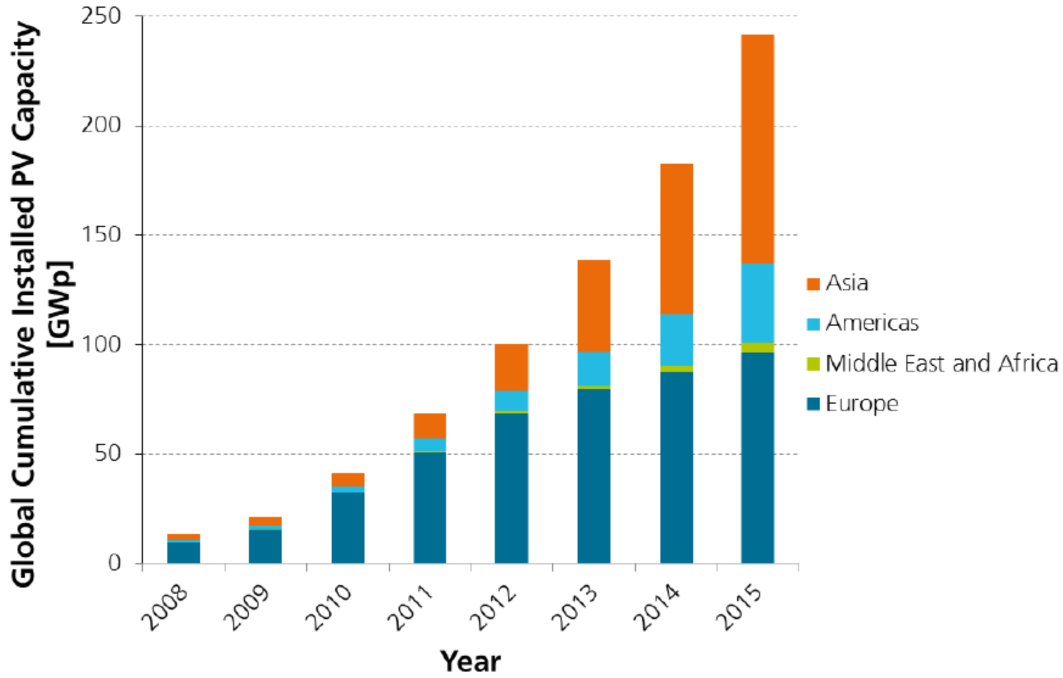
Introduction

➢ Solar energy conversion in electricity well established thanks to:

- continuous increase of solar cells efficiencies
- decrease of photovoltaic cost.

➢ Solar energy is mainly used in outdoor conditions to produce large power.

Crystalline silicon solar cells are dominating the market but other materials are also good candidates for photovoltaic conversion.



Photovoltaic Report, Fraunhofer ISE, 2016

➢ There is an increasing interest to microenergy harvesting by using photovoltaic technologies to power electronic devices using indoor light.

However there is no standard measurement procedures for testing solar cells in indoor conditions.

Several studies have compared the performances of solar cells in indoor conditions.

Outline

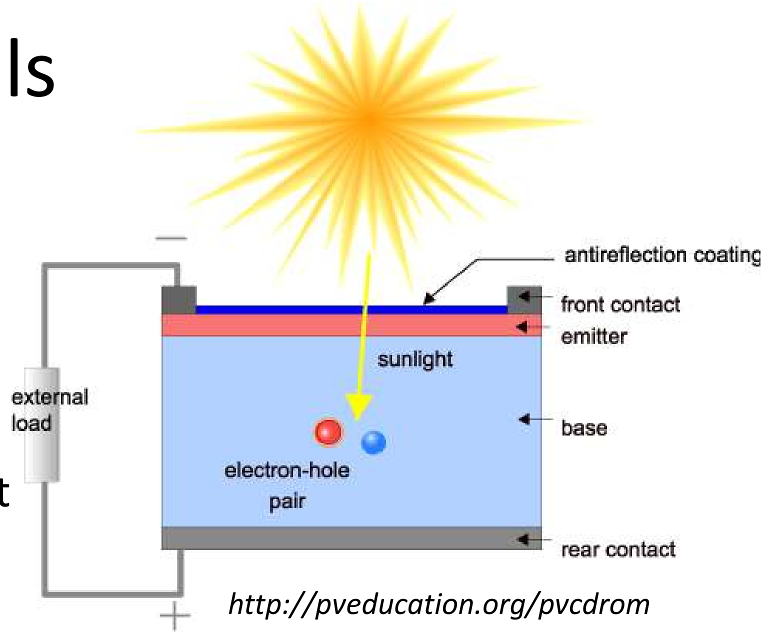
- Operation of solar cells

- Solar cells technologies and state of the art
  - Crystalline Si solar cells
  - Thin films
  - Multijunctions

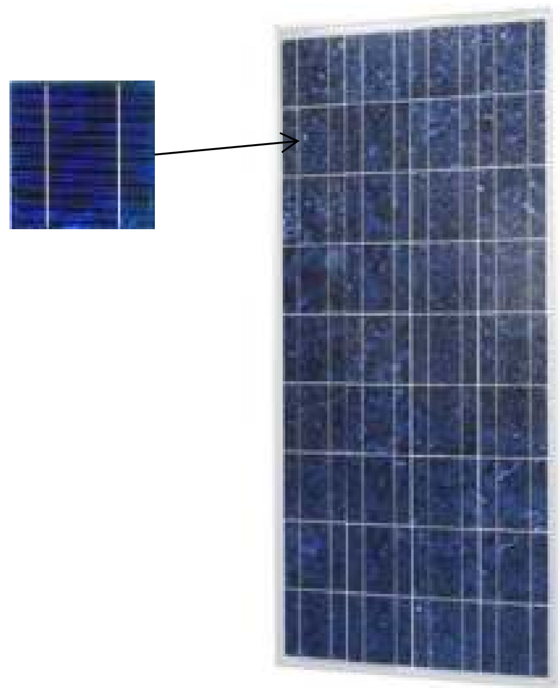
- Solar cells for energy harvesting

I. Operation of solar cells

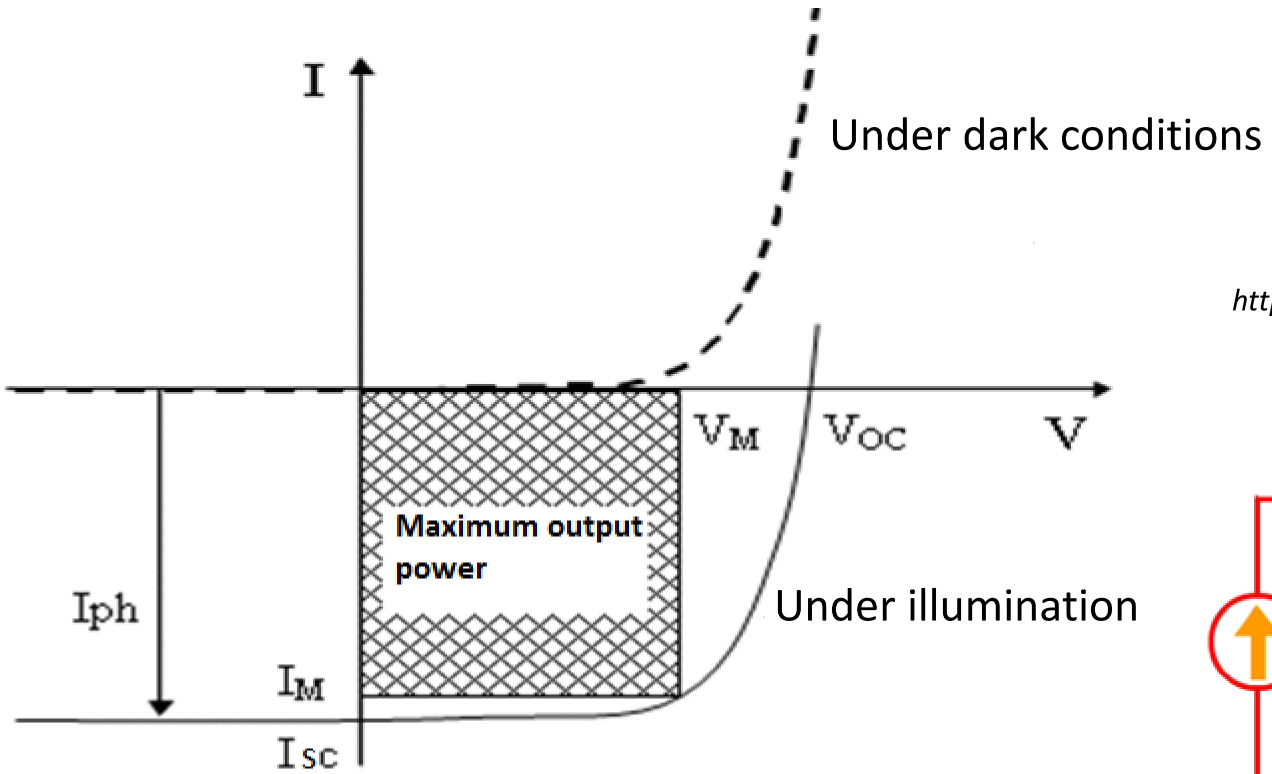
- Incident energy: **the sun or indoor light**
- Absorption of light in **the semiconductor**
  - Light absorbing properties (absorption of light and generation of carriers)
  - Electrical transport properties
- Collection of the photogenerated carriers: the solar cell device
  - Electric field
  - **Diode (P/N junction)**
- **Production of power**: modules (solar cells are interconnected and encapsulated in a module)

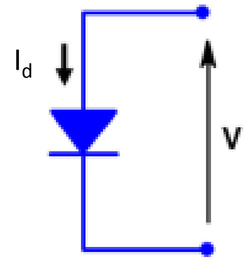


http://pveducation.org/pvcdrom



I. Operation of solar cells





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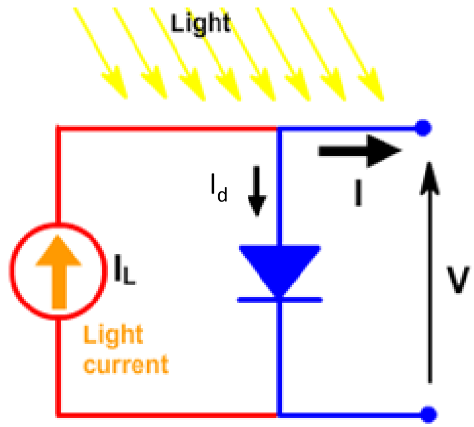


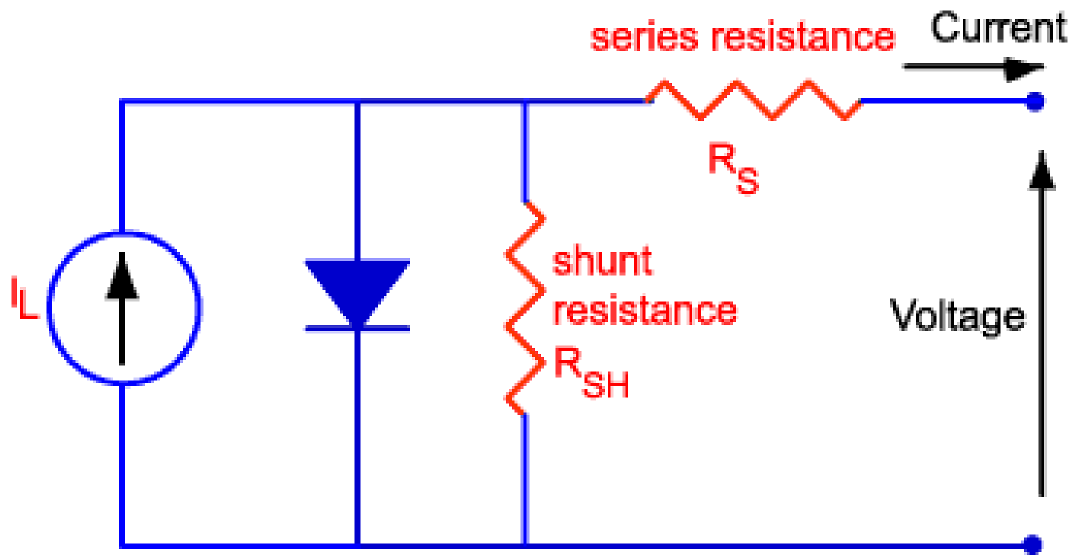
V_{oc}: open-circuit voltage
I_{sc}: short-circuit current
V_m: voltage at maximum output power
I_m: current at maximum output power

Under illumination, the photogenerated current is subtracted from the forward biased diode current:

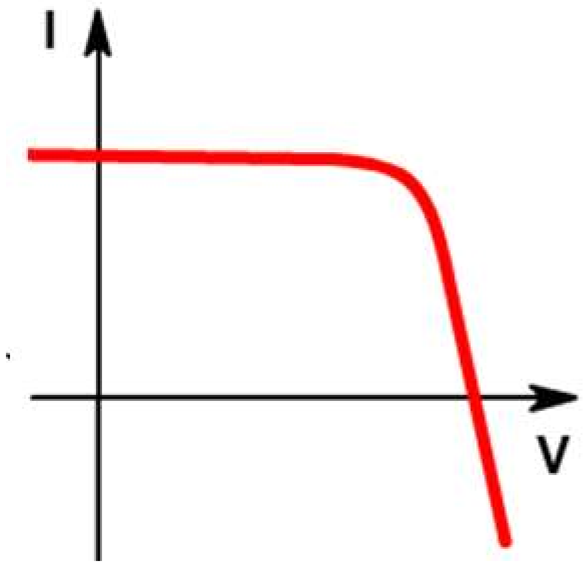
$$I = I_{diode} - I_{photogenerated}$$

Equivalent electrical circuit of a solar cell

➢The solar cell is generating power and the convention is to invert the current axis.



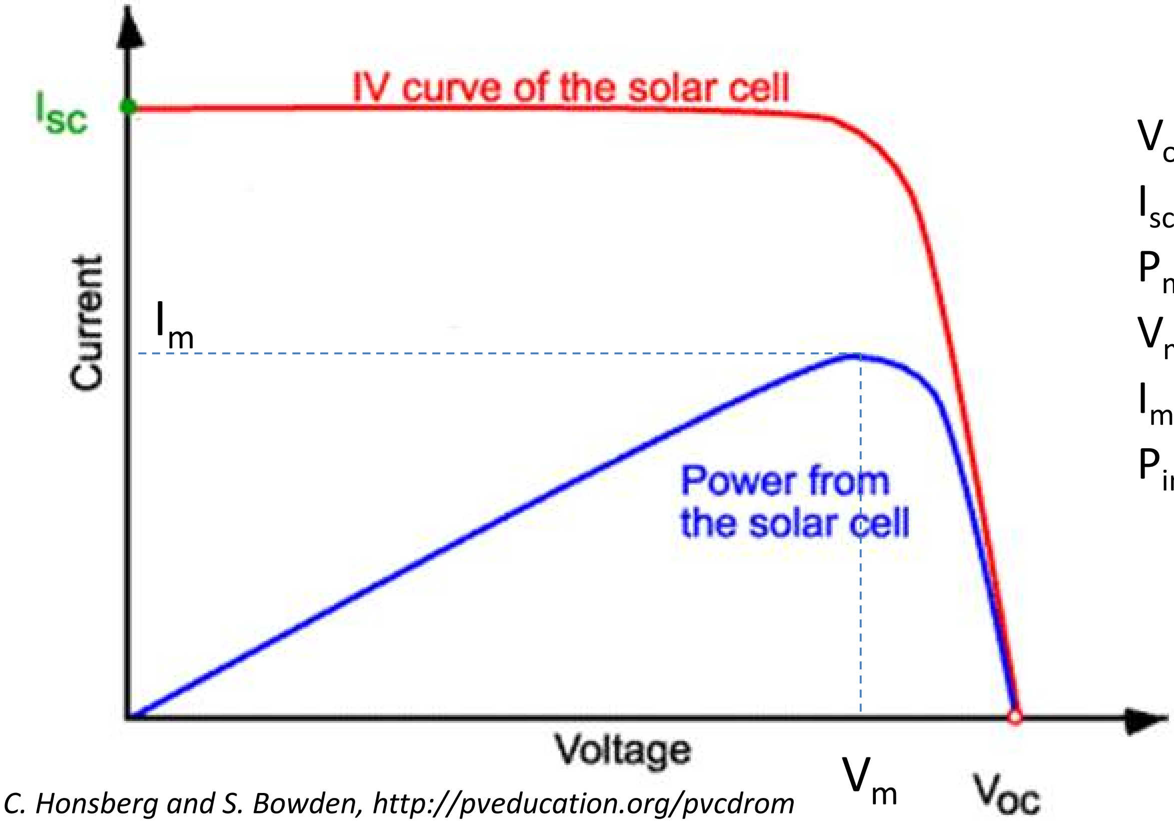
C. Honsberg and S. Bowden, http://pveducation.org/pvcdrom



- R_s: series resistance (semiconductor resistivity, wire resistivity, metal-semiconductor contact resistivity)
- R_{sh}: Shunt resistance: leakage in the device
- I_L: photogenerated current
- I_0, n: saturation current and ideality factor of the diode

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

Important electrical parameters



C. Honsberg and S. Bowden, http://pveducation.org/pvcdrom

V_{oc}: open-circuit voltage
I_{sc}: short-circuit current
P_{max}: maximum output power=$I_m V_m$
V_m: voltage at P_{max}
I_m: current at P_m
P_{inc}: incident light power

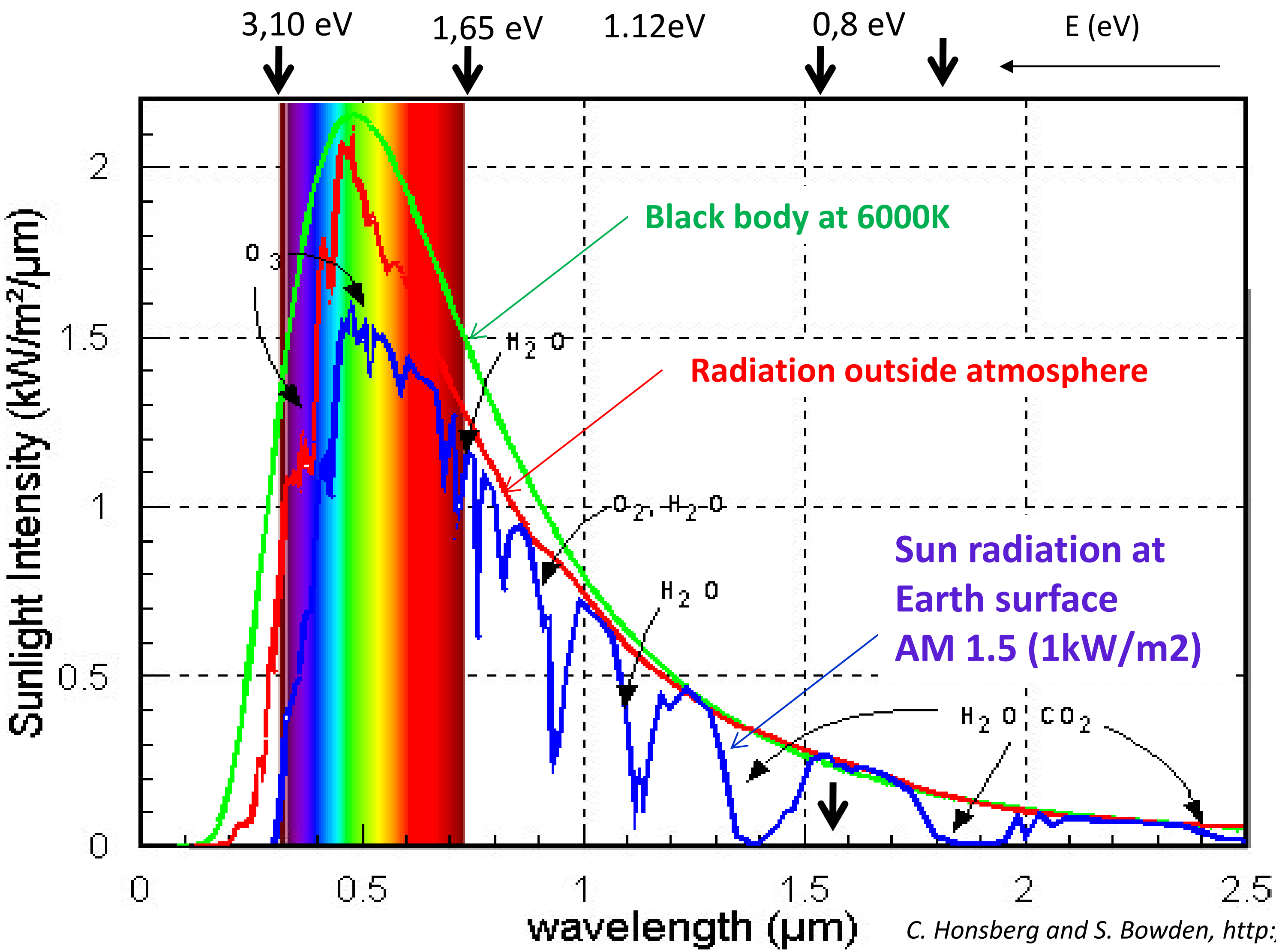
η: efficiency

$$\eta = \frac{P_{max}}{P_{inc}} = \frac{I_m V_m}{P_{inc}}$$

The photogenerated current depends on:
- intensity of light
- absorbing properties of the semiconductor
- quality of the semiconductor

Solar cells Standard Test Conditions (STC)

- Solar spectrum at the Earth's surface : Air mass 1.5 spectrum (AM1.5)
- Intensity of 1 kW/m² (one-sun illumination) -> if η=20% then P_{max}=20 mW/cm²
- Cell temperature of 25 °C



C. Honsberg and S. Bowden, http://pveducation.org/pvcdrom

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- Operation of solar cells
- **Solar cells technologies and state of the art**
  - **- Crystalline Si solar cells**
  - **- Thin films**
  - **- Multijunctions**
- Solar cells for energy harvesting

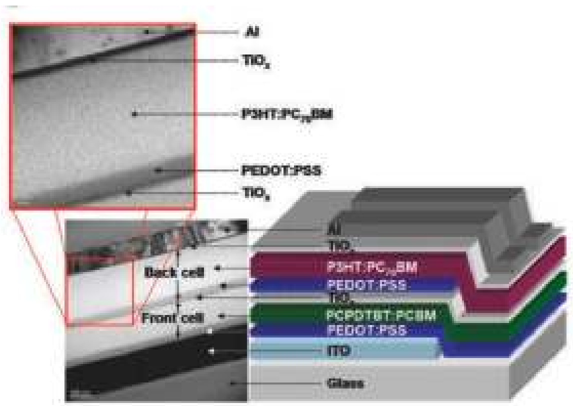
II. Solar cells technologies

- **Bulk silicon**
  - PN junction
  - Well-known technology, 90% of the industrial production

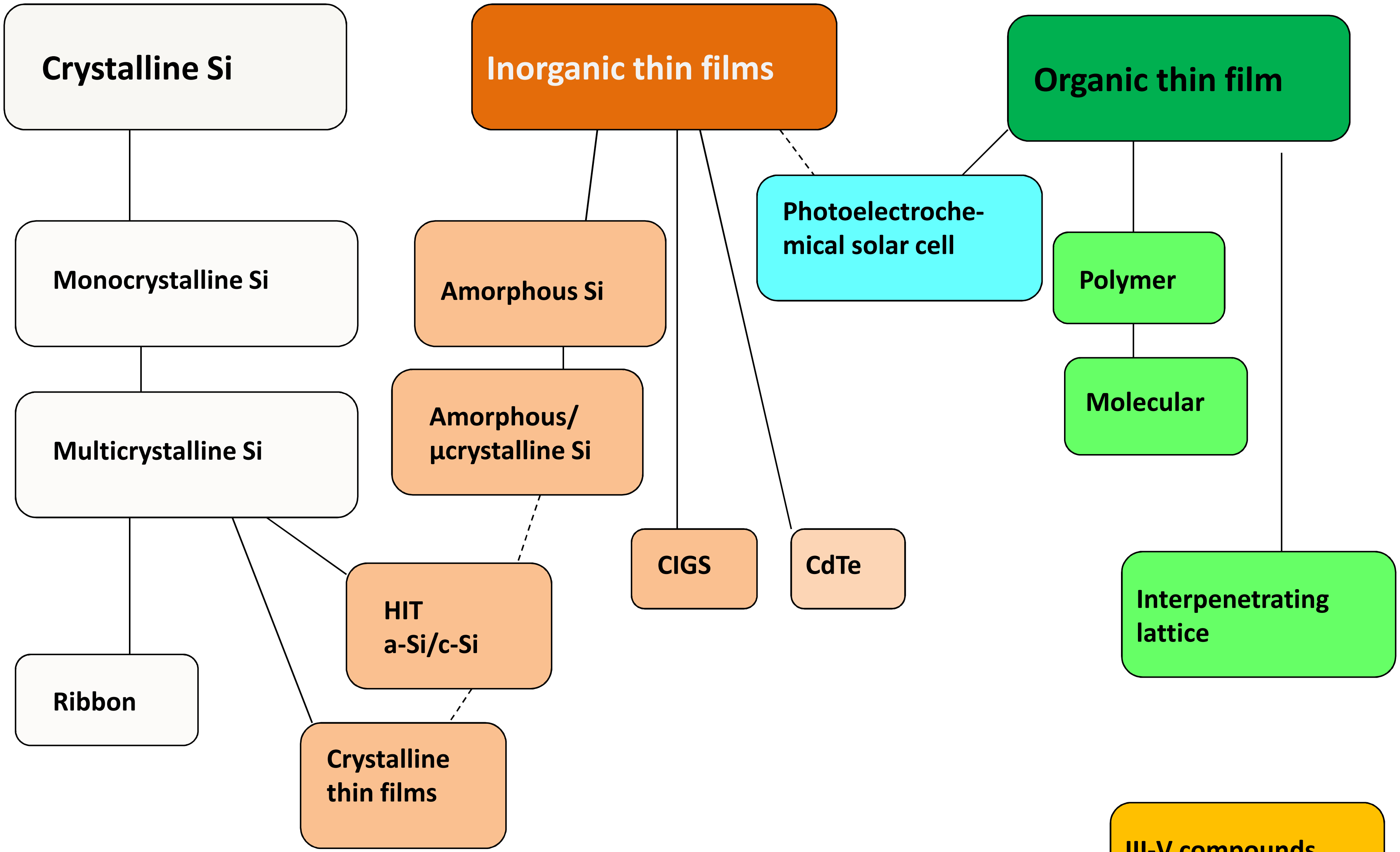
- Thin layers – low cost, flexible
  - Amorphous silicon, CdTe, CIGS
  - Organic, quantum dots, DSSC, perovskite…

- Multijunctions
  - Concentration : III-V materials

  multijunctions…



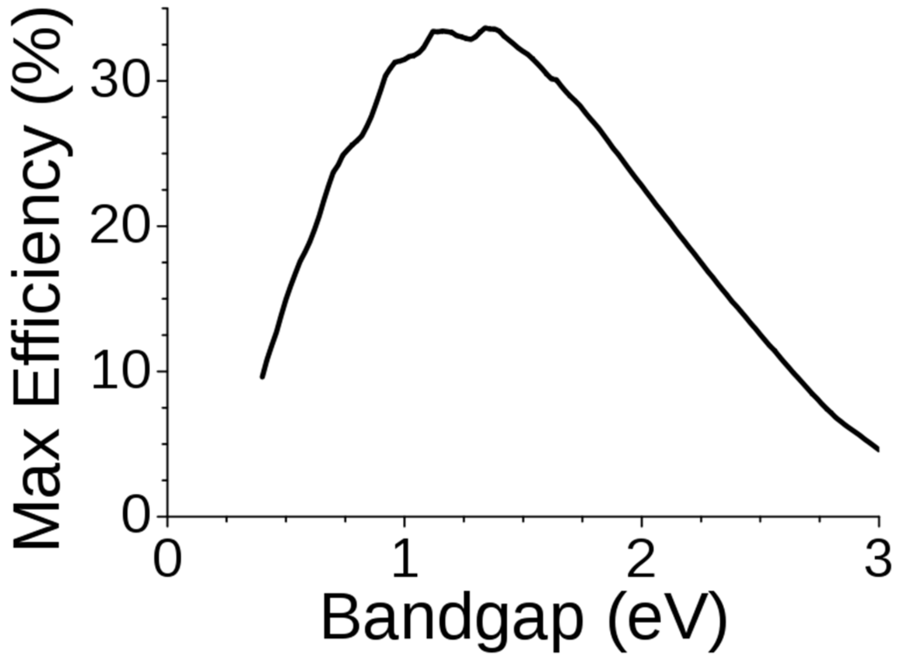
Classification by material



Bulk silicon solar cells

- Si: abundant : 26% of the surface of the earth
- Well-known material (most used material in microelectronics), reliable
- Theoretical maximum efficiency of about 31%
- Industrial efficiencies: 18-22%
- Si solar cells world production ~ 90%

The Shockley-Queisser limit for the efficiency of a single junction solar cell under one-sun illumination.

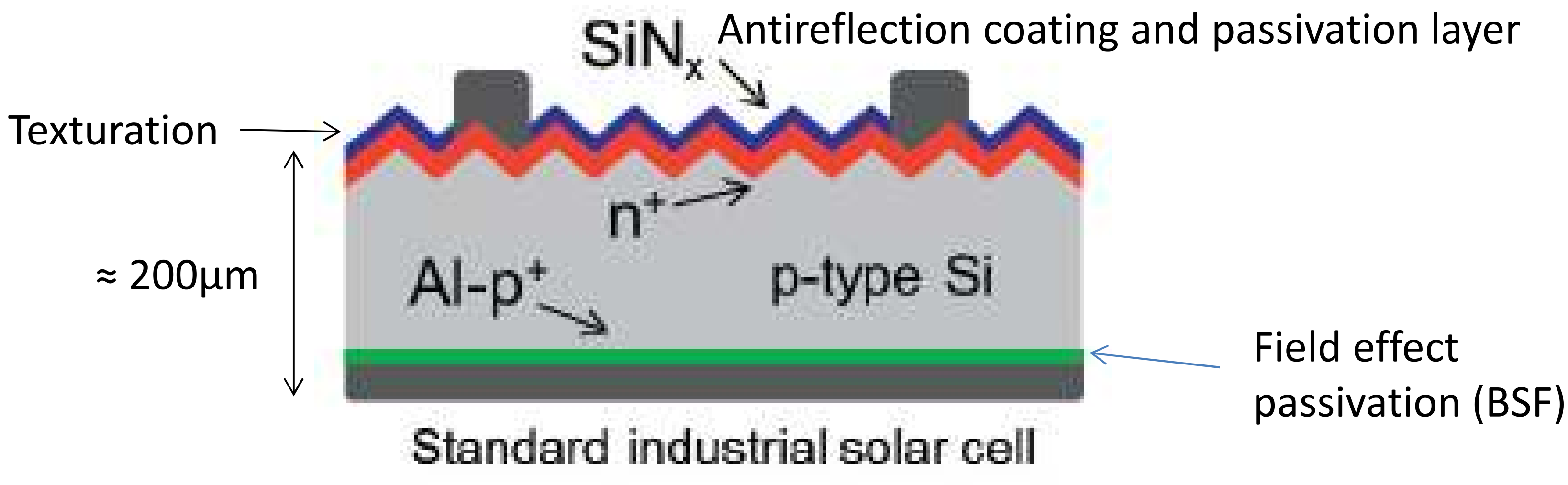


> ➢ For single Si junction: maximum efficiency is about 31%
> ➢ Optimal band gap: 1-1.5eV

Shockley W, Queisser HJ, Journal of Applied Physics ,1961, 32:510-519.

Bulk silicon solar cells

Al-BSF structure (Aluminum Back Surface Field): the most commercialized



Jan Krügener and Nils-Peter Harder, Energy Procedia 38 (2013) 108 – 113

Optimisation by reduction of:

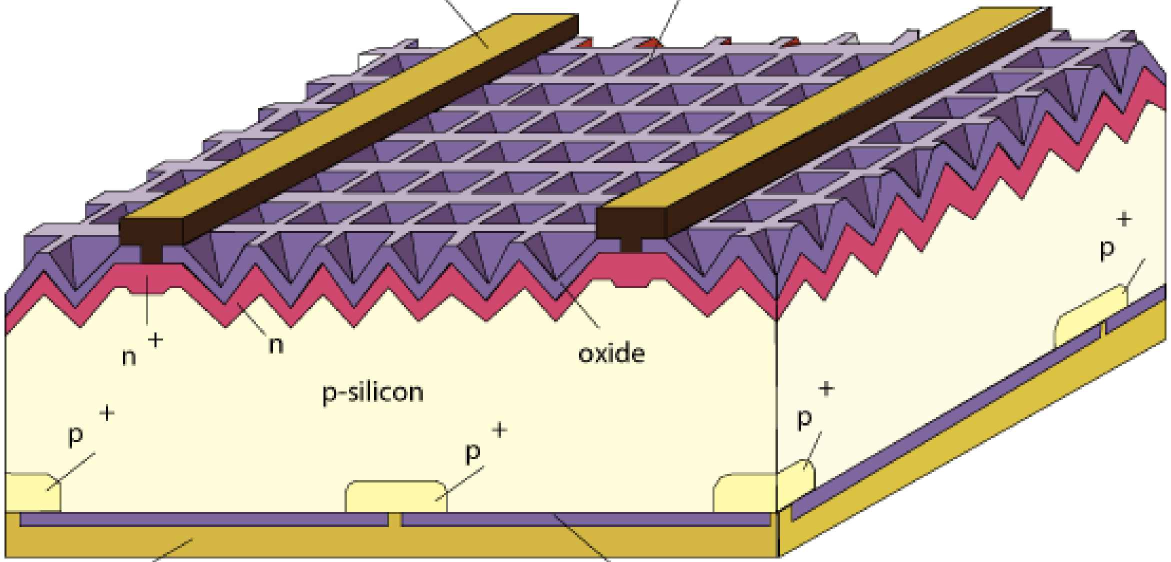
- Optical losses (metal shadowing, reflection…)
- Recombination in the volume (purification, defects, grain boundaries…) and at the surfaces
- Series resistance (due to metallisation, material, contacts…)

High-efficiency concepts of crystalline silicon (c-Si) wafer based solar cells

➢ Improved surface passivation and light trapping and low Rs

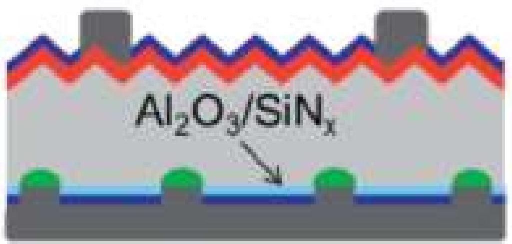
PERL (passivated emitter rear locally diffused) structure : 25% efficiency

M.A. Green, Prog. Photovolt: Res. Appl. 2009; 17:183–189

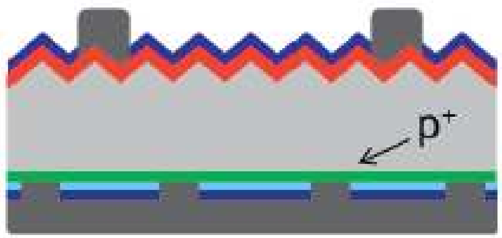


Similar industrial structures

Jan Krügener and Nils-Peter Harder, Energy Procedia 38 (2013) 108 – 113



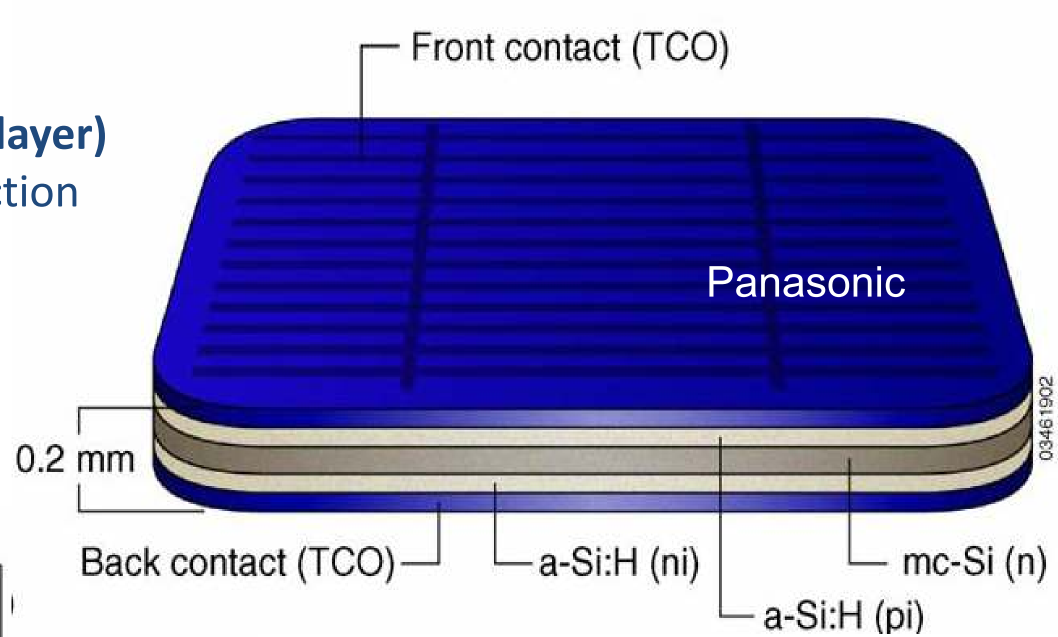
Industrial passivated emitter and rear cell (PERC)

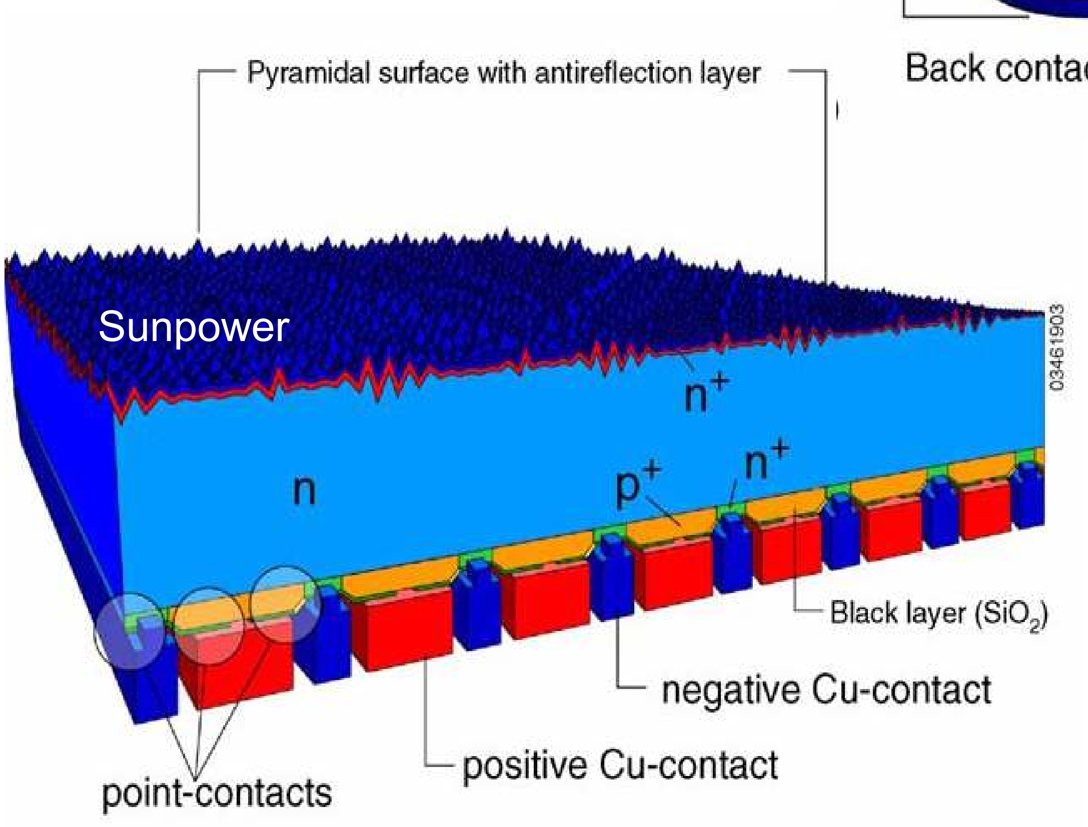


Industrial passivated emitter and rear, totally-diffused (PERT)

High-efficiency concepts of crystalline silicon (c-Si) wafer based solar cells

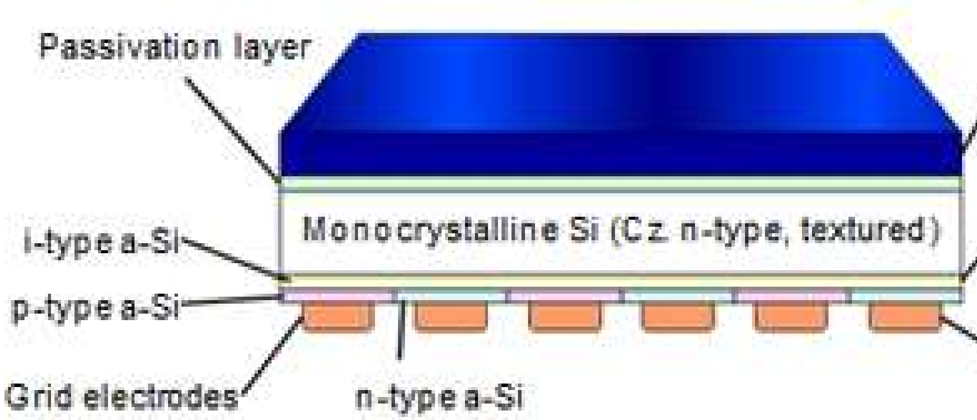
HIT (Heterojunction with thin intrinsic layer)
Passivation of c-Si surface by a-Si: reduction of recombinations





Rear contact solar cell
Reduction of front contact shading

High-efficiency concepts of crystalline silicon (c-Si) wafer based solar cells



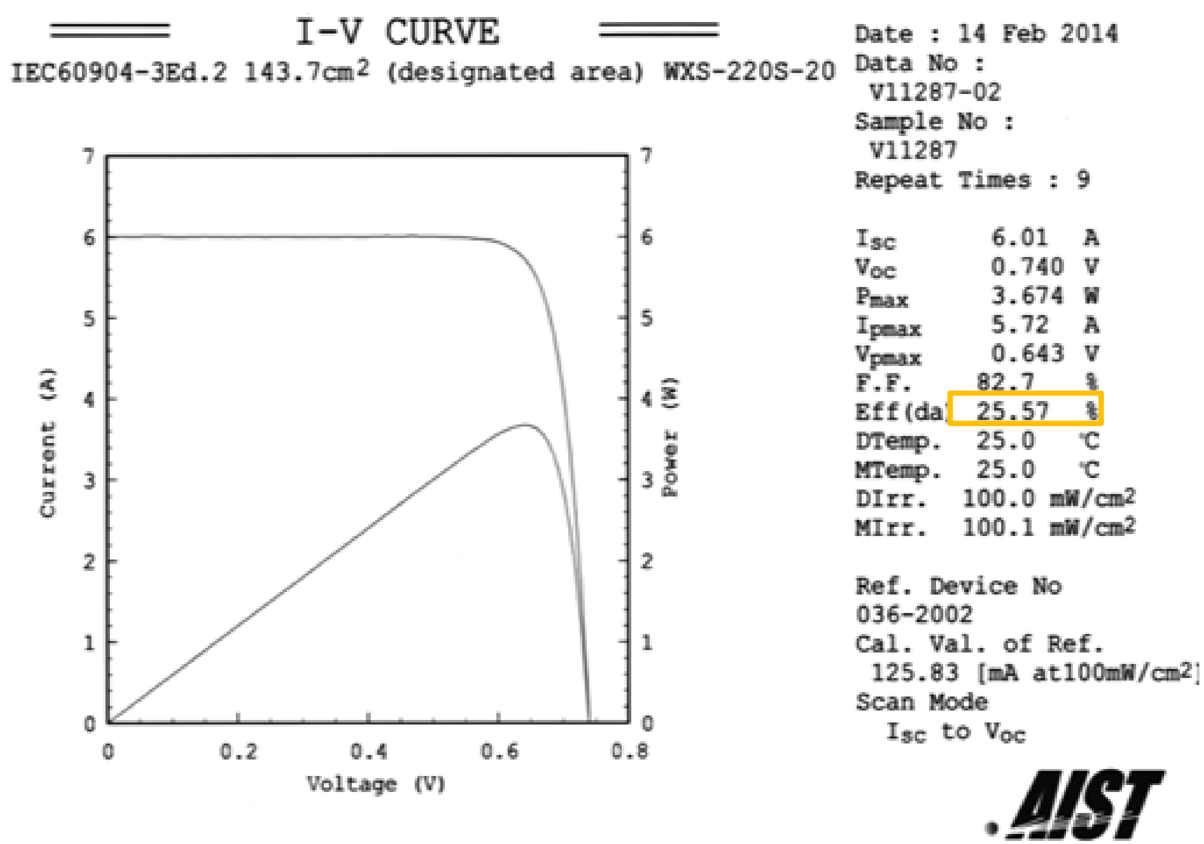
Configuration without light-receiving electrodes minimizes reflection / absorption to maximize light utilization rate (increased Jsc)

Forming of a-Si minimizes recombination loss (increased Voc)

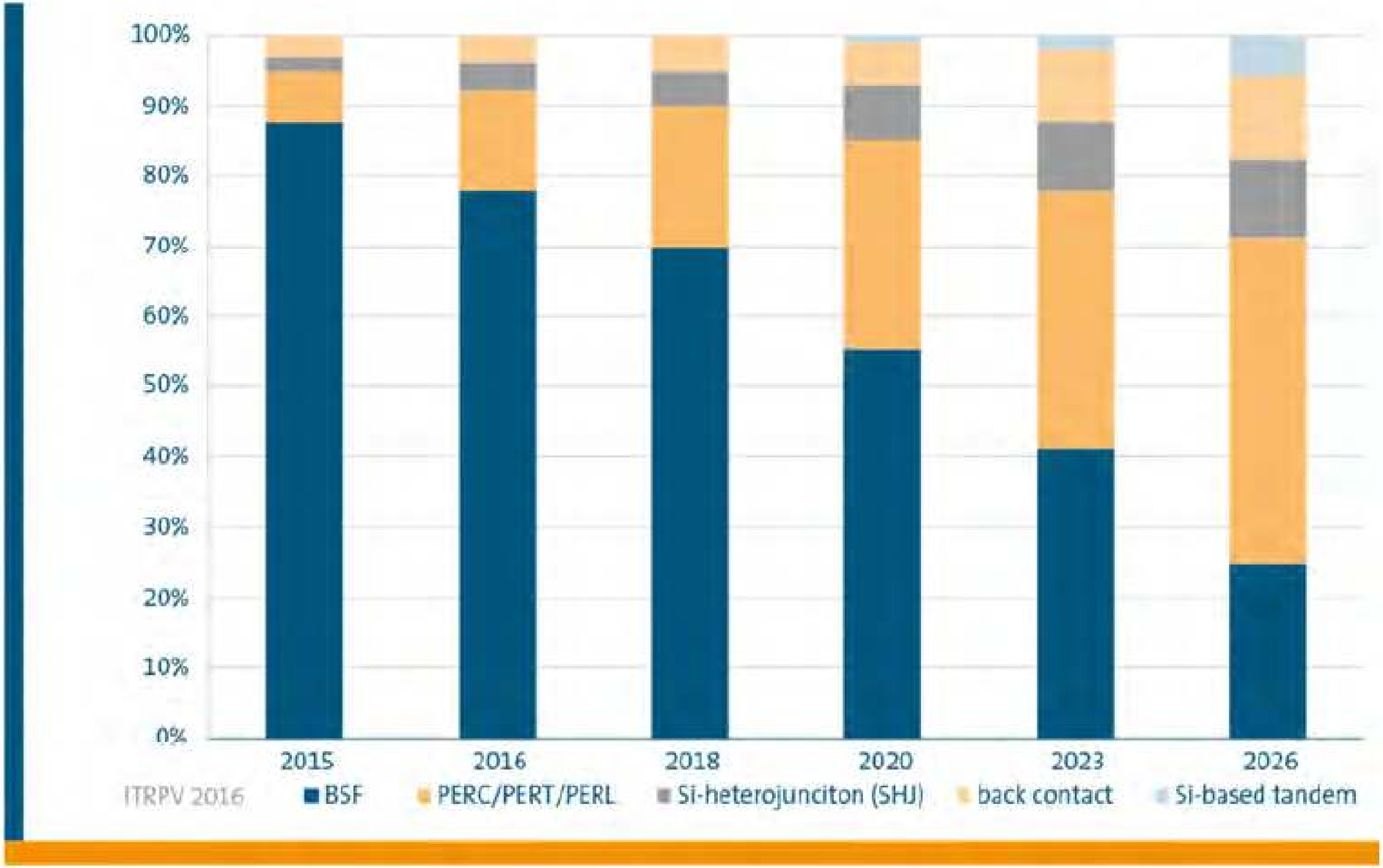
Lowered grid electrode resistance / improved a-Si to lower resistance loss (increased FF)

- Rear contact heterojonction solar cell : record efficiency on c-Si

Masuko K, et al IEEE Journal of Photovoltaics 2014; 4: 1433–1435.

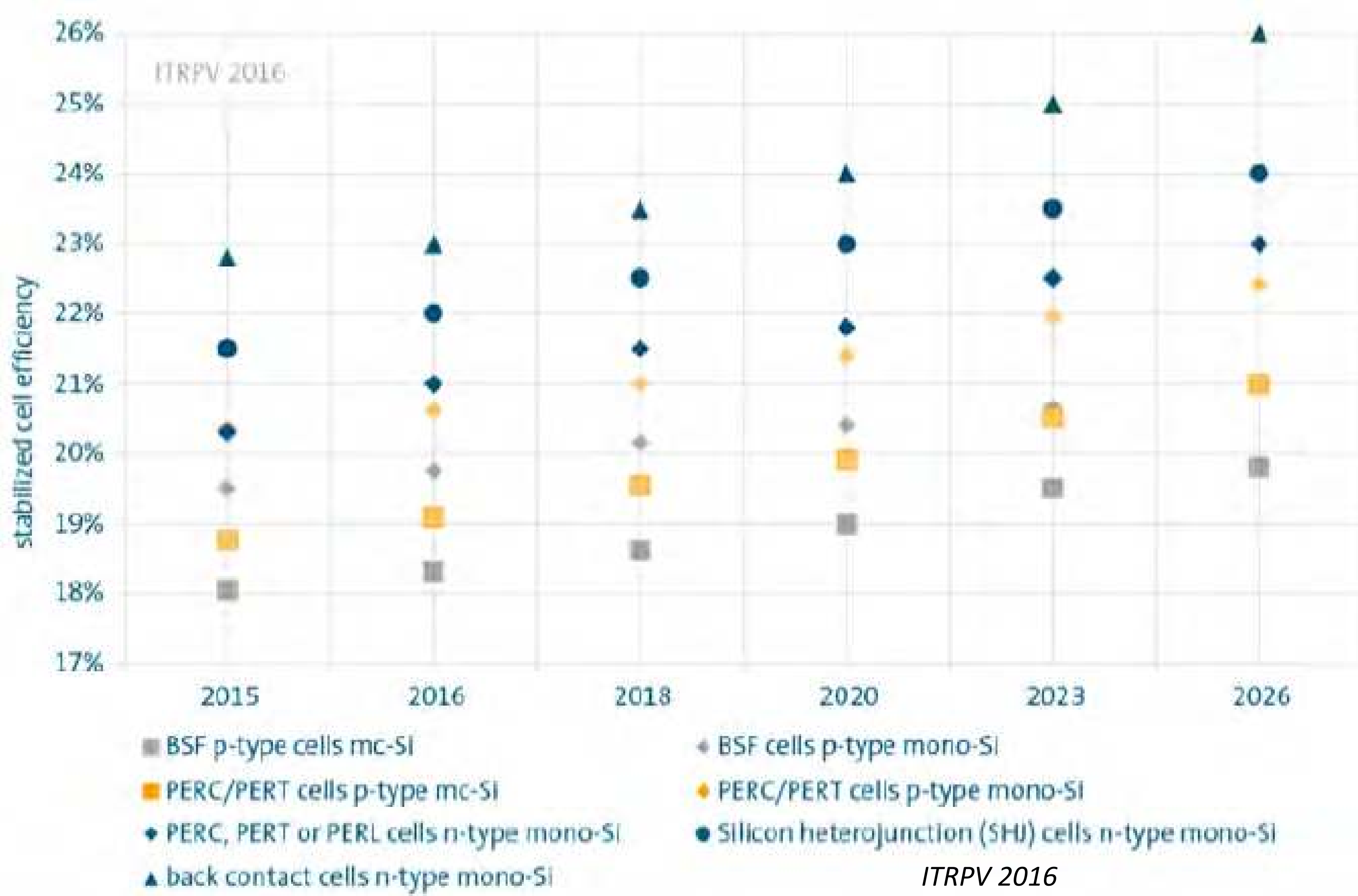


International Technology Roadmap for Photovoltaic (ITRPV 2016) : Worldwide market share for different cell technologies



Expected average stabilized efficiencies

State-of-the-art mass production lines for double-sided contact (BSF, PERC, PERT) and rear-contact cells on multicristalline (mc) and monocrystalline (mono) silicon.



ITRPV 2016

II. Solar cells technologies

- Bulk silicon
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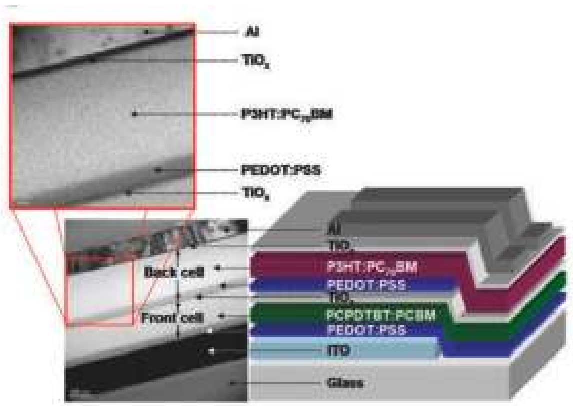
  - Well-known technology, 90% of the industrial production

- **Thin layers – low cost, flexible**
  - Amorphous silicon, CdTe, CIGS
  - Organic, quantum dots, DSSC, perovskite…

- Multijunctions
  - Concentration : III-V materials

  multijunctions…



Thin film solar cells

Drawbacks with crystalline silicon:

- Thick wafers are necessary to absorb most of the sunlight
- Good quality material is required
- Material cost is significant in the total cost of the module

☝ Idea: to use thinner layer of semiconductor with better absorbing properties: **1-10 μm**

- Commercialised: **a-Si, CIGS, CdTe**

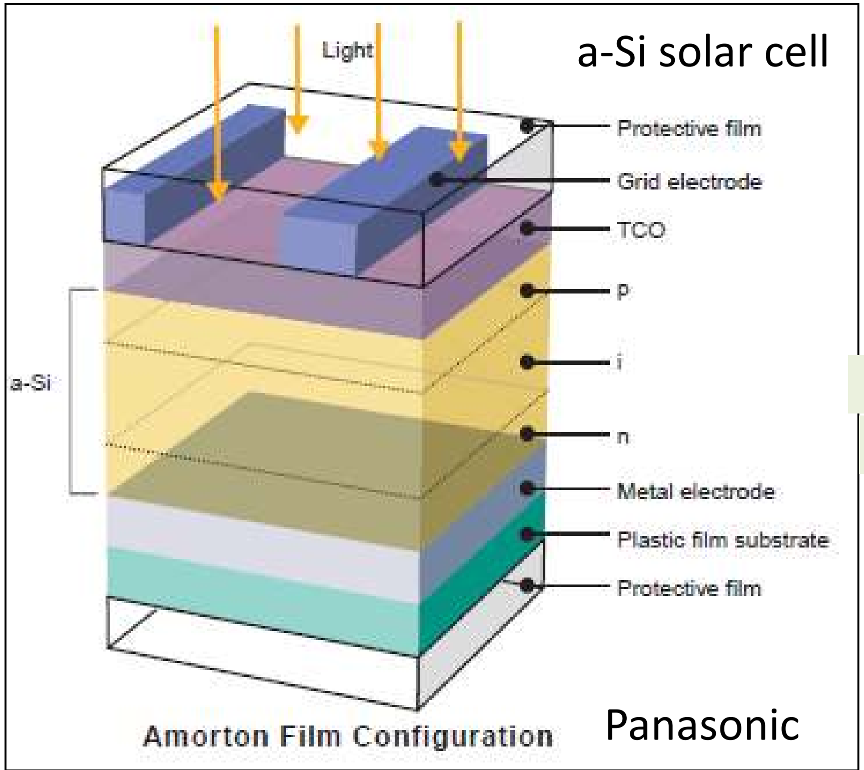
- Under development with some products for sale: organic, DSSC, perovskite,…

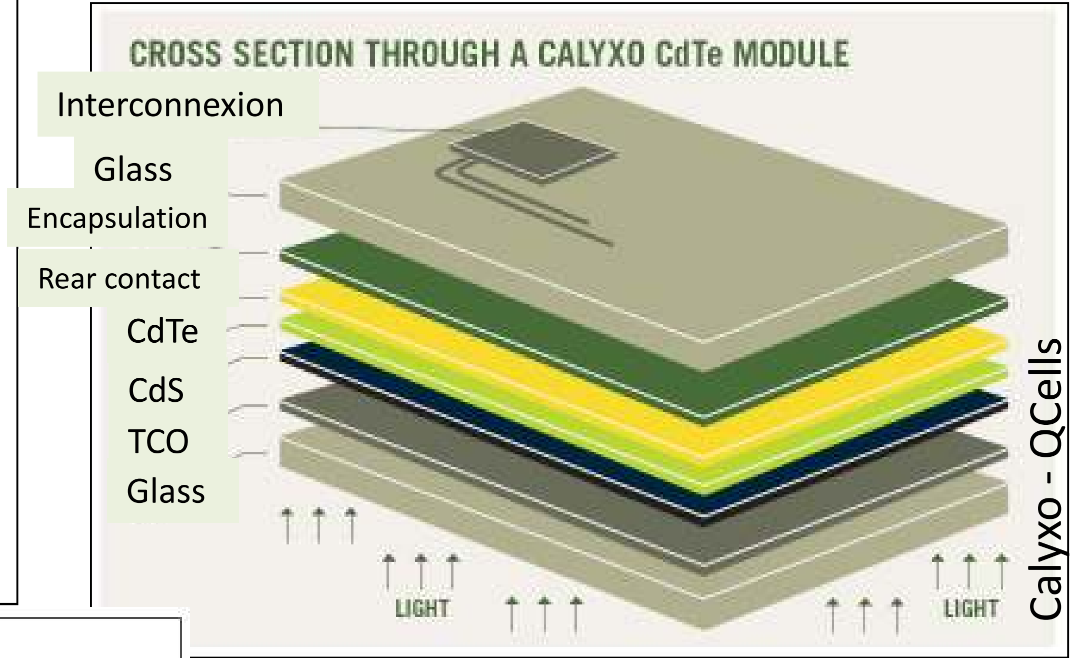
→ **Flexible solar cells are possible**

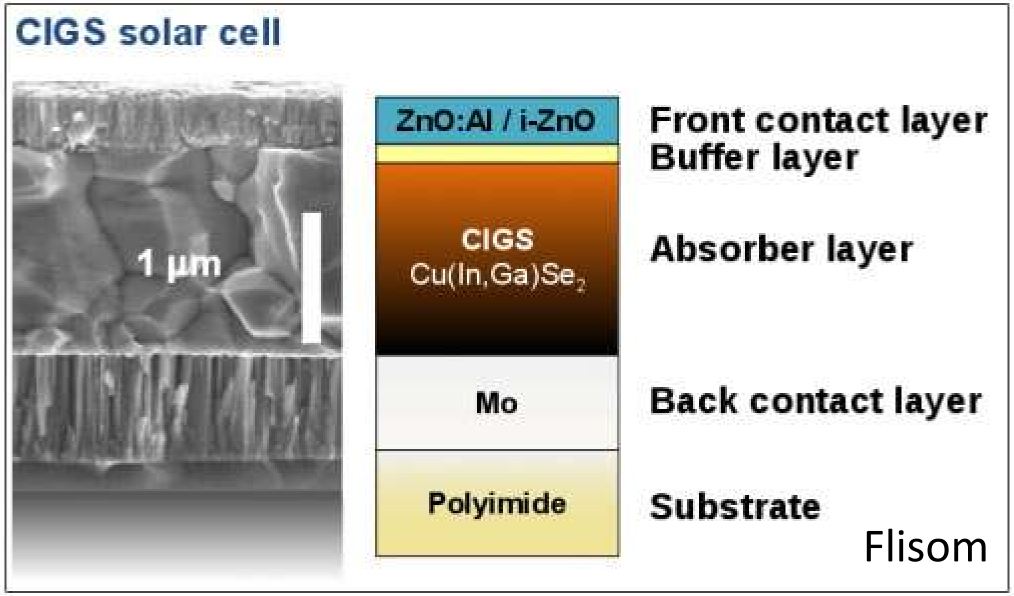
→ **Lightweight solar cells**

➢ Ratio: material cost / efficiency

Thin film solar cells

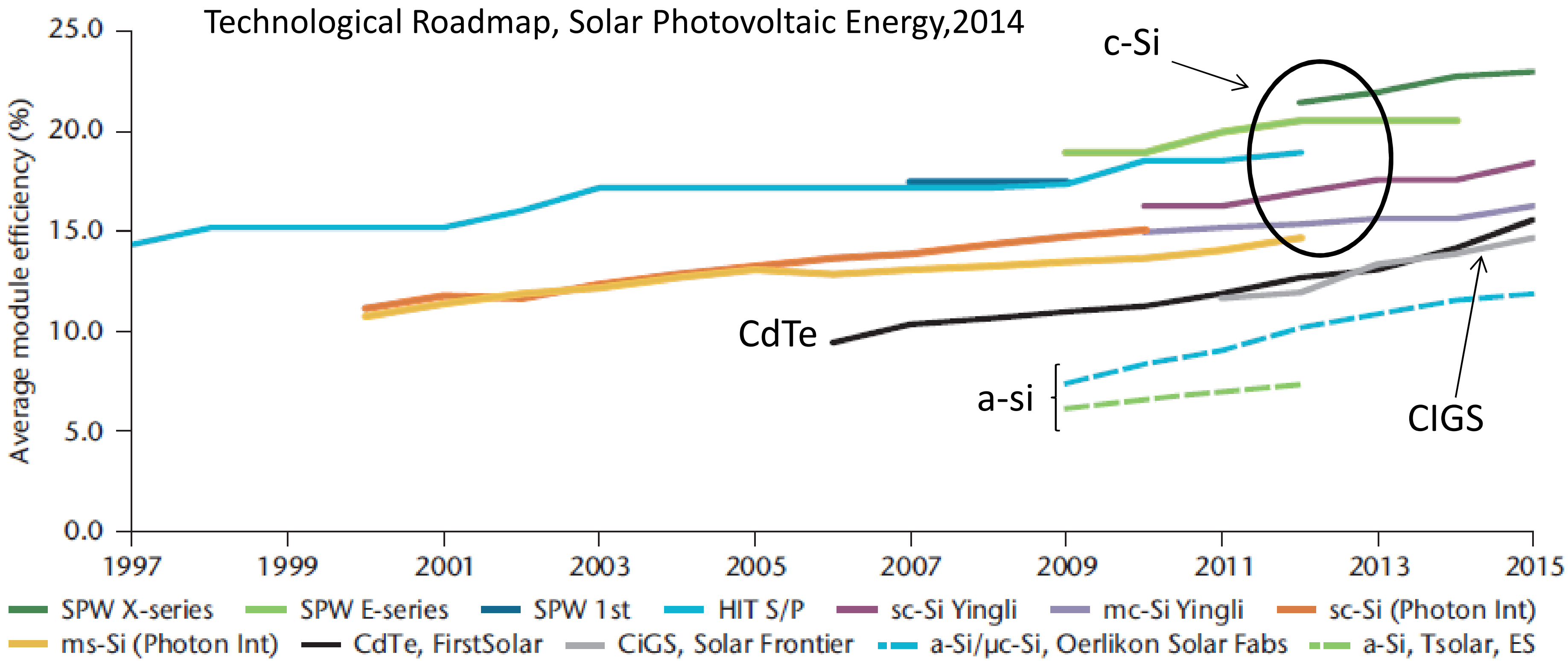






- Three technologies dominate the thin film area:
  - CdTe and CIGS solar cells have efficiency just behind c-Si
  - a-Si presents the lowest efficiency but improvements have been obtained with a-Si/µc-Si

Commercial 1-sun module efficiencies (actual and expected)



Note: SPW stands for *SunPower*, HIT S/P stands for *Heterojunction Intrisic Thin layer Sanyo/Panasonic*.

Source: De Wild-Scholten, M. (2013), "Energy payback time and carbon footprint of commercial PV systems", *Solar Energy Materials & Solar Cells*, No. 119, pp. 296-305.

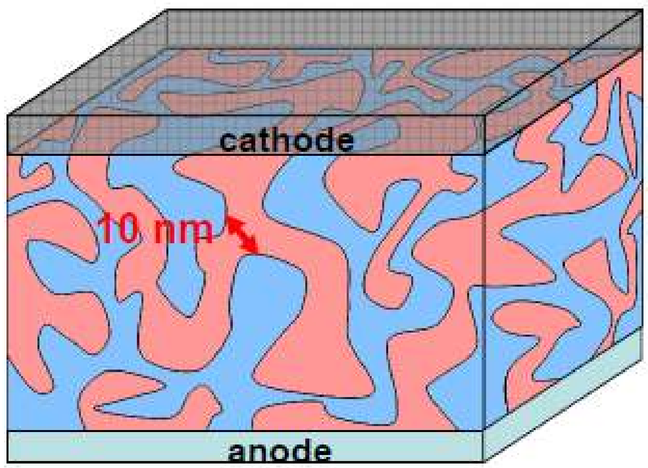
Expected commercial efficiencies improvements:

- 19% (2017) and 22% (2025) for CdTe and CIGS
- 12% (2017) and 16% (2025) for a-Si/µc-Si

Organic solar cells

- **Advantages**: Easy to elaborate, flexible
- **Drawbacks**: Diffusion length ≈ 10 nm, Low efficiency, Unstable materials (oxidation,…), limited solar cell lifetime

In a **Bulk heterojunction BHJ**, the donor and acceptor materials are mixed together. Regions of each material in the device are separated by only several nanometers, a distance optimized for carrier diffusion.



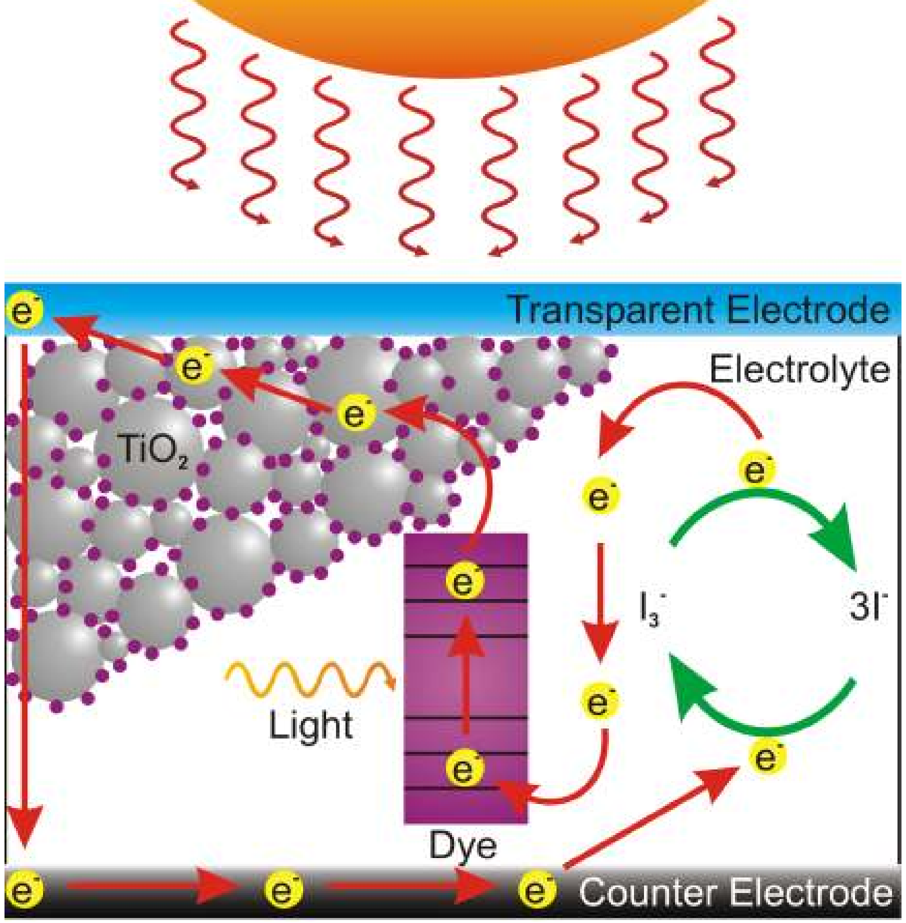
Dye sensitized solar cells (DSSC)

Best efficiencies: about 12%

- **Advantages**: simple technology, semi-transparent
- **Main issues**: the electrolyte, the price of the dye

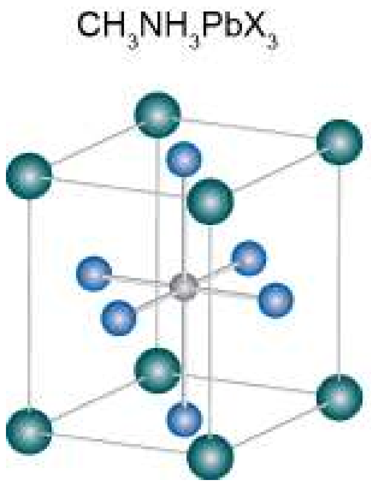
B. O'Regan, M. Grätzel (1991). Nature. 353, 737–740.

The dye converts the photons into electrons. The diffusion of those electrons through the TiO_2 and the TCO creates a current.



Perovskites

ABX$_3$

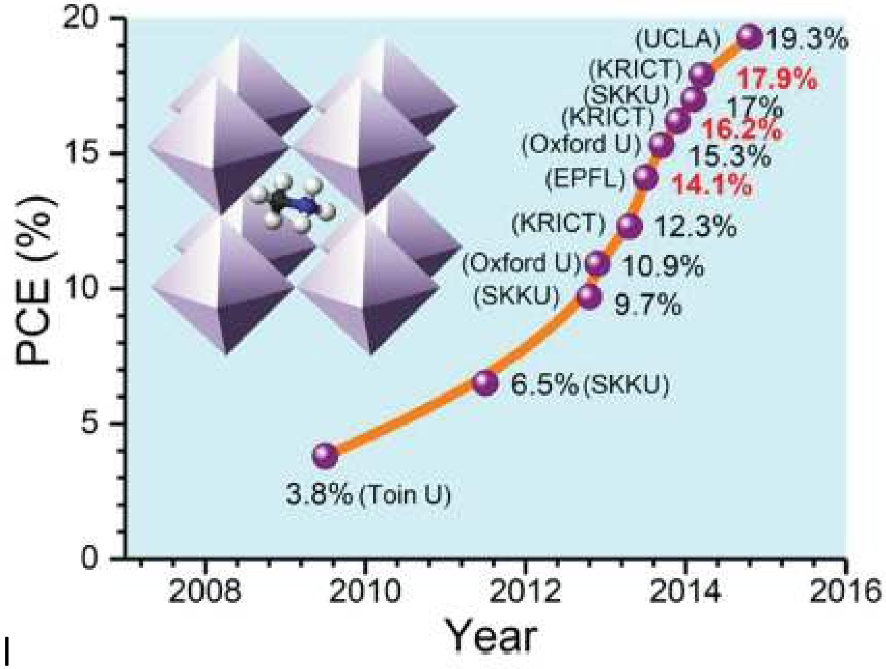


Methylammonium ion

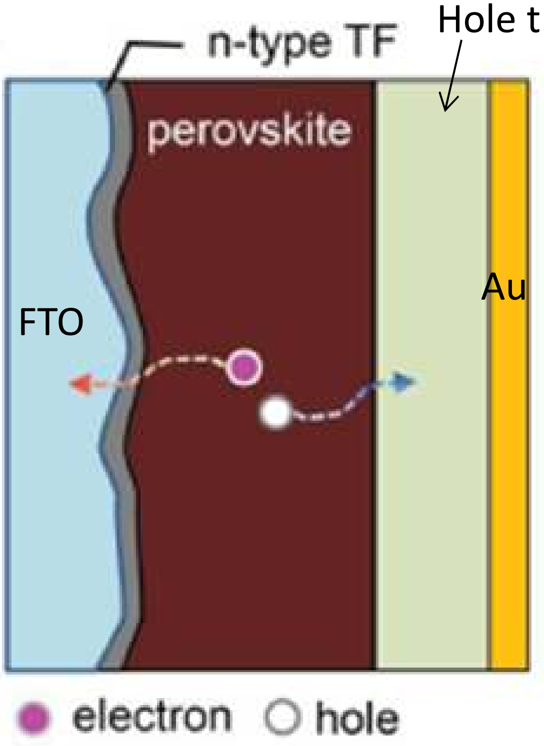
Halogen ion

Lead ion

X: Br, I, Cl

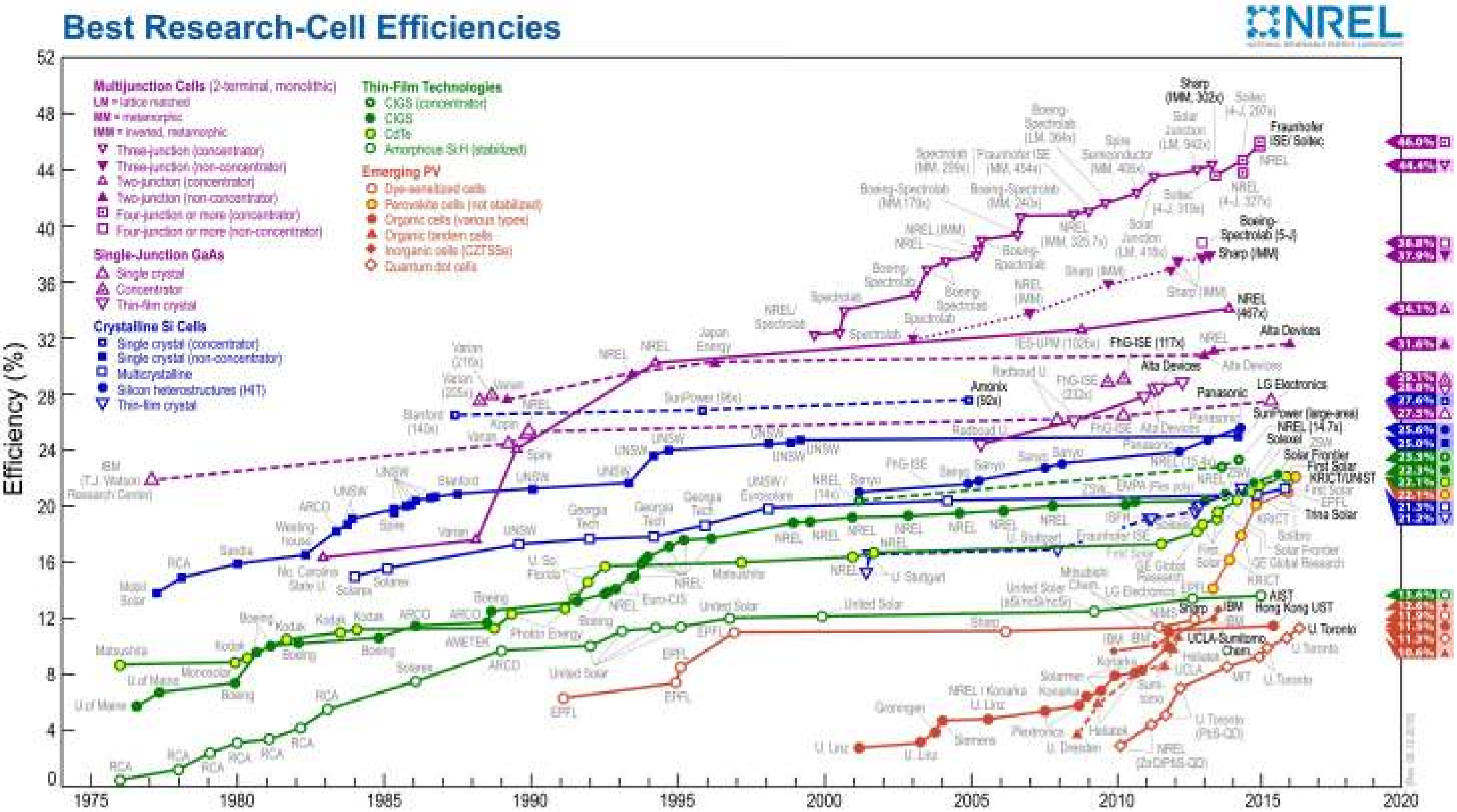


Hole transporting material



- ➢ High absorption, high diffusion length, easy to fabricate, high efficiency.
- ➢ Drawbacks: stability, reproducibility on large area, Pb toxicity.

Hyun Suk Jung and Nam-Gyu Park, Small, Volume 11, Issue 1, pages 10-25, 30 (2014)



http://www.nrel.gov/ncpv/images/efficiency_chart.jpg

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- Thin layers – low cost, flexible
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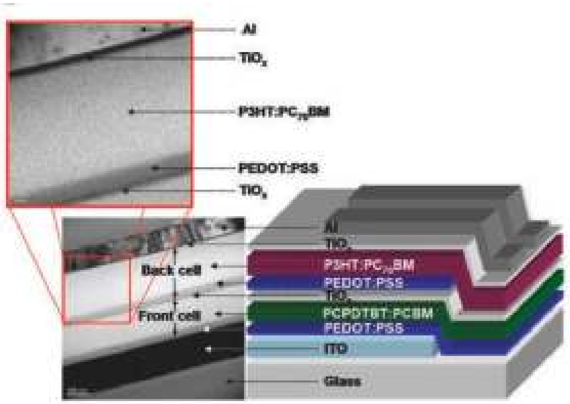
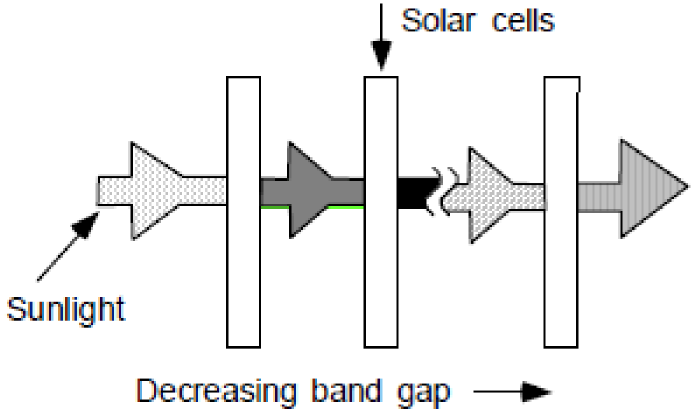
- **Multijunctions**
  - Concentration : III-V materials multijunctions…



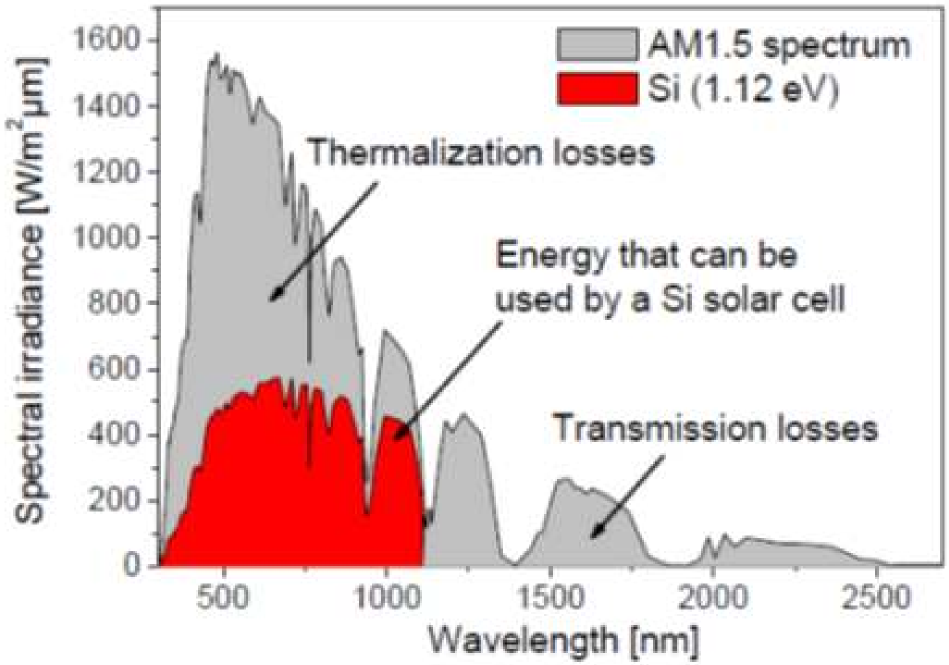
Multijunction solar cells

Solar cells with decreasing band gap are stacked and connected in series:

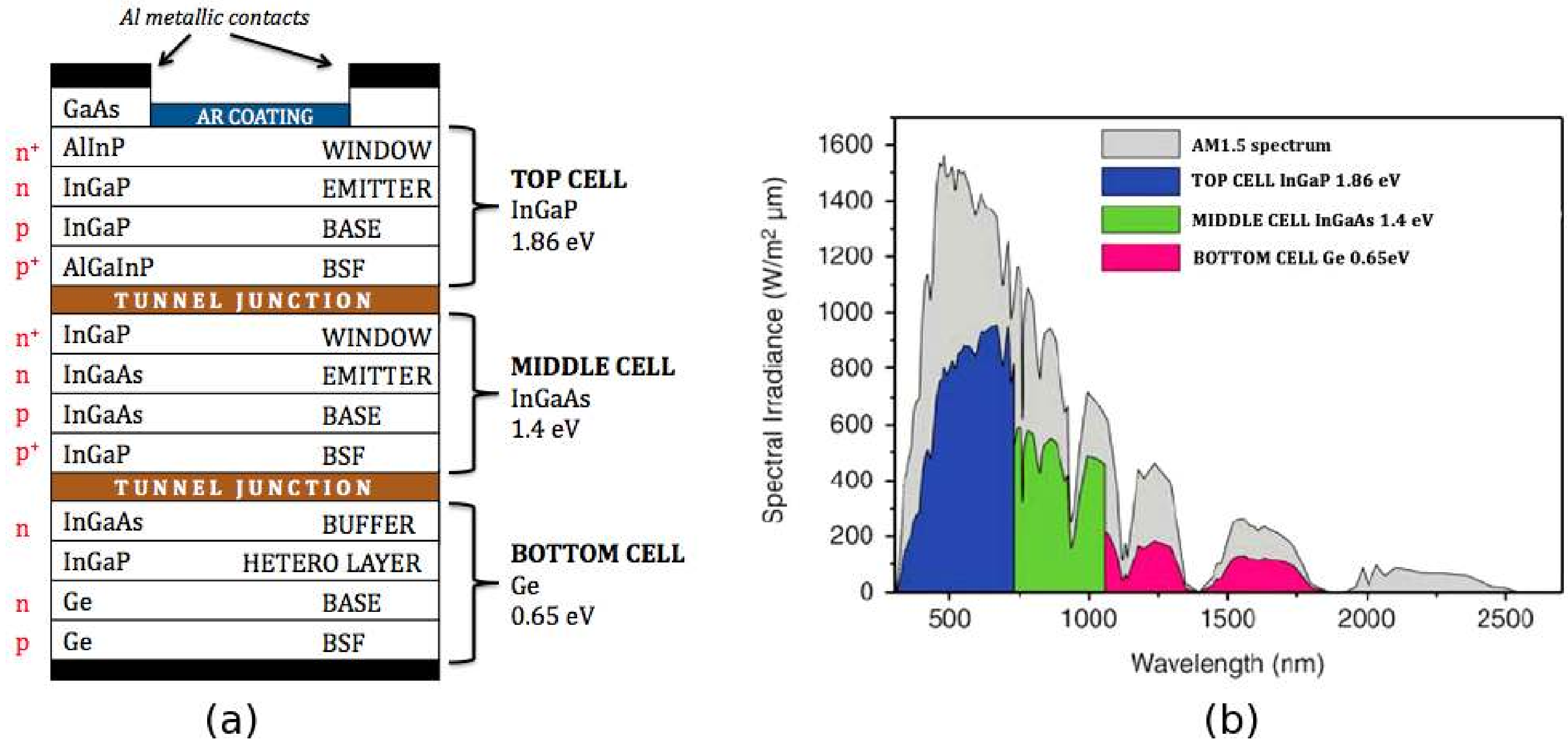


Compared to single junction solar cells, multijunction solar cells permit to:

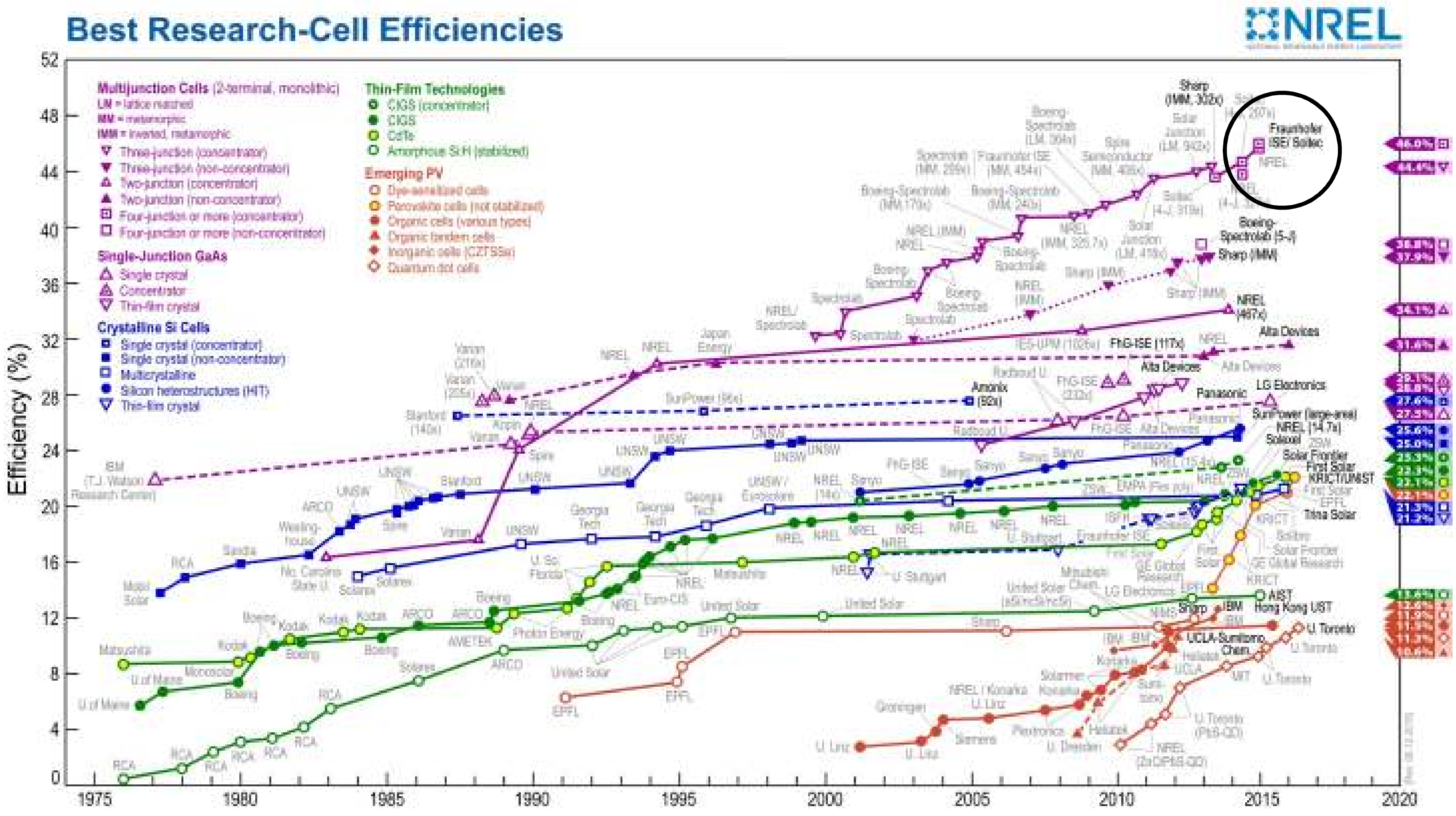
- decrease thermalisation
- decrease transmission of light
- reach higher efficiency compared to single junction solar cells
- reach very high efficiency with concentration of light (CPV)



The most efficient multijunction solar cells: III-V compounds multijunctions
But elevated cost -> mainly used for space applications and high concentration of light.



N.V. Yastrebova (2007). High-efficiency multi-junction solar cells: current status and future potential.



http://www.nrel.gov/ncpv/images/efficiency_chart.jpg

- Record efficiency with 4 junctions: 46% (under concentration : x297sun, *F. Dimroth et al, Prog. Photovolt: Res. Appl. 2014; 22, p277.*
- Under study: tandem solar cells on c-Si, on thin-films, organic multijunctions….

Efficiencies under standard test conditions

Technology	Cell record efficiency (%)	Module commercial average efficiency (%)	Expected cell commercial efficiency (%) 2025
c-Si	25.6	16-21	~ 20-26
CdTe, CIGS	22-23	14-16	~ 22
a-Si, a-Si/µc-Si	13.6	8-11	~ 16
Organic, DSSC	12-13		~ 16
HCPV	46 (297 suns)	38-43 (x-suns, cell) 27-33 (module)	~ 50 (under concentration)

Technology Roadmap, Solar Photovoltaic Energy, IEA, 2014
ITPRV 2016
Photovoltaic Report, Fraunhofer ISE, 2016
Current Status of concentrator photovoltaic (CPV) technology, ISE, NREL, 2016

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- **Solar cells for energy harvesting**

Solar cells for energy harvesting

PV used to harvest light energy will be mainly working in indoor low light level environment (offices, homes).

The amount of power harvested depends on:

- the intensity and spectral content of the light,
- the incident angle of the light,
- the size, sensitivity, temperature and type of solar cells used.

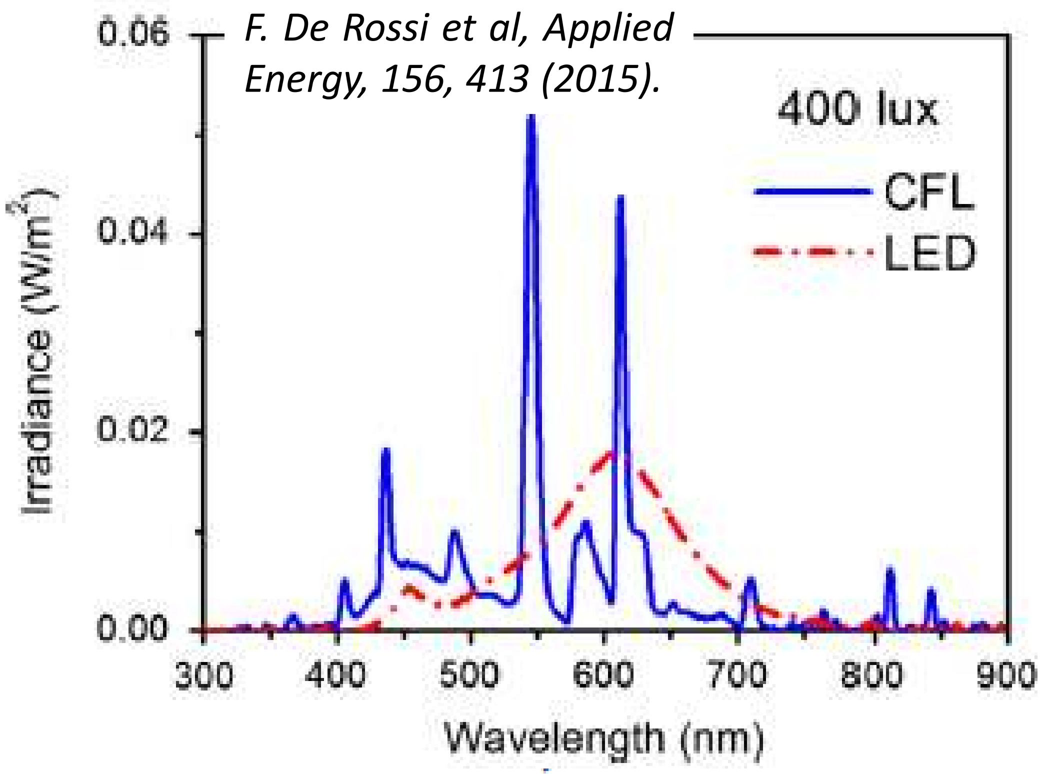
-> Under different illumination conditions, the performances of solar cells varies

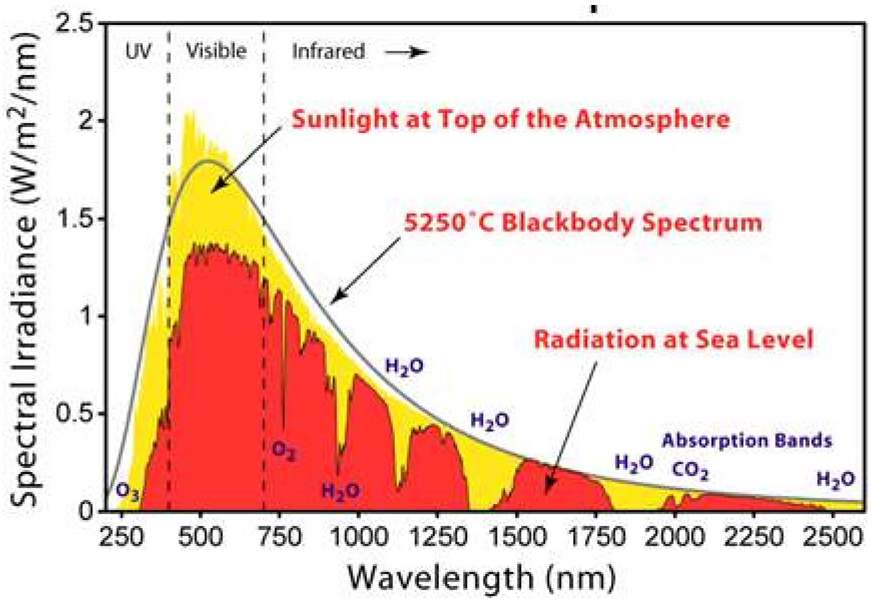
-> The only standard conditions for efficiency measurements are for outdoor sunlight

-> Solar cells are optimized for standard outdoor conditions.

Some studies have been done to compare the behavior of solar cells under outdoor and indoor conditions.

Indoor and outdoor light level





Fluorescent light		Sunlight	
Conditions	Illumination levels (lx)	Conditions	Illumination levels (lx)
Design stands (partially illuminated)	～1,000	Direct sunlight	100,000 ～ 120,000
Offices and conference rooms	300 ～ 600	Bright	10,000 ～ 100,000
Restaurants, coffee shops, dressing/changing rooms	75 ～ 150	Cloudy	10,000 ～ 50,000
Indoor emergency staircases	less than 75	Rainy	1,000 ～ 20,000

Panasonic

- Indoor illumination unit is lux (lx).
- Indoor illumination level is far lower than outdoor light, especially in the red wavelength range

Theoretical optimal band gap for indoor and outdoor conditions

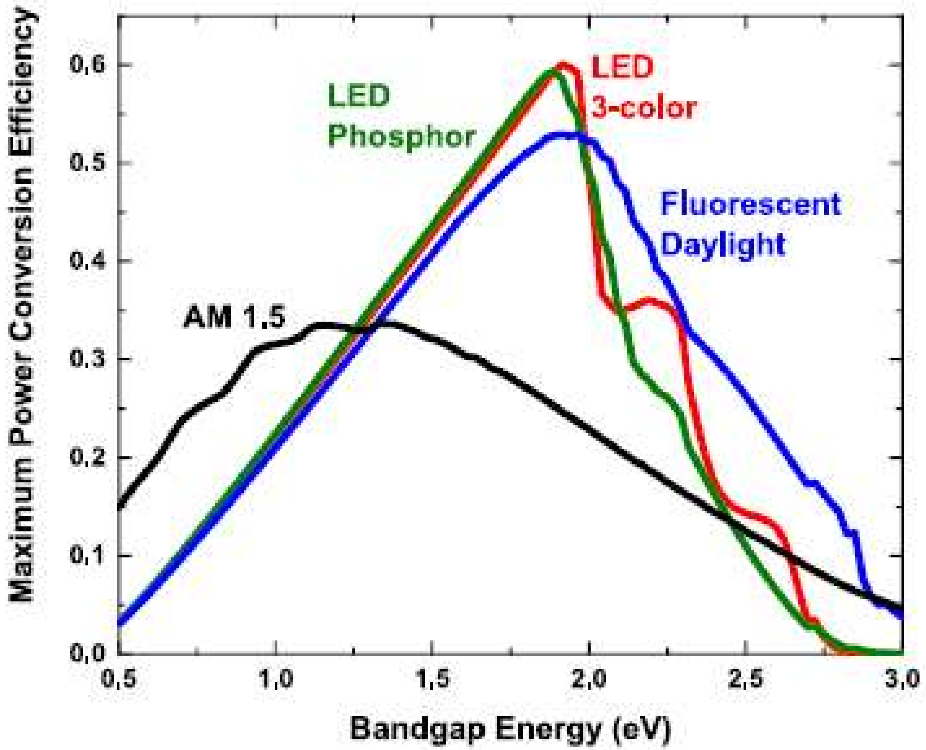


Fig. 1. Calculated maximum power conversion efficiency versus material bandgap energy under various lighting sources revealing an ideal bandgap energy near 1.9 eV for indoor conditions.

Material	Eg (eV)
Si	1.12
CdTe	1.44
Perovskites ($CH_3NH_3PBI_3$)	1.5-2.2
Dye	1.62
a-Si	1.6-1.8
GaInP	1.88
Organic (P3HT:PCBM)	1.9

M. Freunek et al., IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 3, NO. 1, JANUARY 2013

- Ideal band gap for indoor conditions : ~1.9eV
- Ideal band gap for outdoor conditions : ~1.3-1.4eV

Optimisation of resistive losses under indoor conditions

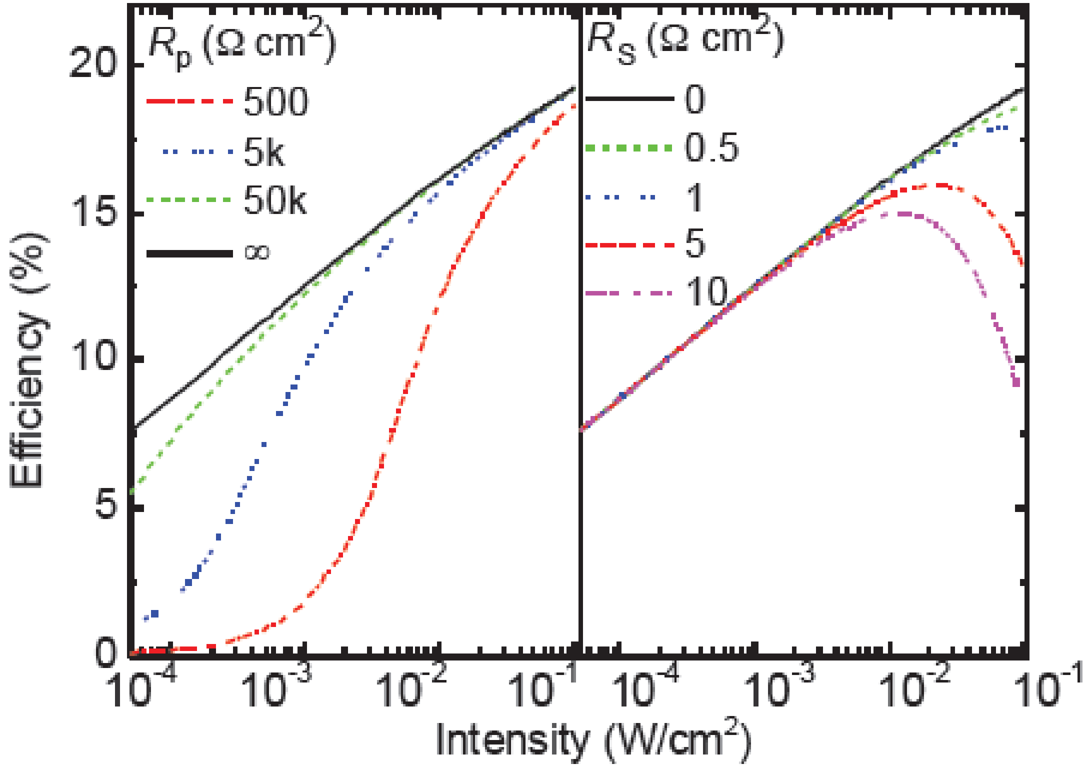


Fig. 3: Variation of efficiency with irradiation intensity for (left) a variation of the shunt resistance R_p and (right) a variation of the series resistance R_s. Typical values for standard outdoor solar cells are in the range of R_p = 5 kOhm and R_s = 0.5 Ohm cm^2. [5]

M. Kasemann et al, AMA Conferences 2013 - SENSOR 2013, OPTO 2013, IRS 2013

- Decrease of the ratio of the photogenerated current to shunt current with light intensity
- Strong influence of R_{shunt} on the low intensity efficiency (R_s on the high intensity efficiency)

Already commercialised for indoor applications : a-Si

Electrical cell data*

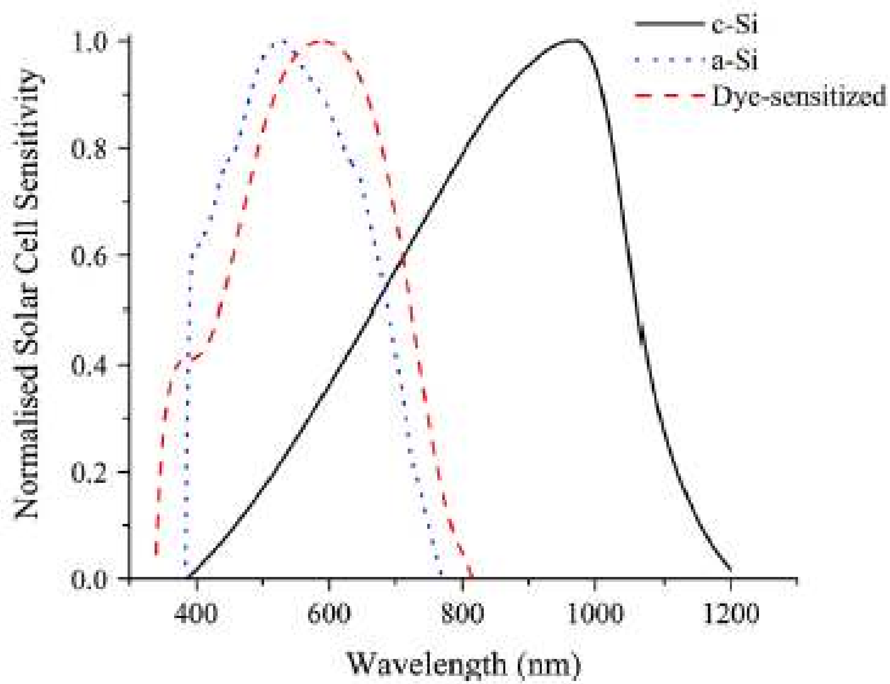
Typical data at			100 Lux	200 Lux	1000 Lux	100 mW/cm²
Voltage at nominal power	U_{mpp}	[mV]	410	430	475	620 mV
Current density at nominal power	I_{mpp}	[µA/cm²]	7.1	14.2	71	11.5 mA/cm²
Open-circuit voltage	U_{oc}	[mV]	585	610	670	820 mV
Short-circuit current density	I_{sc}	[µA/cm²]	7.4	14.8	74	13.5 mA/cm²
Nominal power density	P_{nom}	[µW/cm²]	2.9	6.1	34	7.1 mW/cm²

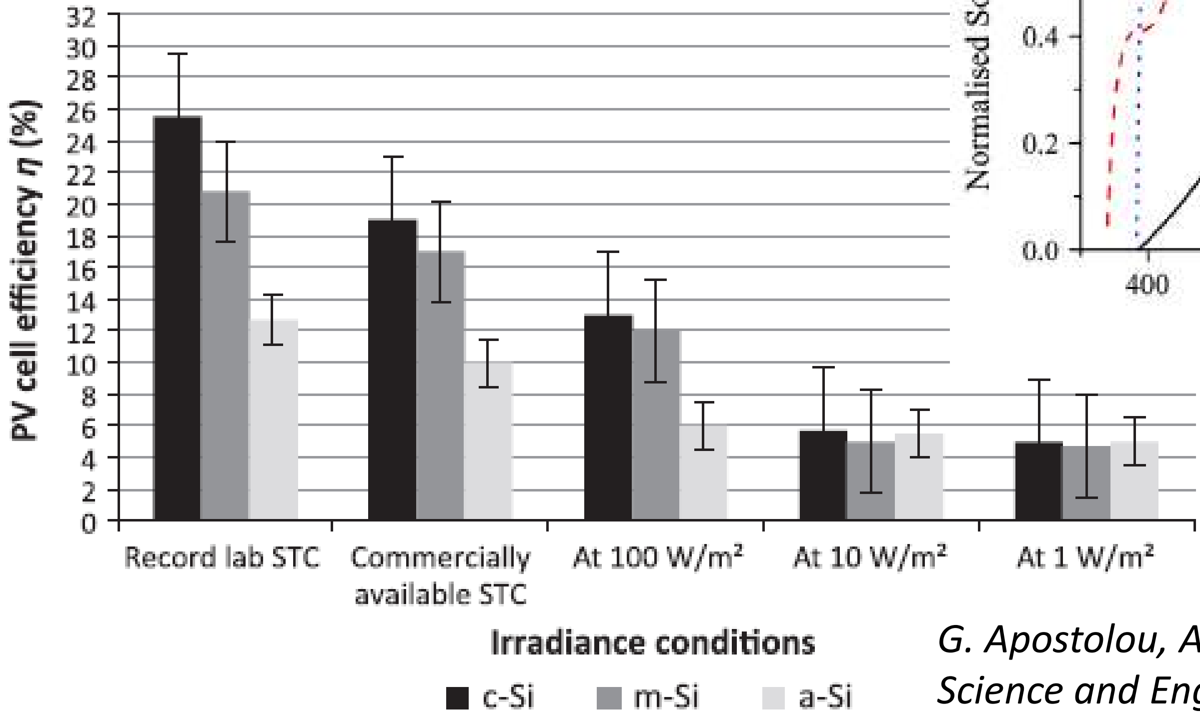
Example : ASI_OEM_indoor - Schott Solar

a-Si is used due to its high sensitivity in the visible range

Already commercialised for indoor applications : a-Si

Y. Li et al, Solar Energy 111 (2015) 21–29

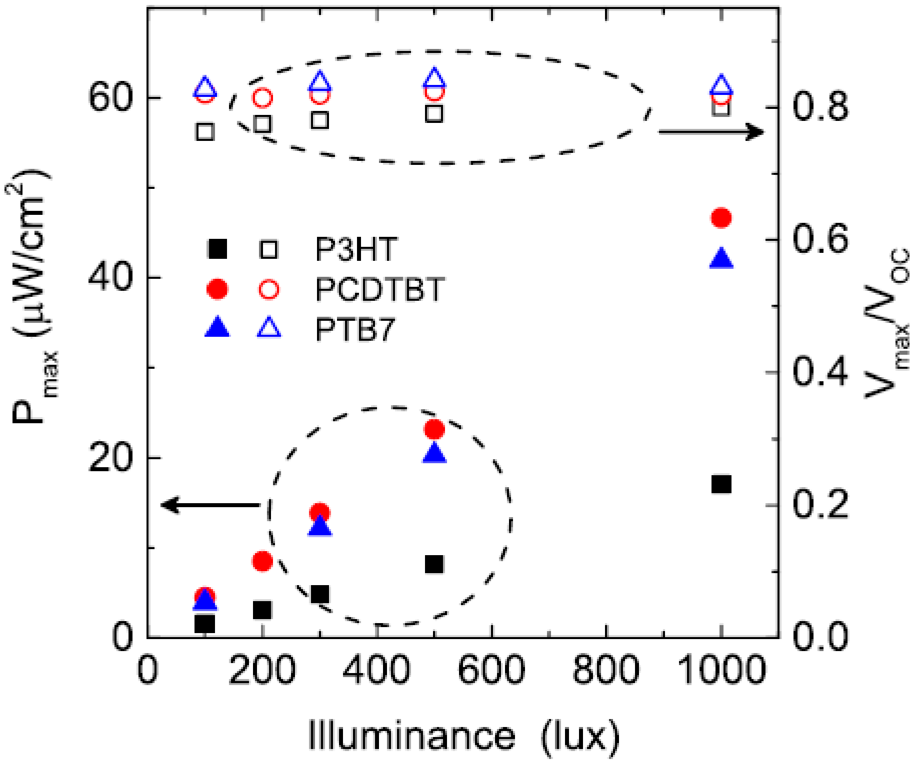




G. Apostolou, A. Reinders, M. Verwaal,, Energy Science and Engineering 2016; 4(1): 69–85.

- c-Si has lower bandgap and sensitivity in visible wavelength range.
- Moreover a-Si solar cells with high R_{shunt} have lower degradation of efficiency at low level illumination.

Other interesting materials : Organic, Dye



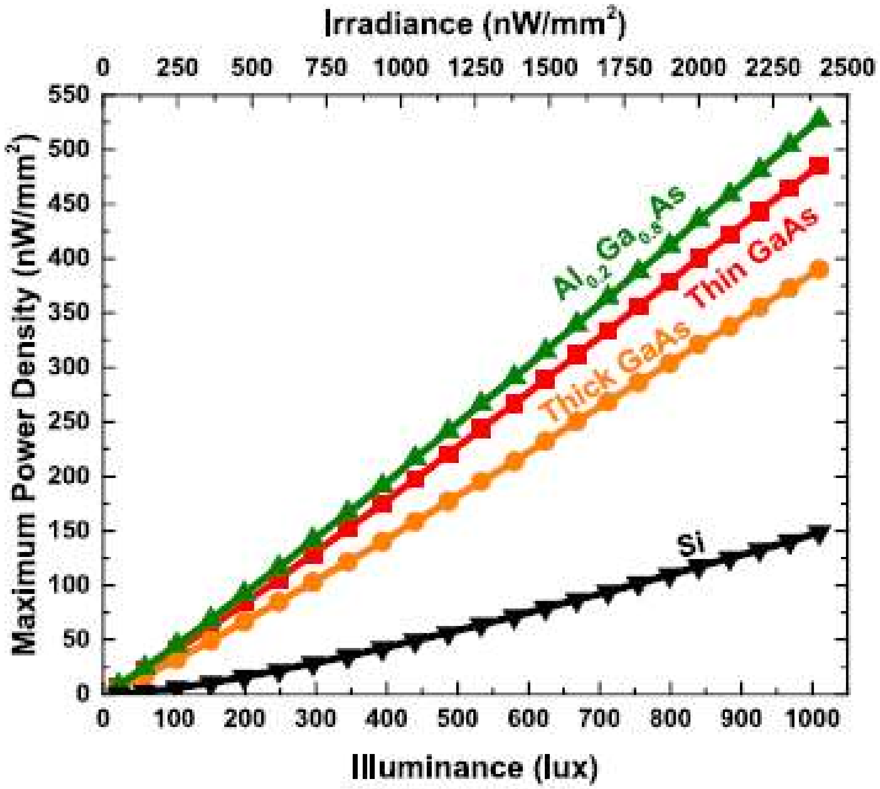
Lee et al, Appl. Phys. Lett. 108, 253301 (2016)

- Efficiencies similar to a-Si are reached
- Interesting devices for short lifetime applications

TABLE I. Performance of P3HT:PCBM, $PCDTBT:PC_{71}BM$, and $PTB7:PC_{71}BM$ OPV cells measured under 300 lx fluorescent lamps. The *PCE* measured under AM1.5 G are shown in the square brackets as reference.

	J_{SC} (μA/cm^2)	V_{OC} (V)	*FF* (%)	P_{max} (μW/cm^2)	*PCE* (%)
P3HT:PCBM	20.6	0.41	56.6	4.8	5.8 [2.4]
$PCDTBT:PC_{71}BM$	27.7	0.72	69.3	13.9	16.6 [6.0]
$PTB7:PC_{71}BM$	28.6	0.61	69.5	12.2	14.6 [6.8]

Other interesting materials: III-V but elevated cost



TERAN et al, IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 62, NO. 7, JULY 2015

Fig. 6. Measured maximum power density versus illuminance of $Al_{0.2}Ga_{0.8}As$ and two differing GaAs cell designs measured under white LED illumination and comparison with a commercial silicon solar cell.

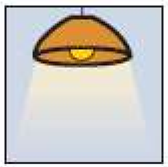
Outdoor Power Output (AM1.5)	26 mW/cm^2
Indoor Power Output at 200Lux	18 μW/cm^2
Weight (unencapsulated)	17 mg/cm^2
Flexibility	2 cm radius of curvature

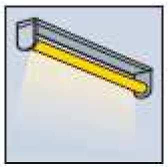
ALTA DEVICES (www.altadevices.com)
GaAs solar cell

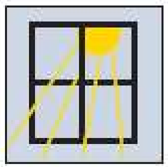
Some values of output power measured under 300lx

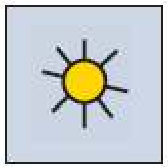
Material	Average output power (300lx) (µW/cm²)	Reference
a-Si	15	Wang W. S. et al, ACM Journal on EmergingTechnologies in Computing Systems, Vol. 6, (2010)
Organic	13.9	Lee et al, Appl. Phys. Lett. 108, 253301 (2016)
Dye	12.5	F. De Rossi et al, Applied Energy, 156, 413 (2015)
III-V	15	Teran et al, IEEE Transactions on Electron Devices, Vol. 62, No. 7, (2015)
	>18.5	ALTA DEVICES

ASI_OEM_indoor
Schott Solar


200 Lux


500 Lux


1.000 Lux


100 – 120 mW/cm²

Conclusion

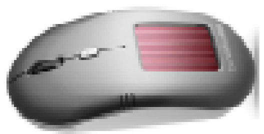
- Mature, relatively large efficiency and low cost solar cells are available for large power outdoor applications.
- c-Si is the dominant technology but thin films still present interesting advantages.
- Emerging technologies and new materials for PV applications are under investigation showing high potential.

- For indoor applications there is a lack of international standard measurement conditions.
- Several technologies present good performances under low light levels.
- Solar cells need to be specifically optimized for indoor applications.

Alta Devices

Sunpartner (Wysips)

Casio



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Logitech

Thanks you for your attention