EPFL

Photovoltaic Devices

N. Wyrsch

EPFL – IMT - PVLab

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Content

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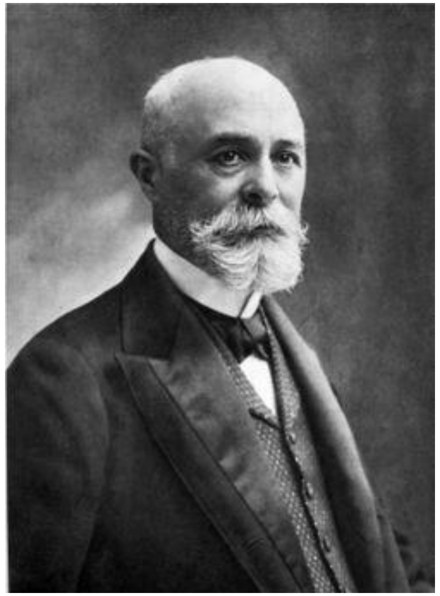
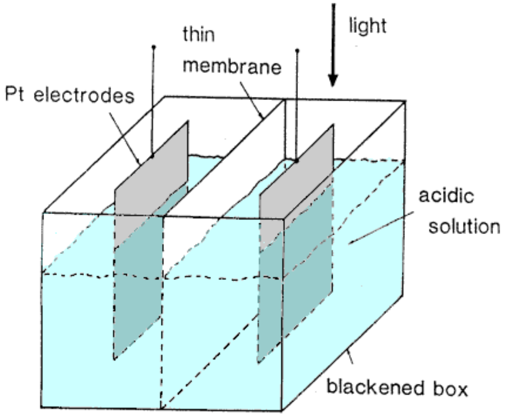
Applications, history and motivation

Photovoltaic effect

Edmund Becquerel, the French experimental physicist, discovered (in 1839, at the age of 19) the photovoltaic effect while experimenting (in his father's laboratory - Antoine-César Becquerel's laboratory) with an electrolytic cell made up of two metal electrodes placed in an electricity-conducting solution--generation increased when exposed to light.

E. Becquerel, 'On electron effects under the influence of solar radiation.' Comptes Rendus 9, 561.





Brief history

1839 : Discovery of photovoltaic effect by Becquerel
1877 : Observation of the photovoltaic effect in solid selenium by W.G. Adams and R.E. Day
1883 : Description of the first solar cells made from selenium wafers by Charles Fritts (with efficiency < 1%)
1888 : Edward Weston receives first US patent for "solar cell"
1905 : Albert Einstein’s paper on the photoelectric effect
1916 : Experimental proof of Einstein’s theory on photoelectric effect by Robert Millikan
1922 : Einstein wins Nobel prize for 1904 paper on photoelectric effect
1941 : First silicon photovoltaic cell developed by Ohl
1954 : First high-power silicon PV cell (achieving 6%) by Bell Labs. The New York Times forecasts that solar cells will eventually lead to a source of "limitless energy of the sun".
1958 : US Vanguard I space satellite powered by a PV array
1963 : Viable photovoltaic module of silicon solar cells produced by Sharp Japan installs a 242-watt PV array on a lighthouse, the world's largest array at that time.

1970s : PV costs driven down by 80%, allowing for applications such as offshore navigation warning lights and horns lighthouses, railroad crossings, and remote use where utility-grid connections are too costly; start of mass production.
2020 : World-wide PV production > 120 GW/year

- **Approx. surface : 600 km^2 (area of Lake of Geneva !)**
- **Equivalent annual energy production of 12-15 nuclear power plants**

Devices and Applications

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- Solar cells
  - Power market (on grid)
  - Standalone systems (off grid)
  - Consumer applications
  - Energy scavenging, microsystems
- Photodiodes
  - Flat panel imagers (a-Si:H)
  - Particle detectors (X, α, β, γ)
  - Light sensors
  - Position detectors
  - Spatial modulators (optical valves)
  - Bio-chips
  - …..

Building integration of photovoltaics






Building integration of photovoltaics

Integration with partial shadowing

PV fields

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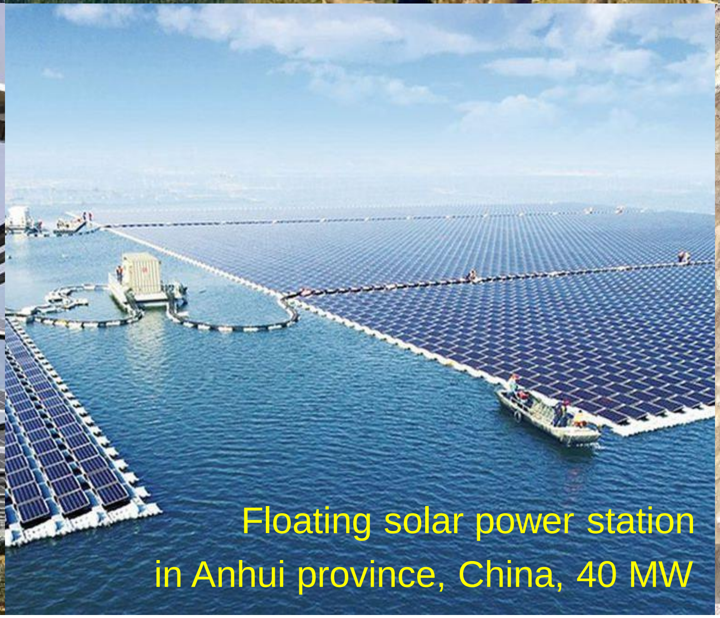
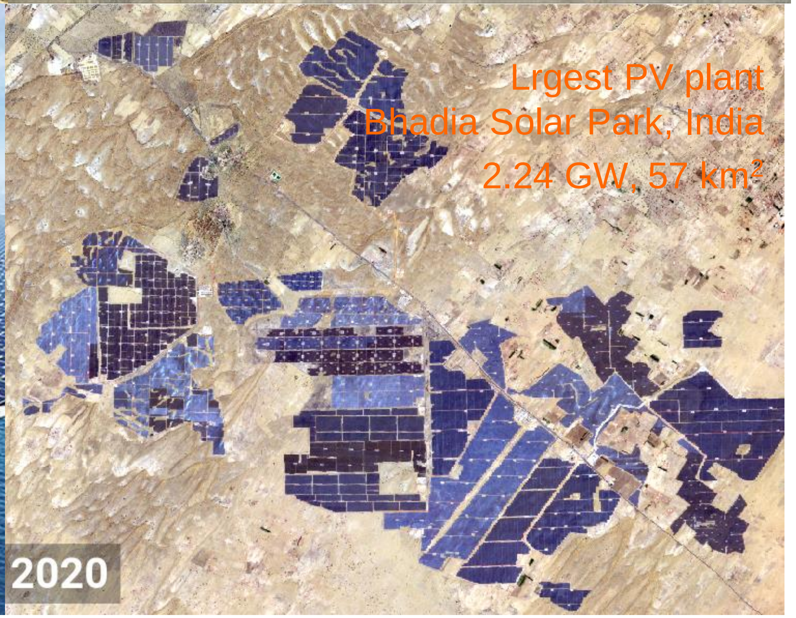
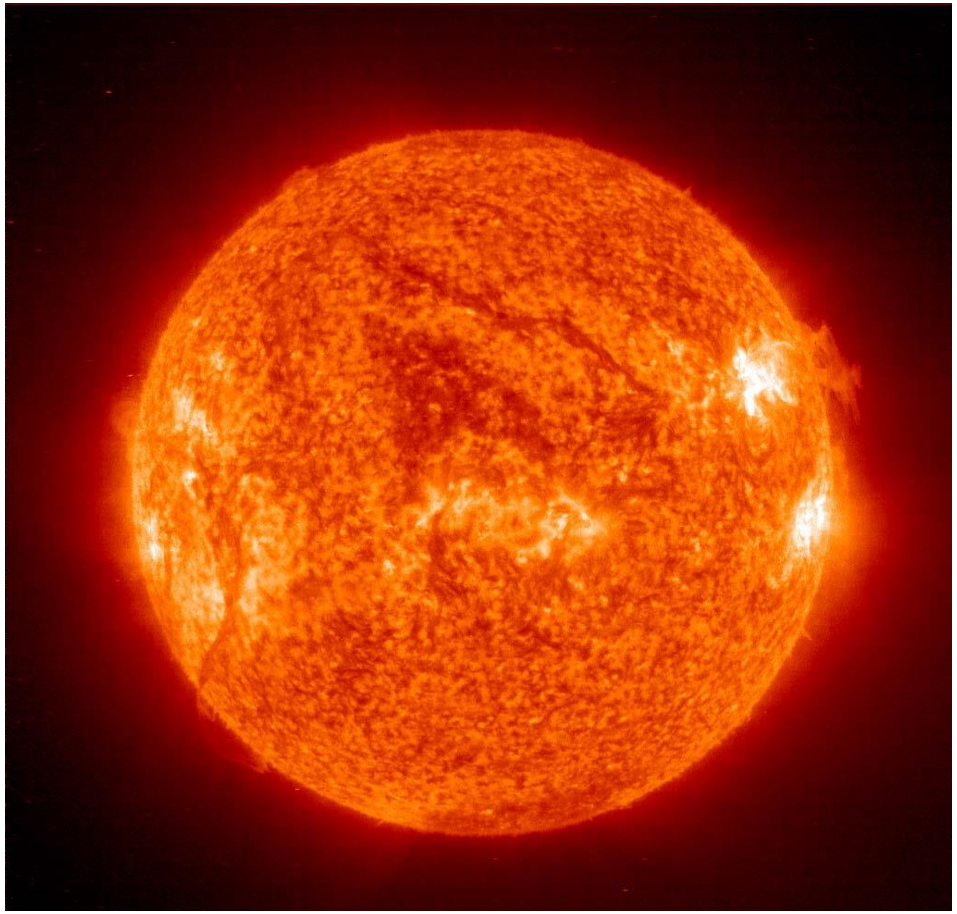




Solar energy potential



- Yearly solar energy irradiation on Earth ≈ 10’000 x World energy consumption
- One hour of solar irradiation on Earth surface ≈ Yearly World energy consumption
- Irradiation (sea level, full sun): 1 kW/m^2
- World primary energy consumption (2019):
  - Energy: >162 PWh (162x10^{12} kWh) (> 16 GToe)
  - Power > 16 TW

Toe : Ton oil equivalent ≈ 10 MWh
(1 liter of petrol ≈ 10 kWh)

Potential of PV electricity generation

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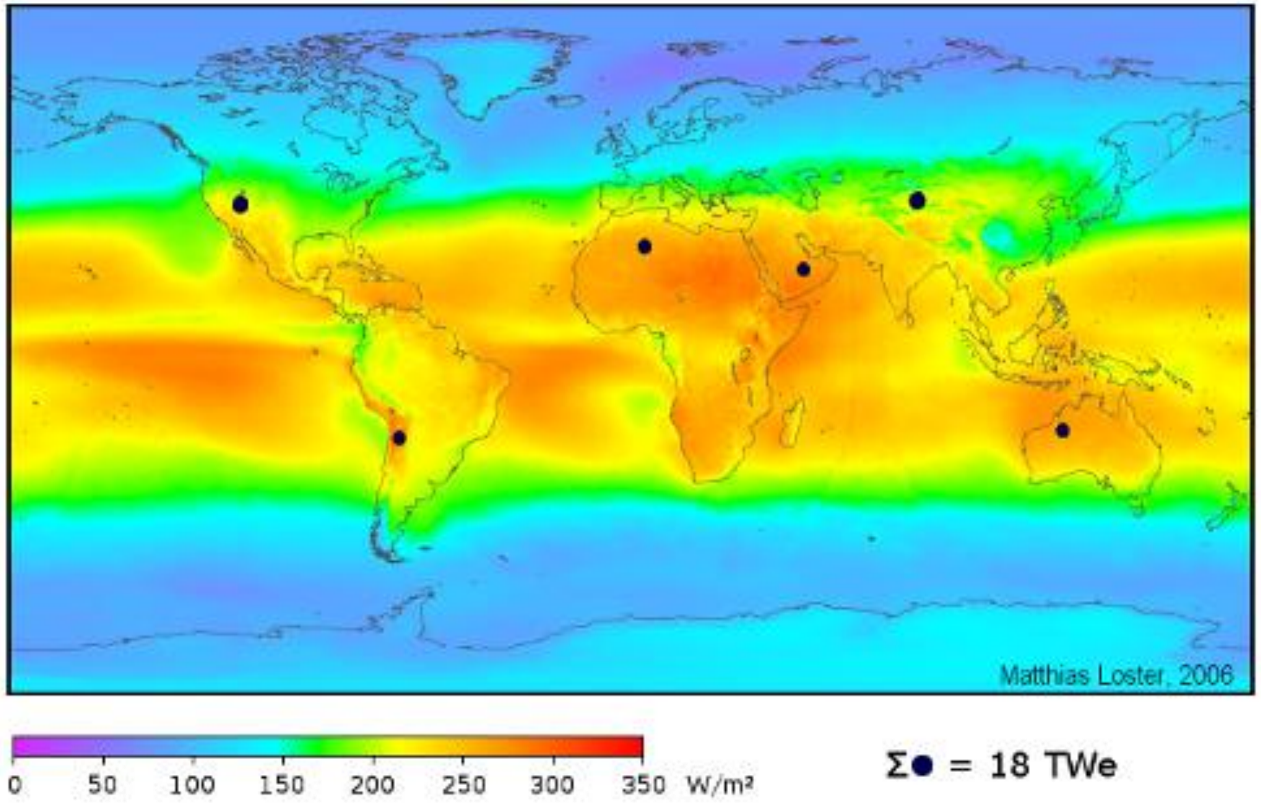
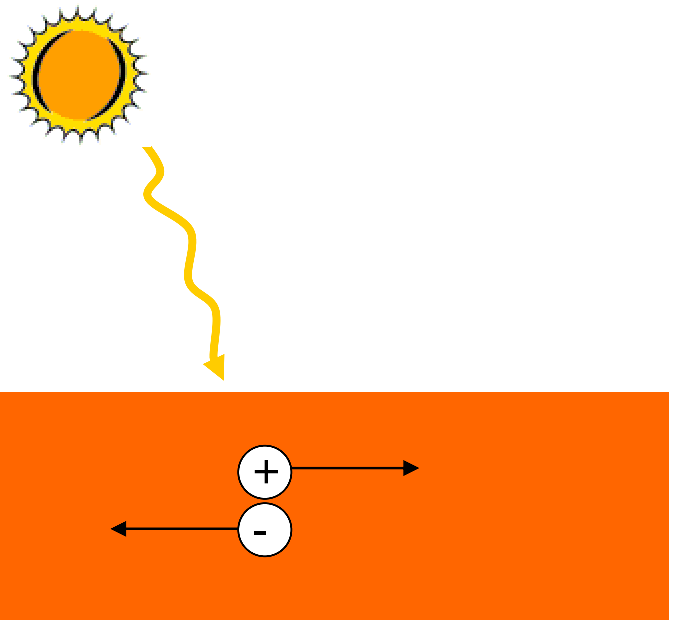


http://www.ez2c.de/ml/solar_land_area/index.html

- Sunlight hitting the dark discs could power the whole world
- 18 TW (averaged) electrical power for solar cells with 8% (low) efficiency covering the area of the black dots!

Basics of PV

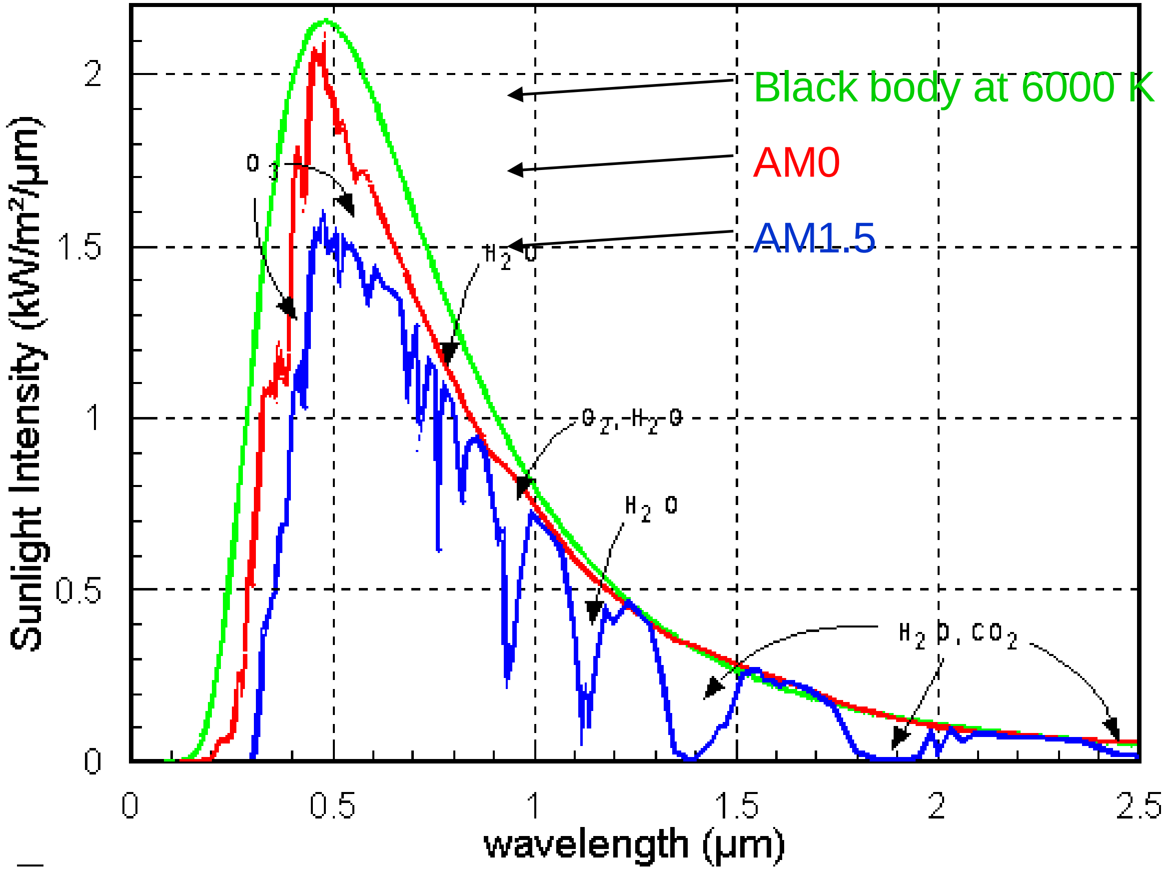
PV device - Physical principle



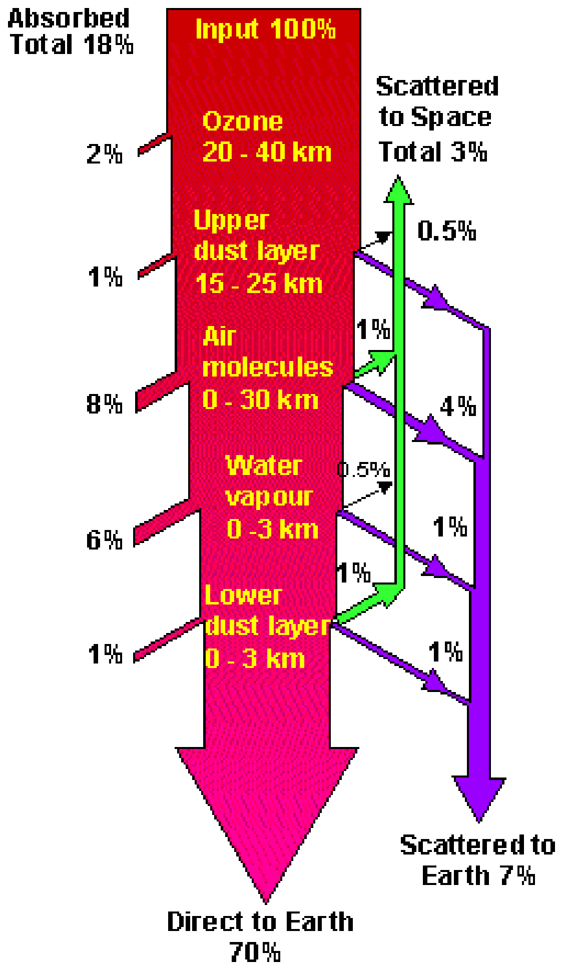
2 step process :

1) Absorption of a photon in a **semiconductor** to create a free electron-hole pair
2) Separation of the electron-hole pair thanks to the internal electric field of a **diode** and carrier collection

Solar spectra



solar radiation reaching the Earth and absorption bands due to the atmosphere.



Typical clear sky absorption and scattering of incident sunlight.

Source PVCDROM

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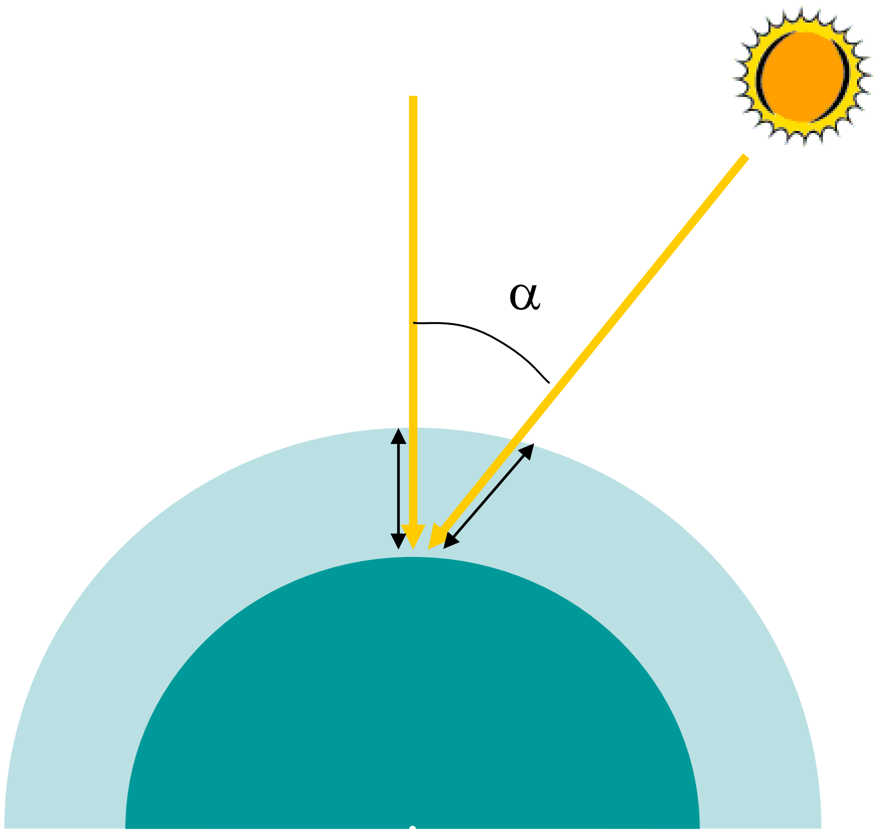
Air mass



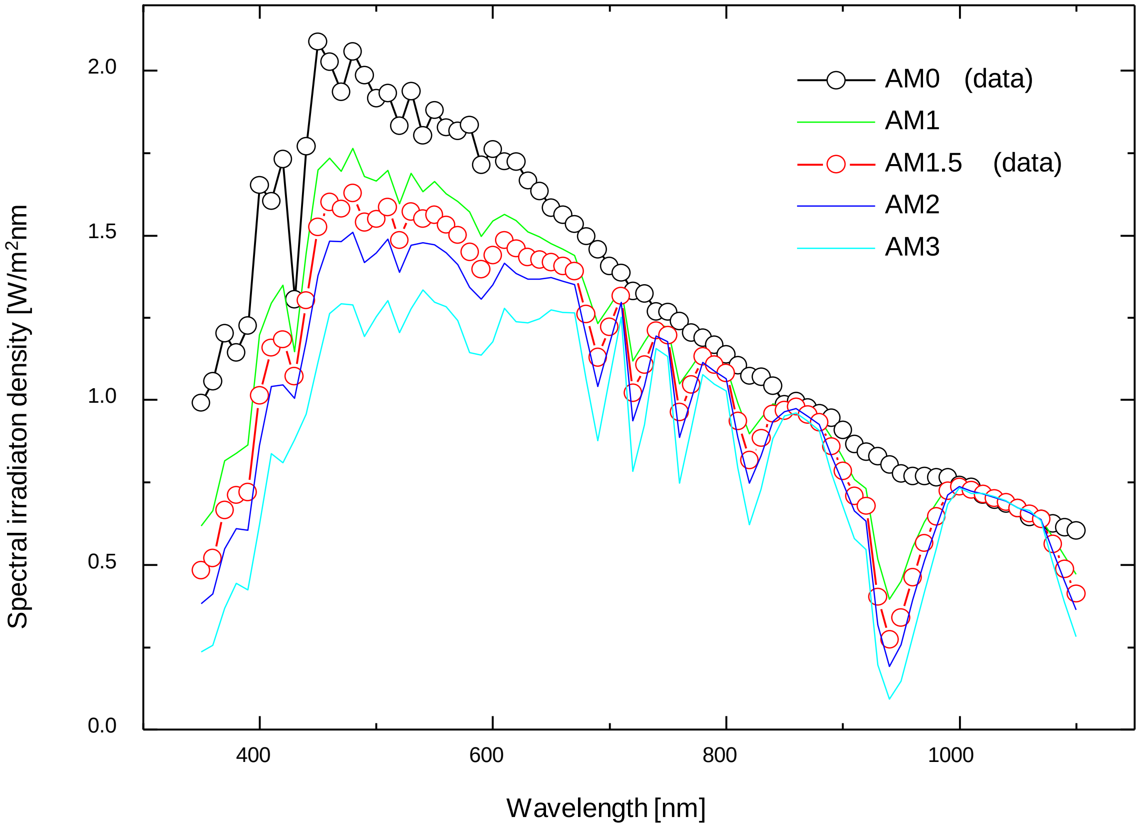
- **Air Mass** : Attenuation (through the atmosphere)

$$AM = 1/\cos\alpha$$

where α is the angle between the sun beam and the vertical direction.
  - AM0: solar spectrum (outside of the atmosphere)
  - AM1: solar spectrum on earth surface when the sun is at the vertical direction
  - AM1.5: angle of 45° of the sun with respect to the vertical direction.
  - AMx defines both the **spectrum and the radiation intensity**.
  - AM1.5 $\rightarrow$ 100 mW/cm^2
  - AM1.5G (Global), AM1.5D (Direct)
- Efficiencies of PV systems are usually calibrated at this intensity.

Spectral change of illumination

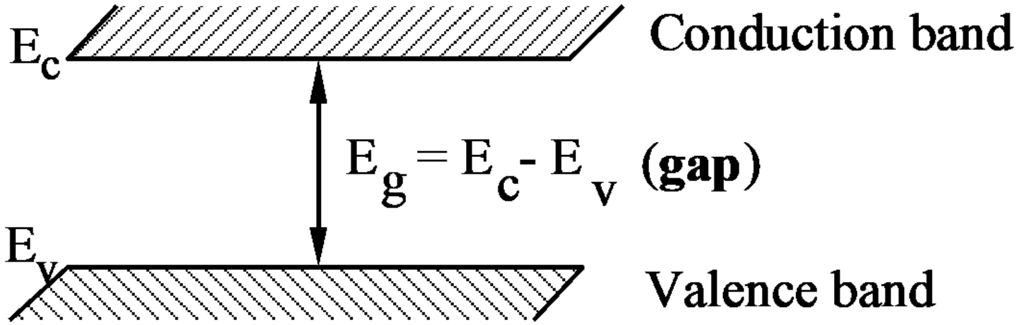
Daily (and seasonal) changes of spectral irradiation density

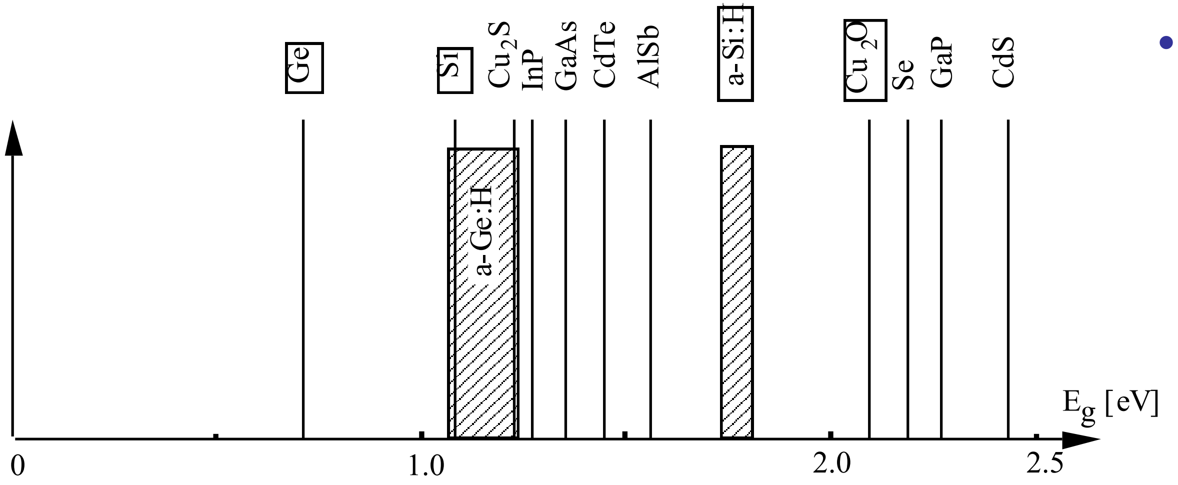


AM0: space
AM1: equator
AM1.5 (central Europe, equinox, noon, 48° above horizon)
30° above horizon
20° above horizon

- Differences mostly in the visible part of the spectrum
- Maximum irradiation (normal surface): 1 kW/m^2
- Yearly irradiation (Switzerland): 800-1200 kWh/m^2/year (dependent on the local climatic conditions)

Forbidden gap





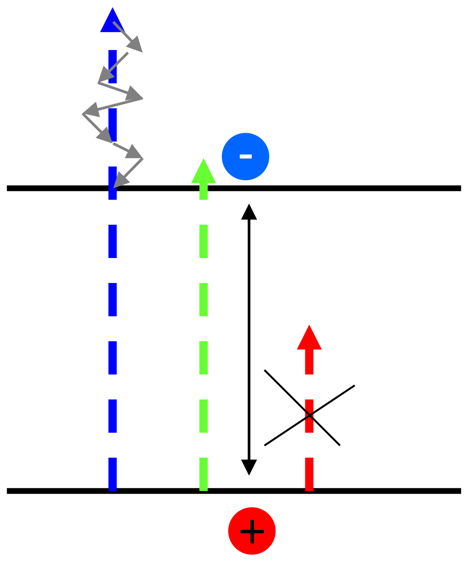
gap E_g of various semiconductor material at T=300 K

- Every semiconductor has a fixed gap E_g,
- E_g is temperature dependent.

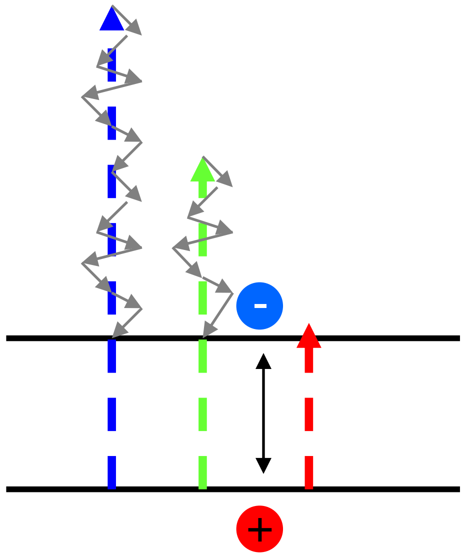
- Direct bandgap (GaAs, InP,..): High absorption coefficient
- Indiret bandgap (Si. Ge, …): Low absorption coefficient
- Non-direct bandgap (dosordered semiconductots: High absorption coefficient

Absorption process

High band gap (e.g. a-Si)



Low band gap (e.g. μc-Si)



Photons with energy less than the band gap are not absorbed

Photon energy in excess of band gap is lost to thermalization

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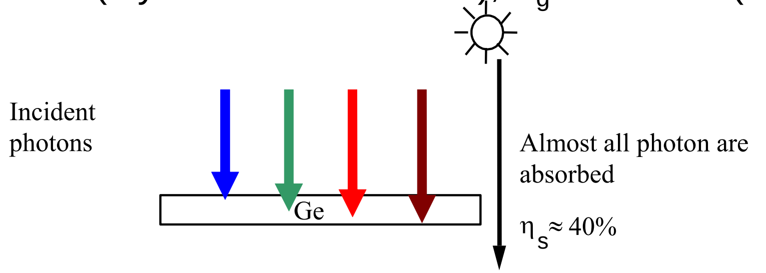
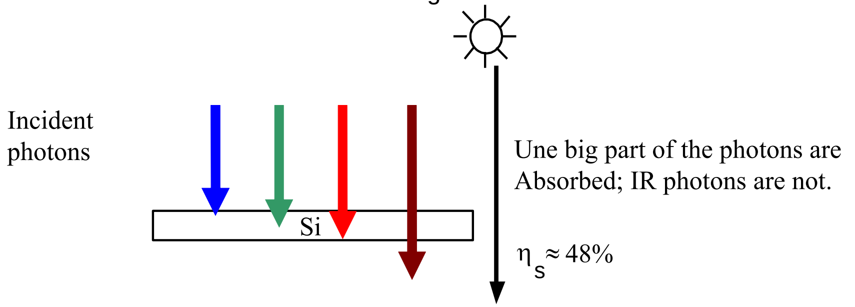
Spectral conversion efficiency

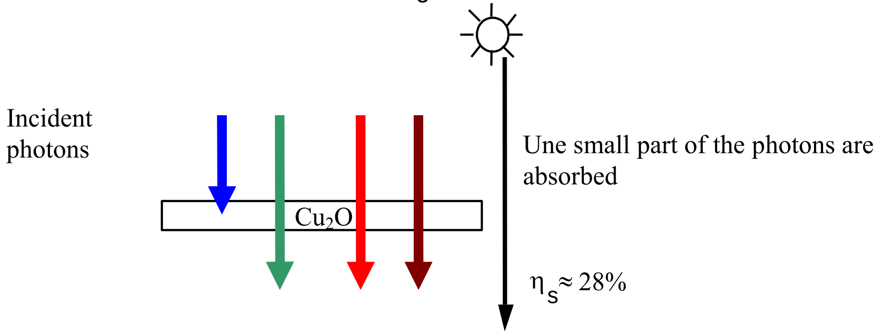
c-Ge (crystalline Germanium), E_g = 0.66 eV (small gap)



c-Si (crystalline Silicon), E_g = 1.12 eV (medium gap)



Cu_2O (Cupper oxide), E_g = 2.1 eV (big gap)



Spectral conversion efficiency η_S (physical limit of the conversion efficiency)

$$\eta_S = \frac{\phi E_g}{\text{Energy content of the solar spectrum per unit of time}}$$

or

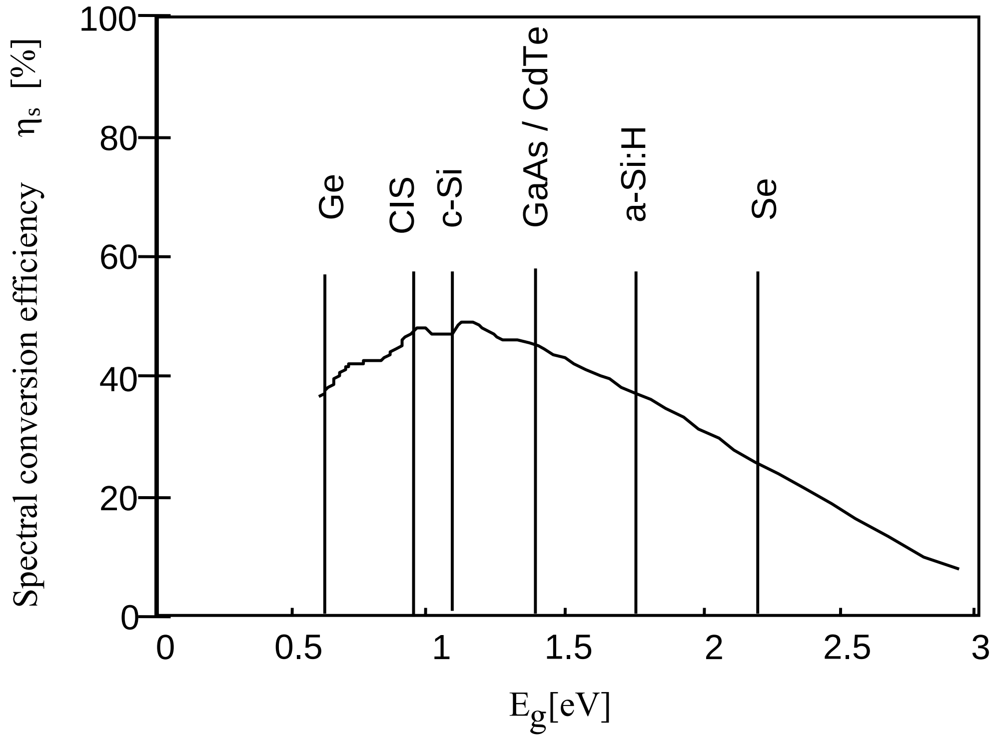
$$\eta_S = \frac{(\phi q)(E_g / q)}{\text{Energy content of the solar spectrum per unit of time}}$$

where ϕ is the photon flux

Remarks:

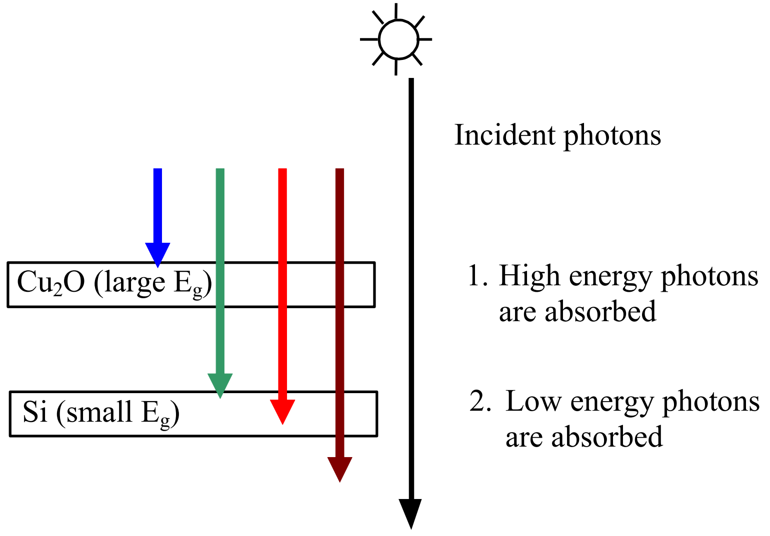
- $(\phi \cdot q)$ corresponds to an electrical current
- (E_g / q) corresponds to an electric potential

Spectral conversion efficiency



spectral conversion efficiency η_s as a function of gap E_g under AM1.5 illumination

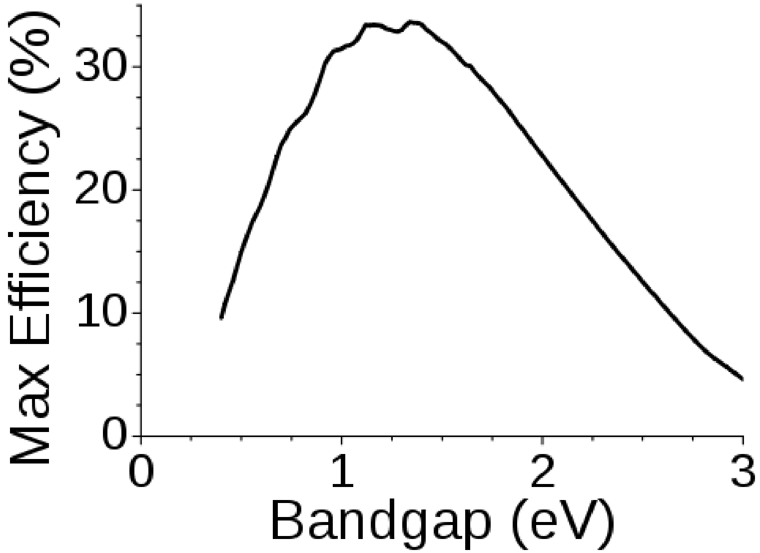
- η_S depends on
  - light spectrum
  - semiconductor gap
- Optimum bandgap for each spectrum
- Combination of semiconductors with different gaps may increase η_S

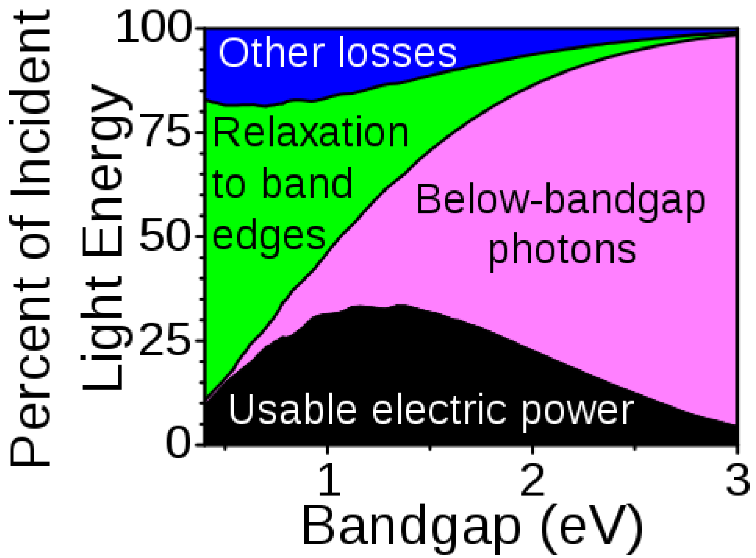


Combination of 2 semiconductors with different gaps:
With these 2 materials: η_s>60%.

Shockley-Queisser limit

- Fundamental efficiency limit of a (single junction) solar cell
- Considerations
  - Blackbody radiation (radiation loss, depends on solar cell temperature)
  - Recombination (only radiative, recombination of free holes and electrons)
  - Spectral loss (no absorption & thermalisation)
- Maximum : 33.7% for AM1.5





Wikipedia

http://sbyrnes321.byethost11.com/sq.pdf

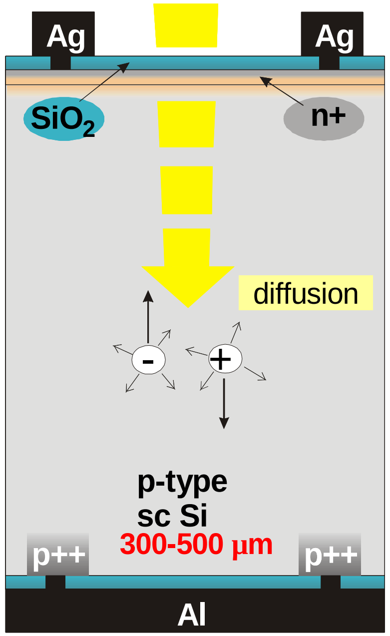
Device operation

Electron-hole pair separation

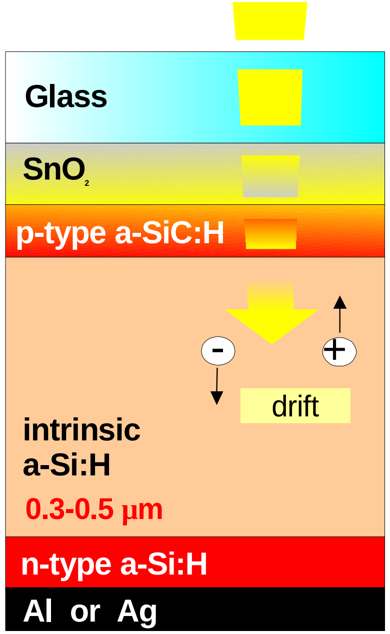
- p-n diode:
  - carriers' collection by diffusion process
  - crystalline solar cells

- p-i-n structure
  - carriers' collection by drift
  - amorphous solar cells
  - photodetectors (crystalline or amorphous)

Crystalline Si solar cell



a-Si:H *p-i-n* solar cell



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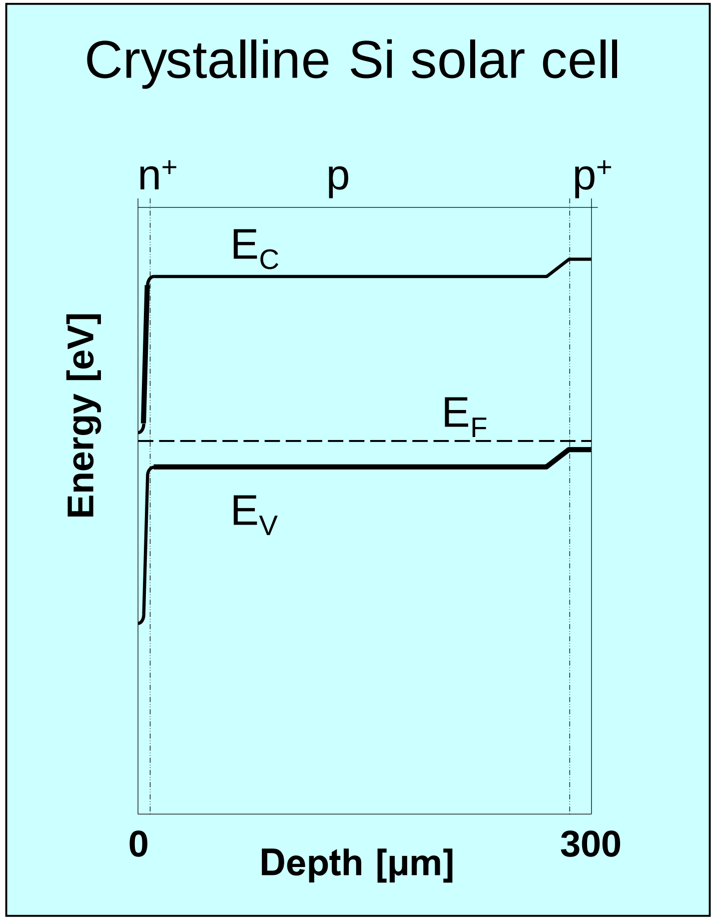
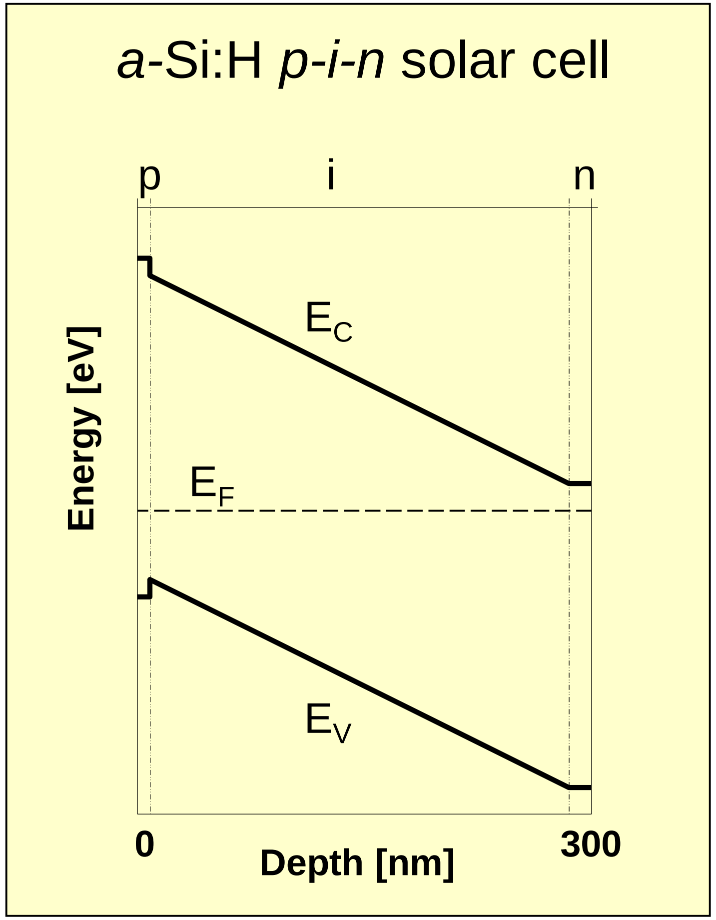
Delft University

Band diagram





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What is a solar cell: First approximation

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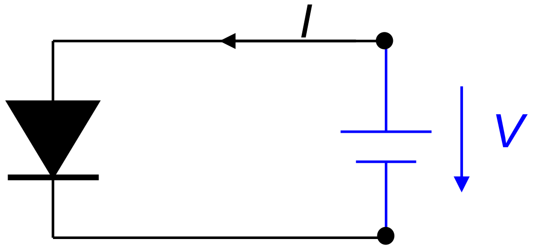
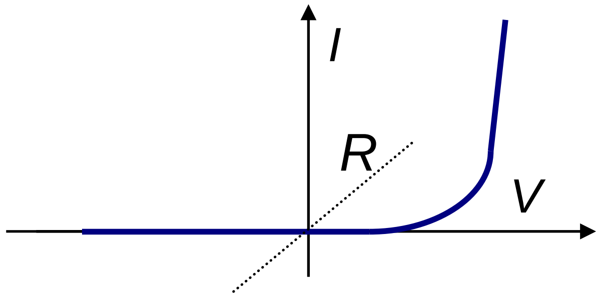
In darkness:
Solar cell = diode



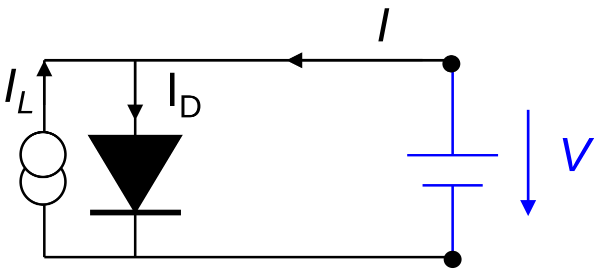


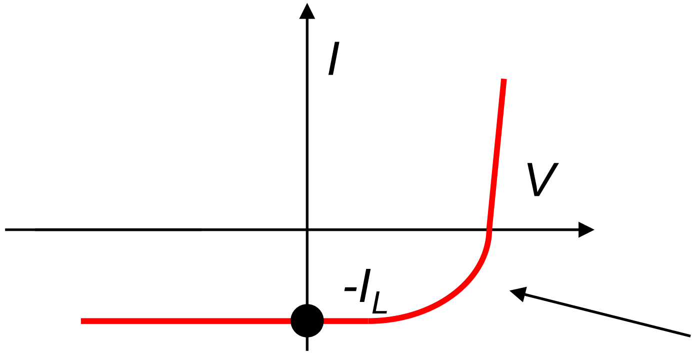
$$I = I_0\left[\exp\left(\frac{qV}{kT}\right) - 1\right]$$

Basic equivalent circuit — I-V (current voltage) curve — Ideal diode equation

Under illumination =
A diode + a current source in parallel with current I_L

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





Power can be delivered to a load !

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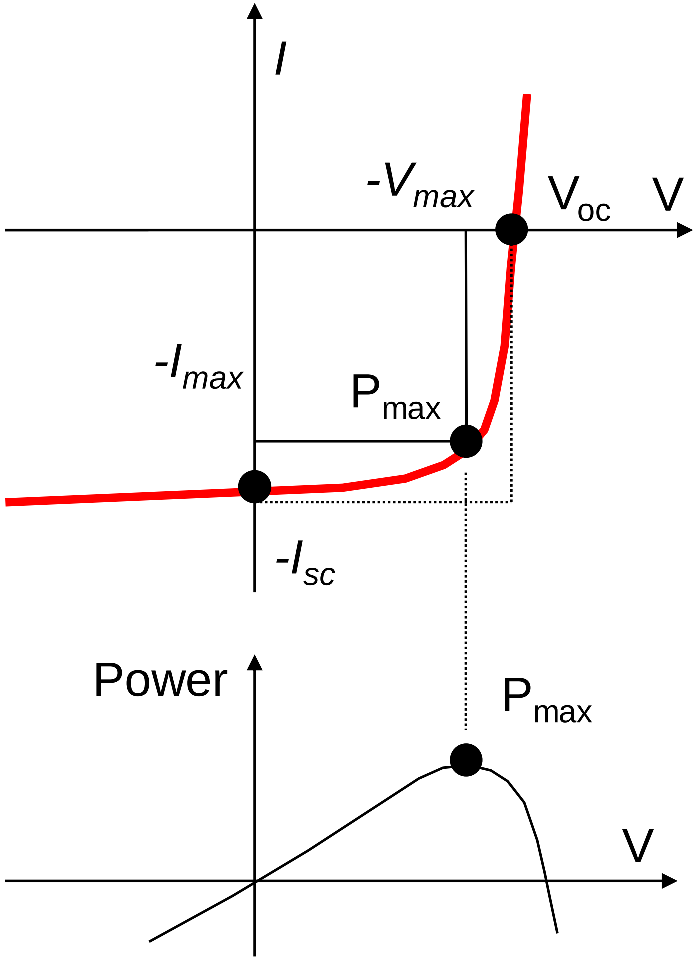
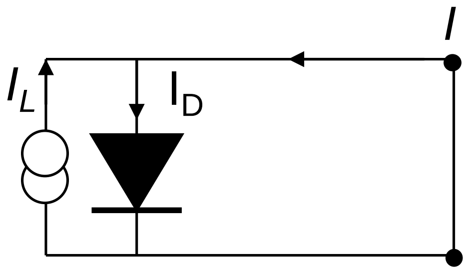
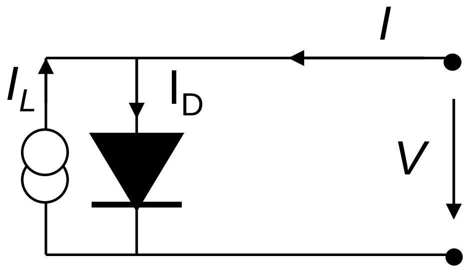
Solar cell I-V curve

Analyses of I-V curve

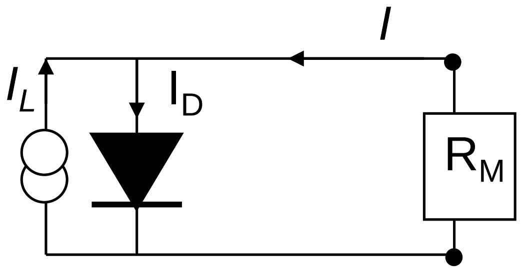




Short-circuit Conditions
$I = -I_{sc}$, $V=0$



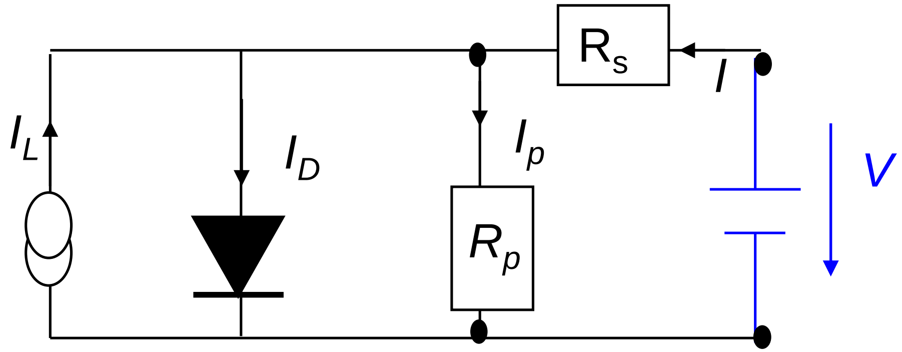
Open-circuit Conditions
$I=0$, $V = V_{oc}$,

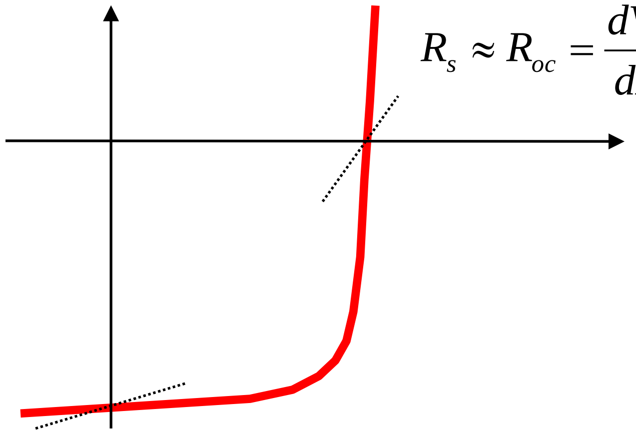


Ideal power dissipation on

$R_M=V_{max}/I_{max}$

Equivalent circuit of a p-n solar cell





$$R_s \approx R_{oc} = \left.\frac{dV}{dI}\right|_{V_{oc}}$$

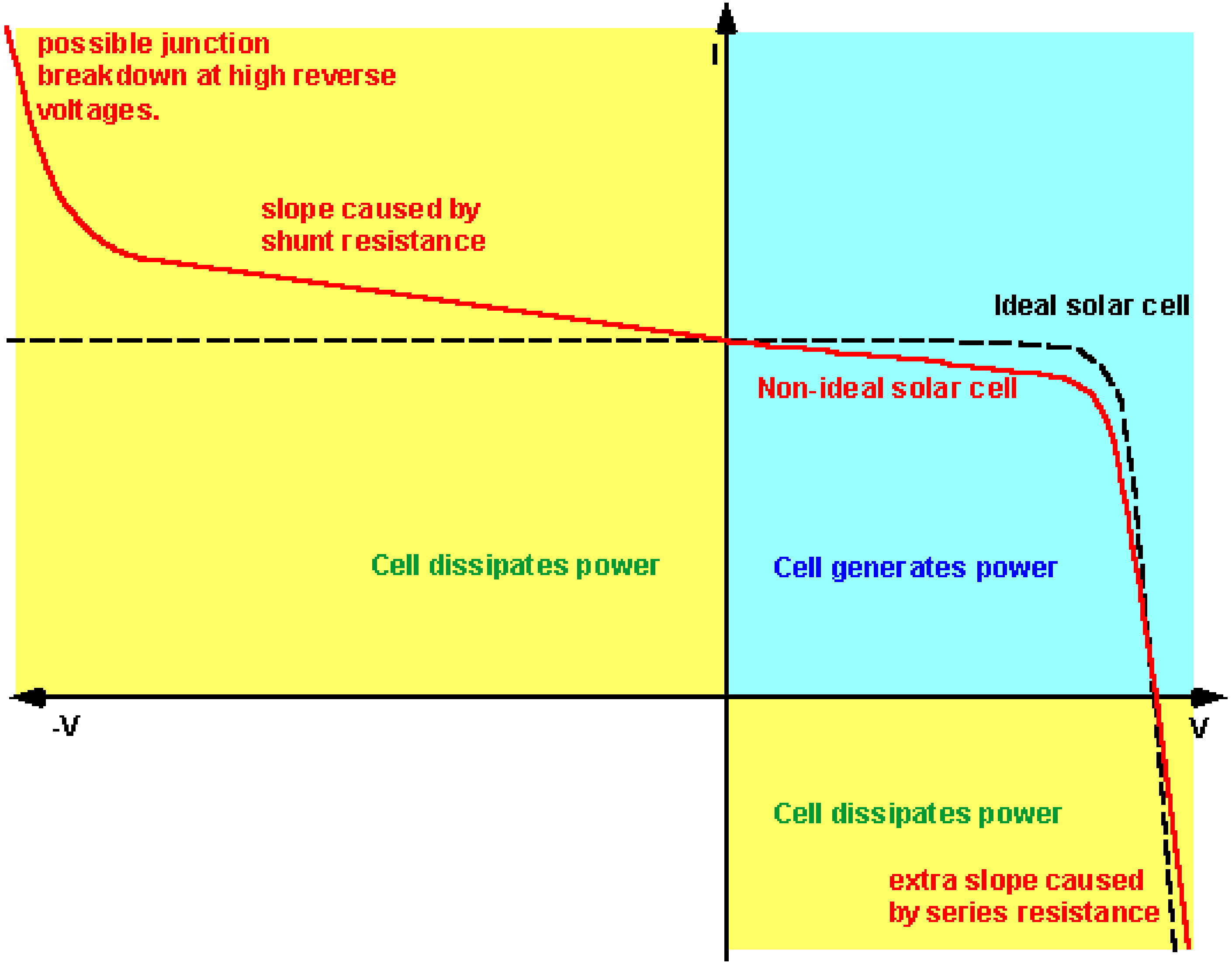
$$R_p \approx R_{Isc} = \left.\frac{dV}{dI}\right|_{V=0}$$

- Strictly applicable to p-n junction (c-Si).
- Approximately applicable to thin-film solar cells
- The series resistance R_s characterizes
  - the resistance of the metallic connections
  - the resistance of the metal-semiconductor interfaces (ohmic contacts);
  - the resistance of the semiconducting layers.
- The parallel resistance (or shunt) R_p characterizes:
  - the leakage currents at the junction periphery
  - the impurities in the junctions
  - additional (with respect to the ideal diode) recombination.

R_s series resistance (must be small)
R_p parallel resistance (must be high)

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

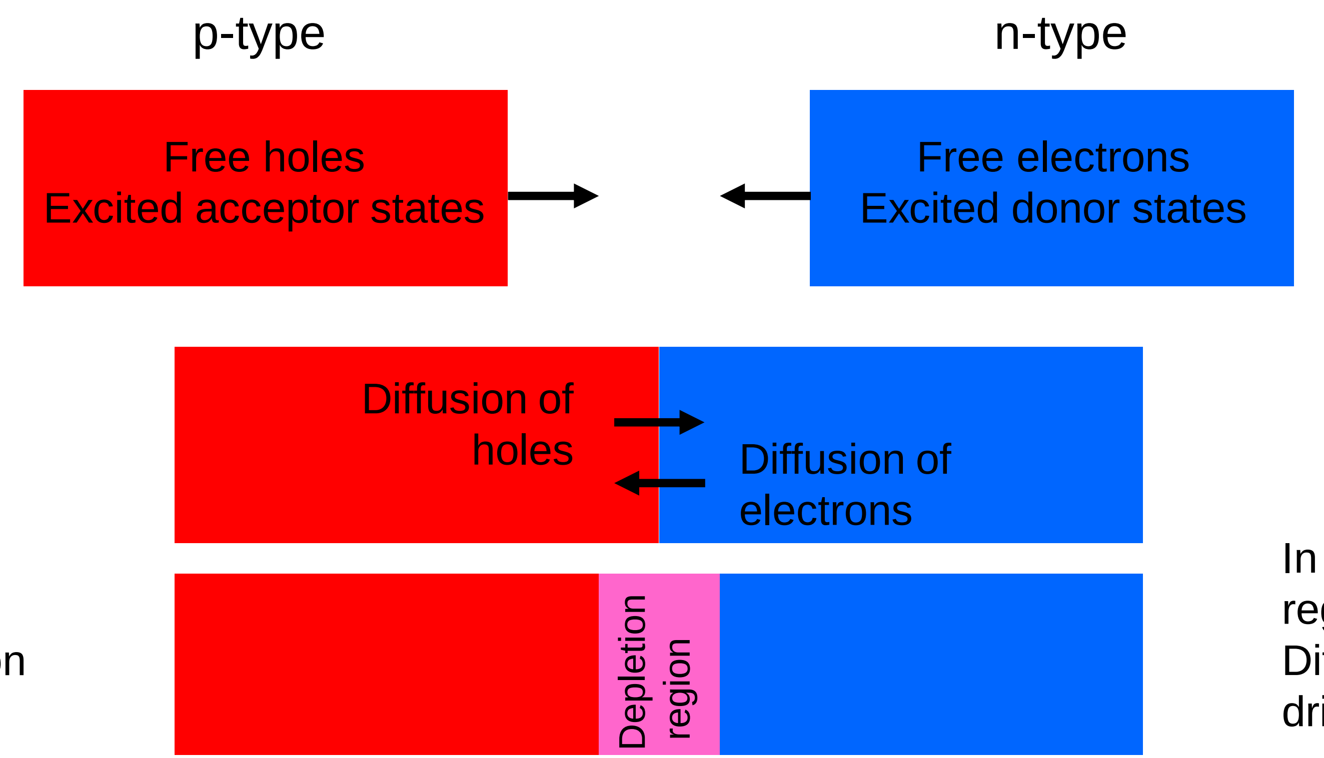
Current generation/dissipation



Photovoltaics CD-ROM

Device performance limits

Ideal p-n junction and junction formation



Depletion region =
Space charge region

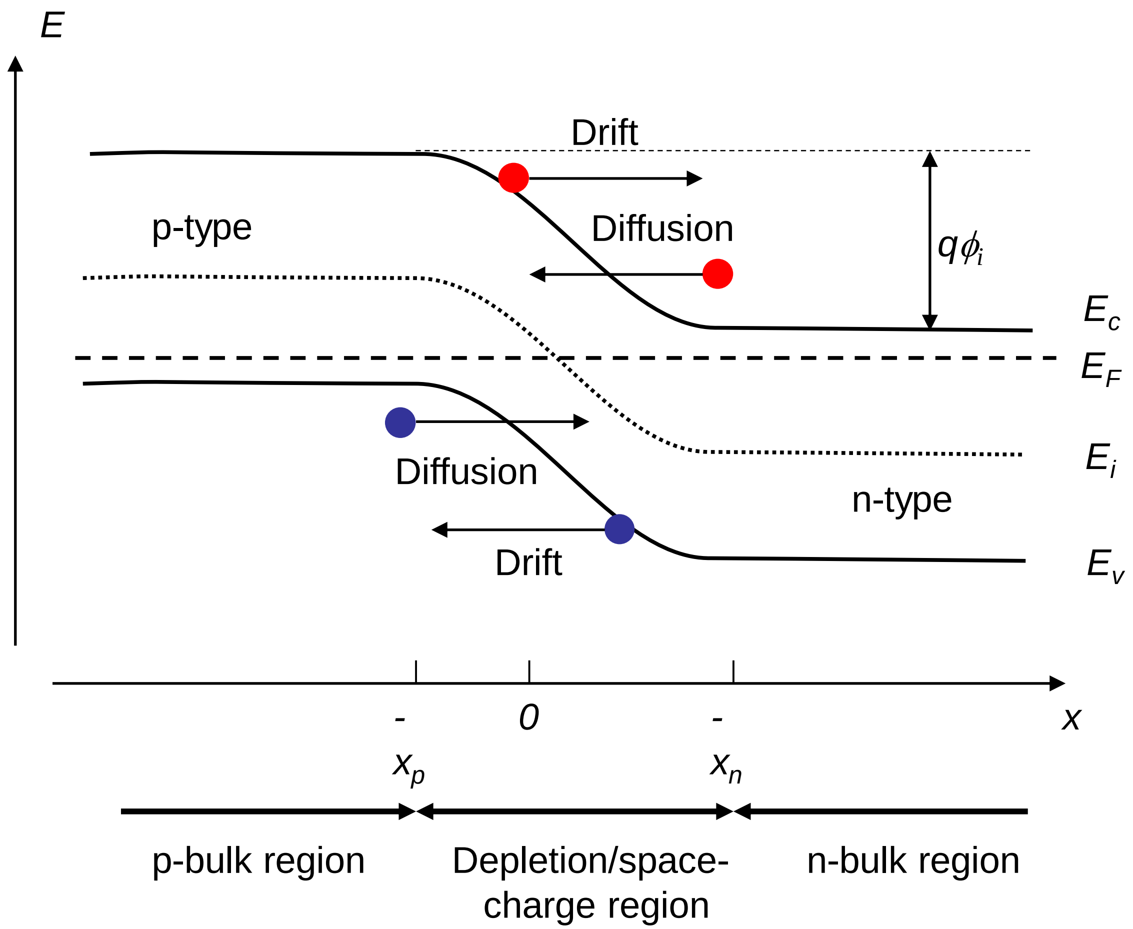
In the depletion region :
Diffusion currents = drift currents

Ideal diode

- Total depletion
  - Quasi neutral bulk region and space region with fully ionized donor/acceptor states

- Sharp interfaces
- n-region with n»p
- p-region with p»n
- Drift process negligible for minority carriers
- Very thin depletion region

Thermal equilibrium diagram



In thermal equilibrium: drift current = diffusion current

Diode equation (Shockley)

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Ideal I(V) characteristics in the dark (diffusion model)

- Solving the transport, continuity and Poisson equations (for an ideal p-n diode):

$$I_{dark} = I_0\left[\exp\left(\frac{qV}{k_B T}\right) - 1\right]$$

with

$$I_0 = A\left[\frac{qD_n n_i^2}{L_n n_A} + \frac{qD_p n_i^2}{L_p n_D}\right]$$

where

k : the Boltzmann constant q: the elementary charge

T: the absolute temperature A: the junction area

n_A, n_D : the dopant densities n_i : intrinsic carrier density

D_p, D_n: diffusion constants of the minority carriers in the p, resp, n region

L_p , L_n: diffusion length of the minority carriers in the p, resp, n region

Empirical expression and ideality factor

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- Saturation current I_0 replaced by a more simple empirical expression where the minimum saturation current I_0 is given by:

$$I_0 = 1.5 \cdot 10^8 \exp\left(\frac{-E_g}{k_B T}\right) \quad in \left[\frac{mA}{cm^2}\right]$$

- This empirical expression is an important basis for the calculation of the theoretical maximum of V_{oc}, FF et η
- When generation and recombination in the depletion region is not neglected:

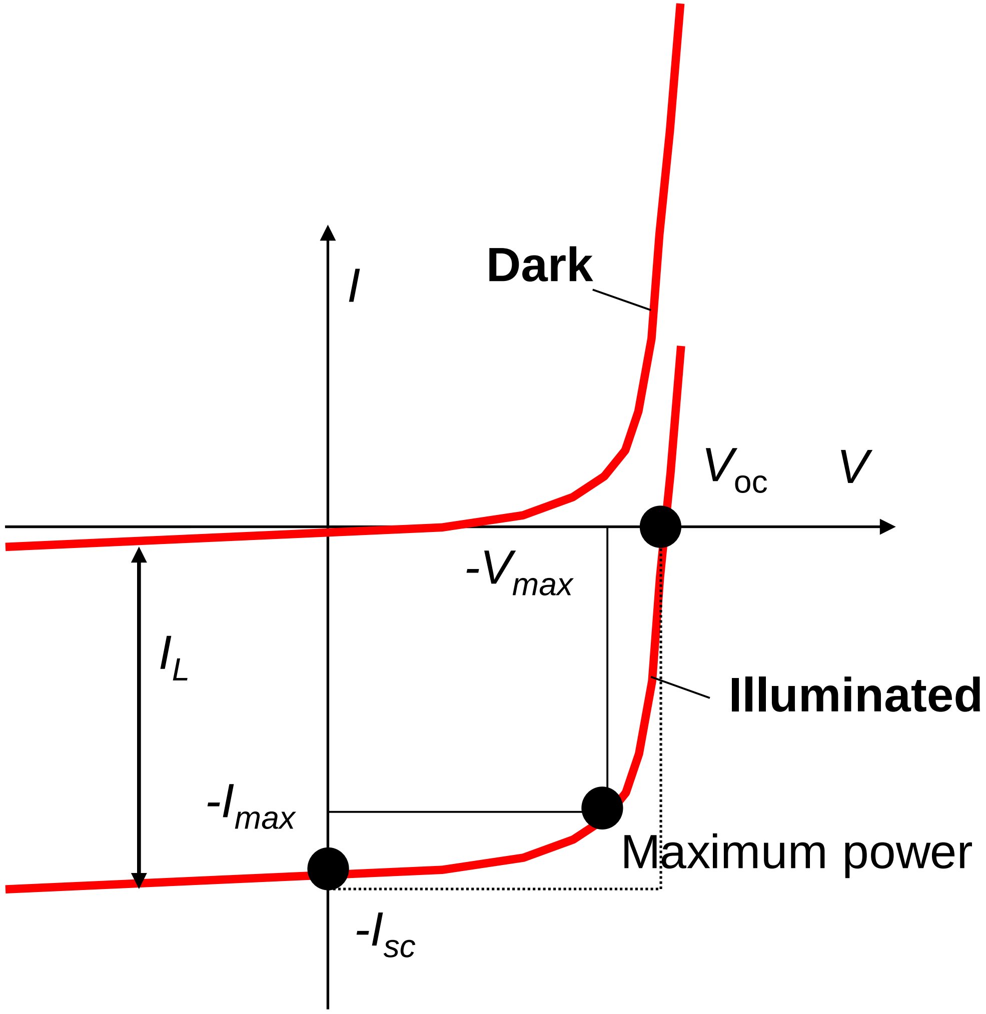
$$\Rightarrow \qquad I_{dark} = I_0\left[\exp\left(\frac{qV}{k_B T}\right) - 1\right] + \underbrace{I_w\left[\exp\left(\frac{qV}{2k_B T}\right) - 1\right]}$$

Additional term due to the recombination, which depends on the gap, carrier lifetimes, doping concentrations, applied voltage, etc.

- Can be replace by $$I_{dark} = I_0\left[\exp\left(\frac{qV}{nk_B T}\right) - 1\right]$$

where n is the **ideality factor** which varies between 1 (ideal case) and 2 (recombination current is dominant)

Superposition principle

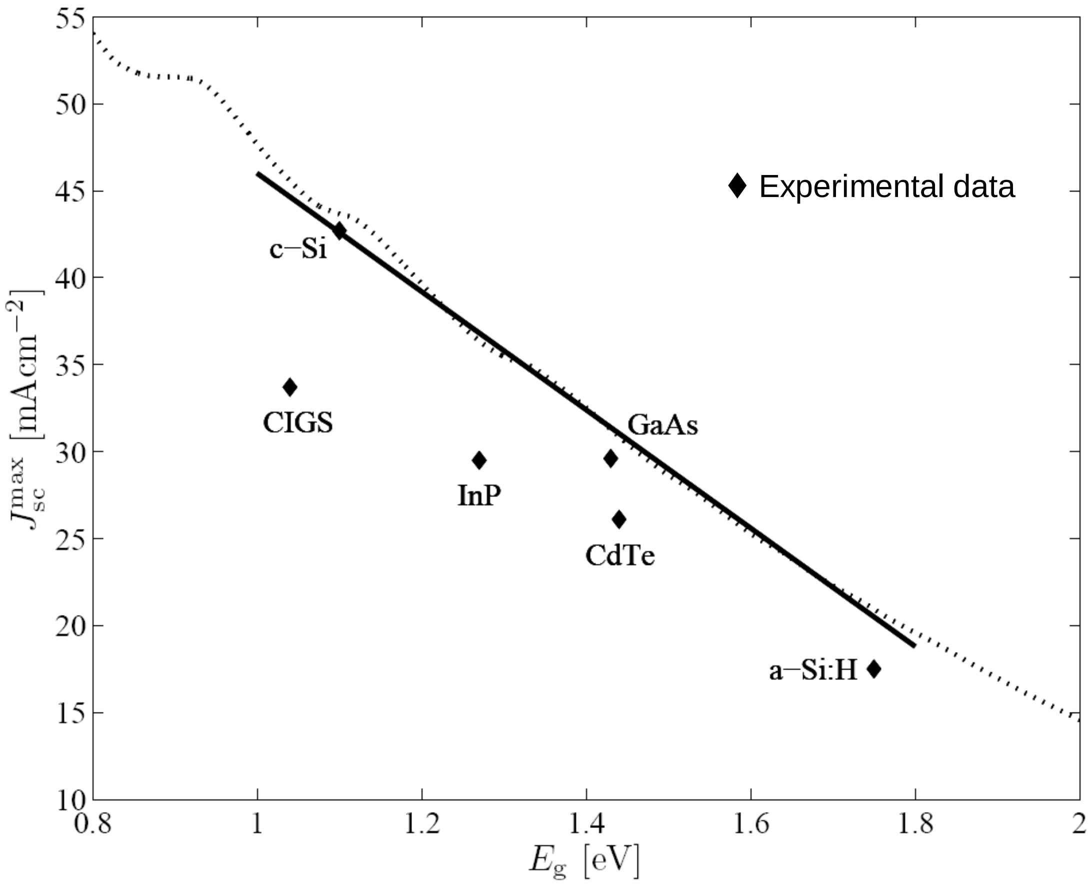


"Superposition" principle of the photogenerated current I_L

$$I(V) = I_{dark}(V) - I_L$$

- Principle valid for a p-n diode in ideal conditions
  (in general not valid for thin film diodes)

Short-circuit current I_{sc}



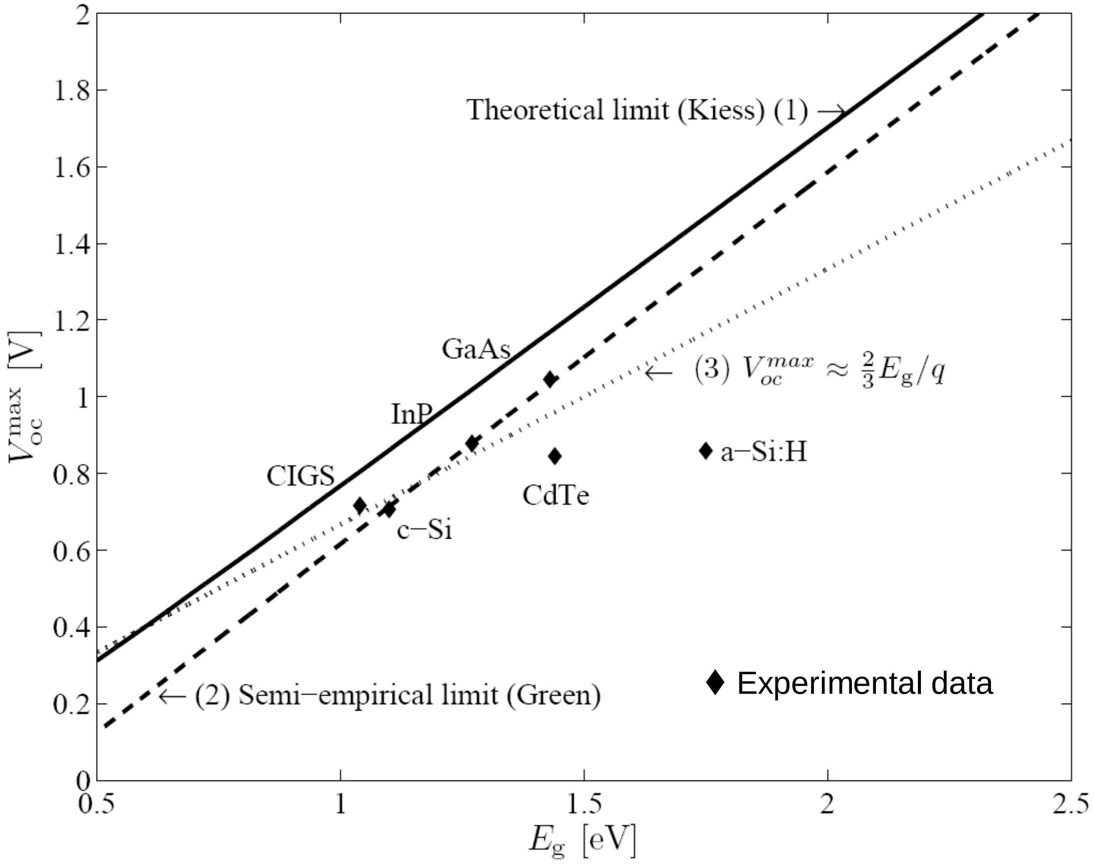
Theoretical maximum short-circuit current under AM1.5 illumination

- Assuming
  - $R_s = 0$ et $R_p = \infty$
  - cell thickness sufficient for absorbing all useful light
  - total collection of the carriers
  - no recombination.
- Ideal illuminated diode in short-circuit condition

$$I_{sc}=I_L$$

- Theoretical maximum of I_{sc} given by :
  - solar spectrum
  - semiconductor gap: $I_{sc}= \phi q$, with
    - ϕ: number of photogenerated "electron-hole" pairs per unit time
    - q: elementary charge
- Effect of the temperature:
  - I_{sc} very weakly temperature dependent (E_g decreases when the temperature increases).

Open-circuit voltage V_{oc}



Open-circuit voltage Voc as a function of the gap for a AM1.5 illumination with the approximations: (3) $V_{oc} \approx \frac{2}{3}\frac{E_g}{q}$

(2) $$V_{oc} \approx \frac{k_B T}{q} ln\left(\frac{1}{1,5\ 10^8} \frac{I_L}{[mA/cm^2]}\right) + \frac{E_g}{q}$$

where the values I_L are obtained from the Fig. 7.26, (1) theoretical limit of Kiess [Kiess, 1995]

- The voltage supplied by a cell directly depends on gap E_g
- From the empirical expression of the ideal p-n diode

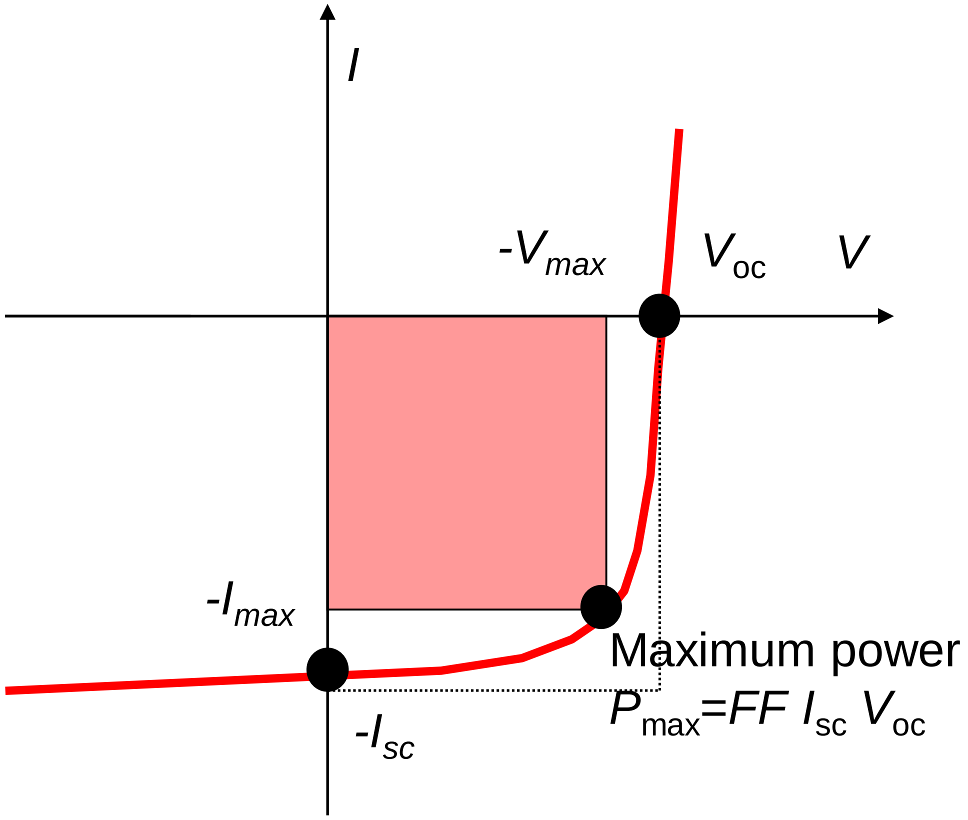
$$V_{oc} \approx \frac{k_B T}{q} ln\left(\frac{1}{1,5\ 10^8} \frac{I_L}{[mA/cm^2]}\right) + \frac{E_g}{q}$$

V_{oc} is a quasi linear function of the gap

$$V_{oc} \approx \frac{2}{3}\frac{E_g}{q}$$

- Limits
  - E_g/q is an upper bound for V_{oc}:
  - V_{oc} increases if I_L increases → advantage of cells working with light concentration (higher efficiencies).
- Temperature effect
  - V_{oc} decreases almost linearly when the temperature increases (0,4% per degree Celsius for c-Si).

Fill-factor and cell power

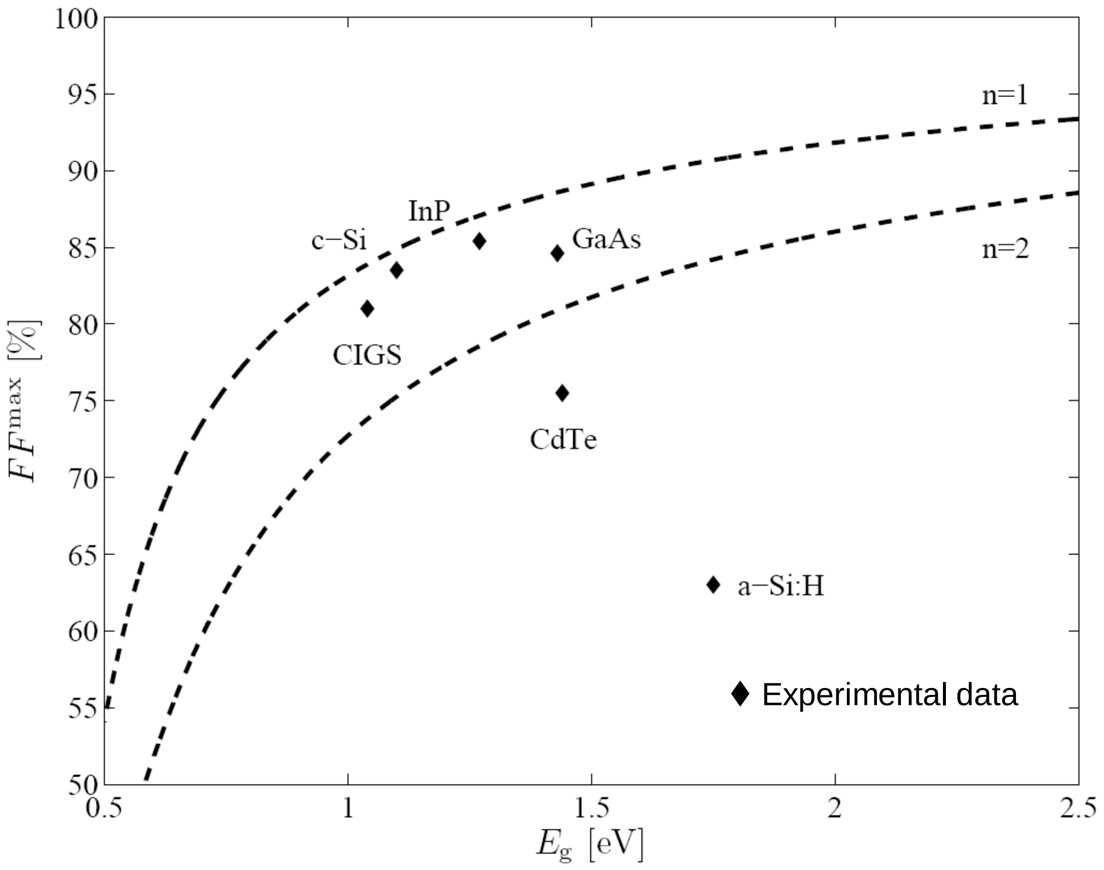


- Fill- factor FF defined as

$$FF = \frac{I_m V_m}{I_{sc} V_{oc}}$$

where I_m, V_m are the current and voltage when the cell output power is maximum (maximum power point)

Fill-factor FF



semi-empirical value of Fill-factor FF as a function of the gap for two values of the ideality factor n and for an AM1.5 illumination.

- FF is only a function of the open-circuit voltage V_{oc} (in the diffusion model of the p-n diode).

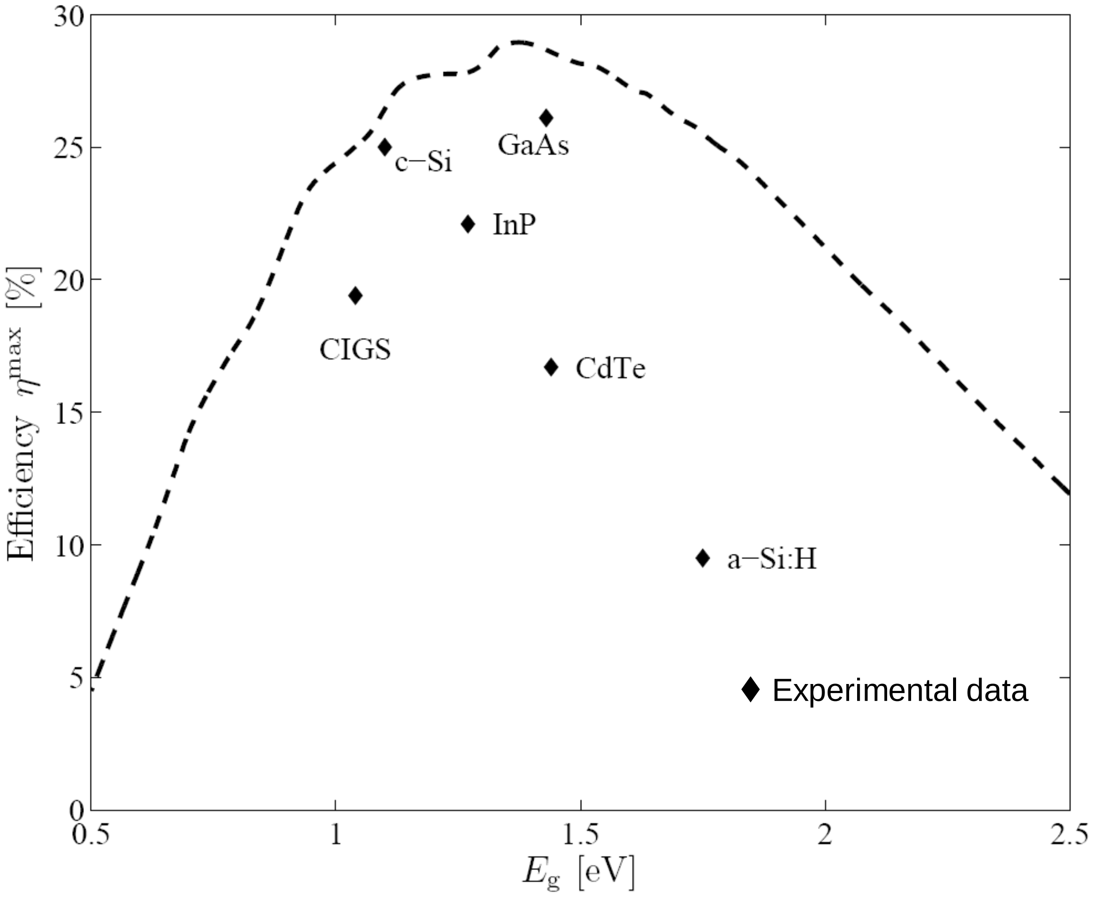
$$FF = \frac{v_{oc} - \ln(v_{oc} + 0.72V)}{v_{oc} + 1}$$

with $$v_{oc} = \frac{V_{oc}}{nk_B T / q}$$

valid for v_{oc} >10, n: ideality factor

- FF is a very sensitive indication of the solar cell quality! For a quality solar cell:
  - 0.7 < FF < 0.8 (a-Si:H)
  - 0.8 < FF < 0.85 (c-Si)
- Temperature effect:
  - FF decreases with an increase of the temperature (due to the change of V_{oc} with temperature).

Efficiency



maximum "theoretical" limit η as a function of gap E_g under AM1.5 illumination

- The efficiency η is defined as:

$$\eta = P_{\max} / P_{inc}$$

with $P_{max} = I_m V_m = FF I_{sc} V_{oc}$

- The total solar cell efficiency is given by:

$$\eta = \eta_{p/n} . \eta_s$$

$\eta_{p/n}$ being the efficiency of the carrier separation (second step)

$$\eta_{p/n} = FF\left(\frac{V_{oc}}{E_g / q}\right)$$

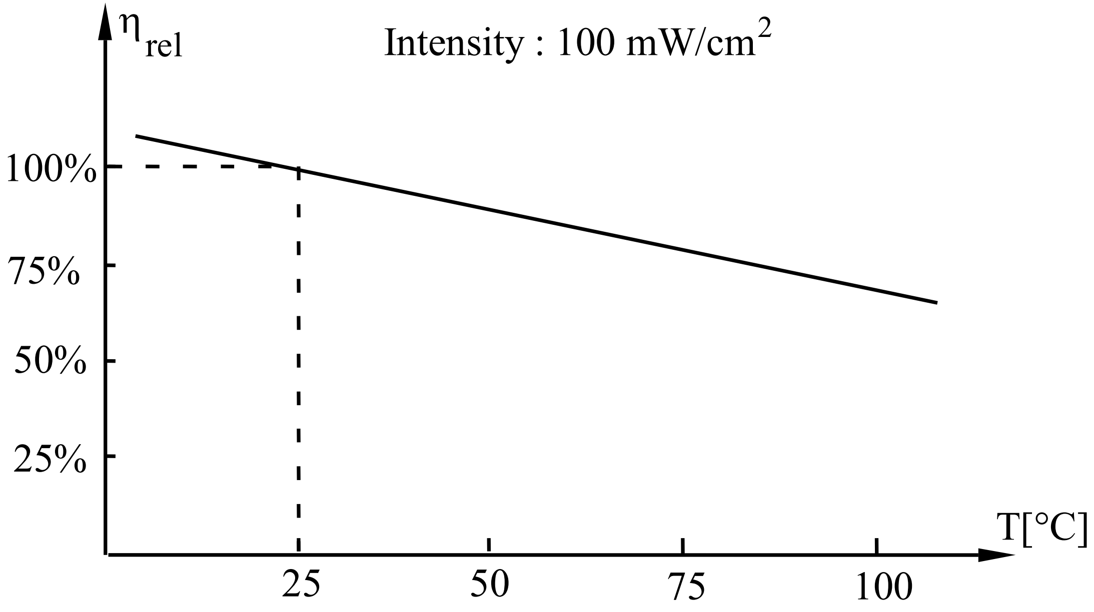
and η_s the spectral conversion efficiency.

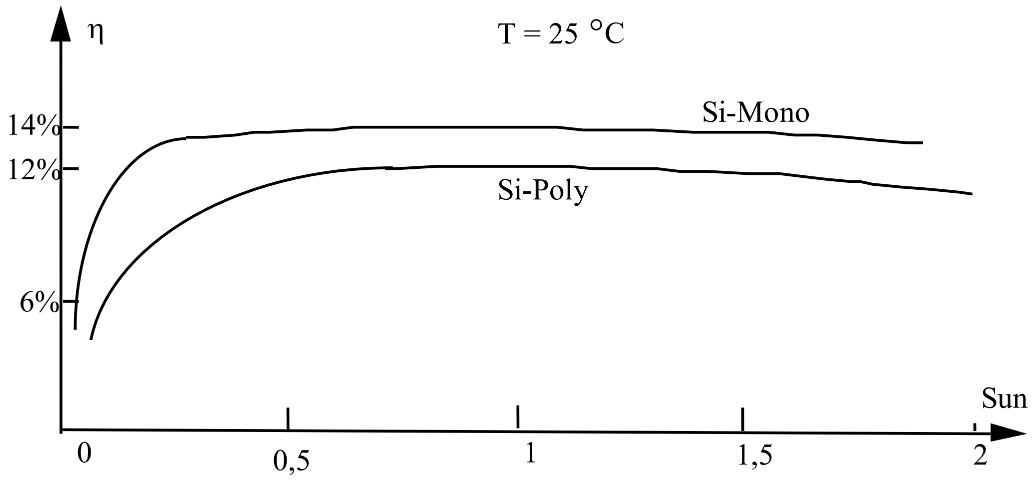
- Practically

$\eta = I_{sc}$ [mA/cm^2] V_{oc} [V] FF / 100 [mW/cm^2]

Efficiency dependences

N. Wyrsch

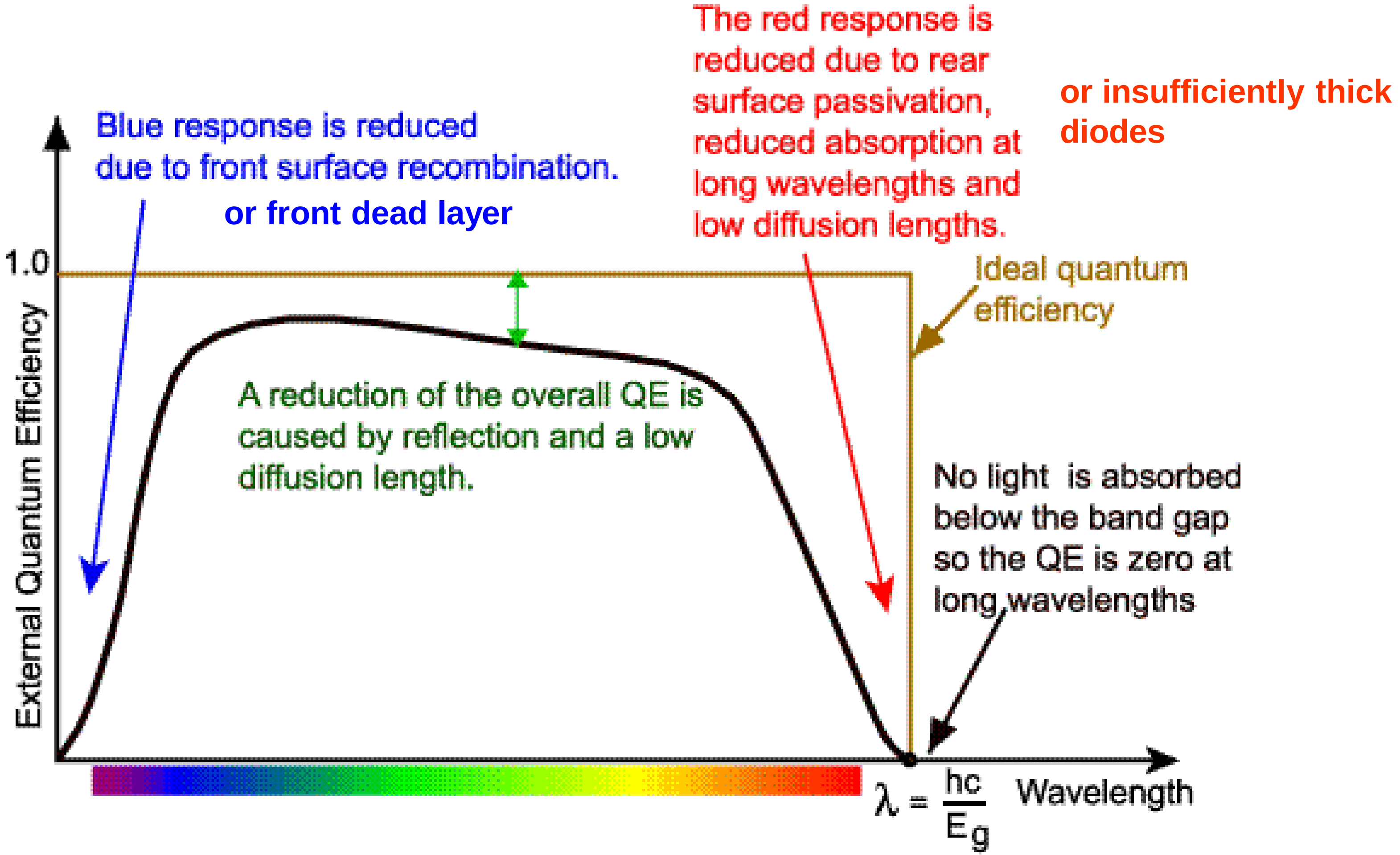


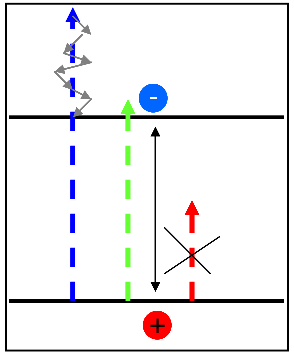


- Effect of temperature
  - For c-Si : η decreases by 0.4-0.5 %/˚C
  - For a-Si : η decreases by 0.2-0.3 %/˚C
  - Decrease is less important for high bandgap materials.

- Effect of the light intensity
  - η decreases with a decrease of the light intensity (I_L/I_0 ration of V_{oc}, and loss in R_p).
  - η decreases at high values of the intensity (loss in R_s, increase of the temperature, diffusion model no more valid for $\eta \rightarrow$ diode model under high injection).

Quantum efficiency





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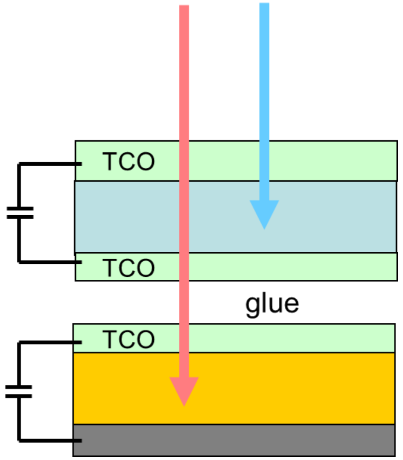
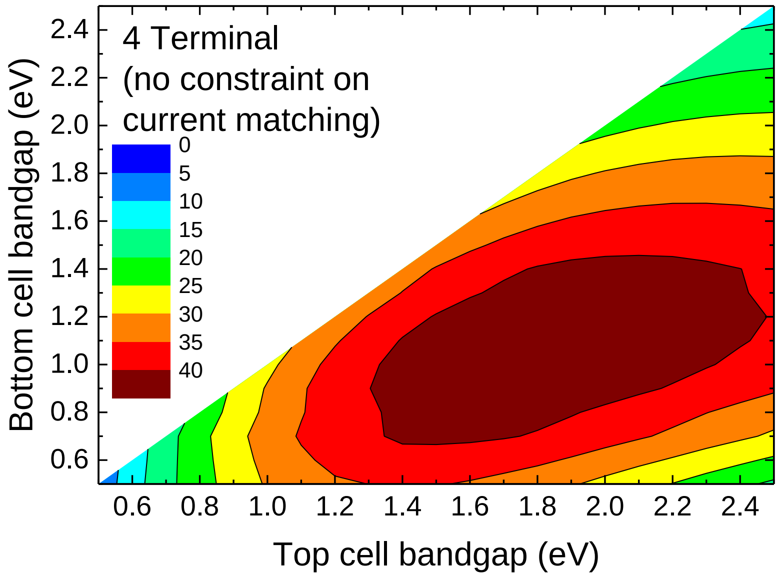
Multi-junction devices

Multi-junction cell efficiency

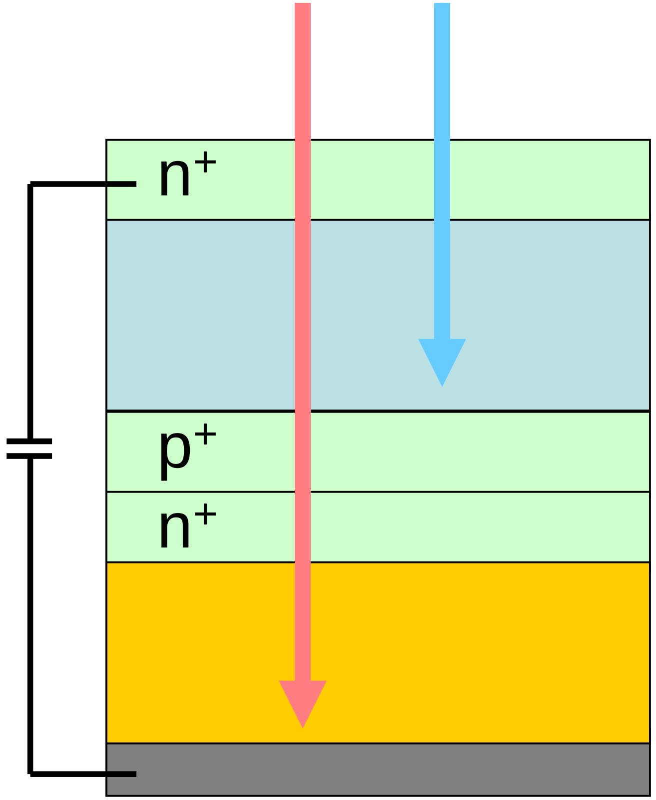
- Increase efficiency by
  - Increasing spectral conversion efficiency
  - Decreasing current (reduction of Joule losses)
- Maximum theoretical efficiency (solar spectrum)
  - Shokley-Queisser limit for single cell : 33.7%
  - Maximum efficiency for single-junction Si: 29.4%
  - Maximum efficiency for tandem: 42%
  - Maximum efficiency for triple-junction : 49%



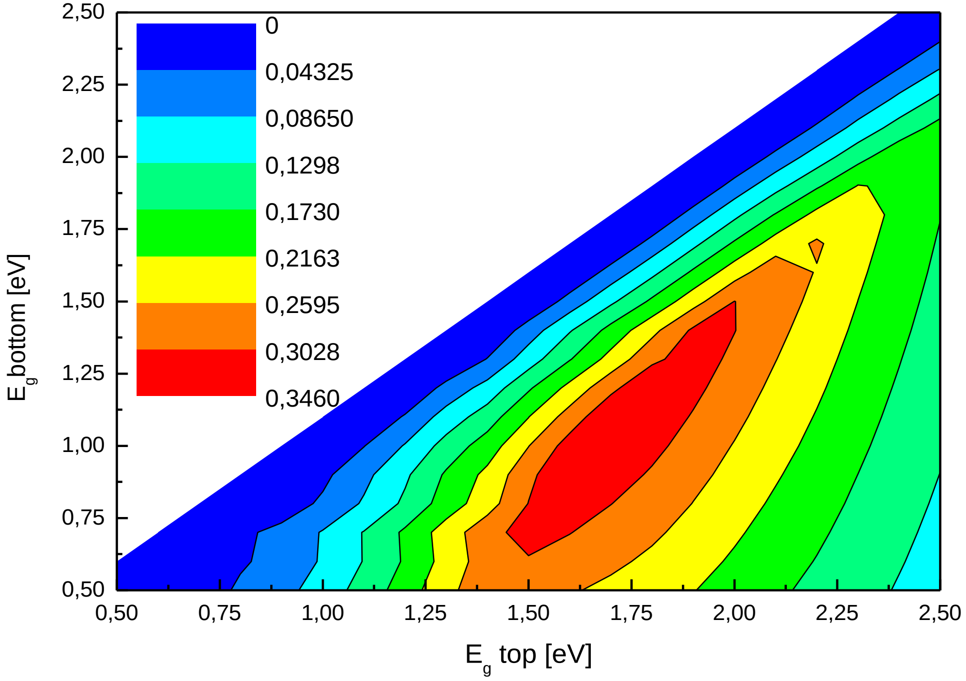
Optimal choic of component materials depends on light spectrum



Monolithic tandem

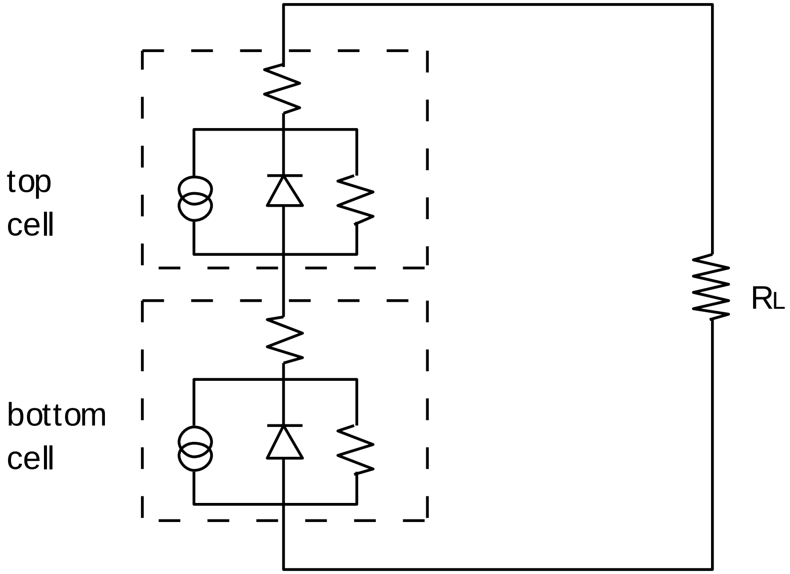


Map of max. efficiency (AM1.5)

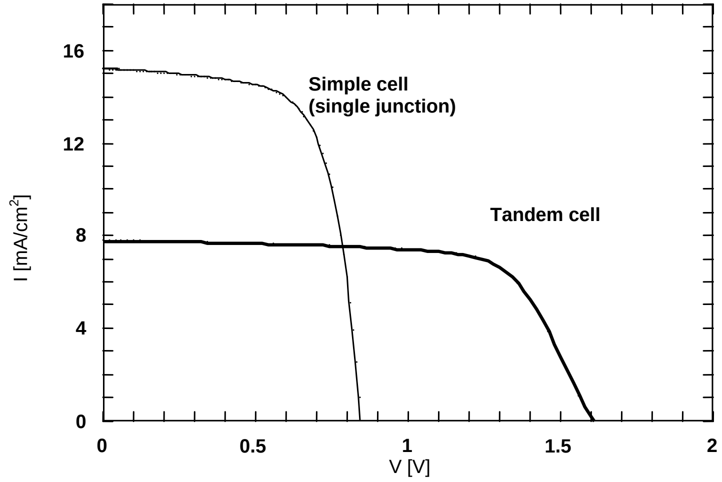


Two terminal device
Current matching required, narrower region of high efficiency compared to four terminal devices

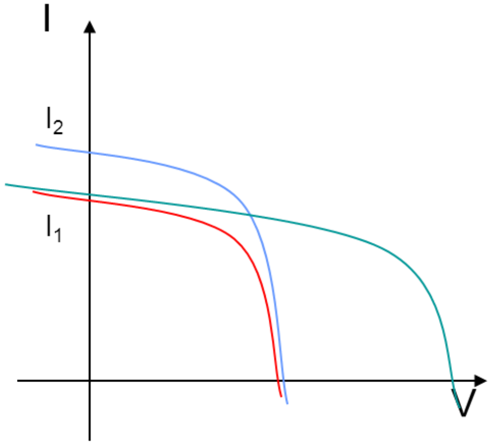
Tandem equivalent circuit



- "Top" cell: $I_{top} = I_{top}(V_{top})$
- "Bottom" cell: $I_{bot} = I_{bot}(V_{bot})$
- Tandem cell:
  - $I = I_{top} = I_{bot}$
  - $V(I) = V_{top}(I) + V_{bot}(I)$
  - I_{sc} @ min ($I_{sc,top}$, $I_{sc,bot}$)
  - $V_{oc} = V_{oc,top} + V_{oc,bot}$



typical $I(V)$ curves of a single-junction and tandem a-Si:H cells

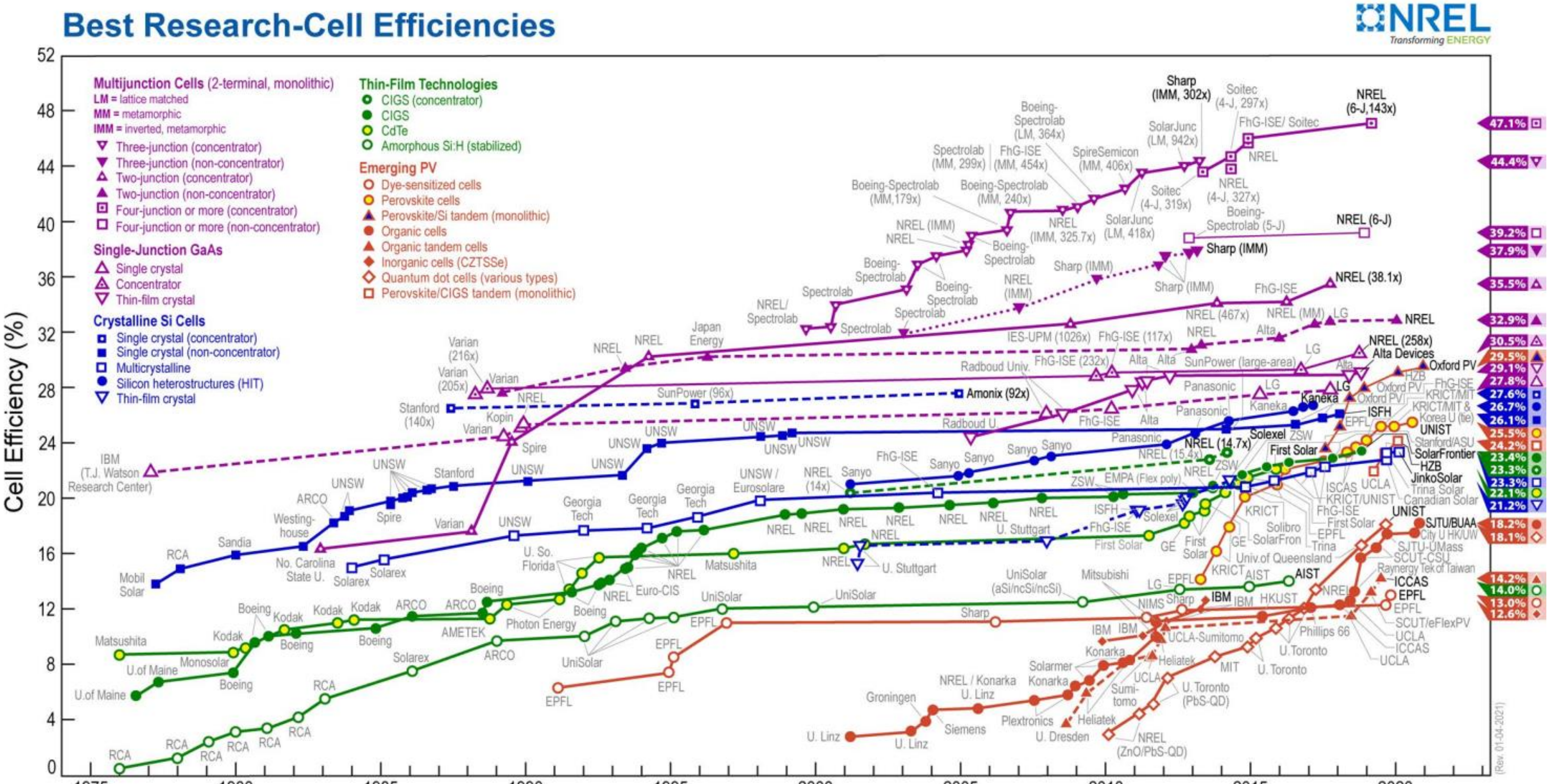


PV technologies

PV technologies

- Bulk technologies:
  - Monocrystalline silicon
  - Polycrystalline silicon
  - Ribbon silicon
  - GaAs (III-V, space application, concentrators), InP (space application)
- Thin-film technologies:
  - Amorphous silicon, micro-/nano-crystalline silicon, micromorph
  - CdTe (Cadmium telluride)
  - CIGS (Cupper Indium Gallium Diselenide)
  - CIS (Cupper Indium Diselenide, Cupper Indium Sulfide)
- Others, emerging technologies
  - Dye cells, “Graetzel”
  - Organic cells, polymers
  - Perovskite based
  - …

Conversion efficiency vs. time



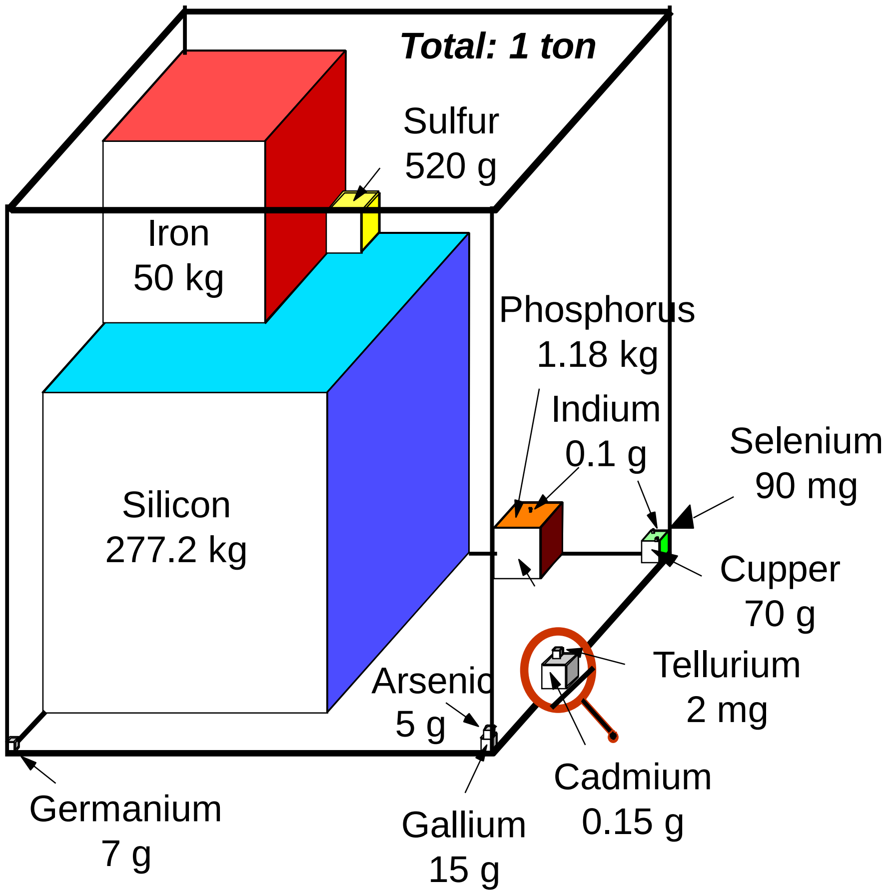
https://www.nrel.gov/pv/cell-efficiency.html

Commercial cells exhibit efficiencies reduced by 20-60%

PV-lab IMT NEUCHATEL

Availability of various materials for PV

N. Wyrsch



Availability of various materials in 1 ton of earth crust

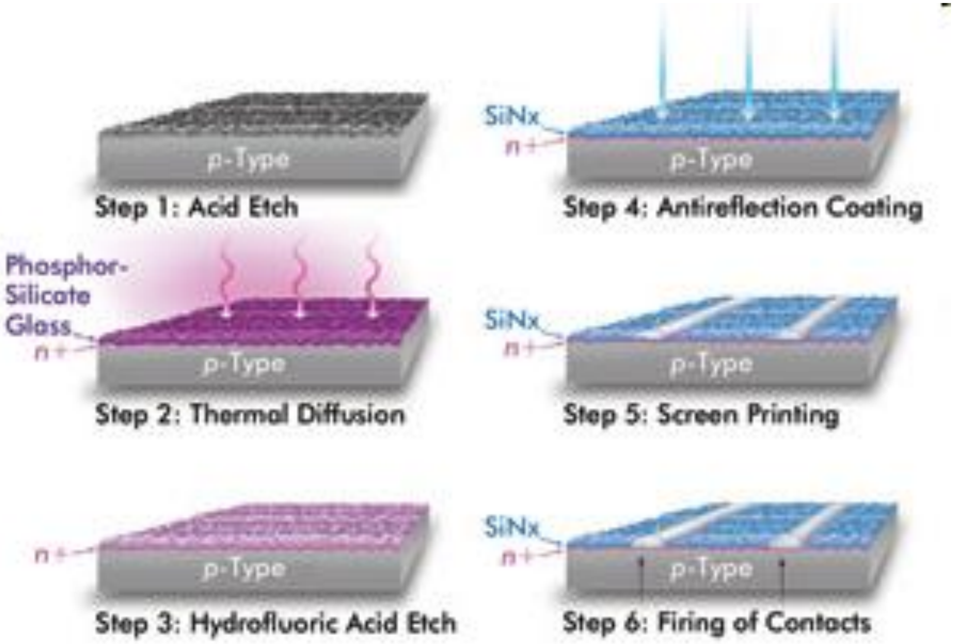
Crystalline silicon materials

- Czochralski (CZ) silicon
  - Quality material with high carrier diffusion length (high lifetime) at moderate costs
  - Standard material for c-Si solar cells
- "Float-zone" (FZ) silicon
  - Very high quality with very high diffusion length
  - Very high costs
  - Used only for very high efficiency cells
- "Multi-crystalline" silicon
  - Polycrystalline material with very large grains
  - Rarely used for solar cells, (could be replaced by + quasi mono)
- Poly-crystalline silicon (bulk)
  - polycrystalline material with large grains
  - Material mostly used for solar cells (but decreasing)
- Poly-crystalline silicon (thin-film)
  - Deposited by CVD or by recrystallization of a-Si:H
  - Research activities, small PV production

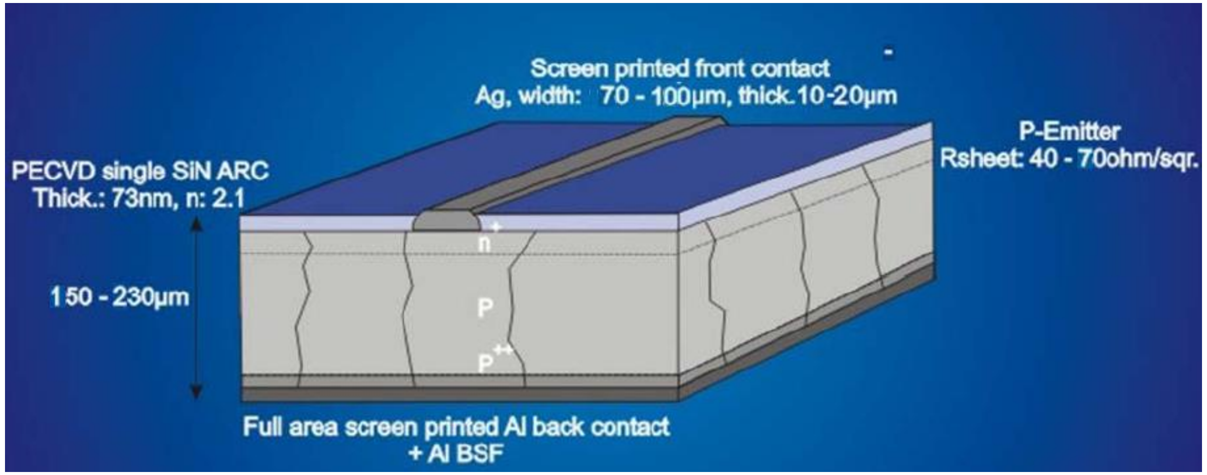
c-Si standard technology

N. Wyrsch

1. Solar grade Si
2. Ingot
3. Wafering
4. Cell fabrication
5. Module



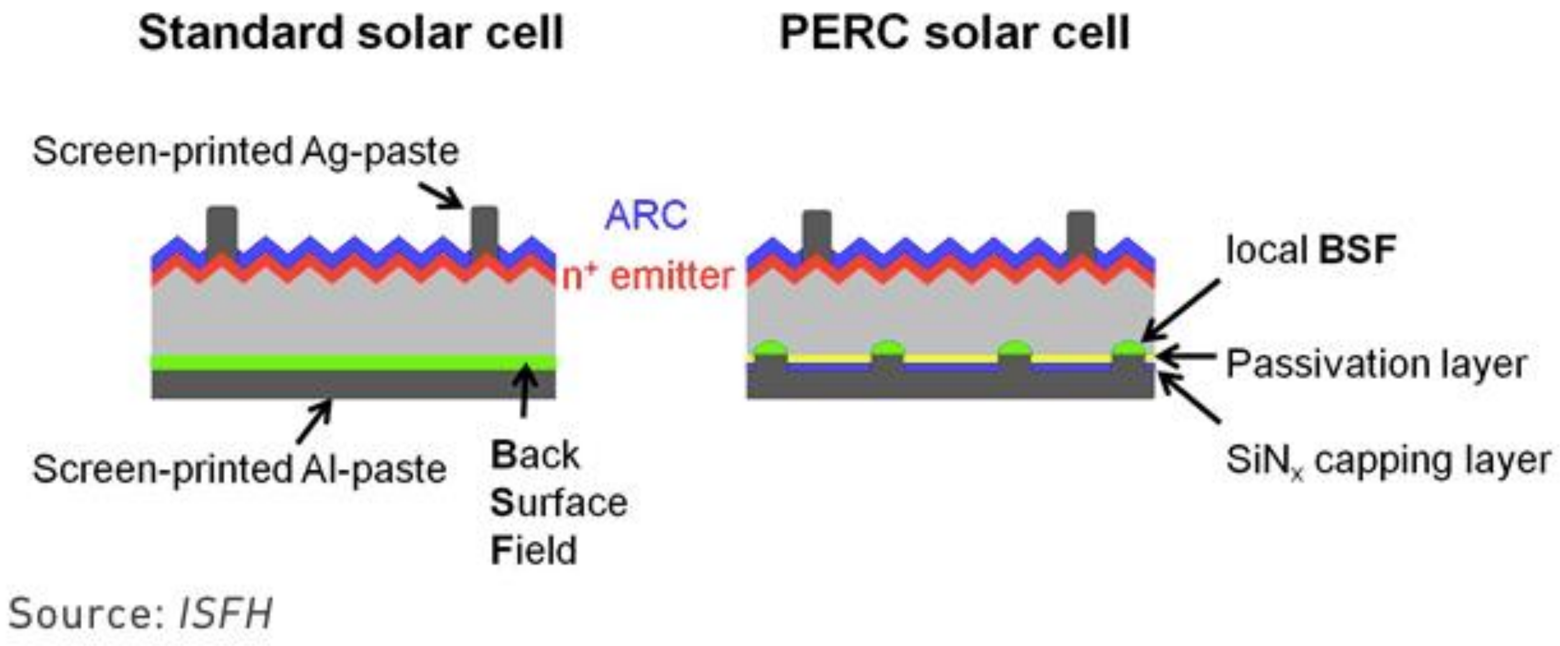
Screen printed solar cells



PVCDROM

Advanced c-Si technology

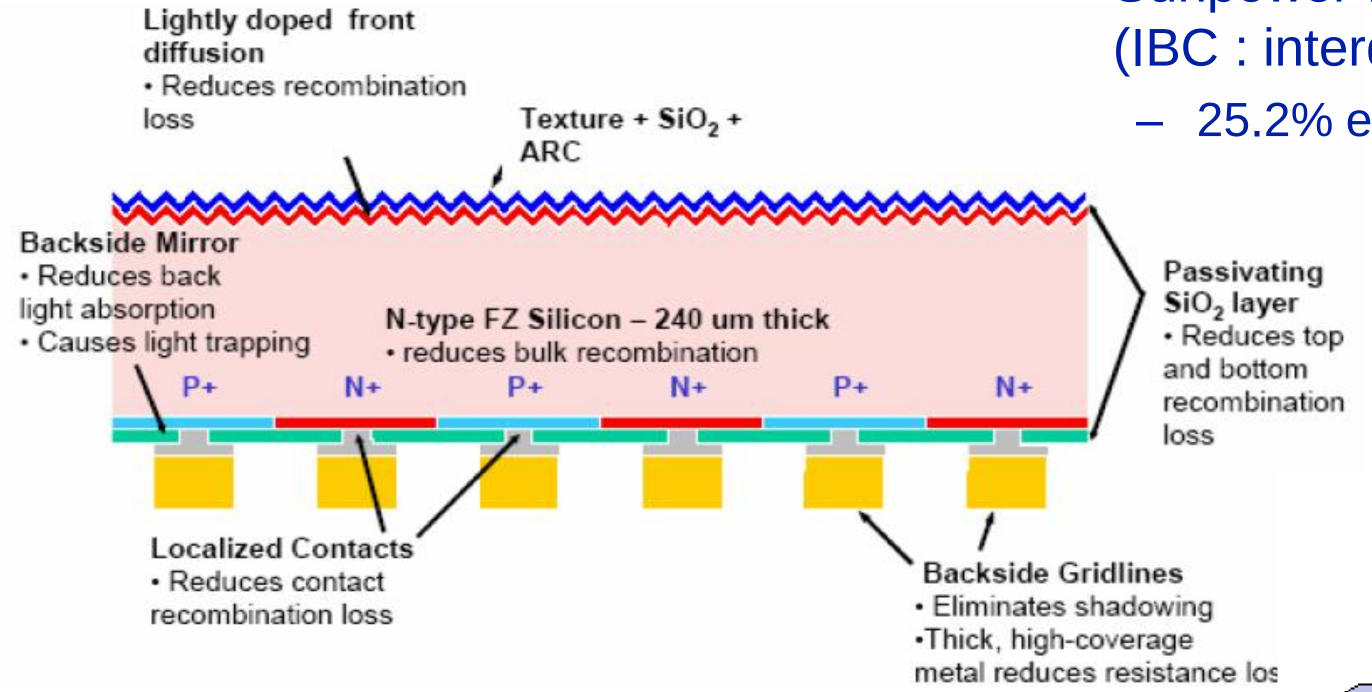
- **PERC cell** (passivated emitter and rear contact), new market standard



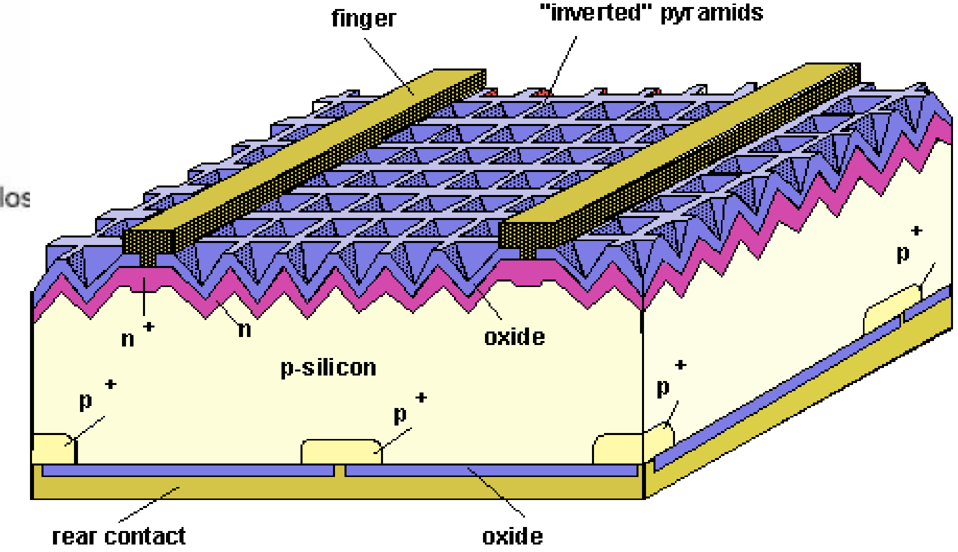
- Limitation of contact between Si and metal contact (less recombination)

High efficiency c-Si cells

- Sunpower back contact solar cells (IBC : interdigitated back contacted)
  - 25.2% efficiency



- UNSW PERL (passivated emitter with rear locally diffused) cell
  - 25.0% efficiency



Si heterojunction cell (HJT cell)

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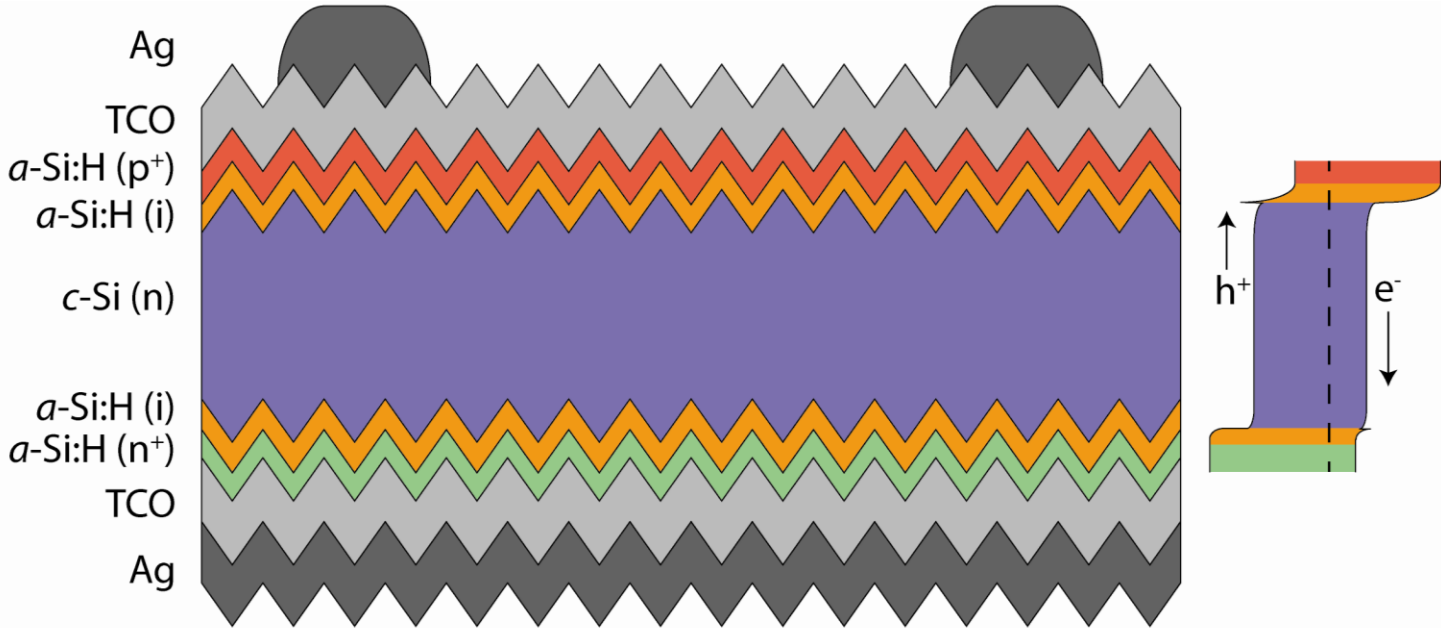
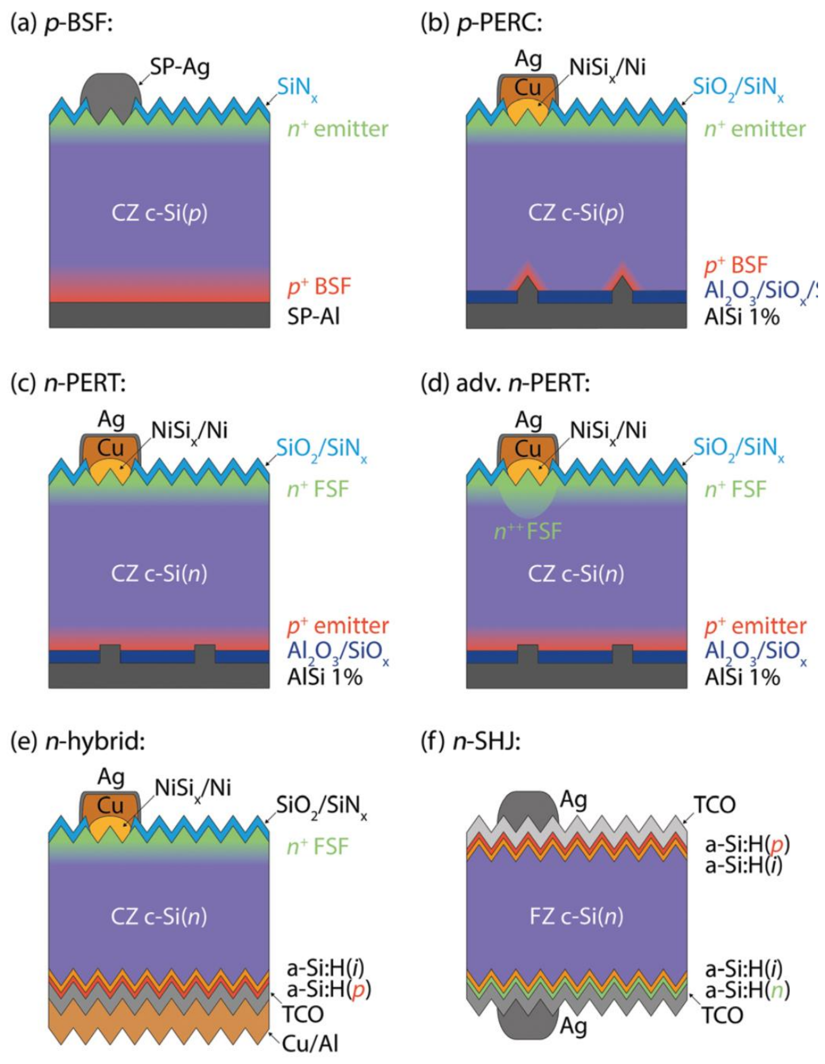
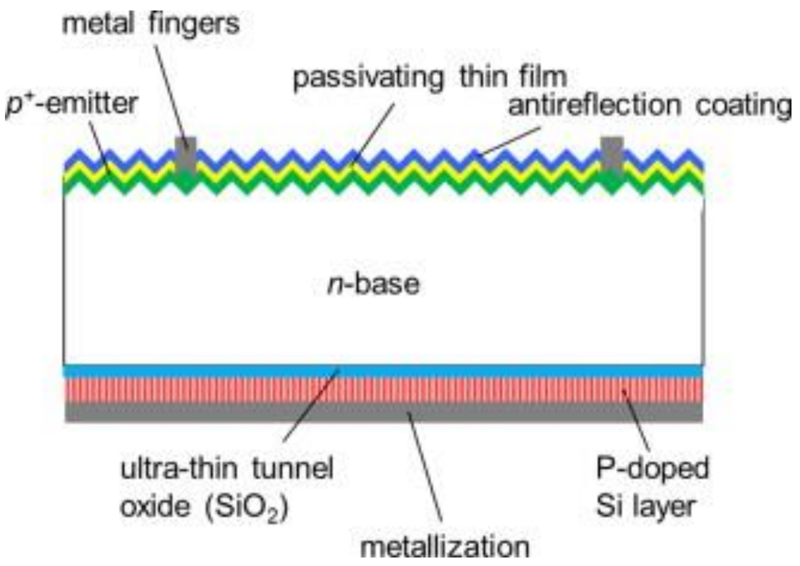


- HJT structure:
  - a-Si intrinsic layers (~ 5 nm) as super-passivation layers, as well as a-Si p+ emitter layer (~ 10 nm) on the front and a-Si n+ contact layer (~ 15 nm) on the rear.
  - ITO (TCO) transparent contact
- Best lab efficiency (Kaneka, IBC structure): 26.7%, V_{oc} > 700 mV
- Highest efficiency for c-Si cells !
- Thermal coefficient: 0.2-0.25%/°C for V_{oc}, 0.25-0.3%/°C for eff. (lower than that of c-Si !)

c-Si cell architectures



- PERC: Passivated Emitter Rear Cell
- PERT: Passivated Emitter Rear Totally Diffused
- SHJ: Silicon HeteroJunction
- Cells with passivating contacts



PV-lab
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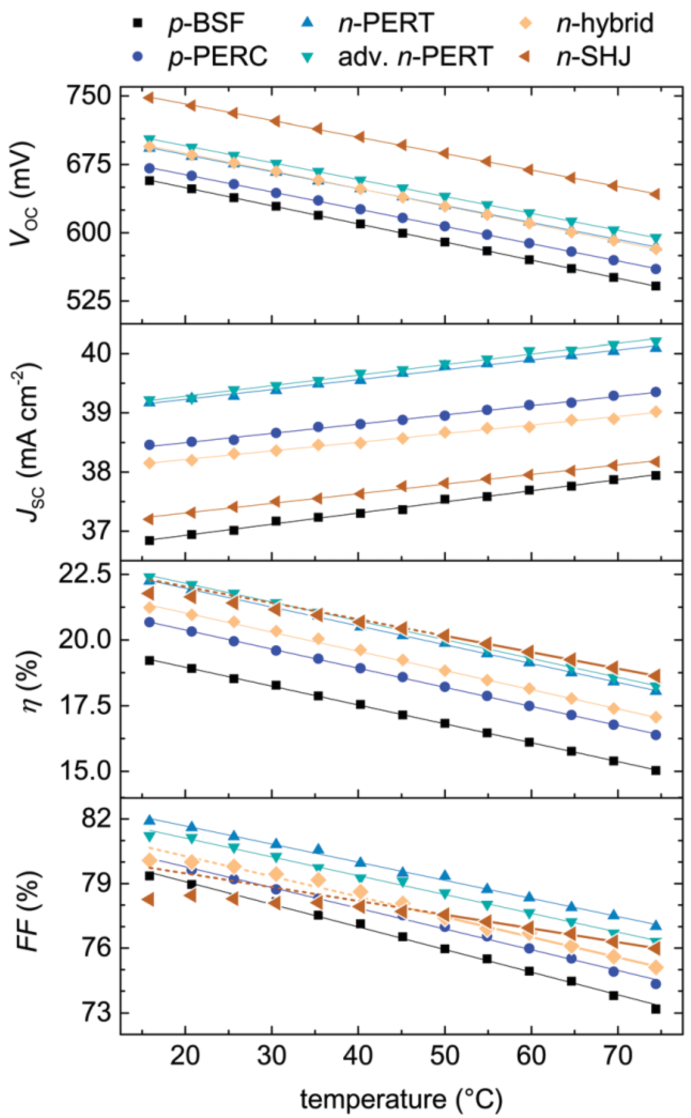
Temperature coefficients

Architecture	$TC_{V_{OC}}$ (%/K)	$TC_{J_{SC}}$ (%/K)	TC_{FF} (%/K)	$TC_{P_{MPP}}$ (%/K)
p-BSF	−0.31	0.05	−0.14	−0.39
p-PERC	−0.29	0.04	−0.12	−0.36
n-PERT	−0.28	0.04	−0.11	−0.33
adv. *n*-PERT	−0.27	0.04	−0.11	−0.33
n-hybrid	−0.28	0.04	−0.12*	−0.35*
n-SHJ	−0.25	0.04	−0.08*	−0.29*

Haschke et al., 10.1039/c7ee00286f

- Depends on technology
- Usual values of up to 0.5 %/°C for P_{max} for standard Si cells
- Lower values for thin-film technologies
- Large influence on energy production

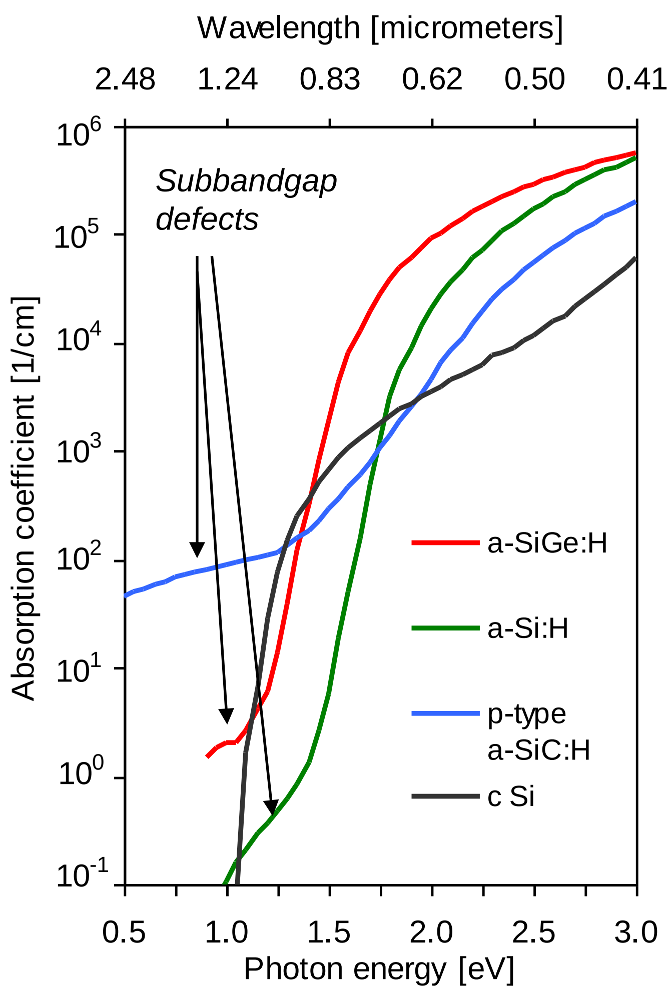


Thin-film technologies

PV with thin film Si

a-Si:H optical absorption

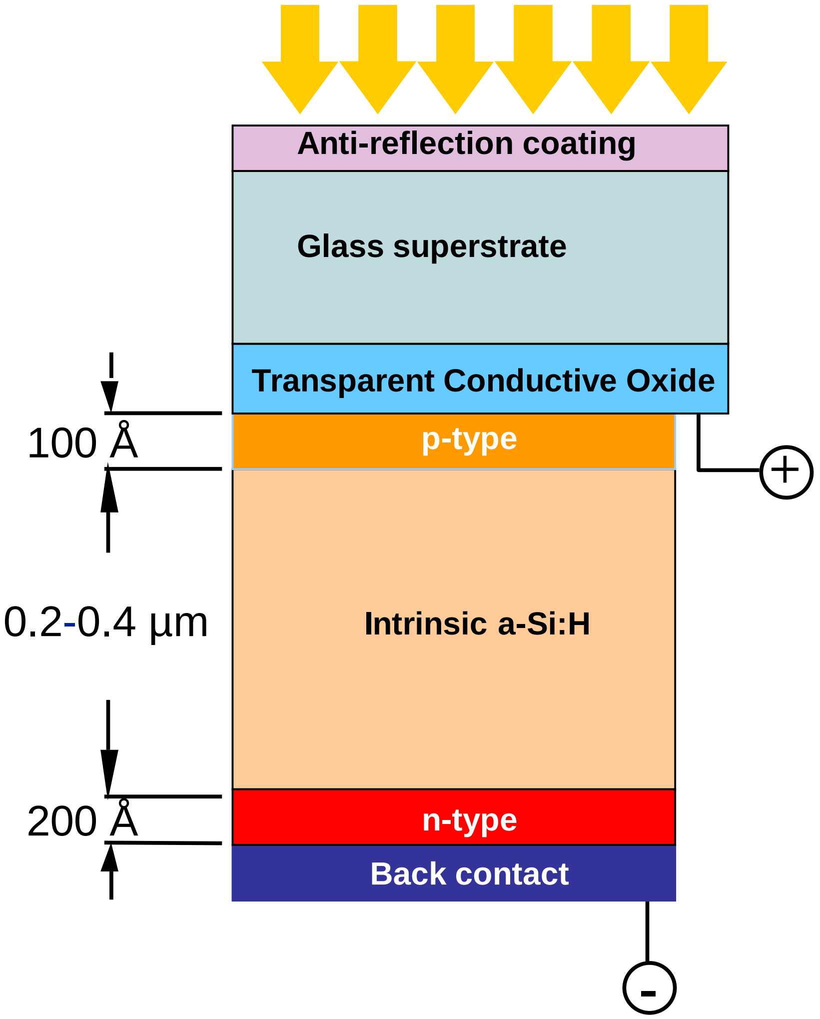
N. Wyrsch



- Amorphous (disordered) semiconductor
- Alloy with H for defect passivation
- Absorption coefficient
  - « non-direct semiconductor »
  - In visible part of spectrum 70 x higher than c-Si
  - Thin film (about 1 micron) absorbs 90% of usable solar energy
- Optical band gap
  - Tunable
  - Depends on H content
  - a-Si:H based materials alloys
    - C increases E_g
    - Ge decreases E_g
- Deposited at low temperature (≈200°C) by PE-CVD

p-i-n solar cell

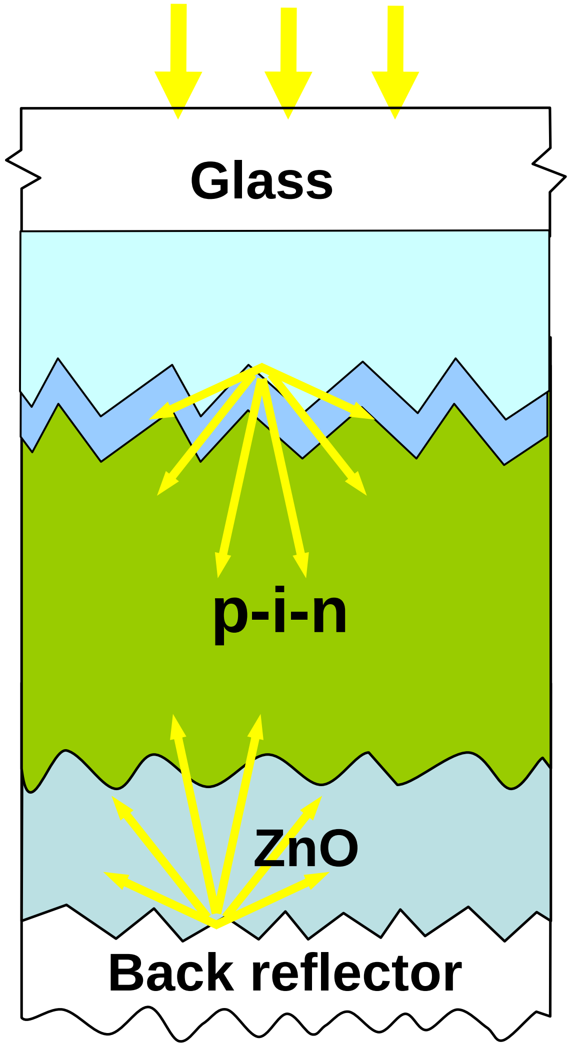
N. Wyrsch



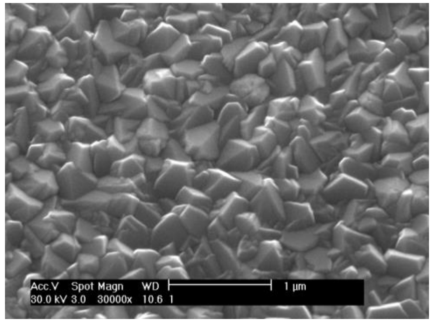
- **p-i-n structure necessary for disordered semiconductors**
  - Doped layer are very defective (dead layers)
  - → Doped layers only serve for electric field build-up through the intrinsic layer
  - The intrinsic layer is the only active layer.
- **Light enters the cell through the p-layer (“window layer”)**
  - Minimization of hole collection path (low hole mobility)
  - Higher bandgap for p-layer (low optical loss)
- **Electrically thin diode**
  - → High electrical field
  - → minimal recombination in i-layer
- **Optically thick diode**
  - → maximum absorption of light
  - → Minimal thickness (processing time)

→ **Light trapping scheme**

Light trapping for thin film silicon cells

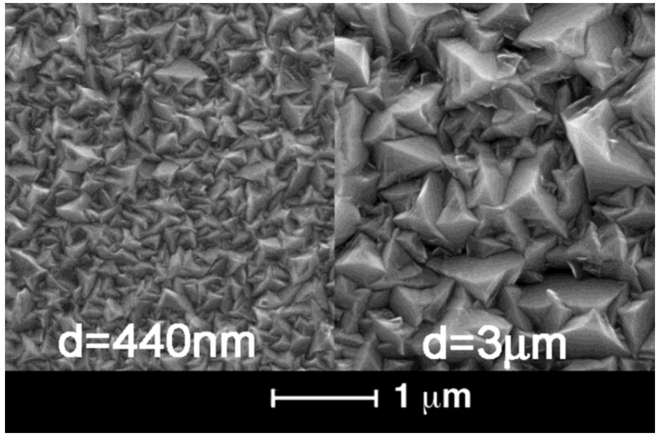


- Rough transparent conductive oxides (TCO)
- Back reflector



Tin Oxide (SnO_2) deposited by AP-CVD

Roughness depends on deposition process



Zinc Oxide (ZnO) deposited by LP-CVD

Roughness depends on film thickness and temperature

Multi-junction device for higher efficiency

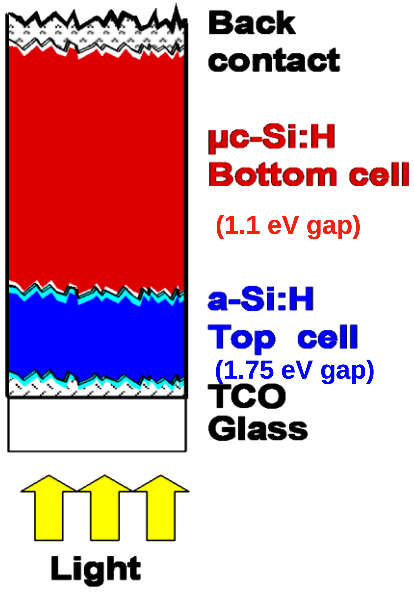
- Tandems
  - a-Si:H / a-SiGe:H
  - a-Si:H / µc-Si:H (mircomorph)
  - a-Si:H / a-Si:H
- Triples
  - a-SiC:H / a-Si:H / a-SiGe:H
  - a-Si:H / a-SiGe:H / a-SiGe:H
  - a-Si:H / µc-Si:H / µc-Si:H
  - a-Si:H / a-Si:H / µc-Si:H
  - a-Si:H / a-SiGe:H / µc-Si:H
  - a-Si:H / µc-Si:H / µc-Ge:H

- Issues
  - a-SiGe:H stability
  - µc-Si:H processing

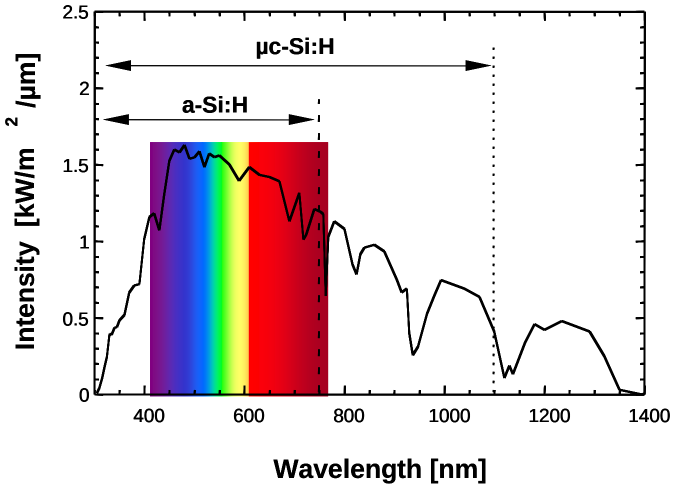
  - a-SiC:H & a-SiGe:H stability
  - a-SiGe:H stability
  - Current matching (thick bottom)
  - Current matching, very thin top
  - a-SiGe:H stability
  - µc-Ge:H processing

(commercially available devices in red, but disappearing for the power market)

Examples



- Micromorph Tandem devices comprising
- Introduced by IMT (EPFL)
- Advantages:
  - Better usage of solar spectrum
  - Higher efficiency and stability



- UniSolar monolithic triple junction, flexible modules on steel:
  - -stable cell efficiency: 13.1%
  - -module efficiency ~8%

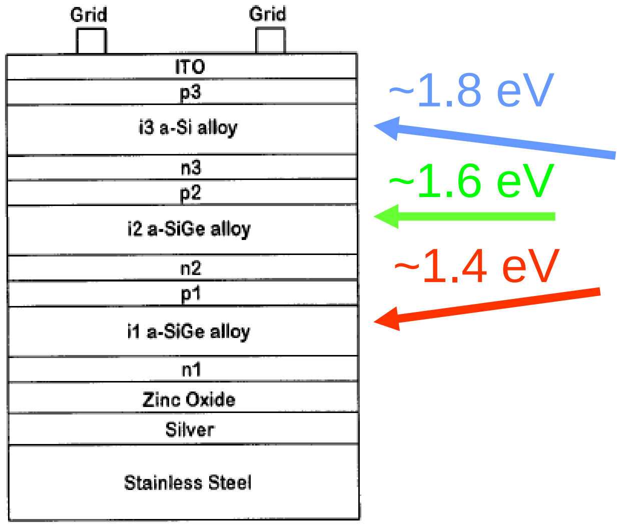


FIG. 1. Schematic diagram of a triple-junction cell structure.

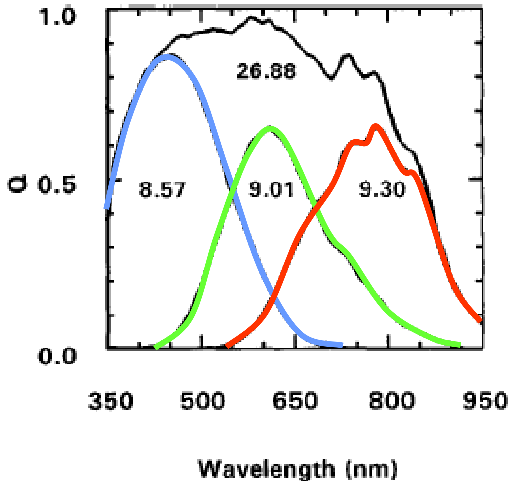
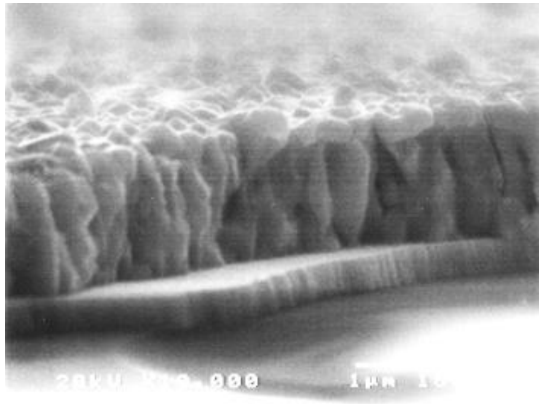
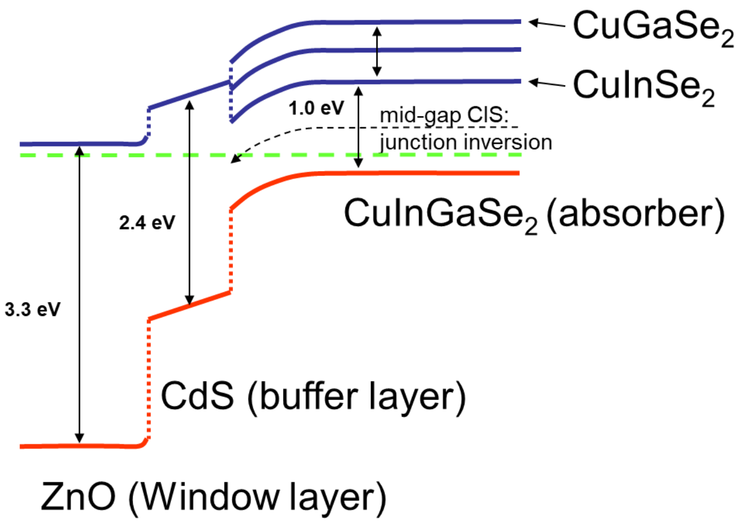


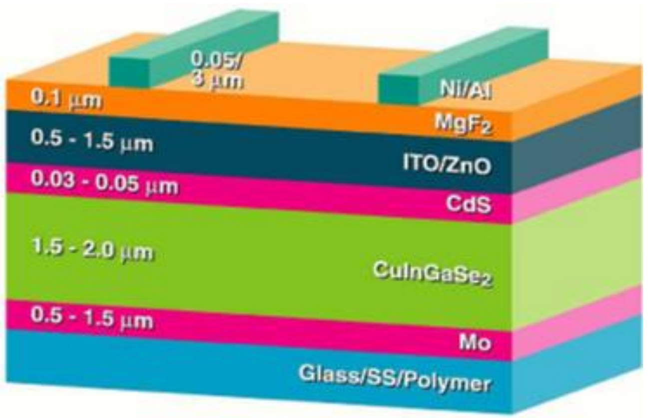
FIG. 3. Initial quantum efficiency of the improved triple cell.

Cu(In,Ga)Se_2 solar cells

- Heterojunction between p-type Cu(InGa)Se_2 and n-type CdS
- Bandgap of CuInSe: 1.0 eV, 1.15 eV for Cu(InGa)Se_2
- Best lab efficiency : 22.9% (Solar Frontier), 20.4% (EMPA on flexible substrate)
- Deposition on flexible substrates (Mo foil, PI, SS)
- Monolithic interconnection of cells in modules
- Relatively high cost (up-scaling, In)

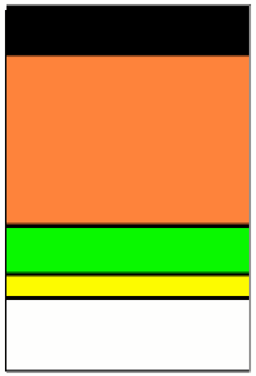


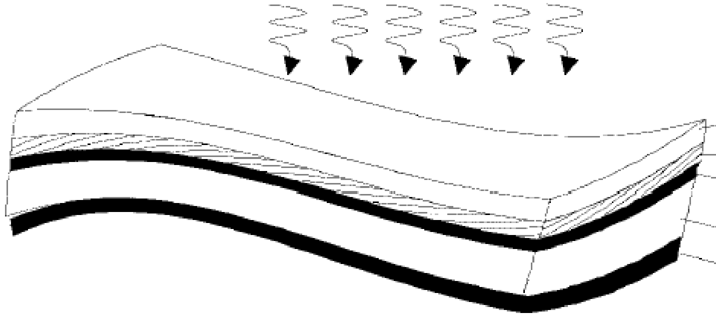




CdTe

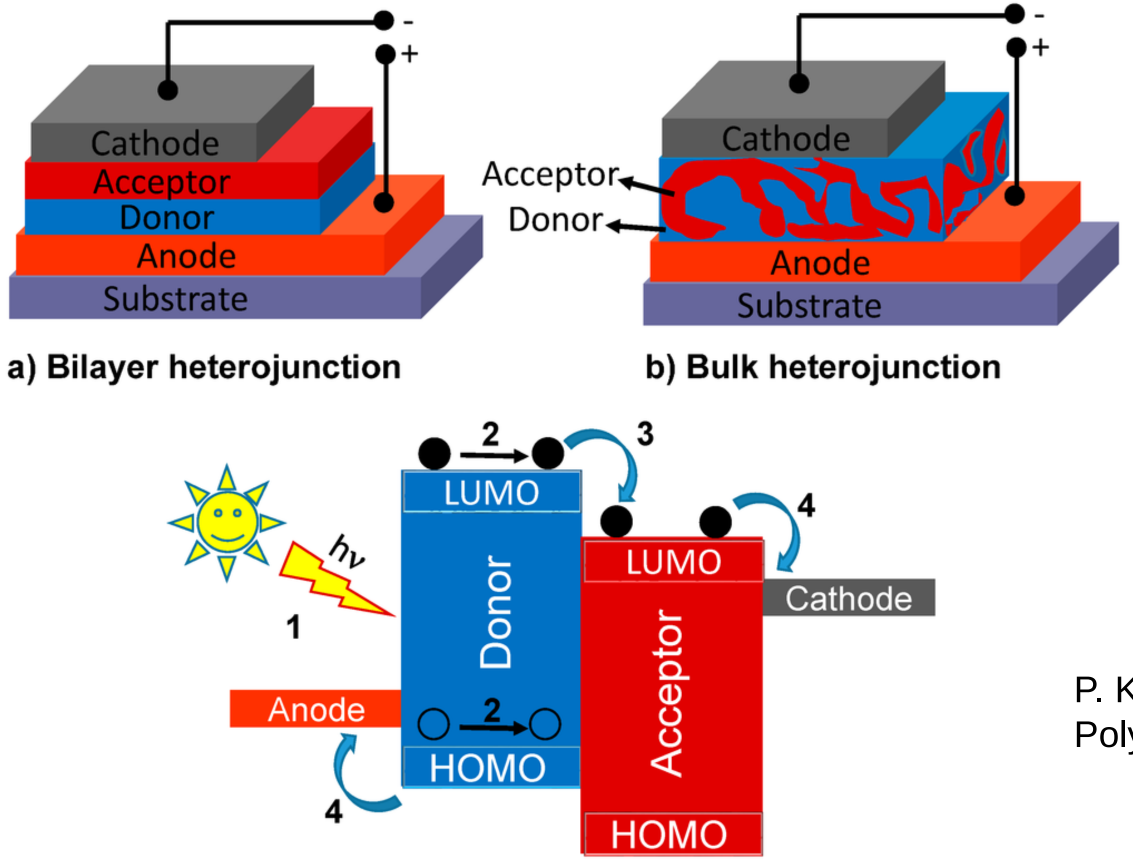
- Heterojunction between p-type CdTe and n-type CdS
- Bandgap of CdTe : 1.45 eV
- Best lab efficiency = 22.1% (First Solar)
- Deposition on flexible substrates possible (spin coated polyimide), lower efficiency (best efficiency 13.8% by EMPA)
- Monolithic interconnection of cells in modules
- Very high radiation hardness (see also next lecture)
- Large production, competitive costs
- Cd issue (CdTe is inert and non toxic)





Emerging technologies

Organic photodiode structure

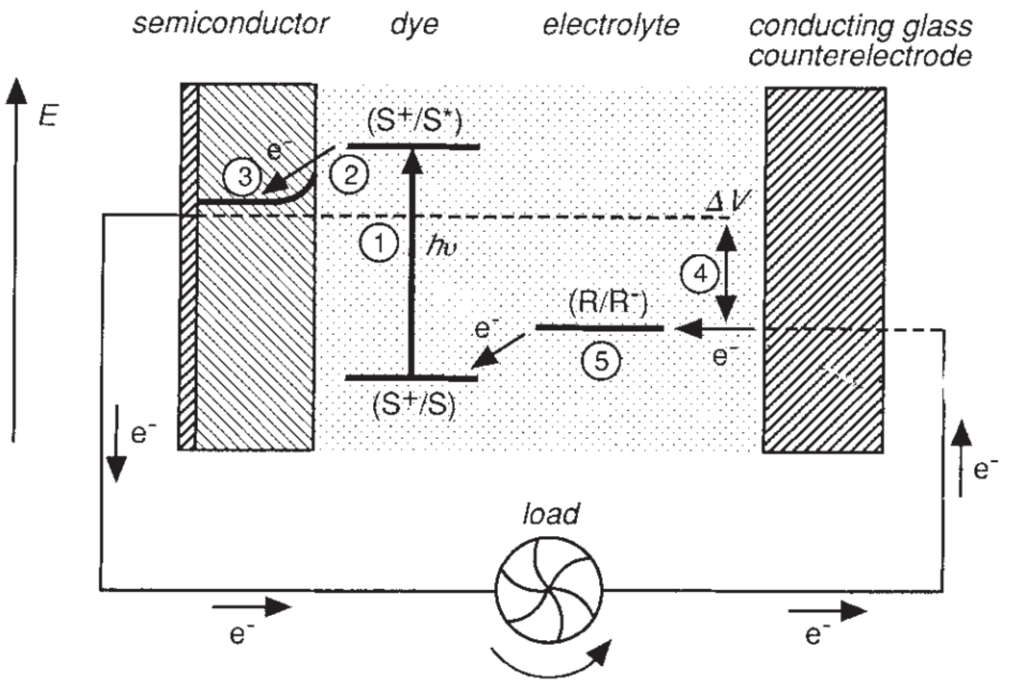


c) Device working principle

P. Kumaresan et al.,
Polymers 6 (2014)

- Best lab efficiency = 12% in tandem 13.2% triple junction (Heliatek)

Dye sensitized solar cells (Grätzel cell)

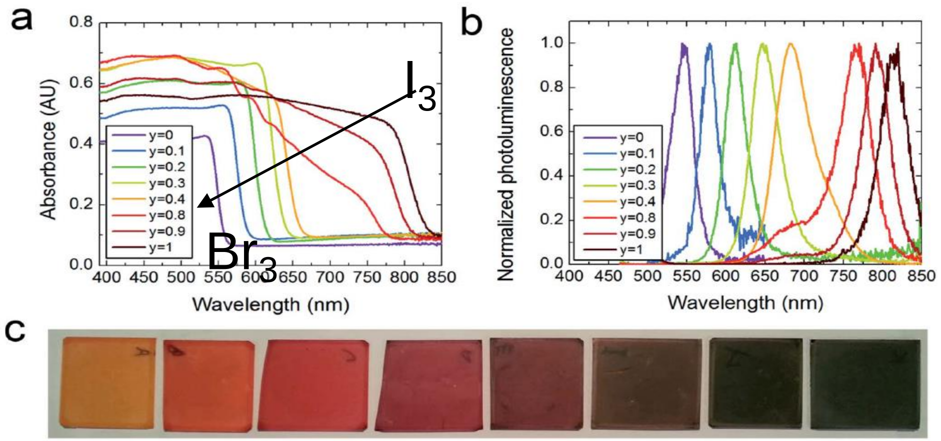


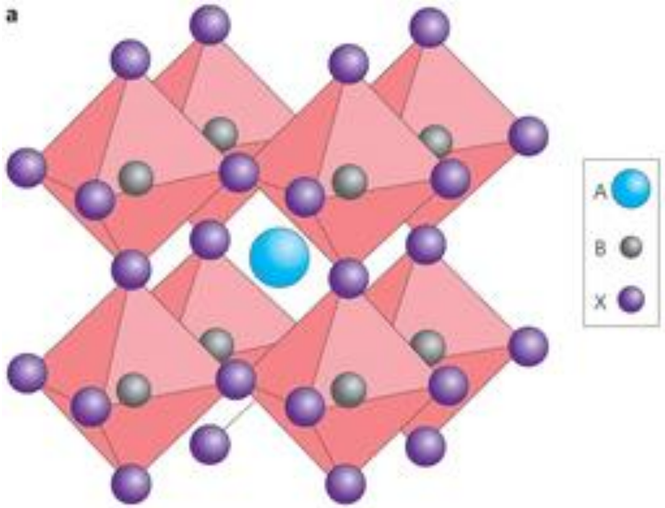
O'Regan, Nature (1991)

- Photochemical excitation
- Invented by Prof. Grätzel (EPFL)
- Absorption in dye molecules, rapid electron transfer to TiO_2 electron collector and replenishment from electrolyte (similar to photosynthesis)
- monolayer absorption $\rightarrow$ adsortion on scaffold of (meso-) porous TiO_2

Perovskites

- Cristallographic form named from Russian mineralogist L. A. Perovski, with cubic cell
- General form *ABX*$_3$, *A,B* : cations, *X* : anion, *A* bigger than *B*
- Crystallographic structure of various common oxides ($CaTiO_3$, $SrTiO_3$, $BaTiO_3$, $PbZrO_3$,…)



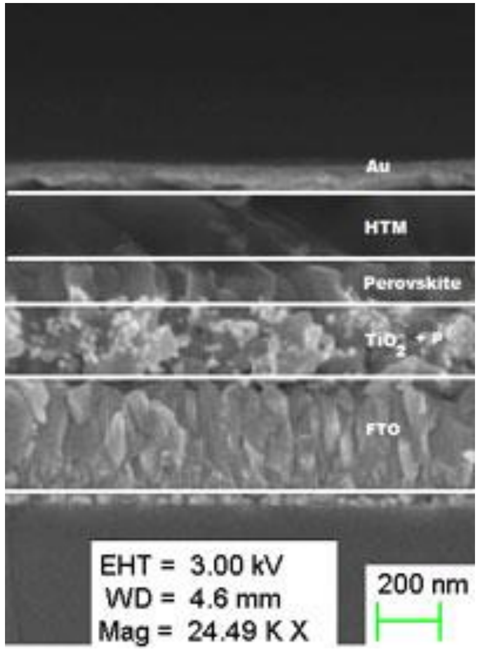


M. Green at al. Nature Photonics (2014)

- Optical band gap tunable from NIR to VIS

Perovskites

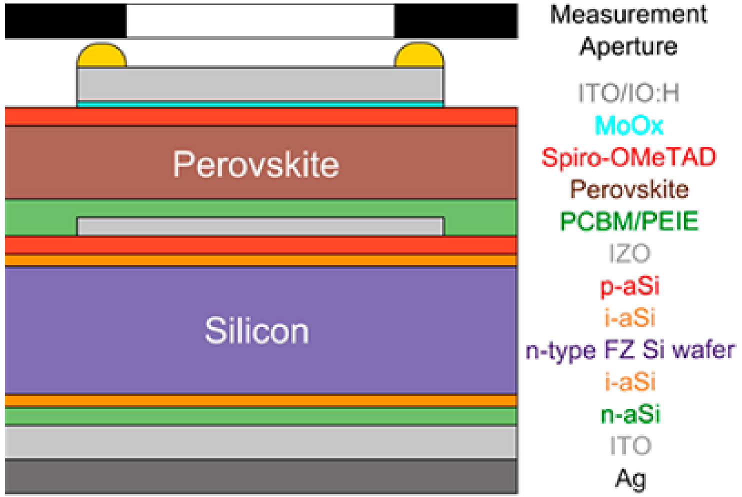
- High interest fo solar cells (lab developments), pioneered by M. Greatzel (EPFL) using lead iodide perovskite ($CH_3NH_3PbI_3$)
  - Structure: Au / P3HT / $CH_3NH_3PbI_3$ / TiO_2 / ITO / Glass
- Best materials:
  - $CH_3NH_3PbI_3$, Methylammonium Lead Iodide ($MAPbI_3$ or MALI),
  - $H_2NCHNH_2PbI_3$, Formamidinium Lead Iodide ($FAPbI_c$ or FALI),
- Best efficiency: 25.5% (UNIST/EPFL)
- Addition of Cl or Cs in perovskite increase stability
- Issues : stability, usage of Pb, hole conducting layer, metal contacts
- Lead free perovkites solar cells with much lower efficiency
- Large interest for c-Si / PK tandems (best efficiency: 28%, Oxford PV)

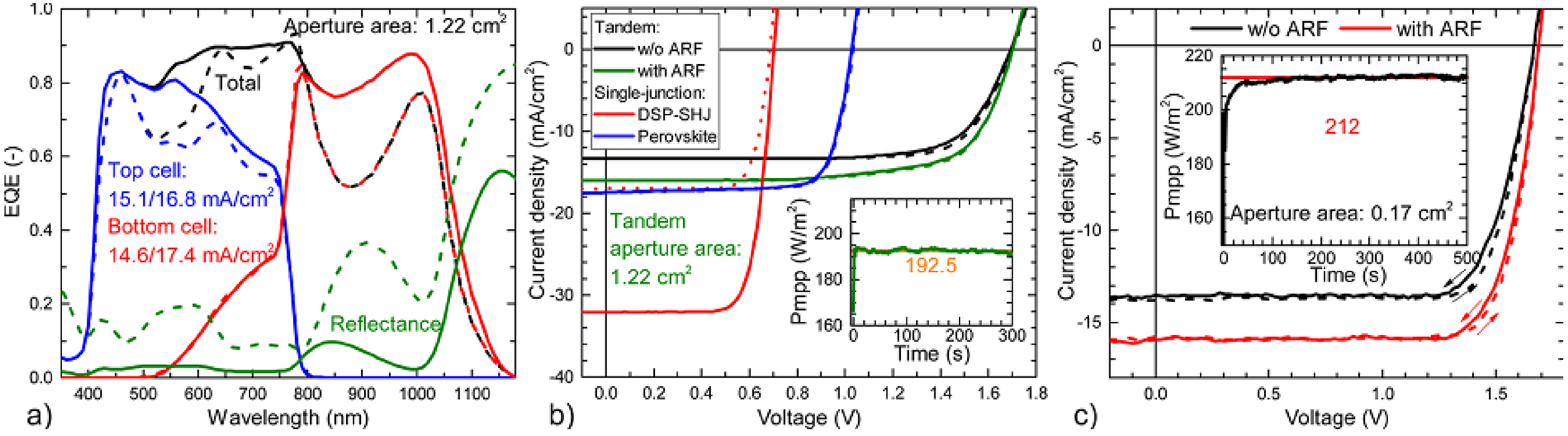


Perovskite/Silicon monolithic tandem

N. Wyrsch

- partner to Si (ideally 1.5 eV < E_g < 2 eV)
- high-efficiency, low-cost
- feasible integration
  (no epitaxial or thermal constraints)
- needs: fully transparent contacts
  flat Si-cell (for spin coating)



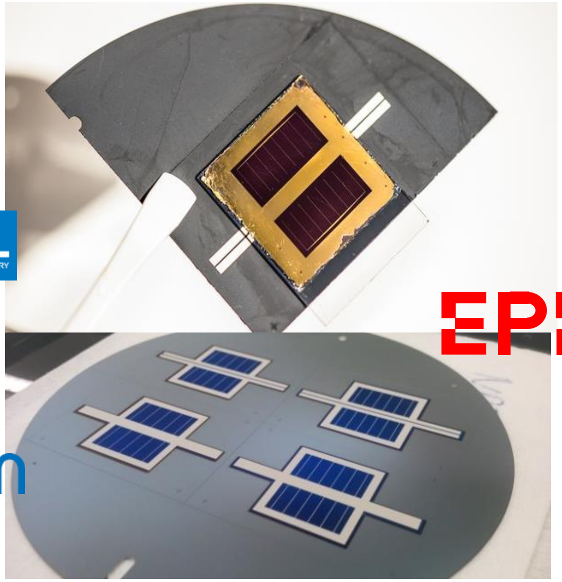


Werner, J. Phys.Chem. Lett. (2016)
(also: Albrecht, EES (2016)

Tandem devices (on Si)

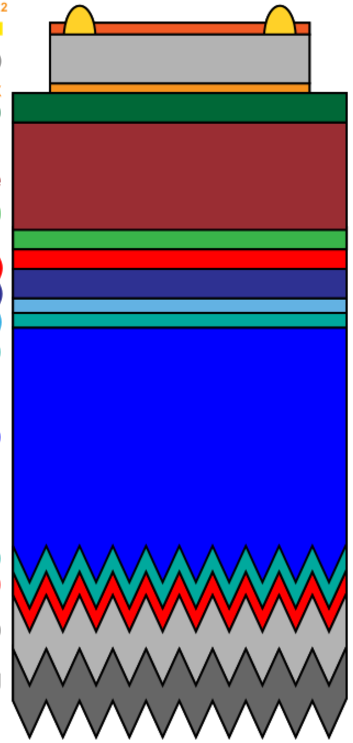
4-terminal tandem 4
Thin AsGa/HJT (c-Si)

> 32.8 % World record



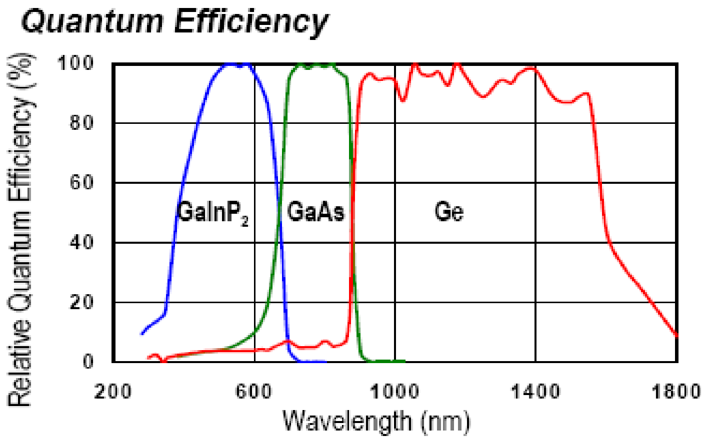
«Perovskites» on HJT (c-Si)

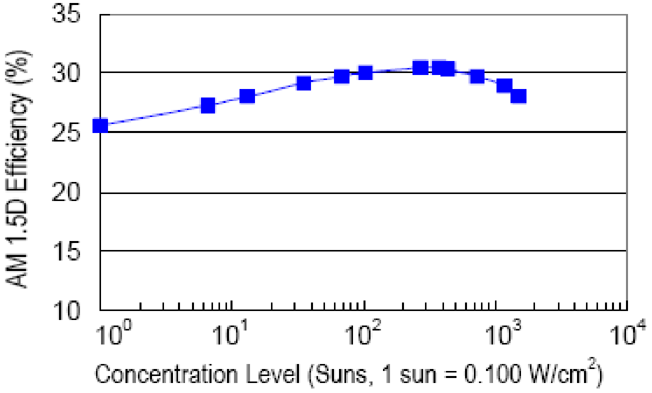
Potential for ≥30%
Record: 29.5% (Oxford PV)

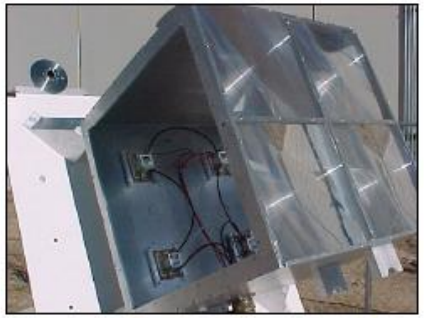


Space cells, cell for concentrated PV

Semiconducteurs III-V (AsGa, GaInP,…)







On-Sun testing at EMCORE Photovoltaics at 520 Suns

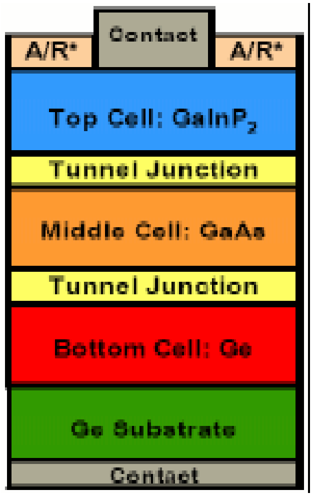
Triple junction, monolithic:

- Efficiency (AM1.5) : 37.9% (Sharp)
- Concentrated PV: 44.4% at 302 suns (Sharp),

Monolithic >3 junctions:

- Efficiency (AM1.5) : 38.8% (5 j, Spectrolab)
- Efficiency(AM1.5) : 39.2% (6 j, NREL)
- Concentrated PV : 47.1% (6 j, Soitec)

www.spectrolab.com
www.emcore.com
www.rwe.com
www.sj-solar.com

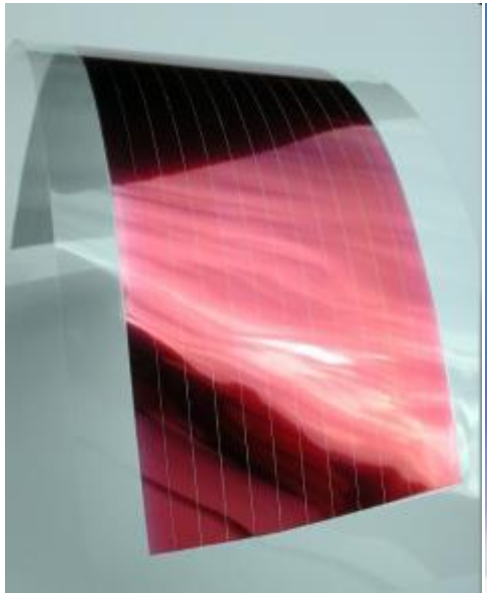


Advantages / disadvantages

Technology	Availability of materials	Material usage	Toxicity of materials	Efficiency	Cost
Crystalline Silicon, monocrystalline	++	-	++	++	--
Crystalline Silicon, multicrystalline	++	-	++	+(+)	-
Crystalline Silicon, ribbon	++	-	++	+	-
Thin film Silicon (amorphe, nano-crystalline)	++	+	++	-	+
GaAs	-	-	-	++	--
CIS / CIGS	--	+	-	+	- (indium!)
CdTe	--	+	--	+	+
Crystalline Silicon, thin film	++	+	++	+	?
Dye sensitized	-	+	?	-- (stability?)	++?
Organic	++	+	+	--	++?
Perovskites	+	+	-	+ (stability?)	+?

PV power market

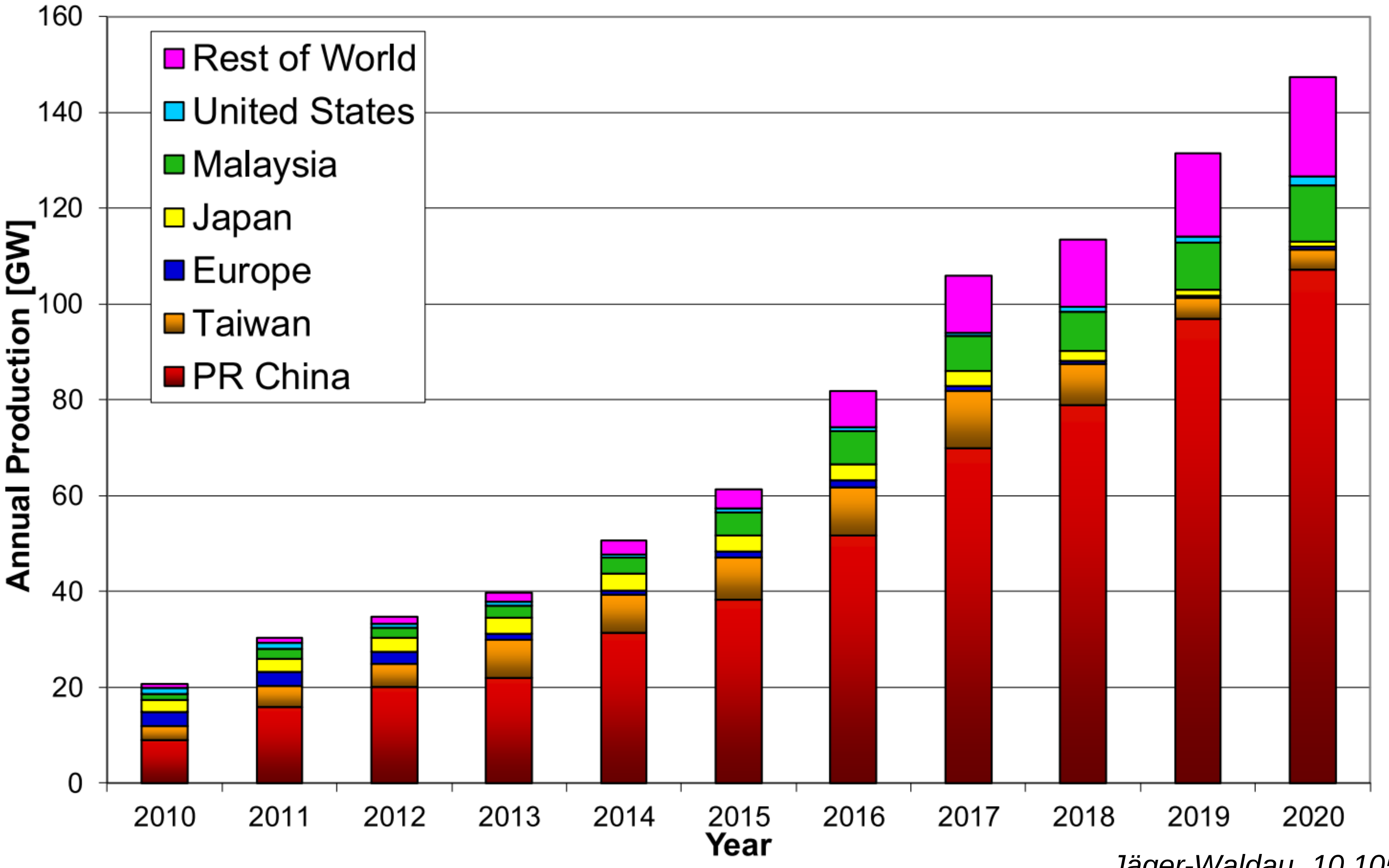
Mature (commercial) technologies

	Organic	Thin film	Crystalline Si	Concentration space cells
	Dye sensited Organic	**a-Si a-Si/µc-Si CdTe CIGS**	**Poly c-Si Mono c-Si**	**III-V based**
Efficiency modules	2-6%	5-16%	15-22%	20-30%
Potential	10%	18%	25%	30-40%

Efficiency →

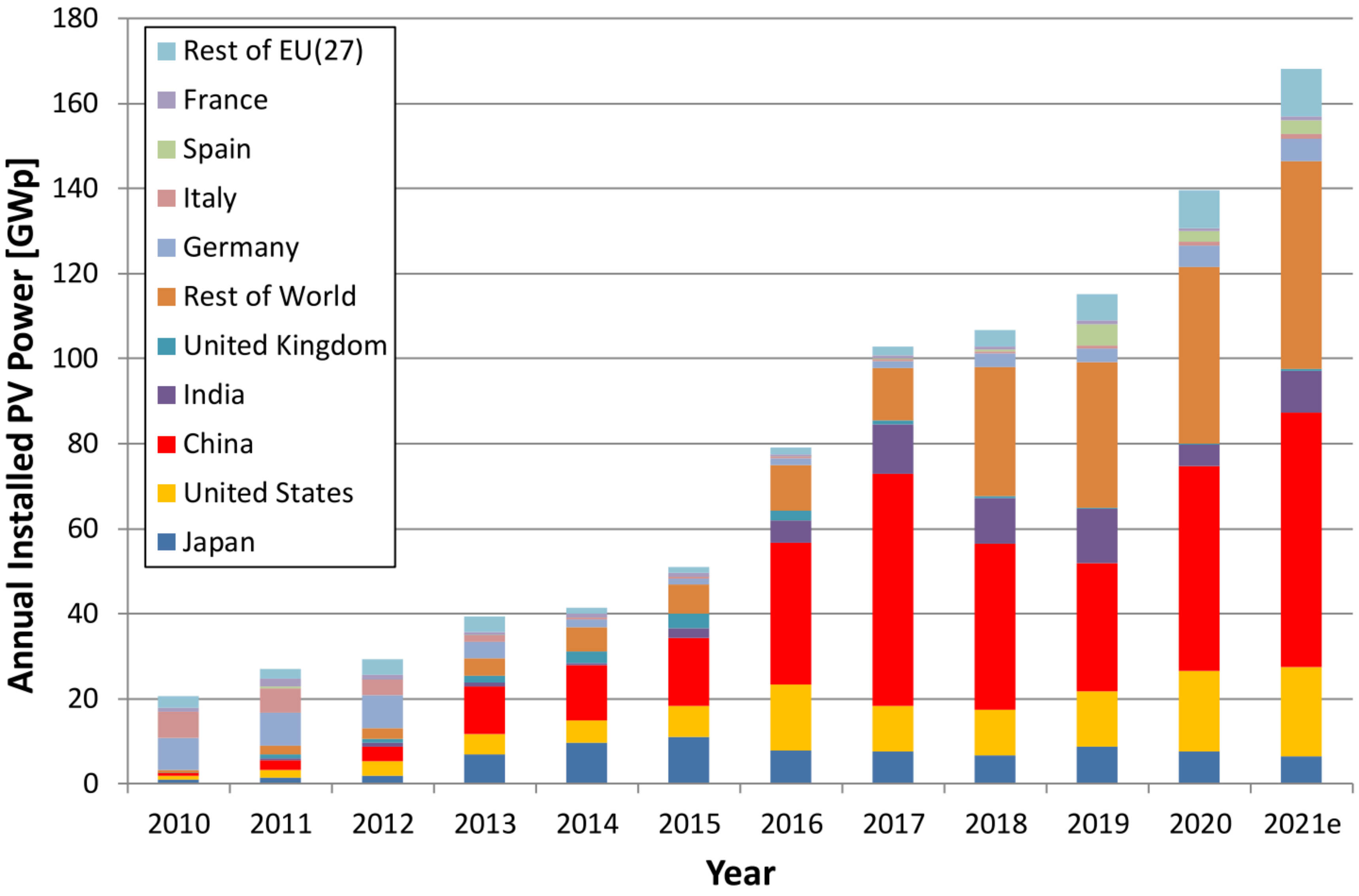
Yearly PV production



Jäger-Waldau, 10.1051/epjpv/2021002

1 GW : Peak power of a nuclear power plant !

Yearly PV installations

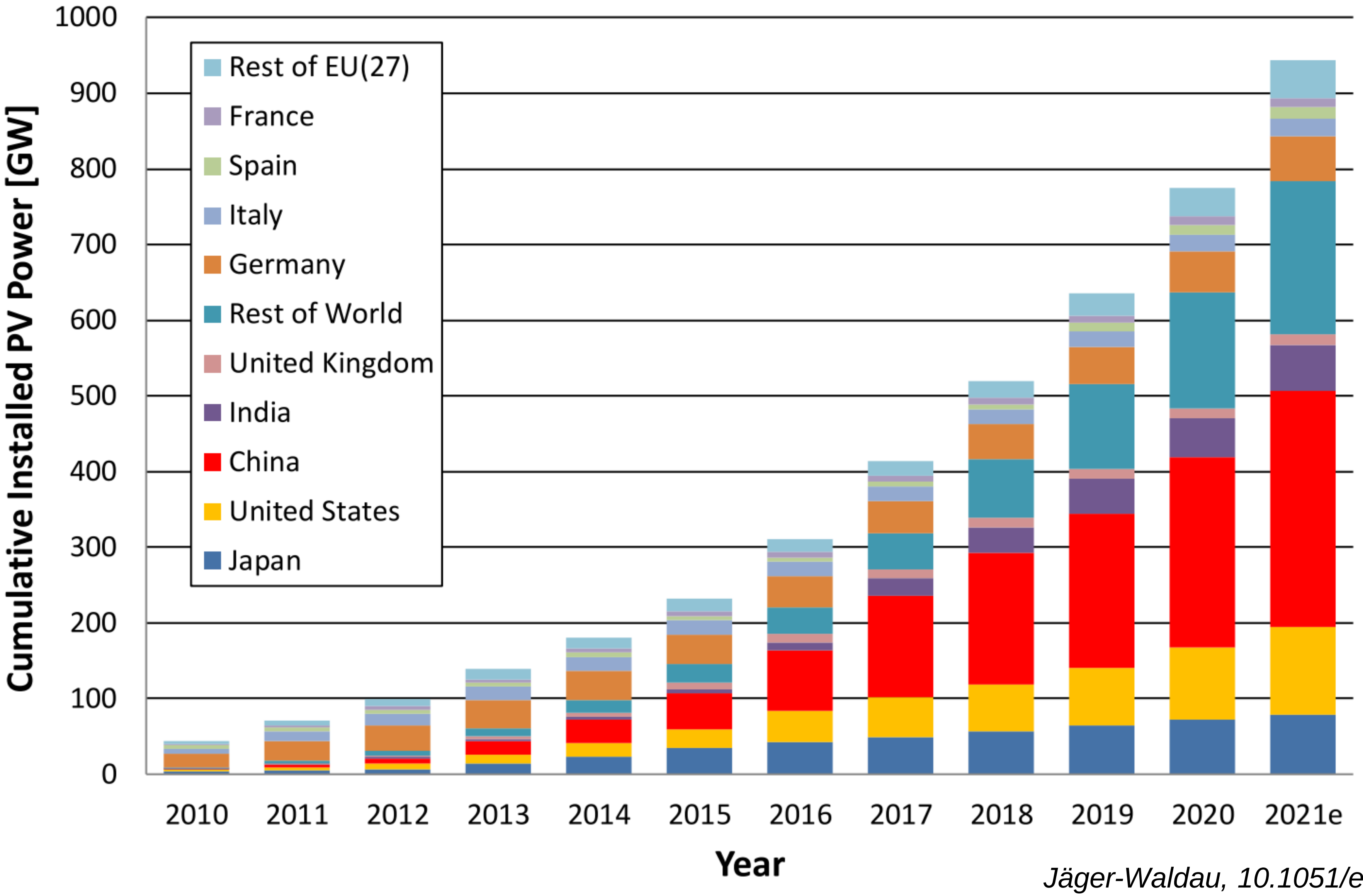


Jäger-Waldau, 10.1051/epjpv/2021002

- ≈ 40% of market in China!

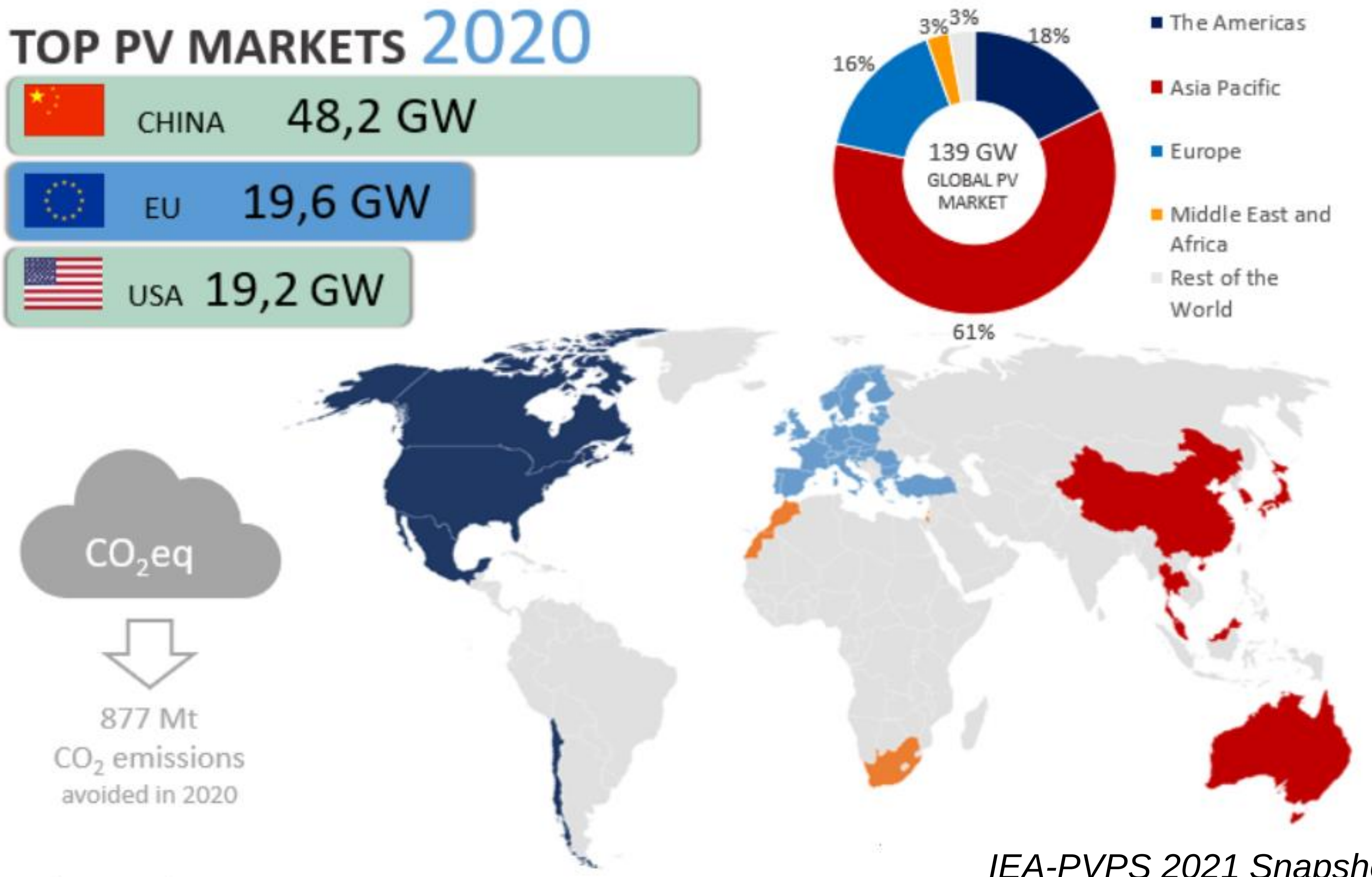
Cumulated PV installation

N. Wyrsch



Jäger-Waldau, 10.1051/epjpv/2021002

Biggest markets (2020)



IEA-PVPS 2021 Snapshot

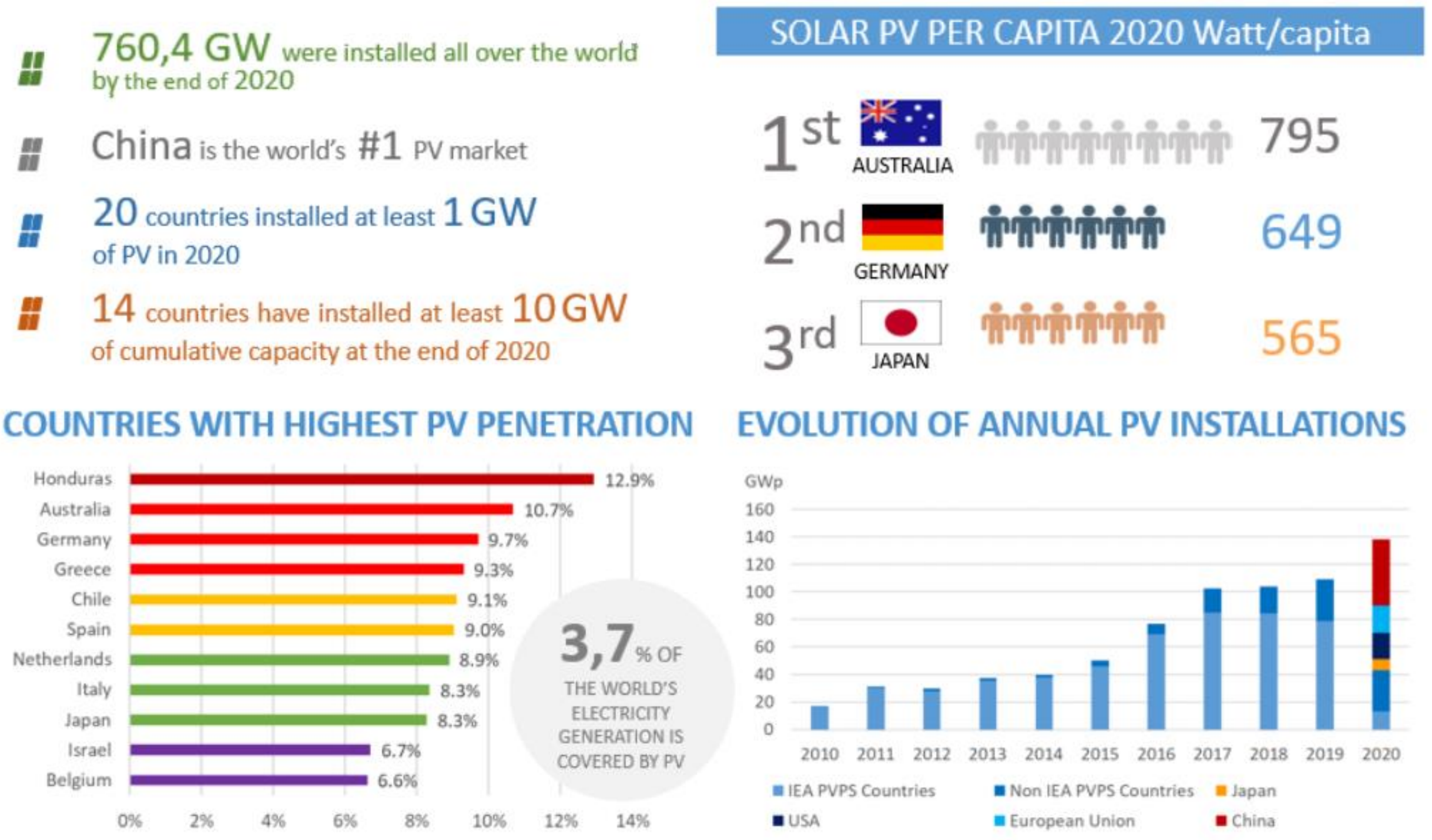
Biggest markets (2020)

TABLE 1: TOP 10 COUNTRIES FOR INSTALLATIONS AND TOTAL INSTALLED CAPACITY IN 2020

FOR ANNUAL INSTALLED CAPACITY			FOR CUMULATIVE CAPACITY		
1	China	48,2 GW	1	China	253,4 GW
(2)	*European Union*	19,6 GW	(2)	*European Union*	*151,3 GW*
2	United States	19,2 GW	2	United States	93,2 GW
3	Vietnam	11,1 GW	3	Japan	71,4 GW
4	Japan	8,2 GW	4	Germany	53,9 GW
5	Germany	4,9 GW	5	India	47,4 GW
6	India	4,4 GW	6	Italy	21,7 GW
7	Australia	4,1 GW	7	Australia	20,2 GW
8	Korea	4,1 GW	8	Vietnam	16,4 GW
9	Brazil	3,1 GW	9	Korea	15,9 GW
10	Netherlands	3 GW	10	UK	13,5 GW

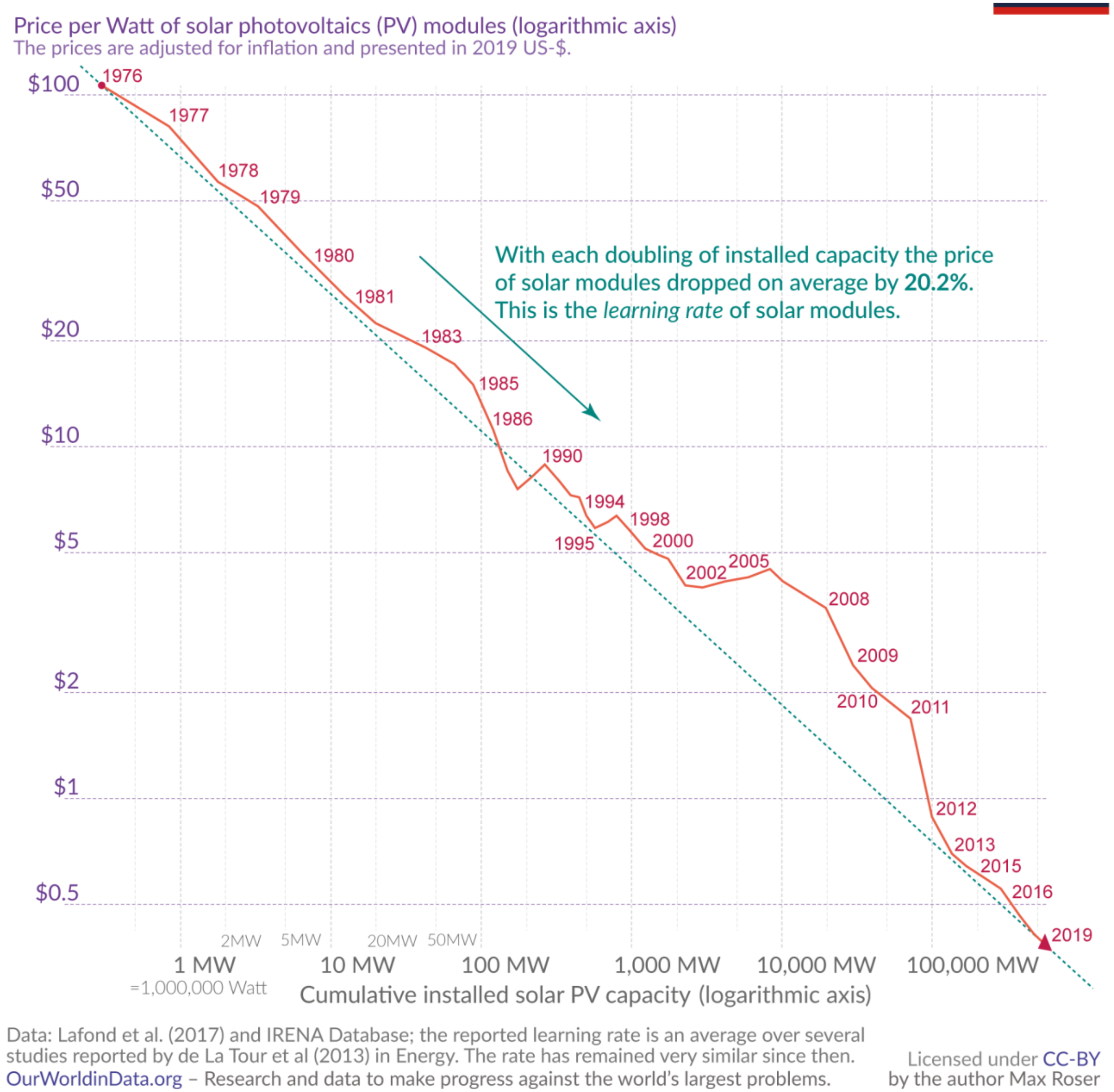
IEA-PVPS 2021 Snapshot

PV share in the electricity mix (2020)



IEA-PVPS 2021 Snapshot

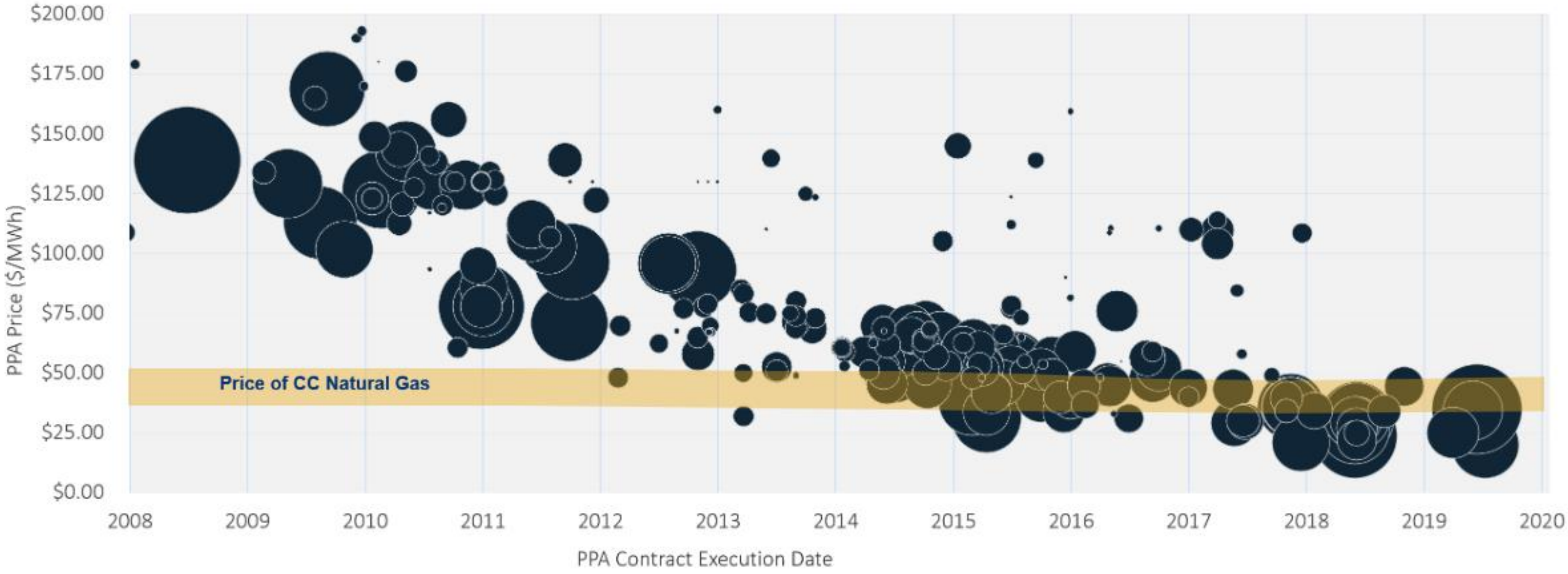
Experience / learning curves



- >20% decrease in price when cumulated PV production is doubled
- Balance of system (BOS) costs play an increasing role !

PV Energy Costs

N. Wyrsch



Source: Wood Mackenzie Power and Renewables

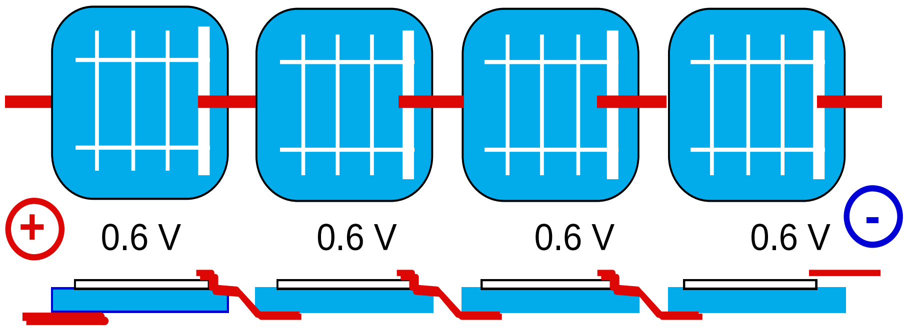
https://www.holocene-energy.com/solar-ppas-pricing/

- PV electricity already offered in sunny countries at <0.02 $/kWh !
  (PPA – power purchase agreements, bids for long term energy purchase)
- PV is the cheapest way of producing electricity !!

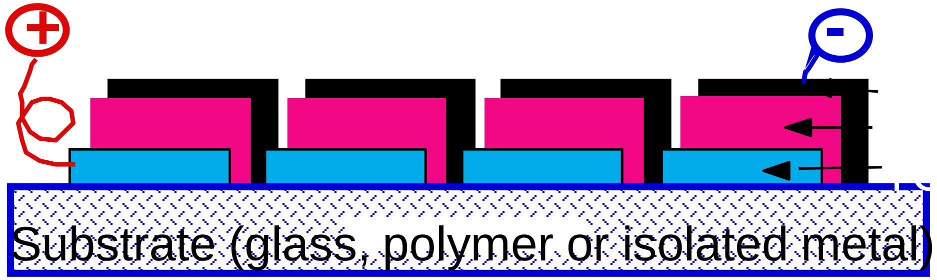
PV modules

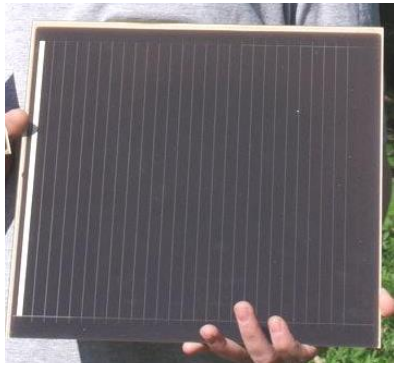
Module serial connection

Bulk technologies



Thin-film technologies





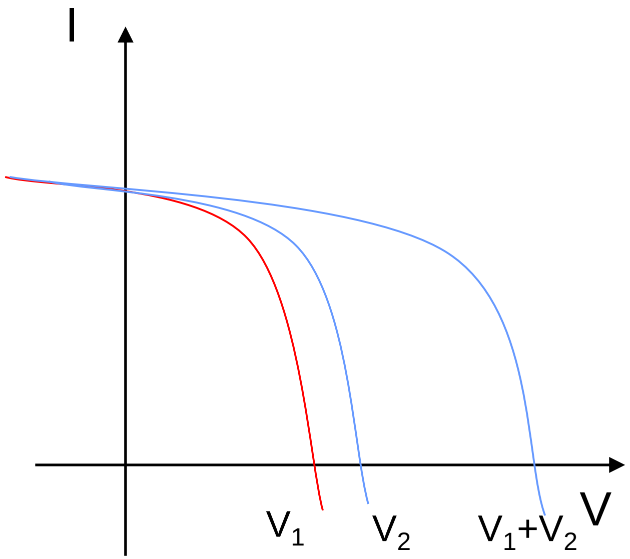
Monolithic interconnection for thin-film cells

- Module output voltage given by the sum of cell voltages
- Module output current given by the minimum cell current (see tandem devices)

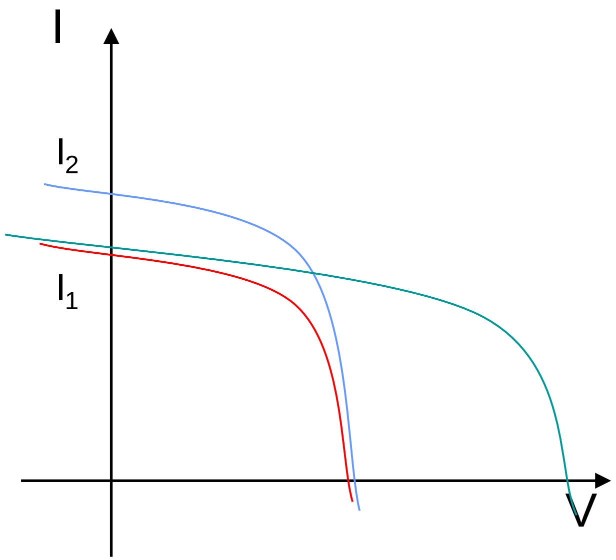
PV-lab IMT NEUCHATEL

Missmatch

- Voltage mismatch



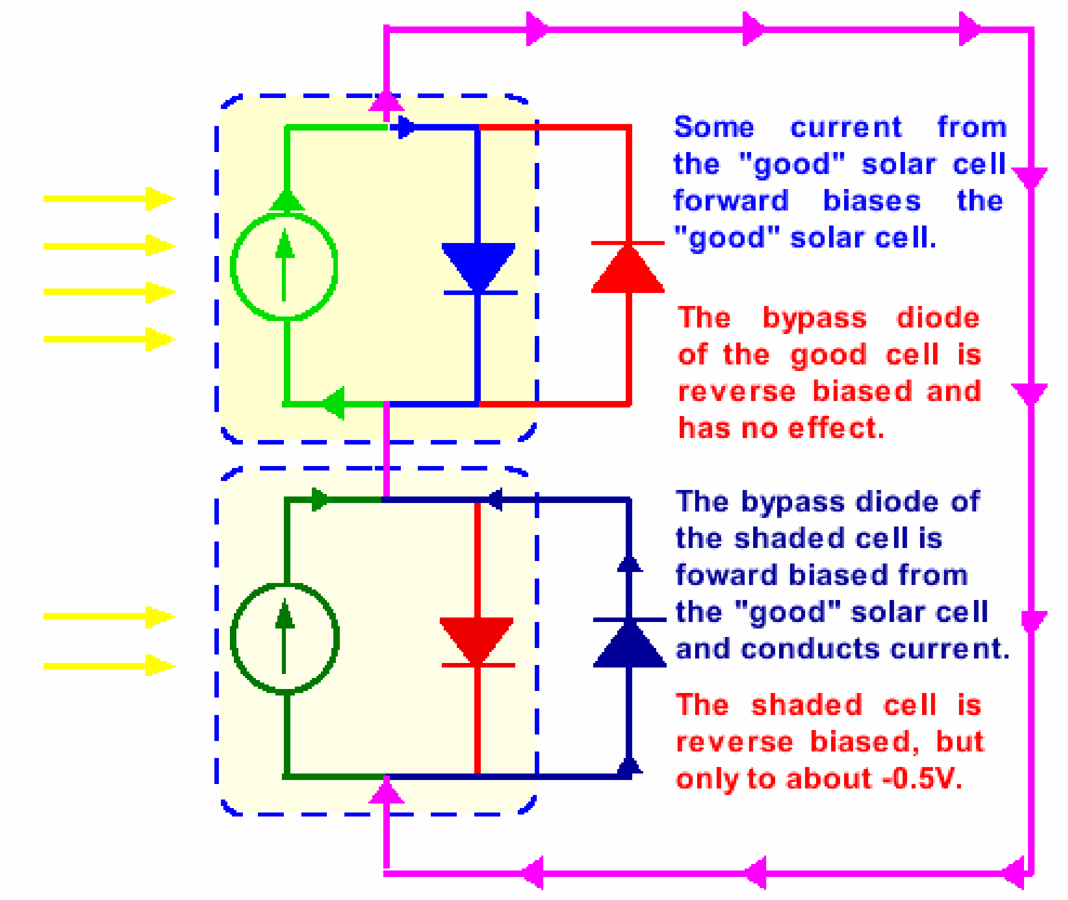
- Current mismatch

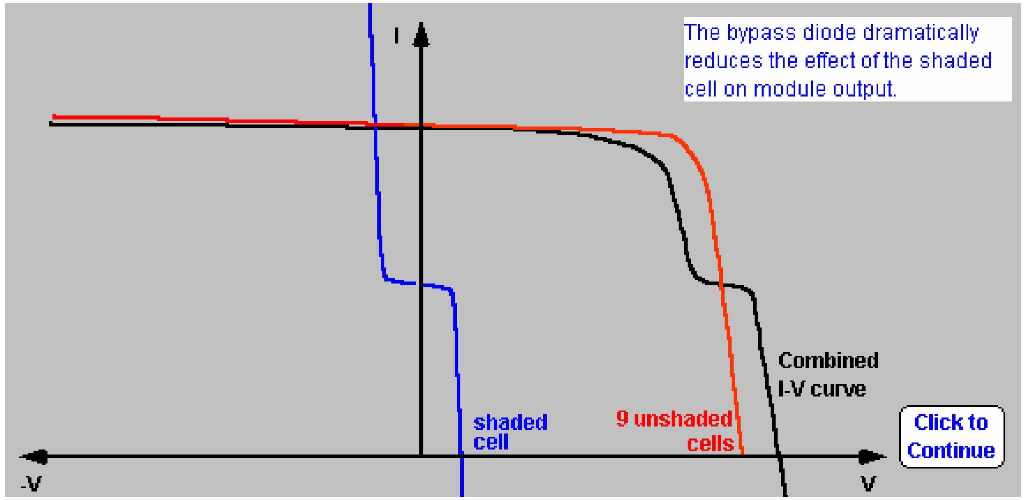


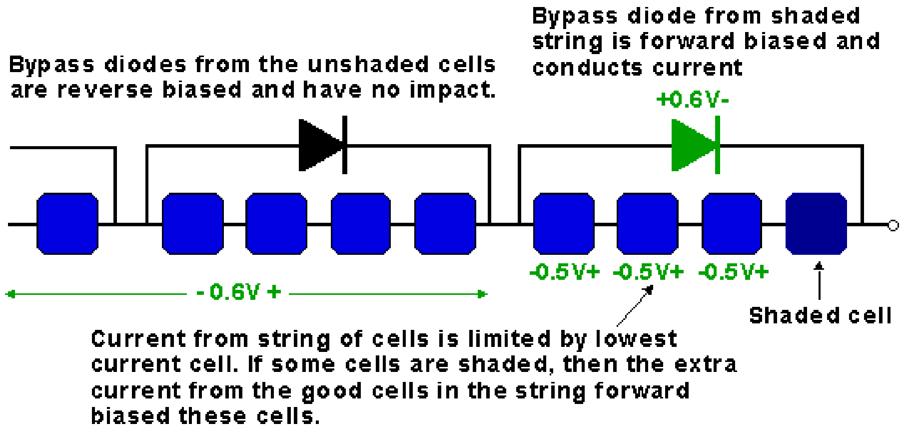
  - Non-illuminated cell possibly in reverse polarization
    - → Power dissipation
    - → Hotspot
  - Bypass diode to avoid breakdown

Bypass diode

N. Wyrsch



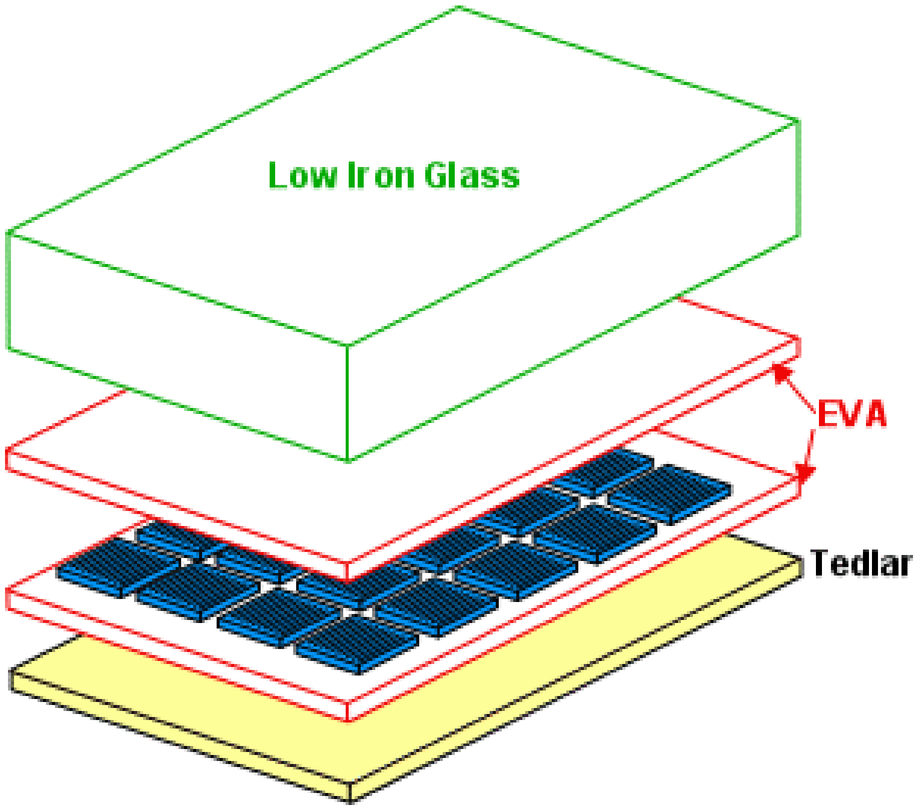




Photovoltaics CD-ROM

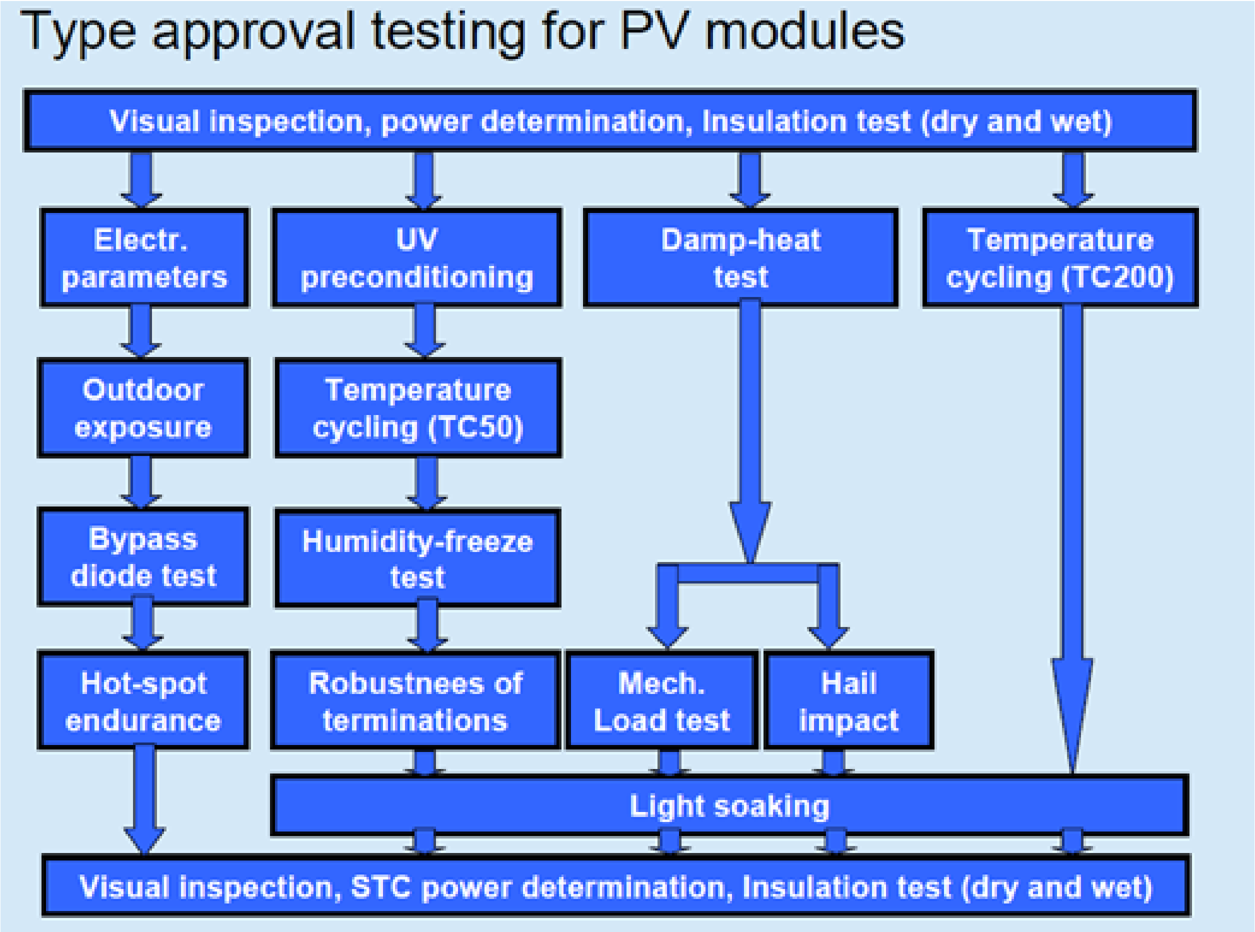
Encapsulation

- Protection against environment
  - Glass-back foil encapsulation



  - Glass-glass encapsulation
- Large variety of materials
- Important cost factor
- Key issue for long term module performance

Standard testing



IEC 61215 standard

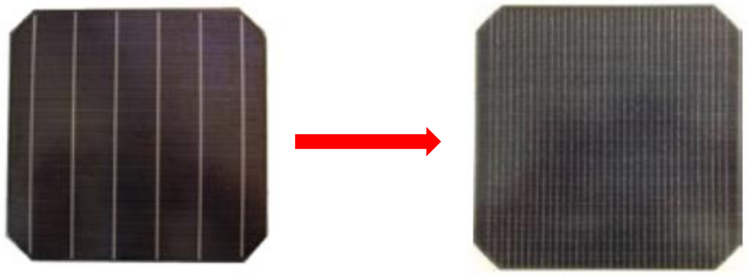
Modules should sustain 25 years of outdoor conditions !

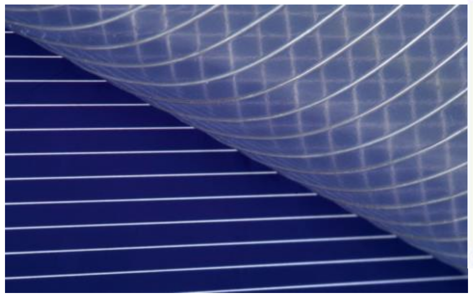
Source:TÜV

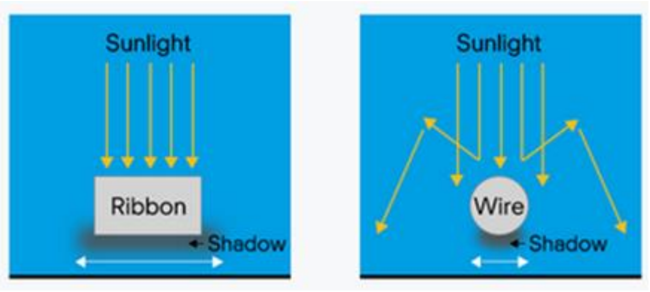
Technology improvement at module level (c-Si)

- Increase «bus bar» number (less Ag, better carrier collection), up to 9-12!

- Replacement of Ag by Cu (cost reduction)
- Smartwire (replacement of «bus bar» by wires), less shading



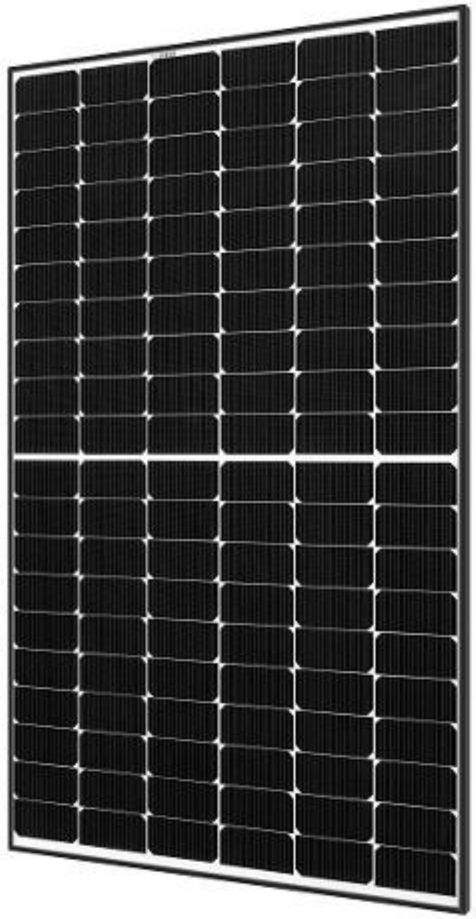




- Half cells for less Joule loss (lower current)
- Bifacial cell, light collection from both sides (diffuse light on back side)

«Best» commercial product

- REC alpha series 380 W
  - Hétérojunction Si cell
  - Temperature coeffcient (P): -0.26 %/°C
  - Half-cells
  - «smart-wire» (no «bus bar»)
  - 20 year warranty



PV devices for energy scavenging

Energy harvesting

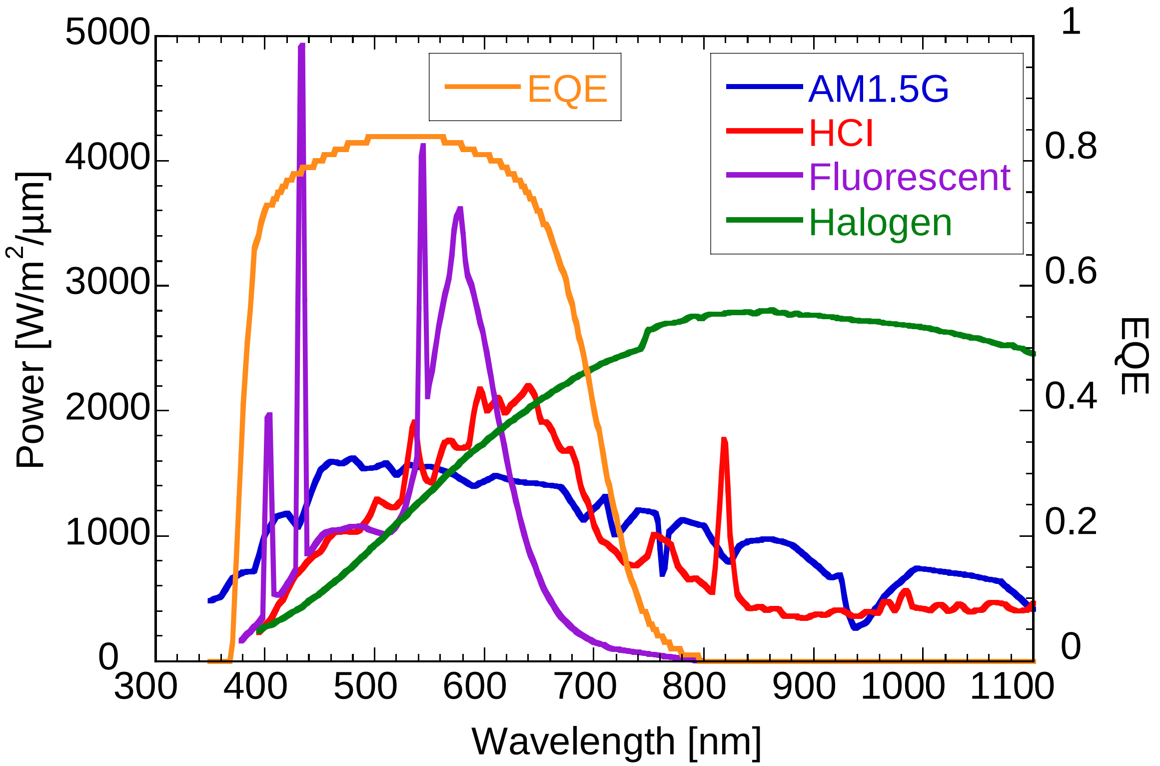
Energy Source	Power Density & Performance
Acoustic Noise	0.003 μW/cm3 @ 75Db 0.96 μW/cm3 @ 100Db
Temperature Variation	10 μW/cm3
Ambient Radio Frequency	1 μW/cm2
Ambient Light	100 mW/cm2 (direct sun) 100 μW/cm2 (illuminated office)
Thermoelectric	60 μW/cm2
Vibration (micro generator)	4 μW/cm3 (human motion—Hz) 800 μW/cm3 (machines—kHz)
Vibrations (Piezoelectric)	200 μW/cm3
Airflow	1 μW/cm2
Push buttons	50 μJ/N
Shoe inserts	330 μW/cm2
Hand generators	30 W/kg
Heel strike	7 W/cm2

F. Yildiz, J of Techn. Studies 35 (2009) 40

Light spectrum and efficiency

N. Wyrsch

Amorphous silicon (a-Si:H) cell

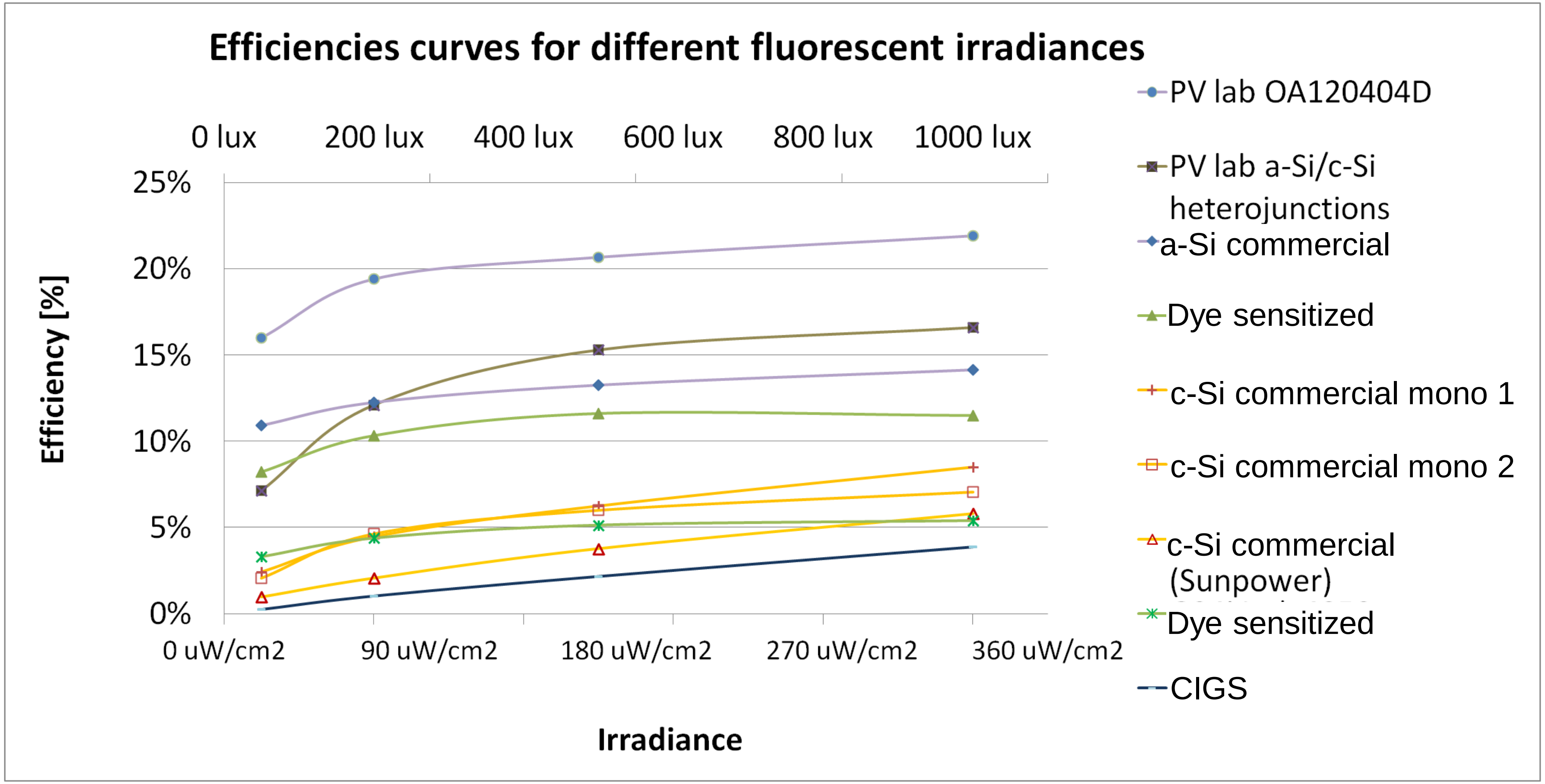


Light source	Efficiency
AM1.5G	10.4%
Metal halide HCI	14.8%
Halogen	6.1%
Fluorescent	23.0%

N. Wyrsch et al. MRS 2005

- a-Si:H band gap well adapted to indoor spectrum
- Superior (to c-Si) performance in low illumination

Low light illumination

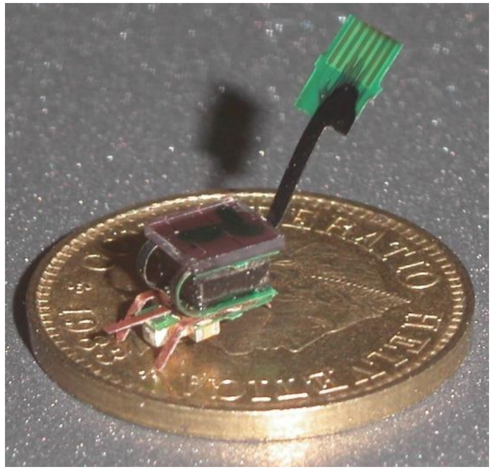


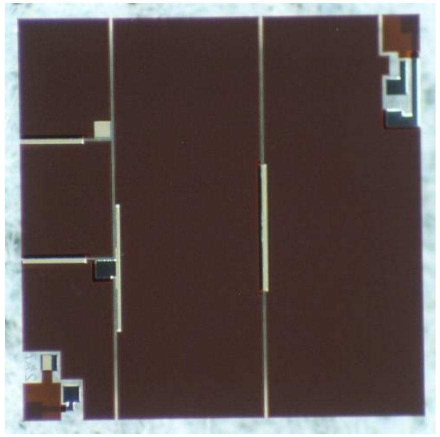
EPFL

Solar modules for micro-systems

N. Wyrsch

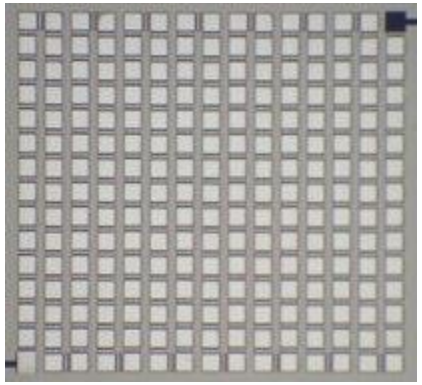
Microrobots

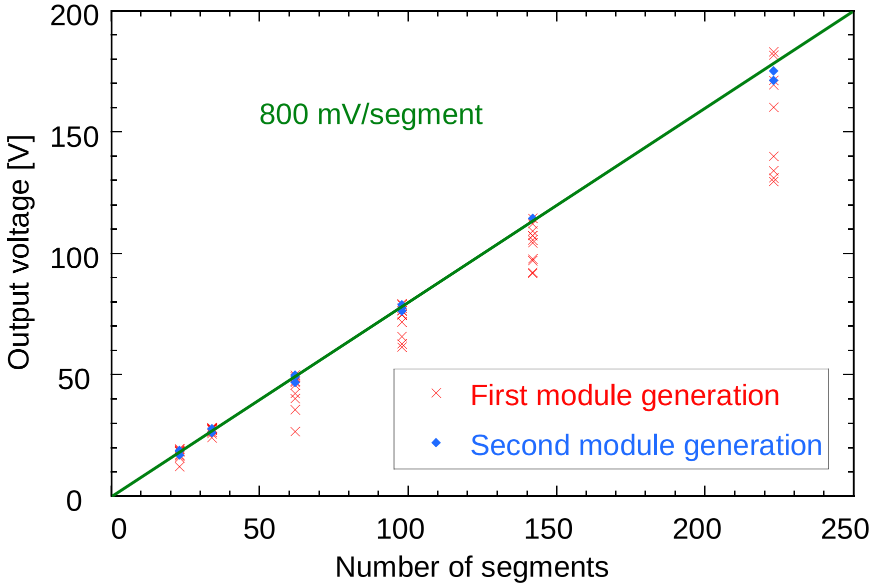




High voltage modules

→Up to 180 V from 3x3 mm²





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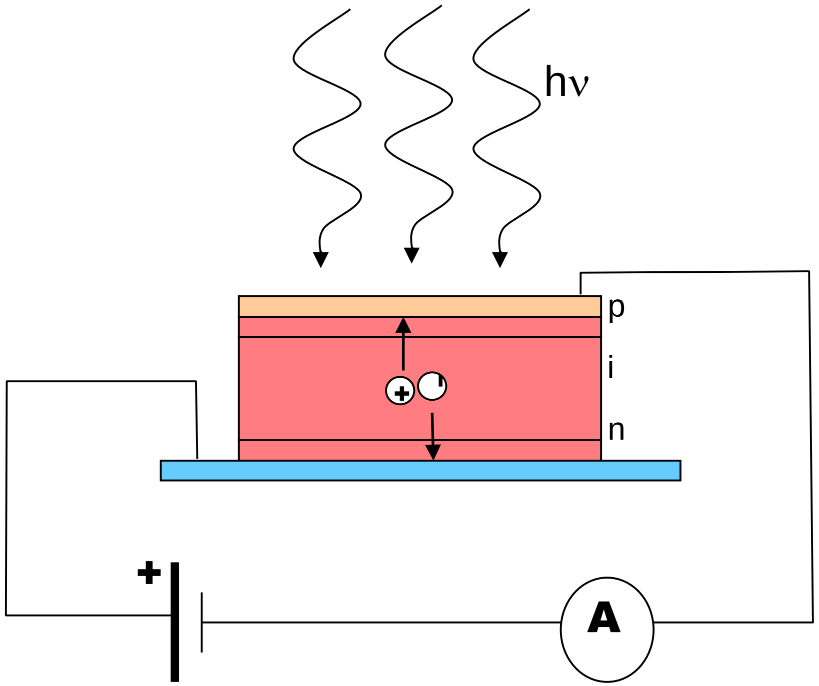
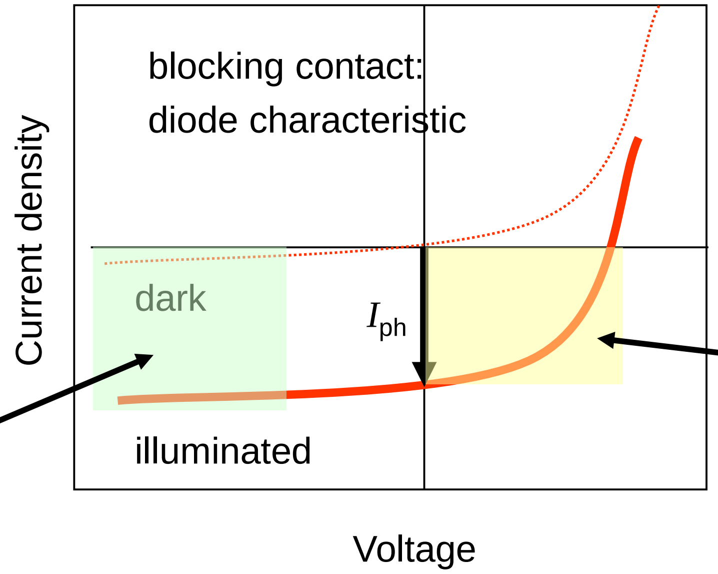
a-Si:H photodiodes & detectors

Thin-film Solar cells vs Photodiodes

N. Wyrsch



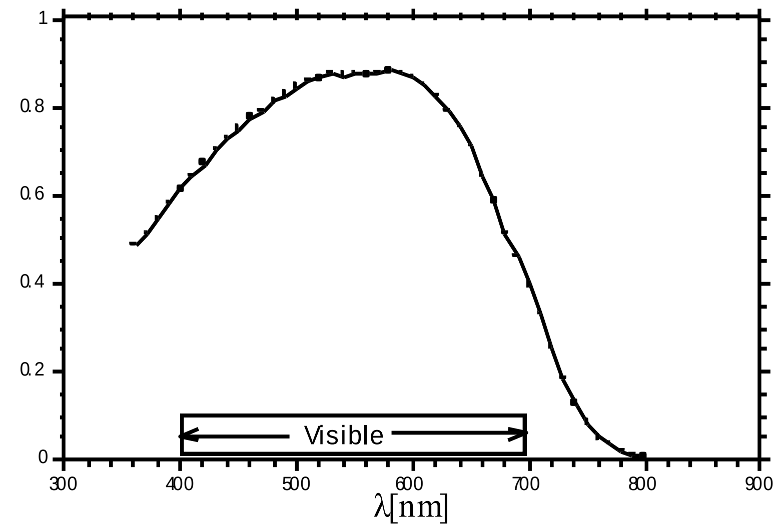
- Using primary photoconductivity (device with blocking contacts) given by the collection of photo-generated carriers
- $I_{ph}=Ge\eta$ with η : quantum efficiency, $\eta \rightarrow 1$ (a-Si:H cells)
- Operation in reverse conditions for best linearity (external field assisted collection)

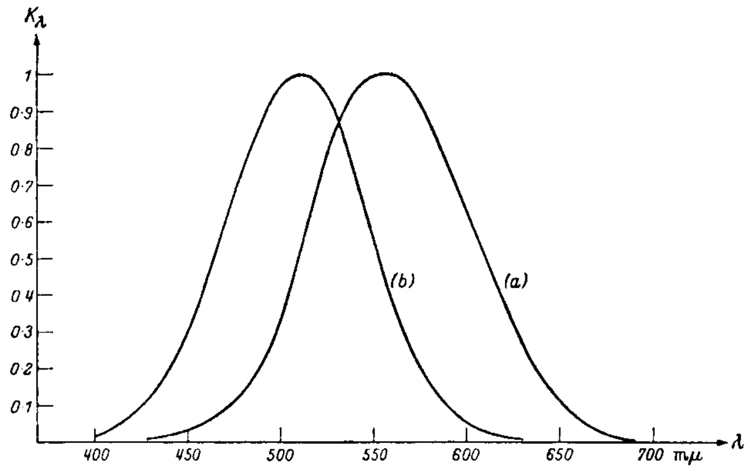


Operation conditions for a photodiode

Operation conditions for a solar cell

Spectral sensitivity





spectral response of a typical 0.5 µm thick a-Si:H p-i-n diode (at -3 V).

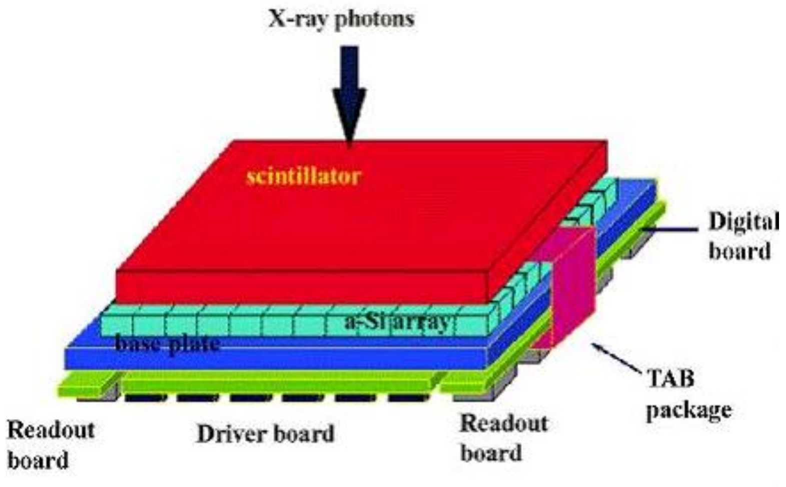
spectral sensitivity of the human eye for (a) daylight and (b) night vision

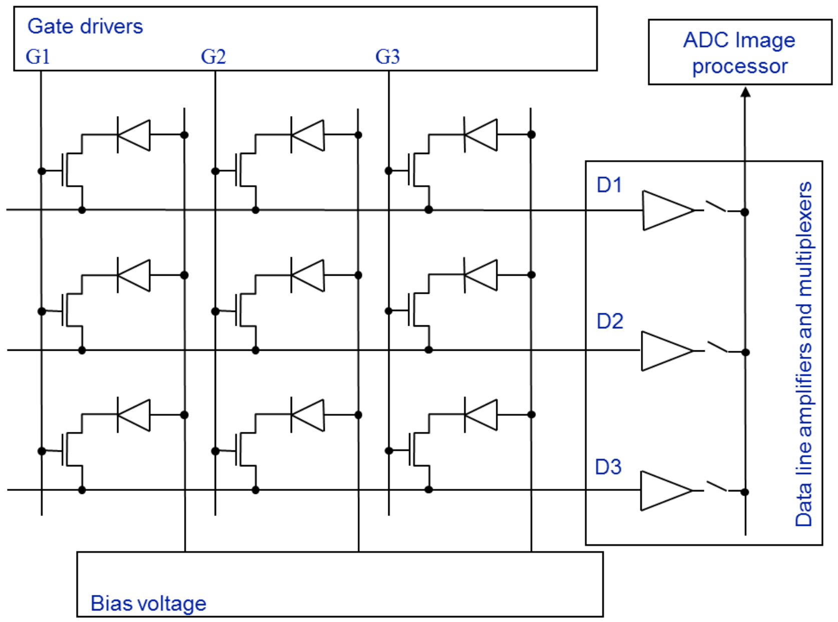
a-Si:H spectral sensitivity match human eye sensitivity !

→ a-Si:H photodiodes used e.g. for display illumination control

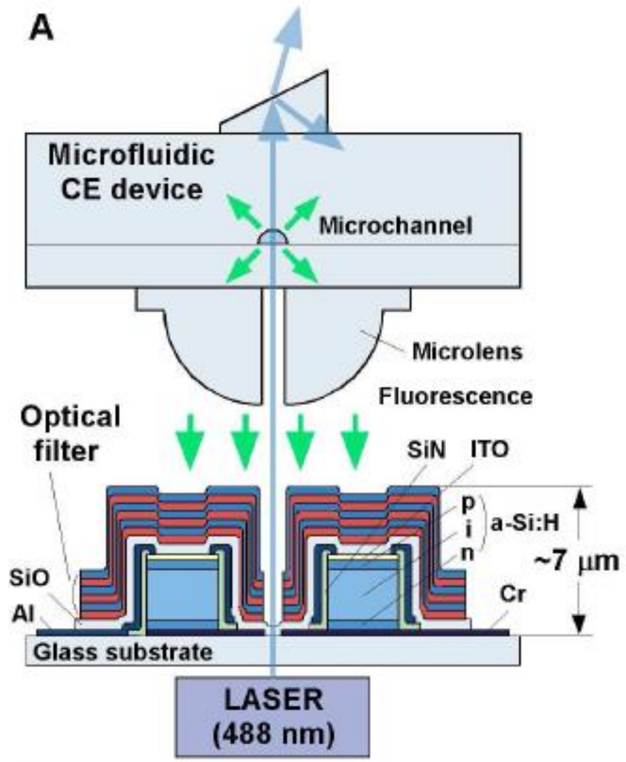
Large area imagers for radiography

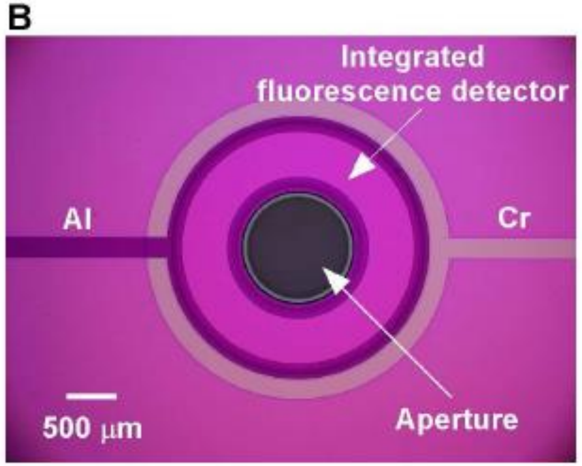
- 2D photodiodes arrays addressed by TFT
- Photodiodes coupled with a scintillator layer (Cs:I) for conversion of x-rays to visible photons
- Extensively used for digital radiography





Fluorescence detector, microfluidic





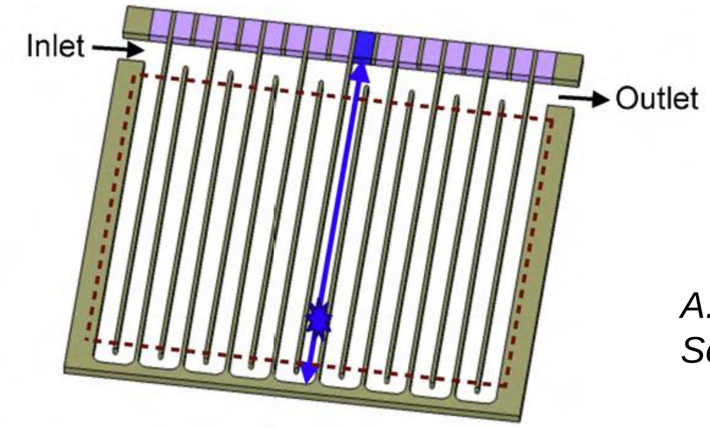
A Schematic crosssectional view of a microlens and an integrated a-Si:H fluorescence detector, forming a compact platform where microfluidic CE device is mounted.

B Optical micrograph of the top view of the integrated fluorescence detector.

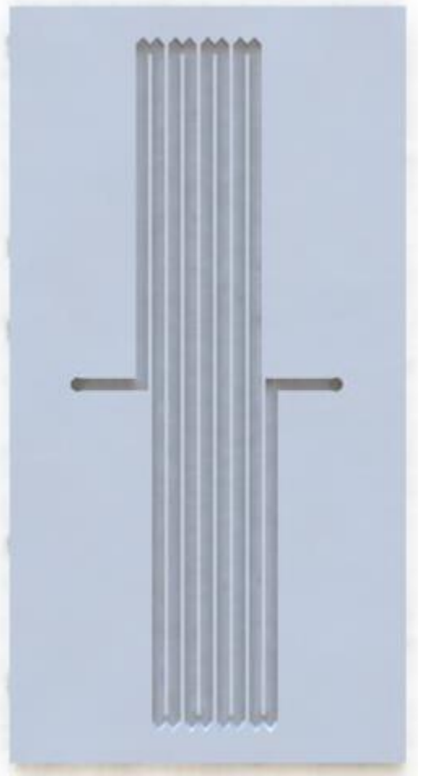
Kamei, MRS 2010

Hybrid detector using microfluidics

- Microfluidic chips filled with liquid scintillator

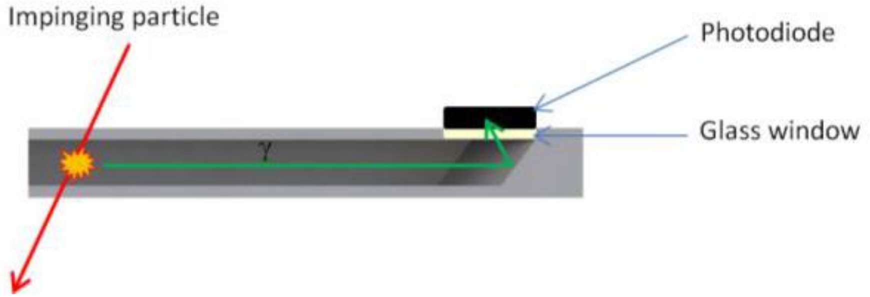


A. Mapelli et al.,
Sensors & Actuators 2010



4.5 x 10 mm^2

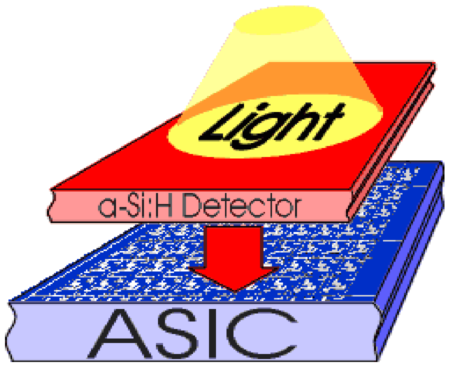
- Detection using integrated a-Si:H diode array at channel end

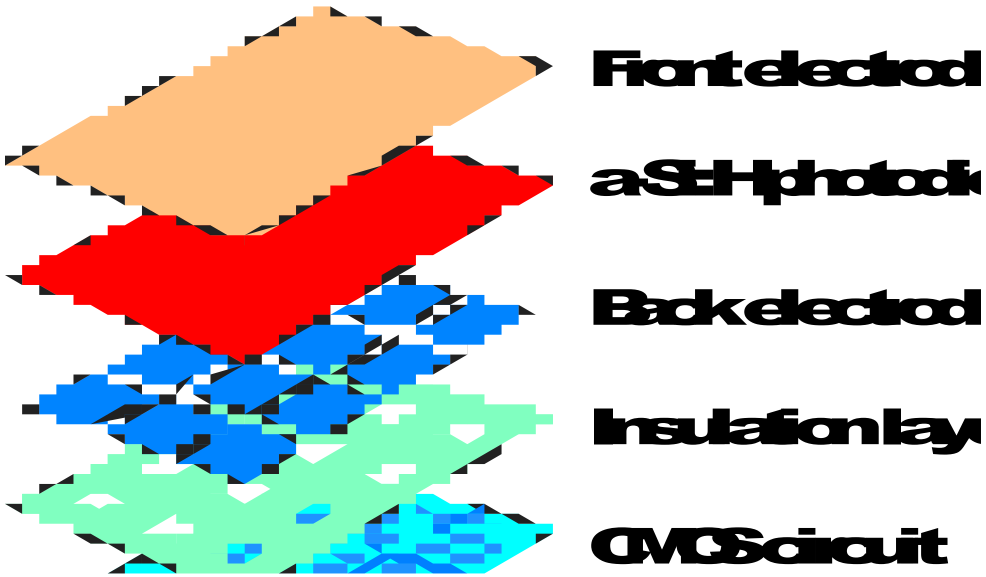


- Under development and tests at EPFL/CERN

EPFL

Vertical Integration of Detector Arrays





- Technology known as
  - Thin-Film on ASIC (TFA)
  - Thin-Film on CMOS (TFC)
  - Above IC technology
  - Elevated diode

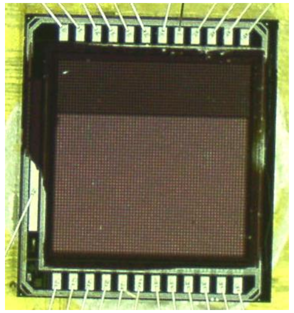
- Benefits
  - High fill-factor, high sensitivity
  - No trade off between sensitivity and circuit complexity
  - No dead area

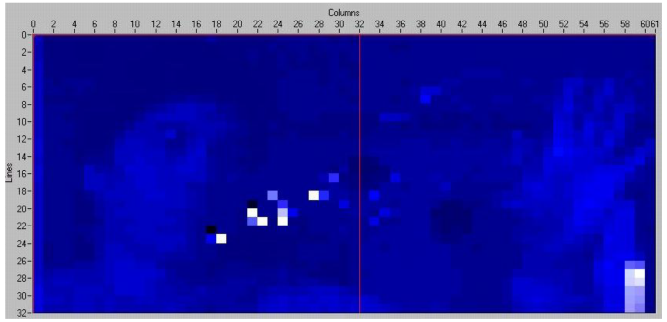
PV-lab IMT NEUCHATEL

TFA imagers

N. Wyrsch

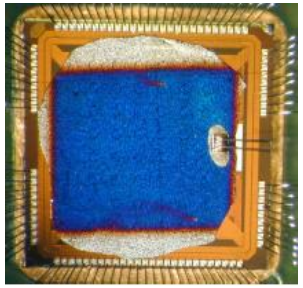
Visible light

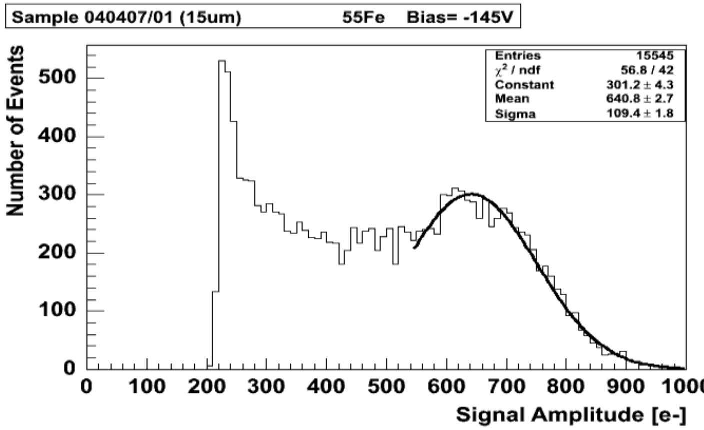




- Metal-i-p a-Si:H diodes deposited on unpassivated chip
  - 64x64 pixels
  - 38.4 µm size, 40 µm pitch
  - 92% fill factor
- Pixels connect to charge integrators
- Dark current as low as 20 pA/cm2
- Noise (fixed patterned noise Sensitivity (@600nm): 56 V/(µJcm2)
- Dynamic Range: >60 dB

X-ray detection





- 4x4 mm^2 ASIC
- 48 pixels with 150 µm size and 380 µm pitch connected to active feedback amplifiers
- 15 µm thick a-Si:H diode

PV ressources

English | Search Site

Christiana Honsberg
and Stuart Bowden

Welcome to PVCDROM

Photovoltaics is a most elegant energy source. Light shines on a crystal and produces electricity. Its as simple as that. There are no moving parts. The fuel source (sunlight) is free, abundant and widely distributed, available to every country and person in the world. At over 165,000 TW the solar resource dwarfs the world's current power usage of 16 TW or even our projected future usage of 60 TW.

The many advantages of photovoltaics lend itself to being the ultimate energy source. However, it required the semiconductor revolution and advances in manufacturing before photovoltaics could begin to reveal its full potential.

For the last two decades, photovoltaics has been the fastest growing industry for its size. Continuing at the present growth rate of 40% for the next two decades will allow photovoltaics to be the worlds largest energy source. To keep growing at 40% a year, however, will require that everyone learn a little bit about how photovoltaics works and for today's engineering students to be conversant in the principles and technologies that will make this growth possible. This site provides casual readers an opportunity to research this new technology and students of physics, engineering, or energy policy the opportunity to deeply explore photovoltaics..

This site is an electronic book on PV. It can either be read from start to finish as a course on photovoltaics or used as a reference. This project started out as an electronic textbook, distributed on CDs and so we have kept the ungainly title of PVCDROM. As the project and the text itself has grown over the years we have added many enhancements unavailable in static textbooks. Be sure to read the instruction page to make sure you have all the appropriate plugins installed and so that you will be aware of all of the features available to learners.

Stuart Bowden and Christiana Honsberg work at the Solar Power Labs at ASU (http://pv.asu.edu/)

http://www.pveducation.org/pvcdrom

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- Other
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    2nd edition online at : **http://www.pveducation.org/pvcdrom**

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