EPFL

Solar Energy Conversion Devices and Plants

Prof. Sophia Haussener

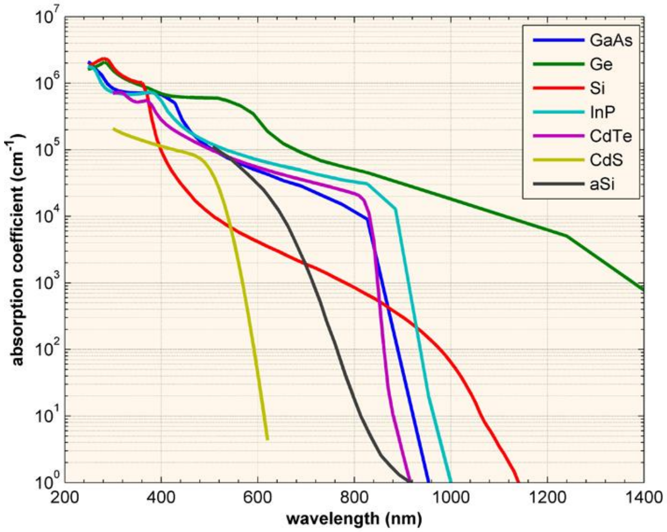
Laboratory of Renewable Energy Science and Engineering

Outline

- Photovoltaics:
  - Physics and working principle
  - Technologies
  - Markets, costs, life cycle

Absorption in semiconductor

- Semiconductor under irradiation:
  - Electron-hole pairs are generated by solar irradiation, if the energy is larger than the band gap energy they are absorbed



  - Absorption depth is inversely proportional to absorption coefficient, according to Beer's law:

$$I = I_0 \exp(-\alpha l) \qquad I \overset{l=1/\alpha}{=} I_0 \exp(-1) \rightarrow 0.36 \cdot I_0$$

  - Generation rate (electron-hole-pairs):

$$G(x) = \alpha N_0 \exp(-\alpha x) = \int_0^\infty \alpha_\lambda N_{0,\lambda} \exp(-\alpha_\lambda x) d\lambda$$

Photonflux [#/m²/s] = *I/E*

$$N_{0,\lambda} = I_{e,\lambda} \frac{\lambda}{hc}$$

Recombination in semiconductors

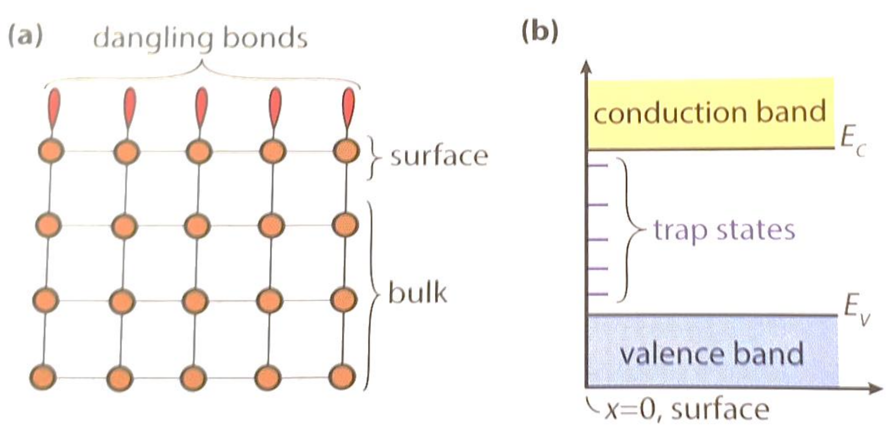
- Once an electron hole-pair is generated, they can recombine:
  - Bulk recombination:
    - Direct recombination (radiative recombination)
    - Shockley-Read-Hall recombination
    - Auger recombination

Recombination rate Diffusion coefficient

$$\frac{1}{\tau} = \frac{1}{\tau_{rr}} + \frac{1}{\tau_{ar}} + \frac{1}{\tau_{srh}} = \frac{R}{\Delta n} = \frac{D}{l^2}$$

Diffusion length

  - Surface recombination



Transport in semiconductors

- Free charge carriers randomly moving, but no net movement
- Net movement only if «driver»:
  - Diffuse in the material according to the concentration gradient

$$J_{x,n} = qD_n \frac{dn}{dx} \qquad J_{x,p} = qD_p \frac{dp}{dx}$$

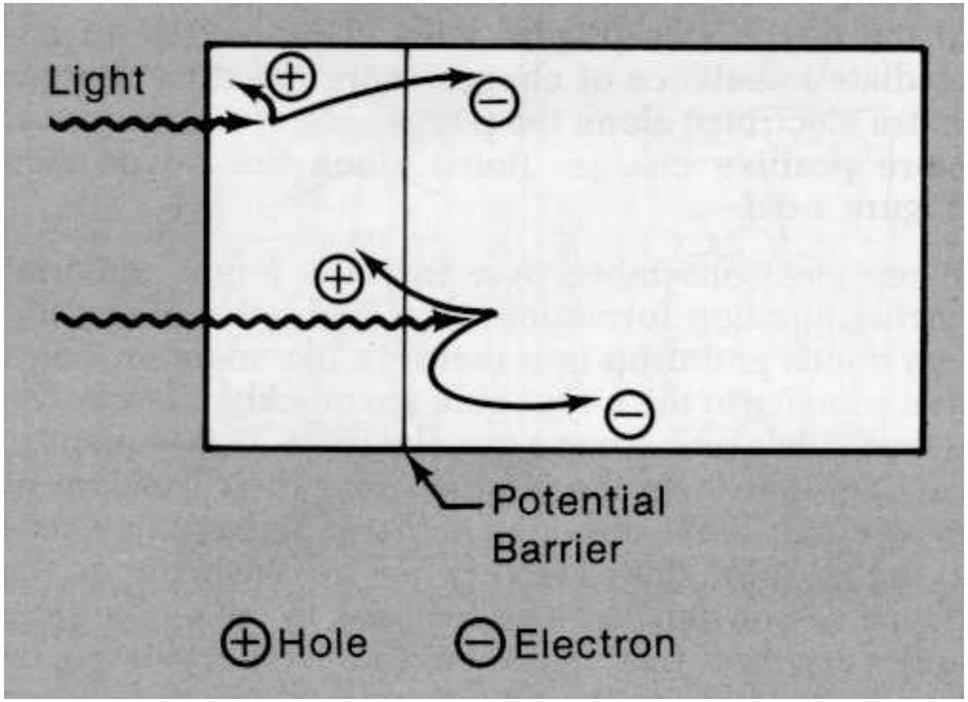
  - Drift in the material according to an electric field

$$J_{x,n} = qn\mu_n \xi_x \qquad J_{x,p} = qp\mu_p \xi_x$$

  - Continuity equation: $\frac{dn}{dt} = \frac{1}{q}\frac{dJ_n}{dx} + G - R \qquad \frac{dp}{dt} = -\frac{1}{q}\frac{dJ_p}{dx} + G - R$

  - Plus Poisson eq. for electric field $\nabla^2 \psi = \frac{q}{\varepsilon_0 \varepsilon_r}\left(n_0 - p_0 + N_A - N_D\right)$

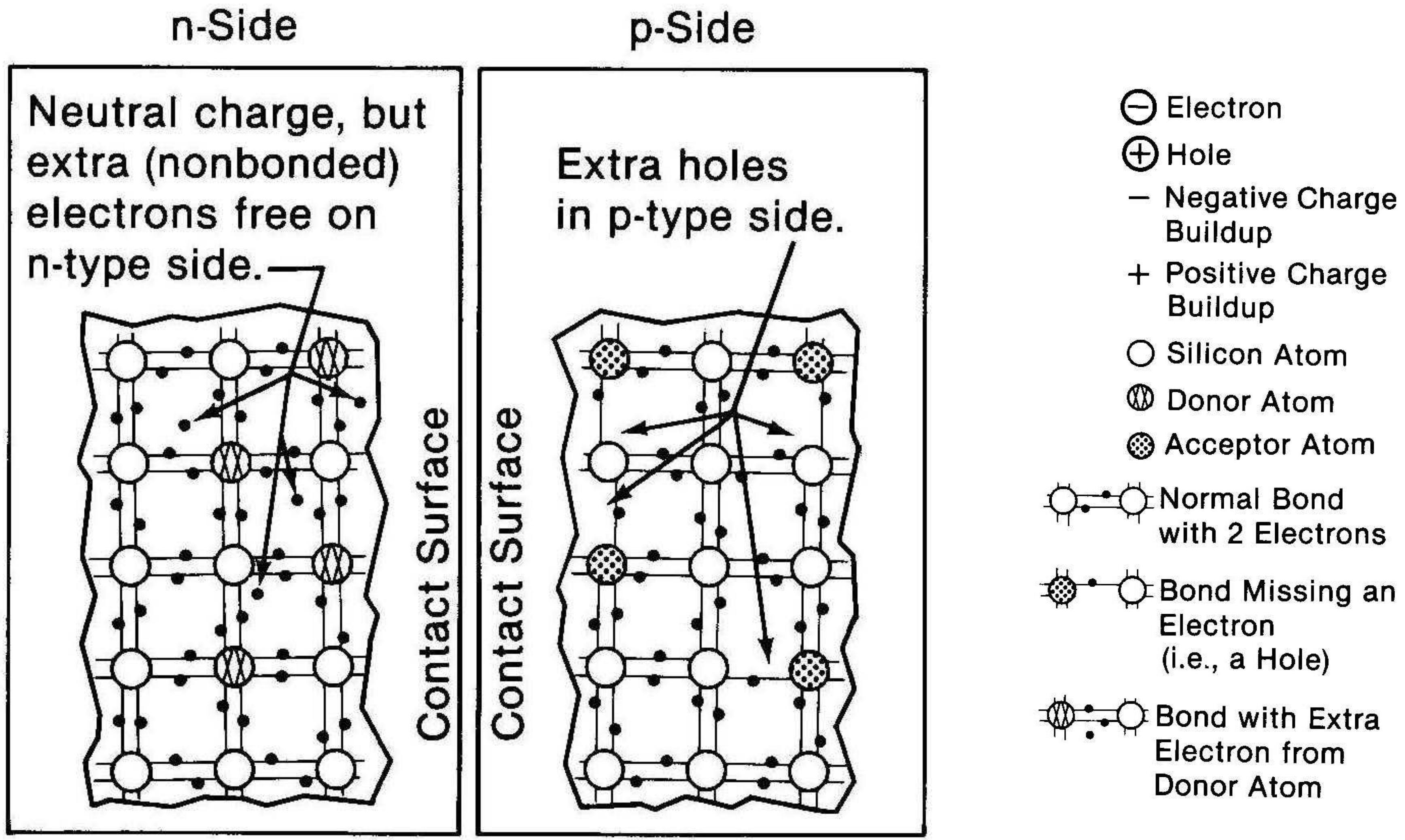
Potential Barrier



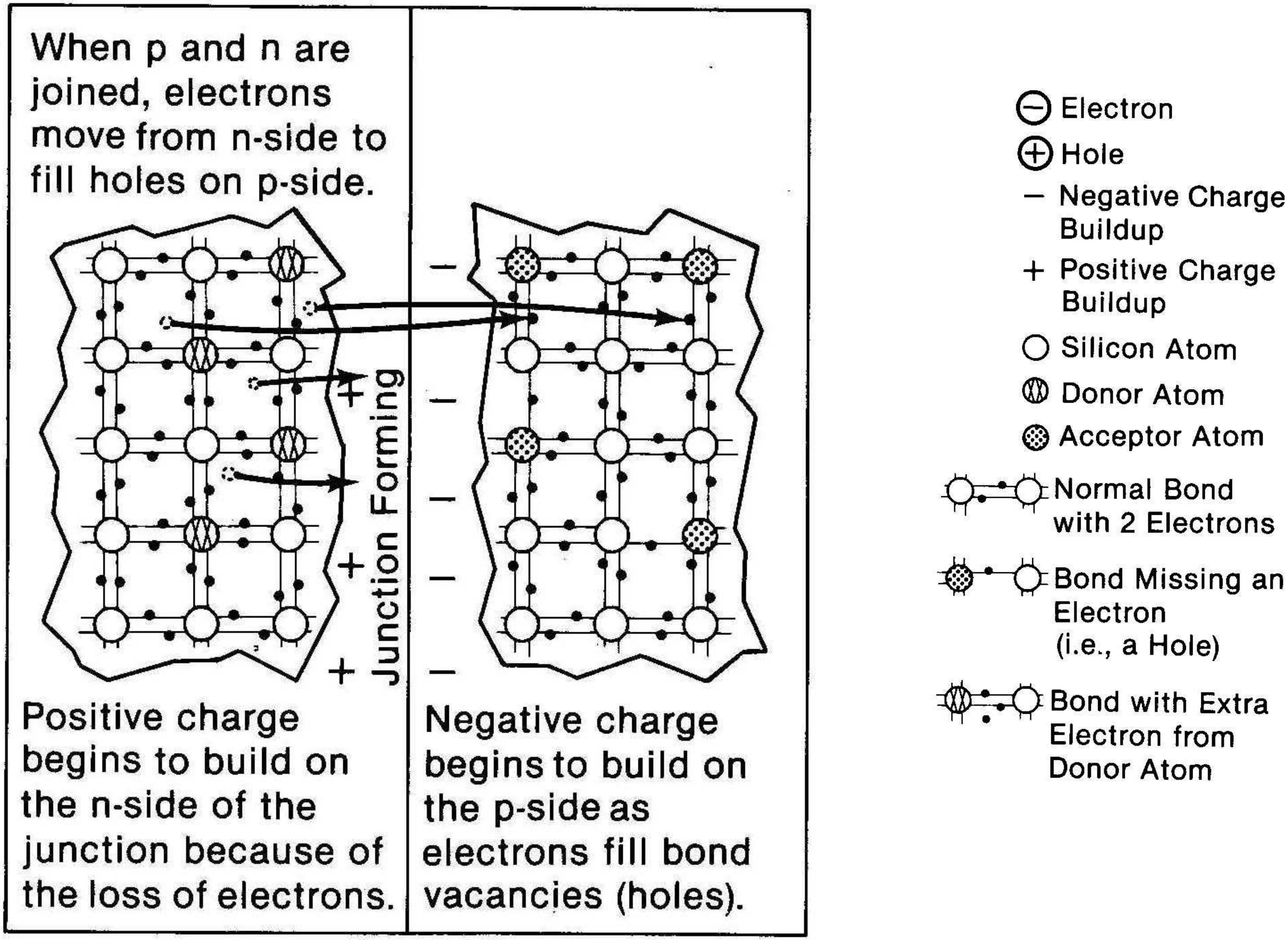
- Need to separate the electron so that it does not recombine with a hole.
- Must create a “potential barrier” to achieve charge separation.
- Electrons and holes are pushed to different sides of the potential barrier, to avoid their recombination.
- This charge separation sets up a voltage difference which can drive an electric current in an external circuit.

- *Basic Photovoltaic Principles and Methods*, 1981.

n-type and p-type Crystals

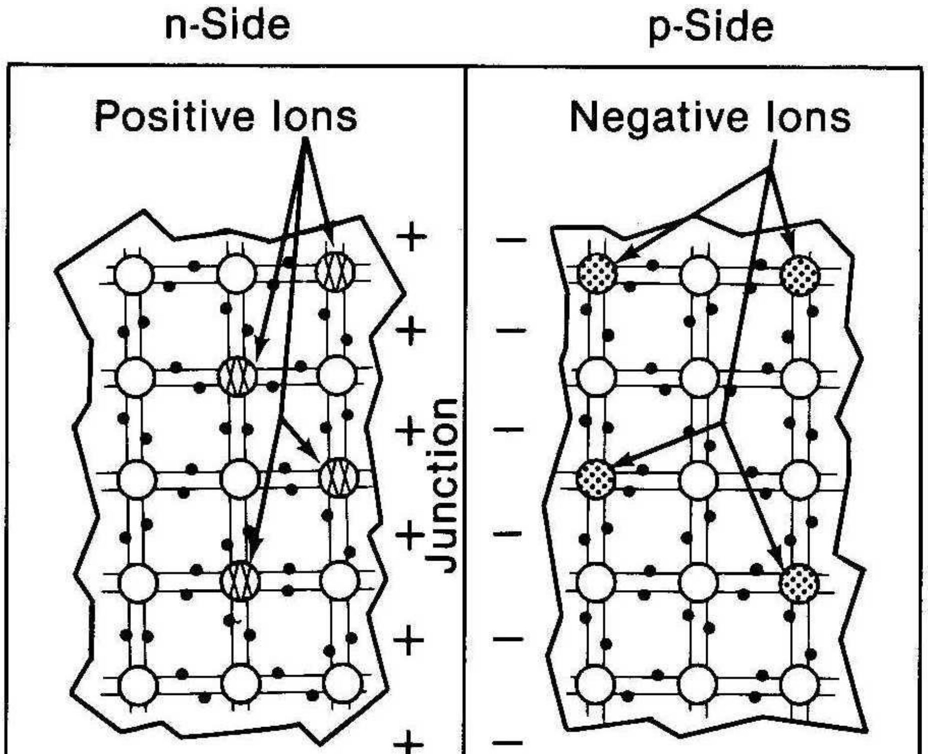


pn-Junction



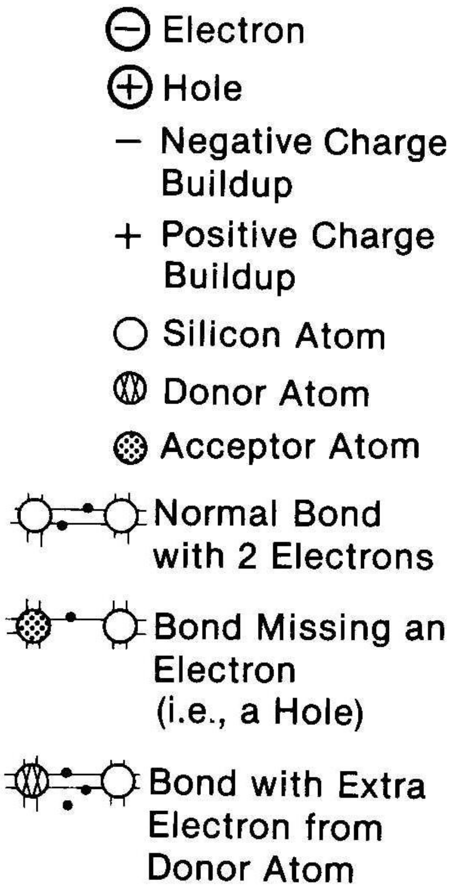
When p and n are joined, electrons move from n-side to fill holes on p-side.
Junction Forming
Positive charge begins to build on the n-side of the junction because of the loss of electrons.
Negative charge begins to build on the p-side as electrons fill bond vacancies (holes).
Electron
Hole
Negative Charge Buildup
Positive Charge Buildup
Silicon Atom
Donor Atom
Acceptor Atom
Normal Bond with 2 Electrons
Bond Missing an Electron (i.e., a Hole)
Bond with Extra Electron from Donor Atom

pn-Junction

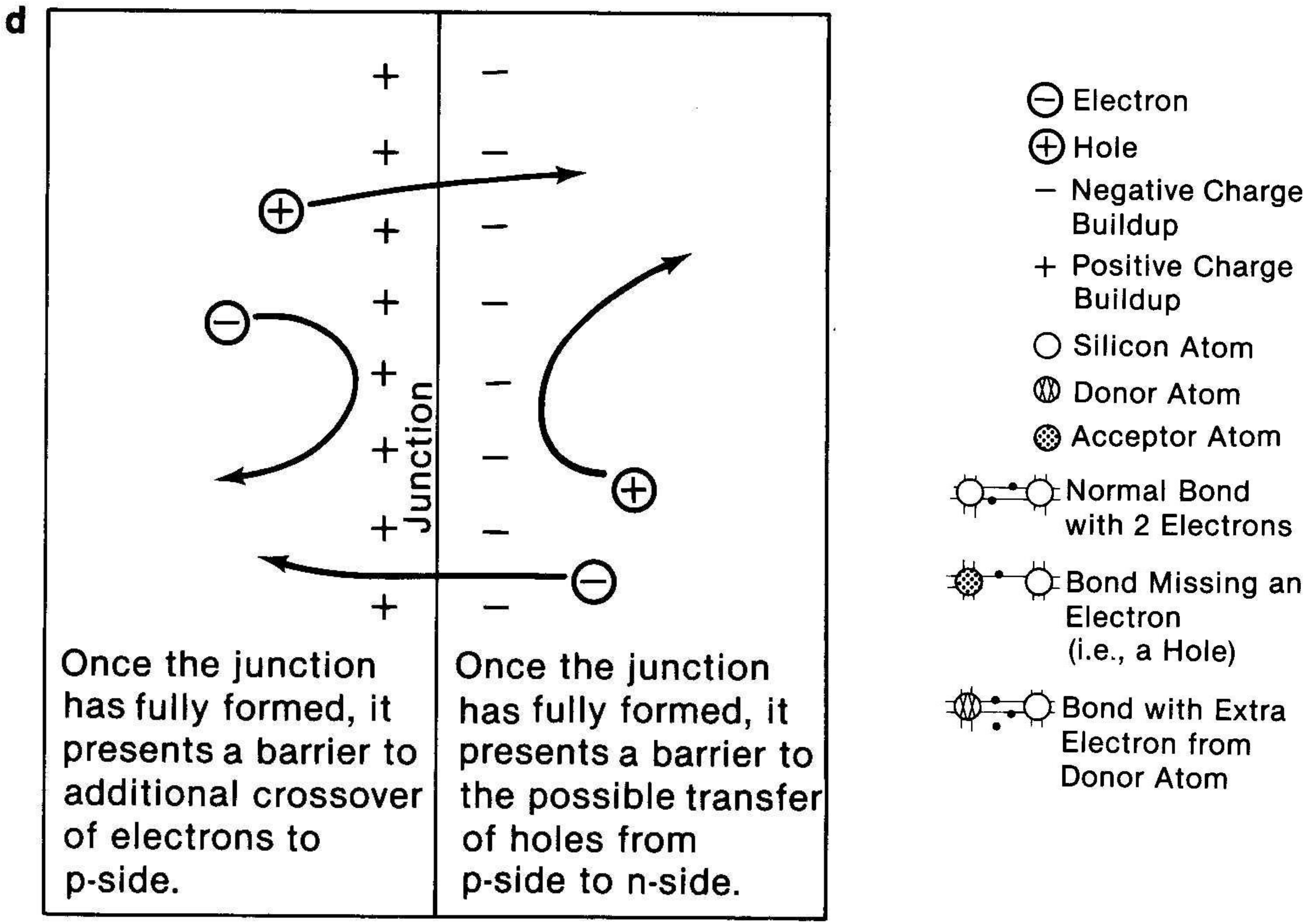


Near the junction, most of the free electrons on the n-side have moved to the p-side, creating a large positive charge at the junction.

Large negative charge is created at the junction because of the transfer of electrons to the p-side to fill holes.



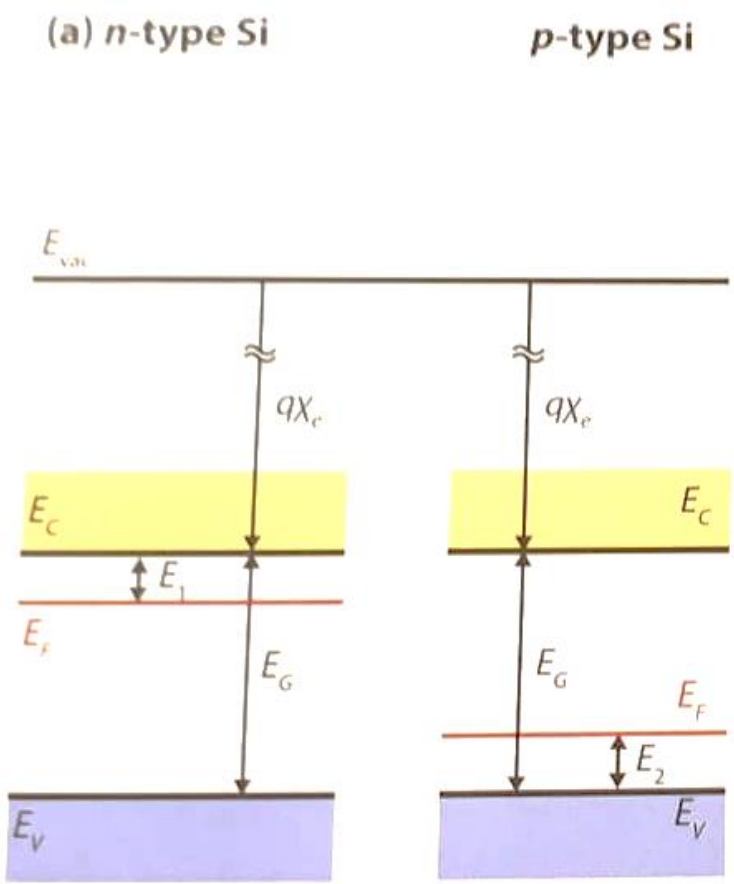
pn-Junction

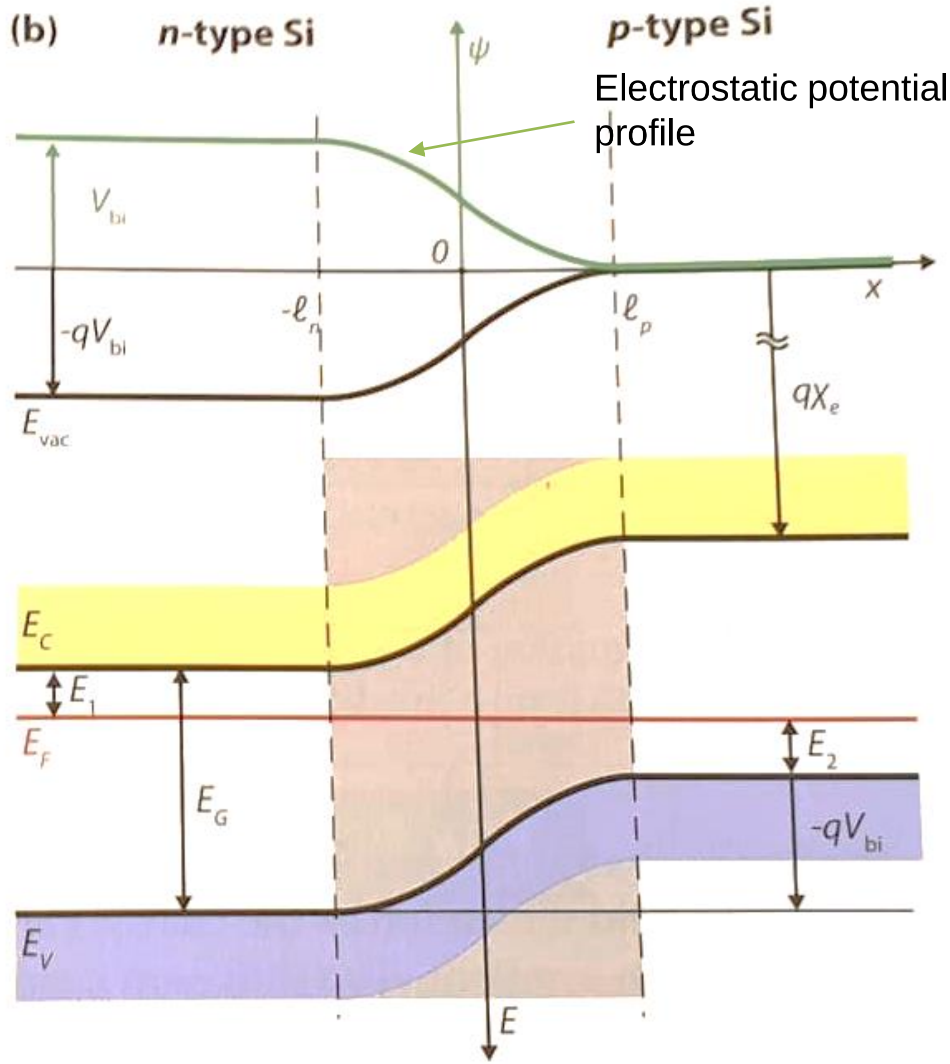

d
Junction
Once the junction has fully formed, it presents a barrier to additional crossover of electrons to p-side.
Once the junction has fully formed, it presents a barrier to the possible transfer of holes from p-side to n-side.
Electron
Hole
Negative Charge Buildup
Positive Charge Buildup
Silicon Atom
Donor Atom
Acceptor Atom
Normal Bond with 2 Electrons
Bond Missing an Electron (i.e., a Hole)
Bond with Extra Electron from Donor Atom

pn-Junction under Equilibrium

Separated

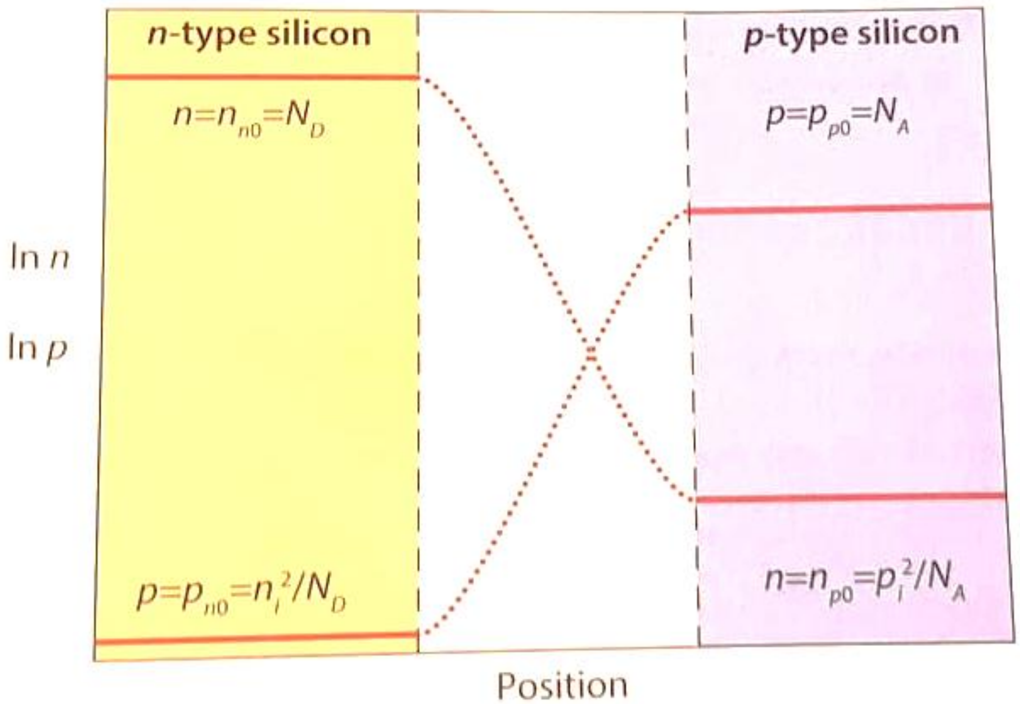
In contact and equilibrium





pn-Junction under Equilibrium

- Concentration profile of mobile charge carriers



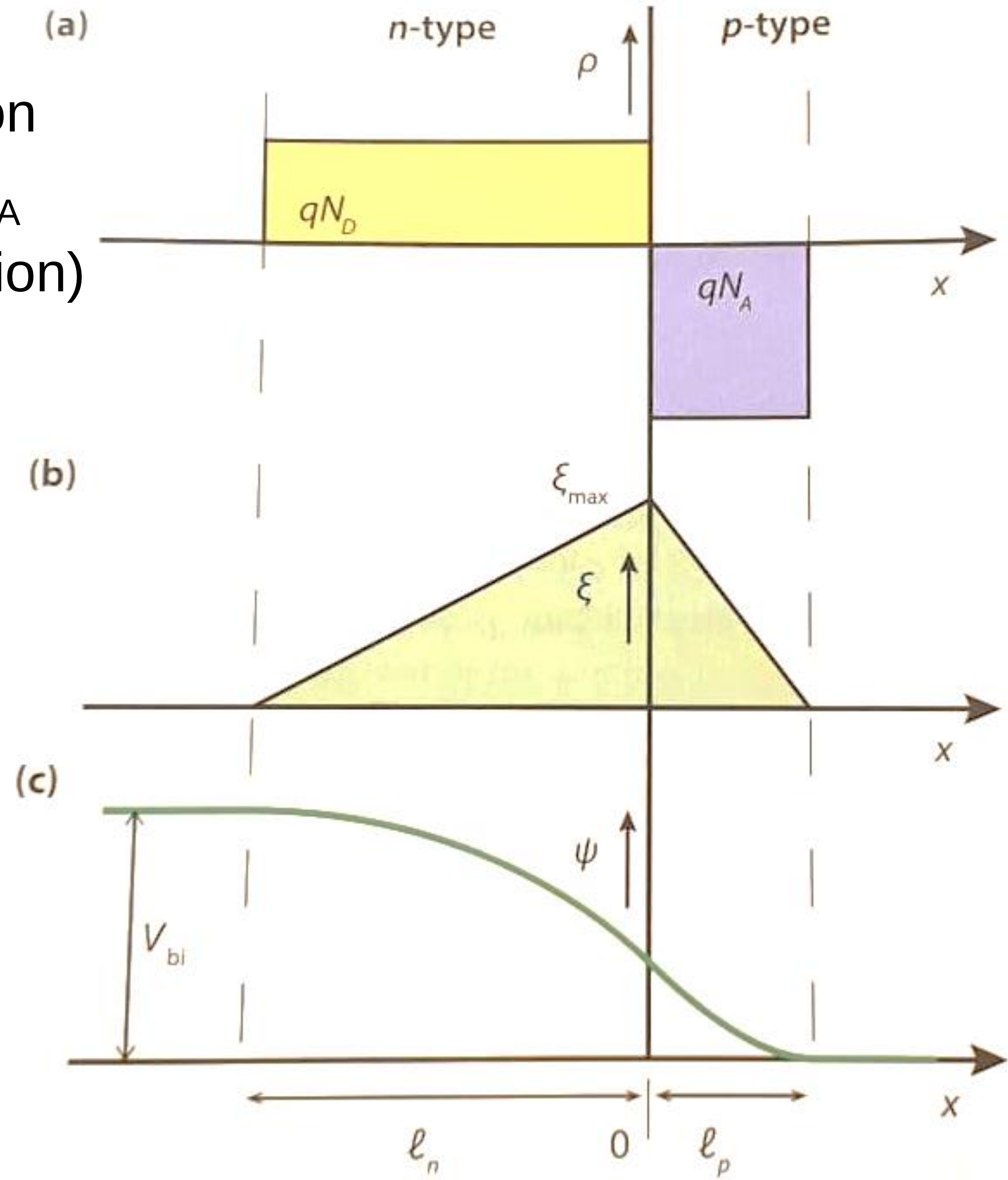
  - Left and right is quasi-neutral regions: concentrations of n and p the same as in isolated doped semiconductor
  - Middle space charge region: majority carrier drop quickly → depleted of mobile carriers

pn-Junction under Equilibrium

- Space charge density
  (is zero in quasi-neutral region
  and determined by N_D and N_A
  else → depletion approximation)

- Electric field

- Electrostatic potential



pn-Junction under Equilibrium

- Space charge density

$$\rho(x) = qN_D \quad \text{for} \quad -l_n \le x \le 0$$
$$\rho(x) = -qN_A \quad \text{for} \quad 0 \le x \le l_p$$

- Electric field

$$\xi = \frac{1}{\varepsilon_0 \varepsilon_r} \int \rho dx$$

$$BC: \xi(-l_n) = \xi(l_p) = 0$$

$$\xi(x) = \frac{q}{\varepsilon_0 \varepsilon_r} N_D (l_n + x) \quad \text{for} \quad -l_n \le x \le 0$$

$$\xi(x) = \frac{q}{\varepsilon_0 \varepsilon_r} N_A (l_p - x) \quad \text{for} \quad 0 \le x \le l_p$$

- Electrostatic potential

$$\frac{d^2 \psi}{dx^2} = -\frac{d\xi}{dx} = \frac{\rho}{\varepsilon_0 \varepsilon_r} \qquad \psi = -\int \xi dx \qquad \psi(l_p) = 0$$

pn-Junction under Equilibrium

- Electrostatic field

$$\psi(x) = -\frac{q}{2\varepsilon_0\varepsilon_r} N_D (x + l_n)^2 + \frac{q}{2\varepsilon_0\varepsilon_r}\left(N_D l_n{}^2 + N_A l_p{}^2\right) \text{ for } -l_n \le x \le 0$$

$$\psi(x) = \frac{q}{2\varepsilon_0\varepsilon_r} N_A (x - l_p)^2 \qquad \text{for} \quad 0 \le x \le l_p$$

- Difference in electrostatic potential

$$V_{bi} = \psi(-l_n) - \psi(l_p) = \frac{q}{2\varepsilon_0\varepsilon_r}\left(N_D l_n{}^2 + N_A l_p{}^2\right)$$

pn-Junction under Equilibrium

- Difference in electrostatic potential based on energy levels:

$$qV_{bi} = E_g - E_1 - E_2$$

- With:

$$E_g = E_c - E_v$$

$$E_1 = E_c - E_f = k_B T \ln(N_c / N_D)$$

$$E_2 = E_f - E_v = k_B T \ln(N_v / N_A)$$

$$n_{\text{int}}^2 = N_c N_v \exp\left(-\frac{E_g}{k_B T}\right)$$

- We get:

$$V_{bi} = \frac{k_B T}{q} \ln\left(\frac{N_D N_A}{n_{\text{int}}^2}\right)$$

pn-Junction under Equilibrium

- Space charge layer dimension:

$$l_n = \sqrt{\frac{2\varepsilon_0\varepsilon_r V_{bi}}{q}\frac{N_A}{N_D}\left(\frac{1}{N_A + N_D}\right)}$$

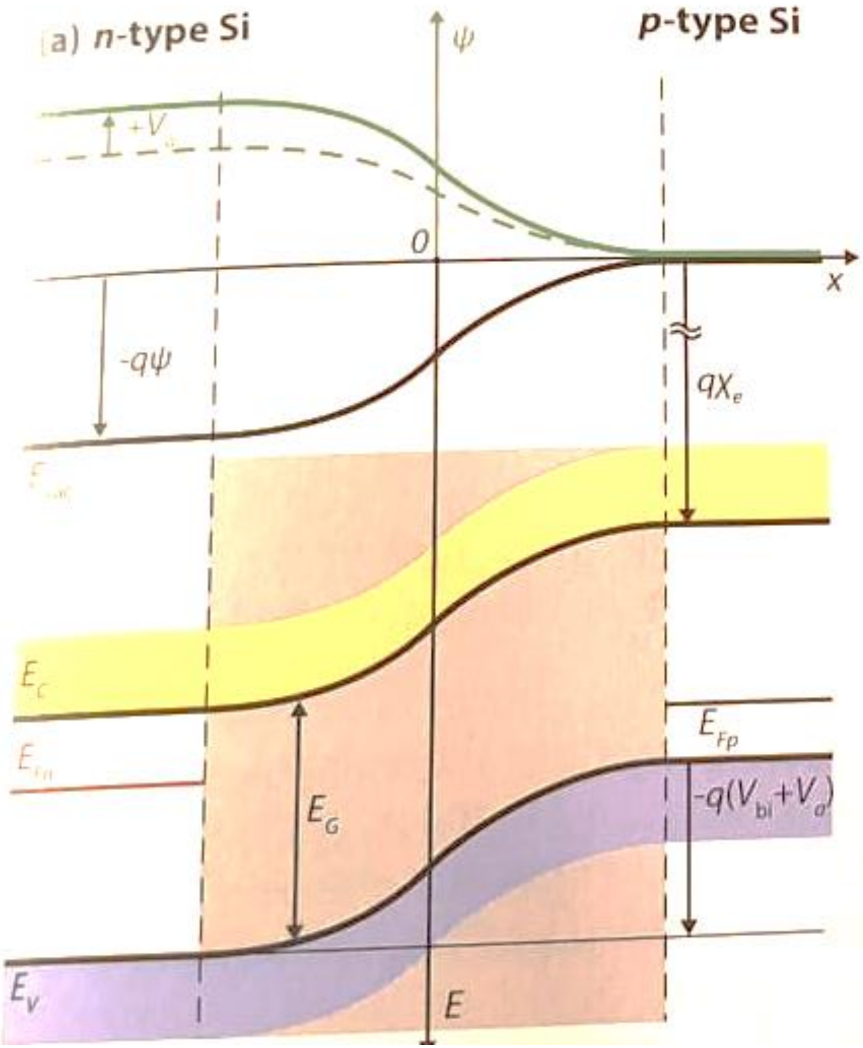
$$l_p = \sqrt{\frac{2\varepsilon_0\varepsilon_r V_{bi}}{q}\frac{N_D}{N_A}\left(\frac{1}{N_A + N_D}\right)}$$

- Maximum internal electrical field:

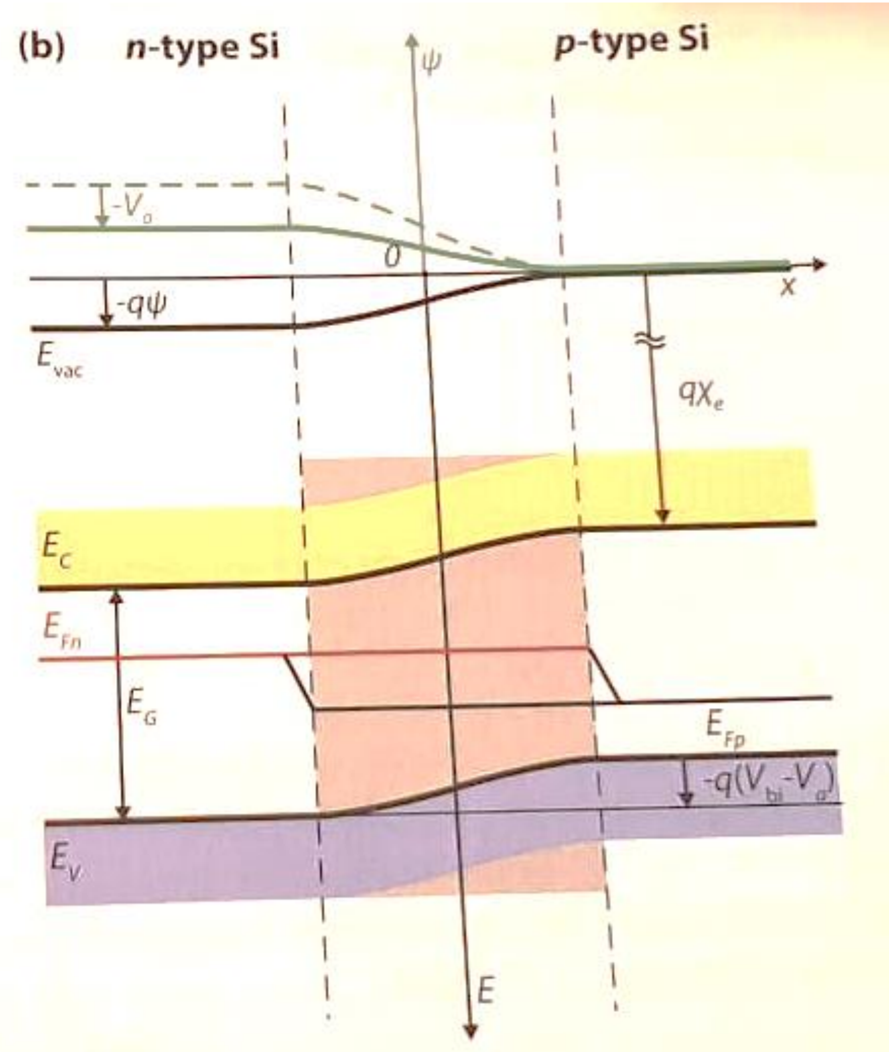
$$\xi_{\max} = \sqrt{\frac{2\varepsilon_0\varepsilon_r}{q}V_{bi}\left(\frac{N_A N_D}{N_A + N_D}\right)}$$

pn-Junction under Applied Potential

Reverse bias



Forward bias

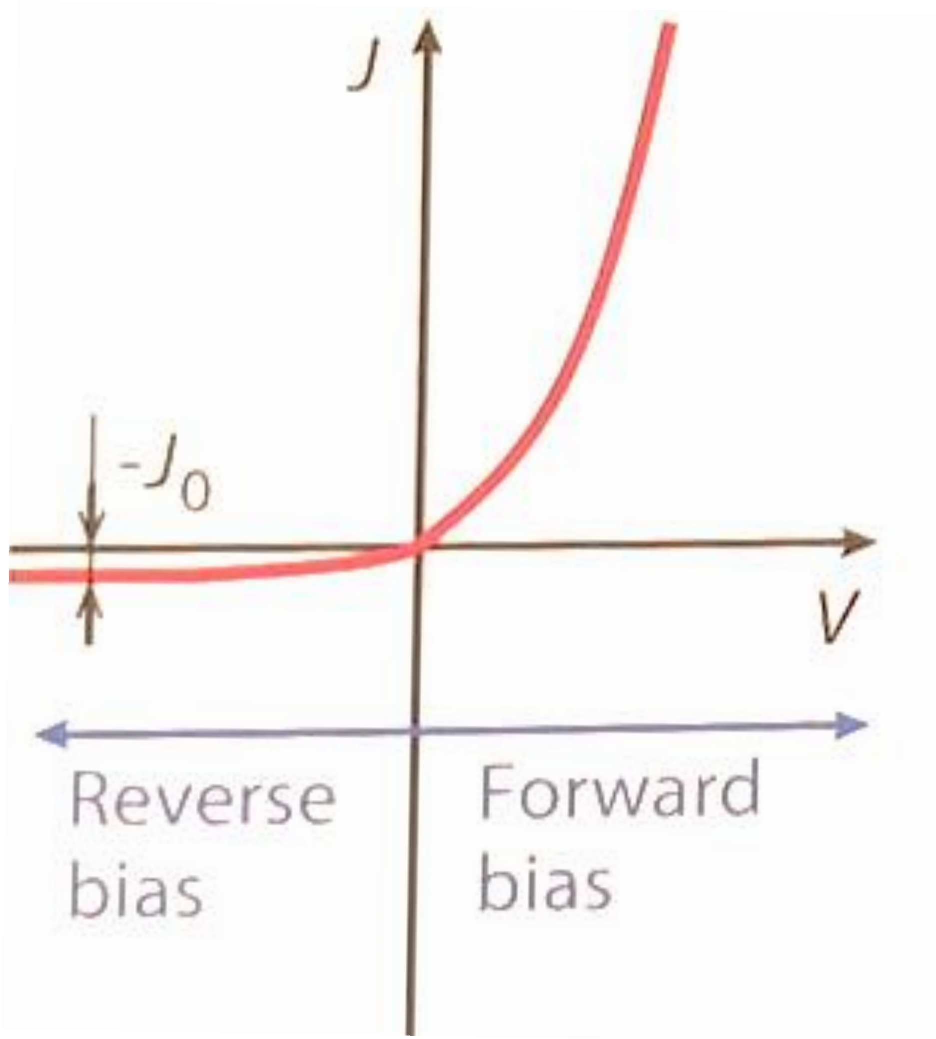


pn-Junction under Applied Potential

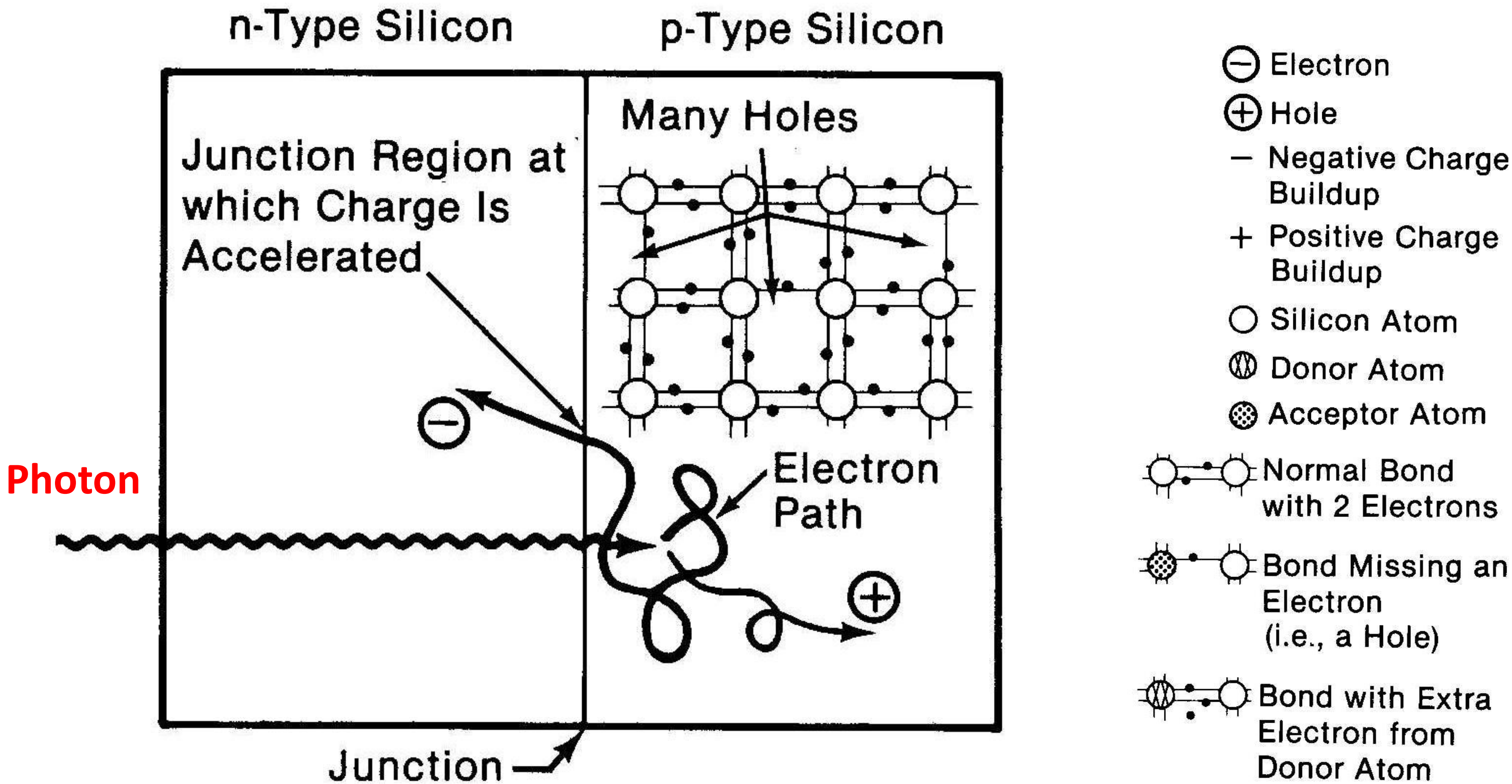
- Current-voltage characteristic

$$J = J_0 \left[\exp\left(\frac{qV_a}{k_B T} \right) - 1 \right]$$

$$J_0 = q n_{\text{int}}^2 \left(\frac{D_n}{L_n N_A} + \frac{D_p}{L_p N_D} \right)$$



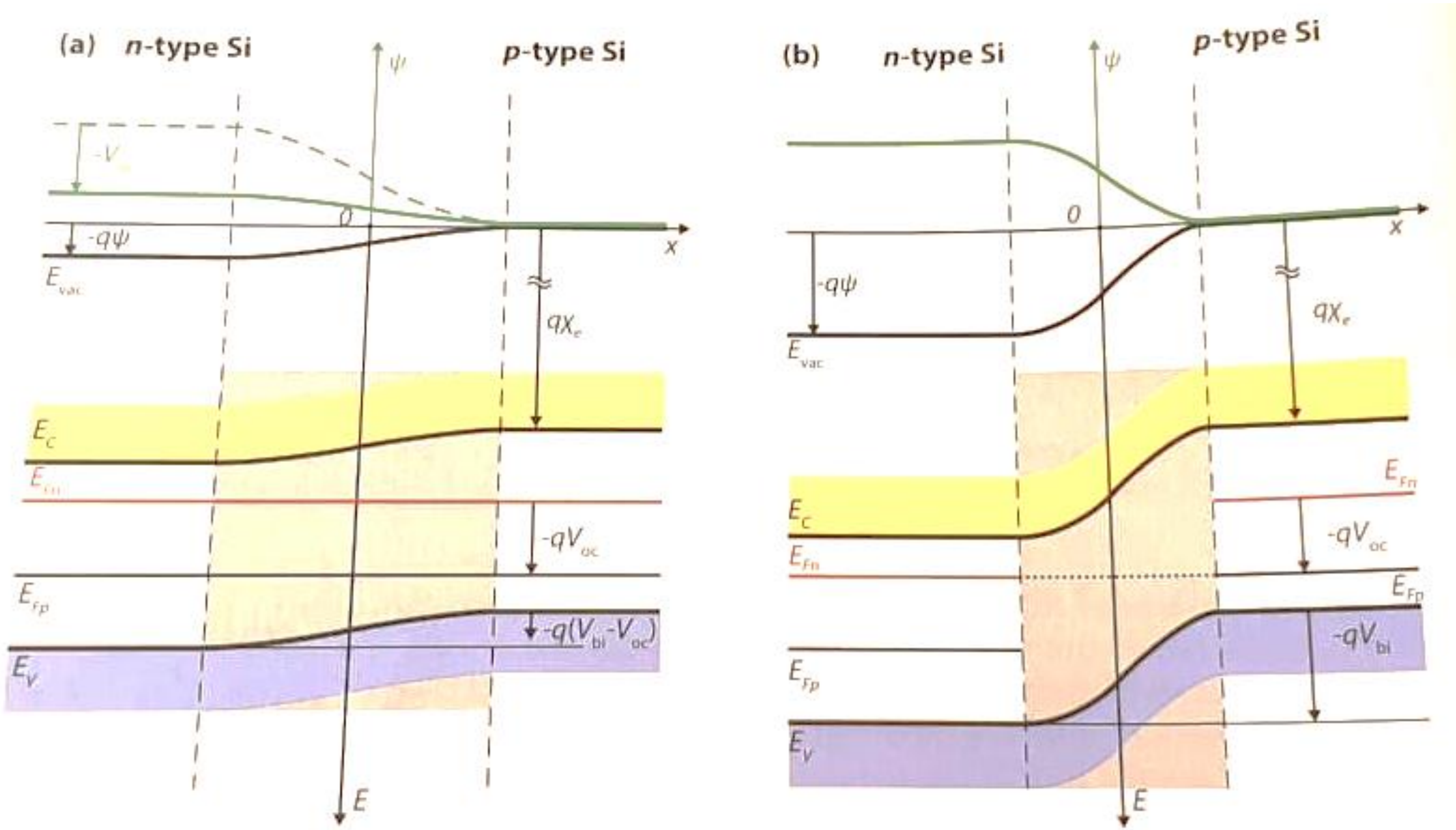
PV Effect



- A photo-generated electron has enough time to move freely and reach the np-junction before recombination.

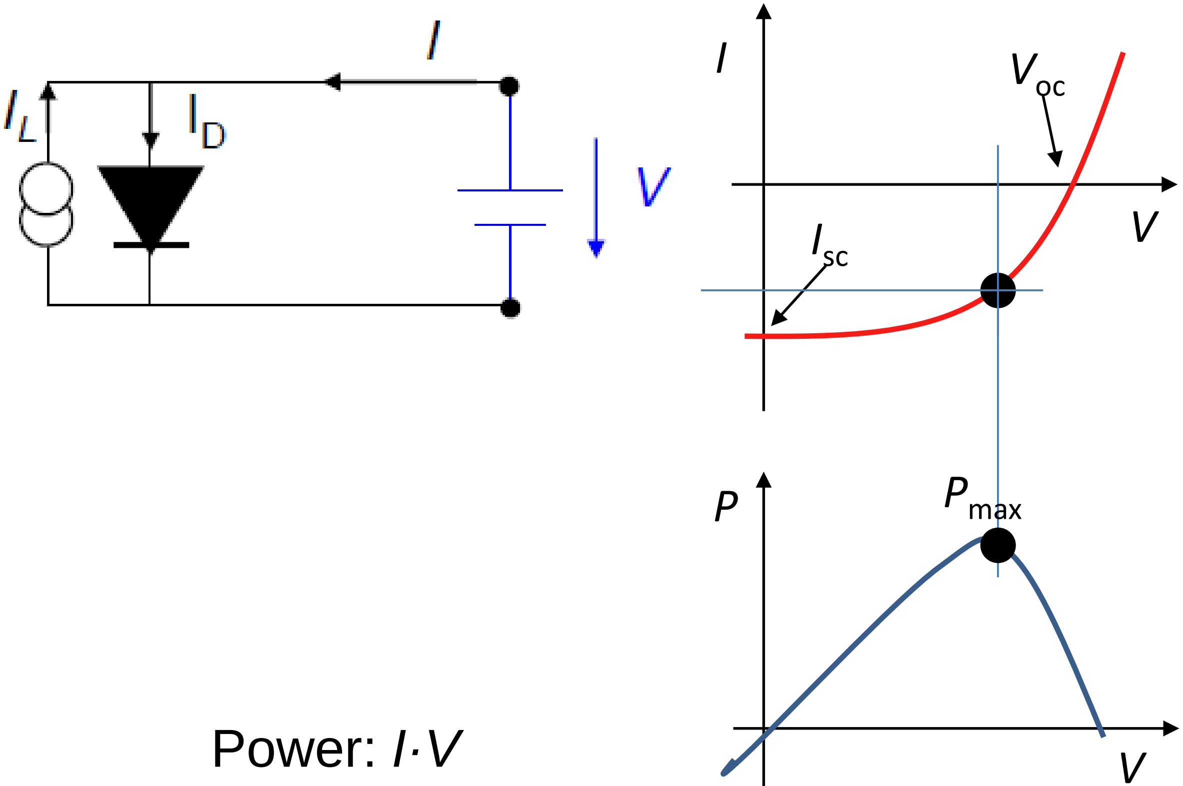
pn-Junction under Illumination

Open circuit | Short current



Performance

- pn-junction in a photovoltaic cell:
  - Light induced current



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

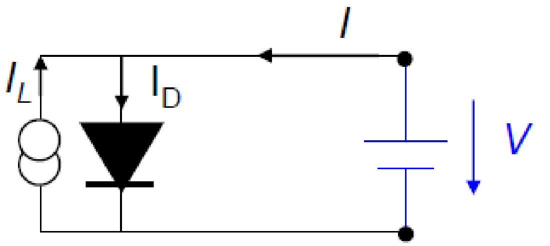
Power: $I \cdot V$

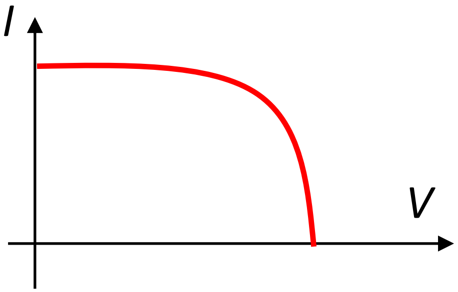
Maximum power: $I_{pmax} \cdot V_{pmax}$

Fill factor: FF= $I_{pmax} \cdot V_{pmax} / (I_{sc} \cdot V_{oc})$

Performance

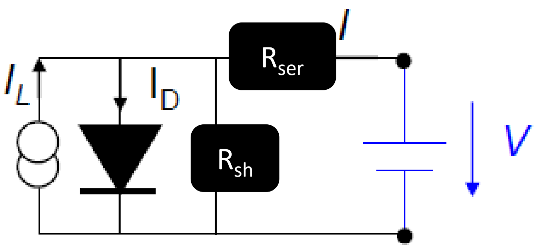
- pn-junction in a photovoltaic cell:
  - Ideal diode

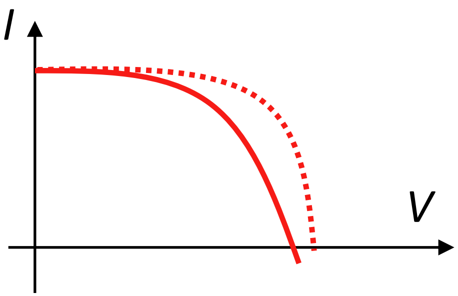




$$I = I_L - I_0\left(\exp\left(\frac{qV}{kT}\right) - 1\right)$$

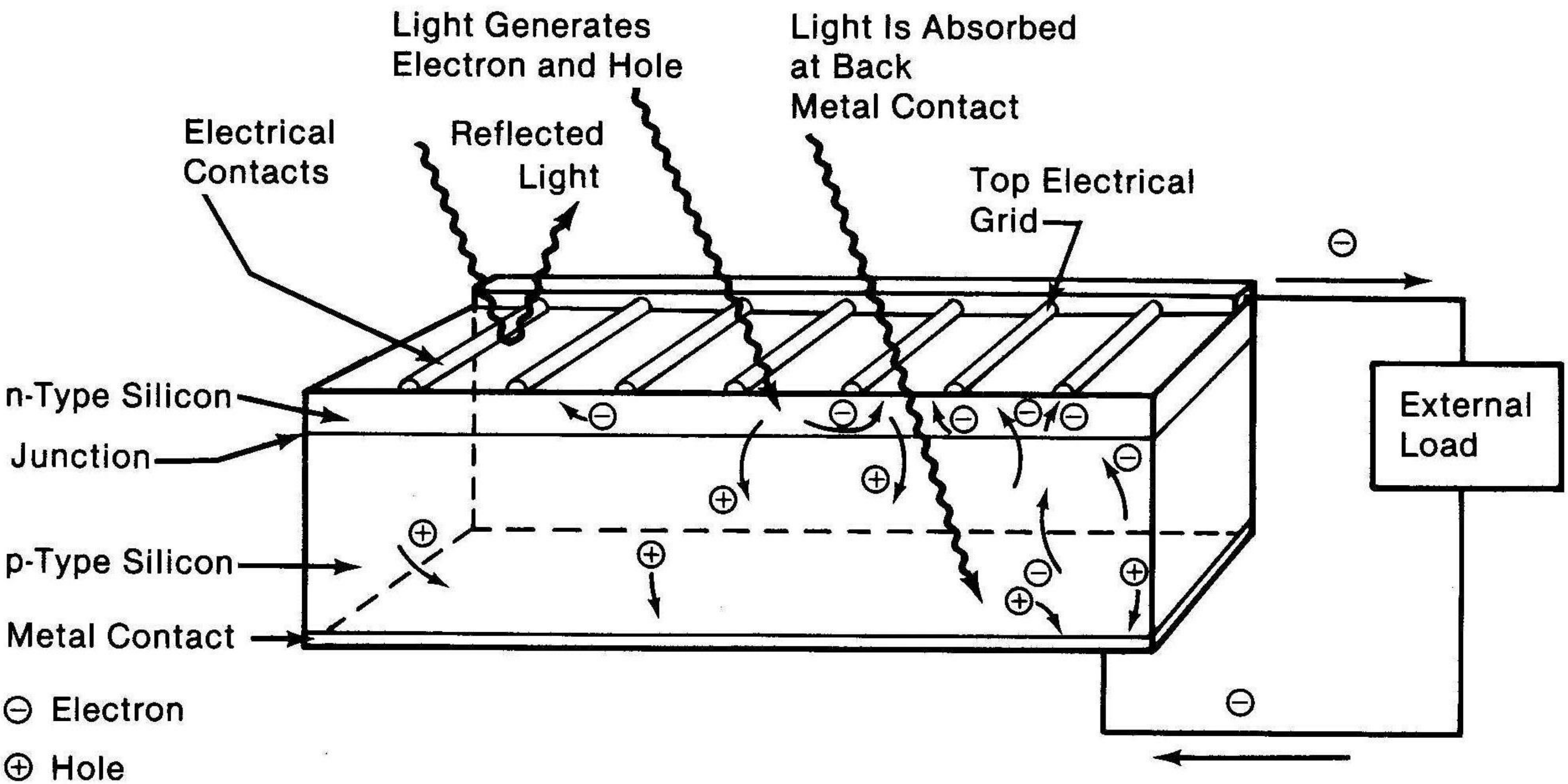
  - Realistic: parasitic resistances





$$I = I_L - I_0\left(\exp\left(\frac{qV + qiR_{ser}}{kT}\right) - 1\right) - \frac{V + iR_{ser}}{R_{sh}}$$

PV Effect



- Absorbed light generates electron-hole pair.
- Electron-hole pair are separated by the potential barriers.
- A voltage is created that induces an electrical current through an external load.

Band Gap Energy

$$E_{Ph,\lambda} = \frac{h \cdot c}{\lambda}$$

$$E_G = \frac{h \cdot c}{\lambda_G}$$

$c = 3 \times 10^8$ m/s

$h = 6.63 \times 10^{-34}$ J·s

1 eV $= 1.6 \times 10^{-19}$ J

Material	E_G in eV
Ge	0.7
$CuInSe_2$	1
Si	1.13
GaAs	1.42
CdTe	1.45
AlSb	1.55
$CuGaSe_2$	1.7
a Si (amorph)	1.7
$Al_{0.85}Ga_{0.15}As$	1.9
GaP	2.3
CdS	2.45

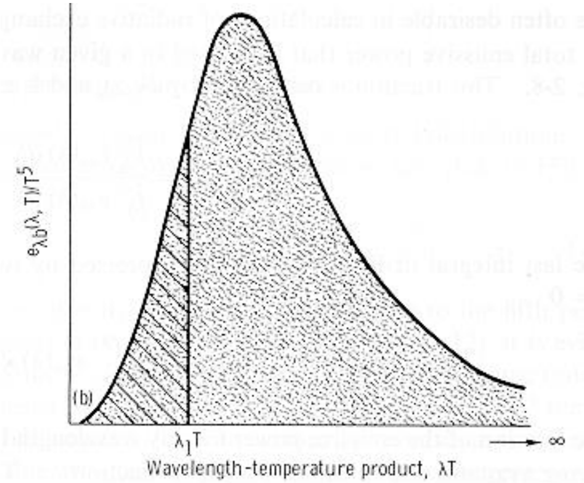
Ge → $\lambda_G = 1.78$ µm

Si → $\lambda_G = 1.13$ µm

CdS → $\lambda_G = 0.51$ µm

Fractional Function

$$F_{0-\lambda T} = \frac{\int_0^{\lambda} e_{\lambda b}(\lambda)\, d\lambda}{\sigma T^4}$$



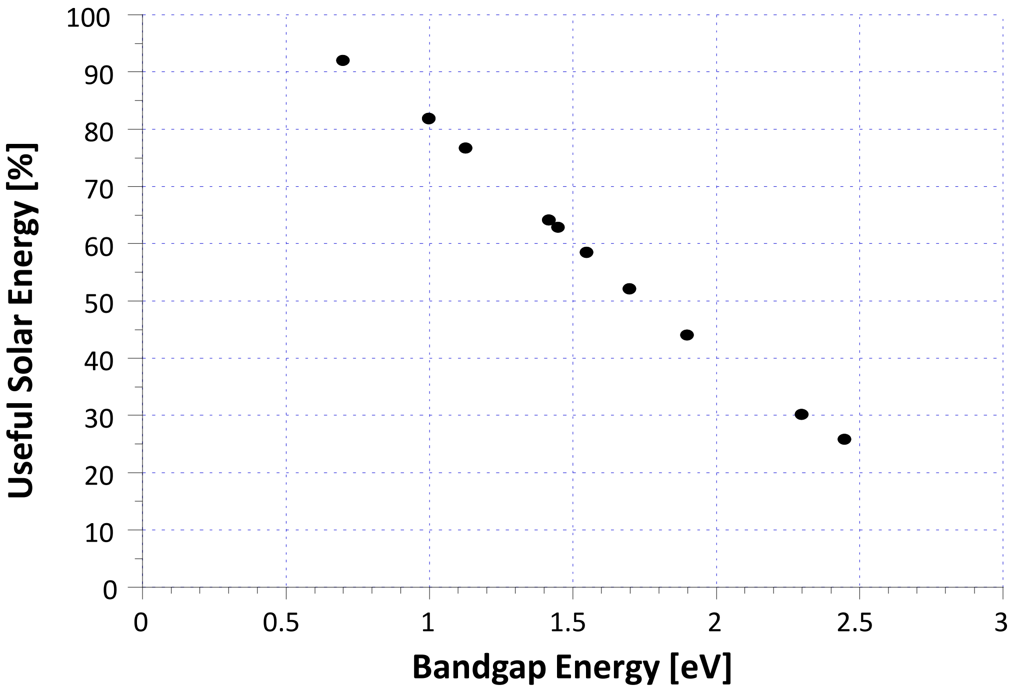
$$\left.\begin{aligned} \lambda_G &= 1.10\mu m \\ T &= 5780\ K \end{aligned}\right\} \rightarrow F_{0-\lambda T} = 77.9\%$$

Material	E_G [eV]	λ_G [μm]	$F_{0-\lambda T}$
Ge	0.7	1.78	91.9%
Si	1.13	1.10	77.9%
CdS	2.45	0.51	25.8%

Useful energy

Material	E_G	λ_G	useful	not useful
	[eV]	[mm]	[%]	[%]
Ge	0.7	1.78	91.94	8.06
CuInSe2	1	1.24	81.84	18.16
Si	1.13	1.10	76.62	23.38
GaAs	1.42	0.88	64.12	35.88
CdTe	1.45	0.86	62.81	37.19
AlSb	1.55	0.80	58.45	41.55
CuGaSe2	1.7	0.73	52.05	47.95
a Si	1.7	0.73	52.05	47.95
AlGaAs	1.9	0.65	43.98	56.02
GaP	2.3	0.54	30.12	69.88
CdS	2.45	0.51	25.80	74.20

$$F_{0-\lambda T} = \frac{\int_0^\lambda e_{\lambda b}(\lambda)\, d\lambda}{\sigma T^4}$$



Theoretical Efficiency

$$\eta = \frac{1}{\sigma T^4}\int_0^{\lambda_G}\left(\frac{E_G}{E_\lambda}\right) e_{\lambda b}(\lambda)\, d\lambda$$

$$= \frac{1}{\sigma T^4}\sum_{i=1}^{N}\left[\int_{\lambda_i}^{\lambda_{i+1}}\left(\frac{E_G}{E_{\lambda_m}}\right) e_{\lambda b}(\lambda)\, d\lambda\right]$$

$$= \sum_{i=1}^{N}\left[\frac{E_G}{E_{\lambda_m}}\left(\frac{\int_{\lambda_i}^{\lambda_{i+1}} e_{\lambda b}(\lambda)\, d\lambda}{\sigma T^4}\right)\right]$$

$$= \sum_{i=1}^{N}\left[\frac{E_G}{E_{\lambda_m}} F_{\lambda_i - \lambda_{i+1}}\right]$$

T = temperature of emitter (sun)

E_G = band-gap energy of PV

E_λ = energy of radiation

λ_m = mean of interval $[\lambda_i - \lambda_{i+1}]$

$\lambda_0 = 0$

$\lambda_N = \lambda_G$

Theoretical Efficiency – Example Si

$$E_G = \frac{h \cdot c}{\lambda_G} \rightarrow \begin{cases} E_G = 1.1\,\text{eV} \\ \lambda_G = 1.10\ \mu\text{m} \end{cases}$$

$$F_{\lambda_1-\lambda_2} = \frac{\int_{\lambda_1}^{\lambda_2} e_{\lambda b}(\lambda)\,d\lambda}{\sigma T^4}$$

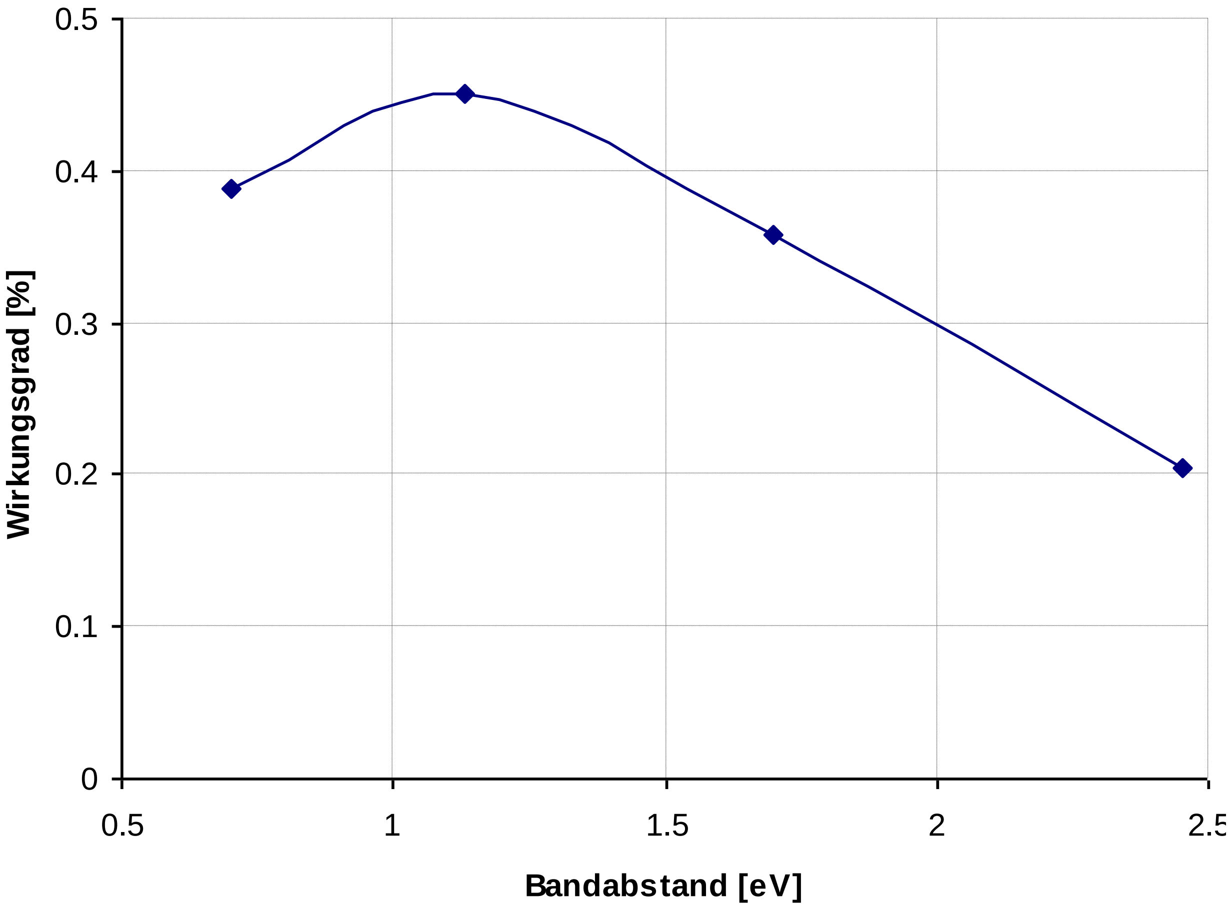
$$\frac{E_G}{E_\lambda} F_{\lambda_1-\lambda_2}$$

Interval	Band interval [μm] λ_{start}	λ_{end}	Mean in band λ [μm]	Energy [eV]	Energy portion $F_{\lambda_1-\lambda_2}$	Useful [%]
1	0.00	0.11	0.057	22.00	0.000	0.000
2	0.11	0.23	0.170	7.33	0.004	0.001
3	0.23	0.34	0.283	4.40	0.056	0.014
4	0.34	0.45	0.396	3.14	0.125	0.044
5	0.45	0.57	0.509	2.44	0.147	0.066
6	0.57	0.68	0.622	2.00	0.133	0.073
7	0.68	0.79	0.735	1.69	0.109	0.071
8	0.79	0.90	0.848	1.47	0.086	0.064
9	0.90	1.02	0.961	1.29	0.066	0.056
10	1.02	1.10	1.074	1.16	0.051	0.049
11	1.10	∞			0.221	0.000
Summe					1.000	**0.438**

$$\eta = \frac{1}{\sigma T^4} \int_0^{\lambda_G} \left(\frac{E_G}{E_\lambda} \right) \cdot e_{\lambda b}(\lambda)\,d\lambda \longrightarrow \eta = \sum_{\text{all intervals}} \left(\frac{E_G}{E_\lambda} \right) \cdot F_{\lambda_i-\lambda_{i+1}}$$

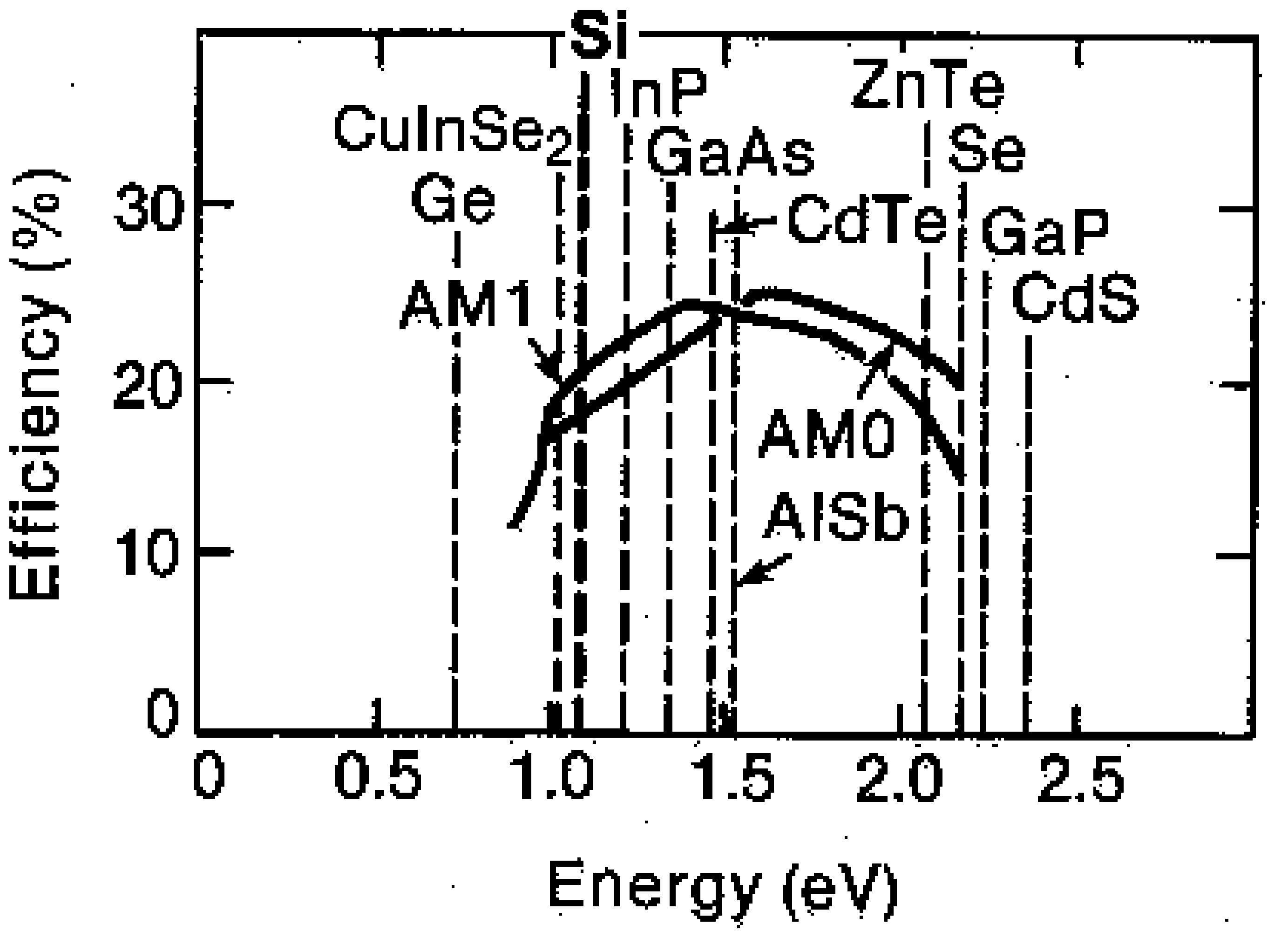
Theoretical Efficiency

	E_g	η
Material	**[eV]**	**[%]**
Ge	0.7	0.389
Si	1.13	0.45
a Si	1.7	0.358
CdS	2.45	0.204



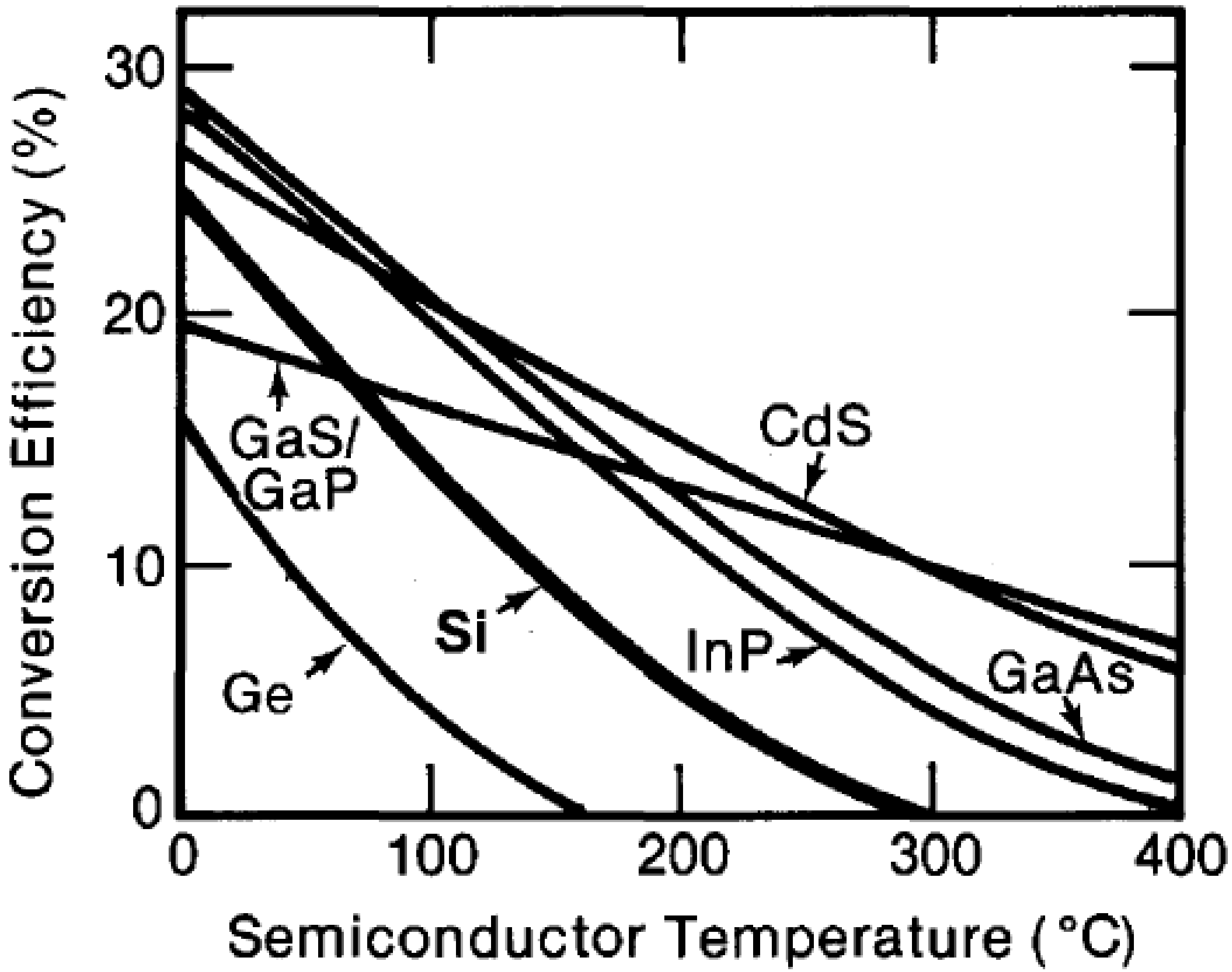
Theoretical Cell Efficiency

$$\eta = \frac{\text{Electrical power output}}{\text{Solar power input}}$$



Ref.: *Basic Photovoltaic Principles and Methods*, 1981.

Efficiency vs Temperature



• *Basic Photovoltaic Principles and Methods*, 1981.

Types of solar Cells

1st generation: wafer based

- mono/polycristalline Si
- mono/polycristalline III-V compounds: GaAs, InP, etc.

2nd generation: thin film

- I-II-VI compounds (Cu-(In,Ga)-$(Se)_2$), called CIGS
- II-VI compound (CdTe)
- amorphous/microcrystalline Si

3rd generation

- Multi-junction (e.g. III-V compounds: GaAs, InP, etc.)
- Dye-sensitized solar cells
- Perovskite
- Quantum dots
- Organic

Solar Cell Technology Evolution

1st generation:

Silicon wafer

Absorber thickness ~200 µm

Rigid

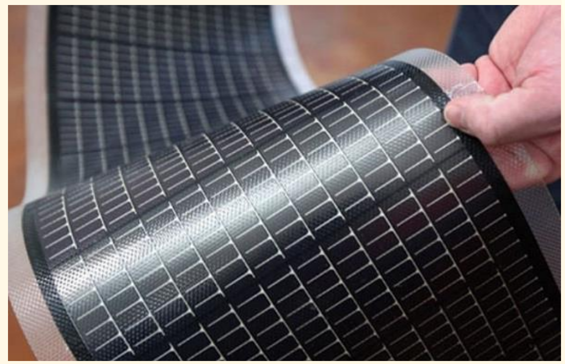
Heavy

>50 years old (mature):

90-95% market share

2nd generation:

Thin film



Absorber thickness <3µm

Rigid or flexible

Light weight

~40 years old (mature):

5-10% market share

3rd generation:

DSSC, Perovskite, QD, Organic, etc.

Absorber thickness <3µm

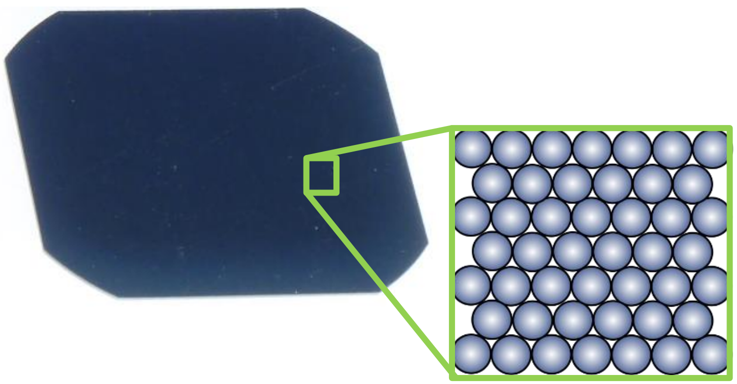
Rigid or flexible

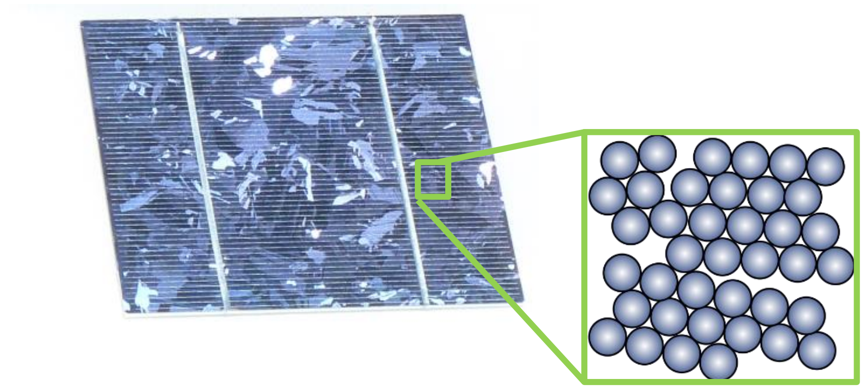
Light weight

<30 years old (research level)

Wafer Based Si Solar Cells

Single crystal (mono c-Si) vs **Polycristalline (poly c-Si)**

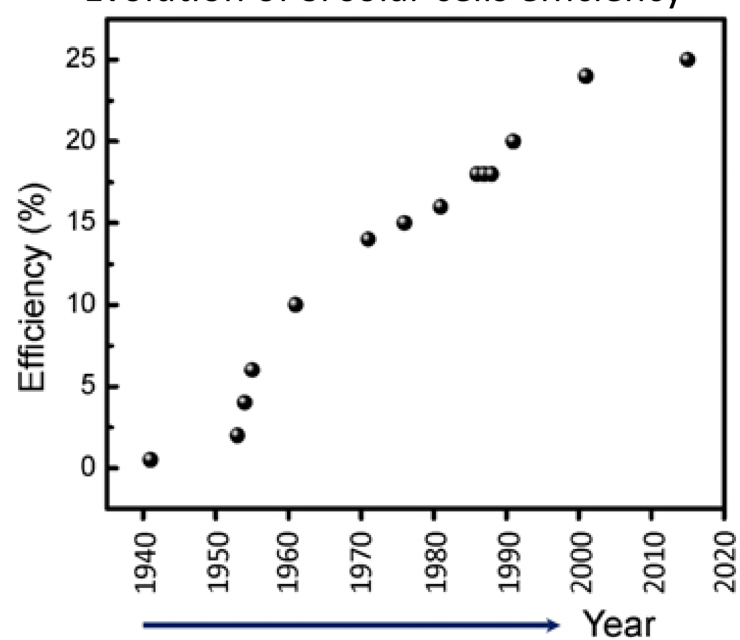




- **Polycrystalline.** Si crystals are oriented randomly, separated by grain boundaries, which introduces efficiency losses. Advantage: more efficient than poly c-Si (10-20% relative difference)

- **Monocrystalline-** Si crystals have no grain boundaries; losses within a solar cell are thus reduced. Drawbacks: more energy/expensive. Advantage: cheaper production than mono c-Si

Evolution of Si solar cells efficiency



Efficiency in 2020:

26.7% for mono c-Si (Kaneka)

23.8% for poly c-Si (Canadian Solar)

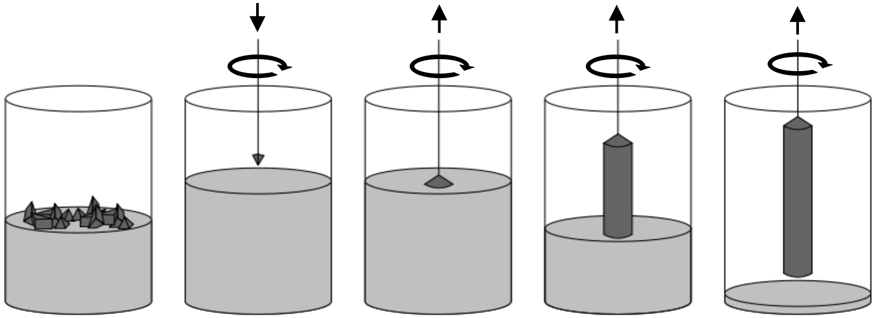
Images sources:
Wikimedia Commons
Aissa B. et al. Front. Nanosci. Nanotech. 2015

Wafer Based Si Solar Cells

Si wafer production

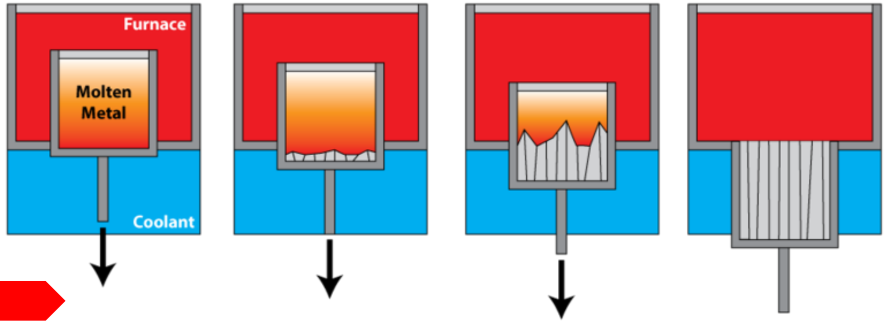
1. Metallurgical grade (98%) Si:
   - $SiO_2 + 2\,C \longrightarrow Si + 2\,CO$ in arc furnace at ~2000K
2. Semiconductor grade (99.999999999%) Si
   - $Si + 3\,HCl \longrightarrow SiHCl_3 + H_2$ at ~300°C with catalyst
   - Fractional distillation of $SiHCl_3$
   - $SiHCl_3 + H_2 \longrightarrow Si + 3\,HCl$ by chemical vapor deposition
3. Si crystals growth

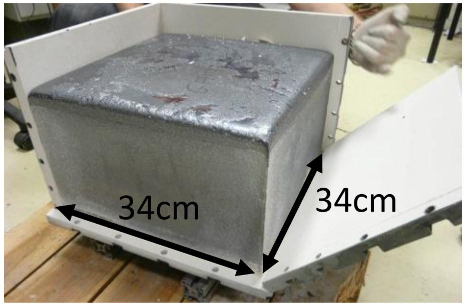
Example: Czochralski (CZ) method for mono c-Si



Crystal size >10cm

Example: Directional solidification (DS) for poly c-Si



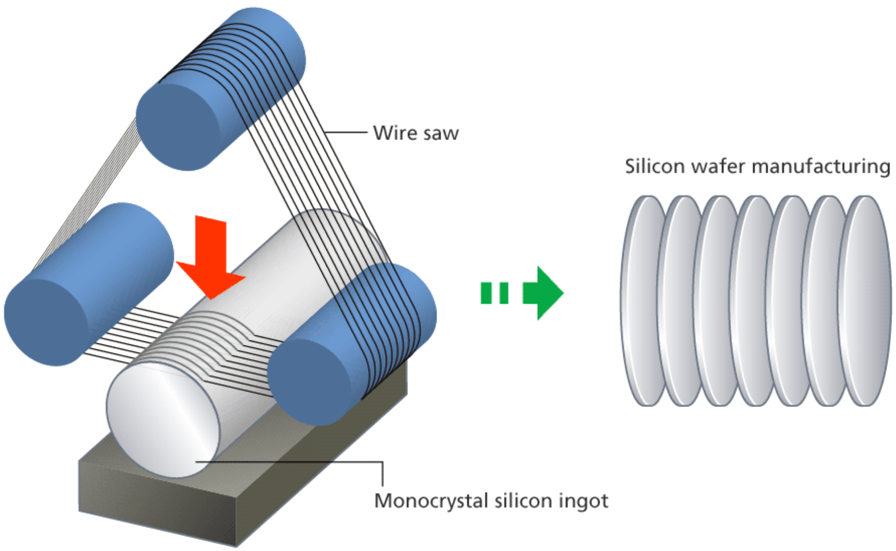


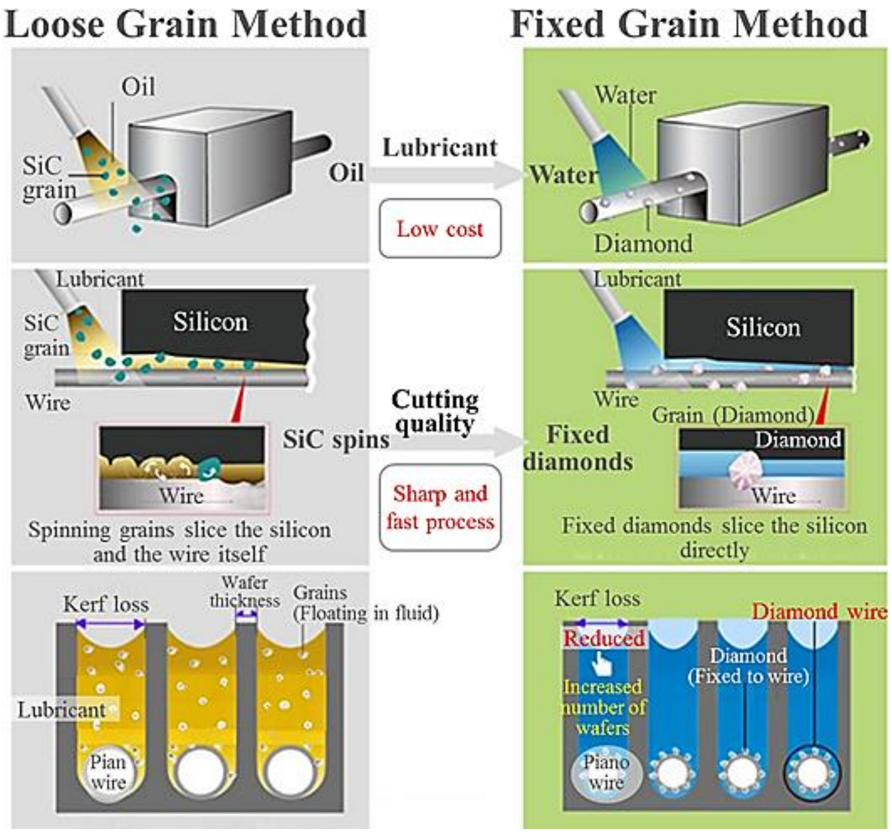
Crystals size 1μm-10cm

Images sources:
Wikimedia Commons
J. Mater. Sci. (2019) 54:11546–11555

Wafer Based Si Solar Cells

- Wafer cutting:





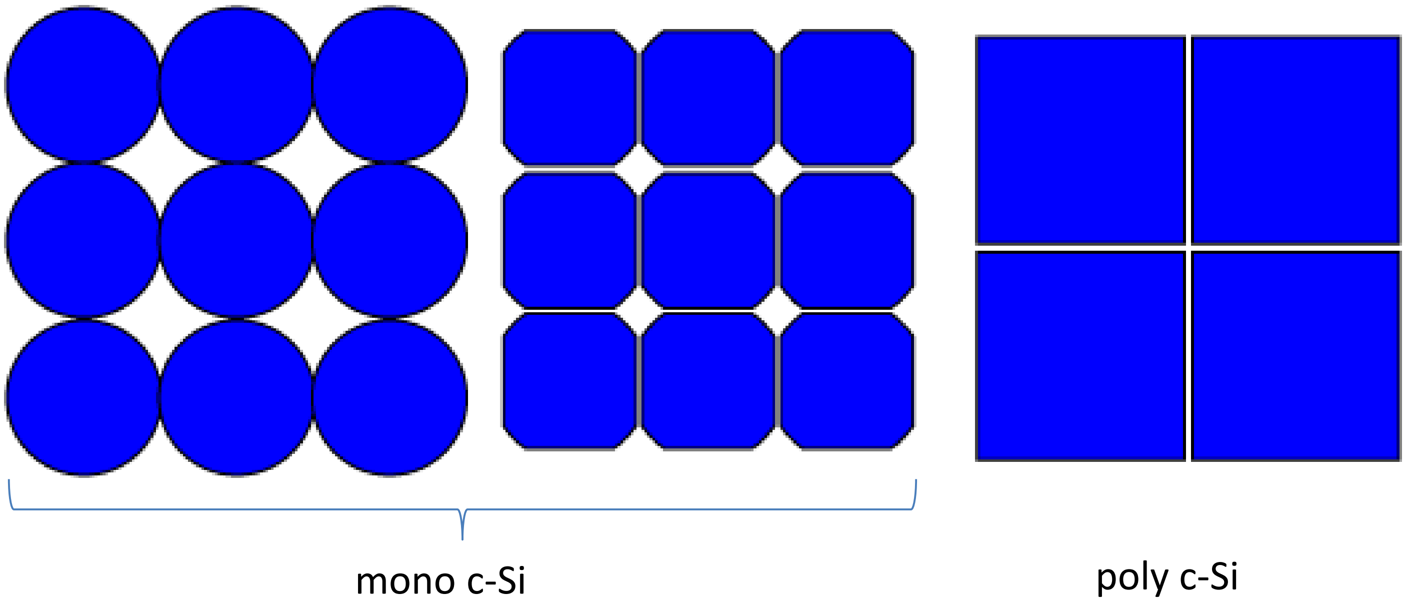
The residual debris is:

- about half of the initial Si ingot
- contaminated with impurities (cannot be recycled)

Images sources:
www.nikon.com
www.nakamura-gp.co.jp

Wafer Based Si Solar Cells

Packing of Si cells in modules

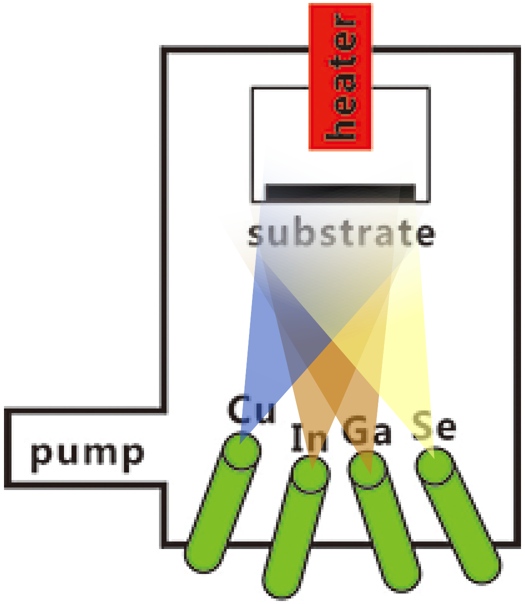


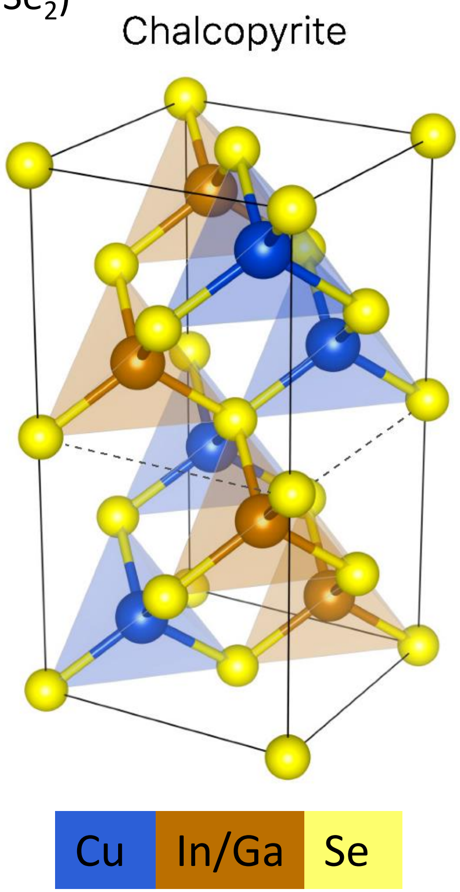
- The cylindrical single crystal ingots give a low packing density so the edges are cut off to produce semi-square cells and higher packing density.
- Polycrystalline material is cast in squares, enabling higher packing density than the ones of single crystal material.

CIGS Thin Film Solar Cells

- Tetragonal crystal structure (chalcopyrite) with formula: $CuIn_xGa_{(1-x)}Se_2$
- Tunable band gap with x, from about 1.0 eV ($CuInSe_2$) to about 1.7 eV ($CuGaSe_2$)
- Typically produced by co-evaporation in vacuum
- Large coating area on different substrates: glass, metal, plastic
- CIGS thin film cell efficiency is 23.35% (Solar Frontiers, 2020)

(ETH spin-off)

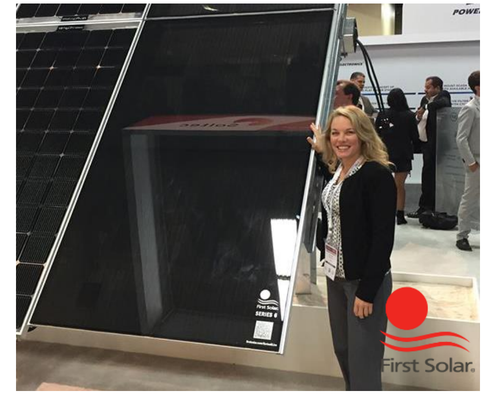




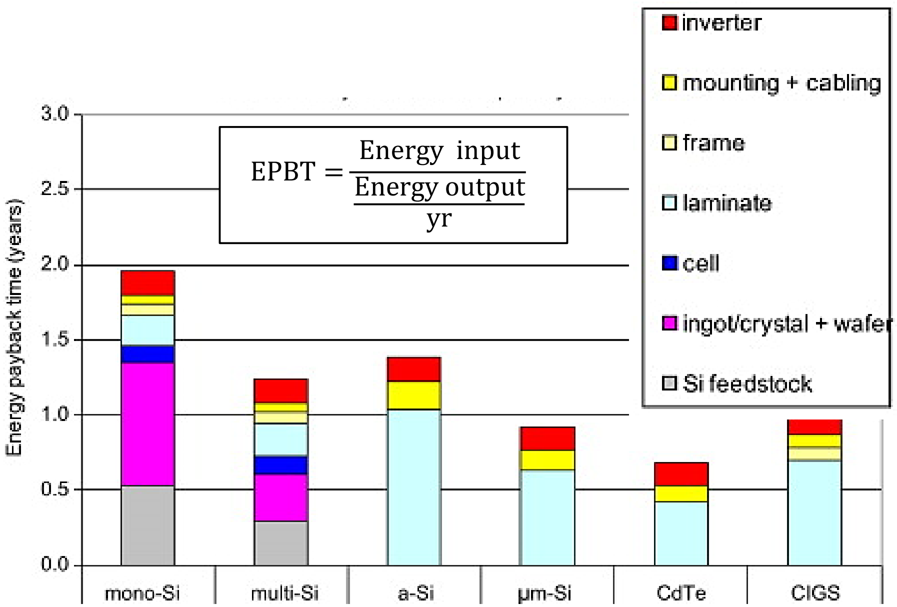
Images sources:
Minerals (2019), 9(4), 227
Tang Y. (2017) Nanostructured Solar Cells
Flisom (2019)

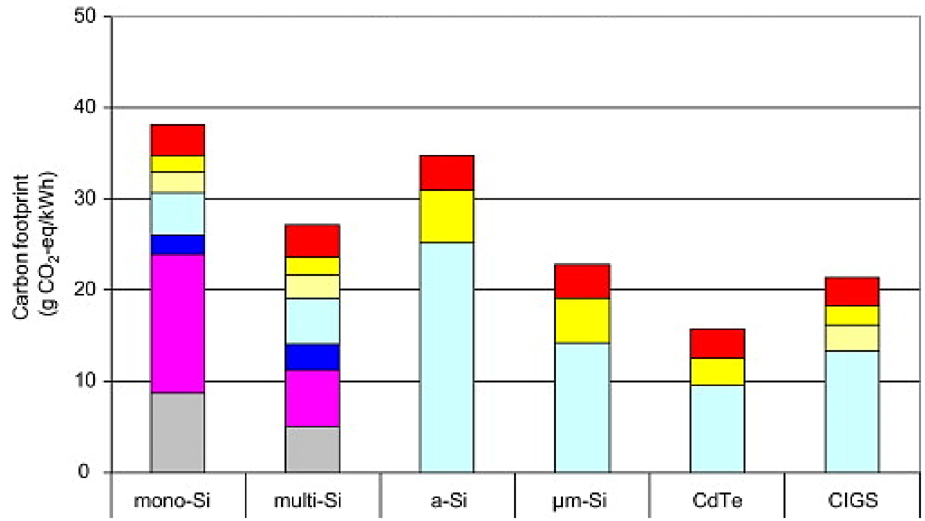
CdTe Thin Film Solar Cells

- Smaller energy payback time, carbon footprint and water use than any other solar cell type[1]
- Efficiency of CdTe solar cell is 21.0% (First Solar, 2020)
- Both Cd and Te are toxic → CdTe modules must be recycled of at the end of the life time
- Both Cd and Te are rare elements → limiting factor to the industrial scalability



420-450W module (Series 6, First Solar)



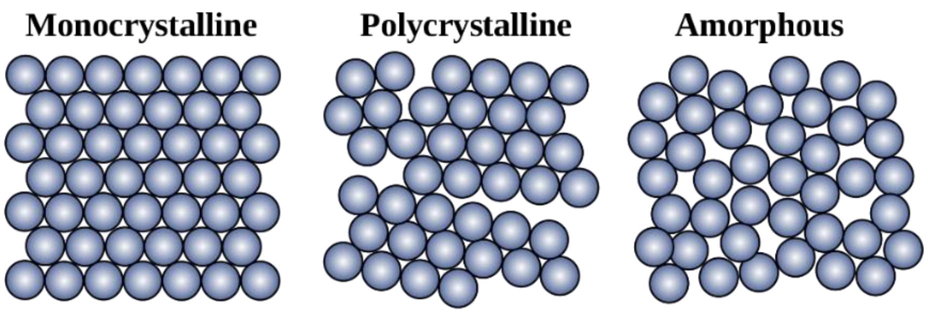


[1] Renewable and Sustainable Energy Reviews, (2013) 19: 255-274

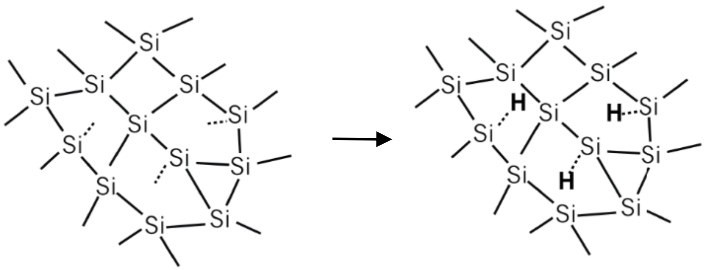
Images sources:
Solar Energy Materials & Solar Cells (2013) 119, 296-305
First Solar (2017)

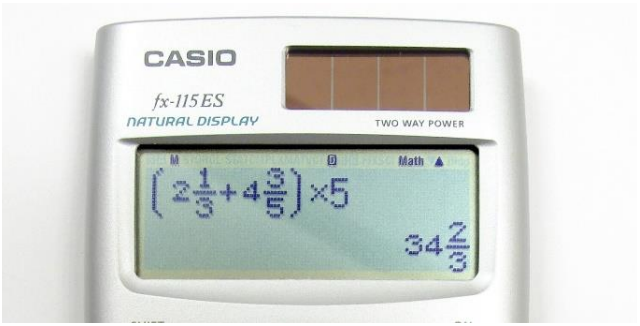
Amorphous/Microcrystalline Si

Type of Si	Grain Size
Single crystal (mono c-Si)	>10cm
Polycrystalline (poly c-Si)	1µm -10cm
Microcrystalline (µm c-Si)	<1µm
Amorphous (a-Si)	1-10nm



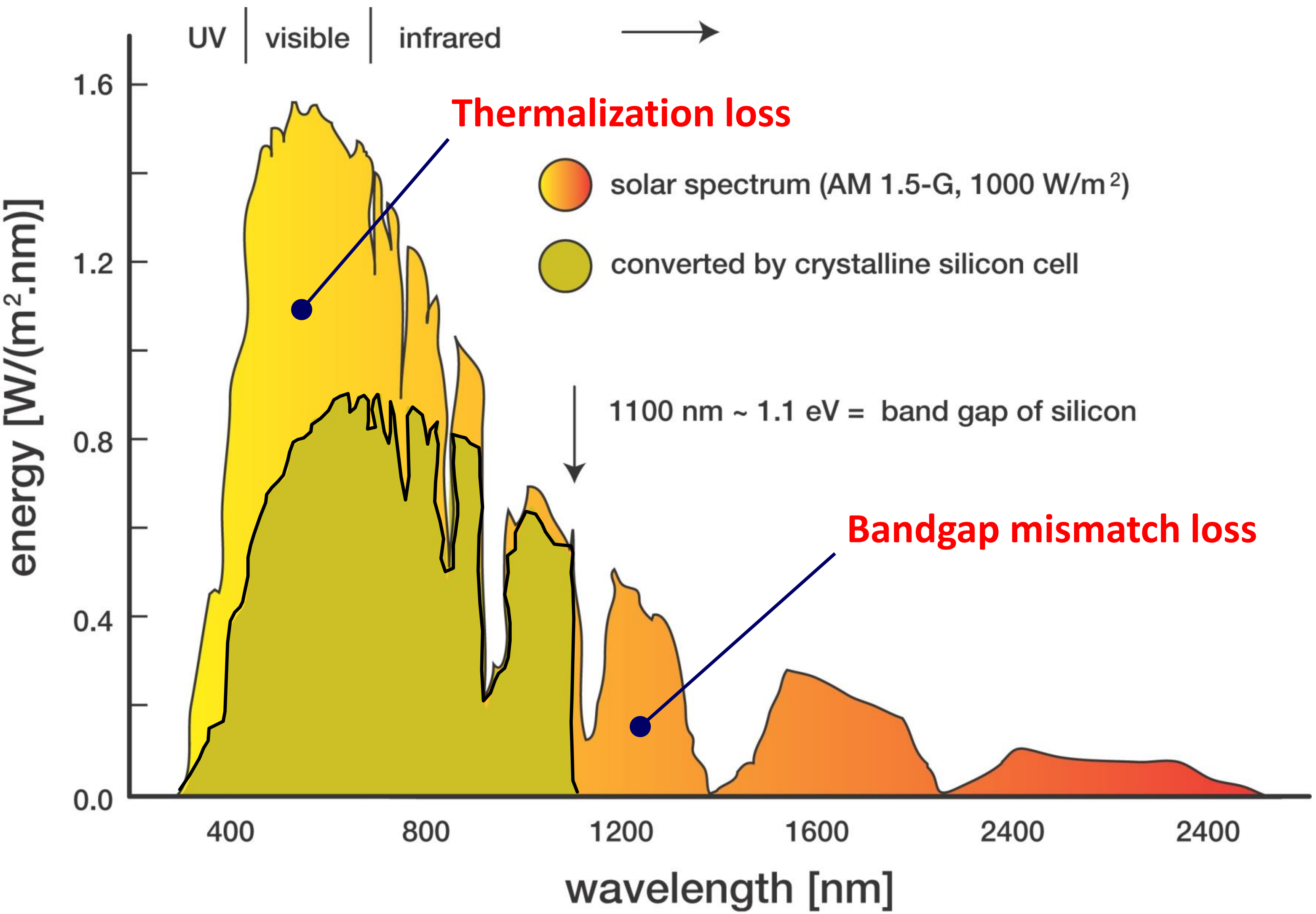
- Presence of dangling bonds (unsatisfied valences)
- Passivation of a-Si with H_2 (5-10%) to give a-Si:H
- Efficiencies: 10.2% for a-Si and 11.9% for µm c-Si (AIST, 2020)
- Typically produced by chemical vapor deposition on different substrates: glass, metal and plastic
- Less Si (About 99%) and less energy-intensive manufacturing than wafer based Si solar cells



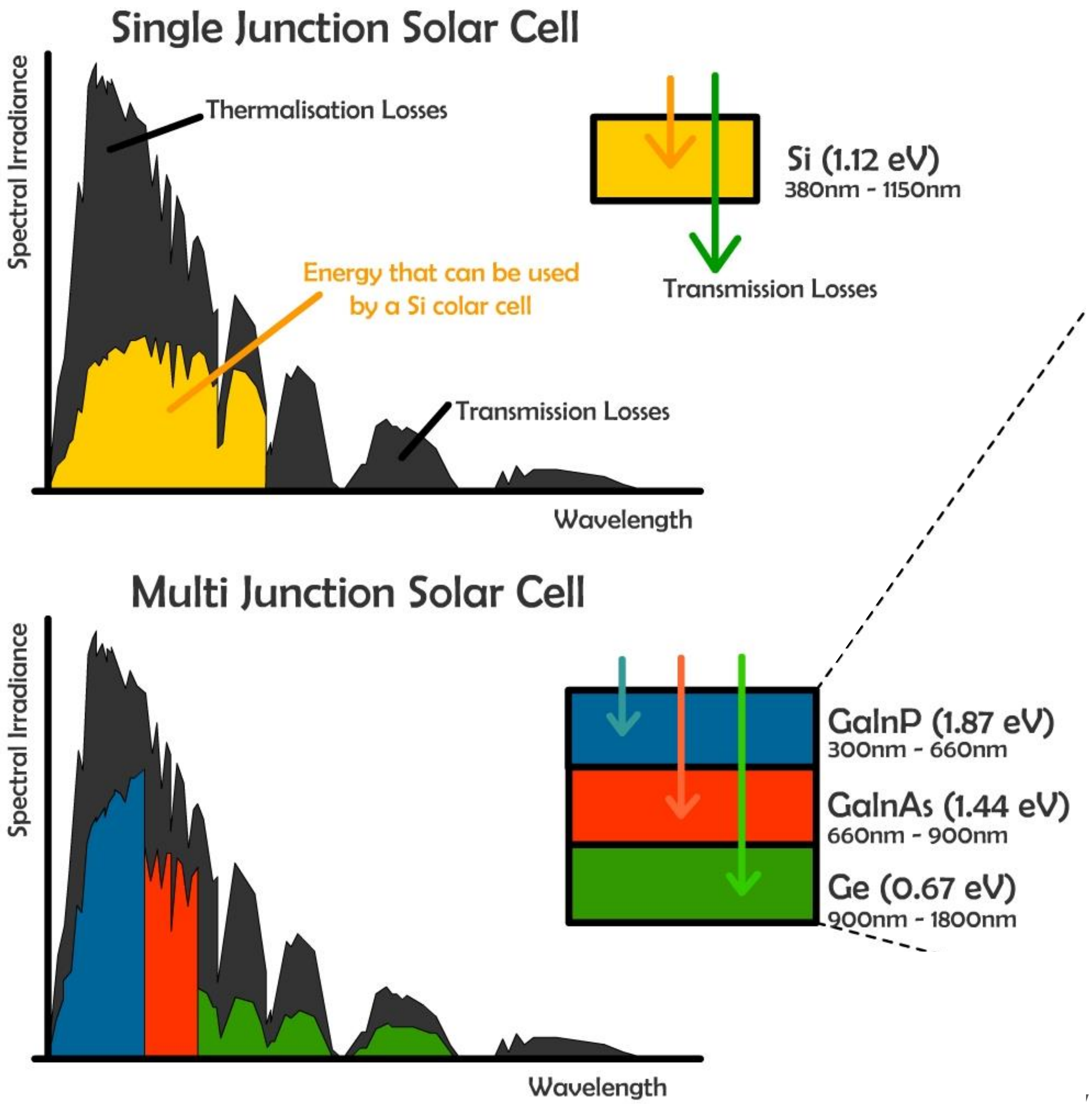


Images sources:
Wikimedia Commons
Vora Ankit (2015), PhD thesis, MTU

Single-junction PV Cells

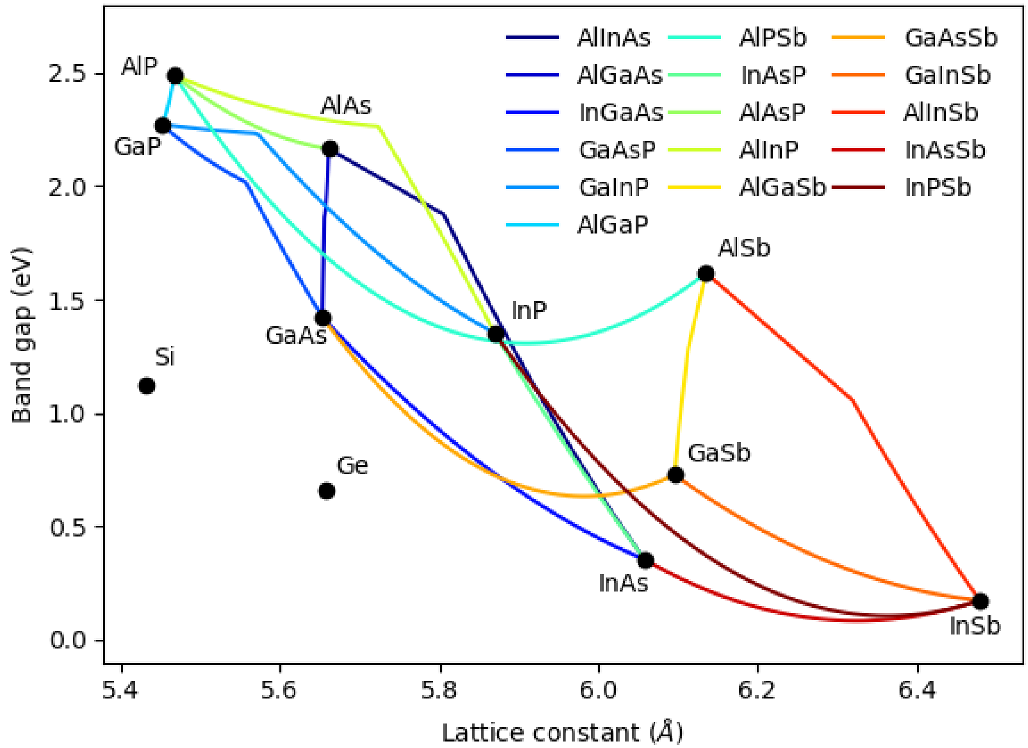


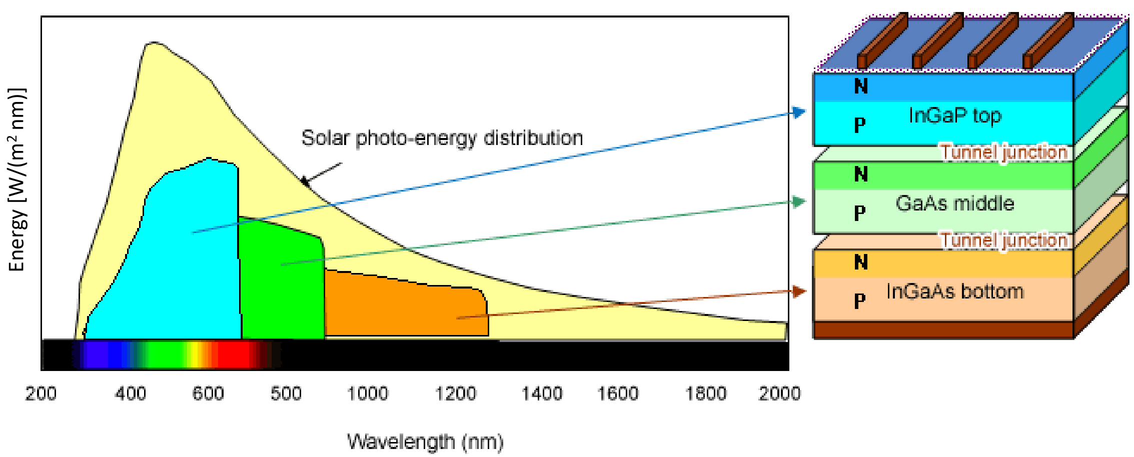
Single-junction PV Cells



III-V Compounds Solar Cells

- Tunable band gap by changing elements in the solid solution → large application in multi-junction cells.
- Can be manufactured in wafer (e.g. via CZ and DS methods) or thin film (e.g. via metalorganic chemical vapour deposition)
- High materials and manufacturing costs limit large-scale commercialization
- GaAs thin film cell features the highest efficiency for a single-junction cell, equal to 29.1% (Alta Devices, 2020)

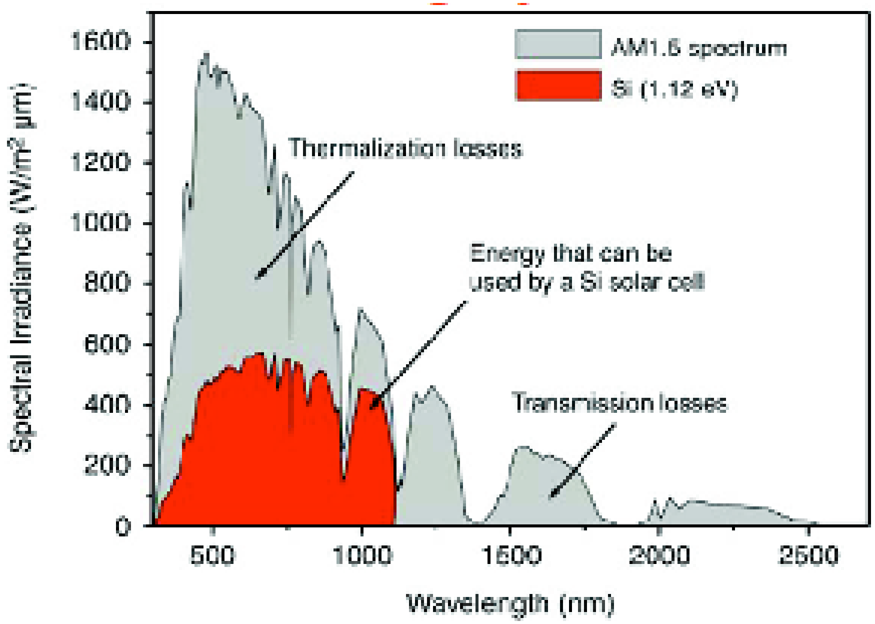




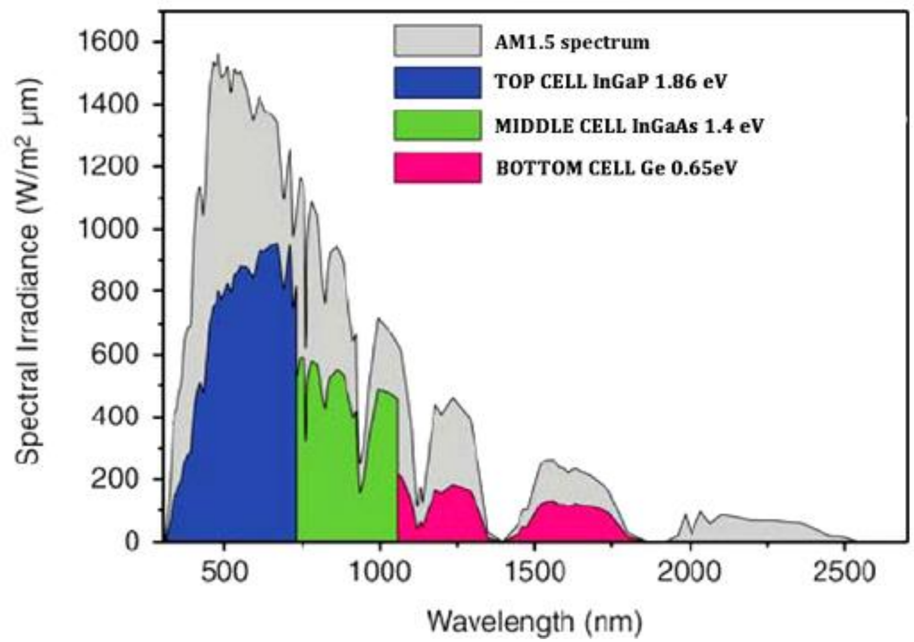
Images sources:
www.docs.solcore.solar
www.global.sharp

Multi-junction PV cells

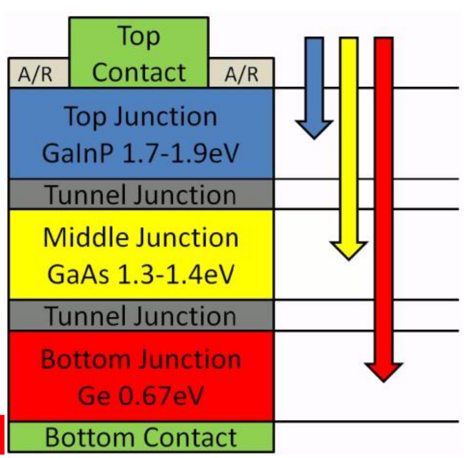
Si single-junction

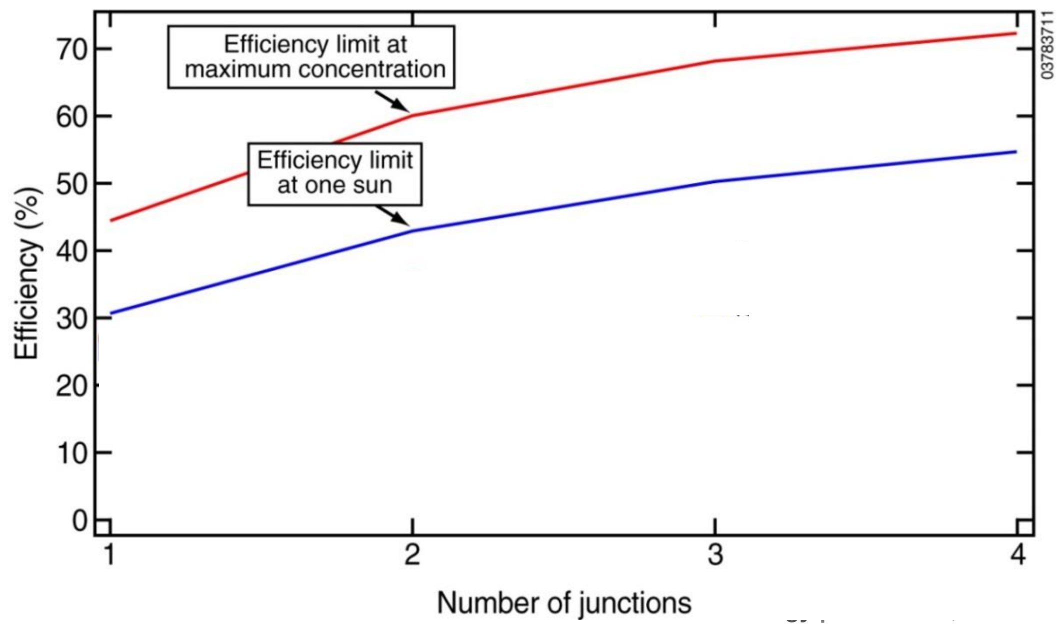


triple-junction



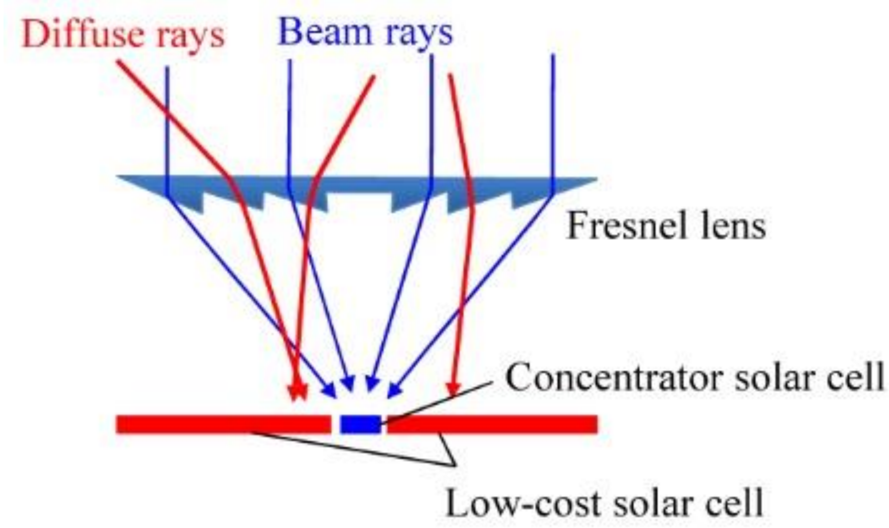
- Concentrated PV
- Cells with band-gaps matched to incoming wavelength

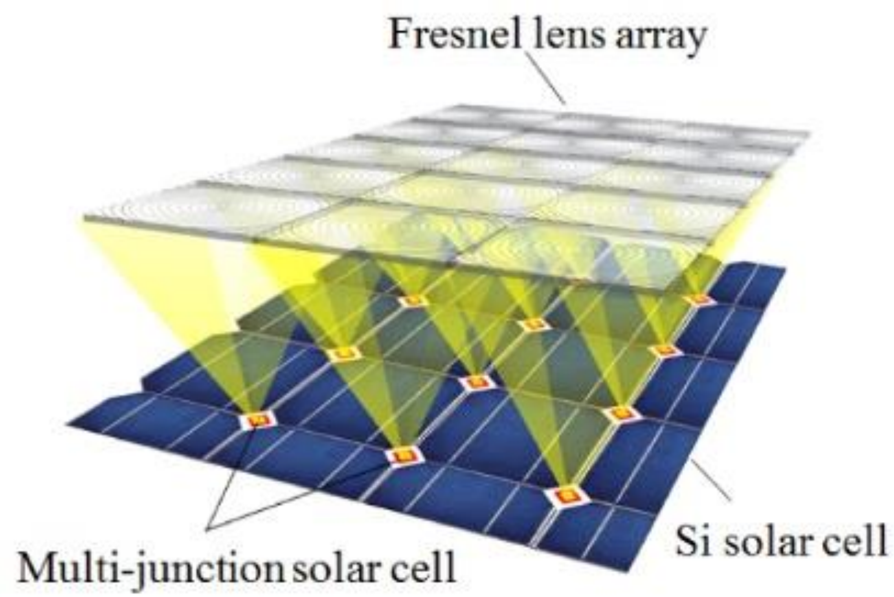


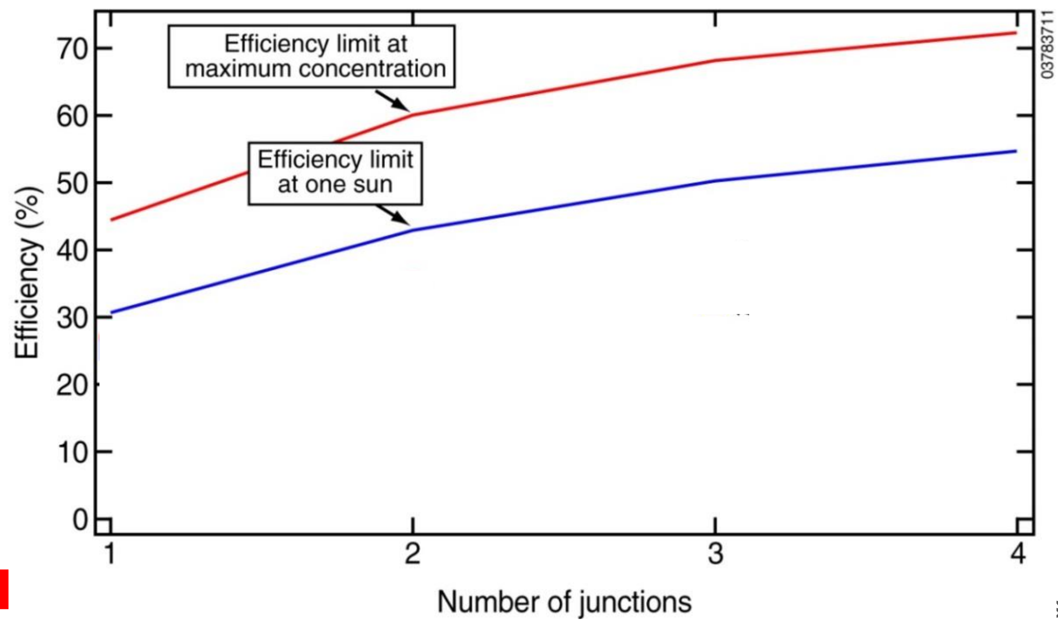


Multi-junction PV Cells

Concentrated PV

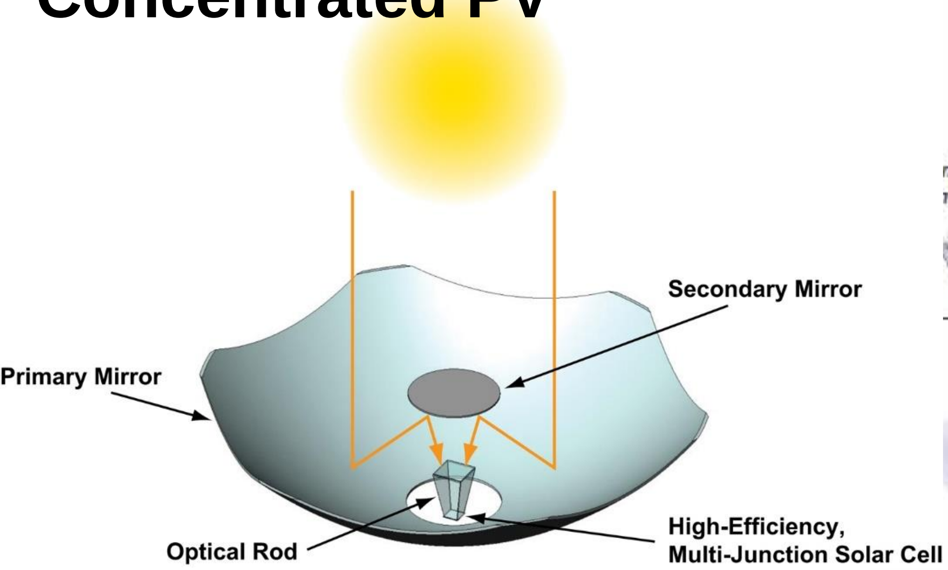


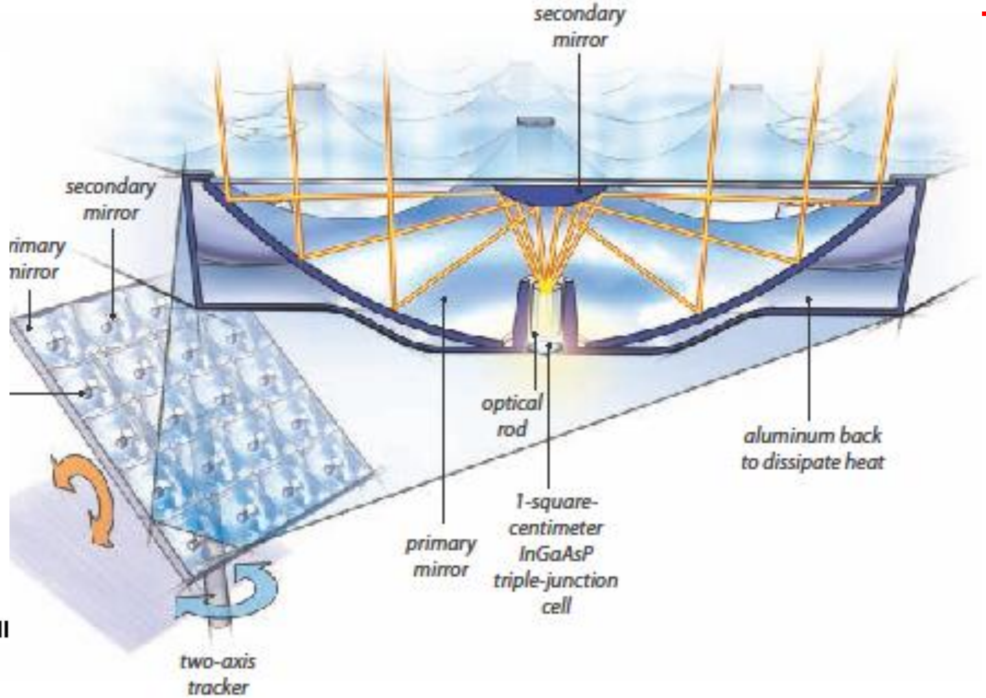




Multi-junction PV Cells

Concentrated PV

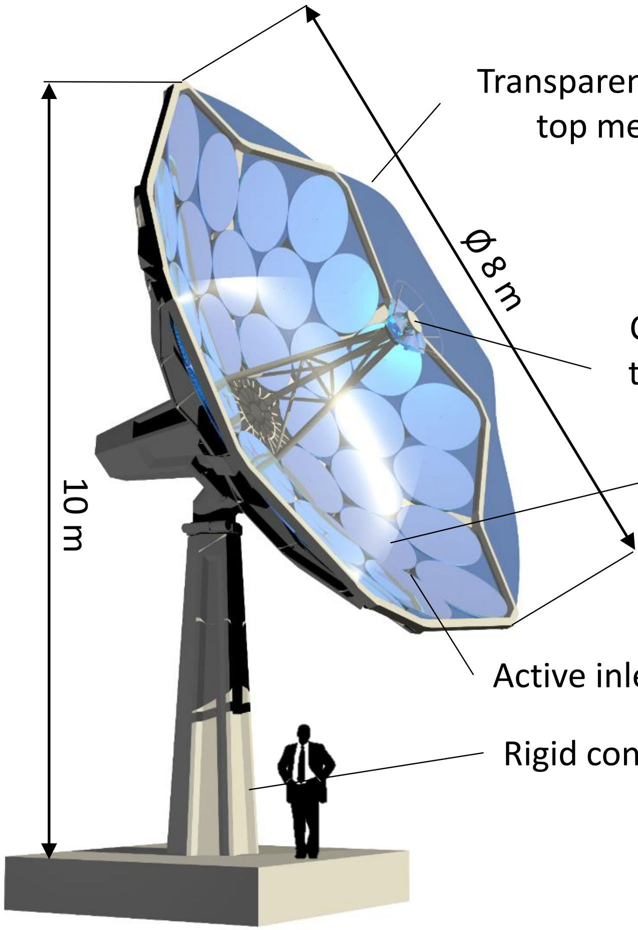


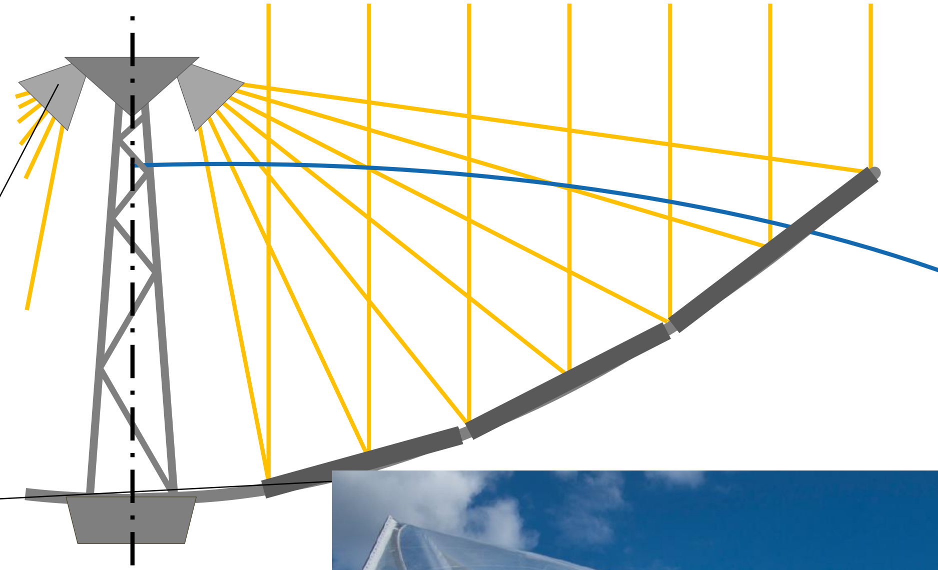


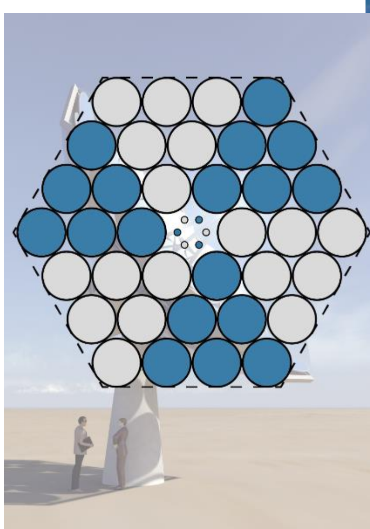
Images sources:
www.solfocus.com

Multi-junction PV Cells

Concentrated PV





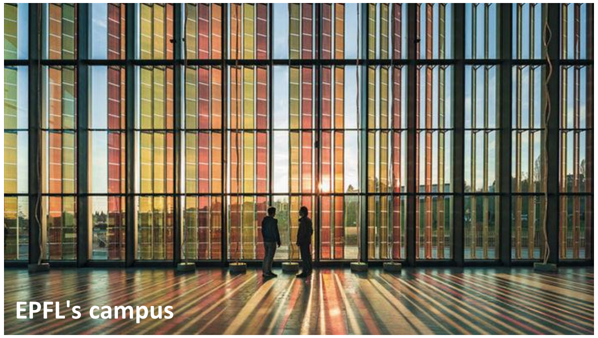


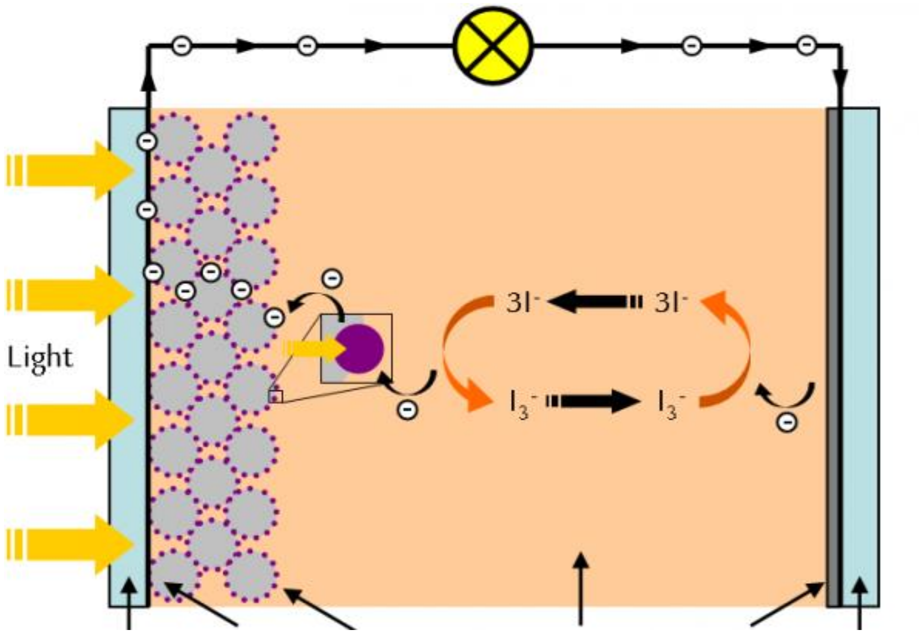
Source: https://prec.ethz.ch/research/solar-power.html

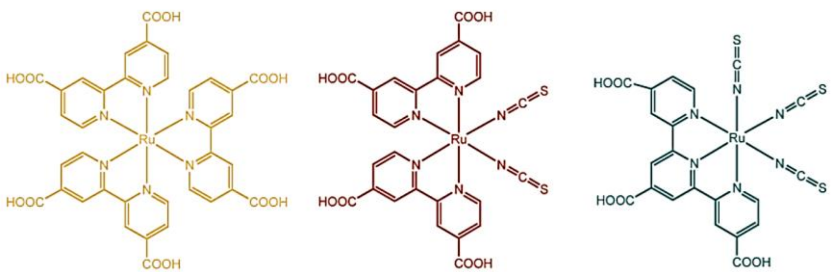
- Size: 12 kW electrical and 21 kW thermal @ 90ºC
- Efficiency: ~30% electrical + ~50% thermal
- Microchannel cooled CPV receiver
- Key Aspects: concrete structure, inflatable mirrors

Dye-sensitized Solar Cells (DSSC)

- Also known as “Grätzel cell” invented by Grätzel and O'Regan in 1991 (7.9% efficiency)
- Tunable dye absorption by varying the metalorganic dye molecules
- Degradation of organic dye and electrolyte due to oxidation, UV radiation and temperature
- Semi-flexible and semi-transparent cells
- Efficiency of DSSC cell is 12.25% (EPFL, 2020)





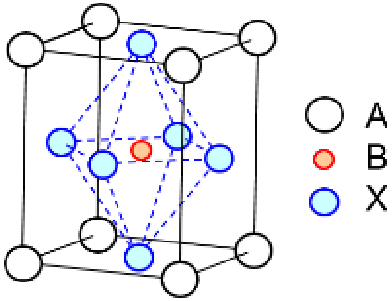


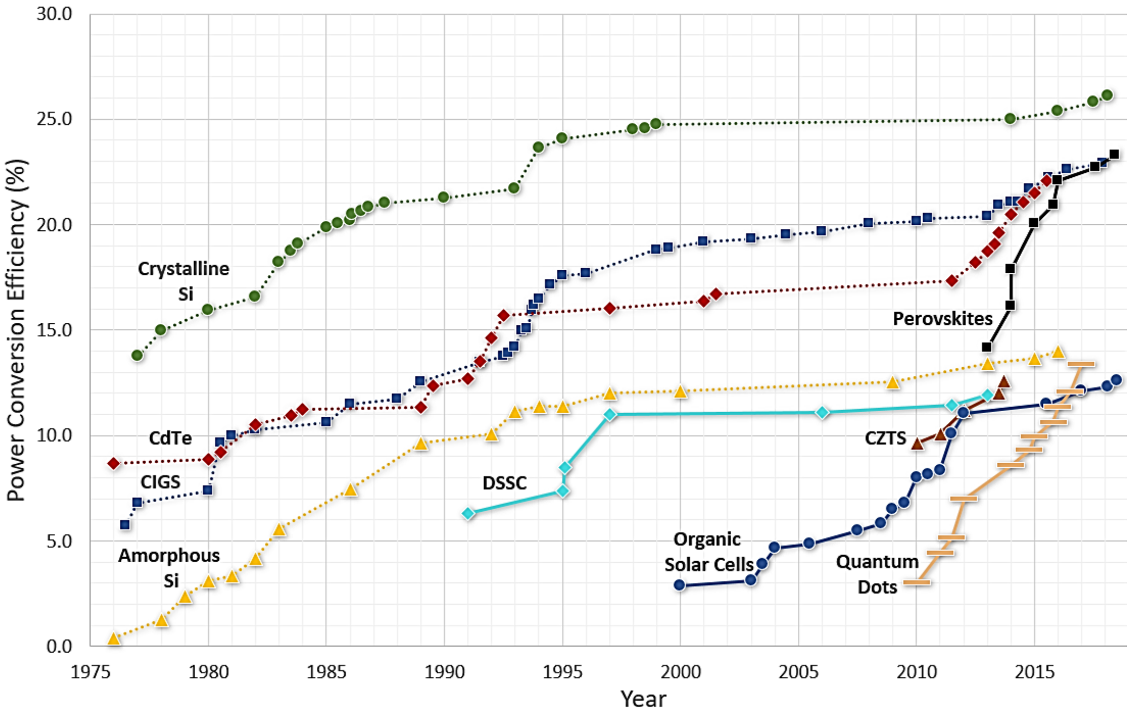
Images sources:
www.gamry.com
Inorg. Chem. 2005, 44, 6841–6851
www.sciencemag.org

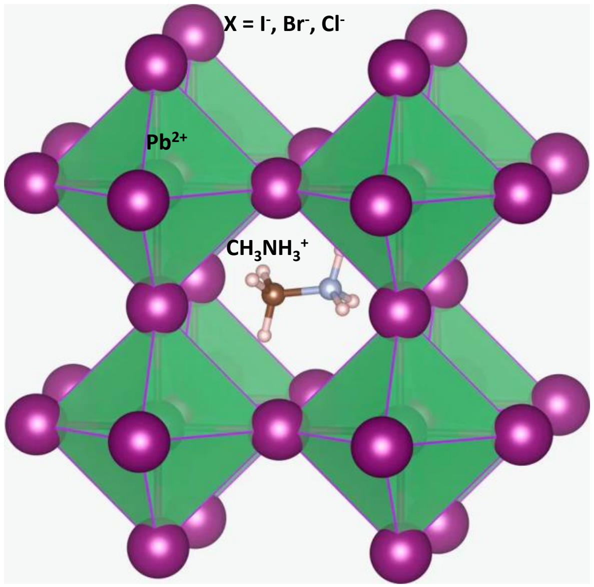
Perovskite Solar Cells

- Perovskites: any materials with orthorhombic crystal structure as $CaTiO_3$. ABX_3
- Most studied absorber are methylammonium lead trihalides: $CH_3NH_3PbX_3$
- High crystallinity and large grains
- Fastest advanment among solar cell technologirs
- Low-cost production methods (spin coating, inkjet printing, vapor deposition, etc.)
- Efficiency of perovskite solar cell: 25.2% (KRICT/MIT, 2020)

General formula:



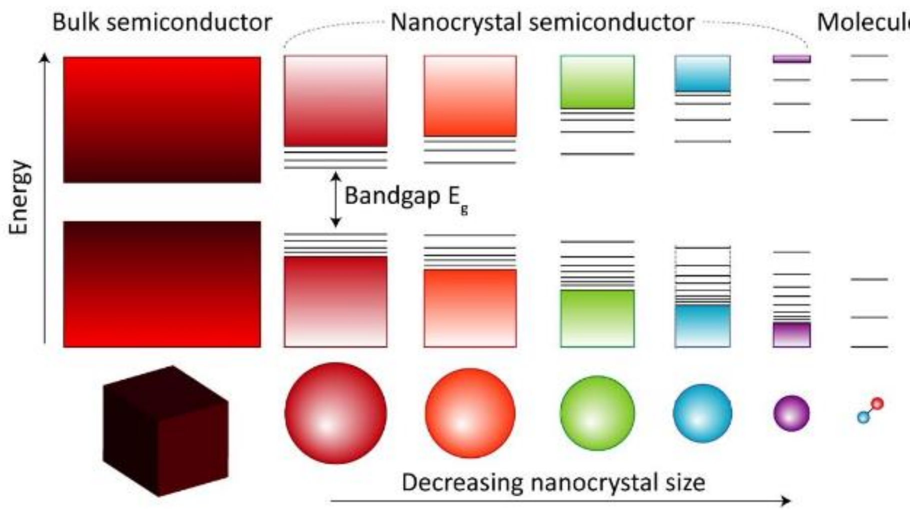


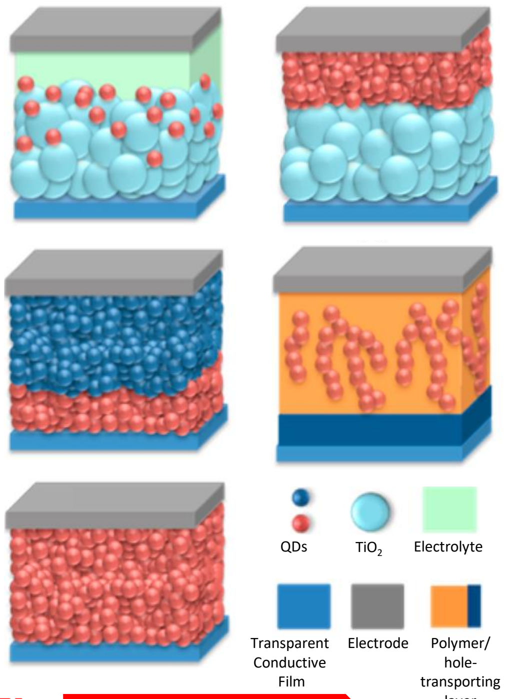


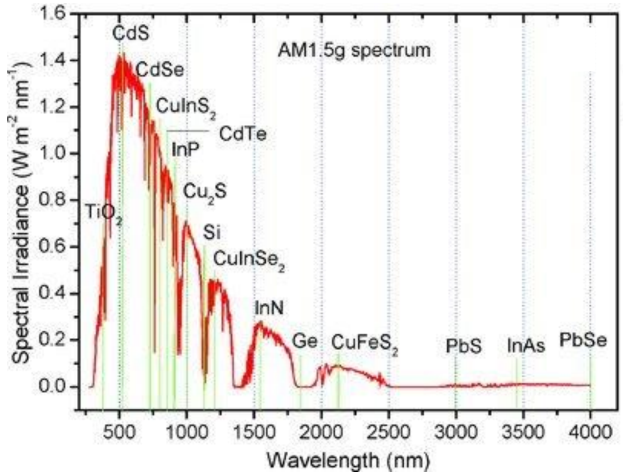
Images sources:
www.helmholtz-berlin.de
www.ossila.com
Eames C. (2015) Nature Communications

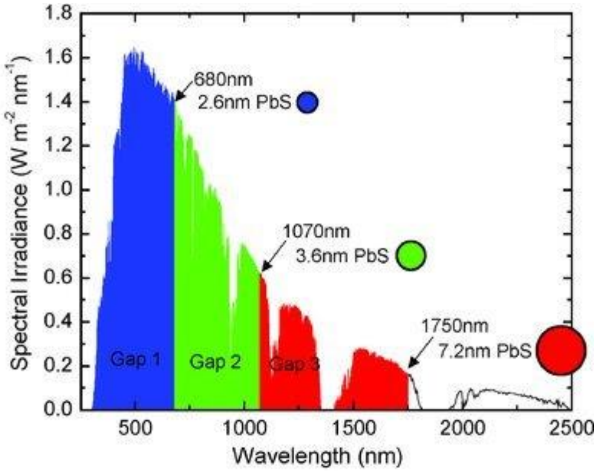
Quantum Dots (QD) Solar Cells

- At bulk level → band gap fixed by the choice of material
- At the nanoscale → discretization of energy levels (quantum confinement effect)
- Tunable band gap by changing particle size
- Efficiency of quantum dot solar cell: 16.6% (Univ. of Queensland, 2020)





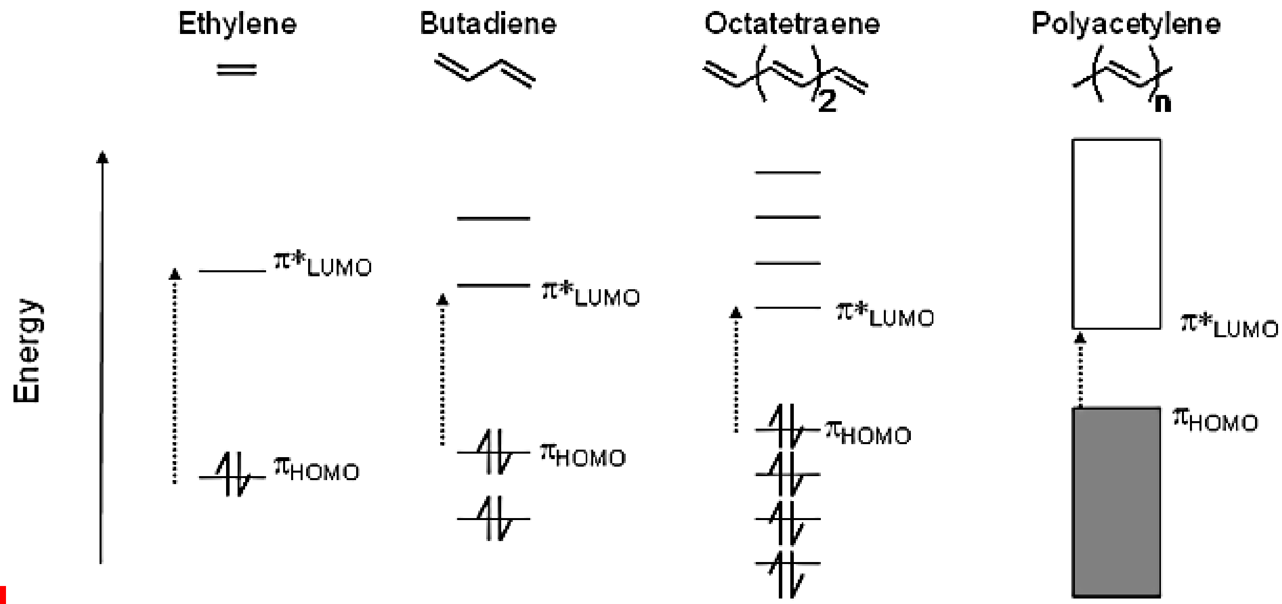




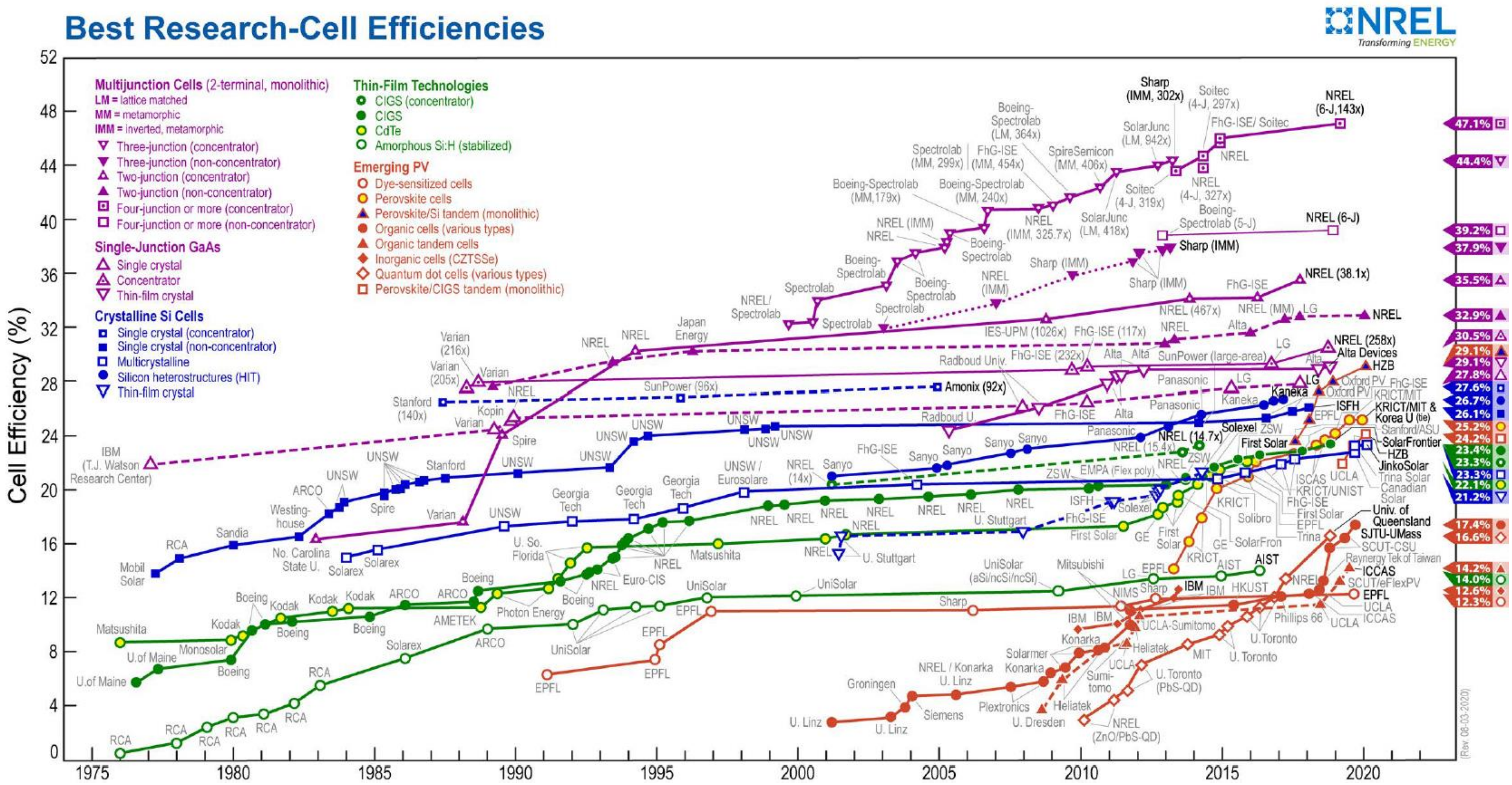
Images sources:
Tang J., Sargent E.H. (2011) Advanced materials
Akkerman Q. A. (2019), PhD Thesis, UNIGE
J. Phys. Chem. Lett. (2015) 6, 1, 85-99

Organic Solar Cells

- Based on organic semiconductors (OSC), either polymers or small molecules
- High level of π-conjugation (alternating single and double bonds) required:
  → band gap will become small enough for light to excite an electron from HOMO to LUMO
  → electrons associated with the double bonds delocalized across the conjugation's length
- Tunable band gap by, e.g., changing functional group or polymer length
- Lower cost and toxicity but higher degradation rate than inorganic cells
- Efficiency of organic cell: 17.35% (SJTU/UMass, 2020)

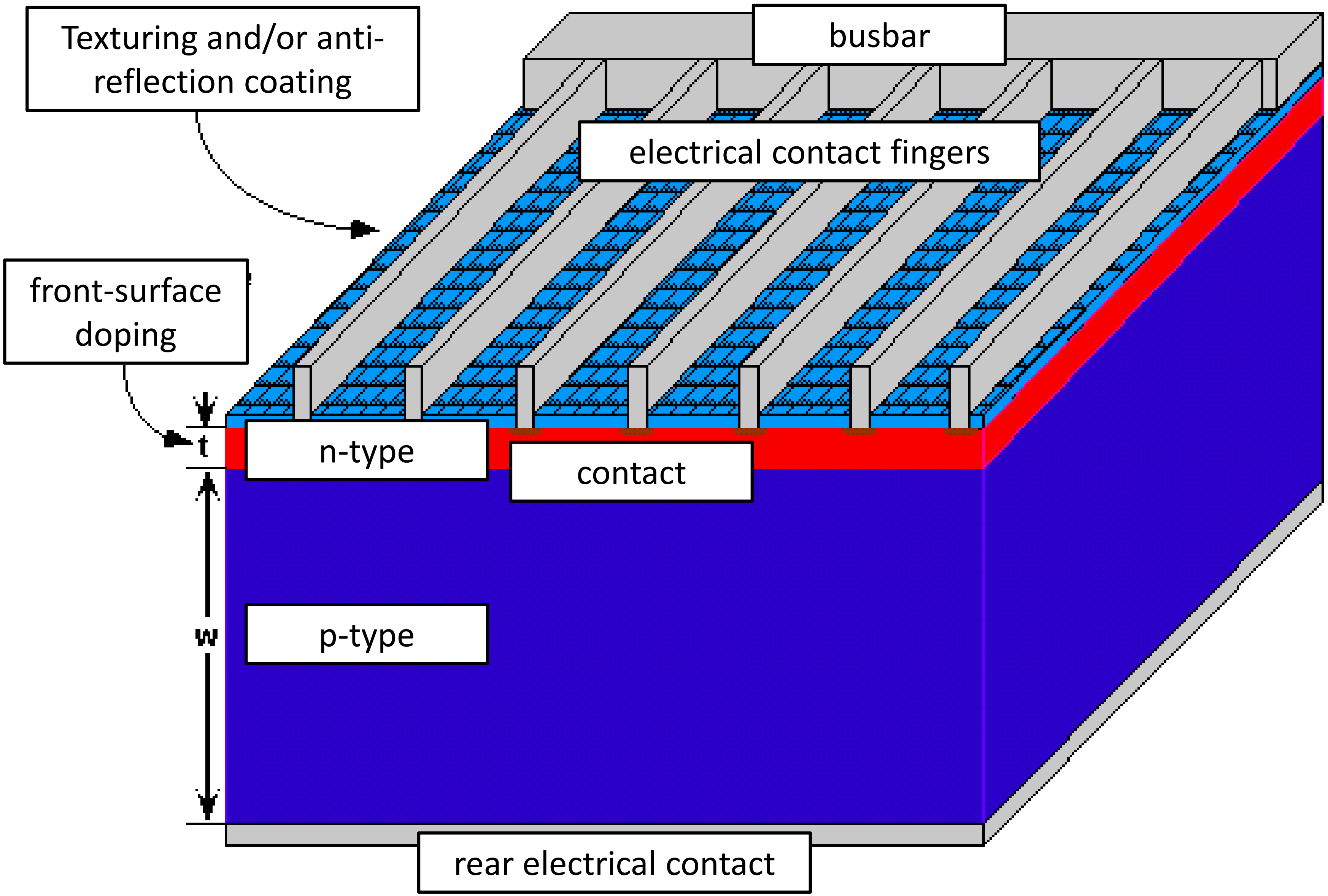


Efficiency History

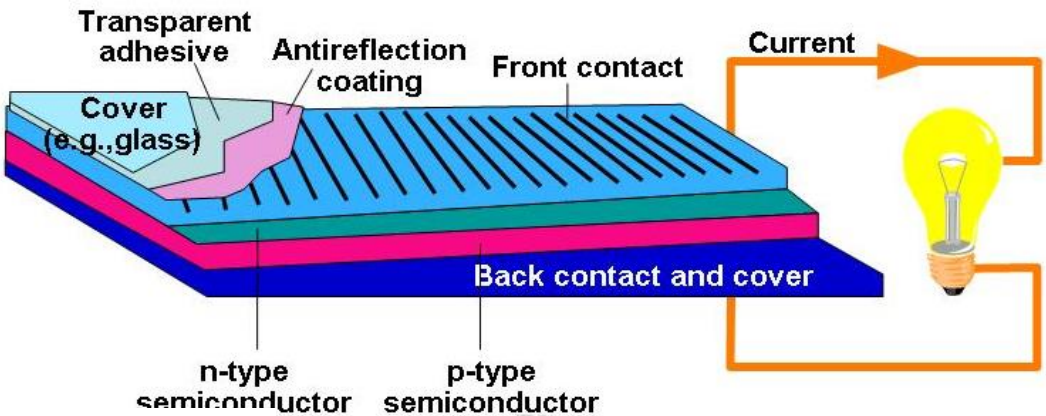


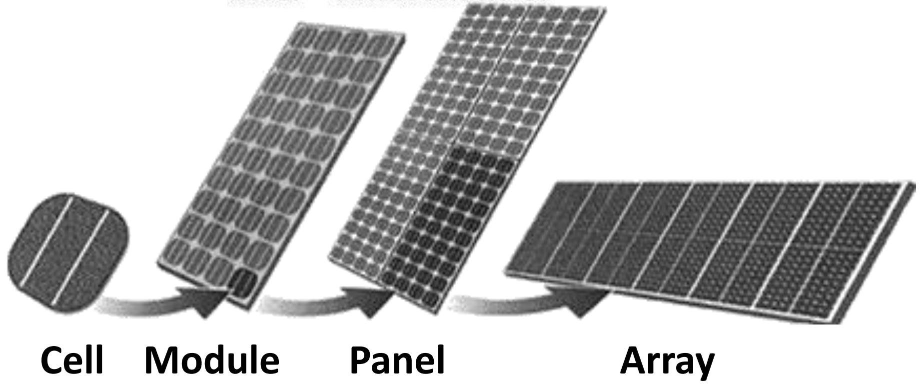
https://www.nrel.gov/pv/cell-efficiency.html

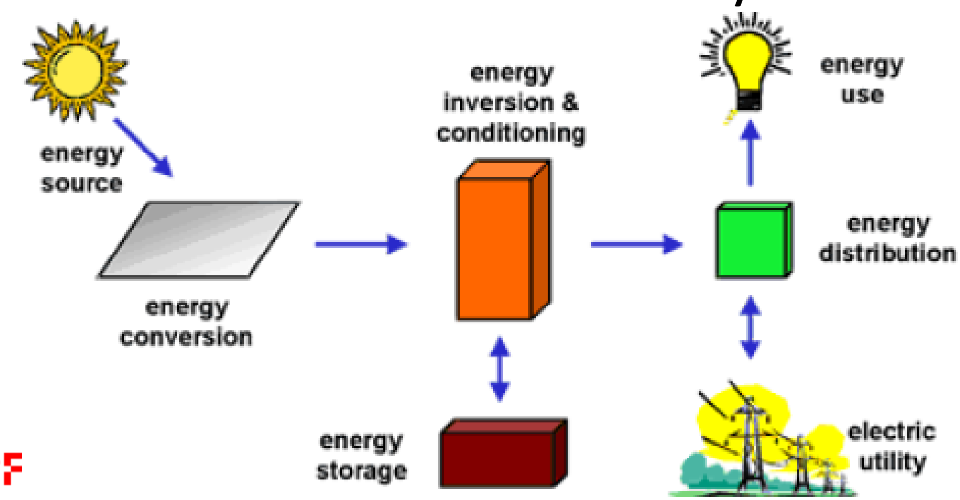
PV Cell Assembly



PV System



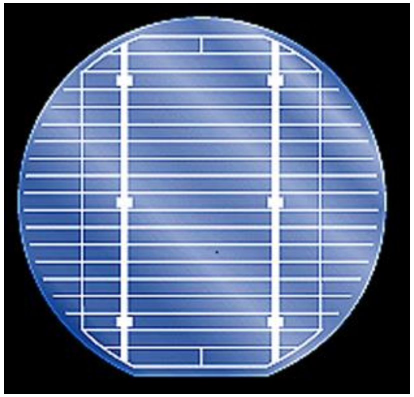




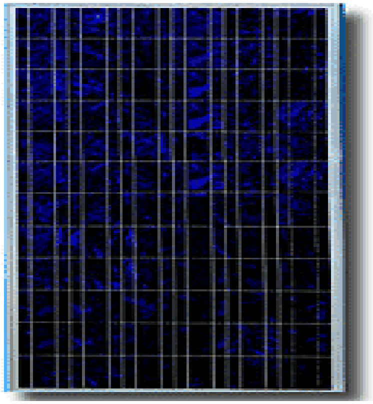
- Standard Test Conditions (STC): T = 25°C, I = 1 kW/m^2, Air Mass = 1.5.
- Actual performance is usually 85-90% of the STC rating.
- Typical service lifetime: 20-30 years
- PV System to control, convert, distribute, and store electrical power.
- BOS (Balance of System): hardware, including wiring, protection and disconnect devices, and other power processing equipment.
- Battery: storing; supply electrical loads during night and cloudy weather; to power electrical loads at stable voltages; and to supply currents to electrical loads and inverters; battery charge controller to protect the battery from overcharge and over-discharge.

PV System

cell



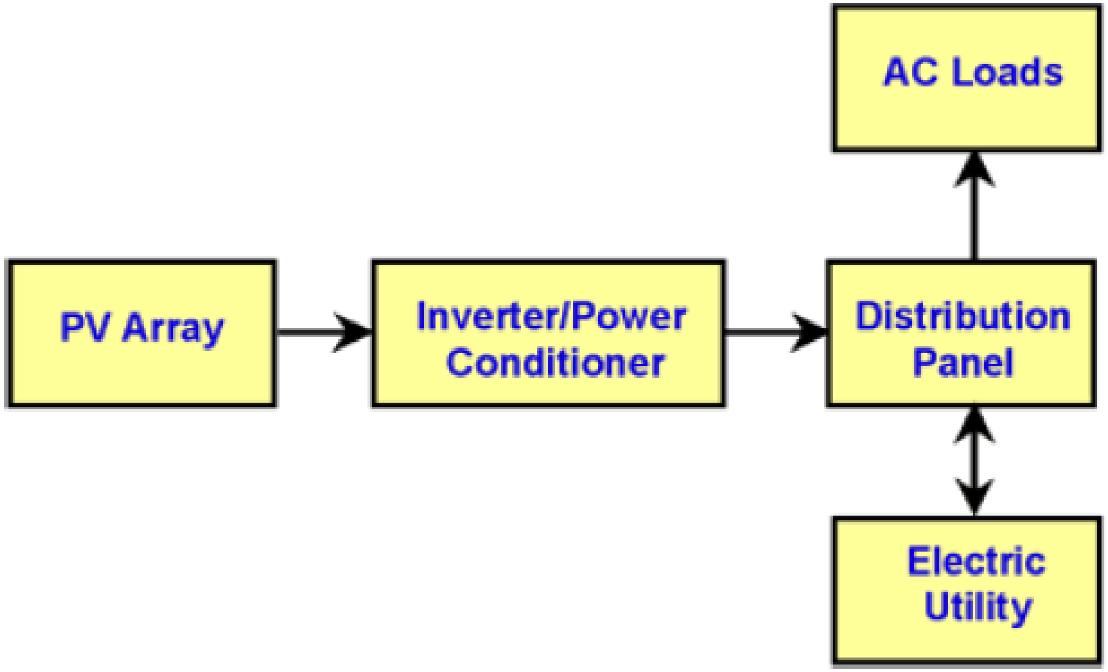
module



panel

array

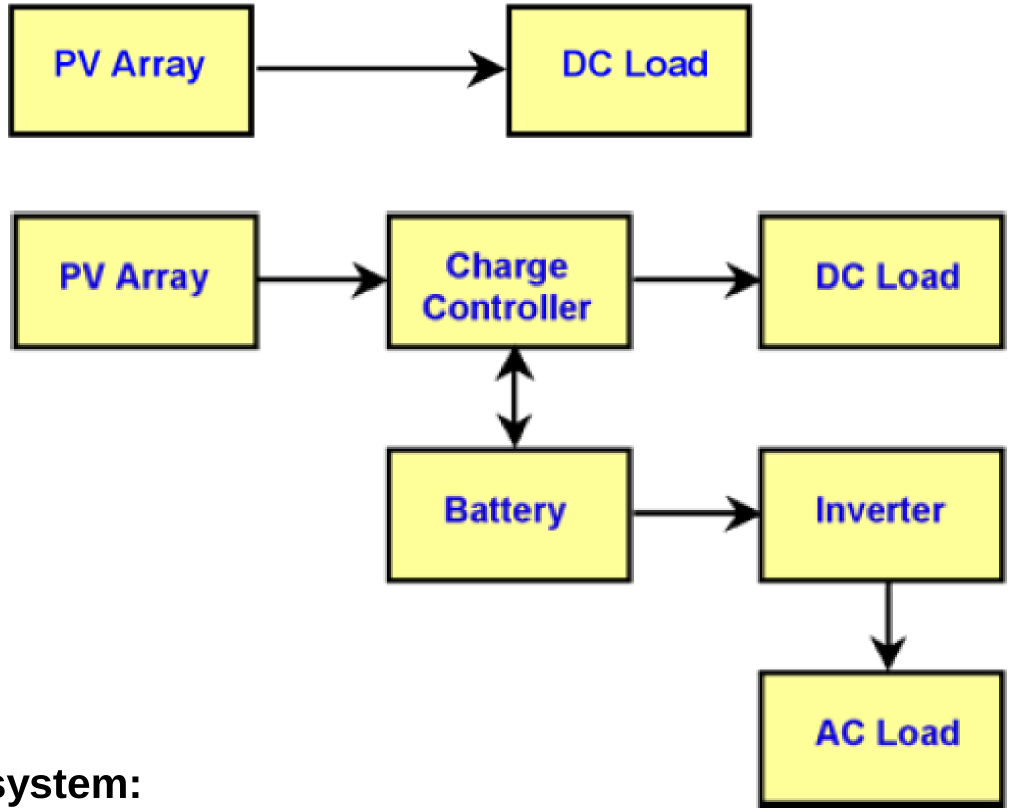
Grid-connected PV Systems



Grid-connected or utility-interactive system:

- PCU: power conditioning unit or inverter converts DC into AC, automatically stops supplying power to the grid when the utility grid is not energized.
- Electrical supply either by PV or utility.
- Distribution Panel: bi-directional interface that allows the AC power produced by PV to either supply on-site electrical loads, or to back-feed the grid when the PV output > on-site load demand. At night and during other periods when the electrical loads are greater than the PV output, the balance of power required by the AC loads is received from the electric utility.

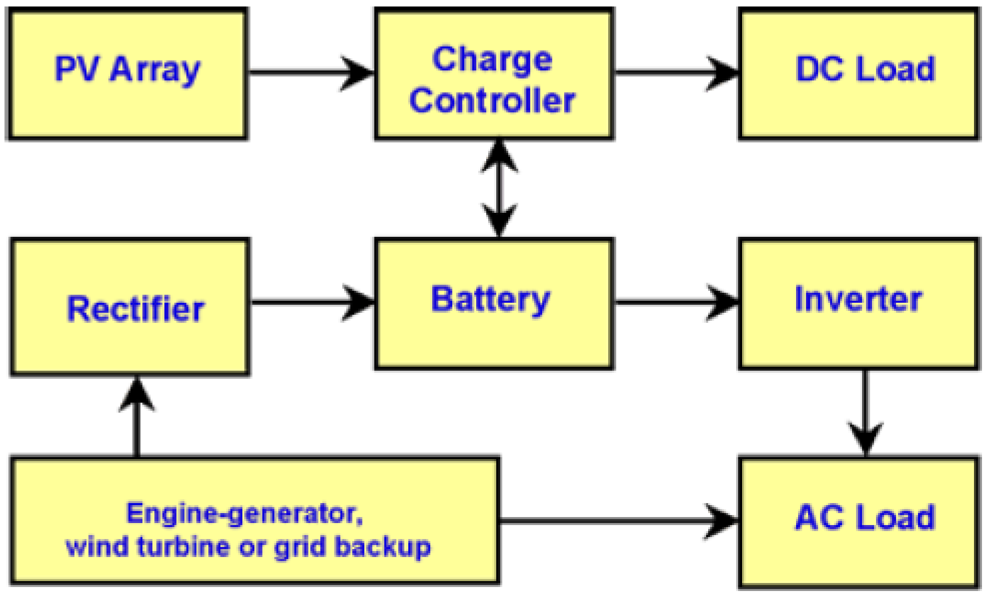
Stand-alone PV Systems



Stand-alone system:

- Supplies power independently of electrical utility grid.
- Direct-coupled: DC output of a PV is directly connected to a DC load. No electrical energy storage. Applications: ventilation fans, water pumps, and small circulation pumps for FPC. Matching the electrical load to the maximum power output of the PV array is critical.
- For DC/AC loads; with/without battery storage; charge controller portects battery from overcharge and overdischarge.

Hybrid Systems



Hybrid System

- Multiple power sources (PV, wind, micro-hydro, etc).
- No electrical distribution network.
- Reliance on any single generating source is reduced.

PV Panel Specifications

Sanyo HIP-190BA3

The HIT 190 panel has a cell conversion efficiency of 18.5% and a panel conversion efficiency of 16.1% that is significantly higher than conventional SANYO solar cells.

High conversion efficiency and lightweight design conserve space and weight. The outstanding conversion efficiency and high power output of the HIT 190 save approximately 20% of installation space. HIT 190 panels can be installed on narrow roof spaces which previously presented difficulties. In addition, with fewer solar panels, there is less weight on the roof.

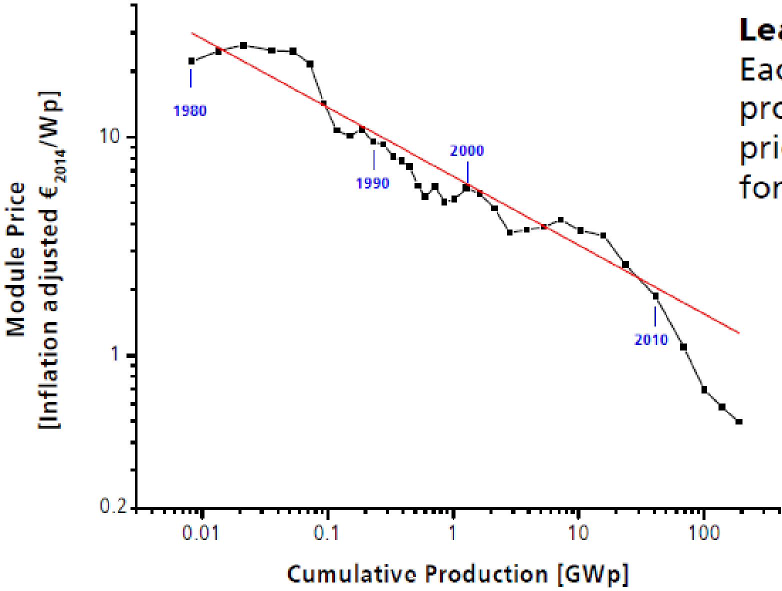
SANYO HIT 190 Specifications:
Model Number: HIP-190BA3
Max. Power (Pmax): 190 Watts
Max. Power Voltage (Vpm): 54.8 Volts
Max. Power Current (Ipm): 3.47 Amps
Open Circuit Voltage (Voc): 67.5 Volts
Short Circuit Voltage (Isc): 3.75 Amps
Cell Conversion Efficiency: 18.5%
Panel Conversion Efficiency: 16.1%
Warranted Minimum (Pmin): 171.0 Watts
PTC Rating: 178.7 Watts
Max. System Voltage: 600 Volts
Series Fuse: 15 Amps
Temp. Coefficient of Pmax (%/C): -0.3
Dimensions: 51.9" x 35.2" X 1.4" (1319mm X 894mm x 35mm)
Weight: 30.9 lbs. (14kg)
Certificate: UL 1703
Class C fire rating
HIT panels can withstand 1 inch diameter hailstones at 50 mph.

Sanyo HIP-190BA3, HIT 190 Watt Solar Panel
$975.00

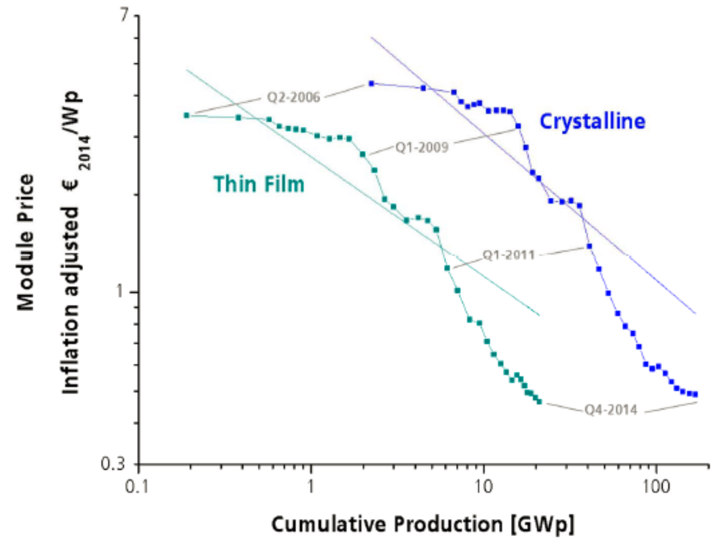
Cost

- Photovoltaics: Learning curve

Includes all commercially available technologies:



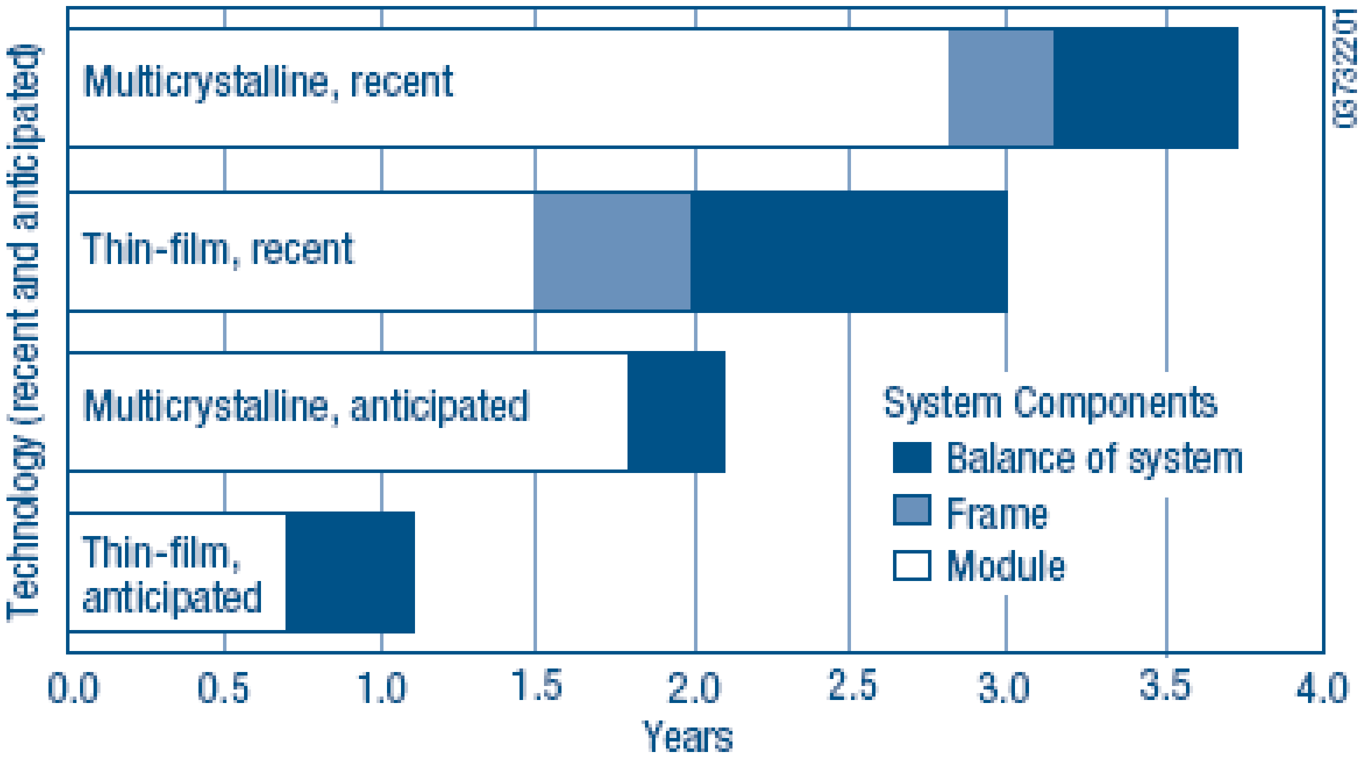
Learning Rate:
Each time the cumulative production doubled, the price went down by 19.6% for the last 34 years.



Data: from 1980 to 2010 estimation from different sources : Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011 to 2014: IHS. Graph: PSE AG 2016

- Price for a Si-based module: ~ 1 €/W_p, ~ 150 €/ m^2

Energy Payback time

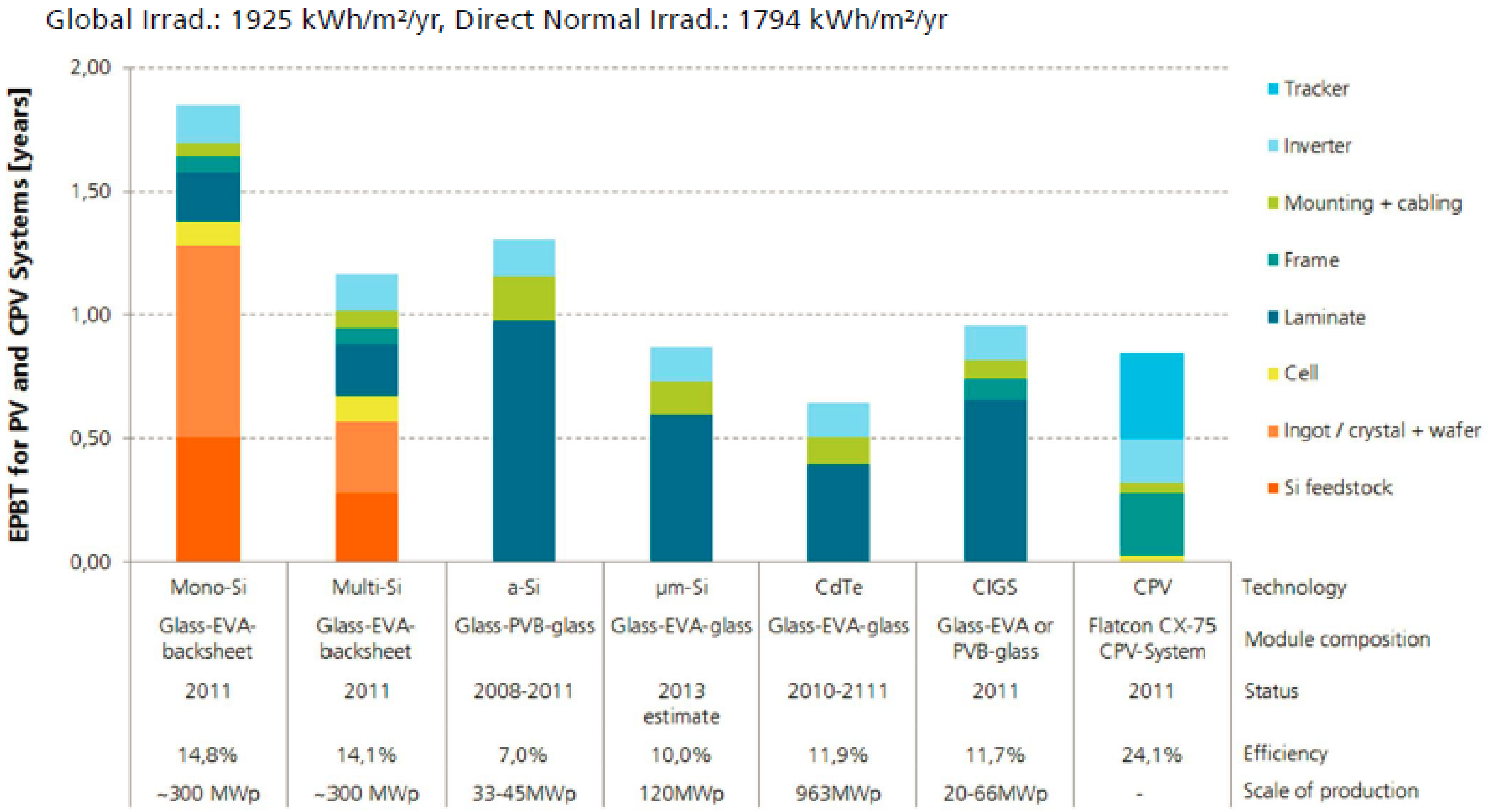


- 120 kWh/m2 to make frameless, amorphous-Si PV modules
- PV systems can repay their energy investment in about 2 years.
- Assuming 30-year system life, PV systems will provide a net gain of 26 to 29 years of pollution-free and CO2-free electrical generation, equivalent to 87-97% of the total energy generated.

Sources:
US-DOE
R. Dones; R. Frischknecht, "Life Cycle Assessment of Photovoltaic Systems: Results of Swiss Studies on Energy Chains." Utrecht University, Report 97072, 1997.

Sustainability

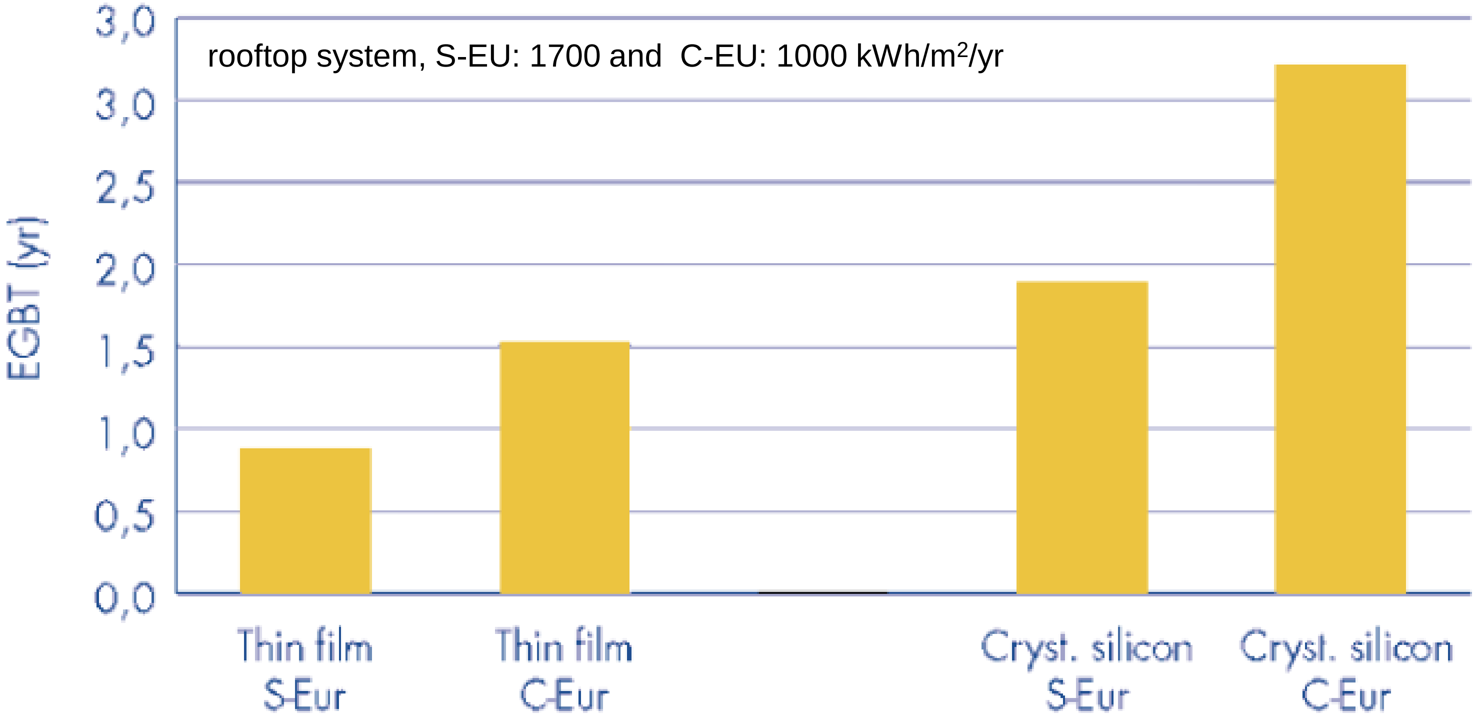
- Photovoltaics: Life cycle assessment - Technology



Data: M.J. de Wild-Scholten 2013; CPV data: "Environmental Sustainability of Concentrator PV Systems: Preliminary LCA Results of the Apollon Project" 5th World Conference on PV Energy Conversion. Valencia, Spain, 6-10 September 2010. Graph: PSE AG 2014

Sustainability

- Photovoltaics: Life cycle assessment - Location



Fthenakis et al., Environmental Science and Technology, 2008

Aesthetics

- Photovoltaics: early modules

- Fully integrated today:

Aesthetics

- Photovoltaics: various colors

- Covered by prints

Literature

- **Solar energy: The physcis and engineering of photovoltaic conversion, technologies and systems**

  by Smets, Jäger, Isabella, van Swaaij, and Zeman

  published by UIT Cambridge Ltd in 2016

- https://www.pveducation.org/