Photovoltaics

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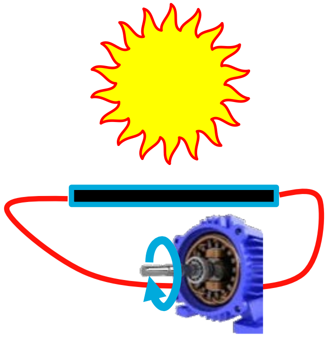
today: Devices

- Overview on technology and economics
- Some semiconductor basics
- Solar cells as p-n junctions

tomorrow: Efficiencies

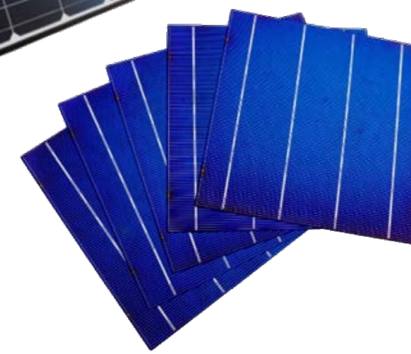
- Fundamental limits to efficiency
- Real efficiencies
- How to go beyond

What is photovoltaics?



solar cells

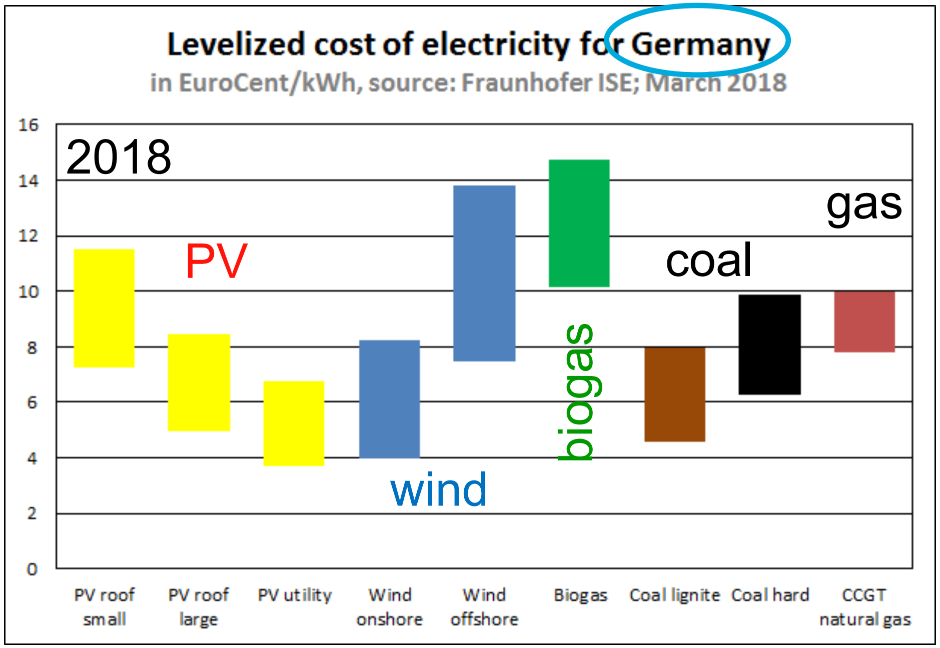
wafer based modules

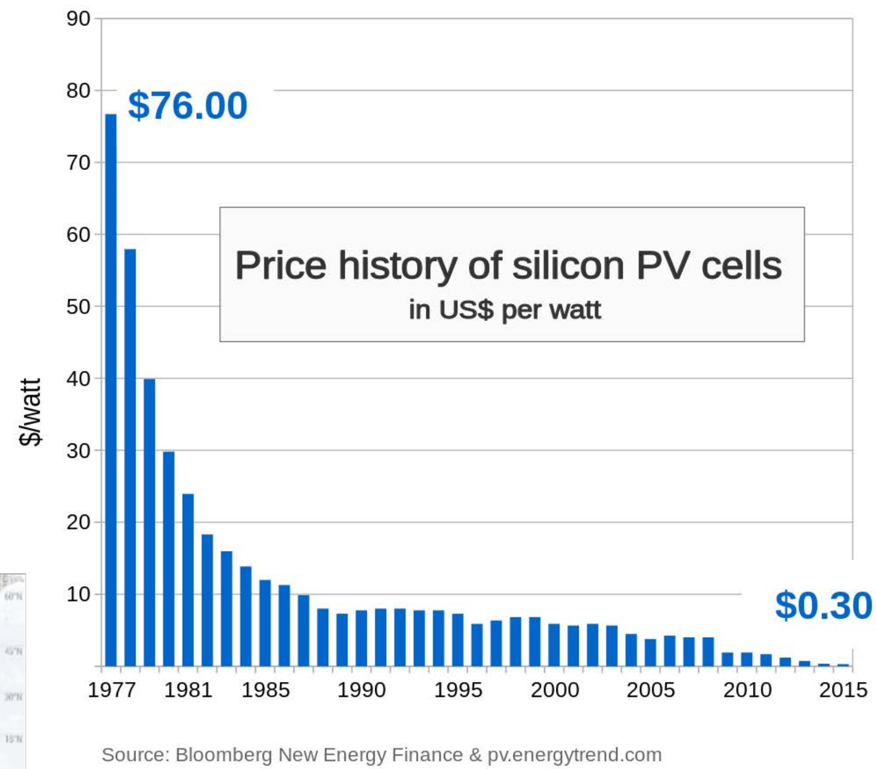


thin film modules

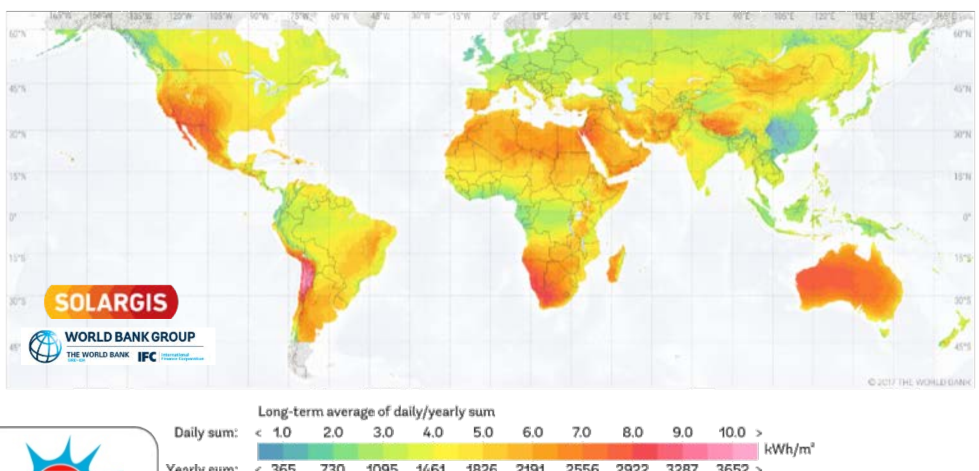
Why do we need solar cells?

cheap electricity



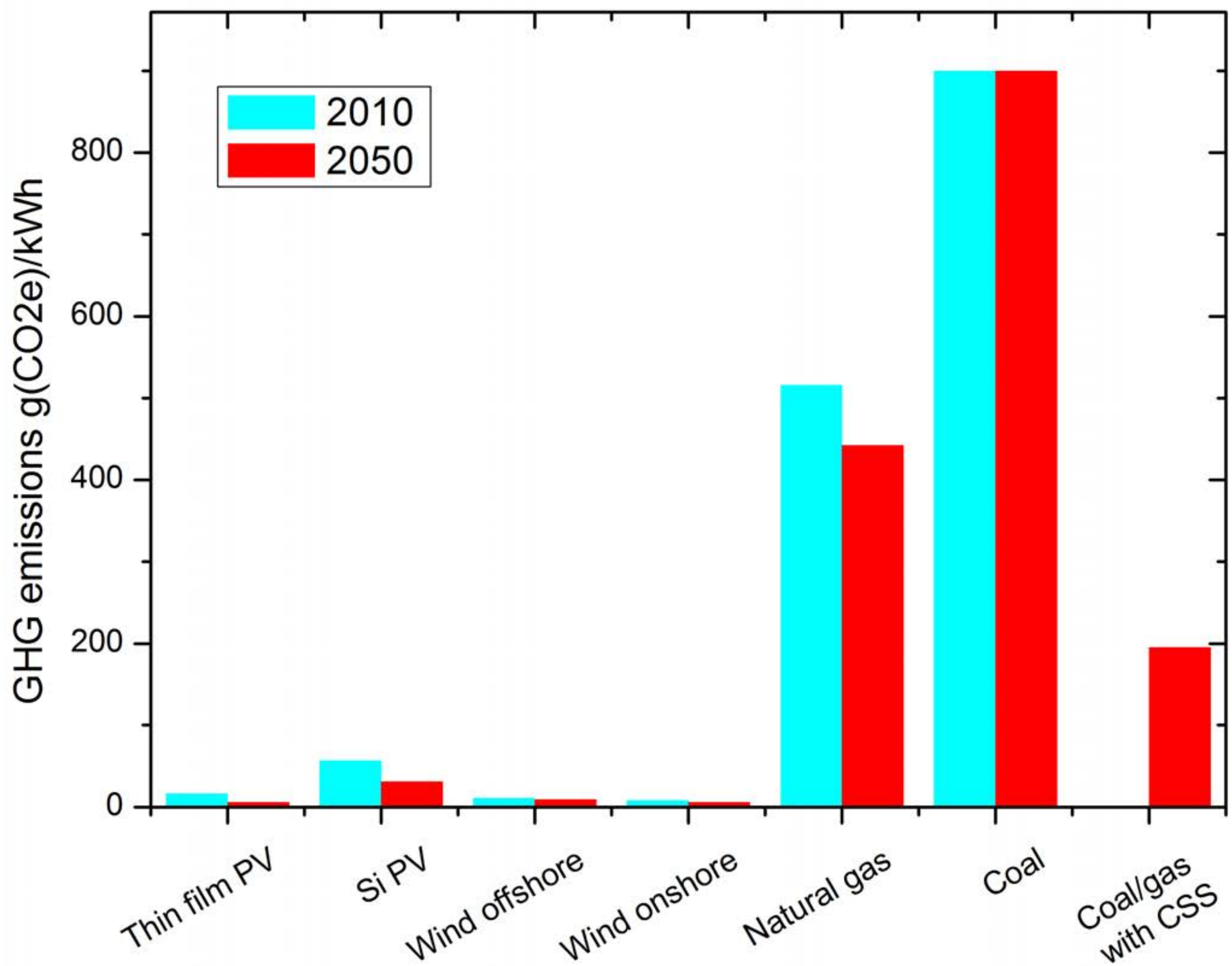


2019: 0.11 $/W
2020: 0.07 - 0.11 $/W



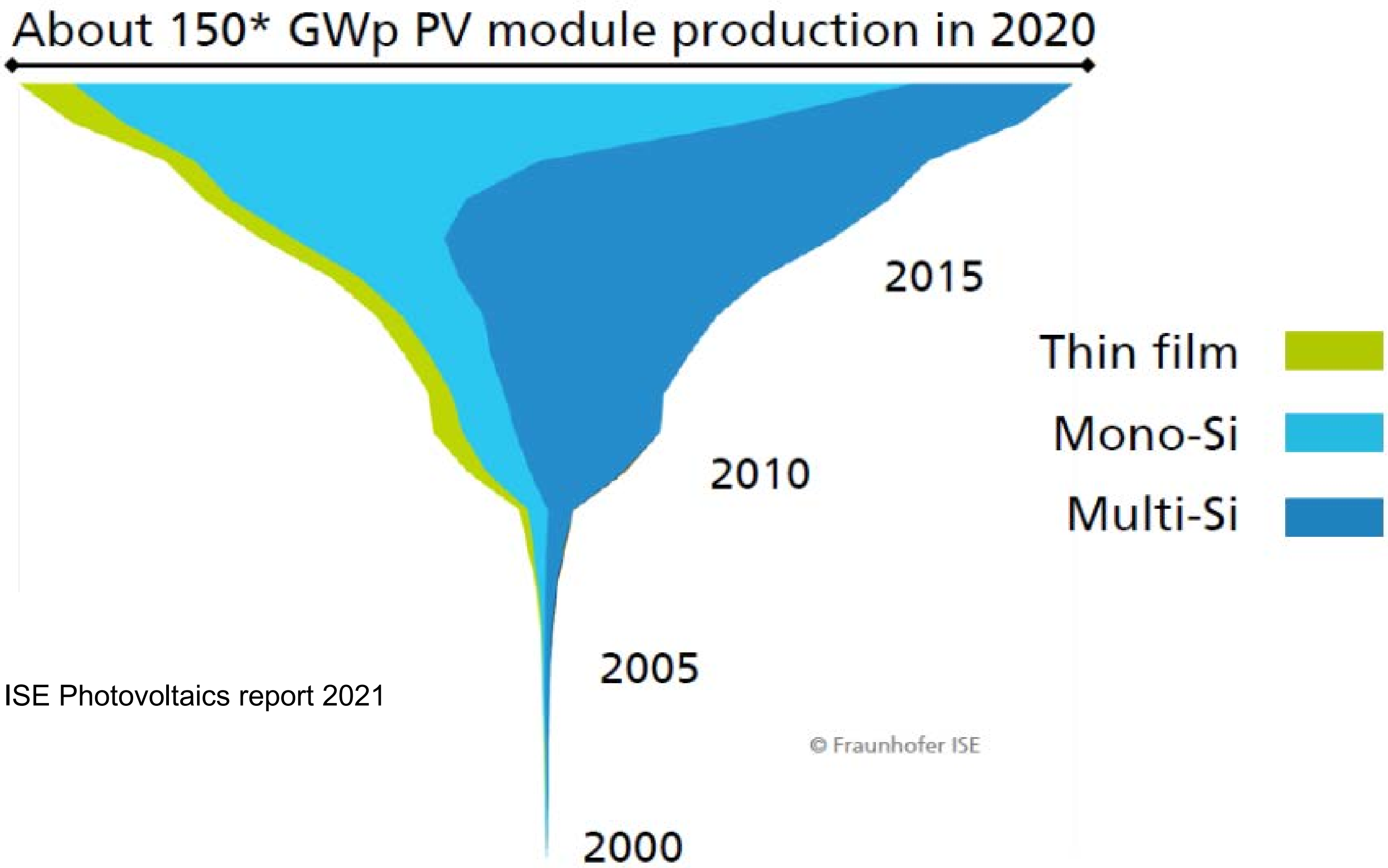
insolation

…and it's good for the planet



UNEP, "Green Energy Choice"
Report of the International Resource Panel. 2016

The PV market



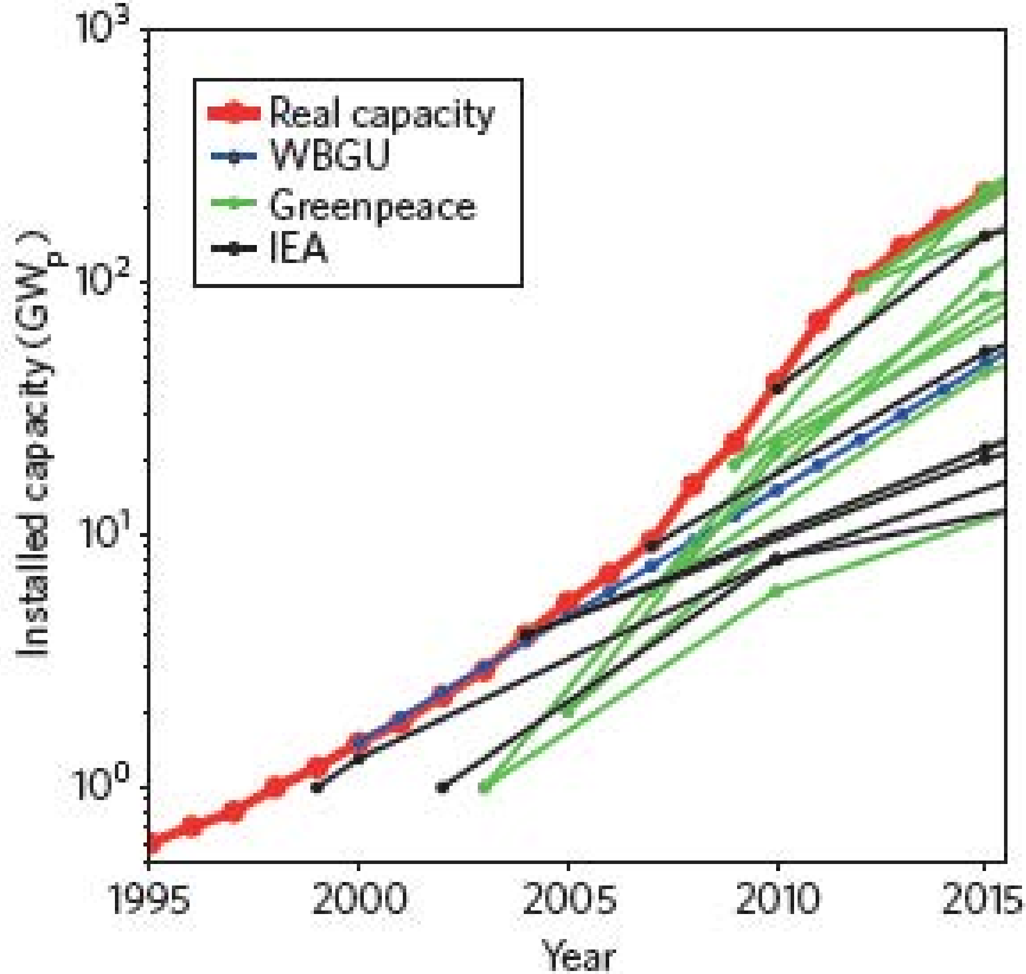
ISE Photovoltaics report 2021

- stong and continuous increase in production

https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html

The underestimated power source

studies vs. reality:

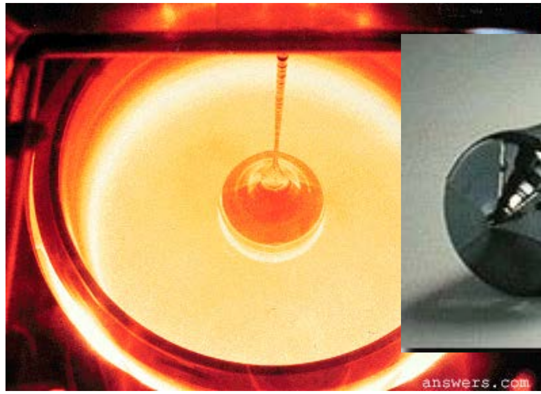


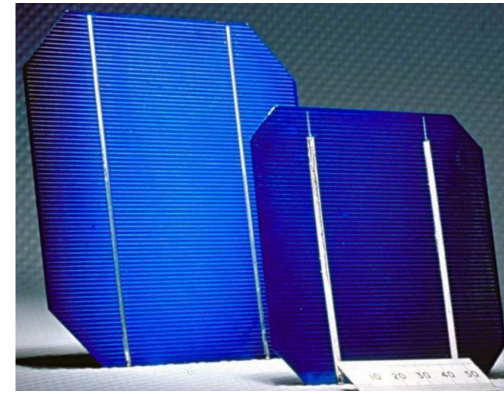
PV grows faster than any prediction

Creutzig, et al. Nature Energy 2, 17140 (2017)

Basic wafer material for Si solar cells

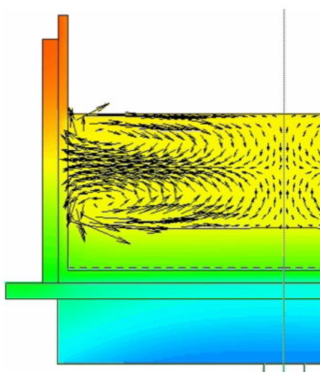
single crystalline



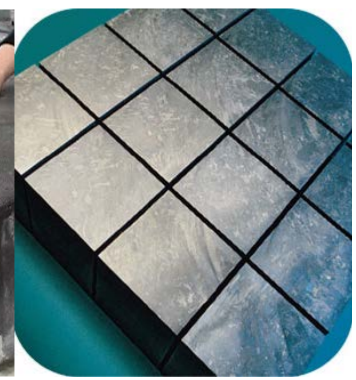


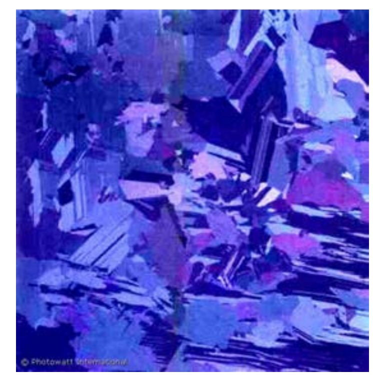
efficiencies of commercial modules up to 23%

multi crystalline



str-soft.com



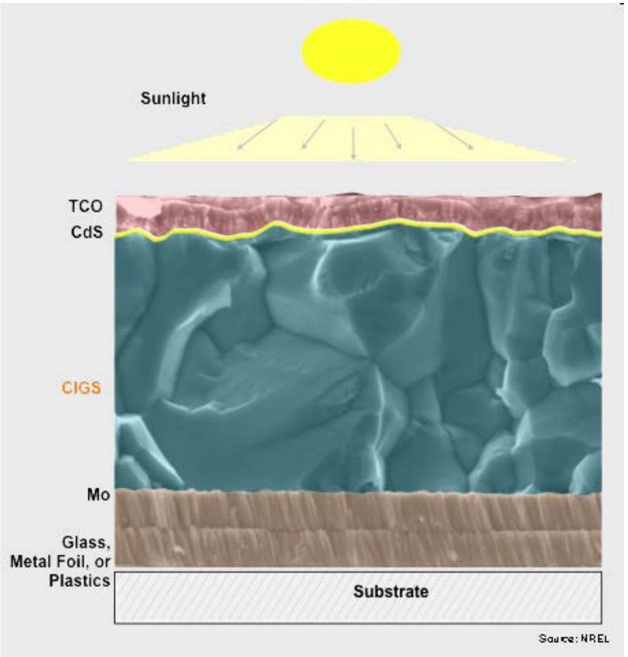


efficiencies of commercial modules typically 18-19 %

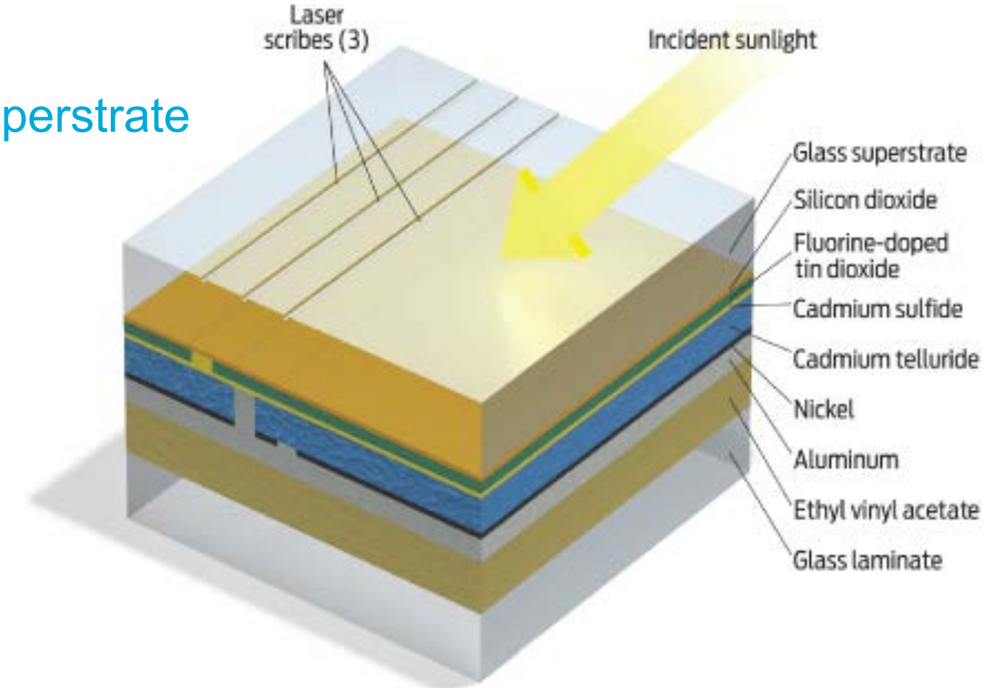
Thin film solar modules

stacks of thin films on glass

substrate



superstrate

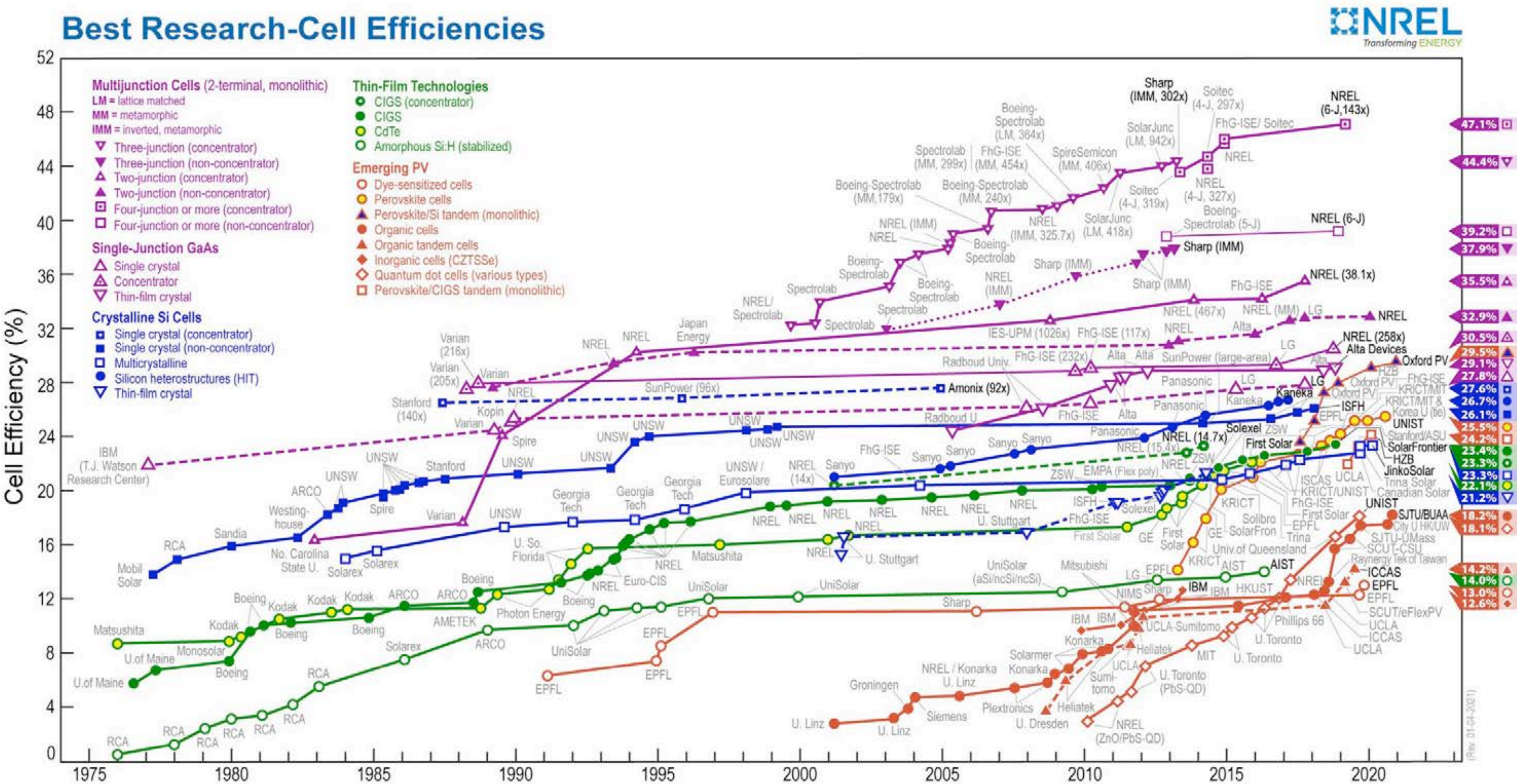


or on metal or plastic foil

- light weight and flexible

Flisom Flexible Solar Modules

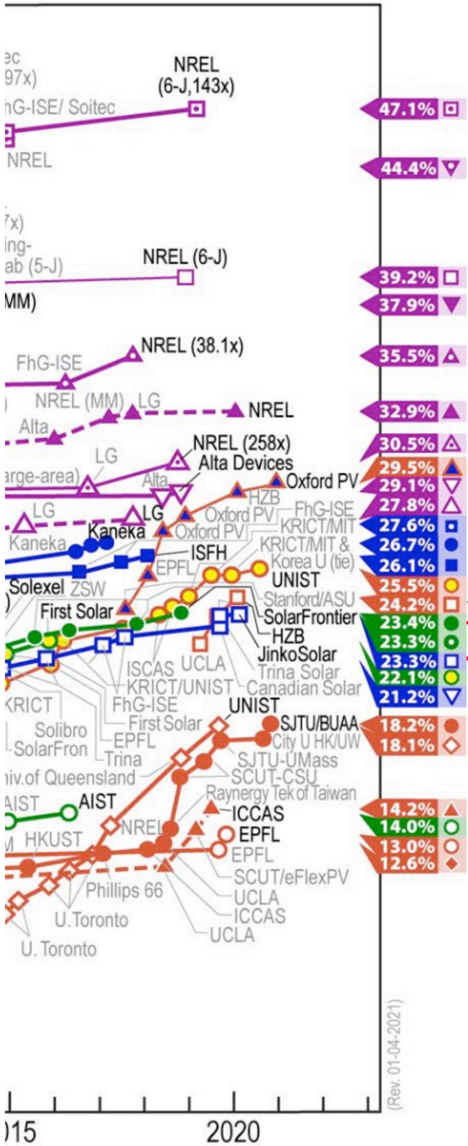
Efficiencies - history



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

Current solar cell efficiencies

NREL Transforming ENERGY



multijunction + concentration

perovskite - Si tandem

GaAs

Si HIT

Si singlecrystalline: 80% market

perovskite (organic-inorganic)

perovskite - CIGS tandem

CIGS: 1.5% market

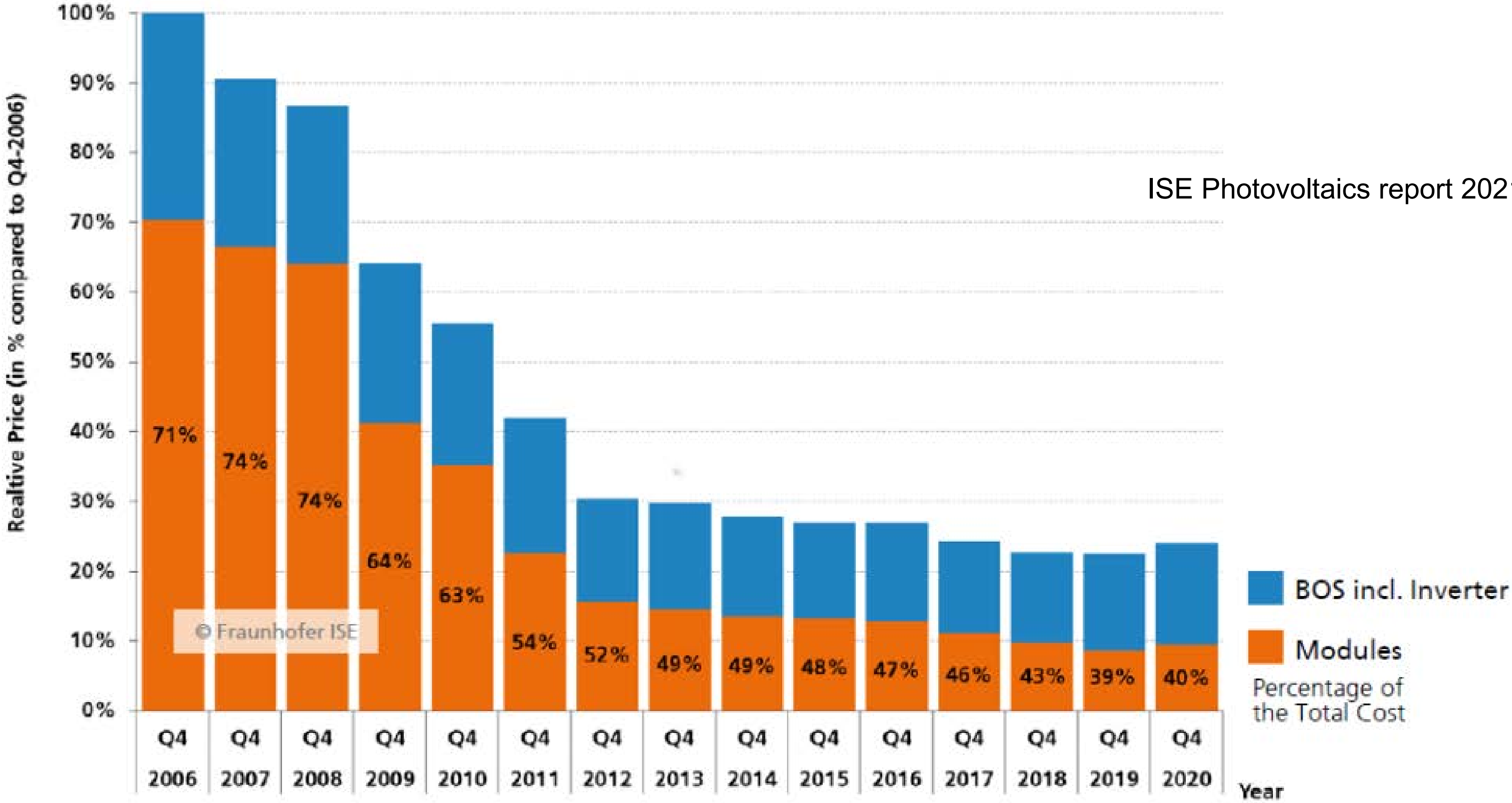
Si multicrystalline: 15% market

CdTe: 4% market

LPV

uni.lu UNIVERSITÉ DU LUXEMBOURG

Why efficiency matters



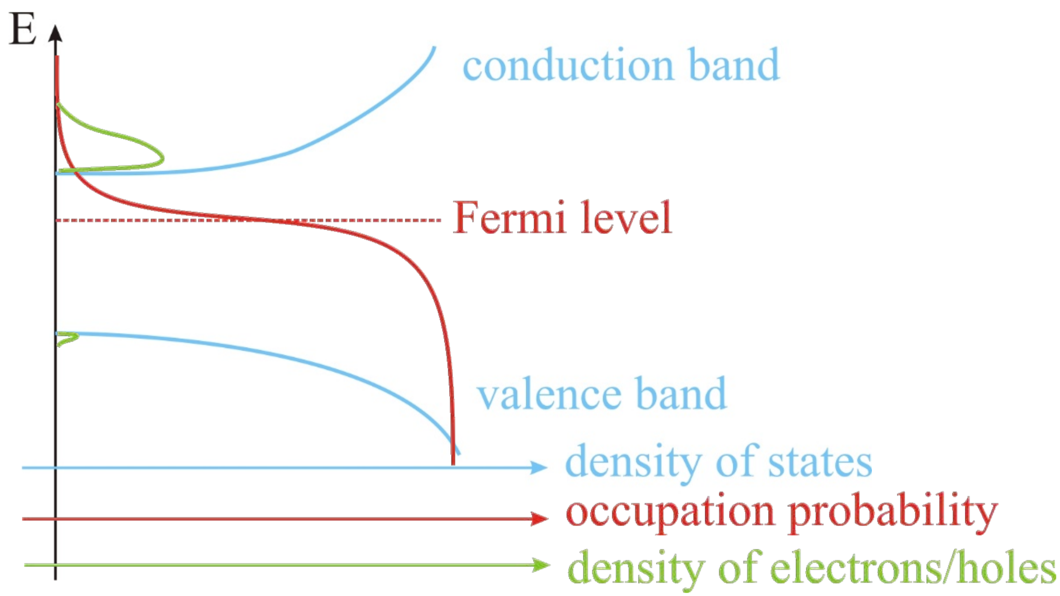
ISE Photovoltaics report 2021

higher efficiency ⇨ smaller area ⇨ lower cost for BOS

and it must to stable over time

semiconductor basics

Doping and Fermi level



electrons: $n = N_C \exp(-\frac{E_C - E_F}{kT})$

holes: $p = N_V \exp(-\frac{E_F - E_V}{kT})$

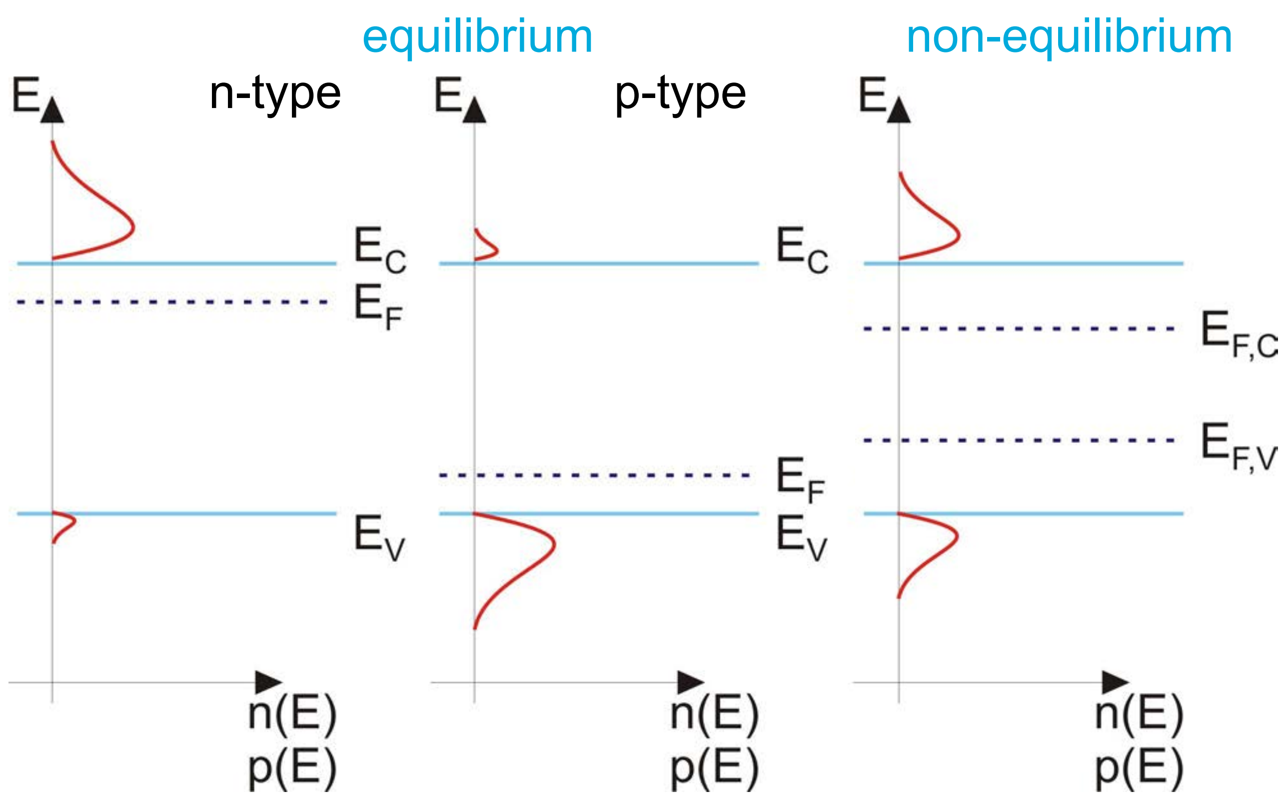
in equilibrium: $np = n_i^2 = N_C N_V \exp(-E_G / kT)$

"intrinsic carrier concentration"

Quasi Fermi levels

excitation: $n > n_0$ and $p > p_0$ with $n_0 = N_C \exp(-\frac{E_C - E_F}{kT})$ $p_0 = N_V \exp(-\frac{E_F - E_V}{kT})$

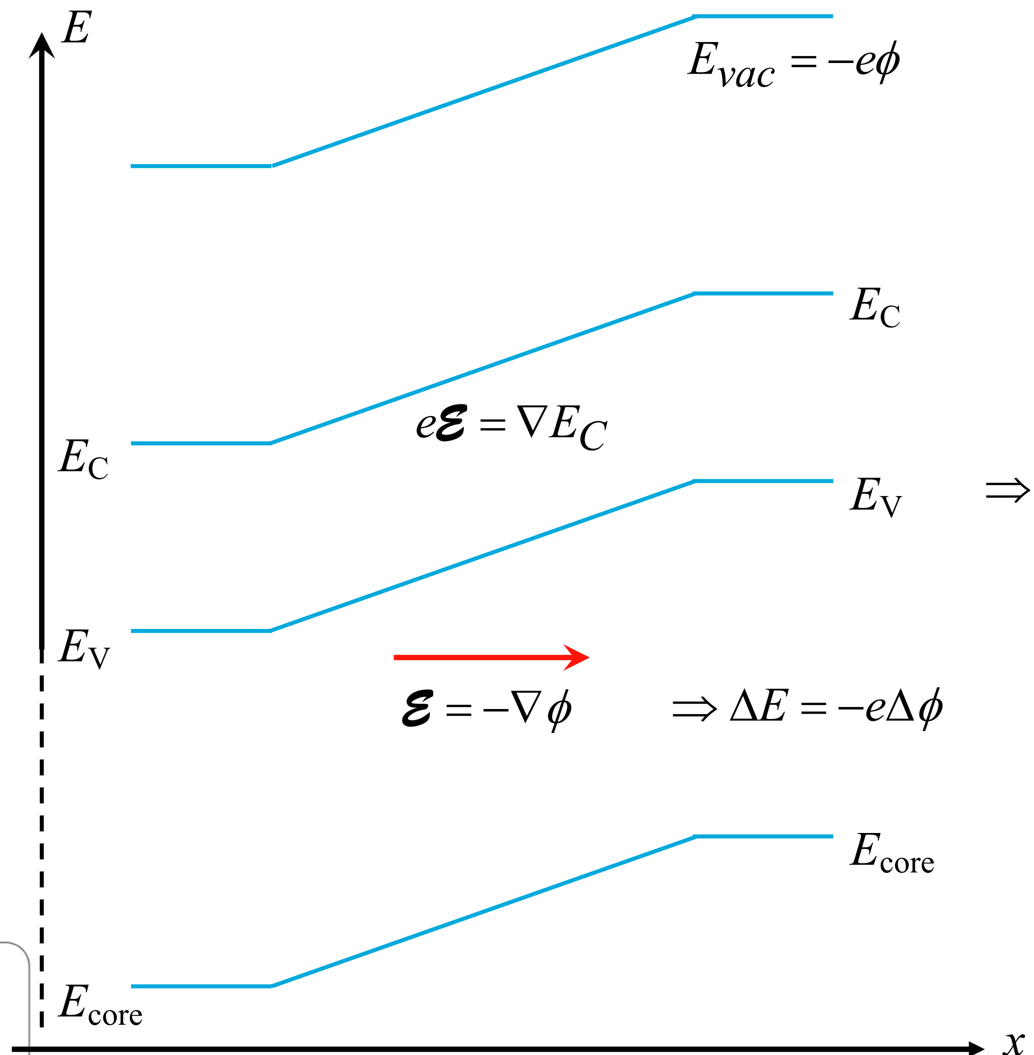
$$\Rightarrow n = N_C \exp(-\frac{E_C - E_{F,C}}{kT}) \quad p = N_V \exp(-\frac{E_{F,V} - E_V}{kT}) \qquad \Rightarrow np = n_i^2\, e^{\Delta E_F / kT}$$



Fields, gradients and trasnport

current: $\mathbf{j} = en\mu\boldsymbol{\mathcal{E}} + \mu kT\nabla n \qquad (T = \text{const})$

drift   diffusion



$$e\boldsymbol{\mathcal{E}} = \nabla E_C$$

$$\boldsymbol{\mathcal{E}} = -\nabla\phi \qquad \Rightarrow \Delta E = -e\Delta\phi$$

$$n = N_C \exp\left(-\frac{E_C - E_{FC}}{kT}\right)$$

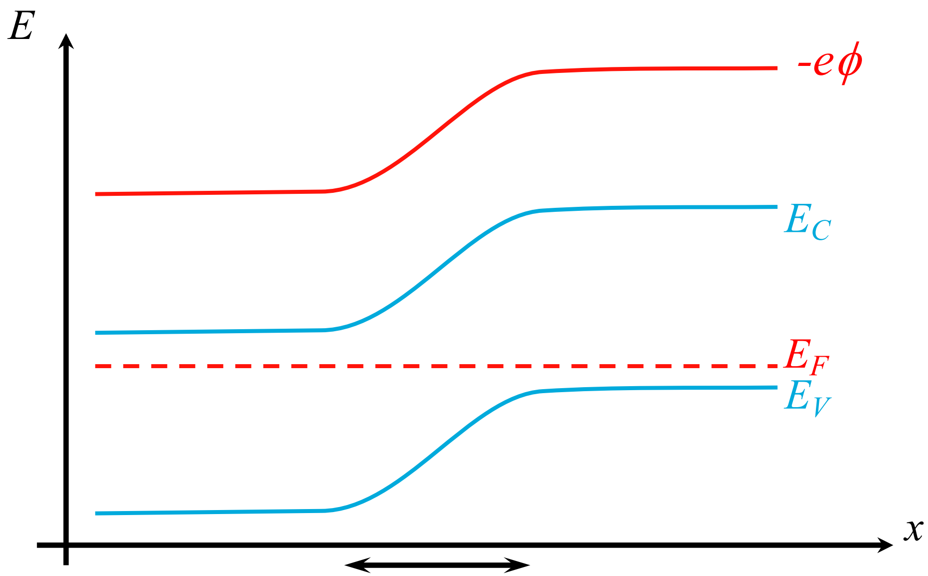
$$\Rightarrow \nabla n = n\left(-\frac{1}{kT}\nabla(E_C - E_{FC})\right)$$

$$\Rightarrow \mathbf{j} = n\mu\nabla E_C - n\mu\,\nabla(E_C - E_{FC})$$

$$\Rightarrow \boxed{\mathbf{j} = n\mu\nabla E_{FC}}$$

pn junctions

pn-junction in equilibrium



n-side:
high density
of electrons

p-side:
high density
of holes

space charge region SCR

upon contact:
diffusion of electrons $\rightarrow$ and holes $\leftarrow$

$\Rightarrow$ separation of charges, space charge region

$\Rightarrow$ electric field, electrostatic potential gradient

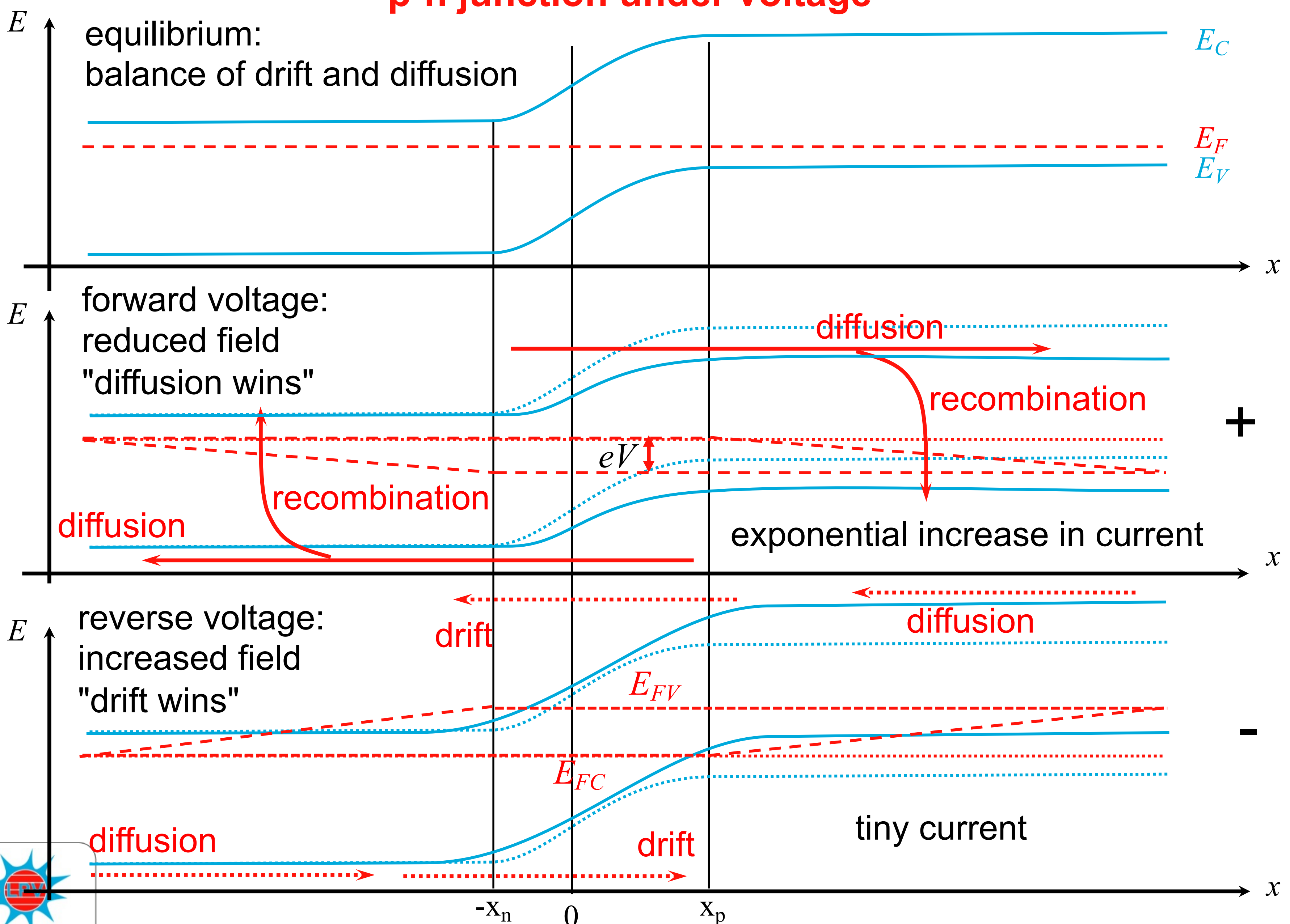
$\Rightarrow$ until drift force = diffusion force

OR:
equilibrium: $\nabla E_F = 0$

far away from junction:
semiconductor unchanged

near junction:
band bending, i.e. electric field

p-n junction under voltage

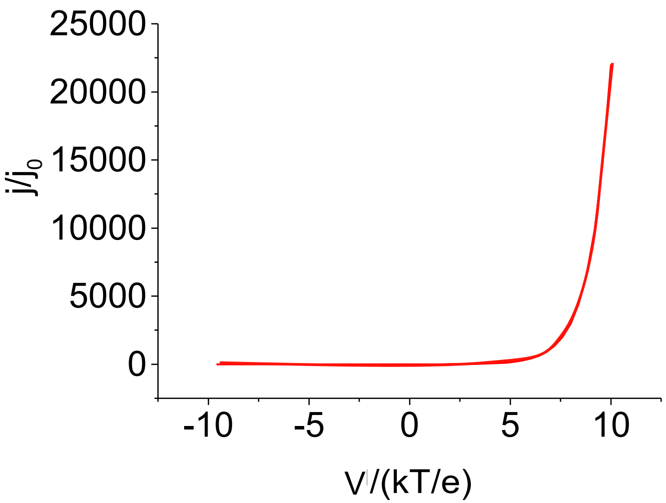


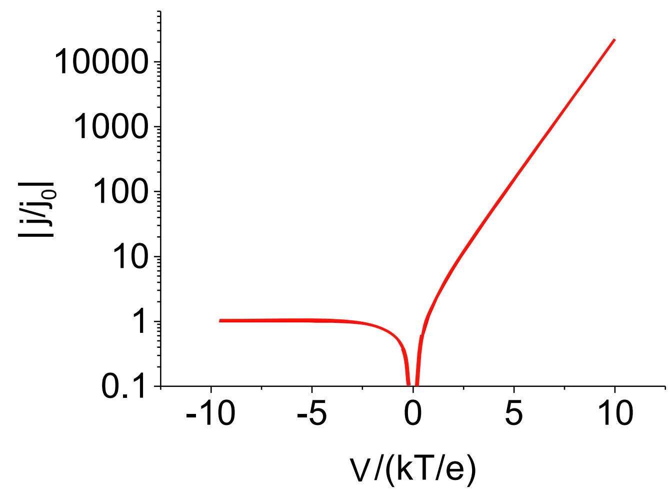
Shockley equation

current voltage dependence: $j = j_0(\mathrm{e}^{eV/k_BT} - 1)$

reverse saturation current

$\Leftarrow$ diffusion and recombination



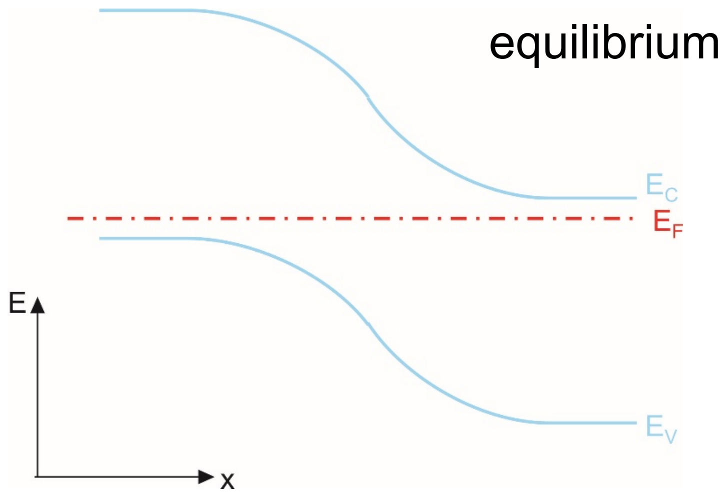


in general: $j = j_0(\mathrm{e}^{eV/Ak_BT} - 1)$ A: diode quality factor

plus series and shunt resistances

pn junction under illumination

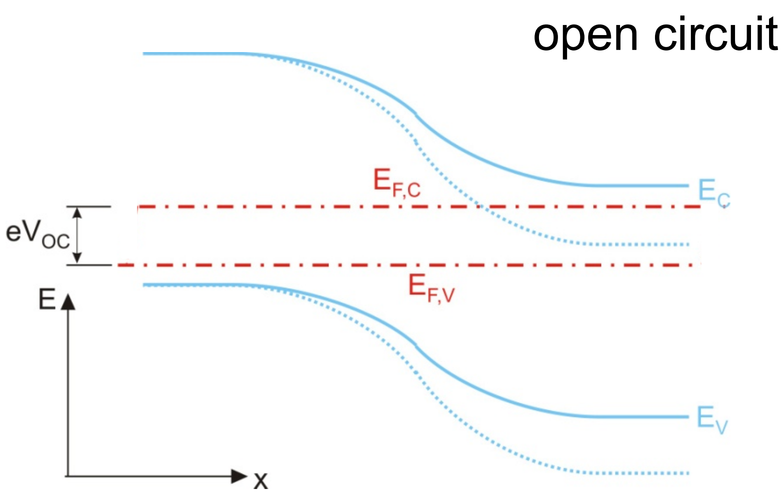
A pn-junction under illumination

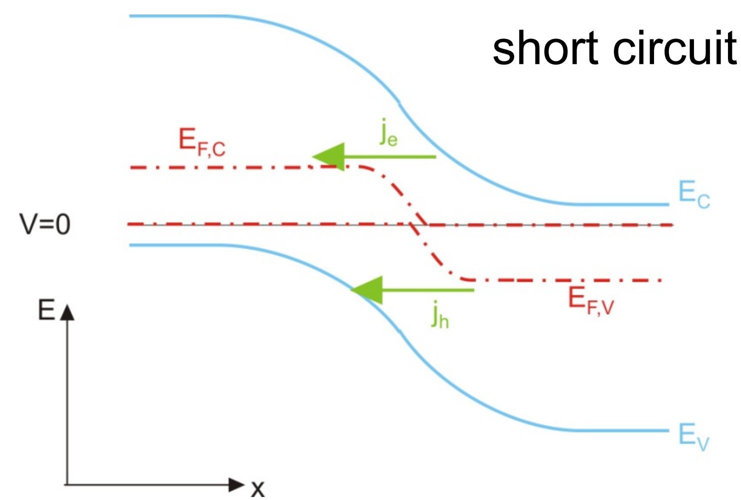


equ: $\nabla E_F = 0 \Rightarrow j = 0, V = 0$

OC: $j = 0 \Rightarrow \nabla E_F = 0 \Rightarrow V = V_{OC}$

SC: $V = 0 \Rightarrow \nabla E_F \approx \dfrac{E_{FC} - E_{FV}}{W_{SCR}} \Rightarrow j = j_{SC}$

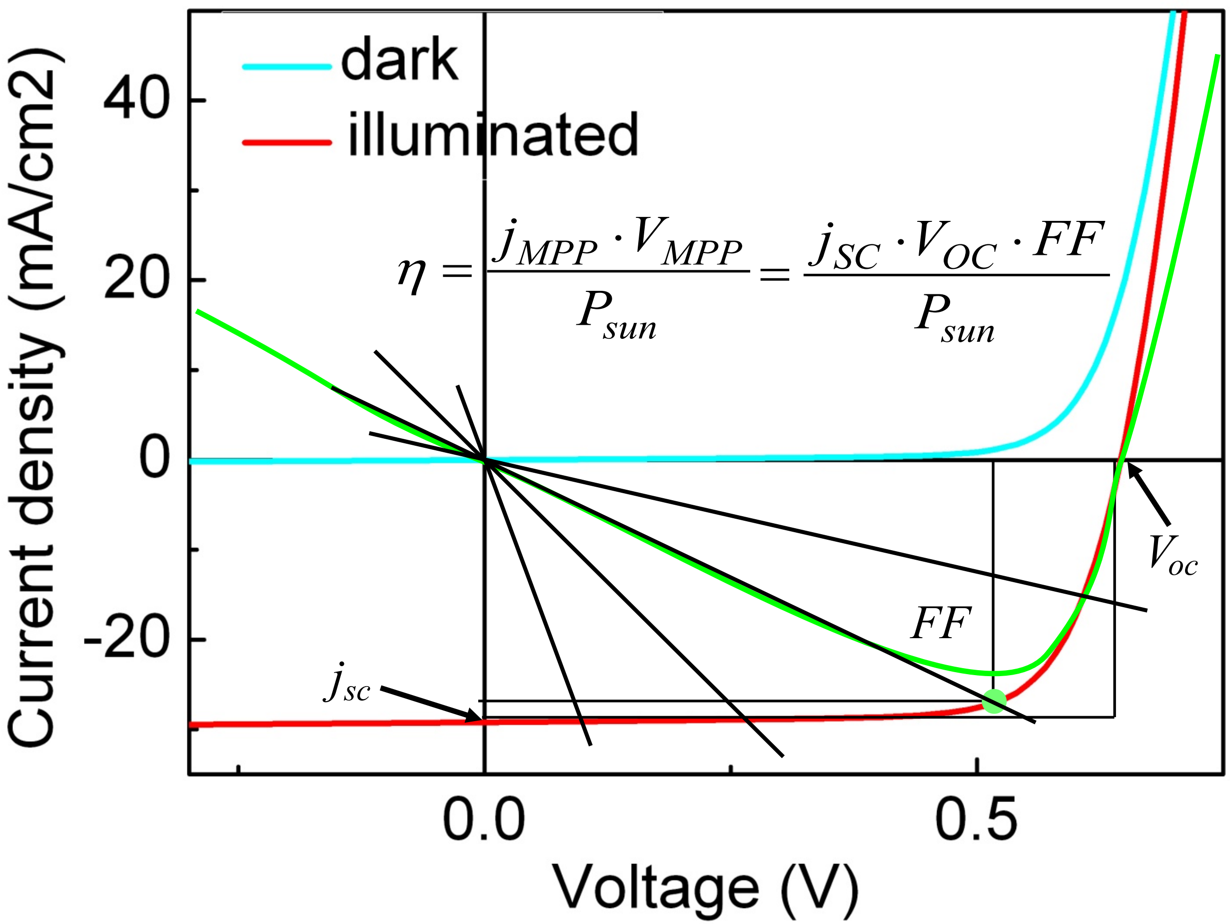




a forward voltage

a current in reverse direction

jV characteristic under illumination



diode equation:

$$j = j_0\left(e^{eV/Ak_BT} - 1\right) - j_{ph}$$

fill factor:

$$FF = \frac{j_{MPP} \cdot V_{MPP}}{j_{sc} \cdot V_{oc}}$$

power

maximum power point MPP

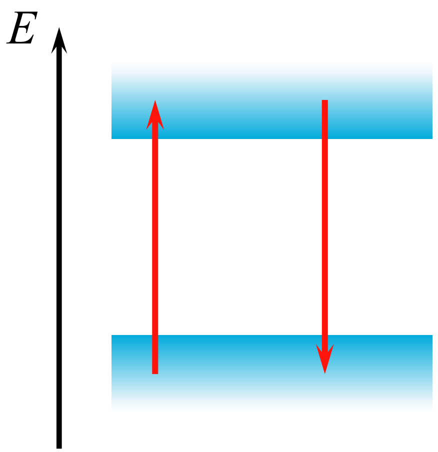
MPP tracker

A solar cell at open circuit

open circuit voltage: $j = j_0\left(e^{eV/Ak_BT}-1\right)-j_{ph} = 0 @ V = V_{oc}$

$$V_{oc} >> kT \Rightarrow j_0\, e^{eV_{OC}/Ak_BT} \approx j_{ph} \quad \Rightarrow V_{oc} \approx A\frac{kT}{e}\ln\frac{j_{ph}}{j_0}$$

recombination



generation

no current!

recombination

carrier lifetime

steady state: $\Delta n = \frac{\Phi_{sun}\cdot\tau}{d}$

thickness

(high mobility)

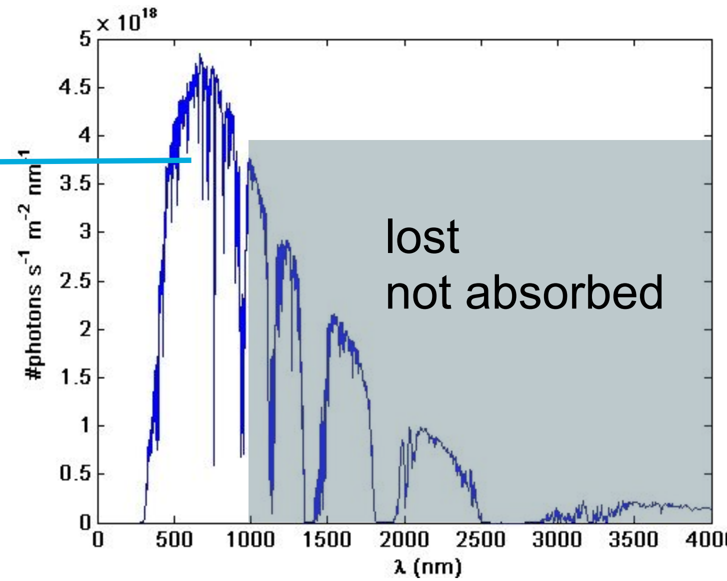
$$\Rightarrow \Delta E_F = k_BT\ln\frac{\Delta n\cdot p}{n_i^2} \geq V_{OC}$$

lifetimes: μs's for radiative recombination
1 - 100's ns non-radiative recombination

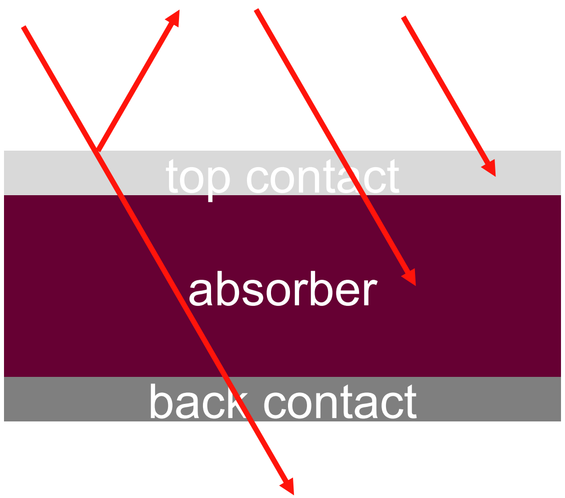
$\Rightarrow j_0$

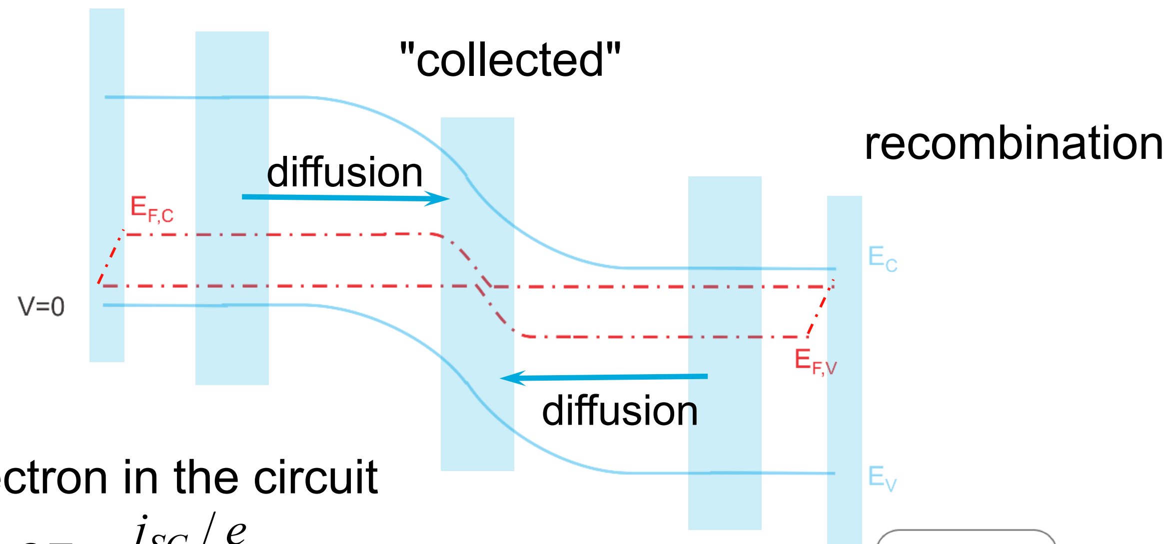
Photocurrent and solar spectrum

the solar spectrum



- e/h pair generated in absorber
- reflected
- absorbed in top contact





not every photon creates an electron in the circuit

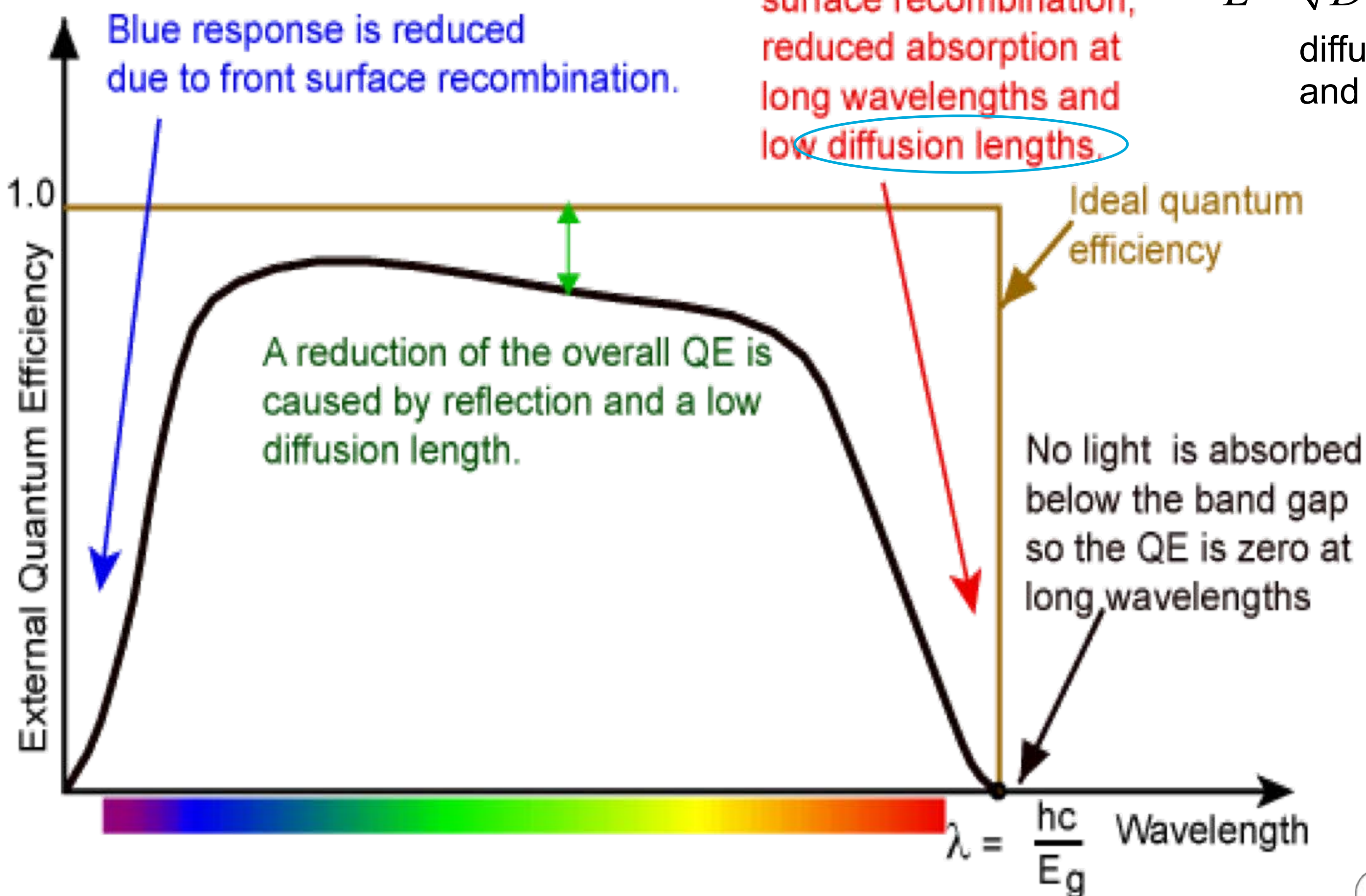
$\Rightarrow$ quantum efficiency $QE = \dfrac{j_{SC}/e}{\Phi_{ph}}$

Quantum efficiency

$$j_{ph} = e\int \qquad \Phi_{sun}(\lambda)d\lambda$$

$$L = \sqrt{D\tau}$$

diffusion constant
and life time



http://www.pveducation.org/pvcdrom/

What to remember...

- efficiency (and stability) is key for PV technology
- pn junctions are governed by the balance between drift and diffusion
- exponential increase of the current in forward direction
- light on pn junction: forward bias and reverse current: V_{OC} and j_{SC}
- maximum power point determines fill factor
- power conversion efficiency $\eta = \dfrac{j_{\mathrm{SC}} \cdot V_{\mathrm{OC}} \cdot FF}{P_{sun}}$
- V_{OC} increases with $\ln(j_{\mathrm{SC}})$ and depends on recombination process
- quantum efficiency is not power conversion efficiency
- QE depends on optical and electrical quality

if you want to know more...

- Robert Pierret "Advanced Semiconductor Fundamentals"
- Marius Grundmann "The Physics of Semiconductors"
- Peter Würfel "Physics of Solar Cells"
- Jenny Nelson "The Physics of Solar Cells"
- Roland Scheer "Chalcogenide Photovoltaics