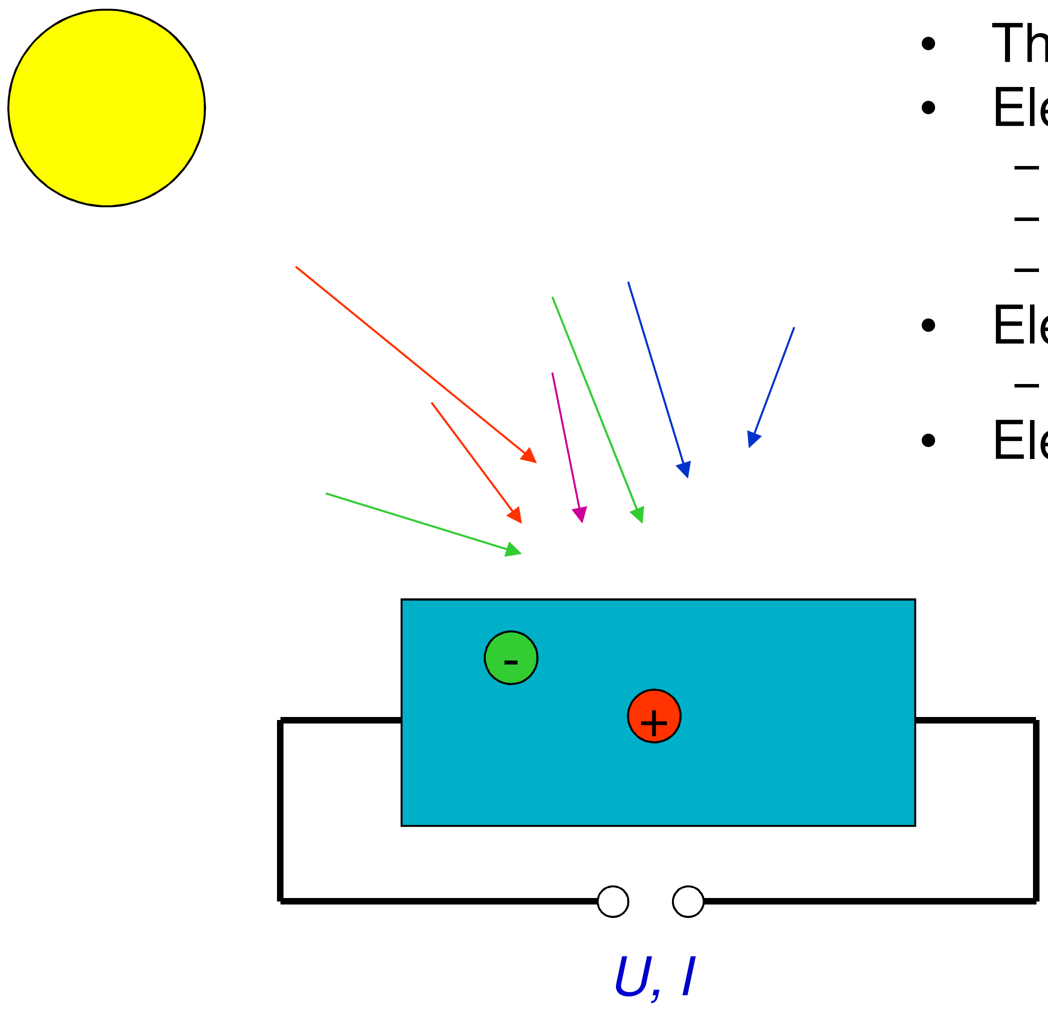
Photovoltaics

Total system

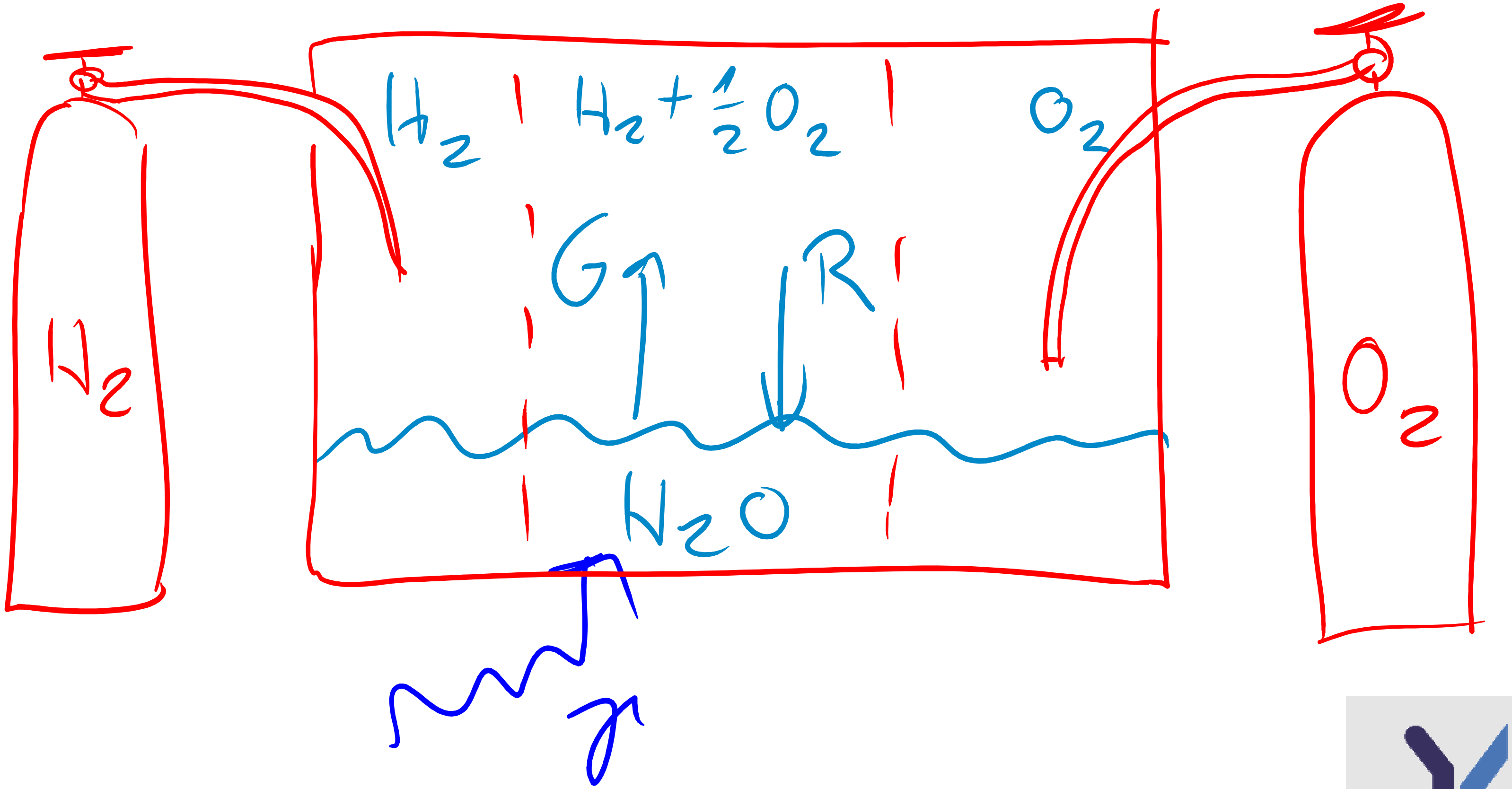


- Nuclear fusion
- Thermal energy
- Electromagnetic radiation
  - Modification of the radiation
  - Damping of the radiation
  - Absorption of the radiation
- Electrical charge carriers
  - Transport
- Electrical energy

Photovoltaics

How solar cells work – chemical analogy

- Light splits up water into hydrogen and oxygen
- Selective membranes enable the transport of hydrogen and oxygen



Photovoltaics

Optimization strategies for solar systems

Absorption spectrum
try to cover as many wavelength as possible

Absorption properties
absorb as many photons as possible

Angle of incidence
cover as many angles as possible for absorption

Conversion efficiency (and electrical transport)
absorbed photons have to carry electrical charges (causing an electrical current or a photochemical reaction)

Operation voltage (photovoltaics)
the open circuit voltage has to be as large as possible to provide a high electrical power

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Photovoltaics

Optimization strategies for solar systems

Fabrication
cost efficient requiring a low amount of energy

Durability
low ageing and constantly high efficiencies

Environmental sustainability
compatibility, toxicity, availability

Design-aspects
appearance, workability, possibility to integrate (in buildings)

Growth
requiring a low amount of energy and organic compounds

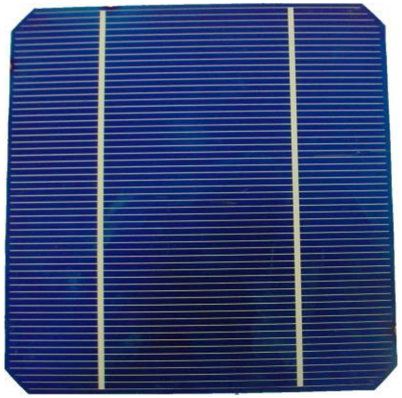
Durability
low ageing during (one season)

Environmental sustainability
compatibility?

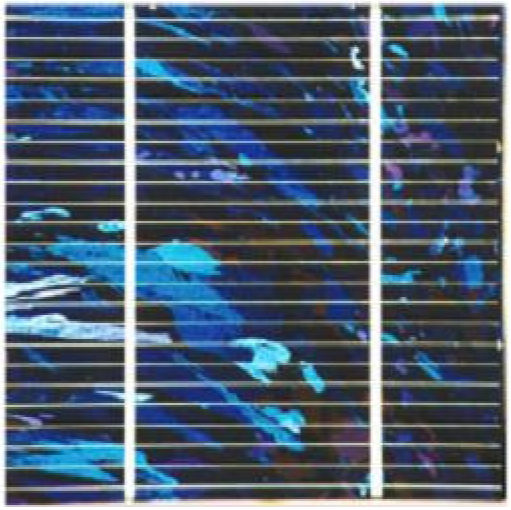
Design-aspects
appearance, integration in the plant physiology

Photovoltaics

Why do we need semiconductors instead of metals?



mono-crystalline
Si-solar cell



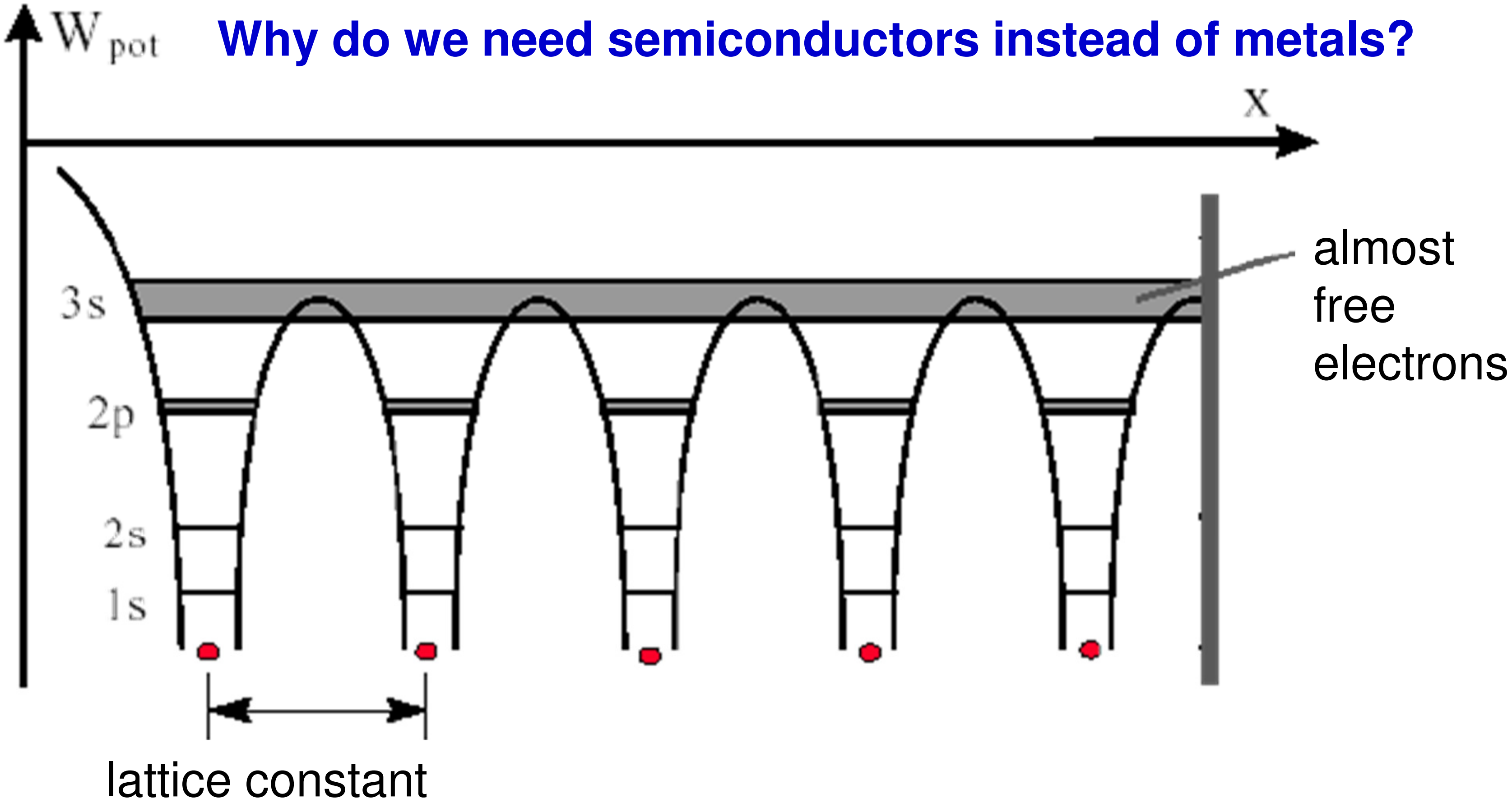
poly-crystalline
Si-solar cell

amorphous solar
cell

no mirrors, but good absorbers needed

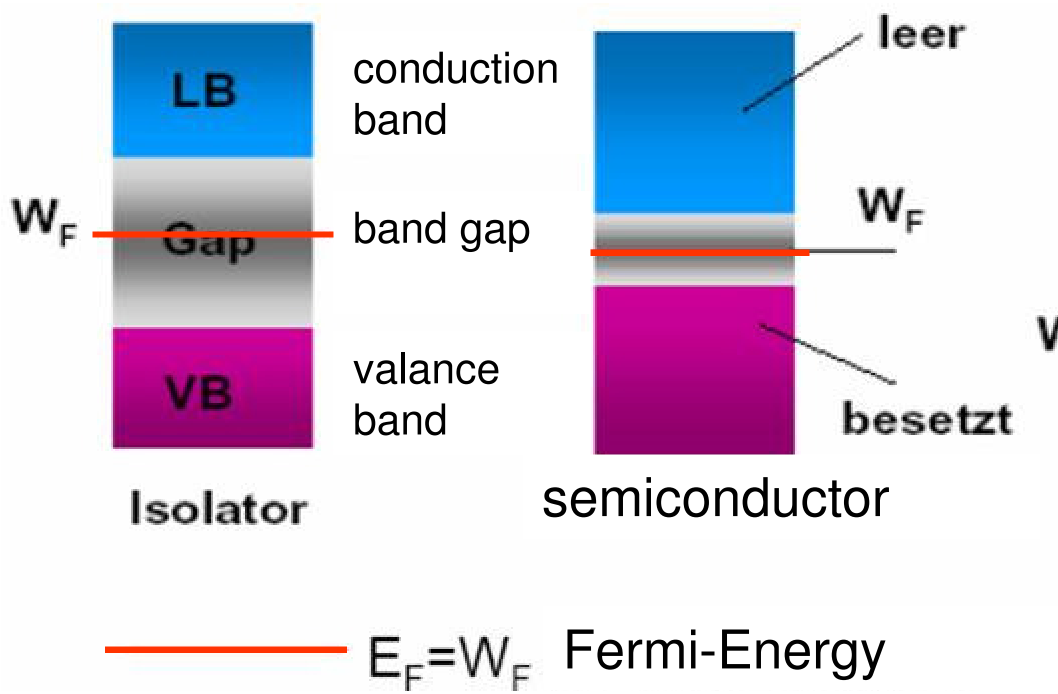
Photovoltaics

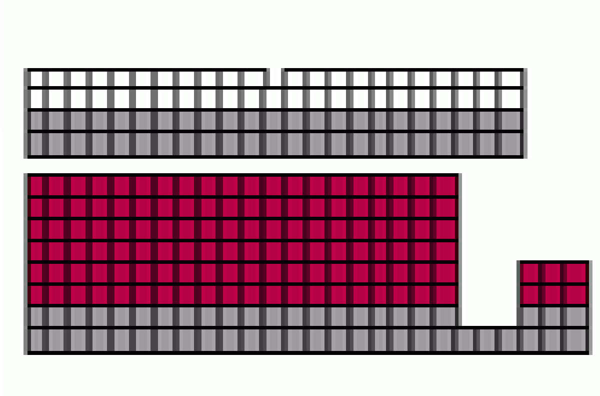
Why do we need semiconductors instead of metals?



- coupling of electron‘s orbits leads to formation of delocalized electrons, conduction and energy bands
- bandgaps are formed – electrons within this energy interval are not allowed

Photovoltaics



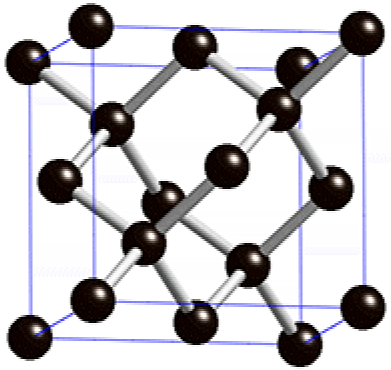


Compare: seats in a cinema

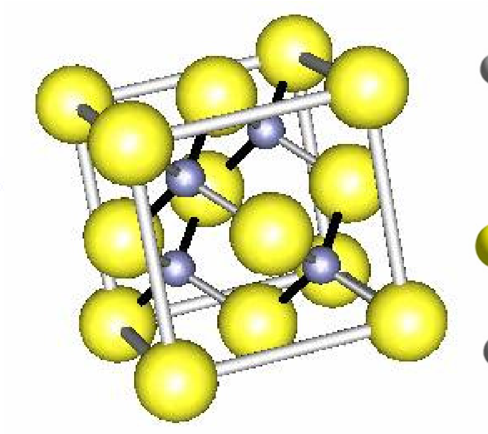
- At T=0 all electrons occupy all possible (energetical) states up to the Fermi-Energy
- The Fermi-niveau (filling level) determines whether the material is an isolator, a semiconductor or a metal

Photovoltaics

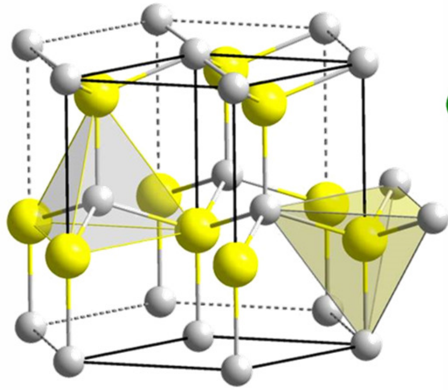
Important lattice types



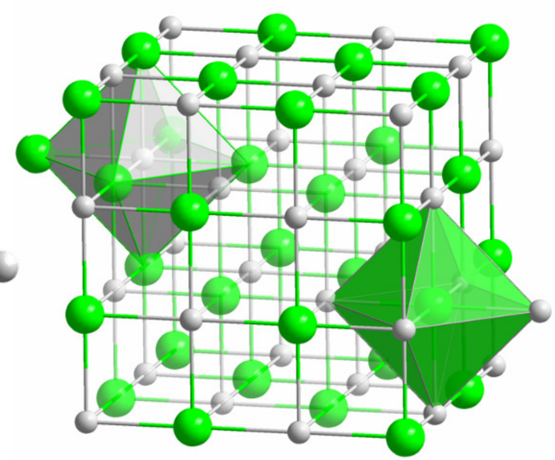
Diamant



Zinc-blende



Wurtzite



Sodiumchloride

Silicon

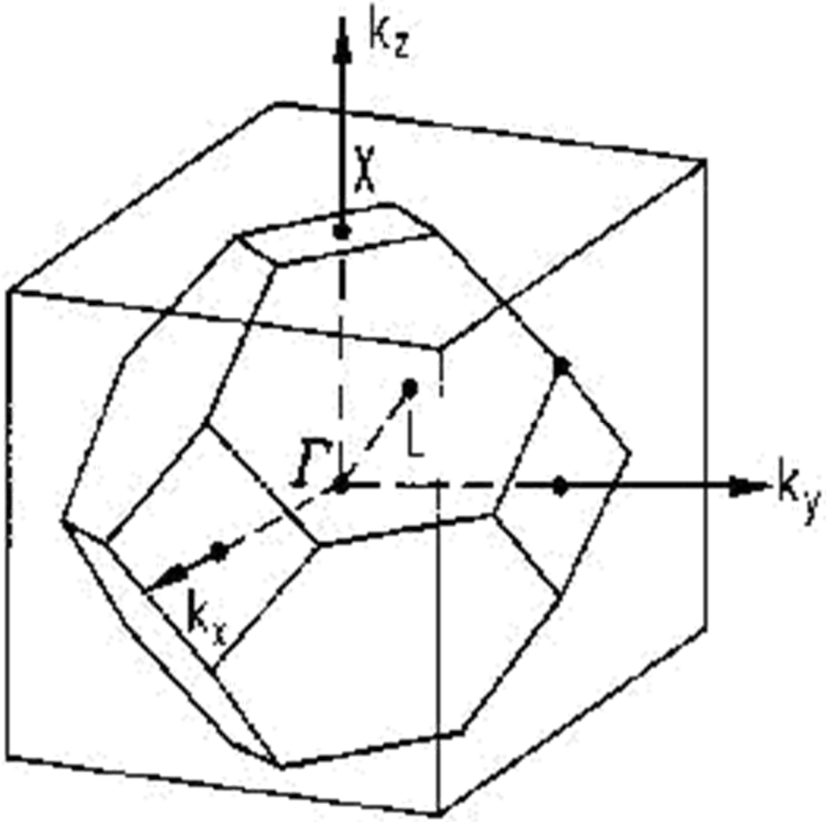
III-V semiconductor

II-VI semiconductor

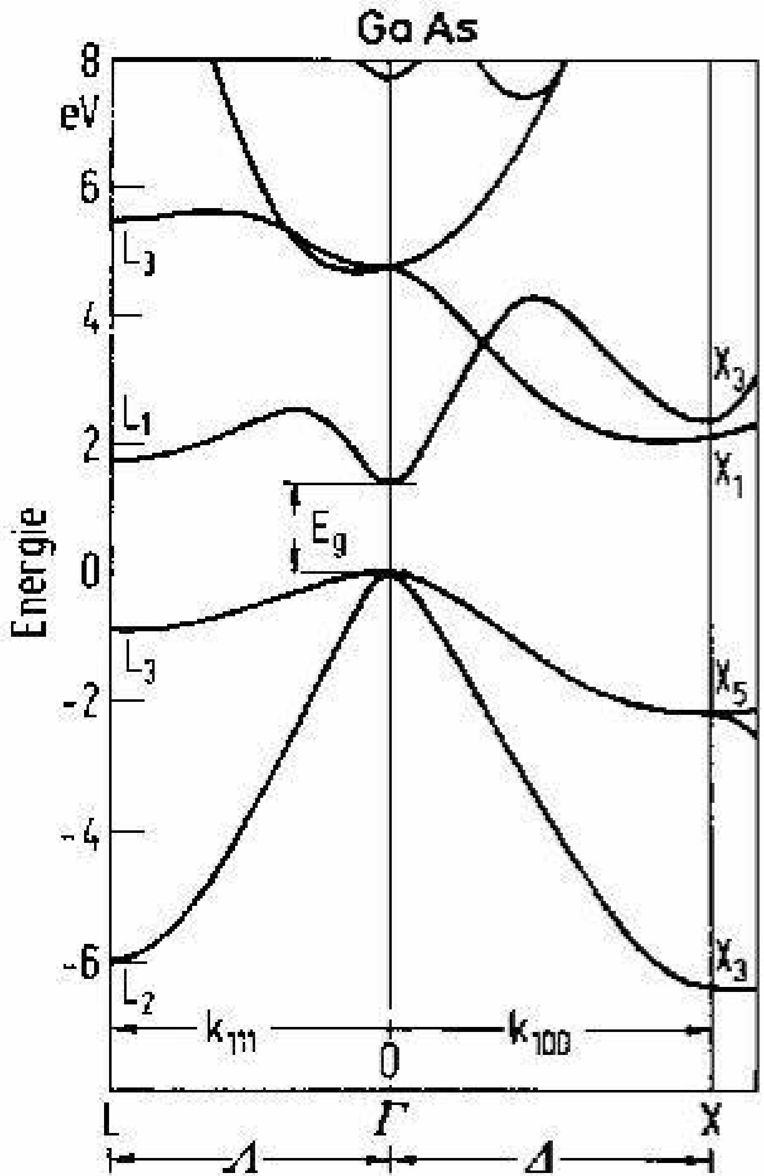
Periodicity is a real 3D-Problem

Photovoltaics

Bandstructure



Brillouin-zone



Photovoltaics

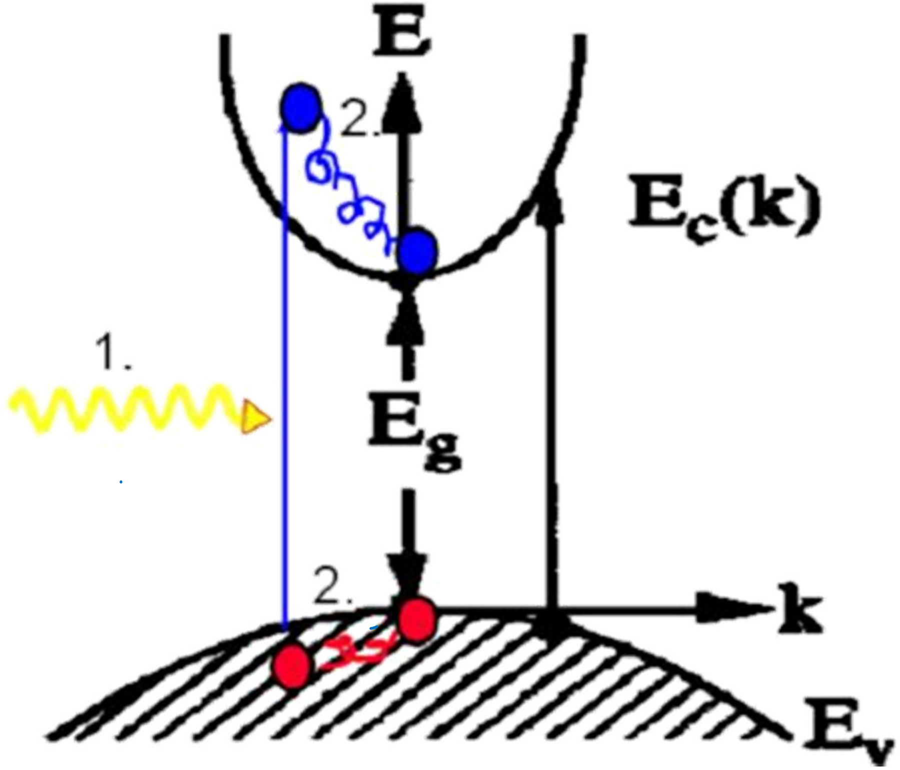
Absorption of light and the birth of an electron-hole pair

Absorption of light

Generation of an electron
hole pair (10^{-15}s)

Electron relaxes to the
minimum of the band
structure (10^{-12}s)

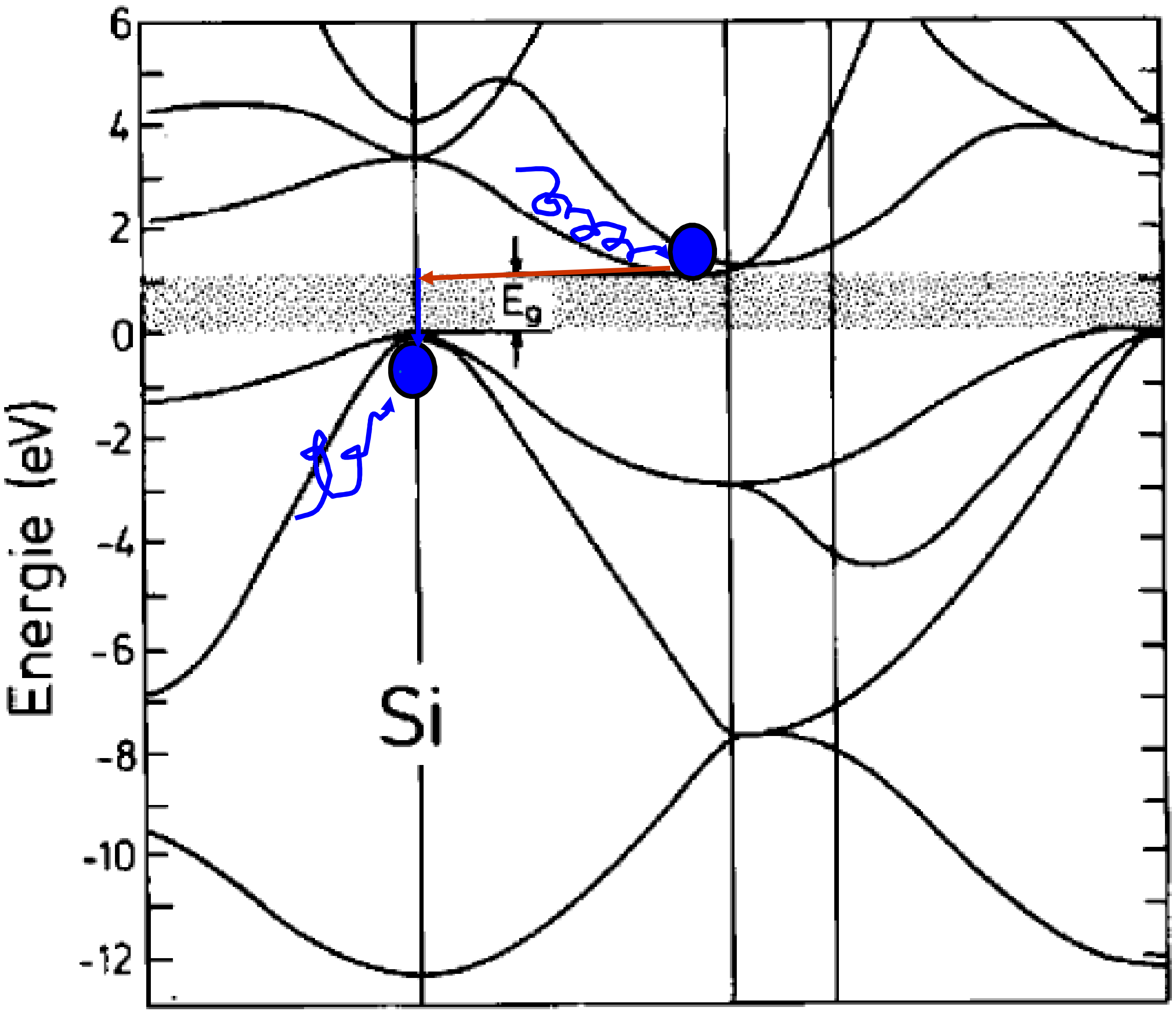
Electron lives in the minimum
until it recombines (ms)



If there was no bandgap, the excitation energy was immediately converted into thermal energy – metals are good for solarthermal systems, but not photovoltaics

Photovoltaics

Why is silicon unsuitable for photovoltaics?



very low probability for a two-step absorption process

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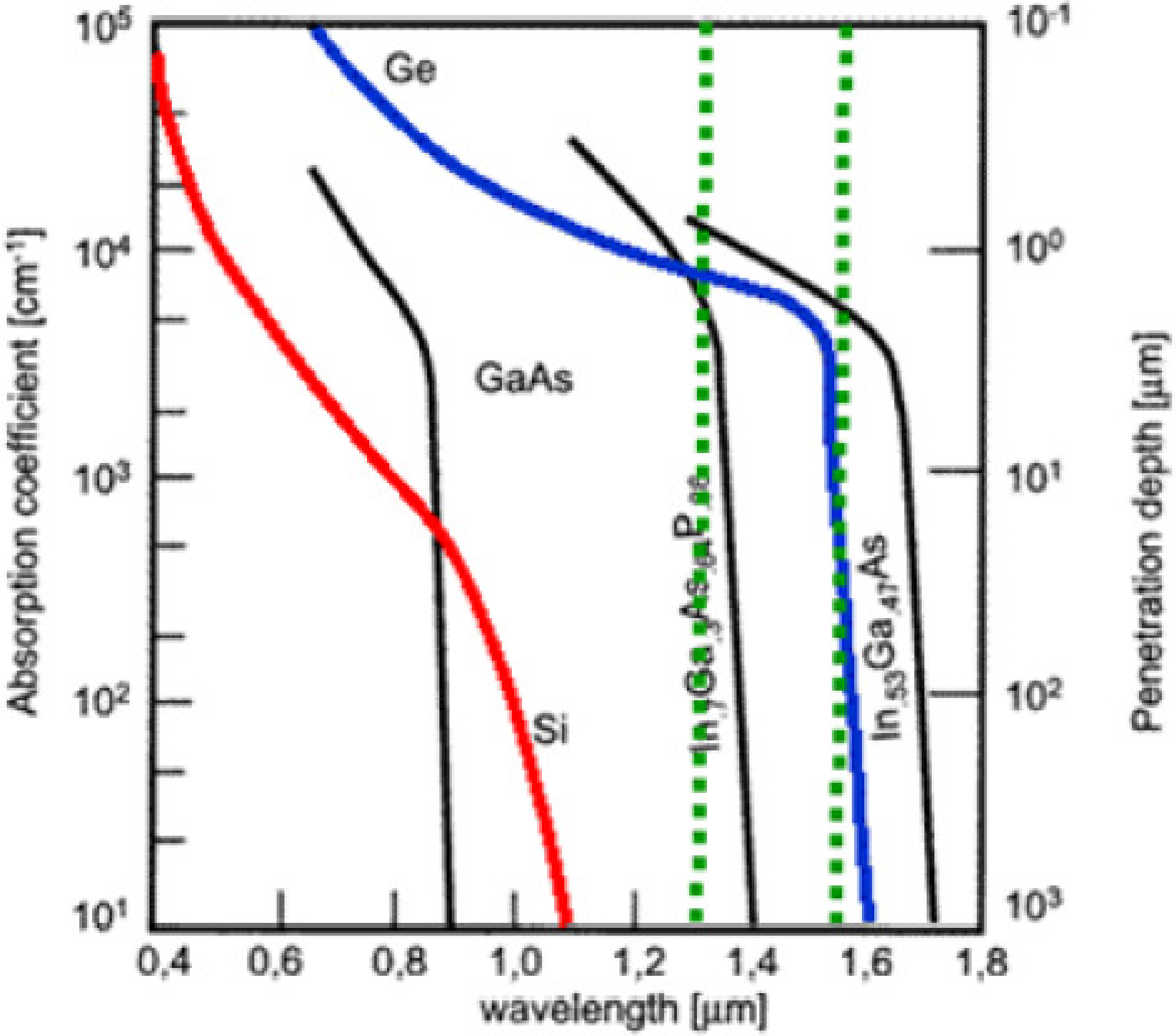
Photovoltaics

Which material is suitable for our sunlight?



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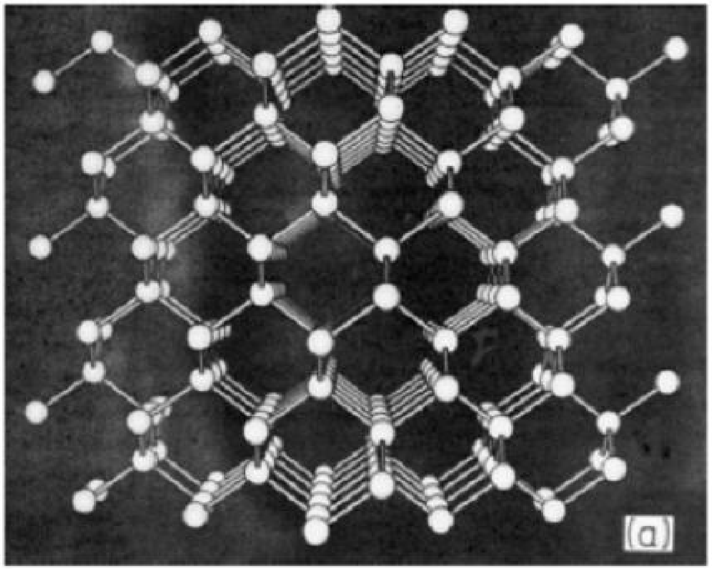
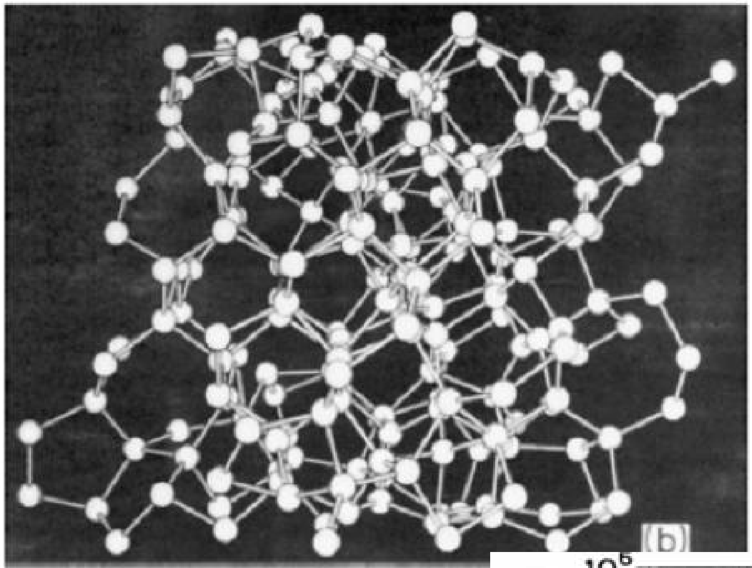
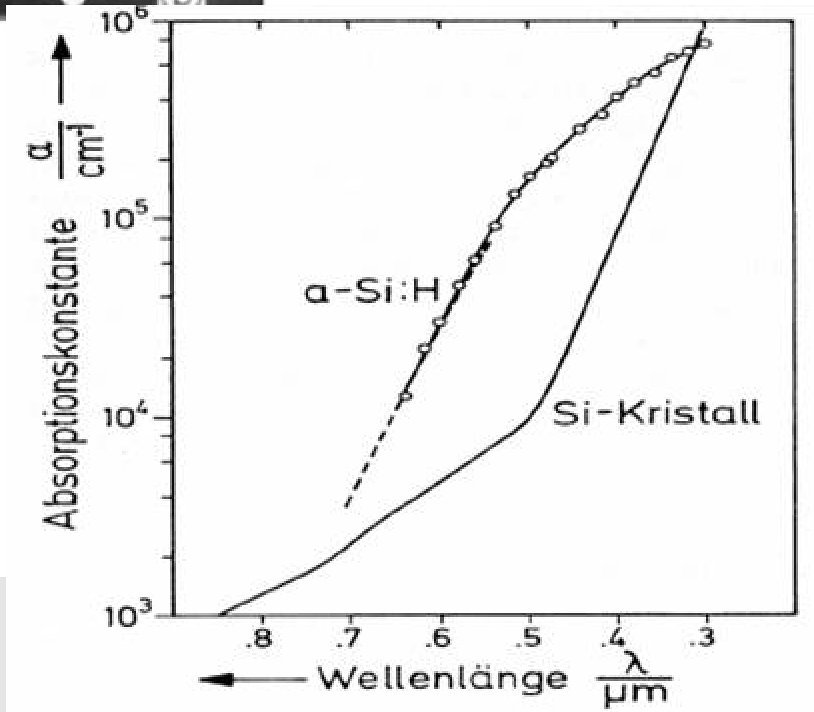
Crystalline vs. amorphous





Bandstructure not well defined in amorphous crystals



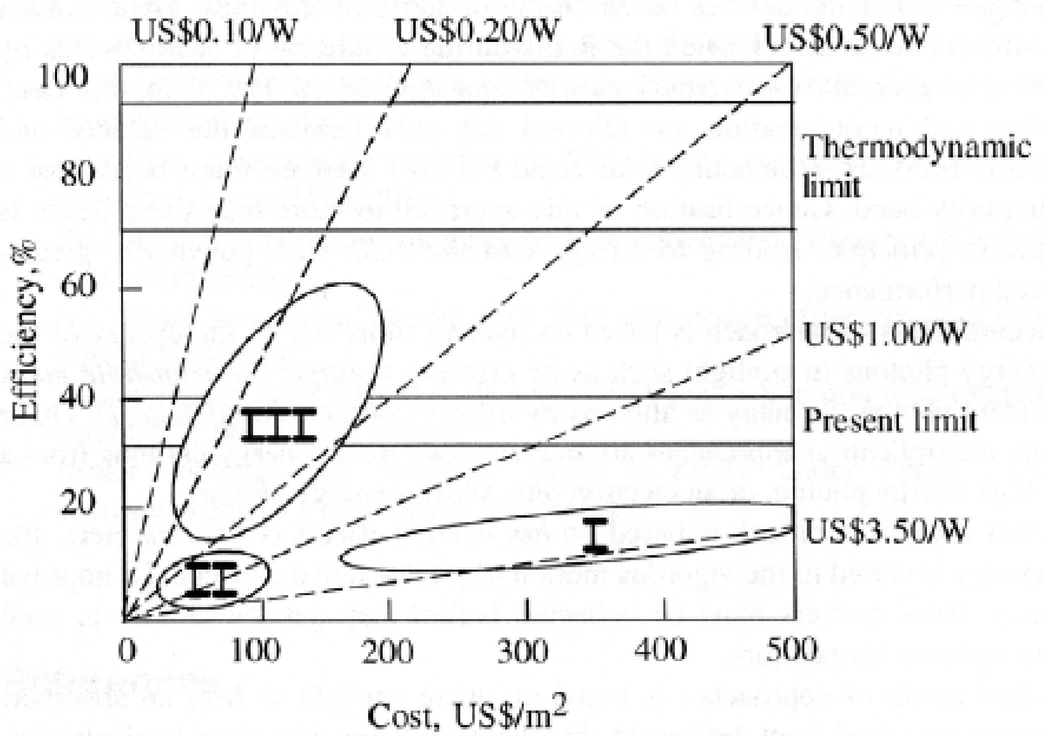
Photovoltaics

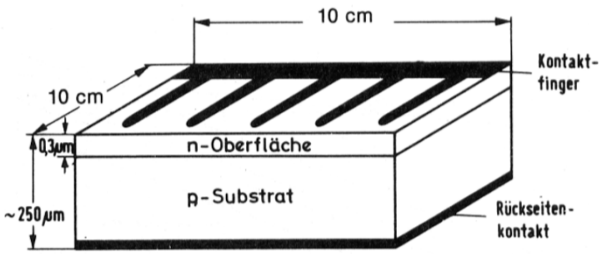
Classification of solar cells (Green)

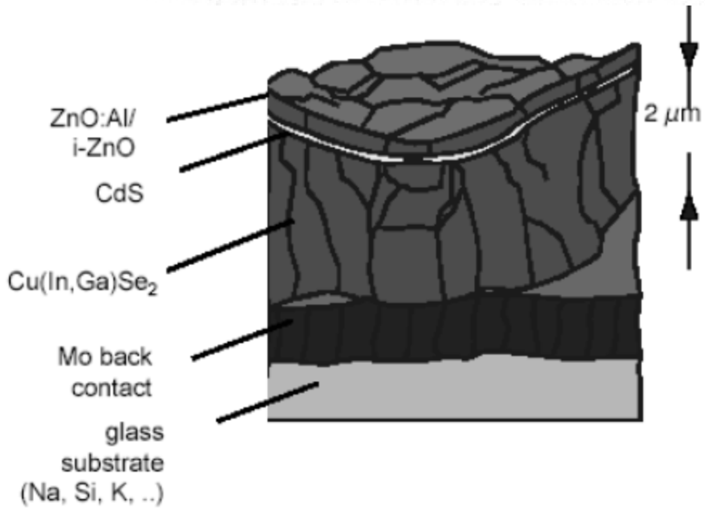
I wafer-based crystalline silicon cells

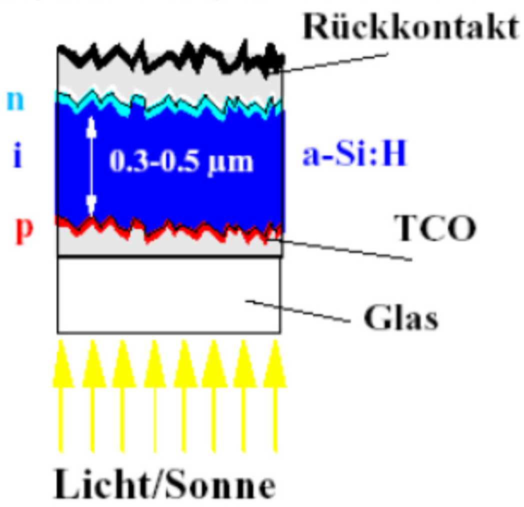
II thin film solar cells (reduced costs, moderate efficiency

III efficiency enhancement about 3fold



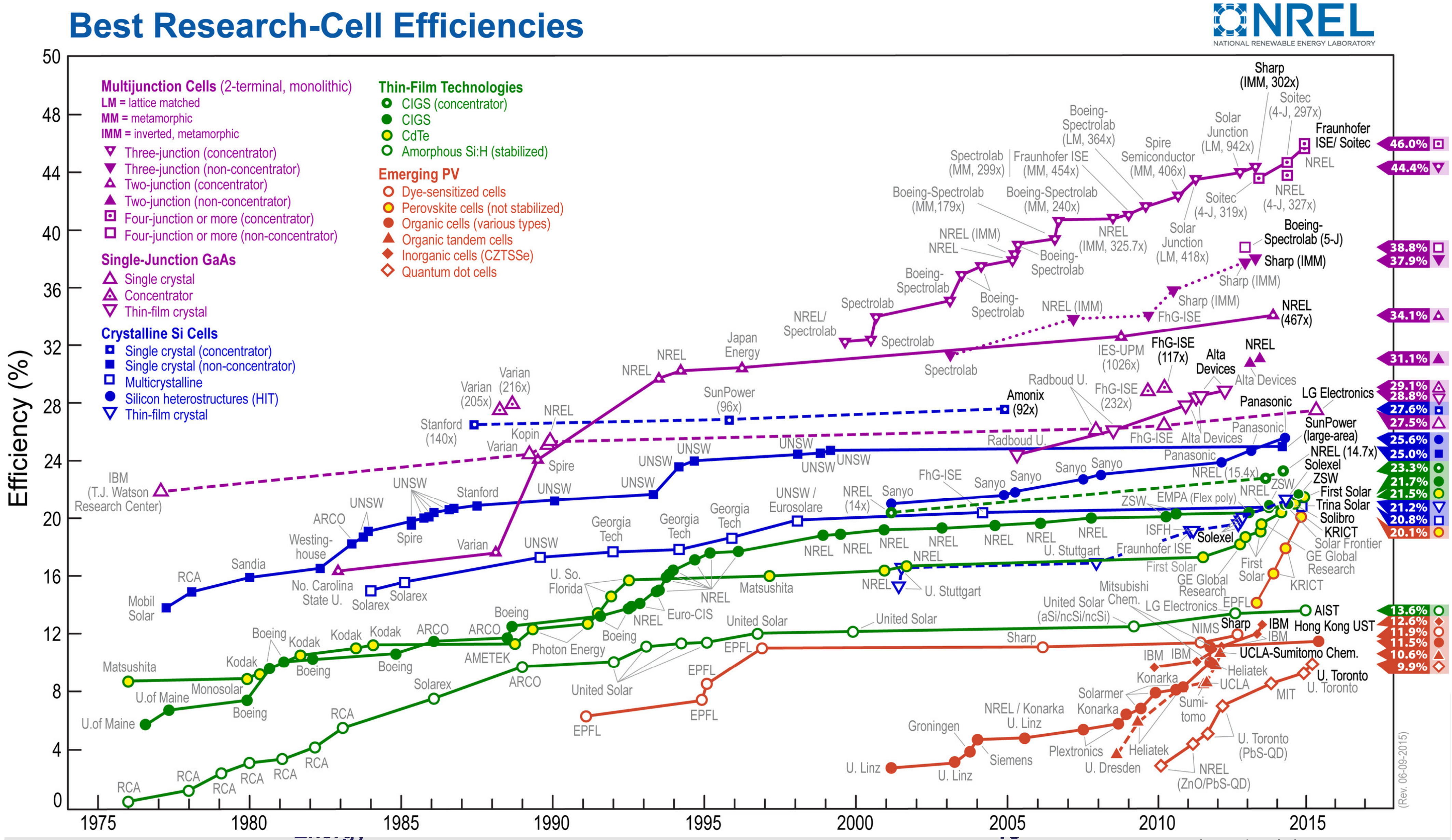






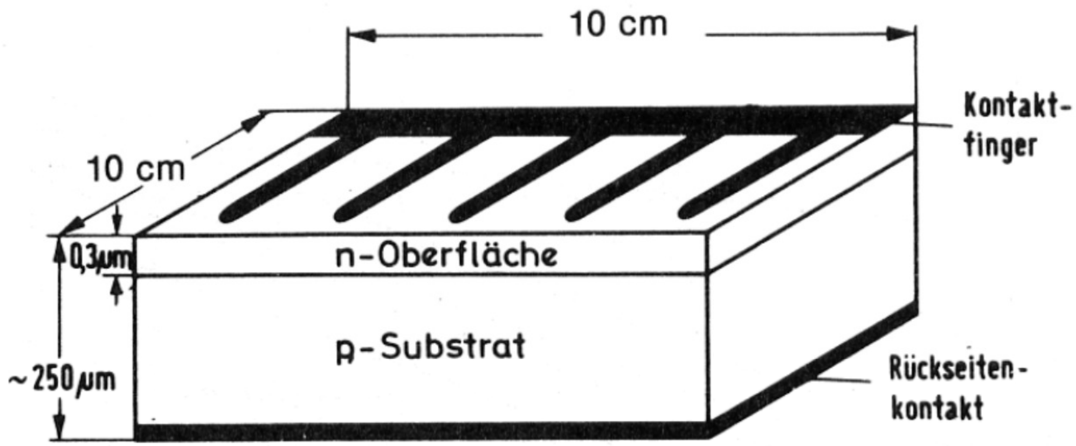
Photovoltaics

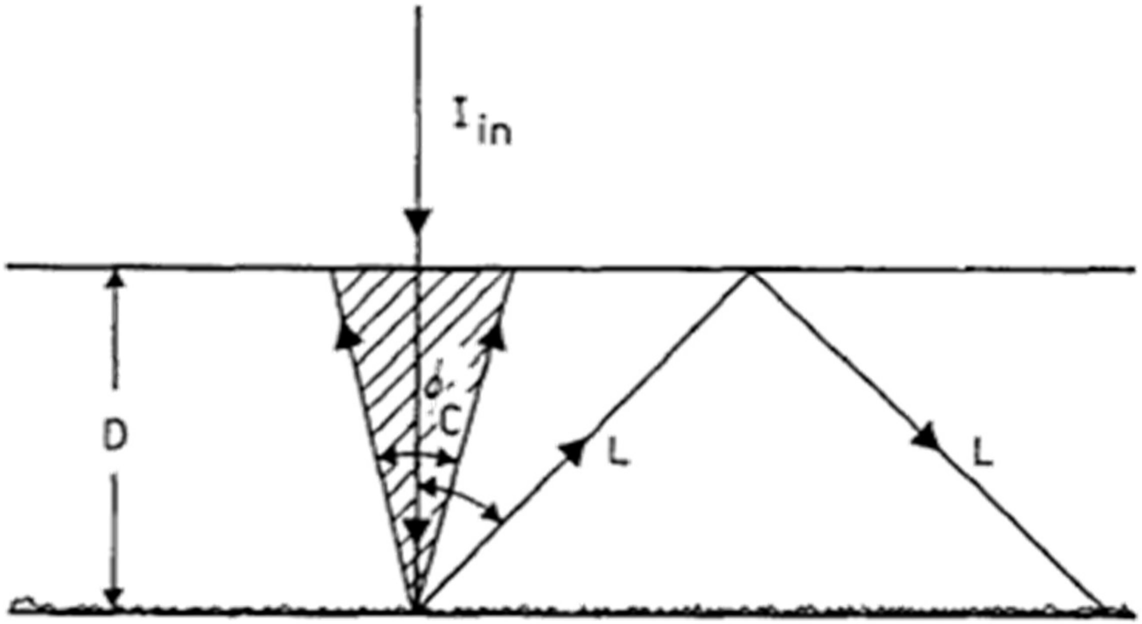
Developments



Photovoltaics

Optical ray tracing





- Illumination from the top (largest intensity)
- Distribution of the photons laterally (largest thickness for absorption)

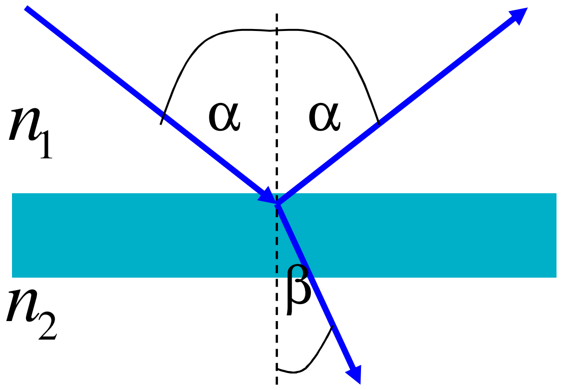
Diffusive reflection is better than perfect reflective back surface

Photovoltaics

Reflection probability at an interface between two media

Origin: steady vector components of **E** and **H**

Fresnel's formula for perpendicular incidence (intensities):

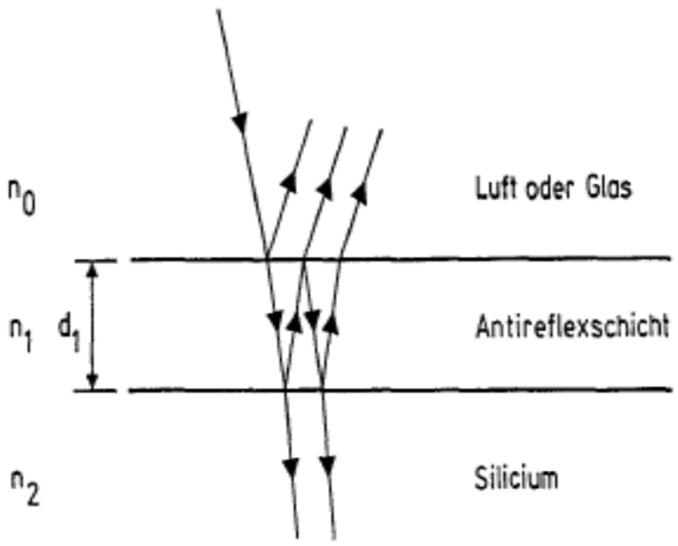


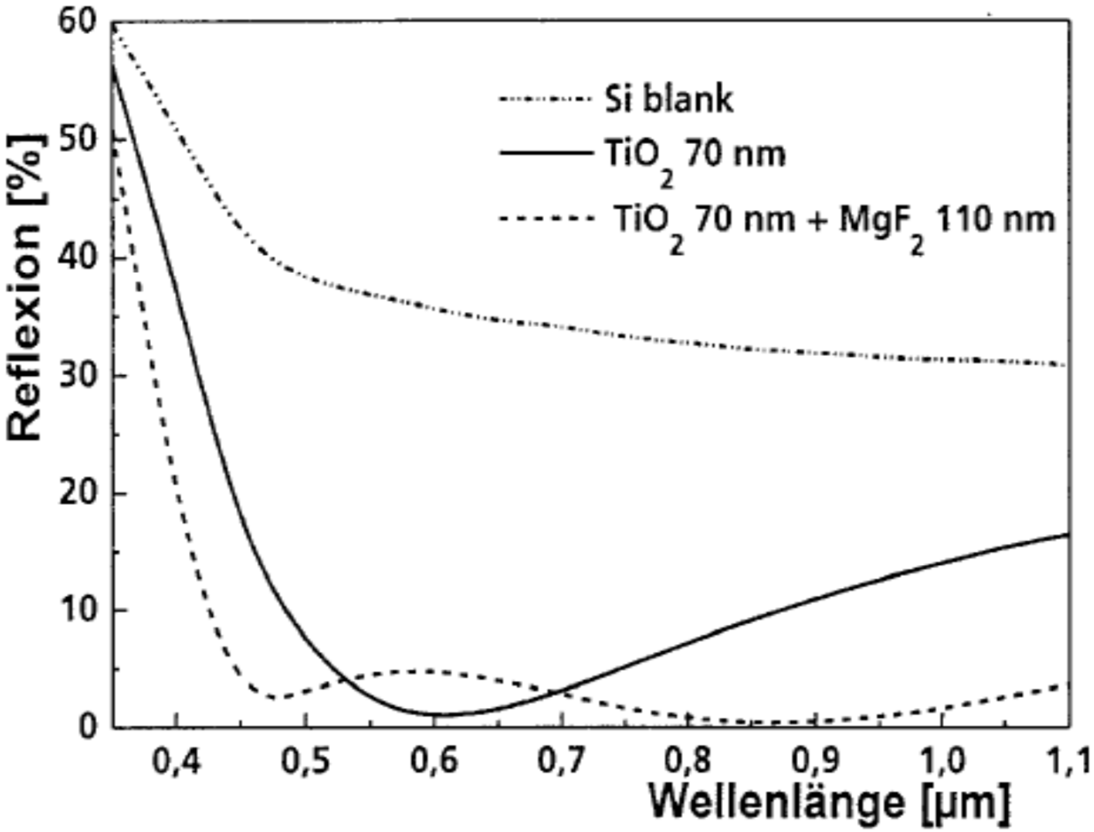
$$R = \left| \frac{n_1 - n_2}{n_1 + n_2} \right|^2$$

$$T = \left| \frac{2n_1}{n_1 + n_2} \right|^2$$

Photovoltaics

Anti-reflection layer(s)





Photovoltaics

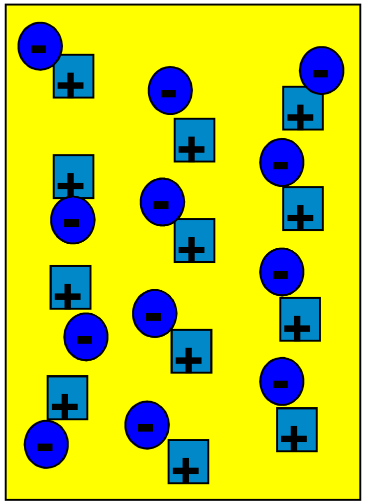
pn-junctions

simplified explanation of a diode

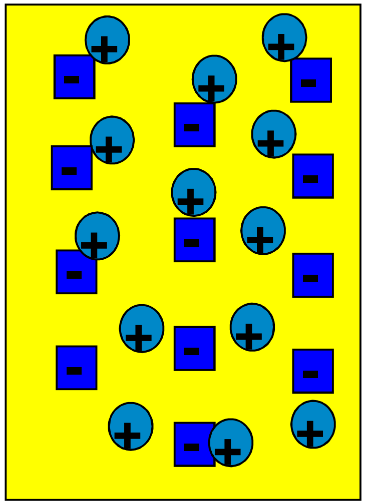
•n-semiconductor have mobile electrons, p-semiconductor mobile holes olny

•Electrons and holes “react” to form a photon and vise versa

$$n + p \leftarrow \gamma \qquad n + p \rightarrow \gamma$$



n-semiconductor

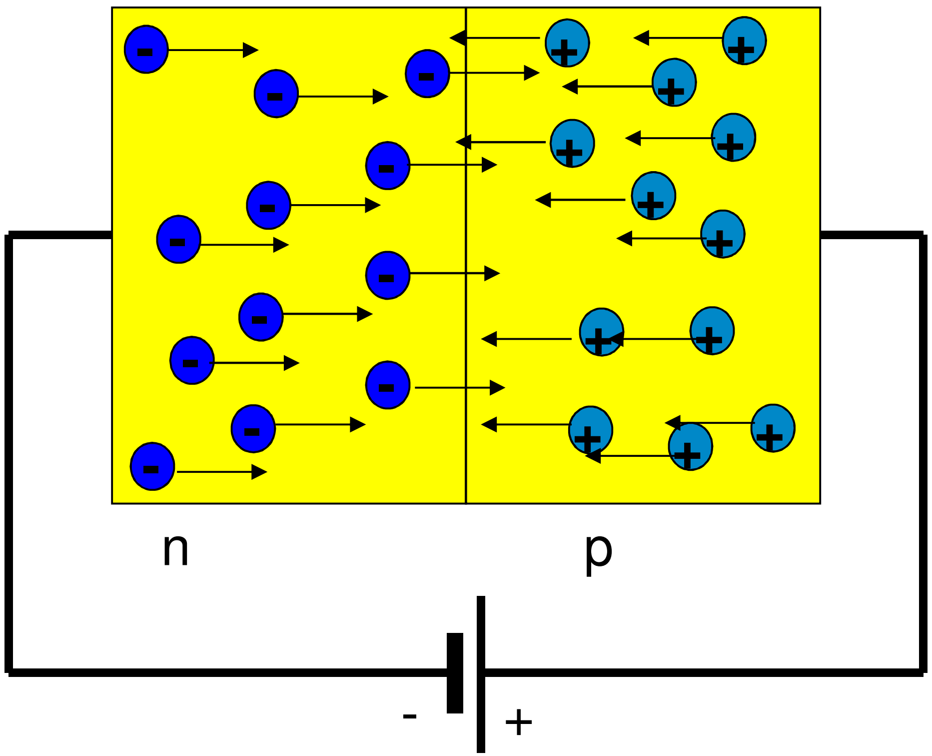


p-semiconductor

Photovoltaics

pn-junctions

simplified explanation of a diode

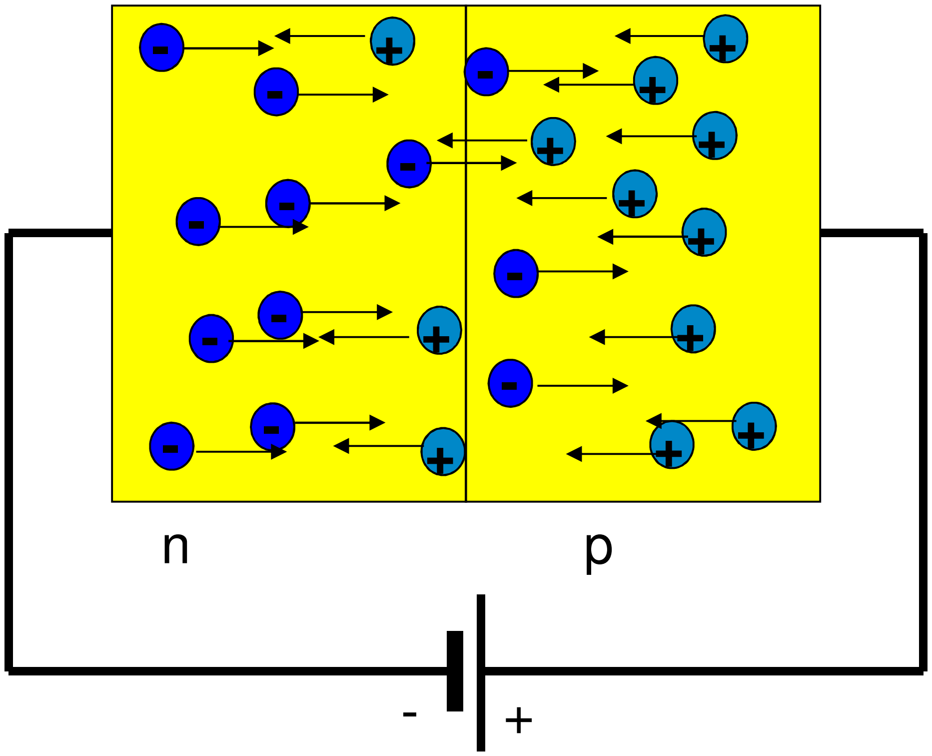


polarity such that a current flows
electrons and holes fly towards each other

Photovoltaics

pn-junctions

simplified explanation of a diode

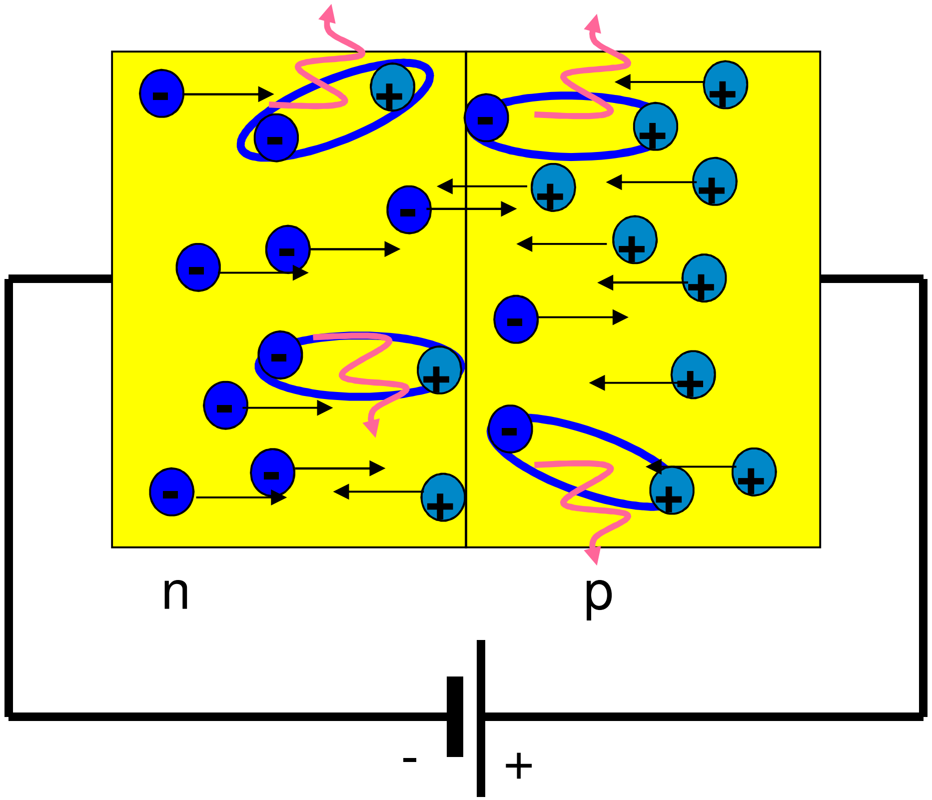


electrons move into the p, holes into the n region

Photovoltaics

pn-junctions

simplified explanation of a diode



electrons and holes meet and recombine to photons – light emitting diode

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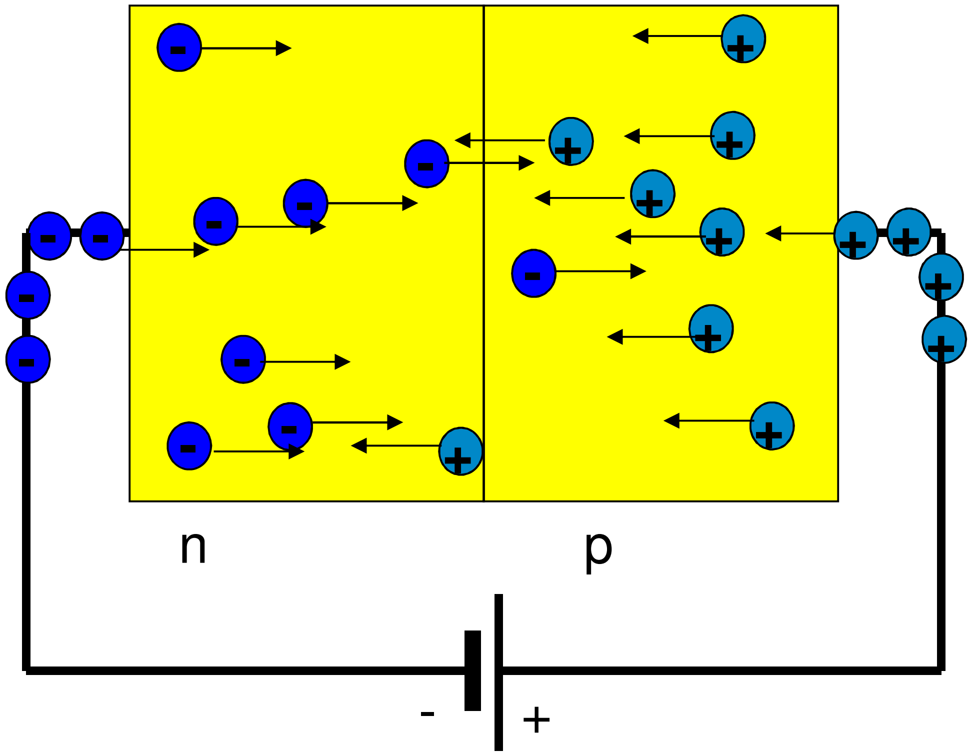
Photovoltaics

pn-junctions

simplified explanation of a diode

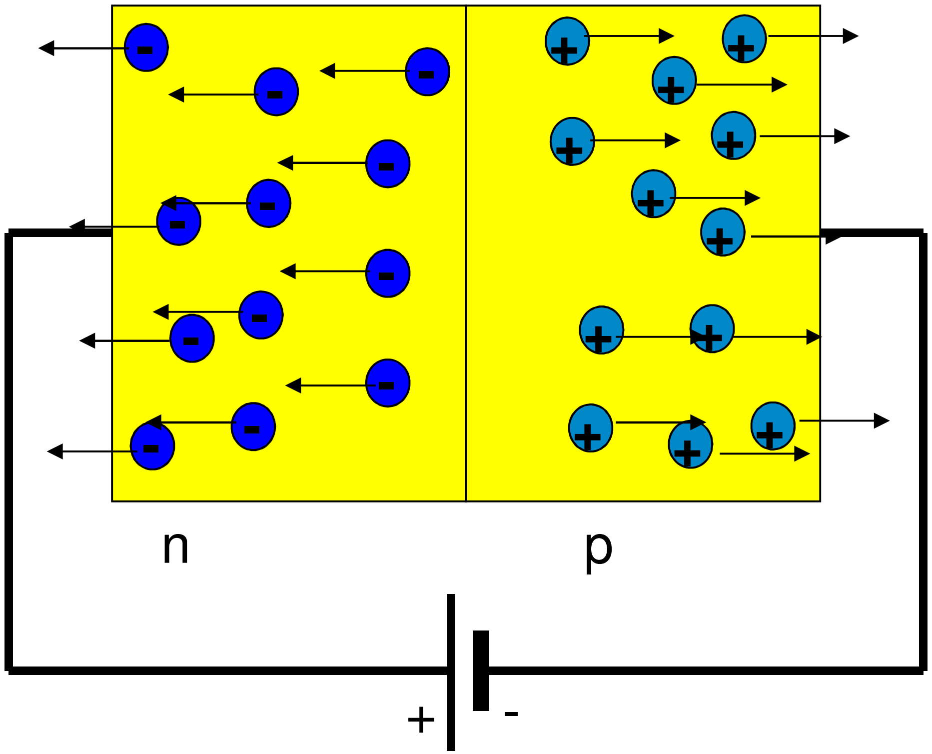


missing electrons and holes are replaced by new charge carriers from the current source

Photovoltaics

pn-junctions

simplified explanation of a diode



opposite polarity – carriers move away from each other

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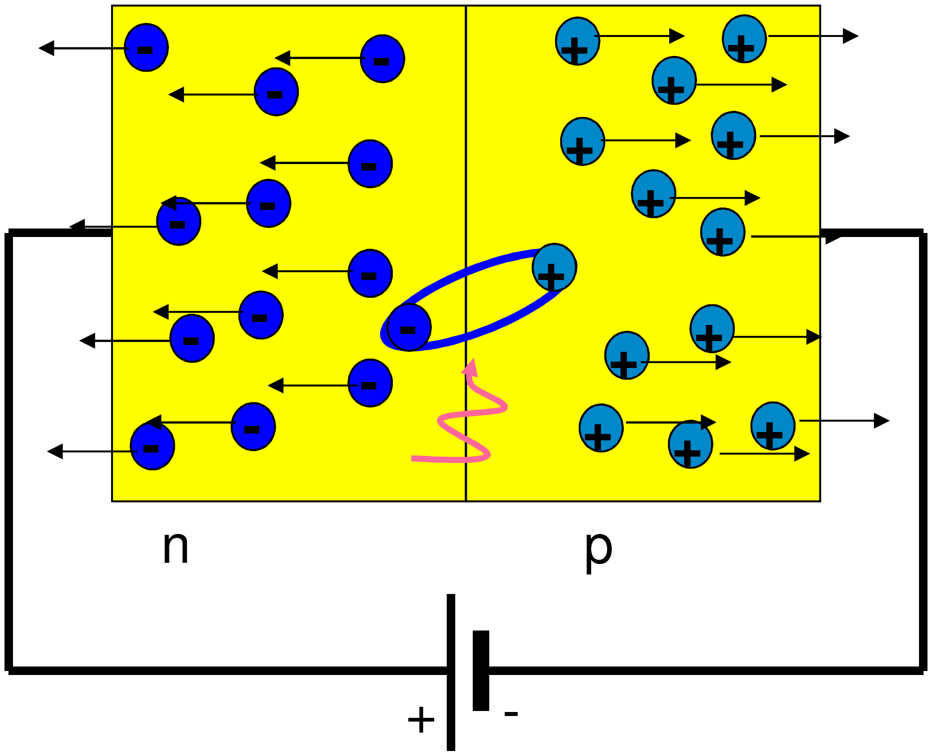
Photovoltaics

pn-junctions

simplified explanation of a diode

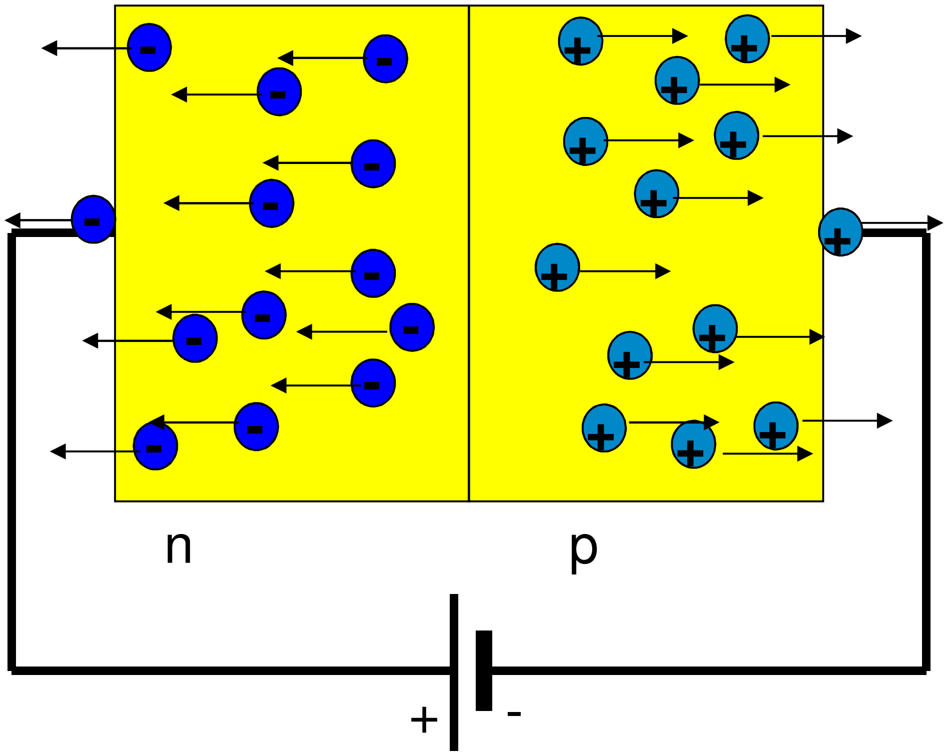


photon can be absorbed and generates an electron hole pair

Photovoltaics

pn-junctions

simplified explanation of a diode

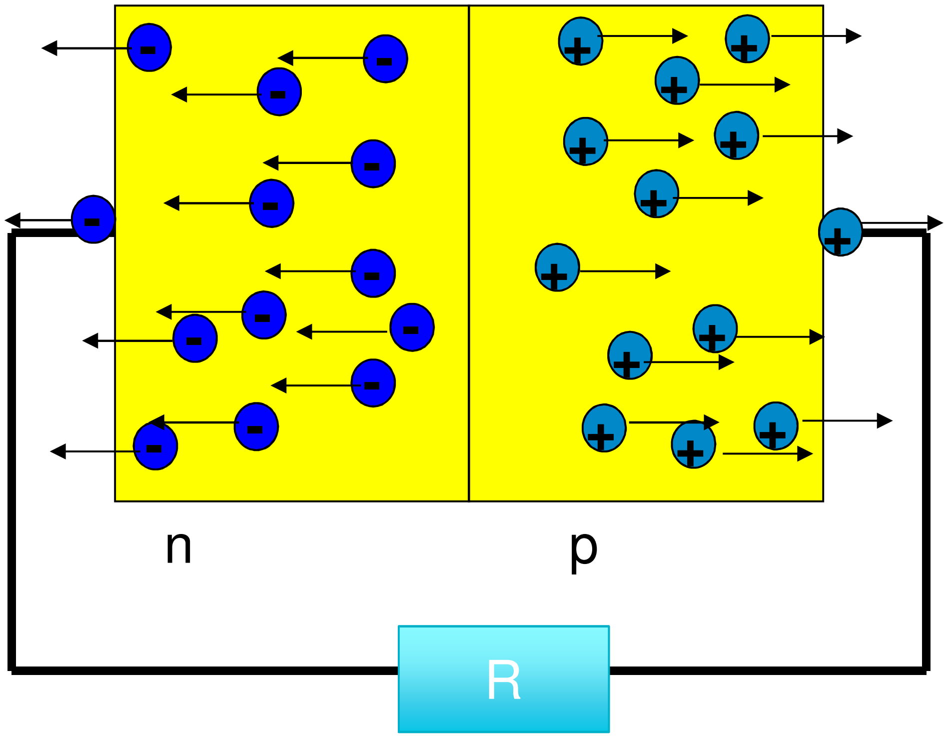


additional charge carriers push a current thru the circuit – photodiode

Photovoltaics

pn-junctions

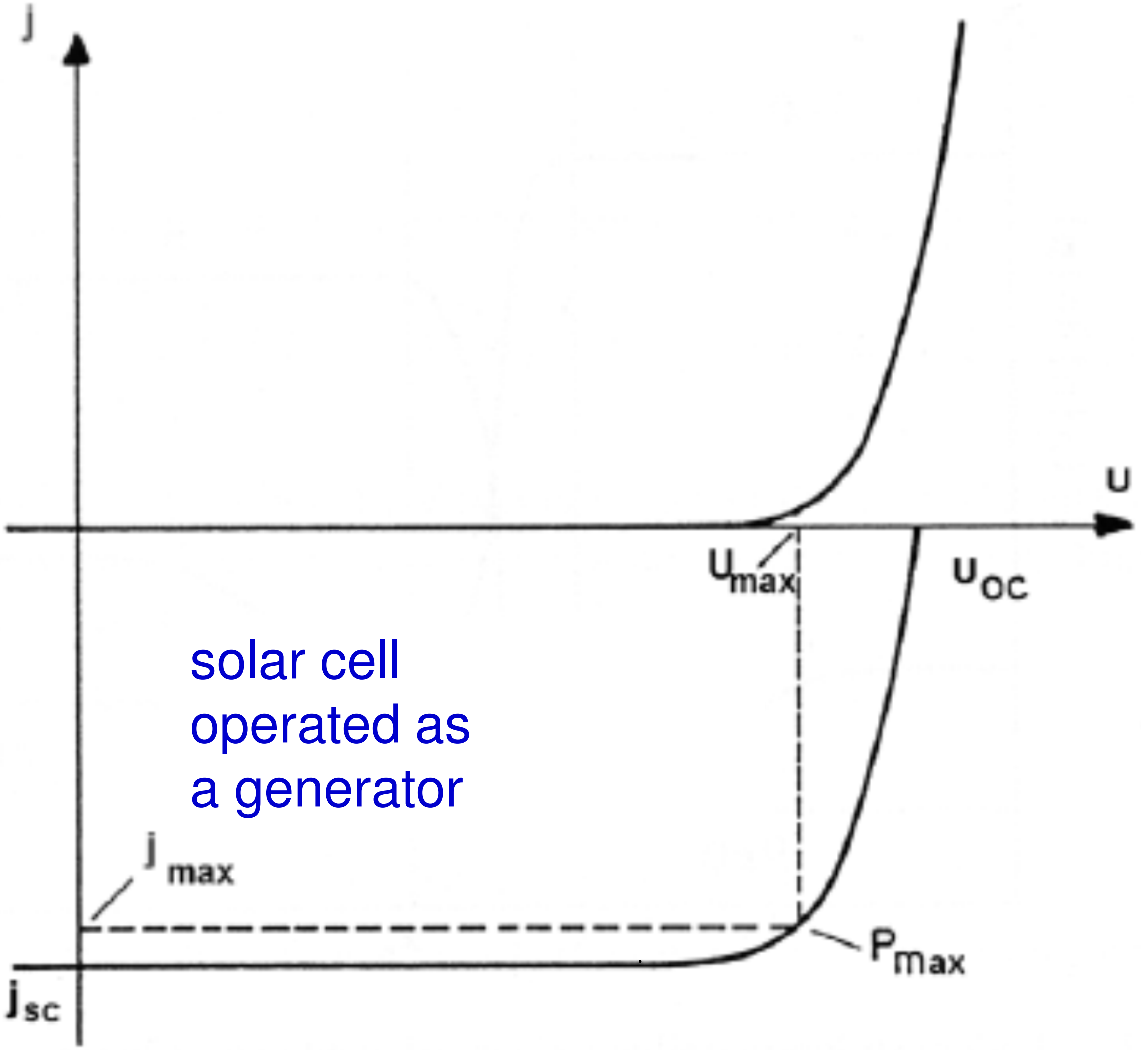
simplified explanation of a diode



additional charge carriers drive an electrical current thru a load – solar cell

Photovoltaics

iv-characteristics with and without illumination



$$FF = \frac{U_{max} I_{max}}{U_{oc} I_{sc}}$$

Filling factor (curve factor) is typically in the range from 0.75 to 0.85 for silicon, depending on the geometry and series/parallel resistances

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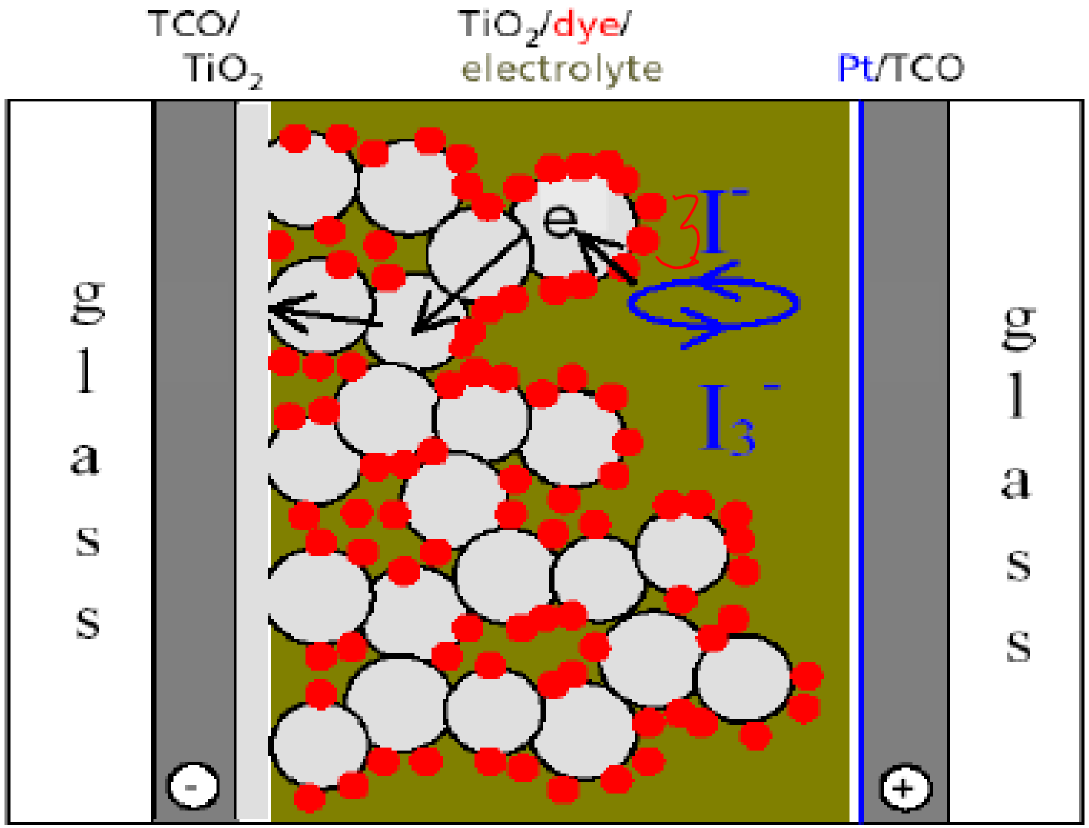
Photovoltaics

Grätzel cell

setup:

•nanoscale particles are in contact
•adsorbed monolayer of dye molecules leads to high absorption due to high surface
•electrical contacts thru electrolytes Iodine



reactions:

$S+hf \rightarrow S^*$ optical excitation
$S^* \rightarrow S^+ + e^-$ electron transfer, oxidization of the dye
$2S^+ + 3I^- \rightarrow 2S + I_3^-$ reduction of the dye
diffusion to the counter electrode
$I_3^- + 2e^- \rightarrow 3I^-$ reduction of tri-iodine to iodine

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Photovoltaics

Mathematical description of the iv-characteristics

$$\boxed{J = J_s\left(e^{\frac{eU}{kT}} - 1\right) - J_L}$$

$$J_L = eG(L_n + L_p + w)$$

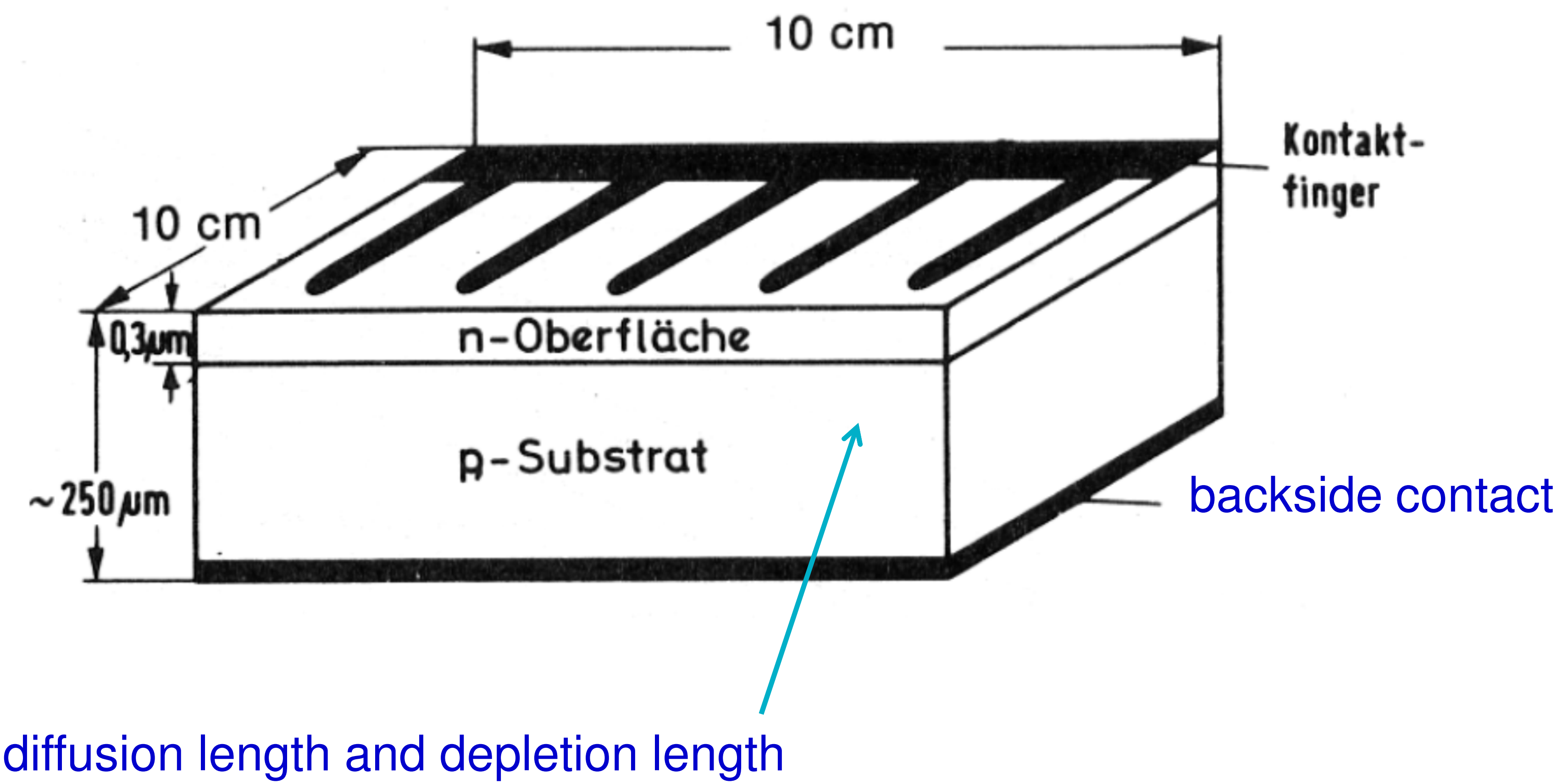
generated charges within the diffusion length or the depletion length

$$J_s = \frac{eD_n n_{p0}}{L_n} + \frac{eD_p p_{n0}}{L_p} \approx \frac{D_n n_i^2}{L_n n_A} + \frac{D_p n_i^2}{L_p n_D}$$

diode characteristics depends on diffusion constants D, diffusion length L, and doping concentrations

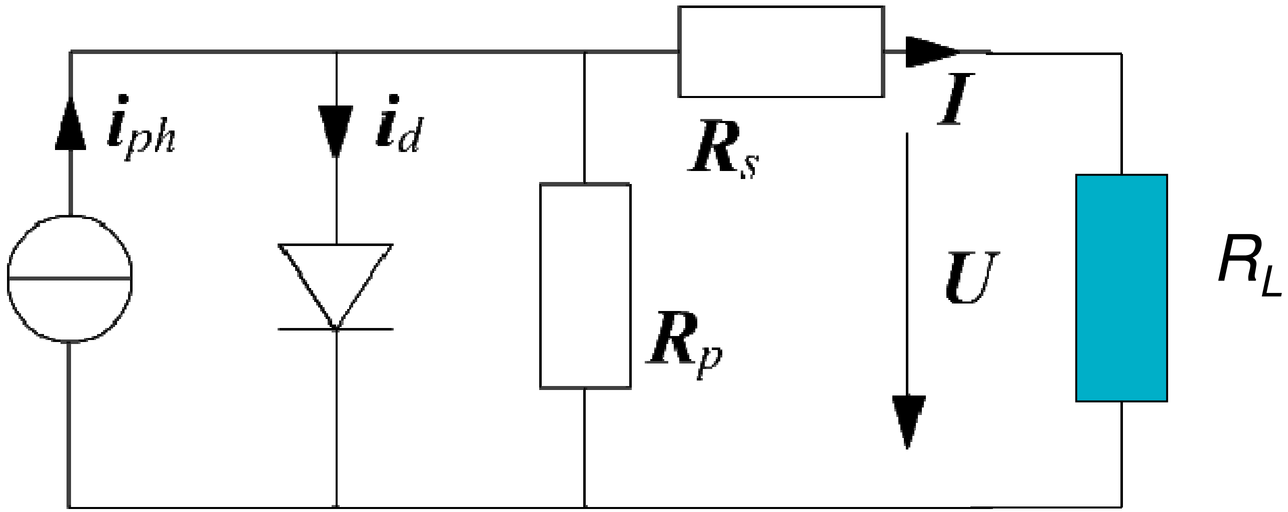
Photovoltaics

Setup of a silicon solar cell



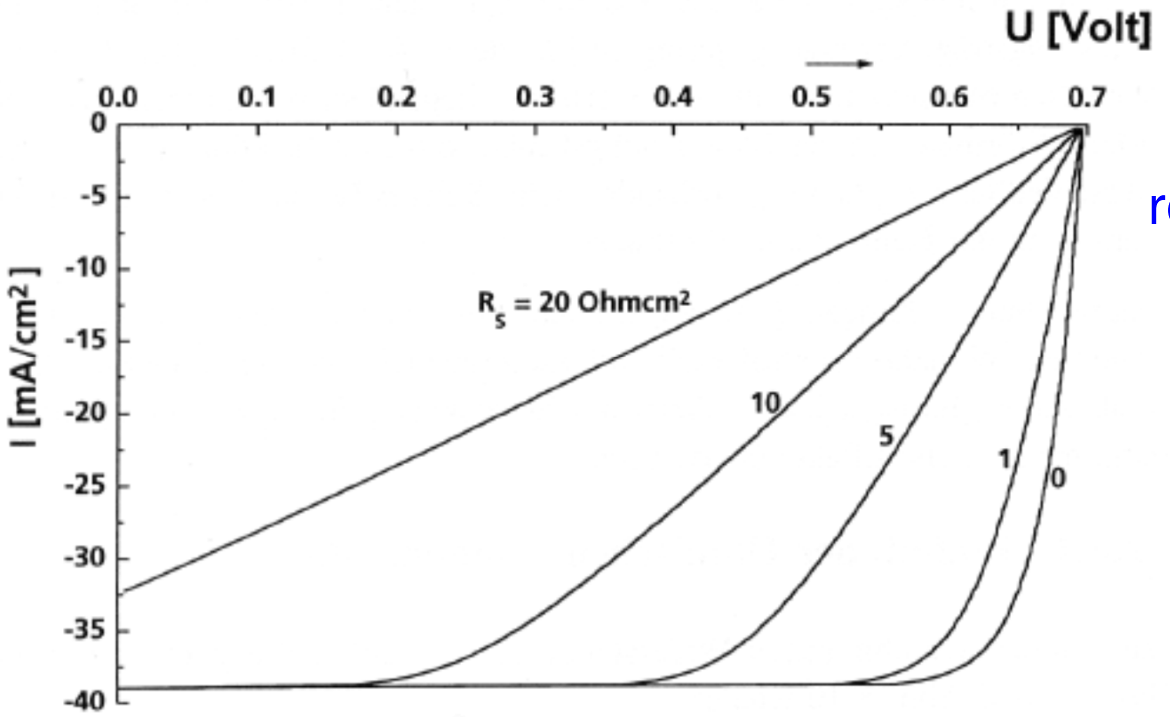
Photovoltaics

Equivalent circuit



Photovoltaics

Impact of series resistances



reduction of the filling factor

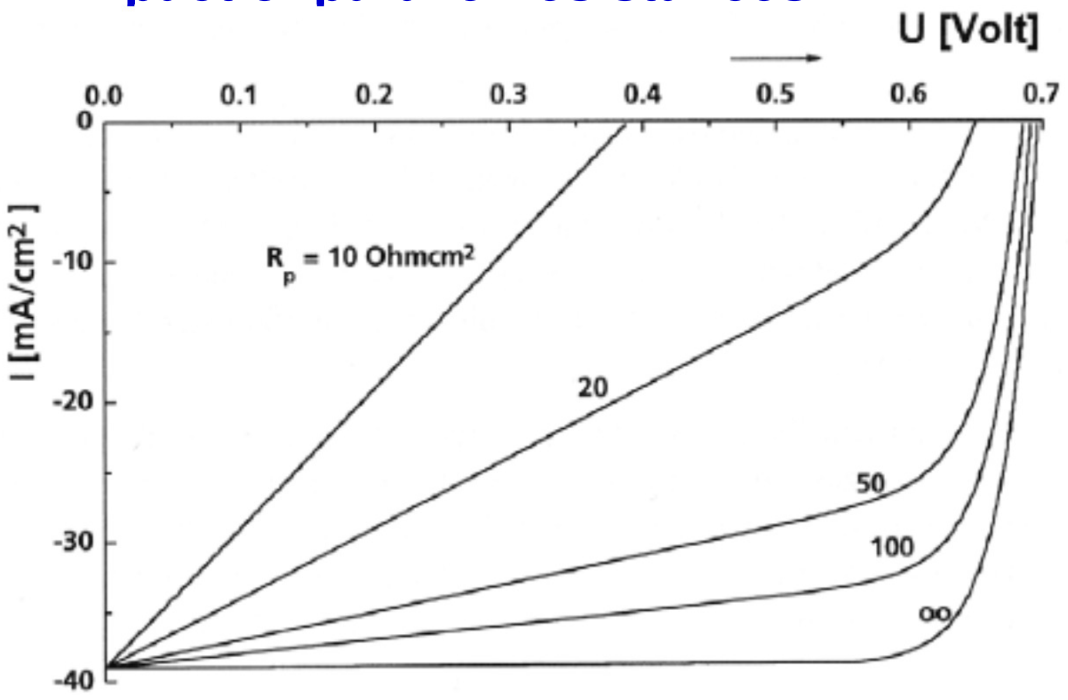
Origin
- Resistances in the neutral regions
- Contact resistances

Solution
- High doping
- metallic comb structure

subsequent problem: small space charge region RZ, small diffusion lengths

Photovoltaics

Impact of parallel resistances



Origin

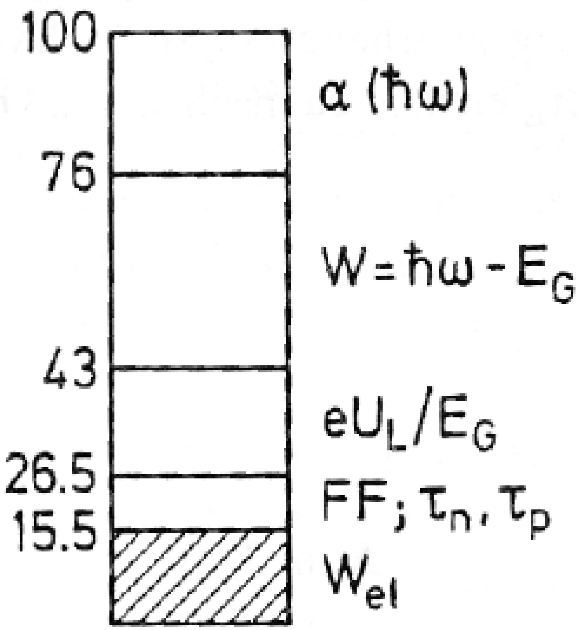
- grain boundaries
- short circuits due to surface states

Solution

- Patterning, passivation
- crystalline material

Photovoltaics

total losses

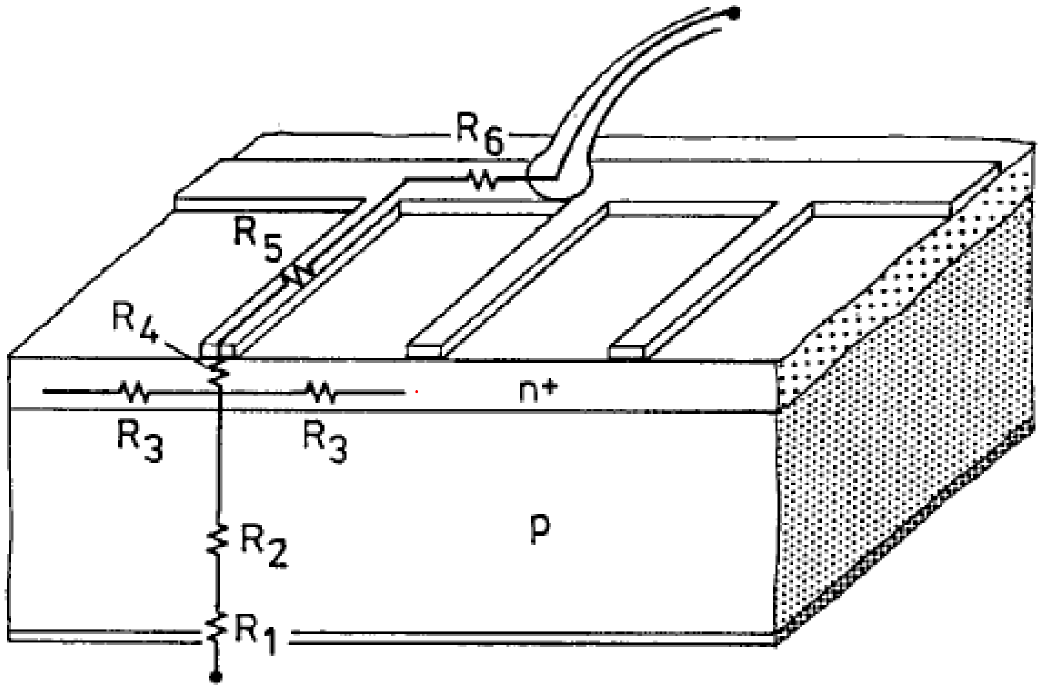


silicon solar cell with
15.5% efficiency

- losses
  - optical
    - •reflection
    - •shading
    - •penetration
  - electrical
    - ohmic
      - •semiconductor (base, emitter)
      - •contact material (finger, bus, transition metal-semiconductor
    - recombinatory
      - •emitter (semiconductor, surface)
      - •base (semiconductor, surface)
      - •space charge zone

Photovoltaics

ohmic losses



R1 metal-semiconductor backside

R2 of the base

R3 lateral emitter

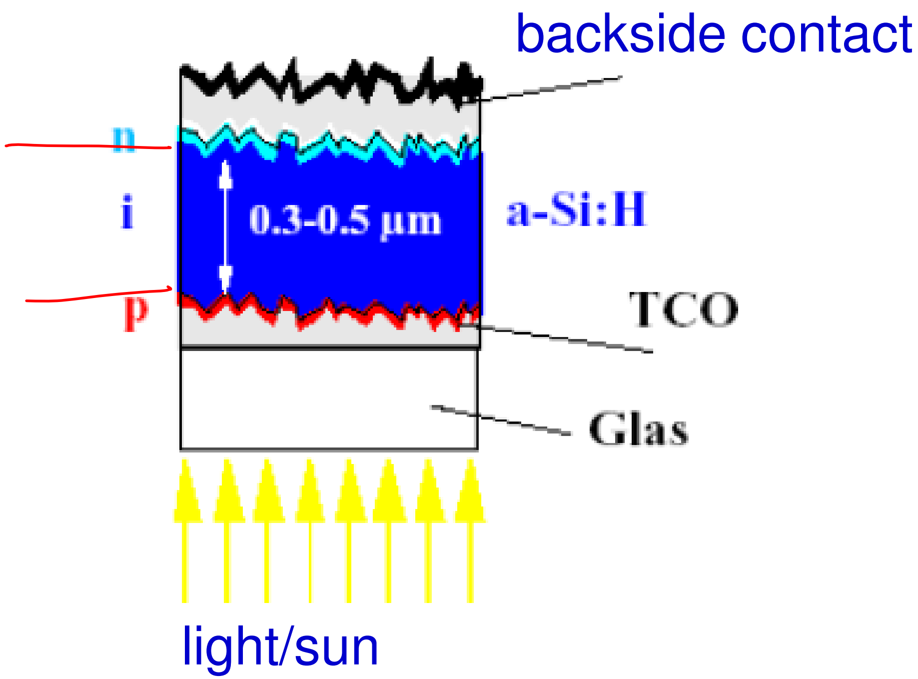
R4 metal-semiconductor comb

R5 comb

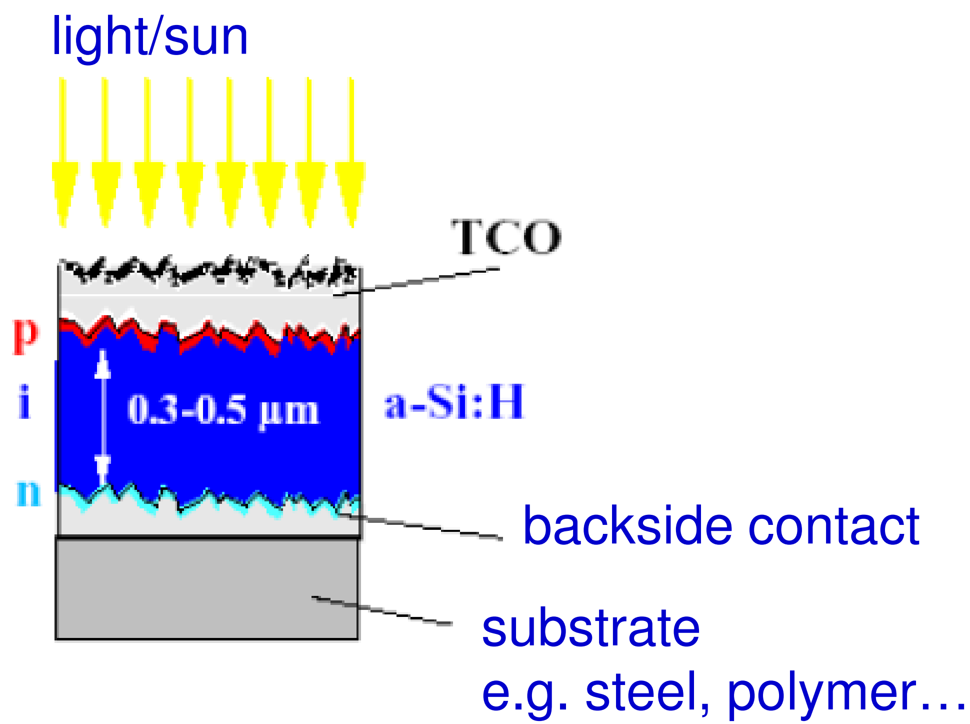
R6 common bus

Photovoltaics

thin film solar cells



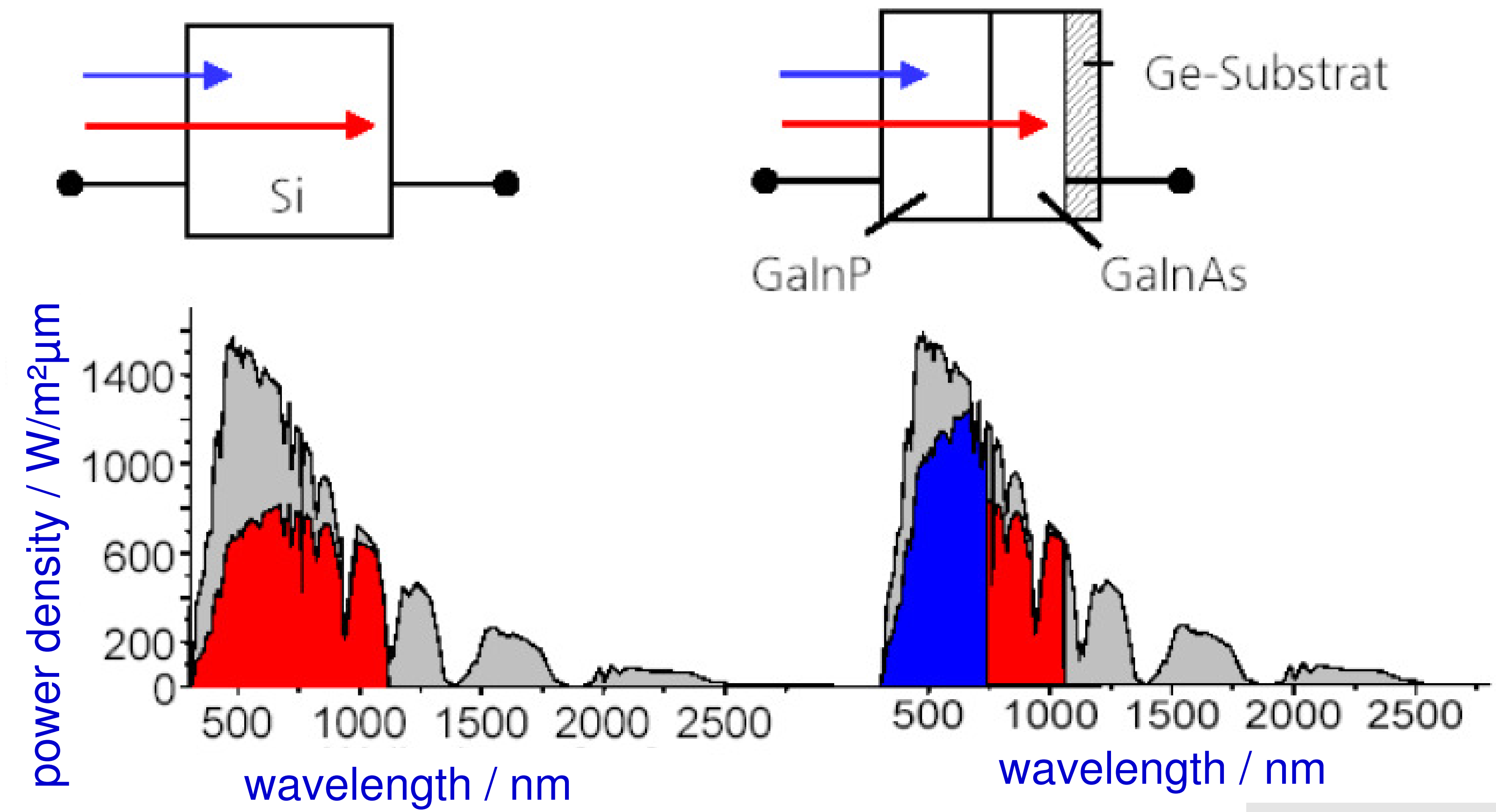
-superstrate



-substrate

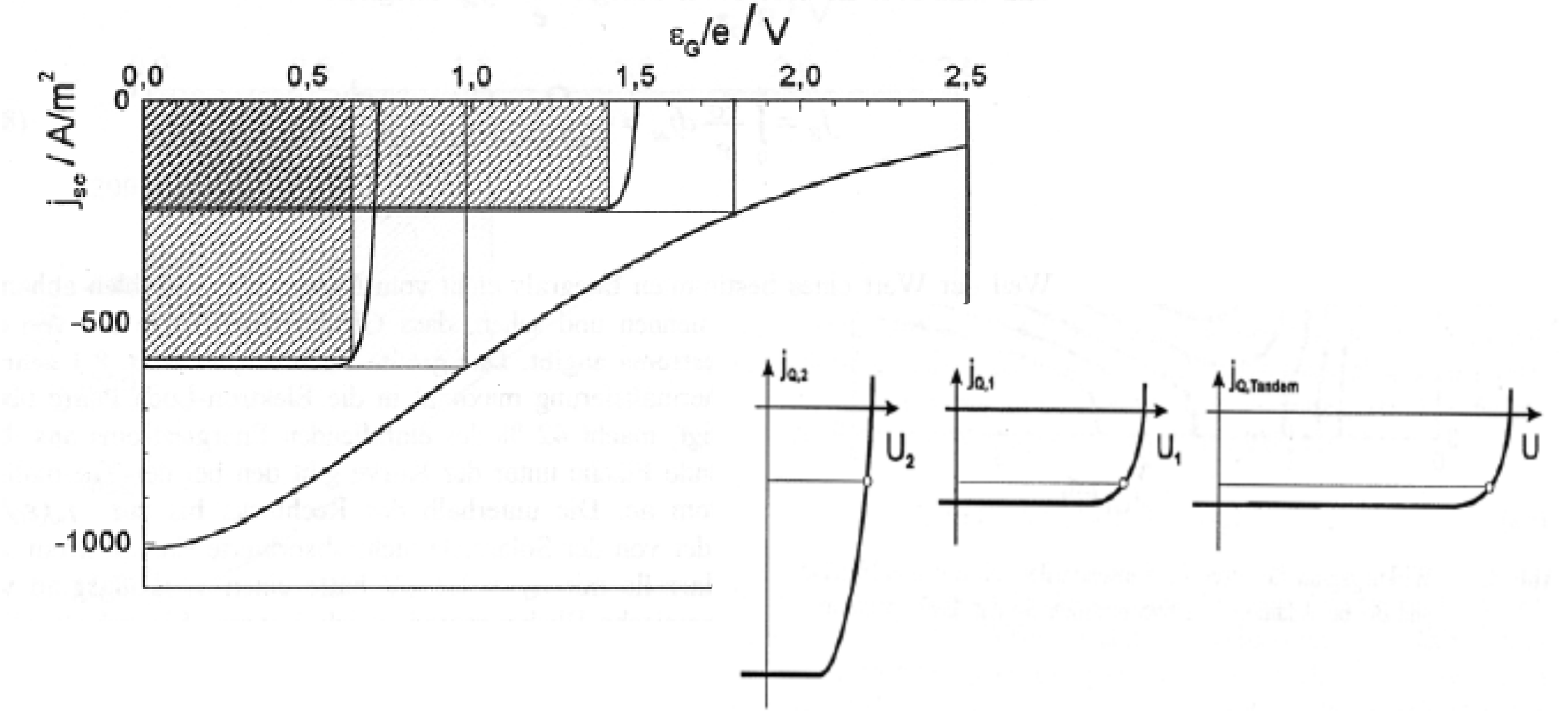
Photovoltaics

stacked solar cells



Photovoltaics

stacked solar cells – iv-characteristics



Problem: Maximum output power is not as high as is could be

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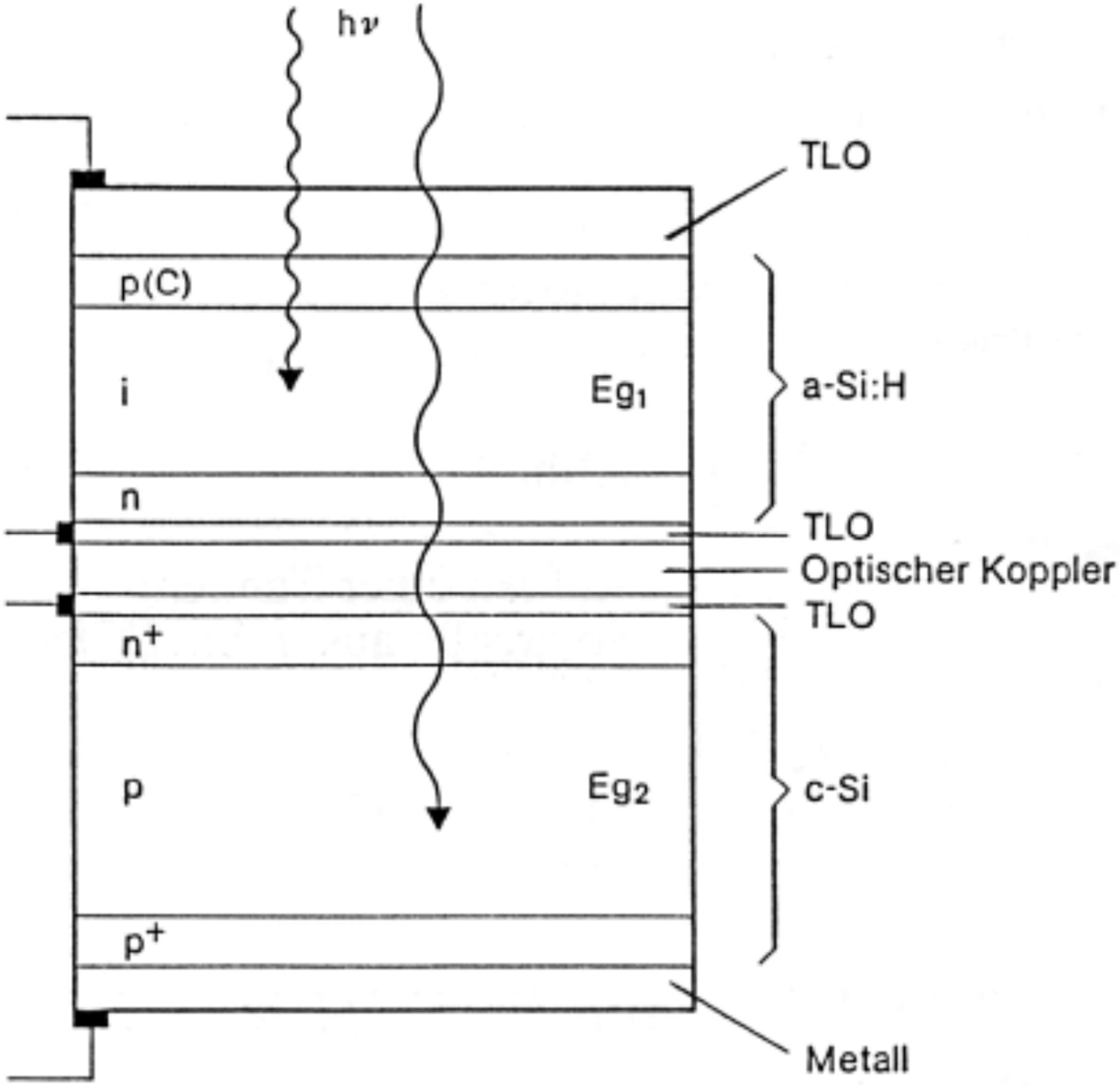
Photovoltaics

stacked solar cells

4 point connection



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Photovoltaics

one more stack:

triple solar cells

Theoretical maximum efficiency for an infinite number of stacked solar cells adapted to the solar spectrum:

86,8%

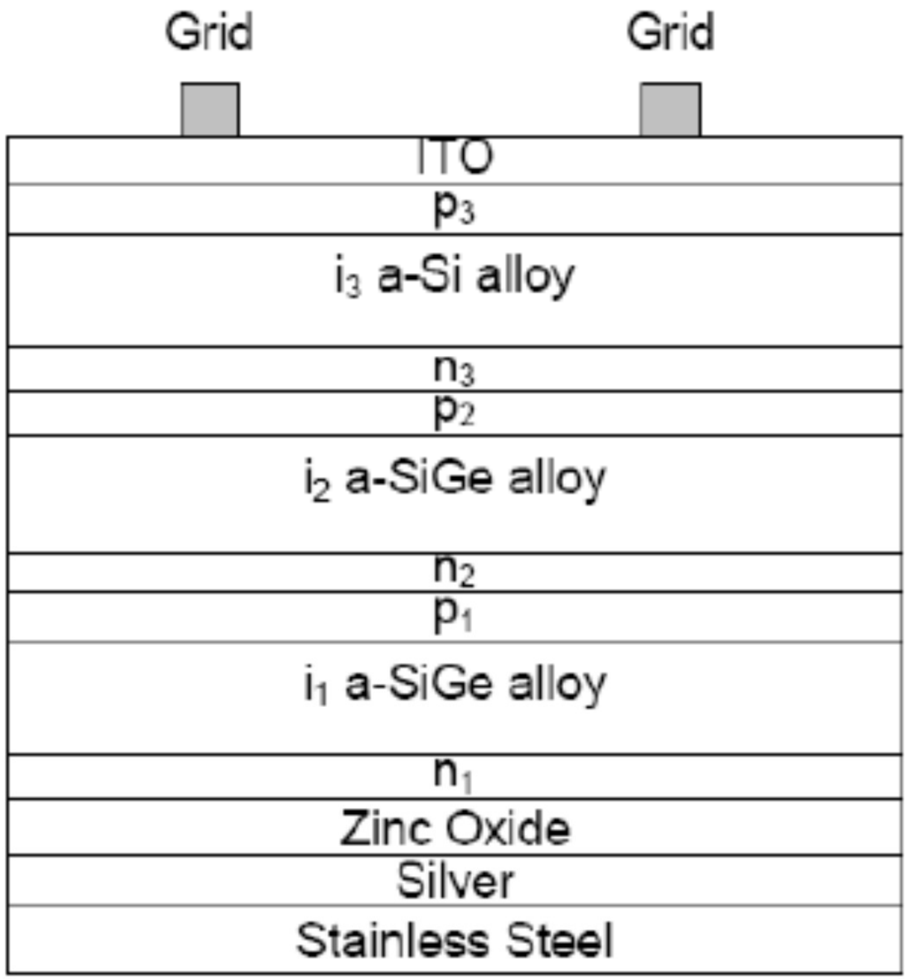
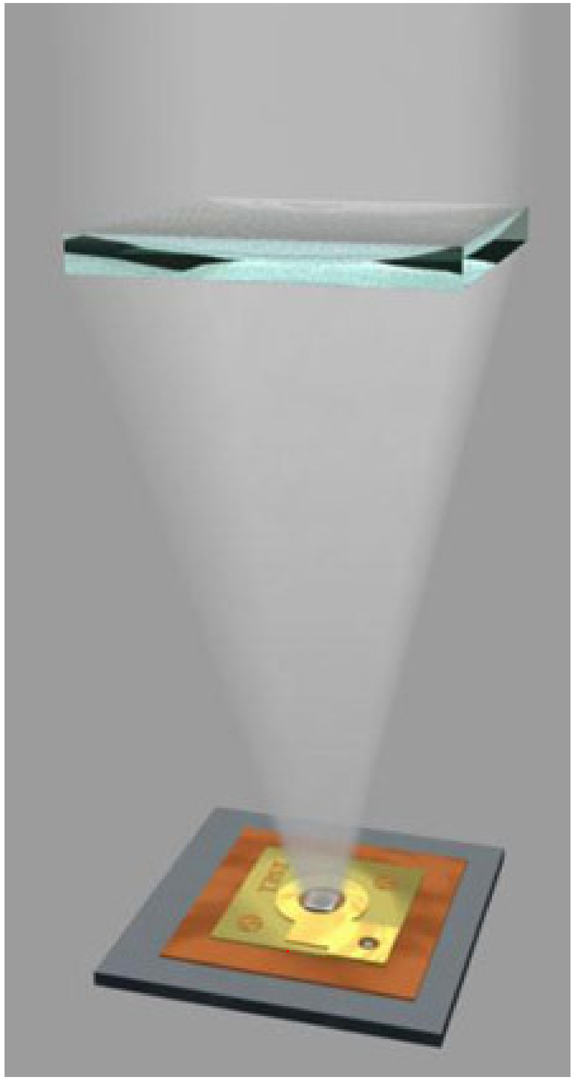


Fig. 1. Schematic of triple-junction structure.

Photovoltaics

Latest development:

concentrator cells



Photovoltaics

Organic solar cells

(like a pin diode)