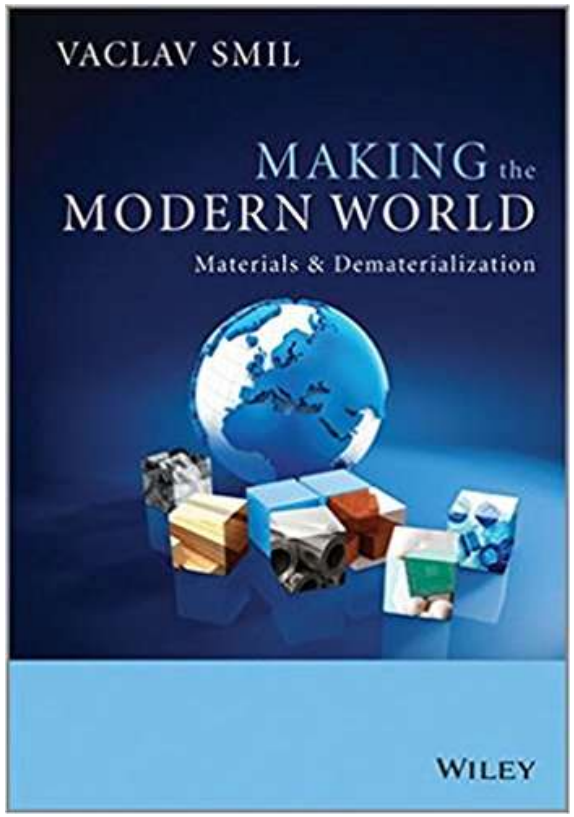
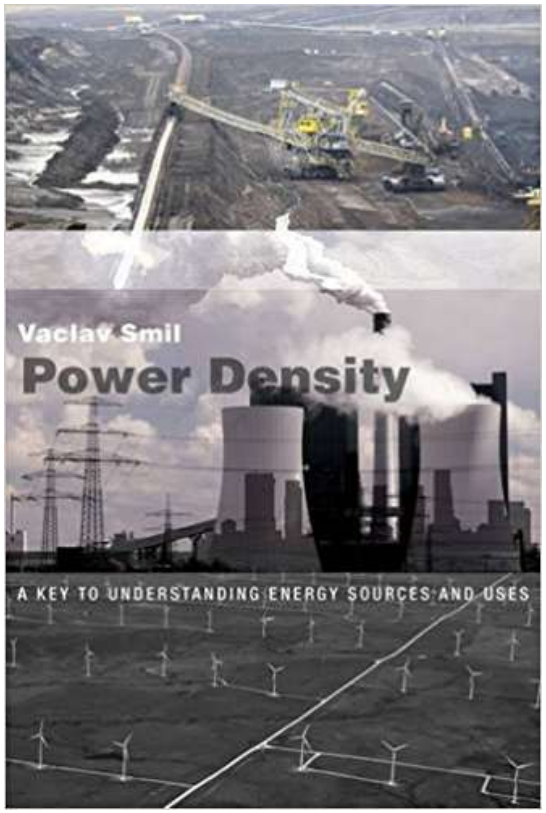
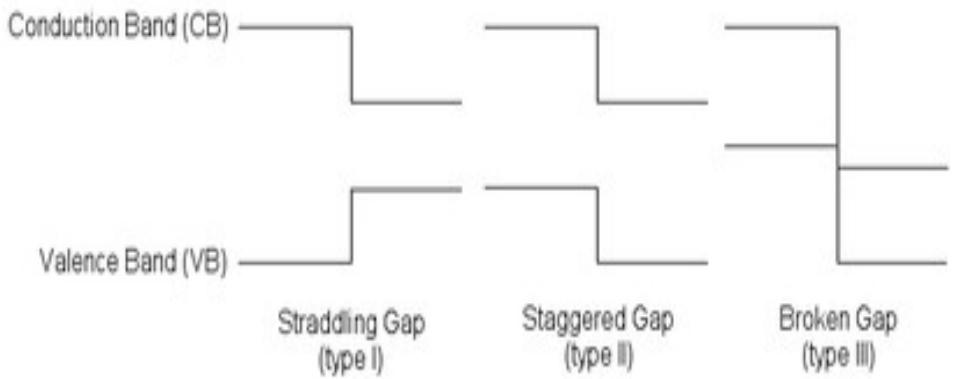
Vaclav Smil Books



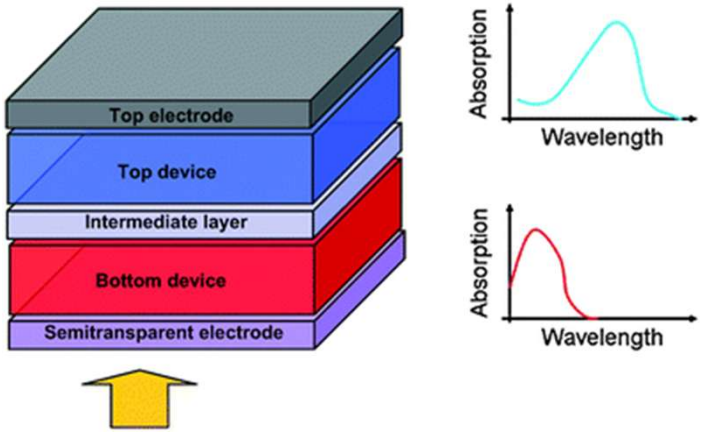


Junctions & Tandem Solar Cells

Junctions



Tandem Solar Cell



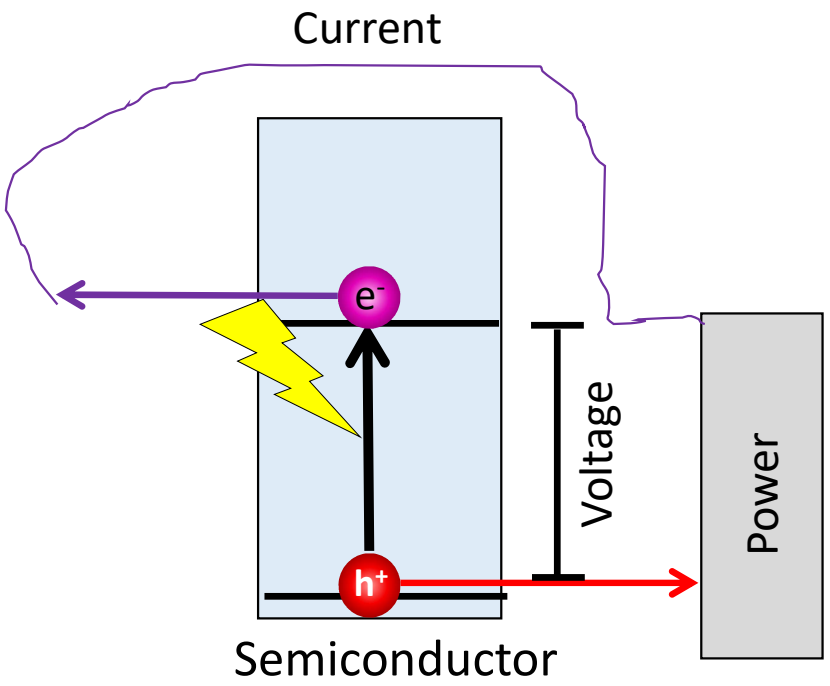
Lecture - Learning Objectives

At the end of this lecture you should:

- Understand the following junctions:
  - p-n junction
  - p-i-n junction
  - Hetero-junction
  - Tunnel junction
  - Schottkey Barrier
- Understand how to apply various junctions to make an overall solar cell device.
- Understand basics of tandem solar cells
- Understand bi-facial solar cells

Solar cells explained in 2 minutes

How do we get the electrons to move one way and the holes to move the other way?



Why would an electron/hole move

- Electrons or holes move due to 1 of 2 reasons:
  - There is more e^-/h^+ at one spot compared to another and they simply diffuse to a lower concentration. This is called *Diffusion Current*.
  - An electrochemical bias is placed across the cell, and this forces e^- and h^+ to go a certain direction . This is called *Drift Current*.
- Mathematically the current can be written as:

Diffusion Drift

h^+ Current $\longrightarrow$ $J_p(r) = q\left(-D_p \nabla \mathrm{p} + \mu_p p \mathrm{F}\right)$

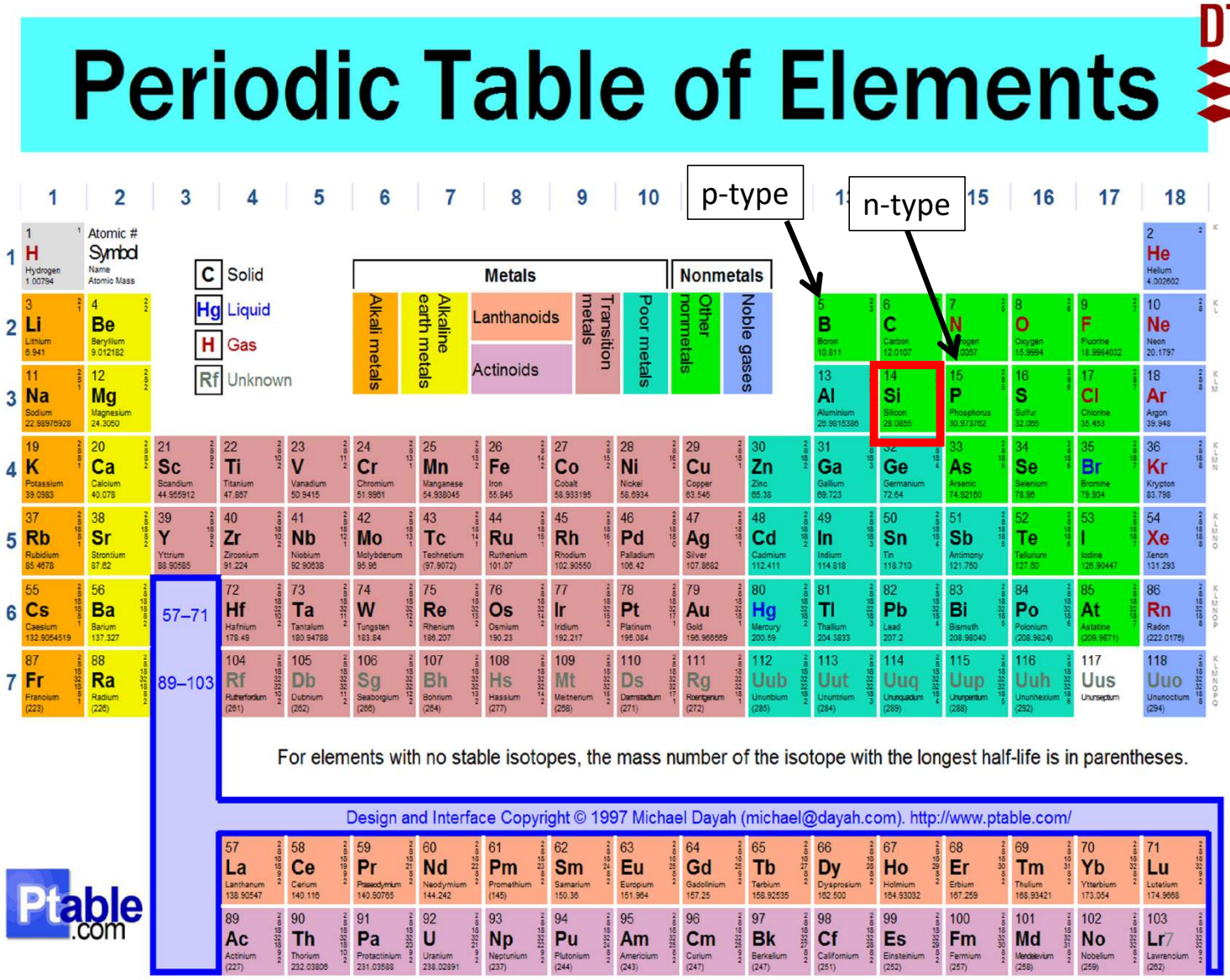
e^- Current $\longrightarrow$ $J_n(r) = q\left(D_n \nabla \mathrm{n} + \mu_n n \mathrm{F}\right)$

D_p = Diffusivity of holes
D_n = Diffusivity of holes
μ_p = Hole mobility
μ_n = Electron mobility
F = Electric Field

p-n Junctions

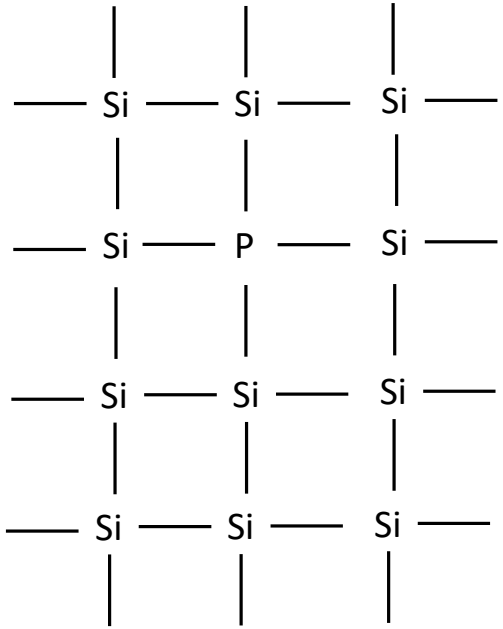
Doping a Semiconductor

i.e.
Changing the Fermi level

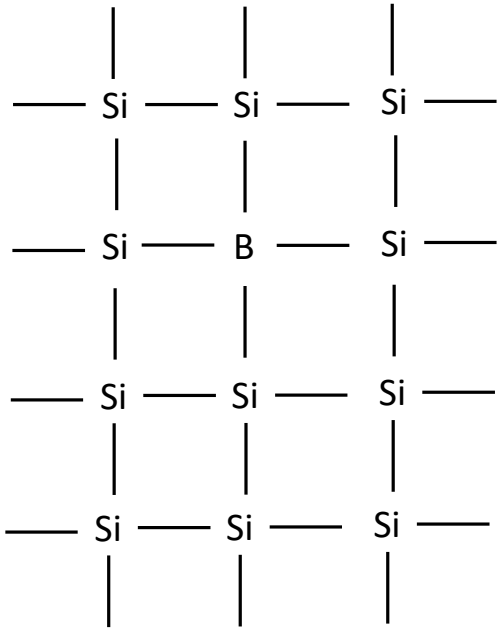


How to get an n-type or p-type material

- Here are the most common ways to make Si n-type or p-type.



n-type



p-type

- Here are the most common ways to make Si n-type or p-type.

Separating the charge

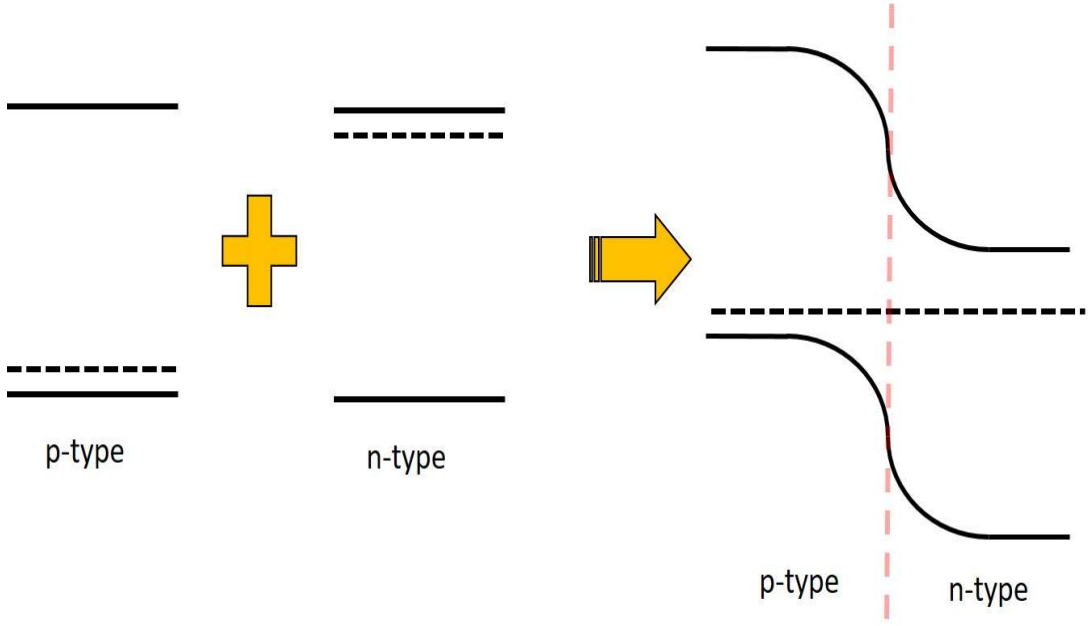
- Creating a p-n junction allows us to create a built in electrochemical bias.
- At the interface charge transfers between n-side and p-side due to diffusion until it builds enough potential to make current = 0.

$$\mathrm{J}_n(r) = q(D_n \nabla \mathrm{n} + \mu_n n \mathrm{F})$$

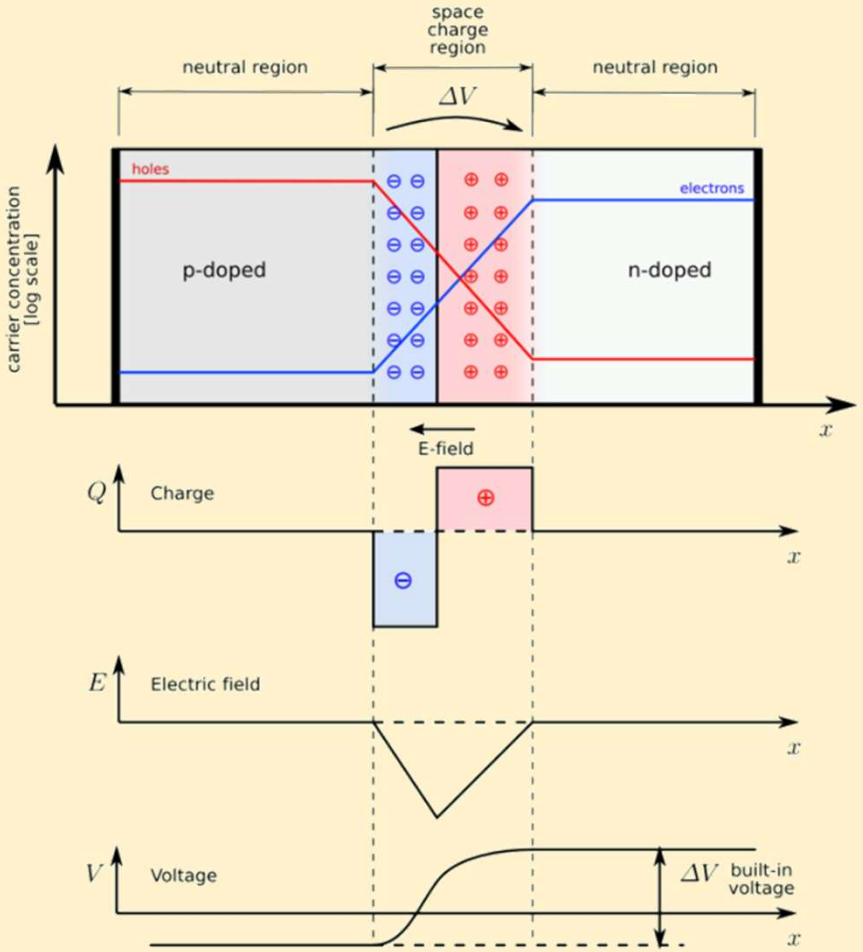
$$0 = q(D_n \nabla \mathrm{n} + \mu_n n \mathrm{F})$$

$$F_{n-side} = \frac{-qD_n \nabla \mathrm{n}}{\mu_n n}$$

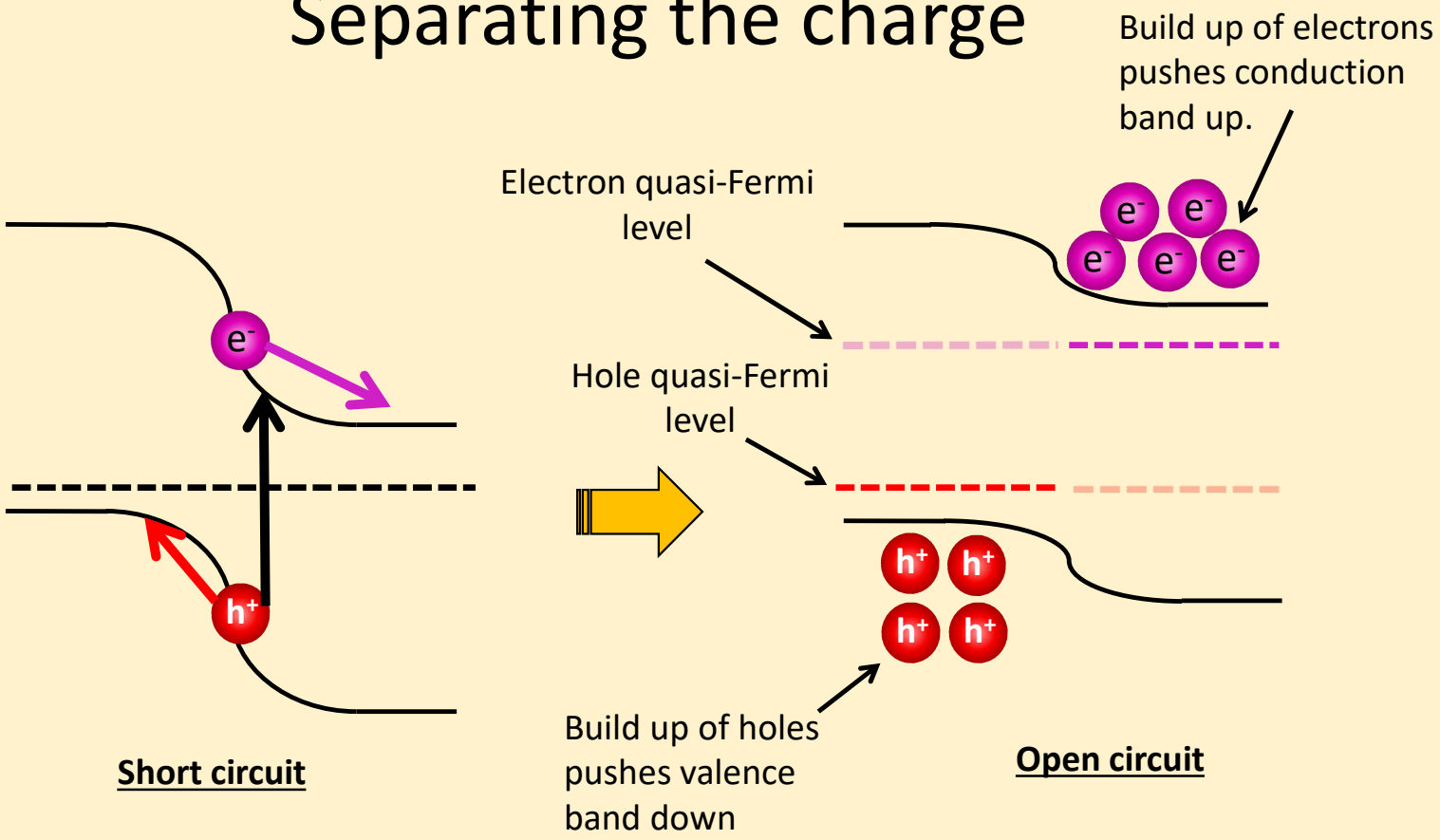
Gradient at p-n junction



Breaking down the p-n junction

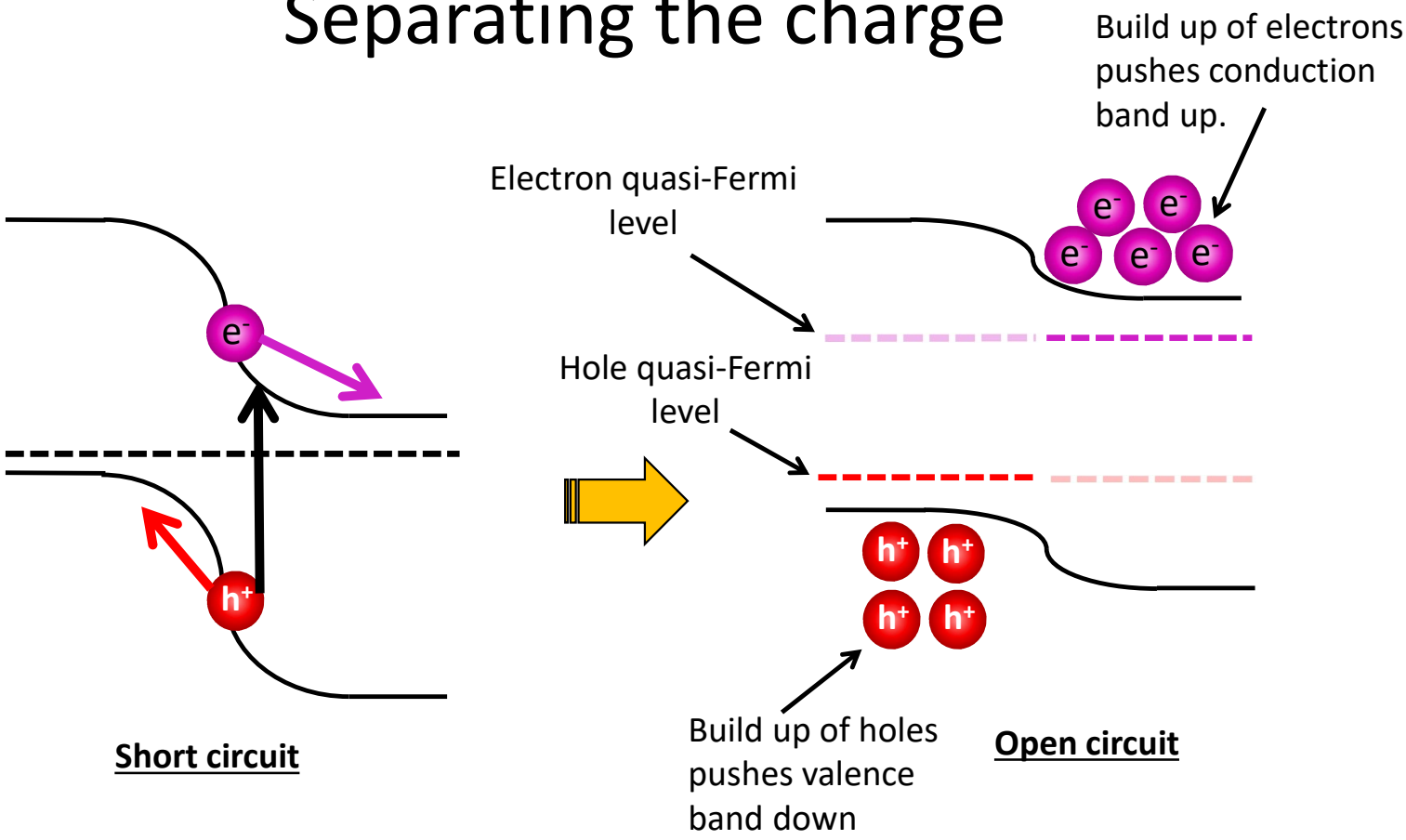


Separating the charge



- Will the band-bending thickness always be equally between the p and n side?

Separating the charge



Doping Profiles

- Basically the high dopant density material has a stronger pull than the lower doped material.
- By using Poisson's equation to distribute the charge, we can determine the depletion width.

Depletion width (band bending thickness)

$$x_p = \left(\frac{N_D}{N_A}\frac{2\varepsilon\varepsilon_0(V_{bias} - V_{photo})}{q(N_D + N_A)}\right)^{1/2}$$

$$x_n = \left(\frac{N_A}{N_D}\frac{2\varepsilon\varepsilon_0(V_{bias} - V_{photo}}{q(N_D + N_A)}\right)^{1/2}$$

N_A = Acceptor (p-type) density
N_D = Donor (n-type) density
ε = permittivity of semiconductor
ε_0 = permittivity in vacuum
V_{bias} = Total band-bending voltage (difference in p-n Fermi levels)
V_{Photo} = Photo voltage
q= elementary charge

Doping Profiles

- The voltage drop on a certain side is inversely proportional to the doping density.

$$V_{p-typ} = V_{Bias} \times \frac{N_D}{N_D + N_A}$$

$$V_{n-ty} = V_{Bias} \times \frac{N_A}{N_D + N_A}$$

N_A = Acceptor (p-type) density
N_D = Donor (n-type) density

- V_{bias} is the potential difference in Fermi levels between the n-type and p-type semiconductor.
- For more detailed description of these equations see Malizia, et al, JMC-A, 2014.

Concept Check

In a p-n junction solar cell, a p-type side has a dopant density of 10^{16} cm^{-3} and an n-type side has a dopant density of 10^{20} cm^{-3}. This means:

a) The p-type has a larger voltage drop across it and a longer depletion layer.

b) The p-type has a larger voltage drop across it and a shorter depletion layer.

c) The n-type has a larger voltage drop across it and a longer depletion layer.

d) The n-type has a larger voltage drop across it and a shorter depletion layer.

Concept Check

In a p-n junction solar cell, a p-type side has a dopant density of 10^{16} cm^{-3} and an n-type side has a dopant density of 10^{20} cm^{-3}. This means:

a) The p-type has a larger voltage drop across it and a longer depletion layer.

b) The p-type has a larger voltage drop across it and a shorter depletion layer.

c) The n-type has a larger voltage drop across it and a longer depletion layer.

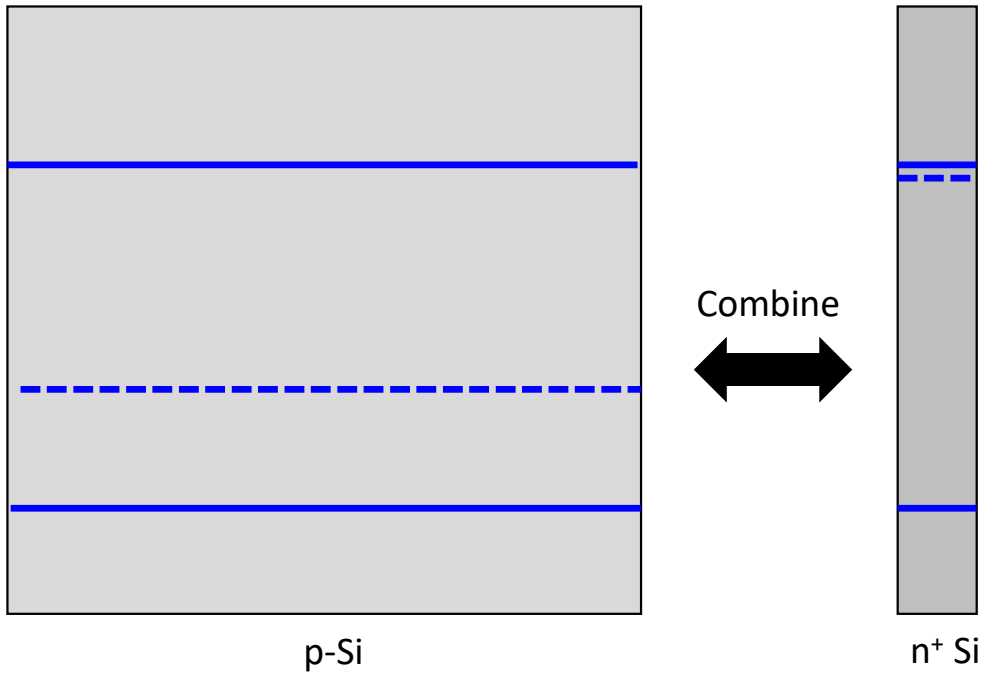
d) The n-type has a larger voltage drop across it and a shorter depletion layer.

Fundamental issue

- We need doping to get n-type or p-type and allow for band bending.
- As the difference in dopant density increases, the band bending increases.
- However dopants are basically contaminants, thus they are recombination sites.
- How do we mitigate this issue?

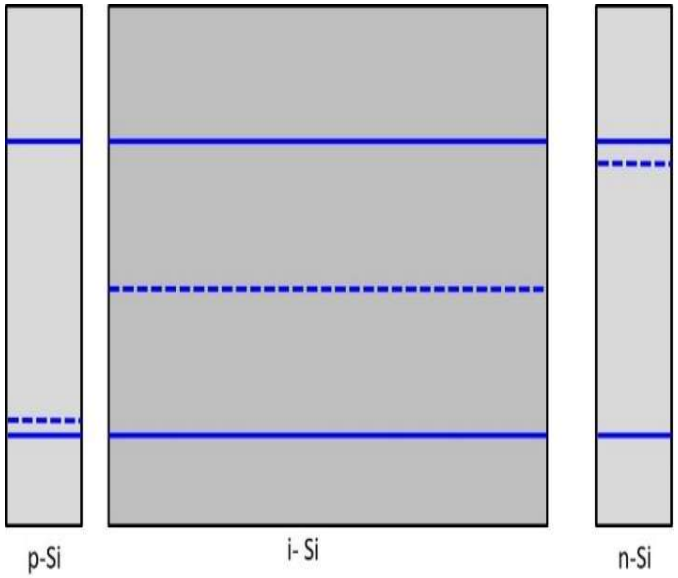
Creating a very highly doped layer

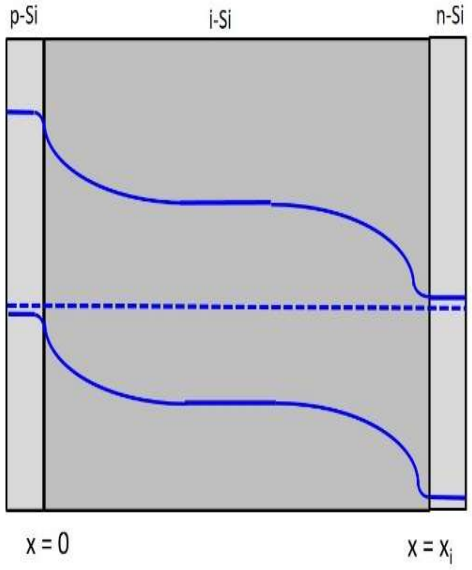
- By having one material highly doped, and the other low doped, we induce large bandbending in the low-doped material.



p-i-n junction solar cell

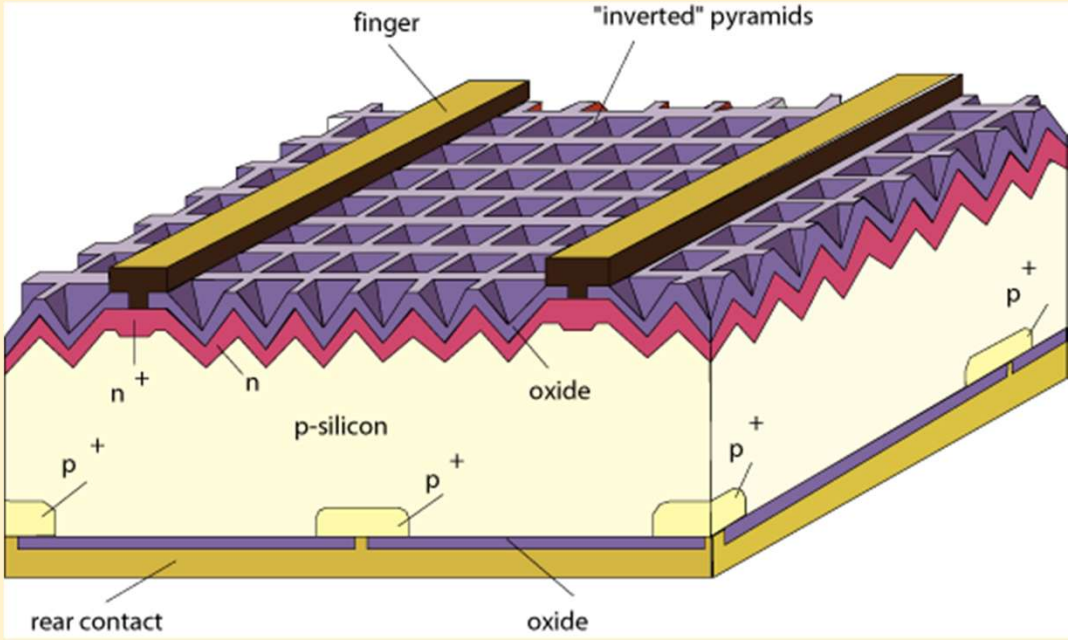
- This approach maximizes depletion layer thickness by having band bending from both sides.
- Almost all solar cells use at least some form of a p-i-n junction.





State of the art from 1999 - 2013

- Creating small point contacts allows for minimal surface recombination.
- Doping both sides prevents charge carriers from going to the wrong contact.
- Creating small point contacts allows for minimal surface recombination.
- This approach gave a record efficiency of 24.7%.



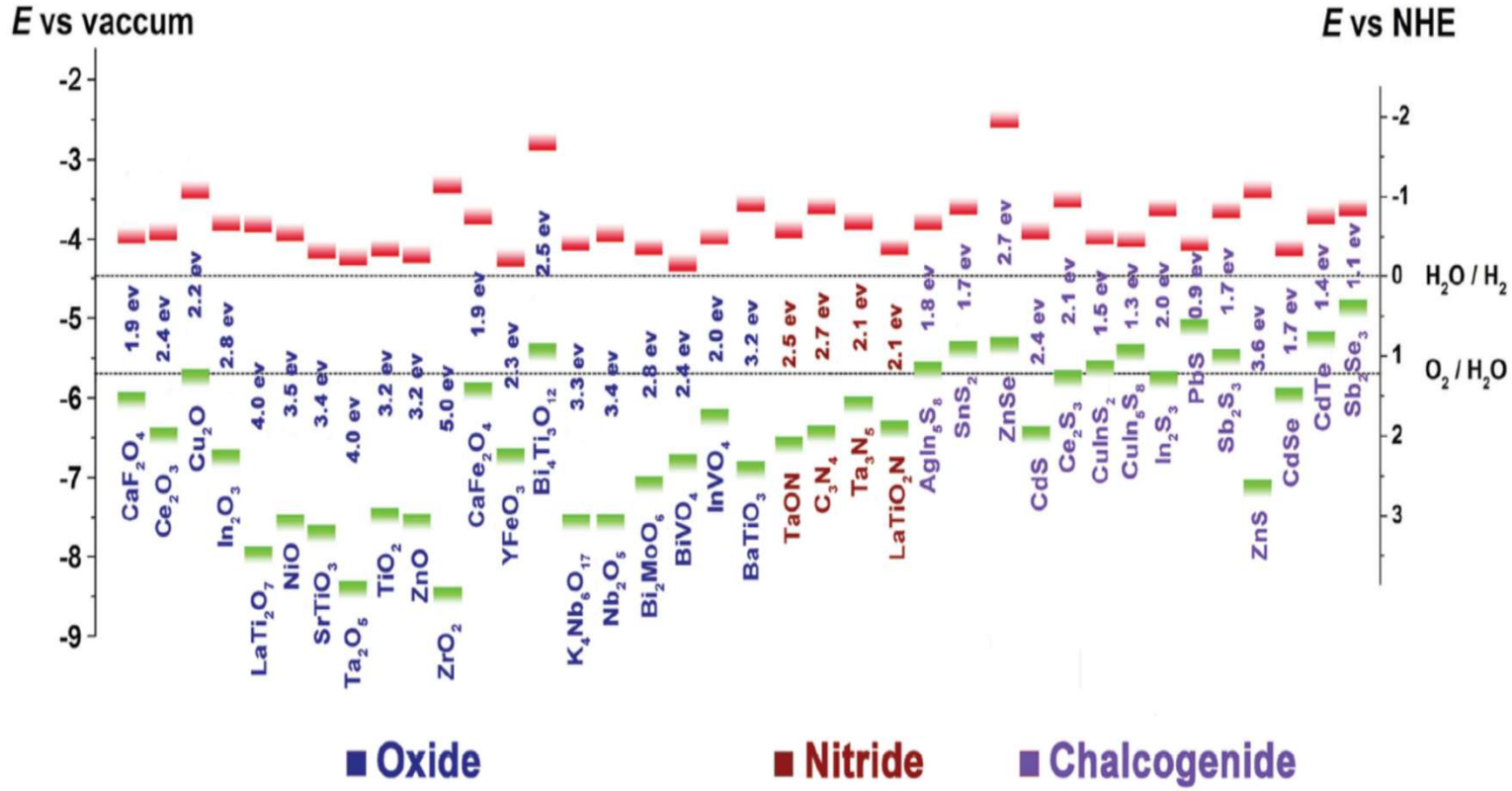
PVeducation.org

- What is the biggest failure of this device?

Different approaches to junctions

Heterojunction

- Heterojunctions is a junction between 2 different materials
- The band alignment is a function of the materials electron affinity.



p-n Hetero-junction

- The band mismatch can create a discontinuity at the interface
- Besides this discontinuity, the junction acts like a normal p-n junction.

Advantages

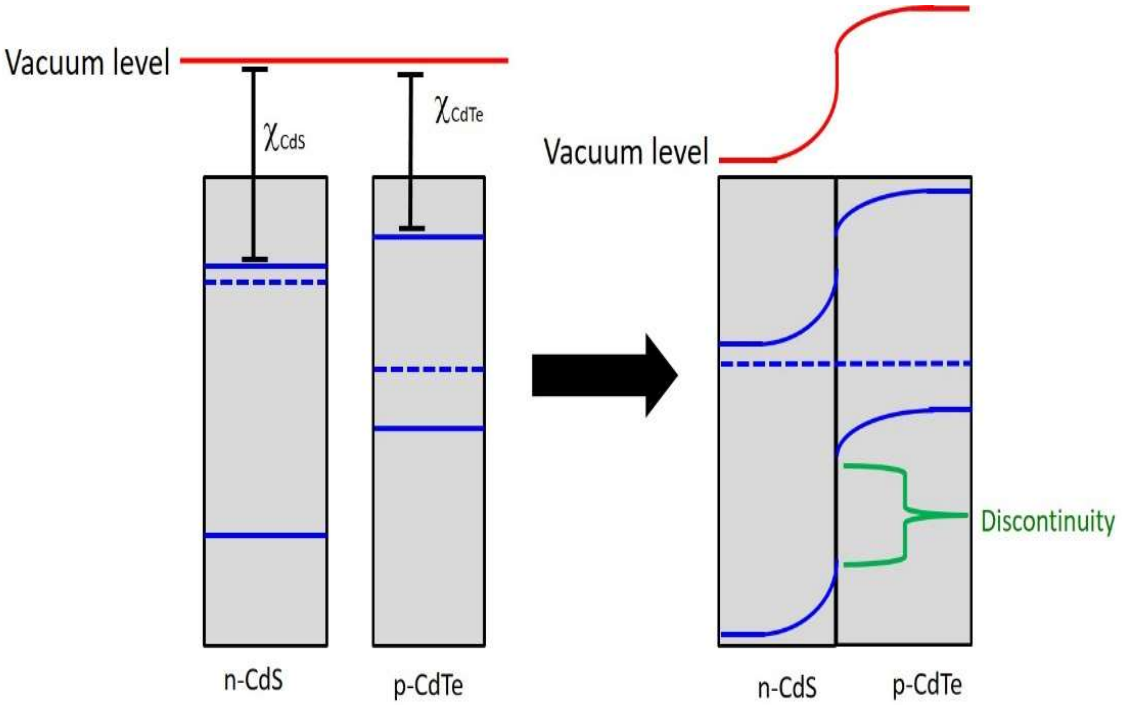
Different band gaps

Can create extreme V_{Bias}

Disadvantages

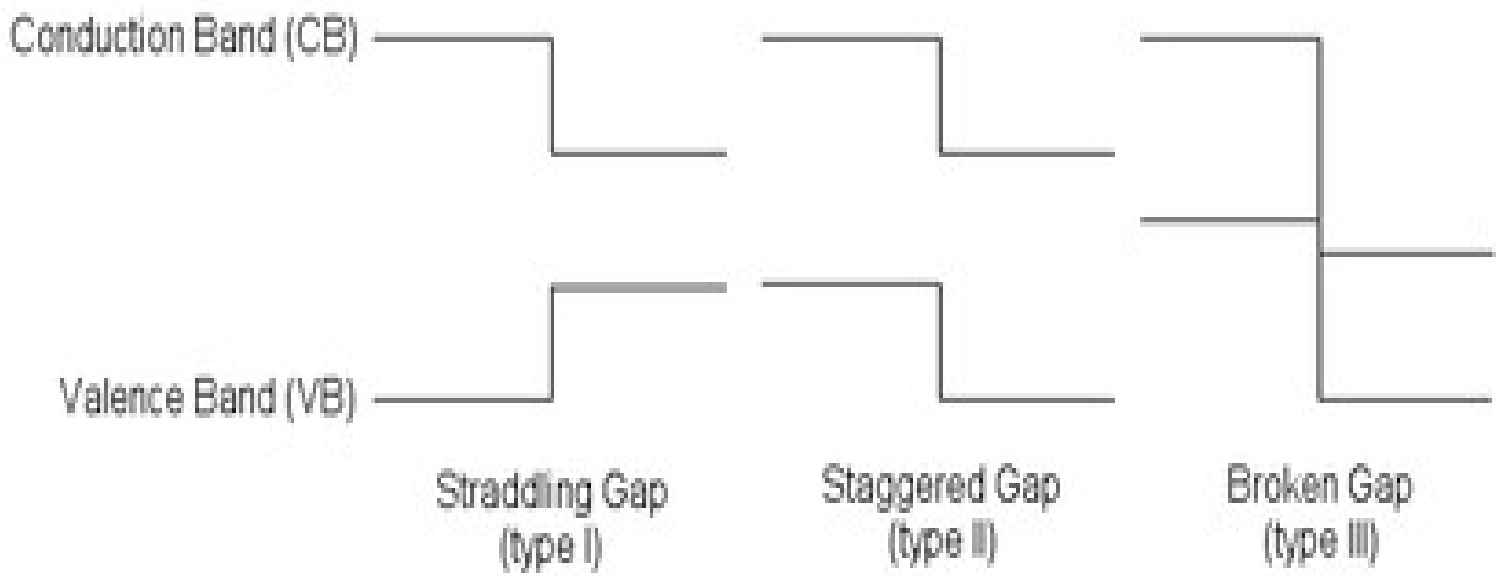
Heavy recombination at the interface

Materials need to be compatible



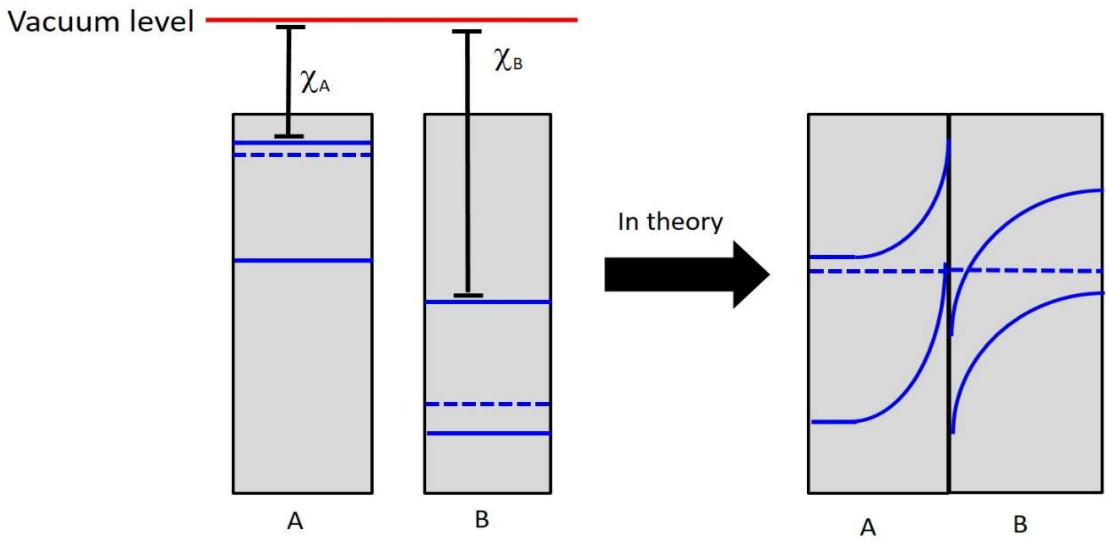
Types of hetero-junctions

- We classify heterojunctions into 3 types
- Type 2 is almost always the type we are interested in.
- Type 1 is great in that is can prevent surface recombination and acts as a wall



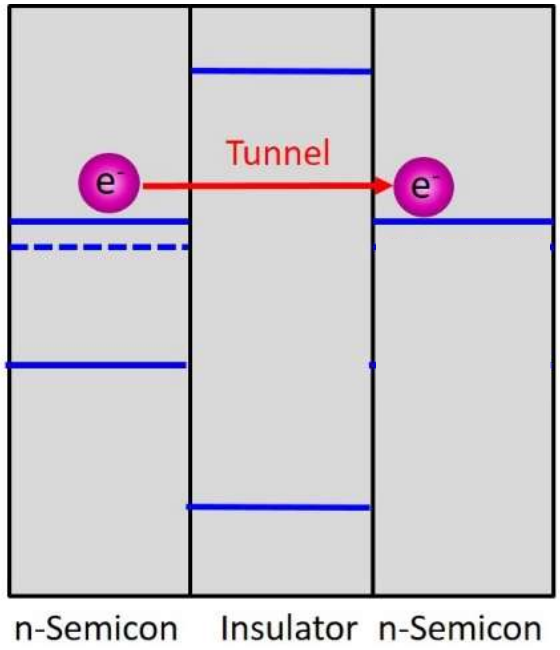
Type 3 junction

- Type 3 is interesting to look at fundamentally.
- This design puts electrons in the conduction band of the p-type and holes in the valence band of n-type even without light.
- There is a barrier at the interface to prevent electrons and holes, thus this approach will fail.



Type 1- Tunnel Junction

- Quantum mechanics says that our electrons can tunnel through a small barrier.
- Our electrons can only tunnel through a short distance (typically 1-5 nm).



Equations for current density (J_t) and tunneling probability (T_t)

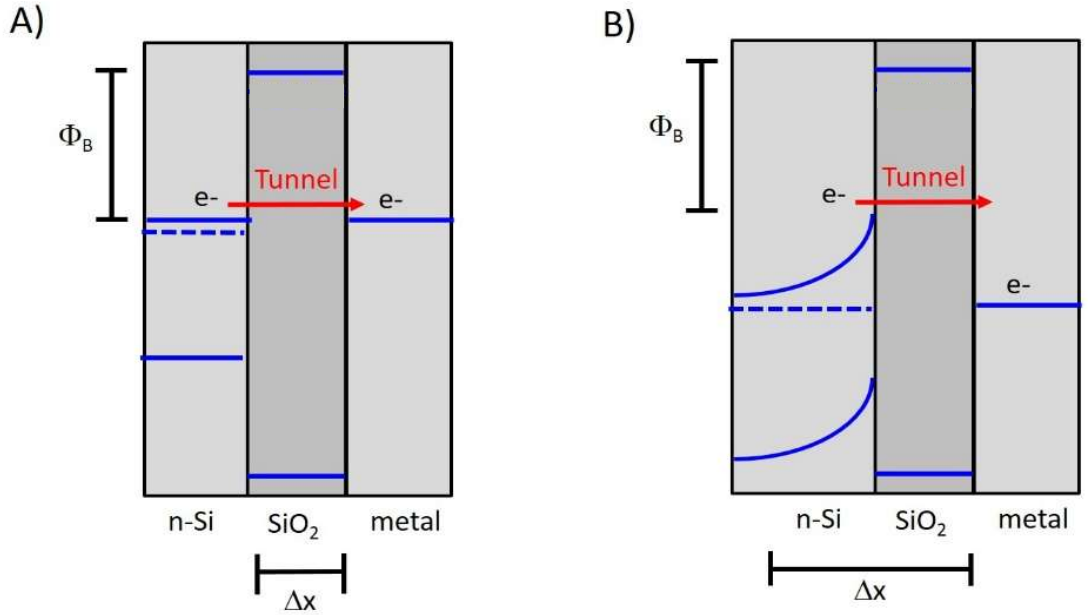
$$J_t = -N_C v_{\mathrm{th,e-}} q T_t$$

$$T_t = exp\left[-\frac{4}{3}\Delta x \sqrt{\frac{2m_{eff}\, q\, \emptyset_b}{\hbar^2}}\right]$$

T_t= tunneling probability
x= tunneling distance
M_{eff}= effective mass of e^- or h^+
H-bar= plancks constant divided by 2 Pi
$\emptyset_b$= barrier height
N_c= effective density of sates
V_{th} = thermal velocity
q = elemenray charge
J_t= tunneling current

Tunneling with band bending

- Metals have different ‘Fermi levels with respect to vacuum’, which is known as ‘work functions.’
- If work function is not the same as the conduction (or valence) band, this will create band bending. Thus we need to tunnel through depletion width + tunnel barrier.

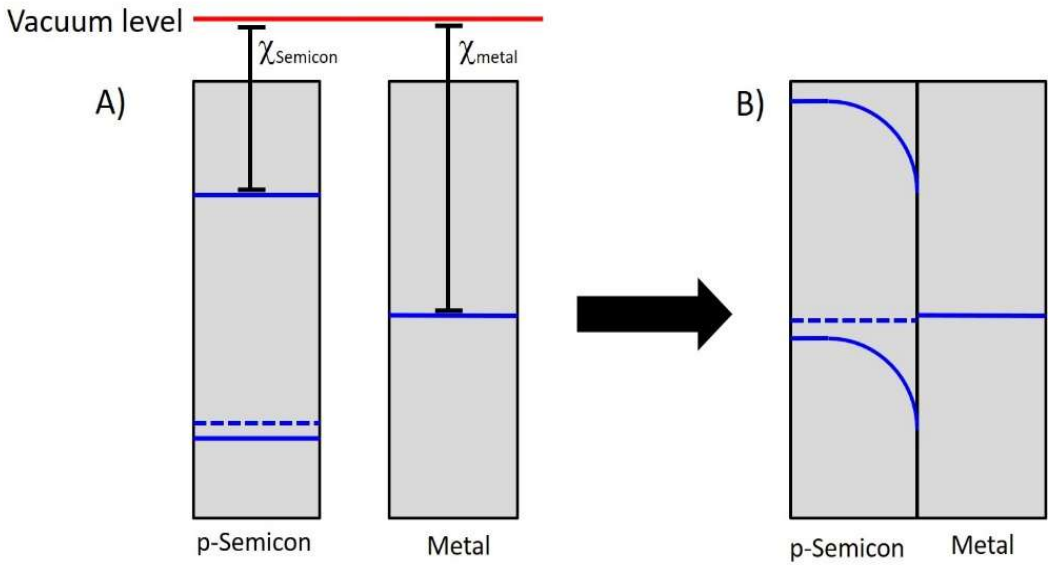


$$T_t = exp\left[-\frac{4}{3}\Delta x\sqrt{\frac{2m_{eff}q\emptyset_b}{\hbar^2}}\right]$$

$$J_t = -N_C v_{\mathrm{th,e}-} q T_t$$

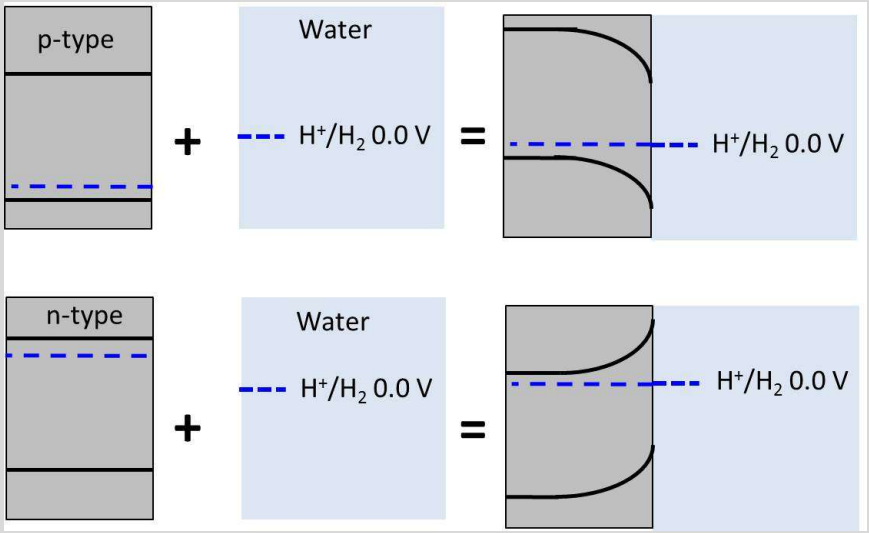
Schottky Barrier

- A Schottky barrier occurs from a metal-semiconductor junction.
- A metal can simply be thought off as a infinitely doped semiconductor.
- We try to avoid these since they rarely line up with a valence or conduction band, and create a lot of defects
- If the semiconductor is highly doped, then tunnelling completely dominates. This then acts like an *'ohmic contact'*.



Water-Semiconductor junction

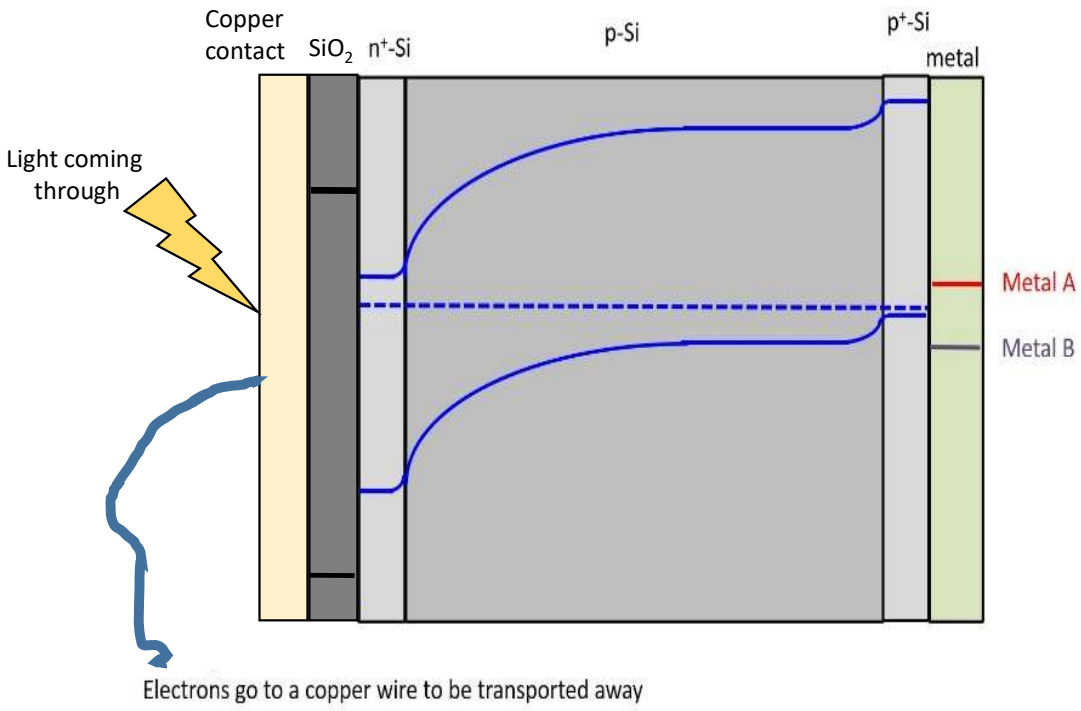
- Water can be used as a junction for semiconductors.
- It is not a good junction, but it can work.
- What happens to the electron when it goes into water?
- Answer- It chemically reduces a species in the water. If there is no species it will reduce water to H_2 gas and OH-.



- The 'Energy Storage' part will focus just on the electron going from metal into solution. There is still an electric field and a potential

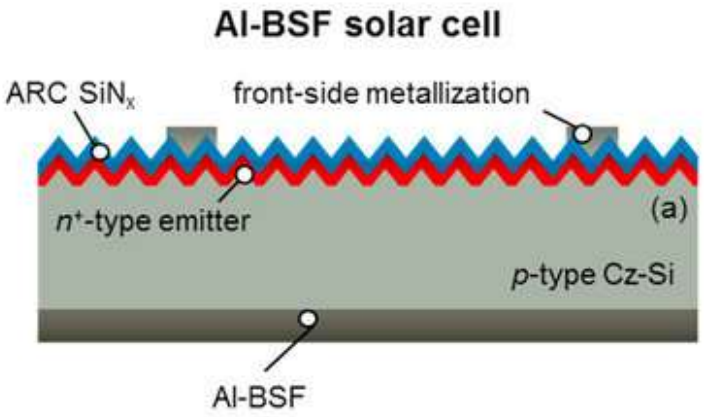
Complete solar cell

- This is a full solar cell with all junction included.
- All solar cells don't have all type of junctions, and people are still trying to find the optimal strategy.



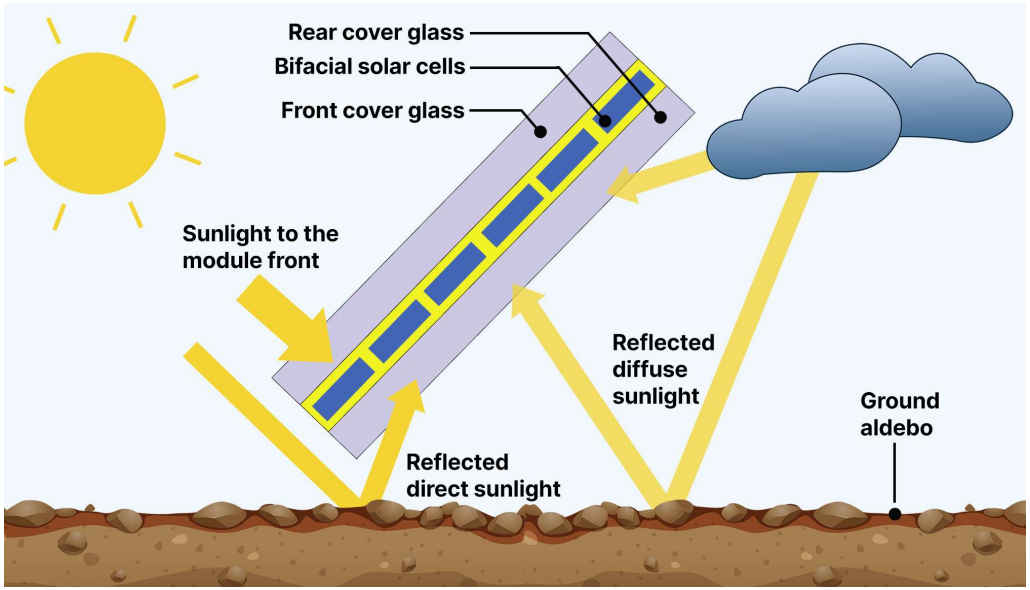
Commercial Si Solar Cells

- The aluminum back surface field (BSF) had >80% of the market until 2015
- Relatively simple design, with no minmal technical challenges
- Efficiency of near 20%



DOI:10.1016/j.egypro.2017.09.308

Bifacial Solar Cells



https://www.solarreviews.com/blog/bifacial-solar-panels

https://www.longi.com/en/news/6933/

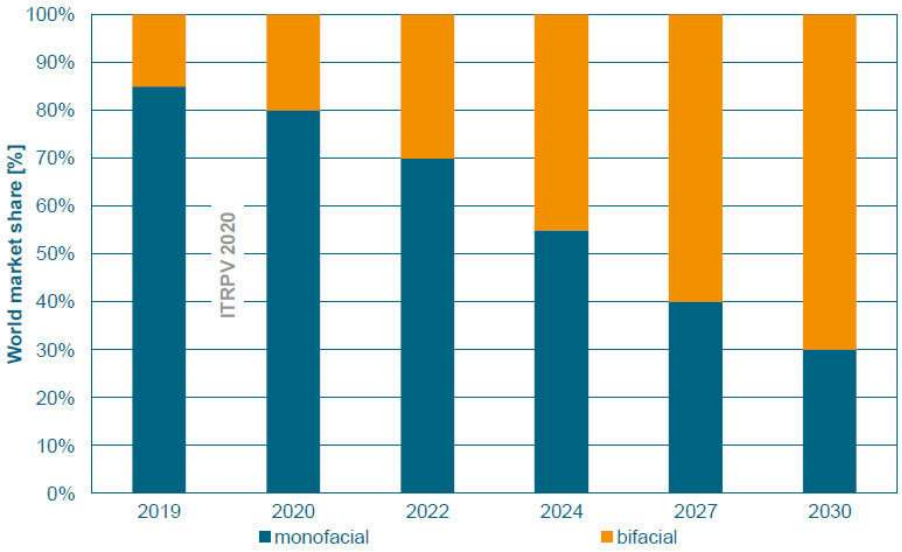
Bifacial Solar Cells

- The idea is simple- let reflected light get absorbed from the back side of the solar cell
- A single solar cell is used, meaning the back needs to be transparent.
- This has potential for solar cell fields, but not roof top solar cell.
- The actual efficiency increases is very hard to accurately calculate, but it believed to be 10-20% of an improvement

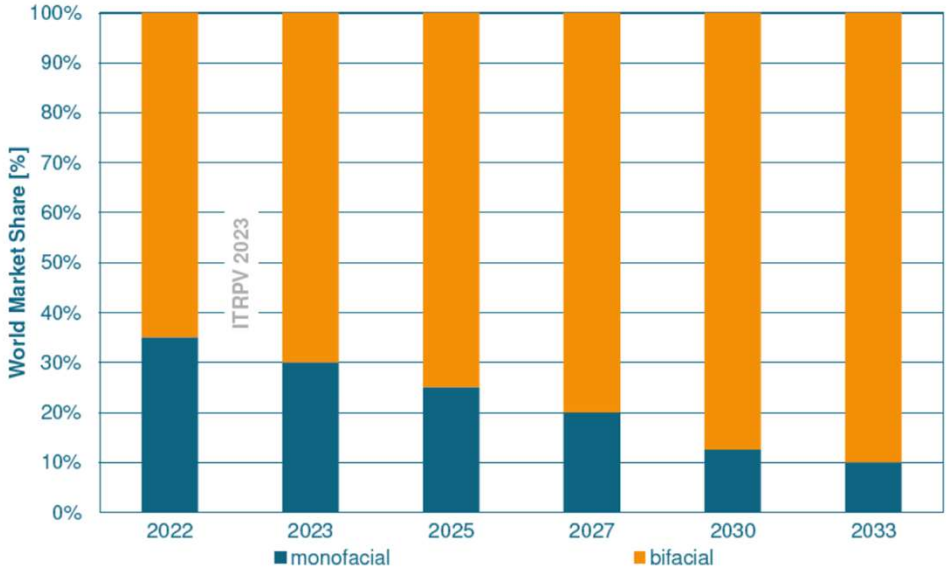
Market Share: monofacial vs bifacial

- Below is percentage of bifacial solar cells in world market

Prediction in 2020



Prediction in 2023

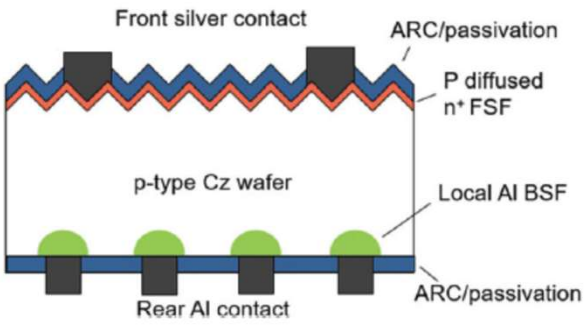


Commercial Si Solar Cells

BSF= Back surface field
ARC= Anti-reflective coating
Emitter = highly doped

PERC

Passivated emitter rear contact

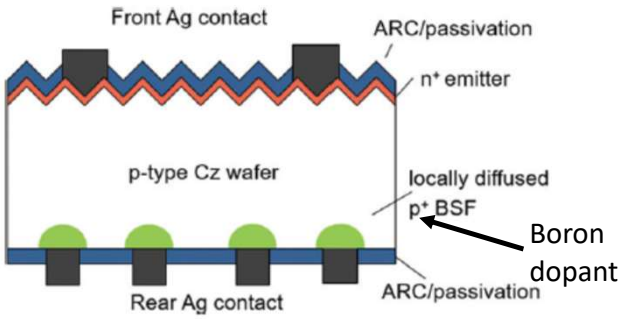


Efficiency : 24.5%

Bifaciality: ~ 80%

PERT

Passivated emitter rear locally diffused

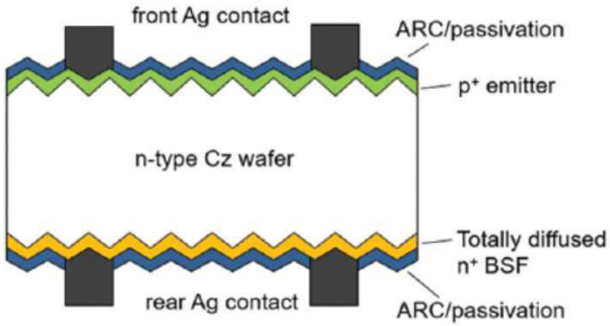


Efficiency : 24.5%

Bifaciality: ~ 89%

PERL

Passivated emitter rear locally diffused



Efficiency: 24.7 %

Bifaciality: ~ 85%

Liang et al, 2019, E&ES, DOI:10.1039/cBee02184h

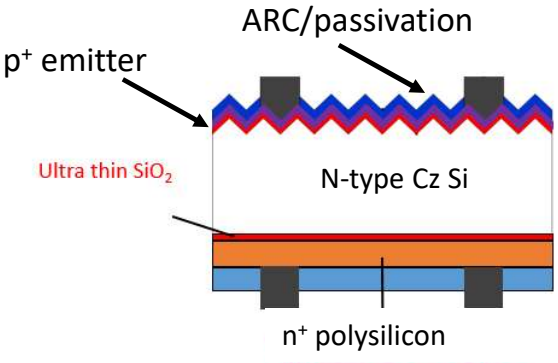
https://www.kschan.com/what-is-a-topcon-solar-cell/

Commercial Solar Cells

BSF= Back surface field
ARC= Anti-reflective coating

TOPCon

Passivated emitter rear locally diffused

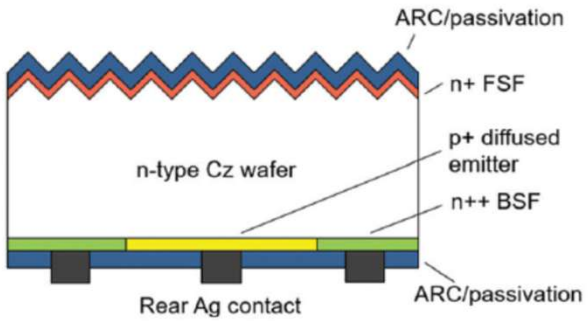


Efficiency: 26.1 %

Bifaciality: ~ 85%

IBC

Interdigitated back contact

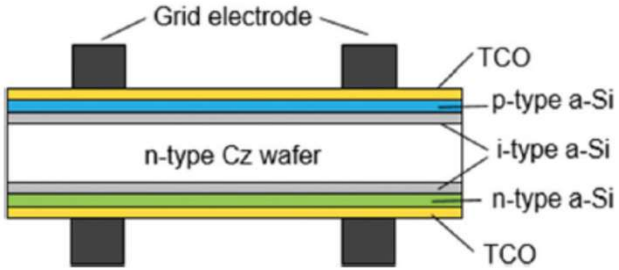


Efficiency: 26.7%

Bifaciality: ~ 75%

HIT

Heterojunction with intrinsic thin-layer



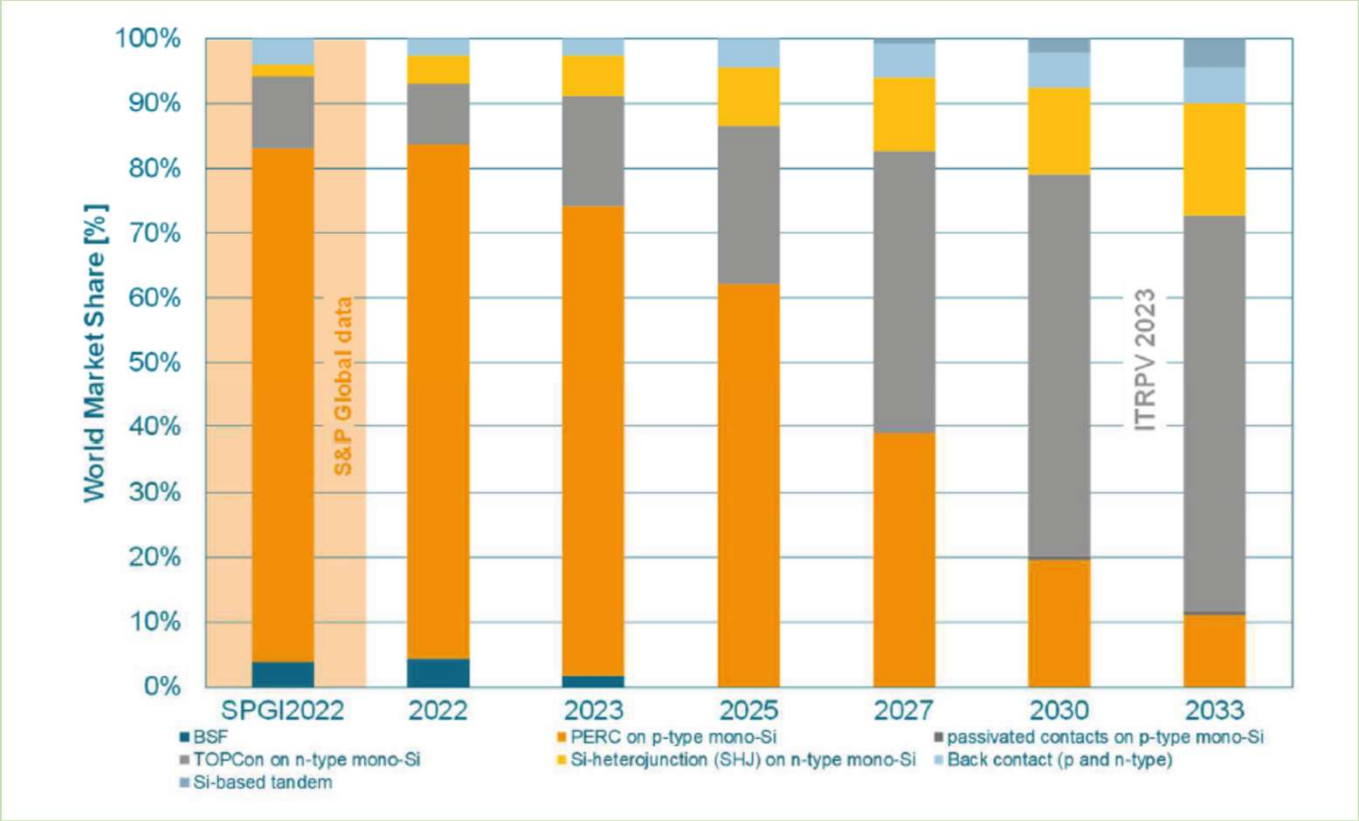
Efficiency (front): 26.5 %

Bifaciality: ~ 95%

https://www.kschan.com/what-is-a-topcon-solar-cell/

Liang et al, 2019, E&ES, DOI:10.1039/cBee02184h

Market Share



Si-Tandem

IBC

HIT

TOPCon

PERC

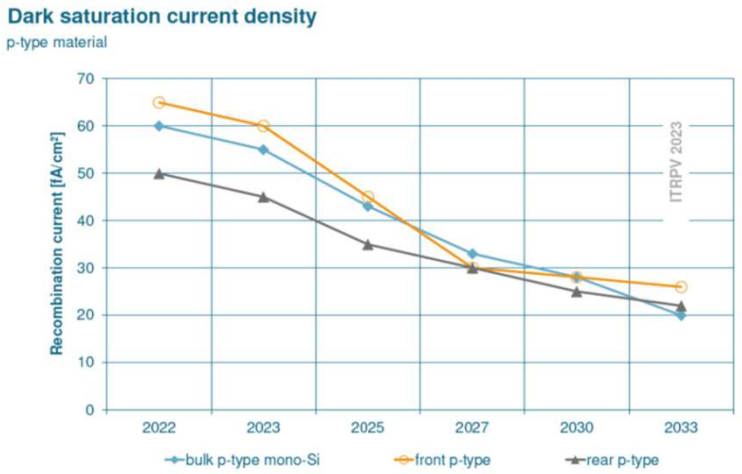
Aluminum BSF

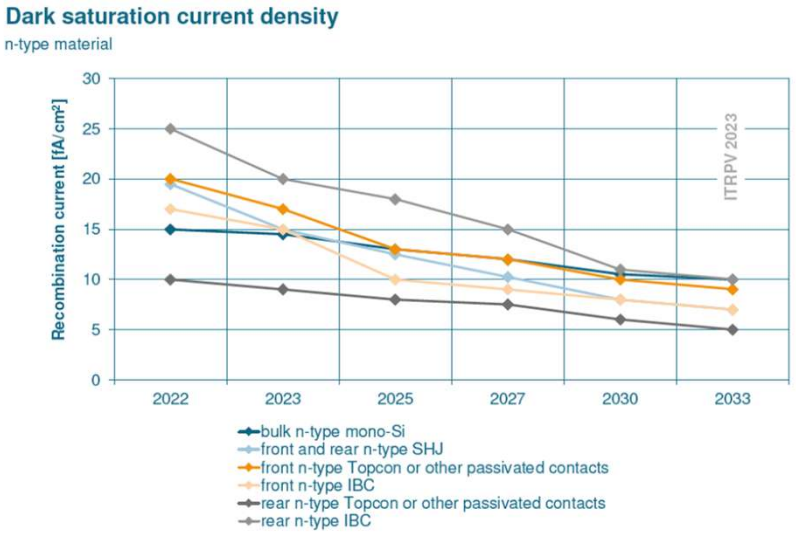
Losses throughout a solar cell

- We can put losses at different spots in terms of dark saturation current, J_o.

$$J_{net} = J_{sc} - J_0\left[exp\left(\frac{qV}{mkT}\right) - 1\right]$$

- While the front and rear losses are compareable to the bulk, the bulk has many e^- and h^+, where the front and back mostly have either e^- or h^+. Both e^- and h^+ are needed for recombination.



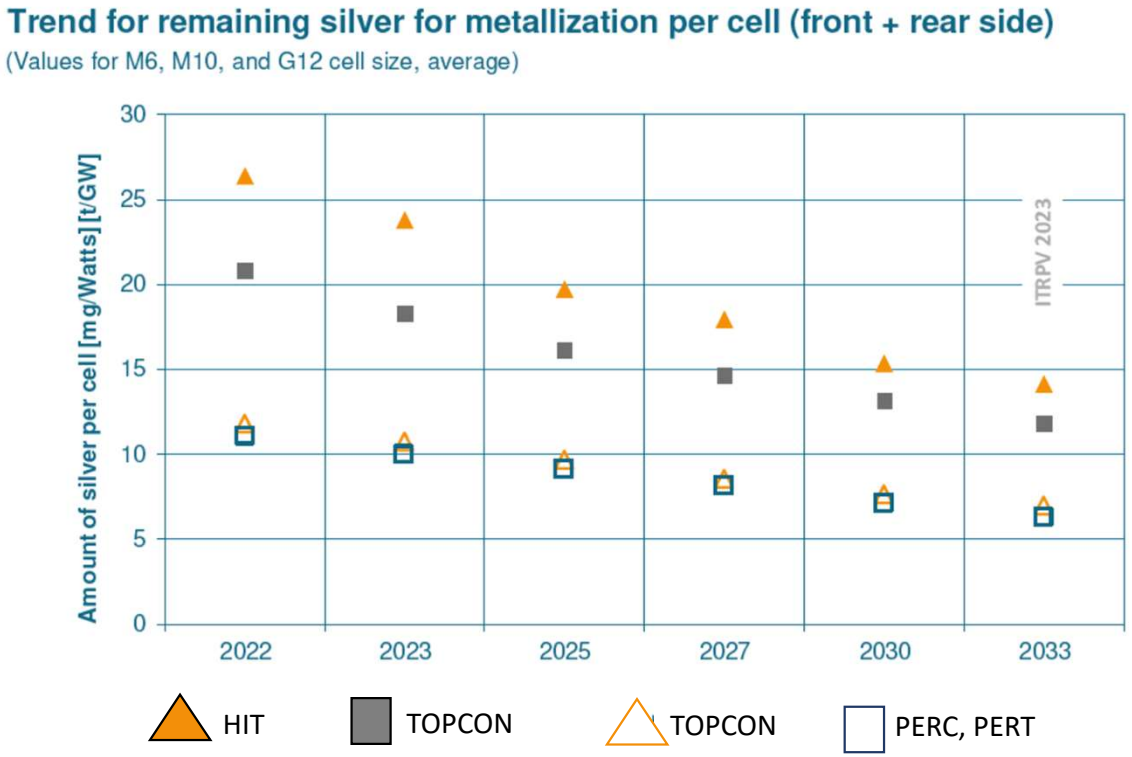


Electrical Contacts

- Ag's conductivity means it is used for connections.

- The price of Ag could effect which solar type is optimal.

Metal	Conductivity, σ (S/cm)
Silver	6.3×10^5
Gold	6.0×10^5
Copper	4.5×10^5
Aluminum	3.5×10^5



From Sand to Silicon

Sand / SiO_2

Coal

Silicon + HCl → $SiCl_4 + 2H_2$

(metallugircal grade)

Purify since $SiCl_4$ is a gas

$2H_2 + SiCl_4$

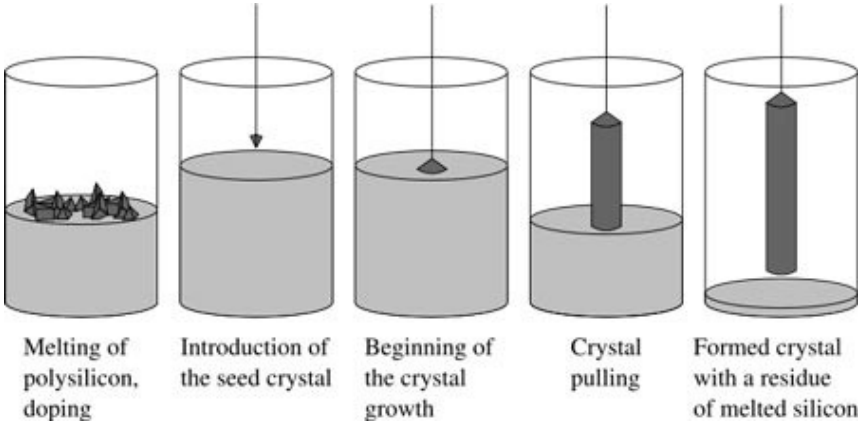
(99.9999% pure [6N])

Si + HCl

(99.9999% pure [6N])

Czochralski (CZ) Si Production

- The Czochralski process of making single crystalline Si is the most popular (75% of all Si)
- The silicon is heated to 1500 °C to melt it.
- A seed crystal pulls up the Si at a rate of 25 mm per hour.
- The wafer size are anywhere from 100mm diameter to 450mm in diameter and 1-2 meters long.
- They have oxygen dopants of 10^{18} cm^{-3}

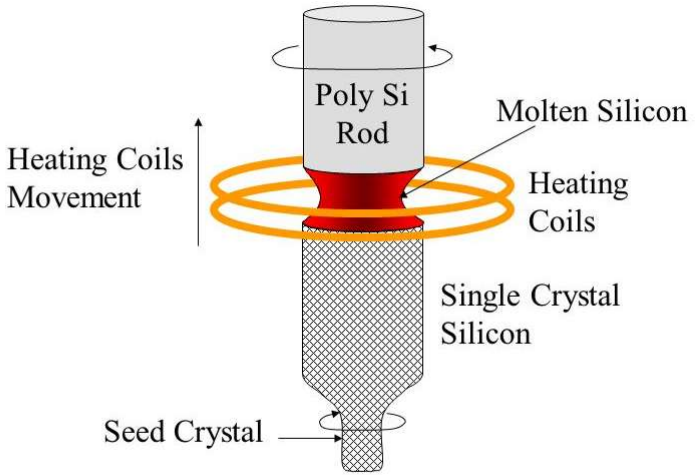


Silicon ingot

Float Zone Si production

- Float-Zone is a more pure way to make single crystalline Si
- A poly-crystalline Si is set on a seed of crystalline Si.
- The Si sidewalls does not touch anything so it is ‘floating’
- A inductive heating coil heats the Silicon and melts a small portion of it
- Once it cools, it settles into a single crystal.
- The melt also concentrates and remove contaminants.
- Typically this Si is too expensive for solar cells.

TOPSIL



Hong Xiao, Ph. D. www2.austin.cc.tx.us/HongXiao/Book.htm

Fabrication of p-n junction

- Creating a highly doped p^+ layer (or n^+ layer is very easy) for Si. (the '+' means highly doped)
- For p^+ dopant put in a boron based gas at elevated temperatures (~ 1000 C) for about 10 minutes.
- For n^+ dopants use a phosphorous gas (such as $POCl_3$).
- The boron (or phosphide) reaches a saturation concentration, thus allowing for high doping.

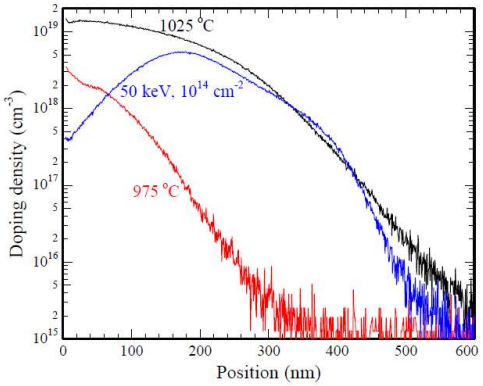


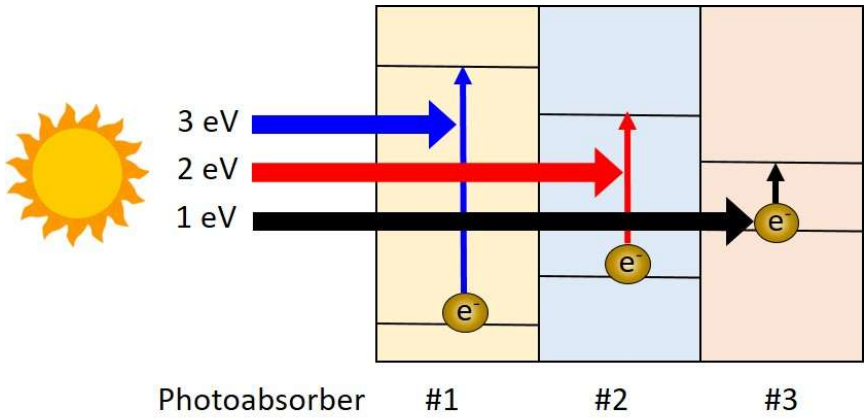
Fig. S6. Dopant profiles (SIMS) of the high (1025 °C) and low (975 °C) doped p^+-Si layer in the 100 nm TiO_2/5 nm Ti/p^+n Si composites. Also shown is the doping profile used for calibration of the SIMS profiles (1×10^{14} cm^{-2} ^{11}B implanted at 50 keV).

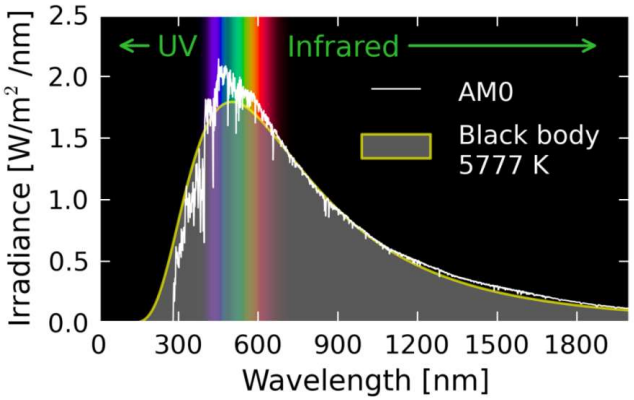
Mei, et. al, J. Phys. Chem., 2015

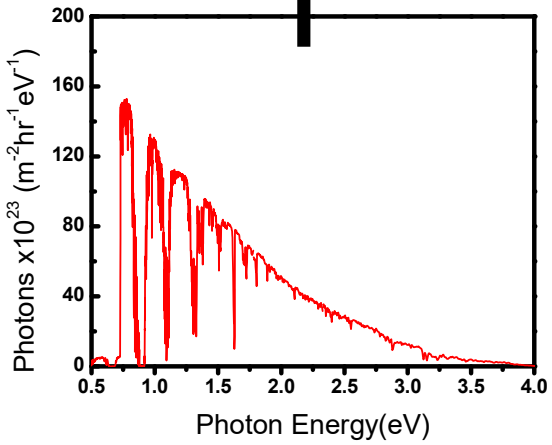
Tandem Solar Cells

Tandem Solar Cells- Basic Principles

- An optimal solar cell, would have a bandgap material for each wavelength from the sun
- For economic reasons, we are interested in 2 or 3 photoabsorbers for a tandem solar cell

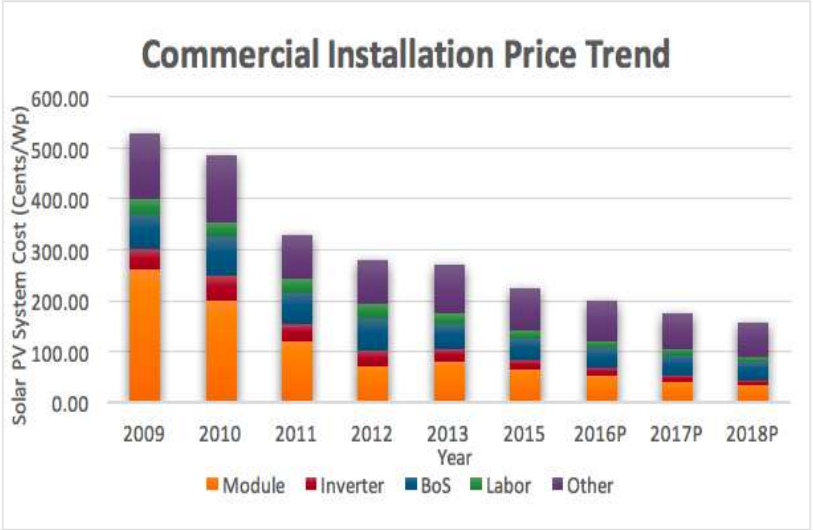






Why tandems are becoming relevant

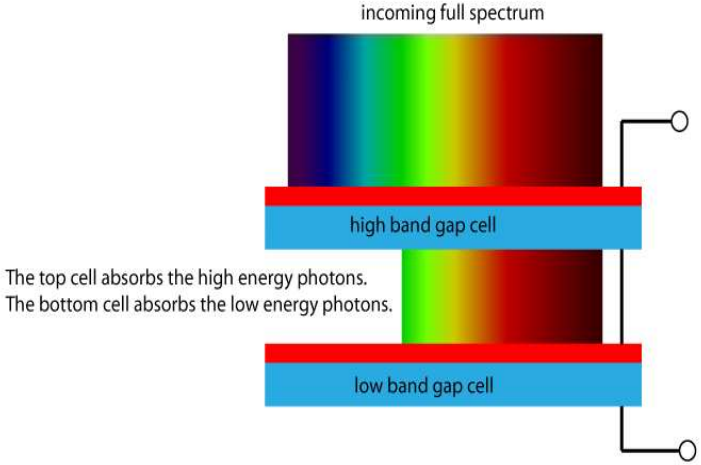
- Since the beginning, the actual solar cell was the largest cost factor for producing solar based electricity.
- While we have been able to greatly reduce solar cell costs, the balance of plant costs have been hard to reduce.
- Now balance of plant costs are the largest costs for solar cells.
- Balance of plant includes
  - Inverters
  - Permitting
  - Steel frames to hold the solar cells
  - Labor
- Tandems allow us to have the same balance of plant, but higher efficiency.

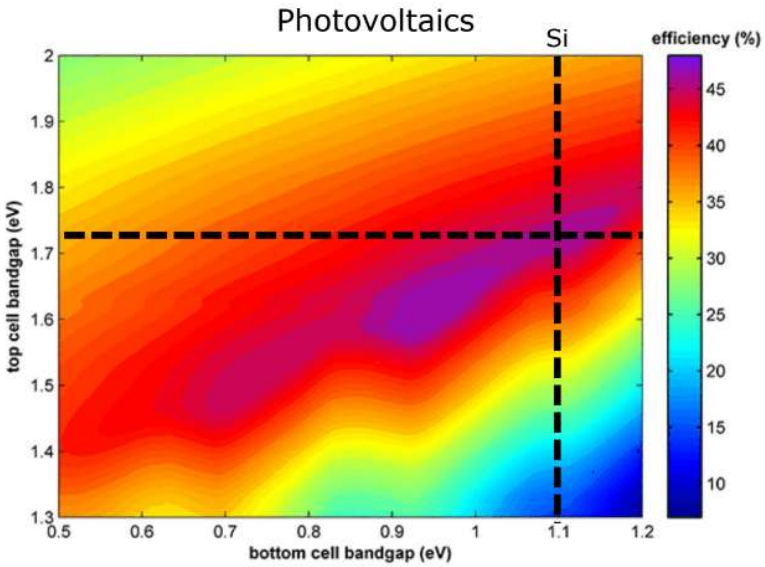


http://www.ezysolare.com

How efficient can we get realistically ?

- Here is a figure relating optimal efficiencies of a 2 photoabsorber device as a function of their band gap.



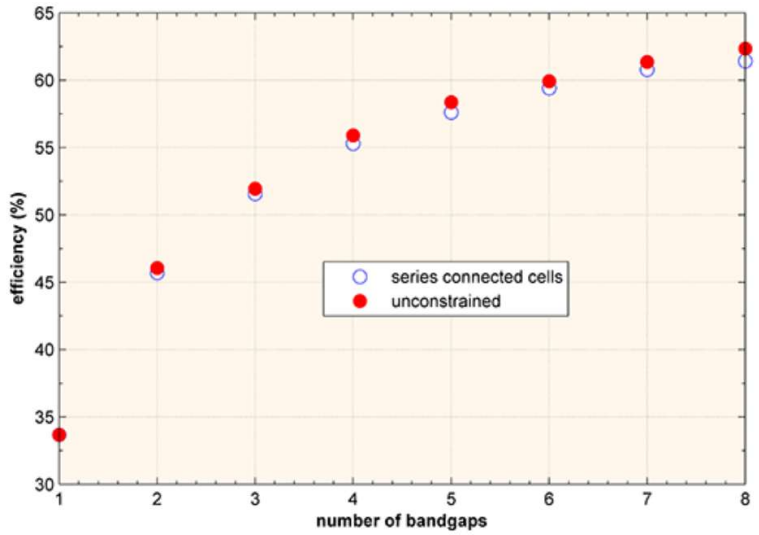


Taken from: https://www.pveducation.org/pvcdrom/tandem-cells

Optimal band gaps for tandem devices

- The graph below is for optimized solar cells.

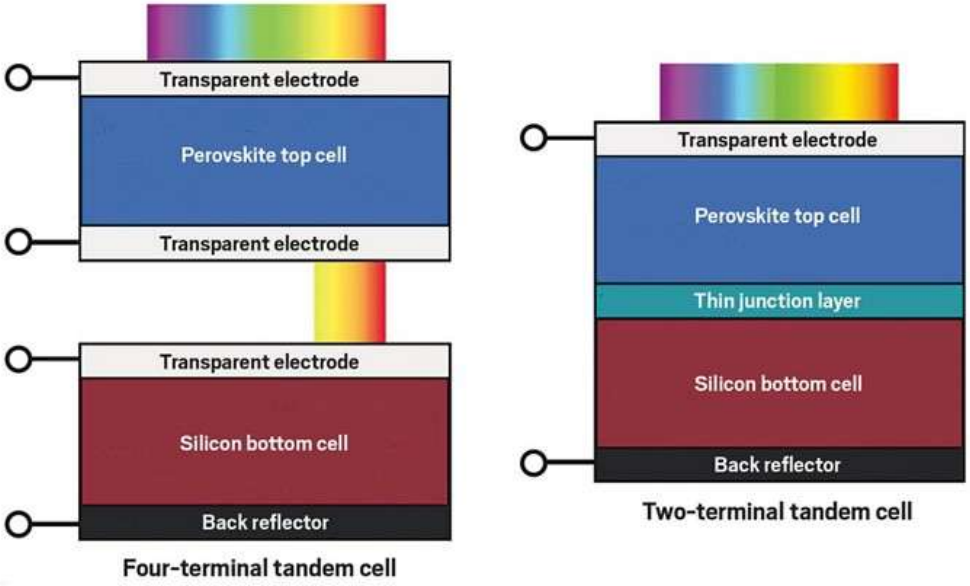
# of cells in tandem device	Bandgap #1	Bandgap #2	Bandgap #3	Bandgap #4
#1	1.3			
#2	1.9	1.0		
#3	2.3	1.4	0.8	
#4	2.6	1.8	1.2	0.8



Marti et al., Solar Energy Materials and Solar Cells 43 (1996) 203-222

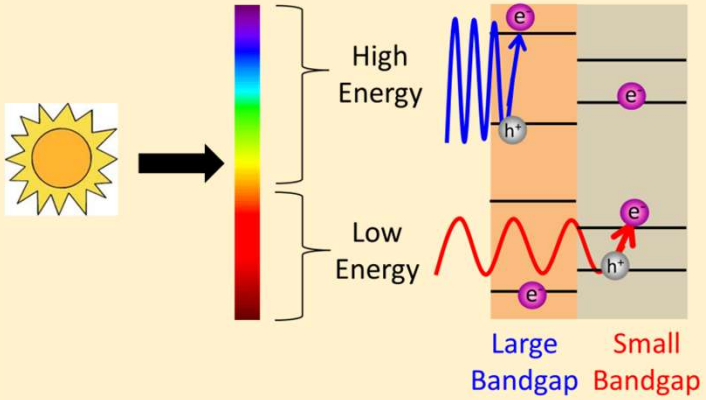
Tandem Solar Cells- Basic Principles

- There are different approaches to making this work.
- The four terminal is simpler to construct.
- The two terminal is theoretically the better way to do it.

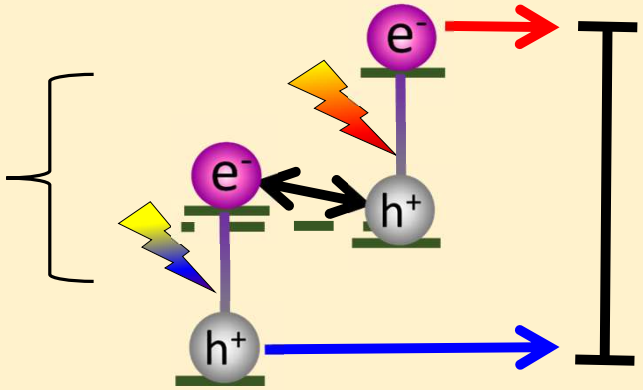


Tandem voltage in 2 terminal approach

Optical Absorption Properties



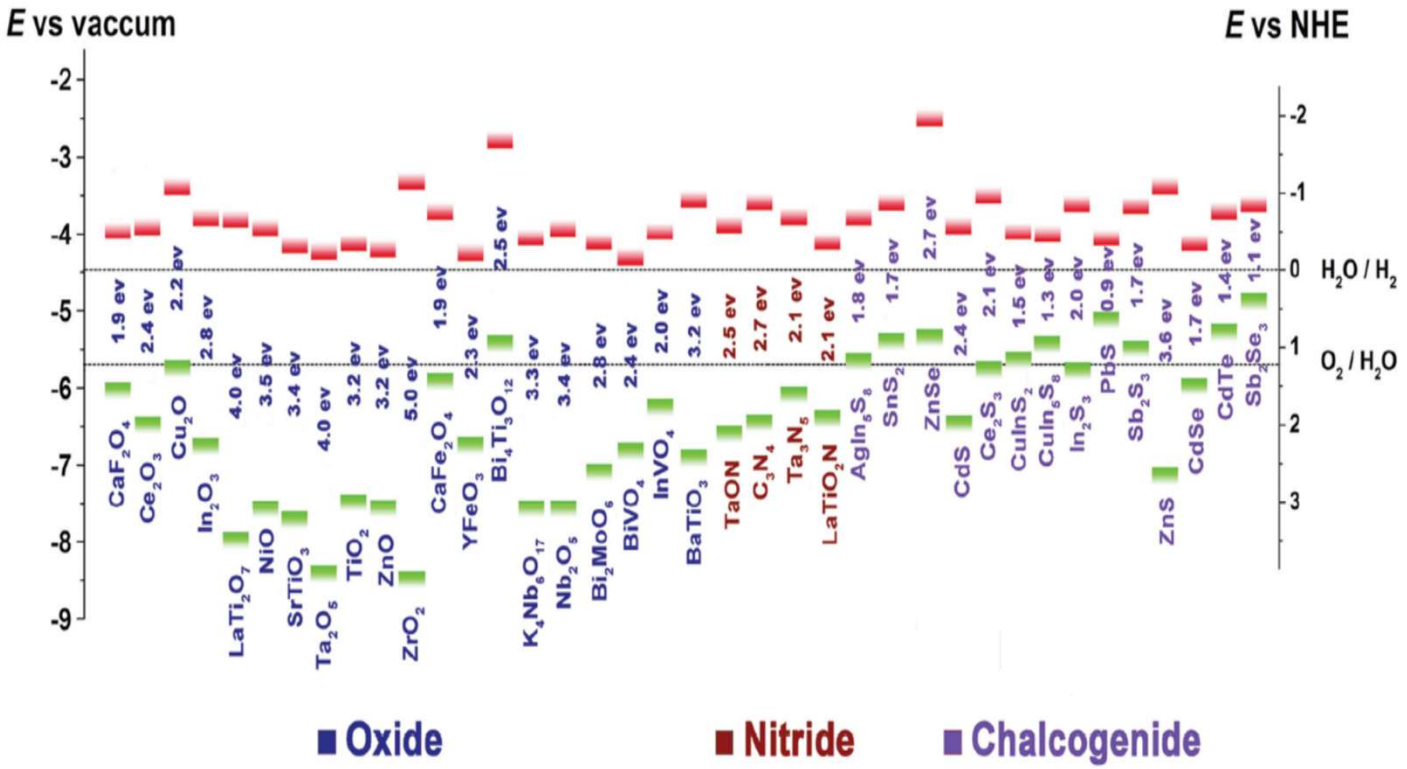
Energetic Properties



- Half the current, but more than double the photovoltage
- Do the energy levels automatically line up?

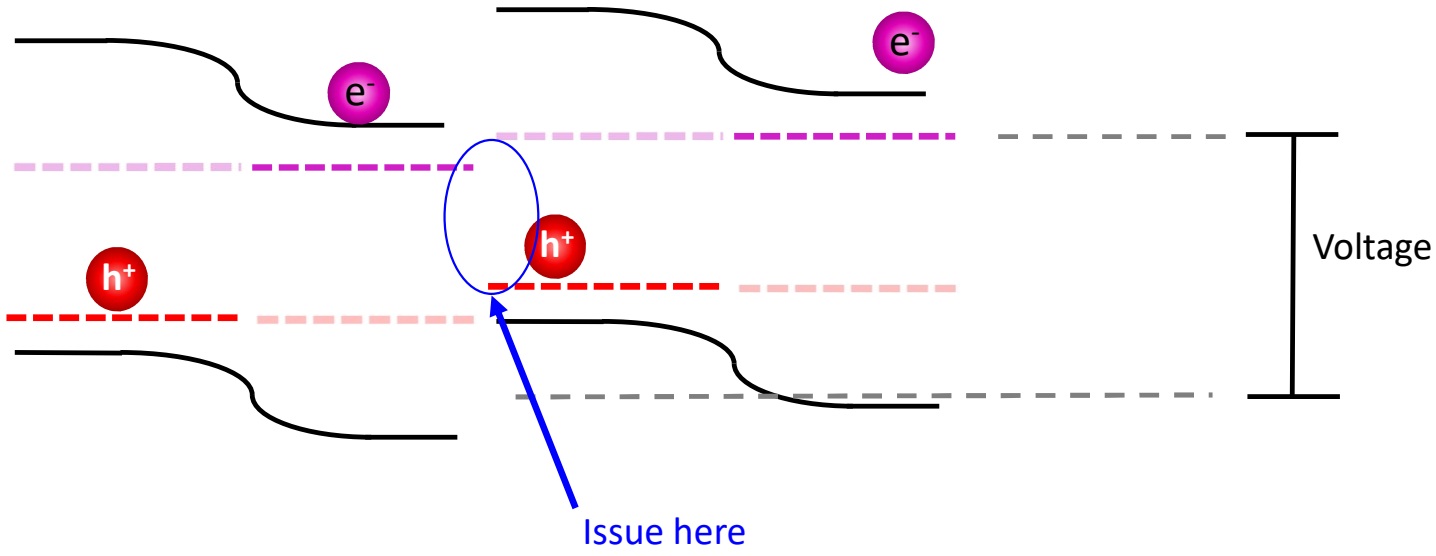
Band position alignment

- It is going to be difficult to find good band alignment between 2 photoabsorbers (that also have optimal band gaps, and semiconductor physics properties)



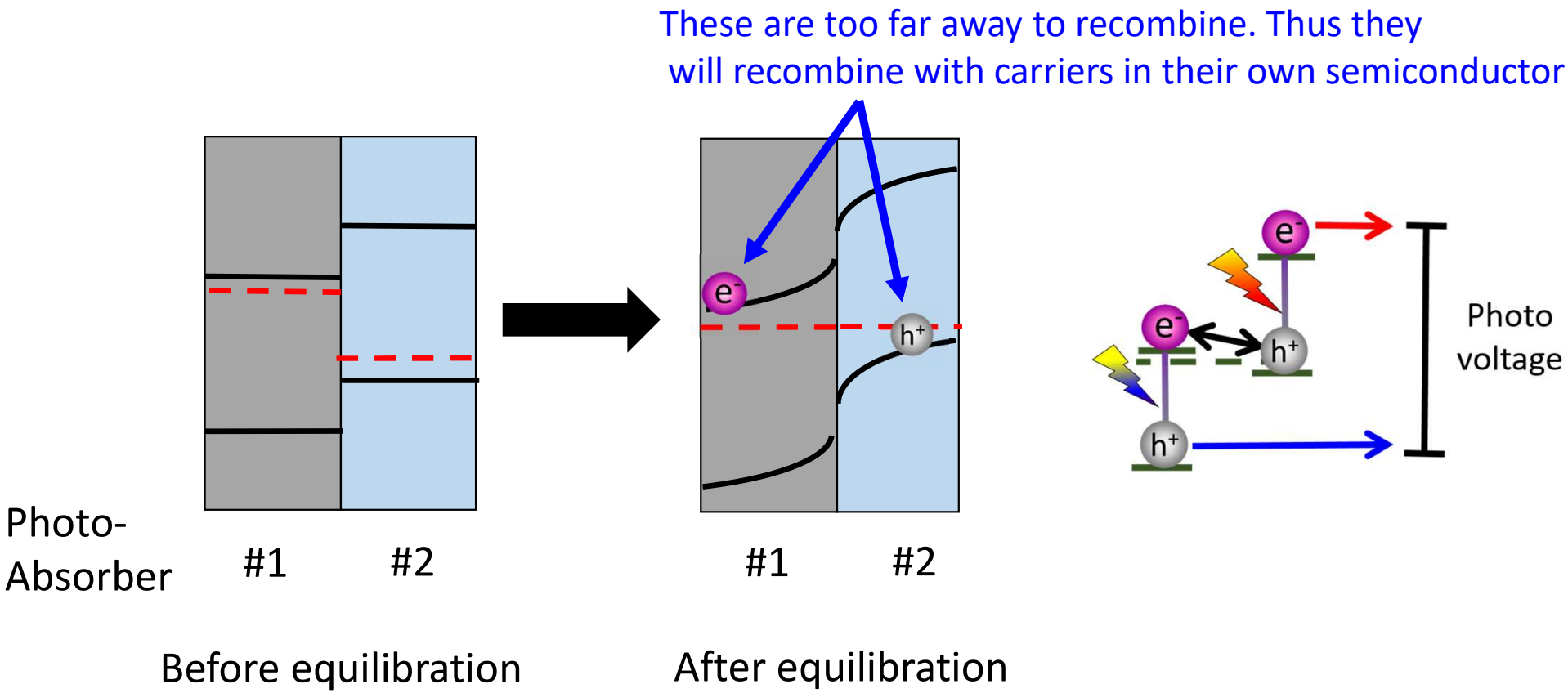
Theory

- If the band positions are not aligned at the inteface we have an offset.
- This interface give us problems due to Fermi level alignment



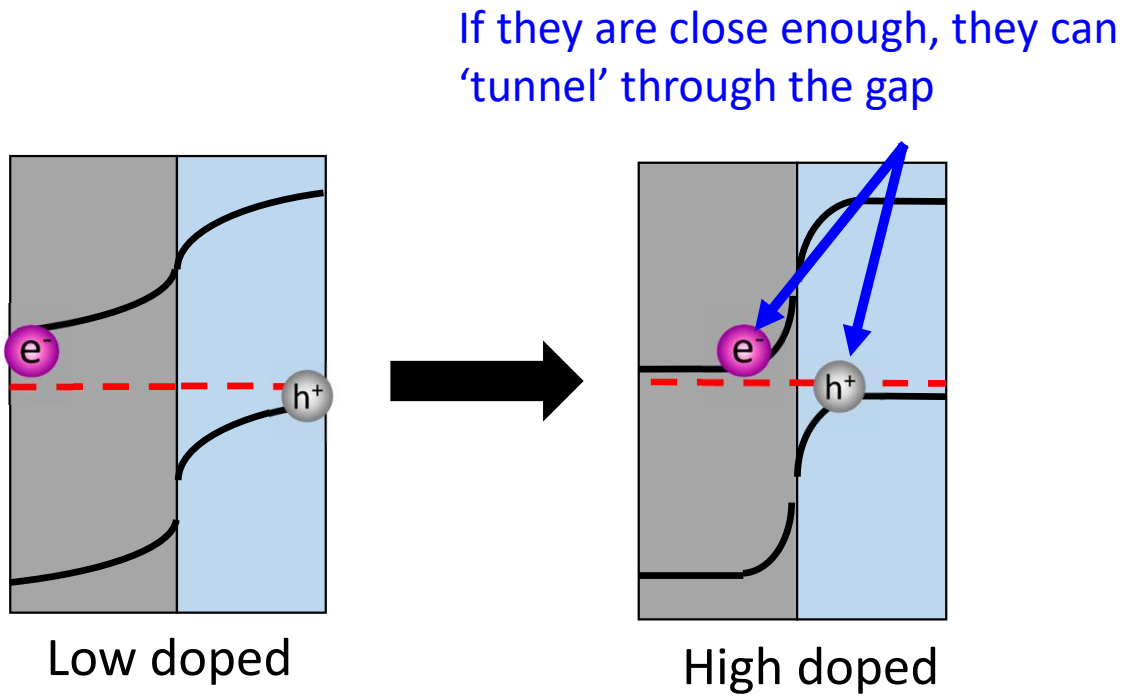
The interface between photoabsorbers

- There is a p-n junction at the interface going the wrong way



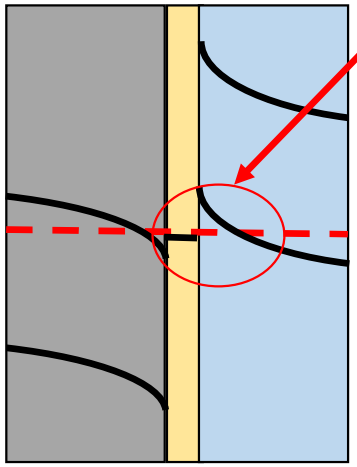
Tunnel Junctions for Tandems

- Tunneling allows us to ‘ohmically connect’ two photoabsorbers
- Highly doping both sides provides a very short depletion layer



Other tunneling approaches

- A thin metal layer can serve as a tunnel junction



Kind of highly doped

- You still need relatively highly doped photoabsorbers, but a metal in the middle cuts your tunneling distance by ~50%

Tunneling probability

$$T_t = exp\left[-\frac{4}{3}\Delta x\sqrt{\frac{2m_{eff}\,q\emptyset_b}{\hbar^2}}\right]$$

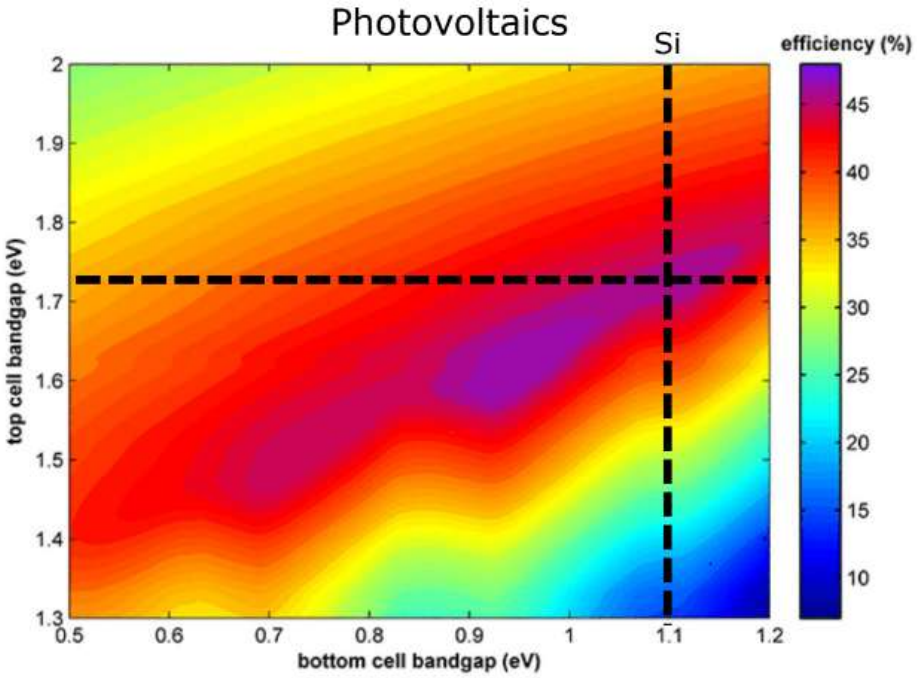
- Metal work function should be close to correct position, but not essential.

Practial tandem materials to match Si

Perovskite solar cells ($CH_3NH_2PbI_xBr_y$)

- Band gaps:
  CH_3NH_2PbI = 1.5 eV
  CH_3NH_2PbBr = 2.2 eV

- Mixtures photo-segregate

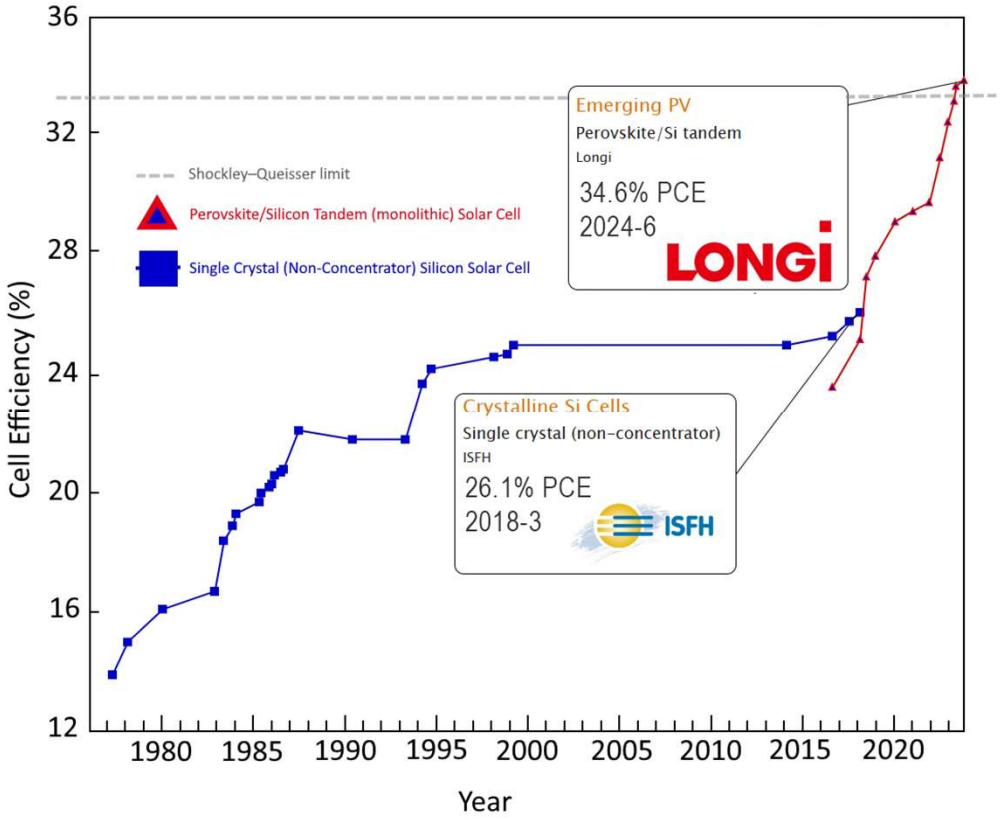


Selenium solar cells

- Bandgap = 2 eV
- Low melting temperature (~200 C)
- First ever solar cell (1883)

Optimal band gaps for tandem devices

- Longi has the record for 2-photabsorbers tandem at 34.85% (April 2025)
- The use a perovskite/Si Tandem cell
- Longi is a company, not a university/research-facility
- Their commercial devices operate at 30.1% efficiency

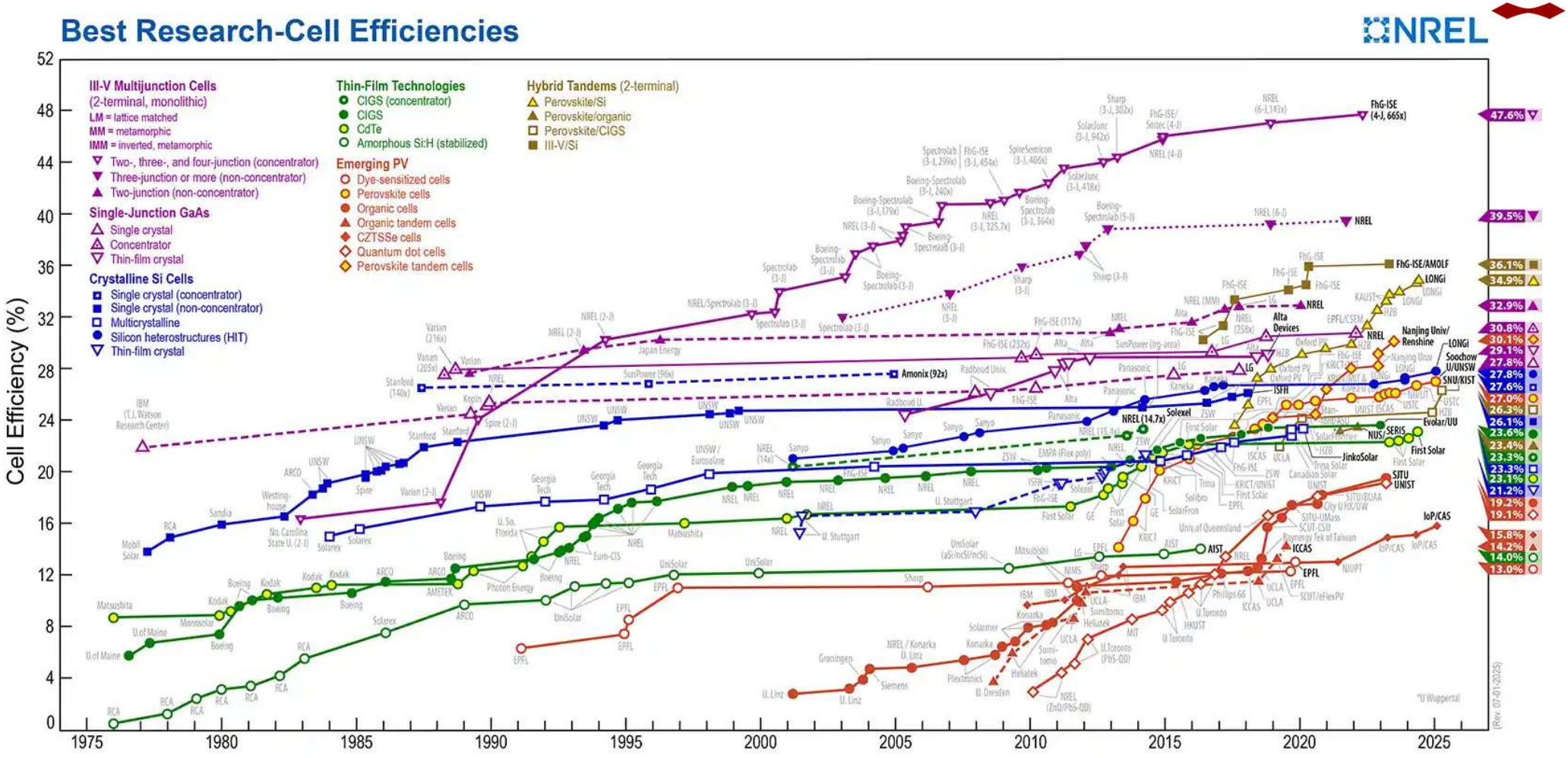


Development of Se-Si at DTU

Peter Vesborg

Tobias Hemmingsen

Certified record solar cell efficiencies



NREL

Lecture - Learning Objectives

At the end of this lecture you should:

- Understand the following junctions:
  - P-n junction
  - p-i-n junction
  - Hetero-junction
  - Tunnel junction
  - Schottkey Barrier
- Understand how to apply various junctions to make an overall solar cell device.
- Understand basics of tandem solar cells
- Understand bi-facial solar cells

Exercises

- If you have a p-n junction Si with the n-type having a donor density of $1x10^{19}$ cm^{-3} and the p-type donor density of 2×10^{16} cm^{-3} plot the band bending at the p-n junction. Just do a rough plot showing the depletion layer and bias voltage.

- If we take Si with a SiO_2 tunnel junction, how thick can the SiO_2 be to still allow 100 mA/cm^2 to pass through.

*(Assume 25C and the barrier height ($q\theta_b$) for Si-SiO_2 is 4.35 eV, and an m_{eff}=1.0 (*mass of electron in vacuum). All other properties for Si can be found online.)*