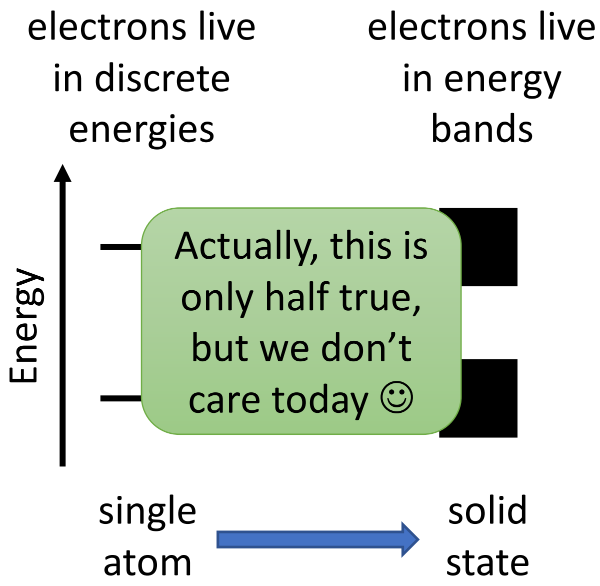
School of Photovoltaic and Renewable Energy Engineering

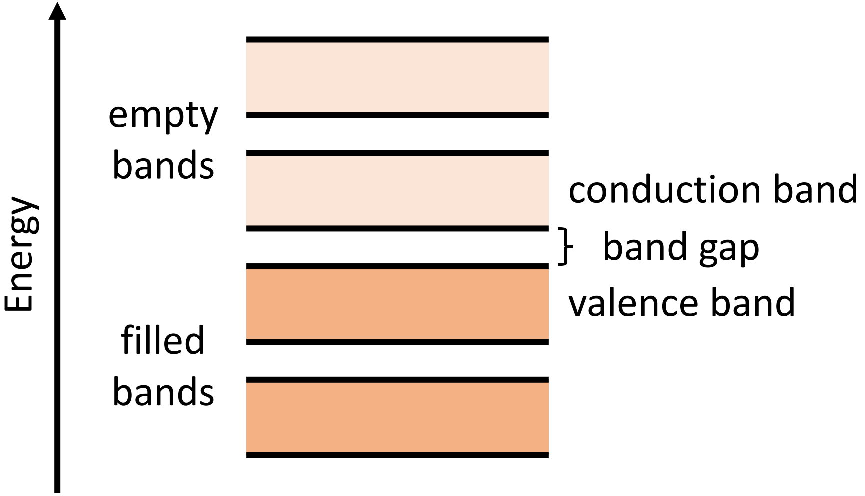
Mini Solar

What you need to know about solar cells

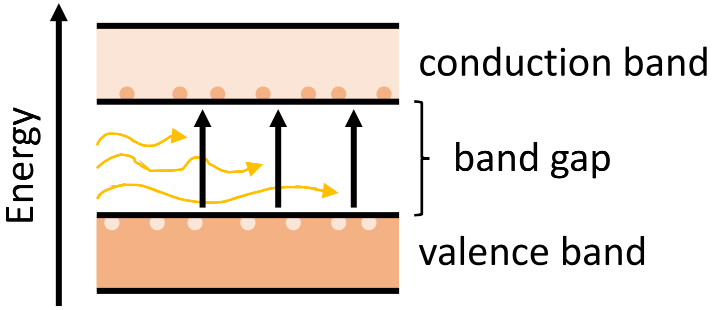
Udo Römer, 20.03.2020

Super-short crash course in semiconductor physics
Energy bands





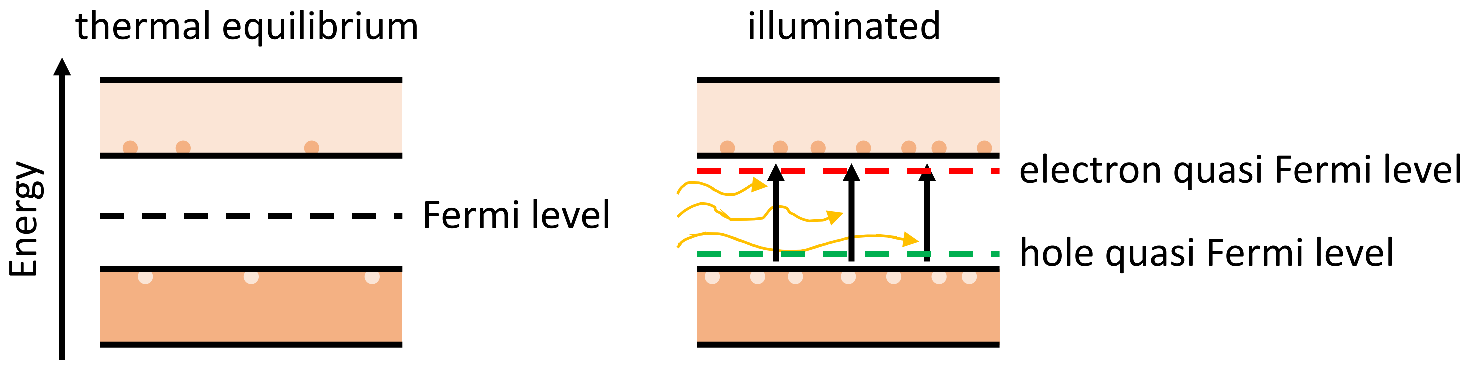
Super-short crash course in semiconductor physics
Semiconductor



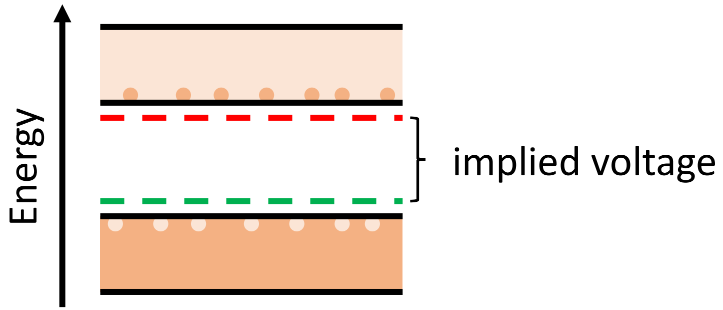
- electrons can only transport energy when unoccupied states are available
- partly filled conduction band
  → **metal**
- empty conduction band & large bandgap
  → **insulator**
- empty conduction band & small bandgap
  → thermal excitations of electrons to conduction band
  → **semiconductor**
  → light can excite electrons to the conduction band, leaving holes in the valence bands

Super-short crash course in semiconductor physics
Fermi level

- Fermi level describes energy of charge carriers
- upon illumination, distribution of electrons and holes can be described by different quasi Fermi levels



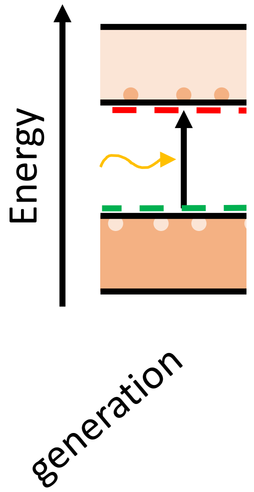
How does a solar cell work?
Implied voltage



from now on all diagrams show illuminated semiconductors

- Energy difference between electron and hole quasi Fermi levels is the implied voltage
- In order to use this voltage, we need contacts

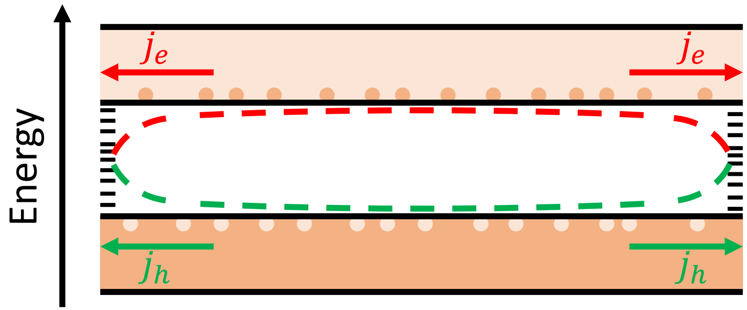
How does a solar cell work?
Recombination



- generation and recombination are in a steady state
- recombination more effective for small energy differences → trap assisted
- strong recombination at surfaces (especially metallised surfaces)
- recombination results in reduced charge carrier densities

  → reduced implied voltage
- if there is a drop in the quasi fermi level, it will result in a current

How does a solar cell work?
Contacts



- if there is a drop in the quasi fermi level, it will result in a current:

$$j_e = \frac{\sigma_e}{e} \mathrm{grad}(\varepsilon_{eQFL})$$

$$j_h = -\frac{\sigma_h}{e} \mathrm{grad}(\varepsilon_{hQFL})$$

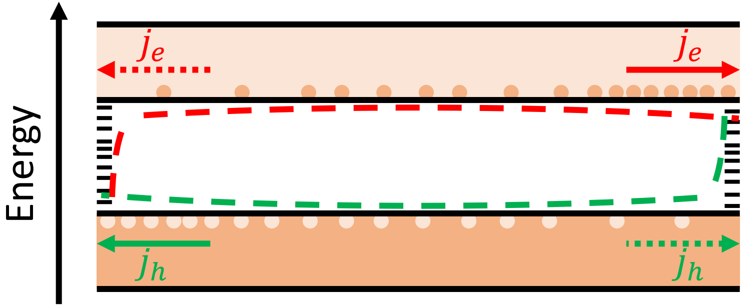
σ: conductivity
ε_{QFL}: quasi Fermi level energy

- if both, electrons and holes can reach the contact we don't get a voltage

→ we need different current-flows for electrons and holes

→ we need different conductivities

How does a solar cell work?
Contacts



Highly *p*-doped region:
$N_h > 10^{18}$ cm^{-3}
$N_e < 10^2$ cm^{-3}

Highly *n*-doped region:
$N_e > 10^{18}$ cm^{-3}
$N_h < 10^2$ cm^{-3}

illumination adds
$\Delta n_e = \Delta n_h > 10^{15}$ cm^{-3}

- How do we change conductivity?

$$\sigma_e = e n_e \mu_e$$

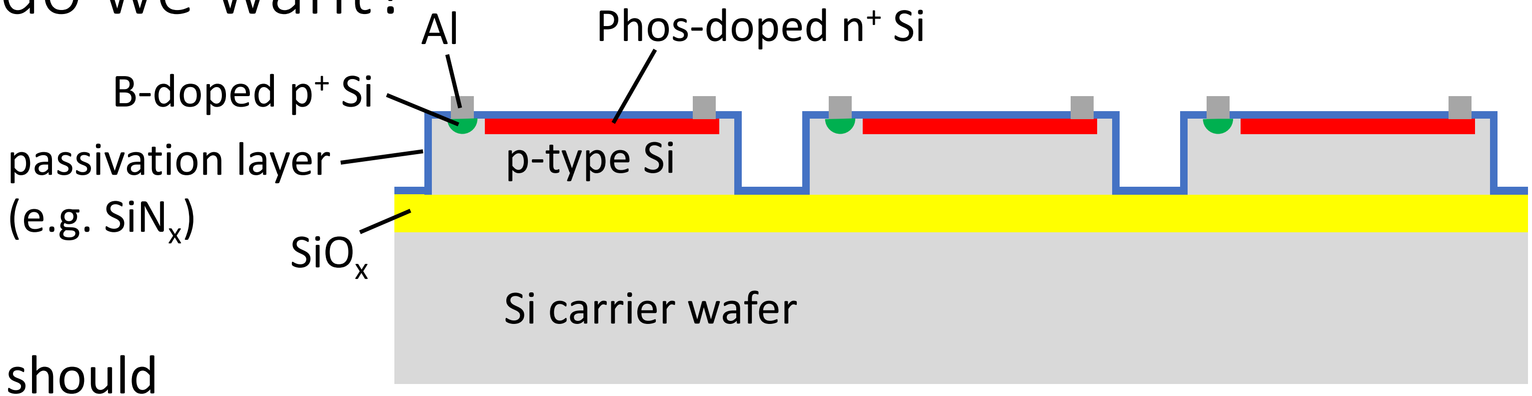
$$\sigma_h = e n_h \mu_h$$

- mobility μ hard to change (selectively)
- charge carrier density *n* can be changed a lot by doping

→ electron contact: low resistivity for electrons, high resistivity for holes

→ hole contact: low resistivity for holes, high resistivity for electrons

Solar cell processing in the Mini Solar project
What do we want?

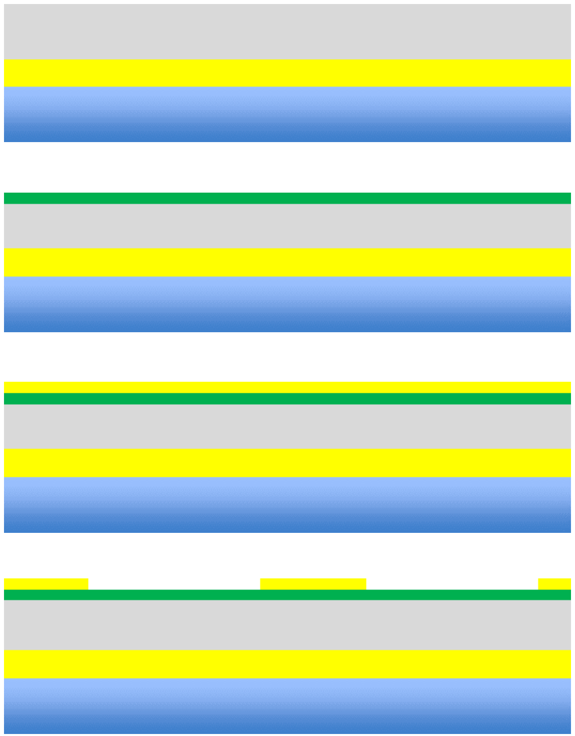


Our PV cells should

- be able to charge a Li ion battery (~4 V would be nice)
  - → 7 cells each producing 0.6 V would do the job
- be electrically isolated from each other
  - → we can fabricate cells on an insulator layer and etch grooves between the cells
- be easy to process in large batches
  - →Fabrication of many cells on a “large” wafer

Solar cell processing in the Mini Solar project

Cross-section



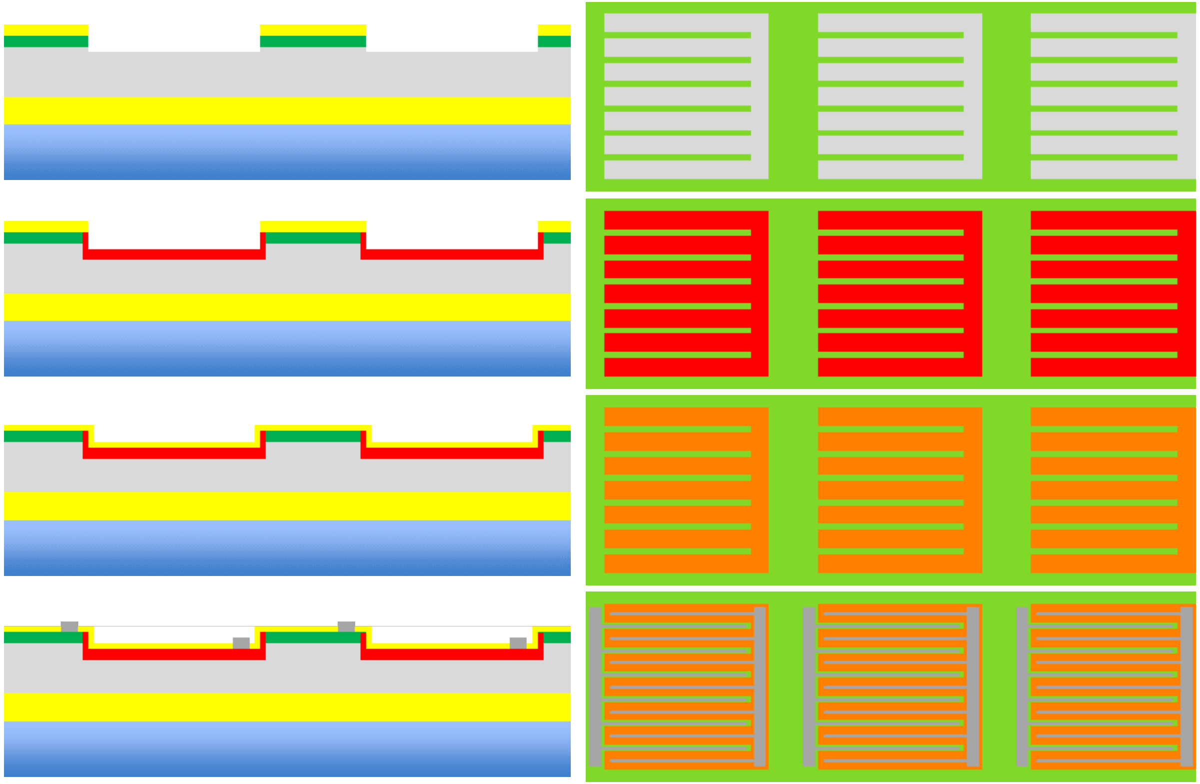
Top view

- Silicon on insulator wafer
  - SiO_2 layer separates active layer from supporting wafer below
- Boron diffusion (full area)
  - as p^+ contact
- Oxidation
  - full area
  - as etch / diffusion barrier
- Structuring of SiO_2 layer
  - protecting p^+ region

Solar cell processing in the Mini Solar project

Cross-section — Top view

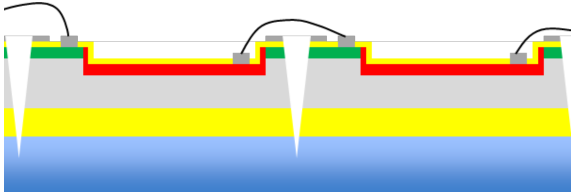
- Etching of Boron region
  - p^+ region protected by SiO_2 layer
- Phosphorus diffusion
  - p^+ region protected by SiO_2 layer
- Oxidation (full area)
  - as passivation & anti-reflection coating
- Metal contact deposition
  - after contact opening



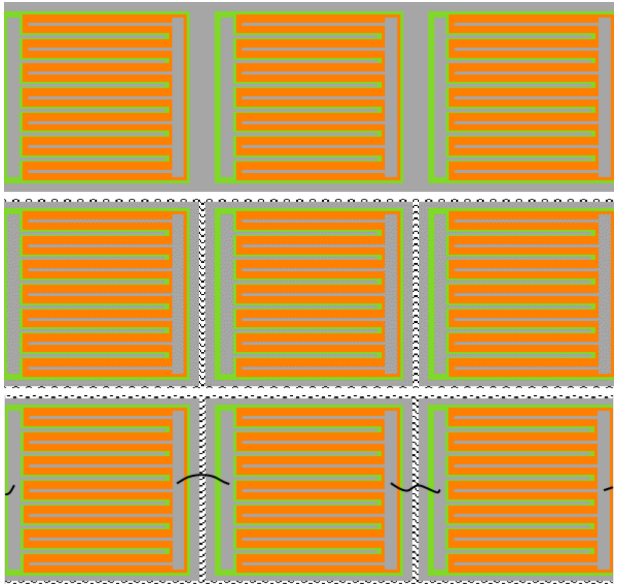
Solar cell processing in the Mini Solar project

- Shadow mask deposition
  - around the cells
  - will explain on next slides
- Laser contact separation
  - electrical cell isolation
- Wire bonding
  - connecting neighbouring cells

Cross-section

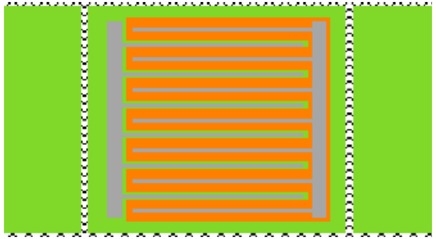


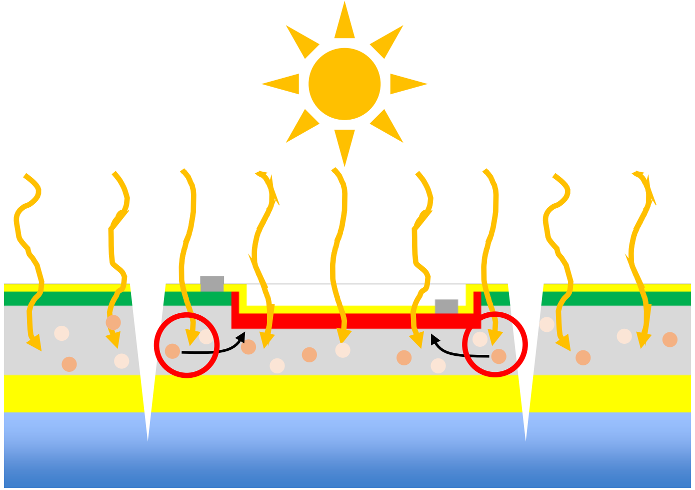
Top view



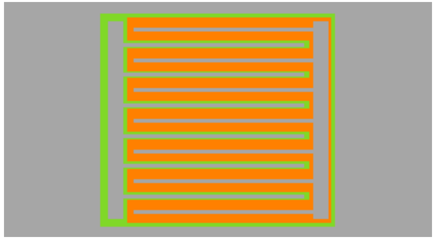
Measurement of small solar cells on large wafer

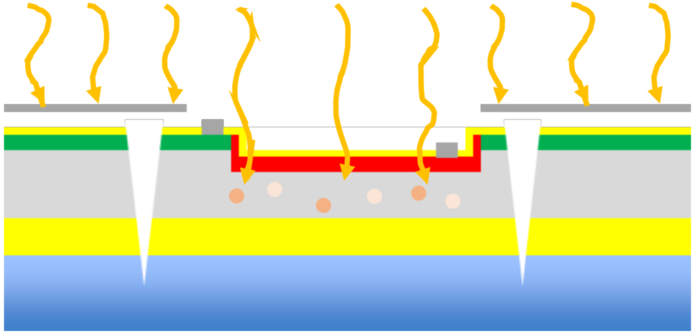
- Cell size smaller than wafer size
- No shadow mask
  - → charge carriers also generated in surrounding region
  - → too high measured current





- Using shadow mask
  - → generation only in illuminated area

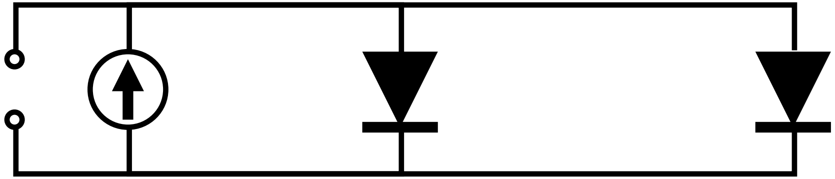




Semiconductor physics part II
What do we actually measure?

- Last week you measured solar cells and used a diode equation for fitting

$$J = J_{sc} - J_{01}(e^{\frac{qV}{k_B T}} - 1) - J_{02}(e^{\frac{qV}{2k_B T}} - 1)$$



two diode model (without series and shunt resistance)

- What does it describe? Only diodes?
- Nope - recombination in a semiconductor
  - n = 1: recombination in low injection ($N_{doping} >> \Delta n$)
  - n = 2: recombination in high injection ($\Delta n >> N_{doping}$)

Semiconductor physics part II
Where does n=2 come from?

- Recombination in a semiconductor

$$J = \frac{qW}{\tau}\Delta n \qquad \frac{n_e n_h}{n_i^2} = e^{\frac{qV}{k_B T}} \qquad \begin{aligned} n_e &= N_e + \Delta n \\ n_h &= N_h + \Delta n \end{aligned}$$

- n = 1: recombination in low injection ($N_h >> \Delta n >> N_e$)

p-type semiconductor

$$\begin{aligned} n_e &\approx \Delta n \\ n_h &\approx N_h \end{aligned} \qquad \frac{\Delta n\, N_h}{n_i^2} = e^{\frac{qV}{k_B T}} \qquad \Delta n = \frac{n_i^2}{N_h}\, e^{\frac{qV}{k_B T}}$$

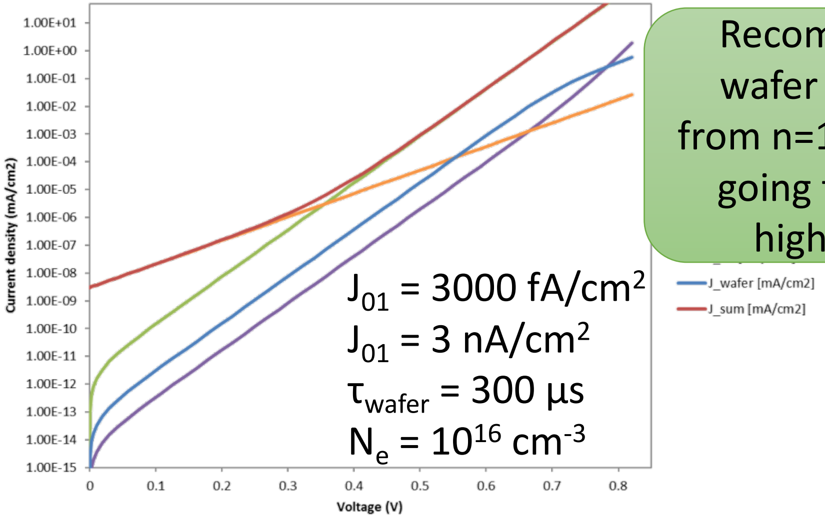
- n = 2: recombination in high injection ($\Delta n >> N_h$)

$$\begin{aligned} n_e &\approx \Delta n \\ n_h &\approx \Delta n \end{aligned} \qquad \frac{\Delta n\, \Delta n}{n_i^2} = e^{\frac{qV}{k_B T}} \qquad \Delta n = \sqrt{n_i^2\, e^{\frac{qV}{k_B T}}} = n_i\, e^{\frac{qV}{2 k_B T}}$$

Semiconductor physics part II
This is all not too important for our solar cells

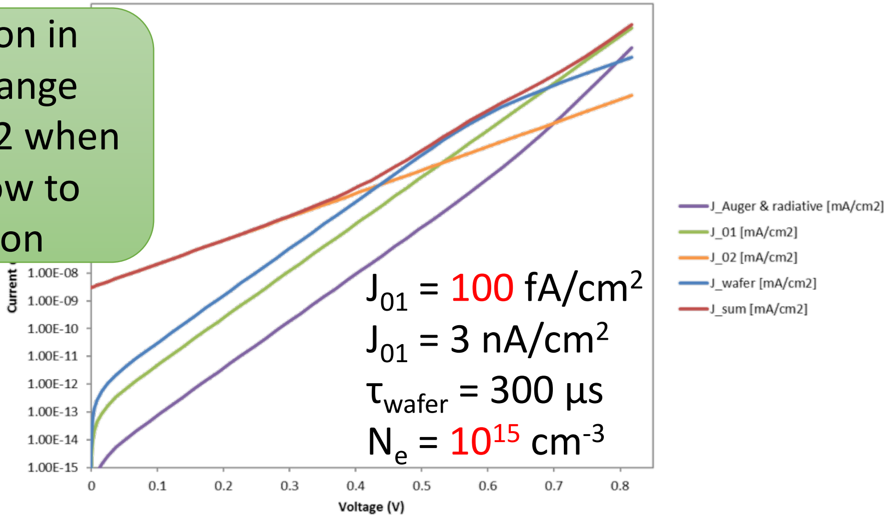
- recombination in a semiconductor
  - n = 1: recombination in low injection (N_{doping} >> Δn)
  - n = 2: recombination in high injection (Δn >> N_{doping})

Solar cells with very low J_{01} & J_{02}-type recombination and low wafer doping can have funny s-shaped curves



J_{01} = 3000 fA/cm^2
J_{01} = 3 nA/cm^2
τ_{wafer} = 300 µs
N_e = 10^{16} cm^{-3}

Recombination in wafer can change from n=1 to n=2 when going from low to high injection



J_{01} = 100 fA/cm^2
J_{01} = 3 nA/cm^2
τ_{wafer} = 300 µs
N_e = 10^{15} cm^{-3}