

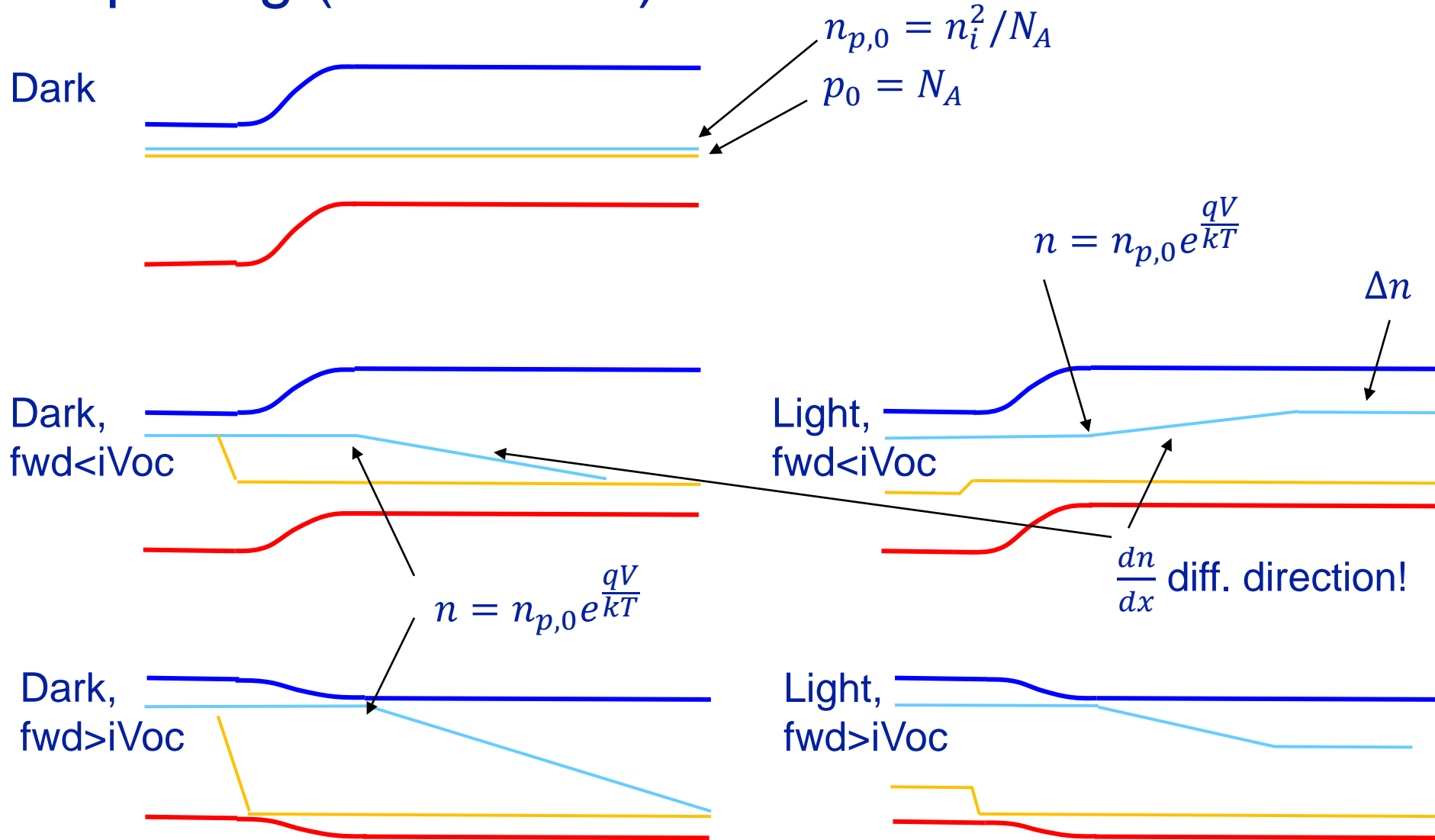
Modern PV-Technologies

3.3: Junctions

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QFL splitting (infinite cell)



Current-voltage characteristic

Simple form of j - V characteristics

$$j = j_0(e^{qV/kT} - 1) - j_{ph}$$

Short circuit current ($V = 0$):

$$j_{sc} = j_{ph}$$

Open circuit voltage ($j = 0$):

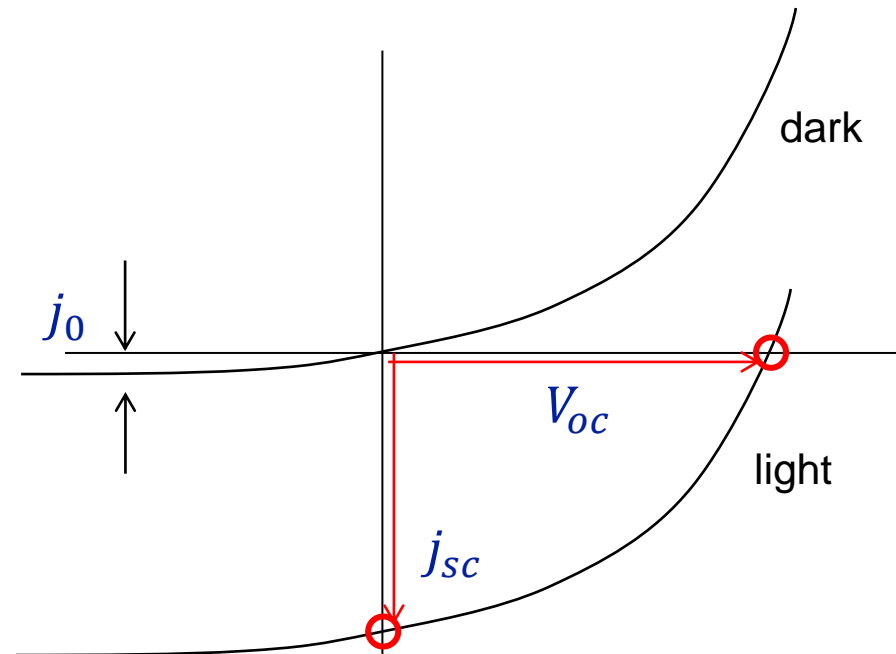
$$V_{oc} = \frac{kT}{q} \ln\left(\frac{j_{ph}}{j_0} + 1\right)$$

Knobs to turn for high V_{oc} :

kT/q is fixed by operating conditions (ambient to approx. +70°C)

j_{sc} is fixed by solar irradiation; slight control via absorption enhancement

j_0 should be as small as possible



EPFL Saturation current

Ideal j_0 for diffusion transport in infinite cell (almost valid for silicon):

$$j_0 = \left(\frac{qD_n n_i^2}{L_n N_A} + \frac{qD_p n_i^2}{L_p N_D} \right)$$

contribution of p-type absorber:

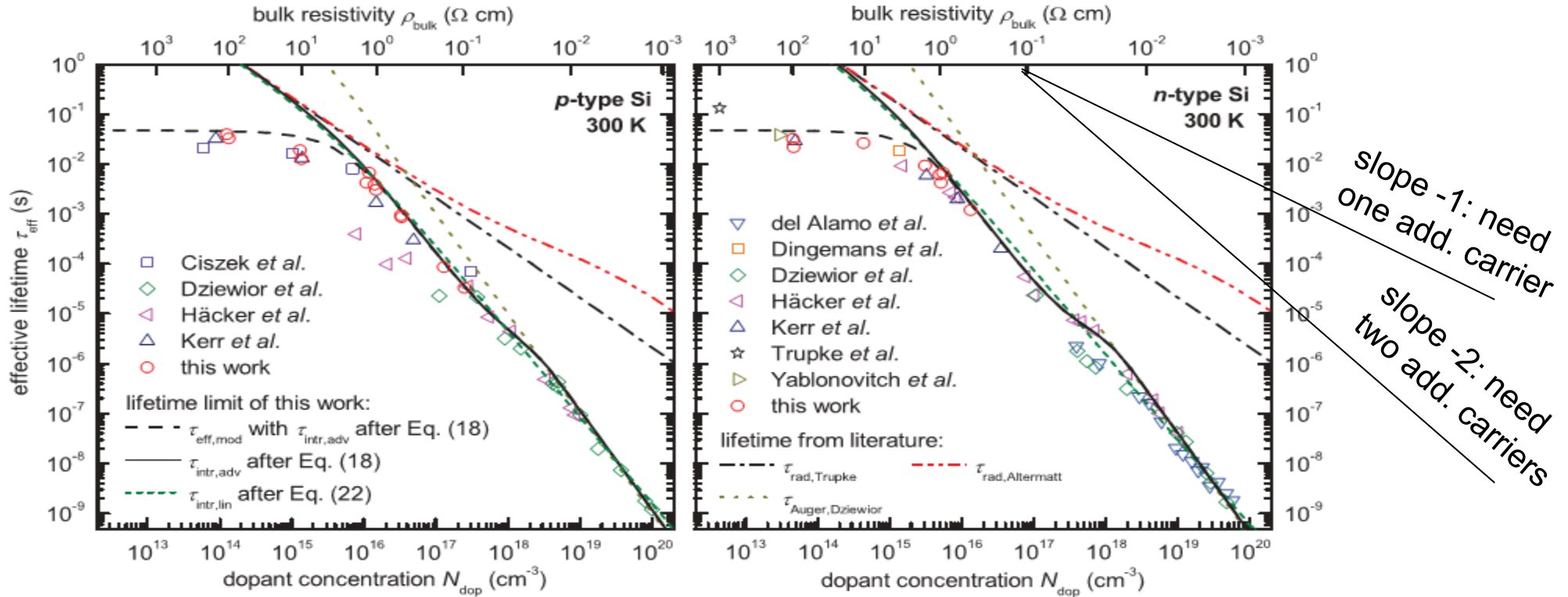
$$j_0 = \frac{qD_n n_i^2}{L_n N_A} = \frac{q n_i^2}{N_A} \cdot \sqrt{\frac{D_n}{\tau_n}}$$

Knobs to turn for small j_0 :

increase N_A (but...)

EPFL Minority carrier lifetime

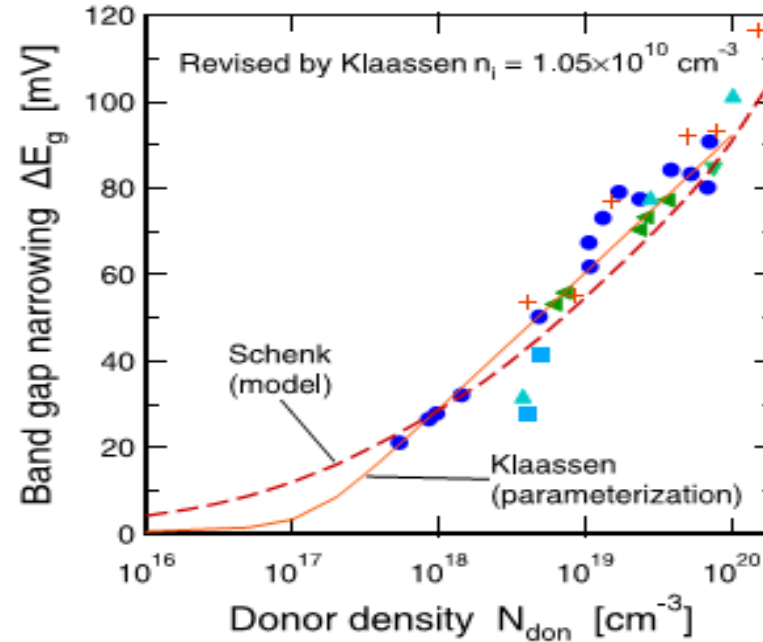
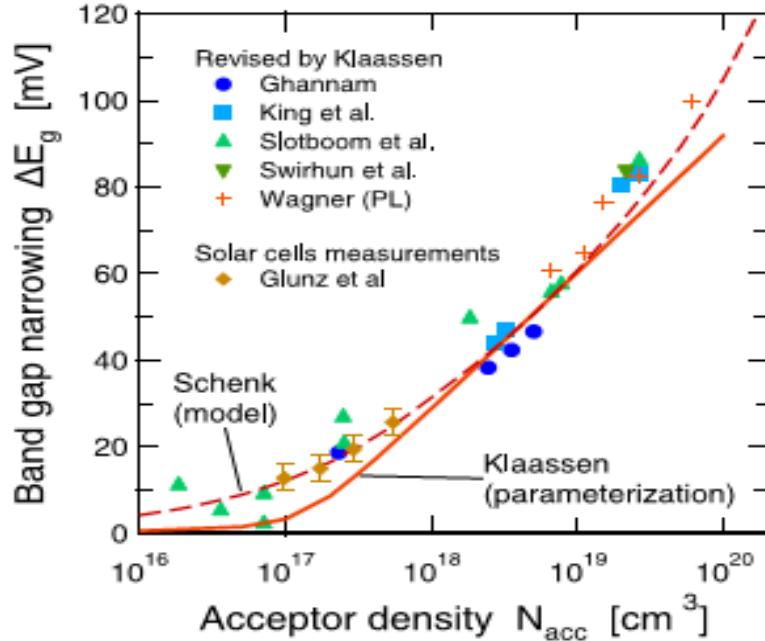
$$\tau^{-1} = \tau_{Auger}^{-1} + \tau_{rad}^{-1} + \tau_{bulk}^{-1}$$



High doping will also decrease τ !

reviews on Auger-limited lifetimes: Kerr, PPV (2003)
 Richter, PRB (2012)
 Niewelt, SEM (2022)

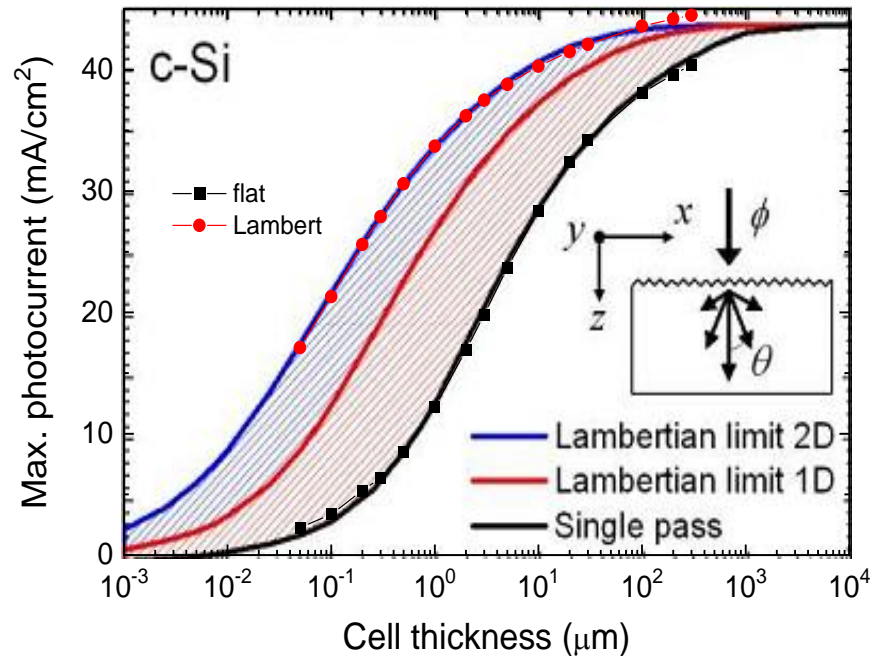
Band gap narrowing (BGN): filling of states close to band edge



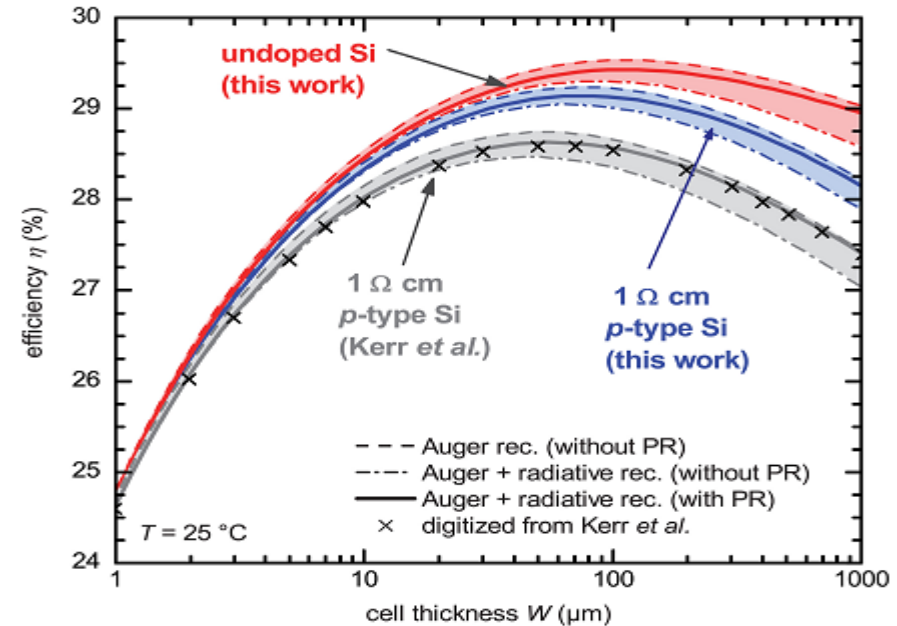
Remember: $n_i^2 \sim e^{-\frac{E_g}{kT}} = e^{-\frac{E_{g,0} - \Delta E_g}{kT}}$

On BGN models: e.g. Altermatt, J. Comput. Electron. (2011)

Photocurrent



Efficiency



Conclusion:

- dope as little as possible and reduce recombination volume (thin cells) !
- maximize j_{sc}

Then: $\eta_{max} = 29.4-29.5\%$

On limiting j_{sc} : e.g. Bozzola, EU-PVSEC (2011)

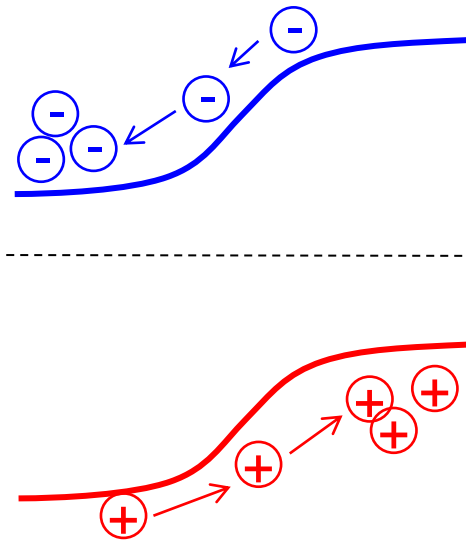
On limiting efficiency: Richter, JPV (2013),

Schäfer SEM (2018)

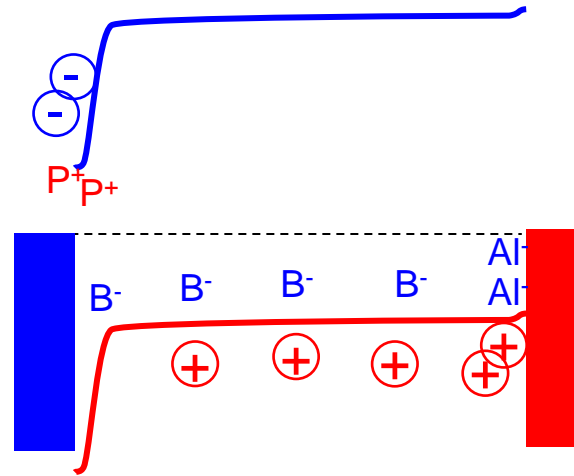
Niewelt, SEM (2022)

How to get current out of the cell

What you often see...

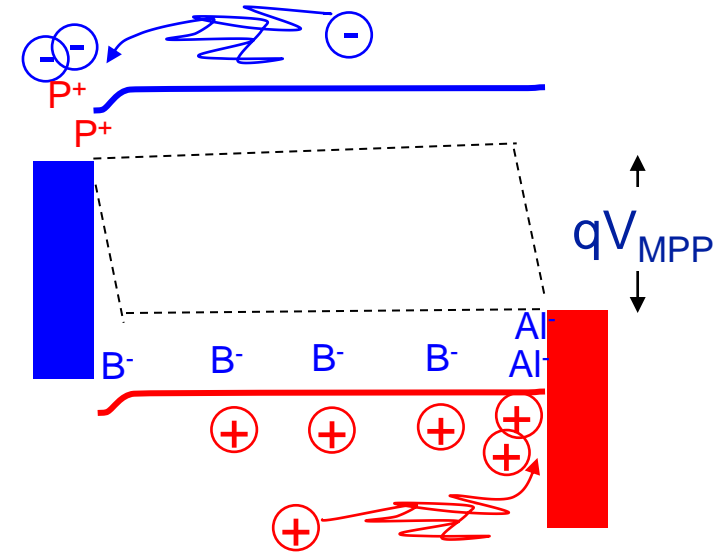


how it actually looks in dark



the field extends over $<1\mu\text{m}$, most of the $200\mu\text{m}$ wafer is neutral

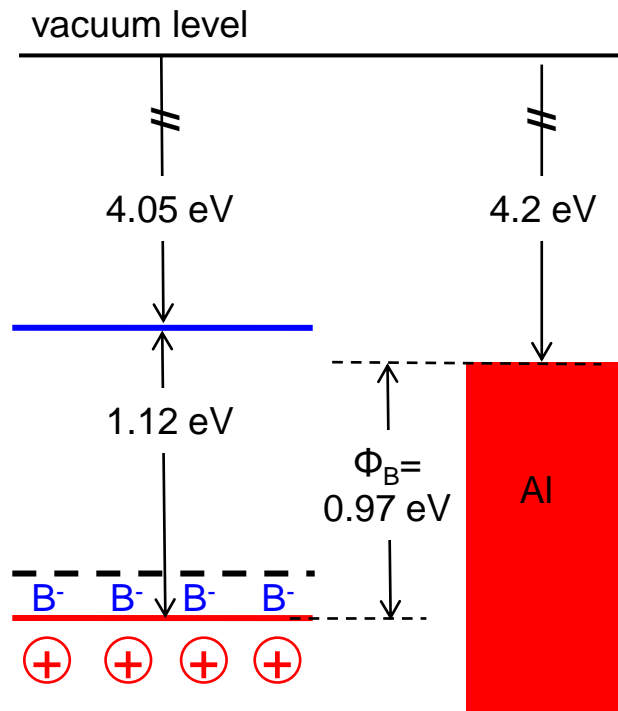
...and how it really works



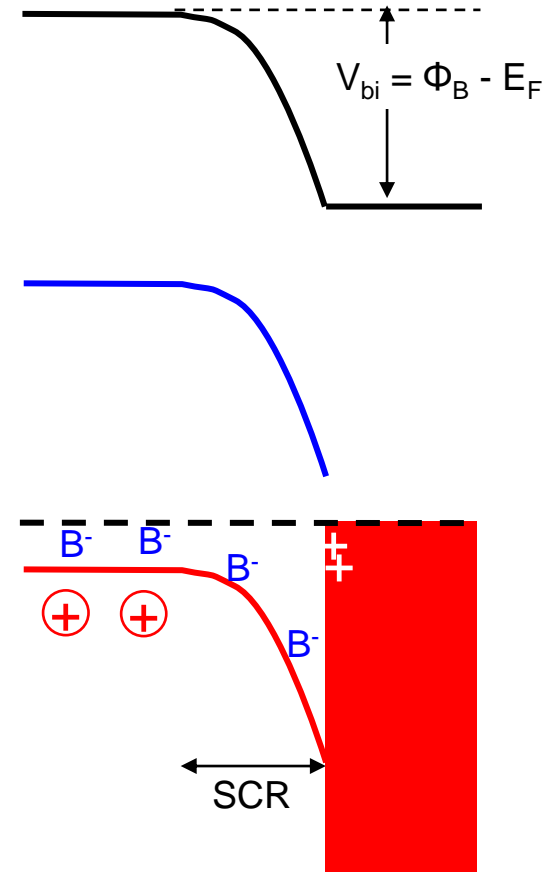
charges diffuse randomly until they "see" a contact region (may be doped, but need not!)

Working principle of metallic rear contact

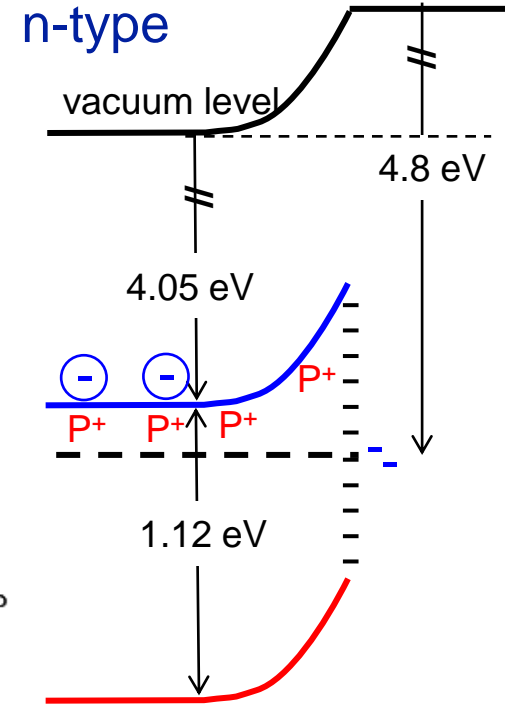
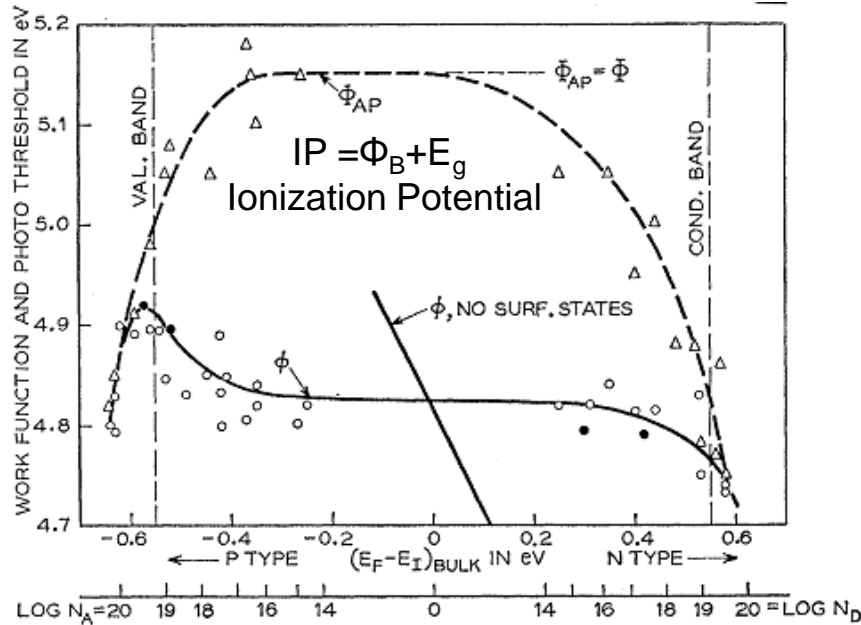
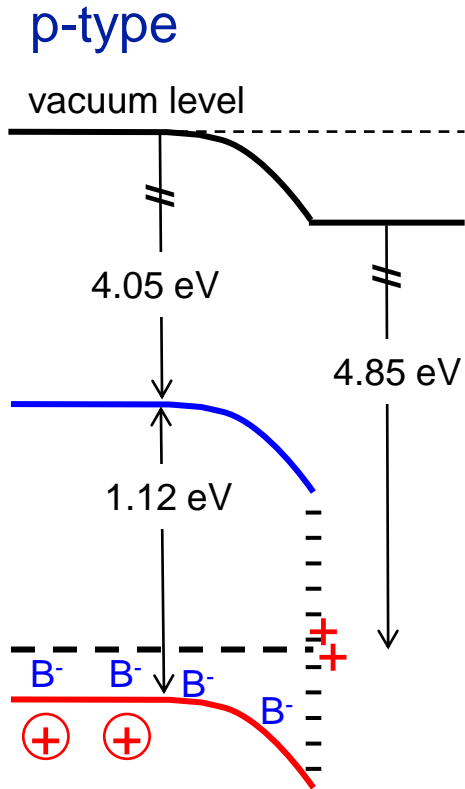
Before contact



Ideal Schottky contact



Attention: Si surface states

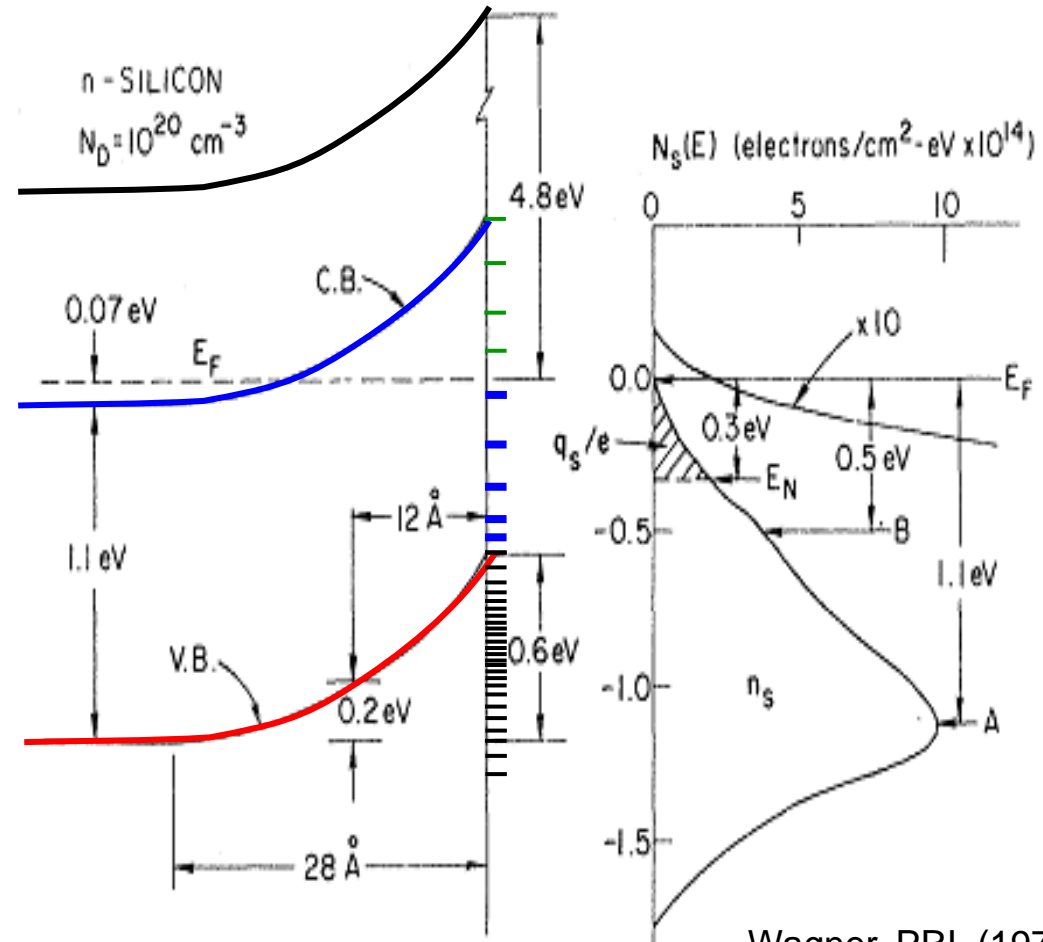
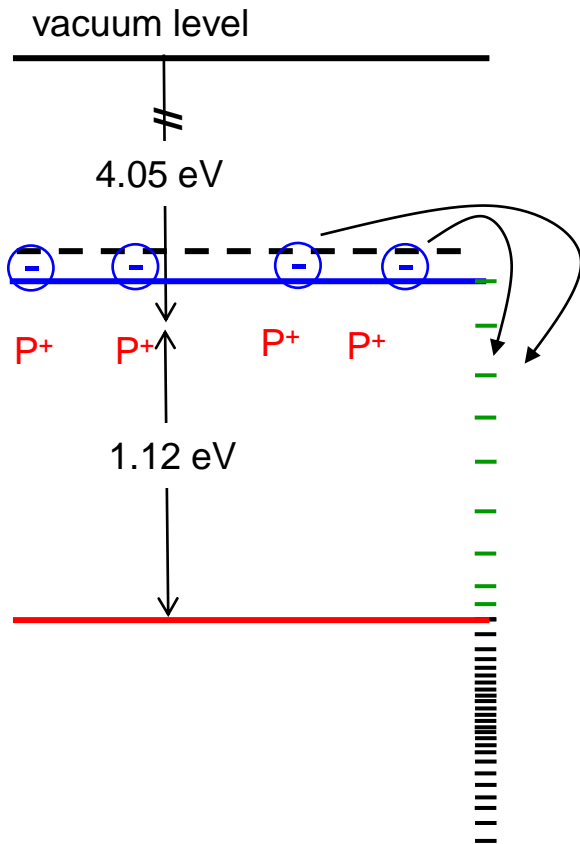


Surface states pin the Fermi-level ca. 0.3 eV above the VB,
work function almost independent of doping type and concentration

Allen, Phys. Rev. (1962)

EPFL Surface state density

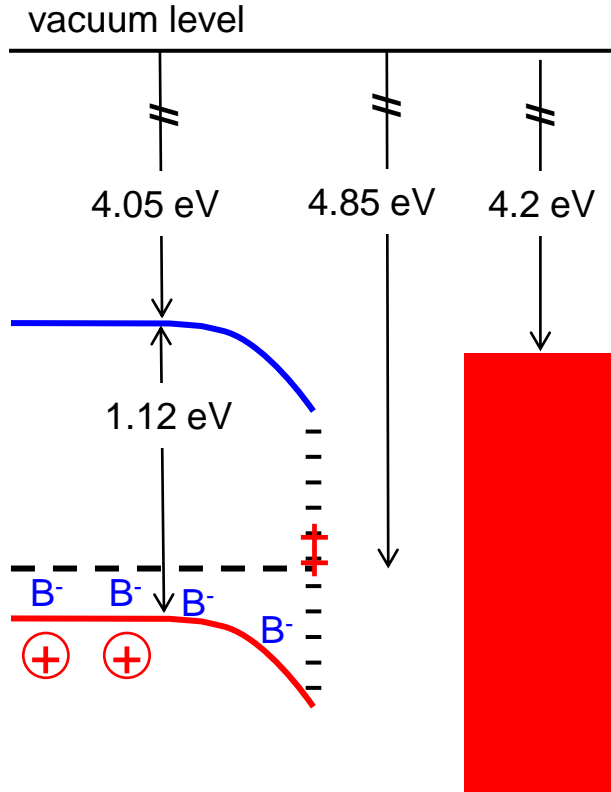
XPS can map filled states (here degenerate n-type)



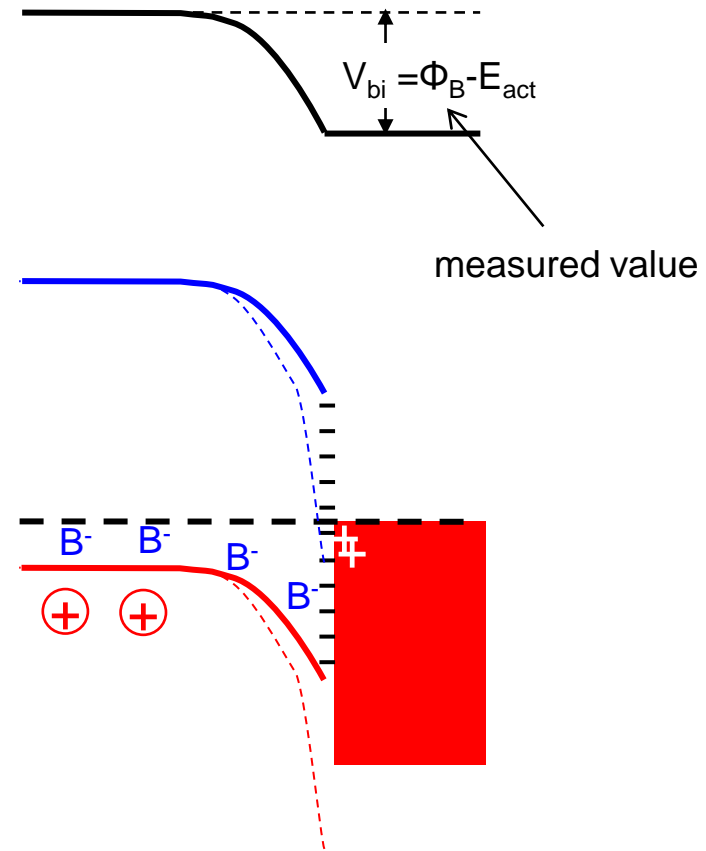
Wagner, PRL (1972)

p-type contact with Fermi-level pinning

Pinning at 4.8 eV

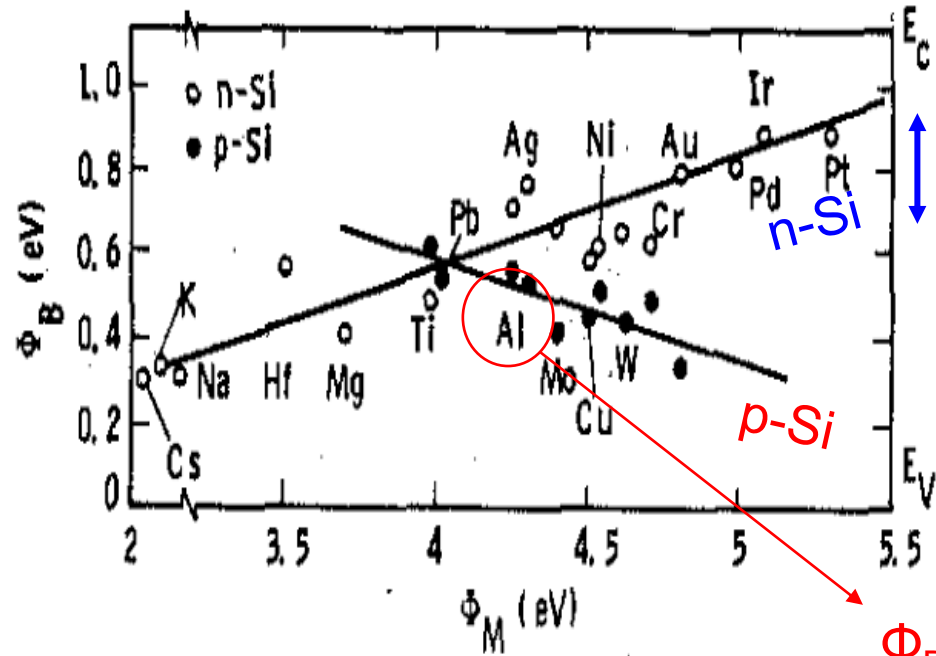


After contact: measured $\Phi_B = 0.5$ eV, different from theoretical alignment



see e.g. Schroeder, TED (1984)

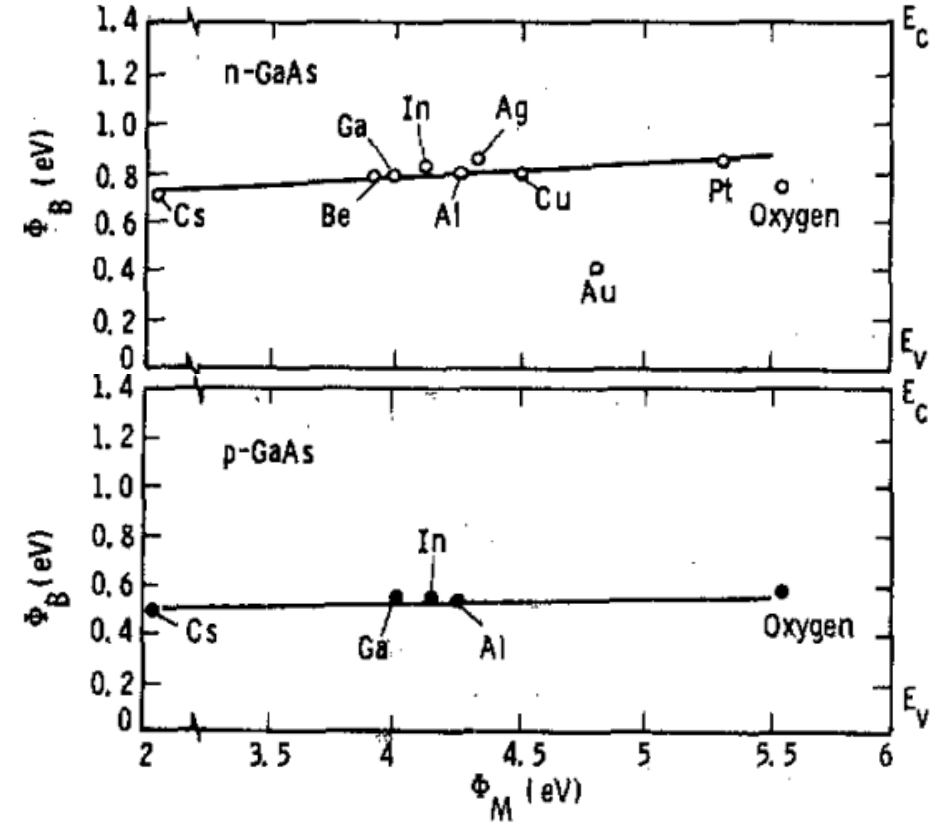
EPFL Barrier heights (experimental)



rule for common metals on n-Si
 $\Phi_B = 2/3$ of E_g

$\Phi_{B,Al} = 0.5$ eV
 (was 0.97 eV from work function)

Likewise: 1/3 rule for p-Si (referenced to VB edge)

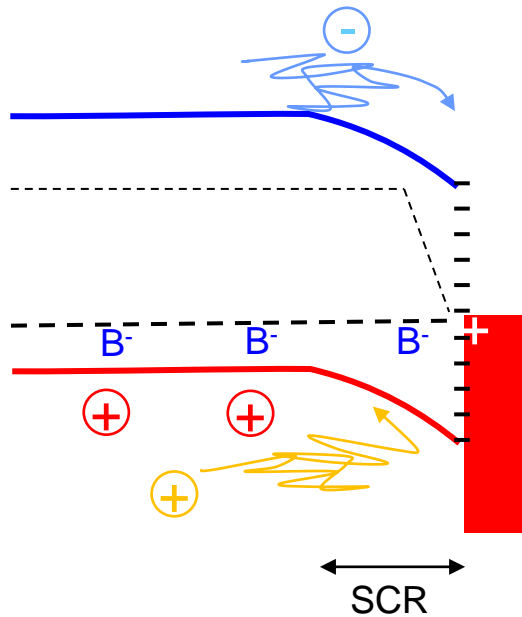


Pinning even worse for GaAs

Schroeder, TED (1984)

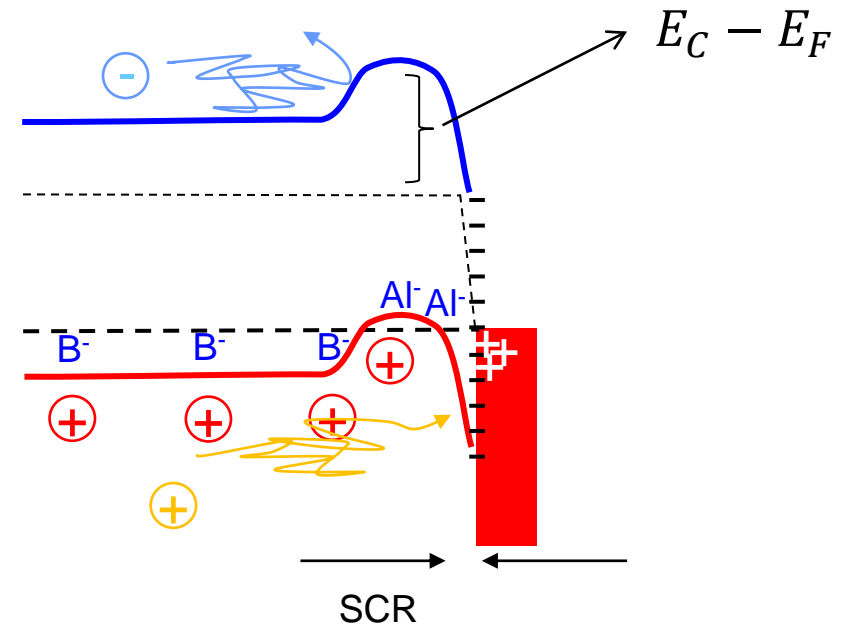
Minority recombination at metallic contacts

Remember contact from above,
add QFL splitting



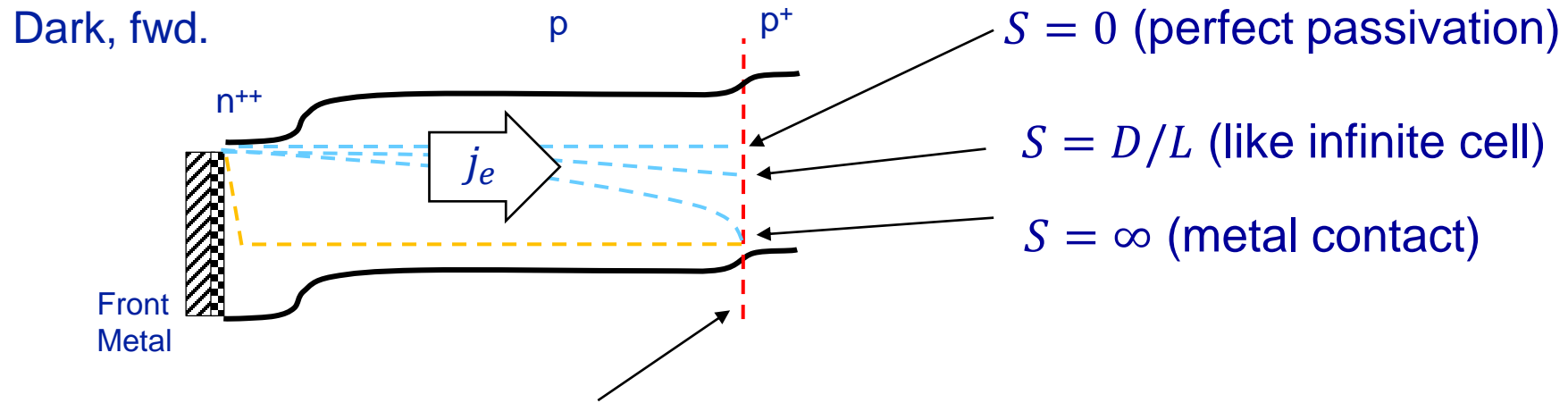
- barrier lowered by fwd bias, but still noticeable for holes (majority)
- electrons (minority) can recombine easily via interface states

Solution: introduce strongly doped region ("BSF")!



- holes tunnel narrow barrier more easily
- electron density is reduced

Surface recombination velocity



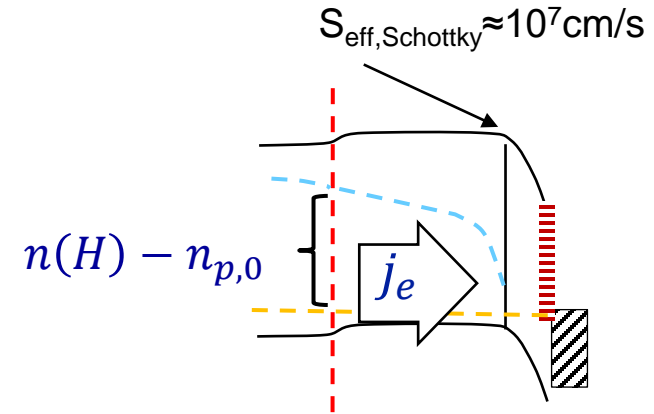
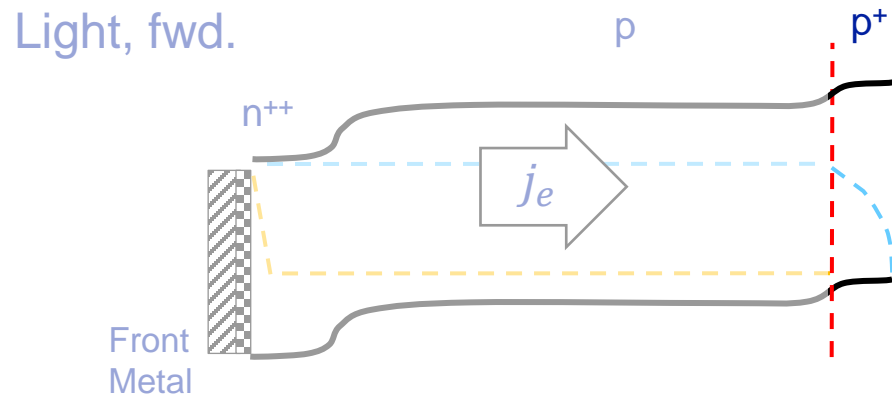
Ignore details of back contact, define eff. surface recombination velocity S_{eff} by: $j(H) = qS_{eff}(n(H) - n_{p,0})$

$$j_{0,B} = \underbrace{\frac{qDn_i^2}{L_n N_A}}_{j_{0,p}^{\infty}} \cdot \underbrace{\frac{S \cdot \cosh H/L_n + D/L \cdot \sinh H/L_n}{S \cdot \sinh H/L_n + D/L \cdot \cosh H/L_n}}_{G_F \text{ (geometry factor)}}$$

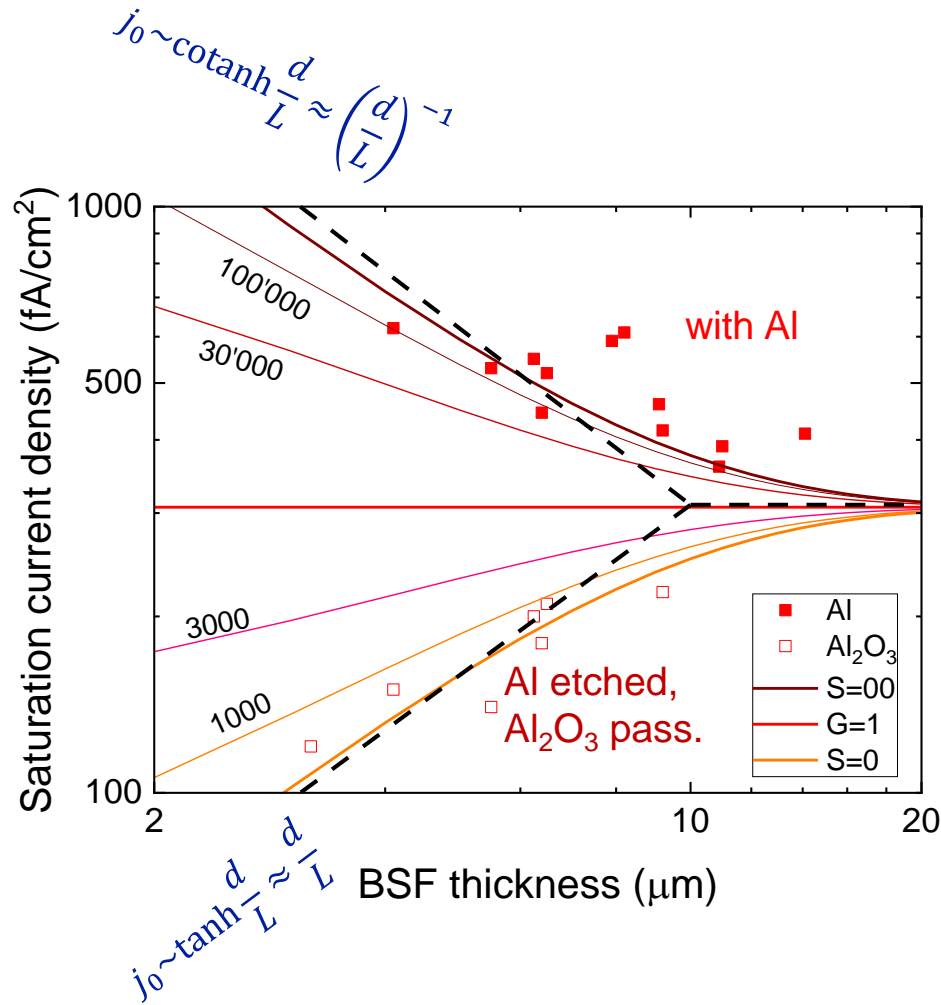
$S_{eff} \sim 300$ cm/s for 1 Ohm cm material

$S_{eff} \sim 500$ cm/s for 2 Ohm cm

EPFL Back-surface field



Use same formalism, apply to highly doped BSF region
(shorter lifetime, lower diffusivity, higher n_i)



Simple model for j_0 :
 approximate with $H = d_{BSF}$,
 $N_A = \text{const} = 3 \times 10^{18} / \text{cm}^3$ (Al saturation conc.)

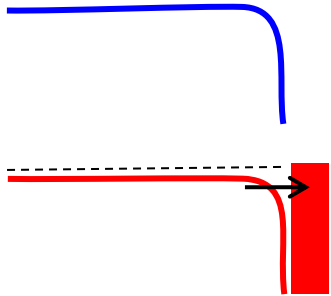
Two branches:

- $S \approx \infty$ (metal contact)
 => better for thick BSF
- $S \approx 0$ (dielectric w. field effect)
 => better for thin BSF

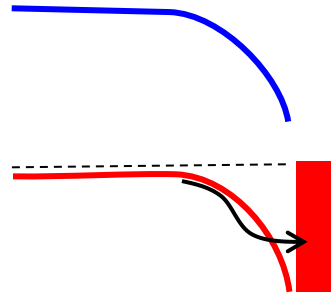
Data: Rüdiger, JAP (2011)

Contact resistance of a tunnelling contact

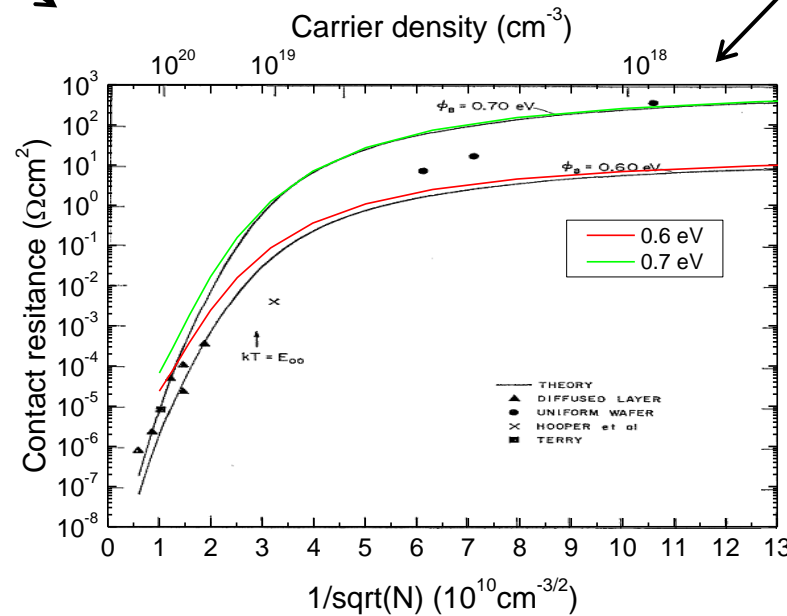
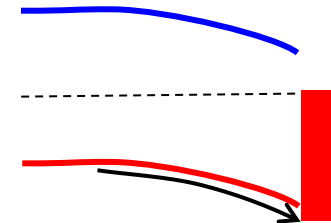
High doping: Field emission (tunnelling)



Intermediate: thermionic field emission (TFE)



Weak doping: thermionic emission (std. Schottky theory)



Padovani, SSE (1966)
 Yu, SSE (1970)
 review by: Schroeder, TED (1984)

Drawbacks of highly doped regions

- Band gap narrowing by merging with adjacent band edge
=> enhanced recombination statistics (scales with $\exp\left\{-\frac{E_g - \Delta E_g}{kT}\right\}$)
- Inactive doping atoms
clustering into dopant-defect pairs (esp. phosphorous)
=> yet more recombination
- Parasitic absorption
absorption by free carrier plasma

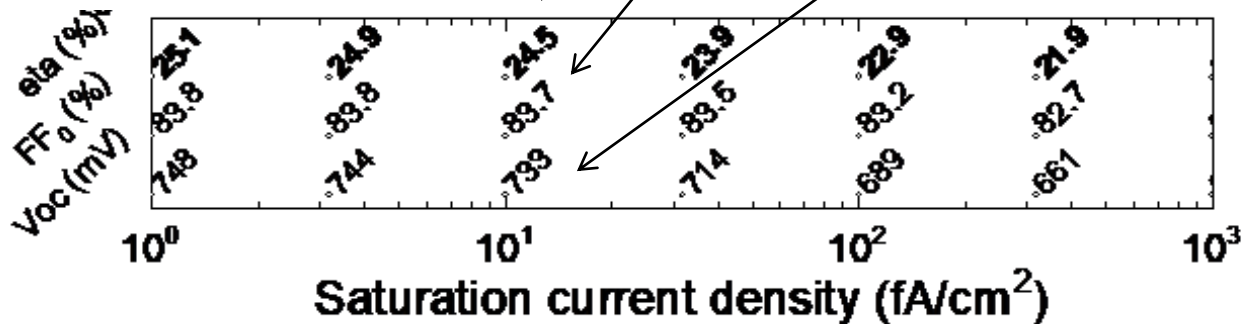
One solution: precise control of doping density and location,
=> complicated process

Efficiency for given j_0 and j_{sc}

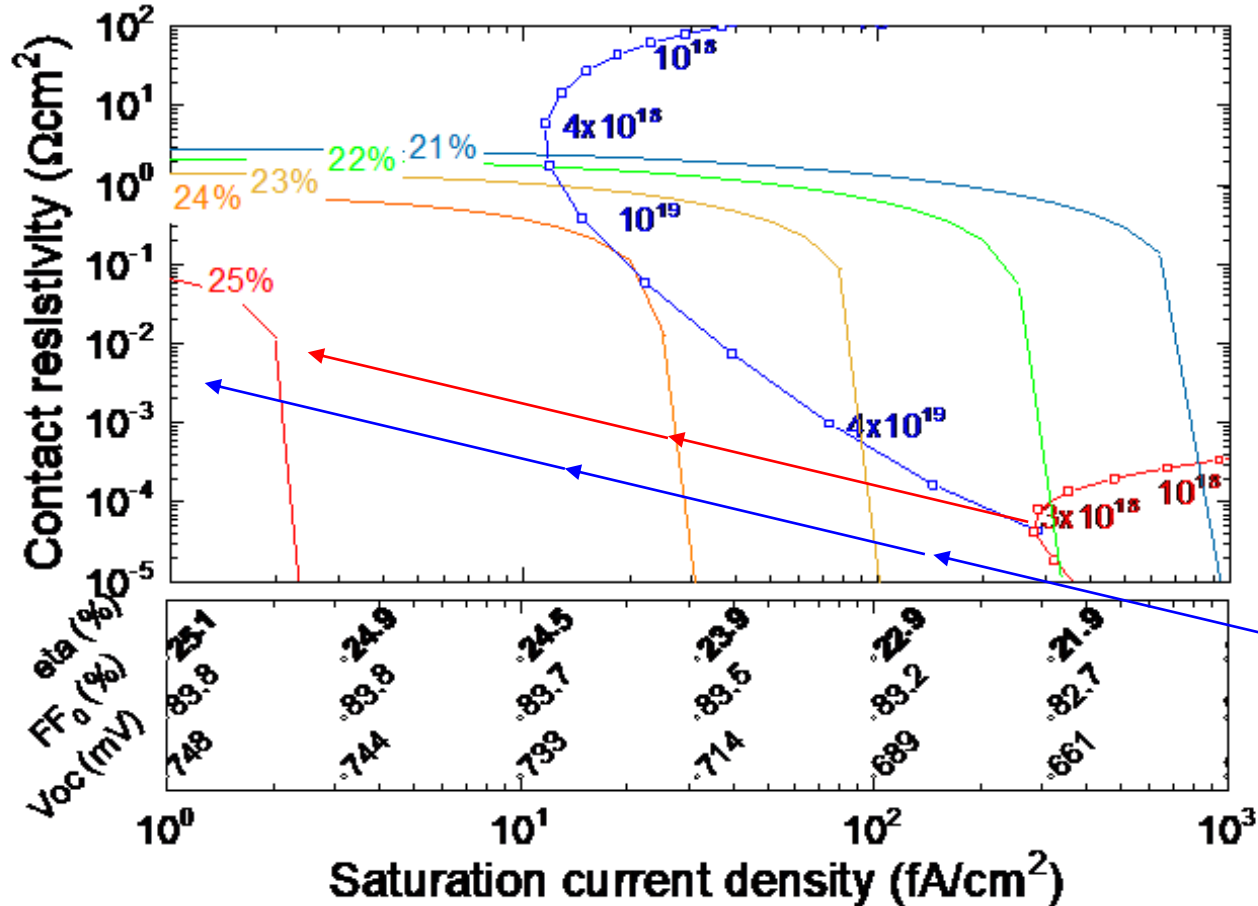
$$\eta_0 = V_{oc} \cdot FF_0 \cdot j_{sc}$$

$$FF_0 = \frac{\frac{qV_{oc}}{kT} - \ln\left(\frac{qV_{oc}}{kT} + 0.72\right)}{\frac{qV_{oc}}{kT} + 1}$$

$$V_{oc} = \frac{kT}{q} \ln \frac{j_{sc}}{j_0}, \text{ assume } j_{sc} \approx 40 \text{ mA cm}^{-2}$$



Combine ρ_c and j_0 for given j_{sc}



Efficiency contours with series resistance:

$$FF_S = FF_0 \left(1 - 1.1 \frac{R_S I_{sc}}{V_{oc}} \right) + \frac{\left(\frac{R_S I_{sc}}{V_{oc}} \right)^2}{5.4}$$

$$\eta = V_{oc} \cdot FF_S \cdot j_{sc}$$

BSF contact (10^{-12} A/cm^2 , $10^{-4} \Omega\text{cm}^2$) \Rightarrow 1% coverage
 Ag front contact: needs higher N_{surf} , 0.1% eff. coverage

Green, SSC (1982)
 Young, E. Proc. (2014)

Architectures with improved passivation

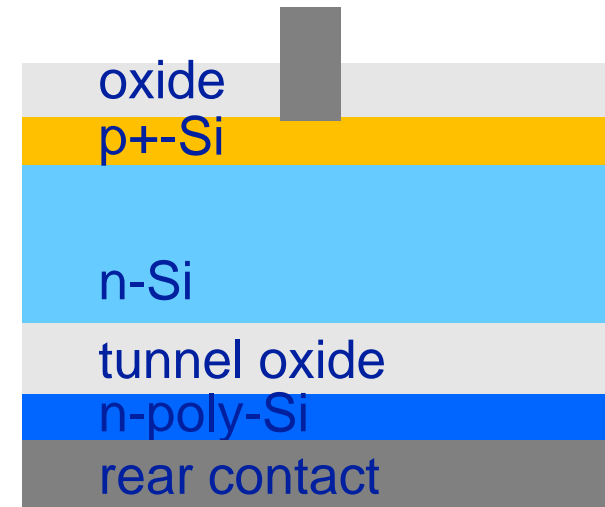
HIT (Hetero junction with Interlayer Technology): $V_{oc} = 740-750$ mV



Taguchi, JPV (2014)

full area concept
chemical passivation by a-Si:H
contacts & field effect by doped a-Si:H
no direct contact btw. c-Si and metal!

TOPCon (Tunnel Oxide Passivating Contacts): $V_{oc} = 715$ mV



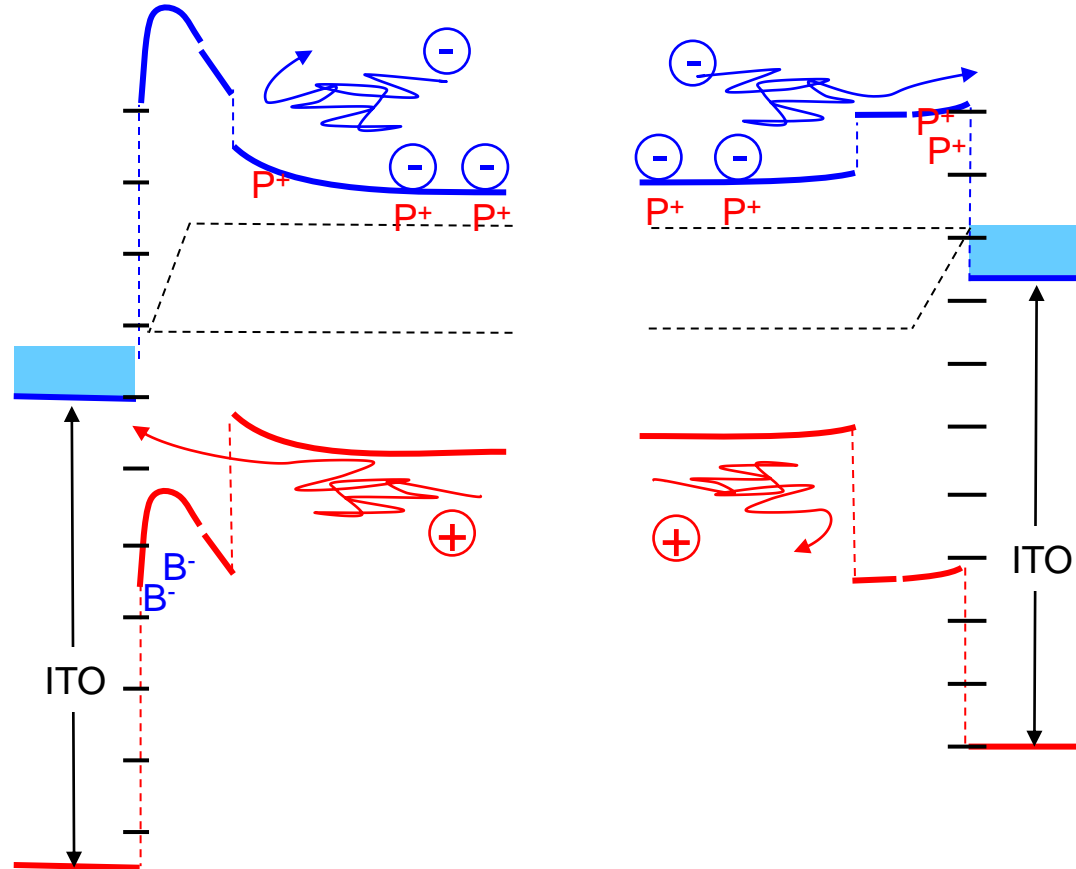
Feldmann, SEM (2014)

full area back contact
chemical passivation by tunnel oxide
(probably used by SunPower as well)

c.f. Gan, Proc. IEEE PVSC (1990)

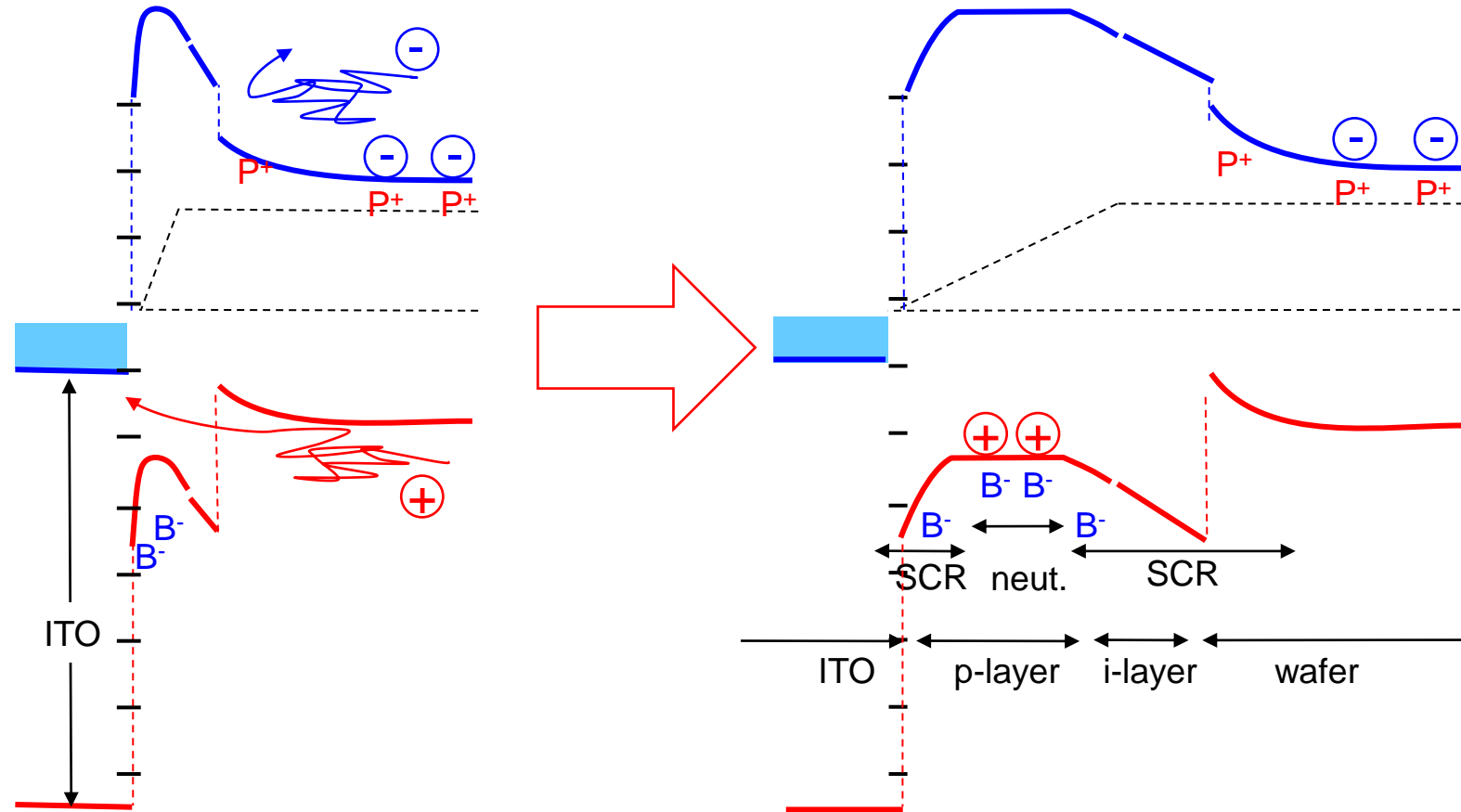
a-Si:H passivating contacts

passivate interface states at c-Si surface with a-Si:H
 $V_{BO} > C_{BO}$: efficient hole repulsion (minority carriers)
 p-layer pulls wafer surface into inversion



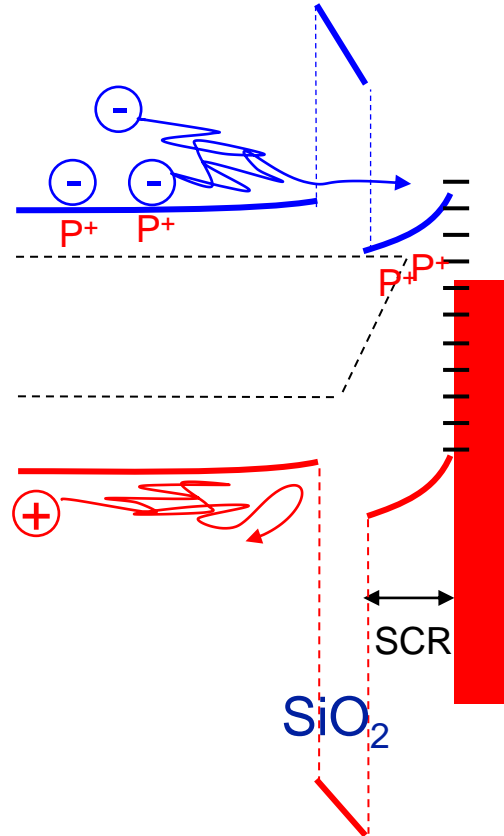
a-Si:H passivating contacts

p-layer pulls wafer surface into inversion => p-n transition in defect-free wafer



EPFL SiO_2 passivating contacts

SiO_2 : $V_{BO} > C_{BO} \Rightarrow$ slight preference for electron tunnelling, but works fine for p-contact with polycrystalline p-layer



BUT: needs ultra-thin tunnelling oxide (ca. 1 to 1.5 nm)

Gan, IEEE PVSC (1990)
Feldmann, SEM (2014)
Preibst, En. Proc. (2015)

- Apparent stagnation of efficiency (25% btw. 1999 and 2014)
- Continuous development of technology behind the scene
- Boost beyond 25% since 2014 along different lines
- Latest record: 26.7% by Kaneka !