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Modern PV-Technologies
3.3: Junctions

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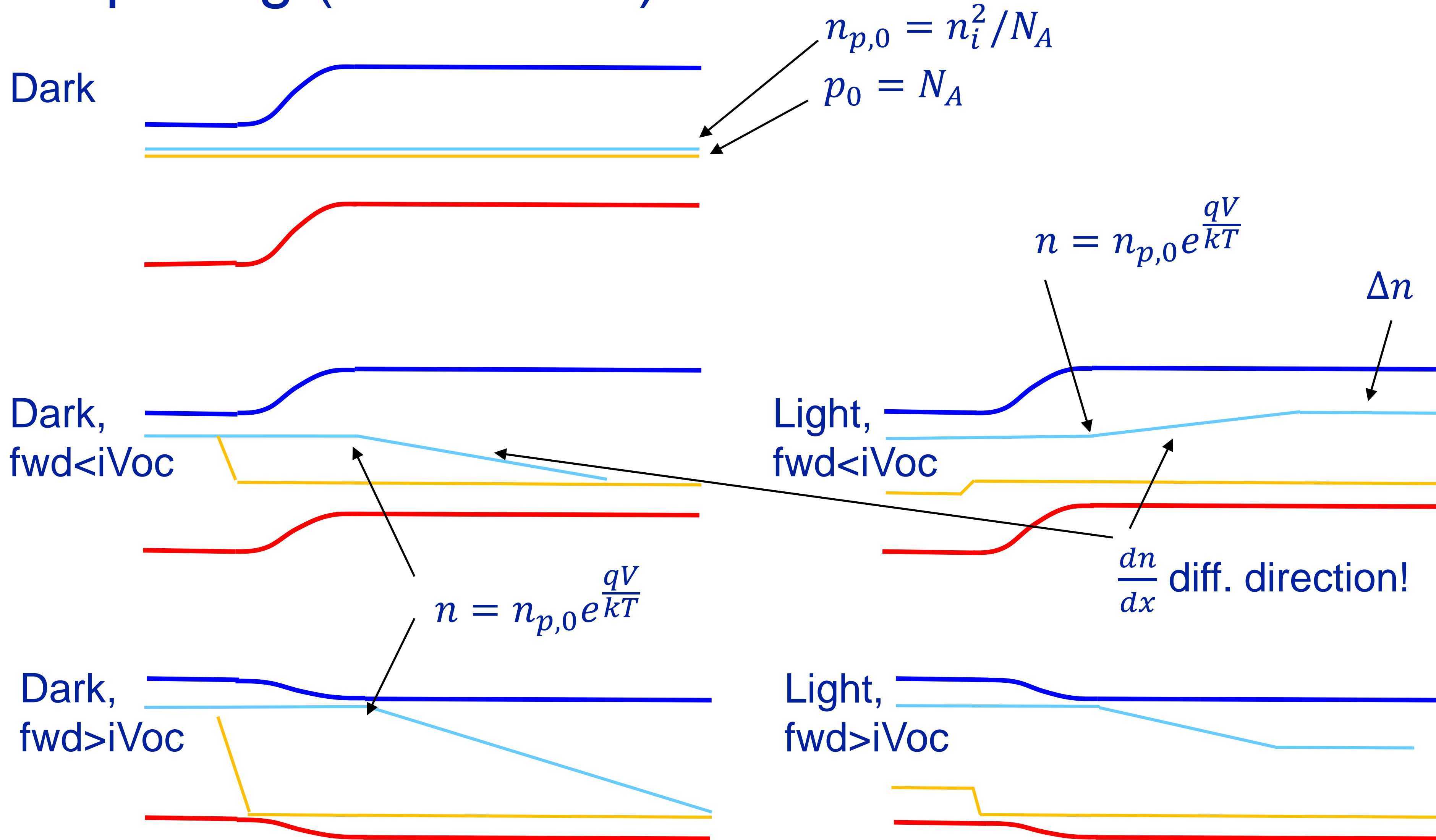
QFL splitting (infinite cell)



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Current-voltage characteristic

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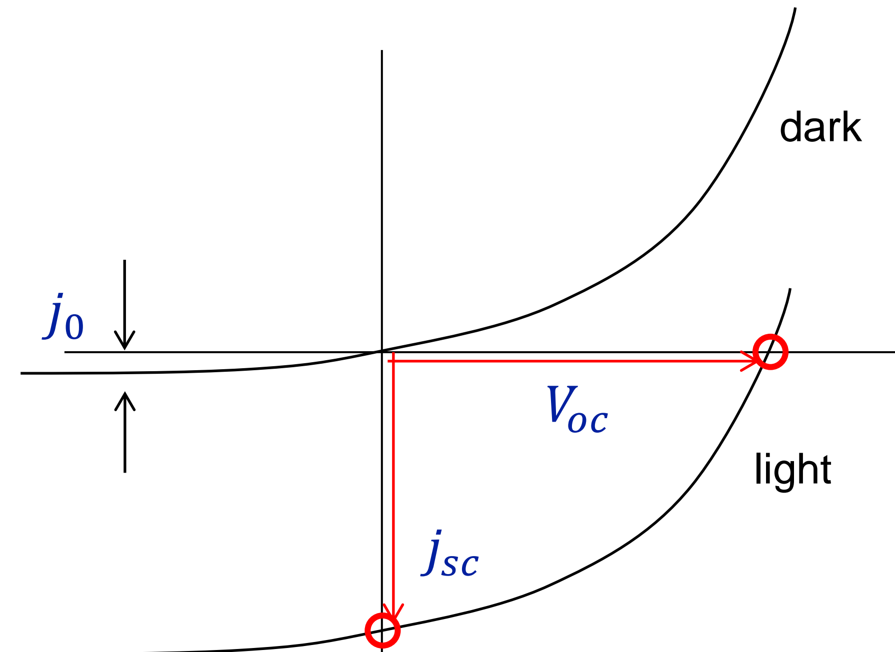
Simple form of j-V characteristics

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

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 insolation; slight control via absorption enhancement
j_0 should be as small as possible

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Saturation current

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

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

for p-type material with highly diffused junction (standard cell configuration):

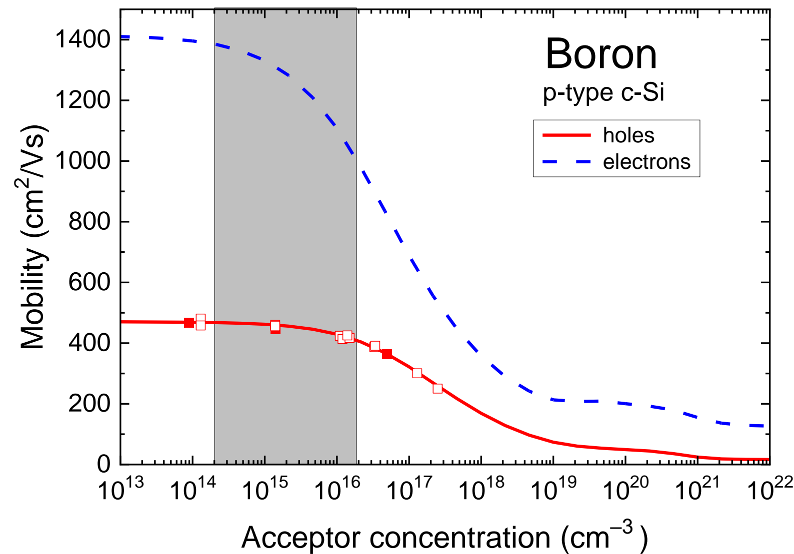
$$j_0 \approx \frac{qD_n n_i^2}{L_n N_A} = \frac{qn_i^2}{N_A} \cdot \sqrt{\frac{D_n}{\tau_n}}$$

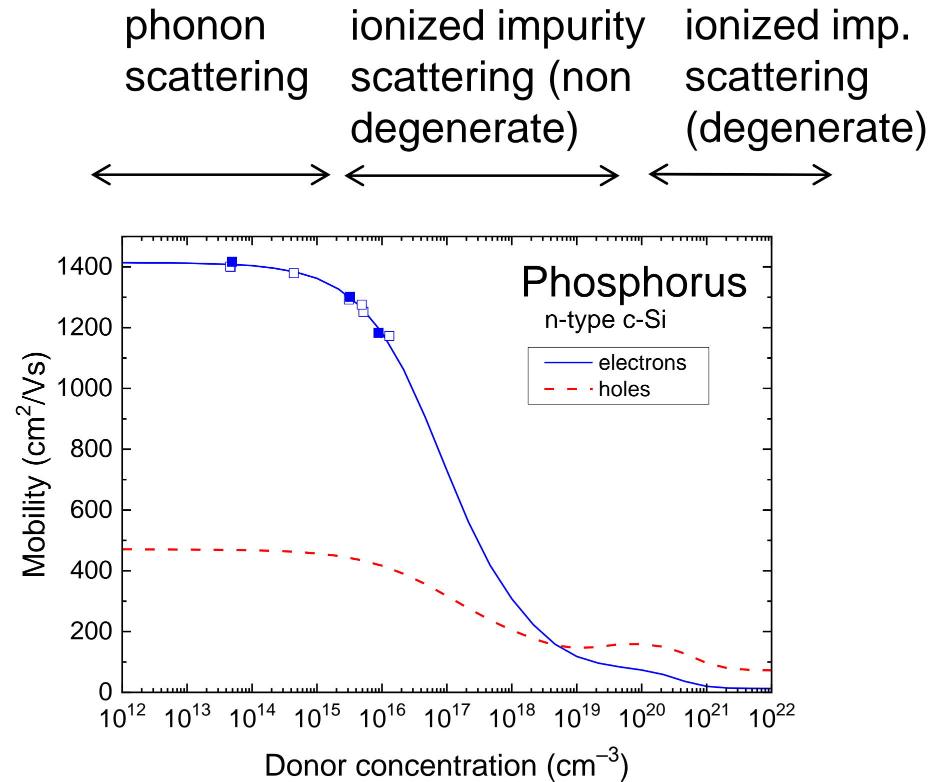
Knobs to turn for small j_0:

increase N_A (but…)

Diffusion coefficient

Einstein relation: $D = \mu \cdot \frac{kT}{q}$



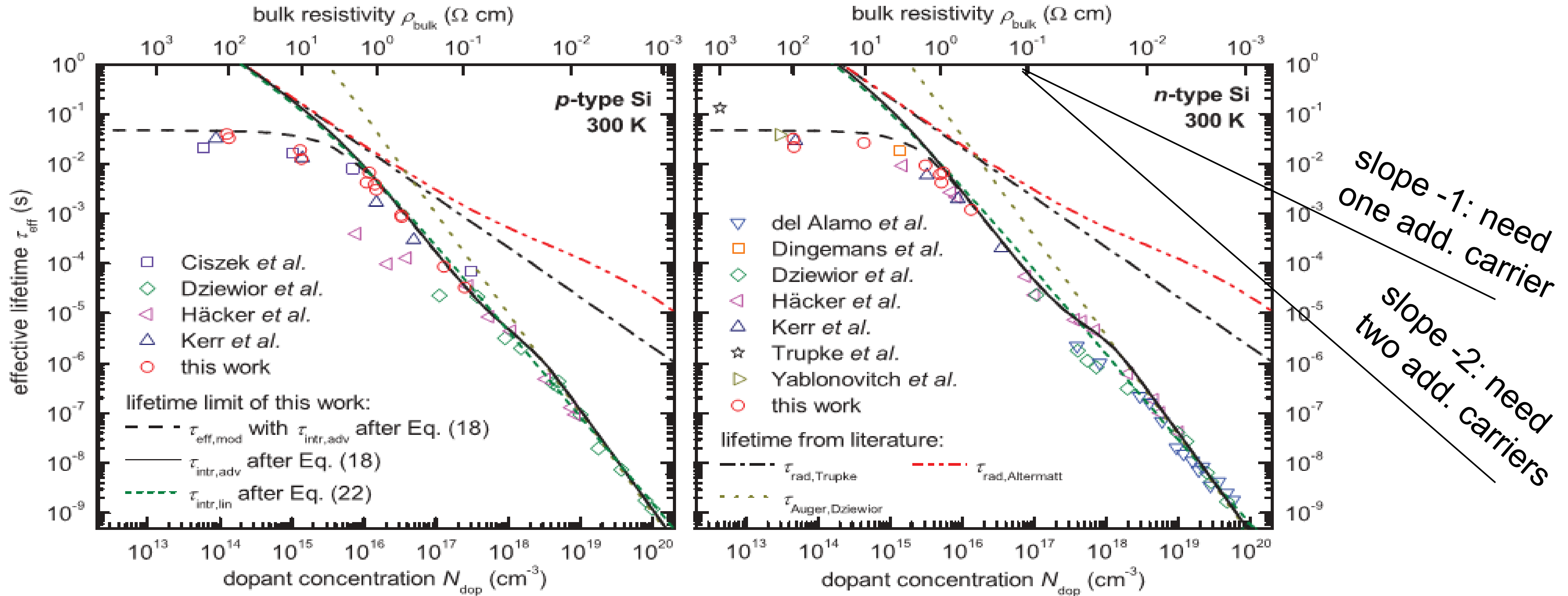


High doping will decrease D (majority and minority, but slightly differently!)

Majority mobility: Thurber, JECS (1980, 1981)
Minority mobility: Swirhun, TED (1986)

Minority carrier lifetime

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

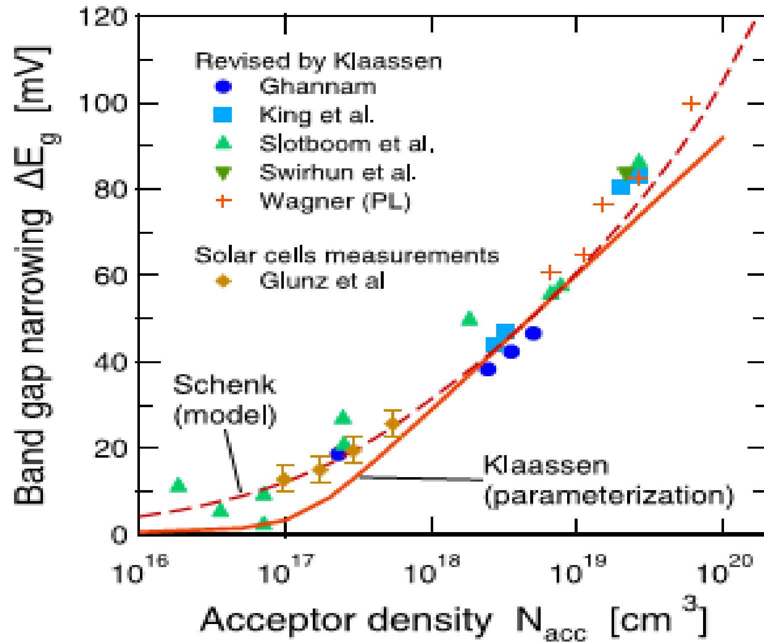


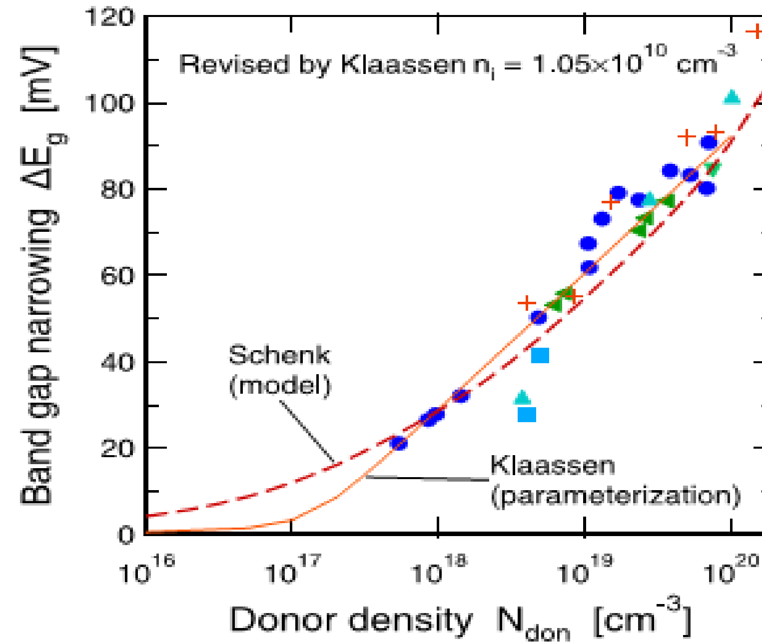
High doping will also decrease τ!

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

Intrinsic carrier density

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



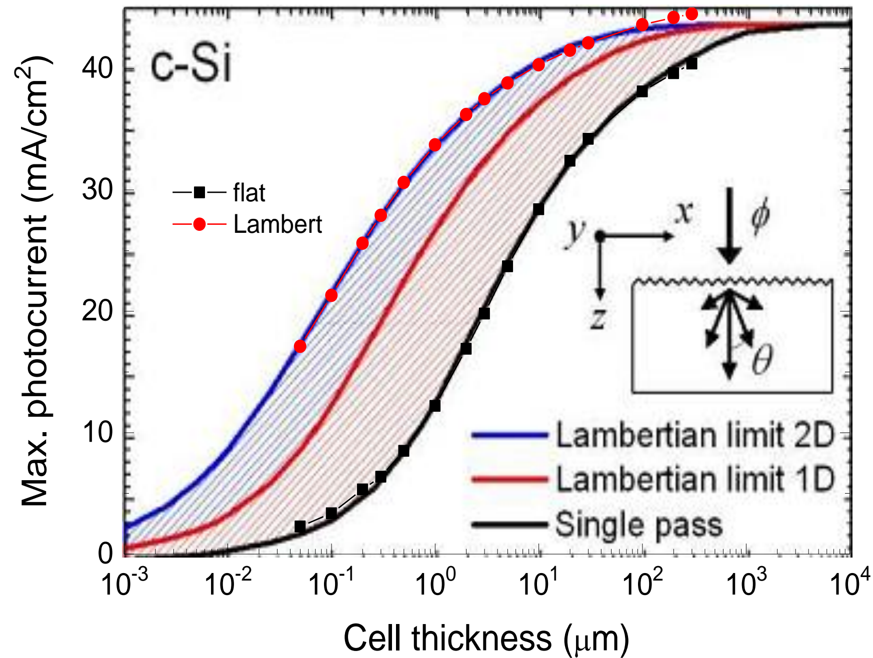


Remember: $n_i^2 \sim e^{-\frac{E_g}{kT}} = e^{-\frac{E_{g,0}-\Delta E_g}{kT}}$

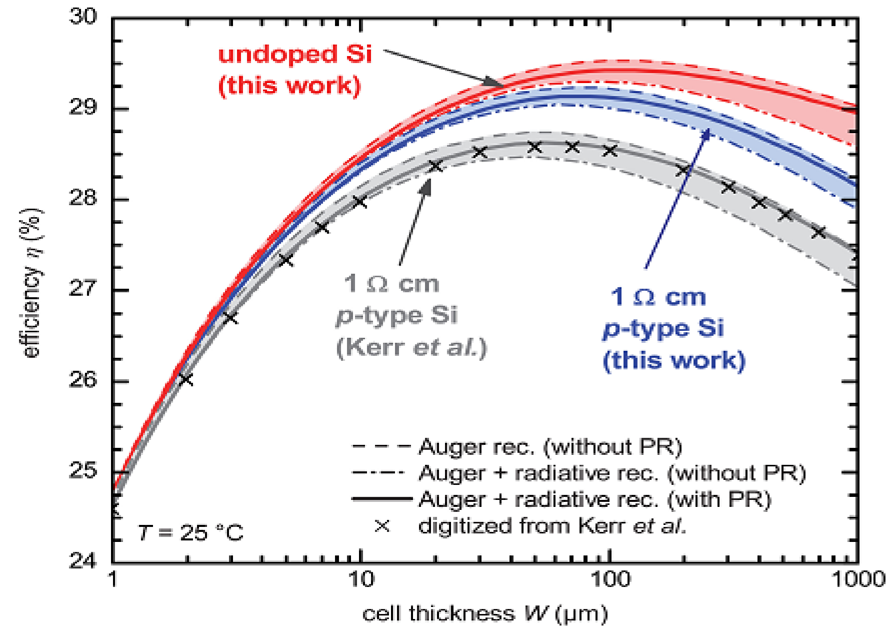
On BGN models: e.g. Altermatt, J. Comput. Electron. (2011)

Limiting efficiency

Photocurrent



Efficiency



Conclusion:

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

Then: η_{max}= 29.4-29.5%

On limiting jsc: e.g. Bozzola, EU-PVSEC (2011)
On limiting efficiency: Richter, JPV (2013),
Schäfer SEM (2018)
Niewelt, SEM (2022)

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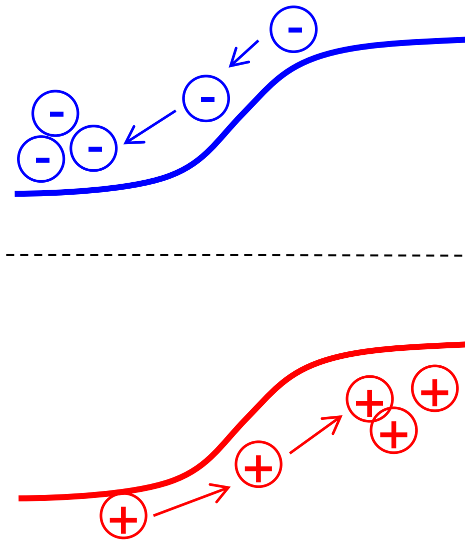
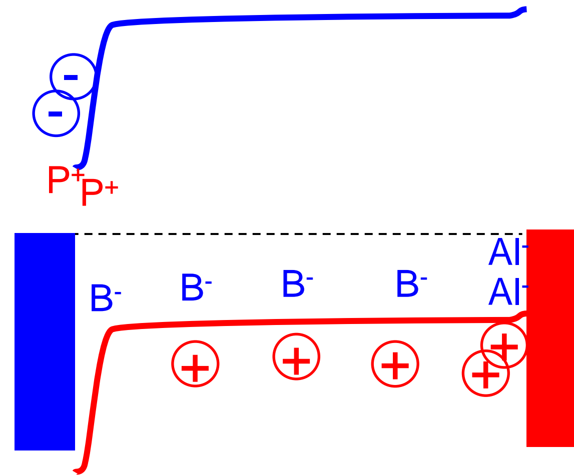
How to get current out of the cell

What you often see…

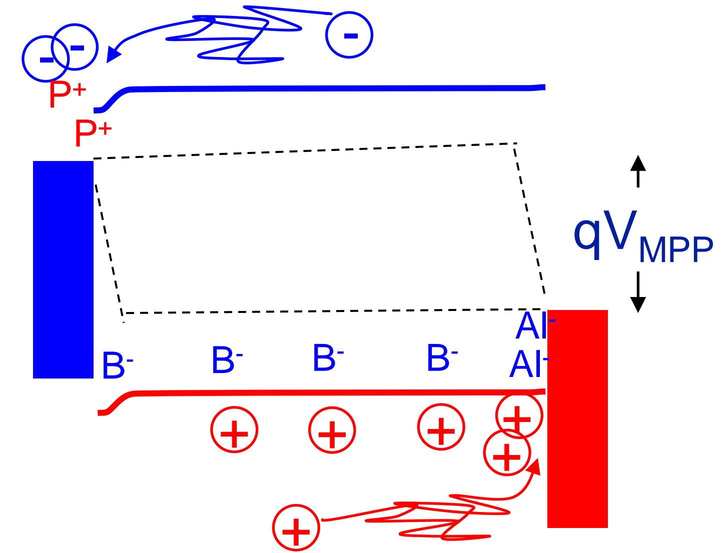


how it actually looks in dark



the field extends over <1µm, most of the 200 µm wafer is neutral

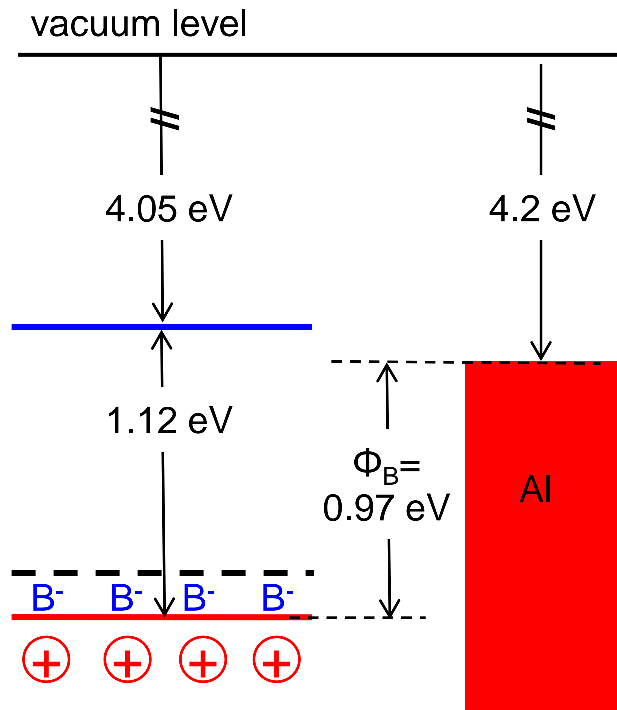
…and how it really works



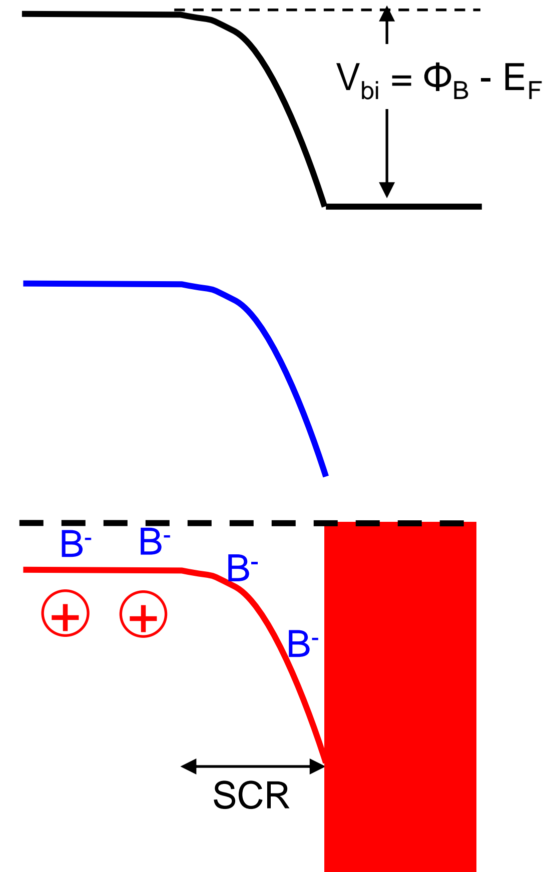
charges diffuse randomly until they "see" a contact region (may be doped, but need not!)

Working principle of metallic rear contact

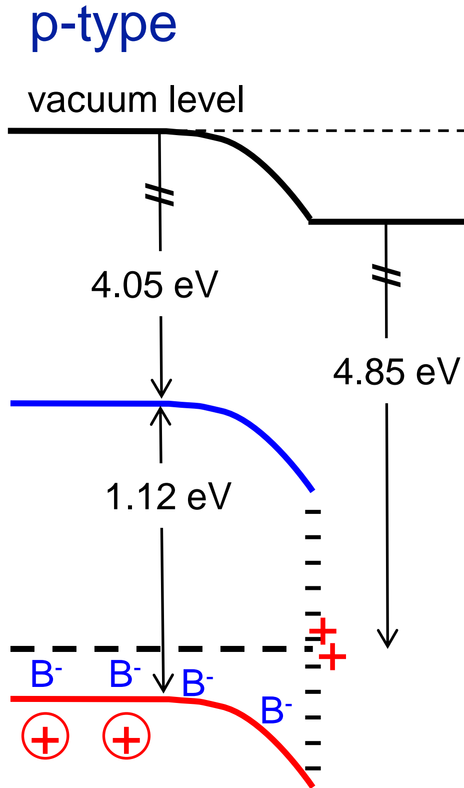
Before contact

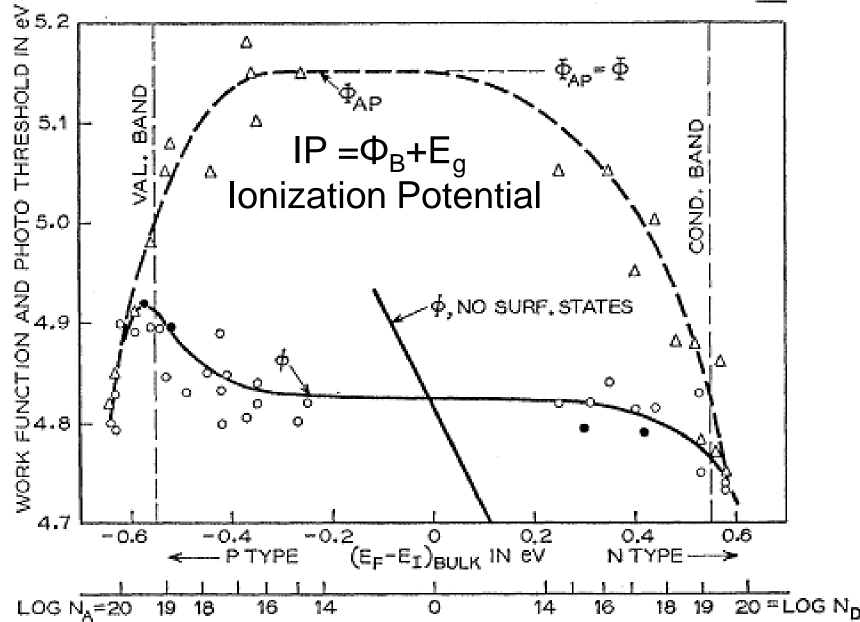


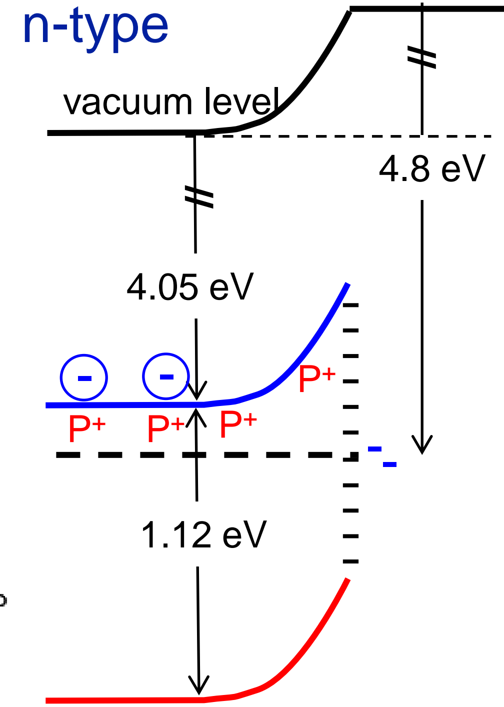
Ideal Schottky contact



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)

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Surface state density

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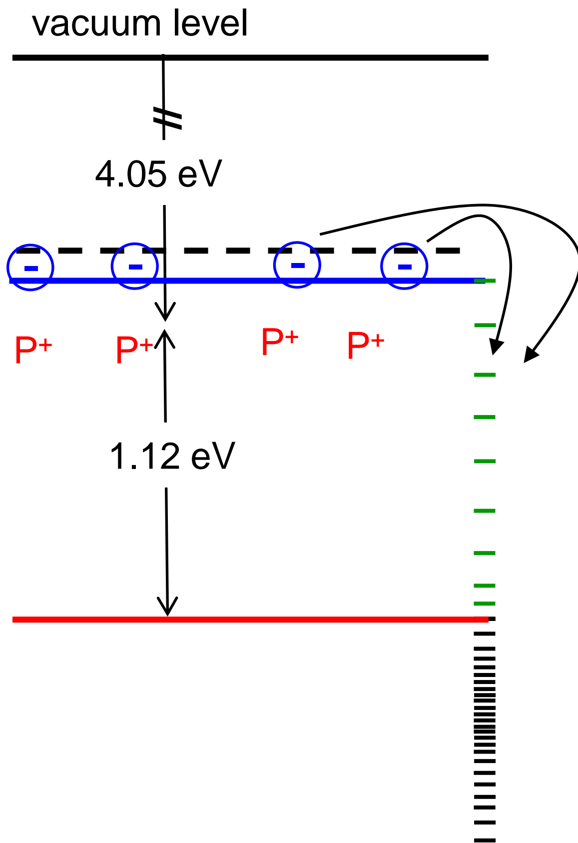
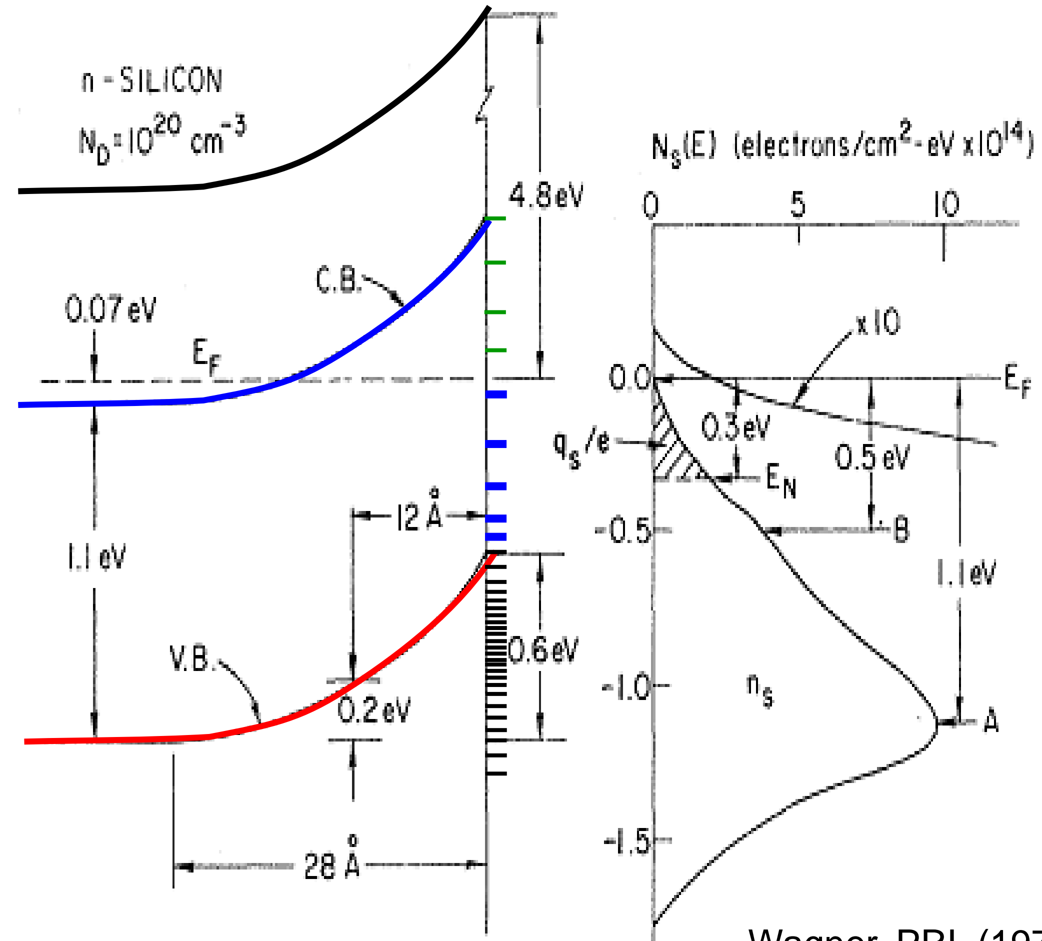
XPS can map filled states (here degenerate n-type)





Wagner, PRL (1972)

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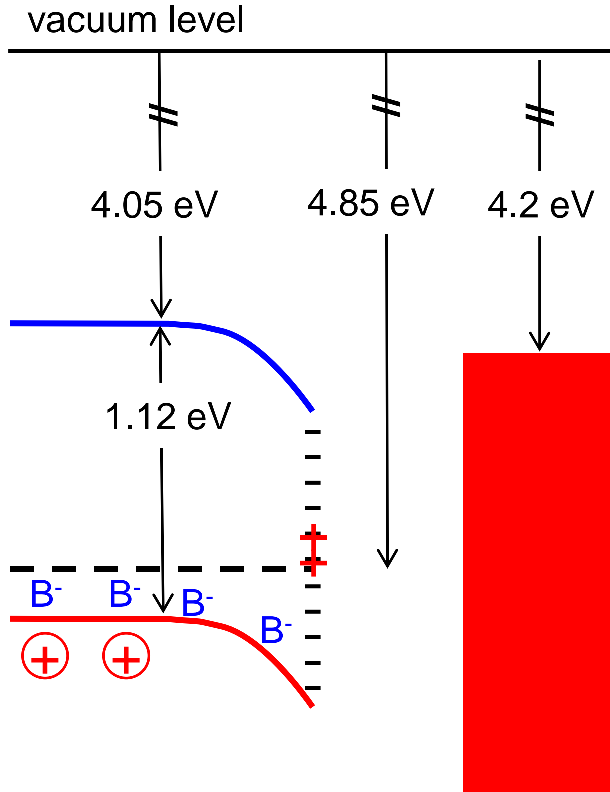
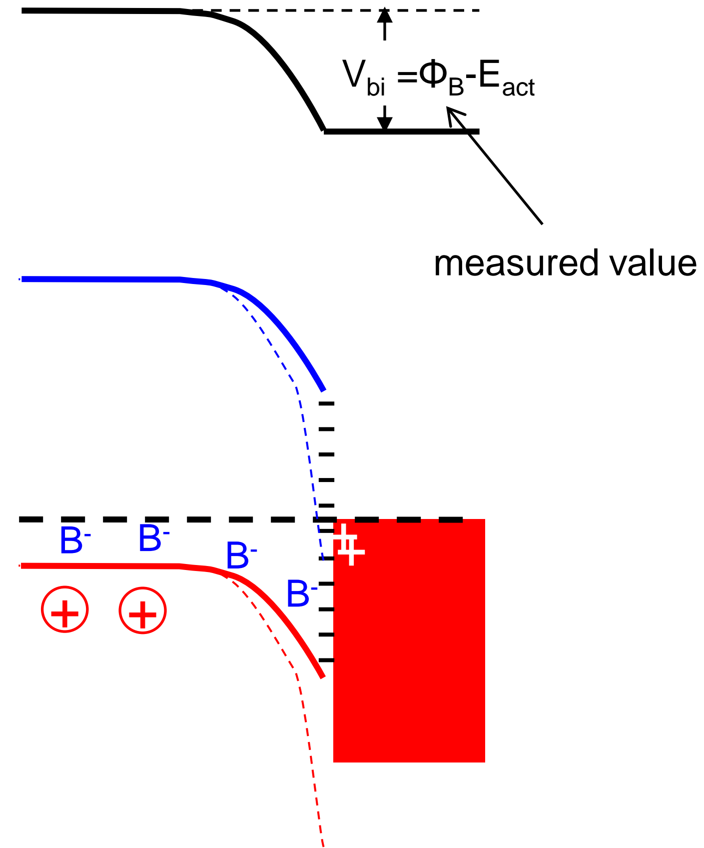
p-type contact with Fermi-level pinning

Pinning at 4.8 eV

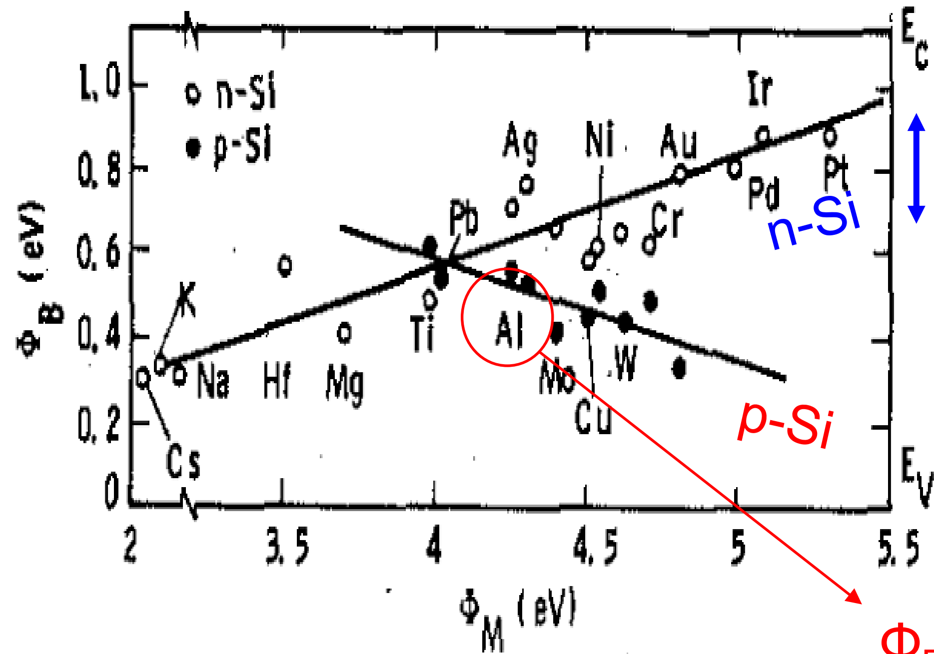


After contact: measured Φ_B =0.5 eV, different from theoretical alignment



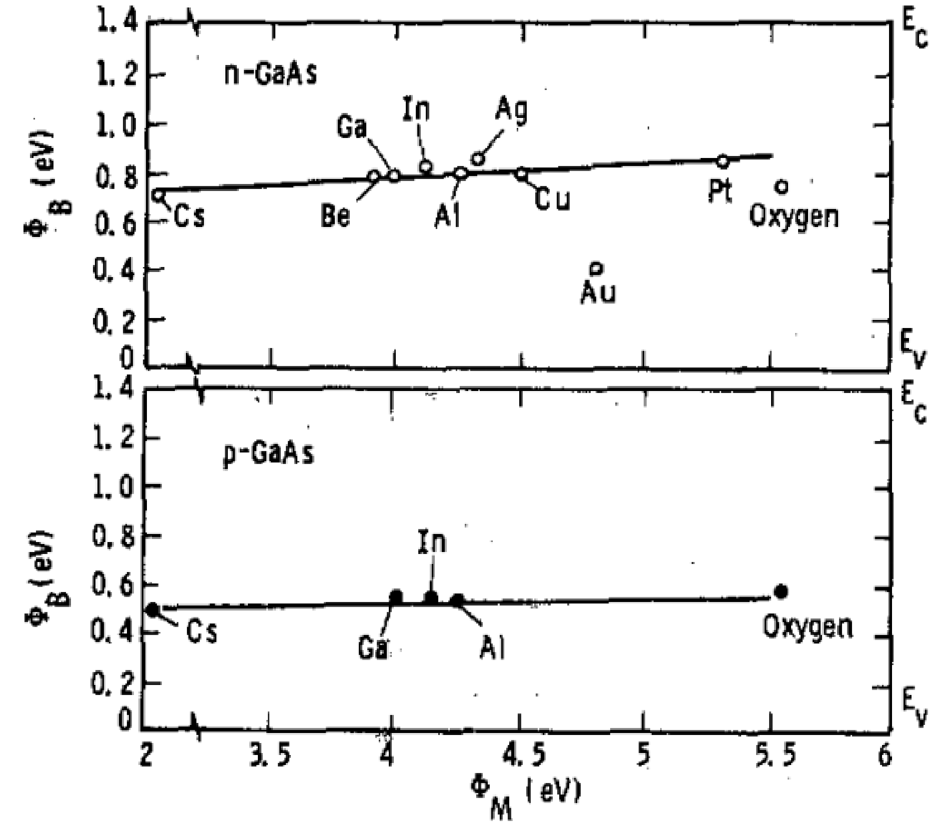
see e.g. Schroeder, TED (1984)

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

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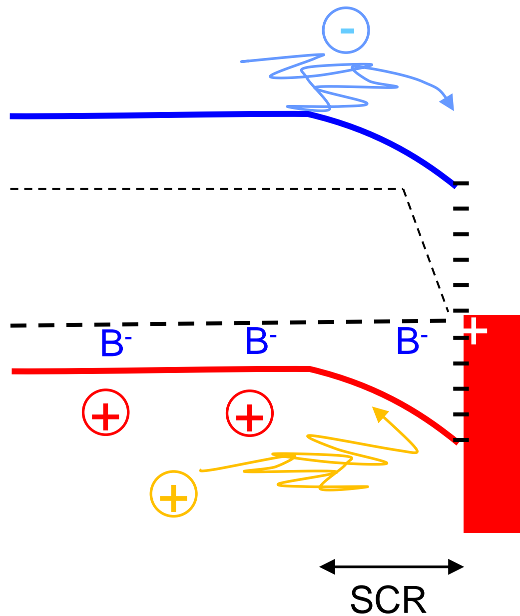
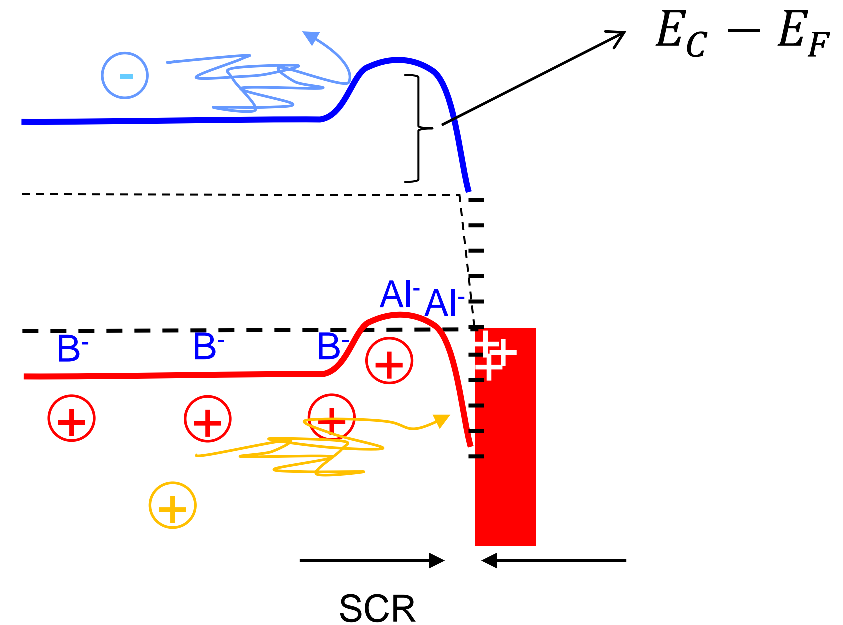
Remember contact from above, add QFL splitting



- 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

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Surface recombination velocity

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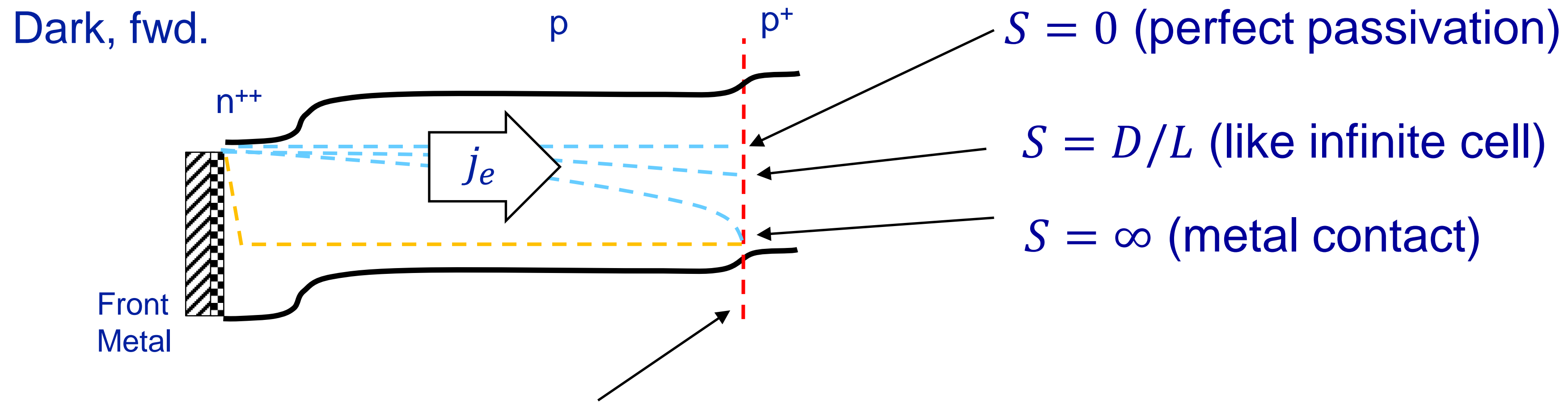

Ignore details of back contact, define
eff. surface recombination velocity S_{eff} by: $j(H) = qS_{eff}(n(H) - n_{p,0})$

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

S_{eff} ~ 500 cm/s for 1 Ohm cm material
S_{eff} ~ 300 cm/s for 2 Ohm cm

Back-surface field

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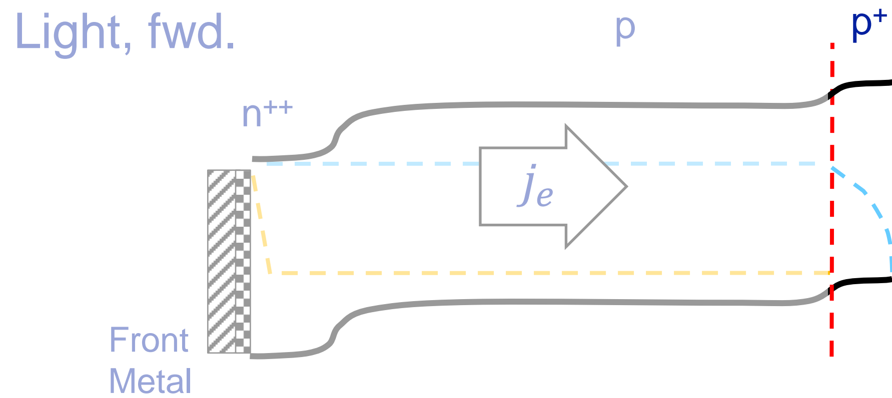

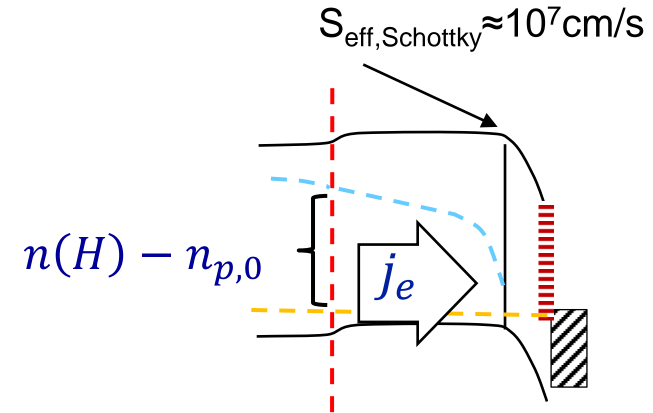

Use same formalism, apply to highly doped BSF region
(shorter lifetime, lower diffusivity, higher n_i)

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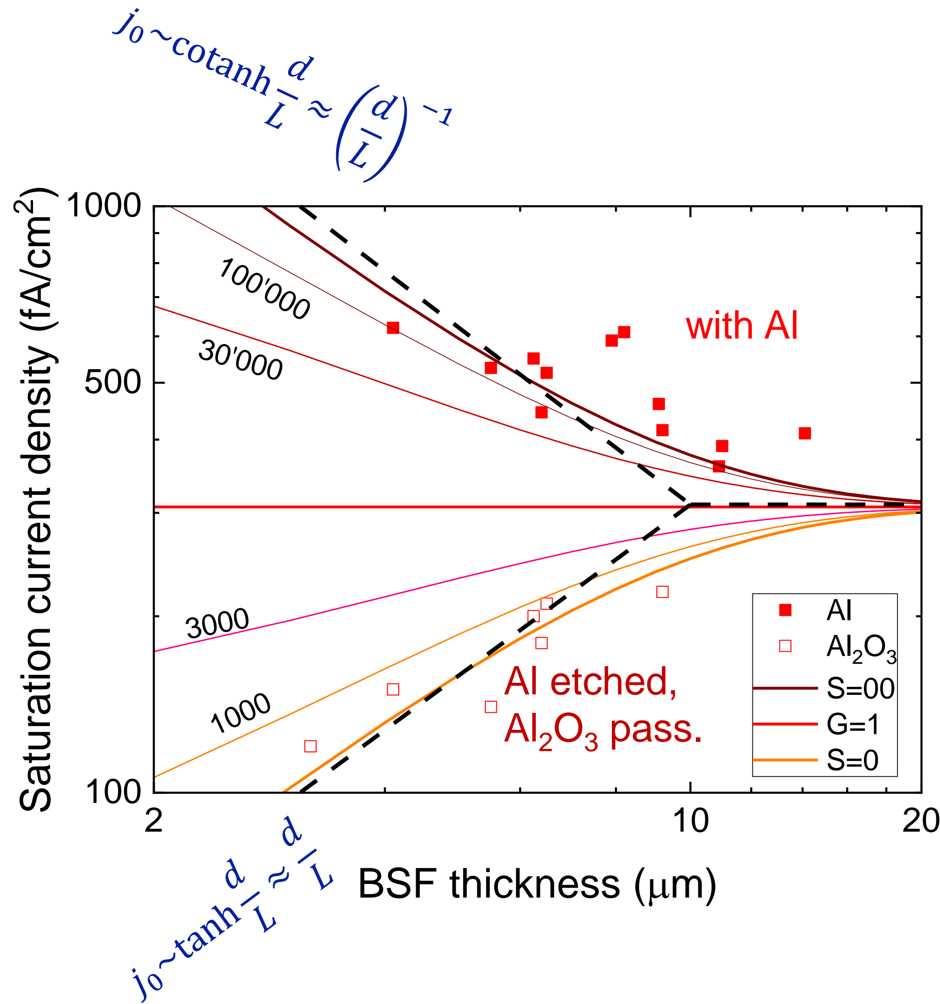
Al-BSF



Simple model for j_0:
approximate with H = d_{BSF},
N_A = const = $3 \times 10^{18}/cm^3$

Two branches:

- S ≈ ∞ (metal contact)
  => thicker BSF, better

- S ≈ 0 (dielectric w. field effect)
  => thinner BSF better

Data: Rüdiger, JAP (2011)

Contact resistance of a tunnelling contact

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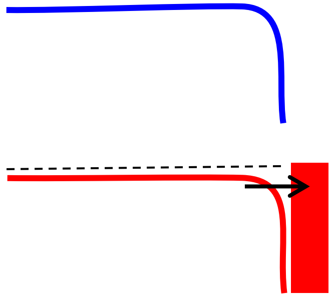
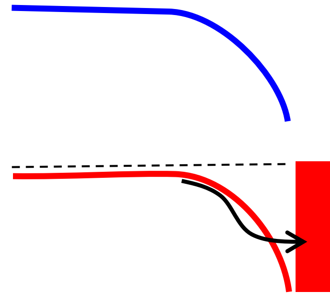
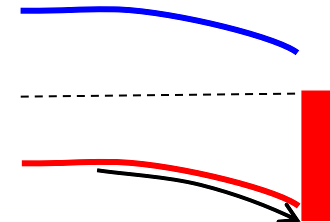
High doping: Field emission (tunnelling)

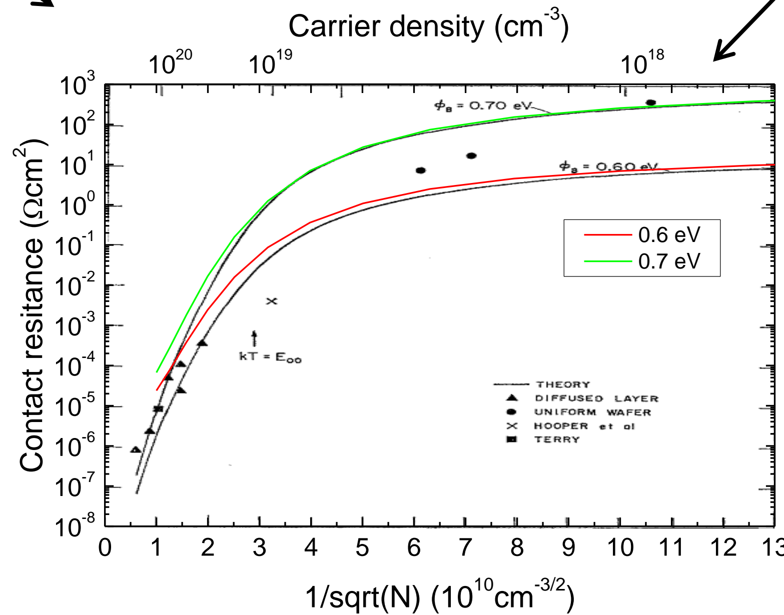


Intermediate: thermionic field emission (TFE)



Weak doping: thermionic emission (std. Schottky theory)





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

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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}

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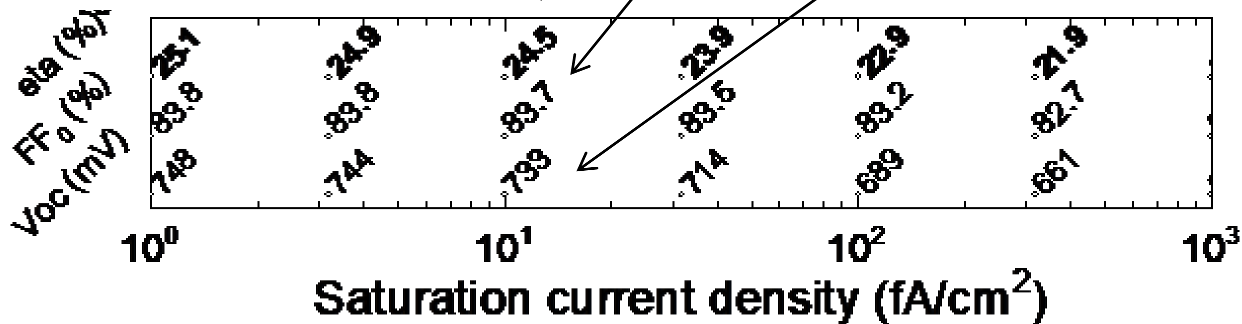
$$\eta_0 = V_{oc} \cdot FF_0 \cdot j_{sc}$$

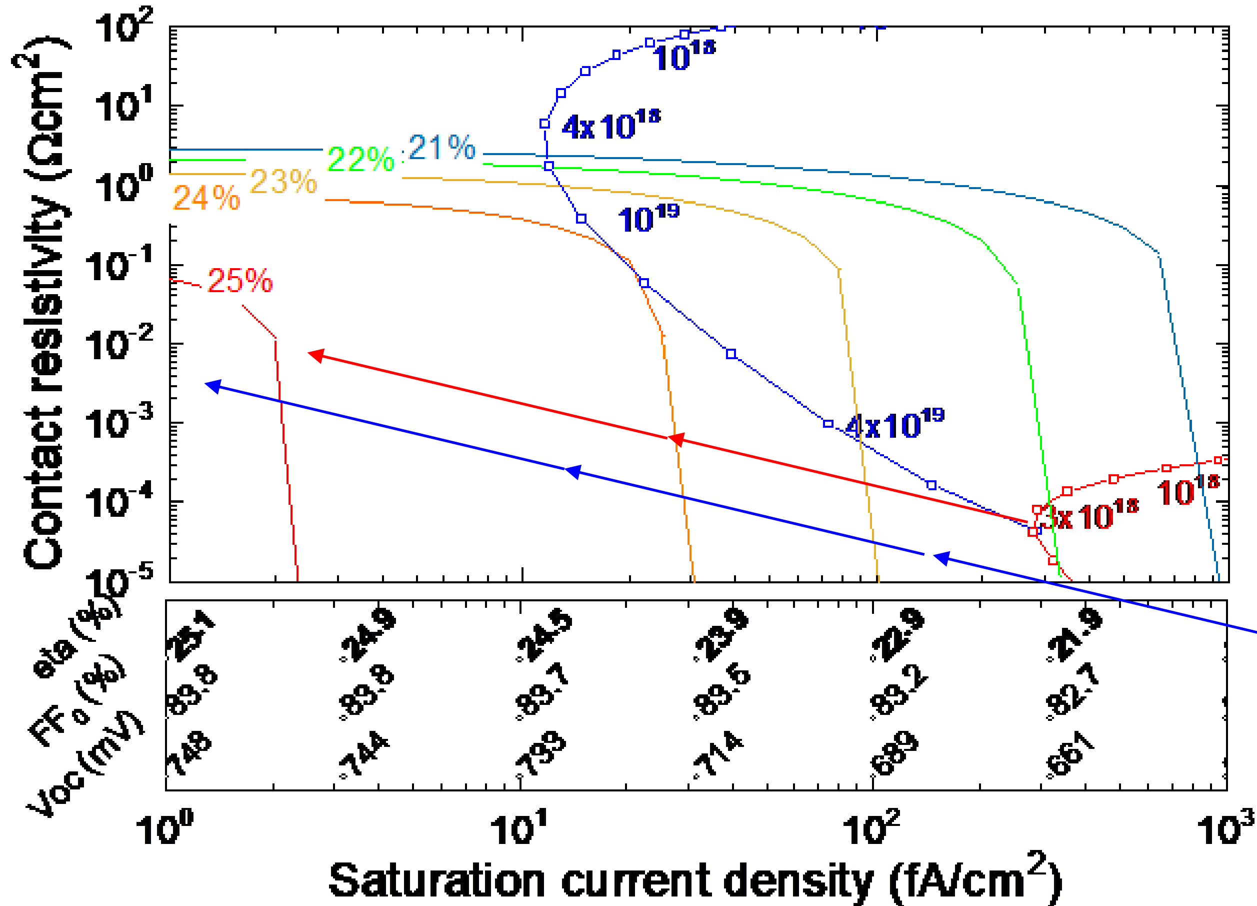
$$FF_0 = \frac{\frac{qV_{oc}}{kT} - \ln\left(\frac{qV_{oc}}{kT} + 0.72\right)}{\frac{qV_{oc}}{kT} + 1}$$

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



Approximation formulae: Green, SSC (1982)

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/cm², 10^{-4} Ωcm²) => 1% coverage
Ag front contact: needs higher N_{surf}, 0.1% eff. coverage

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

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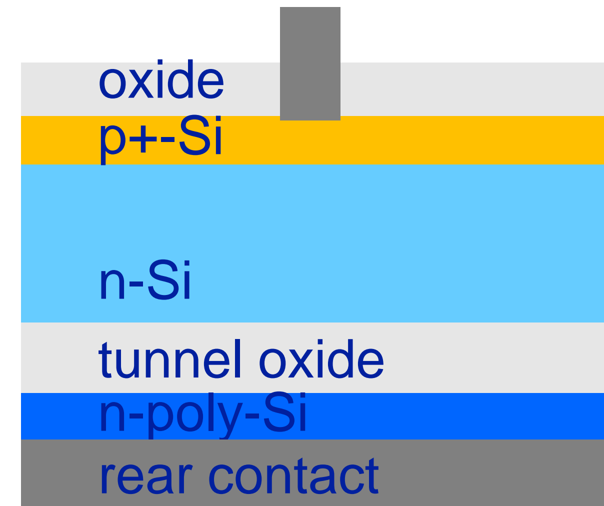
Modern passivation schemes

HIT (Hetero junction with Interlayer Technology): Voc = 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): Voc = 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

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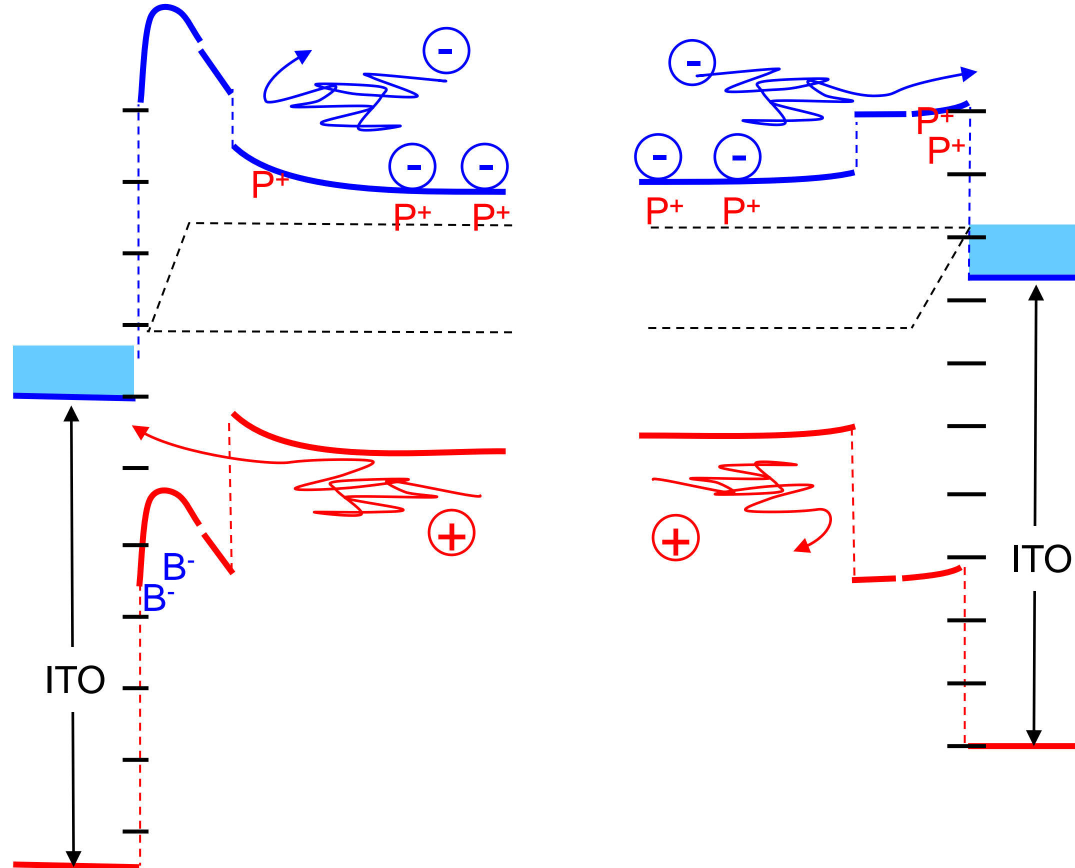
passivate interface states at c-Si surface with a-Si:H
VBO > CBO: efficient hole repulsion (minority carriers)
p-layer pulls wafer surface into inversion



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a-Si:H passivating contacts

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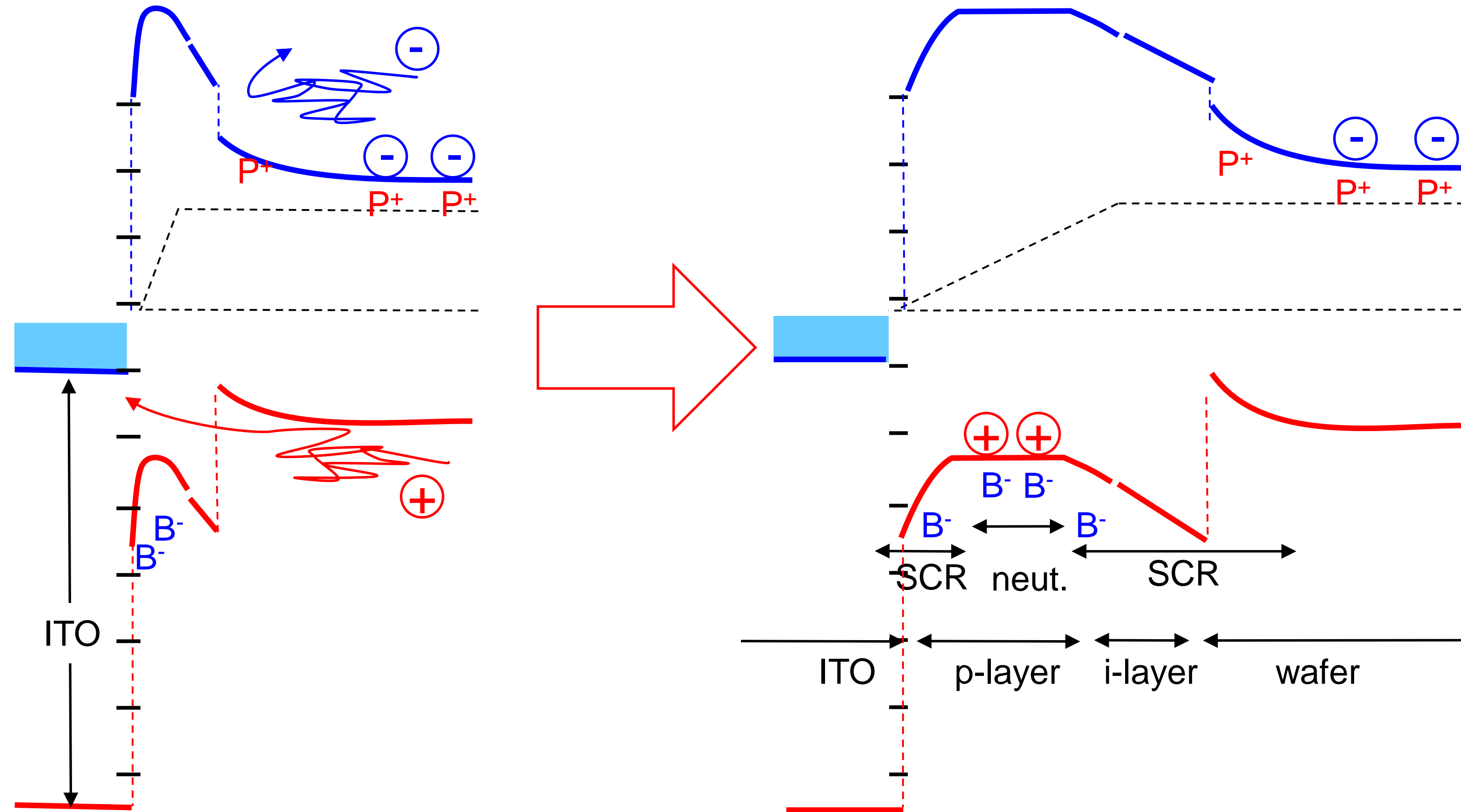
p-layer pulls wafer surface into inversion => p-n transition in defect-free wafer



SiO_2 passivating contacts

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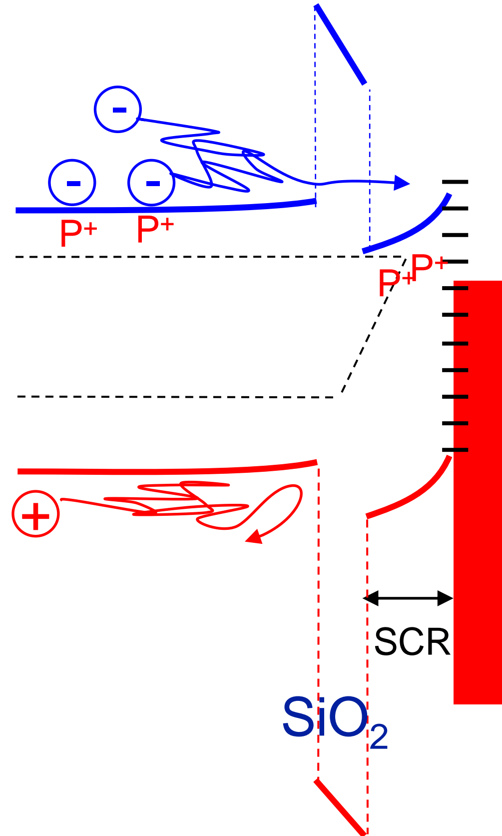
SiO_2: VBO > CBO => slight preference for electron tunnelling, but works fine for p-contact with polycrystalline p-layer



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

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

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Summary

- 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 !