Modern PV-Technologies
3.3: Junctions

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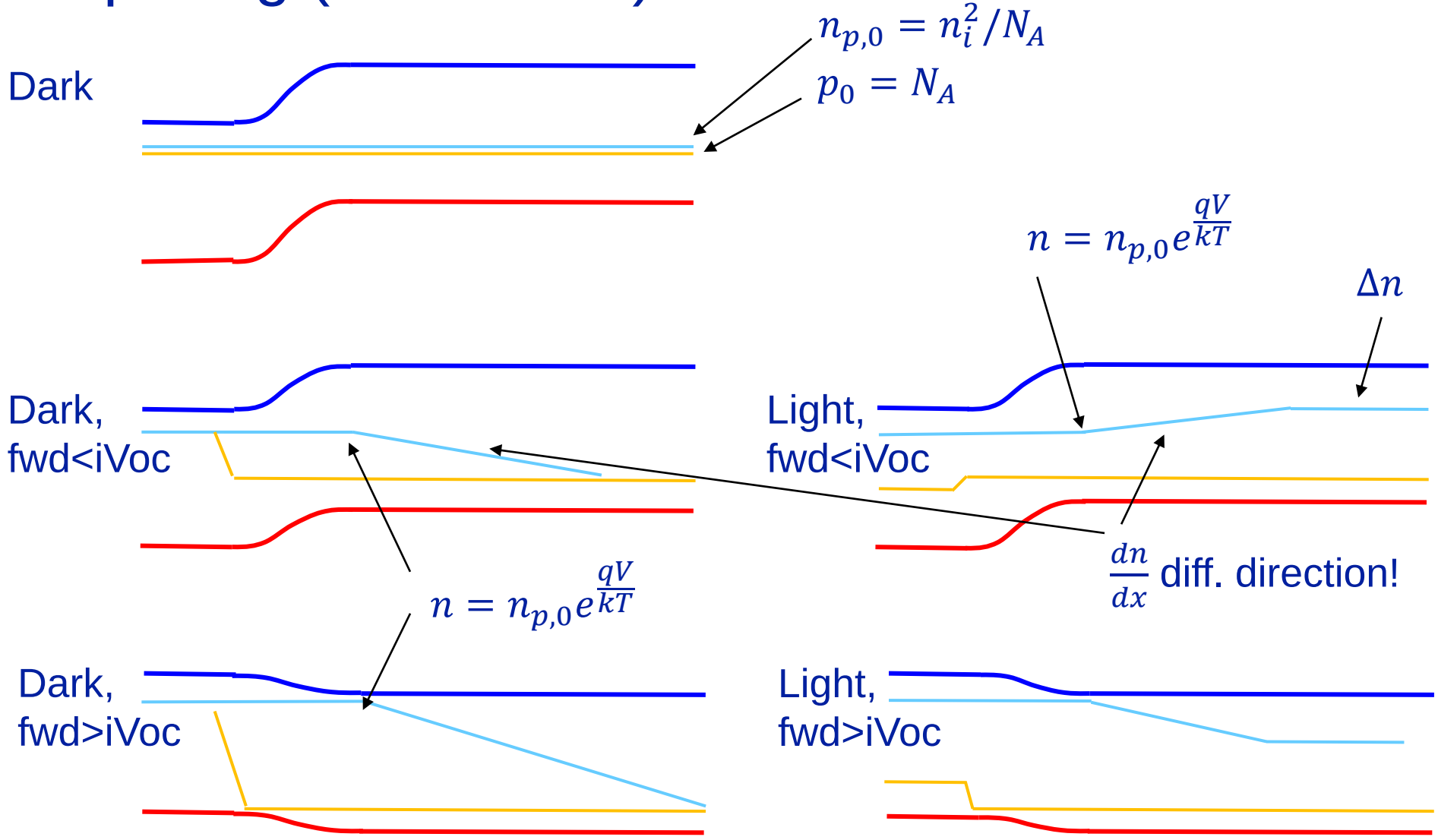
QFL splitting (infinite cell)



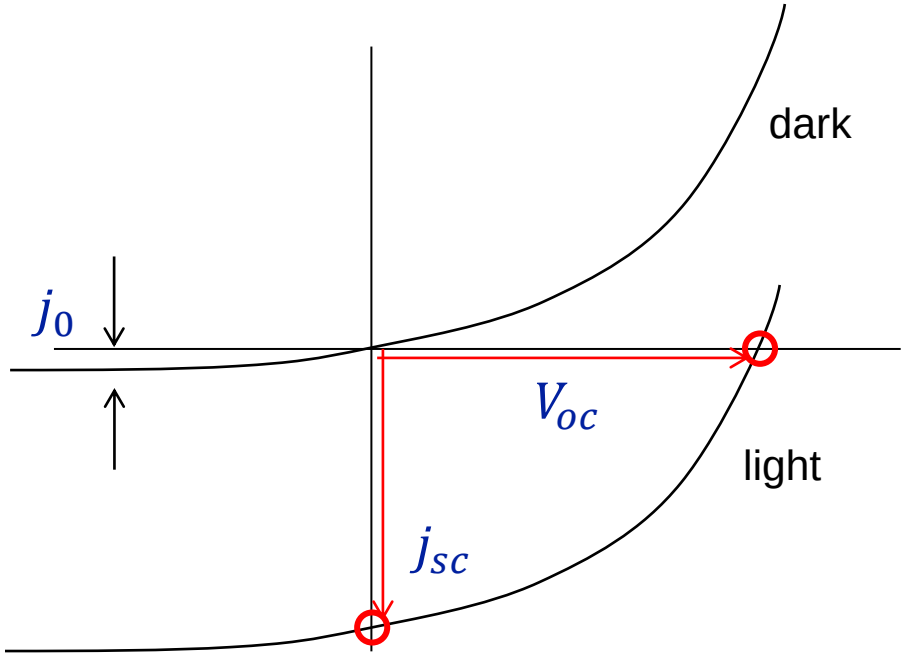
Current-voltage characteristic

Simple form of j-V characteristics

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

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

Saturation current

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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:

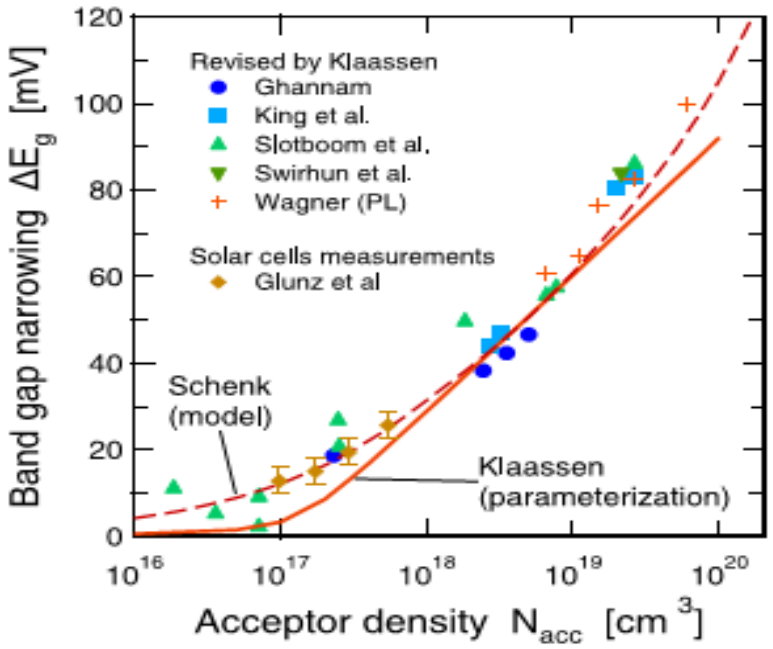
$$j_0 = \frac{qD_n n_i^2}{L_n N_A} = \frac{qn_i^2}{N_A} \cdot \sqrt{\frac{D_n}{\tau_n}}$$

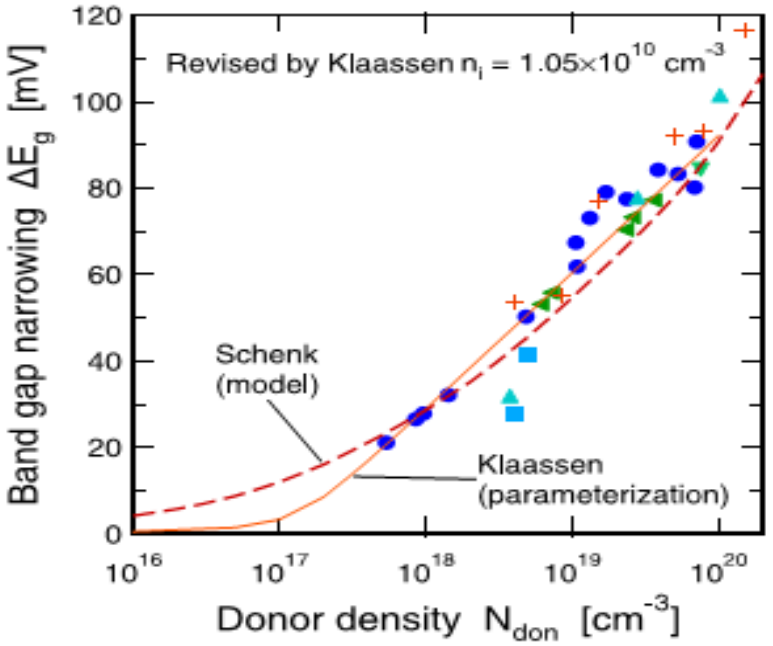
Knobs to turn for small j_0:

increase N_A (but…)

Intrinsic carrier density

Band gap narrowing (BGN)





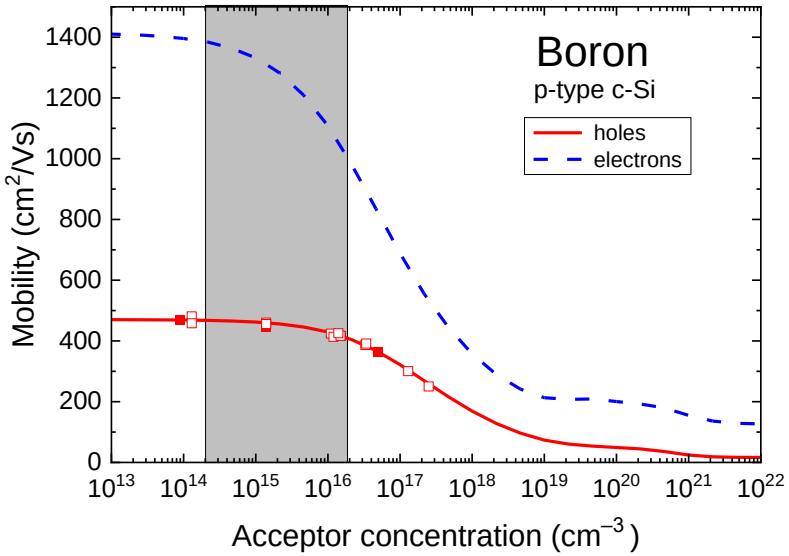
Remember: $n_i^2 \sim e^{-\frac{E_g}{kT}} = e^{-\frac{E_{g,0}-\Delta E_g}{kT}}$

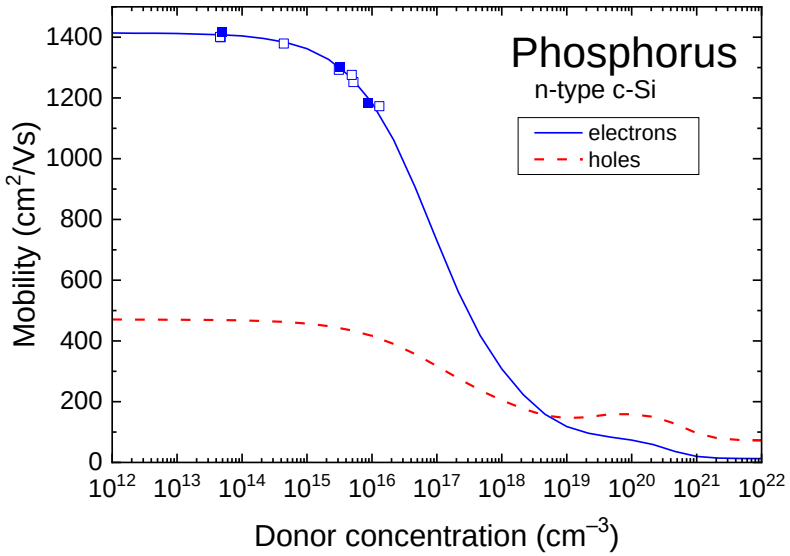
On BGN models: e.g. Altermatt, J. Comput. Electron. (2011)

Diffusion coefficient

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

phonon scattering | ionized impurity scattering (non degenerate) | ionized imp. scattering (degenerate)



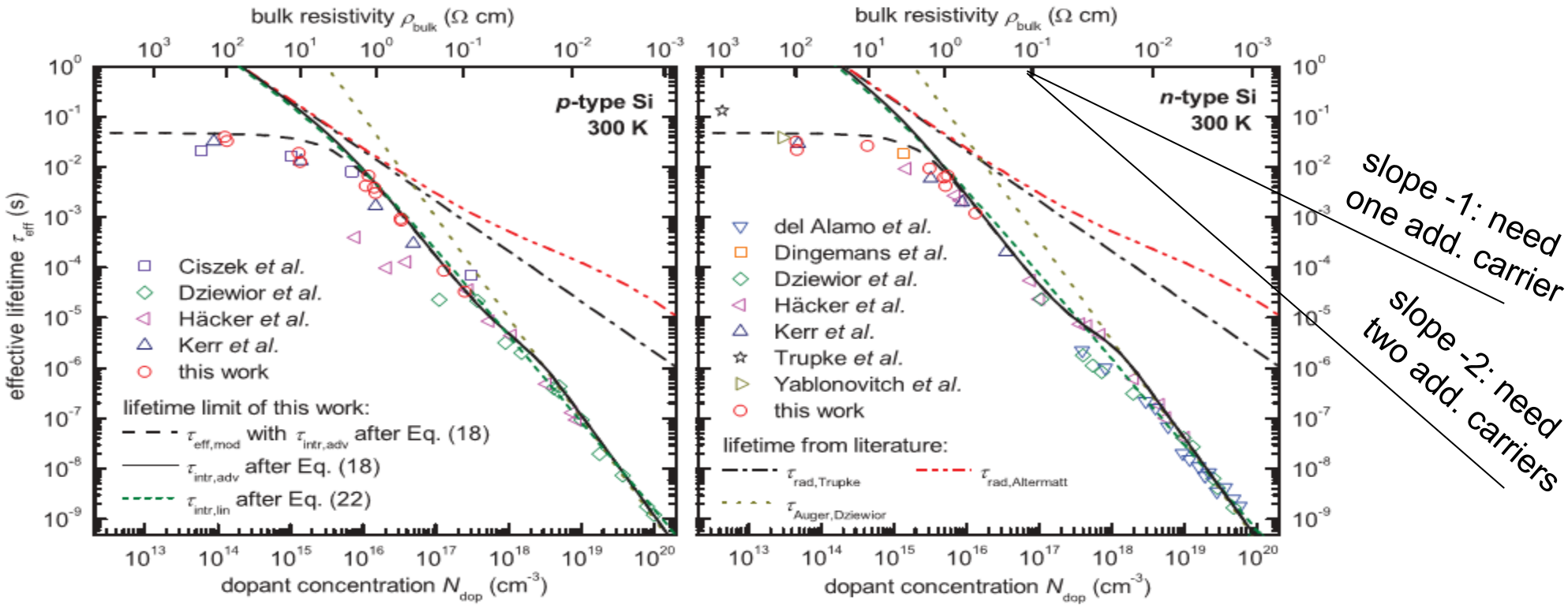


High doping will decrease D (both majority and minority, but slightly differently)

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)

Steady state minority carrier density – QFL splitting

Recombination rate: $R = \Delta n/\tau$

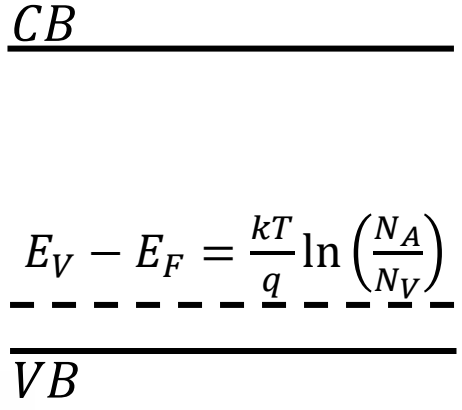
When no carriers are extracted (e.g. semiconductor w/o contacts or solar cell at Voc):
=> Recombination rate R = Optical generation rate G

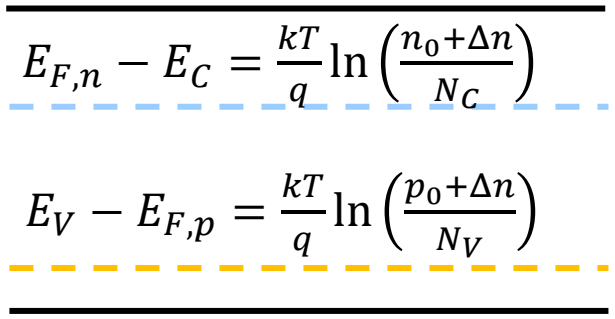
$\Delta n = G\tau$ (excess minority carrier density in steady state)

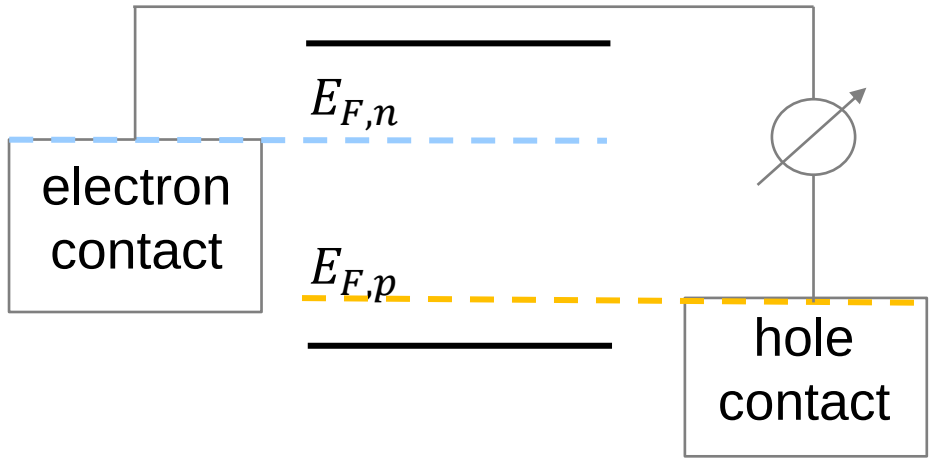
Dark:
thermal equilibrium,
unique Fermi level

Illuminated:
Define independent
quasi Fermi levels (QFLs)

With idealized contacts:
QFL splitting equal to
achievable voltage







Implied open circuit voltage (iVoc)

For ideal contacts: QFL splitting equal to external voltage

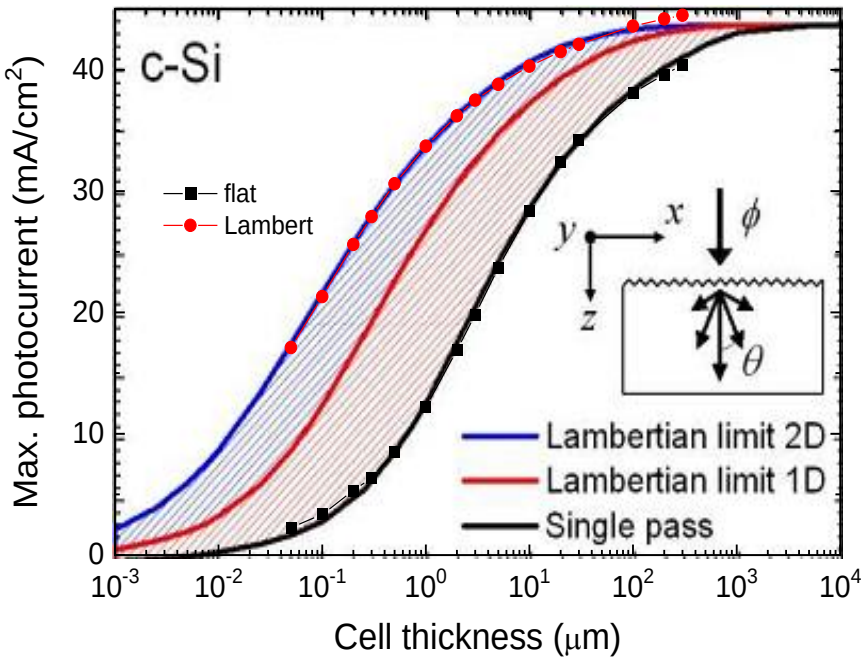
Assume
- $N_A = 10^{16}$ cm^{-3} (= p_0)
- $G \approx 10^{19}$ cm^{-3}s^{-3}
- $\tau \approx 1$ ms (minority carrier lifetime)

$\Delta n = G\tau \approx 10^{16}$ cm^{-3}

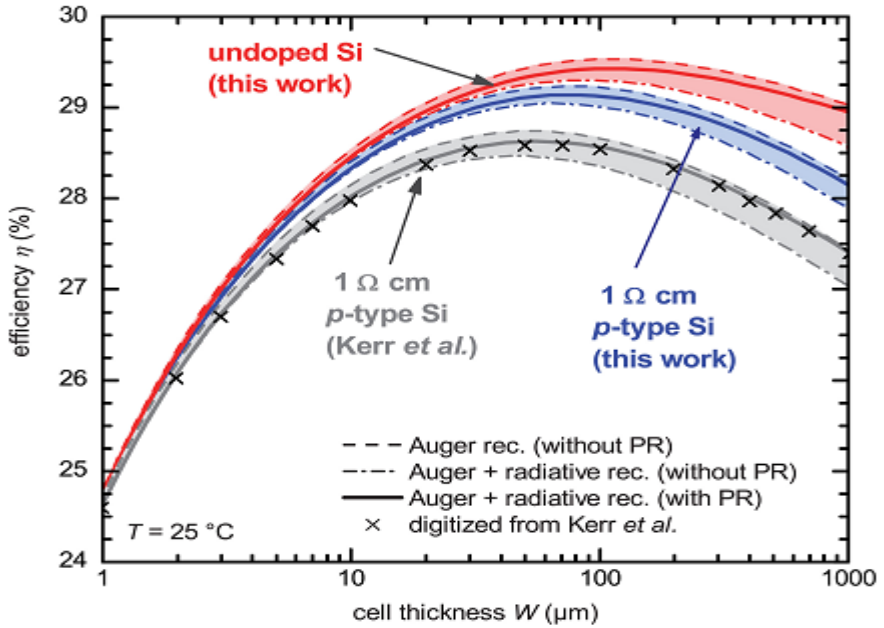
$$iV_{oc} = \frac{kT}{q} \ln \frac{np}{n_i^2} \approx 720 \text{ mV}$$

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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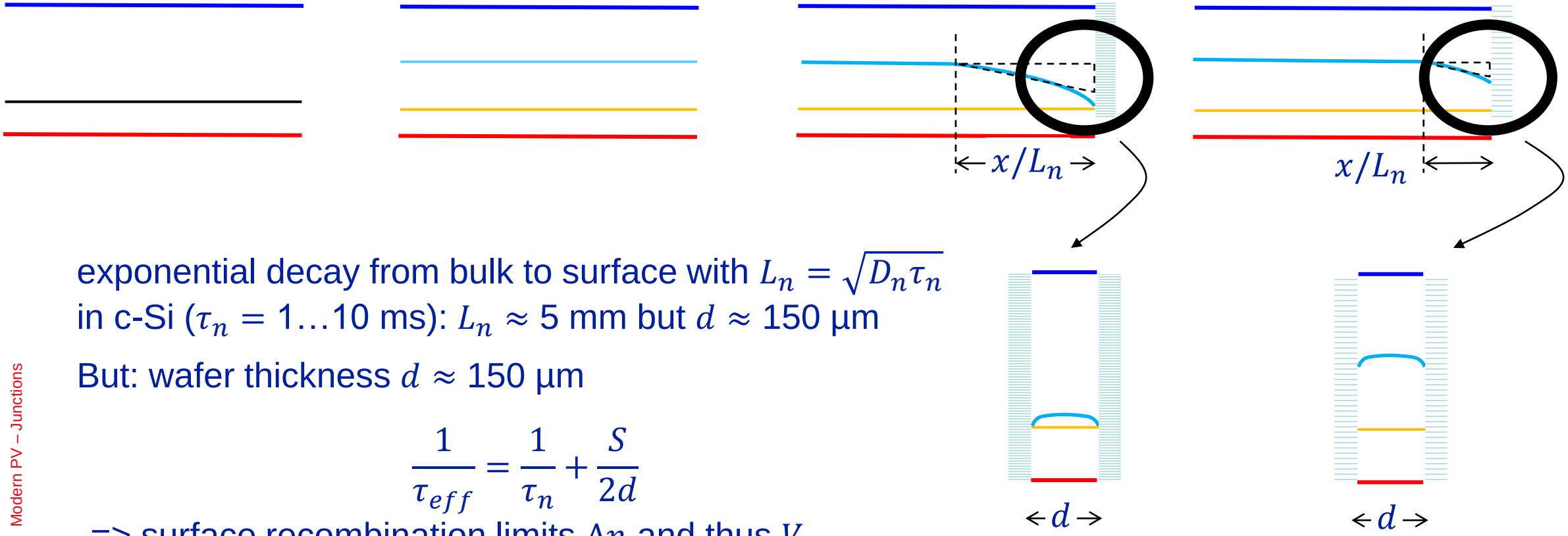
Impact of surfaces

Equilibrium (p-type)

with illumination:
$p \approx p_0\,, n \approx n_0 + \Delta n$

with $S \approx 10^5$ cm/s
(metal contact)

with $S \approx 10..100$ cm/s
(oxide passivation)



exponential decay from bulk to surface with $L_n = \sqrt{D_n \tau_n}$
in c-Si ($\tau_n = 1\ldots10$ ms): $L_n \approx 5$ mm but $d \approx 150$ µm

But: wafer thickness $d \approx 150$ µm

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_n} + \frac{S}{2d}$$

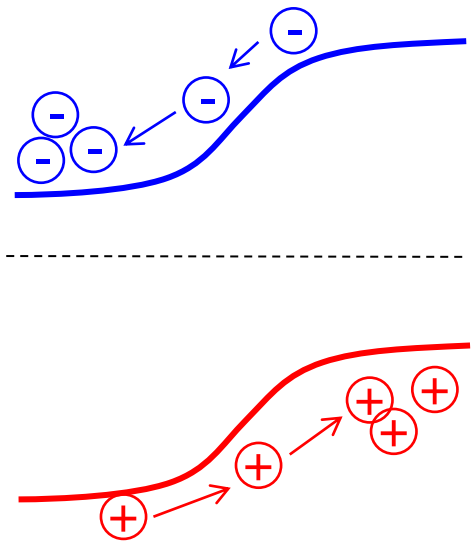
=> surface recombination limits Δn and thus V_{oc}

=> for large L_n of c-Si, surface passivation is imperative

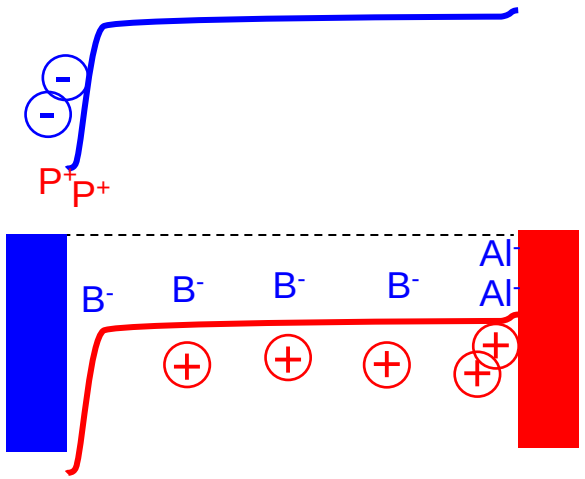
Sproul, JAP (1994)

How to get current out of the cell

What you often see…

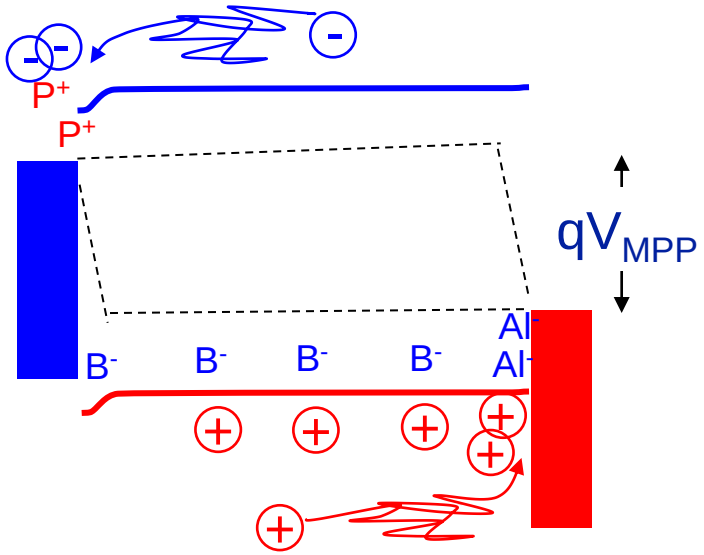


how it actually looks in dark



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

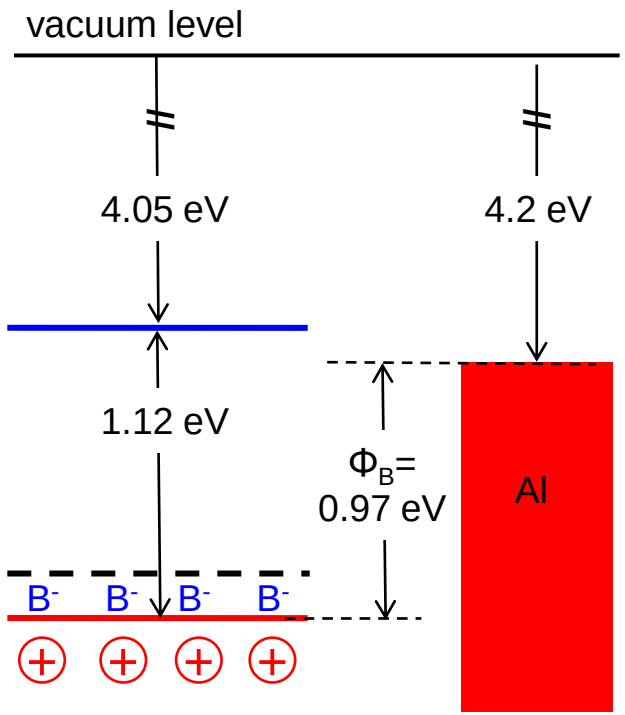
…and how it really works



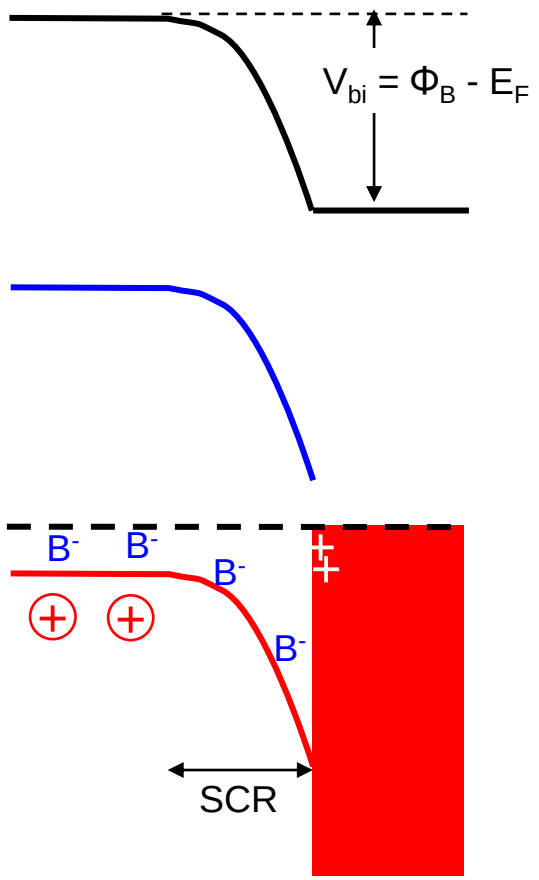
charges diffuse randomly until they “see” a contact region (may be doped, but need not!)

Working principle of metallic rear contact

Before contact



Ideal Schottky contact



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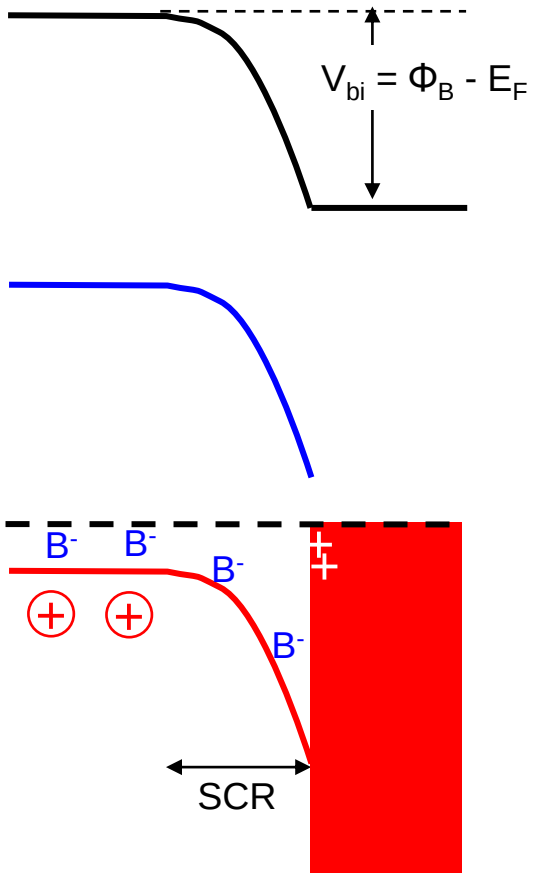
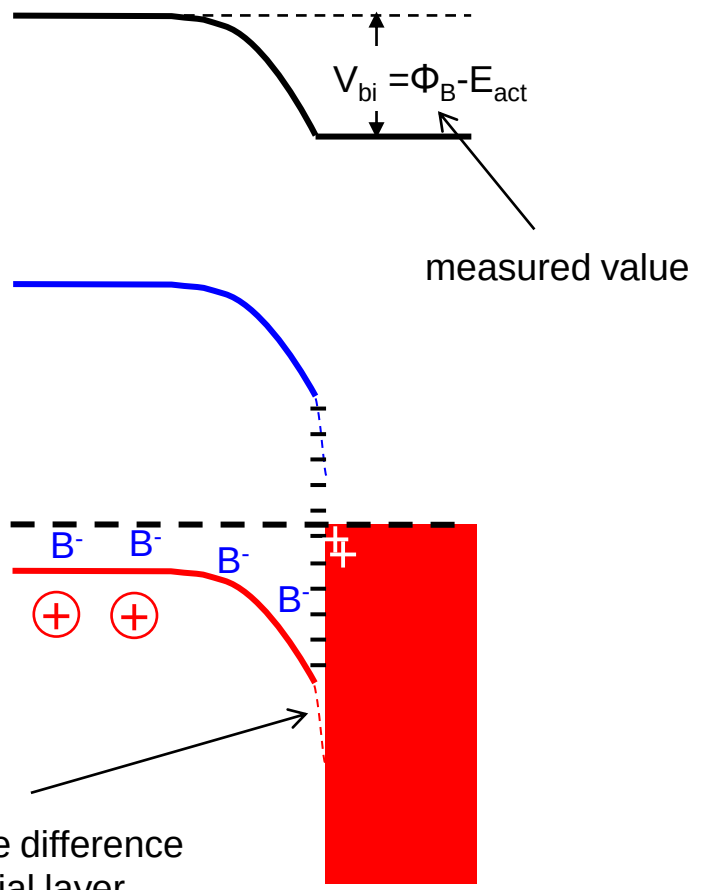
p-type contact with Fermi-level pinning

Ideal Schottky contact: Φ_B = 0.97 eV

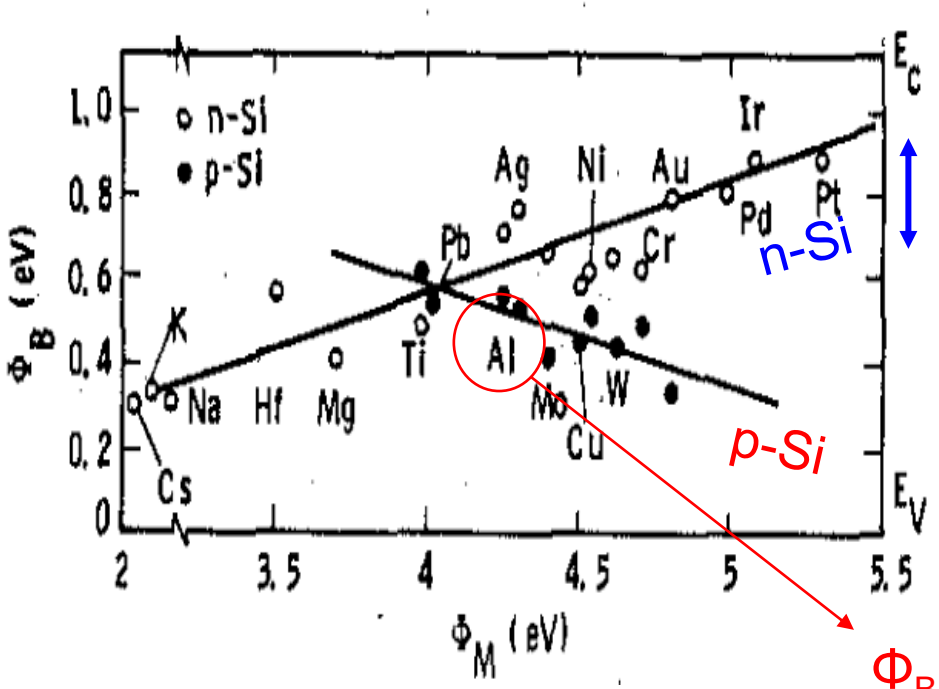


Actually measured: Φ_B = 0.5 eV, difference due to interface states



see e.g. Schroeder, TED (1984)

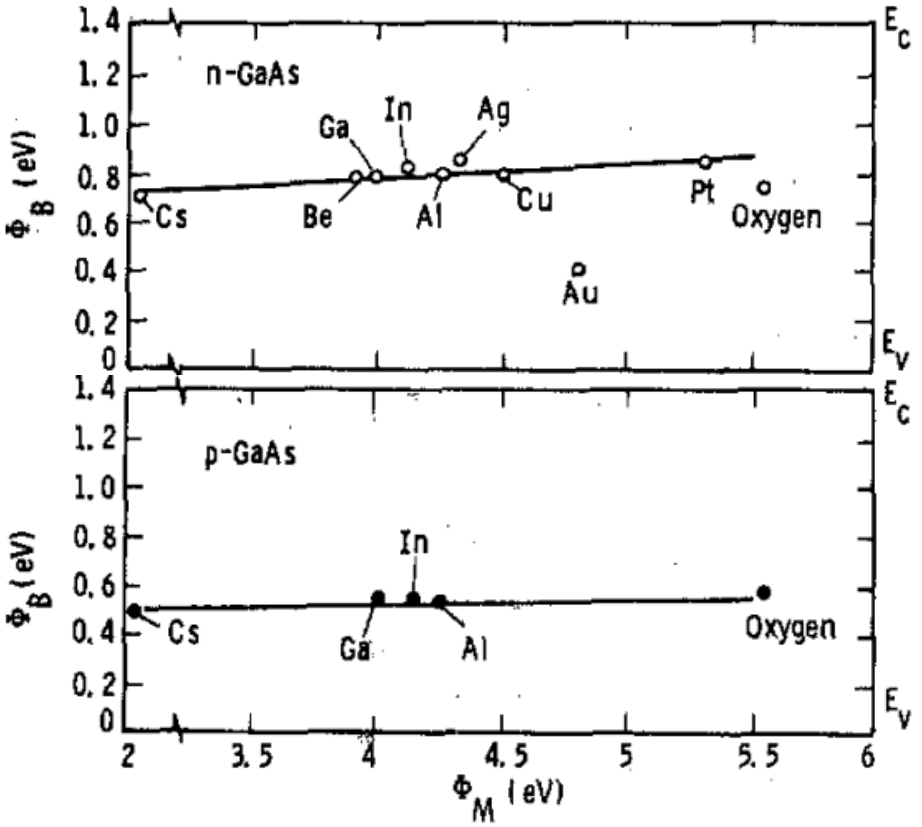
Barrier heights (experimental)



rule for common metals on n-Si
Φ_B = 2/3 of E_g,
"E_F pinning"

$\Phi_{B,Al}$ = 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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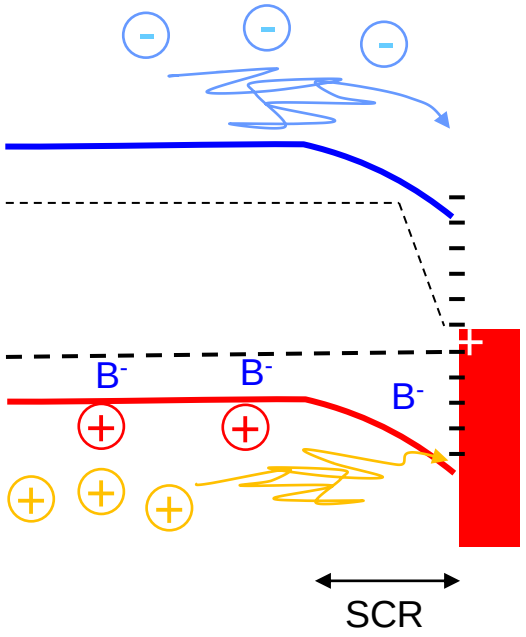
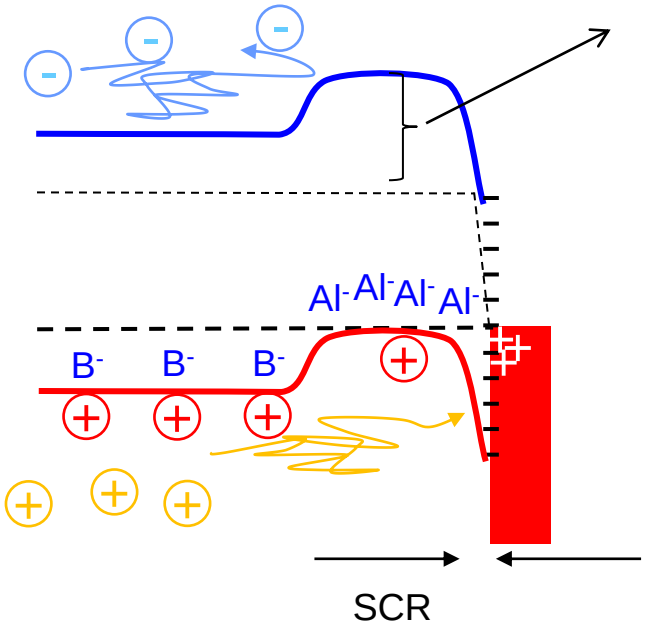
Remember contact from above, add QFL splitting



- electrons (minority) feel QFL gradient and easily recombine easily via interface states

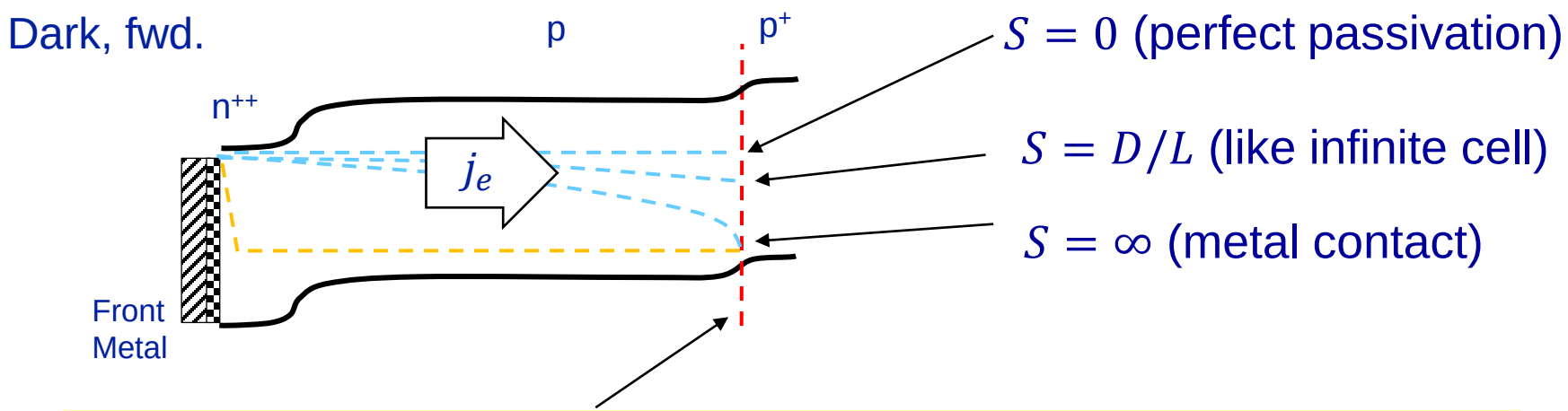
Solution: introduce strongly doped region (“BSF”)!



larger $E_C - E_F$
=> fewer electrons can diffuse to the interface

- electron density is reduced in BSF region
- added benefit: holes tunnel narrow barrier more easily (lower ρ_c)

Surface recombination velocity

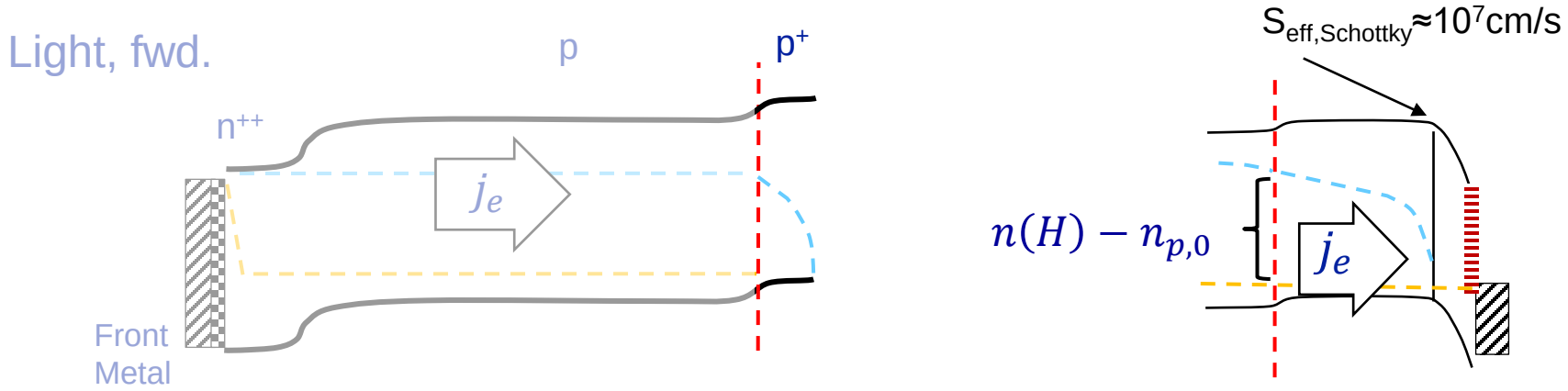


Ignore details of back contact, define
eff. surface recombination velocity S_{eff} by: $j(H) = qS_{eff}(n(H) - n_{p,0})$

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

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

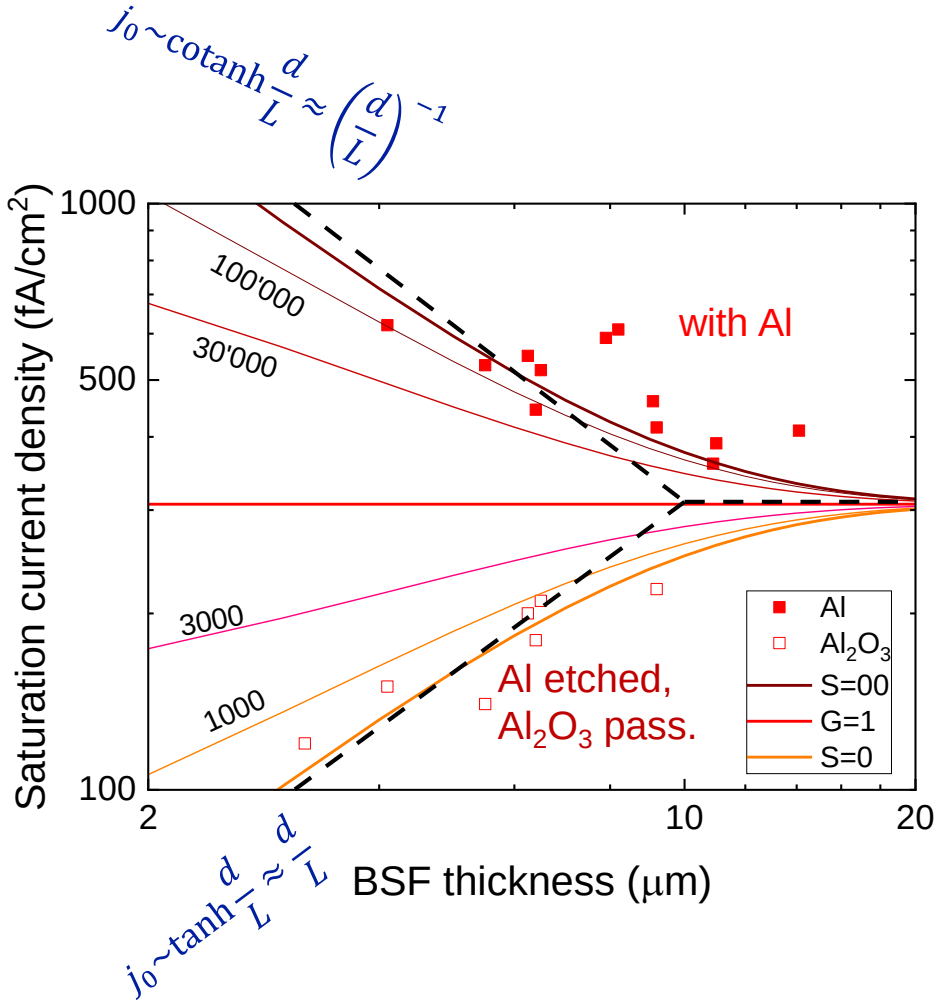
Back-surface field



Use same formalism as for p-n junction:

- minority carrier density fixed at virtual interface by bulk QFL splitting
- injection into highly doped BSF region (shorter lifetime, lower diffusivity, higher n_i)

Example: Al-BSF



Simple model for j_0:
approximate with H = d_{BSF},
N_A = const = $3x10^{18}/cm^3$ (Al saturation conc.

Two branches:

- S ≈ ∞ (metal contact)
  => better for thick BSF

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

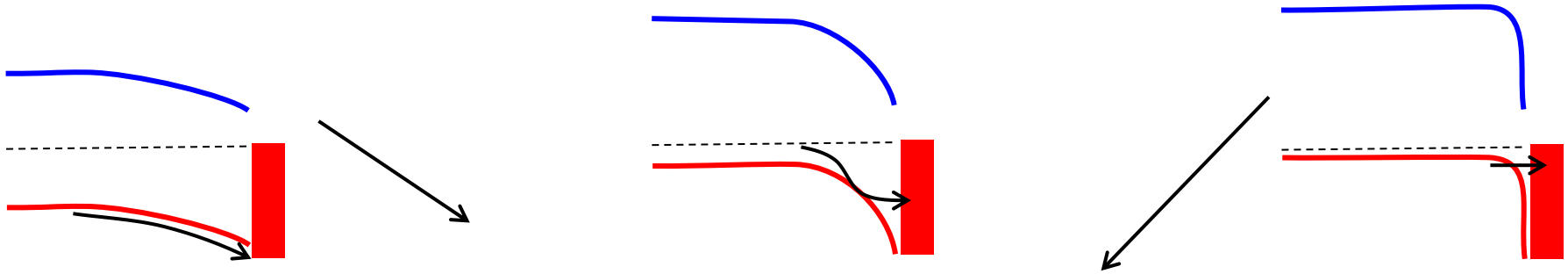
Data: Rüdiger, JAP (2011)

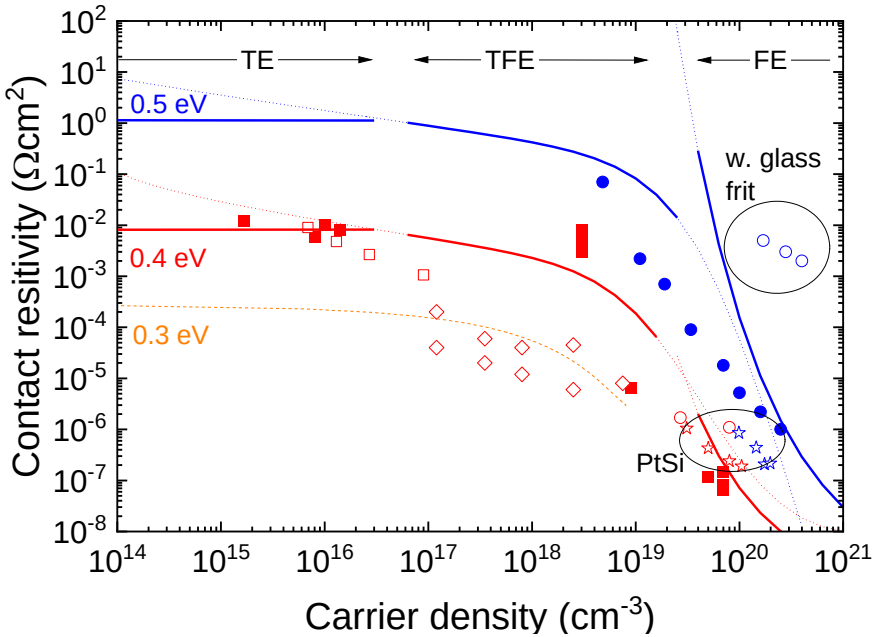
Contact resistance of a tunnelling contact

Weak doping:
thermionic emission
(TE, std. Schottky theory)

Intermediate:
thermionic field emission
(TFE)

High doping:
Field emission
(FE, tunnelling)





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

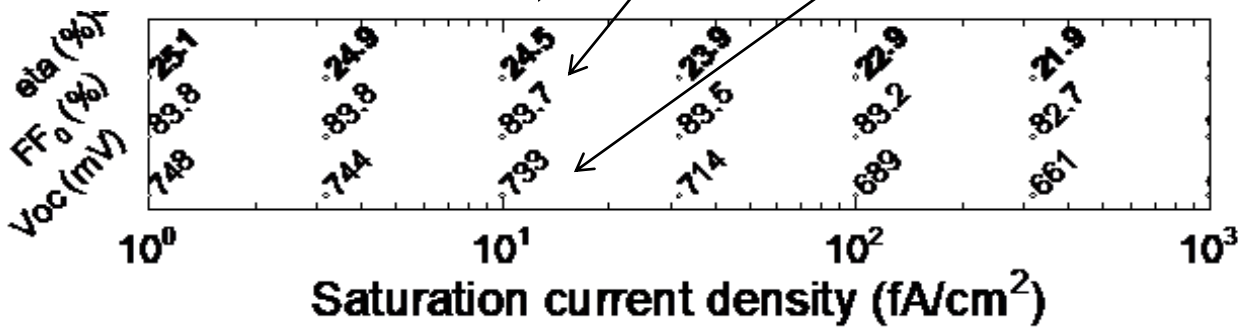
One solution: precise control of doping density and location,
=> complicated process

Efficiency for given j_0 and j_{sc}

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

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

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



Approximation formulae: Green, SSC (1982)

Combine ρ_c and j_0 for given j_{sc}

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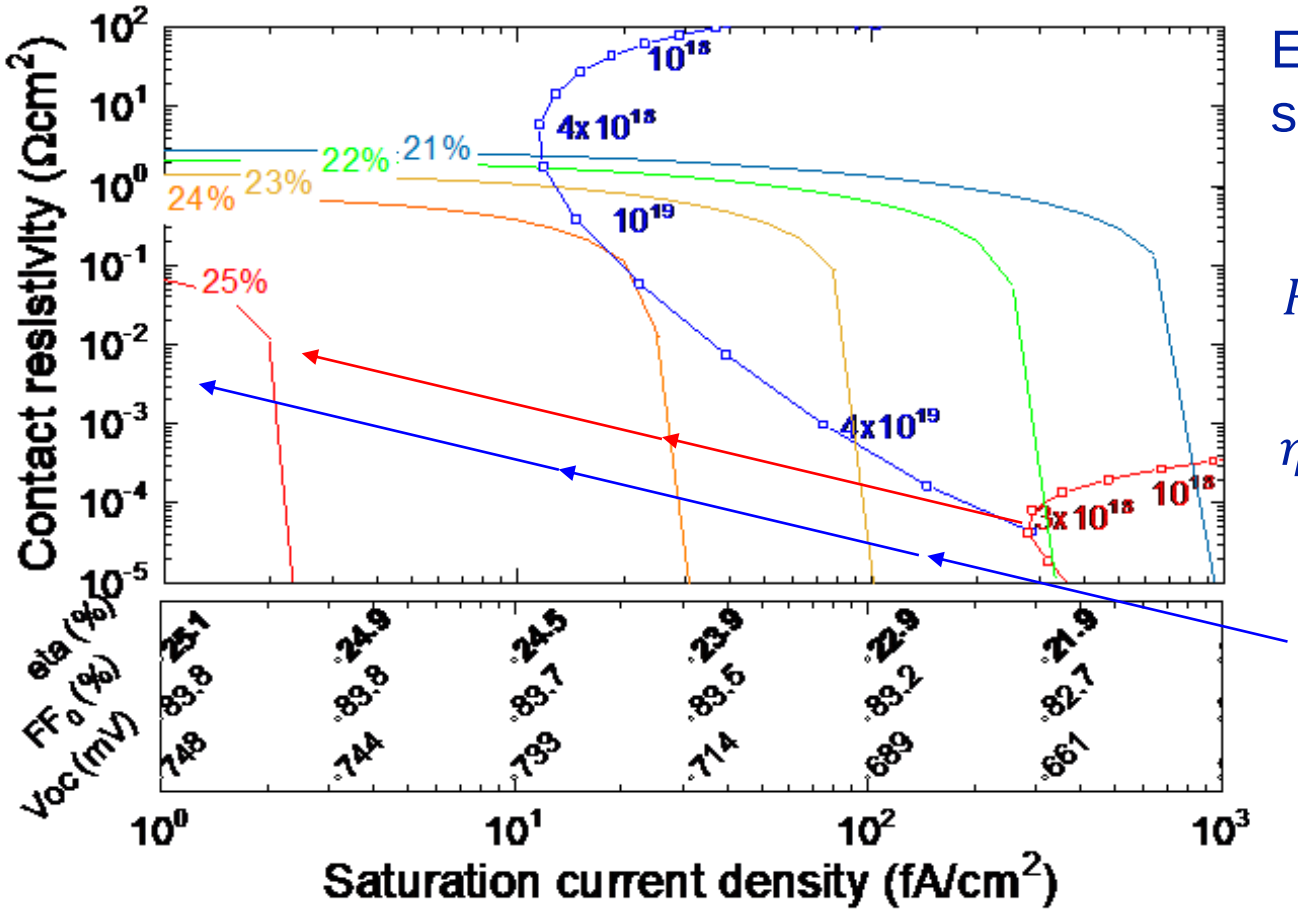


Efficiency contours with series resistance:

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

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

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)

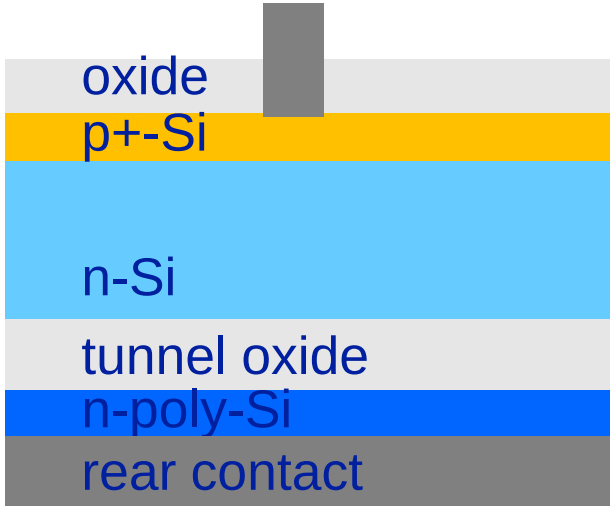
Architectures with improved passivation

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)

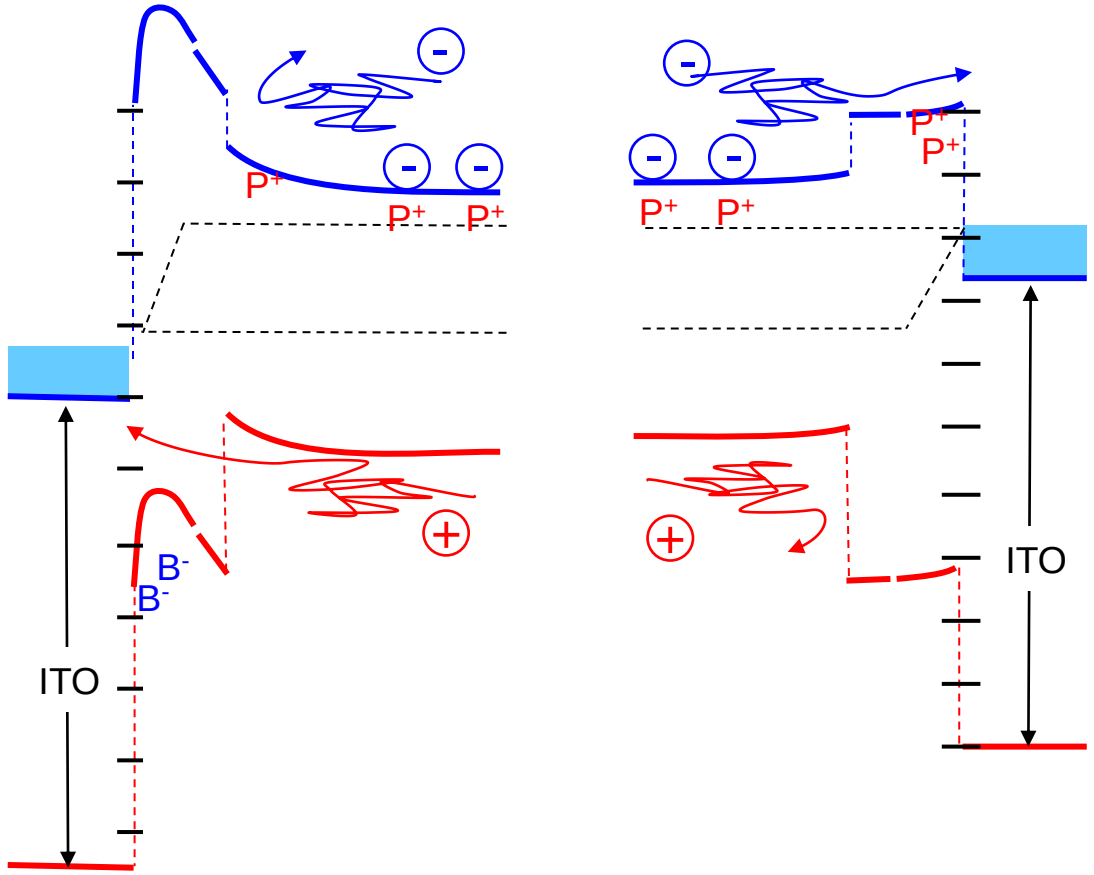
full area back contact
chemical passivation by tunnel oxide

(probably used by SunPower as well)

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

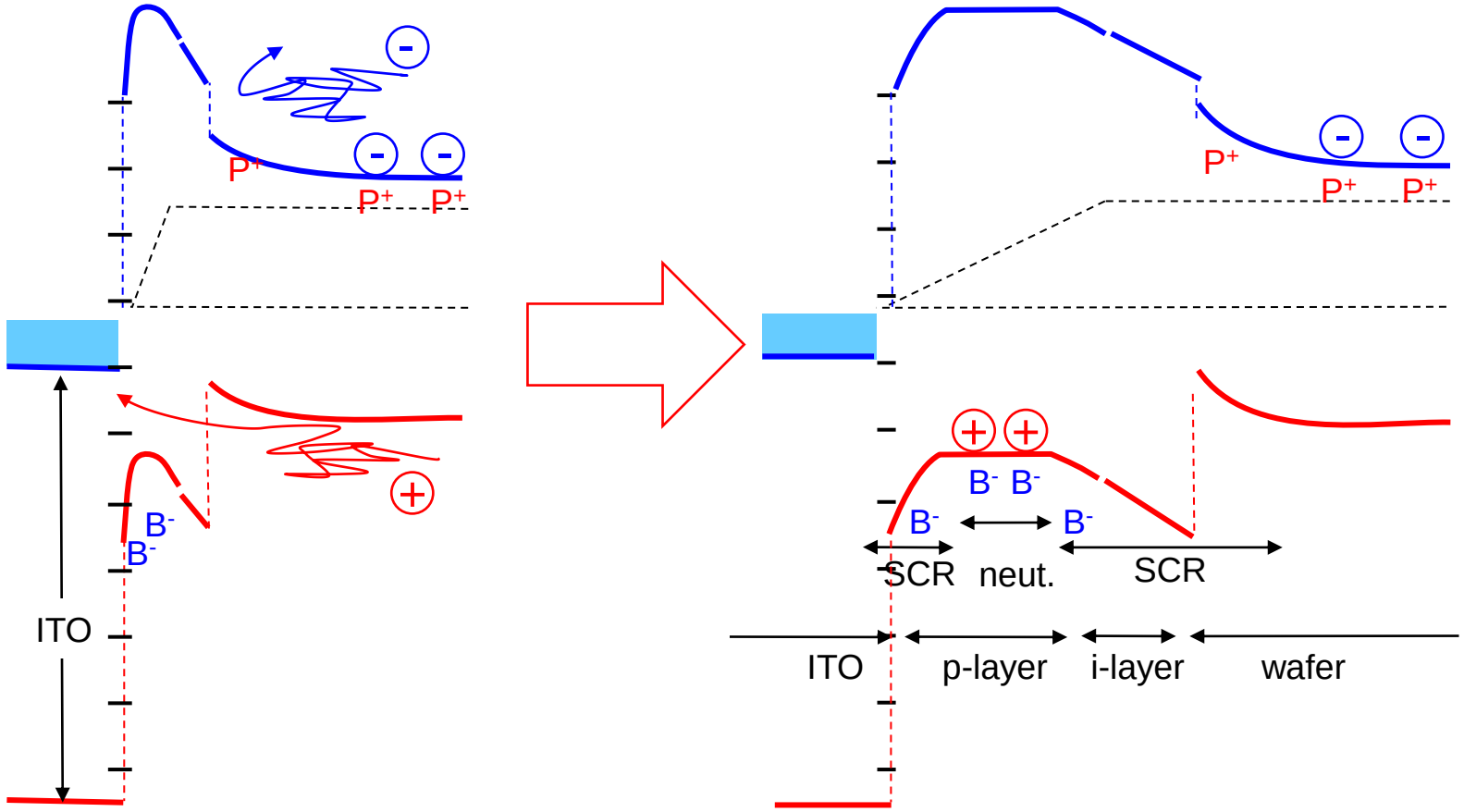
a-Si:H passivating contacts

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



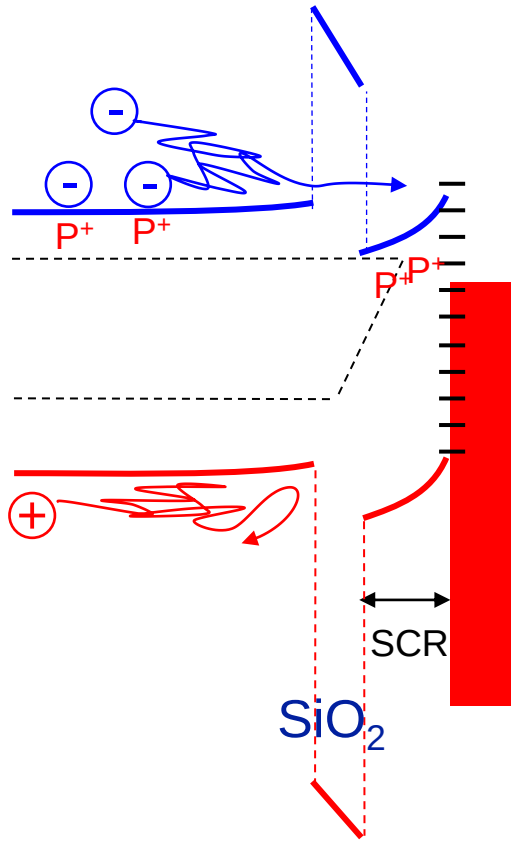
a-Si:H passivating contacts

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



SiO_2 passivating contacts

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)

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 and 27.8% by LONGI