The a-Si:H/c-Si interface - key for high efficiency heterojunction cells

Lars Korte, Erhard Conrad, Heike Angermann, Rolf Stangl, Tim Schulze, Manfred Schmidt

Weierstraß-Institut Berlin, 24. November 2008

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Outline

- *a*-Si:H/*c*-Si heterojunction solar cells
- impact of the heterointerface: passivation and transport
- **experimental results:**
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  - optimization of a-Si:H:
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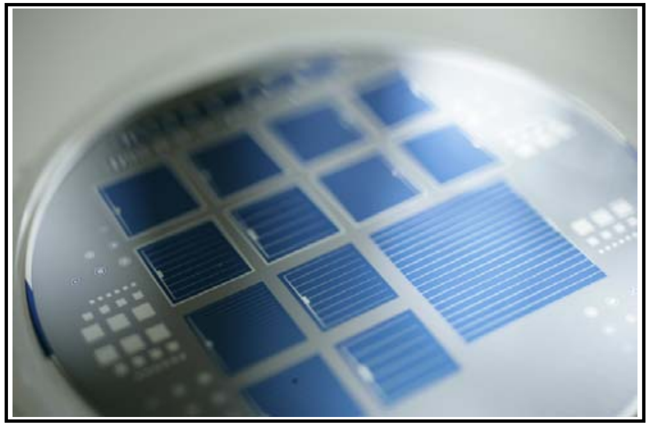
    - optimum doping
  - *a*-Si:H/*c*-Si band offsets
- (older) cell results & summary



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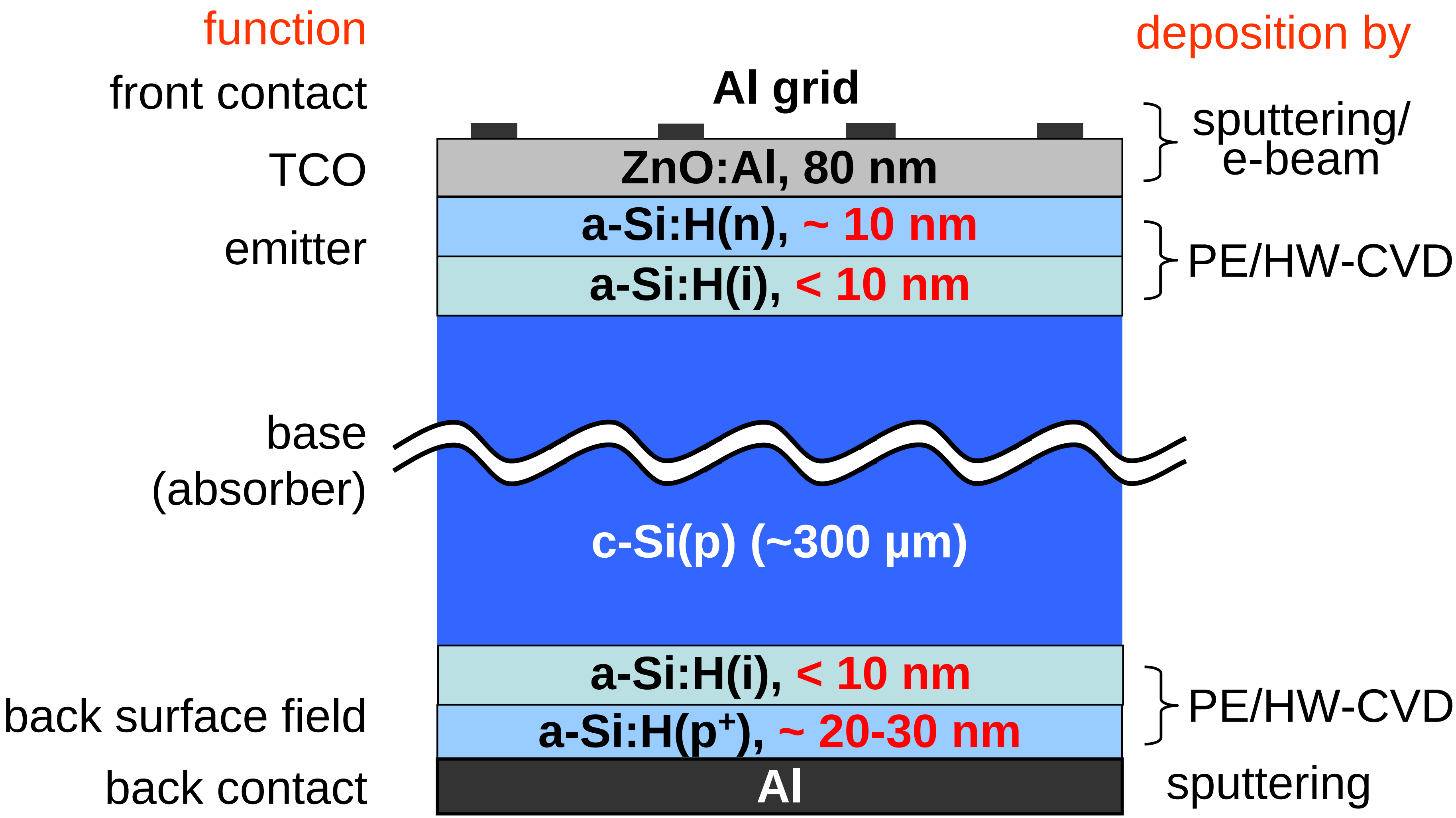
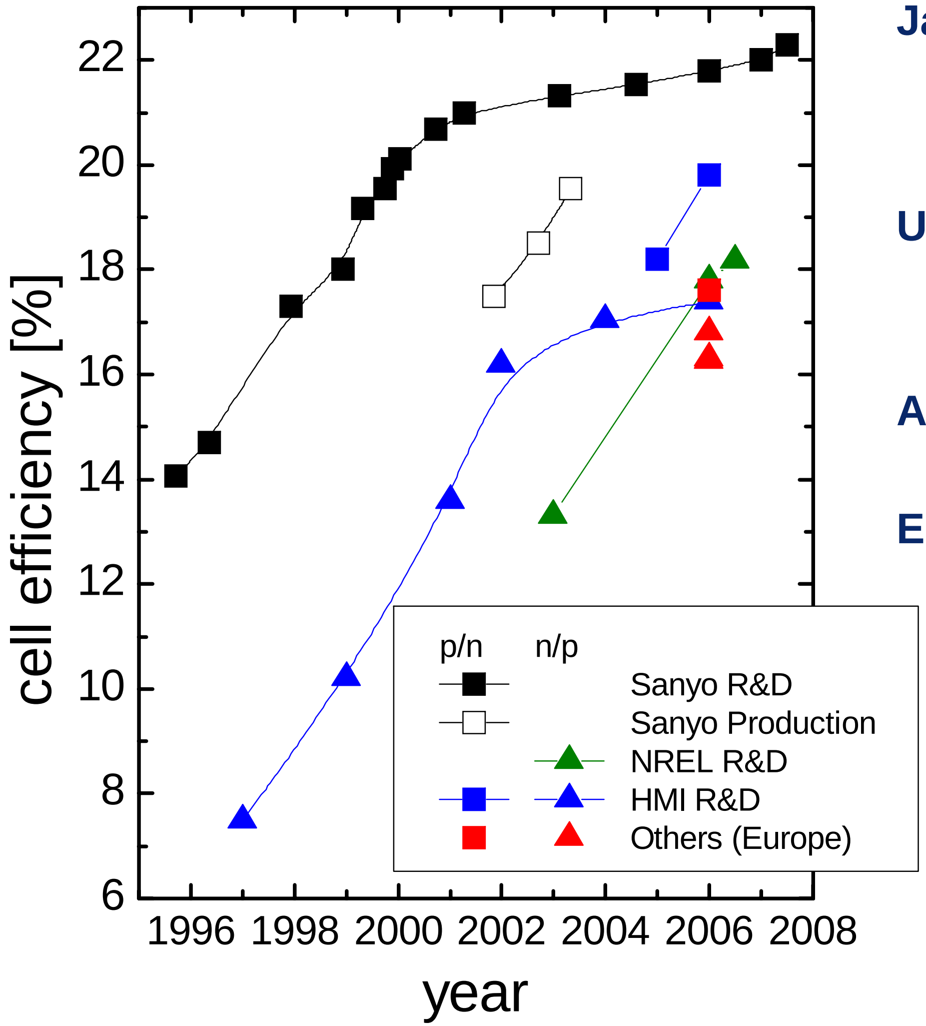
The a-Si:H/c-Si solar cell



Progress in a-Si:H/c-Si cell efficiency



(incomplete) list of R&D on *a*-Si:H/*c*-Si cells

Japan

Sanyo:

- (*p,i*)*a*Si on (*n*)*c*Si (22.3%)
- production: 100cm^2, 19.5%, 350MWp in '08

US

NREL: *p/i on n-type*, 18.2%, **HW-CVD**

UDEL: rear contacted cell, w/ SunPower

Australia

UNSW: p/i on n-type, 17.6% (EPVSEC 22)

Europe

HZB (D):

- n on p-type, 18.4%, and
- p on n-type, 19.8%, **no i-layer**

CEA-INES (F): n, **(i)pmSi** on p, 16.8%, **25cm^2**

U Neuchâtel (CH): n,i on p, **VHF-PECVD**

others:

CNRS (F), ENEA (I), IMEC (B),
U Utrecht (NL), IPE (D), FUH (D), ...

Korte *et al.*, 22nd EPVSEC, Milan (2007) p. 859

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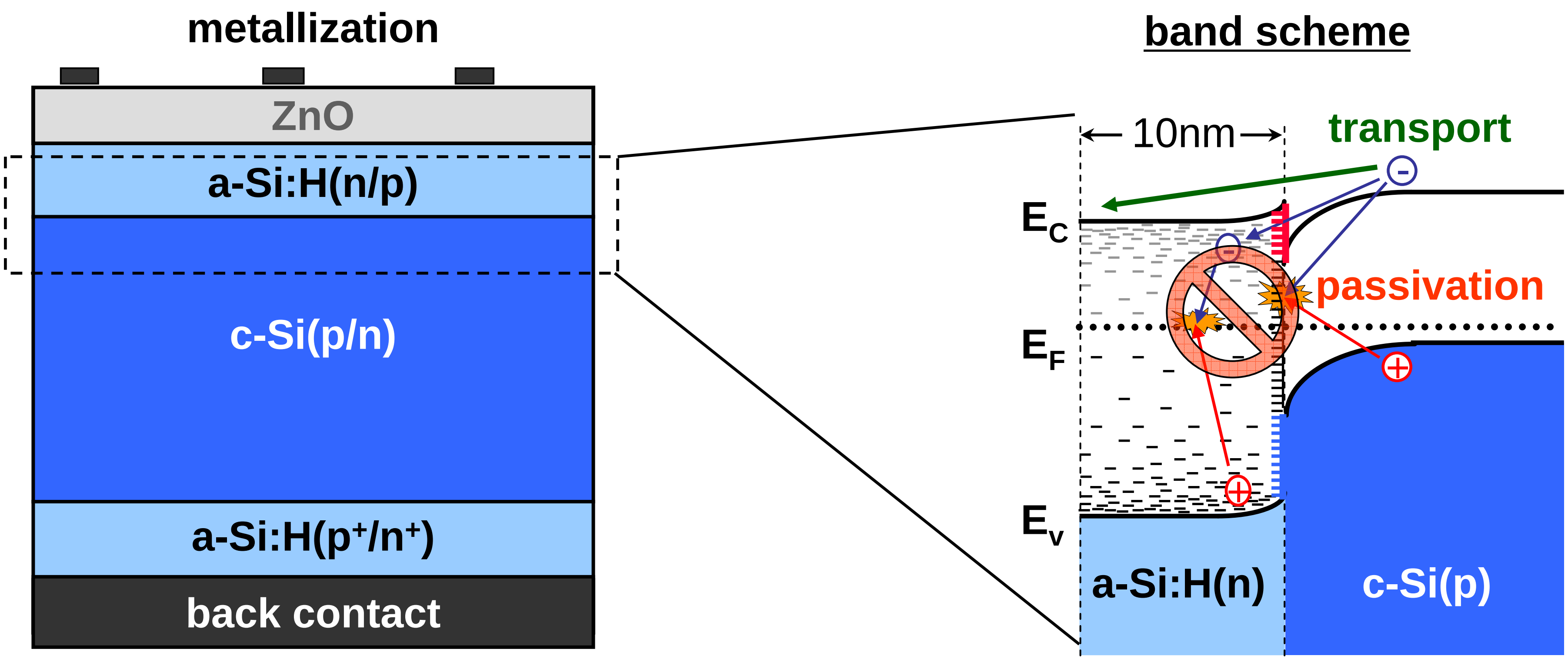
Impact of the heterointerface: Recombination and transport



Tasks:
- minimize recombination losses at/near *a*-Si:H/*c*-Si interface
- maximize efficiency of charge carrier transport over heterointerface

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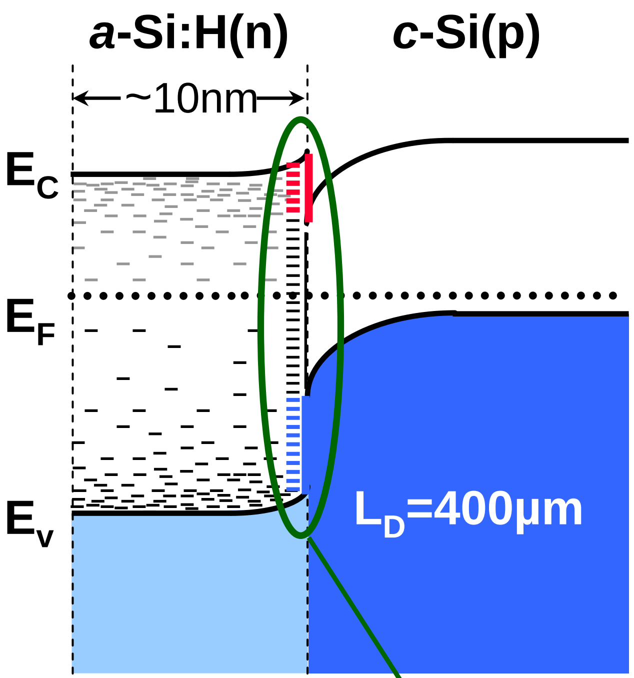
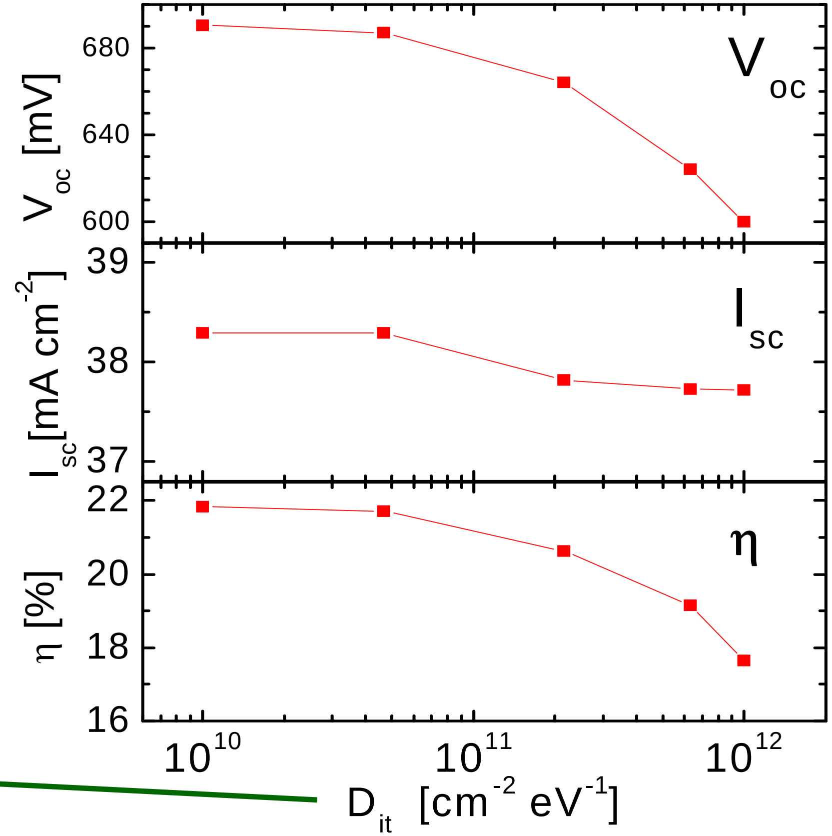
influence of interface defects on cell parameters - simulation study



simulation using AFORS-HET



parameter:
interface state density $D_{it}(E)$

- strong influence of interface recombination at front (and rear) side
- D_{it} <10^{10}cm^{-2}eV^{-1} $\rightarrow$ IF recombination plays no role in cell

Schmidt *et al.*, 4th IEEE WCPEC (2006) 1433

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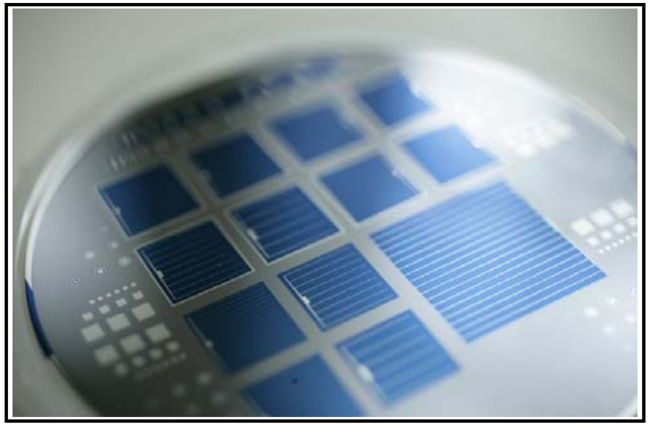

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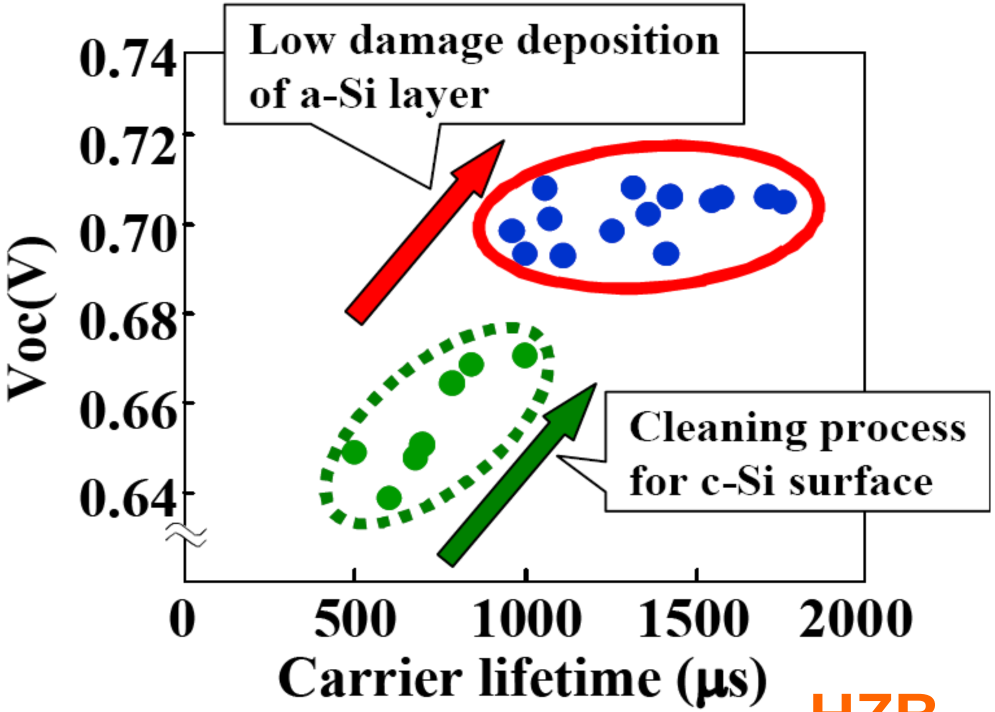
soft deposition of *a*-Si:H - the Sanyo „mantra“



Maruyama *et al.*, 4th IEEE WCPEC (2006)
and also

- Taira *et al.*, 22nd EPVSEC (2007),
- H. Kanno *et al.*, 23rd EPVSEC (2008),
- ...

HZB

low damage deposition?

- RF-PECVD at low power
  at low pressure
- remote plasma
- VHF-PECVD
- hot-wire-CVD
- …?

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Influence of epitaxy at the *a*-Si:H/*c*-Si interface

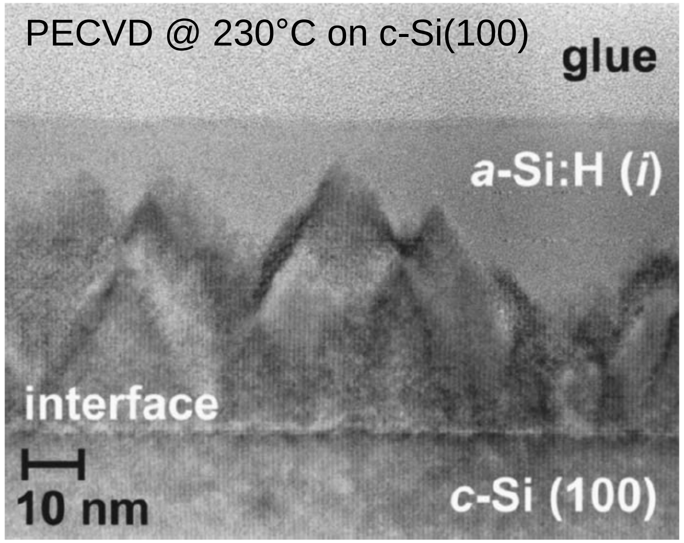
detrimental effect of epi-growth at the a-Si:H/c-Si interface
reported many times:

- E. Centurioni *et al.*, IEEE Trans. El. Devices & 19th EPVSEC, Paris (2004) 1285
- T.H. Wang *et al.*, ibd., p. 1269
- de Wolf & Kondo, Appl. Phys. Lett. *90* (2007) 042111
- ...

usual result: epitaxy up to doped layer → V_{oc} < 600mV

possible explanations:

- epitaxy extends through i-layer
  → surface defect passivation by *doped* a-Si:H: much less effective than (i)a-Si:H
- partial epitaxy/mixed phase (i)a-Si:H
  → increased interface area betw. a-Si & c-Si
- poor conditions for epitaxy
  → epi highly defective



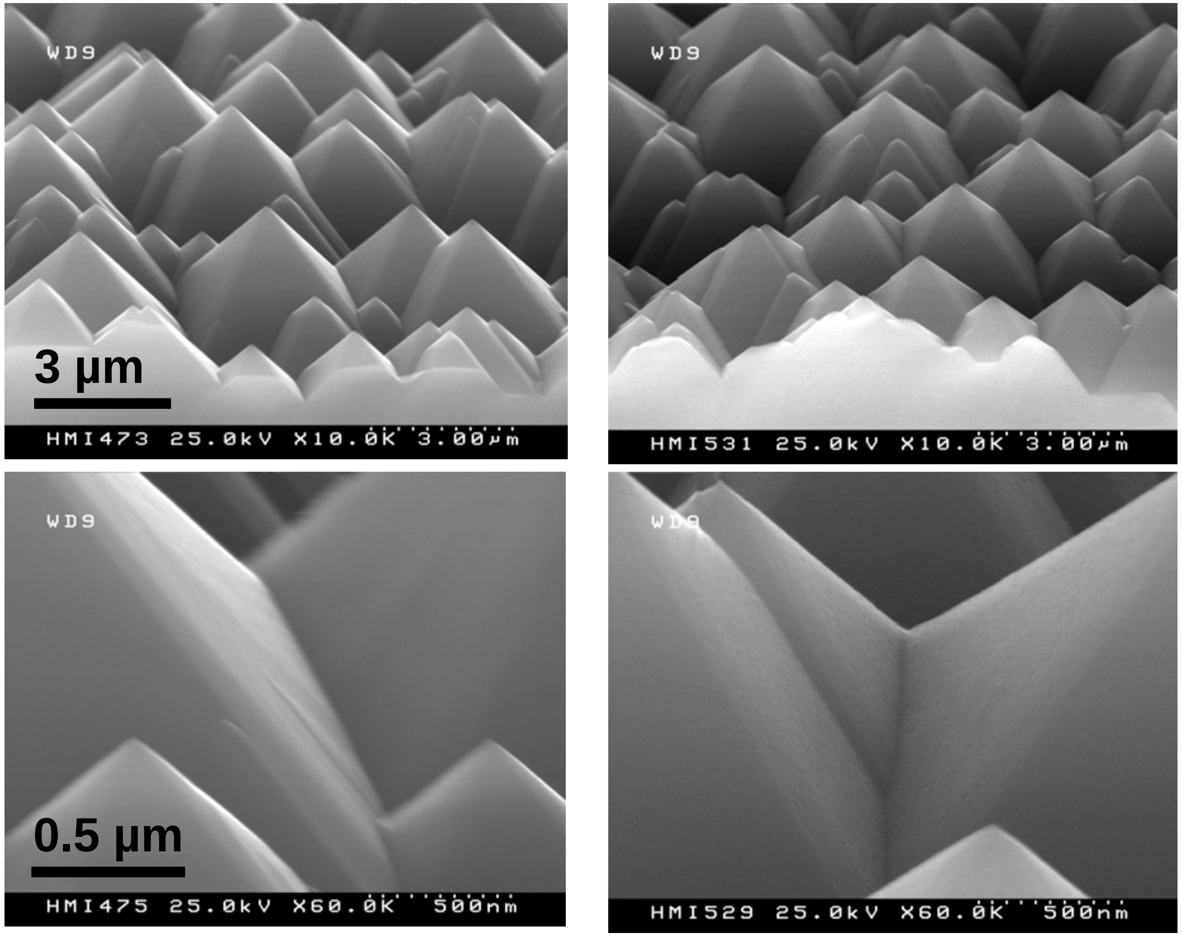
de Wolf & Kondo, Appl. Phys. Lett. *90* (2007) 042111

Smoothing and passivation of pyramids

additional complication: random pyramid surface texture (light trapping)

need optimized chemical pre-treatment of *c*-Si wafer

anisotropic etching → **optimized smoothing**



Angermann *et al.*, Proc. 23rd EU-PVSEC 2008, pp. 1422-6

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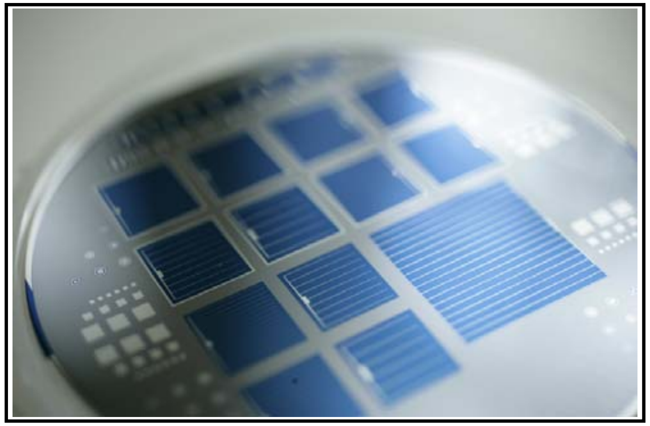
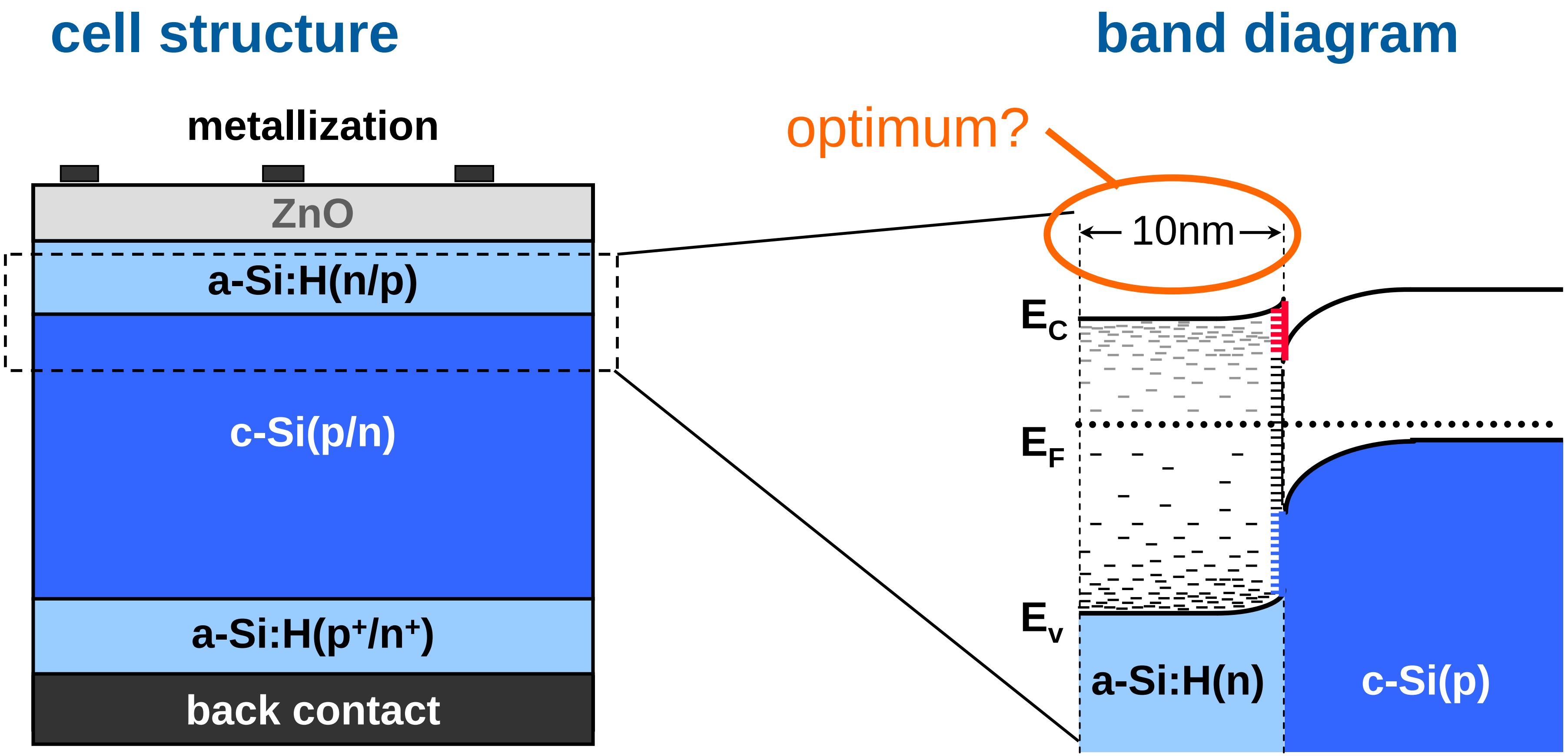
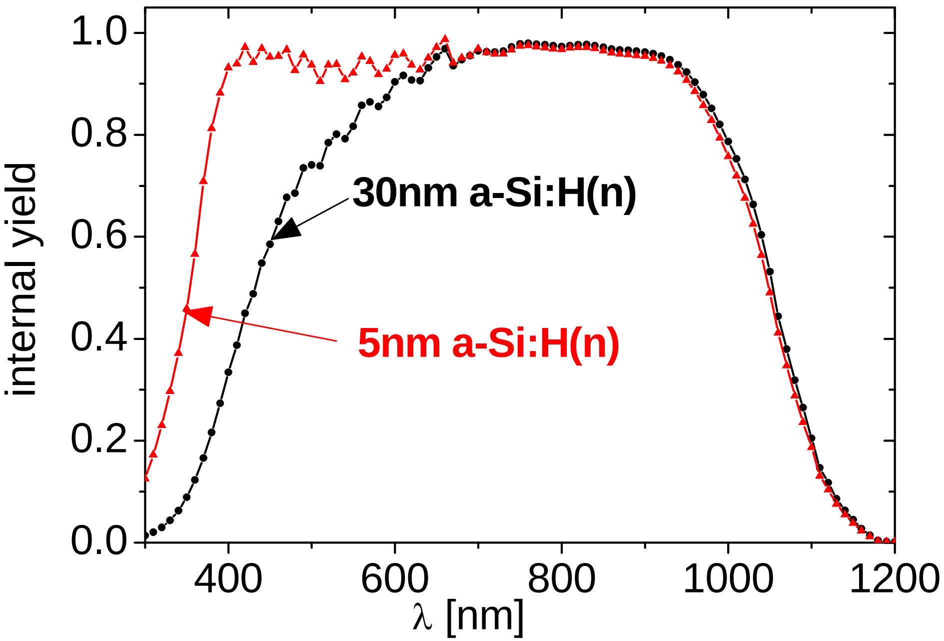



cell structure
band diagram
metallization
optimum?
ZnO
a-Si:H(n/p)
c-Si(p/n)
a-Si:H(p+/n+)
back contact
10nm
EC
EF
EV
a-Si:H(n)
c-Si(p)

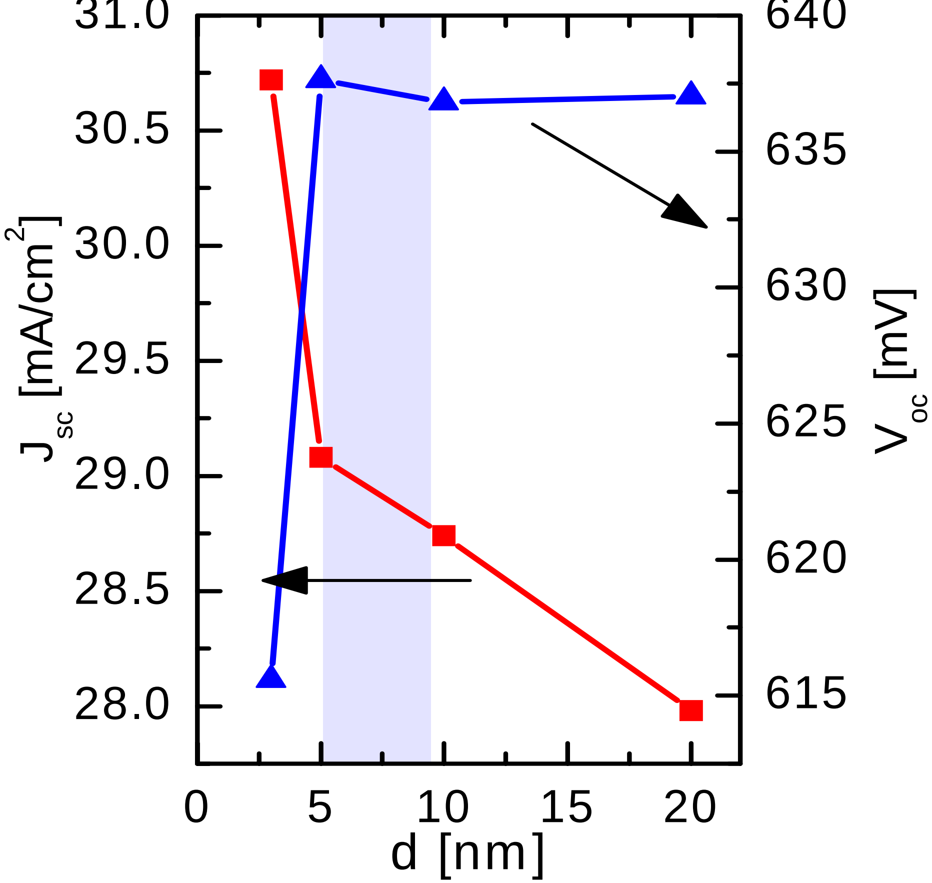
finding the optimal *a*-Si:H emitter thickness

cell structure: TCO/(n)*a*-Si:H/(p)*c*-Si/Al

internal quantum efficiency



solar cell parameters



absorption and recombination in the a-Si:H emitter lead to a decrease in J_{SC}

optimum a-Si:H thickness: 5-10nm – how to analyze its electronic properties?

Stangl *et al.*, 3rd WCPEC (2003) 4P-A8-45

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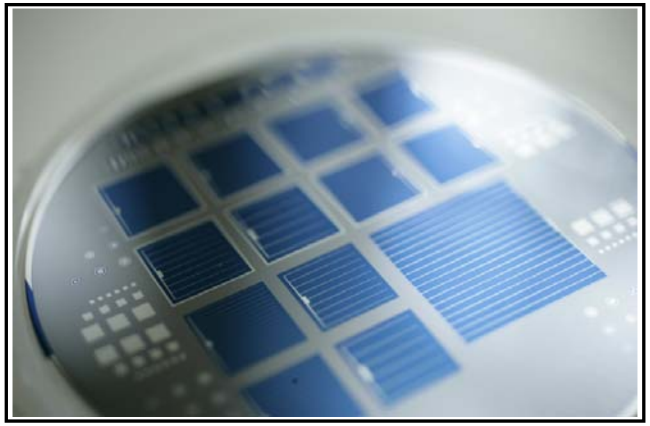
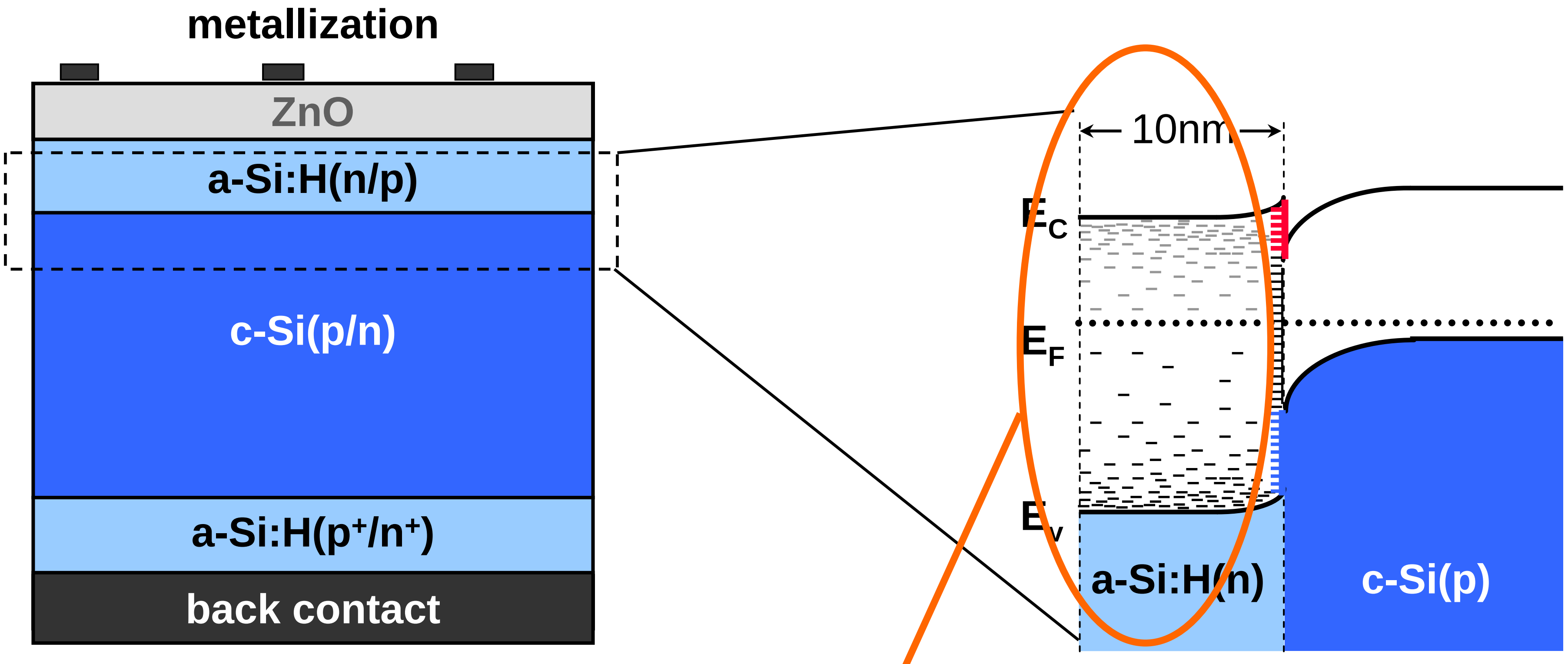


cell structure

band diagram



density of defects? E_F position?

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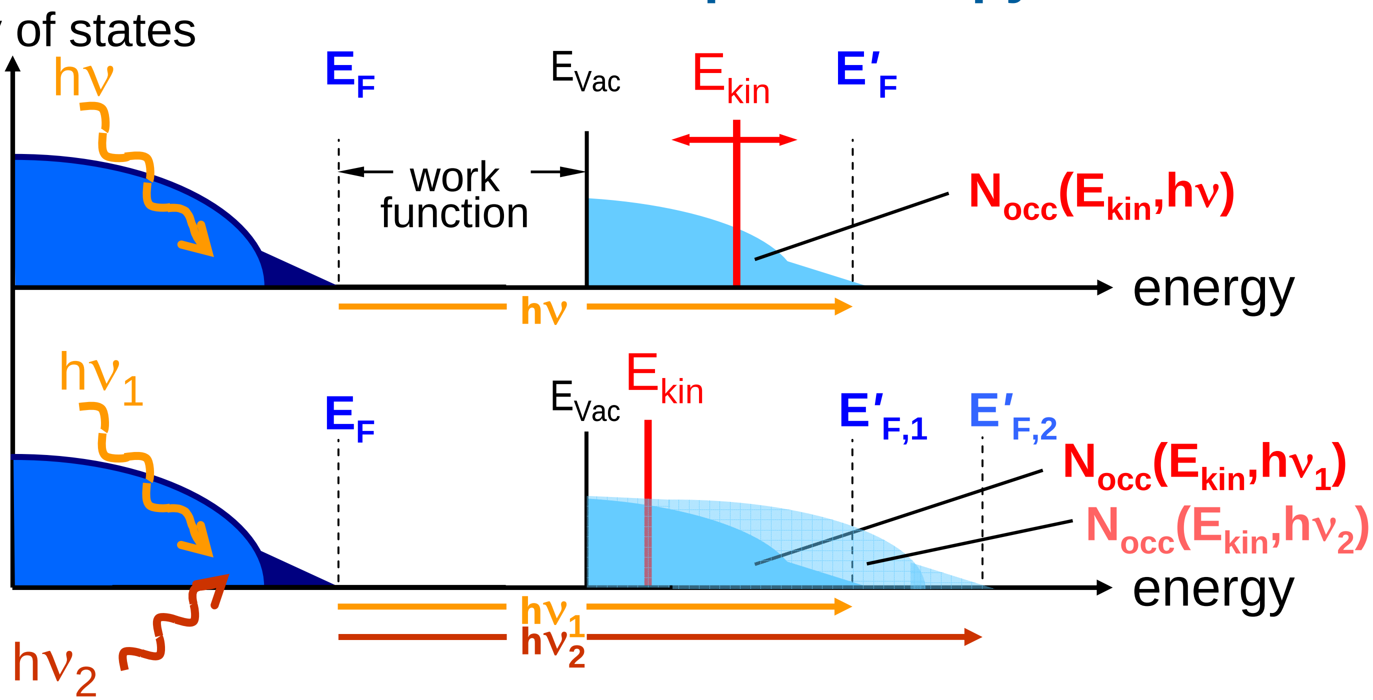
Constant Final State Yield Photoelectron Spectroscopy

'classical' UPS:
$h\nu$ = const.
E_{kin} = var.

CFSYS:
$h\nu$ = var.
E_{kin} = const.

Sebastiani *et al.*, PRL **75**, 3352 ('95)



low excitation energy (4…7 eV)
- high electron escape depth (6-10 nm)
- high excitation cross section (at 4eV: 10^3 times higher than at 21.2eV!)

we obtain: photoelectron yield
- density of occupied states $N_{occ}(E)$
- Fermi level position E_F

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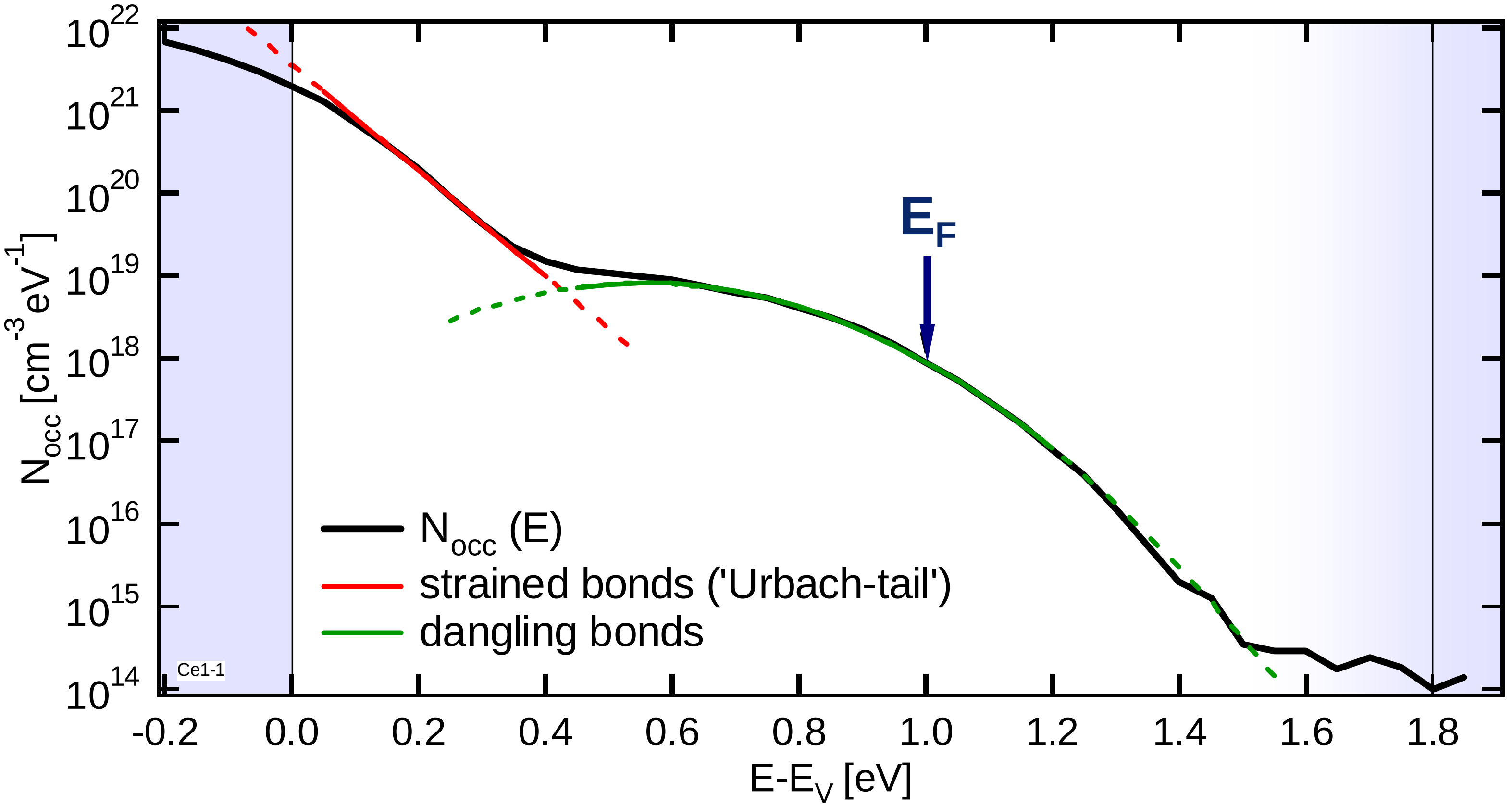
density of *a*-Si:H gap states

near-UV photoemission (CFSYS mode) → $N_{occ}(E)$



$N_{occ}(E)$ = exp. tail ('strained bonds') + Gaussian distribution ('dangling bonds')

Urbach energy E_{0v} **integrated density of deep defects N_D**

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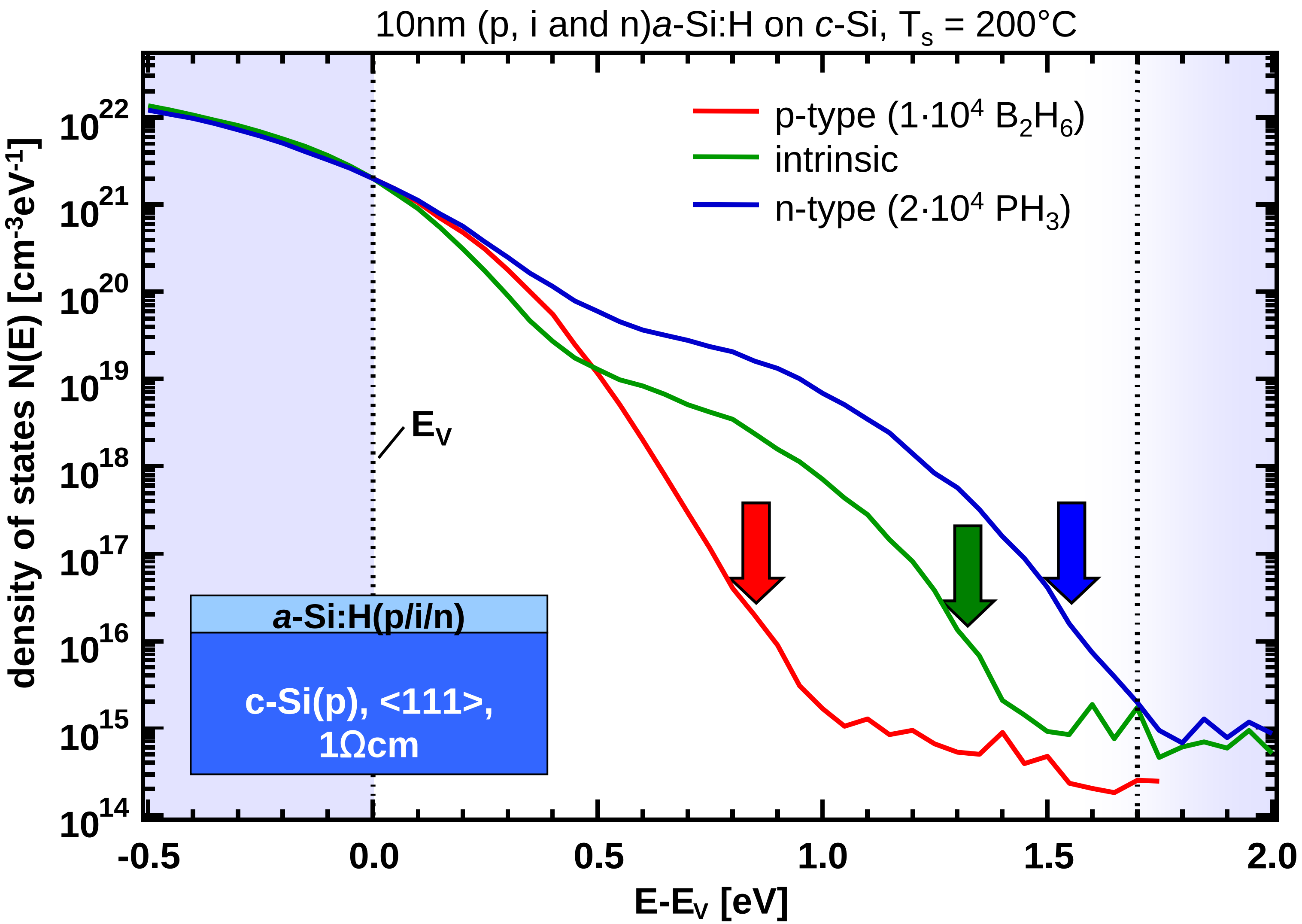
doping dependence of N(E), E_F



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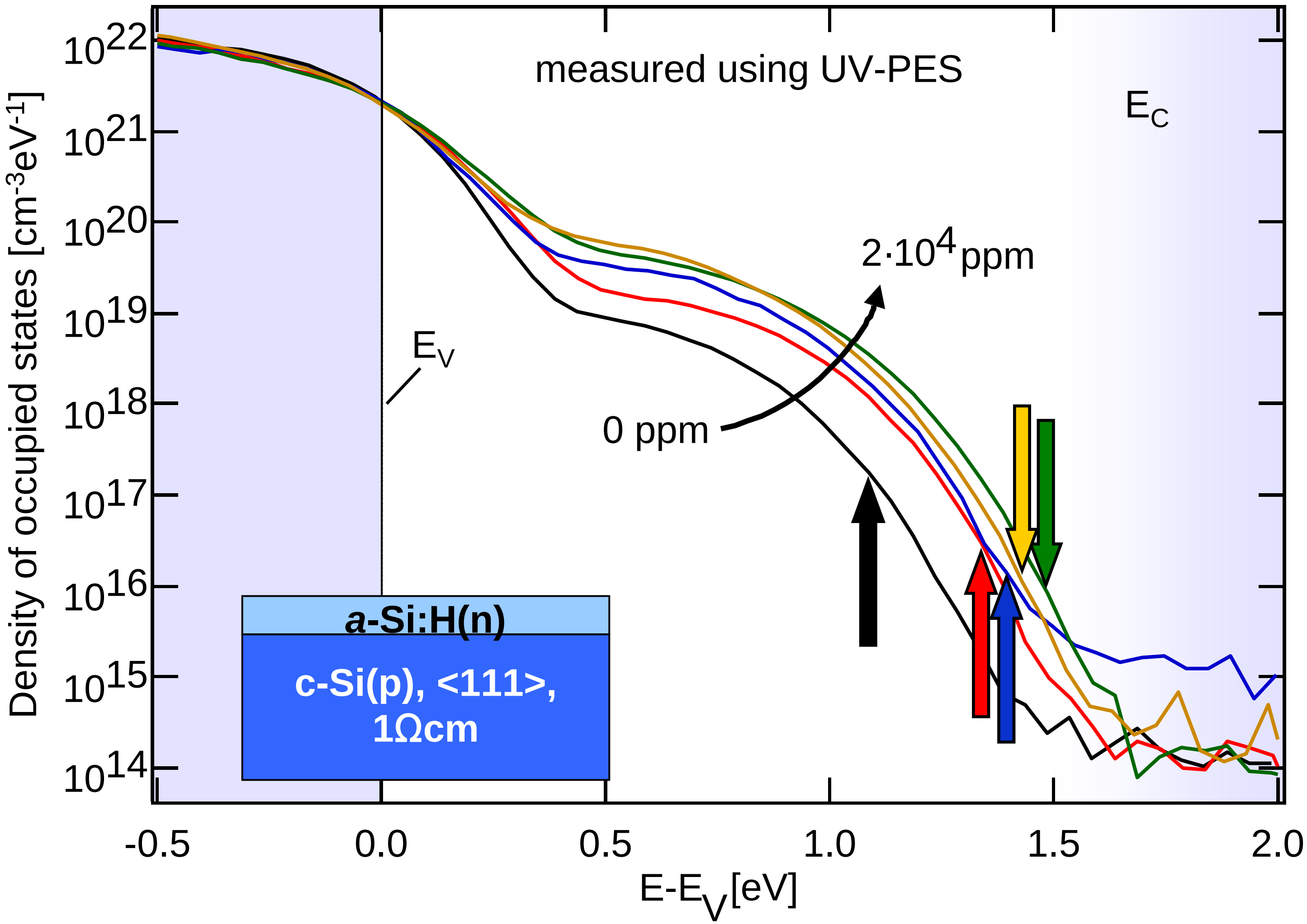
n-type doping series

samples: ~10 nm *a*-Si:H(n) on *c*-Si(p), $[PH_3]/[SiH_4] = 0 – 2\times10^4$ ppm, T_s=170°C



Korte & Schmidt, J. Non-Cryst. Sol. *354* (2008) 2138

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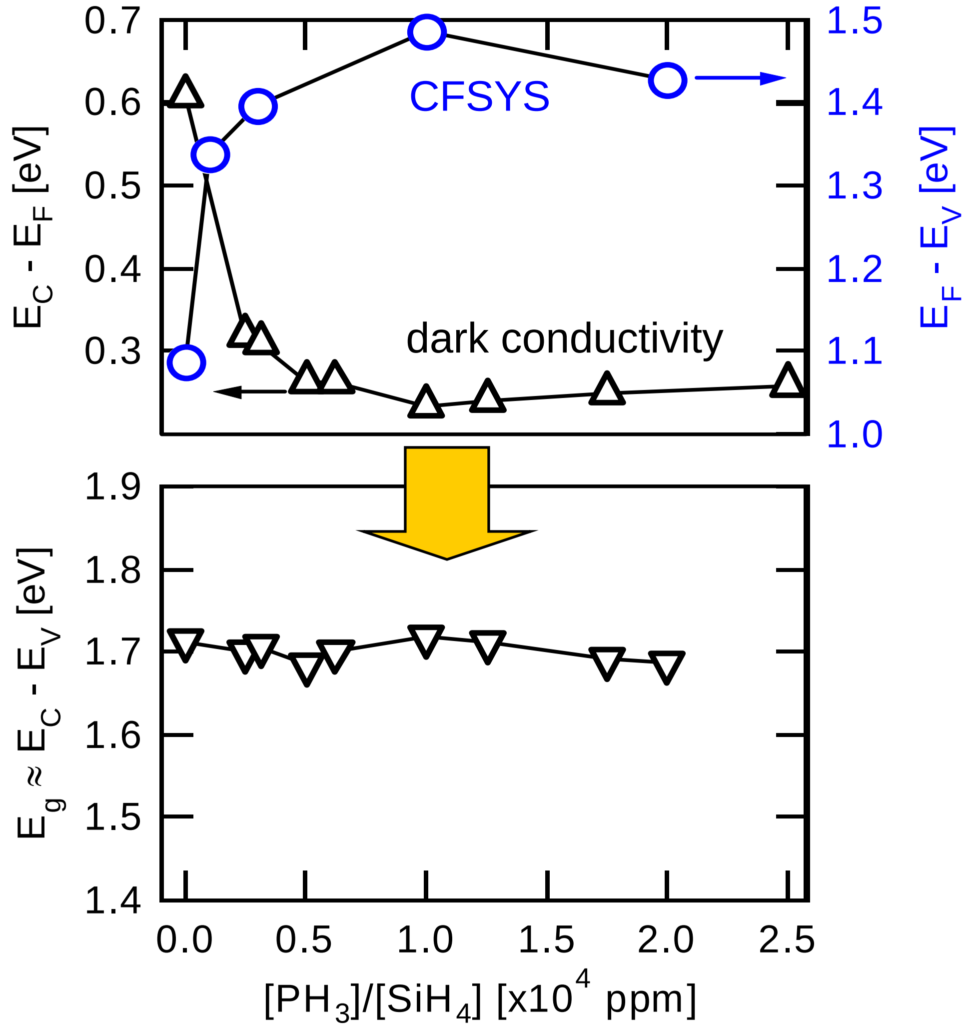

optimum doping:
$[PH_3]/[SiH_4] = 10^4$ ppm?

no change in band gap
with doping (E_g~1.7eV)

same as for thick films
(e.g. V. Chacorn, D. Haneman,
Solid State Comm. *65* (1988) 609)

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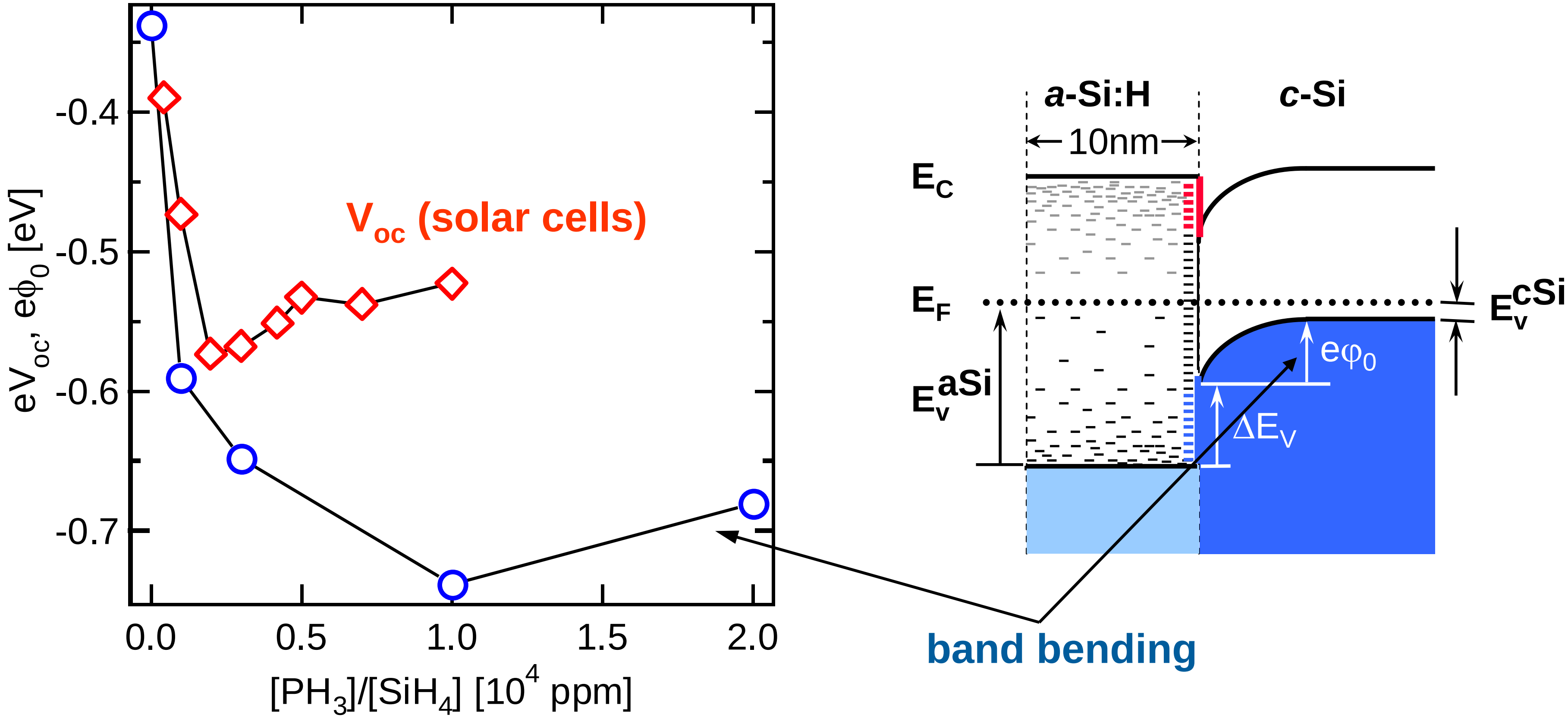
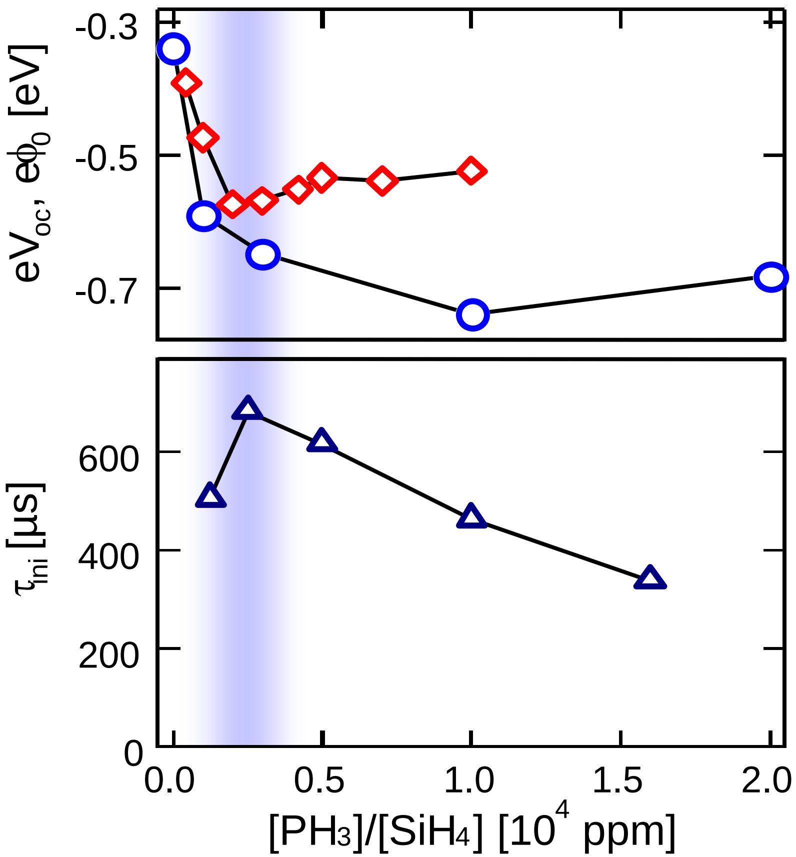


optimum doping ~ 2000ppm - higher doping: enhanced recombination?

Korte & Schmidt, J. Non-Cryst. Sol. *354* (2008) 2138

Band bending, V_{oc} and recombination - optimized a-Si:H doping



calculated band bending

cell V_{oc}

effective charge carrier lifetime at high injection (from surface photovoltage)

SPV data:
A. Laades, PhD Thesis, HMI/TU Berlin

doping > 2000ppm: enhanced recombination ➔ reduced charge carrier conc.
➔ V_{oc} decreases

and also: hopping into a-Si:H via a-Si:H tail states possible, additional recombination
(see also: Boehme *et al.*, J. Non-Cryst. Sol. *352* (2006) 1113)

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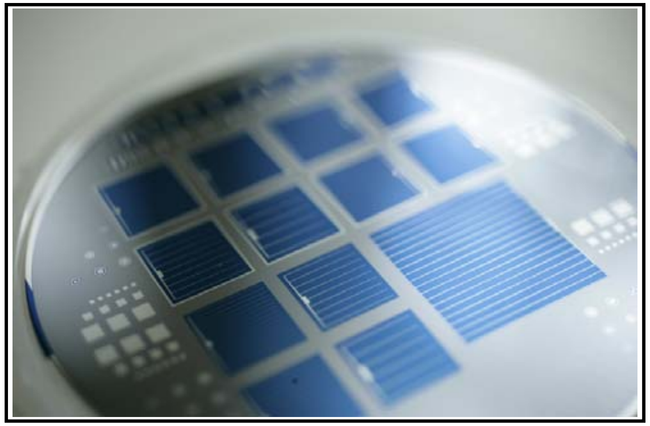

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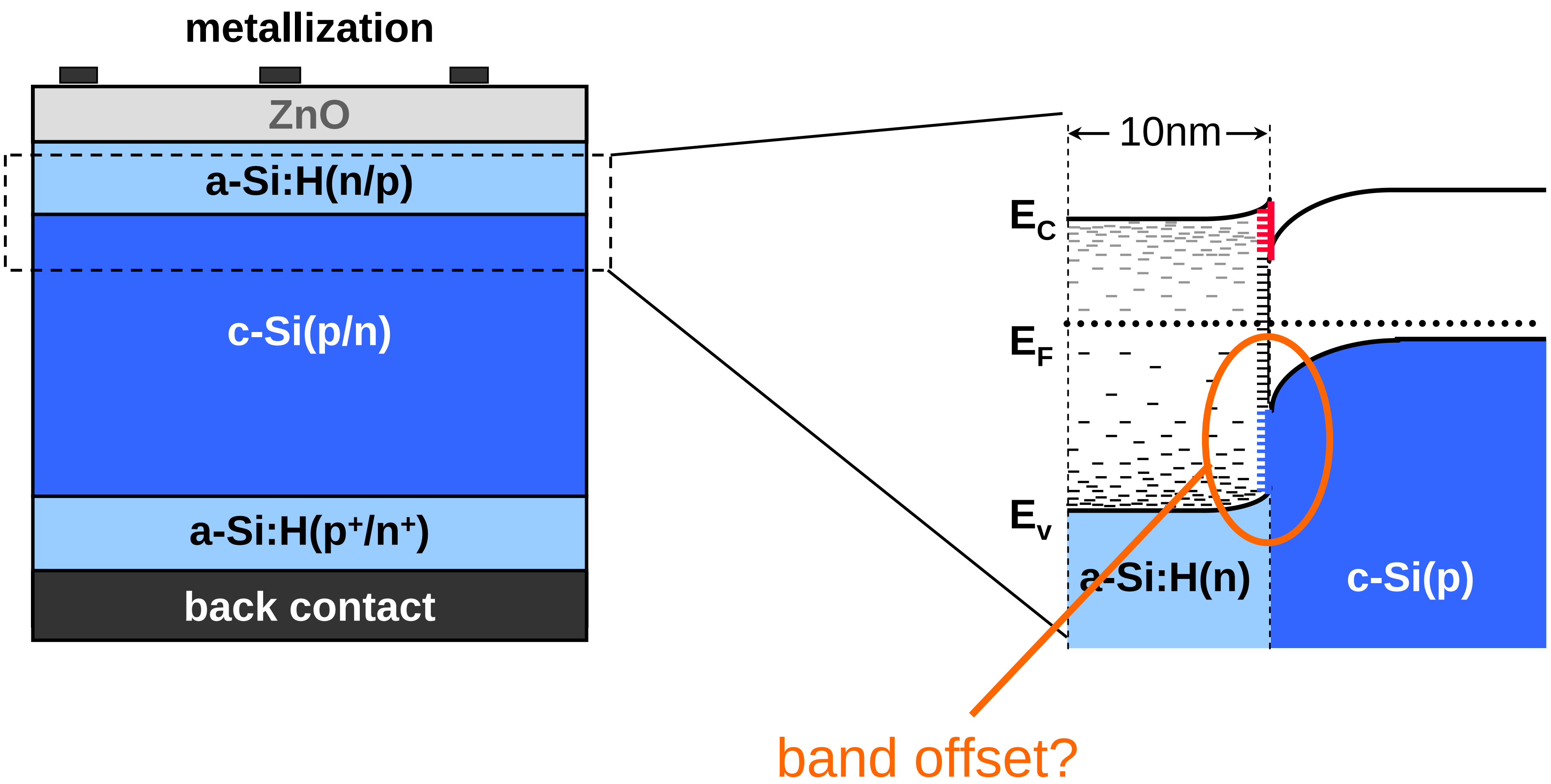
cell structure

band diagram



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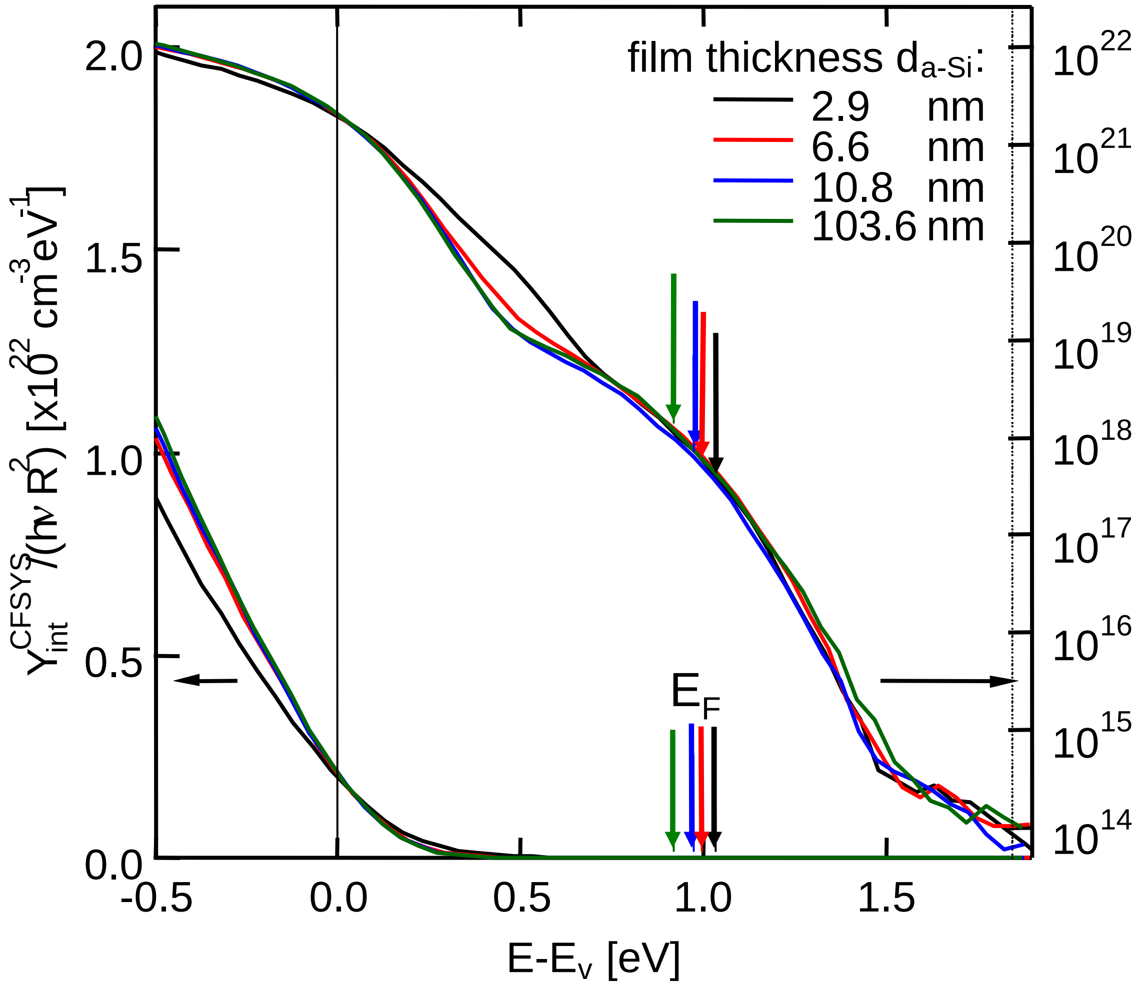
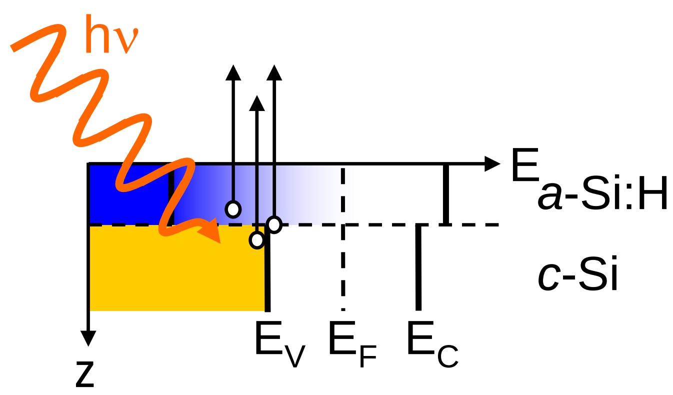
a-Si:H/*c*-Si valence band offset

example: *a*-Si:H(i) / *c*-Si(p)



assumption/model:



d_{aSi} < information depth

photo-electrons from substrate

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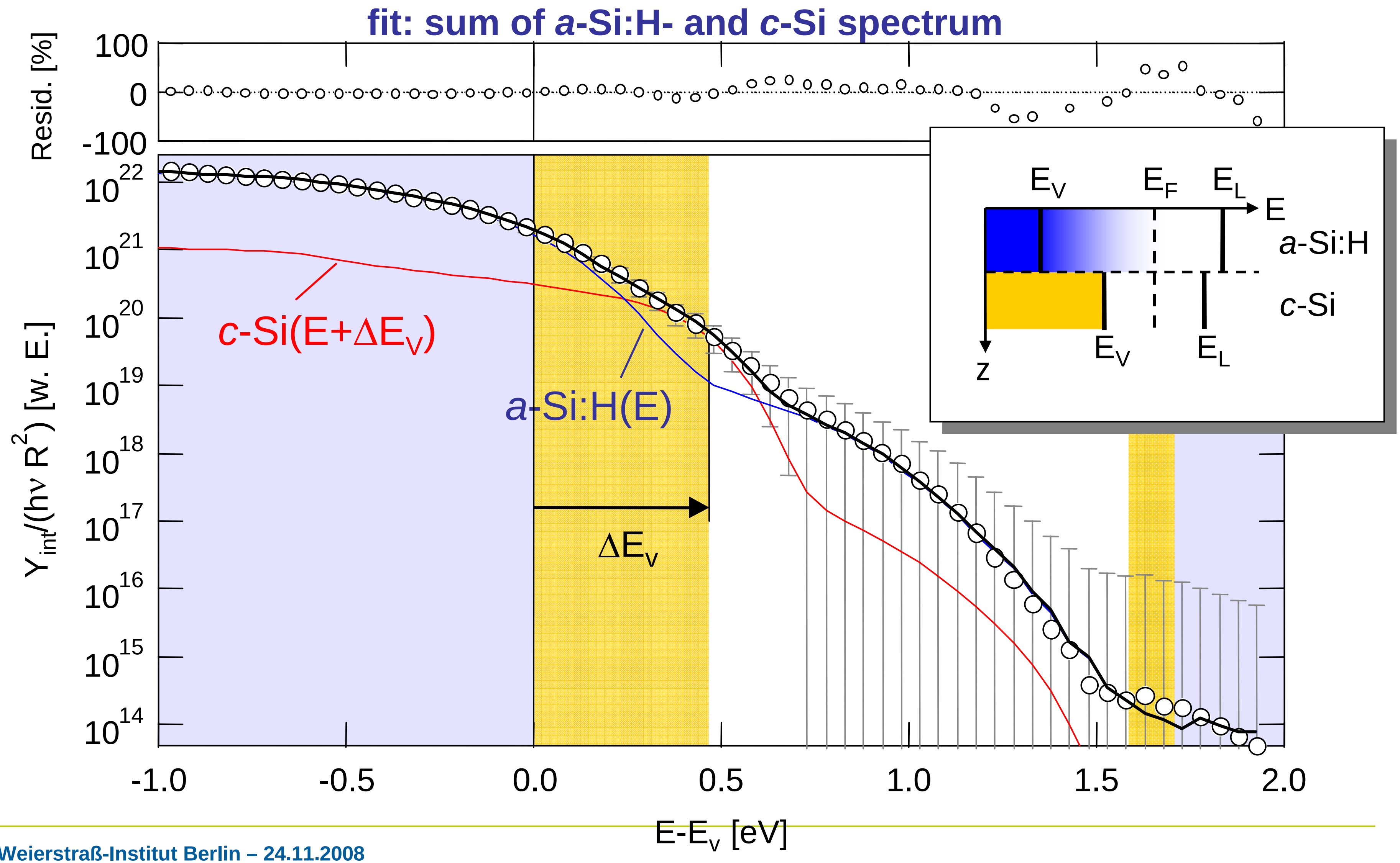
a-Si:H/*c*-Si valence band offset



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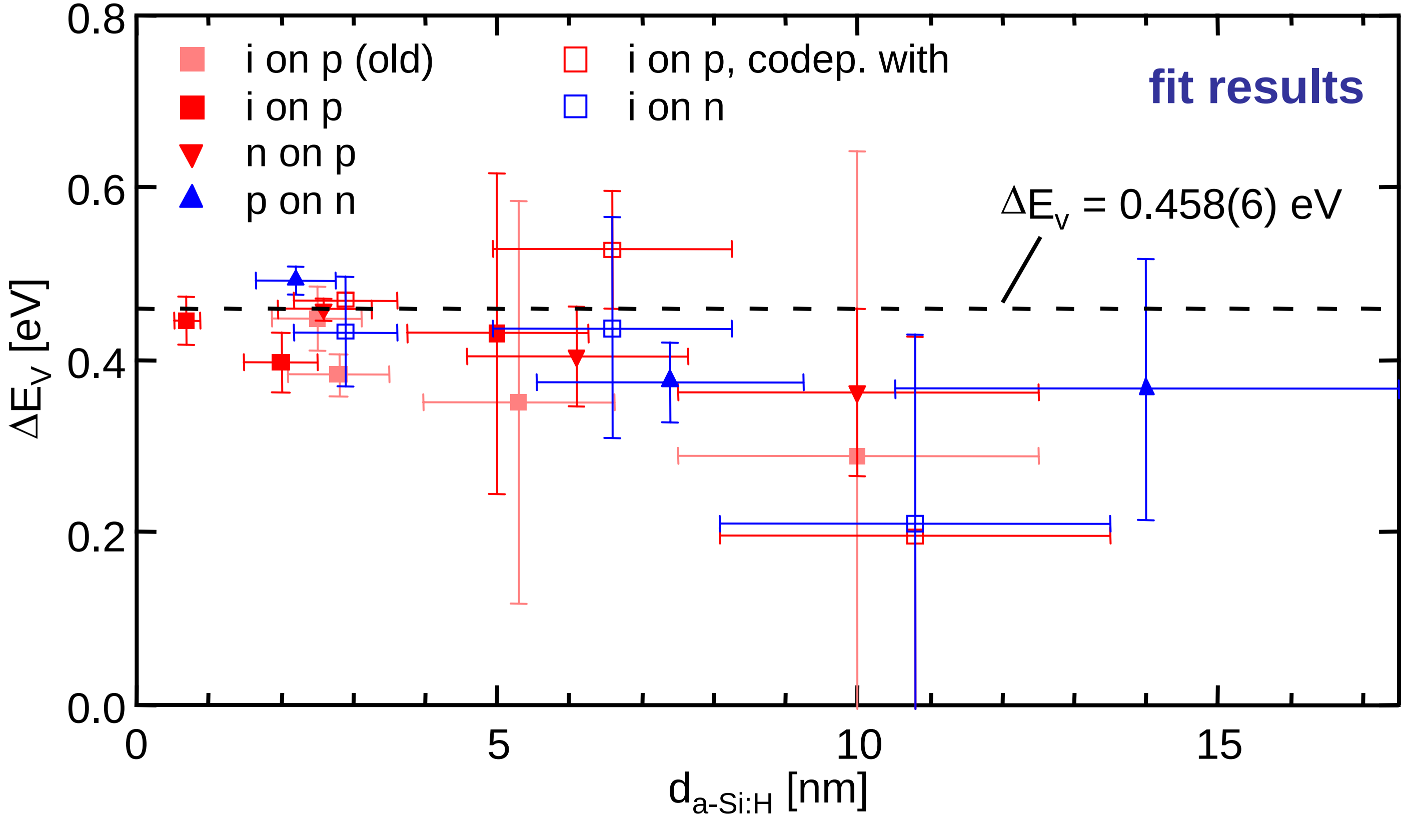
a-Si:H/*c*-Si valence band offset



- **mean: ΔE_V=0.458(6) eV** (systematic error: ~50 meV)
- no dependence on substrate- or film doping
- (weak) trend: decreasing ΔE_V with film thickness - possible explanation: decreasing Si-H interface dipole, because Si-H bonds are substituted with Si-Si

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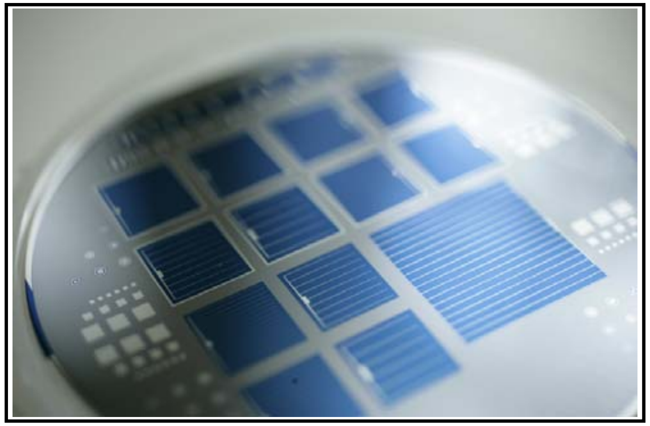
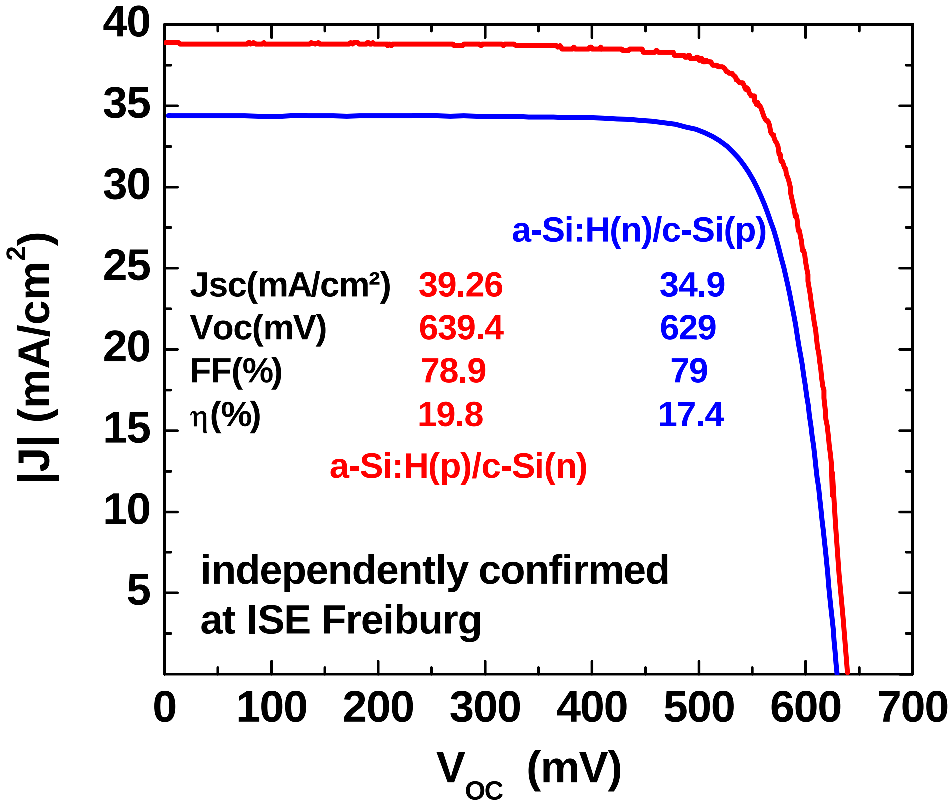
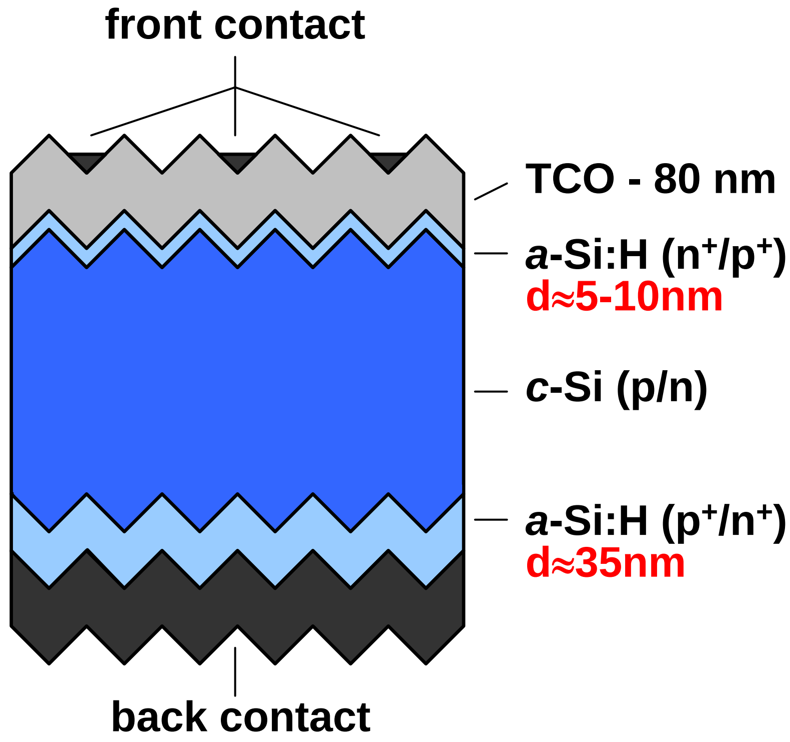


Solar cell results





doping sequence	texture	η	V_{oc}	J_{sc}	area
a-Si(n)/c-Si(p)/a-Si(p)	pyramids	17.4 %	629 mV	34.9 mA/cm²	1 cm²
	pyramids	18.4 % ← uncertified			1 cm²
a-Si(p)/c-Si(n)/a-Si(n)	pyramids	19.8 %	639 mV	39.3 mA/cm²	1 cm²

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Summary

a-Si:H growth

- growth mode on *c*-Si: islands – coalescence – thickening
- high hydrogen content at *a*-Si/*c*-Si interface ↔ enhanced defect density
- **optimum growth conditions:**
  - **high c-Si surface quality** prior to a-Si:H deposition
  - **low plasma damage during growth**
  - **low defect density in a-Si:H "bulk"**
  - → **reduced recombination**

a-Si:H/c-Si interface

- device simulation: (effective) **interface DOS < 10^{10} cm^{-2}**
  → **not detrimental to cell** parameters
- asymmetric band offset: **ΔE_V ~ 460meV** (→ ΔE_C ~ 150-200meV)

n-doped a-Si:H emitters

- Urbach-Energy and N_D increase with doping, comparable to thick films
- **optimum doping for device ~2000ppm**, not at minimum of E_F-E_C – trade-off: doping ↔ defect generation

Thank you

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Aziz Laades
Karsten von Maydell
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Kerstin Jacob
Brunhilde Rabe
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„Grundlagen und Technologie von Solarzellen auf der Basis von a-Si/c-Si Heterostrukturen“

hetsi

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“Heterojunction Solar Cells based on a-Si c-Si”