Frühjahrstagung, Bonn 2010

Hauptvortrag AKE 1.2 (15) Mo, 15.3.2010 14:30 JUR D

Source: http://www.volker-quaschning.de/fotos/REG1/PV1_1024x768.jpg; 13.3.2010

Entwicklungsoptionen für die Photovoltaik mit kristallinem Silicium

Rolf Brendel

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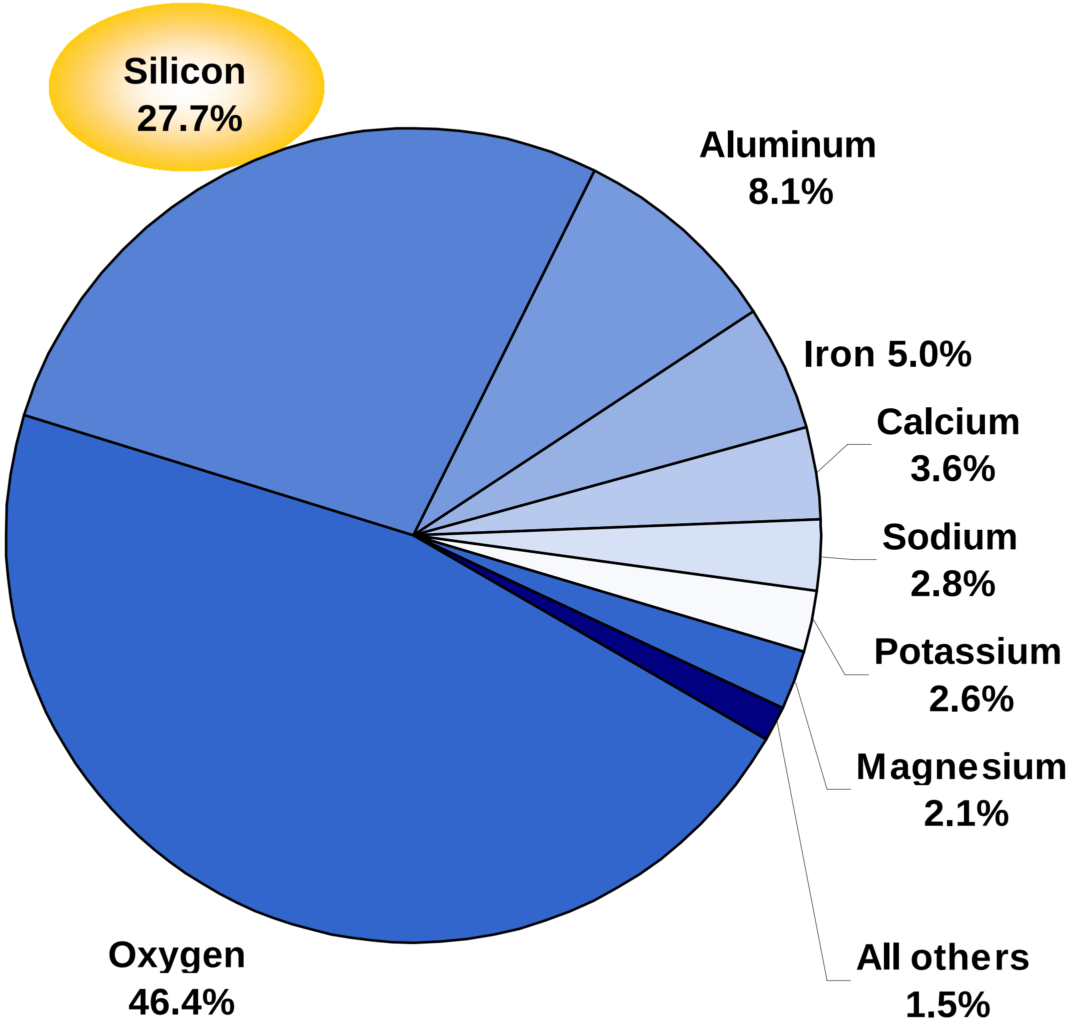
Why crystalline Si?

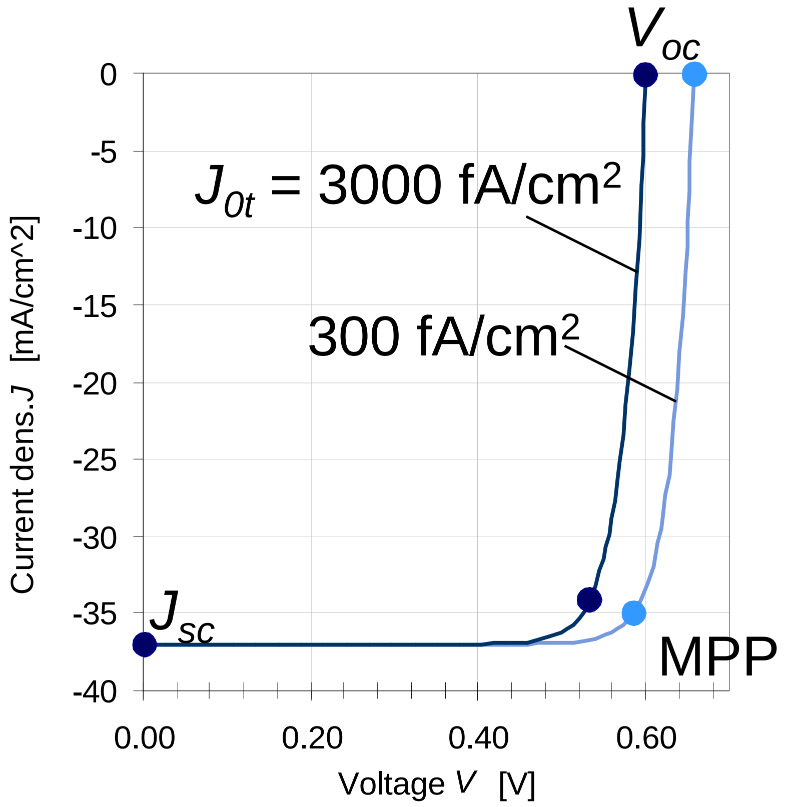


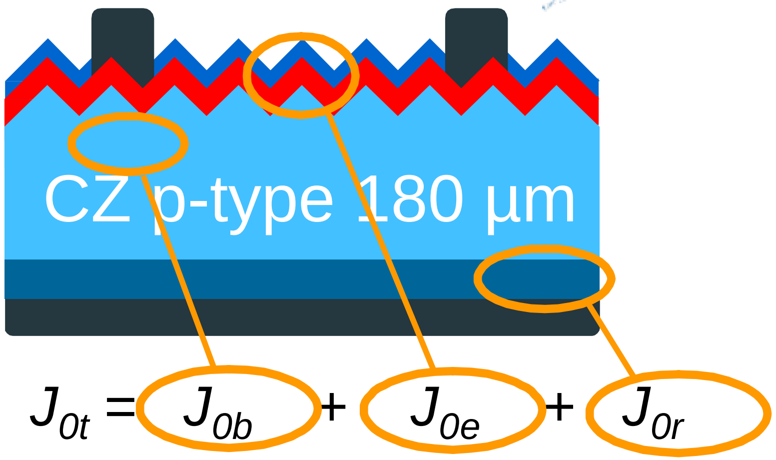
Data source: F. K. Lutgens and E. J. Tarbuck, *Essentials of Geology*, (Prentice Hall, 2000).

- Si is the 2nd most abundant element in the earths crust
- Non-toxic
- Long term reliable

Current voltage curve of a solar cell

$$J(V) = J_{0t}\left(e^{\frac{qV}{kT}} - 1\right) - J_{sc}$$



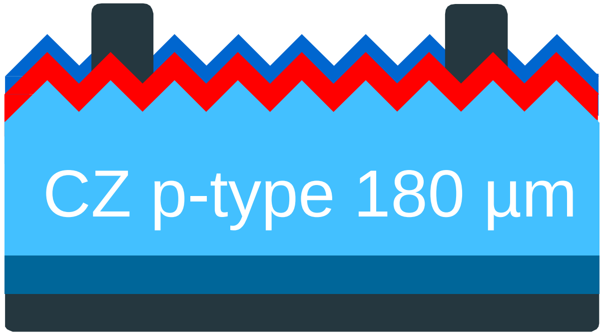


$J_{0t} = J_{0b} + J_{0e} + J_{0r}$

- Diode saturation current describes recombination losses
  due to
  - Radiative recombination
  - **Auger recombination**
  - **Defect recombination**

- Three major locations:
  - Front, bulk and rear

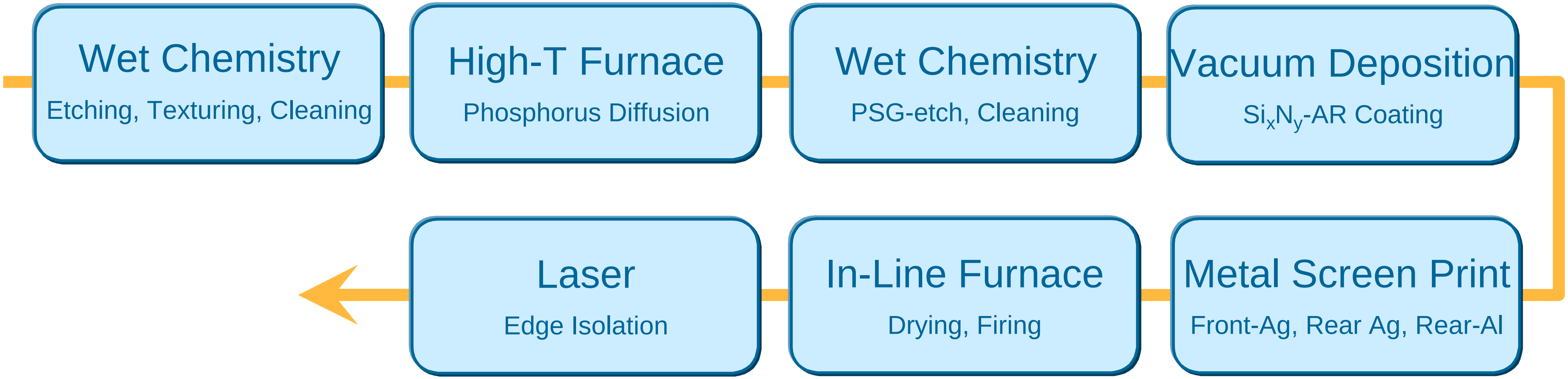
Reference scenario: Standard screen-printed multi cell



Efficiency

η_o=16.0 %

7 Steps
95% yield



Wet Chemistry
Etching, Texturing, Cleaning

High-T Furnace
Phosphorus Diffusion

Wet Chemistry
PSG-etch, Cleaning

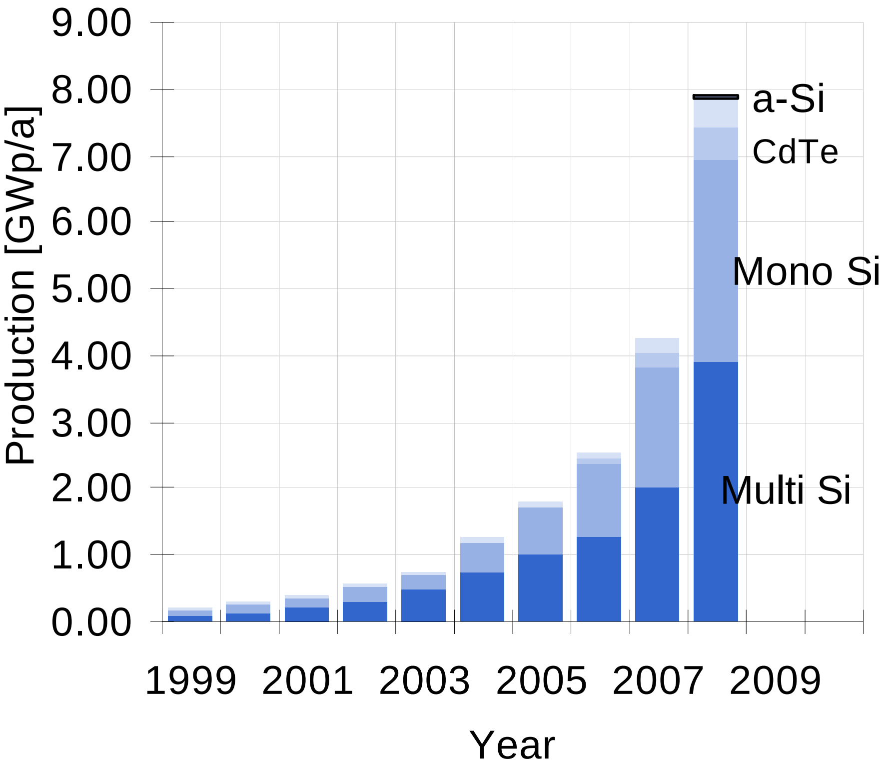
Vacuum Deposition
Si_xN_y-AR Coating

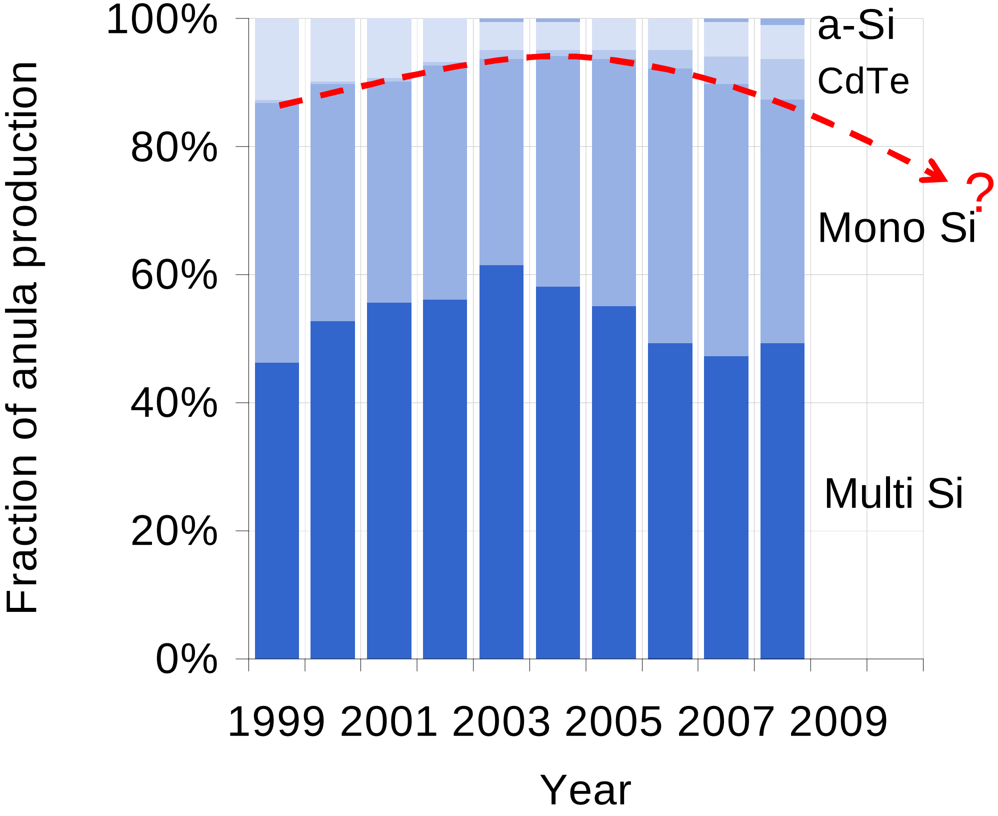
Metal Screen Print
Front-Ag, Rear Ag, Rear-Al

In-Line Furnace
Drying, Firing

Laser
Edge Isolation

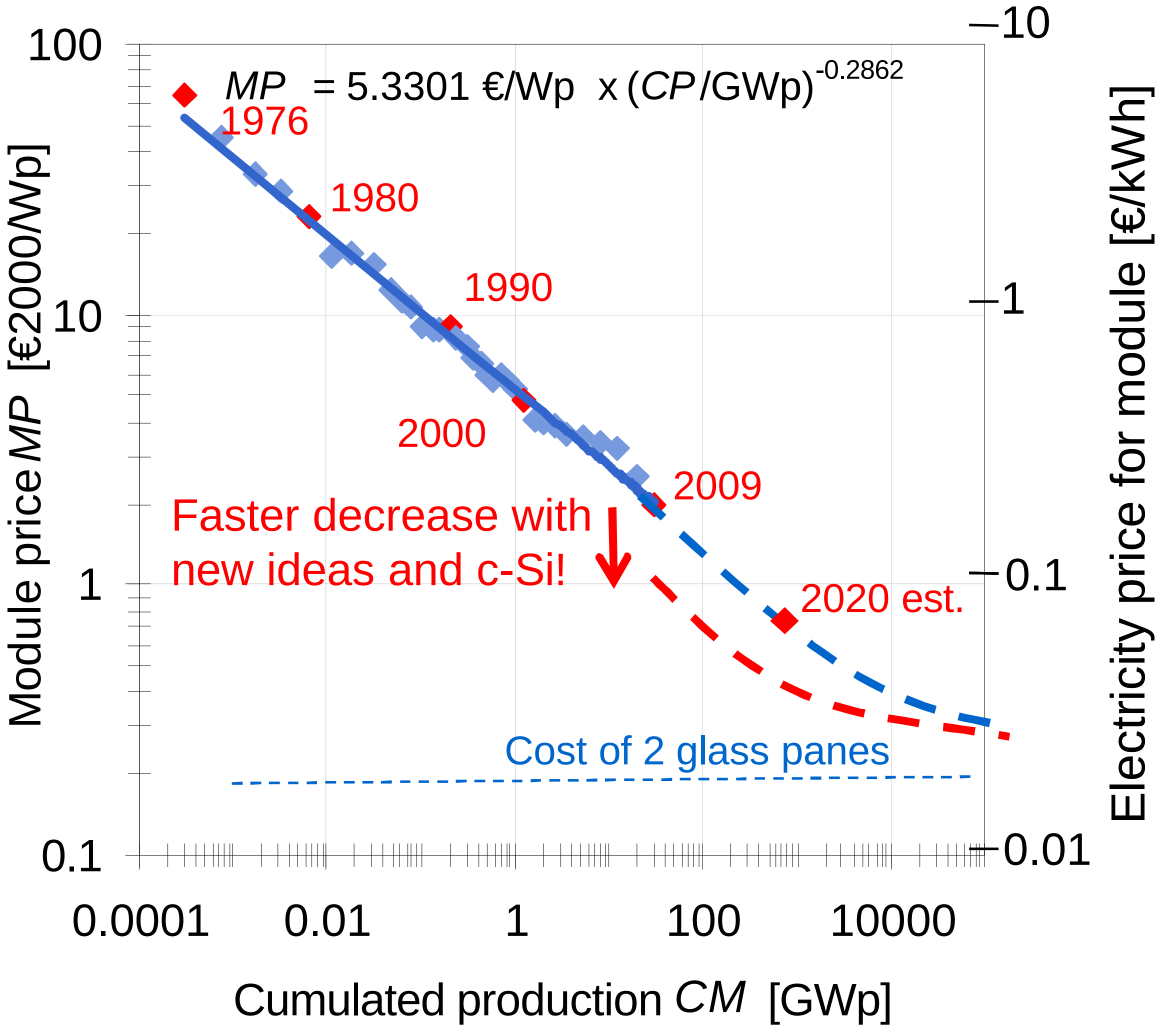
Annual production: c-Si dominates while CdTe is gaining shares





Calculated from data in: Photon 4/2009, p. 57

Learning curve: tremendous progress in manufacturing!



Data Source: Quaschning, Erneuerbare Energien, Hanser 2010, p. 132, conv. with 0.92 €/$
2008 and 2009: own estimates

- Module price decreased by 20 % per doubled cumulated production volume
- 2009’s module contribution to electricity price: 0.17 €/kWh
  (for 20 a lifetime, 4% interest rate and 1% maintenance at 1000 kWh/kW$_p$)
- Learning curves forecast: 2020’s module contribution to electricity price: 0.07 €/kWh

→ How to half costs ?

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Looking at the cost structure to find options for cost reductions

ISFH

- Wafer costs

$$c_w(t,\eta)=0.59\frac{€}{W_p}\frac{\eta_o}{\eta}\left(1+\frac{\eta-\eta_o}{0.22-\eta_o}0.2\right)\cdot\left(\frac{0.38}{n_w}+0.62\frac{t}{t_0}\right)$$

η_0 = 0.16 is reference efficiency
t_0 = 180 µm thickness
+100 µm kerfloss
Wafer for 22% is 20% more expensive than wafer for 16 %.
n_w =1 is number of wafers per sawing. n_w > 1 for splitting technologies.

- Cell costs

$$c_c(\eta,n_c)=0.34\frac{€}{W_p}\cdot\frac{\eta_0}{\eta}\cdot\frac{n_c}{n_{c0}}\cdot 0.95^{\frac{n_{c0}-n_c}{n_{c0}}}$$

n_{c0} = 7 is reference number of steps.
t_0 = 180 µm thickness +100 µm kerfloss is reference consumption.

- Module costs

$$c_m(\eta,n_{m0})=0.39\frac{€}{W_p}\cdot\frac{\eta_0}{\eta}\cdot\frac{n}{n_{m0}}\cdot 0.95^{\frac{n_{m0}-n_m}{n_{m0}}}$$

n_{n0} = 6 is reference number of steps for module.

- BOS costs

$$c_{bos}(\eta,n_{m0})=0.3\frac{€}{W_p}+0.08\frac{€}{W_p}\frac{1}{0.9\eta}$$

Module efficiency is 90% of cell efficiency.

C. Beneking, IEA PVPS, Task 8
3rd phase report, 2009

Phot. Int. 1/2010, p. 83

P. Fath, IEEE PVSEC 2009

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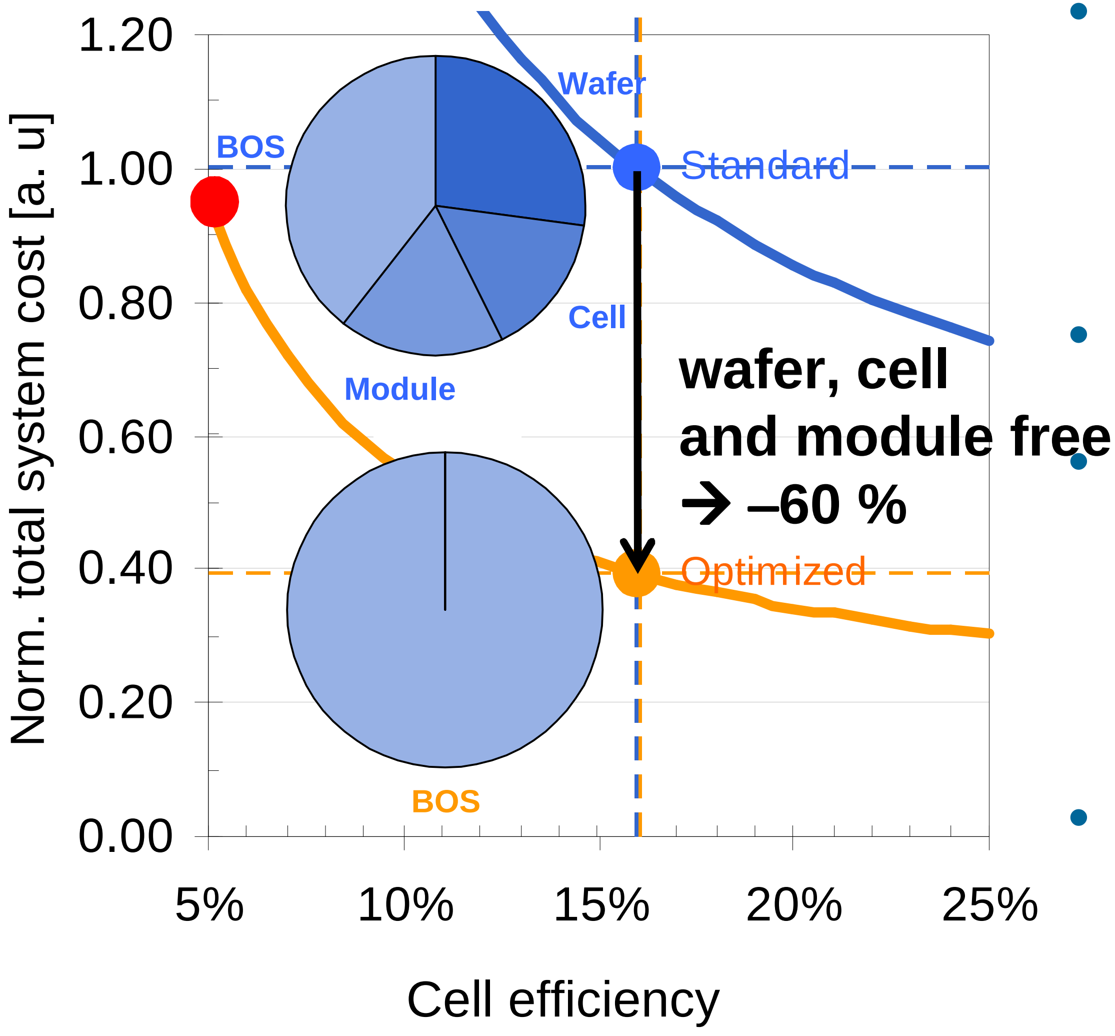
Hannover

Fixed BOS costs limit scope for improvements by the module



wafer, cell and module free
→ –60 %

- Increasing cell efficiency reduces area related costs
  - may require more expensive wafer
  - often increases cell costs
- Module more expensive then cell processing
- BOS limits improvements
  - zero cost for wafer, processing &module
  - → syst. cost down by 60 %
  - → halfing cost requires drastic improvements in BOS also
- New players, e.g. organic PV
  - Assume 5% eff.
  - and 20 a stable on large areas and
  - zero cost for materials and processes
  - → Syst. cost as for *today's* c-Si systems

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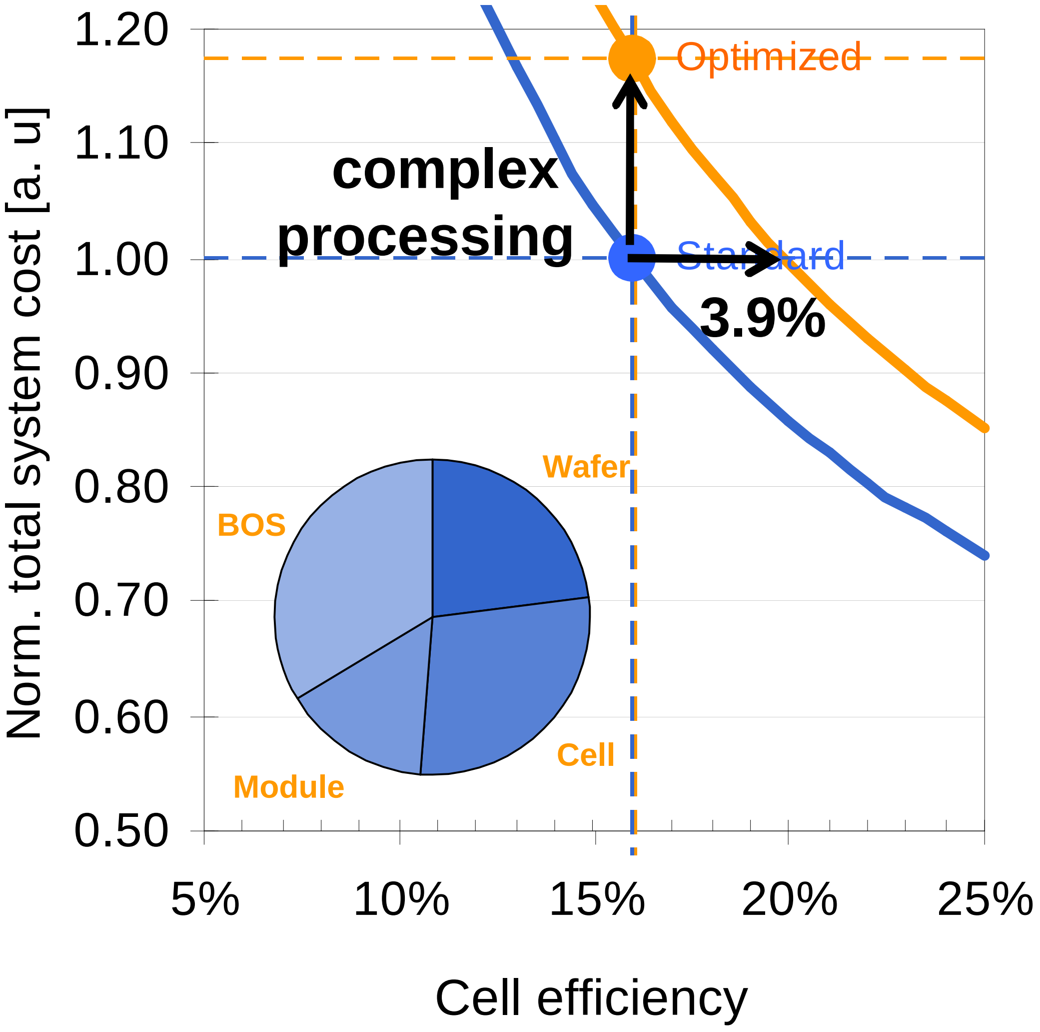
Doubling the number of cell processes…

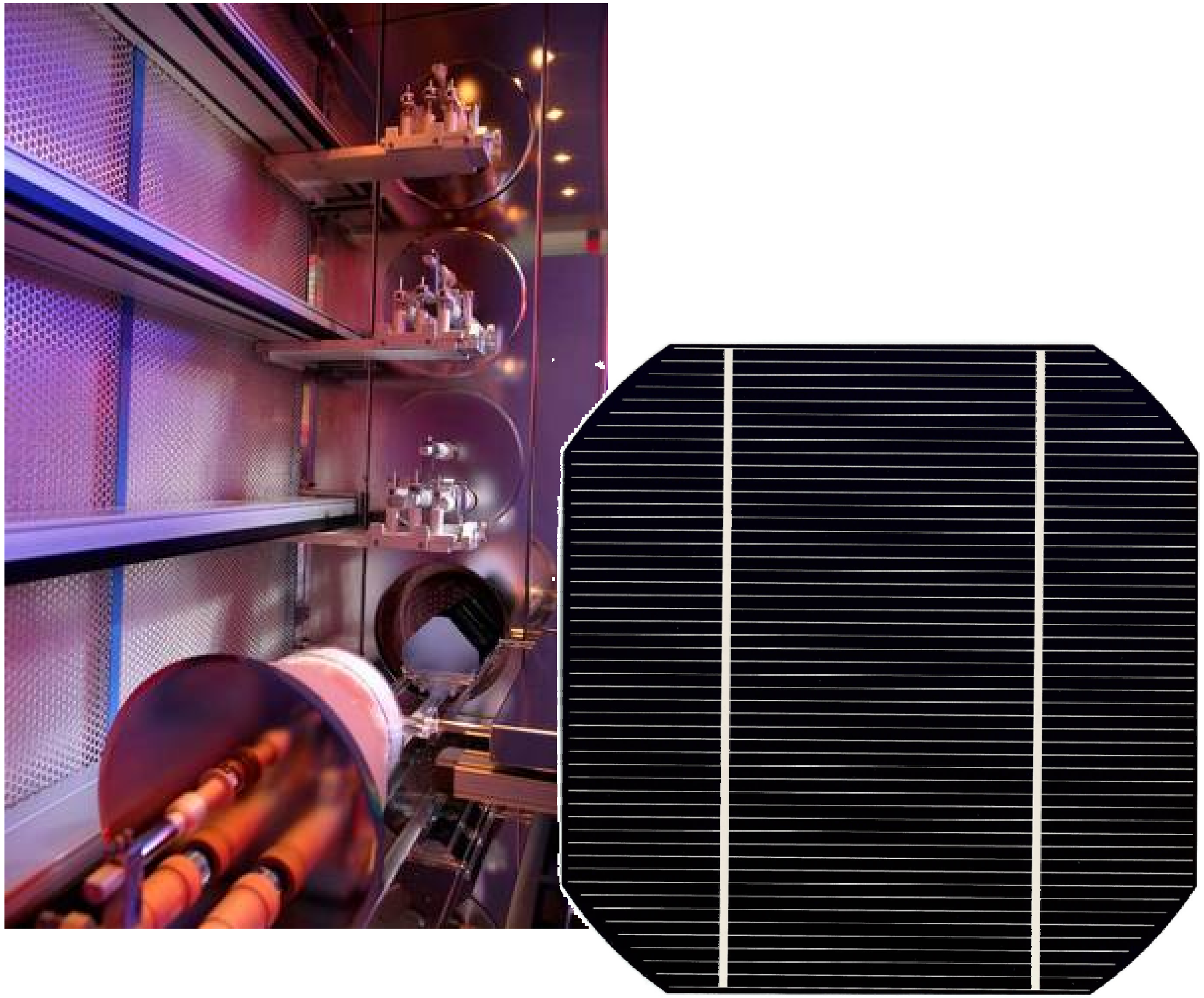


- …costs 3.9 % efficiency!
- Very complex process require efficiency >> 16 + 3.9 =19.9 %

Improving the bulk

by reducing B-O defects

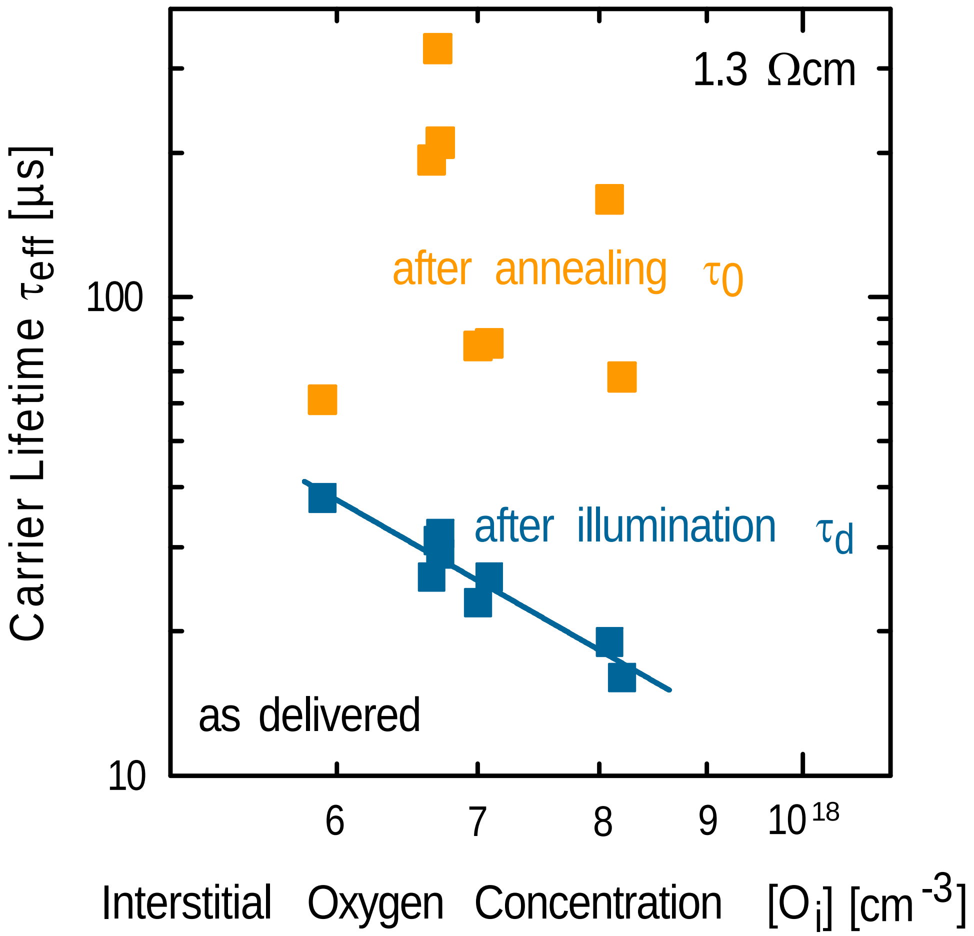
Change from multi- to mono-Si
→ improves bulk quality



- Cell parameters
  - Area 12.5x12.5 cm^2
  - 2 Ωcm, B-doped CZ
  - SiN-Passivation
- Results
  - V_{oc} = 626.8 mV
  - J_{sc} = 35.9 mA/cm^2
  - FF = 77.9 %
  - **η = 17.5 %**
- Lifetime is B-O -limited

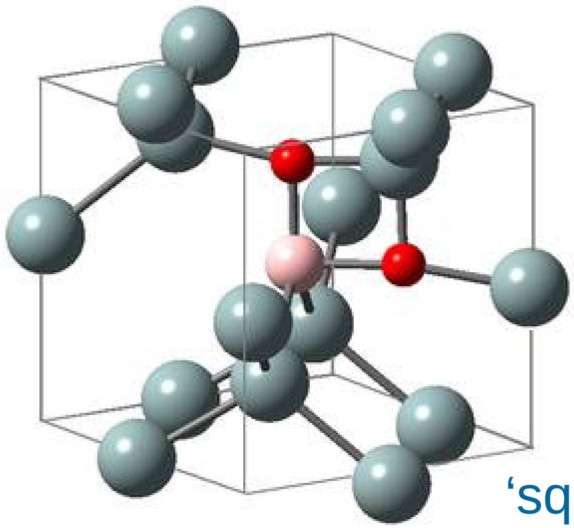
Lifetime in CZ-Si after degradation: Limited to smaller value by B_sO_{2i}

(Group Bothe)



- **Illumination** activates B-O defect
  ⇒ Lifetime limited by **B-O defect**
- **Annealing** deactivates B-O defect

  ⇒ Lifetime limited by **residual defects**



$B_sO_{2i}^{sq}$
'square' form

J. Schmidt and K. Bothe, Phys. Rev. B ***69****, 024107 (2004)*
J. Adey et al., Phys. Rev. Lett. ***93****, 055504 (2004)*

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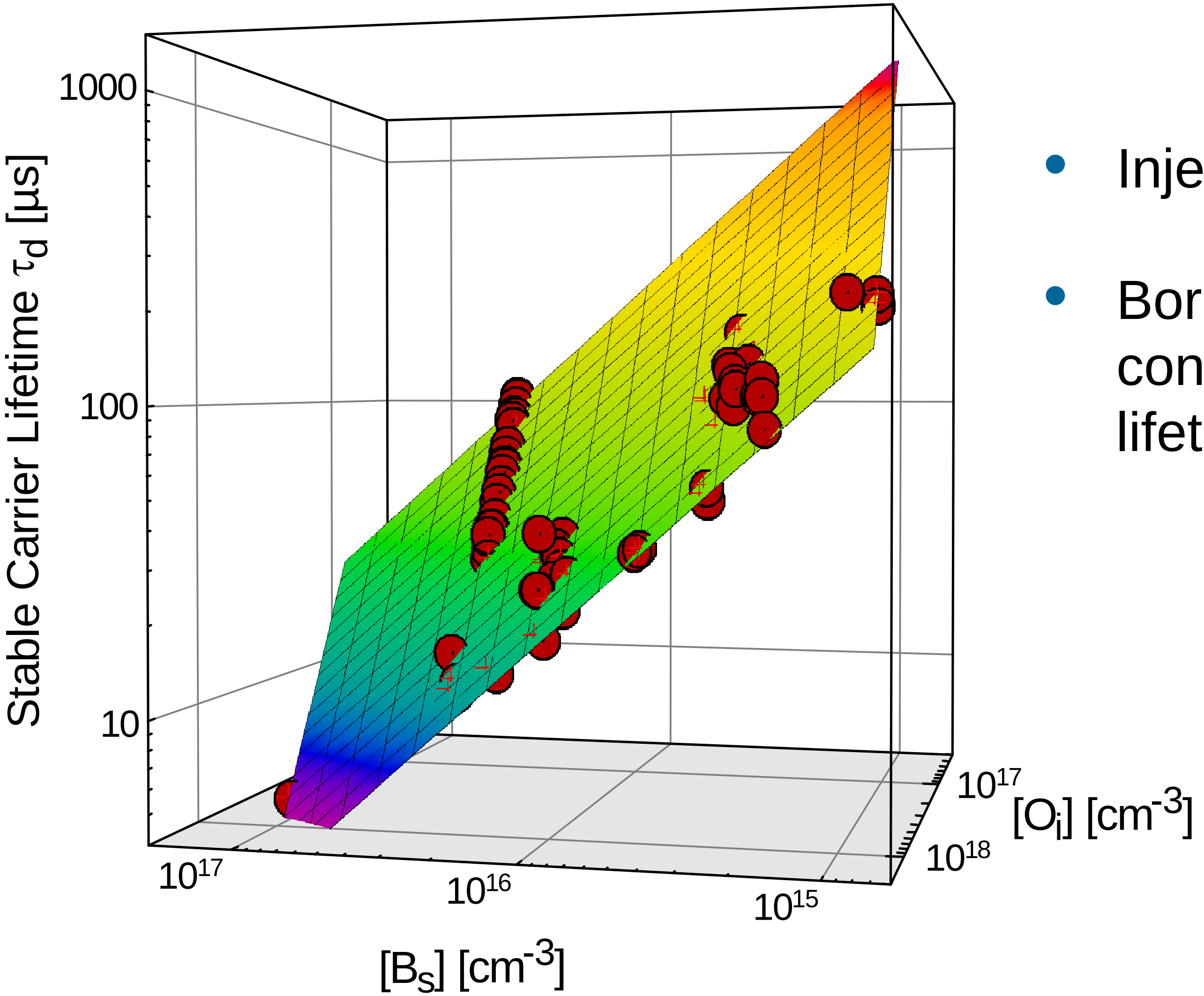
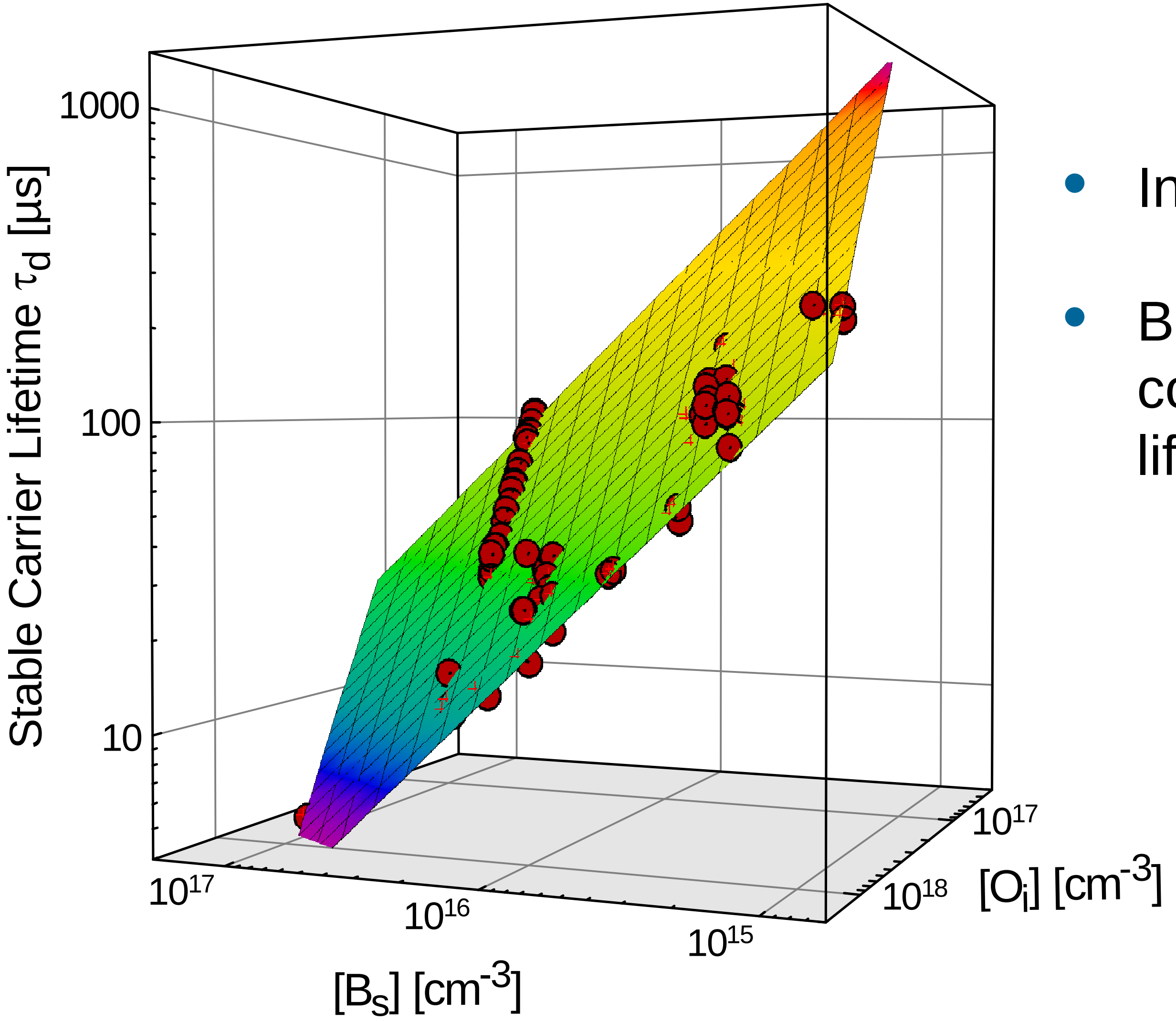
Boron and oxygen concentration control the lifetime



- Injection level $\Delta n/N_A$=0.1
- Boron and oxygen concentration control the lifetime

K. Bothe, R. Sinton, and J. Schmidt, Prog. Photovoltaics ***13****, 287 (2005)*

Boron and oxygen concentration control the lifetime



K. Bothe, R. Sinton, and J. Schmidt, Prog. Photovoltaics ***13****, 287 (2005)*

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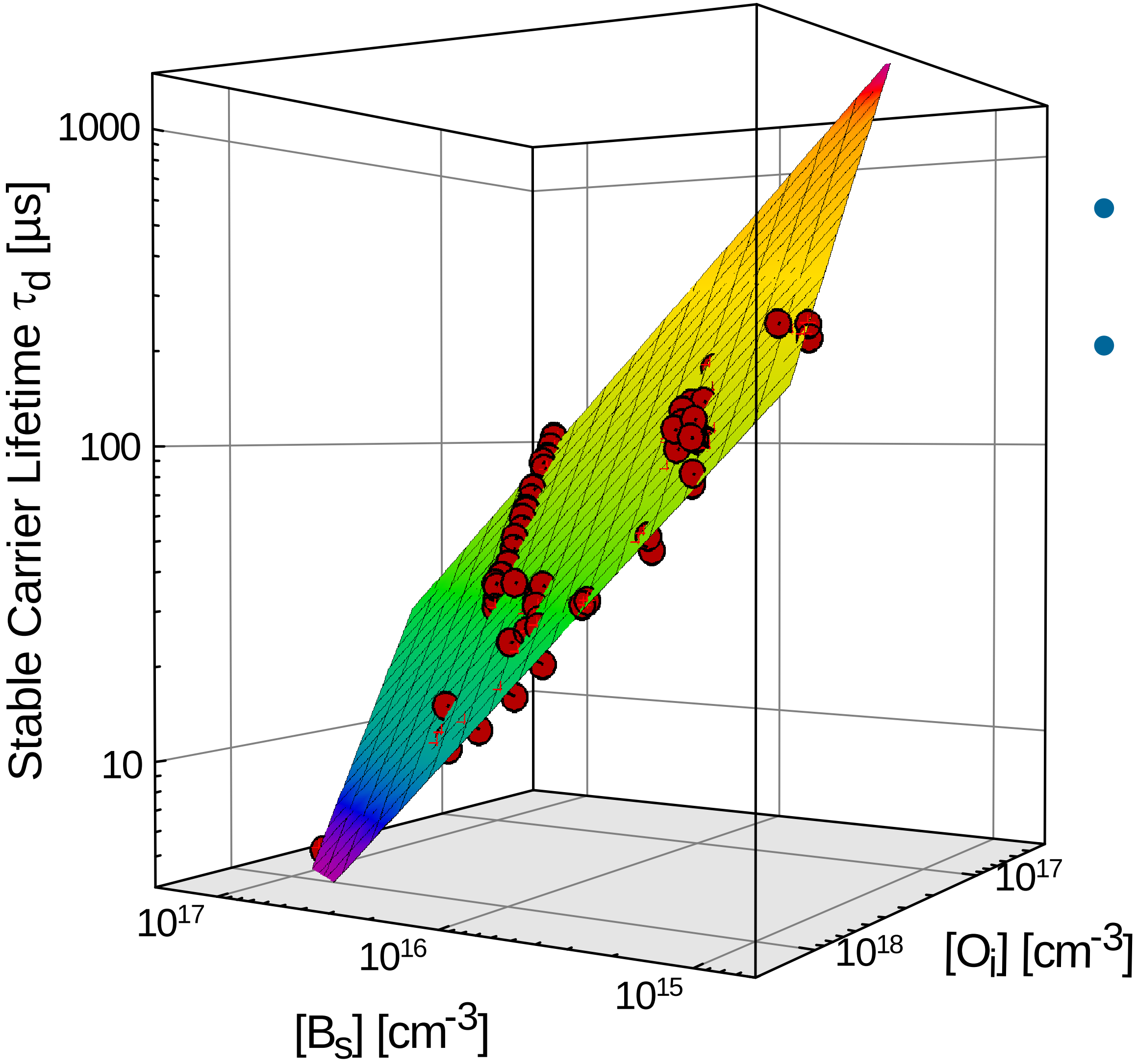

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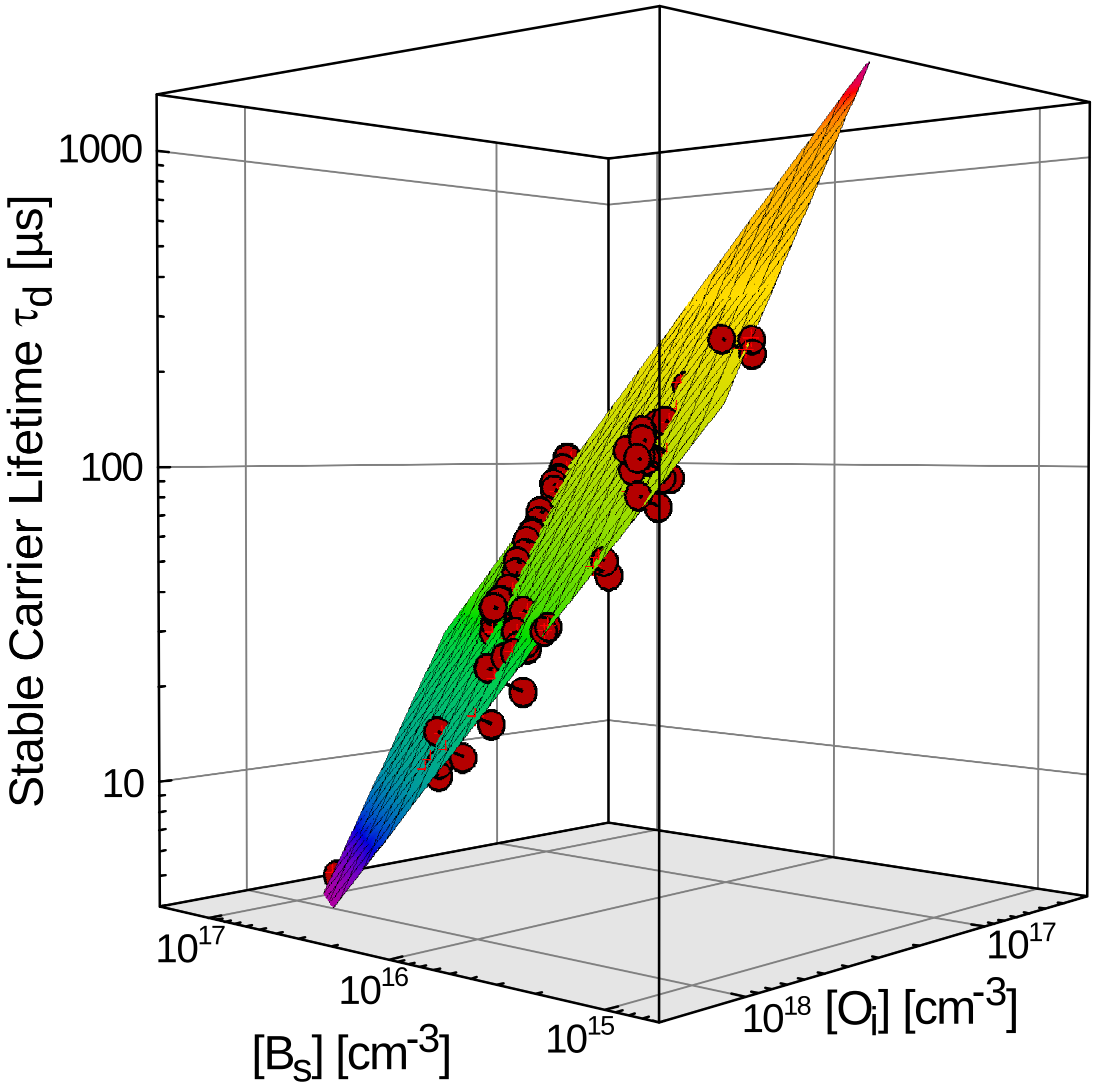

K. Bothe, R. Sinton, and J. Schmidt, *Prog. Photovoltaics* ***13****, 287 (2005)*

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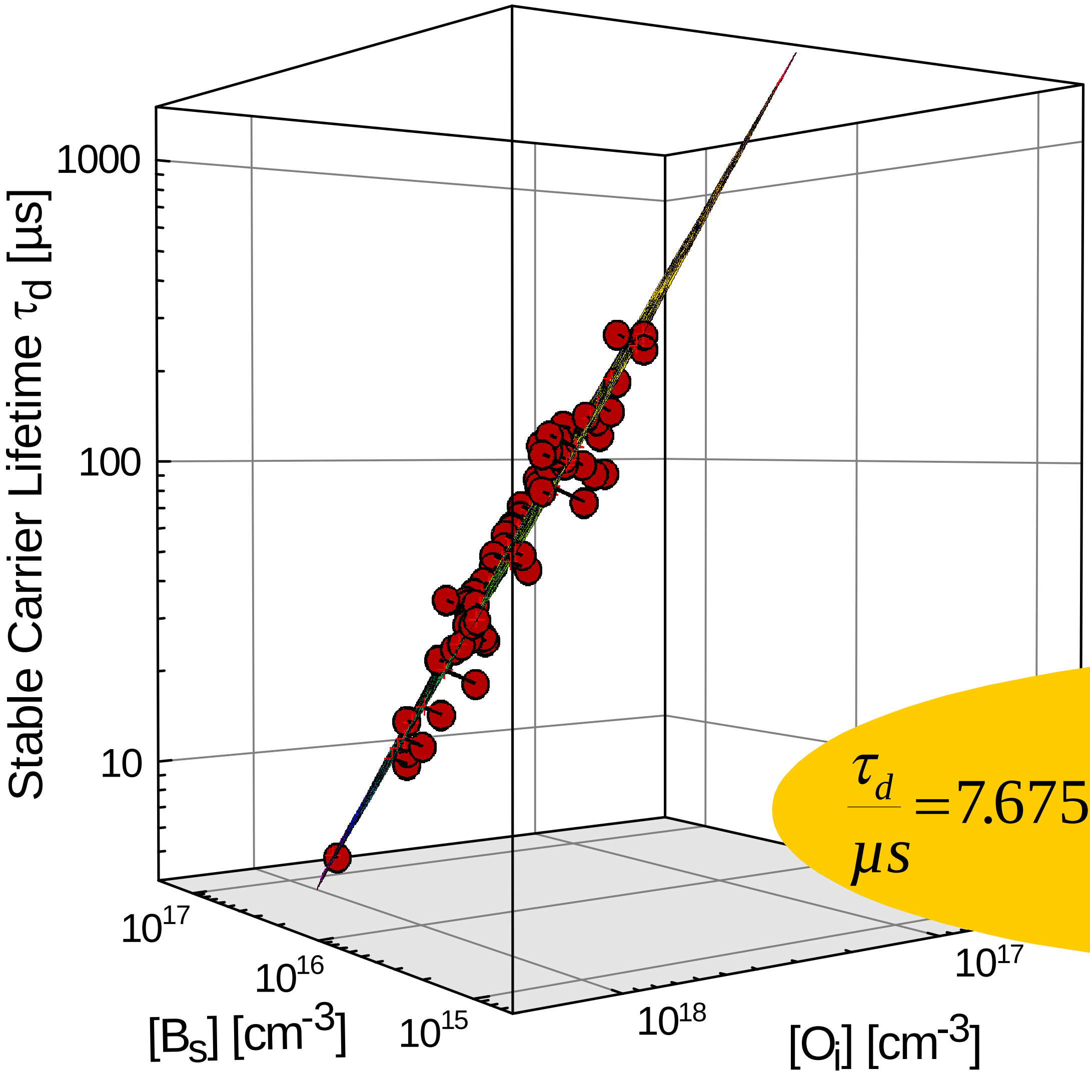
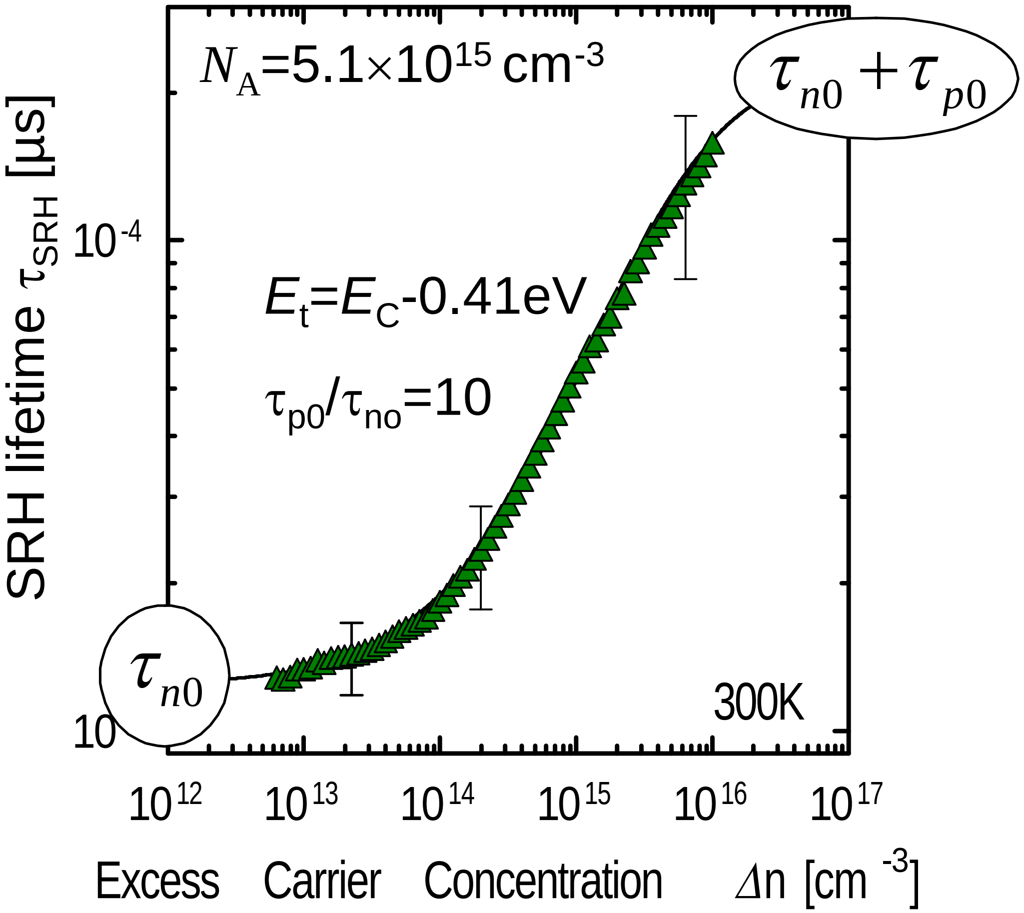


- Injection level $\Delta n/N_A$=0.1
- Boron and oxygen concentration control the lifetime

$$\frac{\tau_d}{\mu s} = 7.675\times10^{45}\cdot\left(\frac{N_A}{\mathrm{cm}^{-3}}\right)^{-0.824}\cdot\left(\frac{N_O}{\mathrm{cm}^{-3}}\right)^{-1.748}$$

K. Bothe, R. Sinton, and J. Schmidt, Prog. Photovoltaics ***13****, 287 (2005)*

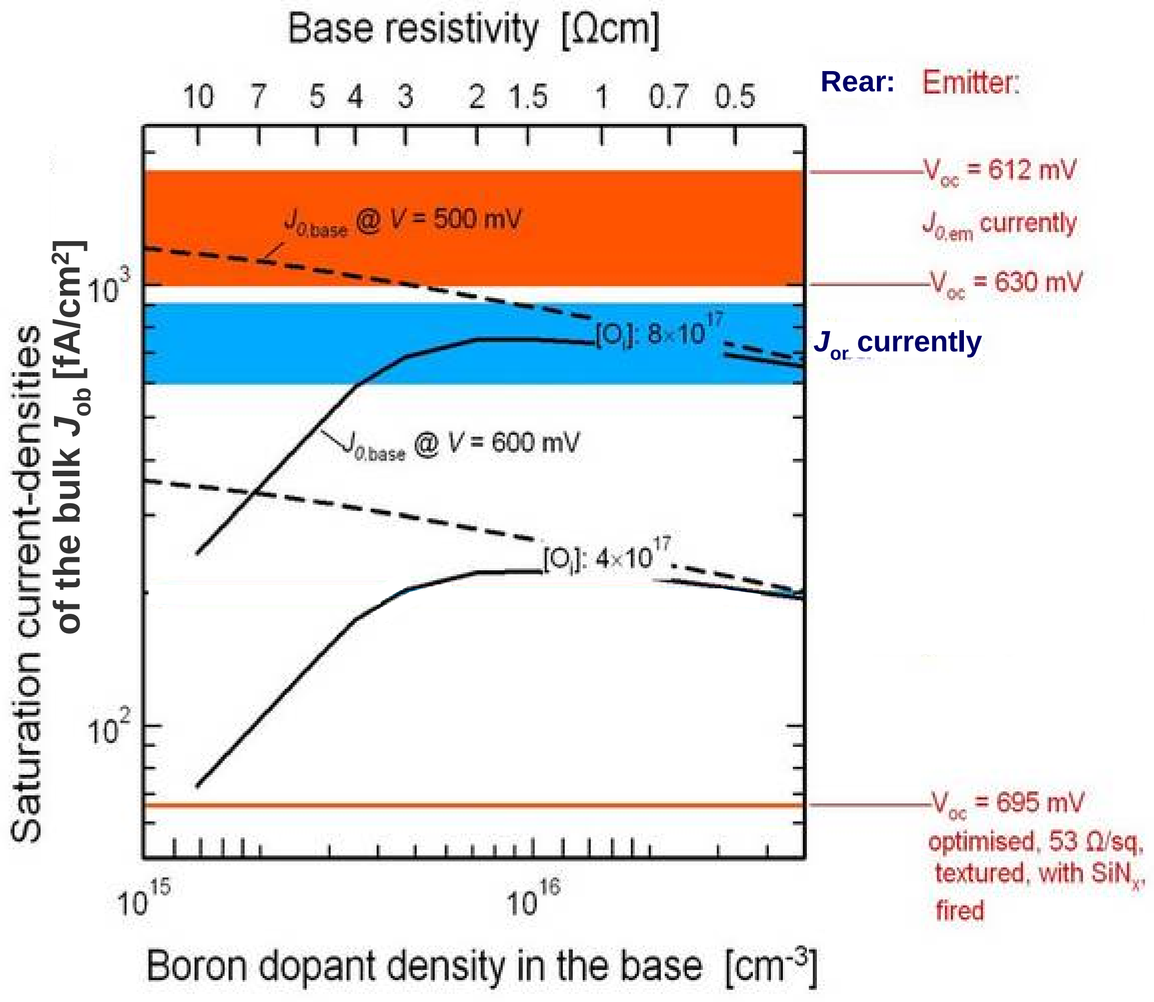
Parameterization of injection dependent lifetime



Defect parameters:

- $E_t = E_C - 0.41$ eV
- $$\tau_{n0} = m\frac{1.1}{2.1}\tau_d(N_A, N_O)$$
- $$\tau_{p0} = m\frac{11}{2.1}\tau_d(N_A, N_O)$$
- $m = 2$ e.g. due to thermal treatment
- Lifetime increases with injection

Cell modeling: Emitter often limits standard cells



P.P. Altermatt et al, 24th EU PV Conf., (WIP, Hamburg, 2009), im press.

- Current cells

  j_{0e} = 1000 to 2000 fA/cm^2
  j_{0r} = 700 to 900 fA/cm^2
  j_{0b} = 600 to 1100 fA/cm^2

- First Improve j_{oe}
- Then improve j_{obsf}

- Improved rear asks for improved bulk

→ Less [B] by higher resistance, Ga-doping or P-doping
Less [O] by improved growth

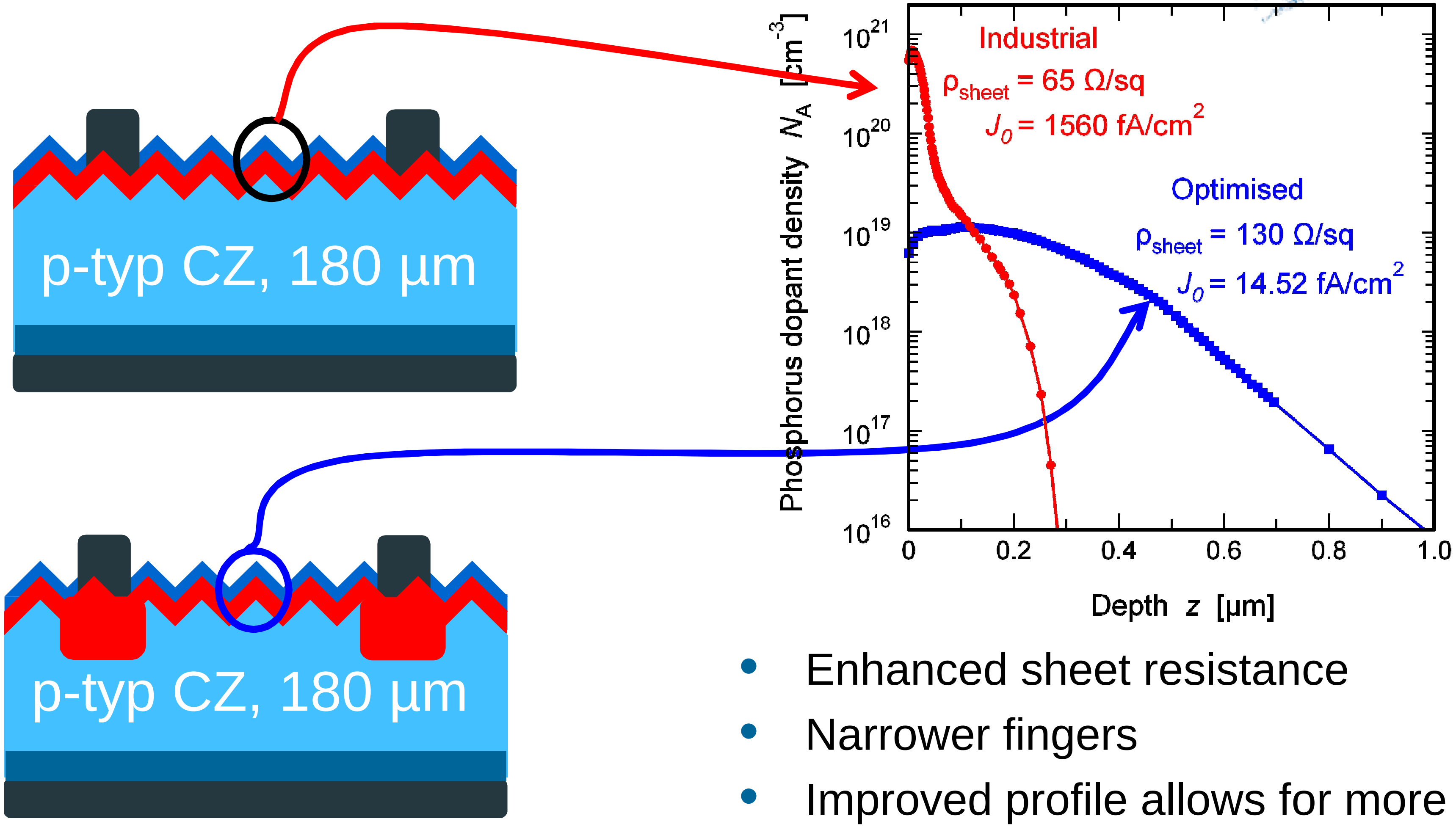
Improving the front side

by reducing Auger recombination in the n^+-type emitter

by reducing front contact recombination

by narrower fingers with less shading

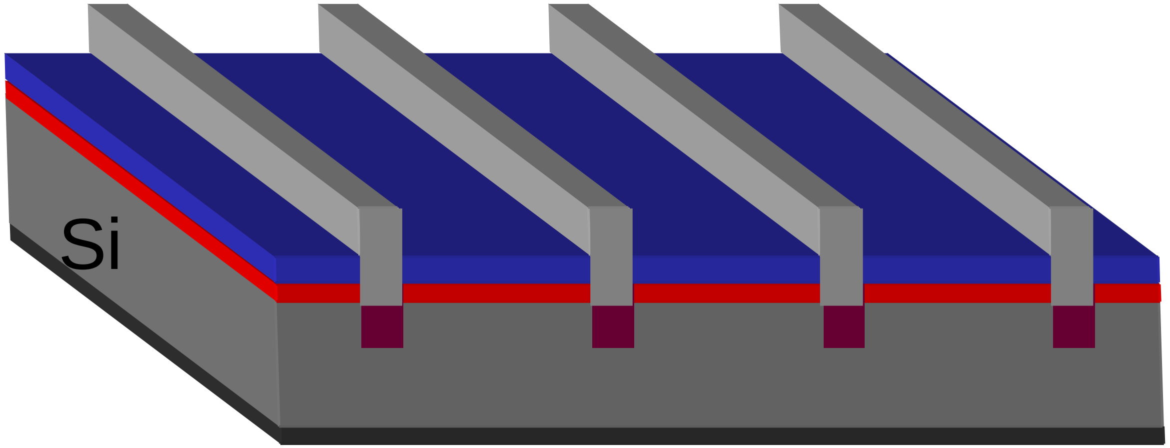
Improved doping profile by less Auger recomb. and selective emitter



- Enhanced sheet resistance
- Narrower fingers
- Improved profile allows for more than an order of magnitude in reduction of J_{oe}
- Higher resistances (e.g. 120 Ω/sq) requires selective emitter

Selective Laser Doping

- Texturization
- Diffusion
- **Laser irradiation**
- PSG removal
- SiN_x deposition
- Metallization



Solar cell results*

cell type	*FF* [%]	V_{oc} [mV]	J_{sc} [mA/cm^2]	? [%]
selective	77.1	629	37.1	**18.0**
standard	78.4	620	36.1	**17.5**

A = 12.5 x 12.5 cm^2, p-type CZ

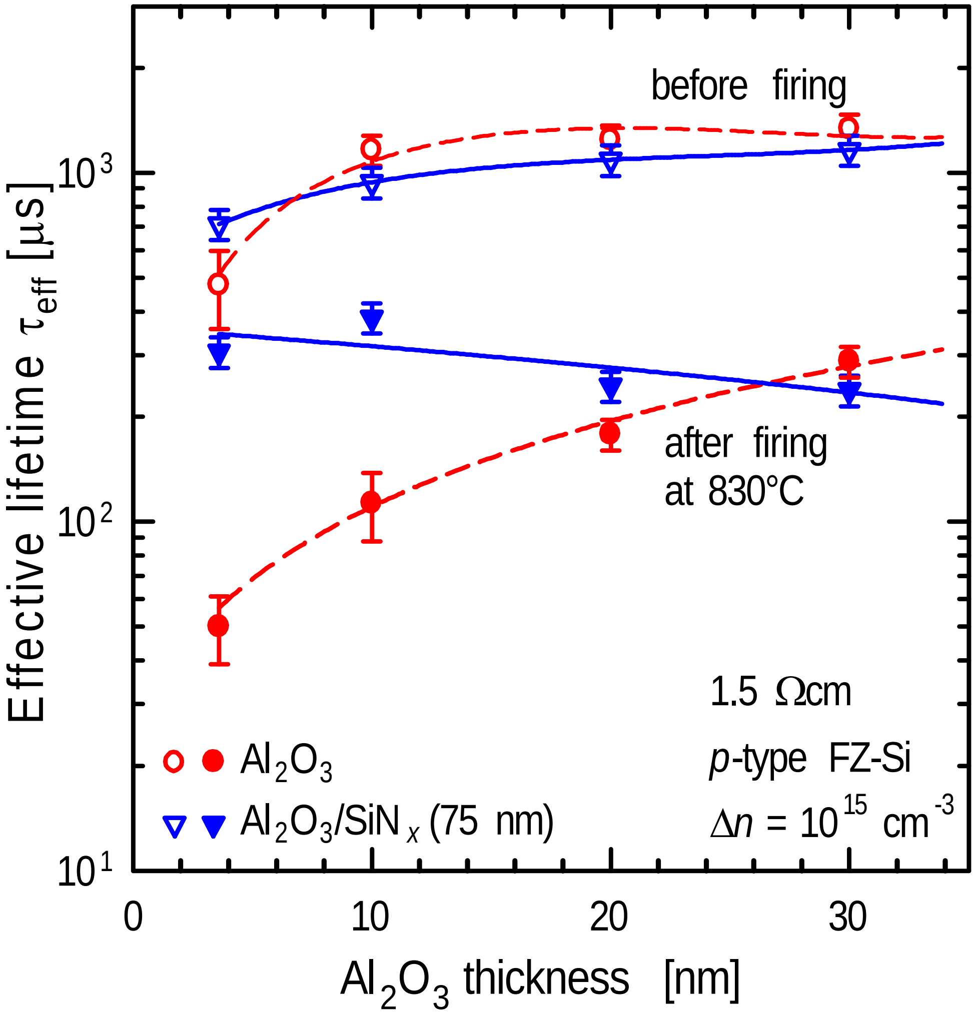
Δη = +0.5% abs

*J. R. Köhler, P. Grabitz, S. J. Eisele, T. C. Röder, J. H. Werner, in *Proc. 24th Europ. Photovolt. Solar Conf.*, (WIP, München, Deutschland, 2009), p. 1847.

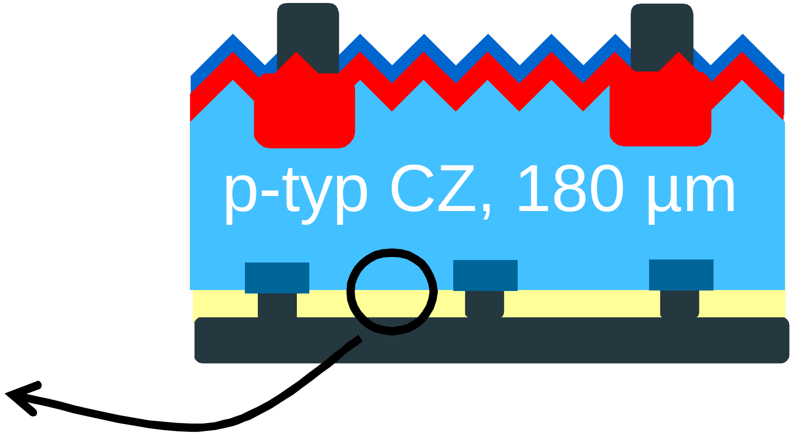
Improving the rear side

by local instead of full area contacts
by improved surface passivation
by B-diffusion

Rear side passivation with Al_2O_3



J. Schmidt, B. Veith, and R. Brendel,
Phys. Status Solidi RRL 3 (2009) 287.



- **Improved firing stability** for **Al_2O_3/SiN_x stacks**
- S_{eff} after firing correponds to **$V_{oc.implied}$ = 695 mV**
- **Al_2O_3 /SiN_x stacks well suited for high-efficiency cells**

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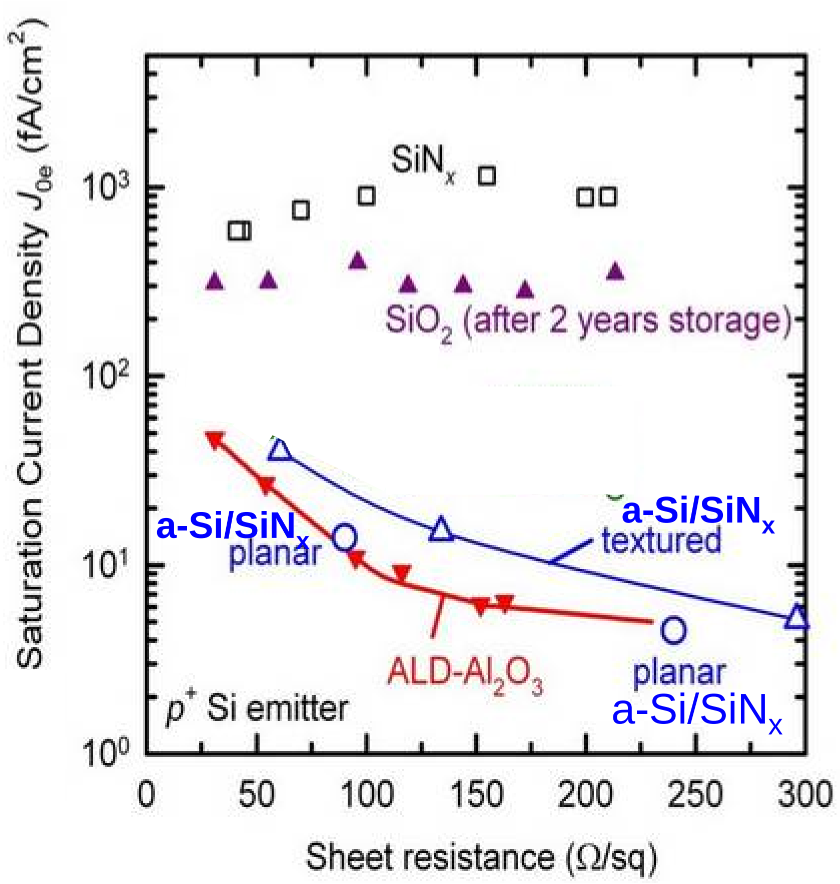
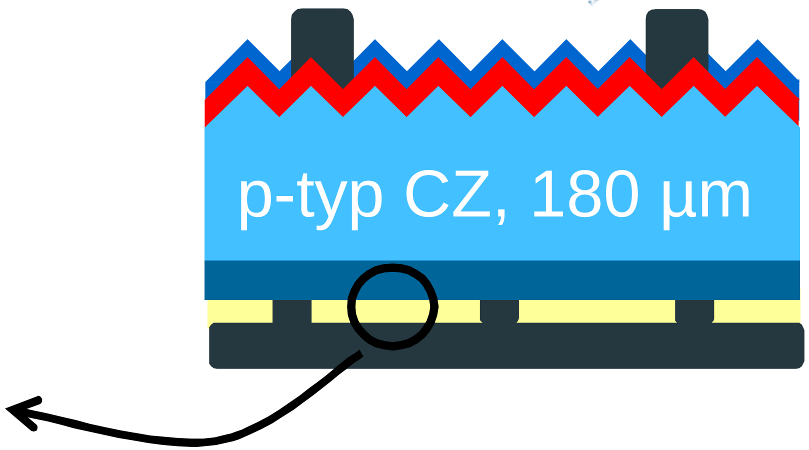
Passivation of boron-doped p^+-type layers by a-Si/SiN



J. Schmidt, B. Veith, and R. Brendel,
Phys. Status Solidi RRL 3 (2009) 287.

S. Gatz, H. Plagwitz, P.P. Altermatt, B. Terheiden, and
R. Brendel, Appl. Phys. Lett. 93, 173502, 2008

M. Kessler, submitted to 35th IEEE PVSEC 2010

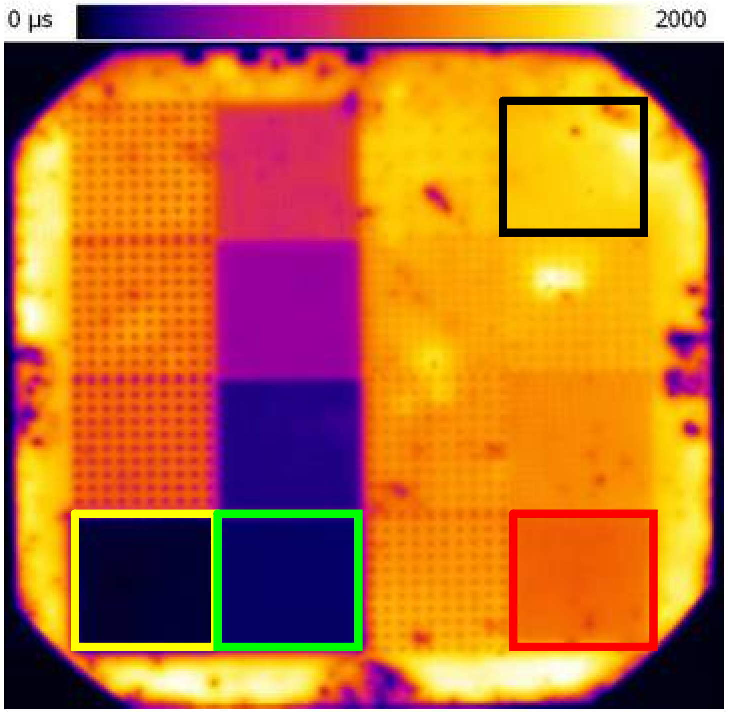


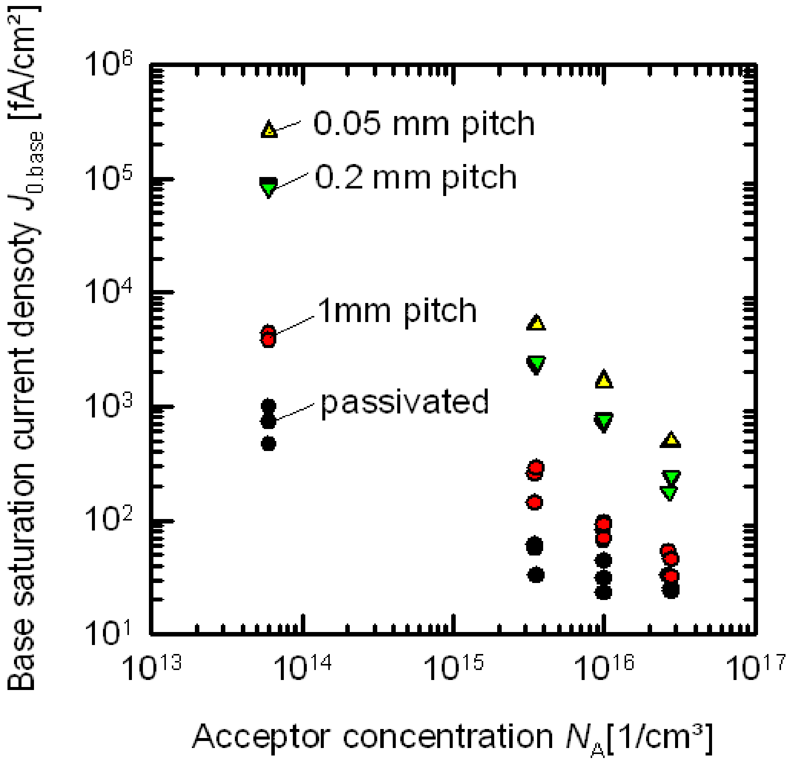
- Textured boron-doped layer with 130 Ω_{sq}

→ j_{0r} = 20 fA/cm^2

- AL_2O_3 /SiN_x and a-Si/SiN_x are resistant against firing of screen printing pastes

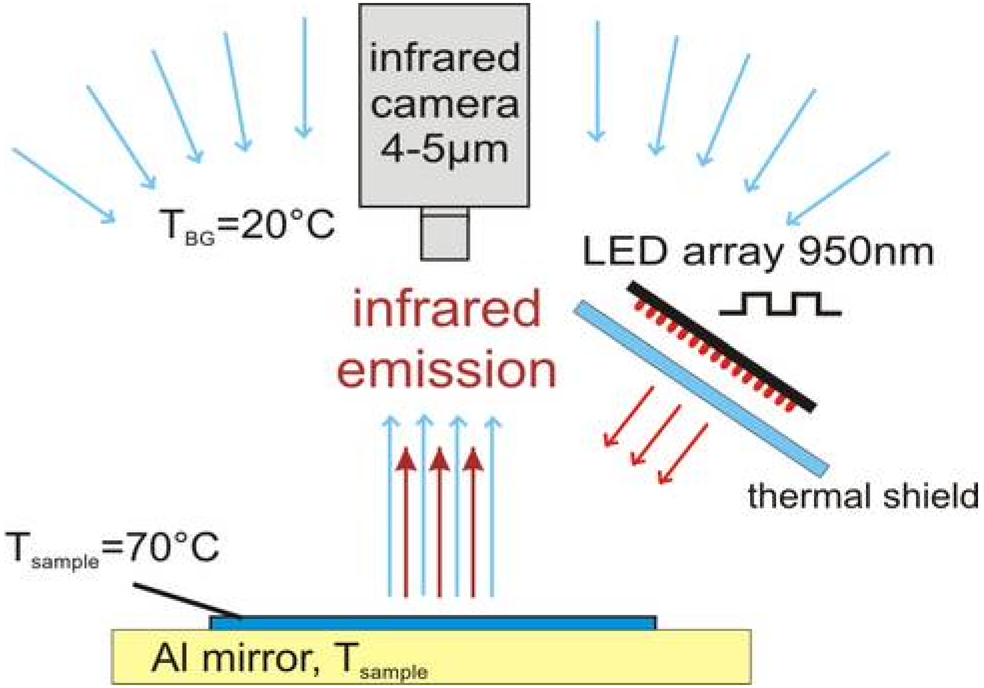
How to measure J_{0r} for a metallized and point-contacted sample?

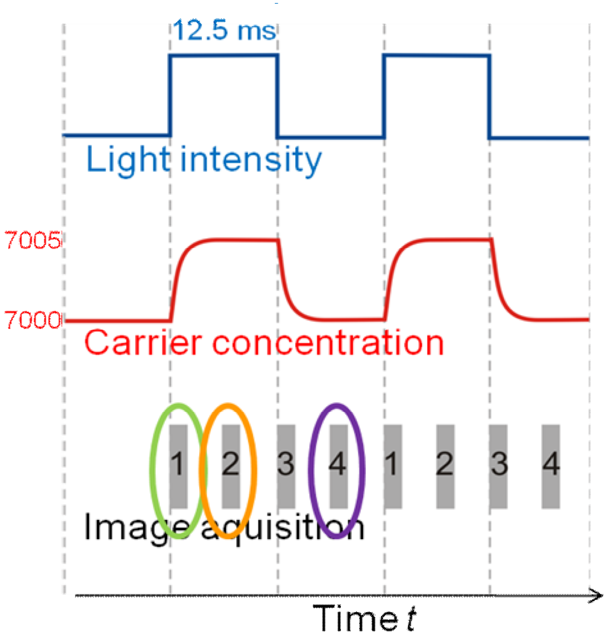




Dynamic ILM for lifetime measurements of metallized wafers

Measures in time domain → calibration free!

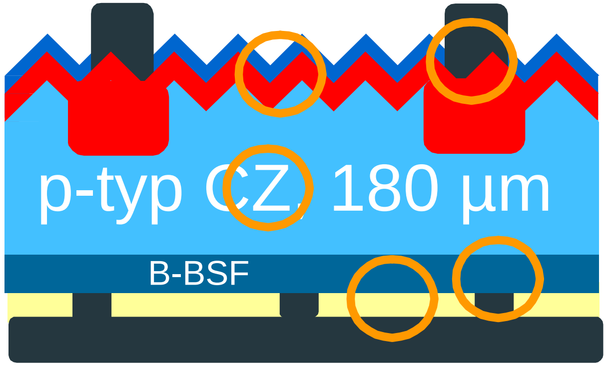




$$\frac{S_{\mathrm{trans}}-S_0}{S_{\mathrm{st\text{-}st}}-S_0}=\frac{\int_0^{t_{\mathrm{int}}}\Delta n(t)\,dt}{\int_t^{t+t_{\mathrm{int}}}\Delta n_{\mathrm{st\text{-}st}}}=\frac{t_{\mathrm{int}}+\tau_{eff}\cdot\exp\left(-\frac{t_{\mathrm{int}}}{\tau_{eff}}\right)-\tau_{eff}}{t_{\mathrm{int}}}$$

K. Ramspeck, S. Reissenweber, J. Schmidt, K. Bothe, and R. Brendel
*Appl. Phys. Lett. **93**, 102104 (2008)*

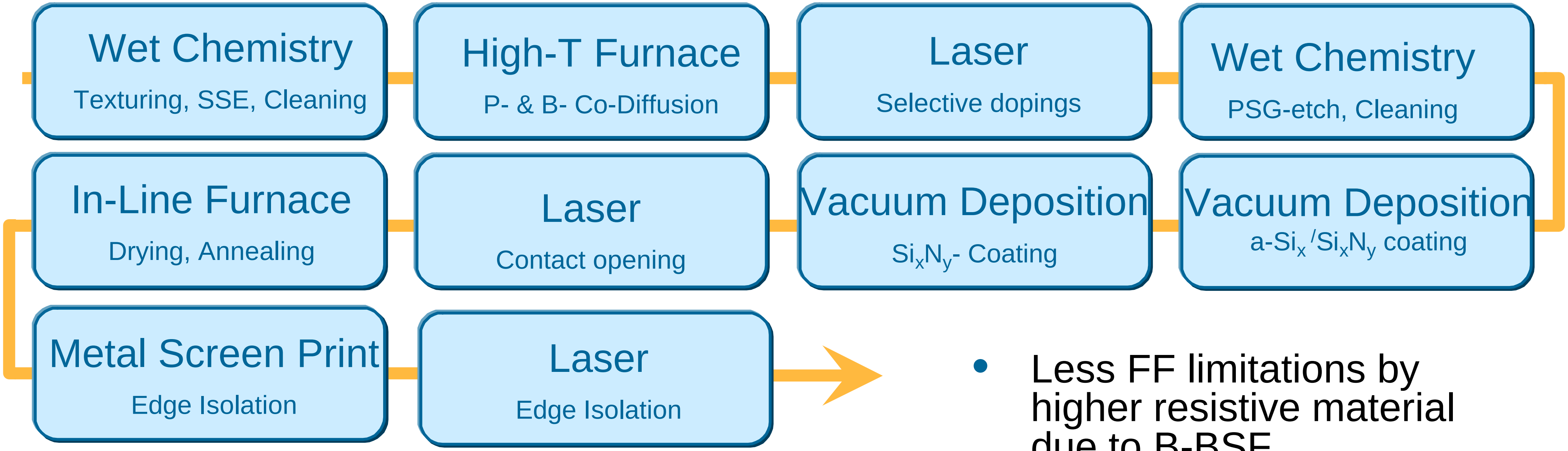
Advanced screen-printed cell



Targeted efficiency

~20 %

10 steps



Wet Chemistry Texturing, SSE, Cleaning

High-T Furnace P- & B- Co-Diffusion

Laser Selective dopings

Wet Chemistry PSG-etch, Cleaning

Vacuum Deposition a-Si_x/Si_xN_y coating

Vacuum Deposition Si_xN_y- Coating

Laser Contact opening

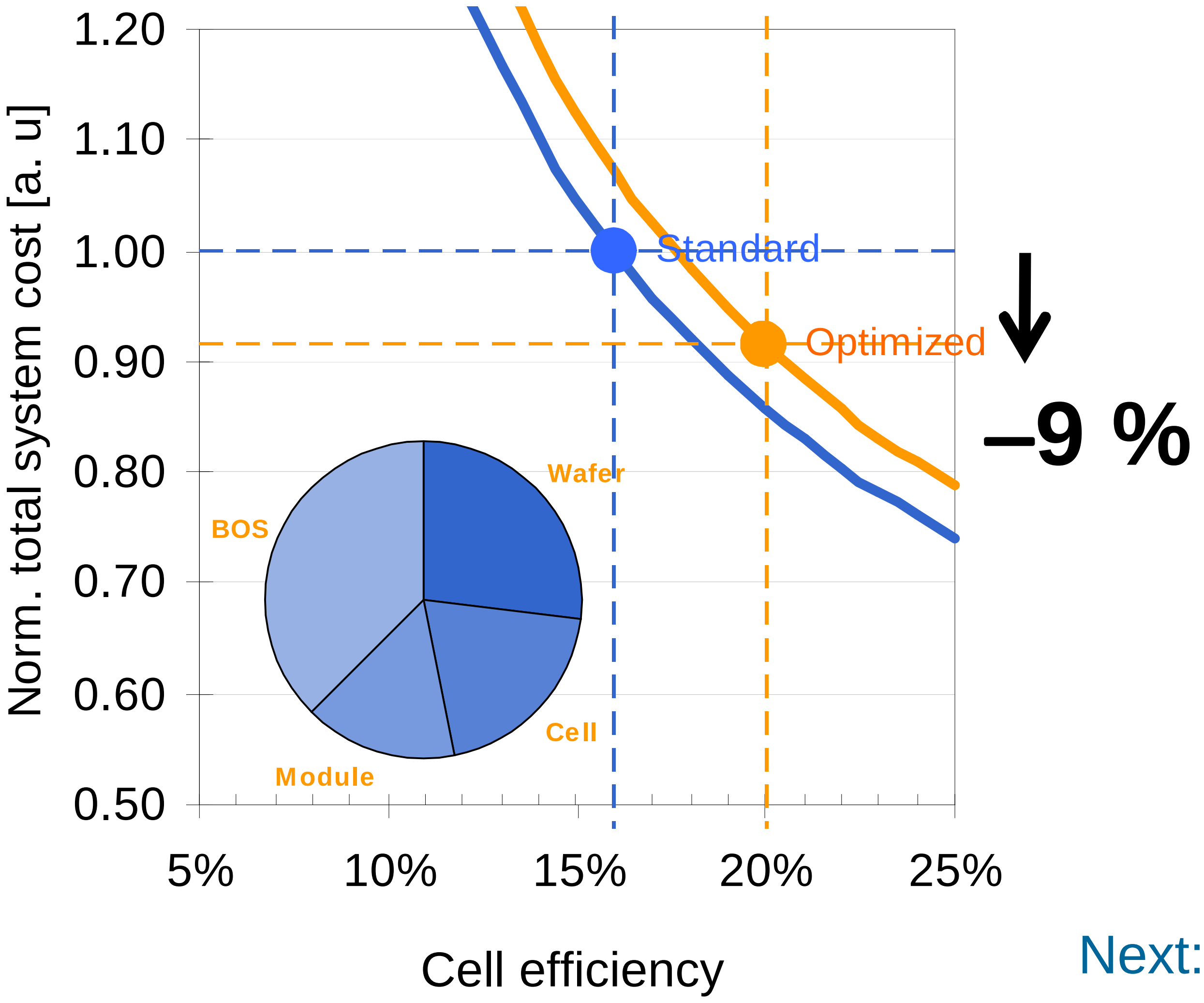
In-Line Furnace Drying, Annealing

Metal Screen Print Edge Isolation

Laser Edge Isolation

- Less FF limitations by higher resistive material due to B-BSF

Advanced screen-printed cell



10 steps

20.0 %

Next: Thickness reduction!

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Thinner wafers require new “soft” processing

by e.g. laser machining and evaporation instead of screen printing

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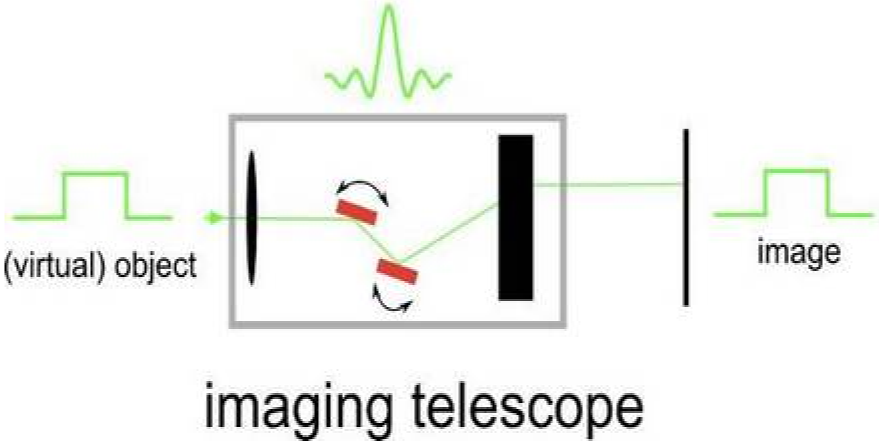
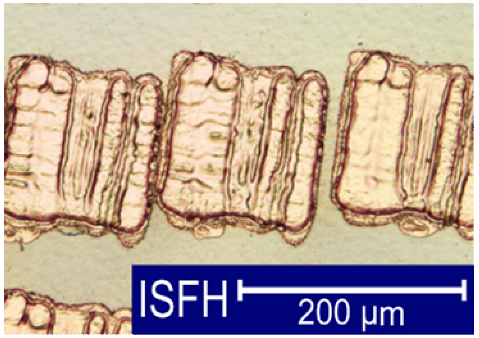
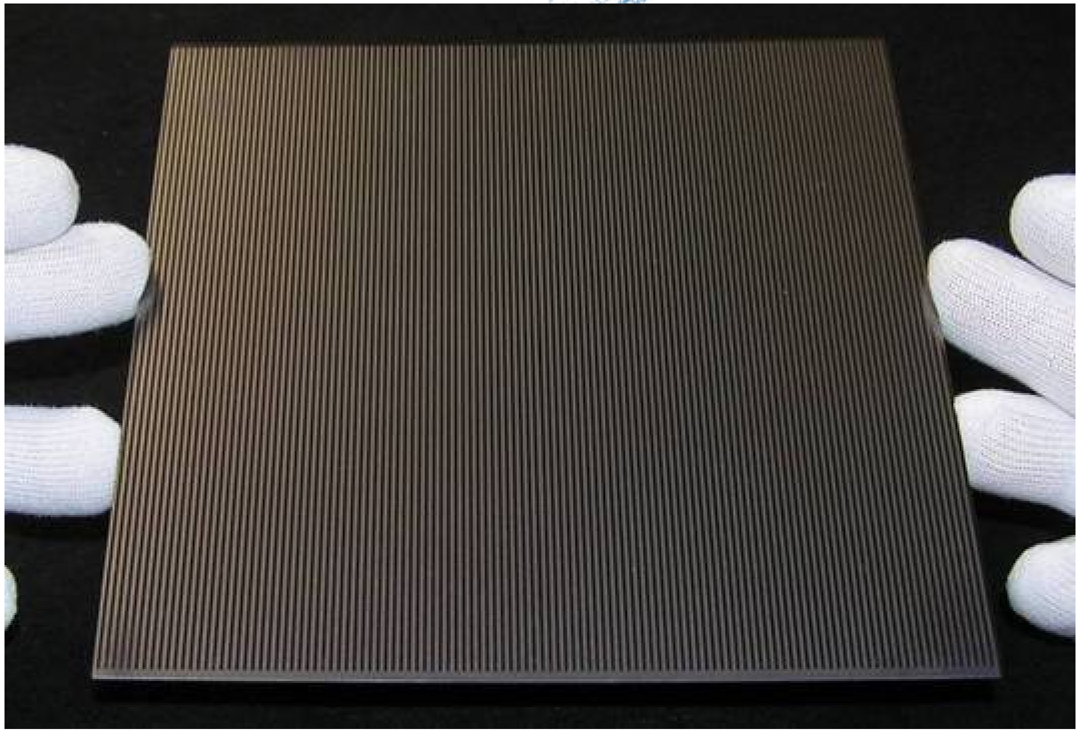
Fast laser processing for structuring



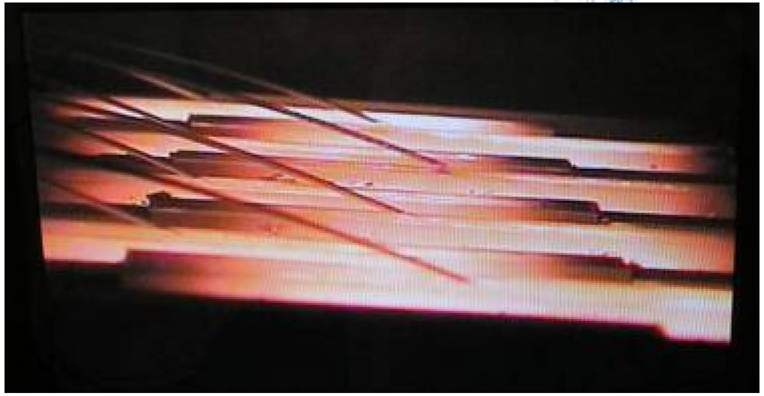


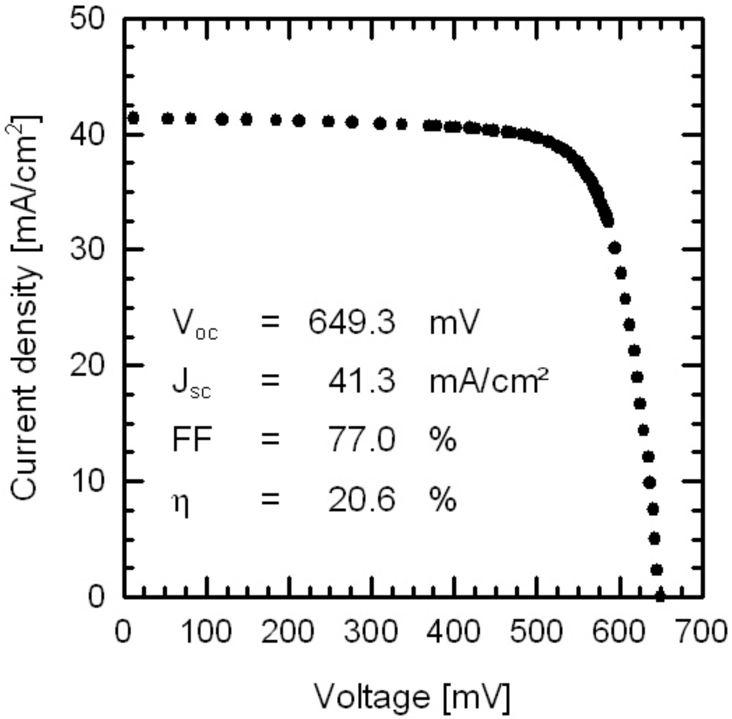


- First time combination of flat top profiling and scanning
- Flat top enhances processing speed by factor 1.8

S. Eidelloth, T. Neubert, T. Brendemühl, S. Hermann, P. Giesel, and R. Brendel, in Proc. 34th IEEE-PVSEC 2009, (IEEE, Philadelphia, 2009), in press.

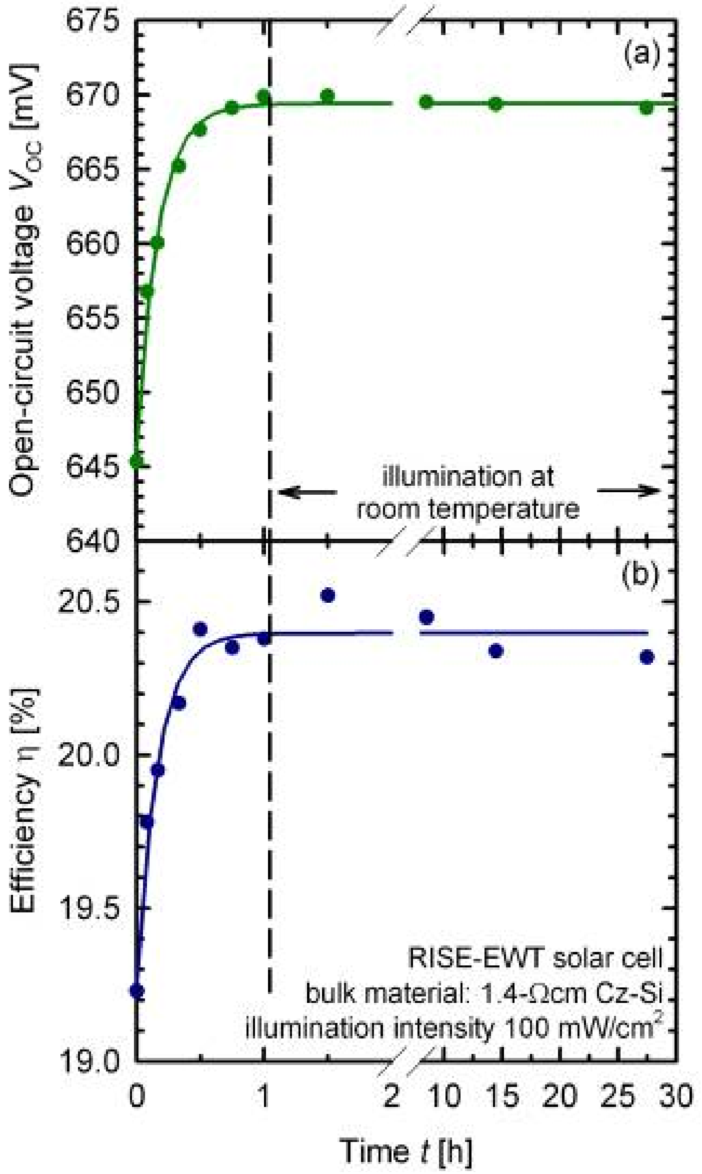
Inline high-rate Al-evaporation



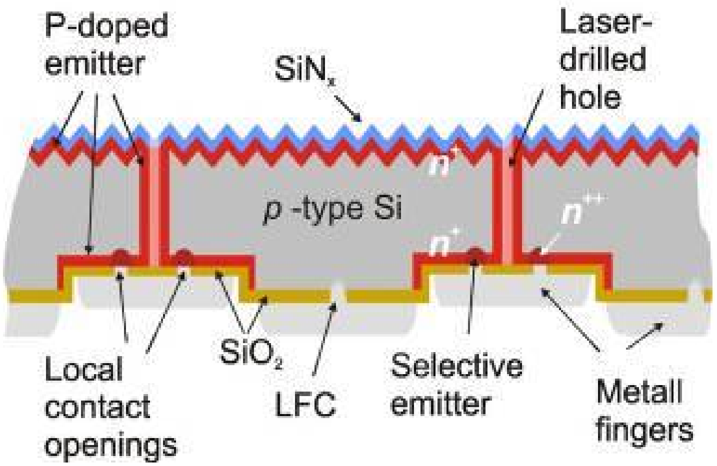


- Inline and multi-pass mode ATON 500
- Dynamic rate 0.1 … 10 µm m/min
- Up to 720 wafers / h
- T_{max} predictable from modeling
- Contact resistance as for lab system
- 20 % efficient rear-contacted cell by in-line evaporation
- Replace pastes by evaporated Al

First cell on low-resistive B-doped Cz-Si with stable efficiency of 20%



B. Lim, S. Hermann, K. Bothe, J. Schmidt, and R. Brendel, Appl. Phys. Lett. ***93****, 162102 (2008)*



- **Permanent deactivation** of light-induced boron-oxygen complex
- **Record-high stable efficiencies** on low-resistive B-doped Cz-Si
- **Multi-functional processing** steps

$\eta = 20.4\%$

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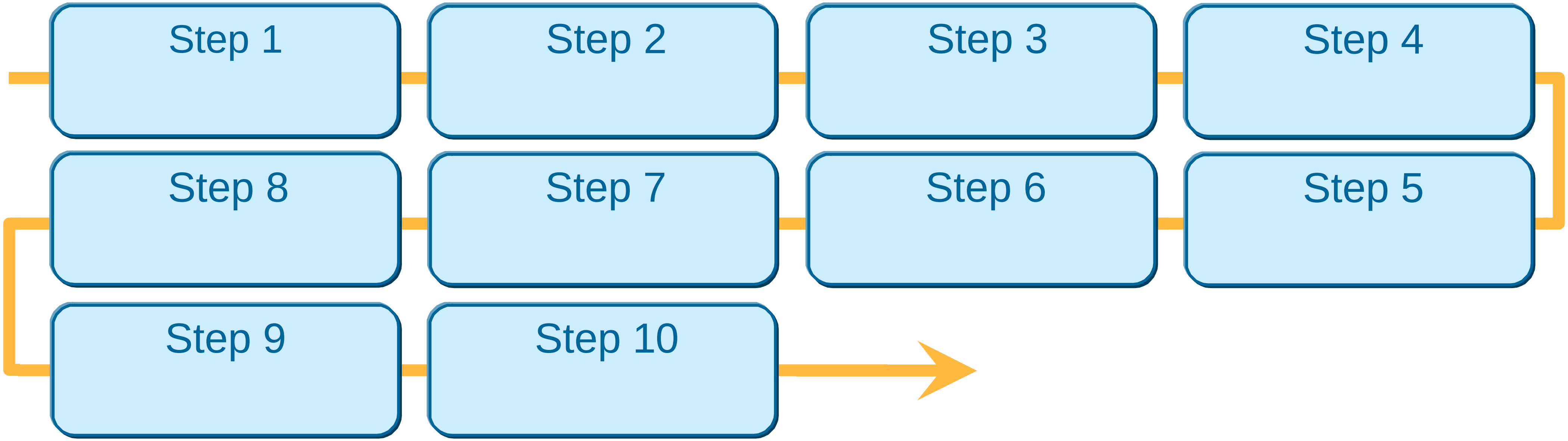
RISE cell

Targeted efficiency

~20 %

11 steps


Step 1

Step 2

Step 3

Step 4

Step 8

Step 7

Step 6

Step 5

Step 9

Step 10

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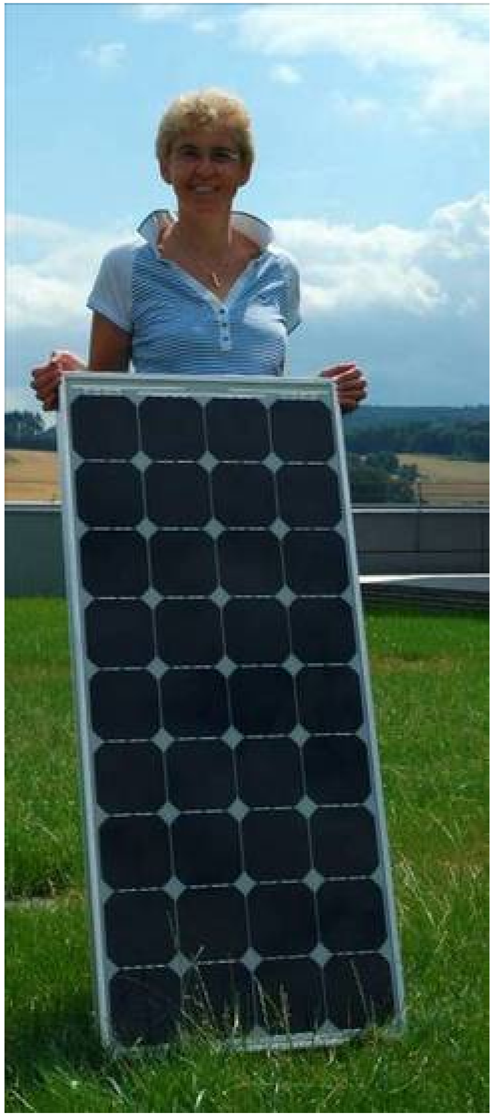
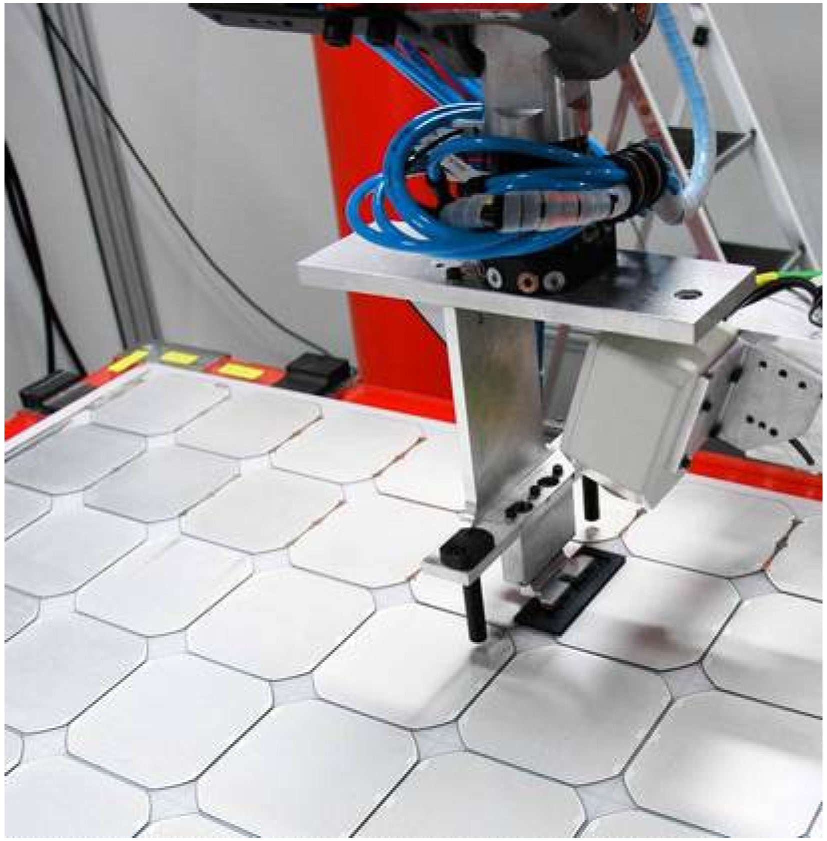
Simplified module process for RISE On-Laminate- Laser-Soldering





- Soldering on the laminate
- Saves two handling steps

In cooperation with:

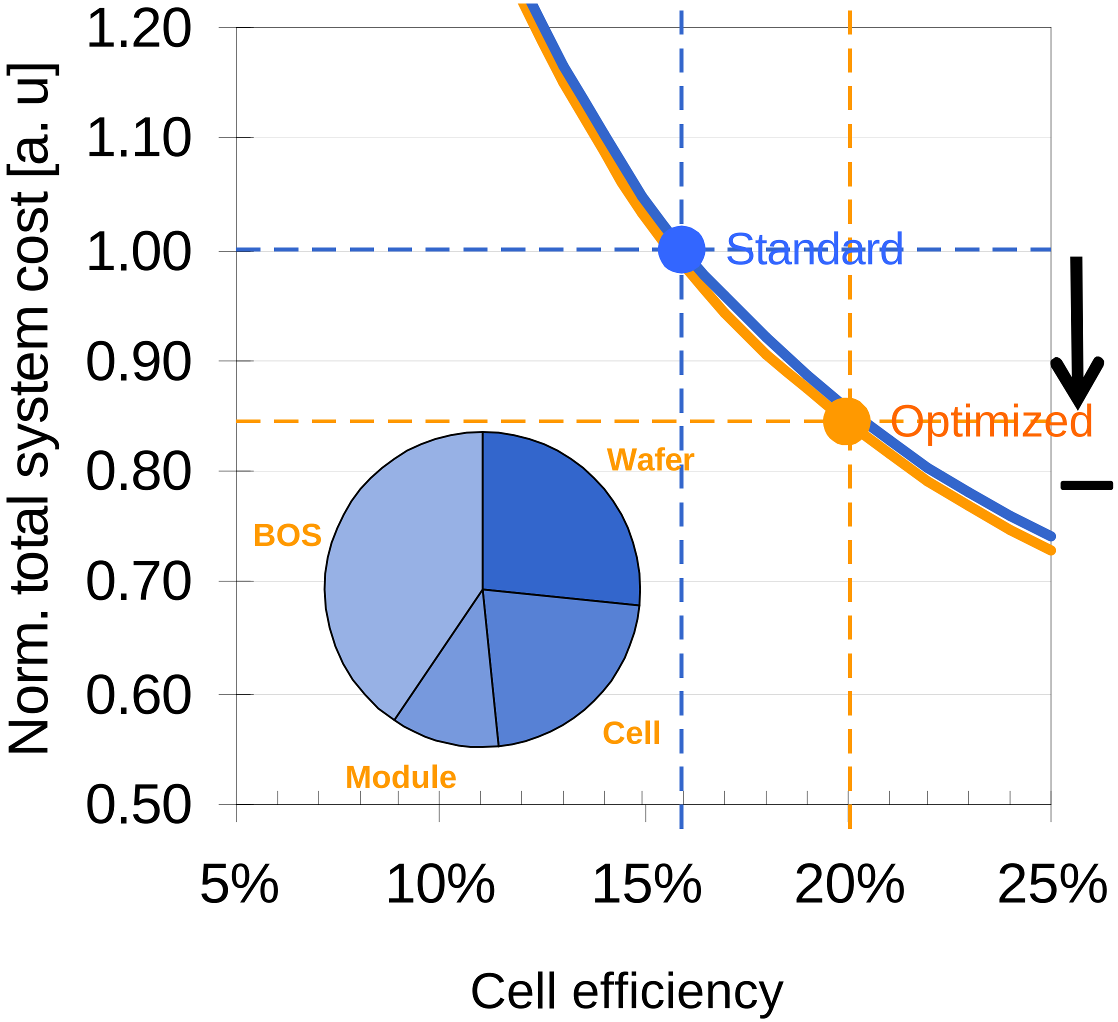
reis SOLAR SYSTEMS

STIEBEL ELTRON

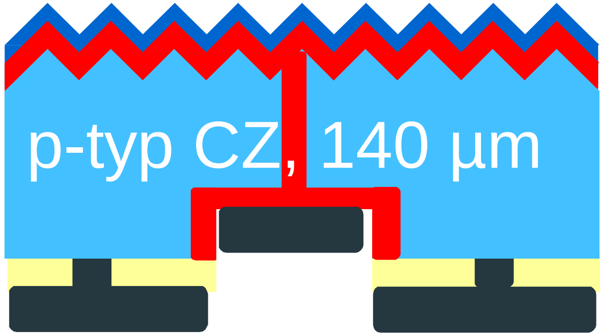
Leibniz Universität Hannover

M. Gast, M. Köntges, and R. Brendel, Progress in Photovoltaics ***16****, 151 (2008)*

RISE cell



–16 %



11 steps

20.0 %

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Reducing wafer costs

by generating and processing very thin-films

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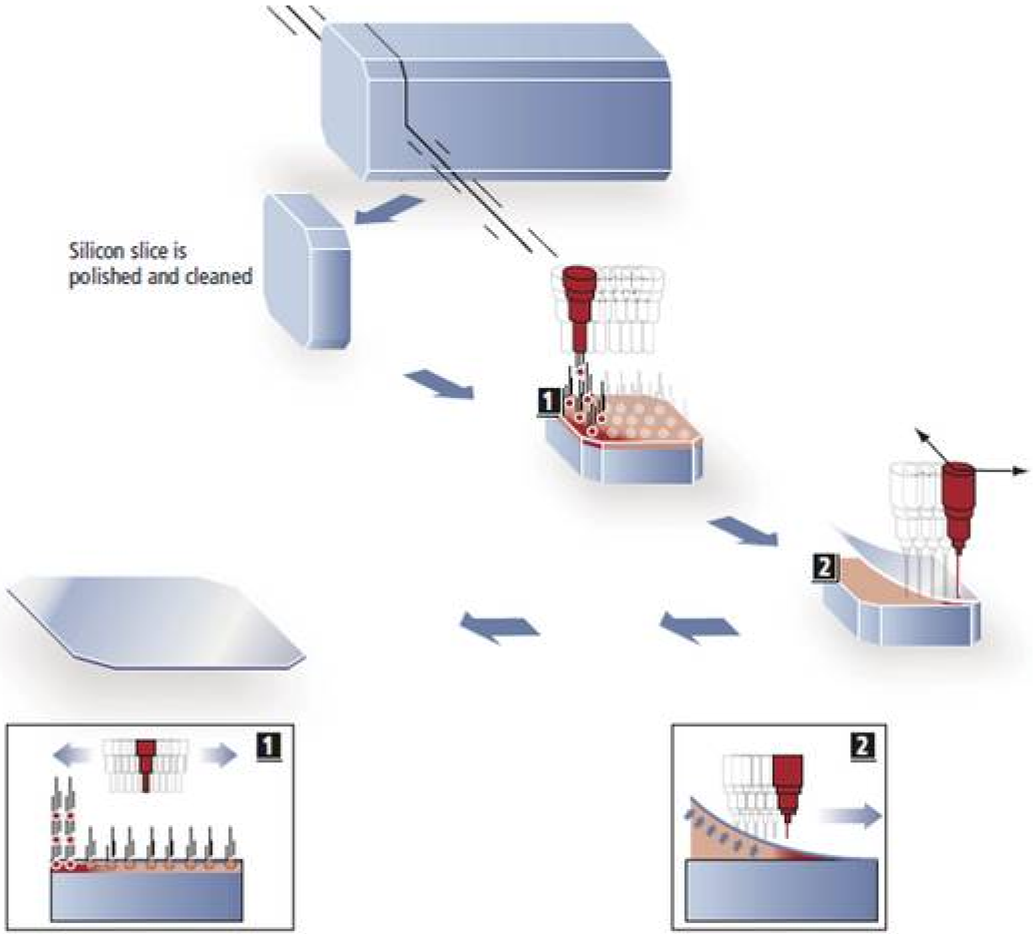
Reducing Si wafer cost: SiGen „kerfless cut“

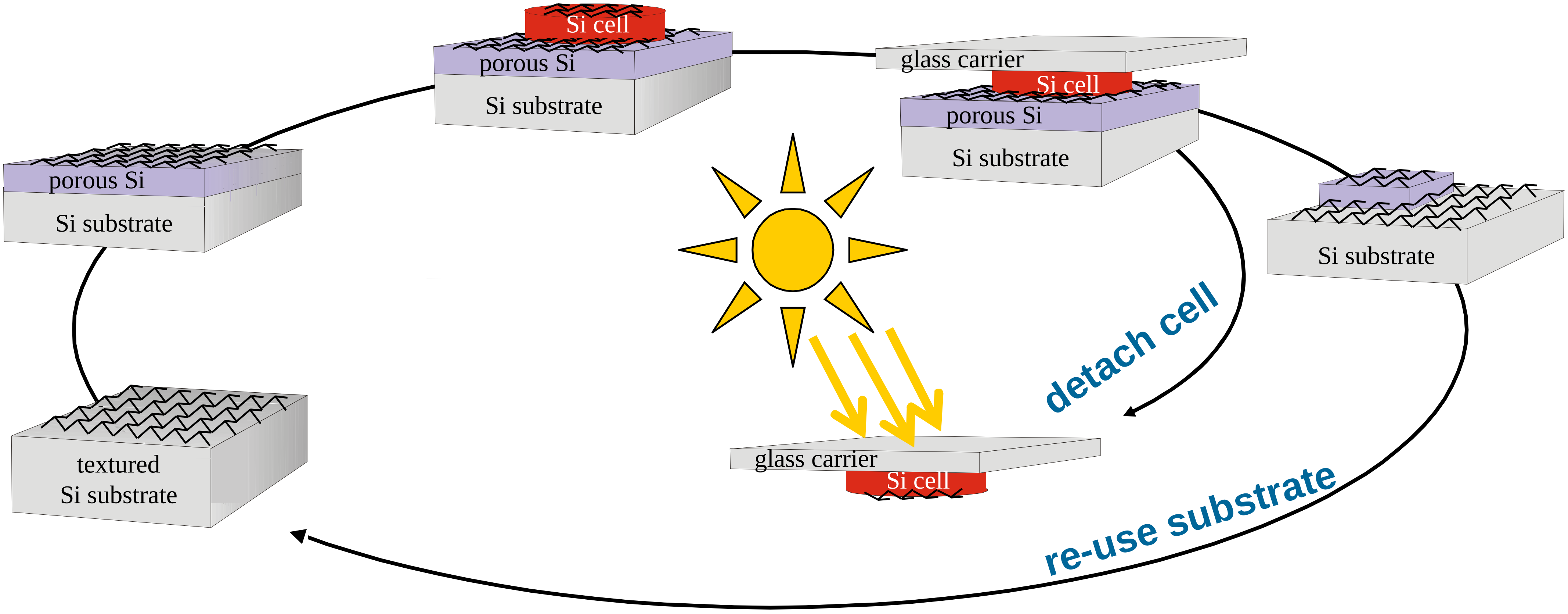


F. Henley, A. Lamm, S. Kang, Z. Liu and L. Tian, in Proc. 23rd European Photovoltaic Conference, (WIP, Valencia, 2008), Paper 2BO.2.3, in press.

Source: Photon International April, 2004

- However: A probably expensive tool is required

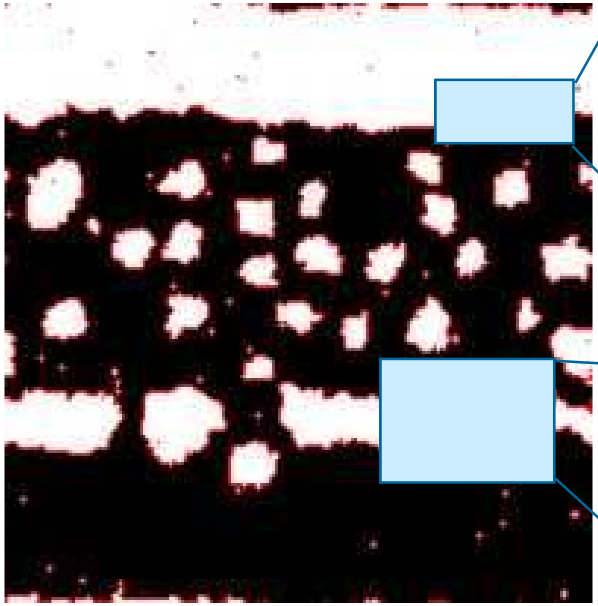
Layer transfer with porous Silicon (PSI-Process)

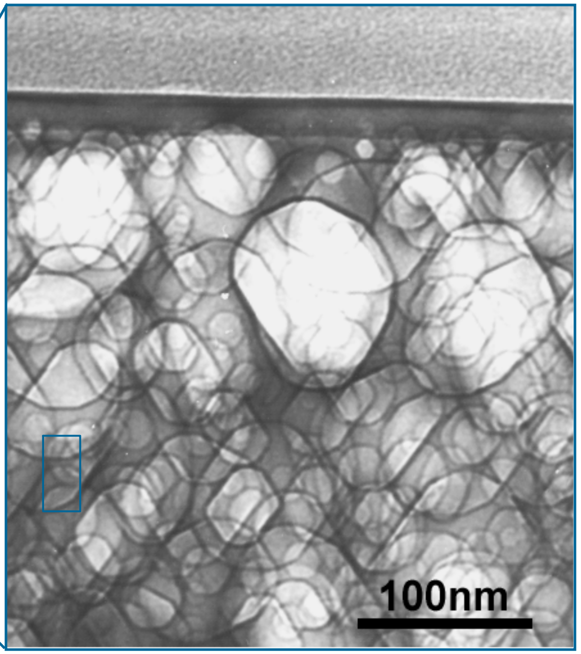


R. Brendel, Proc. 14th EU-PVSEC, (WIP, Barcelona,1997), p.1354.

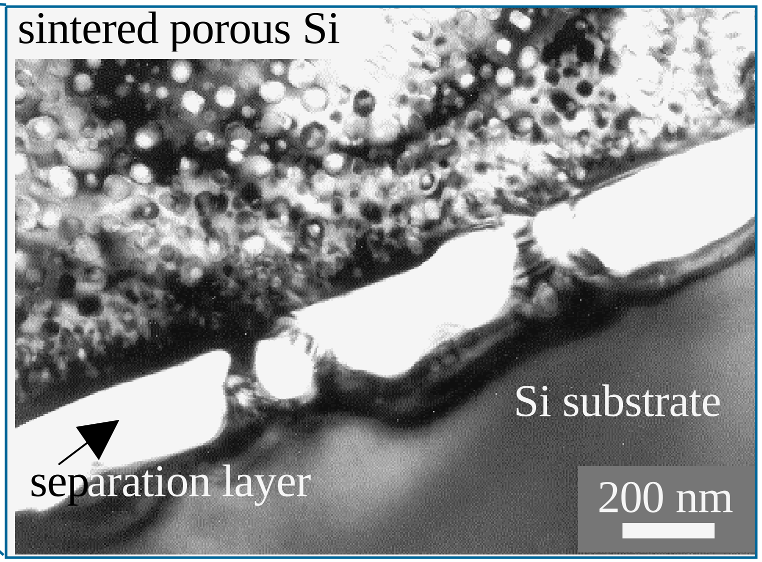
Stable process since structure evolves into minimum free energy

N. Ott, M. Nerding, G. Müller, R. Brendel, and H. P. Strunk, J. Appl. Phys. ***95****, 497 (2004).*



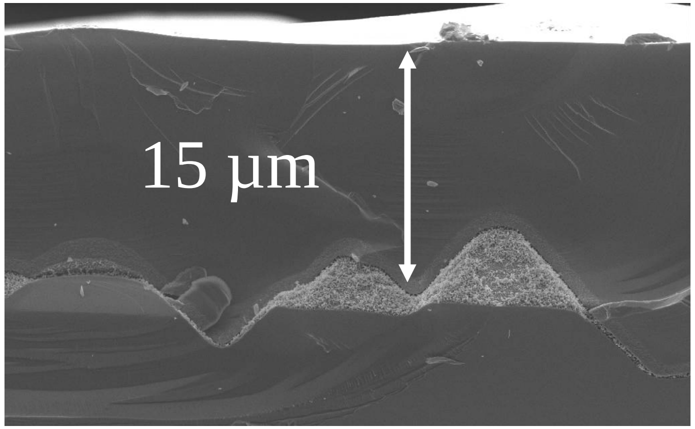


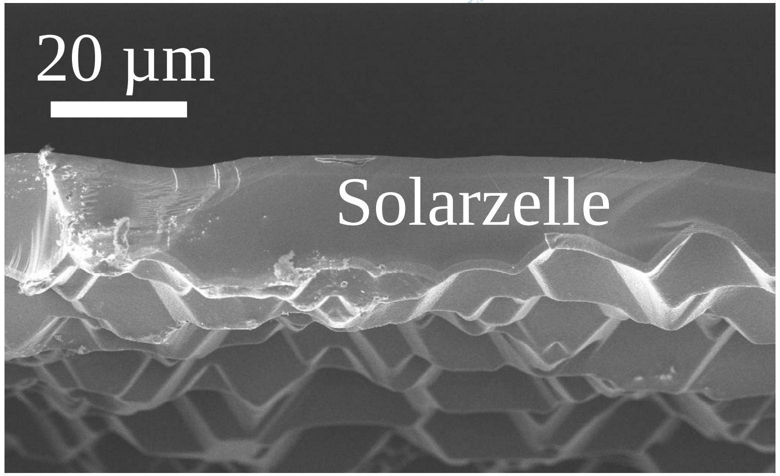
First report on surface closure: *V. Labunov, Thin Solid Films* ***137****, 123 (1986)*

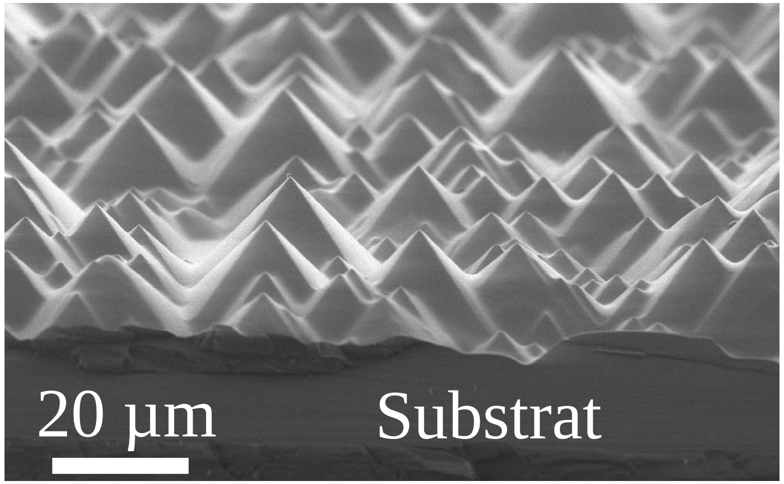


First report on separation layer formation: *H. Tayanaka*, in *Proc. 2nd World Conf., (Vienna 1998), p.1272*

Various cell process are feasible





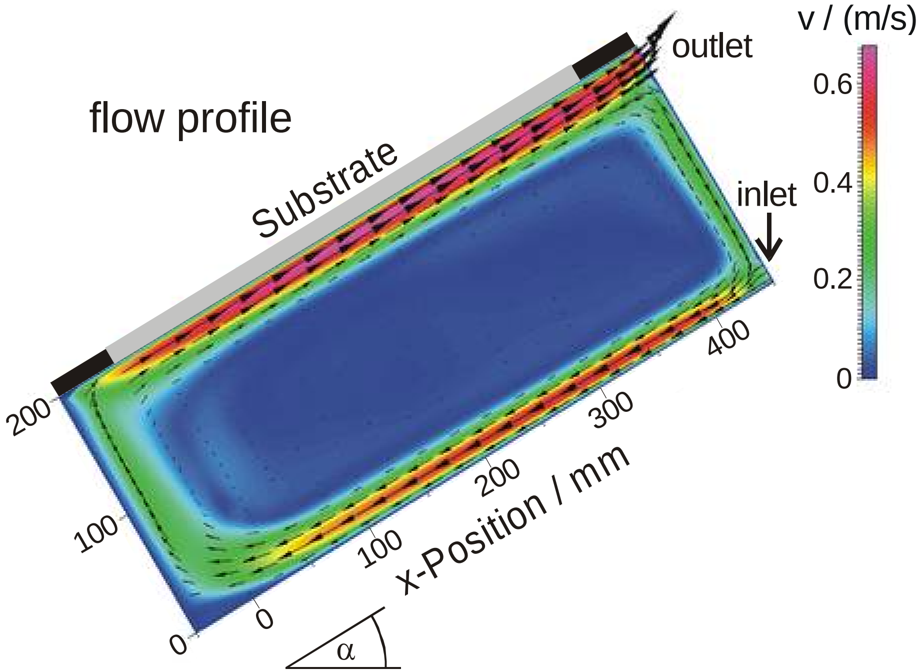


- Texturing on one or the other side
- Diffusion on one or the other side
- Mech. supported monocrystalline Si film

Large-area Silicon epitaxy system (ZAE Bayern group)

T. Kunz et al., Proc. 4th WCPEC, (Hawaii, 2006) p. 1620.

- Convection-assisted deposition (CoCVD)
- Substrate size up to 43 cm x 43 cm



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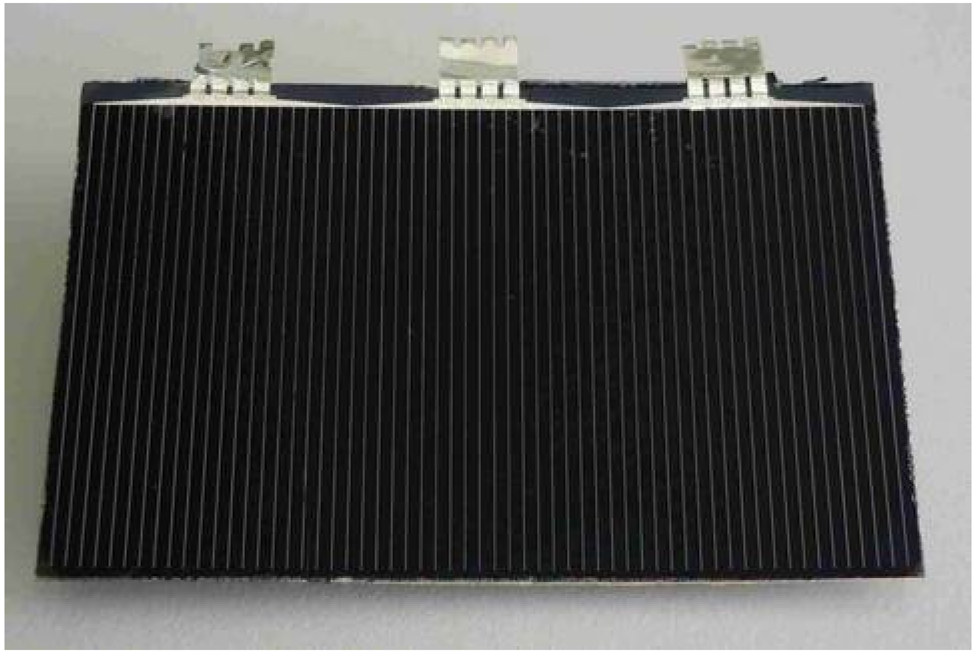
PSI*-process on enlarged area

*Porous Silicon Process



- Process without photolithography
- Cell area **26 cm²**
  Si-Thickness **25 µm**

V_{OC} = 611 mV

J_{SC} = 34.2 mA/cm²

FF = 74.6 %

η = **15.6%**

- However: In-line high throughput epitaxy still needs to be developed

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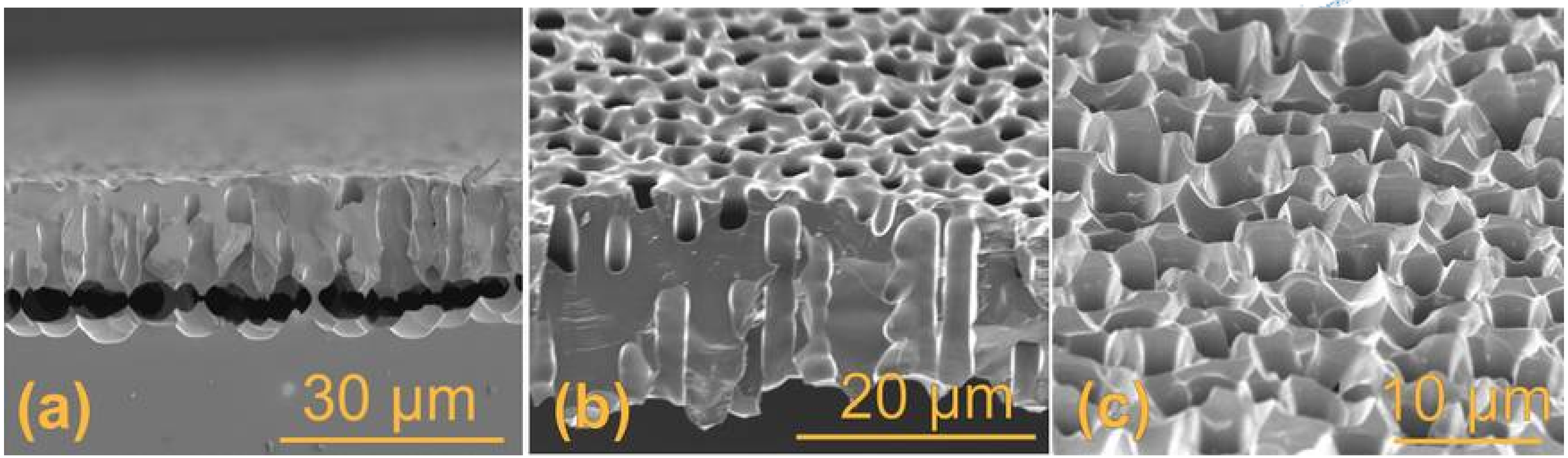
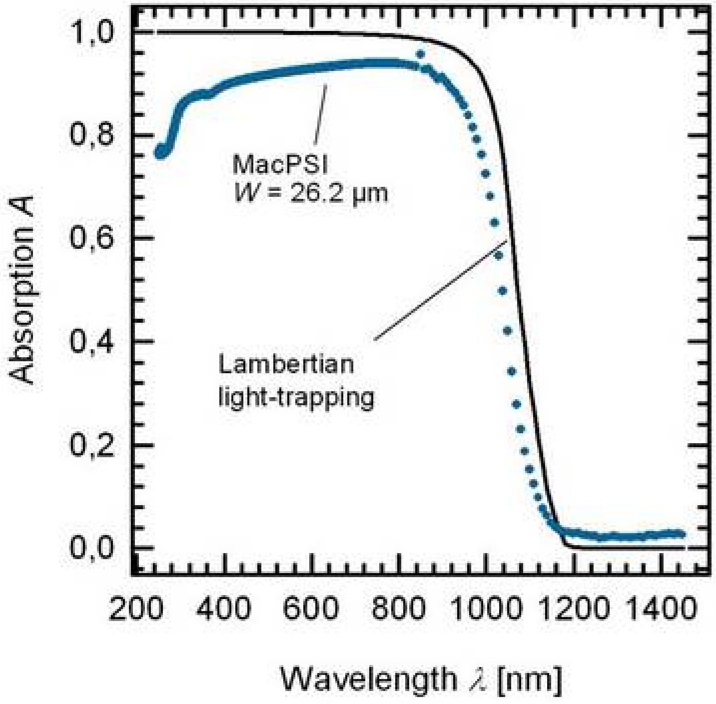
Macroporous Si (MacPSI):
a new thin-film solar cell absorber





- No expensive tool required for splitting and no epitaxy!
- High absorption (37 mA/cm^2)
- Lifetime vs. thickness in agreement with experiment
- Efficiency potential 18 %

R. Brendel and M. Ernst, phys. stat. sol. (RRL) ***4****, 40 (2010)*

Reducing module cost

by integrated c-Si-thin-film module concepts

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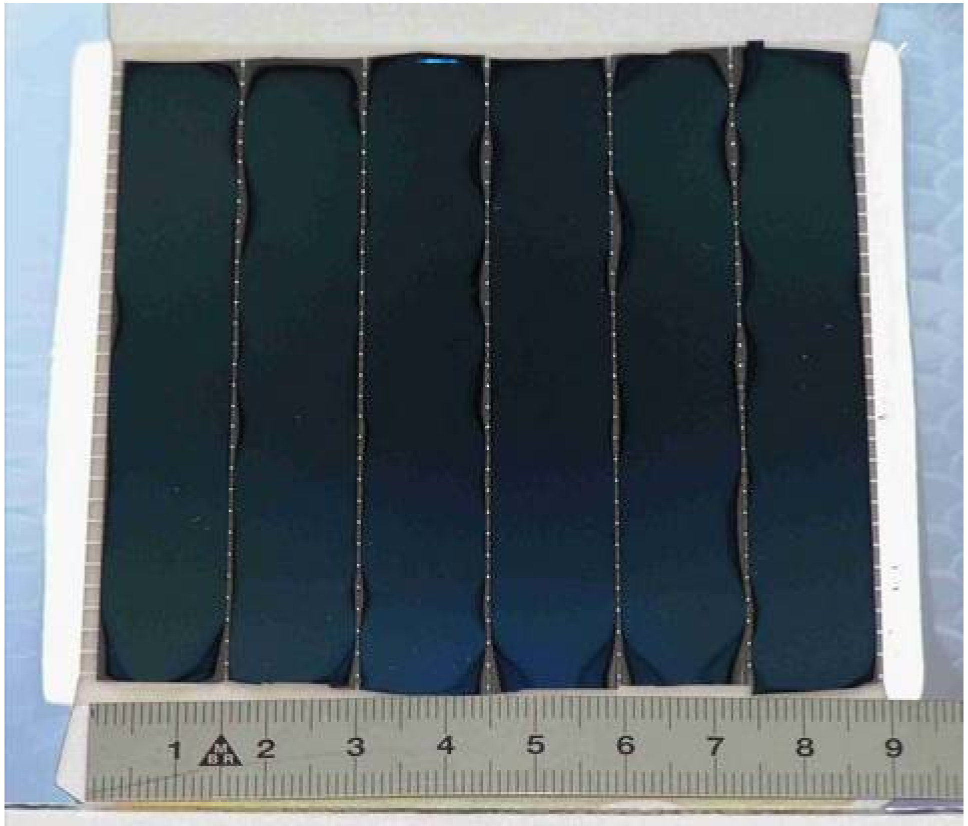
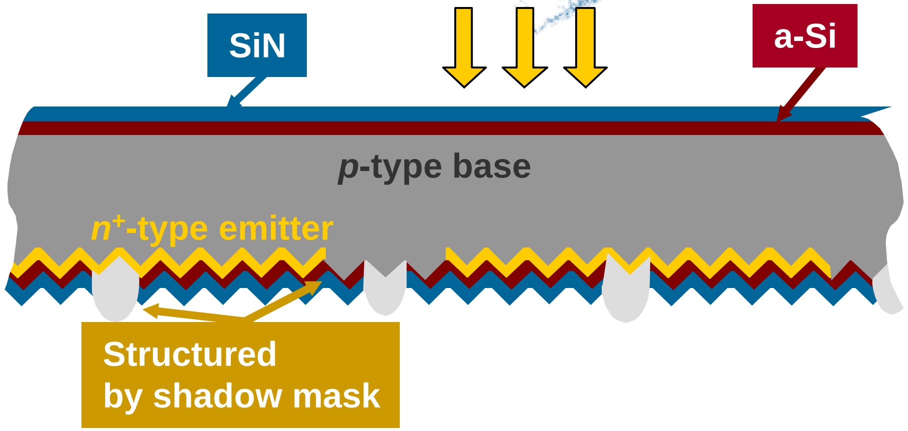
Rear-side contacted integrated PSI-mini-modules



B. Terheiden, R. Horbelt, and R. Brendel , in Proc. 21st EU-PVSEC, (WIP, Dresden, 2006), p. 463.



Structured by shadow mask

Access to contacts by etching

Module area 9.1 x 9.0 cm^2

Thickness 25 µm

V_{OC} = 626 mV per cell

J_{SC} = 28.4 mA/cm^2

FF = 67.3 %

η = 12.0 %

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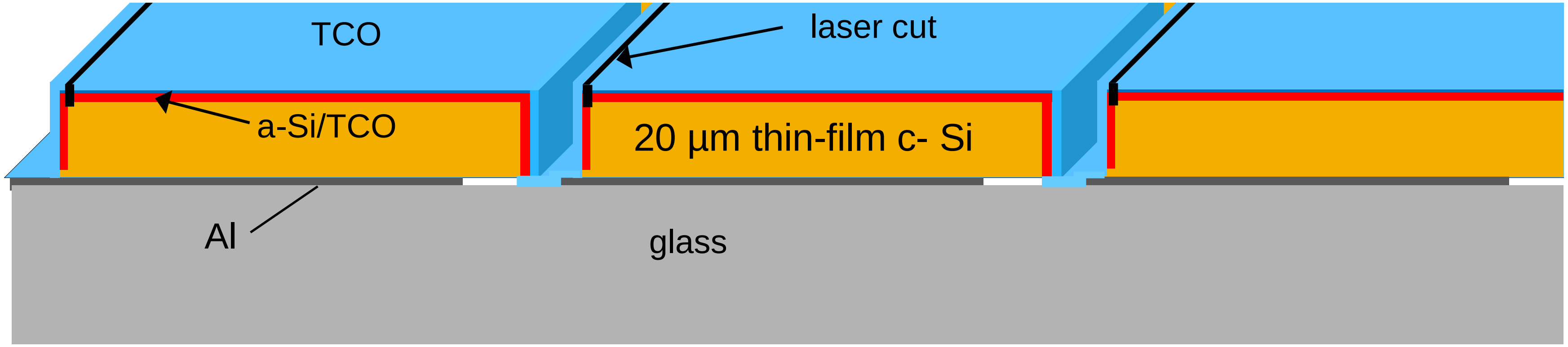
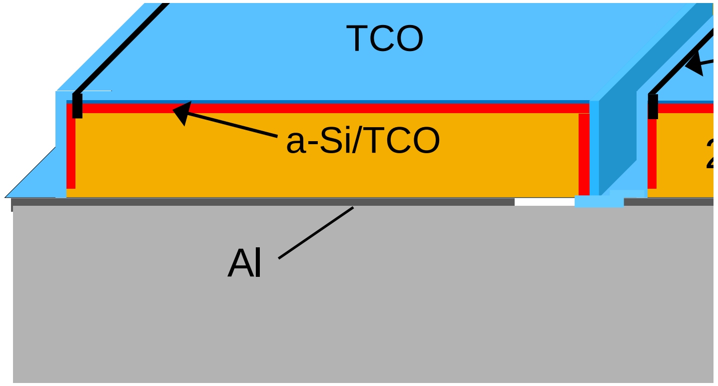
Integrated thin-film c-Si approach: e.g. with a-Si-hetero-junctions (HetSi)



- Thin film monocrystalline c-Si without sawing from “somewhere”
  e.g. epitaxy, MacPSI, SiGen, cleaving …

- Junction formation as in thin-film technologies on large area
- Series interconnection as in thin-film technologies on large area
- Material quality and efficiency as for c-Si technology

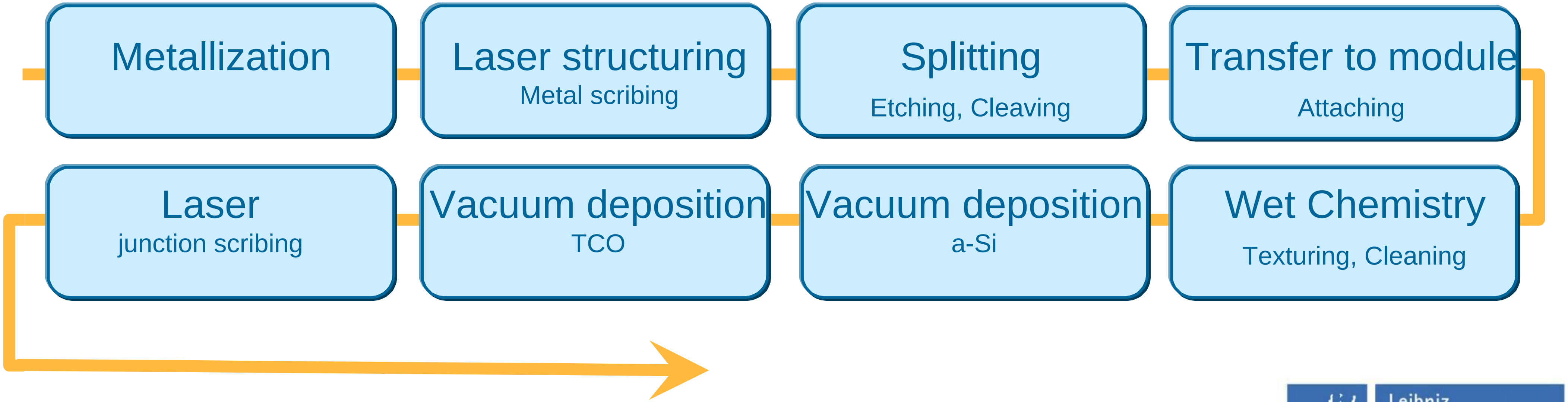
Integrated thin-film c-Si approach: Process large areas



Efficiency

~18 %

8 steps



Metallization

Laser structuring
Metal scribing

Splitting
Etching, Cleaving

Transfer to module
Attaching

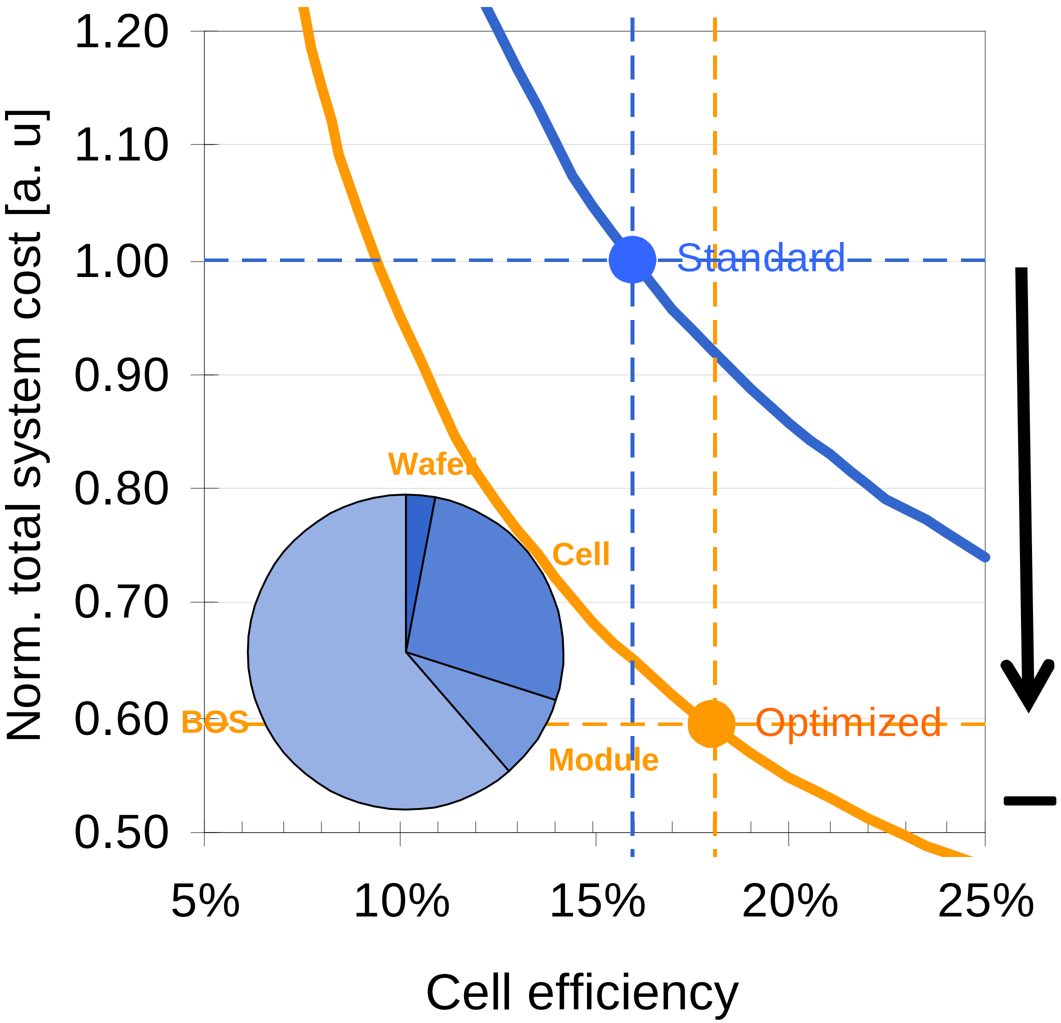
Laser
junction scribing

Vacuum deposition
TCO

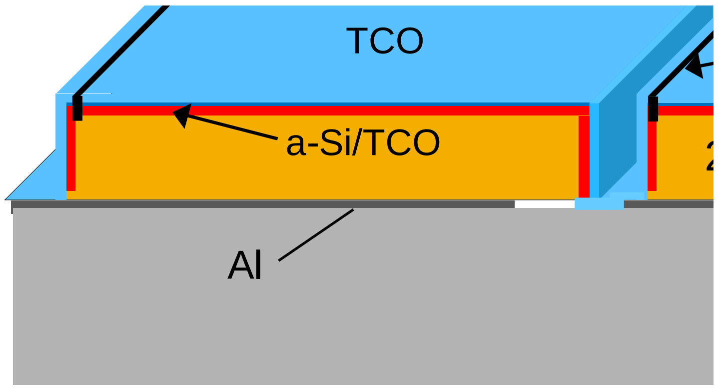
Vacuum deposition
a-Si

Wet Chemistry
Texturing, Cleaning

HetSi integrated c-Si thin-film



– 40 %



8 steps

18.0 %

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Crystalline Si slipstreams thin-film approaches: Teams move faster!

http://p3.focus.de/img/gen/4/6/1246986304_jpeg-214h4906-20090707-img_21742408_1093623_3_dpa_Pxgen_r_311xA.jpg

- Improved rear requires improved bulk
- Efficiency isn't everything → stay simple!
- Clear plan for –20 % system costs by gradual improvements (in 1 to 4 years)
- Disruptive integrated thin c-Si approaches have a syst. cost reduction potential of –40 % (in 5 to 10 years). This is factor of 3 in module cost.
- MacPSI, a new separation technique
- Invest in Si-PV research: Focus on production technology for disruptive concepts → fastest progress
- There is plenty of room at the bottom!

Thanks for cooperation and funding to
ISFH staff & Industry partners & BMU
& State of Lower Saxony

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Institut für Solarenergieforschung close to Hannover

- Photovoltaics and Solar Thermal
- PV focuses on crystalline Si
- Linked to Leibniz Univ. Hannover

- 160 employees
- 52 PhD candidates and students
- 11.3 Mio € turn over (2009)
- 35 % oft that from industry