Perspektiven von kristallinen Siliziumschichten auf Glassubstrat: Auf dem Weg zur Waferqualität

Bernd Rech

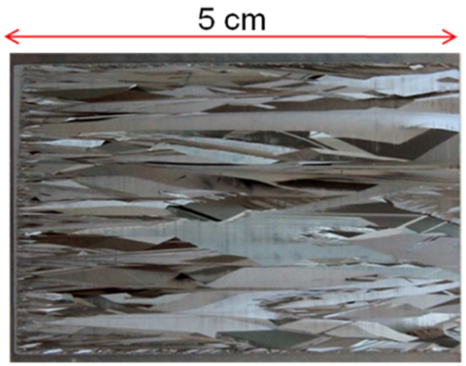
D. Amkreutz, J. Haschke, F. Ruske, S. Steffens, L. Korte, S. Gall, Silicon-Photovoltaics
R. Schlatmann, O. Gabriel, S. Calnan, S. Ring, B. Stannowski PVcomB
C. Becker, V. Preidel, Young Investigator Group Nano-SIPPE
J.-H. Zollondz, A. Heidelberg MASDAR PV GmbH

Thanks to: E. Rudigier-Voigt (SCHOTT AG), D. Hauschild (LIMO GmbH)
U. Blöck, A. Schnegg, and many more colleagues @ HZB

AKE der Deutschen Physikalischen Gesellschaft - Bad Honnef 2014

Outline

- **Introduction&Status PV**
- **Amorphous&Microcrystalline Si (brief)**
  - Technology Transfer
  - BIPV & large scale implementation
- **Large grained poly-Si on glass**
  - Liquid phase crystallisation – a new horizon
  - Material properties
  - Solar cells & perspectives
- **Conclusions&Outlook**



Helmholtz-Centre Berlin

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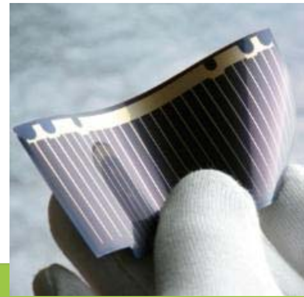
Neutrons

Photons

User Service



Solar Energy

Total Annual Budget: ~110 million EUR

75% ↘ 70% (2015)

25% ↗ 30% (2015)

Total Staff: about 1,100

Scientists: about 400

International Users: about 2,800 p.a.

400

2,400

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BESSY II
3rd Generation Photon Source

- Operational since 1998
- Energy Range from THz to Hard-X-Ray
- **Dedicated to VUV and Soft-X-Ray**
- **Full Polarization** Control
- **Topping-Up** Mode since October 2012

HZB in the Programme EMR

Advanced Analytics especially by

the „Energy Material In-Situ Laboratory“ – EMIL

- **World-wide unique research infrastructure at BESSY II**
  - **Photovoltaic Systems**
  - **Catalytic Systems**
- **together with Max-Planck-Association**
- **Begin of Operation: 2016**

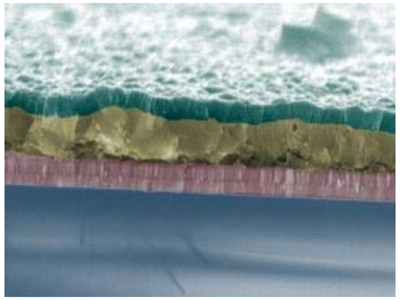
Head of Project: K. Lips

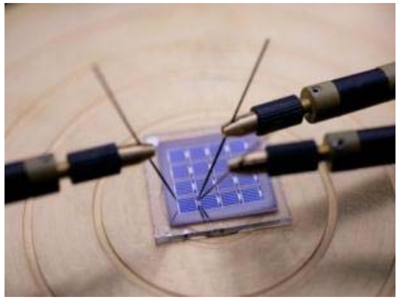
Solar Energy Research

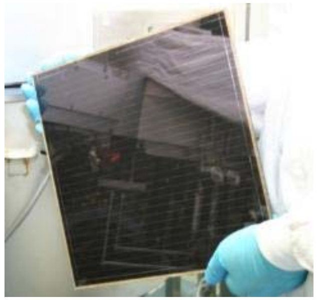
Fundamentals

Development

Technology Transfer

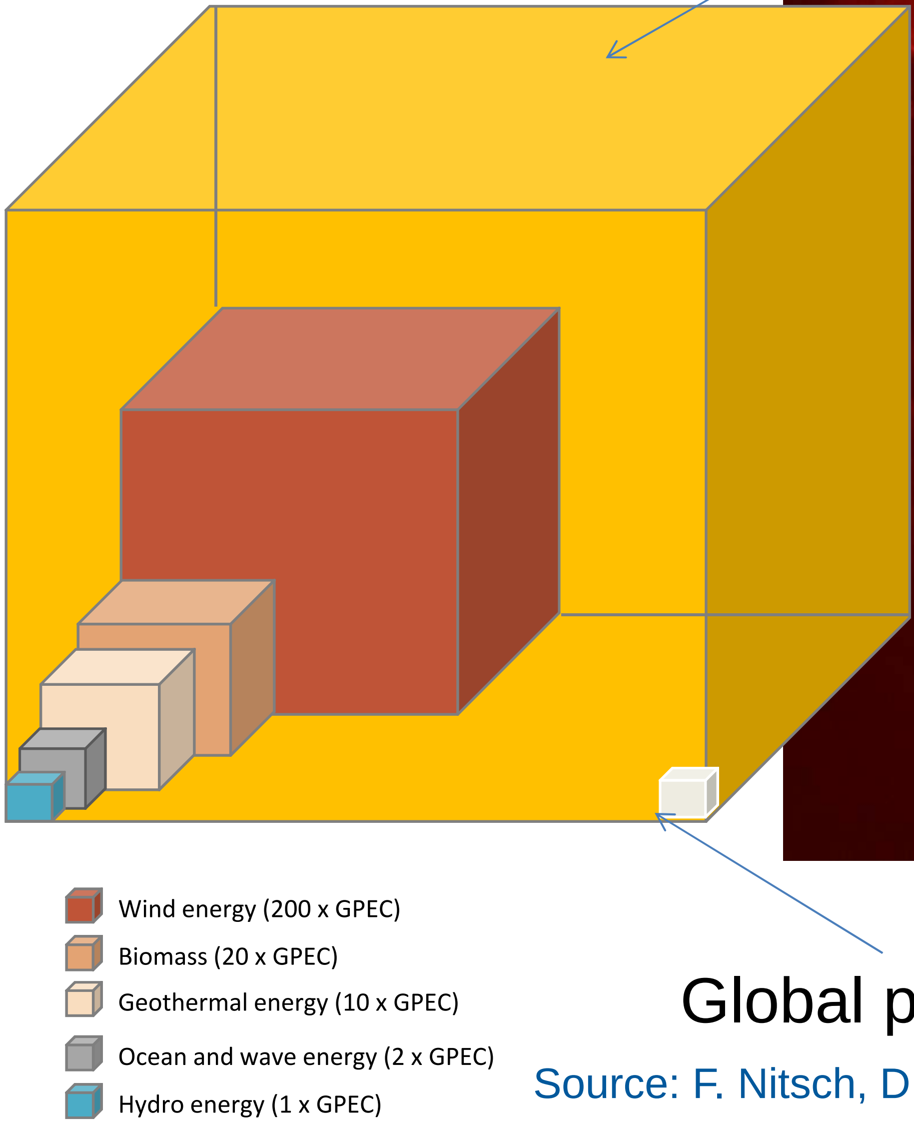


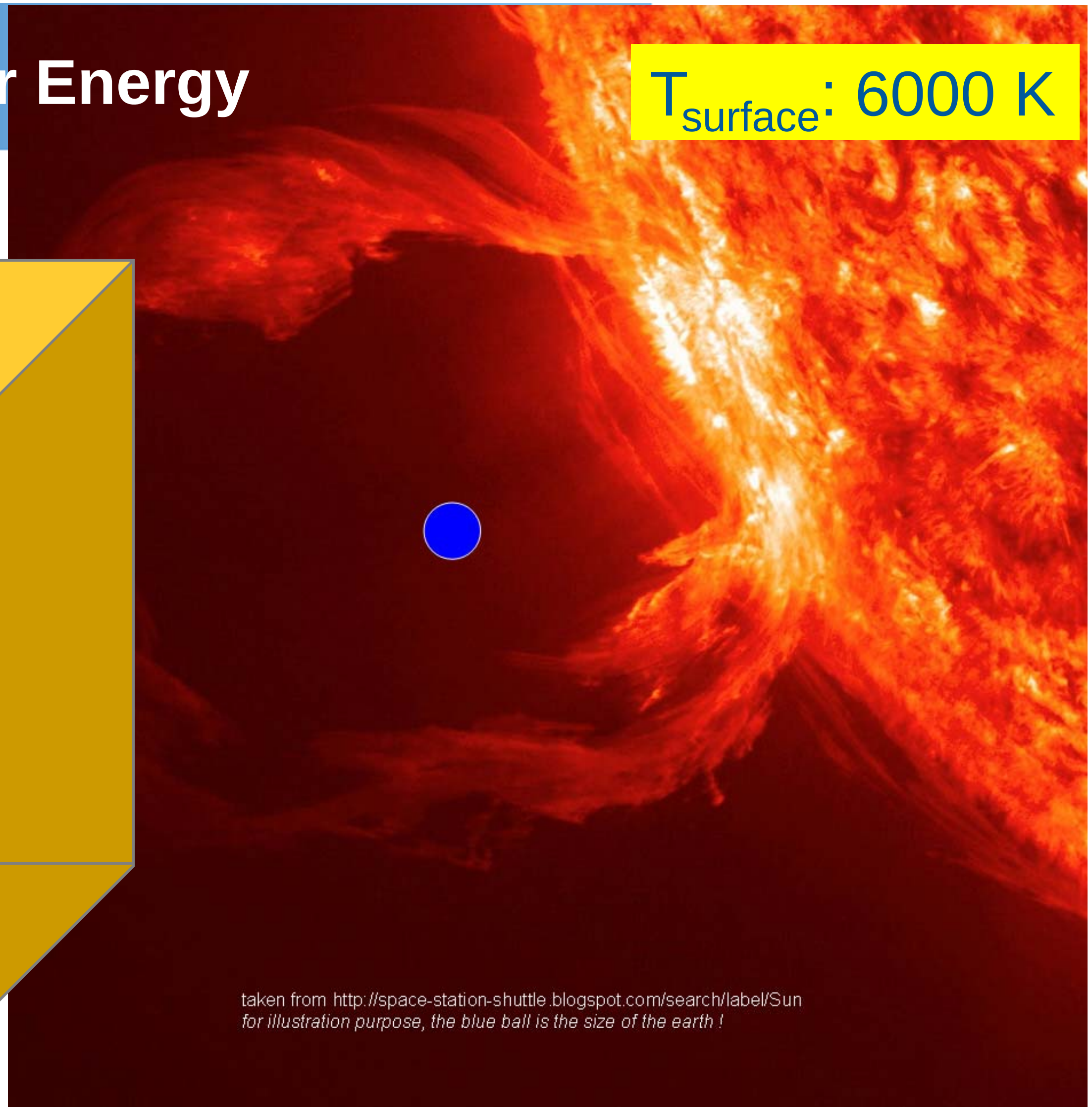




Potential of Solar Energy

Solar energy (continental)

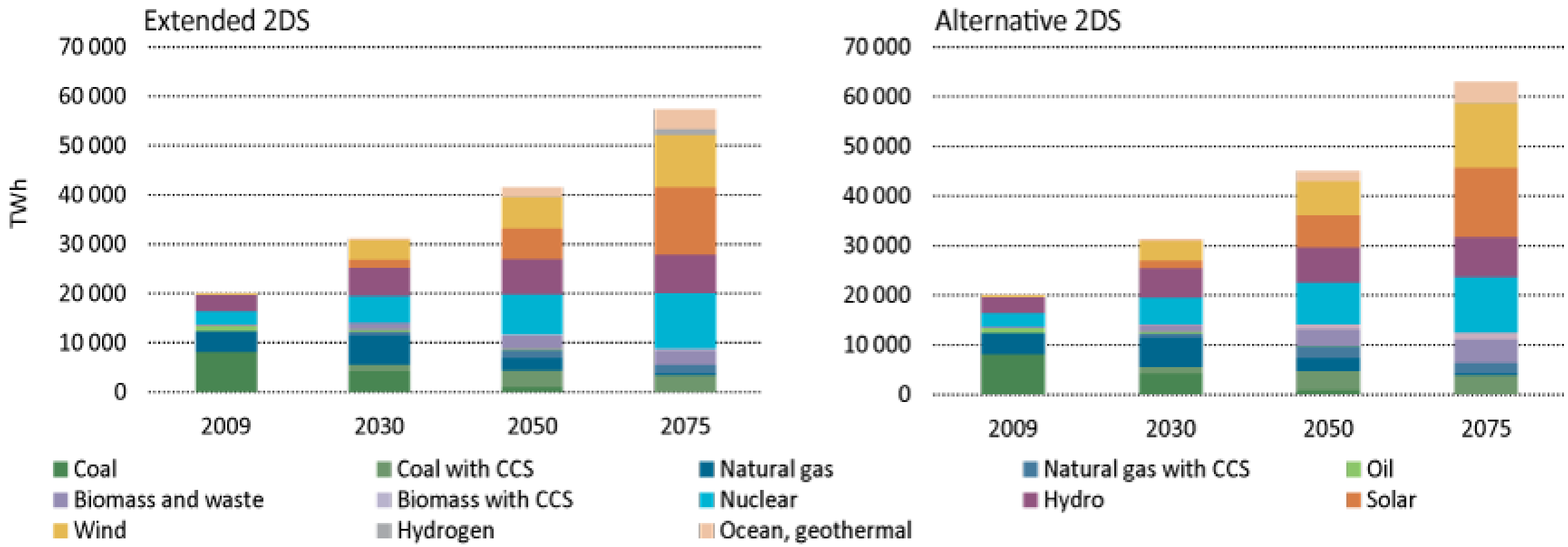




Global primary energy consumption

Source: F. Nitsch, DLR

Renewables in the IEA 2DS Scenario

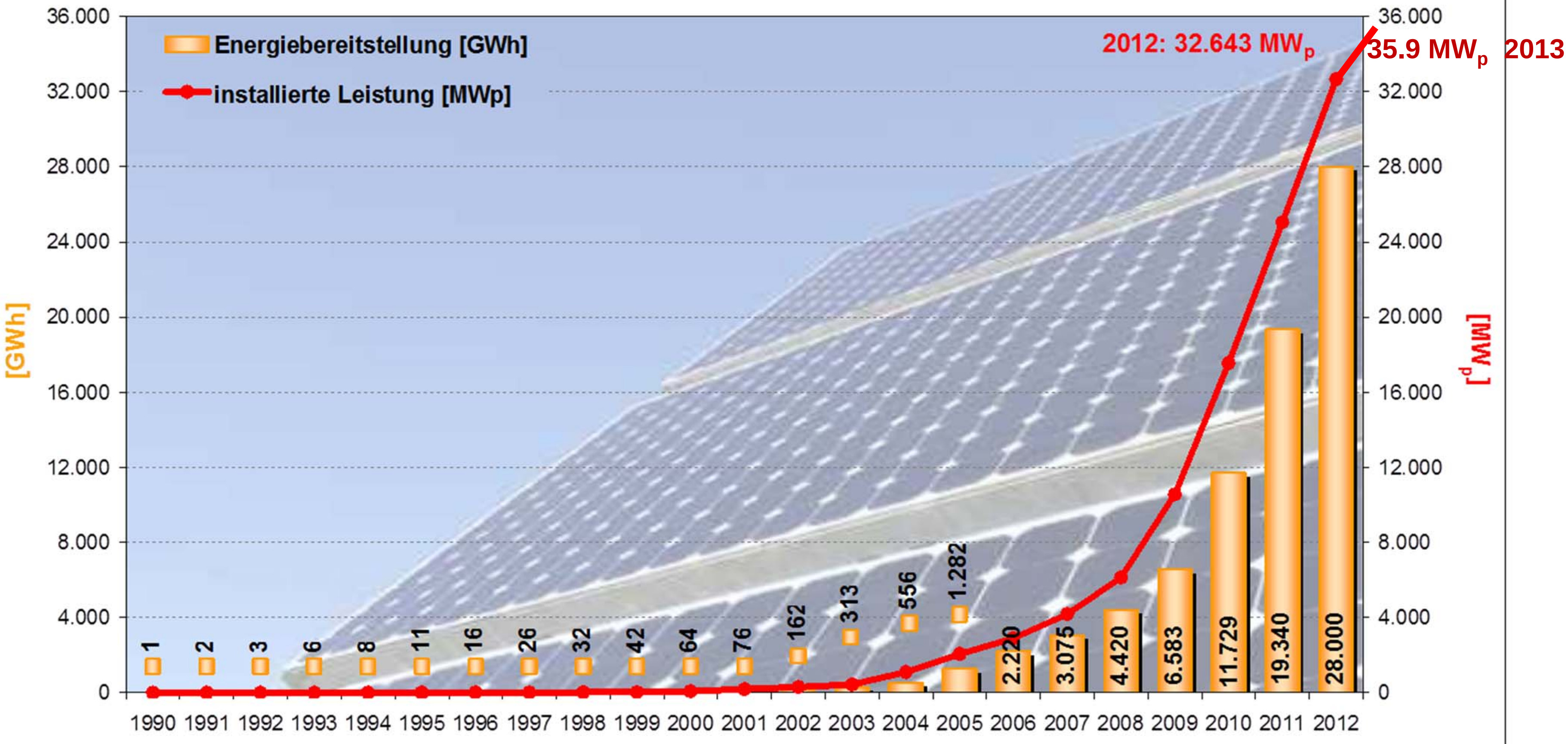


IEA - Energy Technology Perspectives 2012

PV in Germany: 1990 - 2013

Cumulative PV installation in Germany

Global installation approx. 100 GW end of 2012



Quelle: BMU - E I 1 nach Arbeitsgruppe Erneuerbare Energien-Statistik (AGEE-Stat); 1 GWh = 1 Mio. kWh; 1 MW = 1 Mio. Watt;
Hintergrundbild: BMU / Bernd Müller; Stand: Februar 2013; Angaben vorläufig

PV costs in Germany and Feed In Tariff 2006 - 2012

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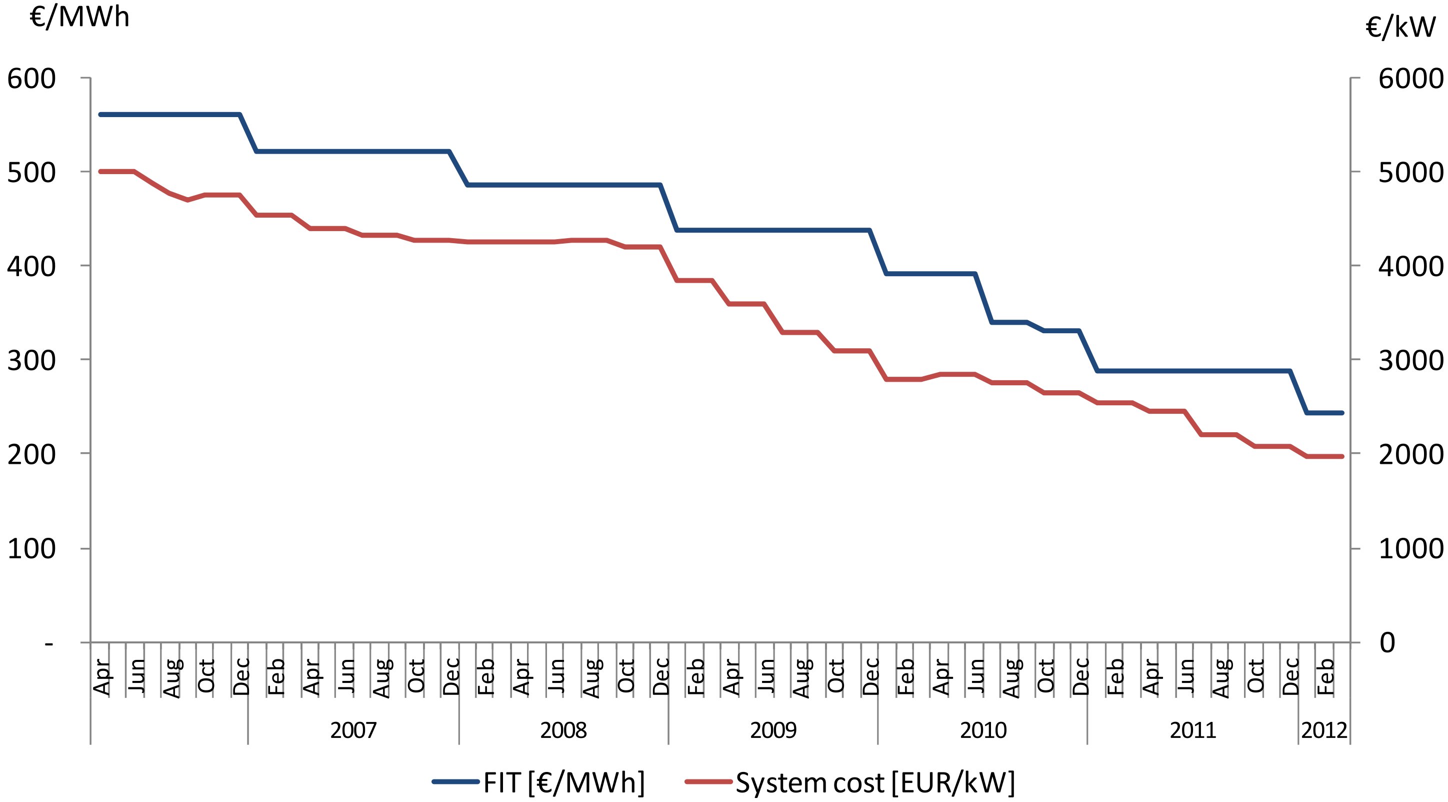
Solar PV system cost and feed-in tariff, large solar plants, Germany 2006-12

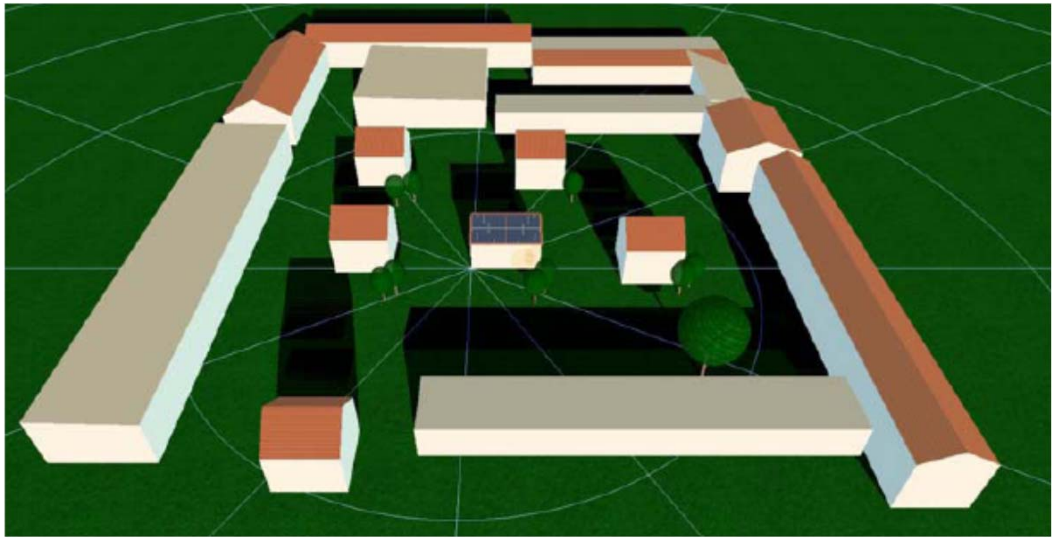


PV in Berlin today – residential home

11.5 KW_p c-Si: grid connection 11/2012
„black design“: η = 15 %
Expected production / y: 10.000 kWh
2013: 10.000 kWh (average y)
2014: 10.500 -11.000 (sunny y)
Electricity generation cost: 18 c/kWh

	costs in €	costs in €/Wp	costs/kWh
Modules	11500.00	1.00	0.10
Inverter	2500.00	0.22	0.02
Installation	7500.00	0.65	0.06
total	21500.00	1.87	0.18

Note: installations in 2014 show significantly lower electricity generation costs



A simple cost model

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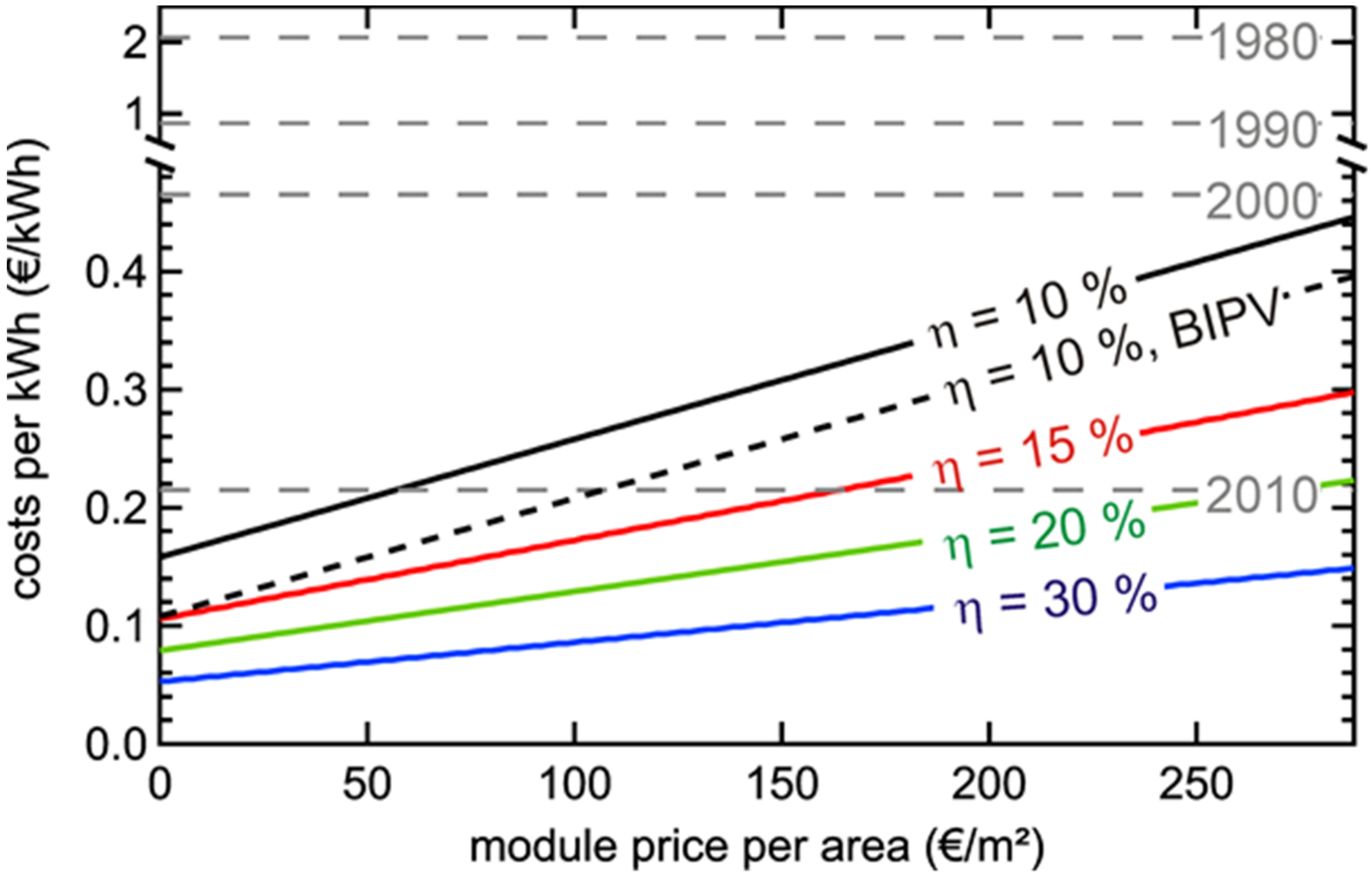

Note: Calculation done for 1000 sunshine hours. An efficiency of 20 % and 1000 sunshine hours is equivalent to a 10 % system in a region with 2000 sunshine hours.

B R, SS Schmidt, R Schlatmann Transition to Renewable Energy Systems, 283-306

Share of Different PV Technologies

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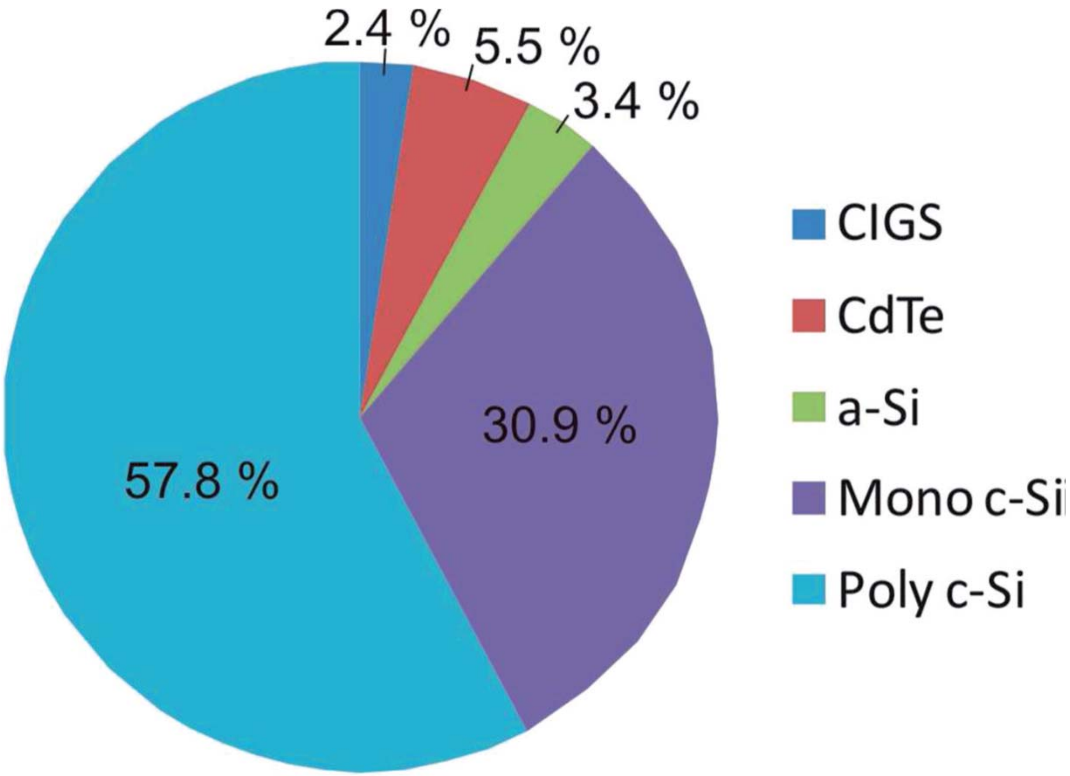

89 % Wafer based Si
11 % Thin film

Photon Europe GmbH (2012)

Wafer based crystalline Silicon

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50 years manufacturing experience

- monocrystalline
- multicrystalline

New cell concepts on industrial scale

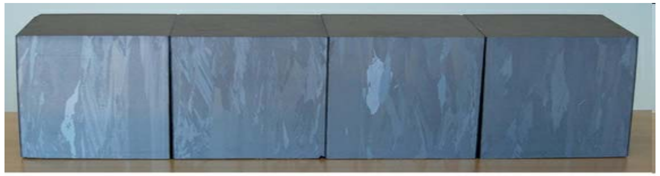
- rear contacts
- improved texturing and passivation

Laboratory cell efficiency:
23% various approaches
(world record lab cell: 25.6 %)

module efficiency range:

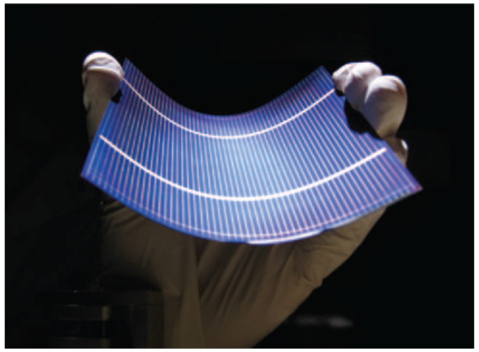
•13 ~ 20%

•18 ~ 22% (longer term)



Bricks of multicrystalline silicon produced via the Vertical Gradient Freeze method at SIMTEC.

Source: SIMTEC/ FHG ISE



source: ECN

PV Status and growth potential

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Unique features of photovoltaics:

- Direct energy conversion
- No movable parts
- Versatile and scalable

Expected developments:

- futher continous cost reductions
- pillar of world energy supply
- Multi-billion dollar market

5 % of electricity supply

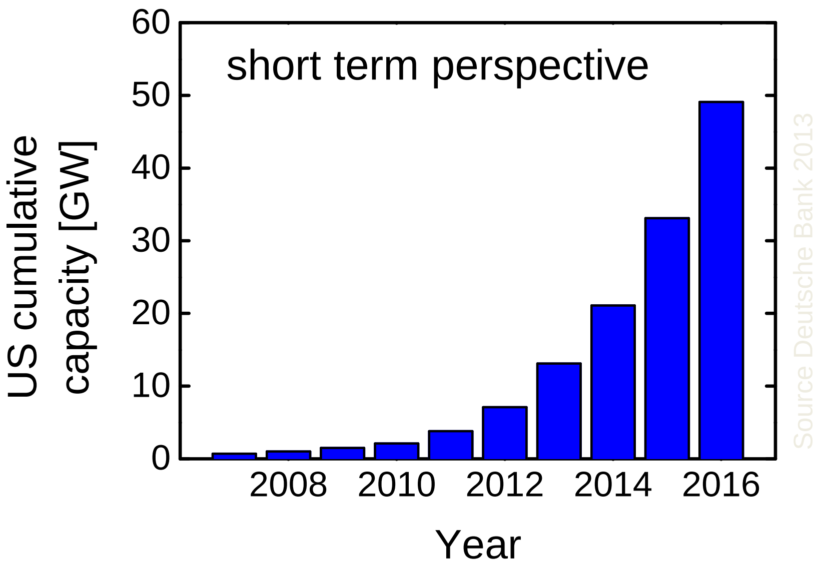
in Germany by PV

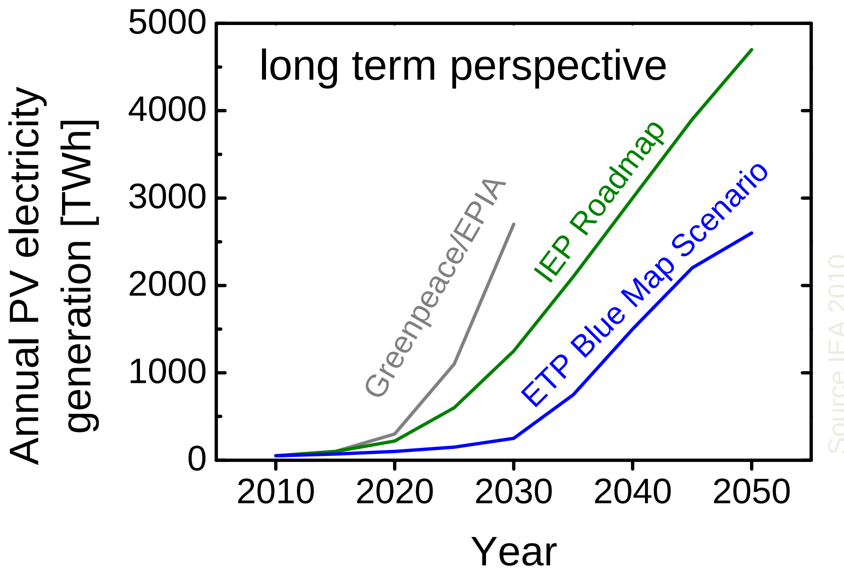
Source AGEE 12.2013

Terawatt scale production

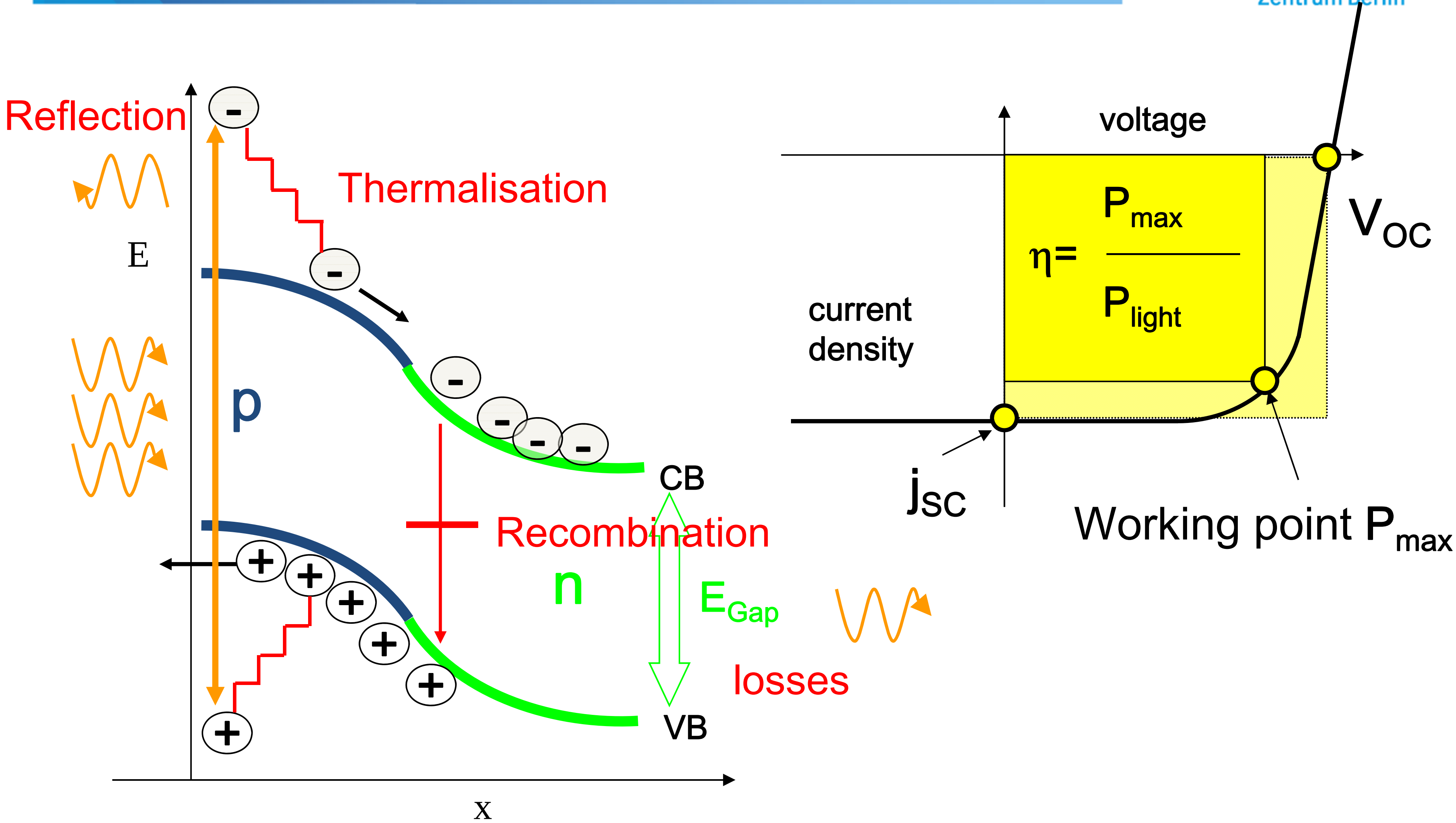
2030: > 2 mio. jobs in PV

Source IRENA 2013



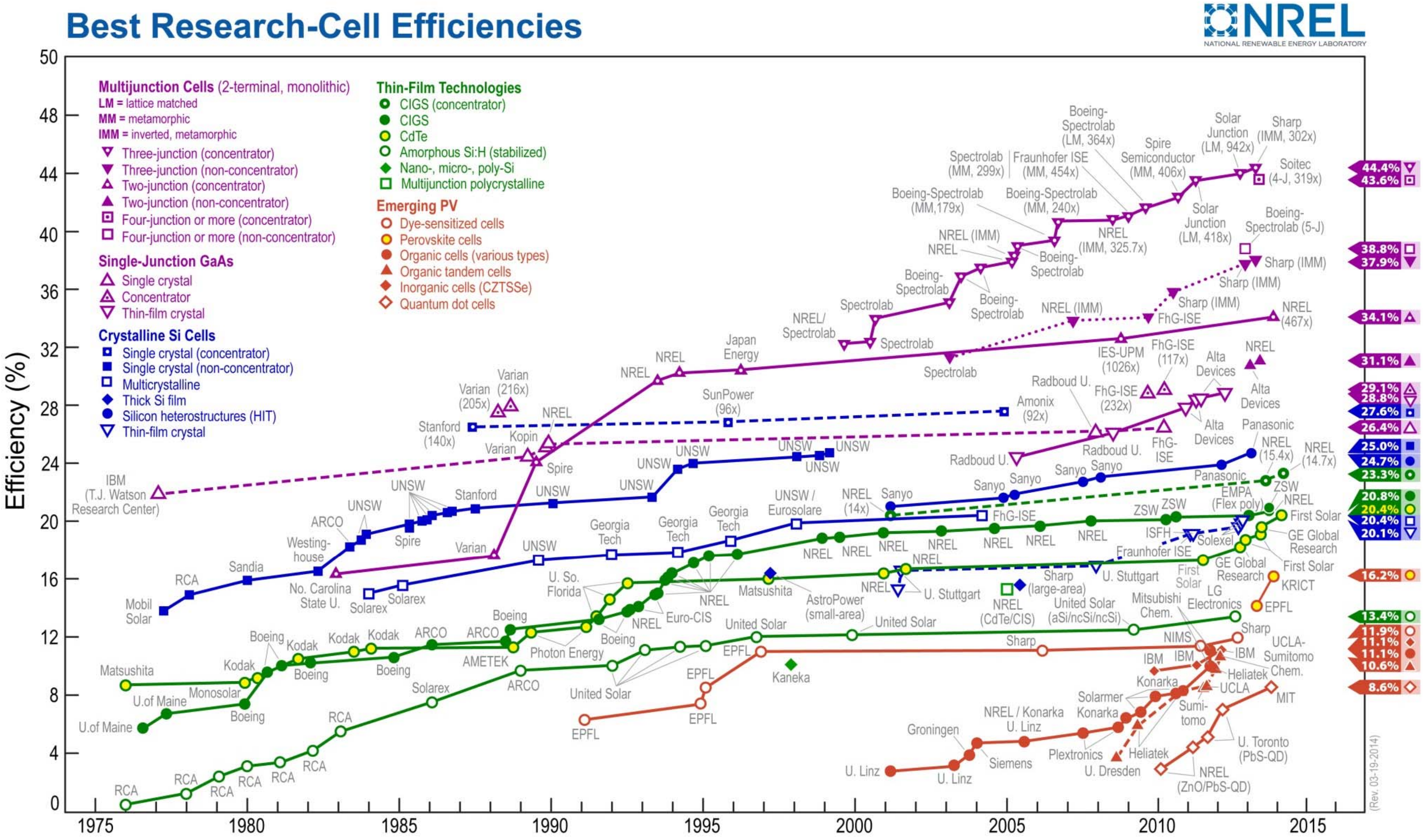


Some Physics



Record Solar Cells

HZB Helmholtz Zentrum Berlin



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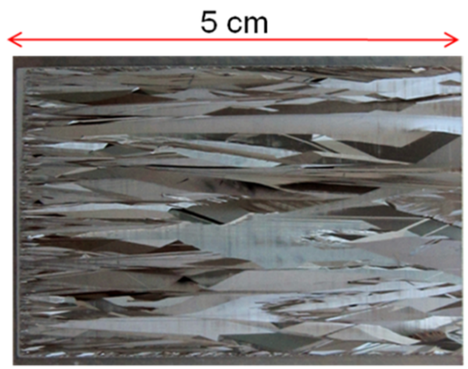
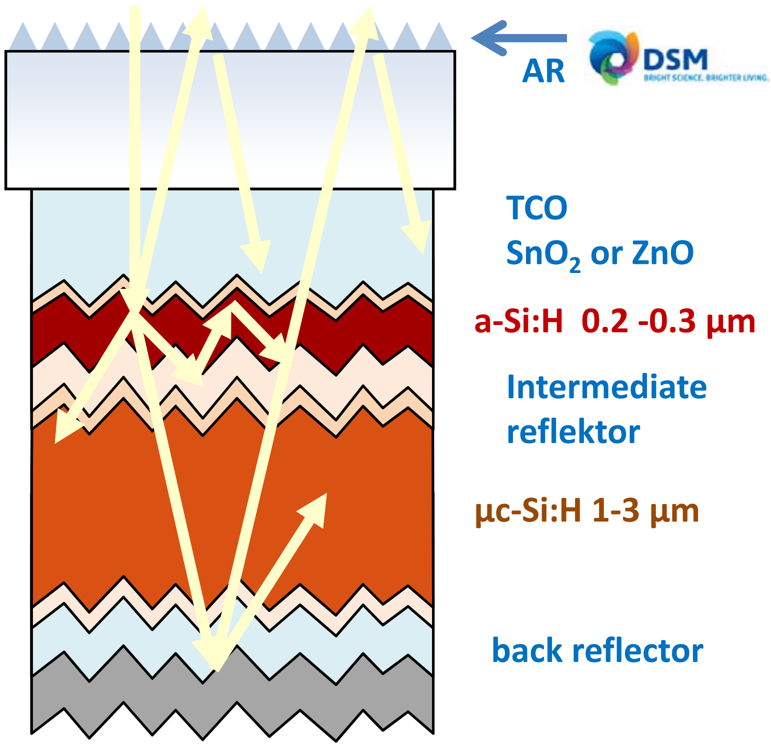
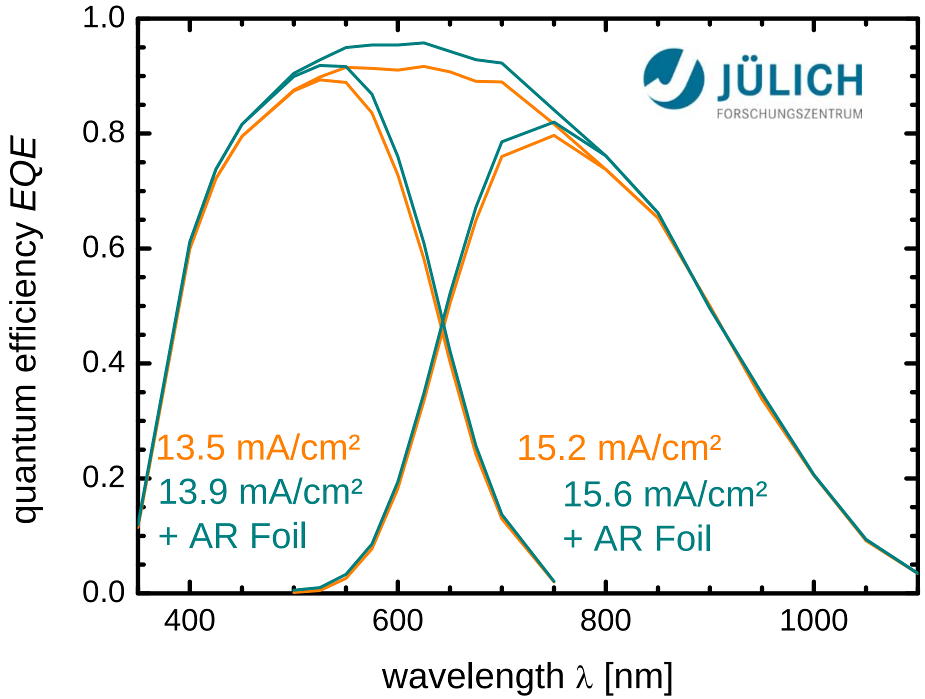


a-Si:H/µc-Si:H Tandem Cells



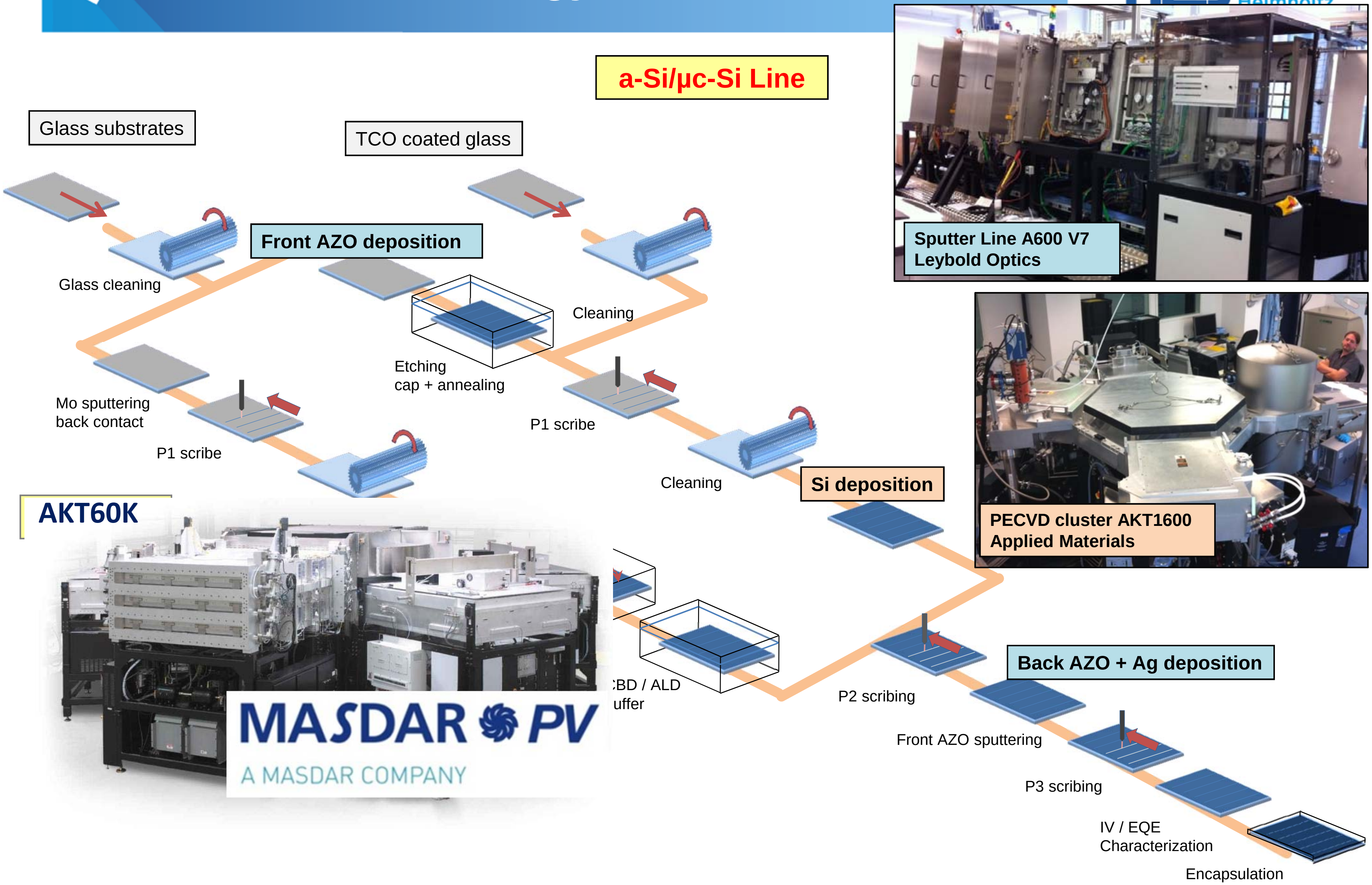


A. Lambertz et al. SolMat 119 (2013).

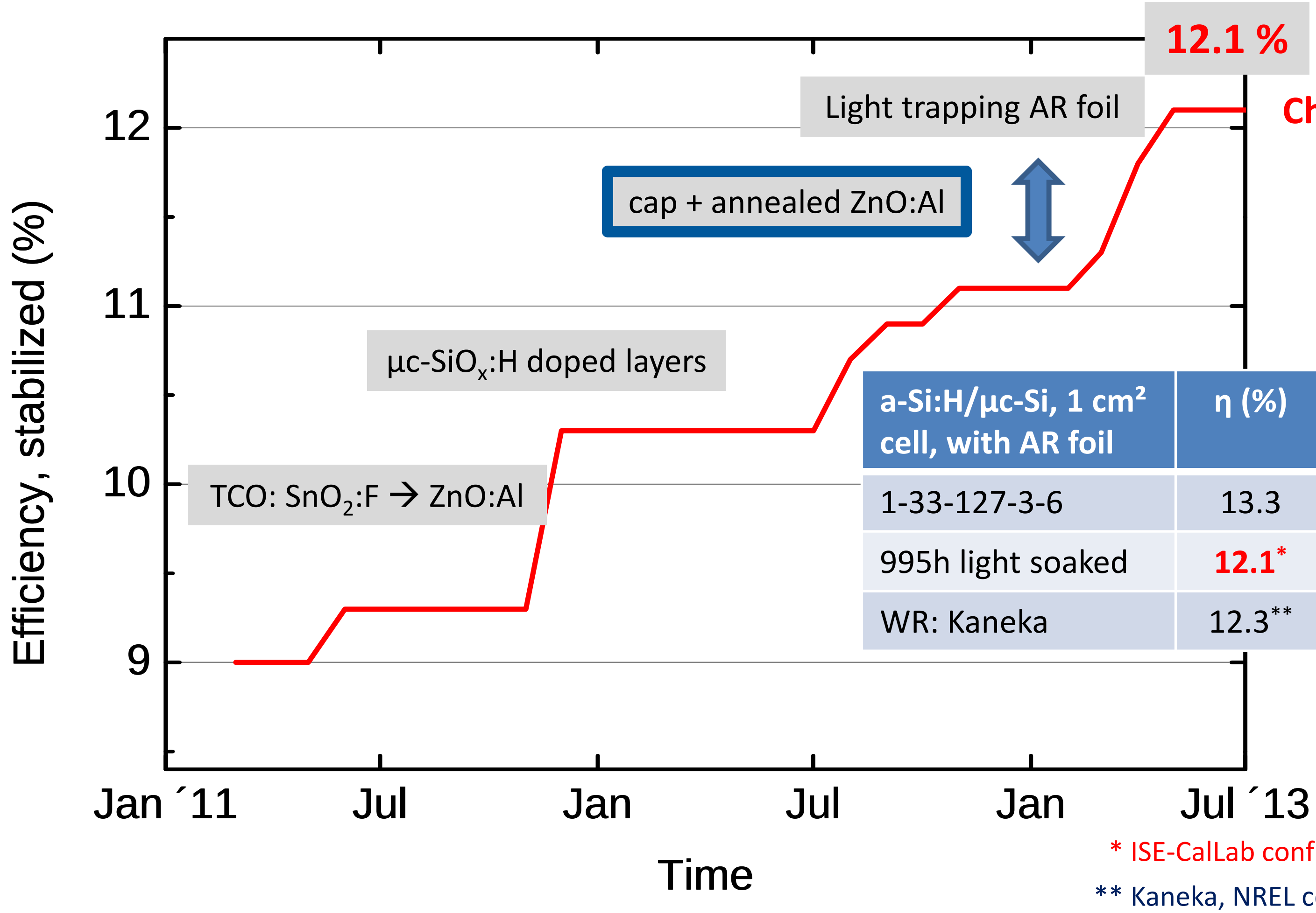
pioneered by J. Meier/ A. Shah et al.
first modules by Kaneka (K. Yamamoto et al.)

Technology status in A. Shah et al. SolMat 119 (2013).

PVcomB technology transfer lines



a-Si:H/µc-Si:H solar cells @ PVcomB



a-Si:H/µc-Si, 1 cm² cell, with AR foil	η (%)	J_{sc} (mA/cm²)	V_{oc} (mV)	FF (%)
1-33-127-3-6	13.3	12.7	1432	73.2
995h light soaked	**12.1***	12.6	1411	67.8
WR: Kaneka	12.3**	12.9	1365	69.4

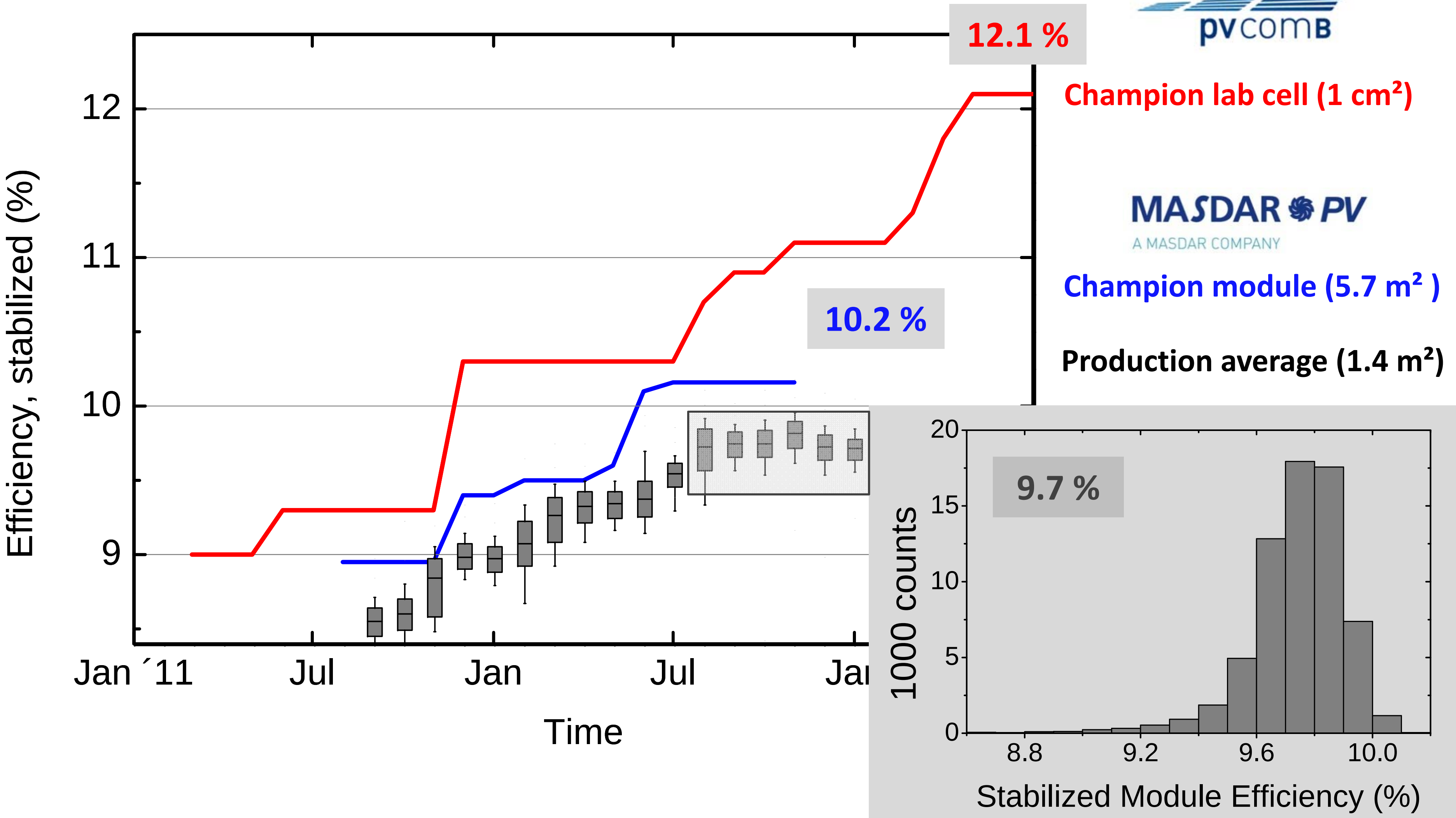
* ISE-CalLab confirmed: 12.11 mW

** Kaneka, NREL certified (M. Green *et al.*, PIP 2013)

B. Stannowski et al., SolMat119 (2013)

S. Neubert et al., PIP (2013) – ZnO integration

a-Si:H/µc-Si:H modules



Power Plants

MASDAR PV
A MASDAR COMPANY

HZB Helmholtz Zentrum Berlin

- 15 MW_p
- 29,826 a-Si/μc-Si modules à 5.7 m²
- 10 % of Mauritania's grid capacity
- Largest PV installation in Africa
- Advantage of a-Si/μ-Si technology in desert climate due to T_{coeff}

Building Integration

MASDAR PV
A MASDAR COMPANY

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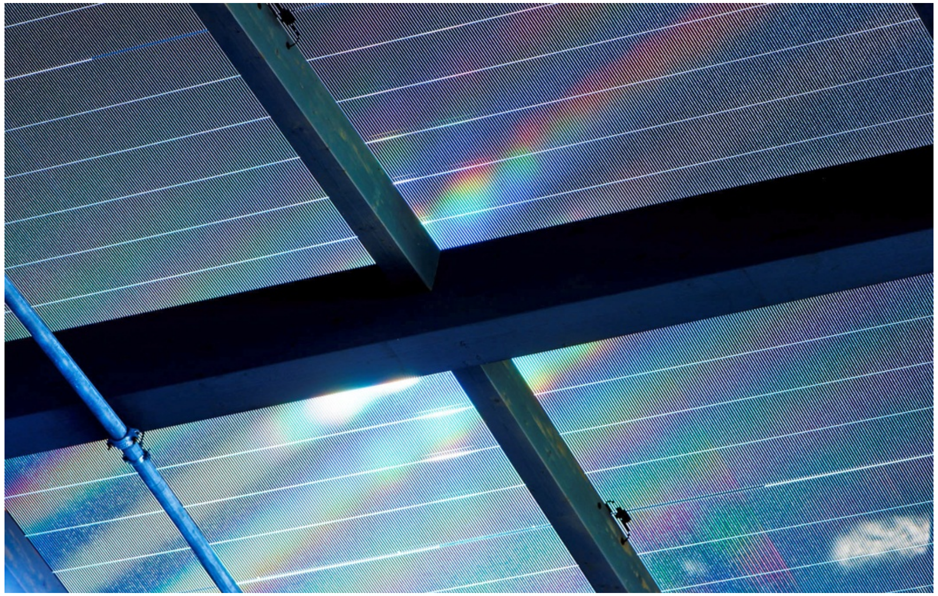
9.6 MW_p a-Si, Belgium, 2011



8.6 kW_p a-Si/µc-Si, Austria, 2012

However, MasdarPV is facing out

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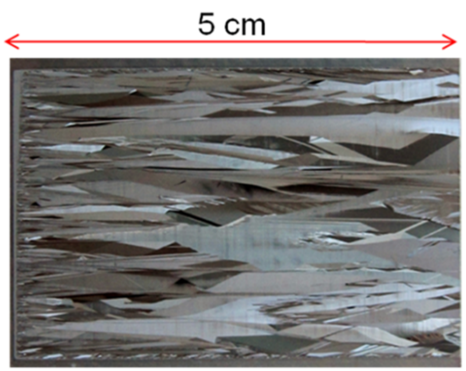


Thin-film Si on glass – status&challenge

HZB Helmholtz Zentrum Berlin

Triple junction cells (1cm²)

(a-Si:H/µc-Si:H/µc-Si:H)

13.4*% LG Electronics

13.6 % UniSolar

Tandem cells (1cm²)

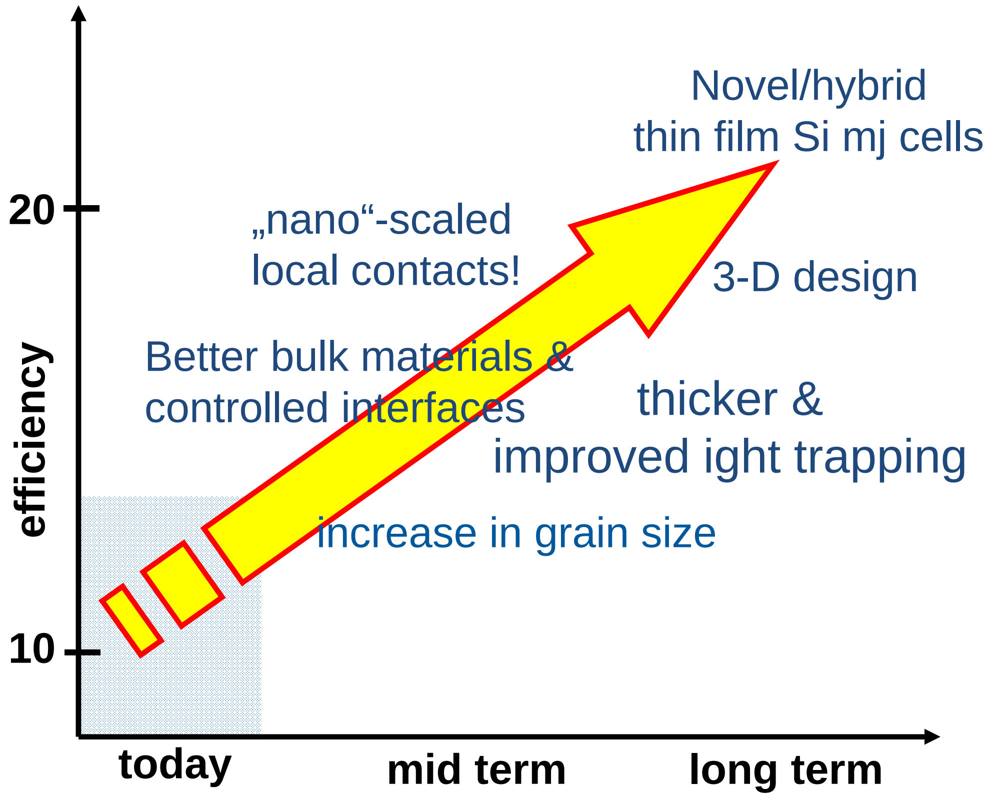
a-Si:H/µc-Si:H: 12.3* % Kaneka

Single junction cells (1cm²)

µc-Si: 10.7*% EPFL/IMT

a-Si:H: 10.1*%TEL Solar

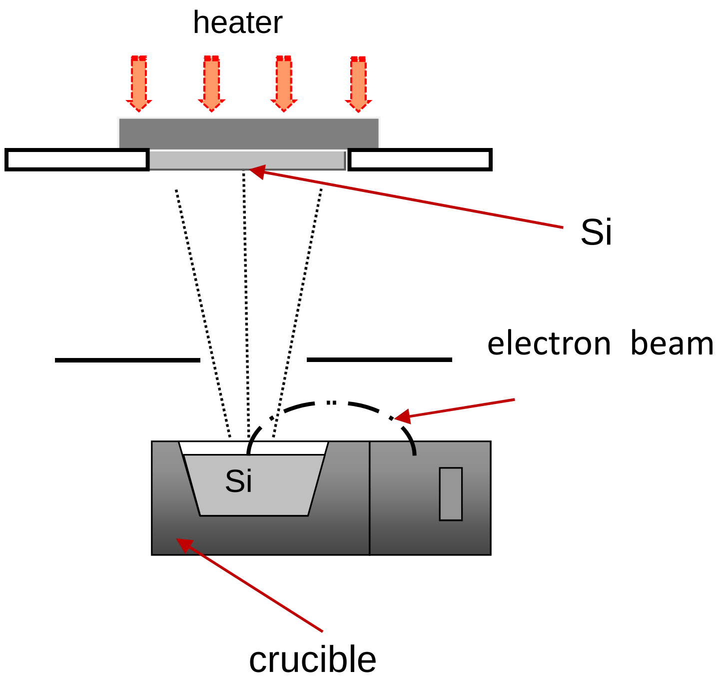
SPC-poly Si: 10.4*% csg solar (94cm²)



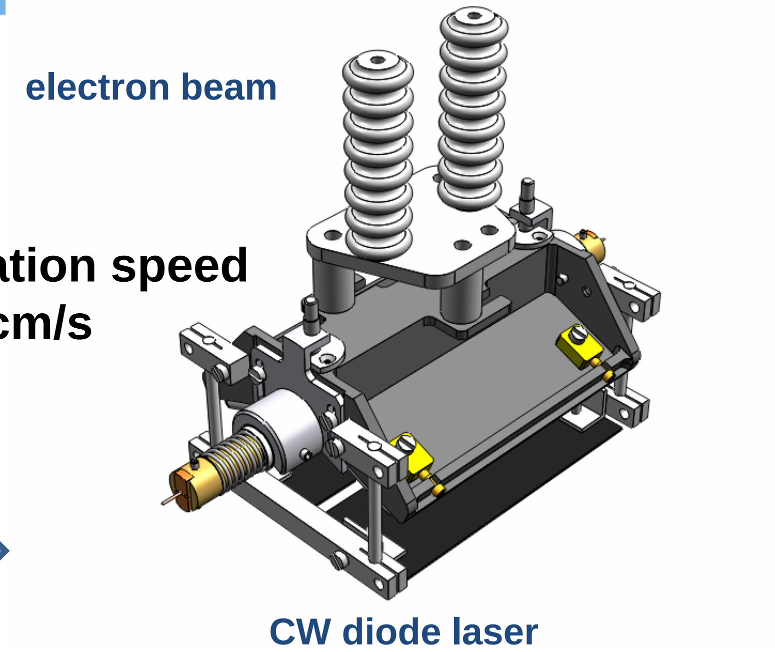
see review articles in special issue
Solar Energy Materials and Solar Cells 119 (2013)
ed. by A. Shah and A.N. Tiwari

Fast Si deposition & fast crystallisation

HZB Helmholtz



crystallisation speed
1 cm/s

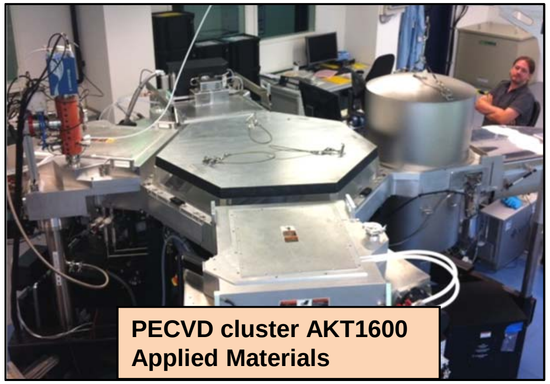


- Deposition rate up to 1µm/min
- film thickness 10-30 µm feasible
- High Vacuum (not UHV)
  (10^{-7} to 10^{-6}mbar)
- No toxic/explosive gases

LIMO
Lissotschenko Mikrooptik

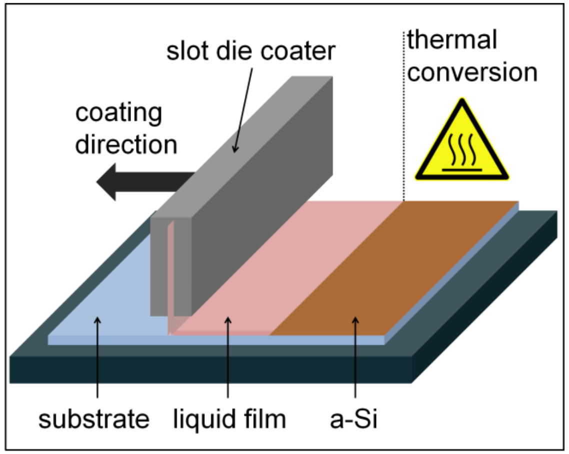
Alternatives for Si precursors at HZB

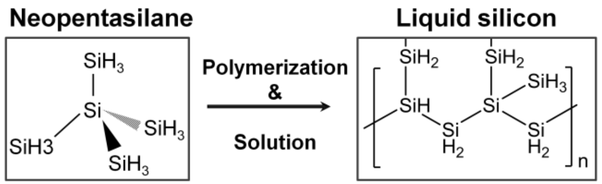
- PECVD + Annealing (for H out-diffusion)



PECVD cluster AKT1600
Applied Materials

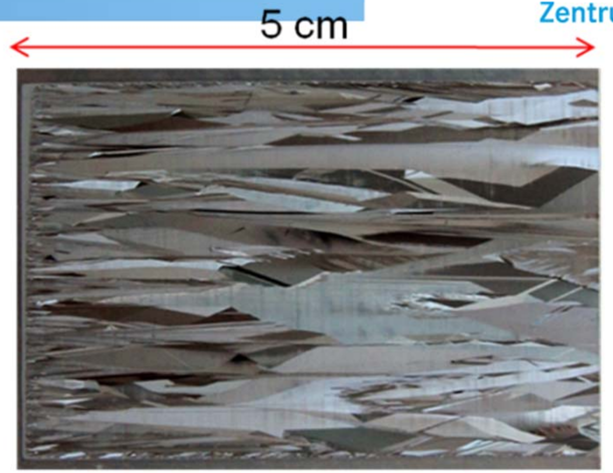
Wet chemical deposition

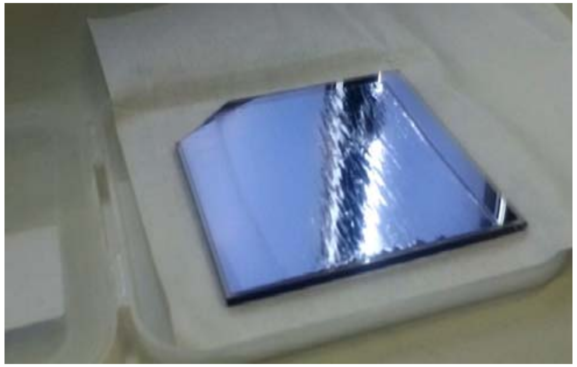




T. Sontheimer et al. Adv. Materials Interfaces, (2014)

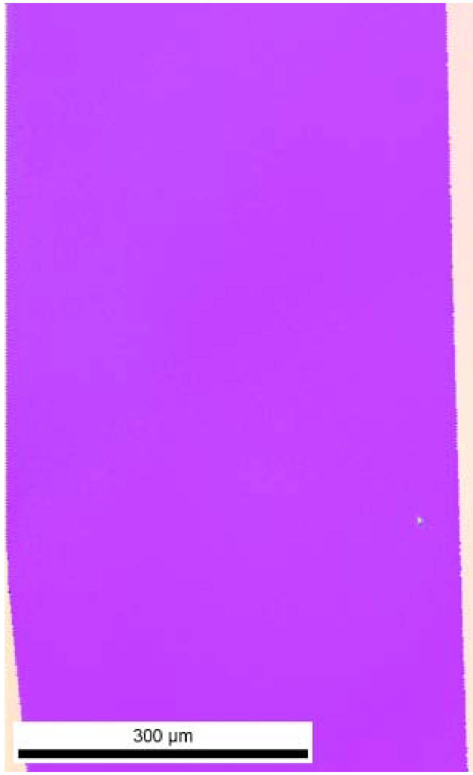
Electron Beam Crystallization on glass





Technische Universität Hamburg-Harburg

Liquid Phase Crystallization on Glass



Grain size / EFG like

up to cm in length

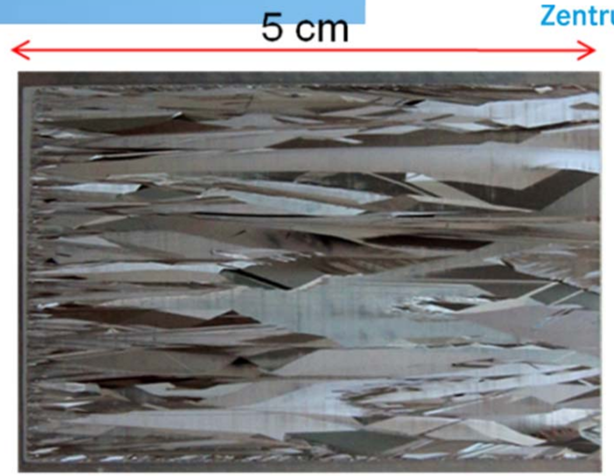
& several 100 µm in width

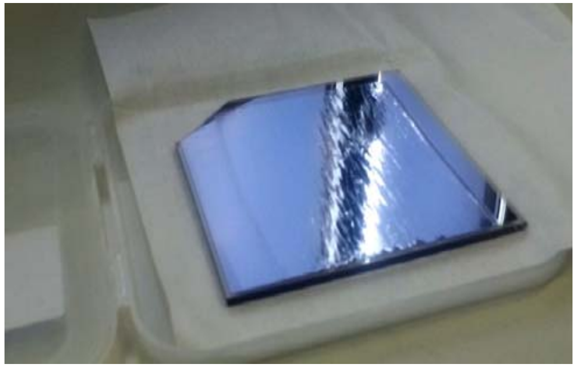
Typical Thickness 10 µm

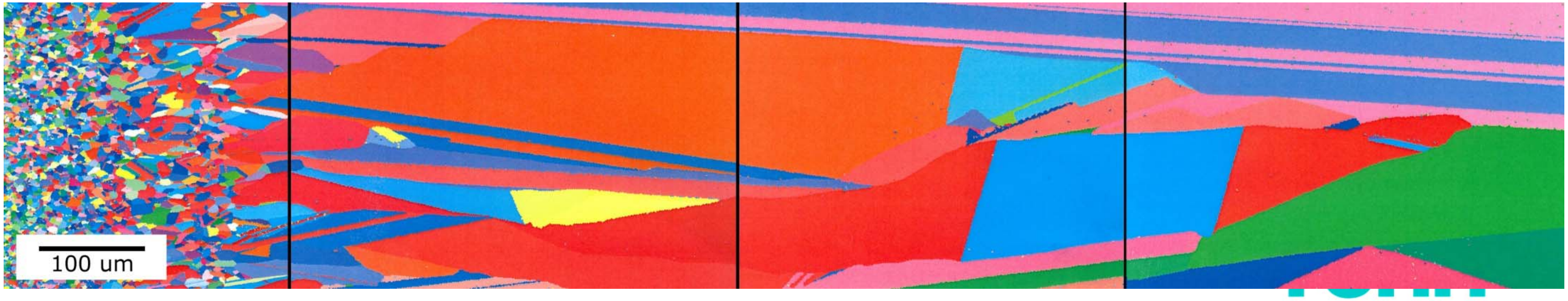
Dislocation densities:

very low in large grains

(comparable to cz-silicon)





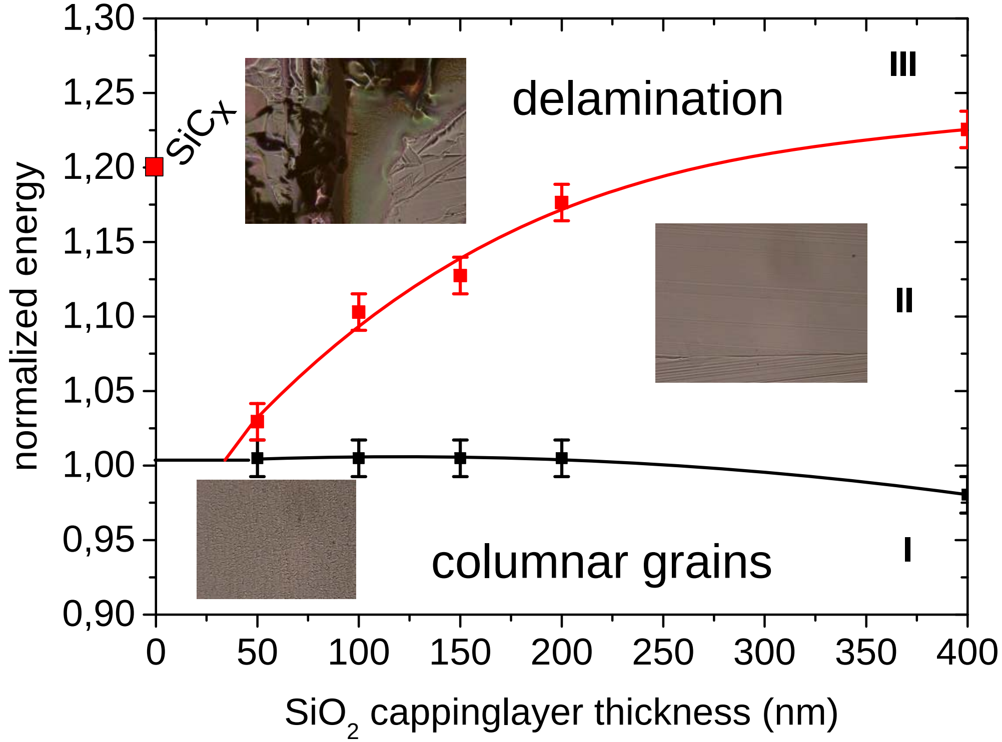


Technische Universität Hamburg-Harburg

Electron Beam Crystallisation

Helmholtz Zentrum Berlin

Process window on SiO_2 and SiC_x

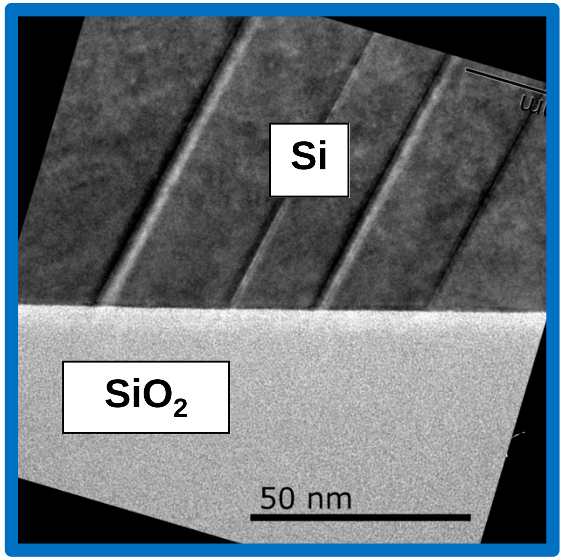


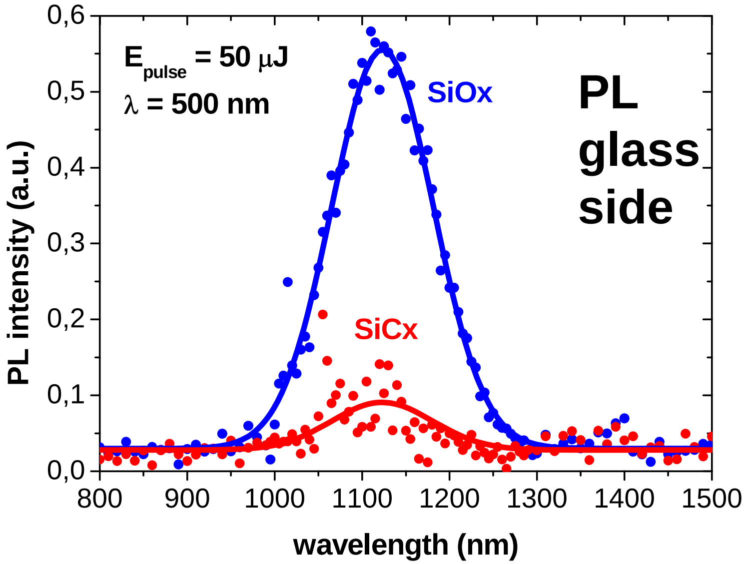
longitudinal grains region II

D. Amkreutz et al., SolMat Vol 123 (2014)

EBC crystallization on glass

HZB Helmholtz Zentrum Berlin



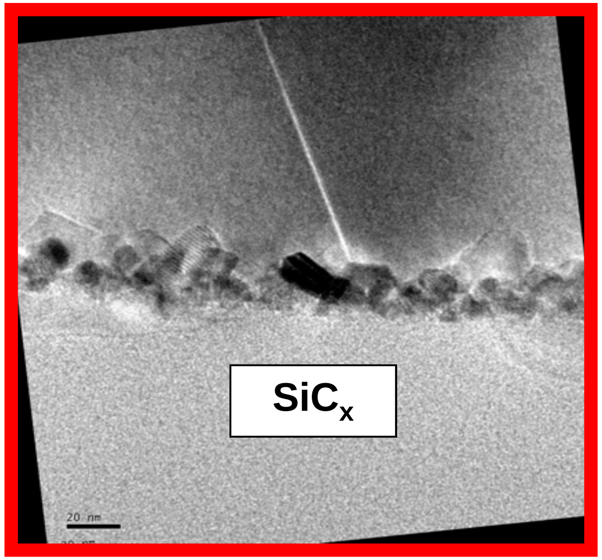


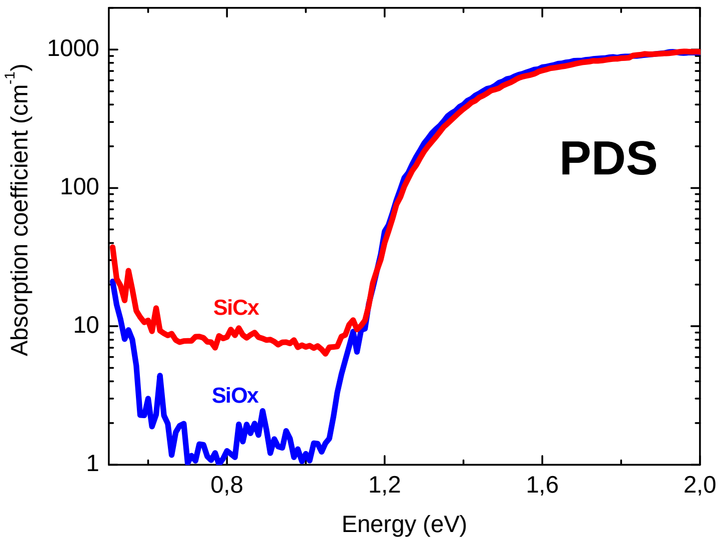
Properties

L_{diff}: several 10 µm

sharp band edge PL (film-side)

Glass side PL depends on buried interface





Defect density (EPR)

~ 10^{16} cm^3 (SPC)

~ 10^{16} cm^3 (EBC/SiC)

low 10^{14} cm^3 (EBC/SiO)

Poly-Si on glass – towards wafer quality

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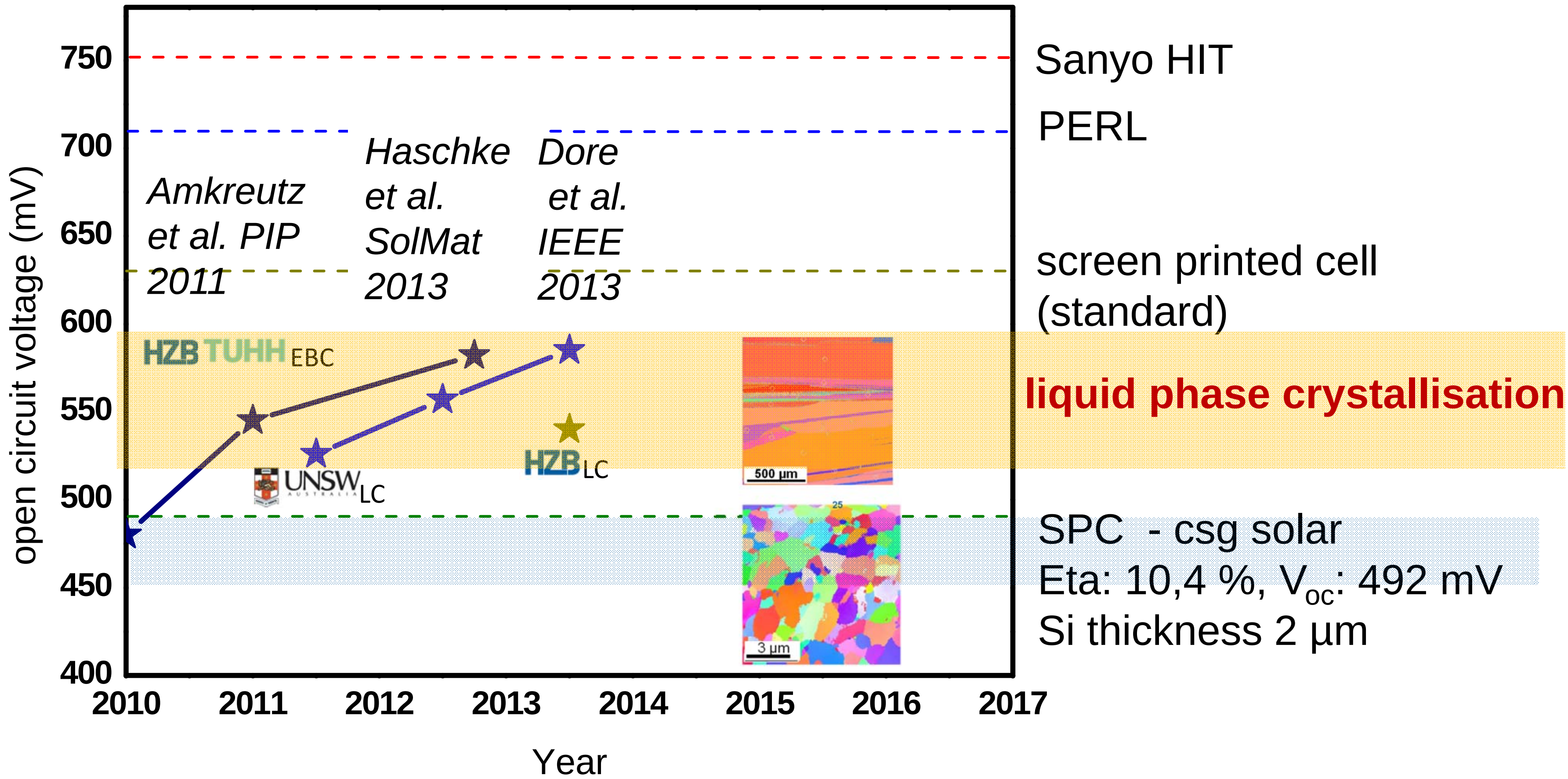
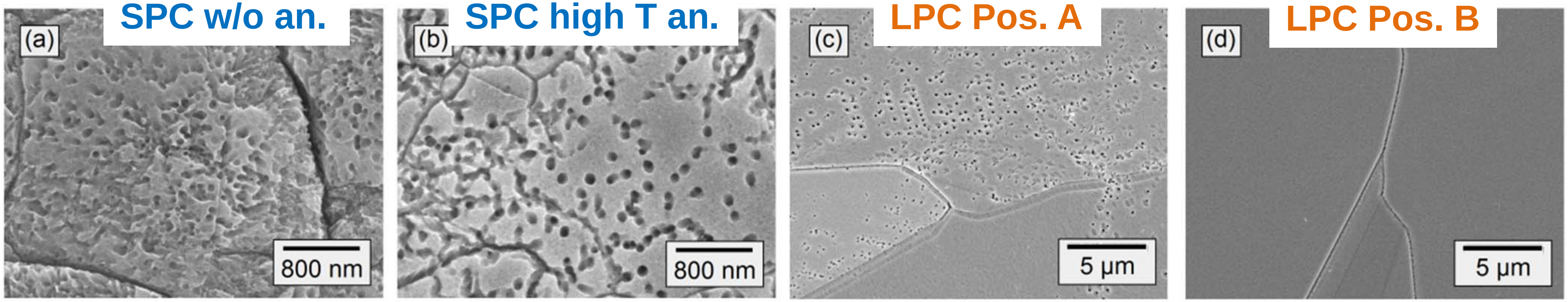
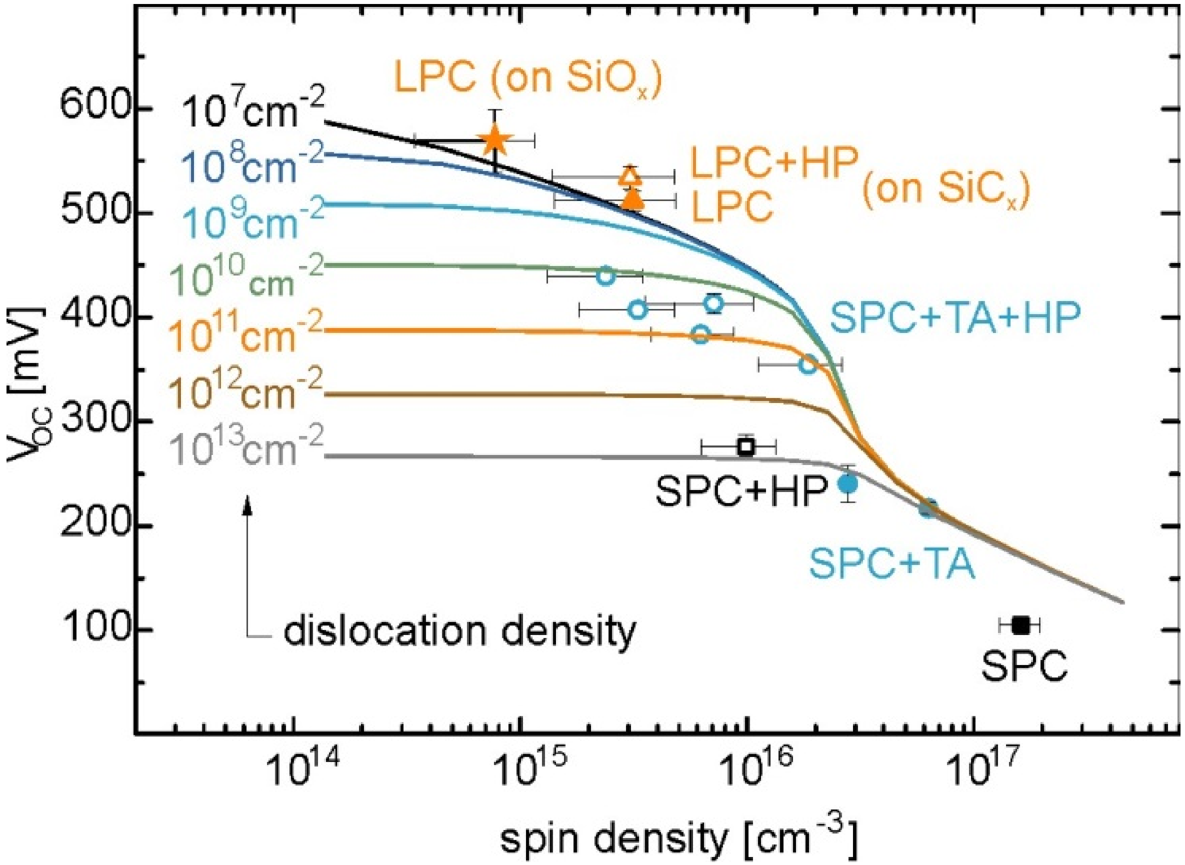


EBC: Electron Beam Crystallisation

LC: Laser Crystallisation (LIMO – line shaped)

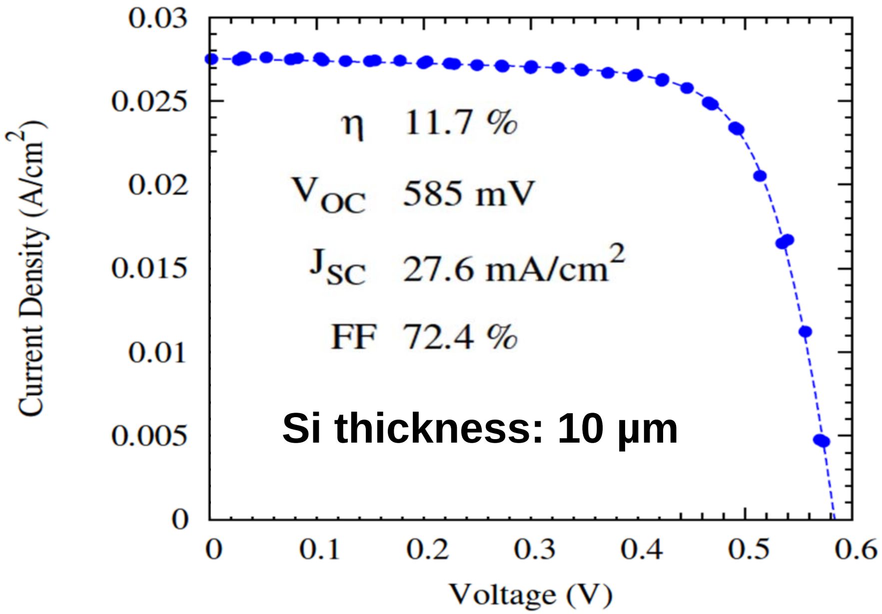
SPC: Solid Phase Crystallisation

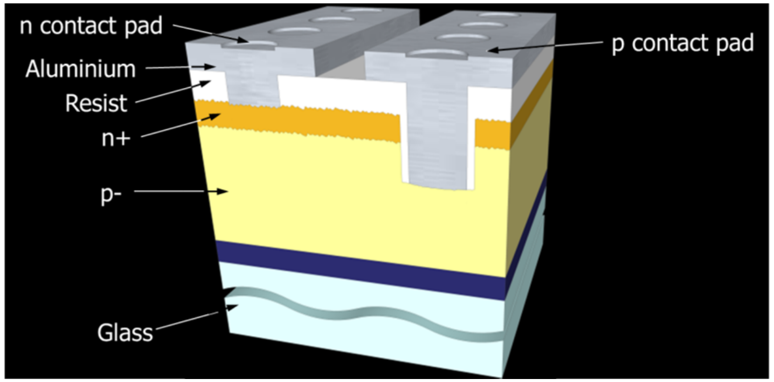




S. Steffens et al., APL 2014

Liquid phase crystallised Si on glass
Status in Sydney





Special features

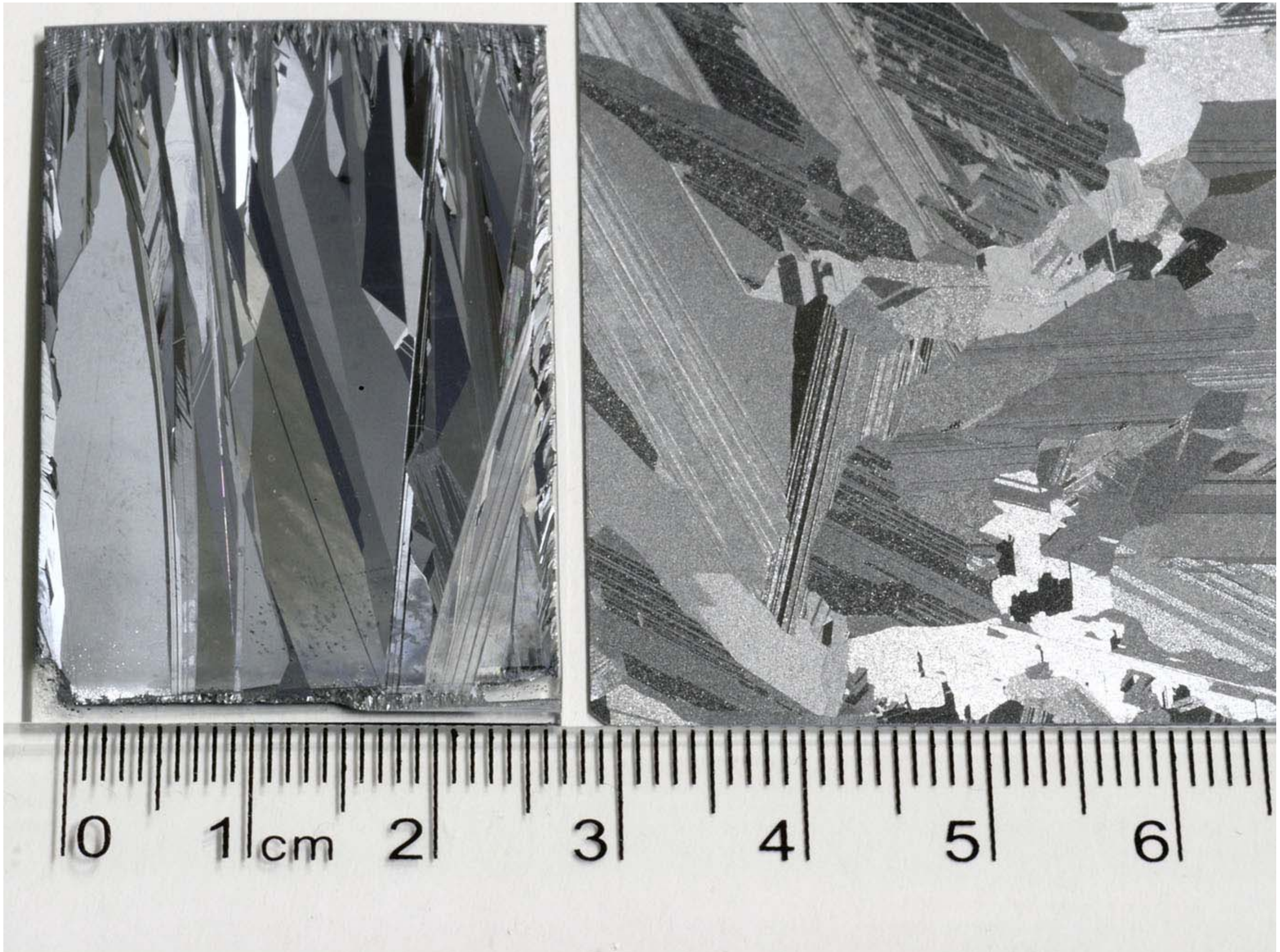
- Superstrate configuration
- High blue response / good passivatior of the buried interface
- Glass/SiO/SiN/SiO/Si AR coating
- Textured silicon surface
- Laser crystallisation

J. Dore et al. IEEE 2013
S. Varlamov et al. SolMat 119 (2013).

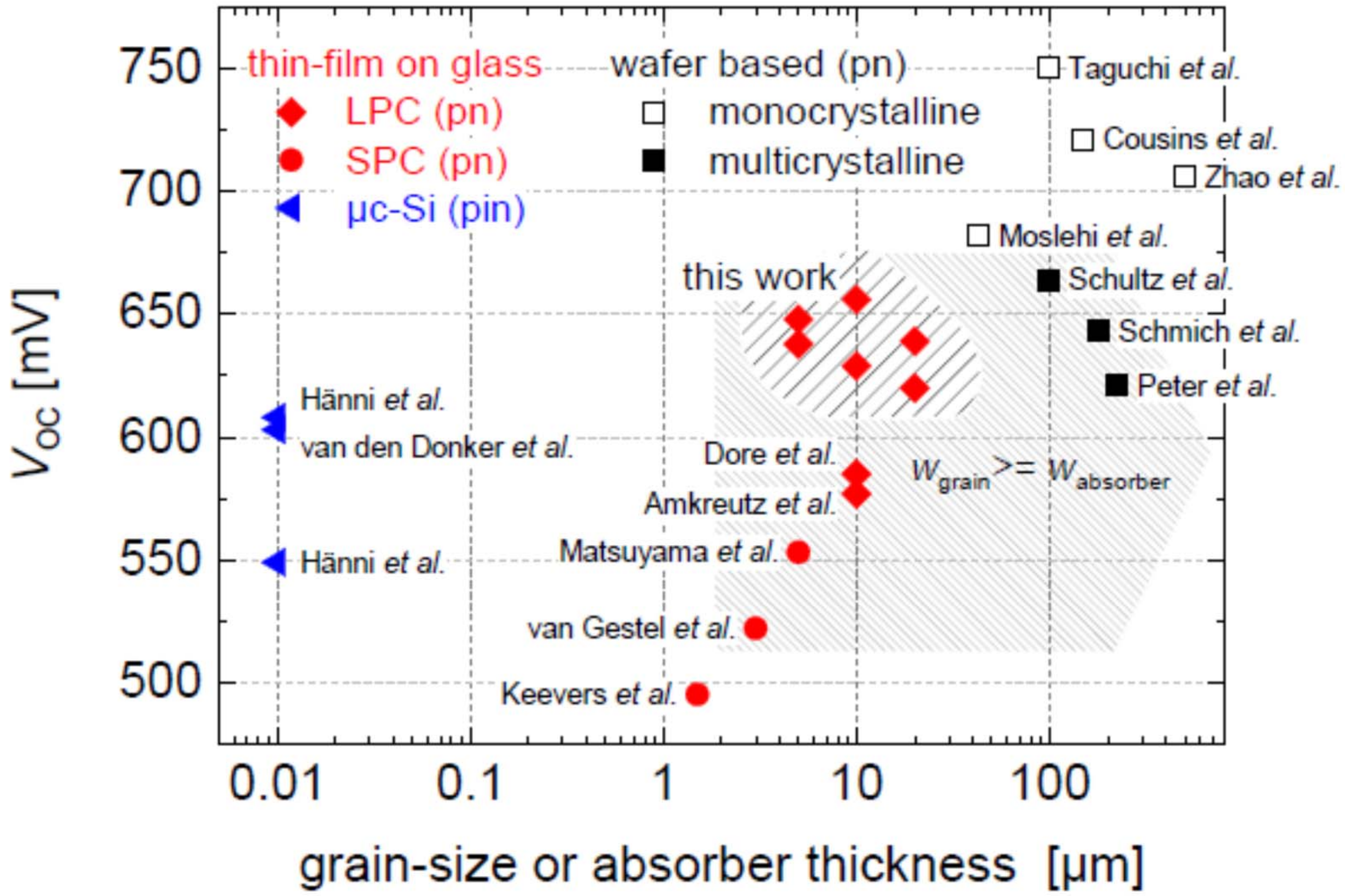
Latest progress towards wafer quality

40 µm crystallised Si on glass

Multi-crystalline Si wafer



Switching to n-type poly Si absorbers

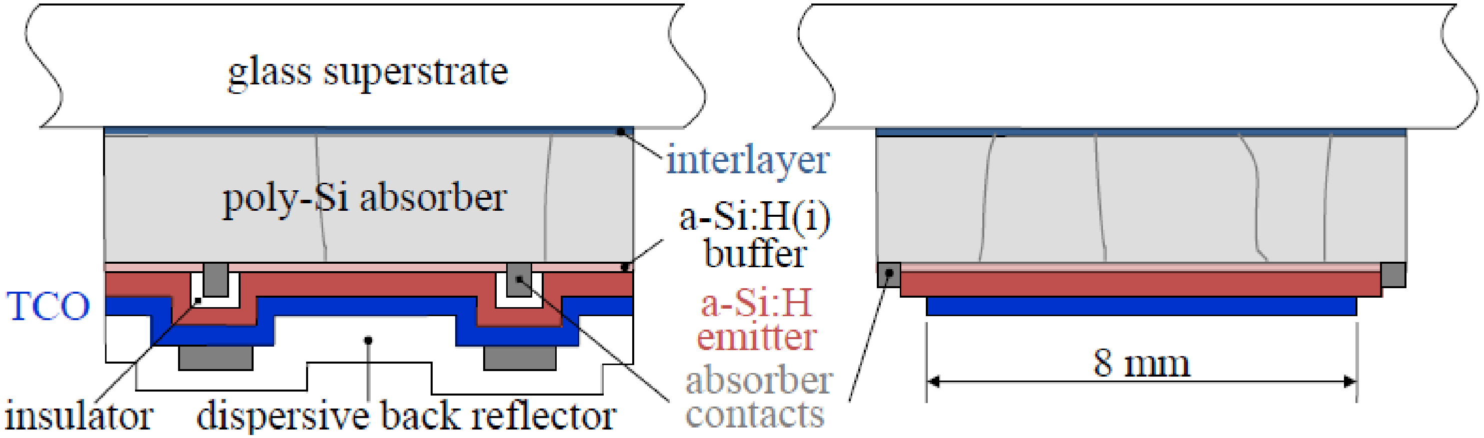


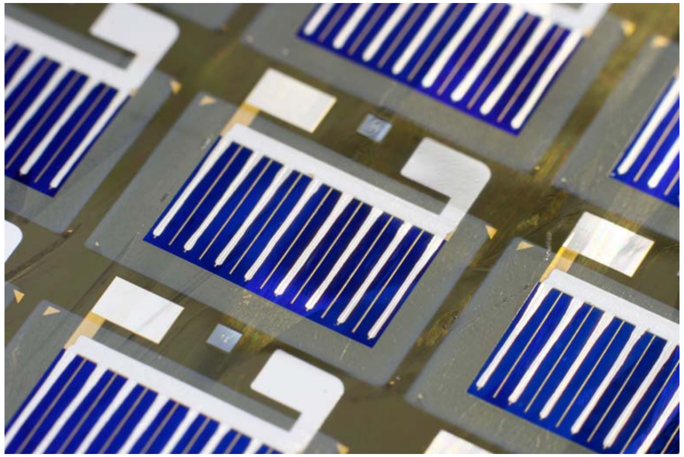
Jan Haschke et al. SOLMAT 2014
Latest results in Daniel Amkreutz et al. IEEE-J-PV, 2014

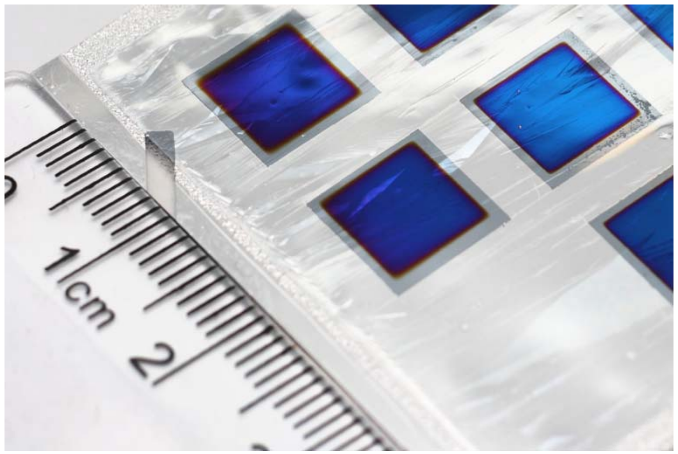
Solar cell structures

„advanced“ design - A

simple design - S

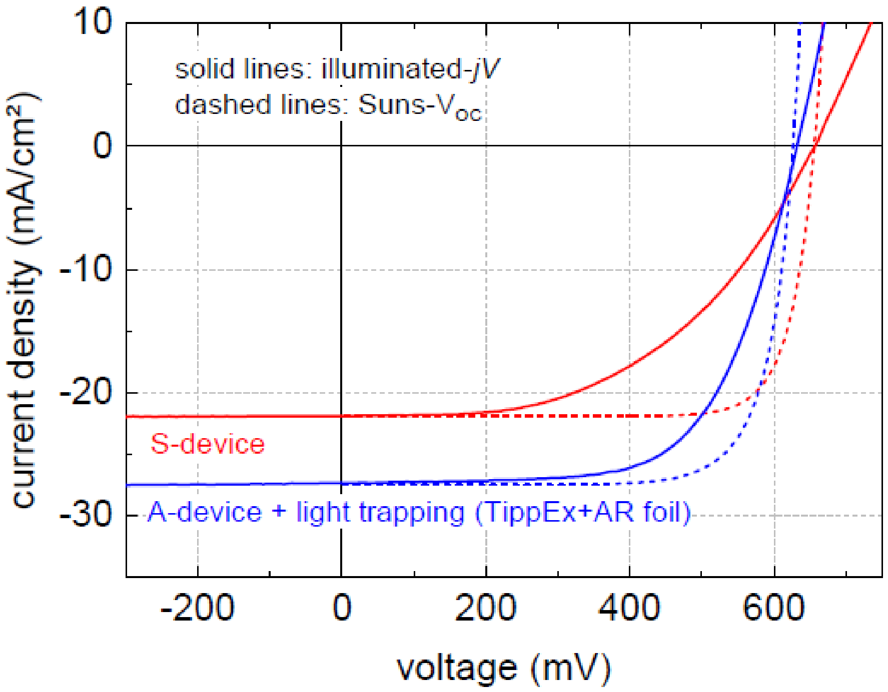


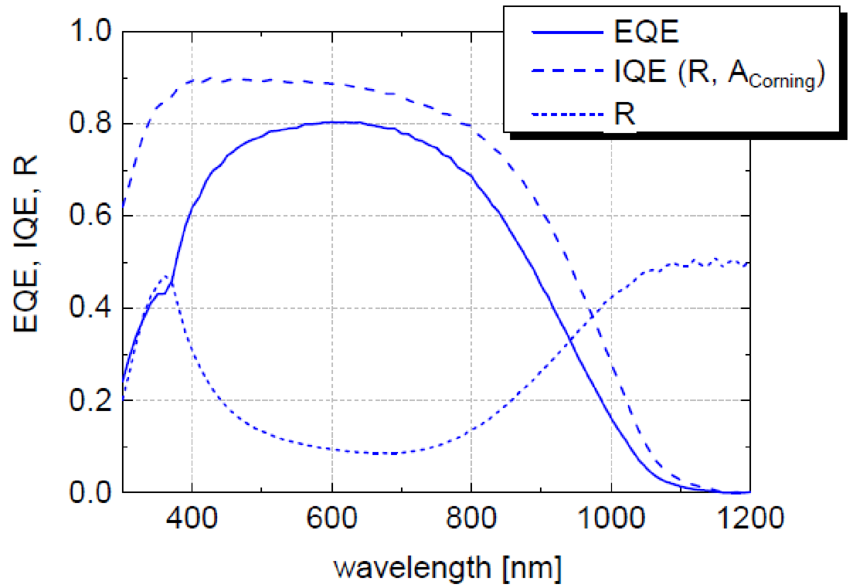




Jan Haschke et al. SOLMAT 2014, D. Amkreutz et al. IEEE JPV 2014, acc.

Solar cell performance



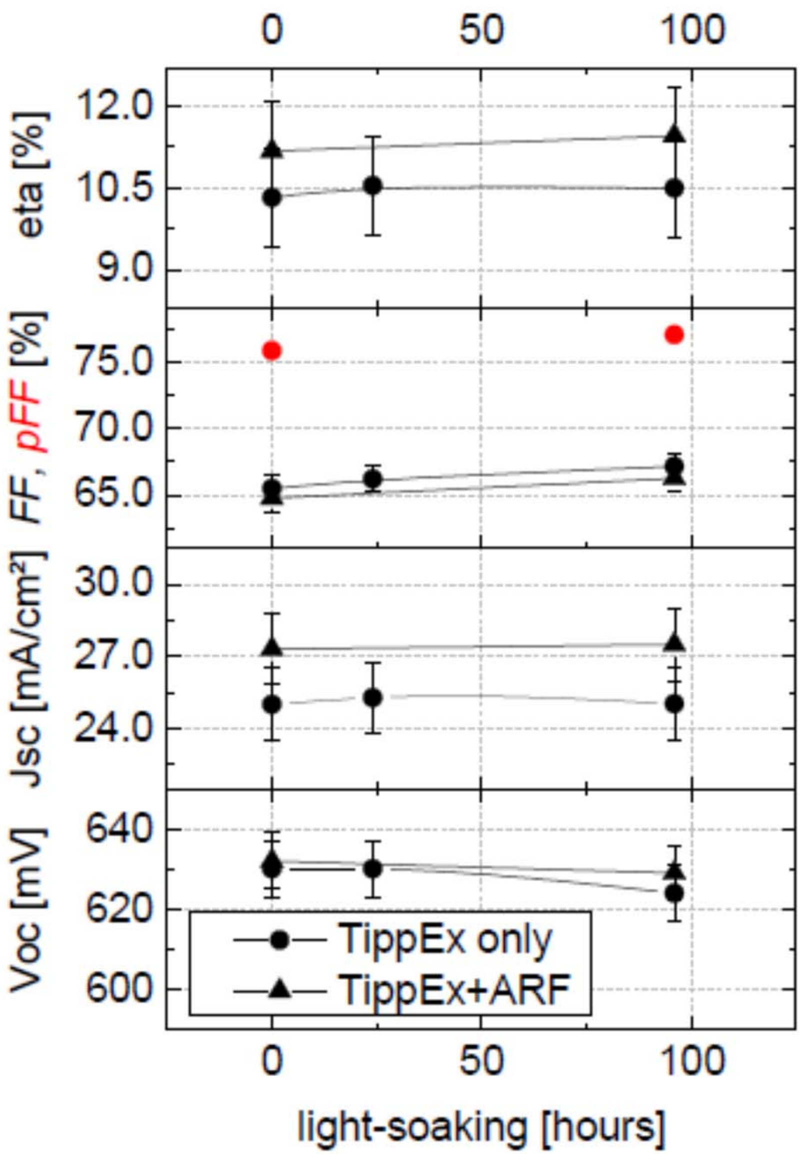


	V_{OC} [mV]	j_{SC} [mA cm^{-2}]	FF [%]	η [%]	pFF [%]
S-device[1,i]	656	21.9	50.0	7.2	80.2
A-device (w/ TippEx & ARF)[2,i]	632	27.3	64.8	11.2	75.8
A-device (w/ TippEx & ARF)[2,ls]	629	27.5	66.2	11.5	77.0

Jan Haschke et al. SOLMAT 2014

Latest efficiency: 11,8 %
Amkreutz, IEEE

First light soaking data



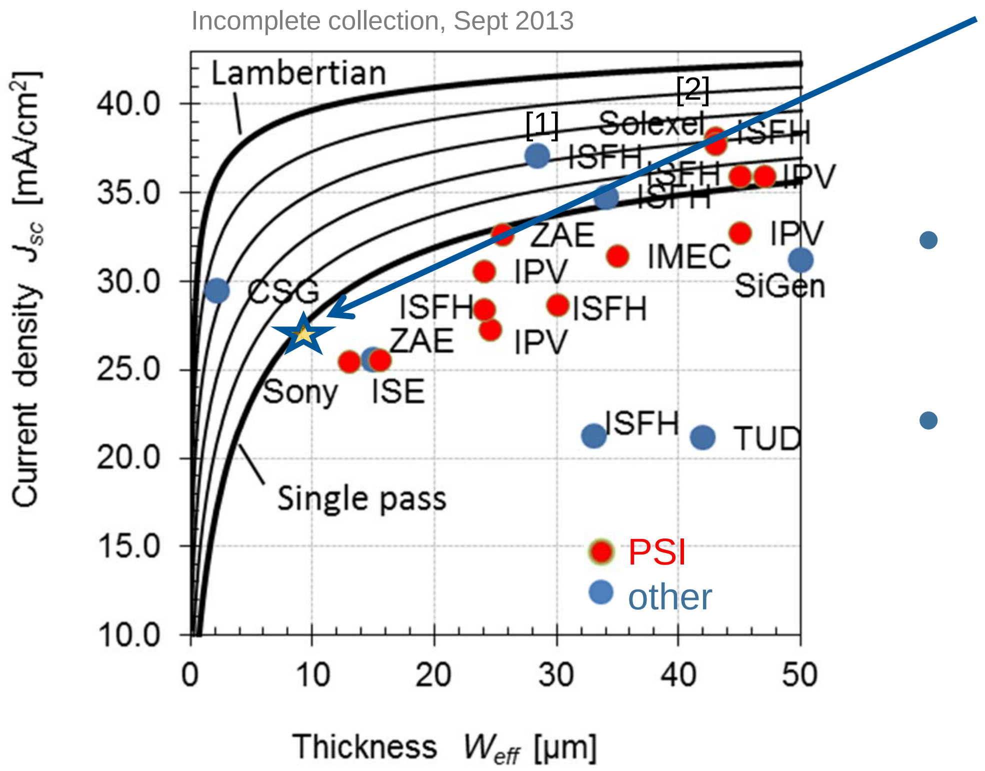
- Within error bars no degradation
- Slight improvement in FF
- Performance data can only by simulated by assuming high quality surface passivation and low defect densities in the Si absorber

Still plenty of room for Improvement:
- high pseudo FF
- high internal QE

Efficiencies above 15 % seem in reach?!

Jan Haschke et al. SOLMAT 2014

Poor light trapping in most kerfless thin c-Si cells



- Lab results for $A > 1cm^2$
- Most cells: Less current than single pass photogeneration would allow

[1] M. Ernst, R. Brendel, IEEE Journal of Photovoltaics (99), 723 (2013). http://dx.doi.org/10.1109/JPHOTOV.2013.2247094
[2] M. A. Green, K. Emery, Y. Hishikawa, W. Warta and E. D. Dunlop, Progress in Photovoltaics **21**, 1 (2012). http://dx.doi.org/10.1002/pip.2352

Going – 3 D in thin film Si

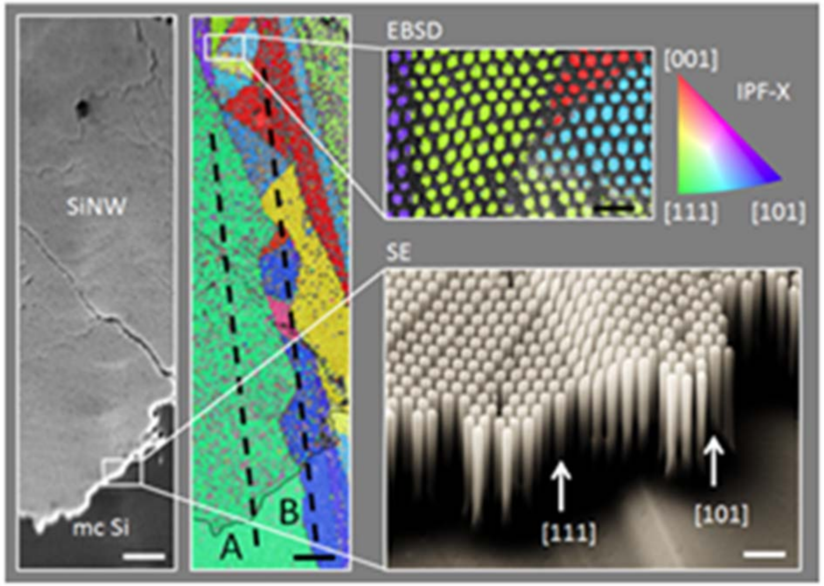
HZB Helmholtz Zentrum Berlin

Very high light absorption

Additional freedom for optimisation

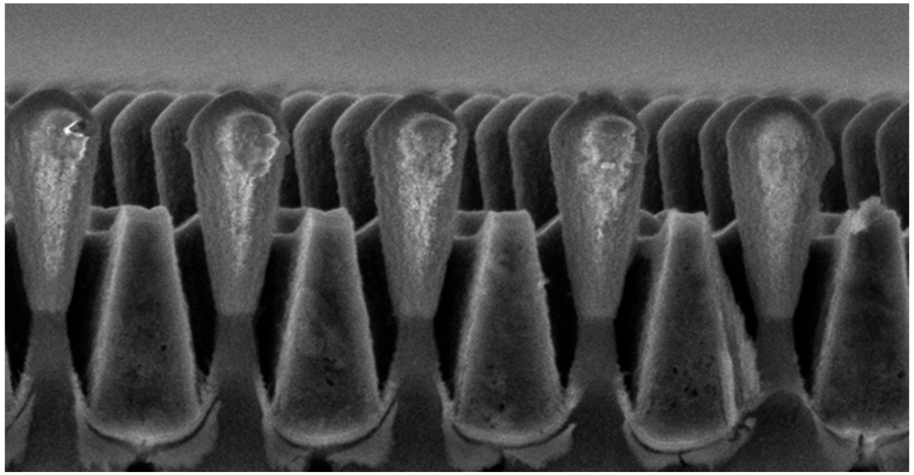
Removal of poor quality material

„cheap is possible“



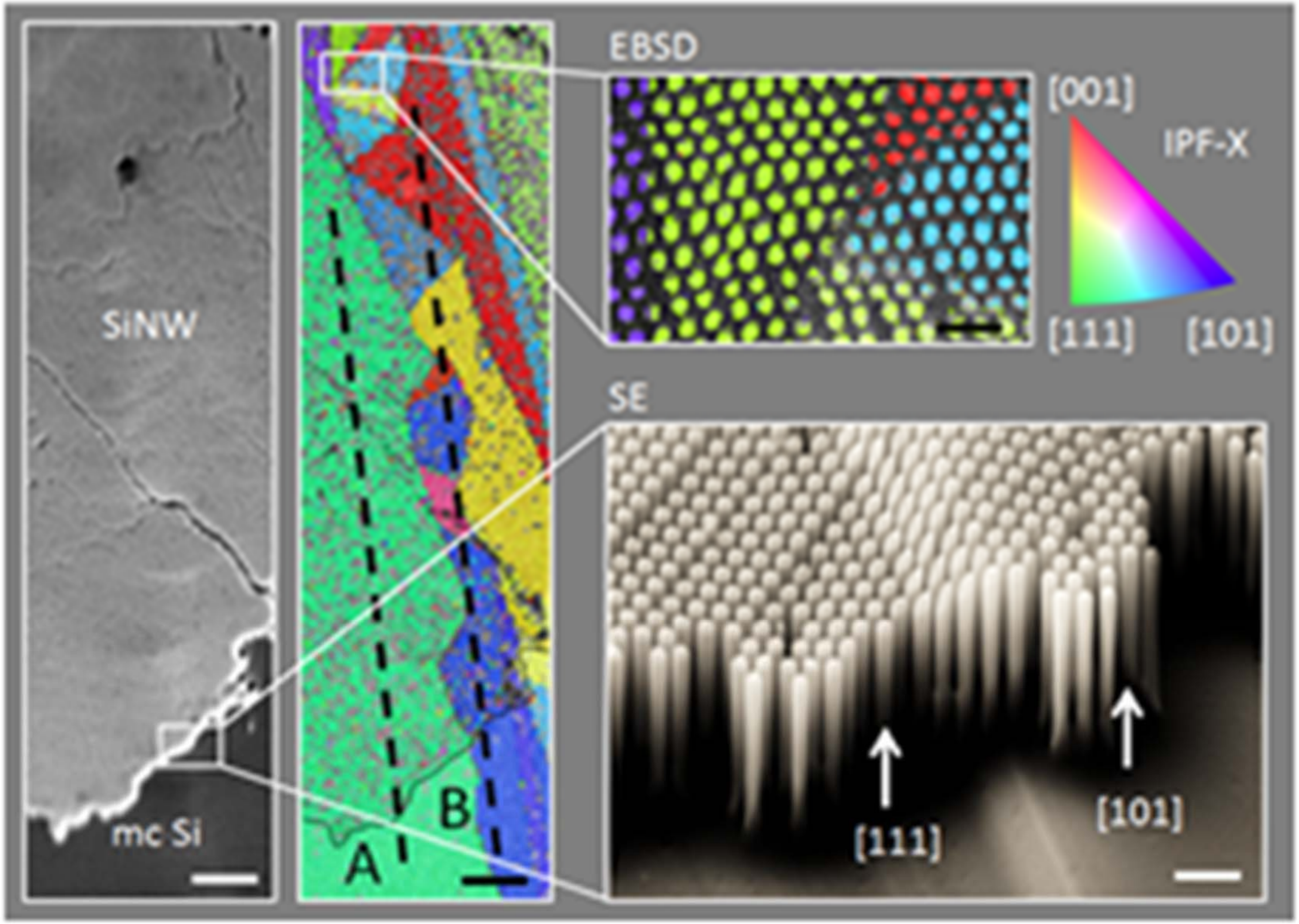
New Institute „Nanoarchitectures
Silke Christiansen

SCHOTT
glass made of ideas



Young Investigator Group of Christiane Becker

Going 3 D in thin film Si

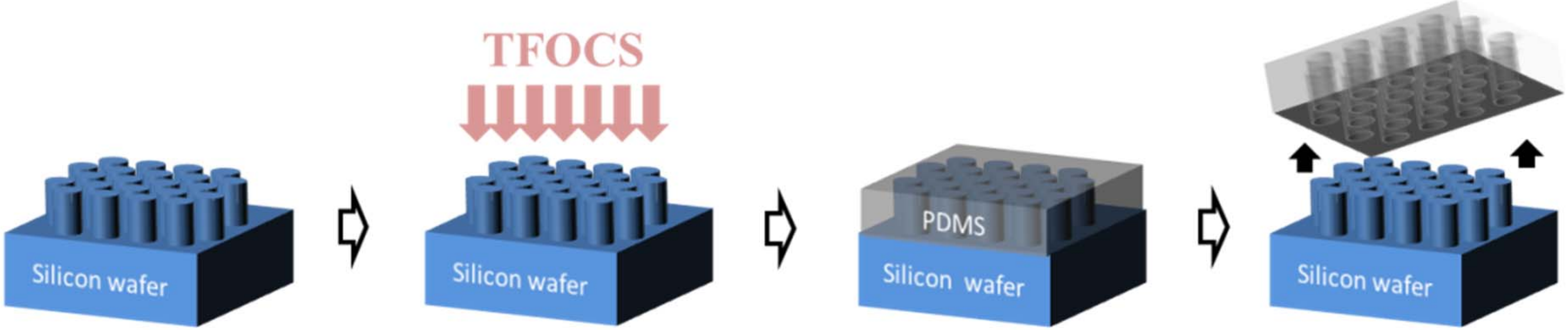


50 µm 3 µm

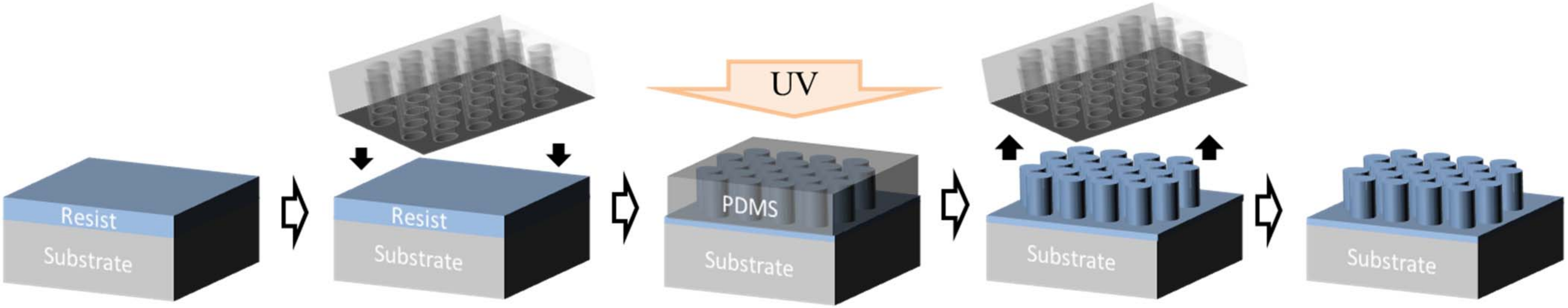
In cooperation with S. Christiansen HZB&MPI Erlangen
S.W. Schmitt et al. Nanoletters 2012

Master Replication
UV-Nanoimprint Lithography

Step 1: Fabrication of the PDMS-stamp



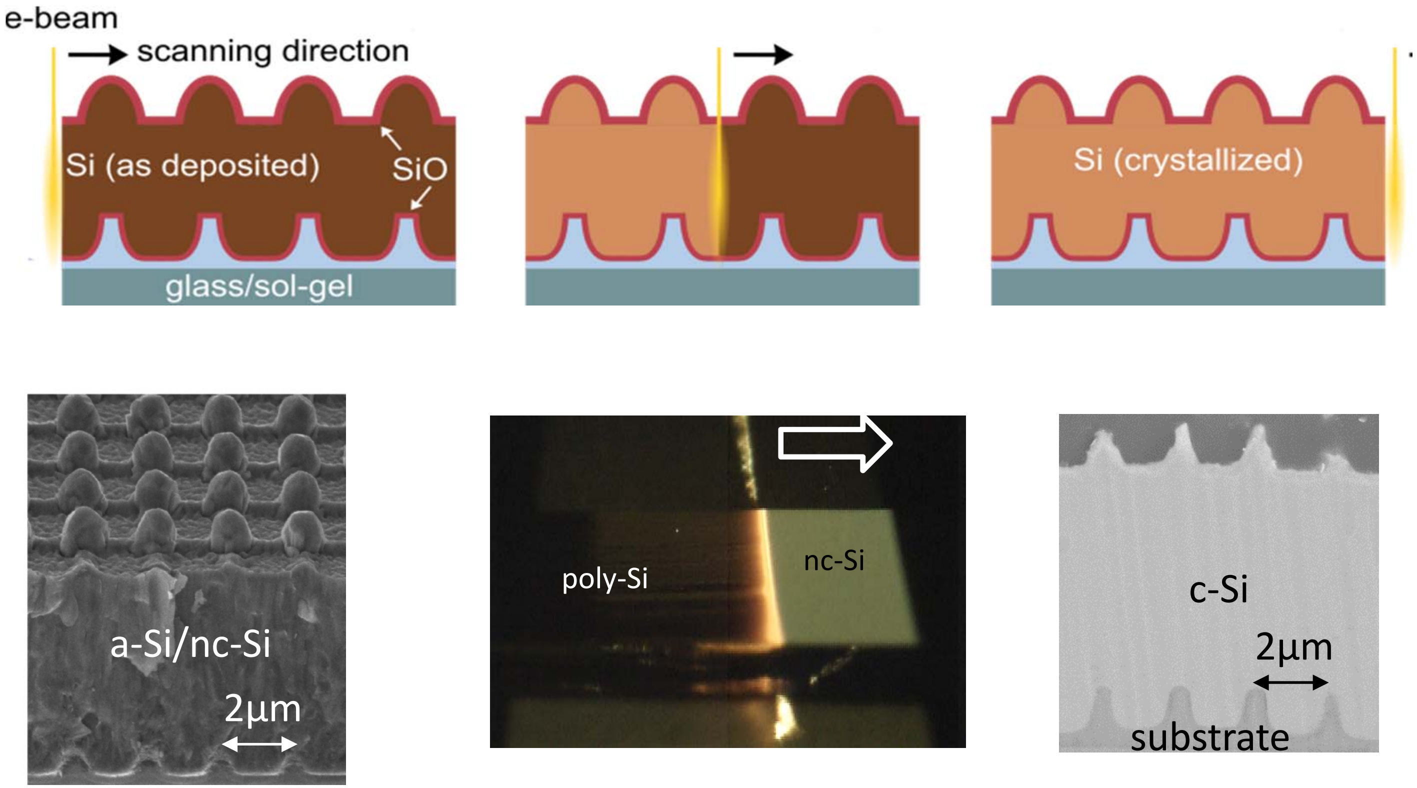
Step 2: Imprinting of the UV-curable sol-gel



- **Repeatable, high throughput**

Liquid phase crystallized textured Si films

Double side textured Si architectures by electron-beam crystallization

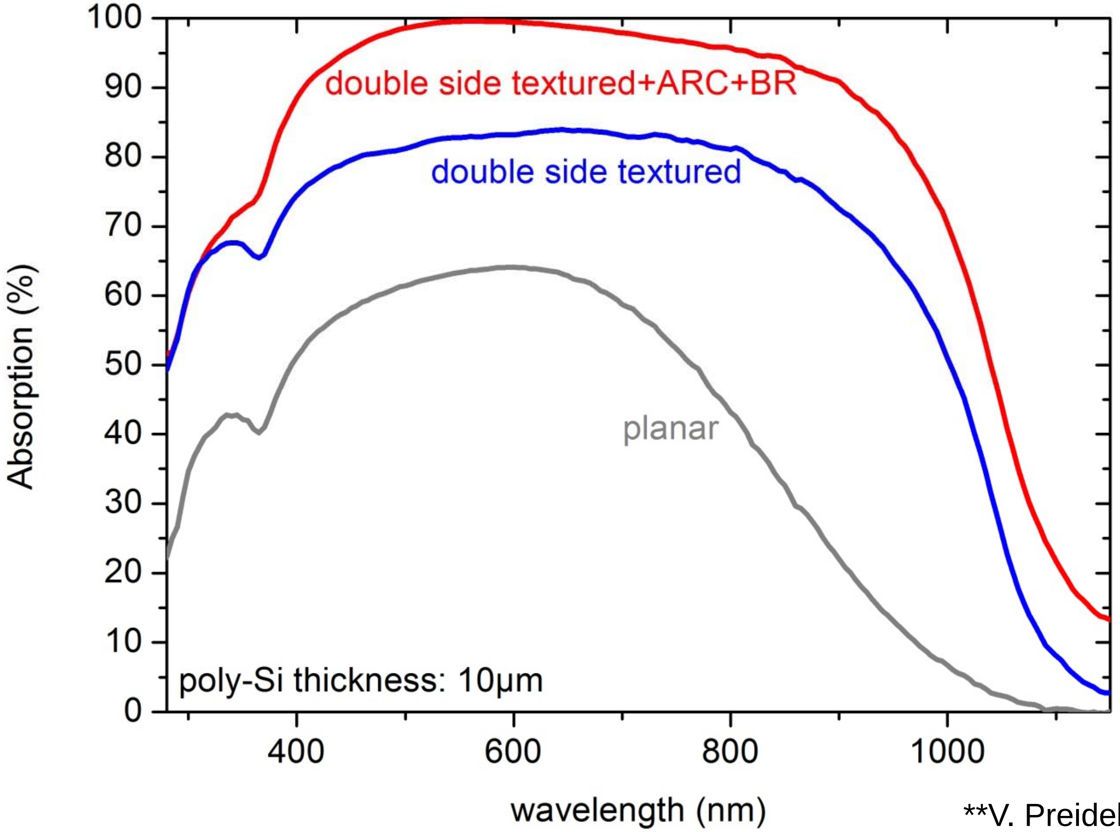


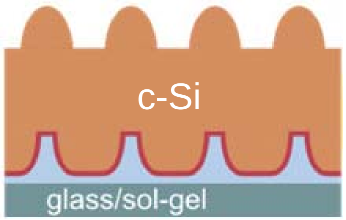
T > 1414°C (Si melting point)

**V. Preidel et al., Proc. SPIE 8823, 882307 (2013)

Double-side textured crystalline silicon film

Absorption enhancement in liquid phase crystallized Si films





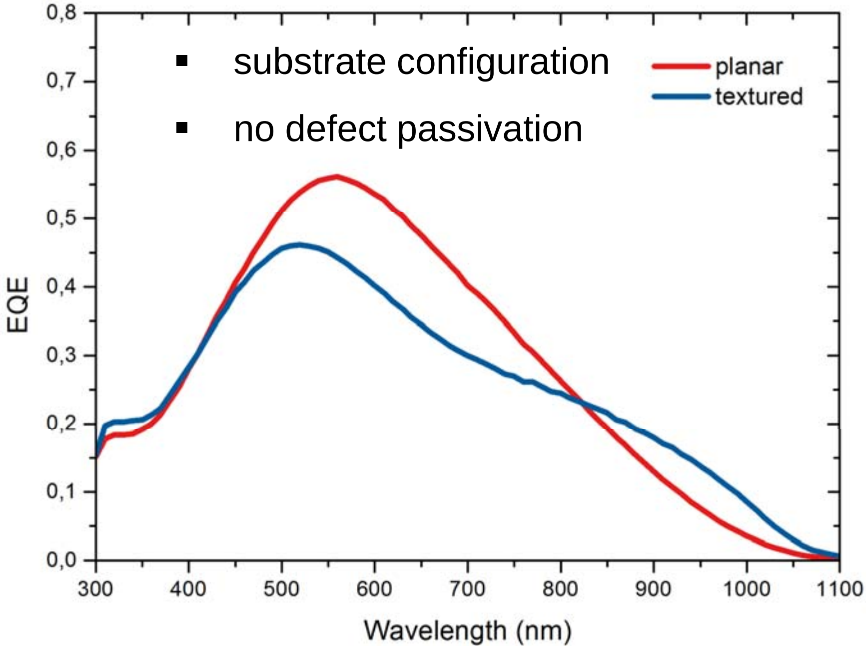
Double side texture

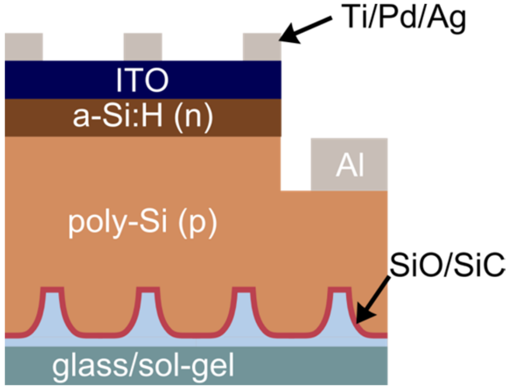
**V. Preidel et al., Proc. SPIE 8823, 882307 (2013)

- Absorption enhancement stable up to 60° angle of incidence
- Optical potential for t_{Si} = 10 µm: $J_{sc,max}$ = 38.2 mA/cm^2 (double side texture)

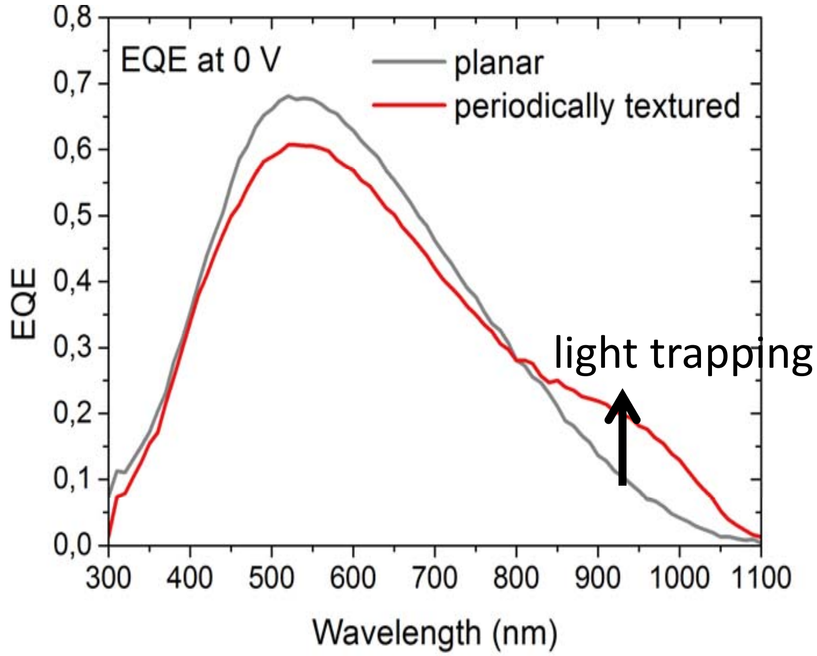
The challenge: carrier extraction

Poly-Si on SiC barrier



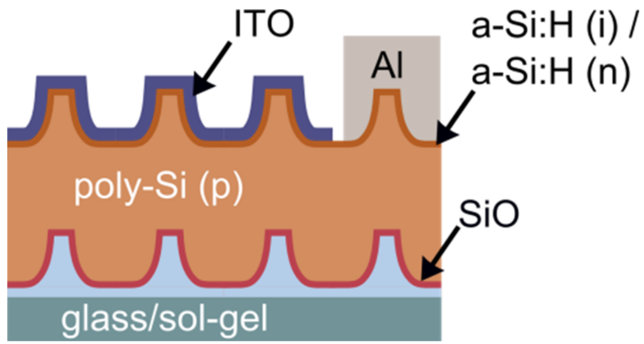


Poly-Si on SiO_2



- Light trapping in near IR
- Improved QE on SiO_2

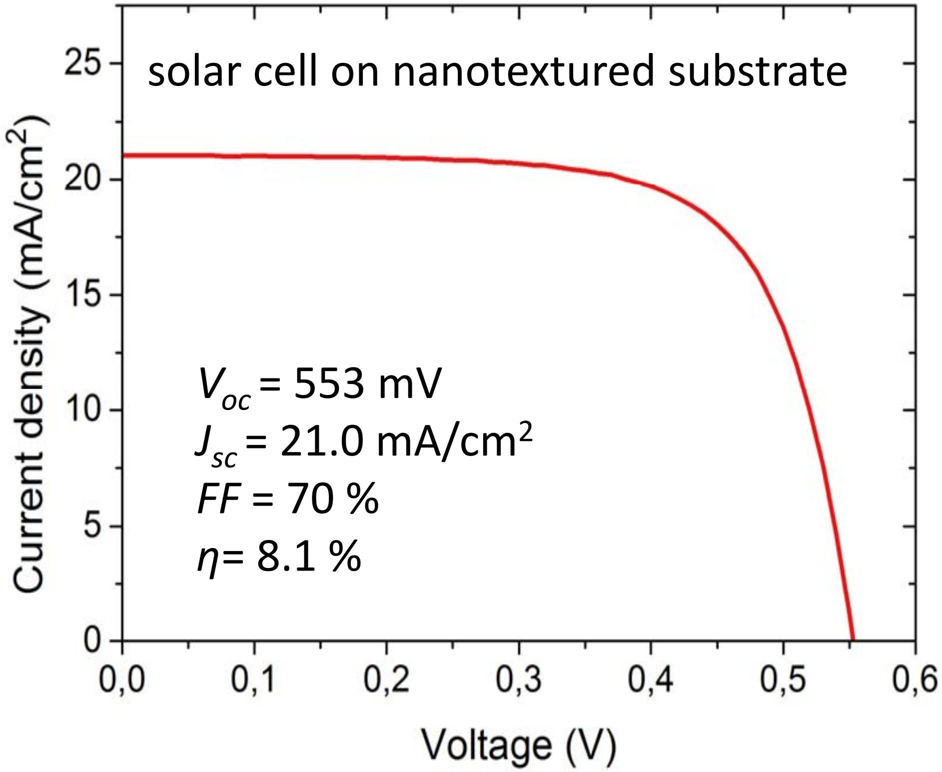
However, still too high surface recombination at buried interface



**V. Preidel et al., Proc. SPIE 8823, 882307 (2013)

Double-side textured Si thin-film solar cell

HZB Helmholtz Zentrum Berlin



Challenge: optimise buried interface with respect to:

- Film adhesion/grain size
- and surface passivation

Average solar cell parameters (7 cells)

	V_{oc} [mV]	J_{sc} [mA/cm²]	FF [%]
textured	551	20.0	67
planar	554	21.1	68

V. Preidel et al., Proc. SPIE 8823, Thin Film Solar Technology V, 882307 (2013)

Conclusions & Outlook

HZB Helmholtz Zentrum Berlin

Advantages of thin film silicon

- Unlimited raw material availability & low energy consumption
- Unique products & applications
- Thin-film silicon technology is a key for for wafer technology („HIT- approach“)

Challenge or Drawback?

- Defects & tails in a-Si:H and µc-Si:H limit bulk quality

Opportunity

- Large grained liquid phase crystallised Si on glass - a new player

    - material properties are approaching wafer quality (**>650 mV**)

    - high-rate deposition for silicon precursors (prior to crystallisation)

    - alternative processes for silicon deposition feasible (e.g. via liquids)

    - back contact design and module concept required

⇒ **strong efforts in research & development still needed!**

Conclusion&Outlook II

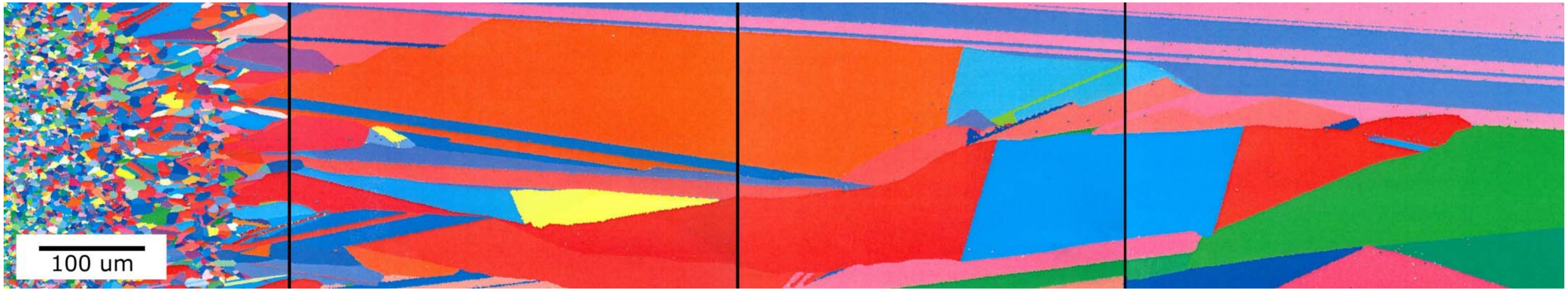
- Solar energy will become a (the) major energy source in the future. The transformation of the energy system is one of the key global challenges!

- PV has proven that it is an Energy and not a Niche Technology
  - strong market penetration is needed on a global scale
  - system integration is a key

- PV has emerged as a major global industry facing strong competition

- R&D challenge & opportunity:
  - cheaper
  - more efficient !
  - new appliations
  - storable

Thank you for your attention.



This work was supported by the Federal Ministry of Education (BMBF) and the state government of Berlin (SENBWF) in the framework of the program “Spitzenforschung und Innovation in den Neuen Ländern” (grant no. 03IS2151) and by the BMBF and the Federal Ministry for Environment, Nature Conservation and Nuclear Safety (BMU) in the framework of the program “Innovationsallianz Fotovoltaik” (grant no. 0325317C).