Perspectives and challenges of thin-film crystalline silicon solar cells on glass

B. Rech, D. Amkreutz, Jan Haschke, Stefan Gall, S. Kühnapfel, C. Klimm
Institute Silicon-Photovoltaics
O. Gabriel, B. Stannowski, R. Schlatmann PVcomB
V. Preidel, C. Becker, Young Investigator Group Nano-SIPPE

Thanks to: E. Rudigier-Voigt (SCHOTT AG), D. Hauschild (LIMO GmbH)
S. Christiansen and many more colleagues @ HZB

DPG Frühjahrstagung, AKE, Berlin 2015

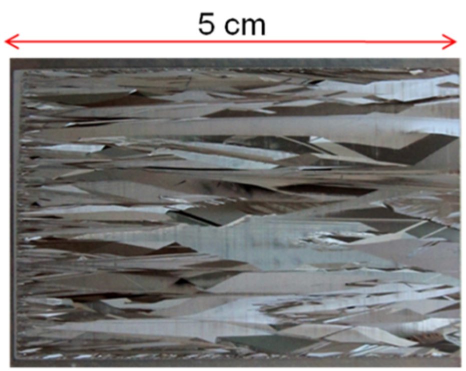
Outline

- **Introduction&Status PV**

- **Thin-Film Si multi-junctions (brief)**
  - Technology Transfer
  - BIPV & large scale implementation
  - a-Si meets organics

- **Large grained poly-Si on glass**
  - Liquid phase crystallisation – a new horizon
  - Material properties
  - Solar cells & perspectives

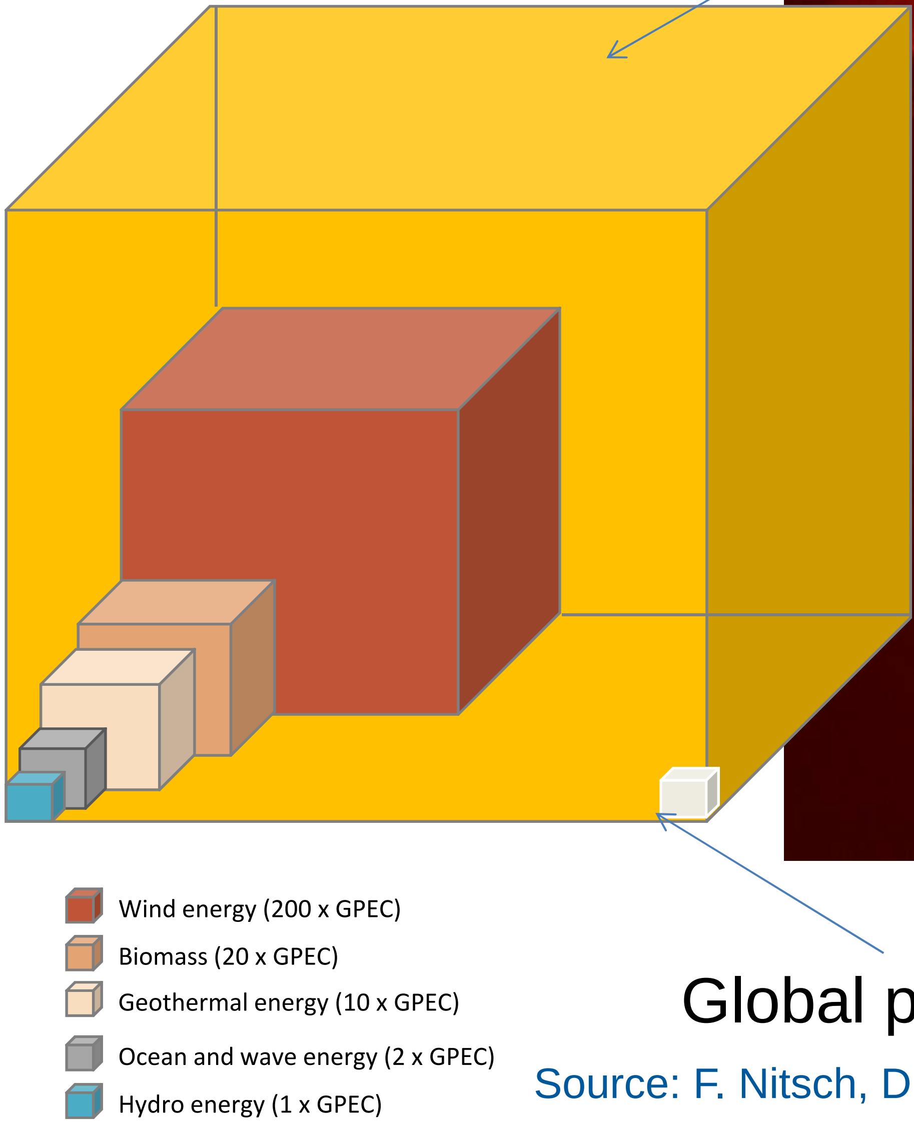
- **Conclusions&Outlook**

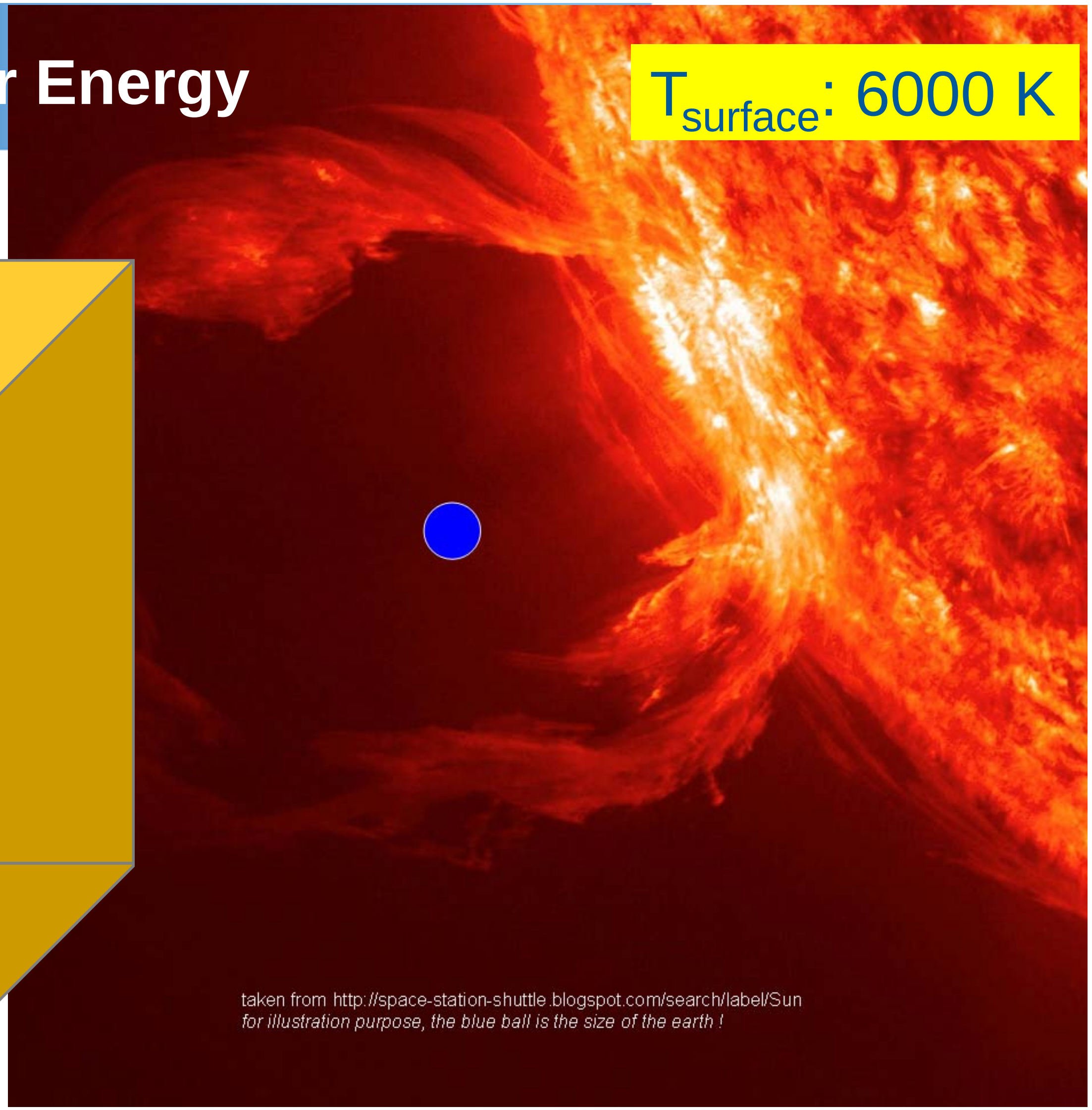


Bernd Rech, DPG Frühjahrstagung, AKE, Berlin 2015

Potential of Solar Energy

Solar energy (continental)

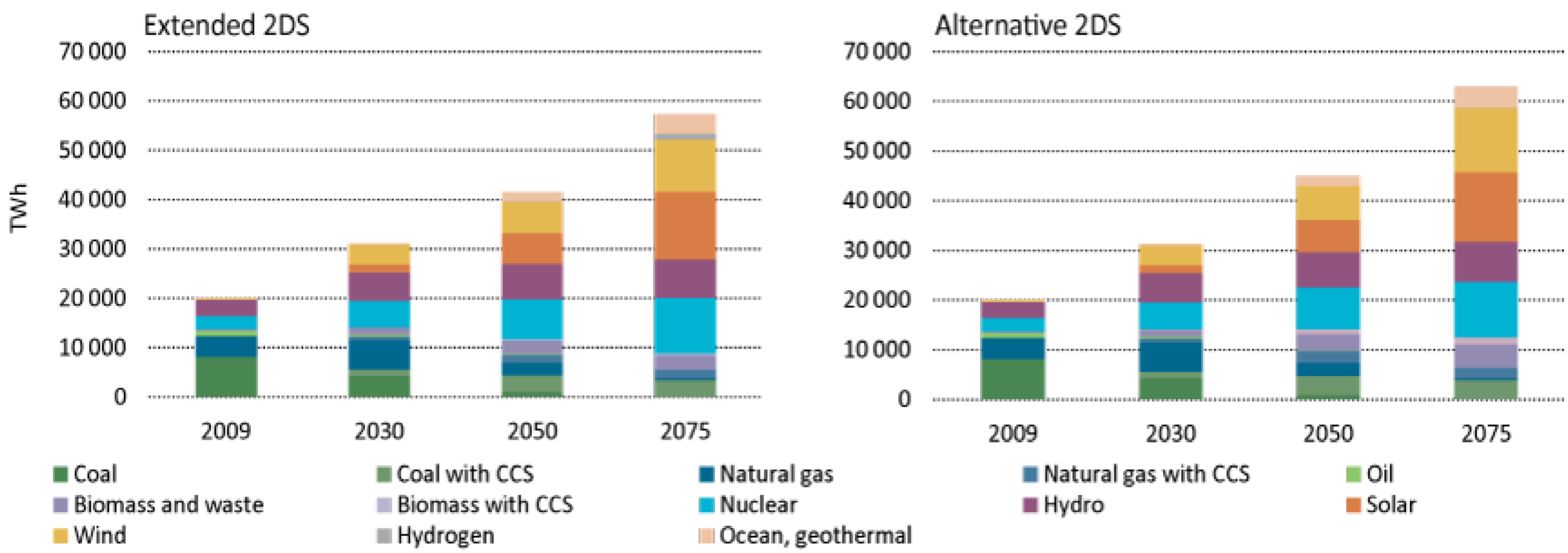




Global primary energy consumption

Source: F. Nitsch, DLR

Renewables in the IEA 2DS Scenario



IEA - Energy Technology Perspectives 2012

PV Status and growth potential (global)

HZB Helmholtz Zentrum Berlin

Unique features of photovoltaics:

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

6 % of electricity supply

in Germany by PV in 2014

Source AG Energiebilanzen

Expected developments:

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

Terawatt scale production

2030: > 2 mio. jobs in PV

Source IRENA 2013

… PV has been developed faster than anticipated and by 2020 will probably reach twice the level previously expected. …

… PV´s share of global electricity rising up to 16 % by 2050, compared to 11 % in the 2010 roadmap

Maria van der Hoeven, Executive Director IEA,
in Foreword Technology Roadmap Solar Photovoltaic Energy 2014

Source Deutsche Bank 2013

PV in Berlin today – residential home

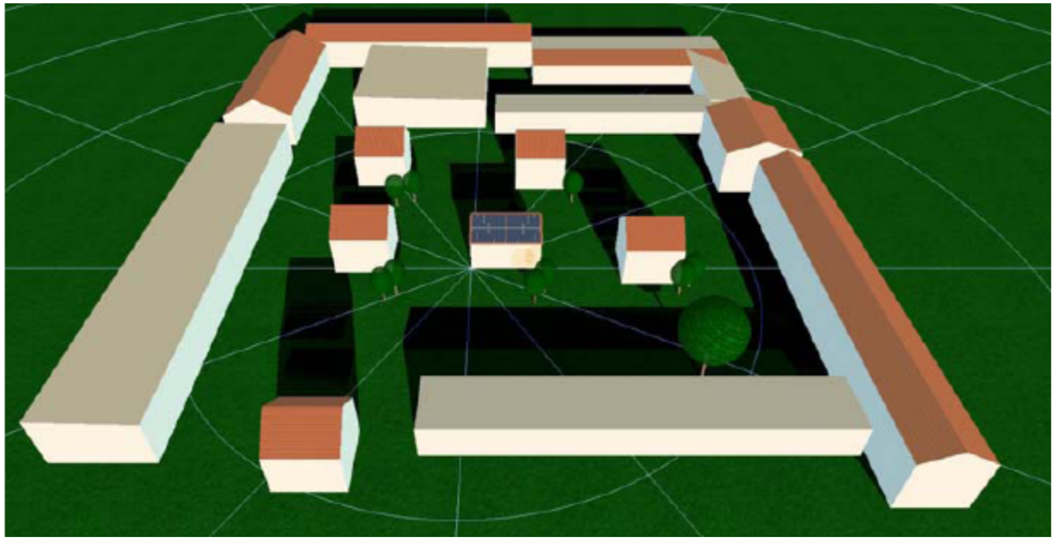
11.5 KW$_p$ c-Si: grid connection 11/2012
„black design“: η = 15 %
Electricity generation cost: 18 c/kWh

	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

Installation 2014: 14 c/kWh, on more sunny places (or larger systems) lower costs!

„Solar power will soon be the cheapest form of electricity in many places of the world“

Fraunhofer ISE (2015): Current and Future Cost of PV, Agora Energiewende



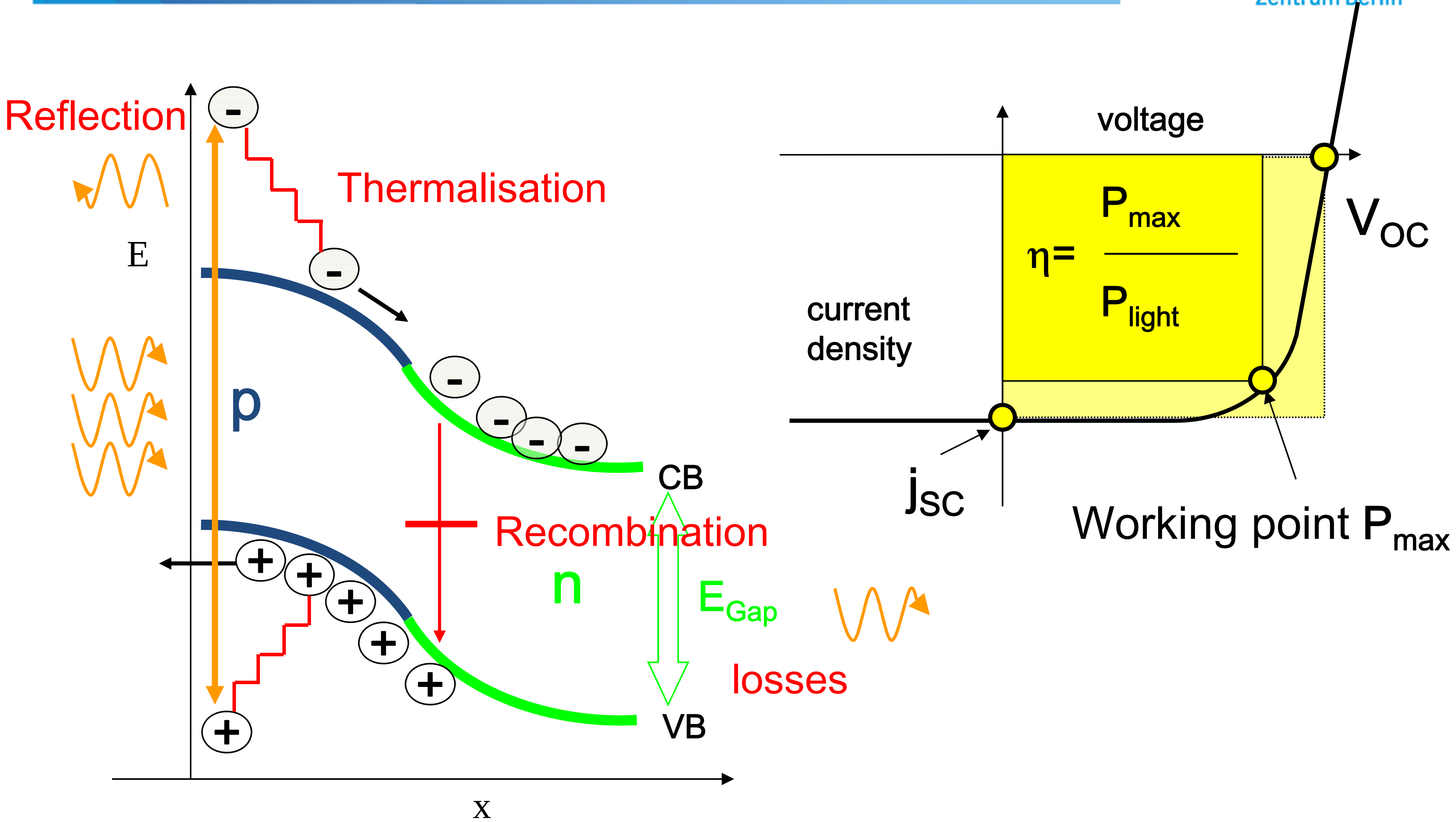
Challenges in R&D

- increase conversion efficiencies
- reduce production costs
- Increase life-time

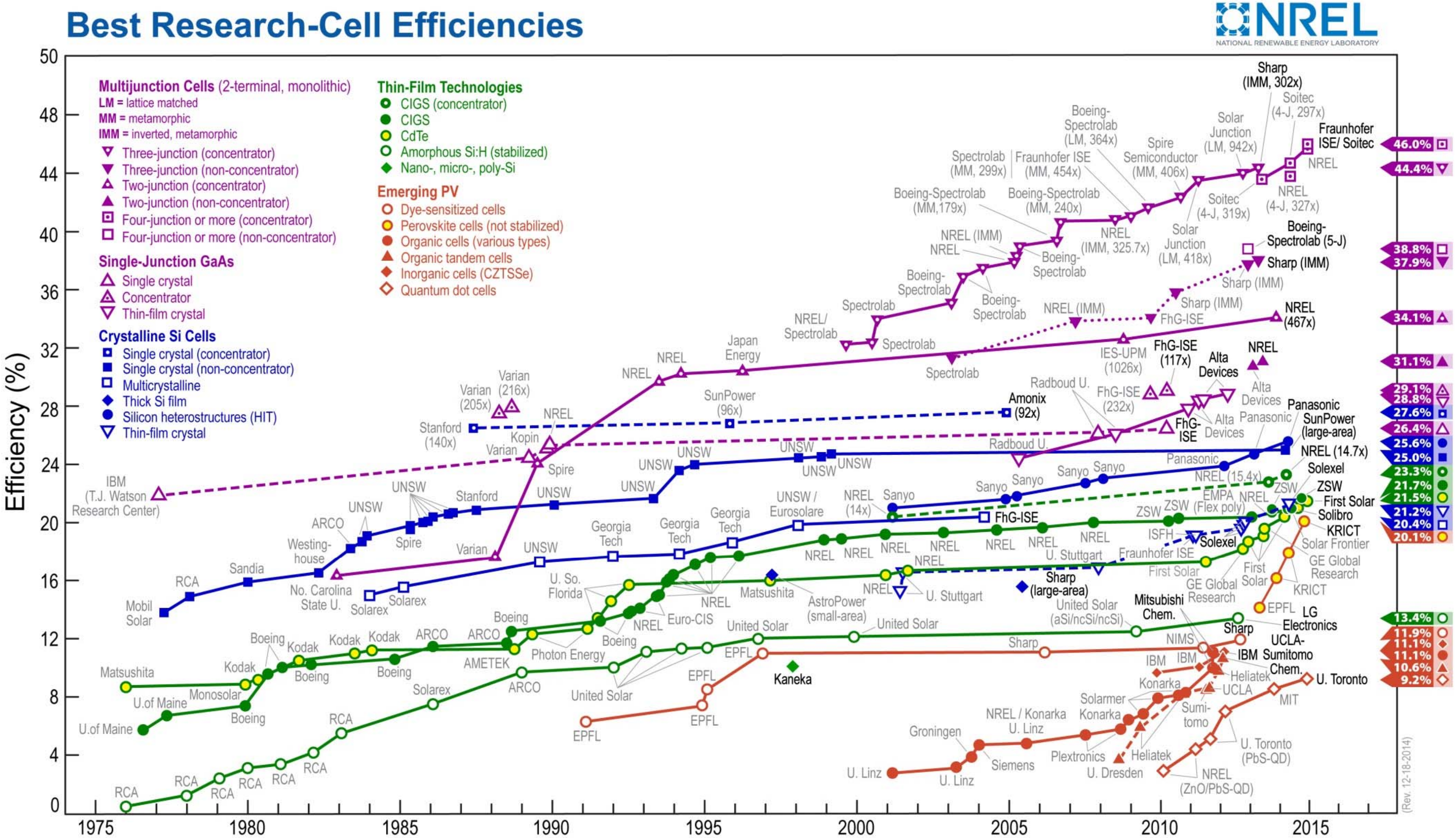
sustainable materials & processes

- open-up new applications/markets
- system integration & system solutions

Some Physics



Record Solar Cells



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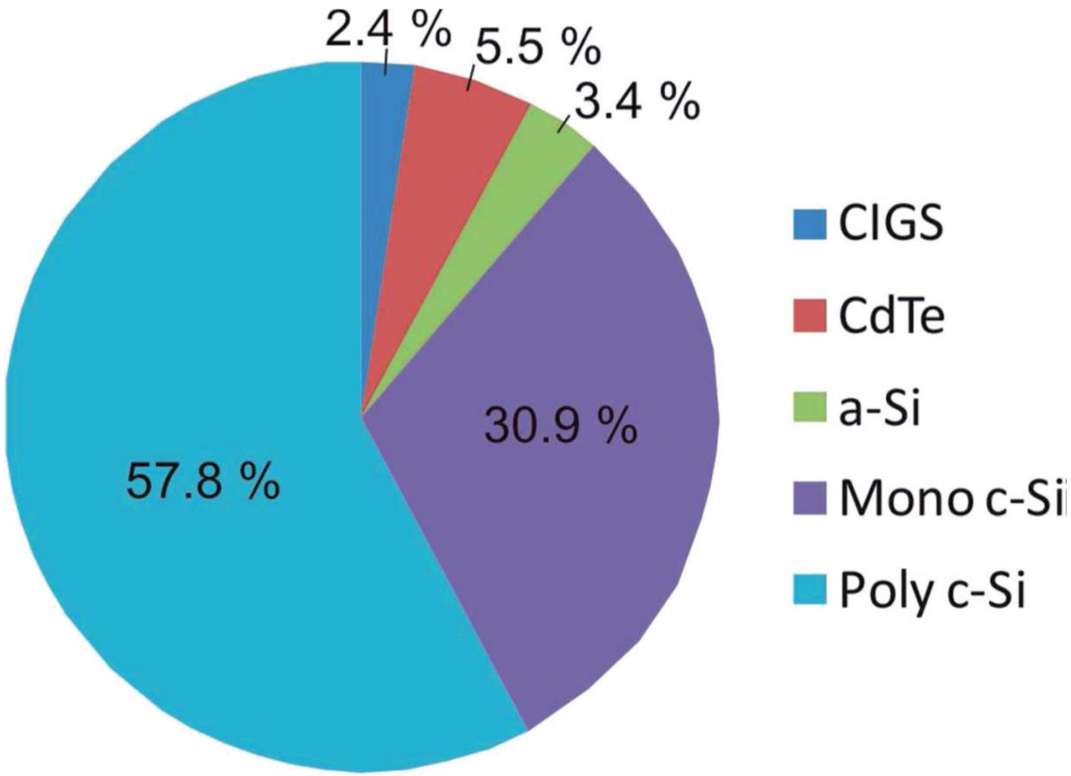
Share of Different PV Technologies



89 % Wafer based Si
11 % Thin film

Photon Europe GmbH (2012)

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- **Amorphous&Microcrystalline Si (brief)**
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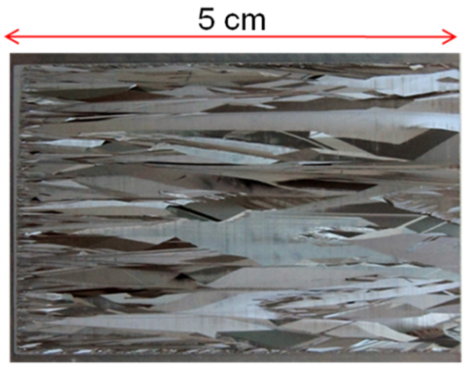
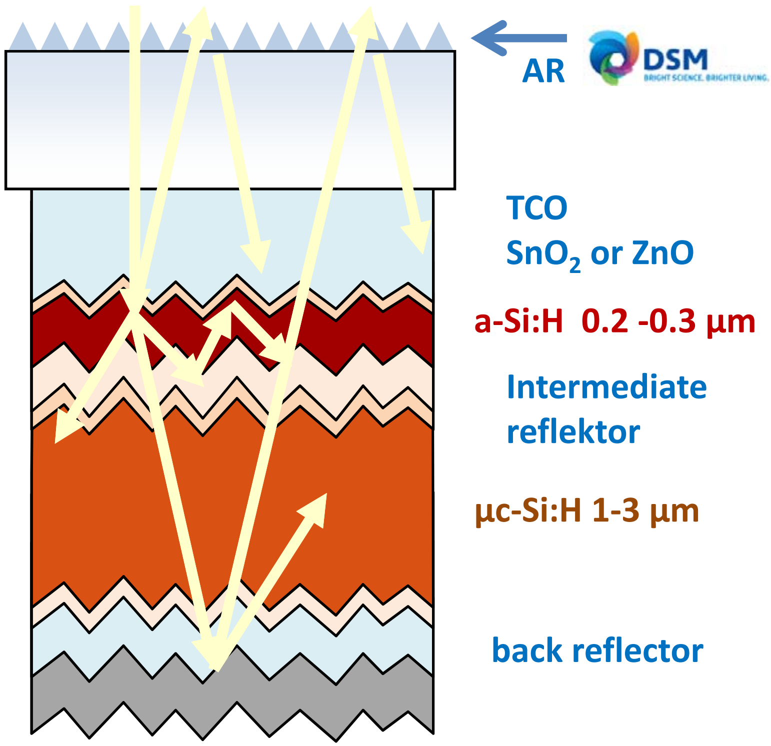
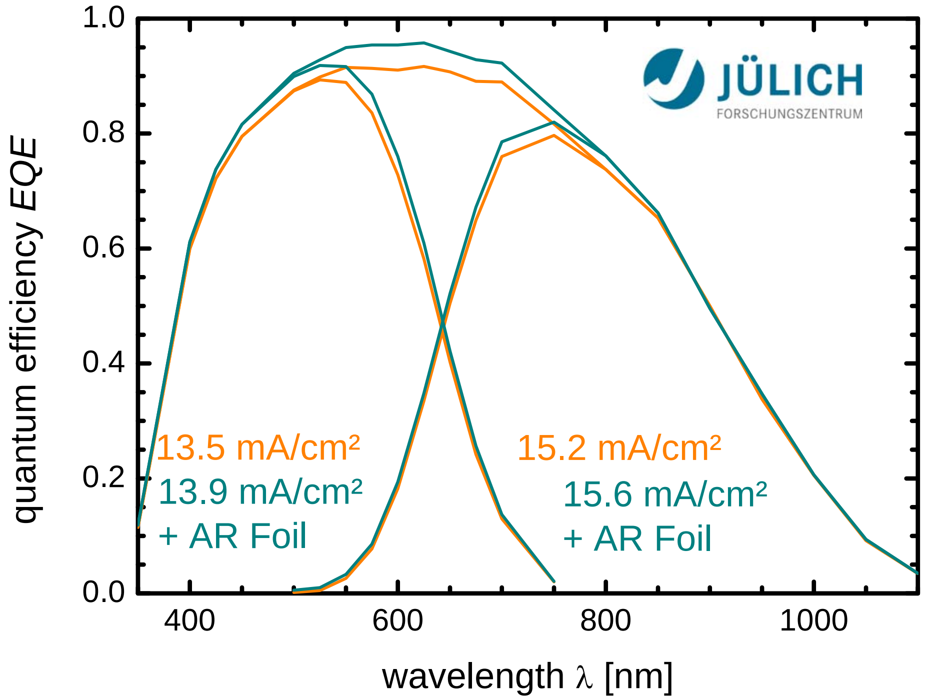
  - Liquid phase crystallisation – a new horizon
  - Material properties
  - Solar cells & perspectives
- Conclusions&Outlook



a-Si:H/µc-Si:H Tandem Cells



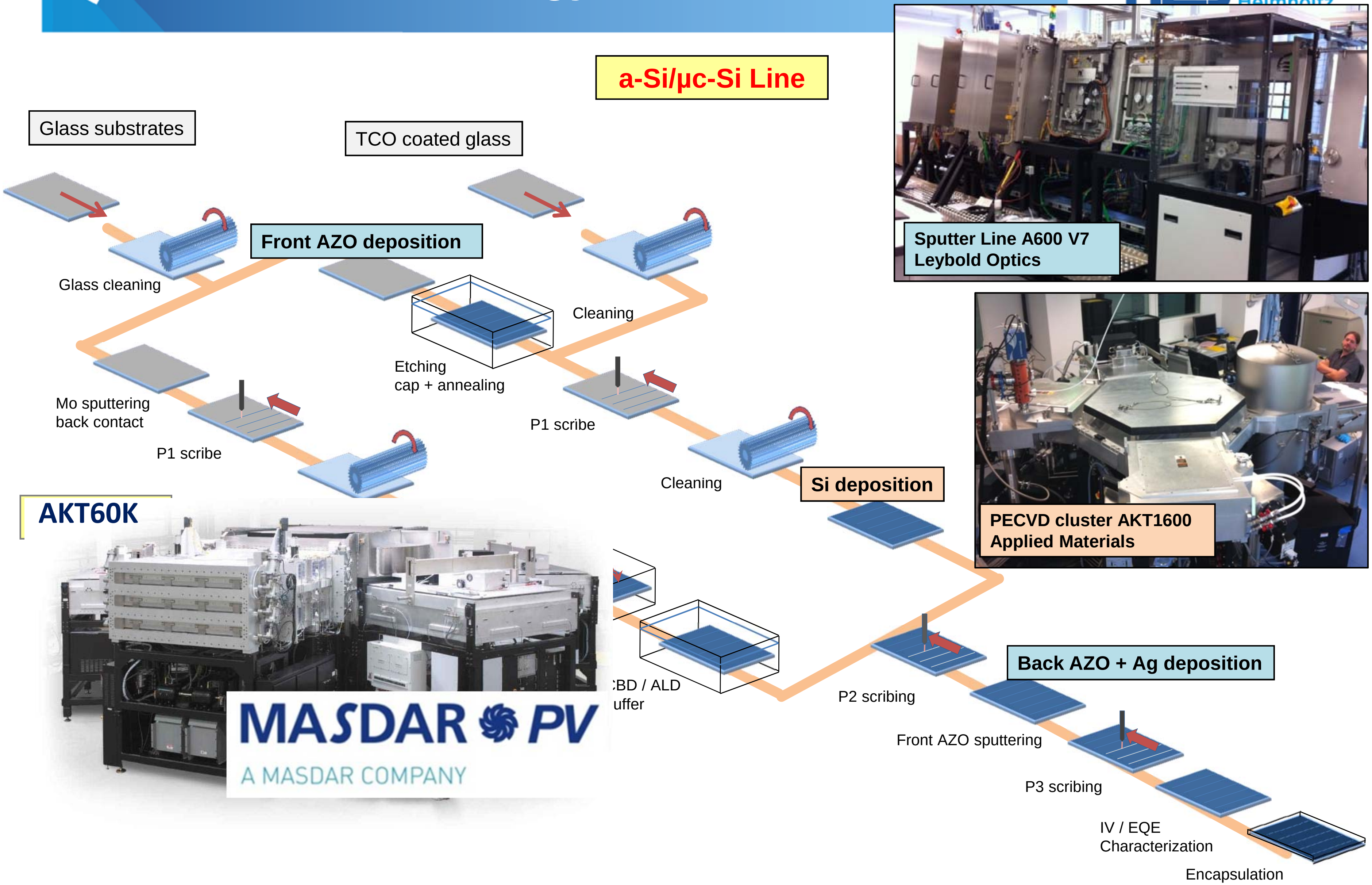


A. Lambertz et al. SolMat 119 (2013).

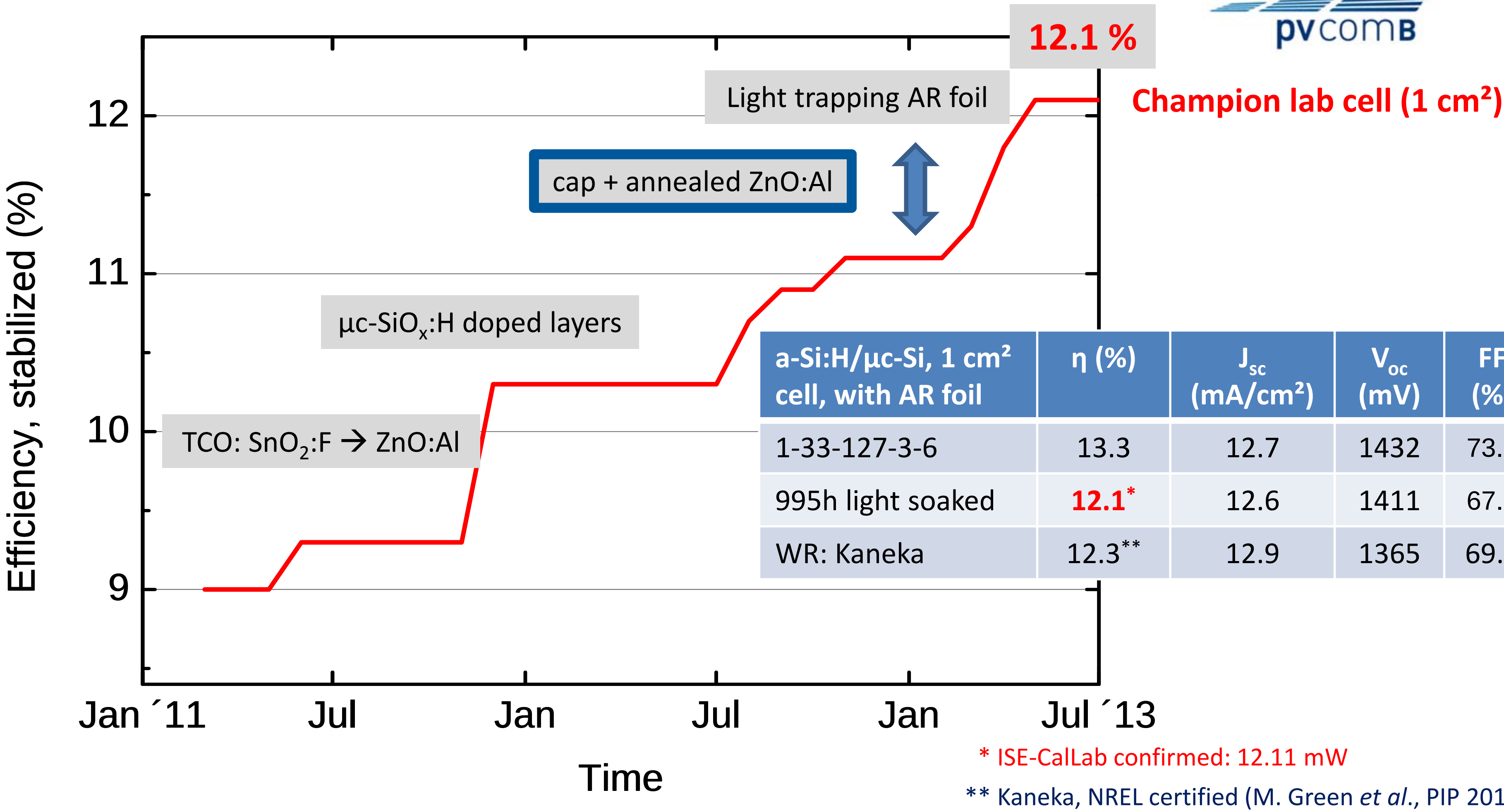
pioneered by J. Meier/ A. Shah et al.
first modules by Kaneka (K. Yamamoto et al.)

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

PVcomB technology transfer lines



a-Si:H/µc-Si:H solar cells @ PVcomB



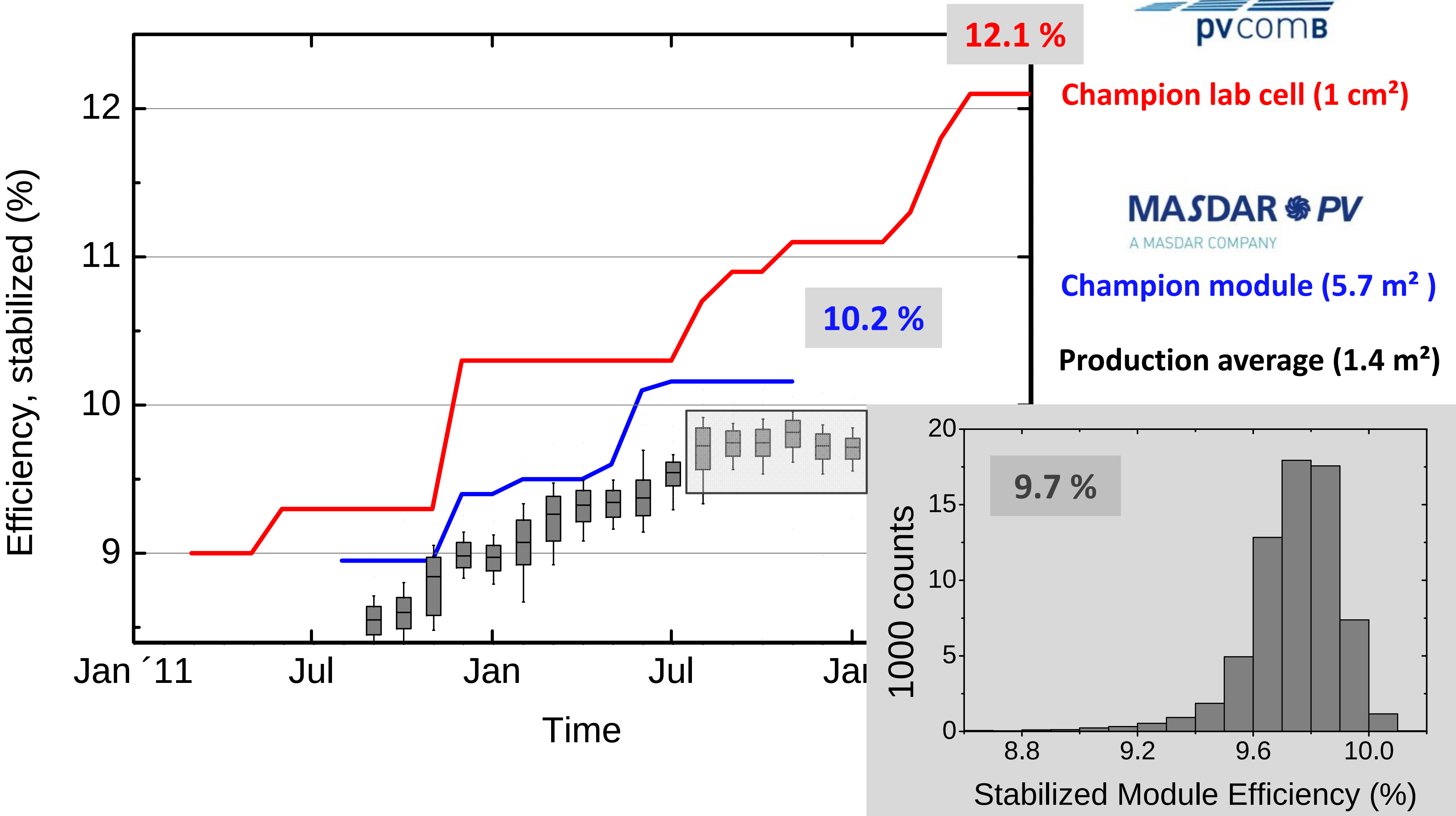
a-Si:H/µc-Si, 1 cm² cell, with AR foil	η (%)	J_{sc} (mA/cm²)	V_{oc} (mV)	FF (%)
1-33-127-3-6	13.3	12.7	1432	73.2
995h light soaked	**12.1***	12.6	1411	67.8
WR: Kaneka	12.3**	12.9	1365	69.4

* 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



Bernd Rech, DPG Frühjahrstagung, AKE, Berlin 2015

Power Plants

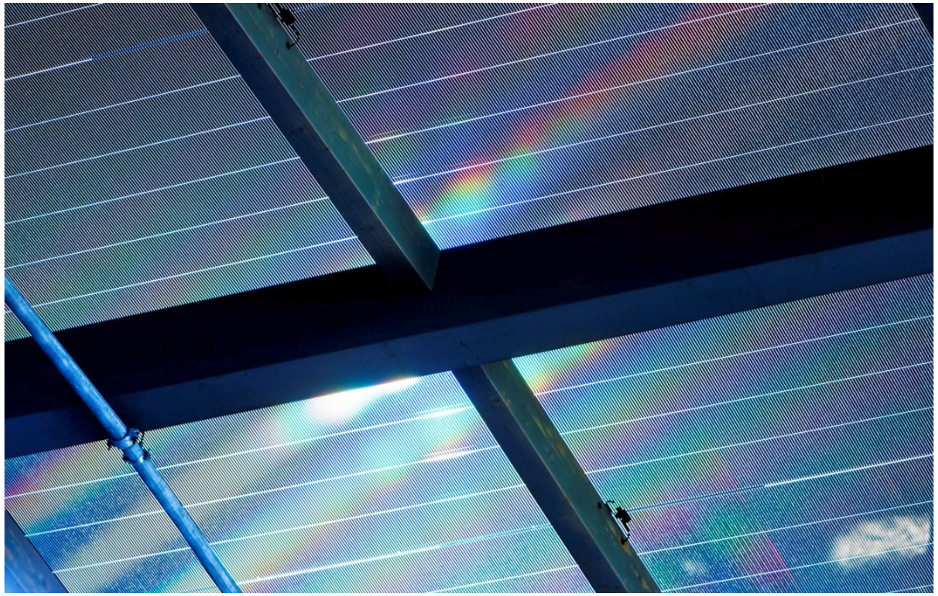
- 15 MW_p
- 29,826 a-Si/µc-Si modules à 5.7 m²
- 10 % of Mauritania's grid capacity
- Largest PV installation in Africa
- Advantage of a-Si/µ-Si technology in desert climate due to T_{coeff}

Building Integration

MASDAR PV
A MASDAR COMPANY

HZB Helmholtz Zentrum Berlin


9.6 MW_p a-Si, Belgium, 2011



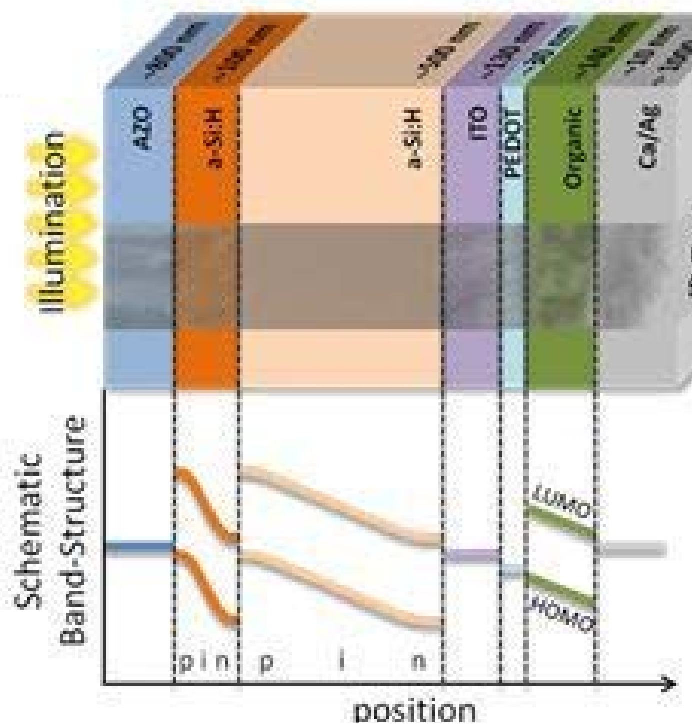

8.6 kW_p a-Si/µc-Si, Austria, 2012

However, MasdarPV stopped PV business end of 2014

Amorphous Silicon meets Organics

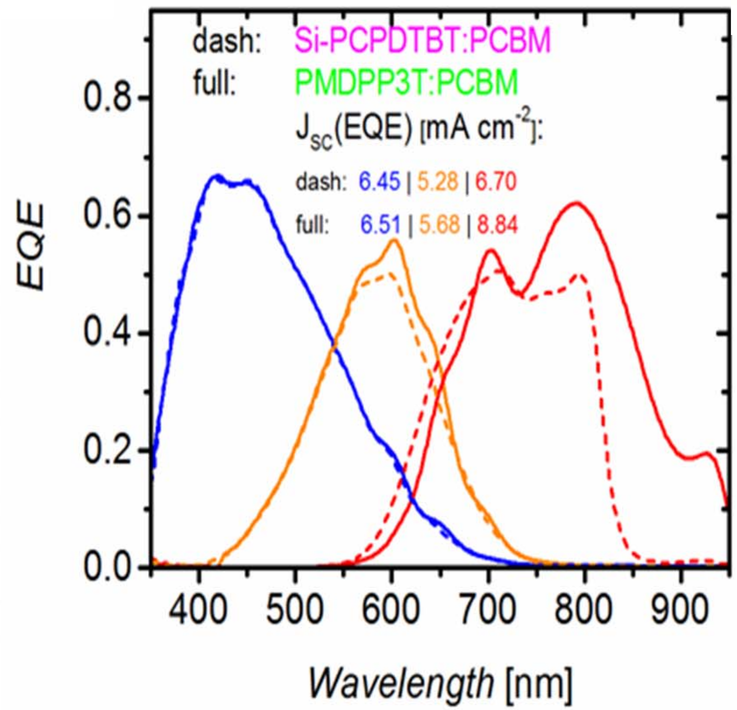
HZB Helmholtz Zentrum Berlin

Universität Potsdam



S. Roland et al. Advanced Materials, 2015

cell efficiency 11.7 %



See also: a-Si/organic tandem 10.5 % eff., J. Kim et al. nature comm. (2015)
And for more on organics see next talks

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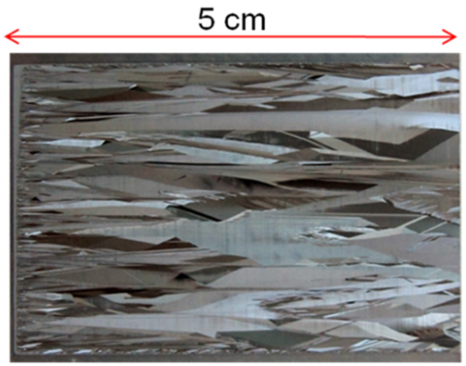
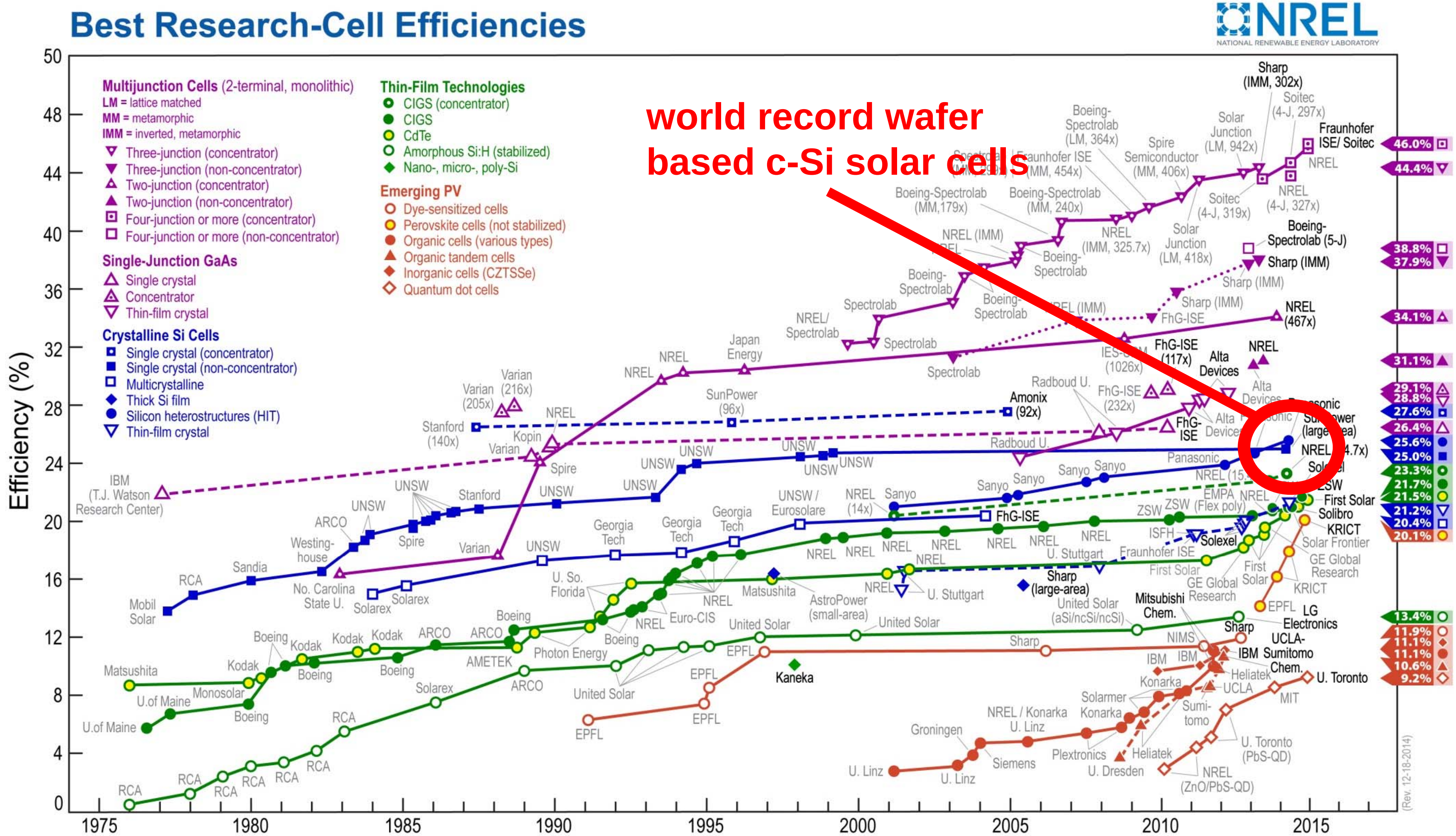


Record Solar Cells

world record wafer based c-Si solar cells



Bernd Rech, DPG Frühjahrstagung, AKE, Berlin 2015

From Wafers to Thin Films

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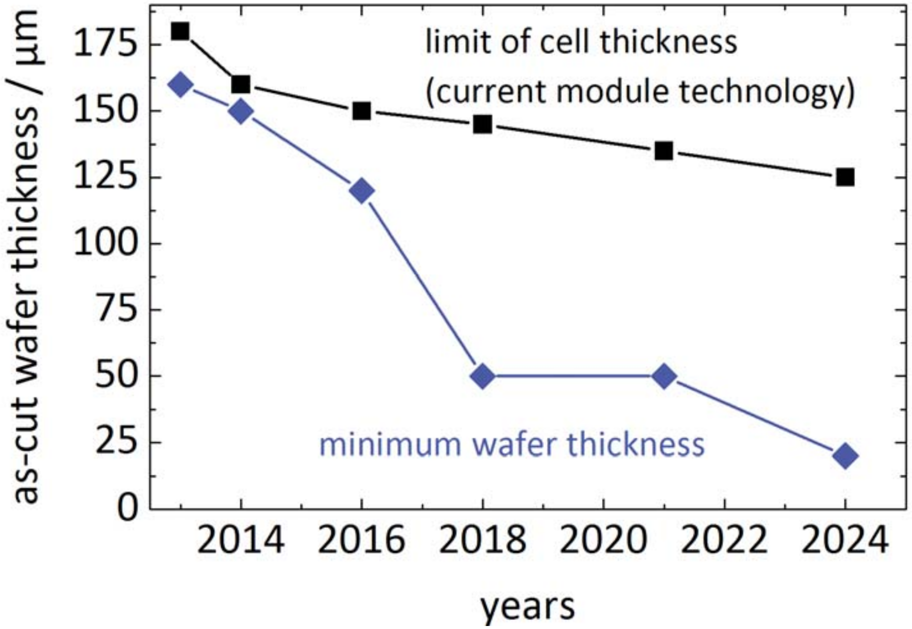
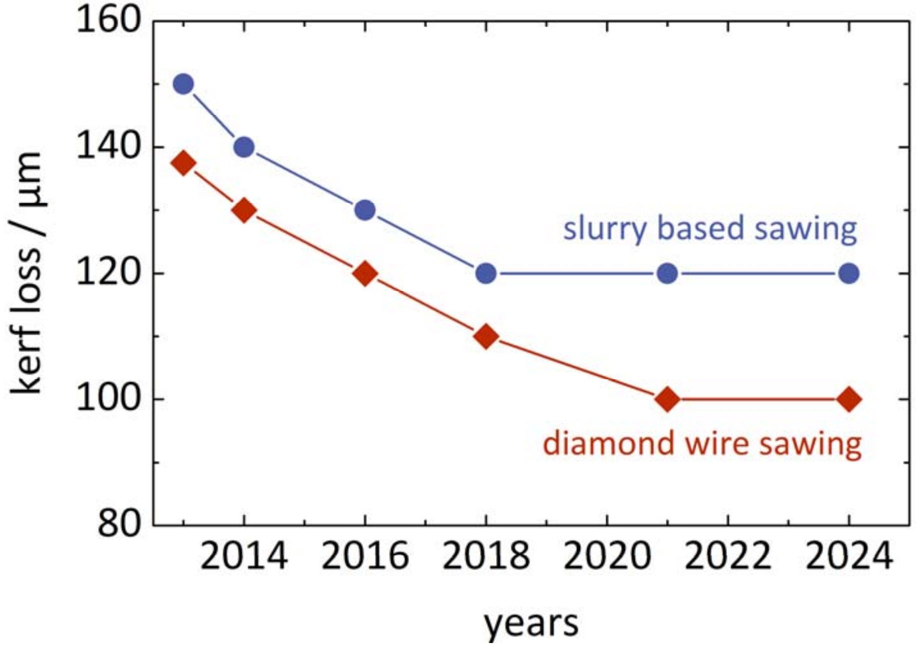
ITRPV 2014





absorber thickness will go down (material/cost reduction, higher *η*)

- kerf loss share?

  → lift-off processes (waferbased)

  → **direct preparation of crystalline Si <u>on glass</u>**

graphs adapted from ITRPV Roadmap, Fifth Edition, Revision 1, 24 March 2014
http://www.itrpv.net

Single side contacted *a*-Si:H/*c*-Si solar cells

from wafers to thin films

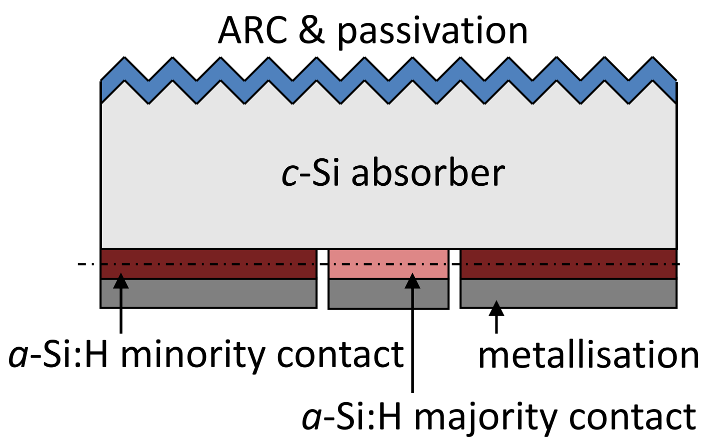
waferbased

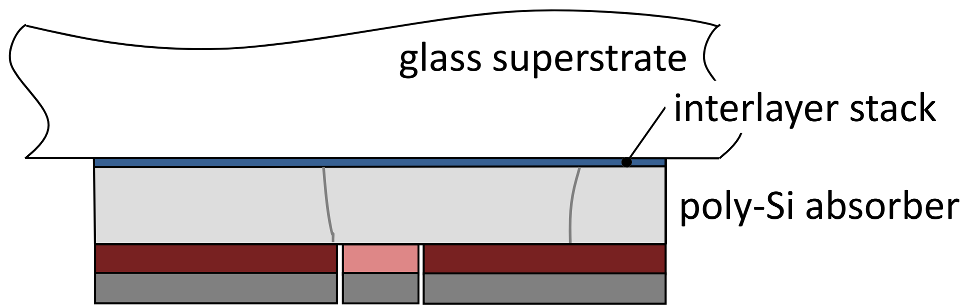
(back contacted solar cells)

- **no optical shading**
- **excellent surface passivation** by a-Si:H (high V_{OC})
- **World record efficiency: 25.6 %**
  Panasonic HIT IBC

thin-film

(liquid phase crystallised Si on glass)





Single side contacted *a*-Si:H/*c*-Si solar cells

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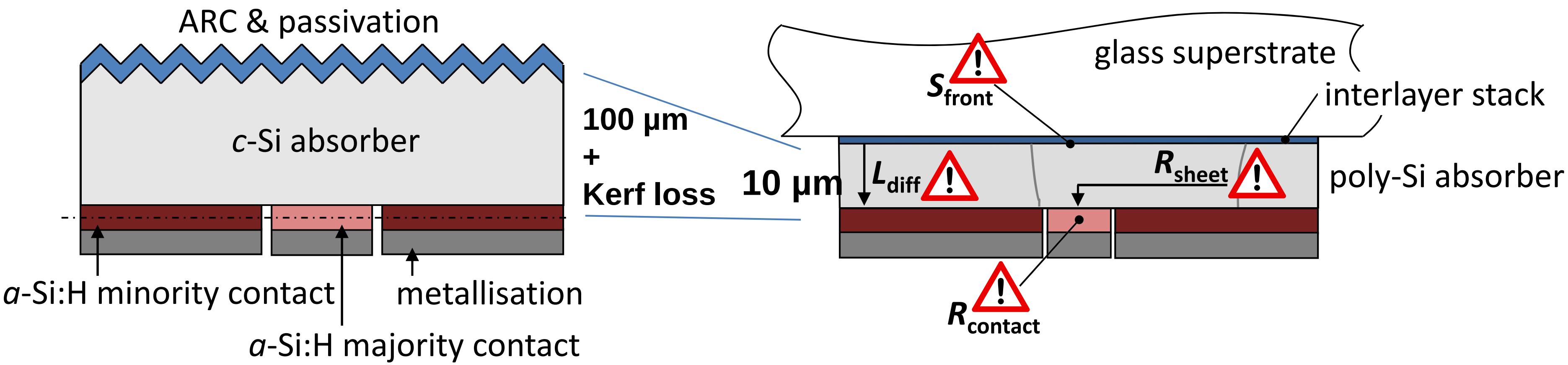
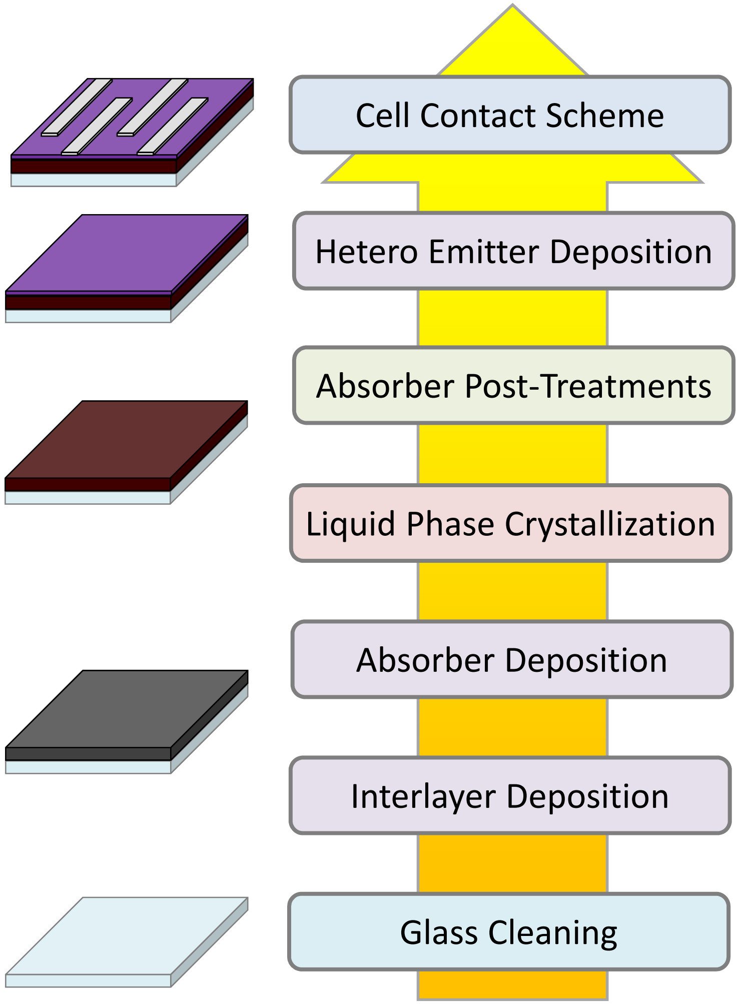
- **no optical shading**
- **excellent surface passivation** by a-Si:H (high V_{OC})
- **efficiency 25.6 %** Panasonic HIT IBC

thin-film
(liquid phase crystallised Si on glass)

- **sufficient diffusion length and passivation @buried interface!**
- **Back side contact scheme!**
- **Light management**



Process flow: back contacted thin-film c-Si cell



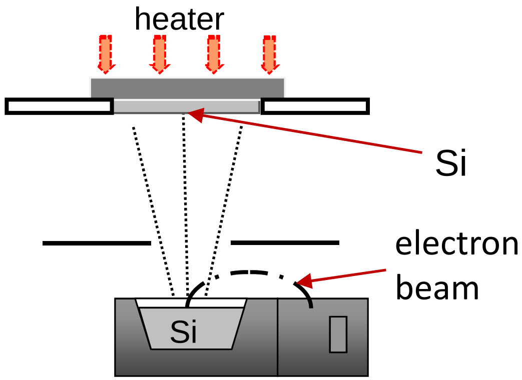
- PVD, Screen Printing, Lithography, Laser Scribing etc.
- PECVD @ 200 °C
- H_2 Plasma Passivation
- Wet Chemical Etching
- Laser LPC
- E-Beam LPC
- E-Beam Evaporation
- PECVD

@ 600 °C

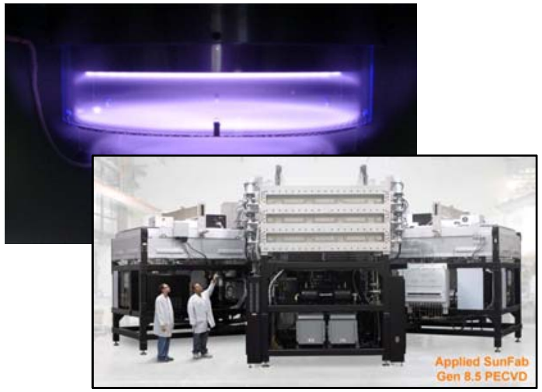
- PECVD
- PVD
- Alkaline Cleaning Agent + Rinsing in DI Water

Precursor deposition & Crystallisation

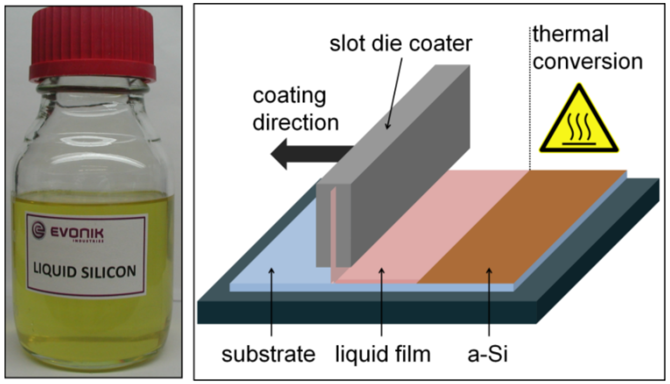
high rate evaporation (PVD)



PECVD

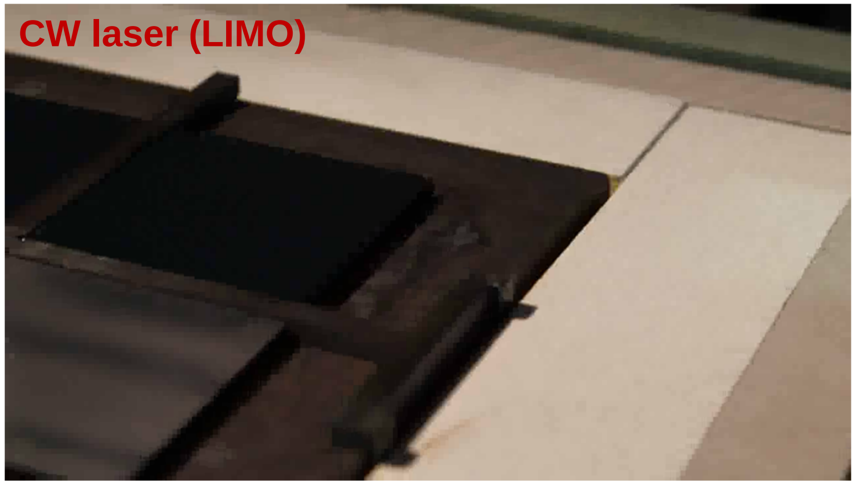


liquid silicon



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

and subsequent crystallization



D. Amkreutz et al. *Prog. Photovolt. Res. Appl.* 19, 937 (2011)

J. Dore et al., IEEE Journal of Photovoltaics 4, 33 (2014)

Electron Beam Crystallization on glass

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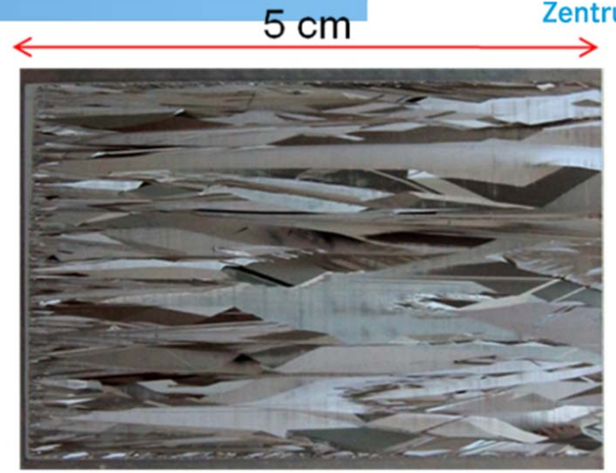

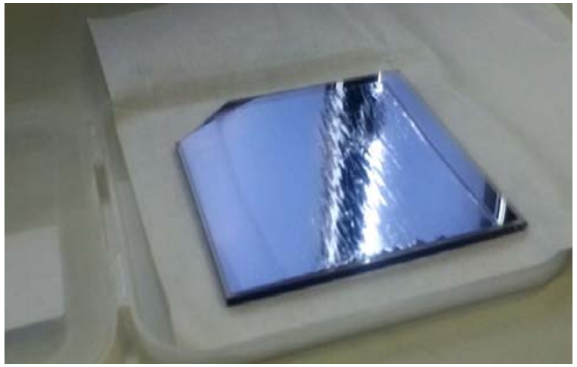

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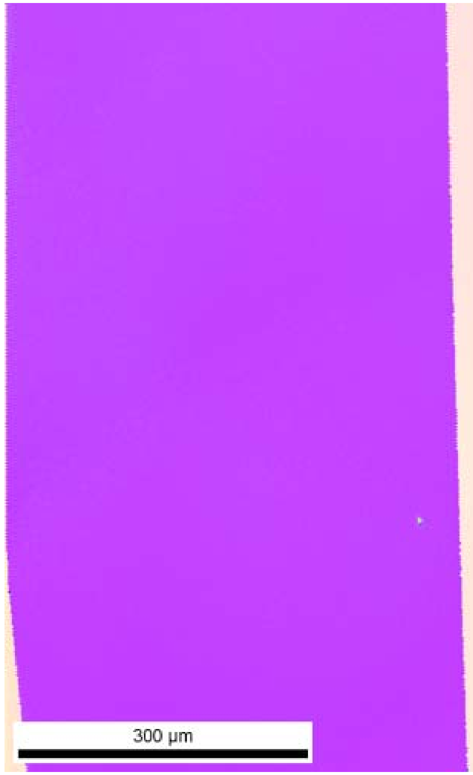
Technische Universität Hamburg-Harburg

Liquid Phase Crystallization on Glass



Grain size / EFG like

up to cm in length

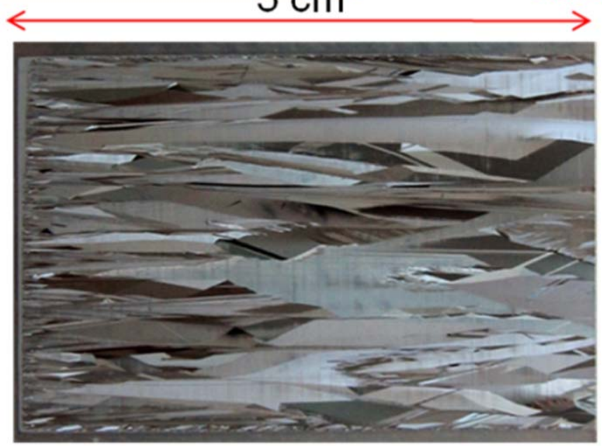
& several 100 µm in width

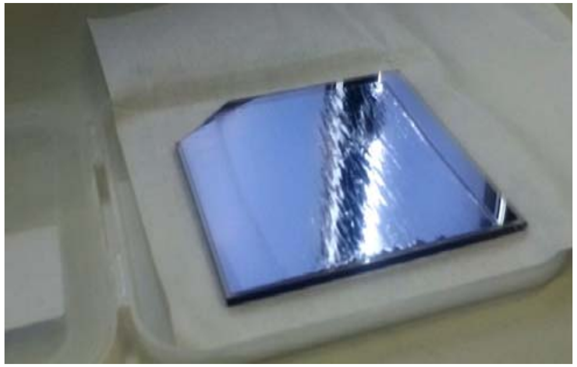
Typical Thickness 10 µm

Dislocation densities:

very low in large grains

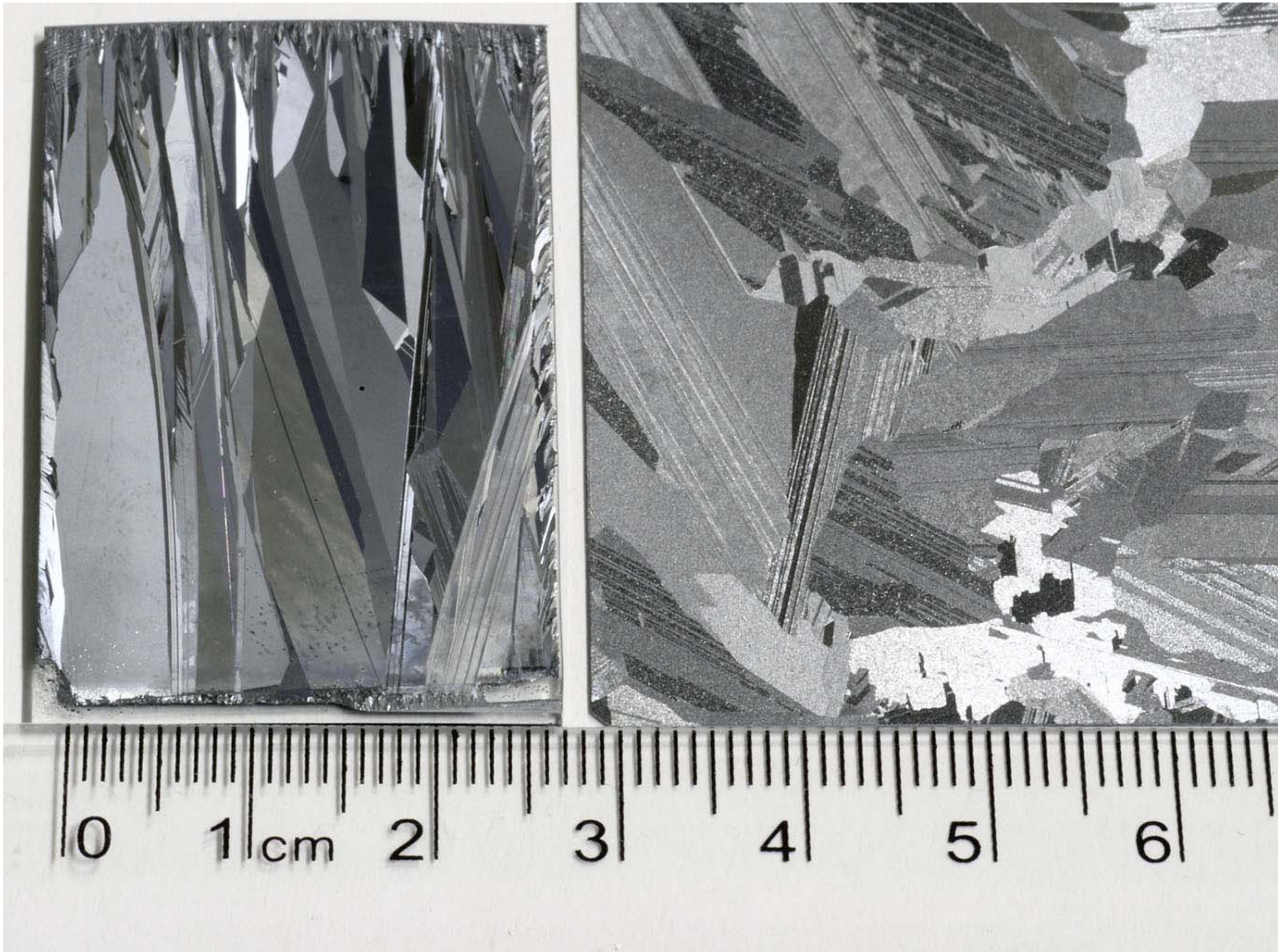
(comparable to cz-silicon)





Latest progress towards wafer quality

40 µm crystallised Si on glass | Multi-crystalline Si wafer



Bernd Rech, DPG Frühjahrstagung, AKE, Berlin 2015

Crystallization on Glass: SiO vs SiC

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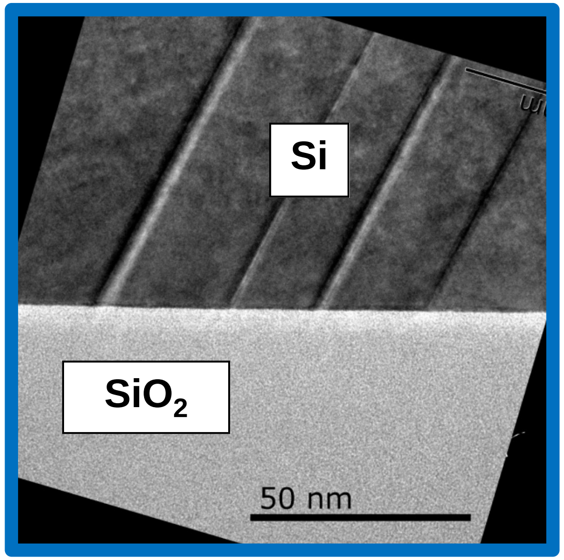
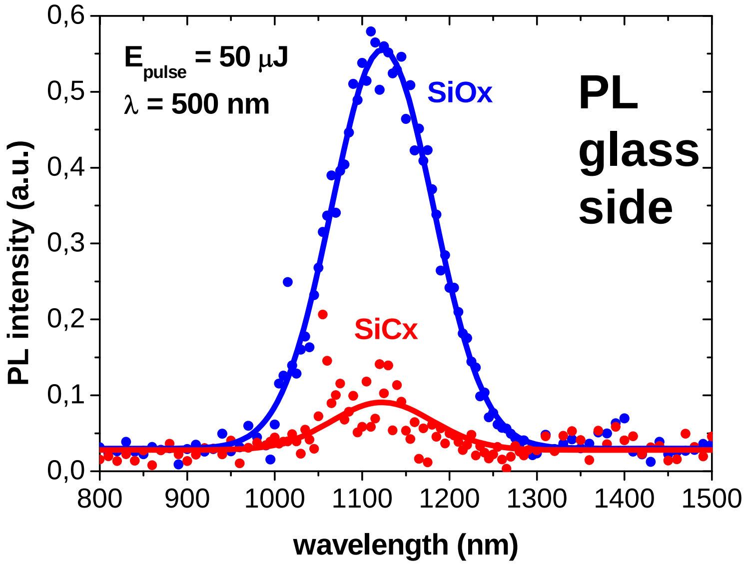


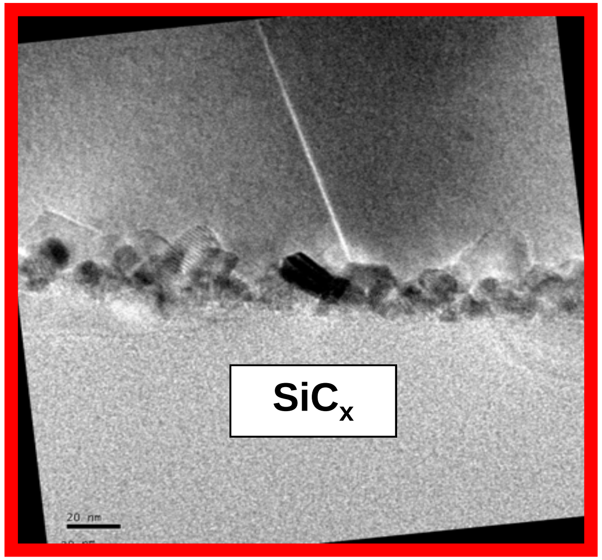


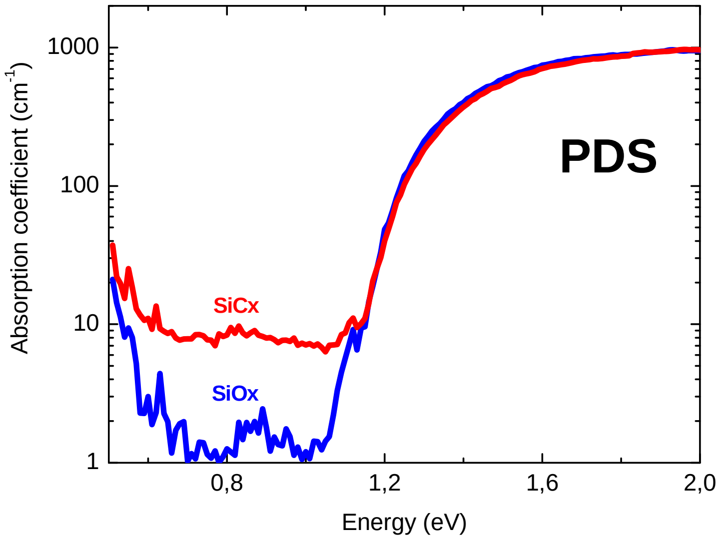
Properties

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)

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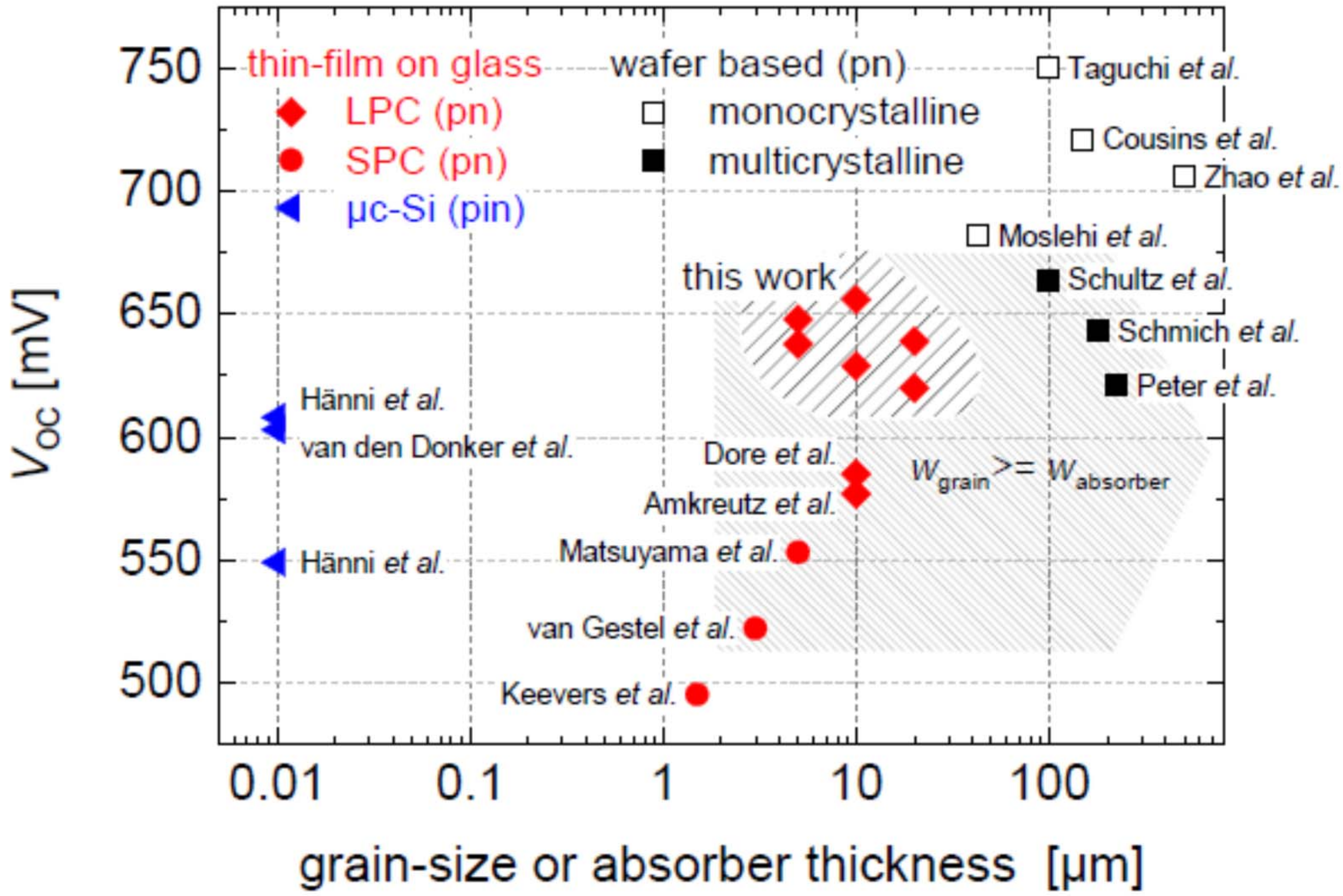
Switching to n-type poly Si absorbers



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

Solar cell structures

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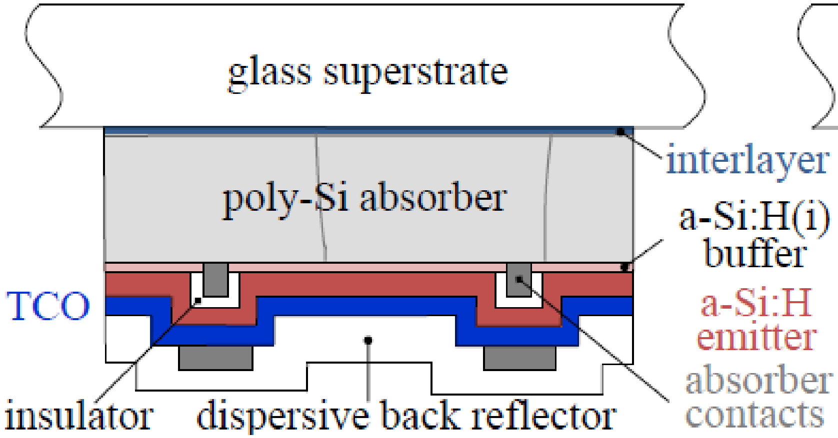
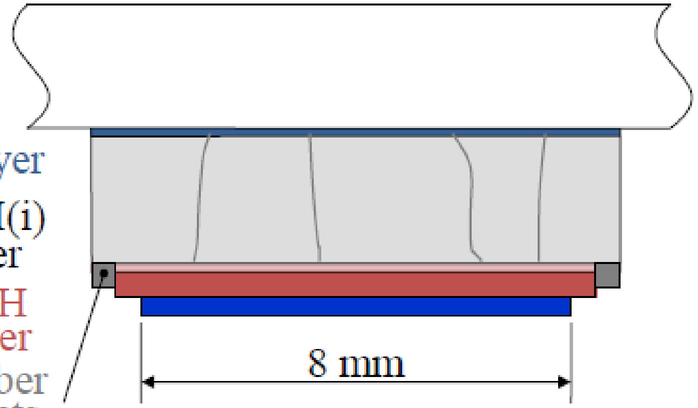
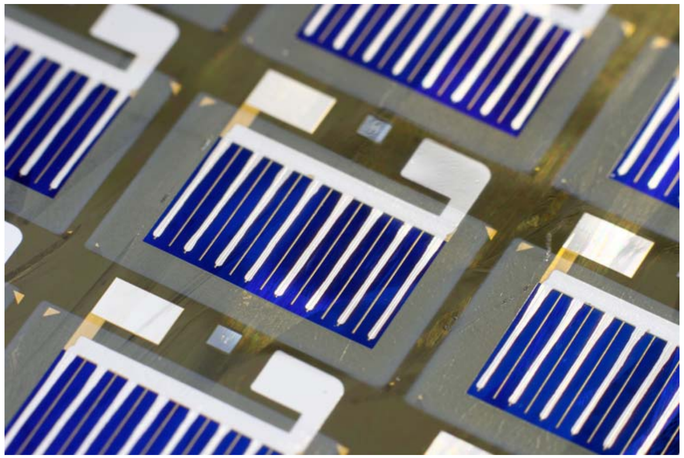
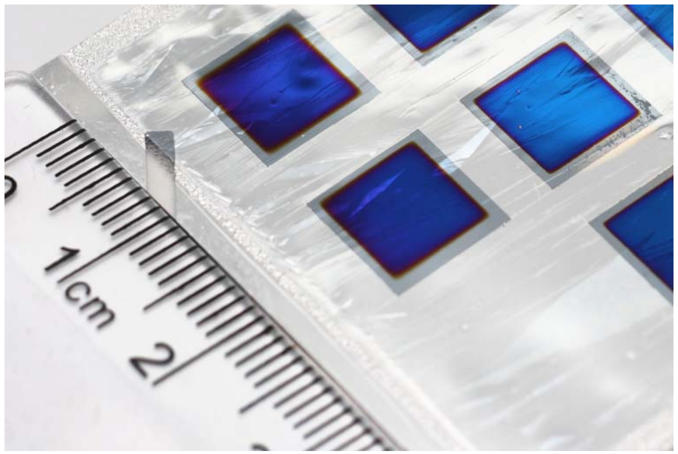
„advanced“ design - A

simple design - S



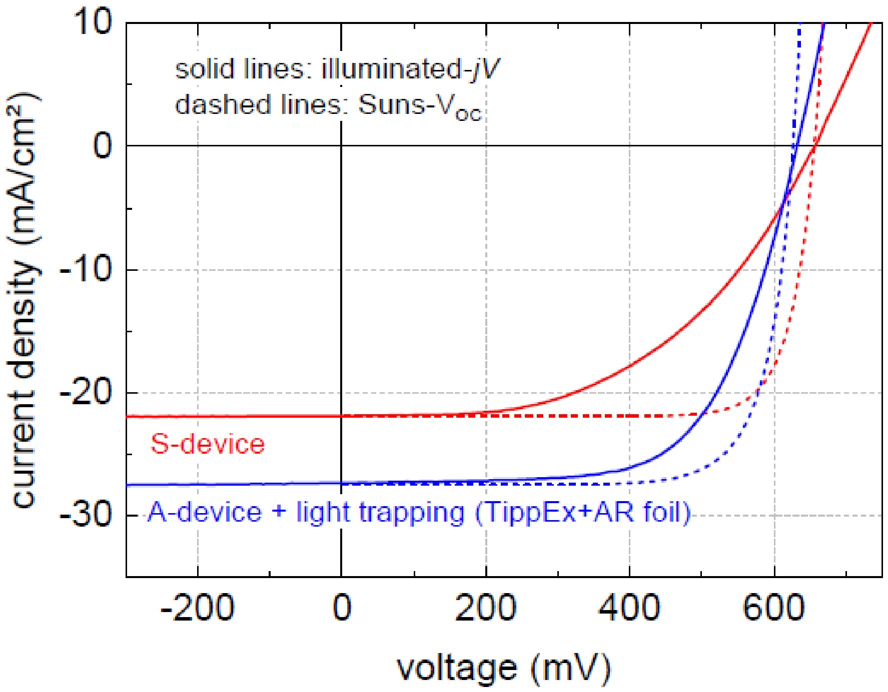


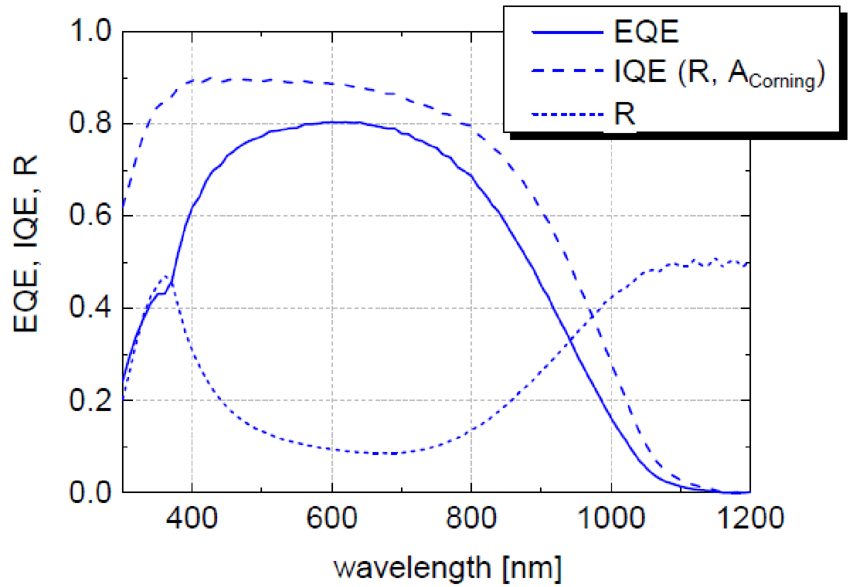




Jan Haschke et al. SOLMAT 2014, D. Amkreutz et al. IEEE JPV 2014, acc.

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

Latest efficiency: 11,8 %

Jan Haschke et al. SOLMAT 2014

Amkreutz et al., IEEE JPV

Frijns et al. 12,1 % to be published

Light Management

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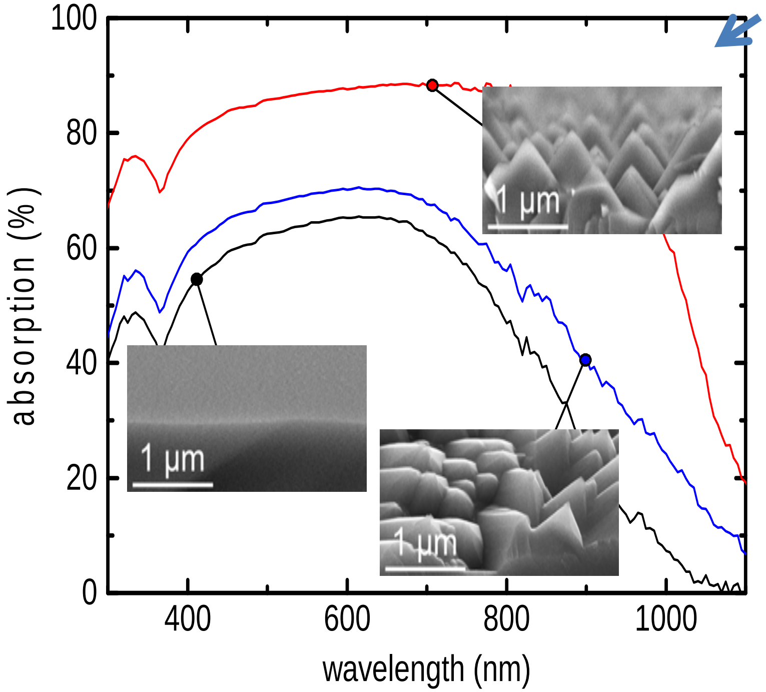
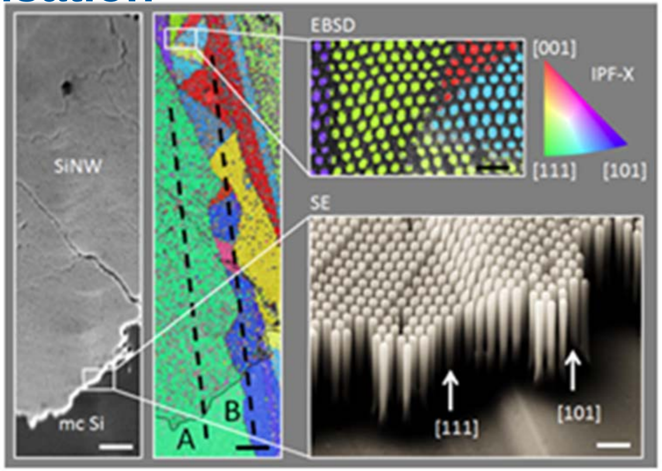
Controlled crystallisation

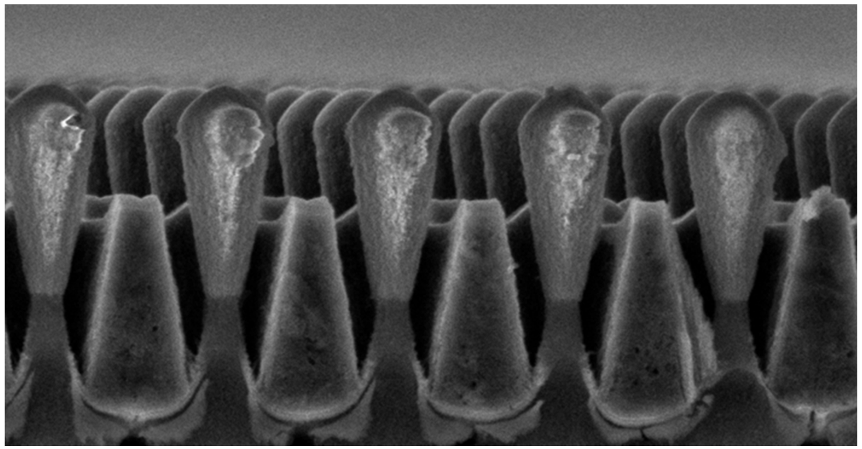


Controlling Crystall Growth



Nanowires
New Institute Nanoarchitectures
Silke Christiansen

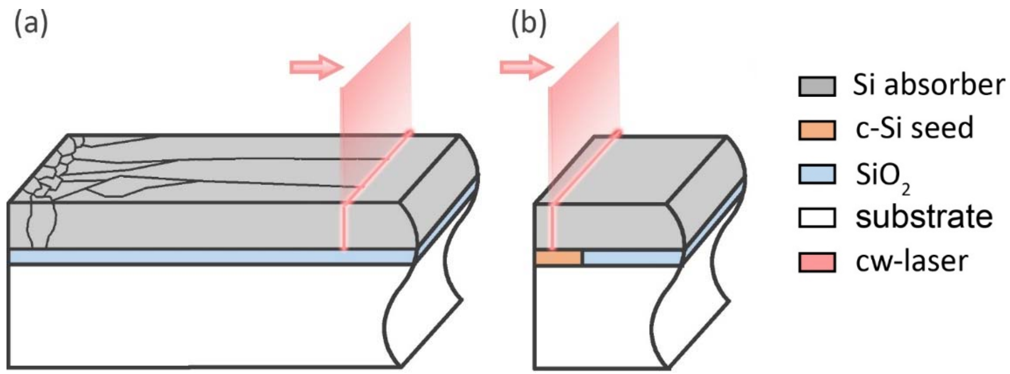
Nano-Imprint Lithography
Young Investigator
Group of Christiane Becker

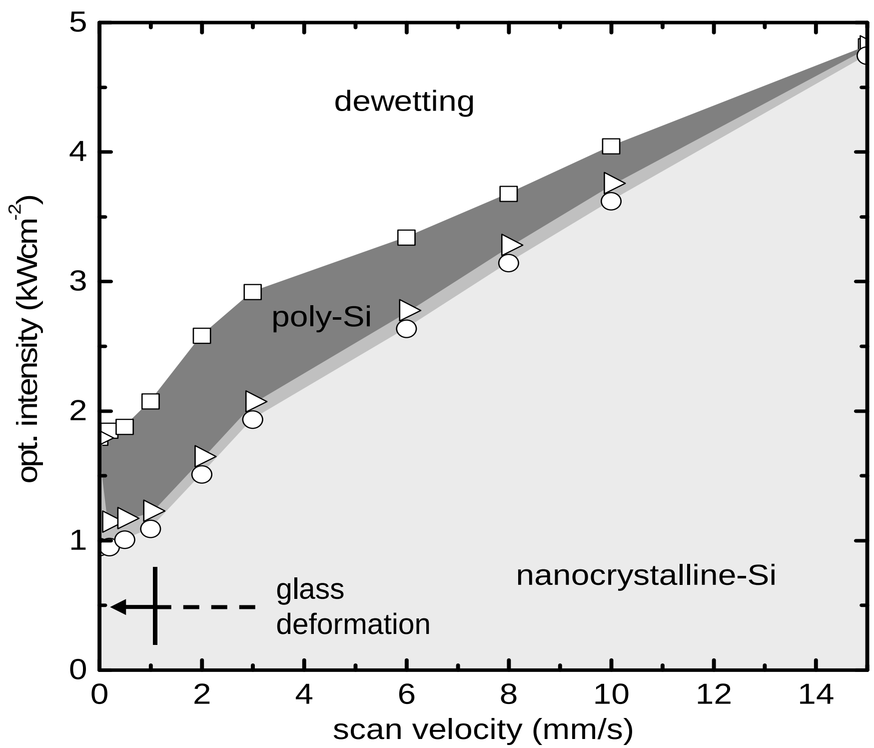


Controlled Crystallisation

const.: T_{heater} **= 700 °C**

variation: $I_{opt.}$ **&** v_{scan}

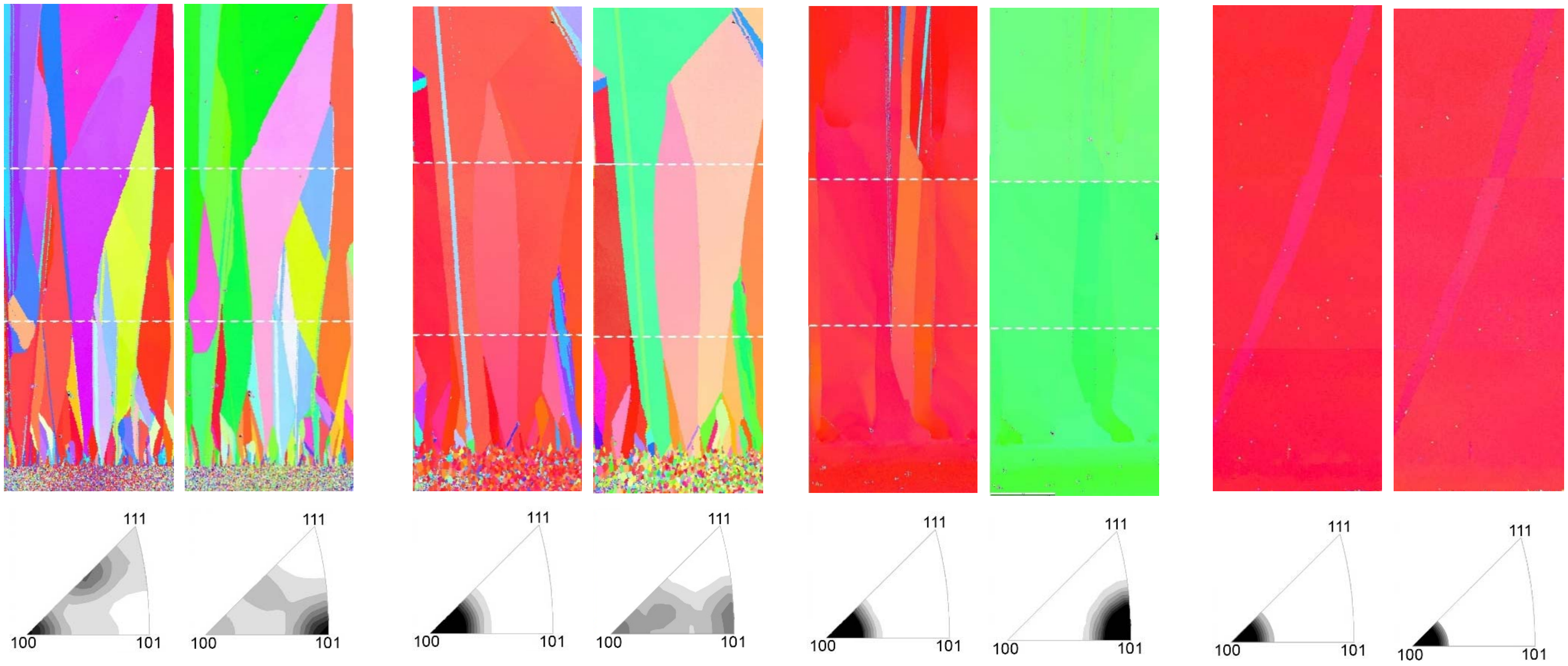




x

Controlled Crystallisation

standard crystallization | optimized crystallization[1] | seed layer crystallization[2]



random orientation of the crystals in surface normal and in scanning direction

preferential orientation of the surface normal and random orientations in scanning direction

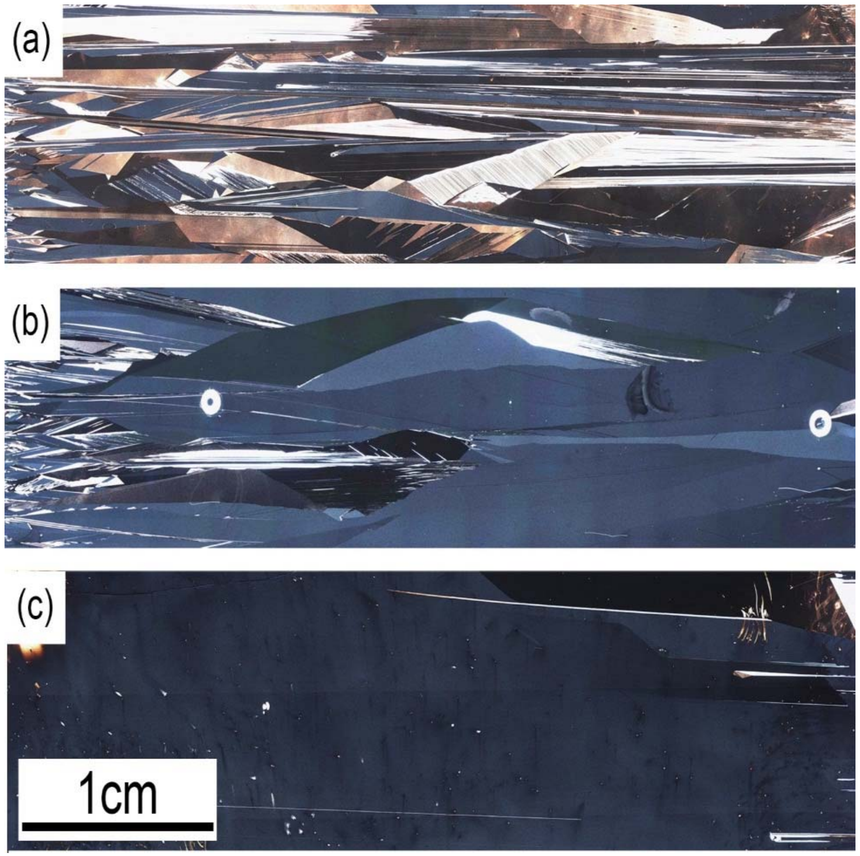
preferential orientation of the surface normal and in scanning direction

[1] S. Kühnapfel et al., *Thin Solid Films* 576 (2015)
[2] S. Kühnapfel et al., *submitted to Solmat*

Pyramid Etching and Surface Orientation

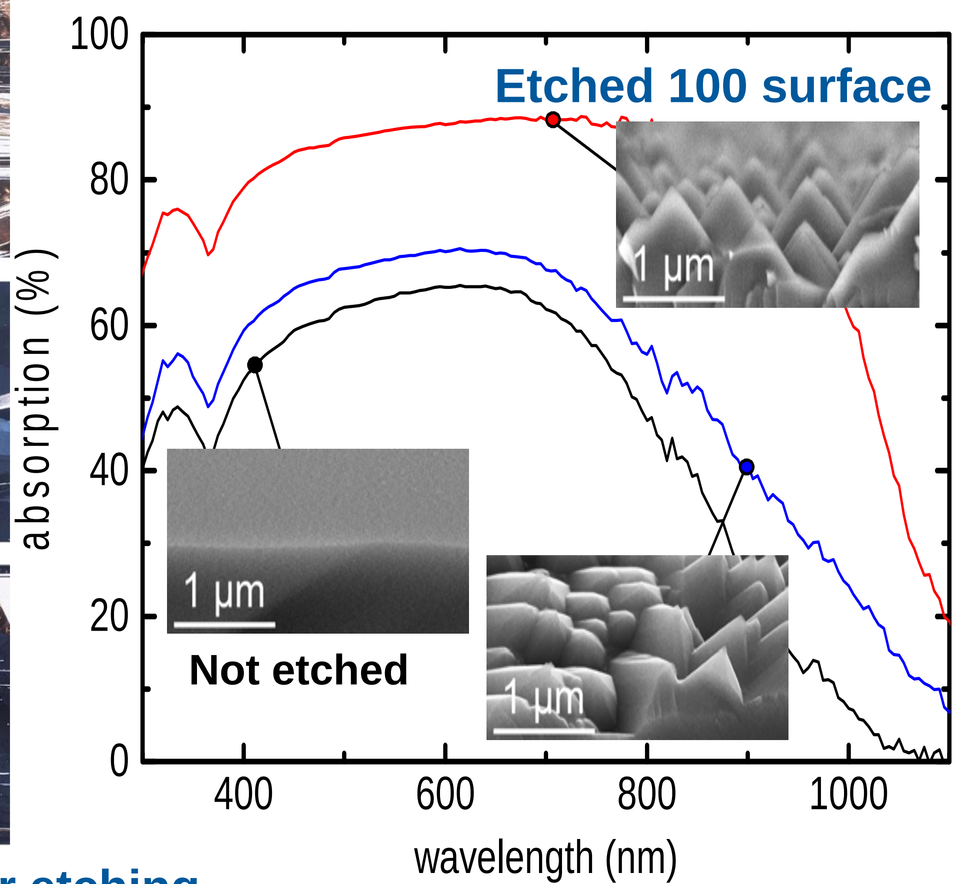
HZB Helmholtz Zentrum Berlin

Photograph of etched surfaces



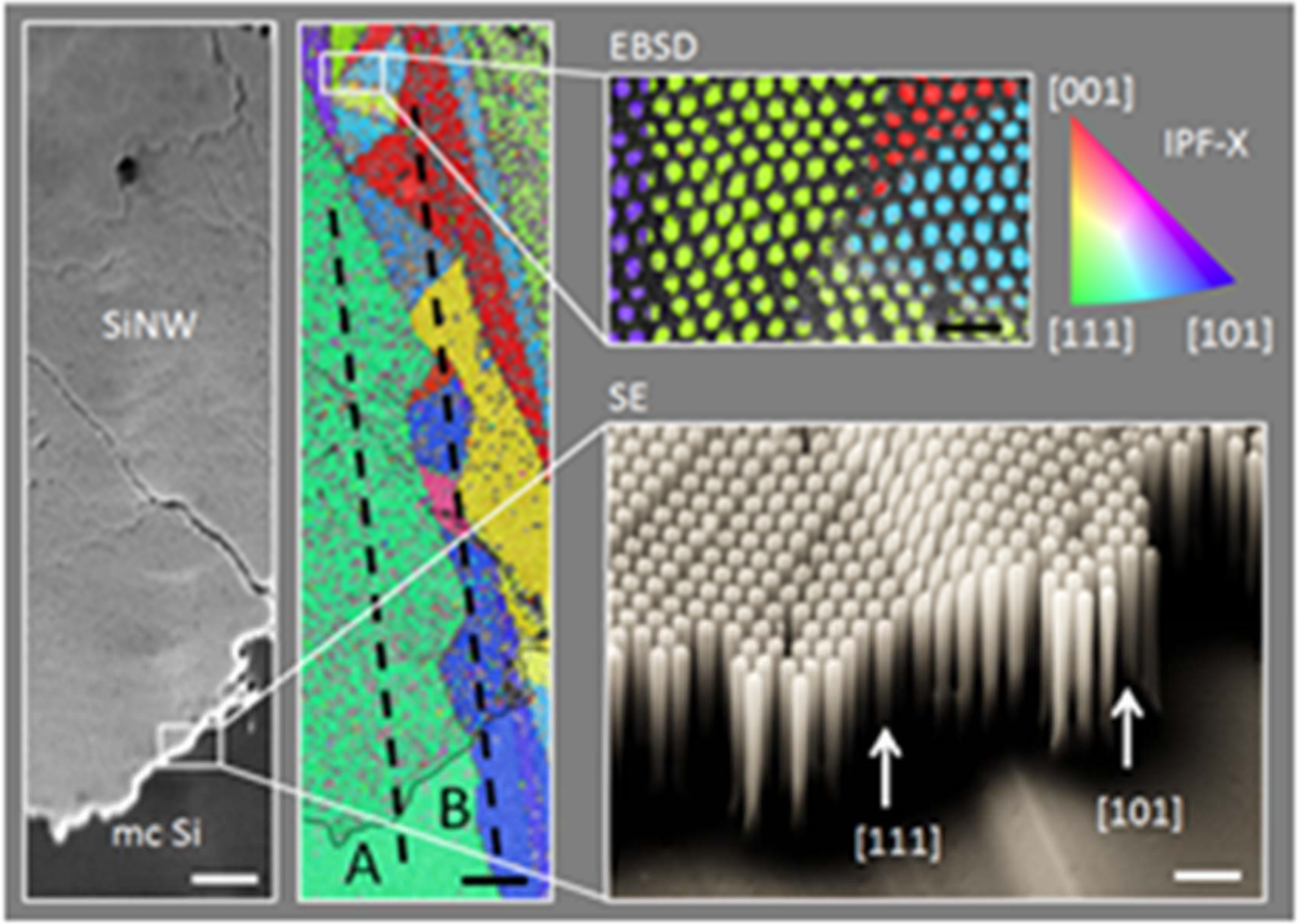
100 surface – black appearance after etching

Optical Apsorption



[1] S. Kühnapfel et al., *Thin Solid Films* 576 (2015)
[2] S. Kühnapfel et al., *submitted to Solmat*

Going 3 D in thin film Si

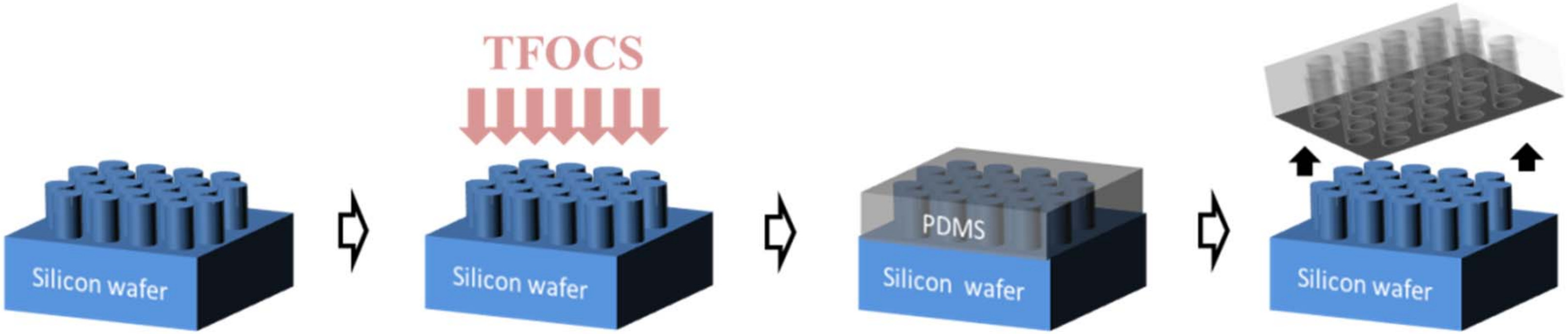


50 µm 3 µm

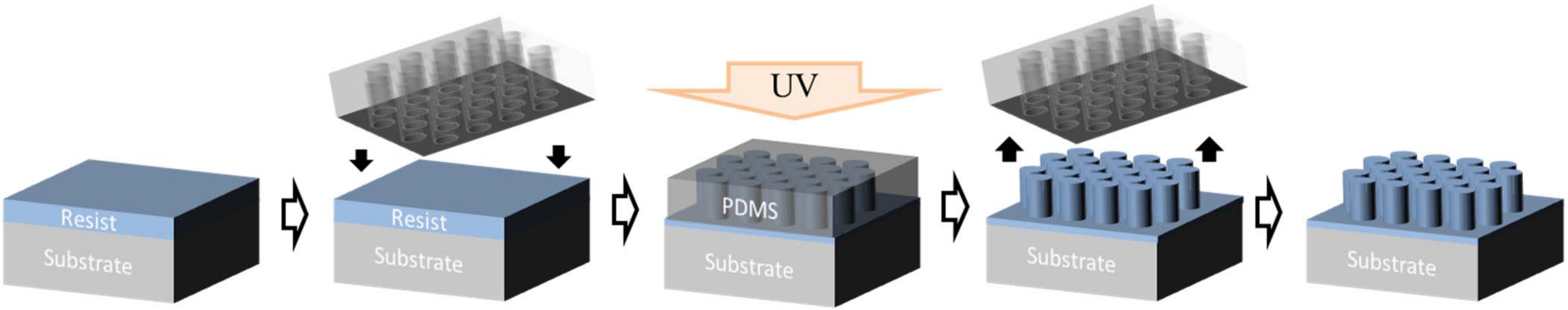
In cooperation with S. Christiansen HZB&MPI Erlangen
S.W. Schmitt et al. Nanoletters 2012

Master Replication
UV-Nanoimprint Lithography

Step 1: Fabrication of the PDMS-stamp



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

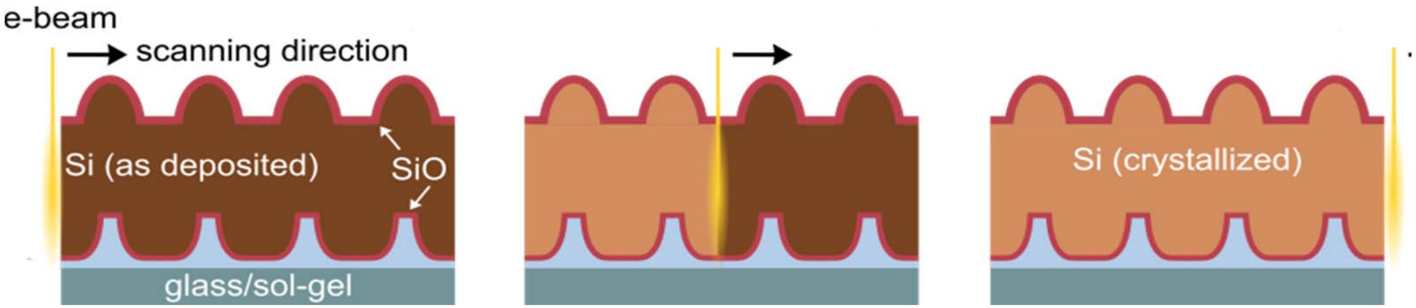


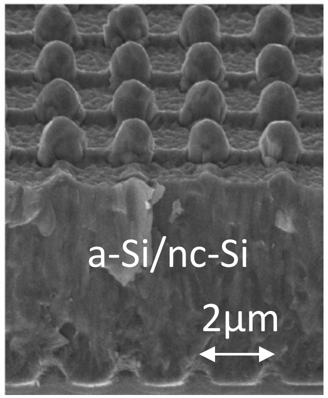
➢ **Repeatable, high throughput**

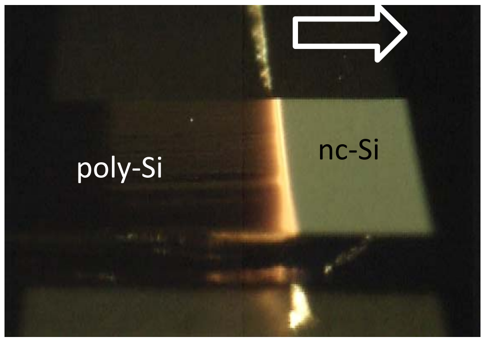
Liquid phase crystallized textured Si films

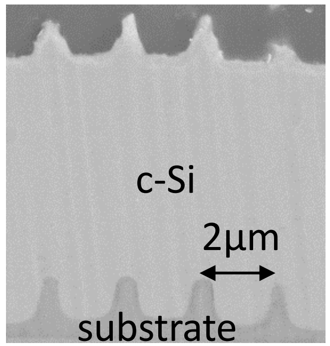
HZB Helmholtz Zentrum Berlin

Double side textured Si architectures by electron-beam crystallization







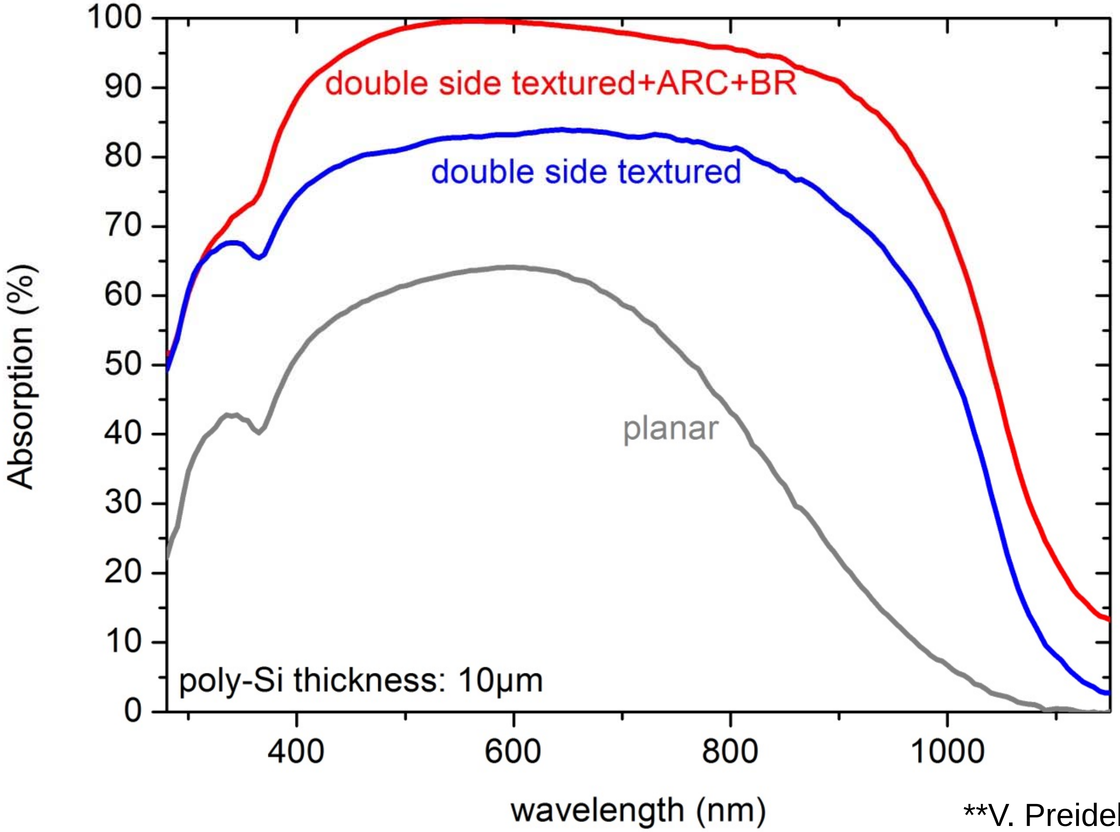


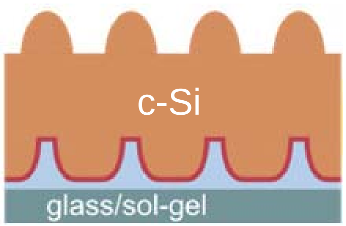
T > 1414°C (Si melting point)

**V. Preidel et al., Proc. SPIE 8823, 882307 (2013)
C. Becker et al., SolMat 2015

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/cm² (double side texture)

Conclusions & Outlook

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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")

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)

  - back contact design and module concept required

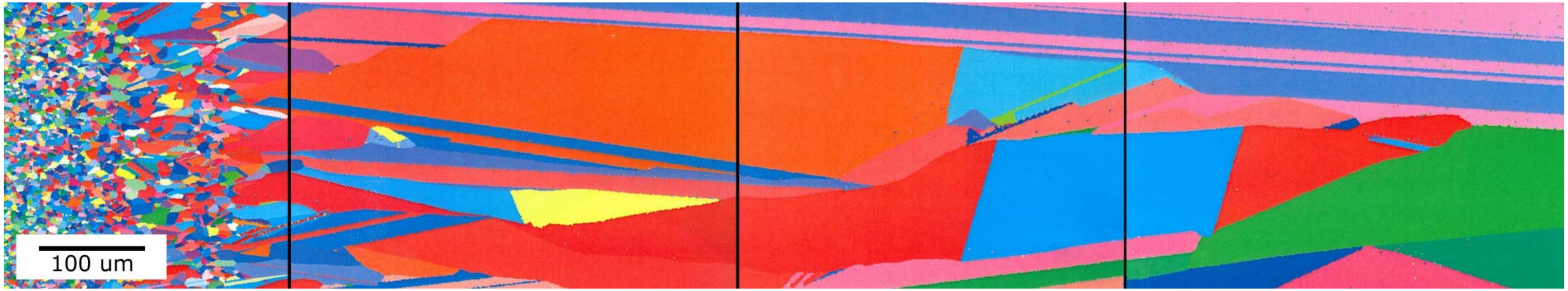
  - light trapping

  strong efforts in research & development still needed!

Conclusion&Outlook II

- The transformation of the energy system is a key global challenge!
- Solar energy will be a (the) major energy source in the future.
- PV is an Energy and not a Niche Technology anymore
- PV is major global industry, hoiwever, facing strong competition
- R&D challenge & opportunity:
  - cheaper
    - more efficient !
      - new appliations
        - storable

Thank you for your attention.



Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit

Bundesministerium für Bildung und Forschung

Berlin

SPITZENFORSCHUNG & INNOVATION IN DEN NEUEN LÄNDERN

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