HELMHOLTZ ZENTRUM BERLIN
für Materialien und Energie

WIAS 2008

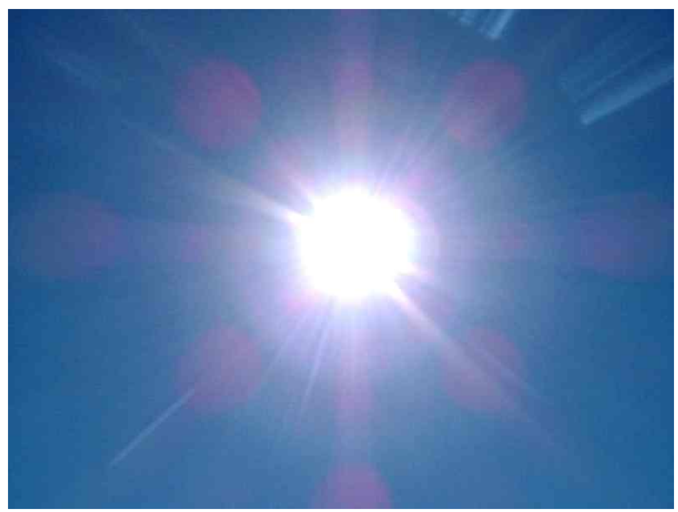
Solarzellen aus dünnen Siliziumschichten – Stand der Technik und Herausforderungen für die Zukunft

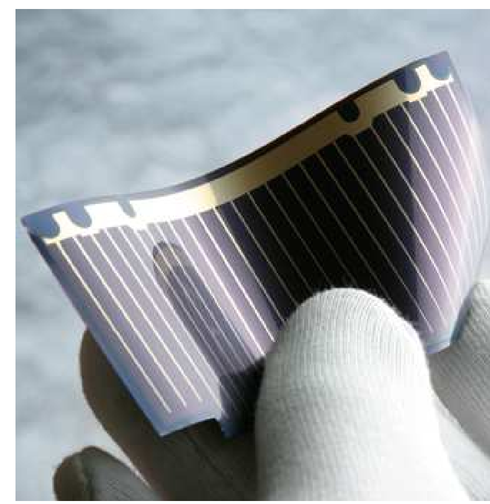
Bernd Rech
Helmholtz-Zentrum Berlin (HZB) and Technische Universität Berlin

Many thanks to my colleagues from HZB and FZ-Jülich (Uwe Rau et al.), Michael Powalla from ZSW – Stuttgart and industry partners

Outline

- Motivation and Background
- Thin Film Solar Cell Technologies and Applications
- Amorphous and Microcrystalline Based Silicon and Tandem Cells
- Poly-Crystalline Si Thin-Films
- R&D Challenges and Conclusions





“Theoretical Efficiency”

HELMHOLTZ ZENTRUM BERLIN für Materialien und Energie

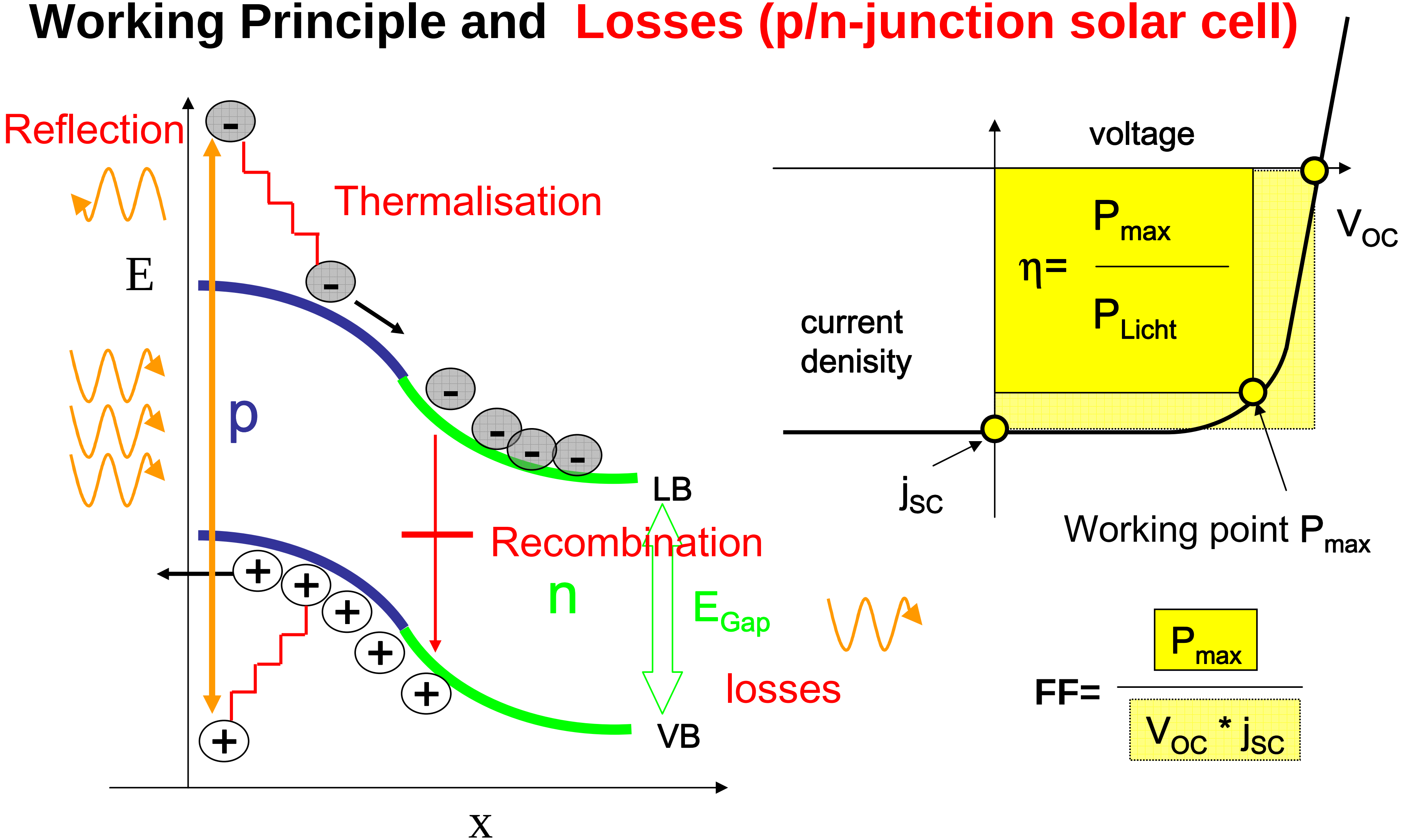
Thermodynamic limits – Generation of electricity in a Carnot process:

$$\text{Carnot efficieny} = \frac{T_{sun} - T_{earth}}{T_{sun}} = 95\ \%$$

This is an absolute upper limit, however, unavoidable losses of entropy reduce the thermodynamic limit towards 85 % (see e.g. Würfel, Physik der Solarzellen)

Note: due to the T_{sun} of 5800 K solar radiation is of high energetic value

Working Principle and Losses (p/n-junction solar cell)

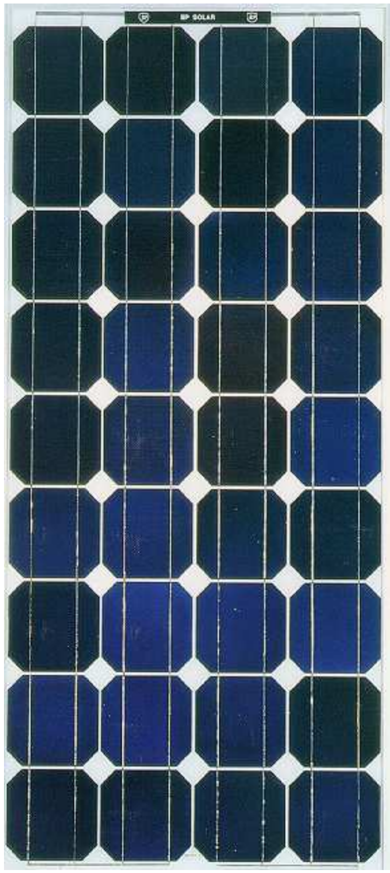


$$FF = \frac{P_{max}}{V_{OC} * j_{SC}}$$

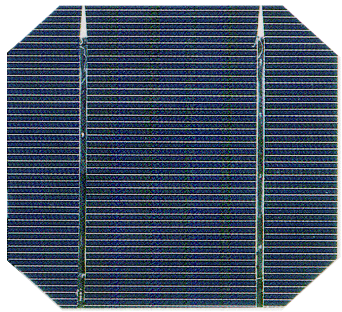
“Some Commercial Efficiencies”

HELMHOLTZ ZENTRUM BERLIN
für Materialien und Energie

c-Si wafer technology



c-Si solar cell



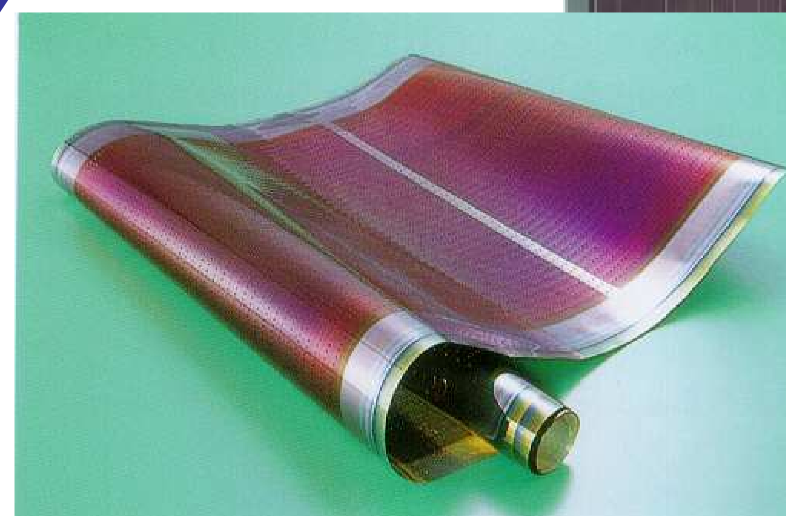
Si-thickness
200-300 µm

(η = 12 – 17 %)

a-Si thin-film technology

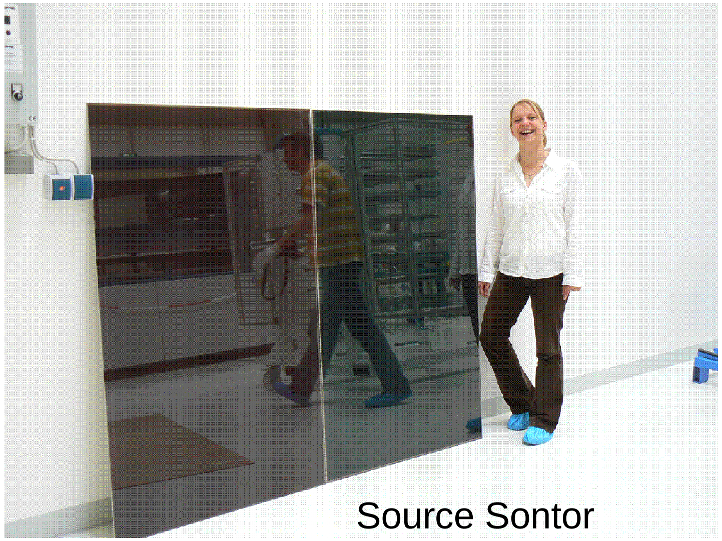
Si-thickness
0.5 µm

(η = 5 – 7 %)



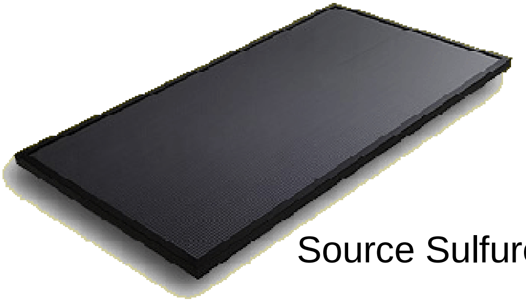
Thin film advantages

- Material usage/cost (1-5 vs 200 µm)
- High productivity (large area)
- Monolithic series connection
- Short energy pay back time
- New products (e.g.. flexible)



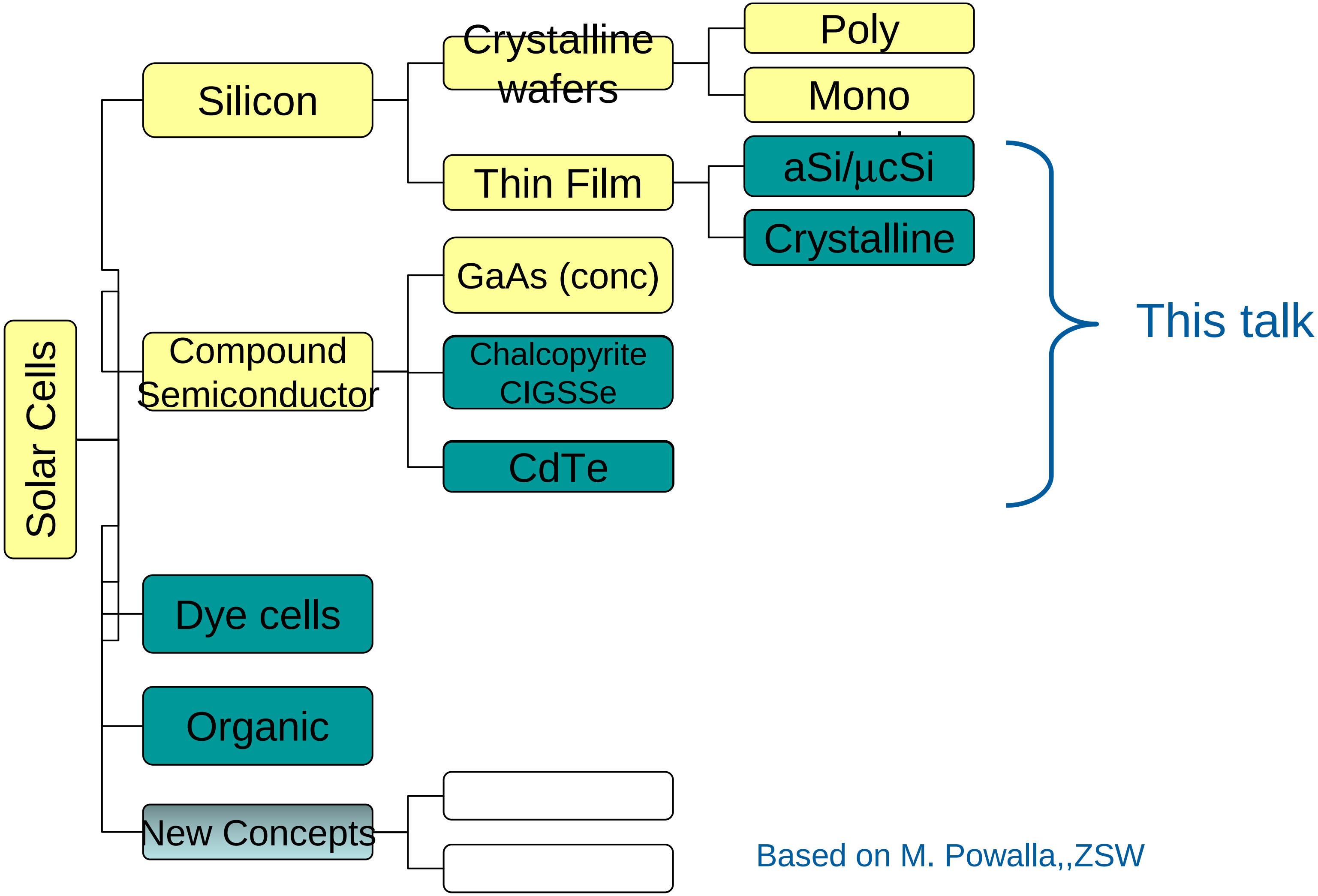
Source Sontor

Source Solar Integrated Technologies



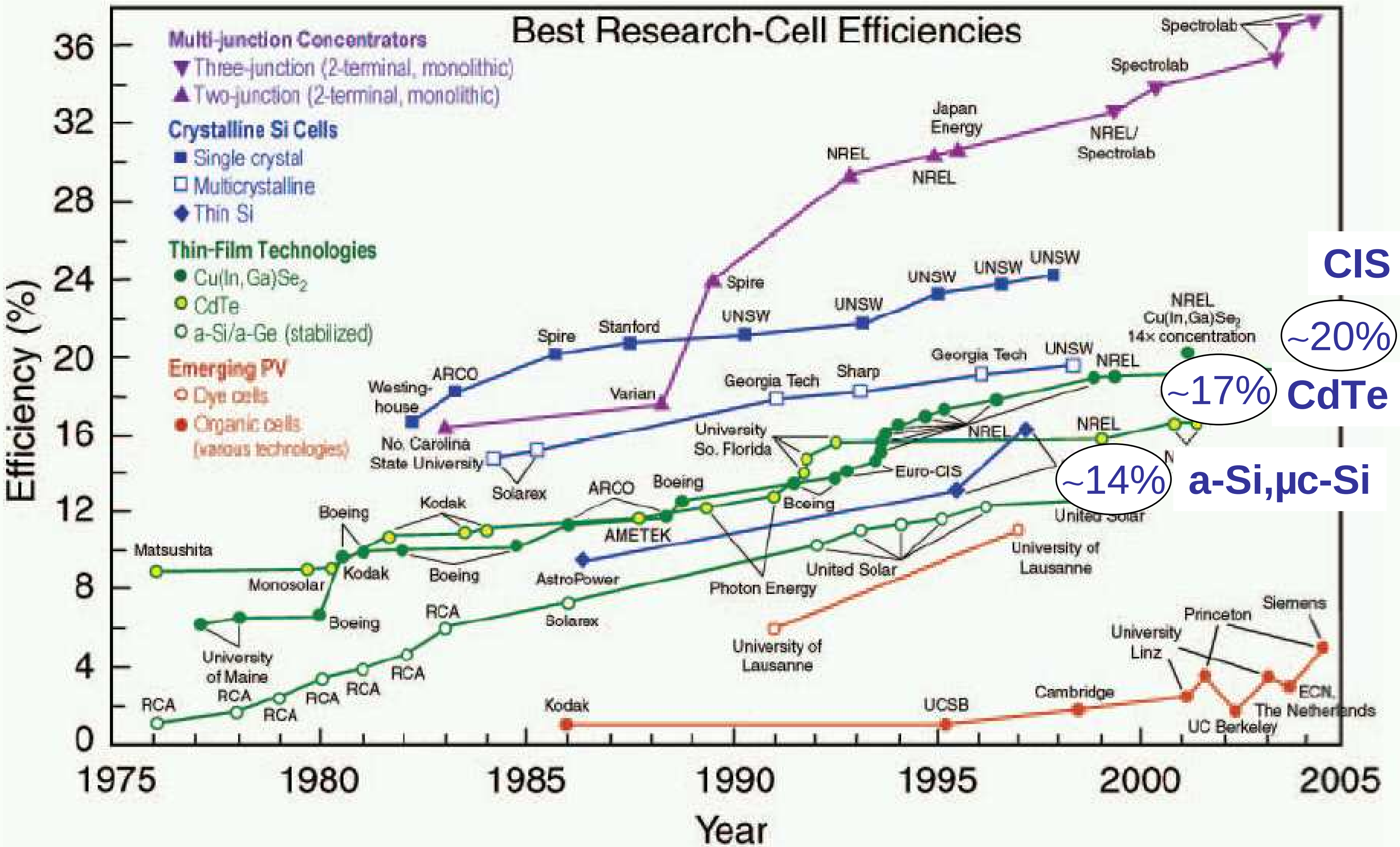
Source Sulfurcell

Overview of photovoltaic material classes



Based on M. Powalla,,ZSW

Evolution of Record Solar Cells



Source: Brabec, MRS Bulletin, Jan. 2005

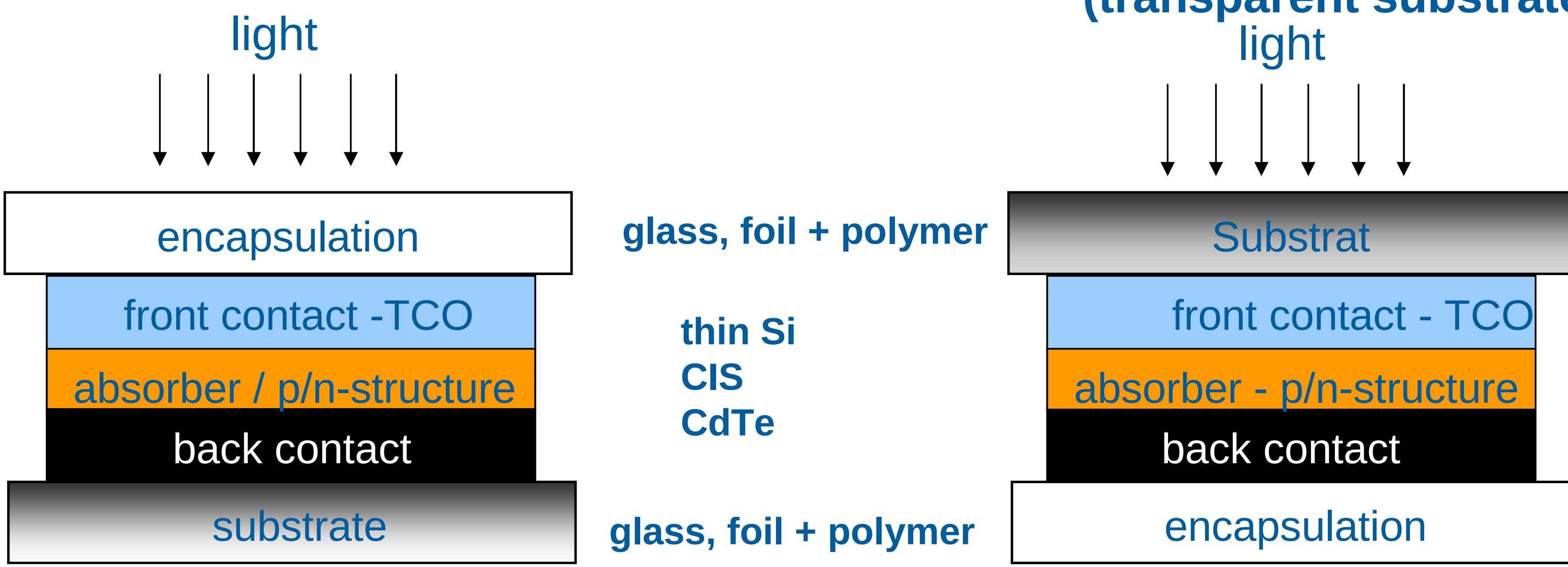
Thin film PV technologies

The primary idea is a tiny amount of expensive material (1 micron or so) and lots of cheap glass and wire and metal and plastic

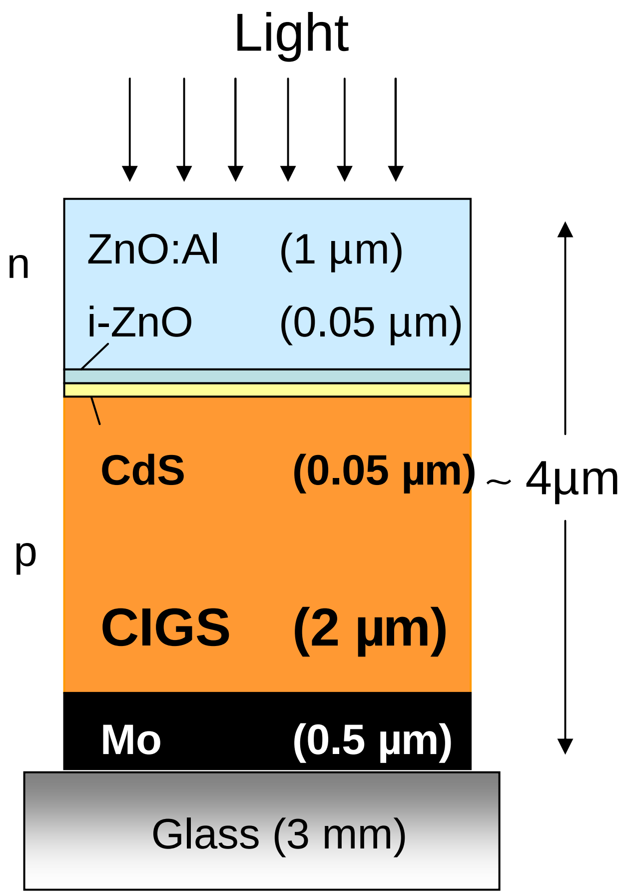
Ken Zweibel, NREL, 2004

Substrate technology

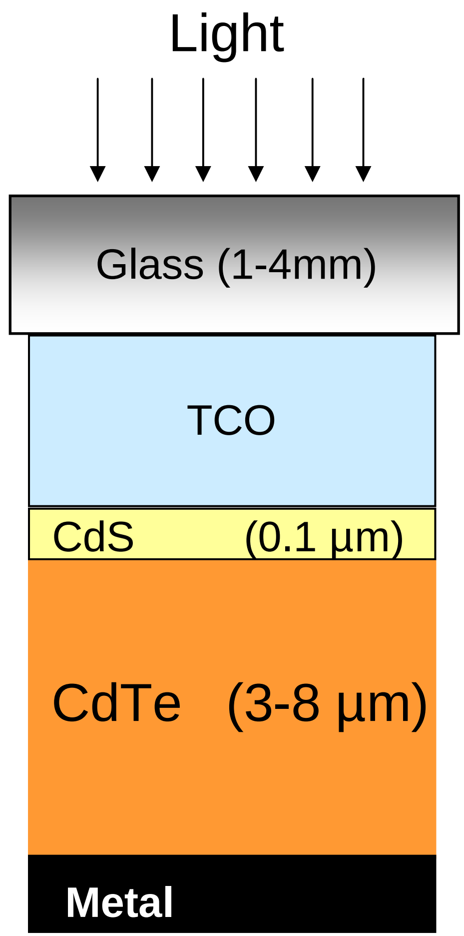
Superstrate technology (transparent substrate)



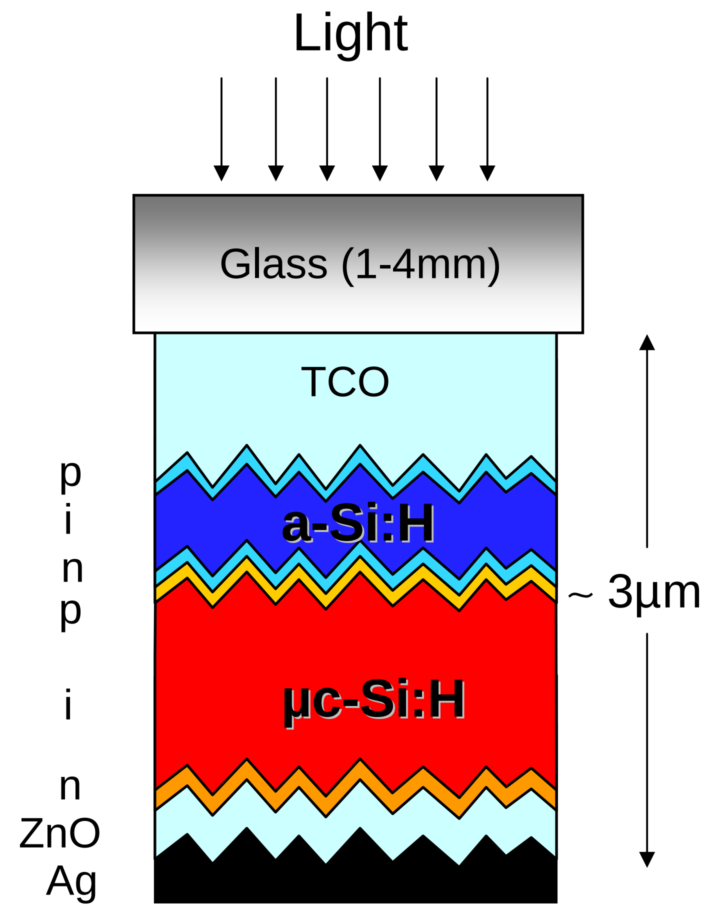
CIGS-solar cells:
$CuIn_{1-x}Ga_xSe_{1-y}S_y$



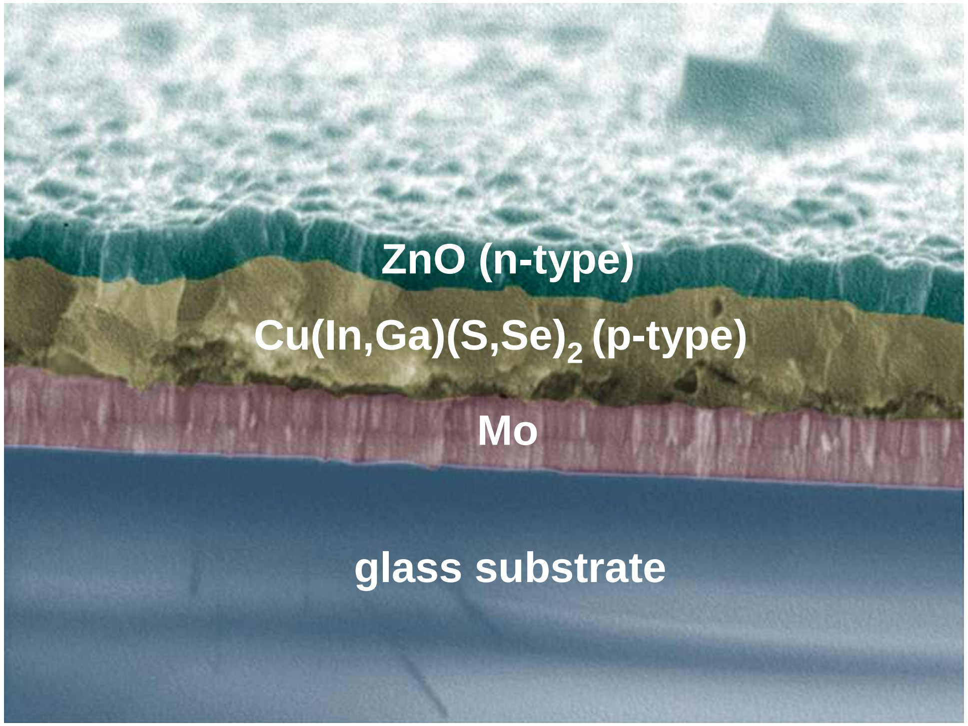
CdTe-solar cells:
CdTe

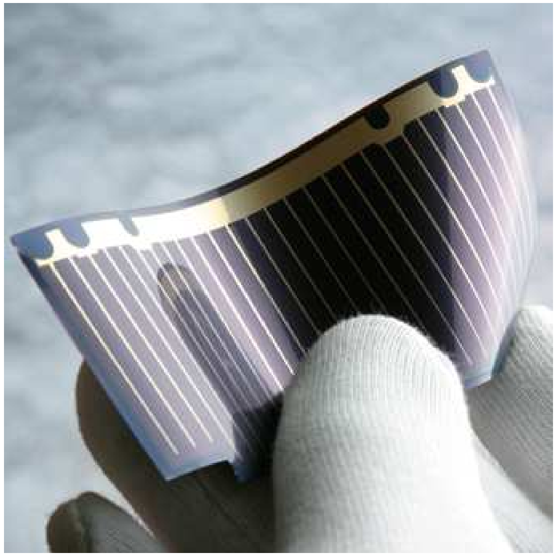


a-Si technology
Example:
a-Si/µc-Si tandem cell
(„Micromorph“)



Example CIGS-Solar Cell

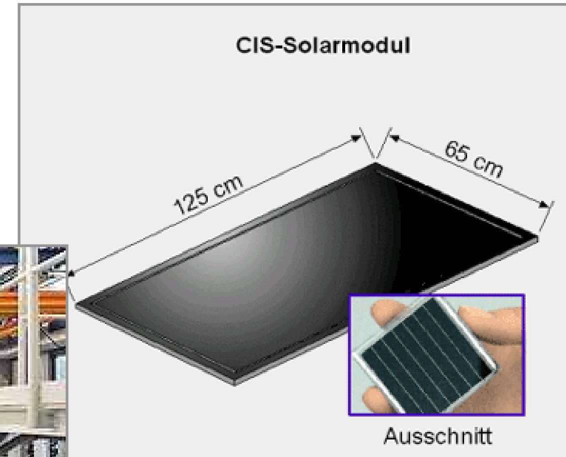


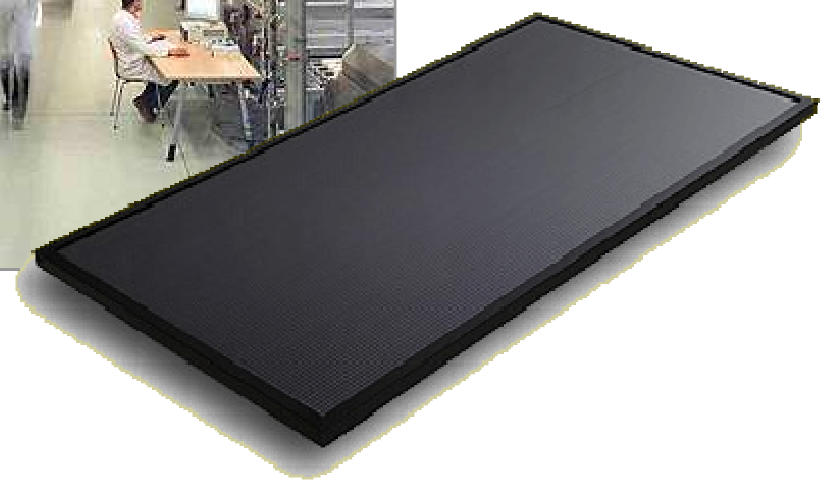


Flexible solar cell on titanium foil

HZB: Spin-off Company

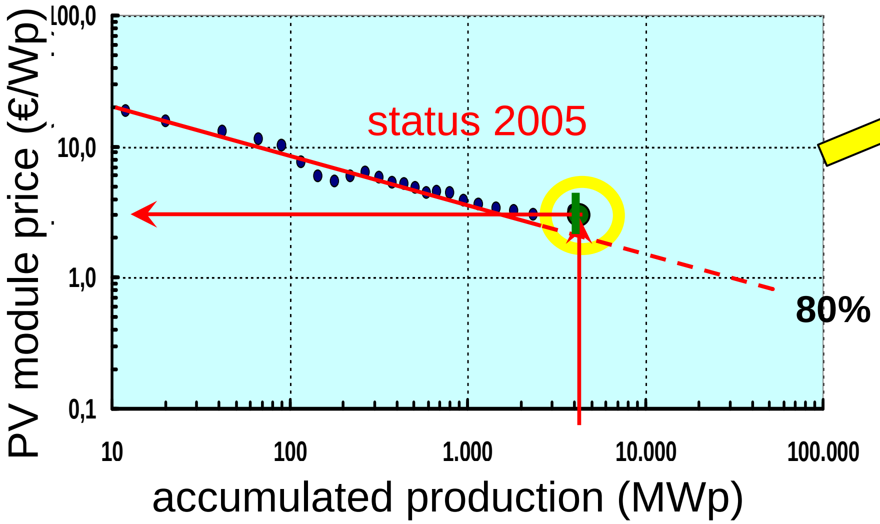
SULFURCELL



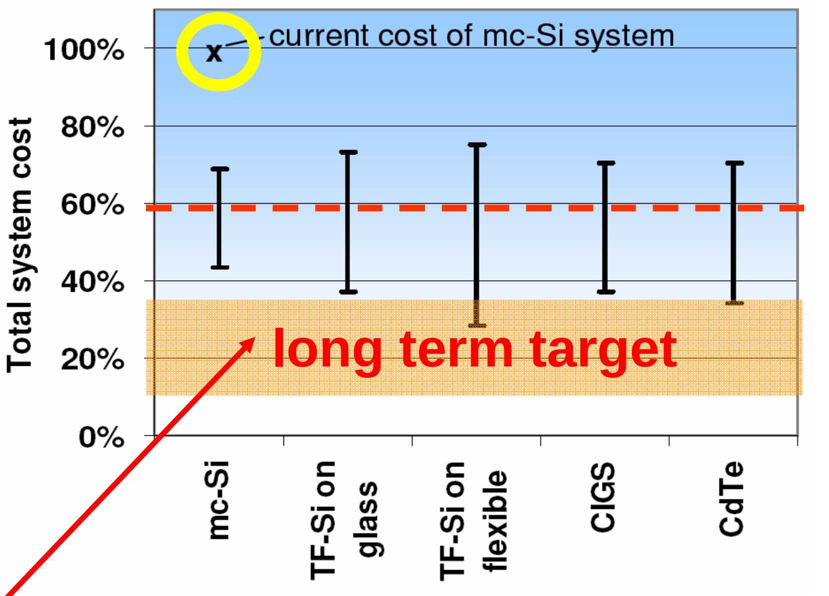


Cost reduction strategies

Cost reduction has different options



source: T. Surek NREL



O. Hartley, J. Malmström, A. Milner, 21st EUPVSC, Dresden 2006

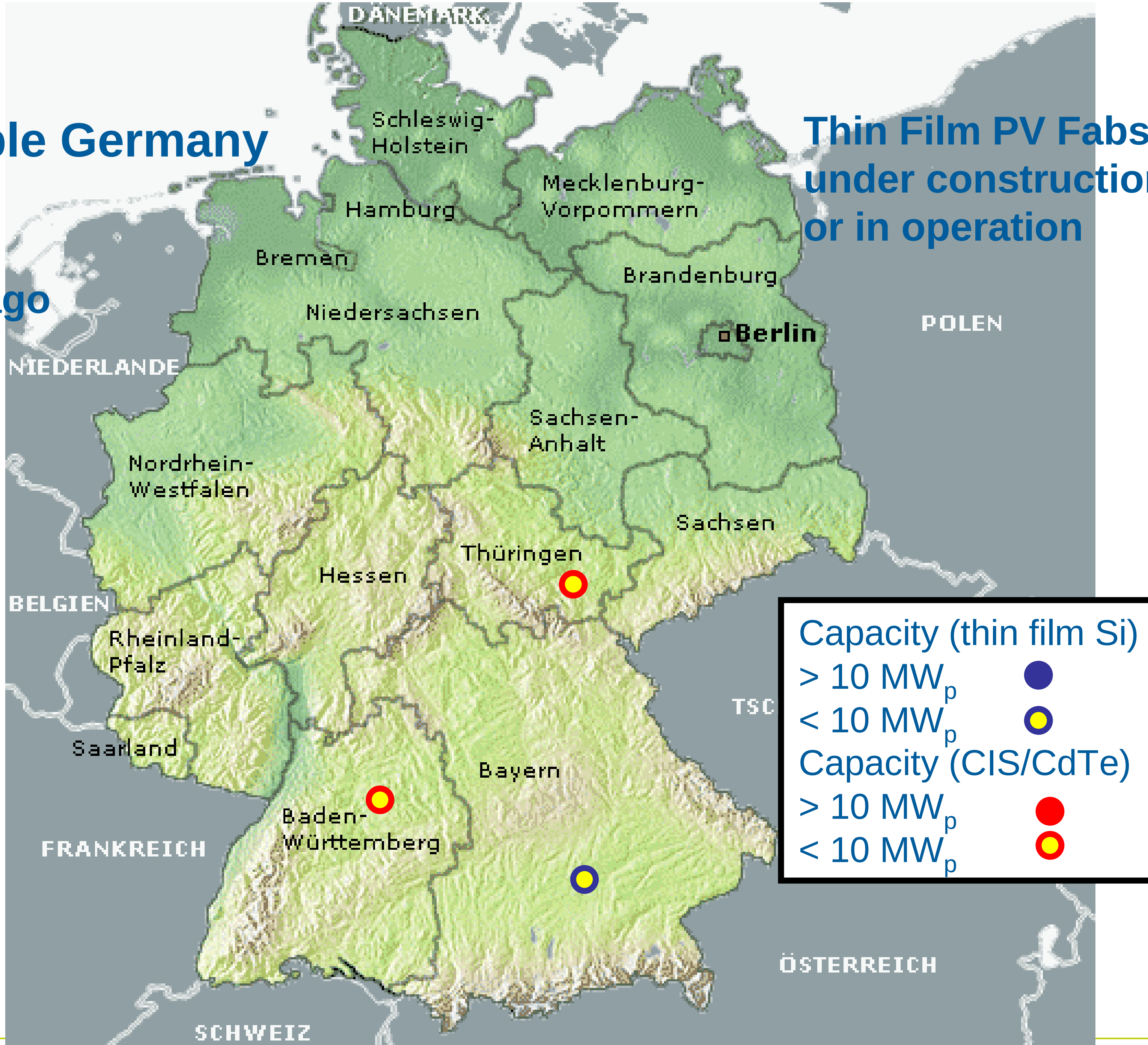
Required:
- **Mass production**
- **Technology development**
- **Fundamental R&D**

Example Germany

a view

years ago

Thin Film PV Fabs: under construction or in operation

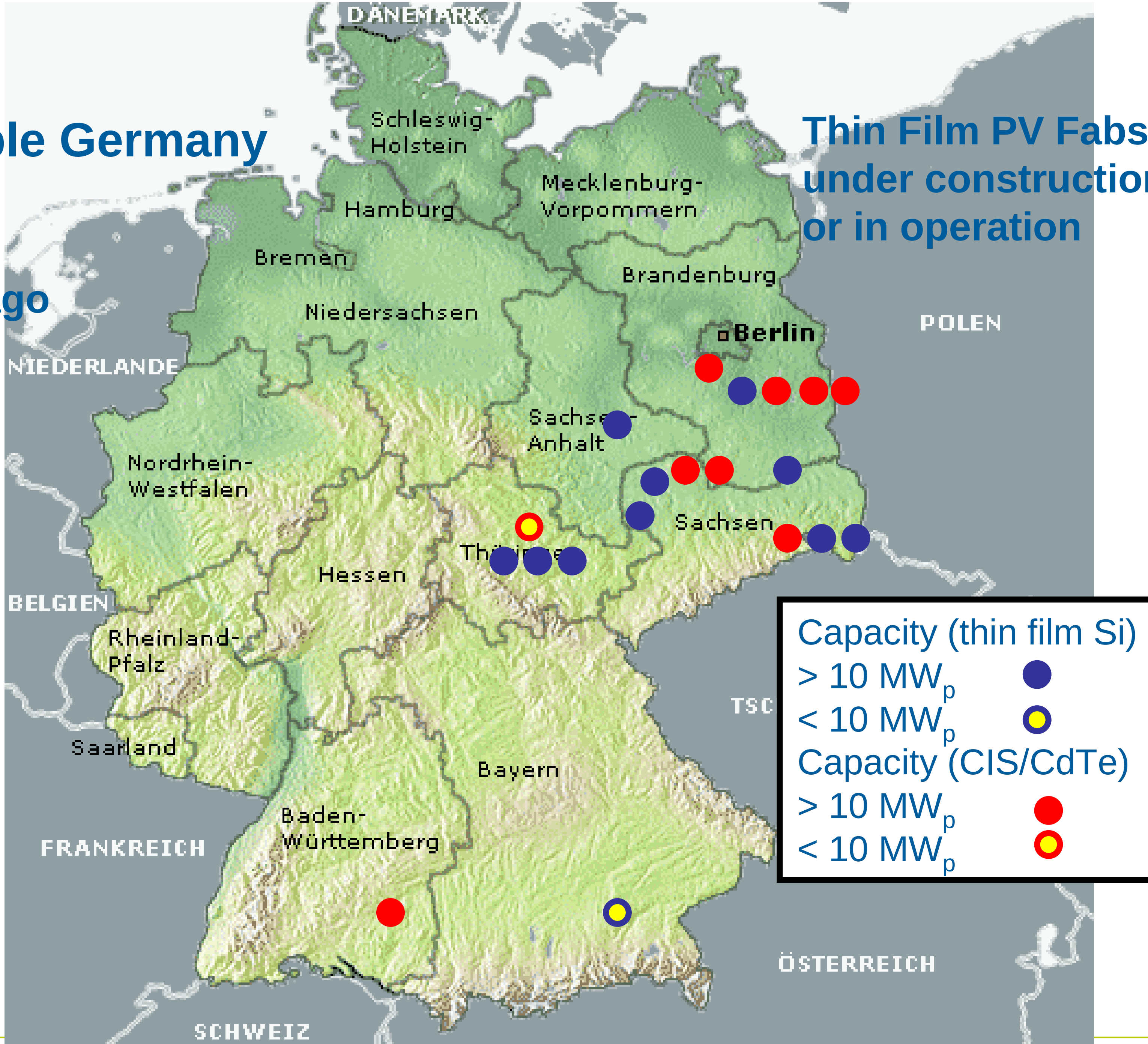


Example Germany

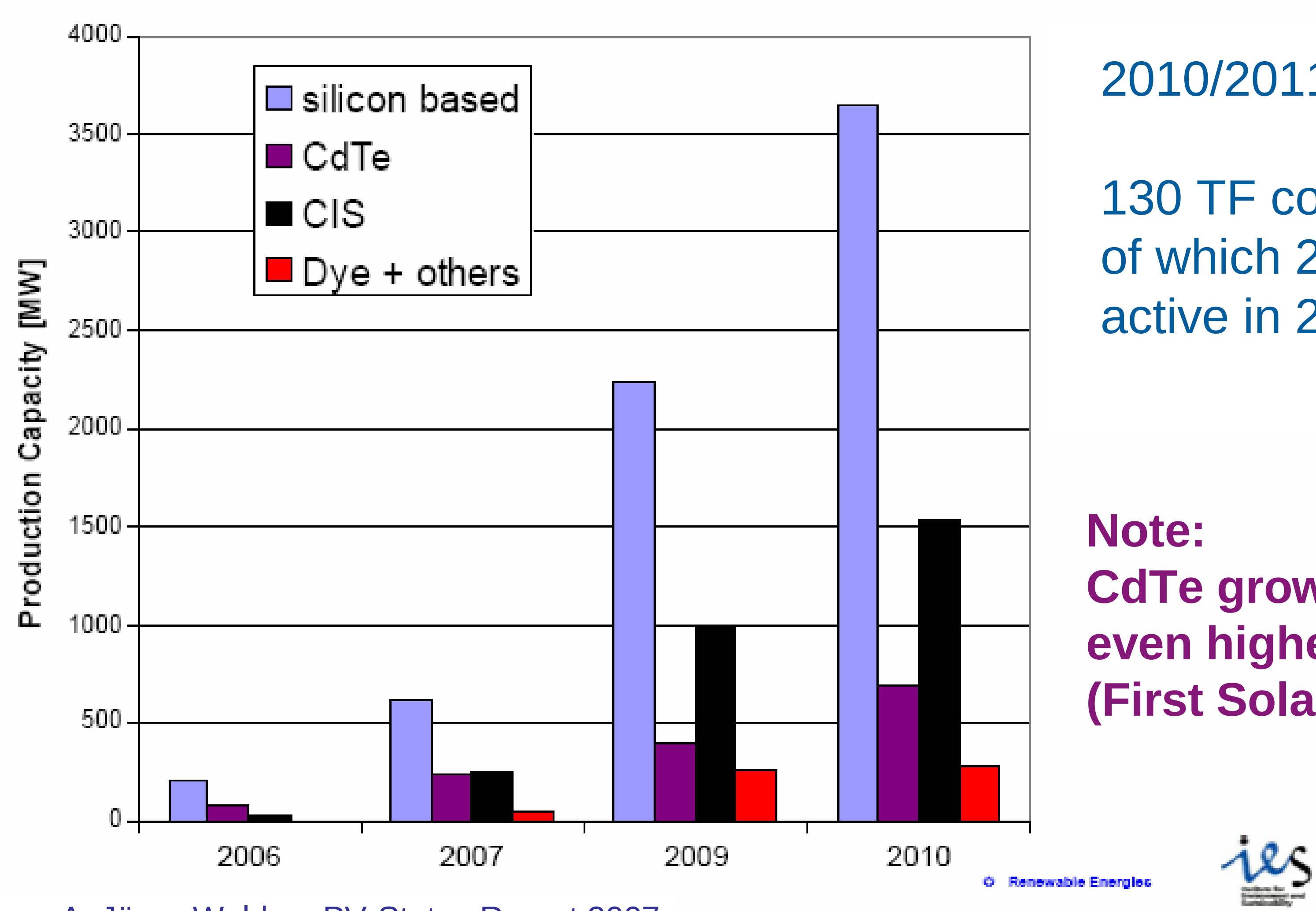
a view

years ago

Thin Film PV Fabs: under construction or in operation



Announced capacity by thin film type - world



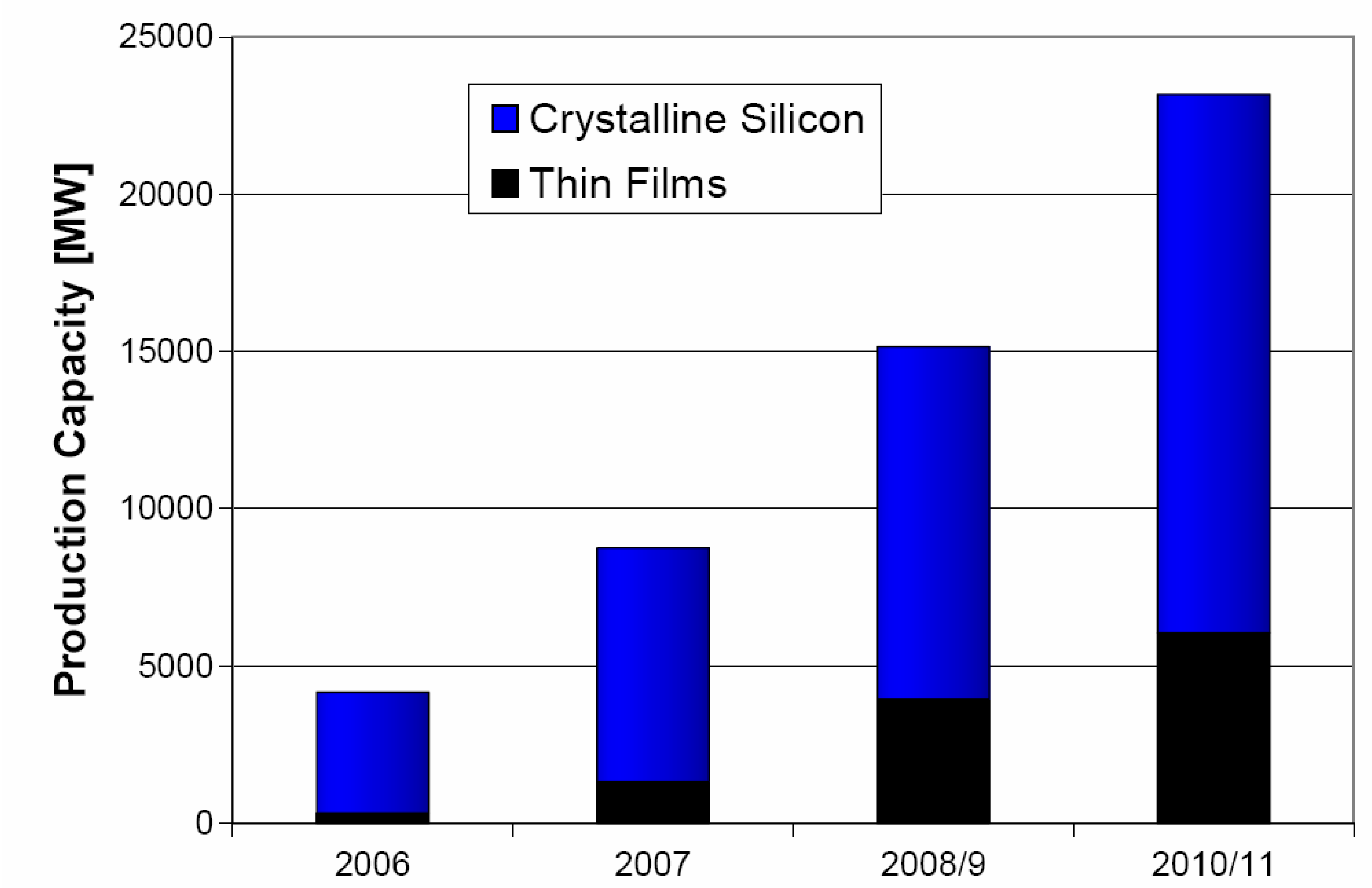
Source: A. Jäger-Waldau, PV-Status Report 2007

2010/2011: 6 GW_p!

130 TF companies of which 21 were active in 2006

Note: CdTe growth even higher (First Solar)

Thin Film vs. Wafer Based Crystalline Si



Quelle: A. Jäger-Waldau, PV status report 2007

Thin-Film PV applications

HELMHOLTZ ZENTRUM BERLIN für Materialien und Energie

Solarpark Buttenwiesen – amorphous silicon
Quelle: Phönix SonnenStrom AG

Gescher-Estern
Entsorgungs-Gesellschaft Westmünsterland (EGW),
put in operation August 2006.
One of the biggest roof-top installations
(1.4 MWp, CdTe, First Solar) 23 430 thin-film modules on an area of ca. 17 000 m² and an investment of € 5.6 Mio.

Source: Reinecke + Pohl Sun Energy AG

BIPV *(3S AG Megaslate* System)

Roof integration – family homes

Würth-Solar CIGS modules

Solar fassade

Optic Center Wales, CIS-Module, 85 kW_P, 2004

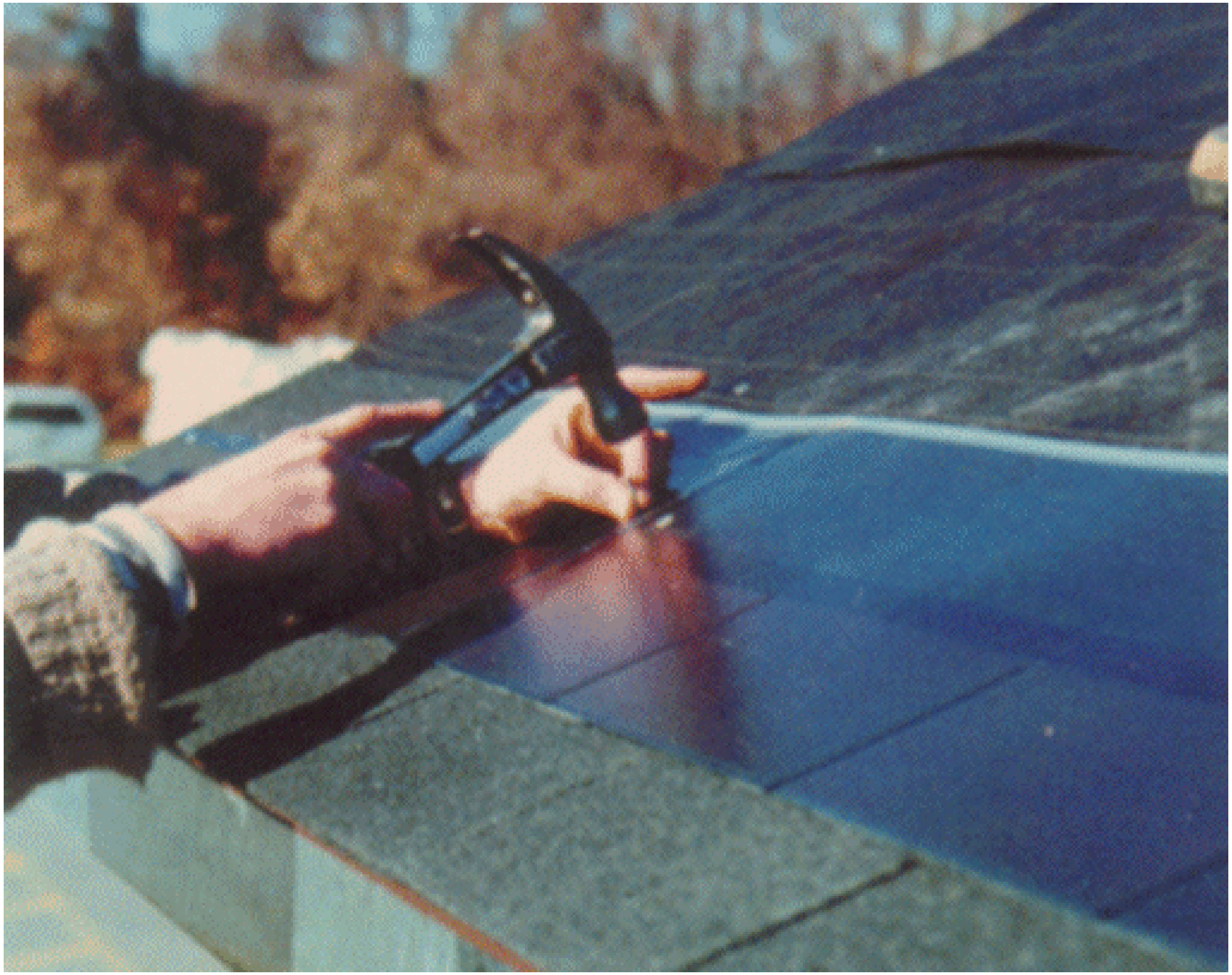
source: AVANCIS (www.avancis.de)

Semitransparent Modules

Schott Solar – a-Si

Würth Solar

Flexible thin-film PV



Source: Unisolar

Flexible thin-film PV

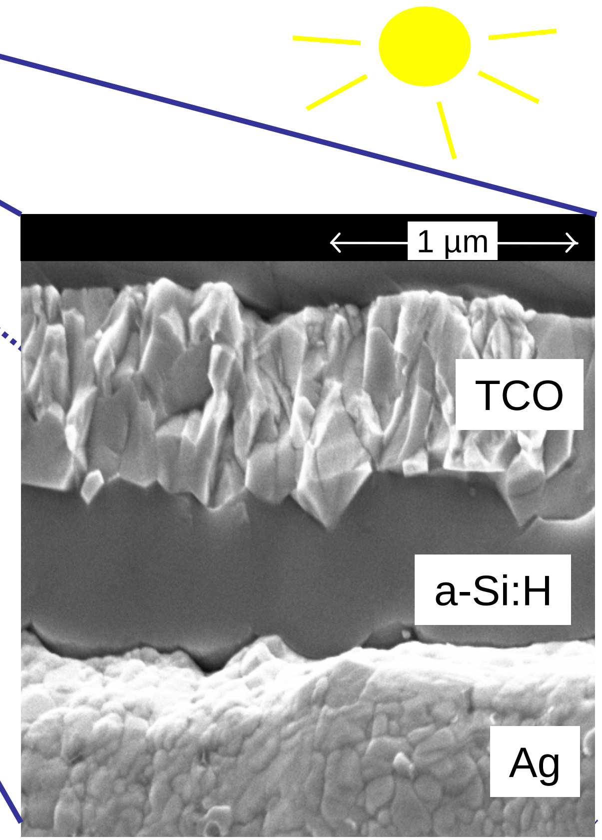
SOLAR INTEGRATED TECHNOLOGIES™

Outline

- Motivation and Background
- Thin Film Solar Cell Technologies and Applications
- **Amorphous Silicon and Microcrystalline Based Silicon and Tandem Cells**
- Poly-Crystalline Si Thin-Films
- R&D Challenges and Conclusions

Amorphous Silicon Based Solar Cells

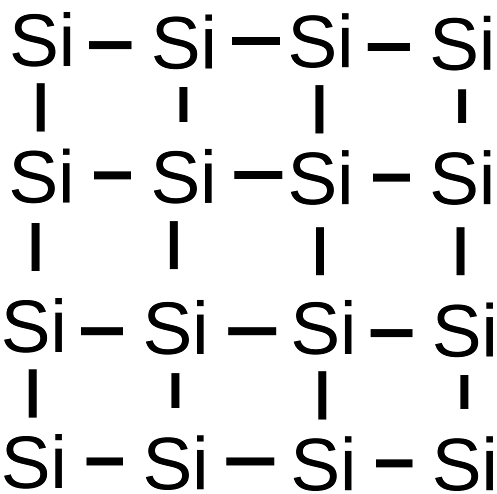
BIPV:
Stillwell Avenue Terminal, New York
ca. 210 kWp, installed 2004
Source: SCHOTT Solar



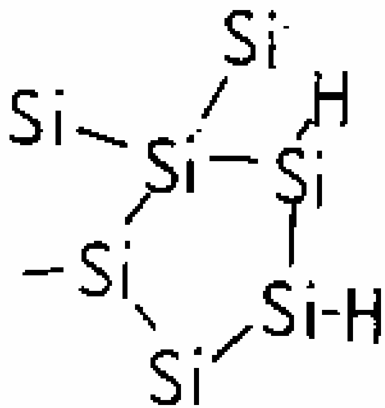
a-Si:H solar cell cross section

Structure of Silicon

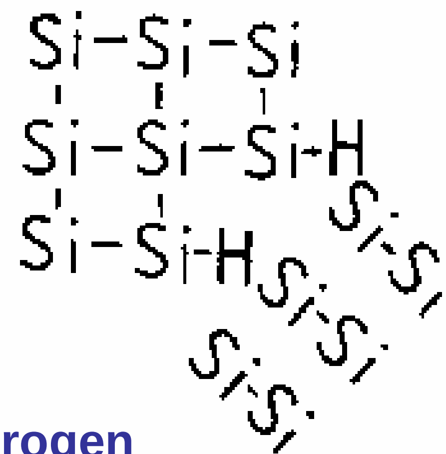
single-crystalline Si
c-Si



amorphous Si
a-Si:H



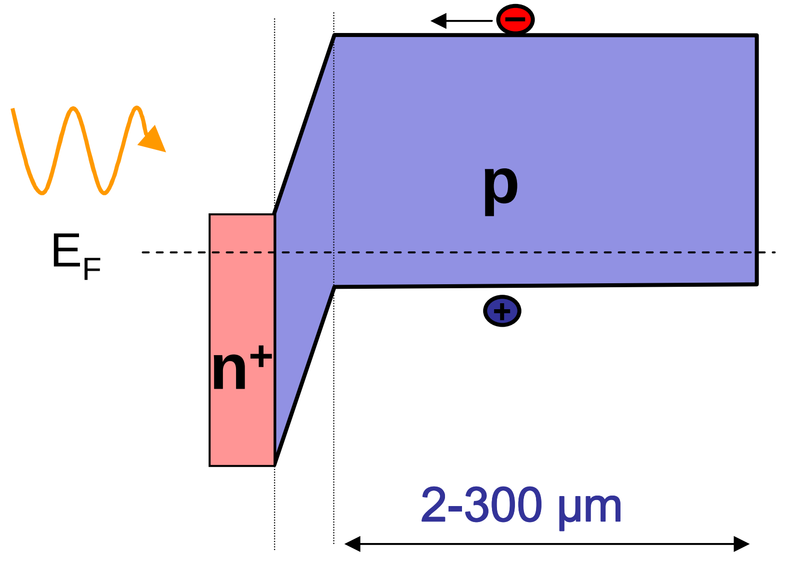
mikro-crystalline Si
(µc-Si:H)



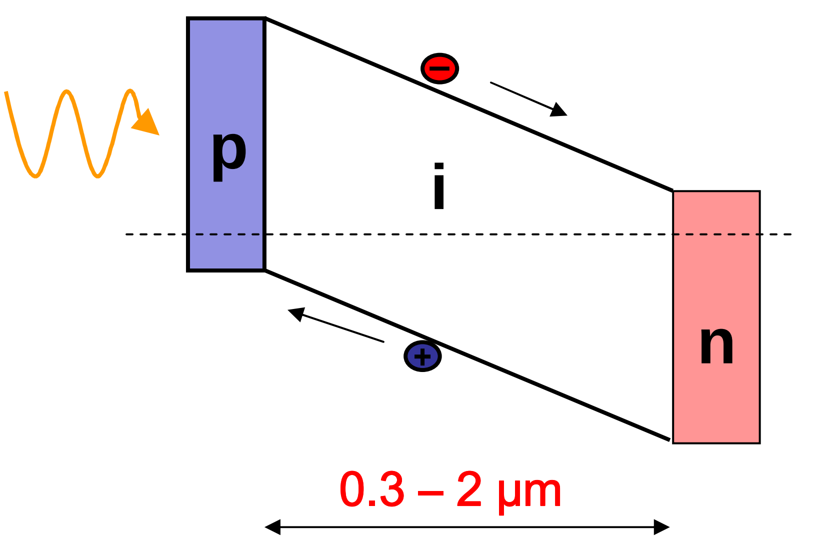
5-15 % Hydrogen

Device Structure of Si Solar Cells

mono- and poly c-Si



a-Si:H, µc-Si:H



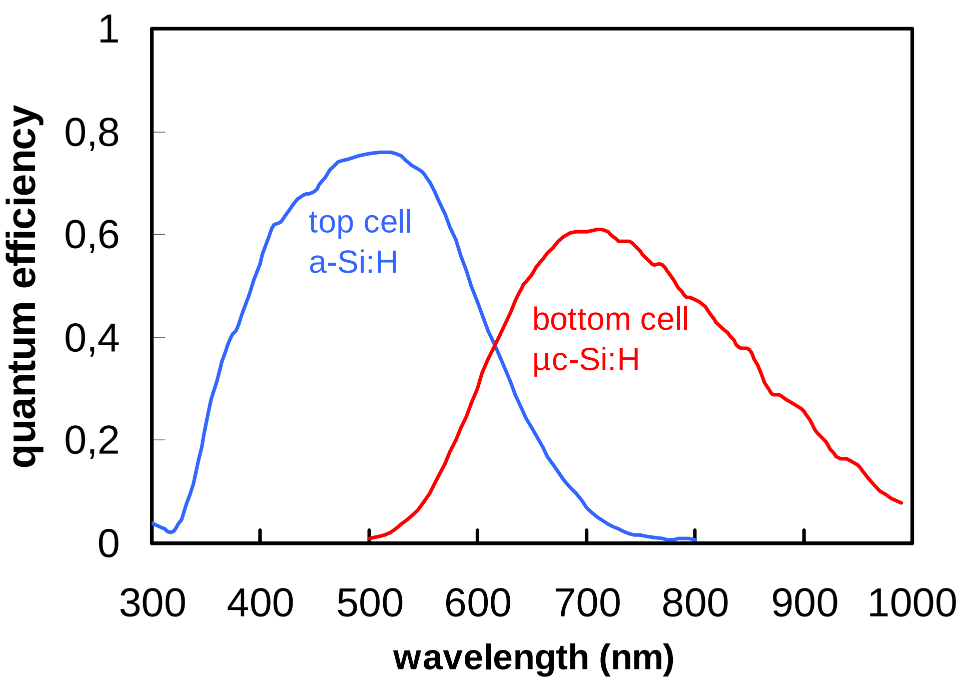
"diffusion controlled"
"interface limited"

"drift controlled"
"bulk limited"

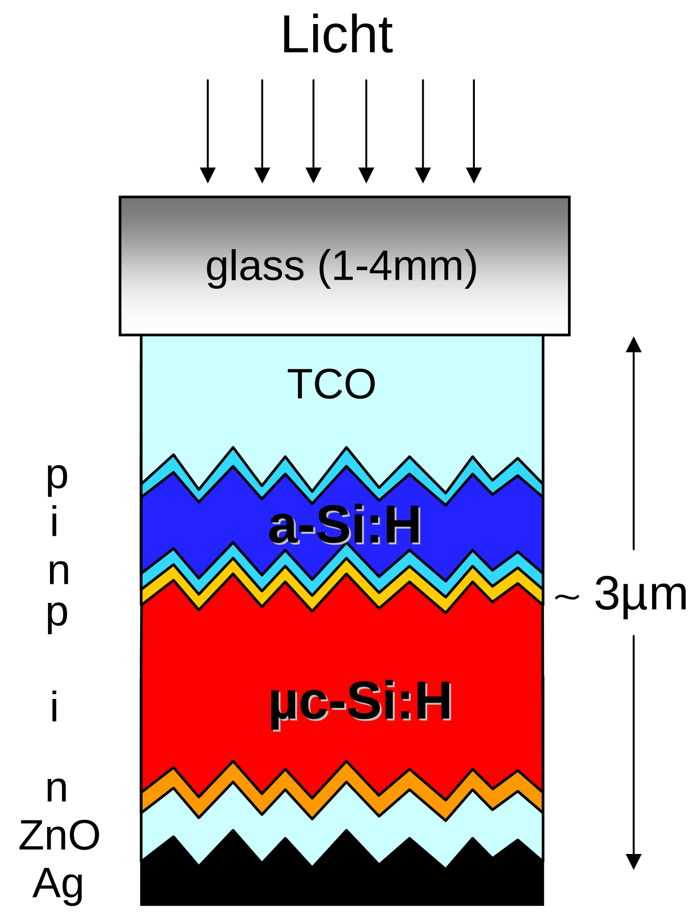
Microcrystalline Silicon (µc-Si:H)

Advantages and challenges:

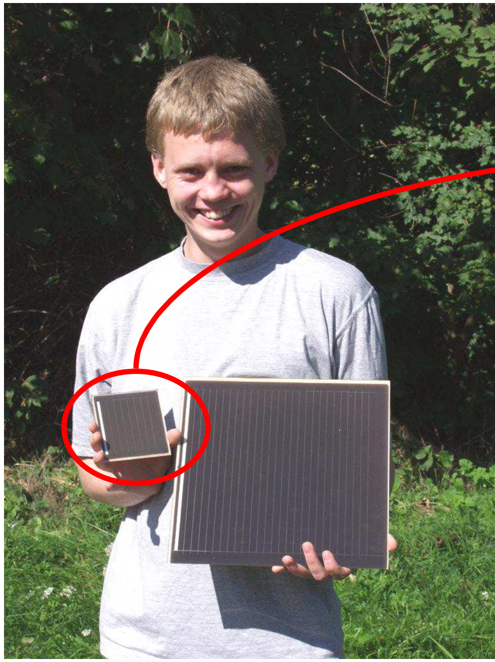
- „red/IR-response“ µc-Si:H
- no/small SWE ⇒ high stability
- preparation with PECVD
- indirect semiconductor: light trapping!
- high growth rate and process control!



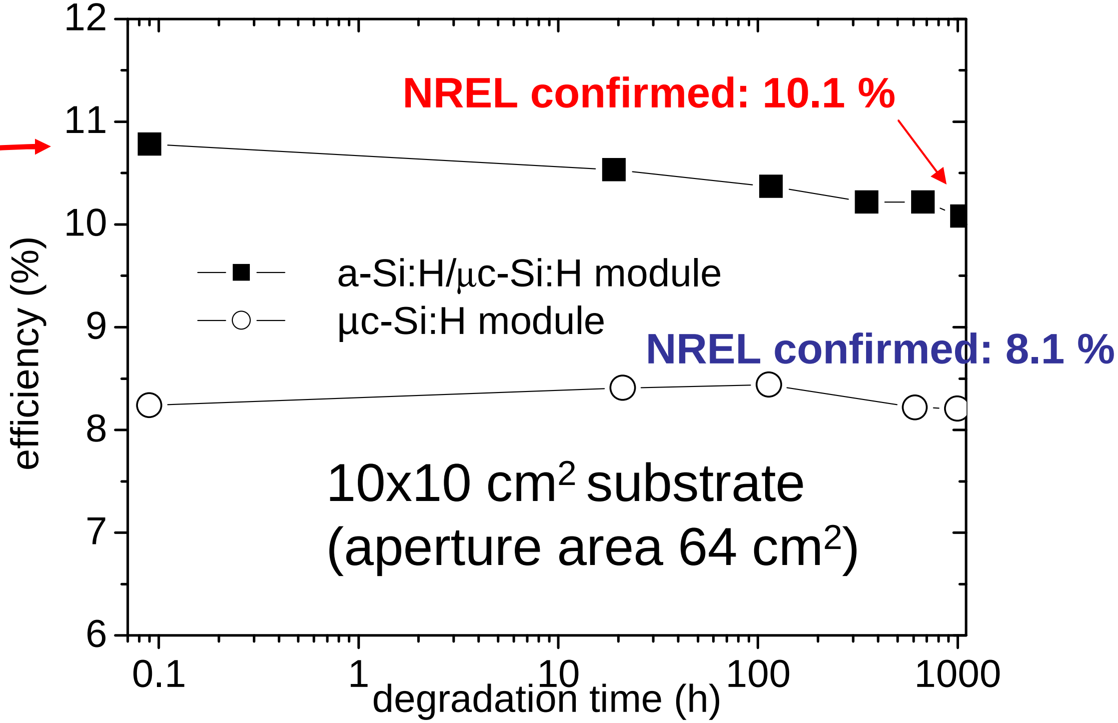
a-Si/µc-Si tandem cell



pioneered by University of Neuchatel 1994
see: Uwe Rau next talk, tomorrow
first solar modules by Kaneka, J (2001)



source: FZ-Jülich

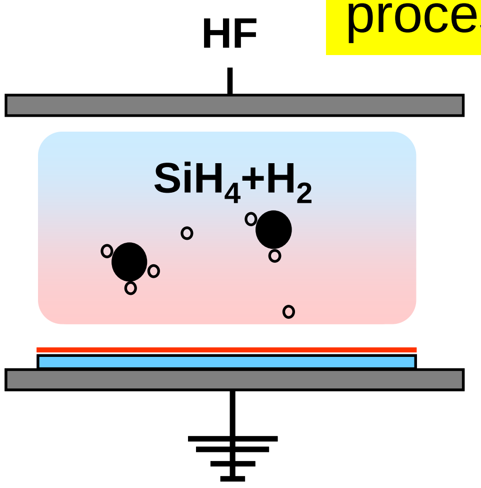


BR et al. TSF 2006

Silicon growth by PECVD

(plasma enhanced chemical vapour deposition)

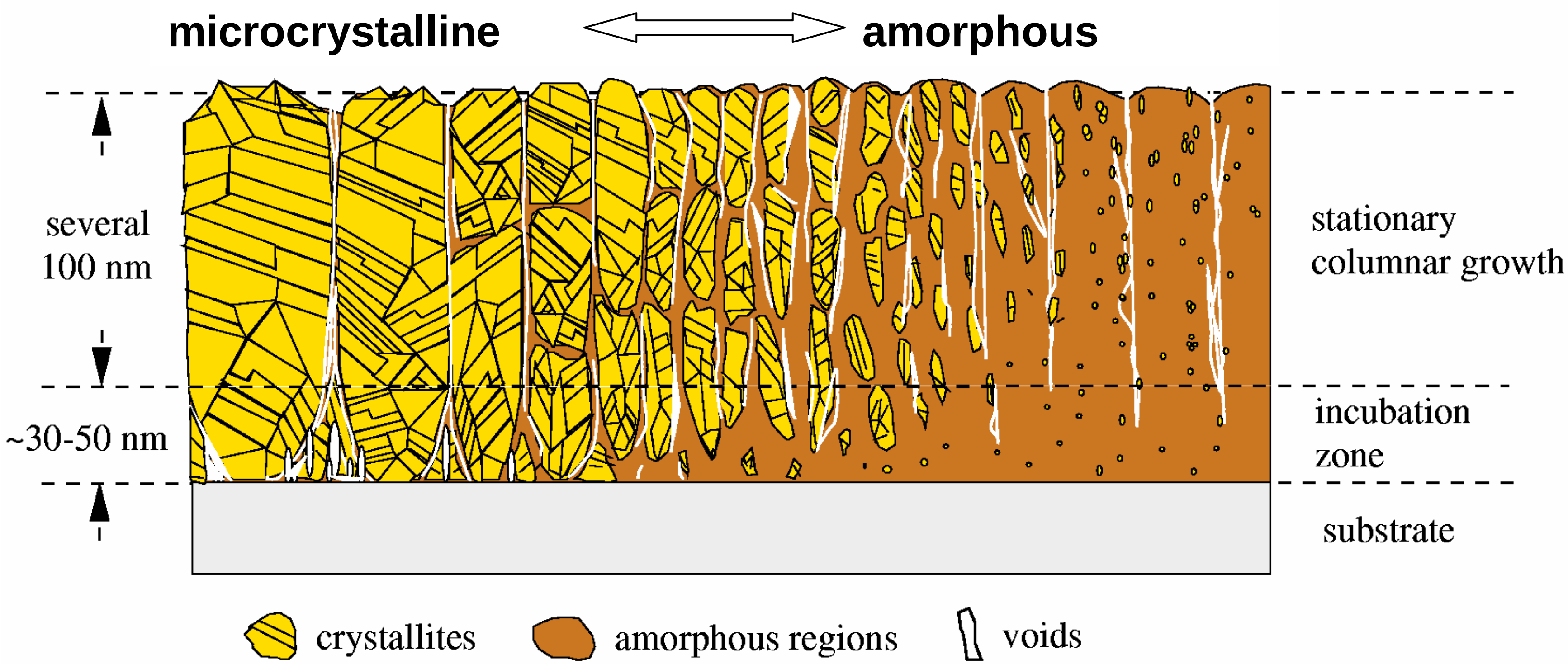
process parameters: amorphous ⇔ µ-crystalline growth



- SiH_4 / H_2-gas flow ratio
- Pressure,
- RF power,
- Excitation Frequency
- Substrate temperature
- ...

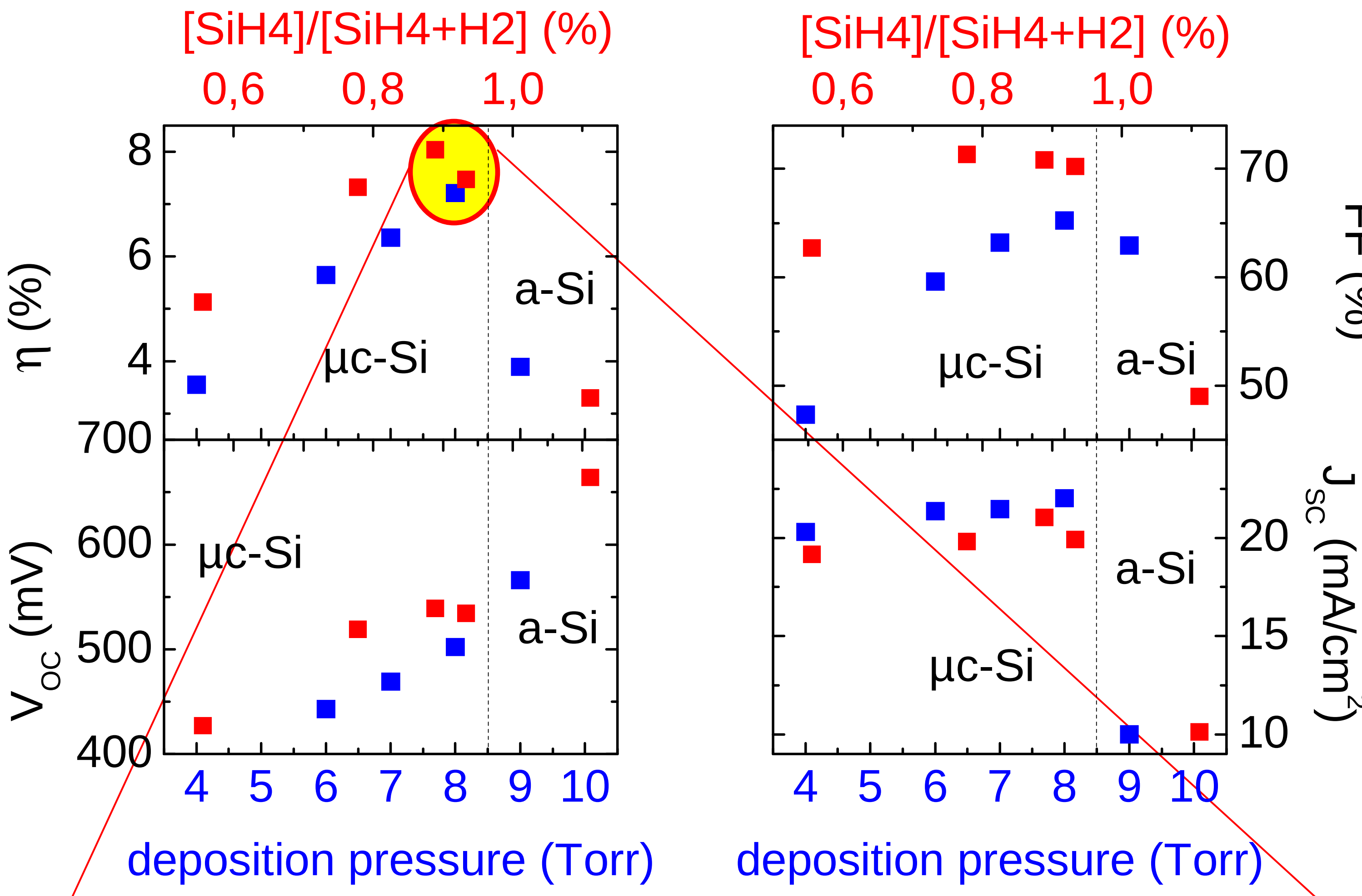
source: FZ-Jülich

Structure of µc-Si:H



L. Houben, Dissertation, FZJ (IFF/IPV), Uni Düsseldorf
O. Vetterl et al., Sol. Energ. Mat. Sol. Cells 62 (2000) 97-108

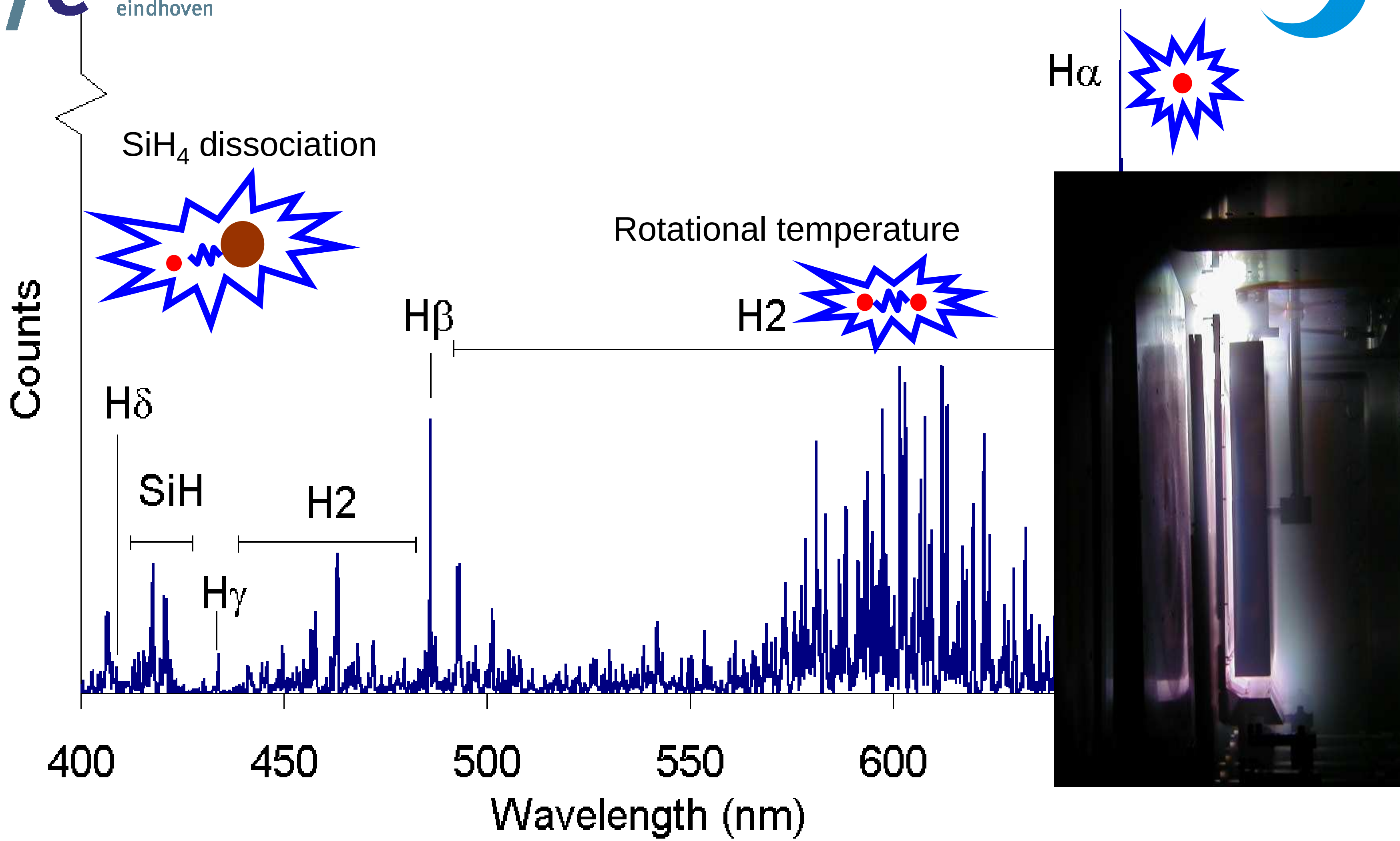
µc-Si:H Solar Cell Process: 13.56 MHz Regime



very narrow process window for optimised µc-SI:H

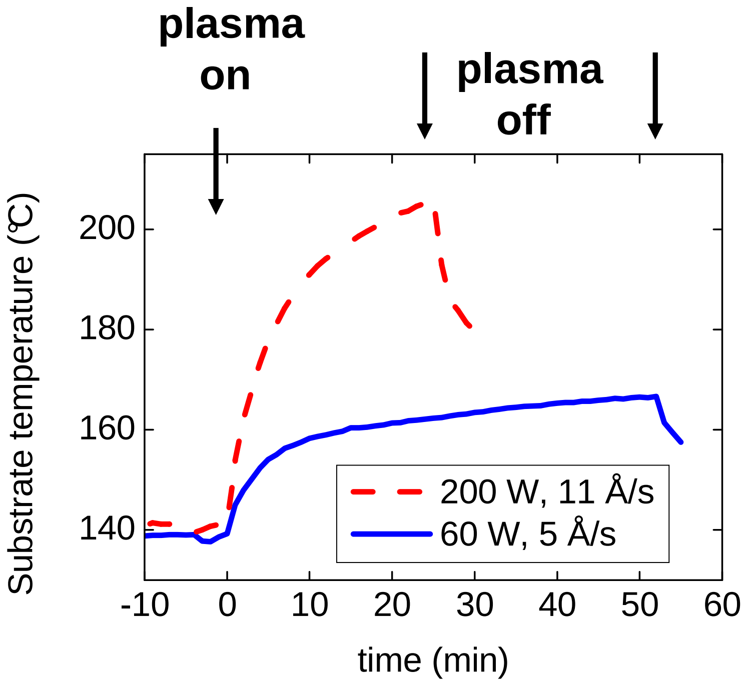
BR et al, TSF 2003

Optical Emission Spectroscopy (OES)

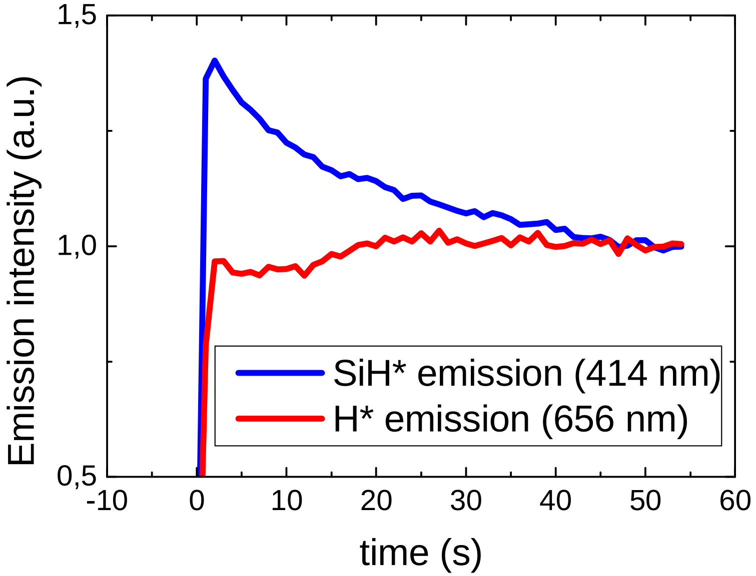


µc-Si:H – control of film growth

Plasma-induced substrate heating

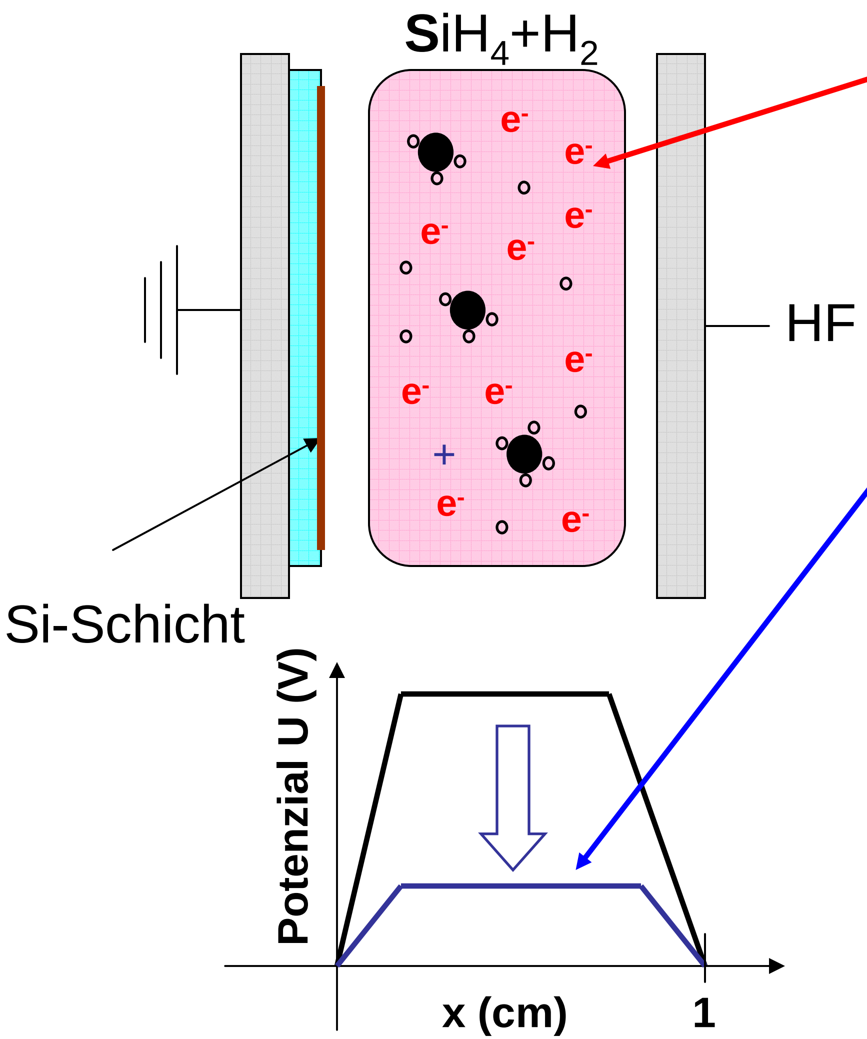


Amorphous growth conditions @plasma start



M.N. van den Donker et al., TSF 2006

Summary: µc-Si:H Process Conditions



- **high power**
  - ⇒ high plasma density (n_e)
  - ⇒ high growth rate
- **high pressure**
  - ⇒ low plasma potential
  - ⇒ low ion bombardment
  - "soft" deposition

very narrow process window
and drift of the plasma properties during growth*!
⇒
up-scaling extremely challenging !

*** see PL0001 van de Sanden et al.**

BR et al, TSF 2006

a-Si:H/µc-Si:H: From laboratory towards production

Joint development:
Applied Materials, Sontor, FAP, FZJ

Goal:
cost-effective production technology for highly efficient solar cells

>1 m^2

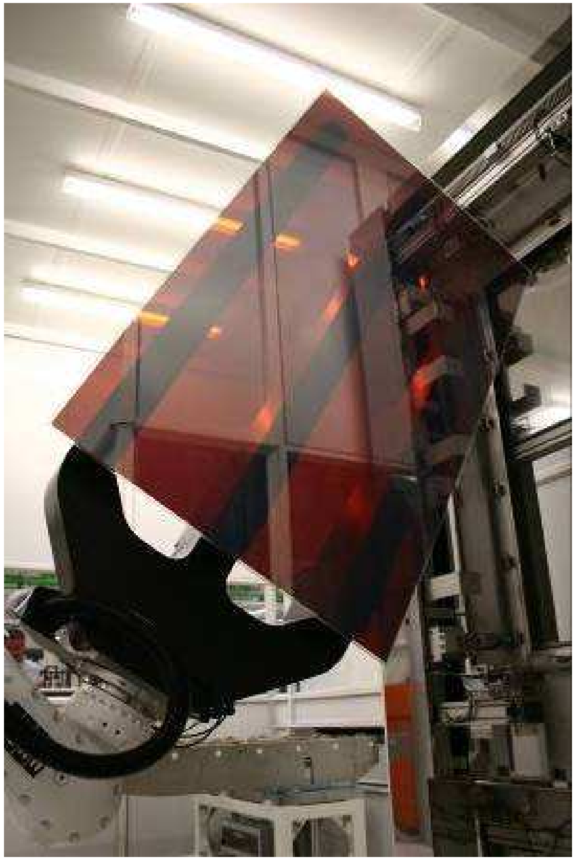
30 x 30 cm^2

Starting point

10 x 10 cm^2

Development@IPV, FZ-Jülich

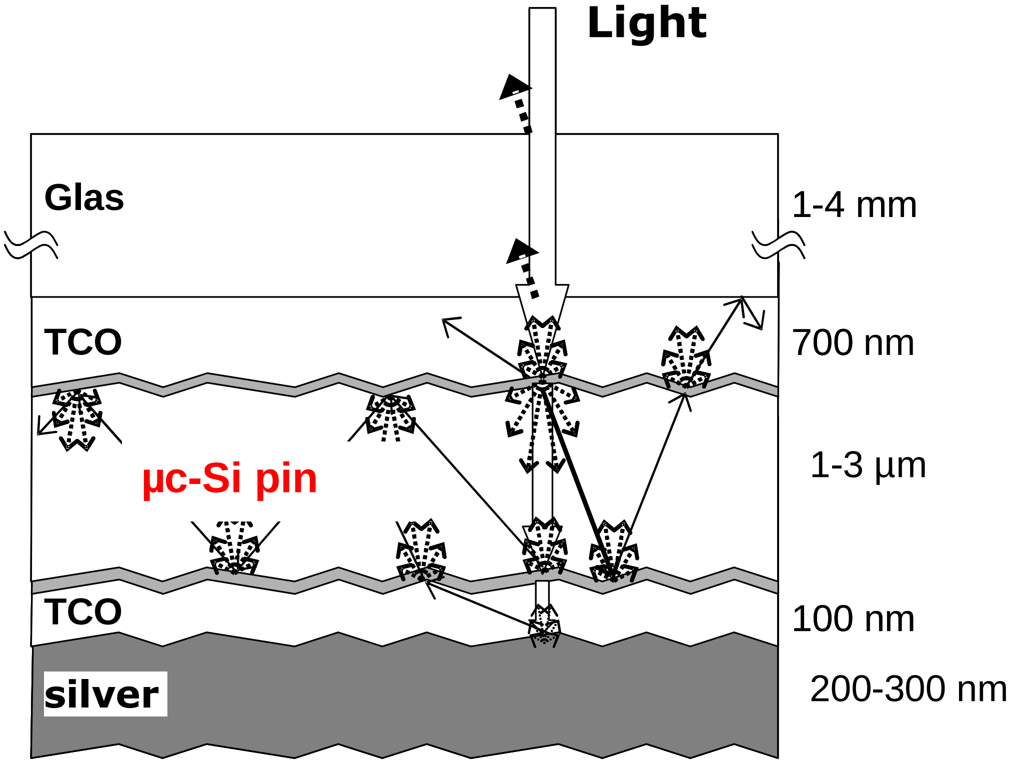
Successful Scale-Up @ Sontor

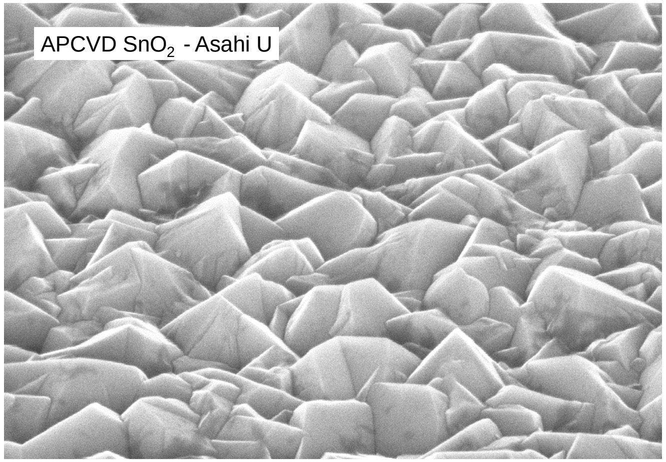


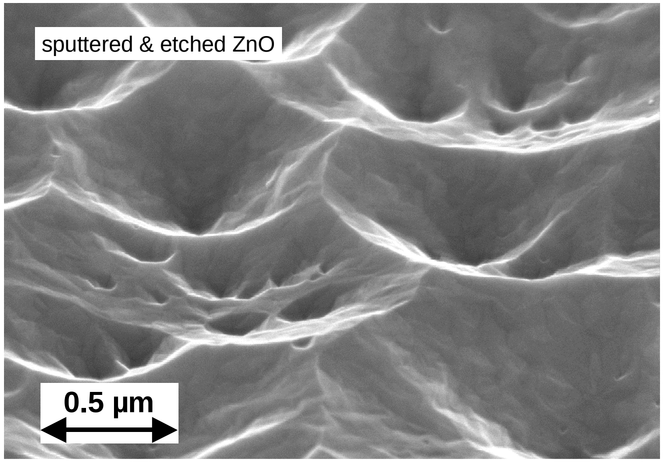
Module size: **1.8 m²**
Status: ~7.5 % (stab. tot. area) production average

sontor

„Light-Trapping“ by Surface-Textured ZnO





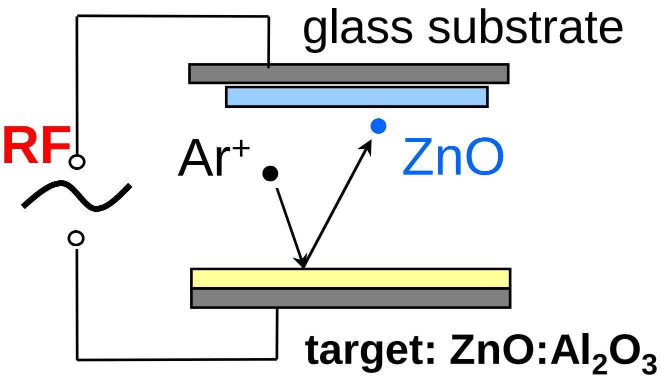


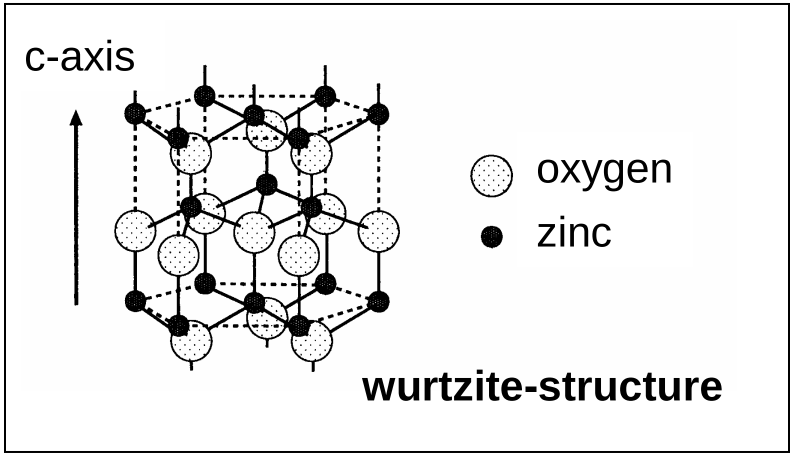
source: FZ-Jülich

Sputtered ZnO:Al Films as Front TCO

Sputter techniques:

- rf/dc ceramic targets
- mf metallic targets, high rate





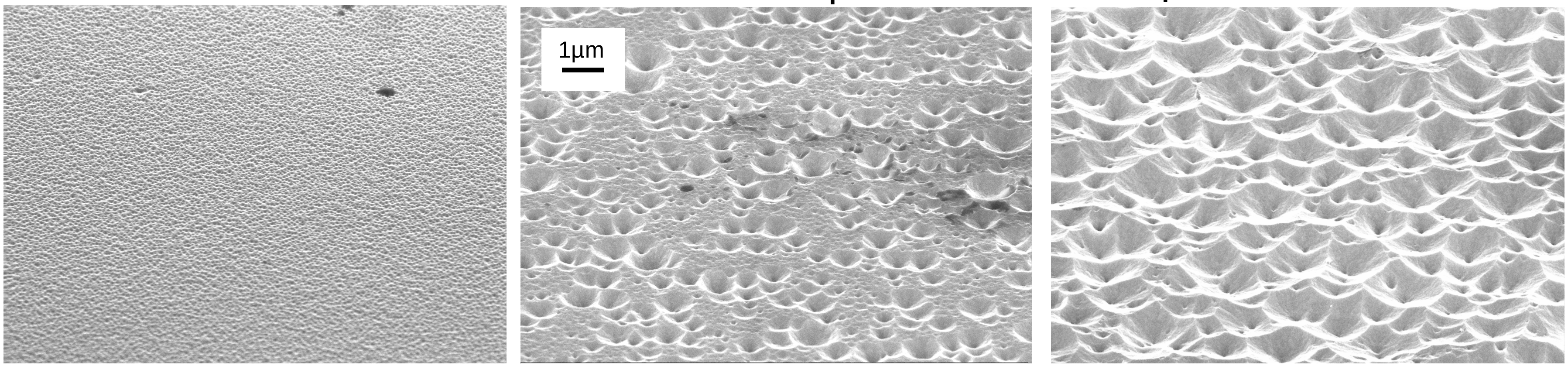
Properties of ZnO:Al

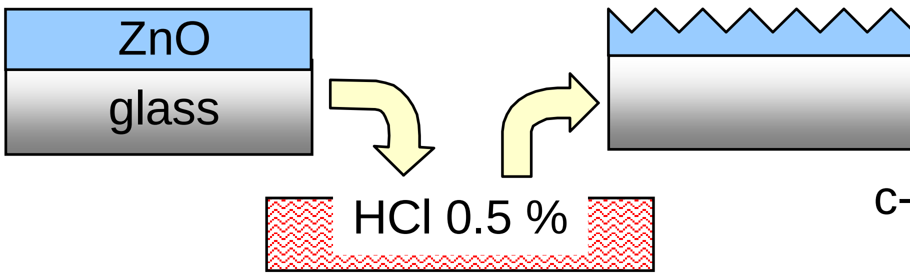
- highly transparent & conductive
- c-axis oriented
- resistant against H_2-plasmas
- smooth surface

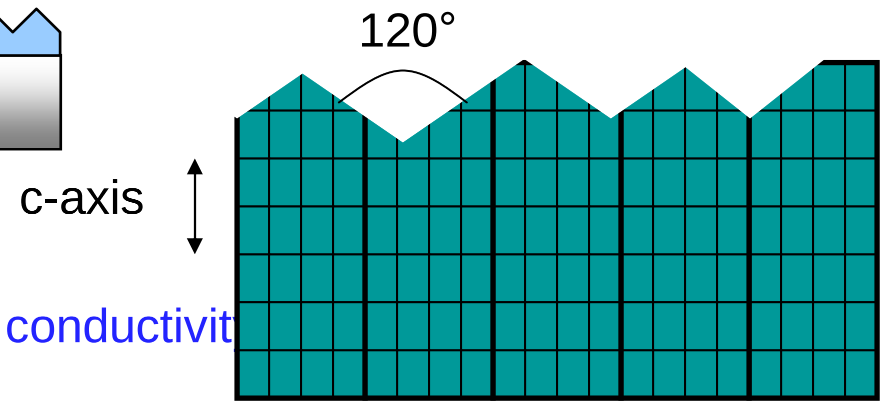
• surface-texture by etching (depends on initial film properties!)

Optimised ZnO for Si Thin-Film Solar Cells

smooth | short dip | optimised texture





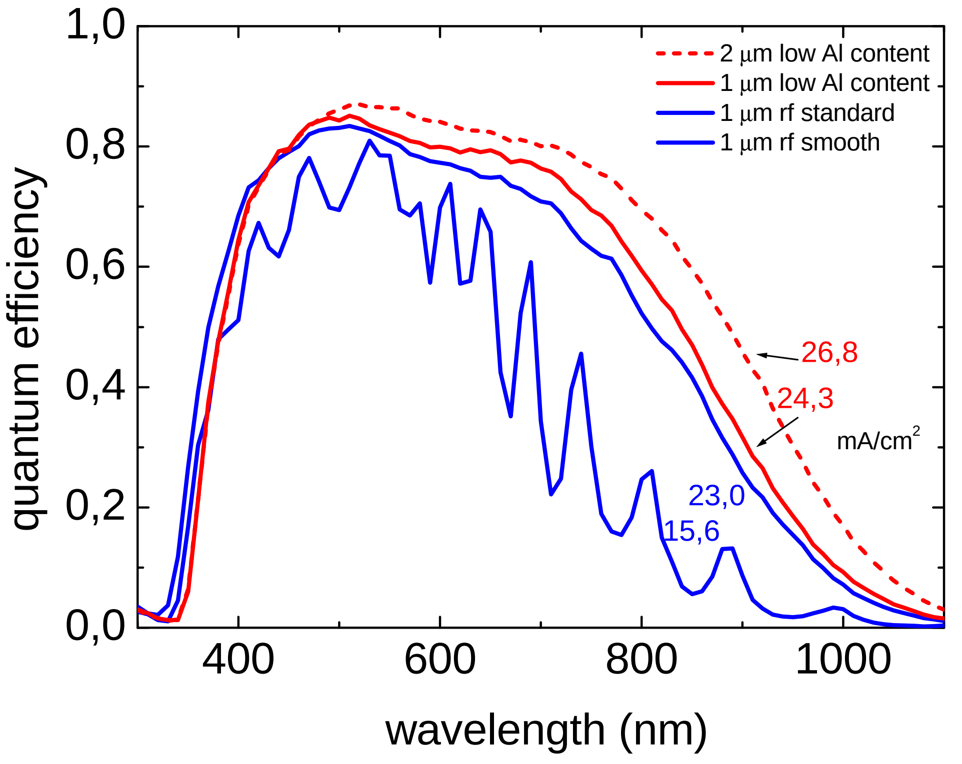


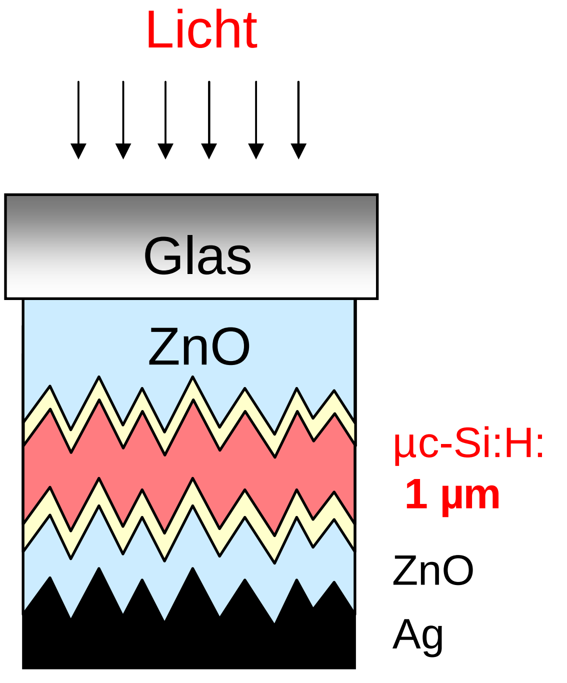
Schematic cross section

- δ_{rms} up to 150 nm, high transparency and conductivity
- crater size 100-2000nm
- cristallite size δ < 50 nm
- phenomenologic model (Kluth et al. TSF, 2003)

microscopic model?

"Light Trapping" in µc-Si:H Solarzellen





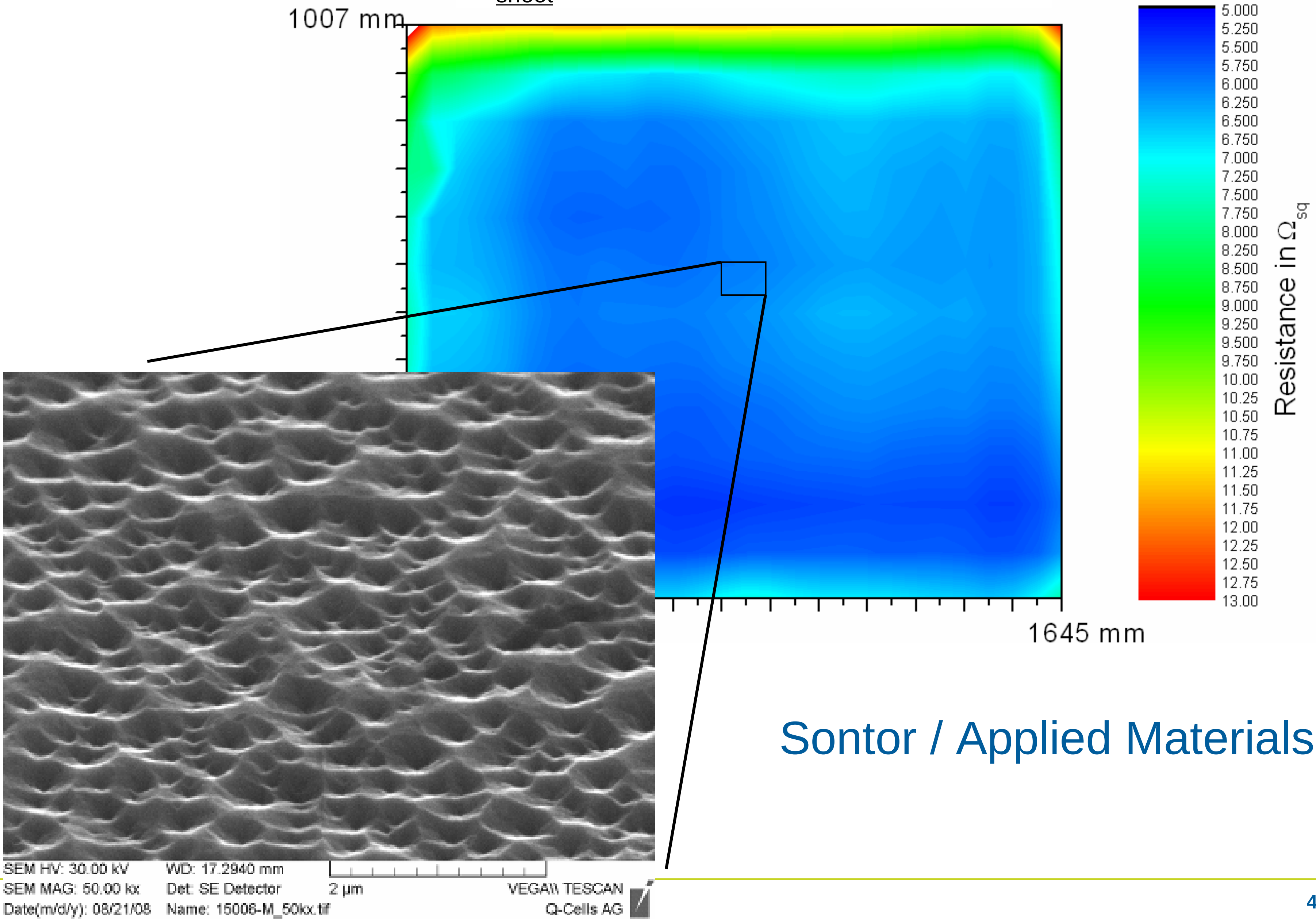
Tailor-made surface roughness and surface features ⇒

- AR-effect by index-matching
- efficient light trapping for long wavelength light
- low free carrier absorption

B R et al. TSF, 2006

Large Area Surface-Textured ZnO

R_{sheet} after etching:

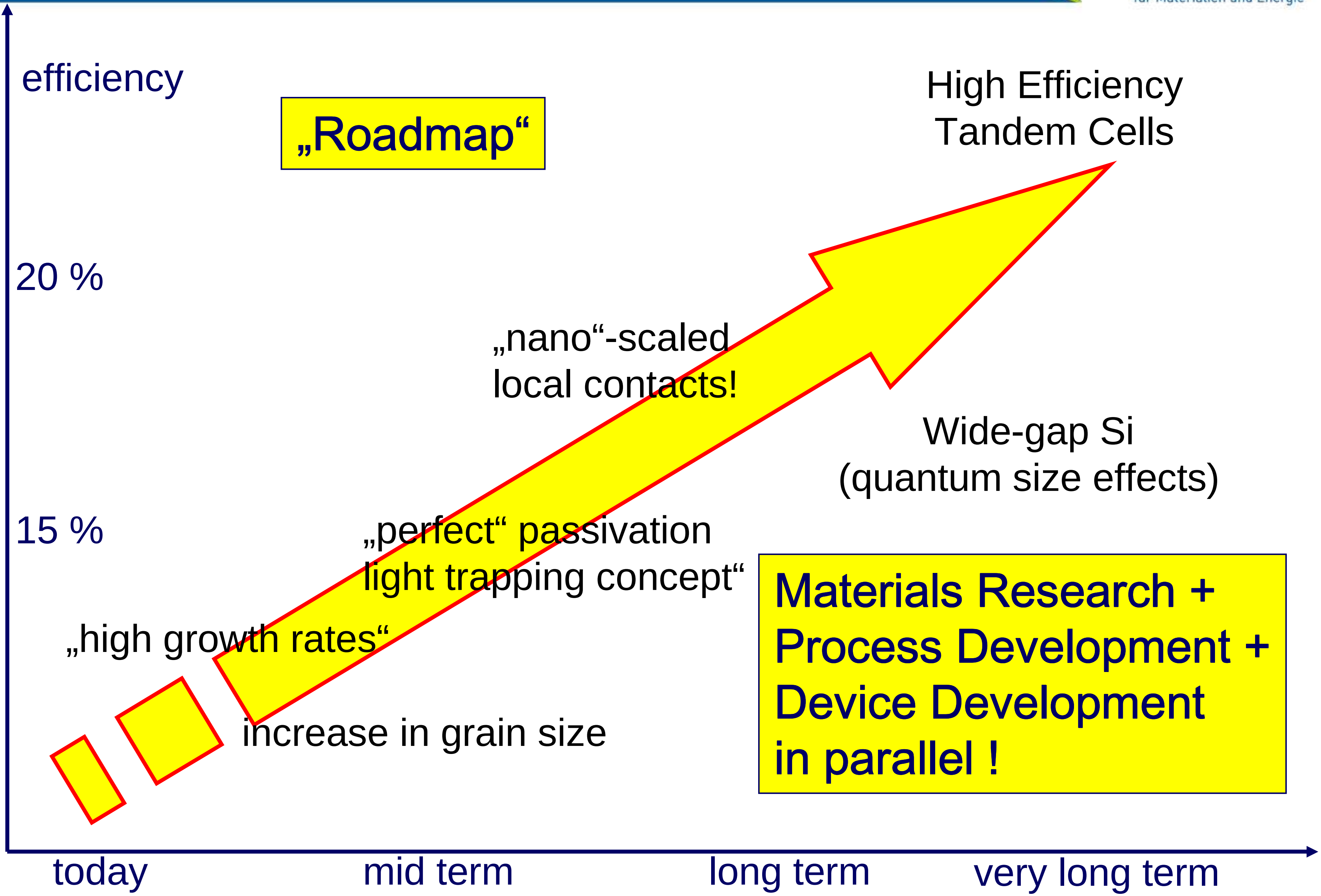


Sontor / Applied Materials

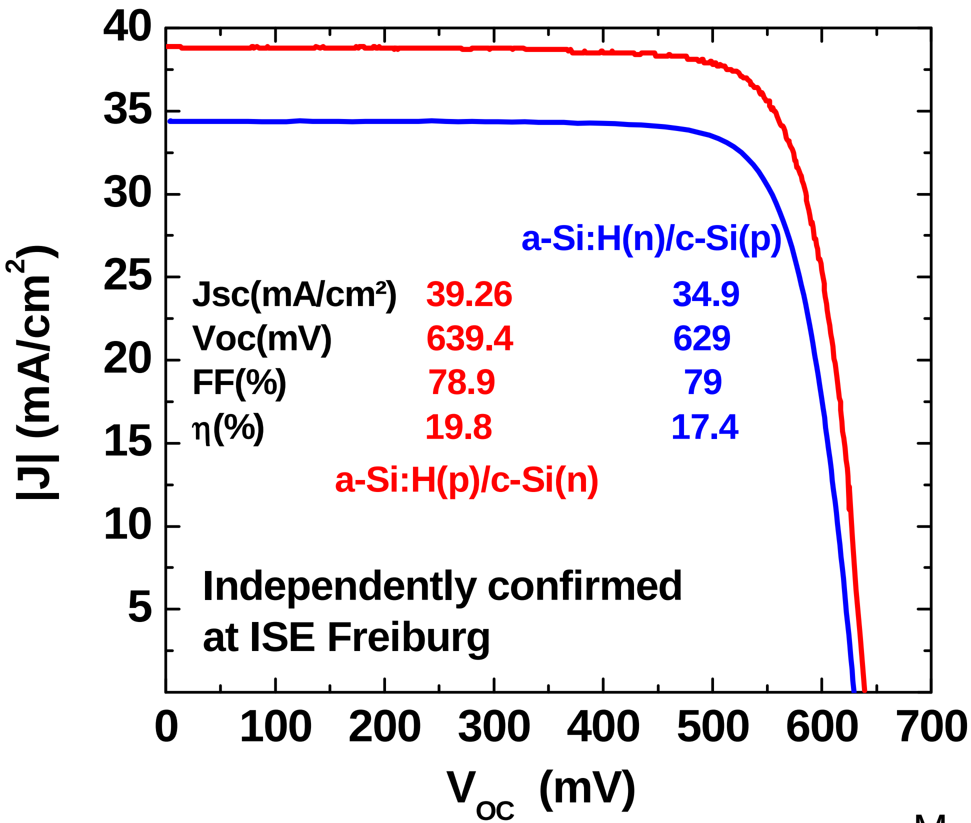
Outline

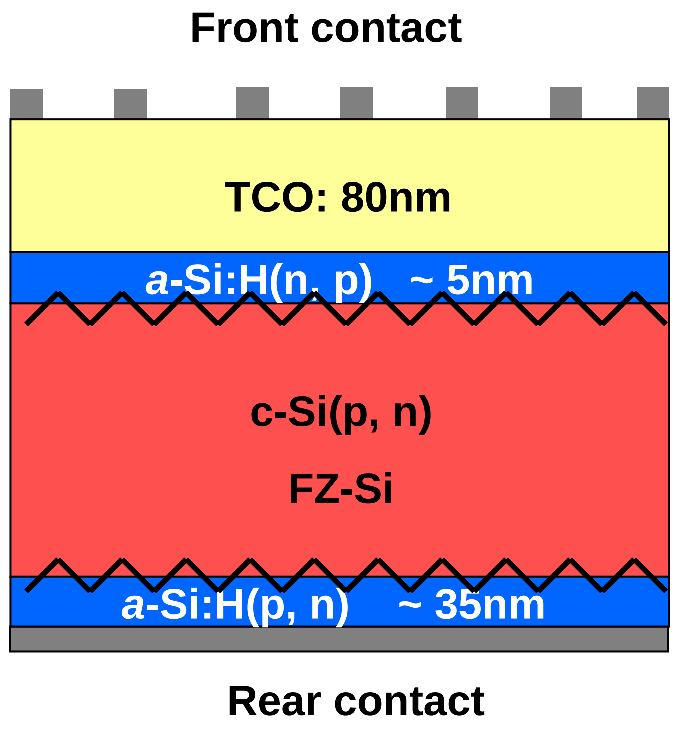
- Motivation and Background
- Thin Film Solar Cell Technologies and Applications
- Amorphous Silicon Based Solar Cells
- Microcrystalline Silicon and Tandem Cells
- **Poly-Crystalline Si Thin-Films**
- R&D Challenges and Conclusions

Towards High Efficiency Thin Film Si Solar Cells



a-Si:H / c-Si Wafer Based Cells

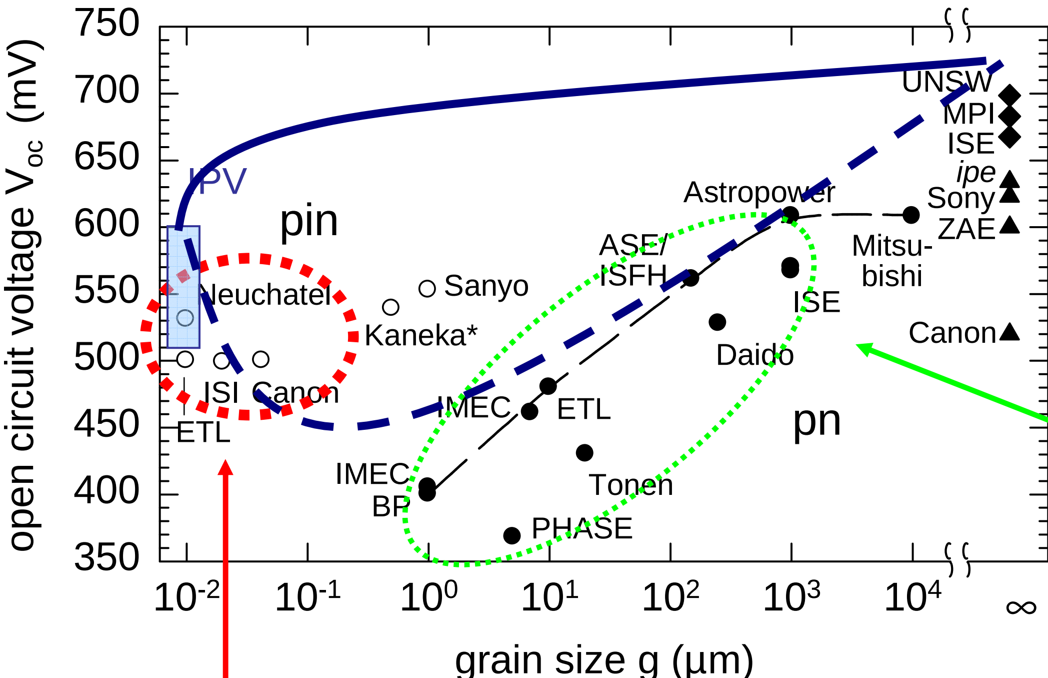




M. Schmidt et al. TSF 2007

a-Si(n)/c-Si(p)/a-Si(p)	Pyramids	17.4 %	629 mV	34.9 mA/cm²	1 cm²
a-Si(p)/c-Si(n)/a-Si(n)	Pyramids	19.8 %	639 mV	39.3 mA/cm²	1 cm²

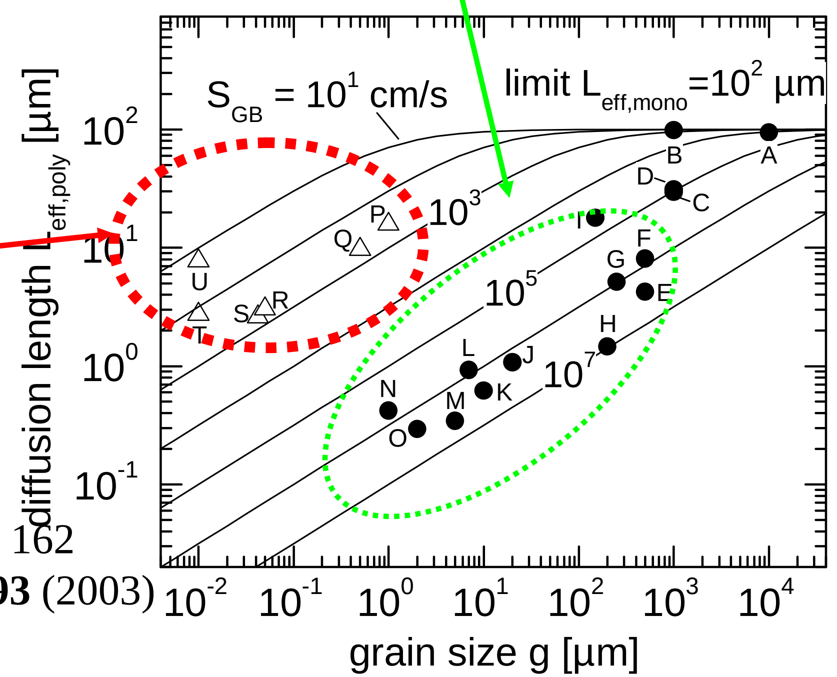
Note: Record efficiencies of these cell type > 22 % by Sanyo



single crystalline

Recombination @ grain boundaries

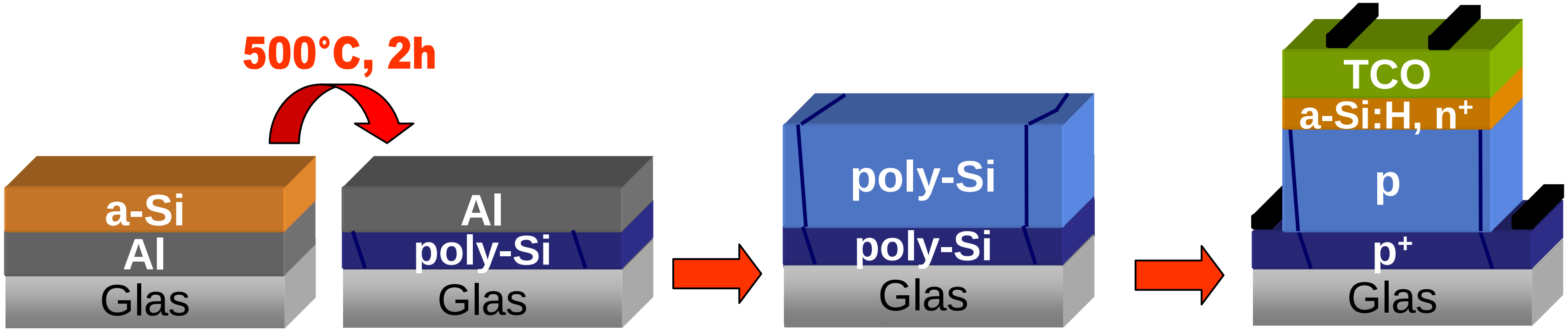
well passivated grain bounderies



R. Bergmann, J.H. Werner, TSF 202-204 (2002) 162

K. Taretto, U. Rau, J.H. Werner, J. Appl. Phys. **93** (2003)

Poly Si thin film @ HZB



Seed layer concept
Aluminium-induced layer exchange
(ALILE)

Epitaxial growth
of absorber layer
by high rate deposition
(e.g. E-Beam evaporation)
Growth rate >1.2µm/h

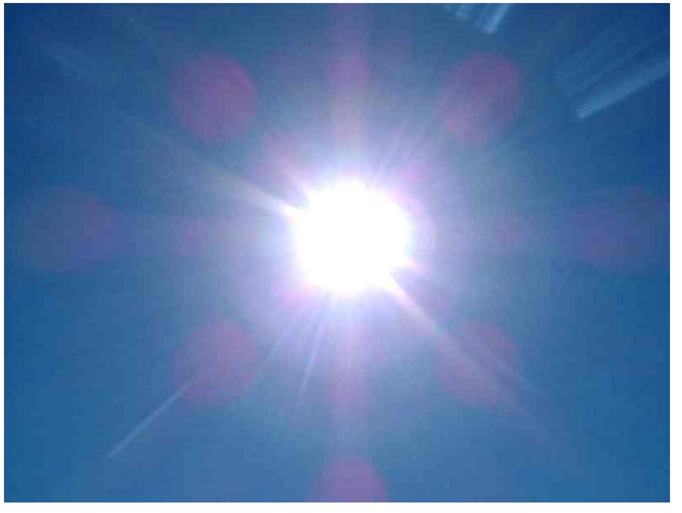
solar cell
processing

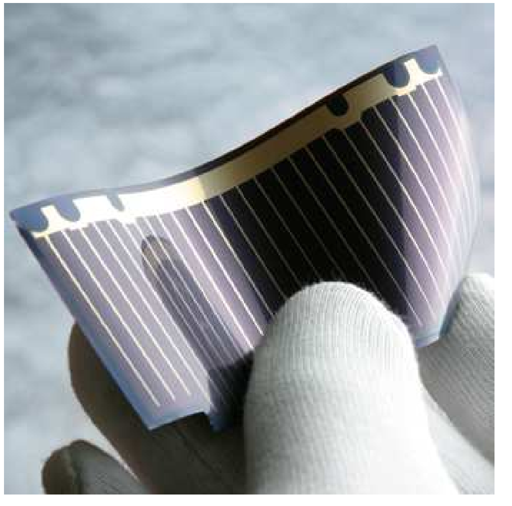
Alternative Pathes:

- solid phase crystallisation (first product by CSG Solar)
- laser crystallisation
- E-beam crystallisation

Outline

- Motivation and Background
- Thin Film Solar Cell Technologies and Applications
- Amorphous Silicon and Microcrystalline Based Silicon and Tandem Cells
- Poly-Crystalline Si Thin-Films
- **R&D Challenges and Conclusions**





Technology Value Chain

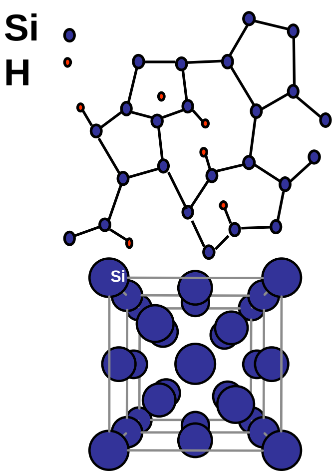
In Thin-Film PV

Solar module development:
From materials via devices towards complete systems

Application in systems

Large area industrial processing

Solar cells and prototypes



Fundamental Material properties

…and „vice versa“ problems from application $\Rightarrow$ applied and basic R&D

Goals for applied and fundamental R&D prerequisites to realise the production roadmap!

	2008-2013	2013-2020
Prototype/test modules	Demonstrate η > 12%	**Concept for η > 15 %**

hot topics

- **Large area PECVD (high rate, process control)**
- **Alternative techniques for absorber deposition**
- **Quantitative understanding of materials interfaces and device**
- **improved/new materials (e.g. µc-SiGe,SiC,…)**

- **New deposition reactor concepts (very high growth rates, full gas usage)**
- **Incorporate quantum or spectrum-converting effects**
- **Combine thin-film Si with other PV technology**
- **Understand fundamental limitations of thin-film Si**

source: Strategic Research Agenda for PV (PV Technology Platform)

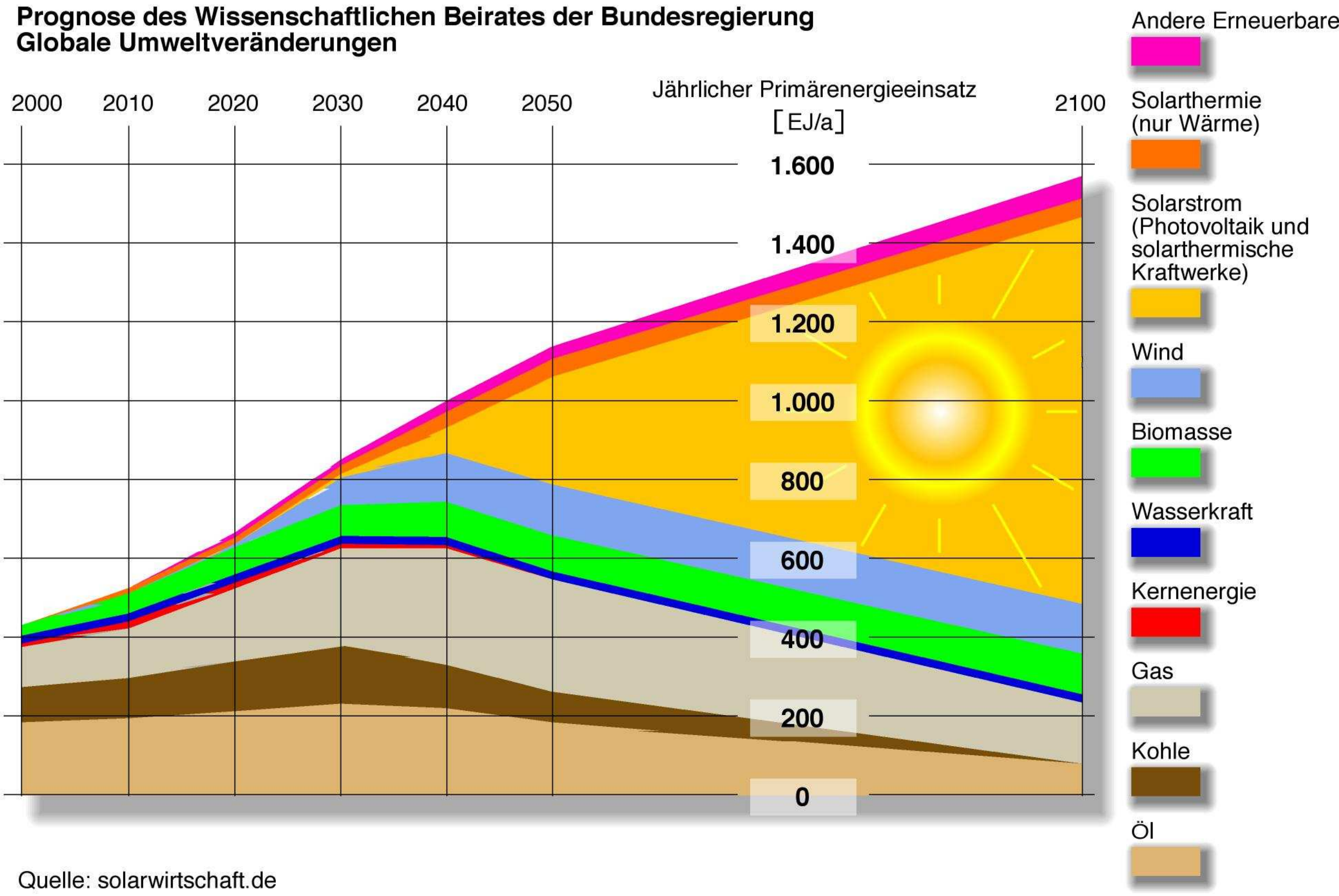
Conclusions

- Thin-film solar modules will become major PV technologies within the next decade. $\Rightarrow$ The proof of concept for a variety of technologies exists.

- The transfer of lab developments / prototypes into a cost effective production is the challenge today.

- There is a strong need for broad R&D to improve existing concepts and develop new thin-film technologies to open the path for higher efficiencies and lower production costs.

Scenario for the world´s primary energy mix in 2100



„Key Product for the Bavarian Market flexible thin-film solar cells for cold beer“