NEW MARKET AND FUTURE PROSPECT OF PV INDUSTRY: THE ROLE OF ACCURATE PERFORMANCE MEASURES

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Fraunhofer Institute for
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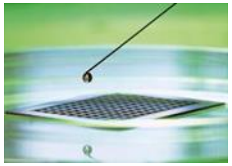
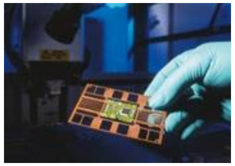
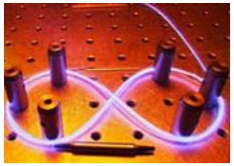
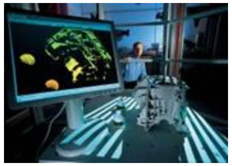
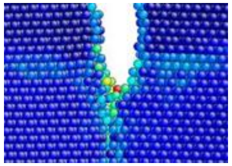
The Fraunhofer-Gesellschaft

Largest Organization for Applied Research in Europe

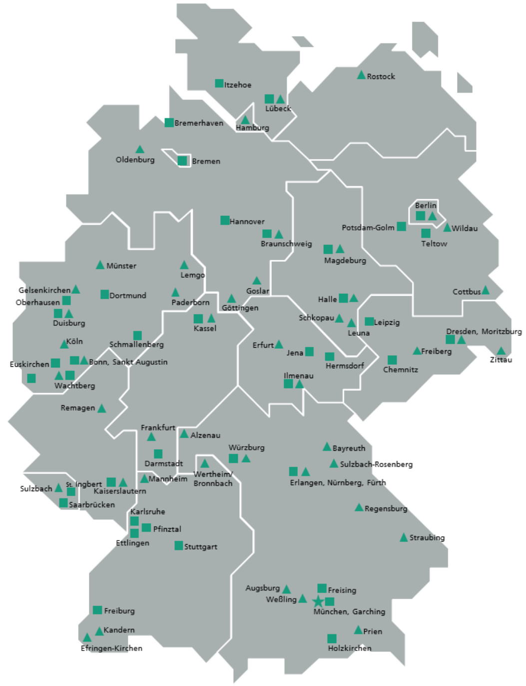
      

66 institutes and independent research units

Staff of more than 22,000

€1.9 billion annual research budget totaling

International cooperation



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Fraunhofer-Institute for Solar Energy Systems ISE

Largest European Solar Energy Research Institute

About 1300 members of staff (incl. students)

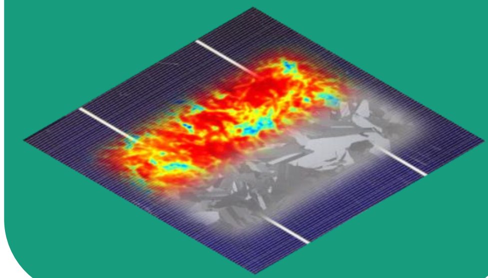
16% basic financing
84% contract research
29% industry, 55% public
€ 87 M budget (2013)

Areas of business:

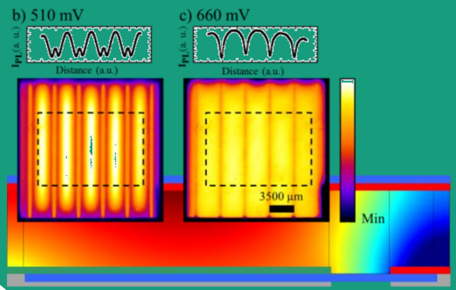
- **Photovoltaics *(Si, CPV, OPV)***
- Solar Thermal *(ST, CST)*
- Renewable Power Generation
- Energy-Efficient Buildings & Technical Building Components
- Applied Optics and Functional Surfaces
- Hydrogen Technology

Department Characterisation and Simulation/CalLab Cells
Division Solar Cells – Development and Characterisation
Topics

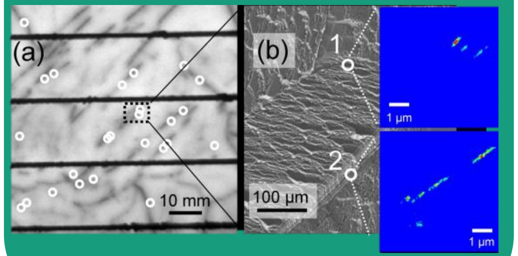
Material Evaluation



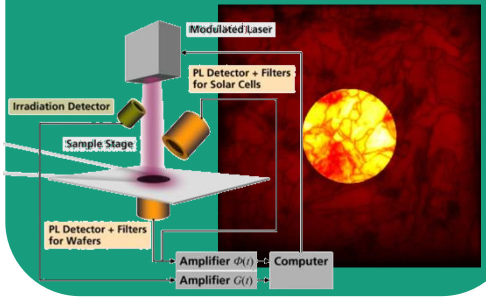
Advanced Cell Characterization



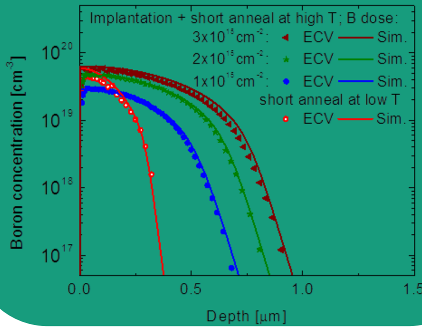
Defect Analysis



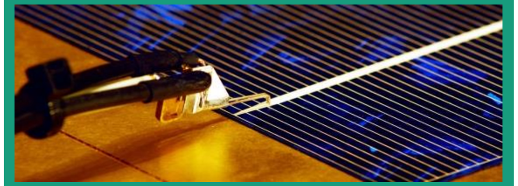
Method Development



Simulation



CalLab PV Cells



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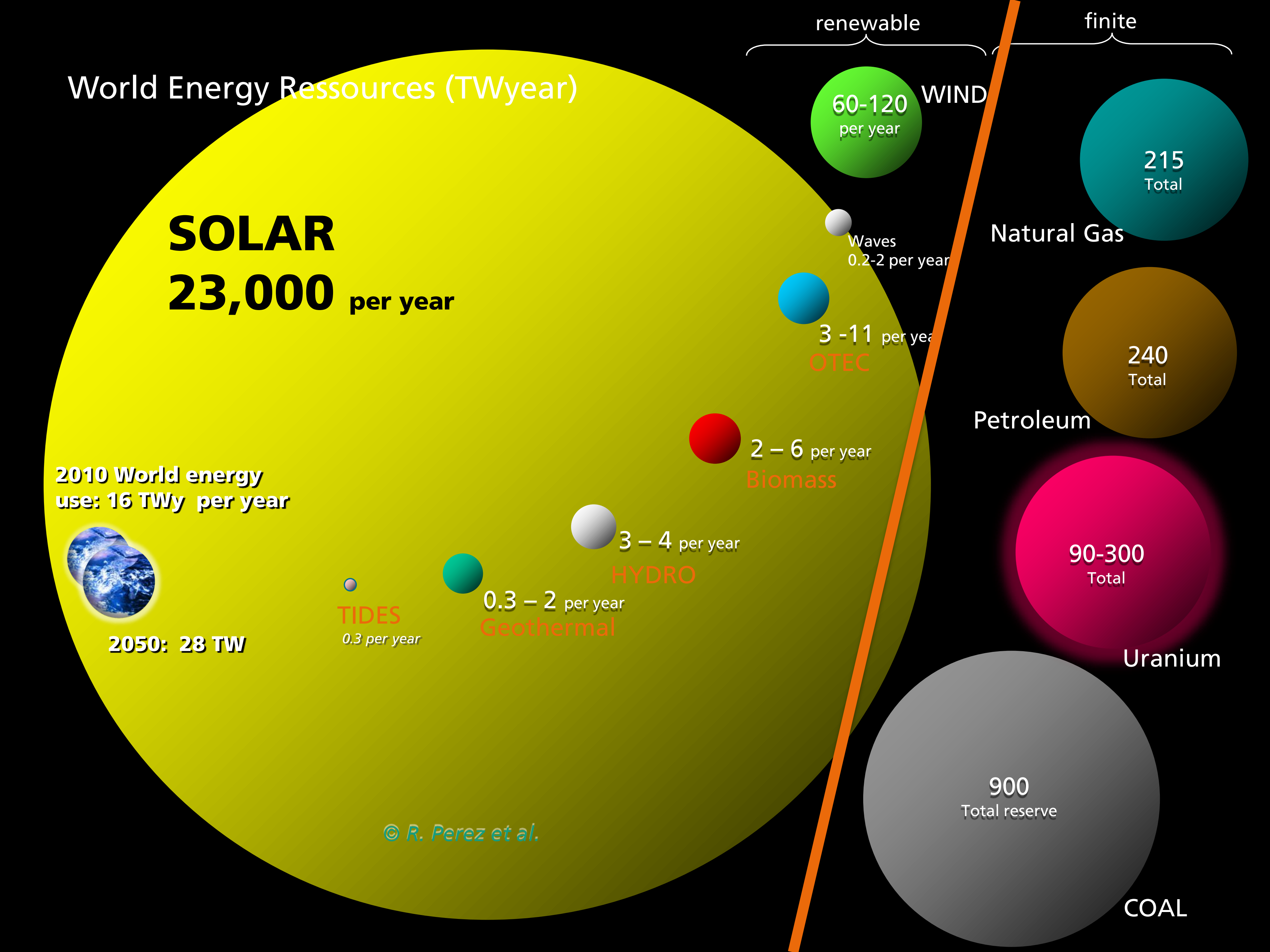
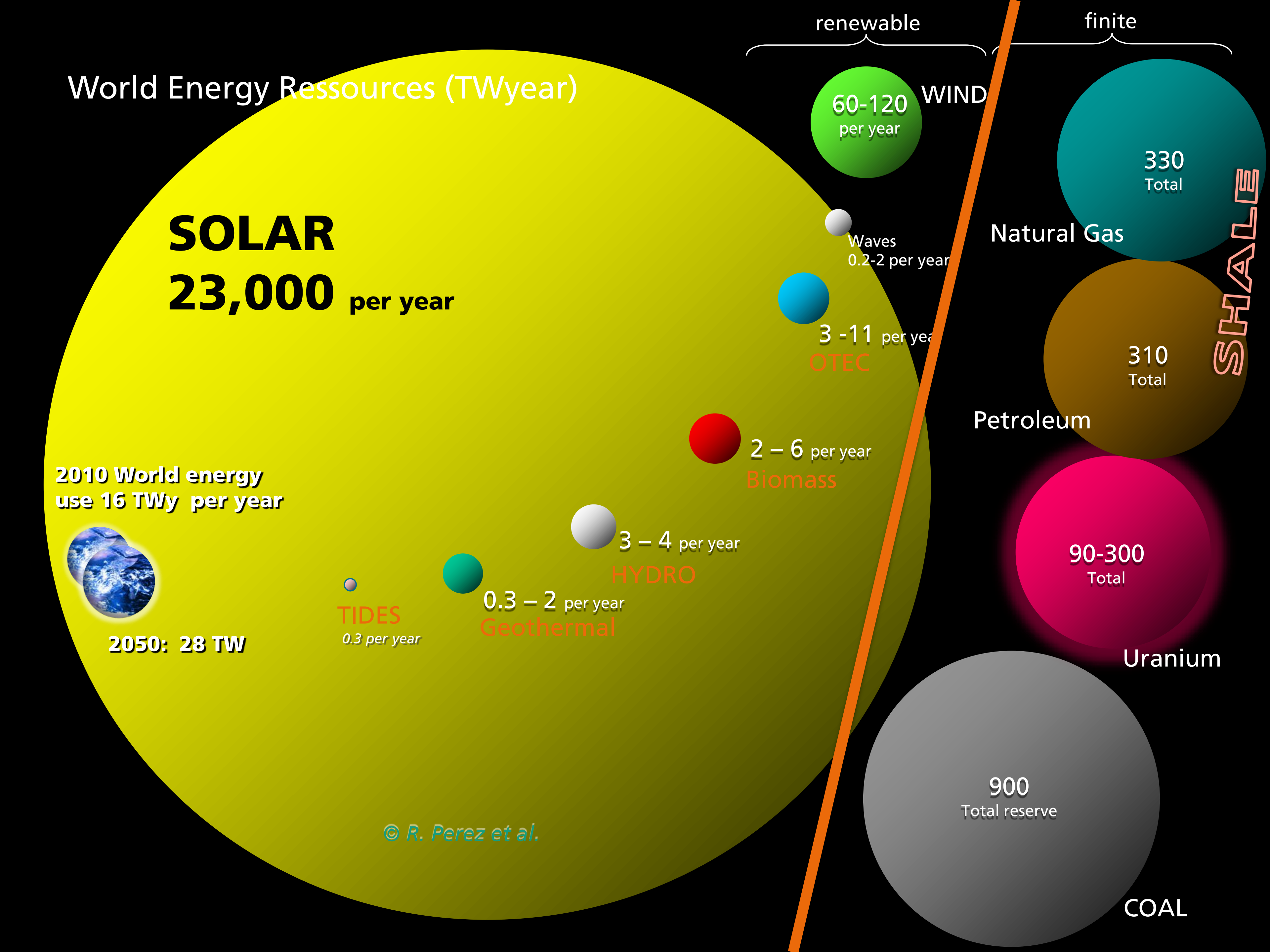

World Energy Ressources (TWyear)
renewable
finite
SOLAR
23,000 per year
60-120 per year
WIND
Waves
0.2-2 per year
3 -11 per yea
OTEC
2 – 6 per year
Biomass
3 – 4 per year
HYDRO
0.3 – 2 per year
Geothermal
TIDES
0.3 per year
2010 World energy use: 16 TWy per year
2050: 28 TW
© R. Perez et al.
215
Total
Natural Gas
240
Total
Petroleum
90-300
Total
Uranium
900
Total reserve
COAL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330
Total
Natural Gas
SHALE
310
Total
Petroleum
90-300
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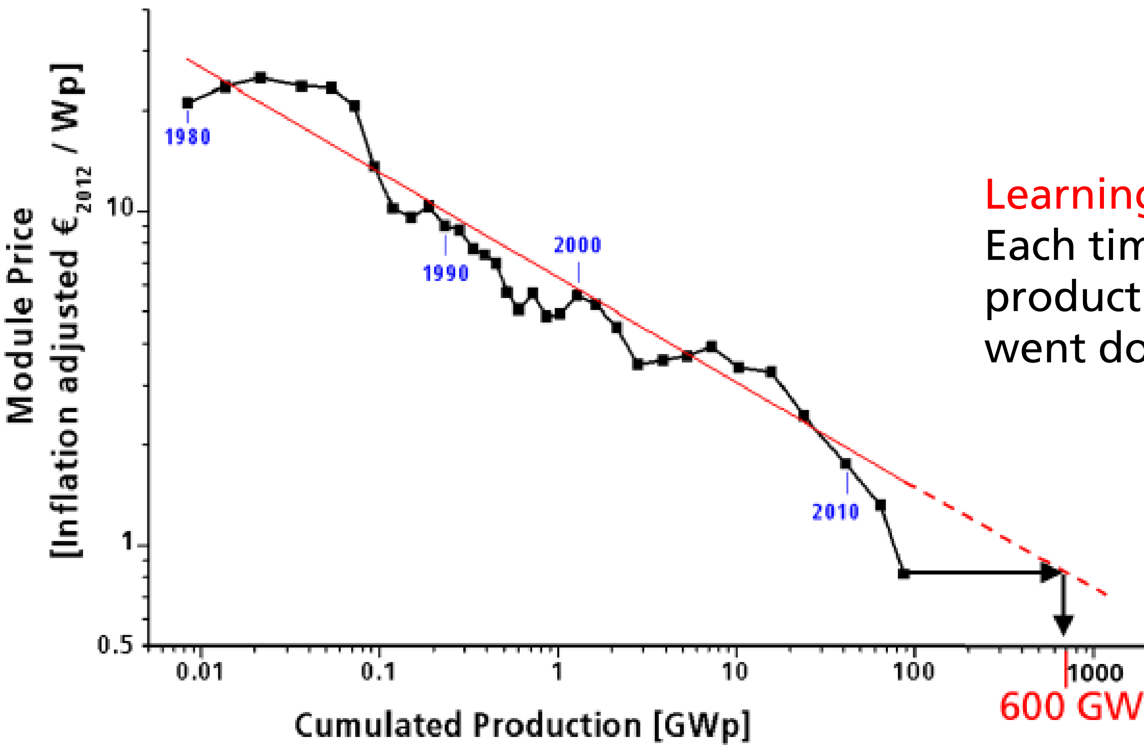
Uranium
900
Total reserve
COAL

Costs of Solar Energy
Price Learning Curve (all c-Si PV Technologies)



Learning Rate:
Each time the cumulative production doubled, the price went down by 20 %.

Price Learning Curve of PV Module Technologies since 1980.

Source: Navigant Consulting; EUPD PV module prices (since 2006), Graph: PSE AG 2012

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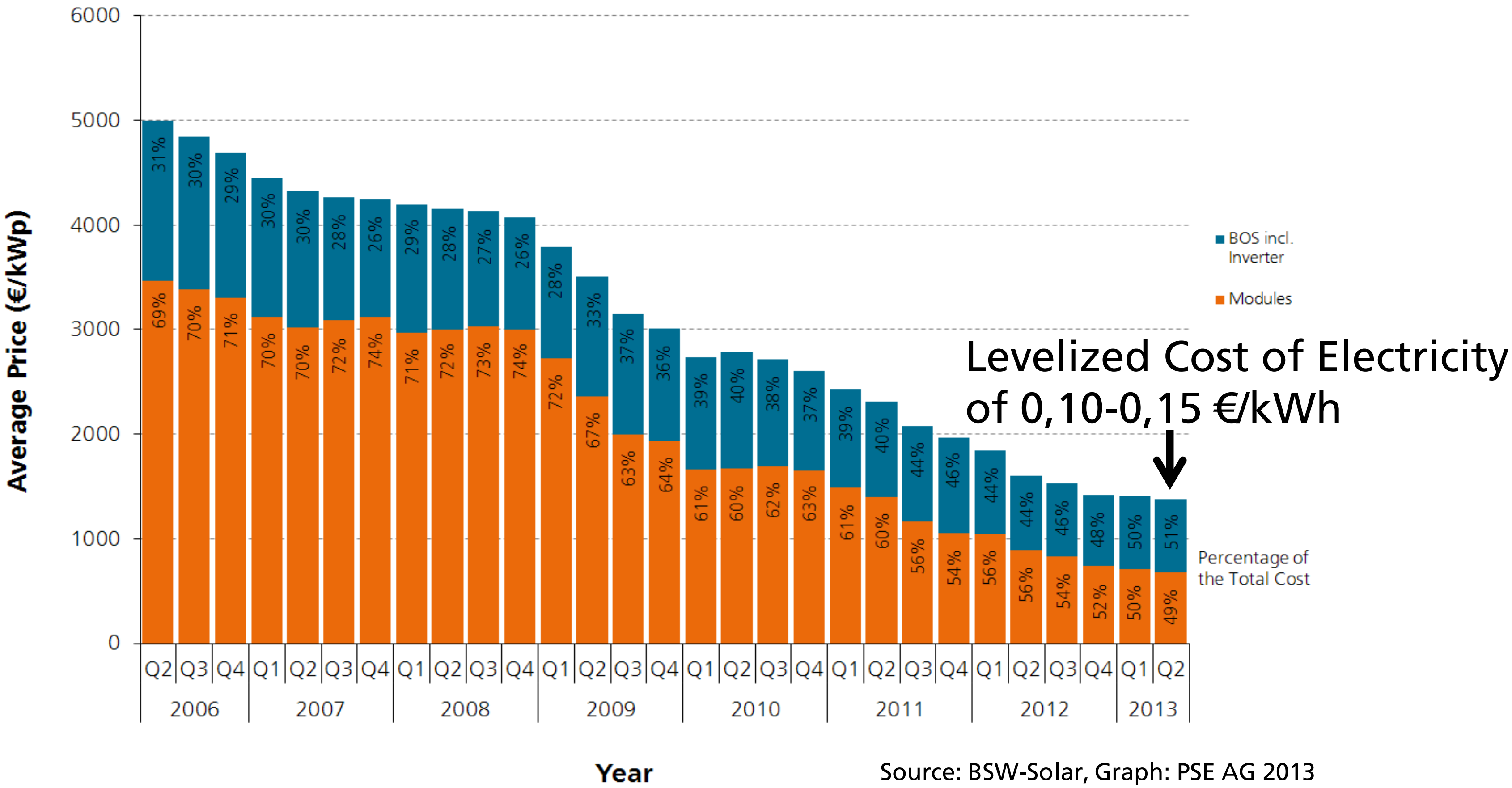
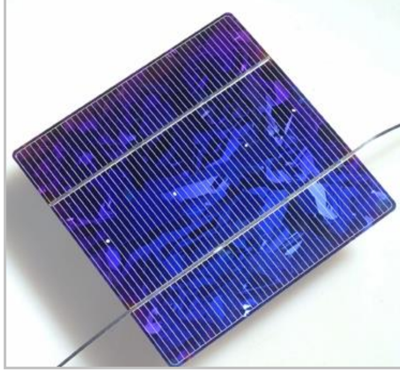
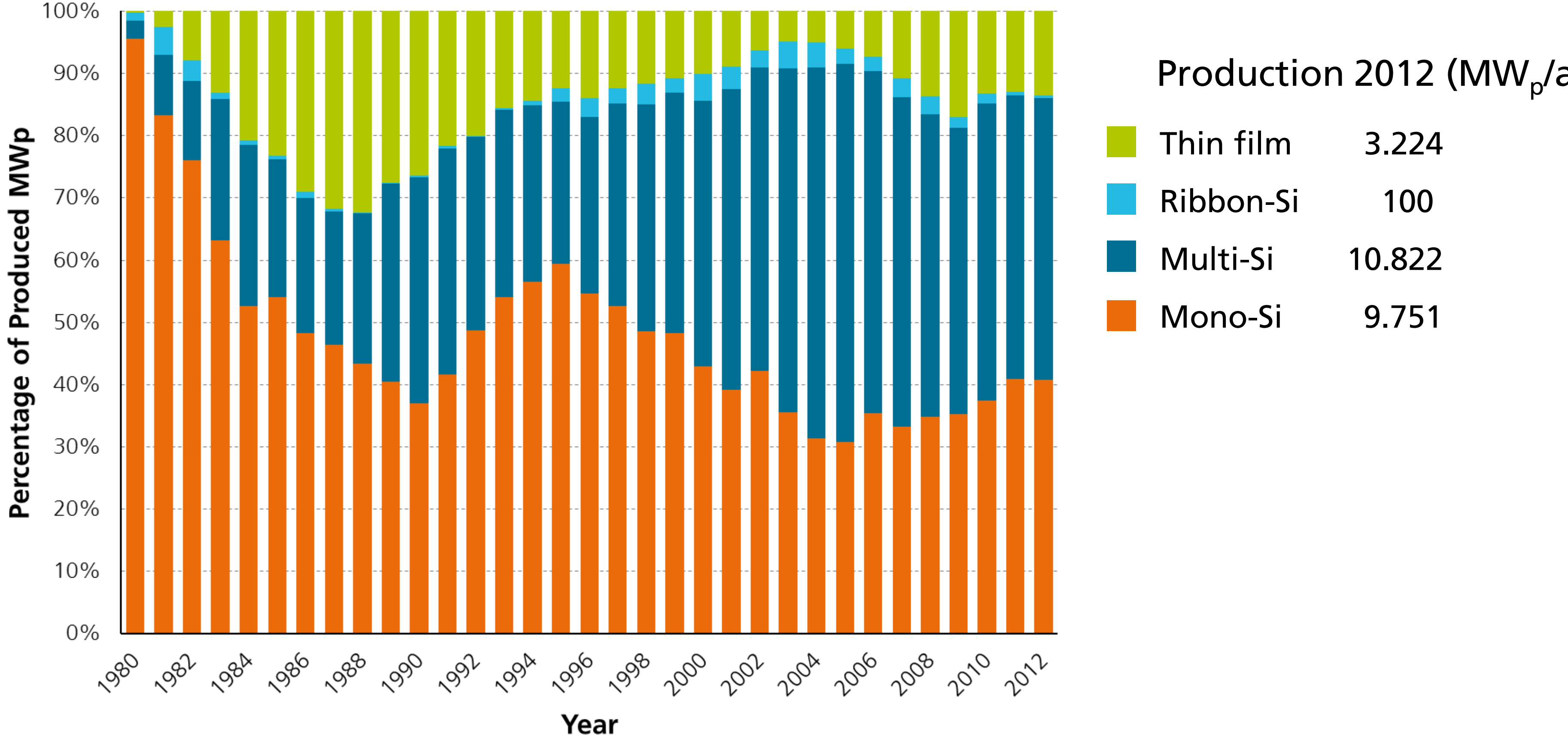
Average Price for Rooftop PV Installations in Germany (10 kWp - 100 kWp)



Source: BSW-Solar, Graph: PSE AG 2013

Harvesting Solar Energy: Photovoltaics (PV)
PV Production Development by Technology





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Outline

- Accurate performance measures:
  Why are they needed and how can they be realized?
- Highly efficient silicon solar cells with low complexity
  - Summary of future developments
  - Challenges for performance measurements:
    Bifaciality, contacting
- Emerging technologies and their measurement challenges
  - Perovskite cells
  - Multi-junction cells
    - III-V concentrator cells
    - Organic cells

Thin film technologies (CdTe, CIGS, a-Si…) not discussed

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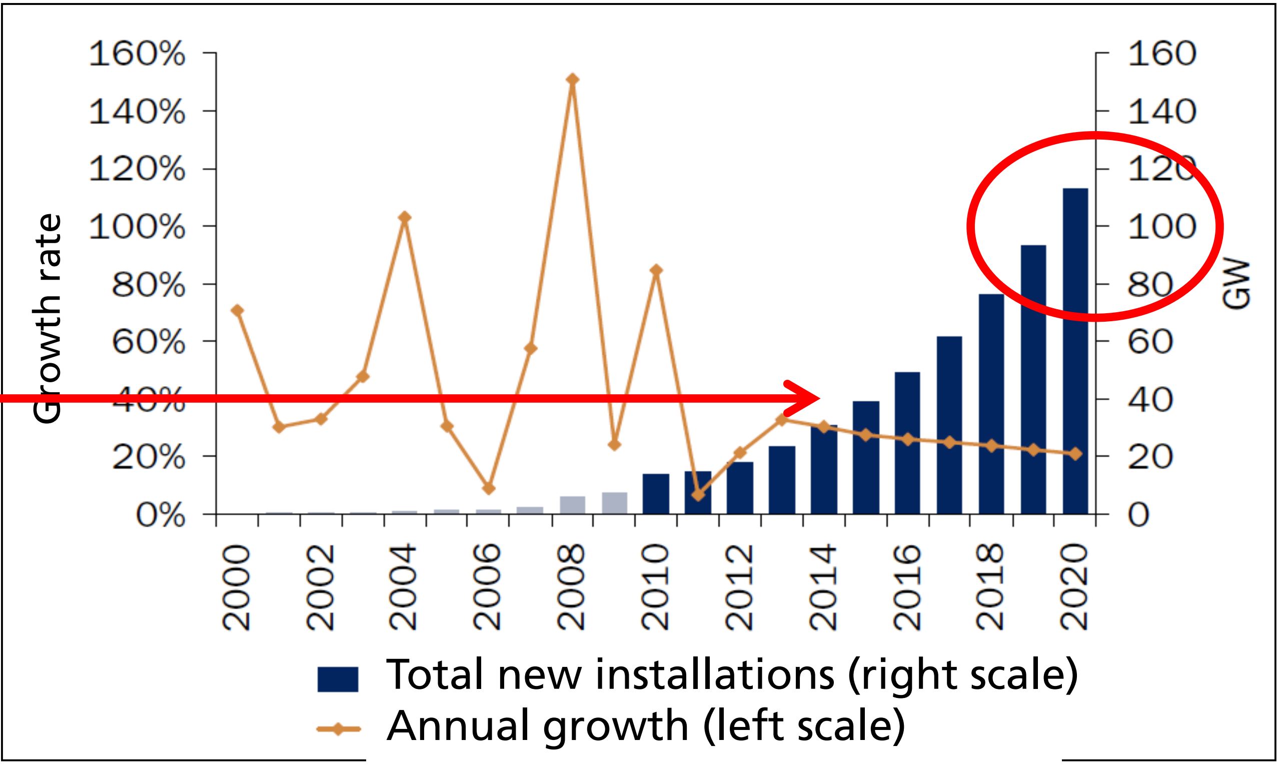
World Market Outlook: Experts are Optimistic
Example Sarasin Bank, November 2010

market forecast: 30 GW_p in 2014, 110 GW_p in 2020
annual growth rate: in the range of 20 % and 30 %

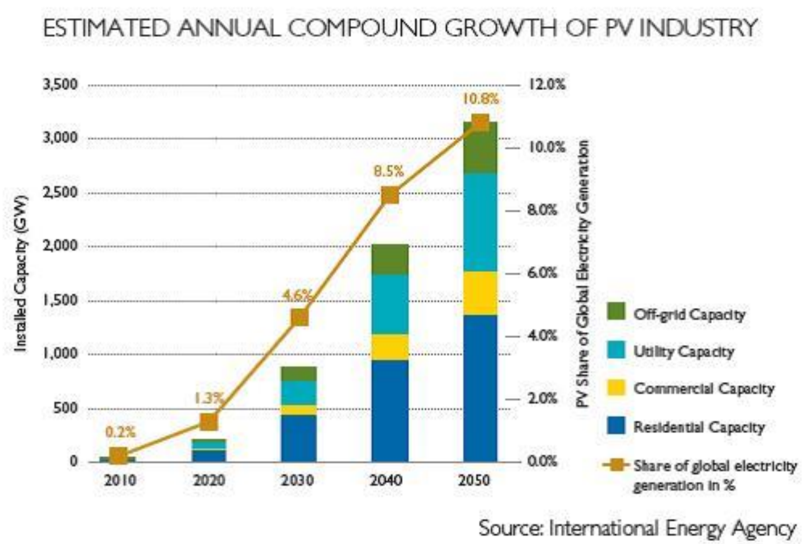
2014:
ca. 46 GW_p,
50 % above
forecast!



Source: Sarasin, Solar Study, Nov 2010

Increasing Economic Impact of Measurement Uncertainty
IEA Outlook on PV Production Worldwide

- Rapidly declining cost of PV generated electricity opens up new market opportunities.
- Current 45 GWp/a market will increase to a 100+ GWp/a market in 2020; for 2050 IEA expects more than 3000 GWp of globally installed PV capacity; for only 10 % of energy demand we need more than 10,000 GWp!



Huge economic impact of uncertainty:
±1% of 45 GWp/a PV world production ➡ ± 450 Mill. €

Competitive world market needs precise power comparability

Why is Accuracy of PV Cell Calibration a Challenge?
Solid Basis: Standard Testing Conditions (STC, IEC 60904)

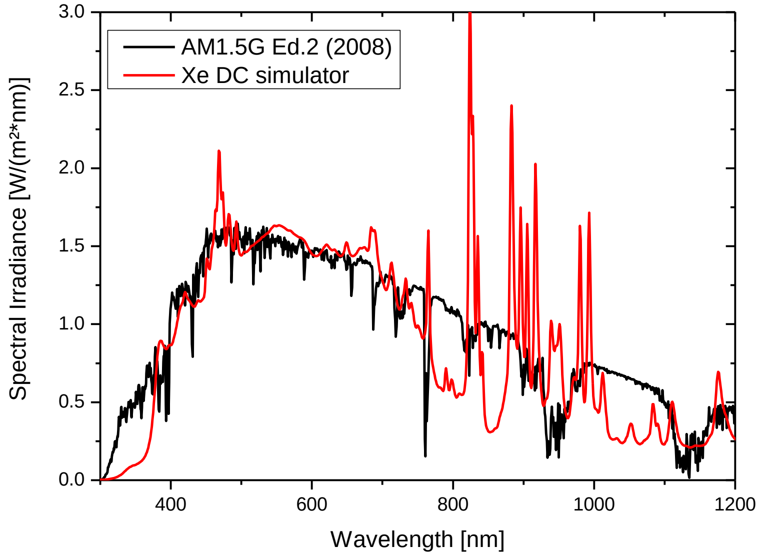
- Main sources of measurement uncertainty:
  - Spectral dependent values
  - Large areas

Temperature 25°C

Irradiance 1000 W/m²

Spectral distribution

AM1.5g



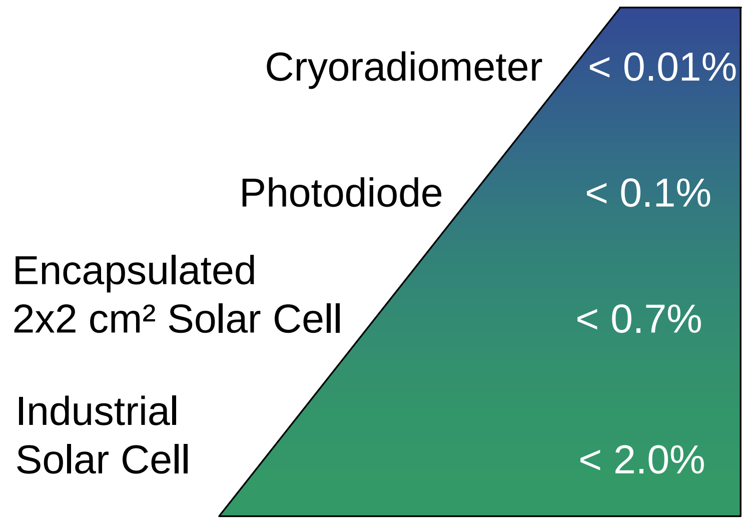
Example: Uncertainty of Reference Calibration (I_{SC})

Traceability Chain at ISE CalLab PV Cells

Planck spectrum, small diode

Synthetic irradiation, small cell

Simulator irradiation, large area



Economic view:
Contributions > 0.1 % count!

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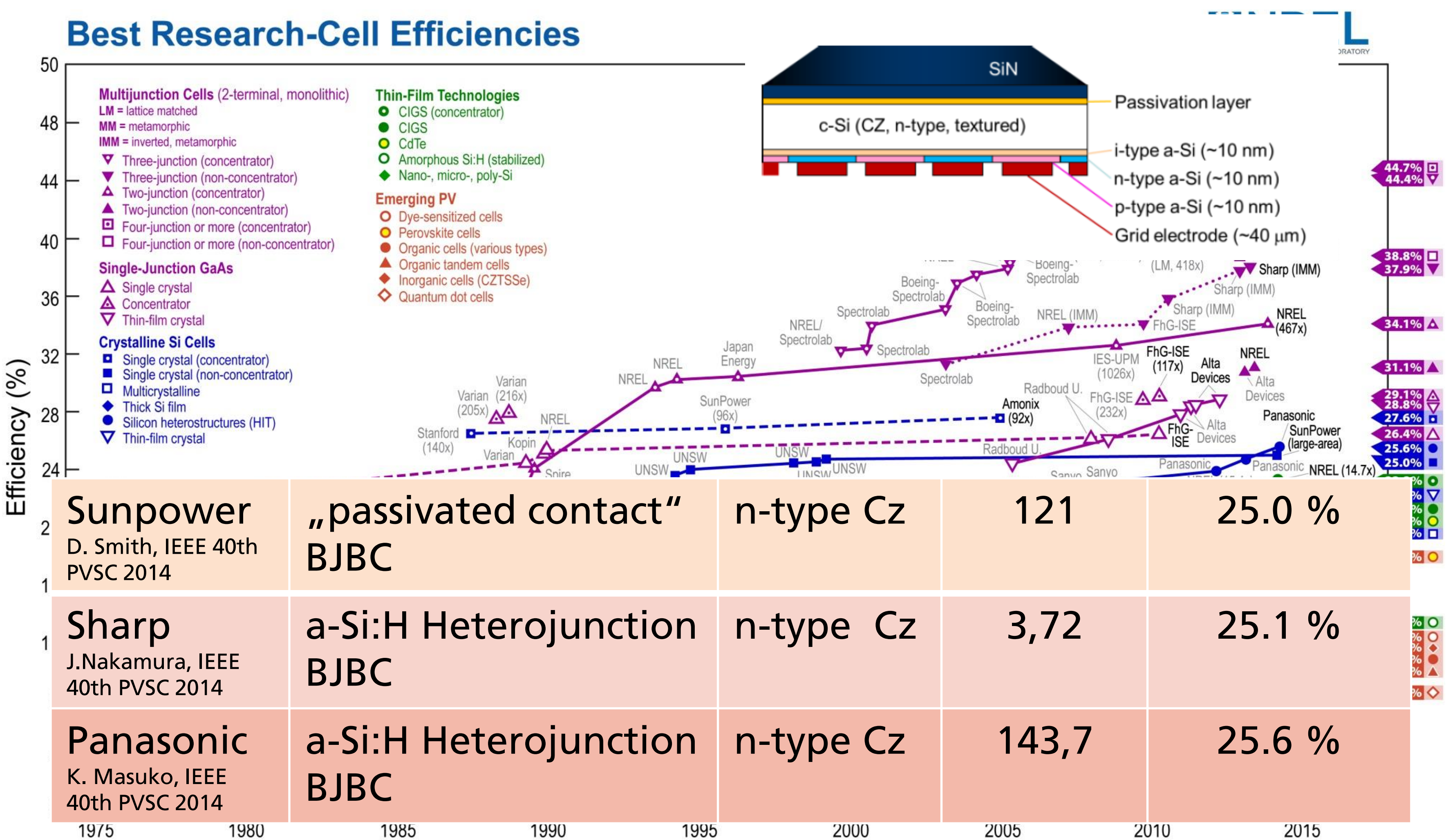
Thin film technologies (CdTe, CIGS, a-Si…) not discussed

Trend 1: Highly Efficient Solar Cells with Low Complexity



Sunpower D. Smith, IEEE 40th PVSC 2014	„passivated contact“ BJBC	n-type Cz	121	25.0 %
Sharp J.Nakamura, IEEE 40th PVSC 2014	a-Si:H Heterojunction BJBC	n-type Cz	3,72	25.1 %
Panasonic K. Masuko, IEEE 40th PVSC 2014	a-Si:H Heterojunction BJBC	n-type Cz	143,7	25.6 %

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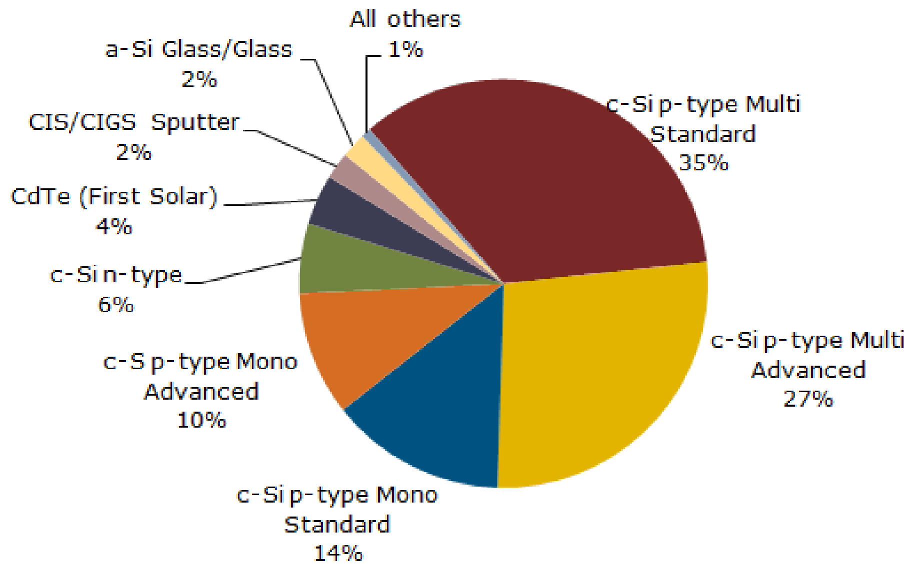
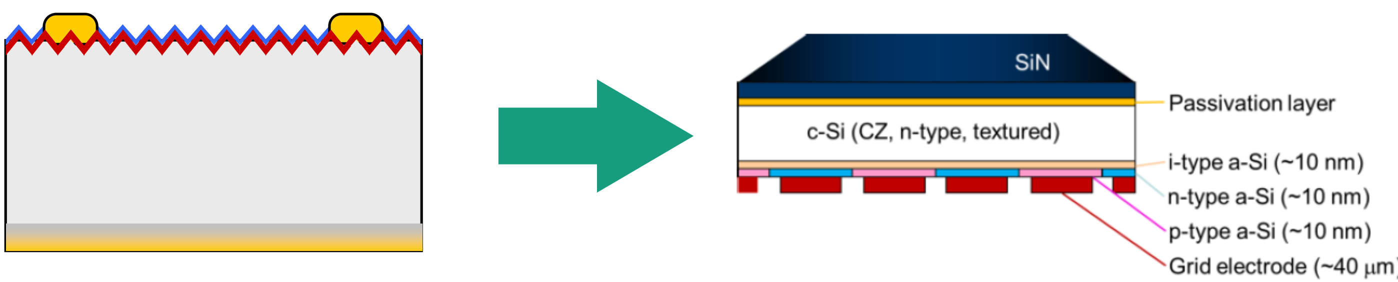
Highly Efficient Solar Cells with Low Complexity
State-of-the-Art Silicon Solar Cell

- Current reality in PV
- 91 % silicon
- **62 %** multi crystalline p-type silicon
  - > 90 % Al-BSF cells



Will there be a transition to the more complex n-type BJBC with passivated contacts?



http://www.solarbuzz.com/news/recent-findings/multicrystalline-silicon-modules-dominate-solar-pv-industry-2014

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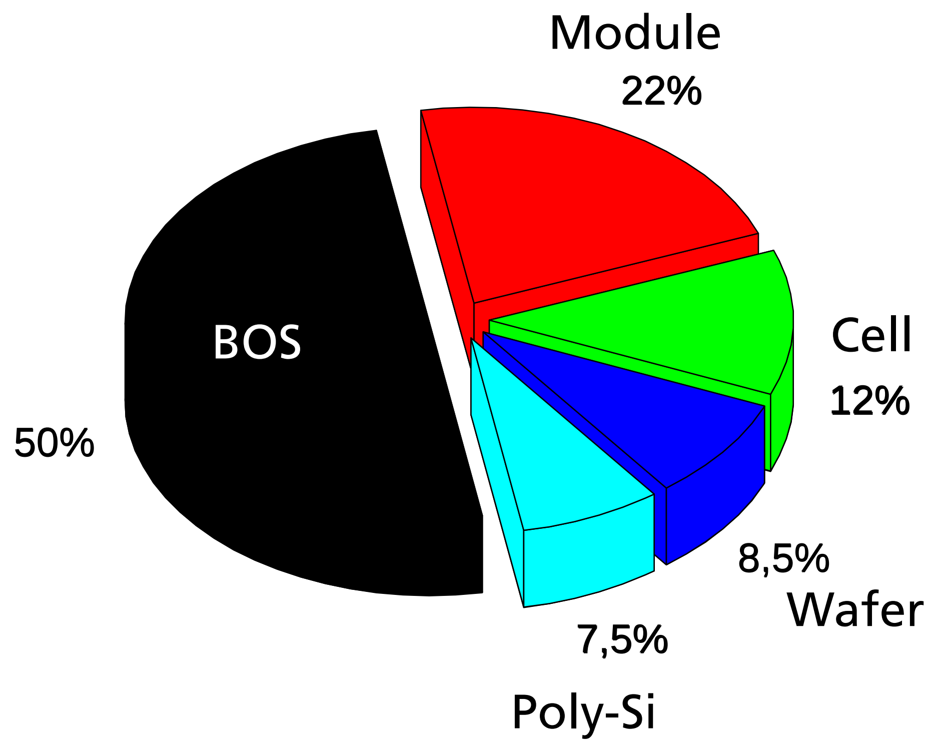
Why Going to High Efficiencies?
System costs

- Share of Balance of System costs (**BOS**) increases from 31 % in 2006 to now about **50 %**
- Large fraction of system cost scale with the **solar cell efficiency**



→ **High efficient solar cells reduces your system cost**

http://www.itrpv.net/

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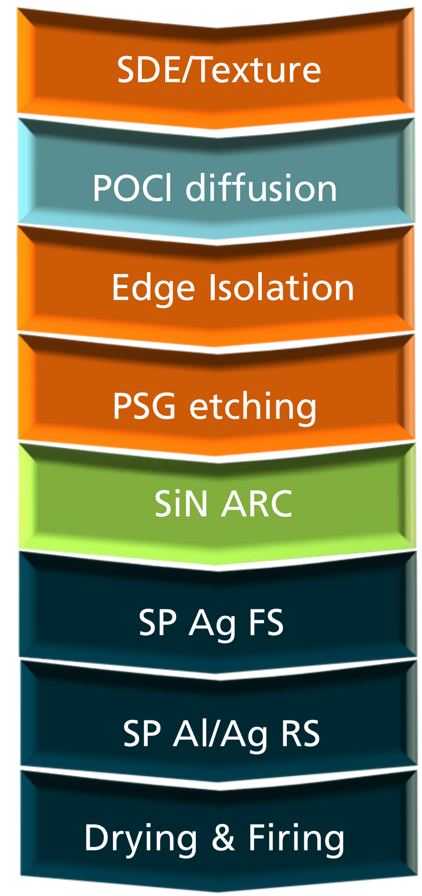
Why Going to High Efficiencies?
Levelized Cost of Electricity (LCOE)

- What really matters are the Levelized Cost of Electricity (LCOE)
- To rate new solar cell concepts, they have to be compared with the LCOE of the **p-type mc Al-BSF cell**
- Reference system:
  - p-type mc Al-BSF cell
  - Cell efficiency 18,5 %
  - 900 kWh/kWp, 25 years

LCOE~10 €ct/kWh



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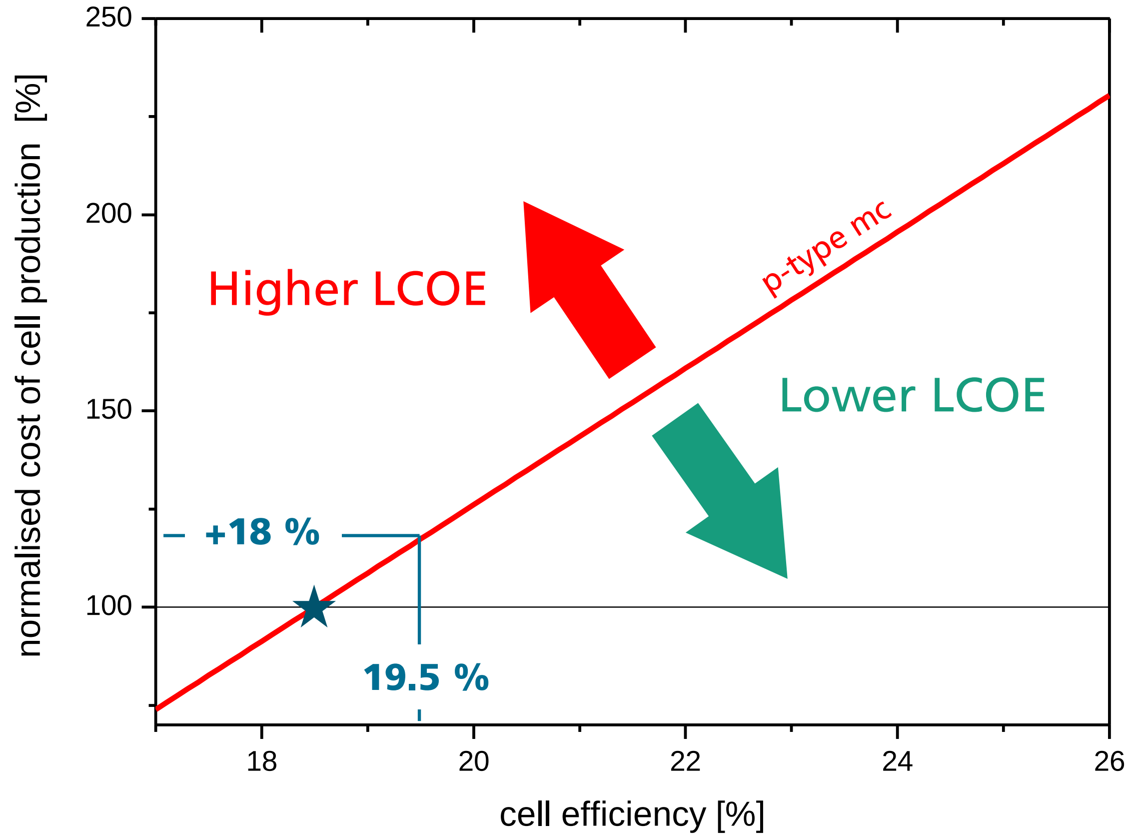
Why Going to High Efficiencies?
Efficiency versus Cost

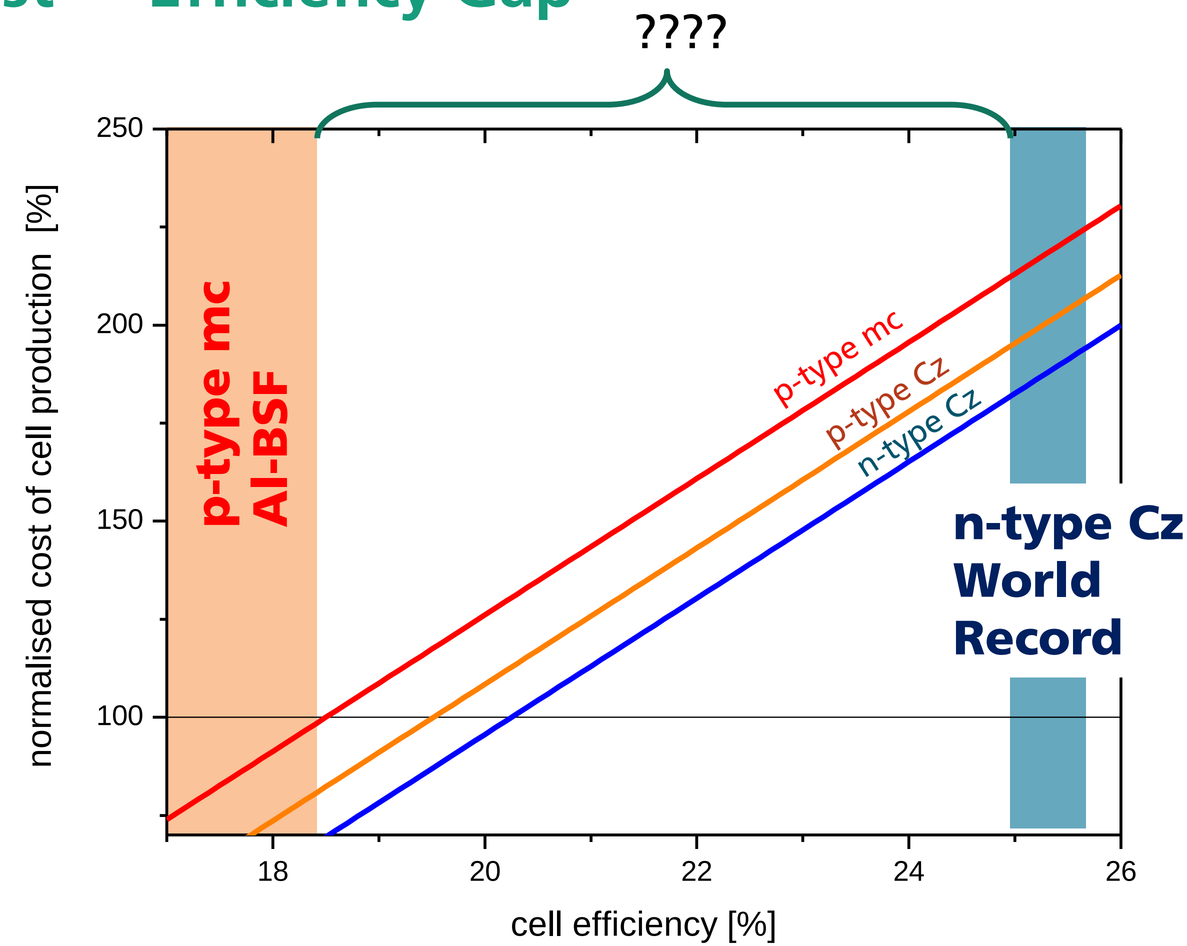
- What are the allowed additional costs in cell production to get the same LCOE
- Simplified assumption: **All system costs (except inverter) scale with efficiency**



More detailed model: S.Nold et al. , EUPVSEC 2012

Why Going to High Efficiencies?
Efficiency versus Cost - Efficiency Gap

- Which solar cell concepts can fill the efficiency gap between p-Type mc Al-BSF and the world record cells?
- Is there an economical maximum?



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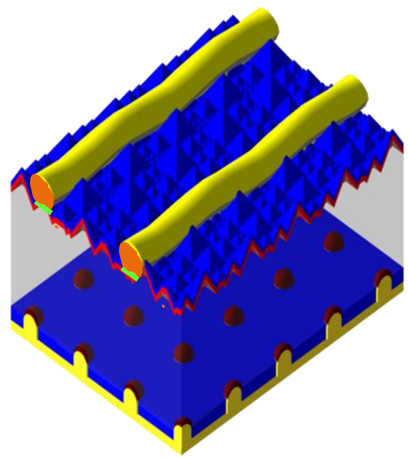
Solar Cell Concept to Close the Gap
p-Type PRC – The Evolutionary Path

- Replacement of the full area Al-BSF with **a partial rear contact (PRC)**
- Two additional process steps
  - Dielectric passivation
  - Local contact opening (LCO) or Laser fired contact (LFC)
- **Advantage:** Can be used for **mc** und **Cz** silicon



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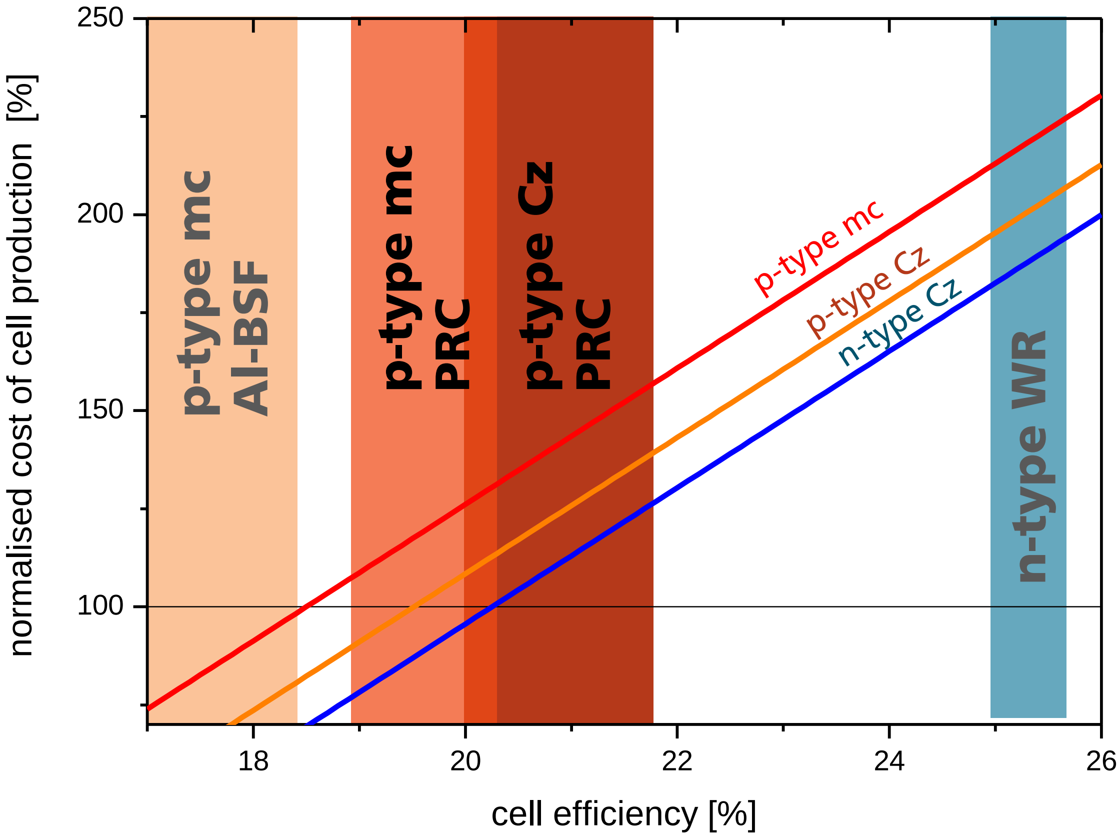
Solar Cell Concept to Close the Gap

p-Type PRC – The Evolutionary Path

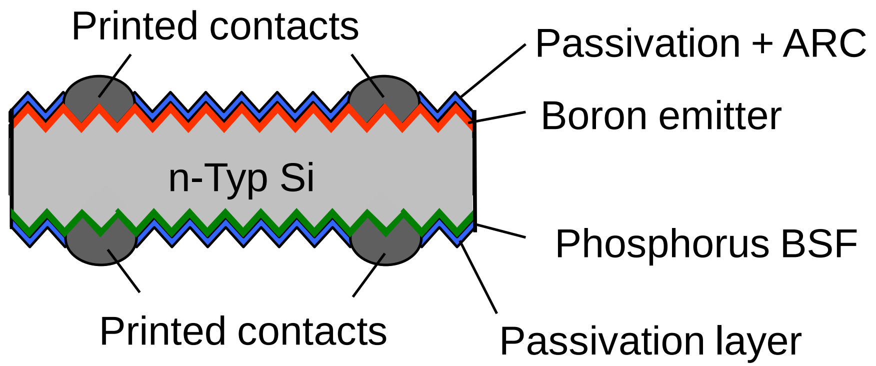
- Due to the large p-type capacity we will see an increase in efficiency
- Key developments are an improved emitter and metallization
- Bulk lifetime become a limiting factor for Cz PRC cells



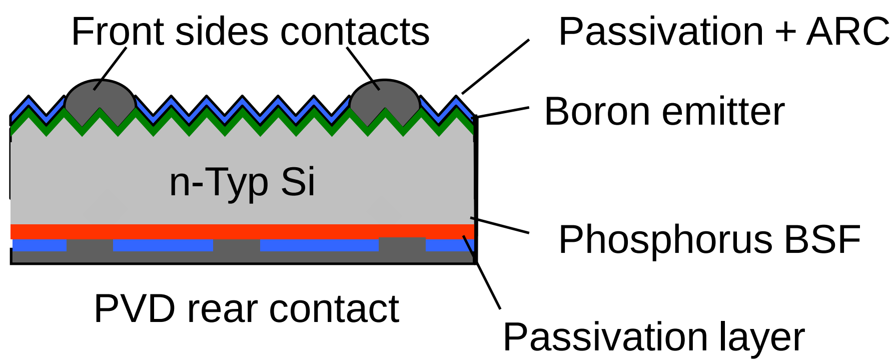
Solar Cell Concept to Close the Gap
n-Type PERT – Bifacial or Monofacial

Two configurations:

- **Bi-facial** with printed contacts on both side
- Different concepts for the realization of diffused regions



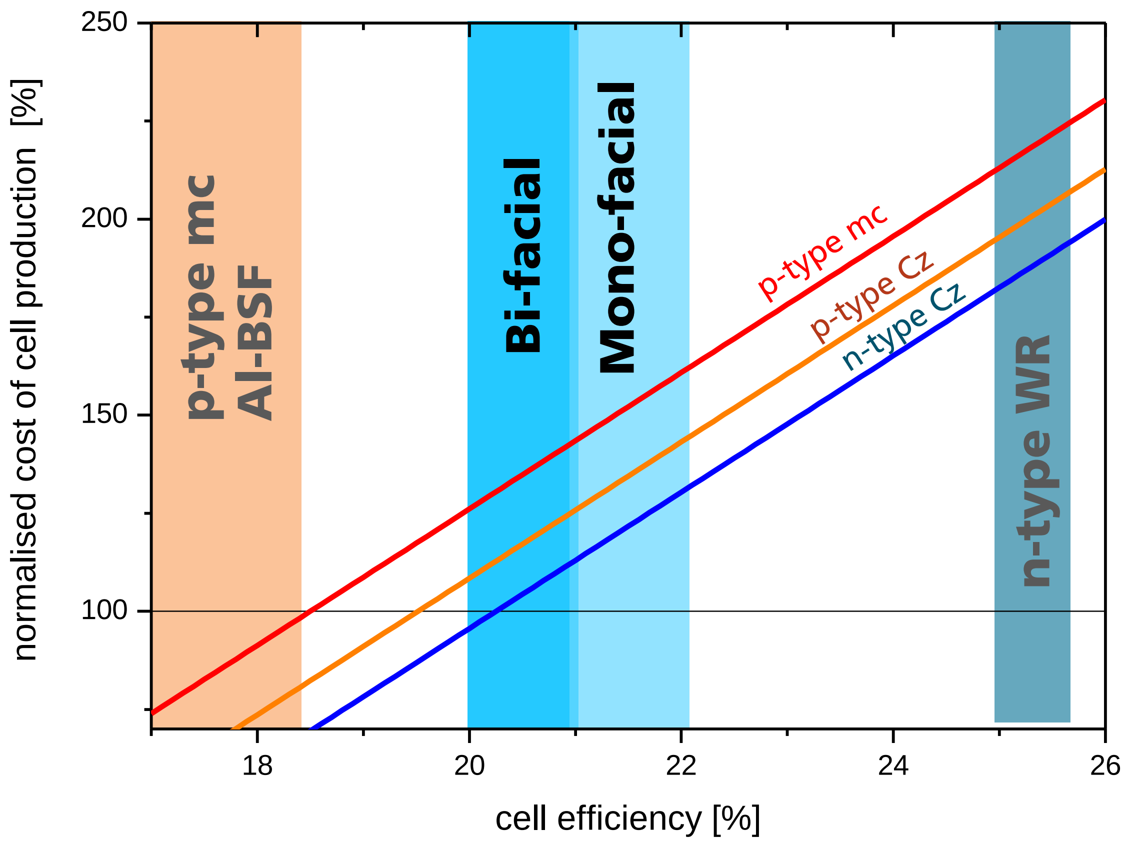
- **Mono-facial** with different contact technologies



Solar Cell Concept to Close the Gap

n-Type PERT – Bifacial or Monofacial

- Bifacial cells currently limited by the metallization
- **Bifacial** cells allow **higher energy yield → lower LCOE**
- **Rear emitter** configuration offers high efficiency potential for Mono-facial design



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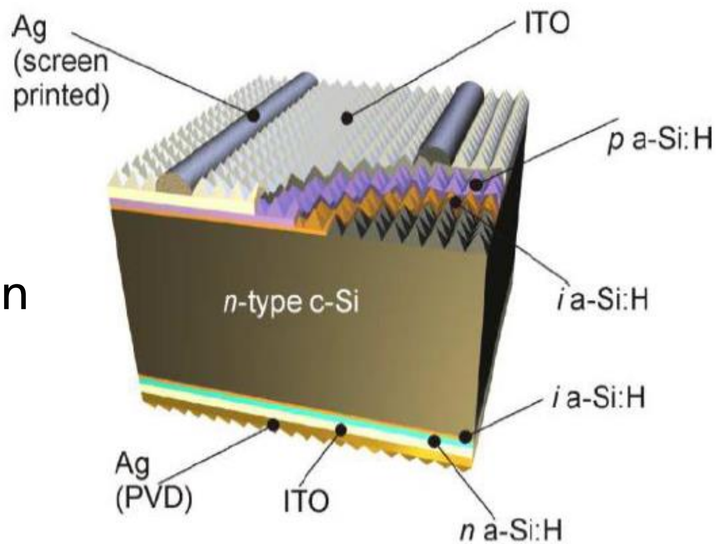
Solar Cell Concept to Close the Gap

n-Type Heterojunction – A “simple” cell structure

- Lean process flow
- Highly efficient carrier selective contacts
- High V_{oc} and low T_k
- High efficiencies for thin wafers



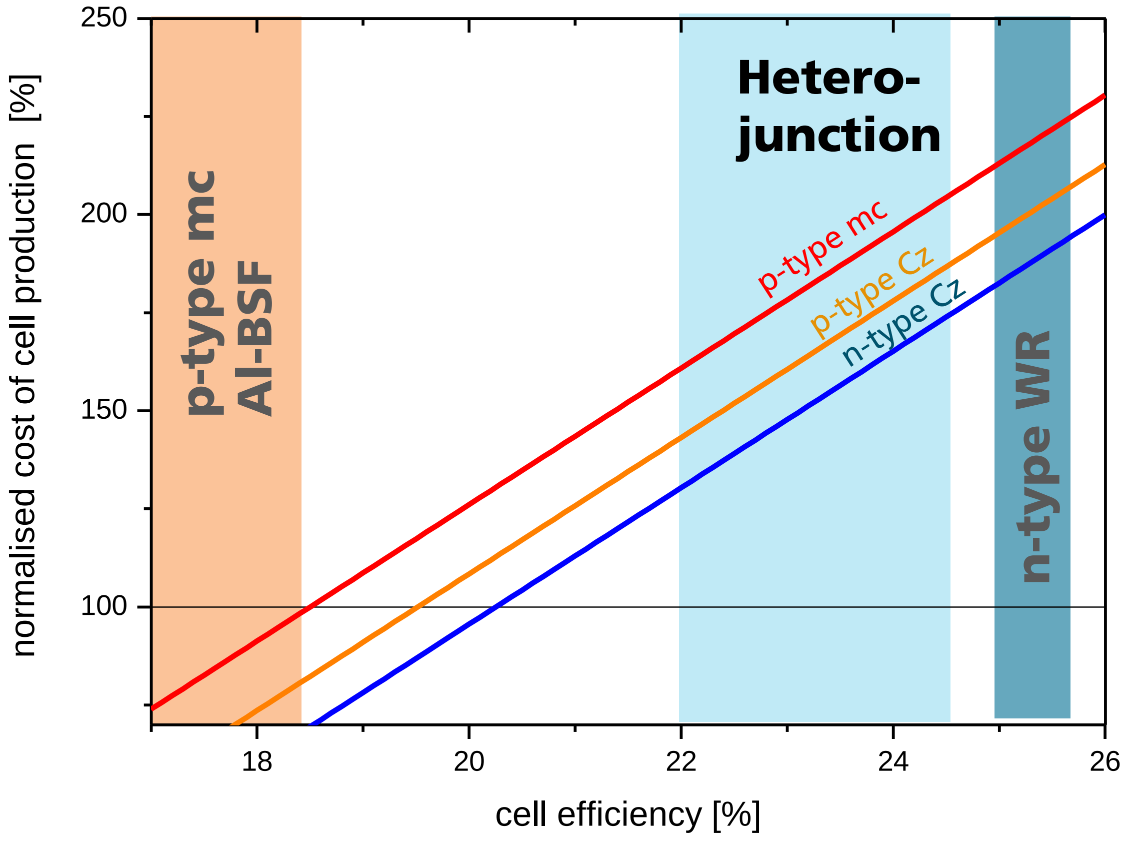
- Texture
- Cleaning
- i/p-a-Si
- i/n-a-Si
- TCO front
- TCO rear
- PVD Al rear
- SP Ag VS
- Curing

from: D.Bätzner Silicon PV 2014

Solar Cell Concept to Close the Gap

n-Type Heterojunction – A “simple” cell structure

- High efficiencies are proven
- Rear emitter configuration looks promising
- Metallization is still an issue
- Cost efficient large scale production >1 GWp has to be shown



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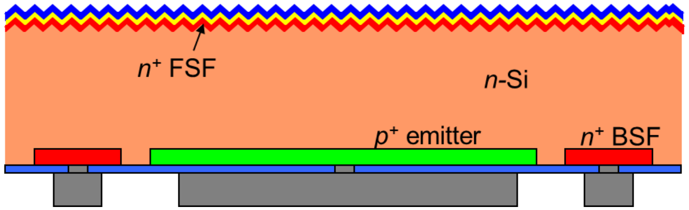
Solar Cell Concept to Close the Gap
n-Type BJBC– without "passivated contacts"

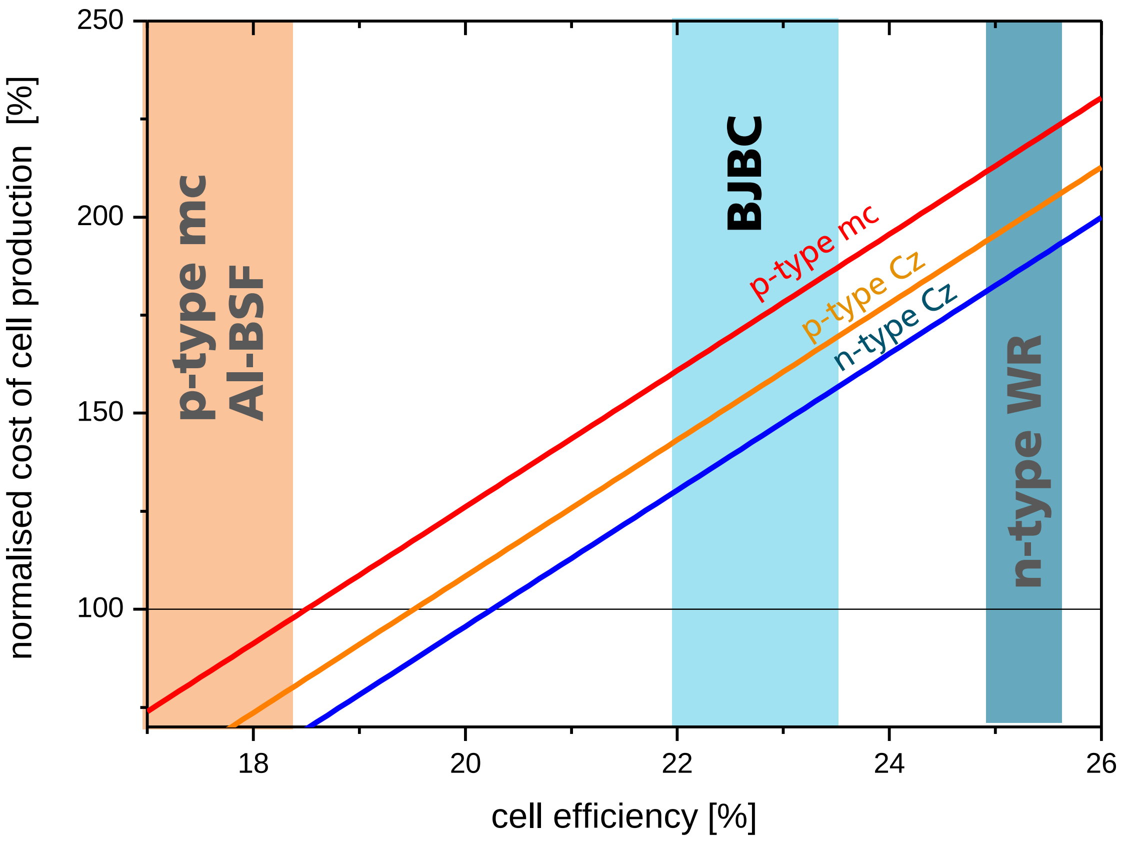
- Large volume production by Sunpower since more than 10 years
- Developments of new technology equipment offers new process routes
  - In situ masked ion implantation
  - Laser doping



Solar Cell Concept to Close the Gap

n-Type BJBC– without "passivated contacts"

- Ion Implantation offers new routes for BJBC cell production
- New approach "Blocking of boron diffusion by implanted phosphorus" further reduces the process complexity



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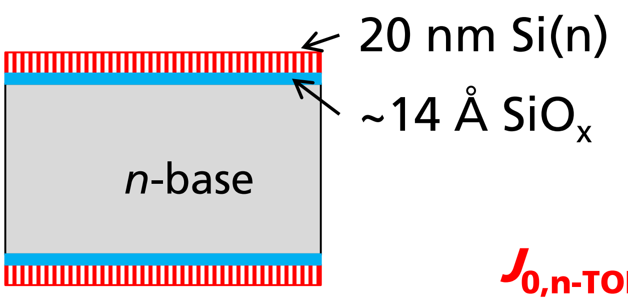
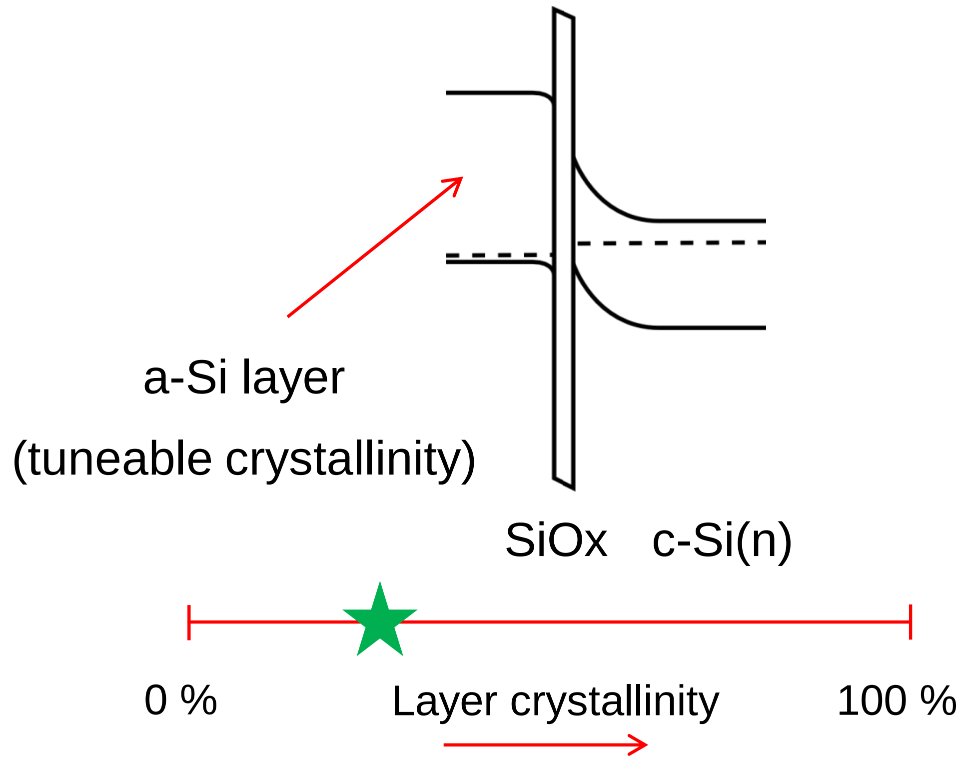
Solar Cell Concept to Close the Gap

n-Type Hybrid TOPCon Cell – TOPCon layer

- **T**unnel **o**xide **p**assivated **con**tact (**TOPCon**)
- Tunnel oxide using wet chemical or UV/O_3 growth
- PECVD single side deposition of amorphous Si layer
- Furnace Anneal + H-passivation



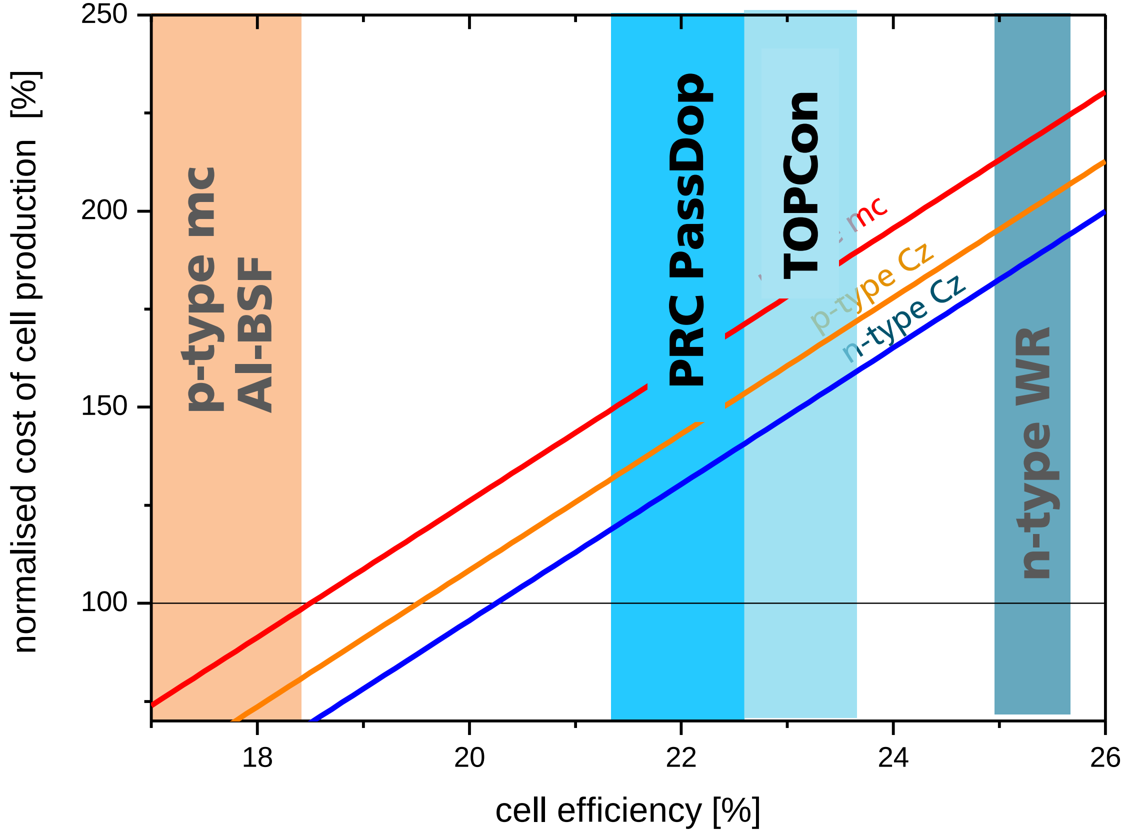


$J_{0,n\text{-}TOPCon} \approx 7$ fA/cm²

F. Feldmann et al SOLMAT **120** 2014

Solar Cell Concept to Close the Gap
n-Type PRC and TOPCon

- *PassDop* and *TOPCon* approach offer a concept for 22 % and above
- Advanced metallization is necessary to fully exploit the potential



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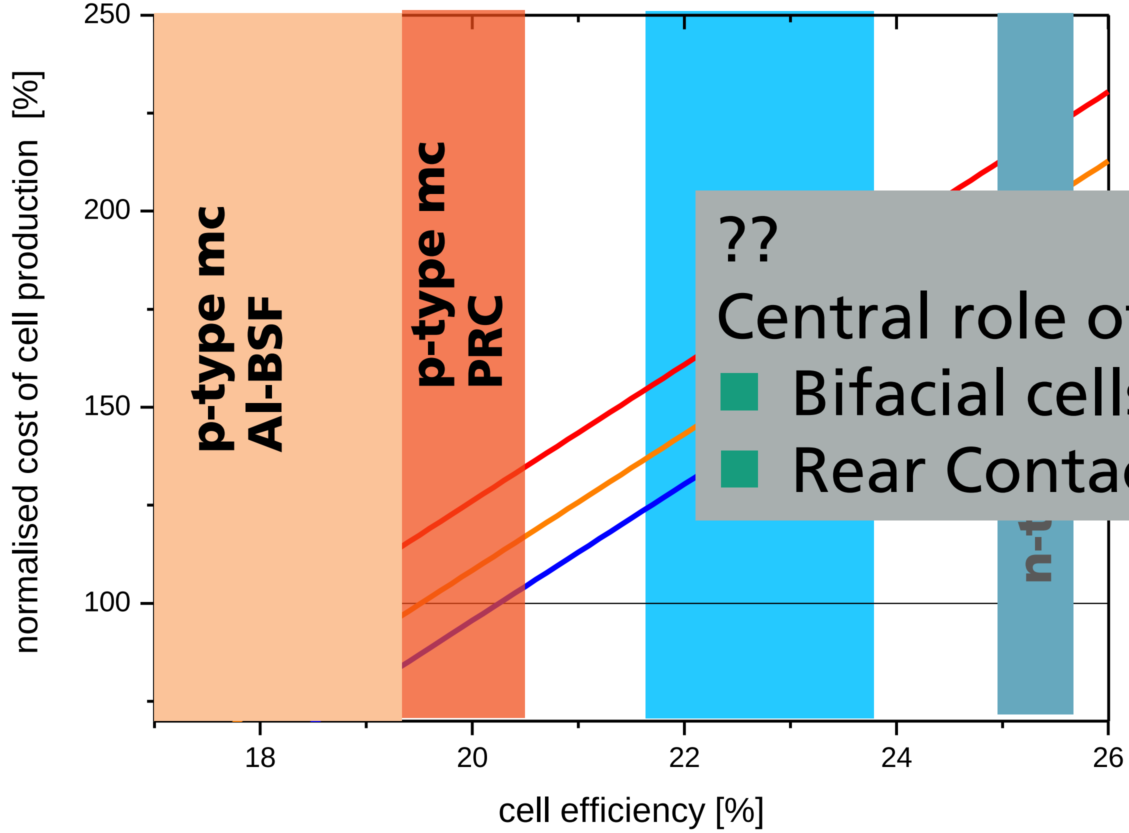
Solar Cell Concept to Close the Gap

What will we get in the "near" Future?



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Central role of

- Bifacial cells
- Rear Contacted Cells

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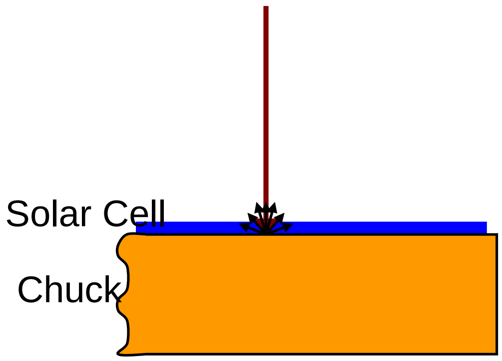
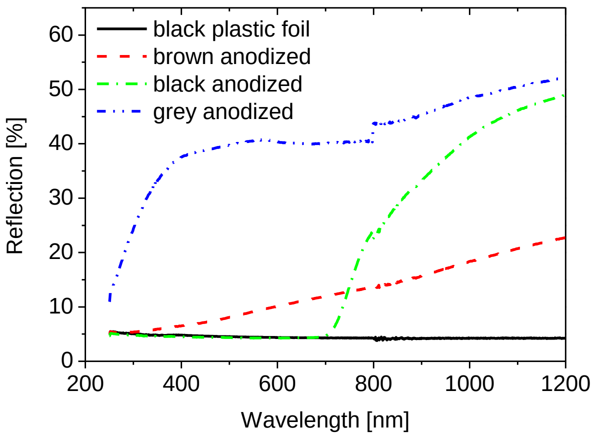
Challenges for High Efficiency Cell Calibration
Bifacial Cells





- Comparable measurements of bifacial cells require definition of background

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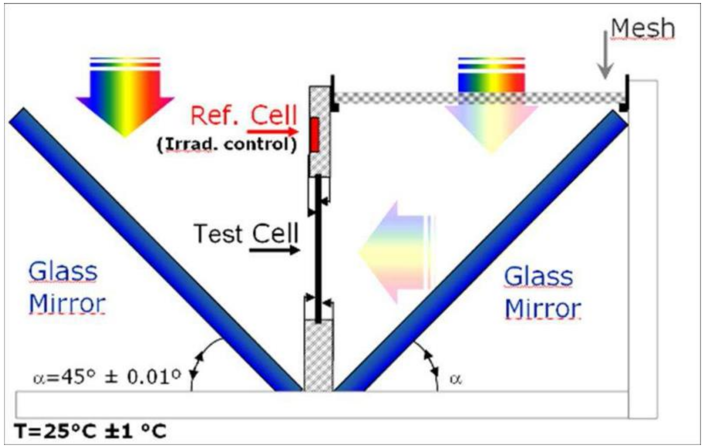
Challenges for High Efficiency Cell Calibration
Performance Gain of Bifacial Devices

- Bifacial modules on a white roof: up to 30% more power output
- How can investors calculate the LCOE of a bifacial installation?
- Proposals in literature for
  - measurement setups, e.g. [2]
  - definitions of figures of merit e.g. [3]
- Internationally agreed standards urgently needed!


[1]



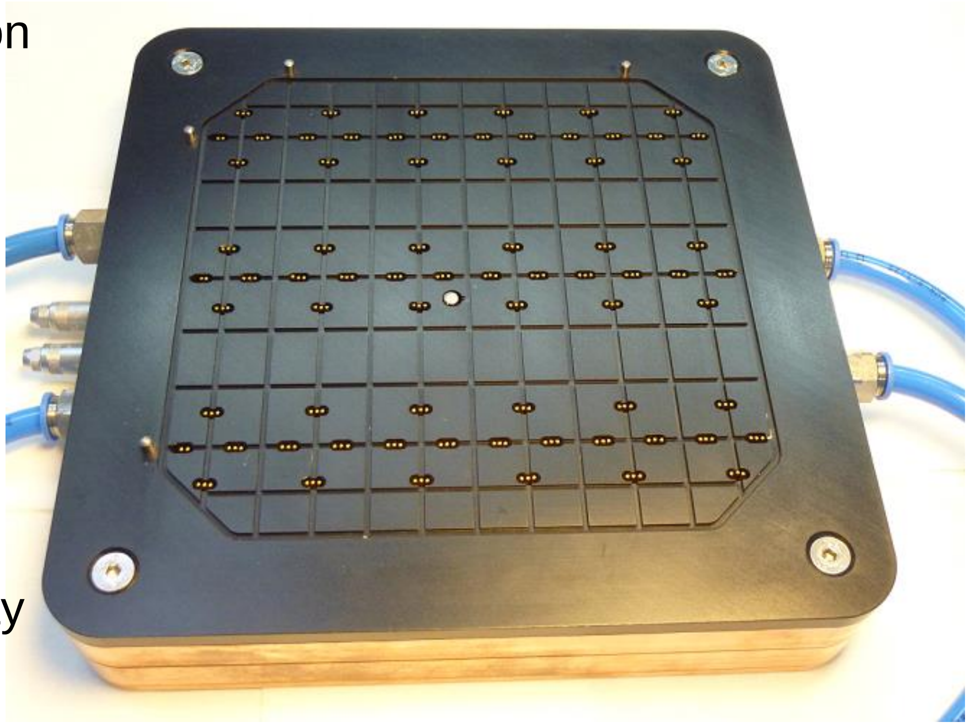
[2]

[1] bSolar 2012
[2] M. Ezquer et al. 23rd EU-PVSEC Valencia 2008
[3] J.P. Singh et al. solmat 127, 2014

Challenges for PV Cell Calibration

Chuck Development for Back Contacted Solar Cells

- Concept for concurrent realization of thermal and electrical contact
- No front glass for
  - tactile temperature measurement
  - unaffected radiation
- low lateral temperature variation under 1000W/m² steady state
- Universal chuck for a wide variety of contacting schemes available



M. Glatthaar, J. Hohl-Ebinger, A. Krieg, M. Greif, L. Greco, F. Clement, S. Rein, W. Warta, and R. Preu, 25th EUPVSEC. 2010. Valencia, Spain

Fraunhofer ISE

Large area back contact solar cells

Calibrated *I-V* measurements

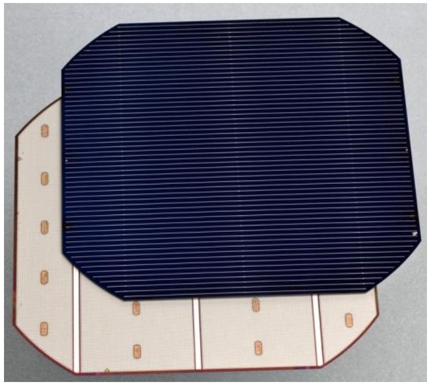
- Back contact silicon solar cells promise high efficiency potential

IBC concept

Interdigitated Back Contact

MWT

Metal Wrap Through



Large area back contact solar cells
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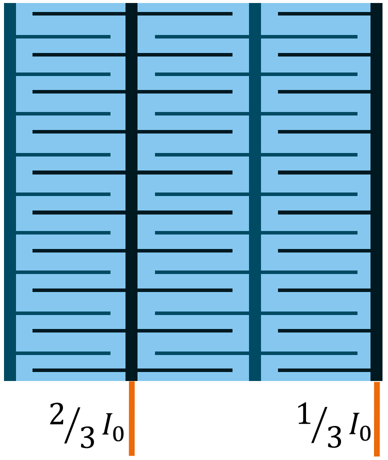
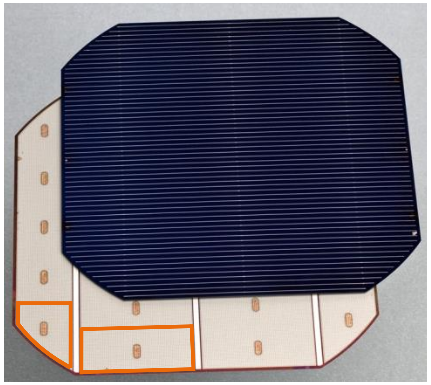
- Back contact silicon solar cells promise high efficiency potential
- Require designs with different current per pad or busbar for the same polarity

IBC concept
Interdigitated Back Contact



MWT
Metal Wrap Through



Fraunhofer ISE

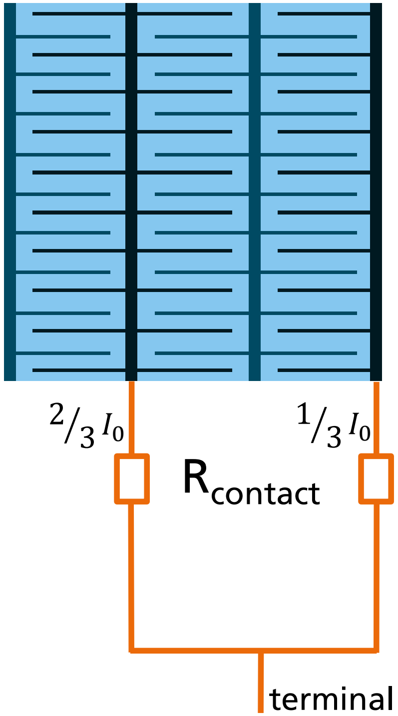
Large area back contact solar cells

Calibrated *I-V* measurements

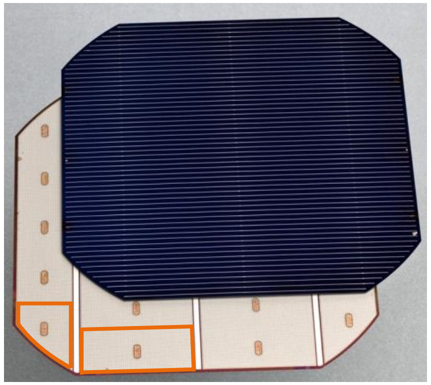
- Back contact silicon solar cells promise high efficiency potential
- Require designs with different current per pad or busbar for the same polarity
- Contact resistances can lead to non-negligible potential inhomogeneities during I-V measurement

  ➡ FF measurement errors [1]

IBC concept
Interdigitated Back Contact



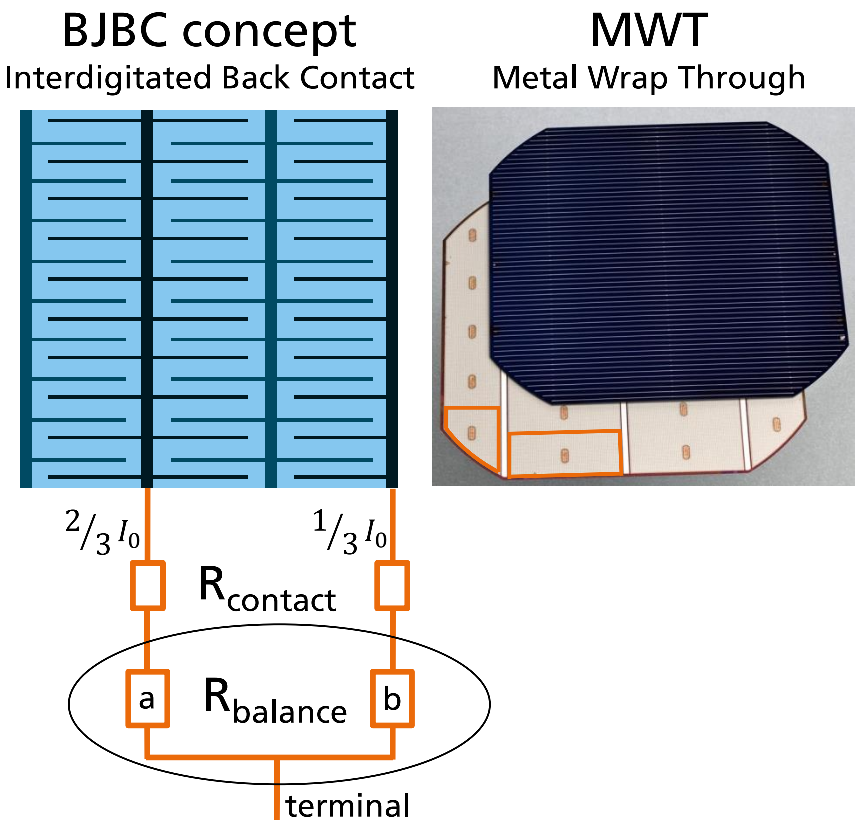
MWT
Metal Wrap Through



[1] C. Schinke *et al.*, 10.1109/JPHOTOV.2012.2195637

Large area back contact solar cells
Calibrated *I-V* measurements

- Balancing resistors [1]
  - Dominating contact and external circuit resistance
  - Adjusted so that voltage drop from terminal to pad/busbar is equal for all contact points

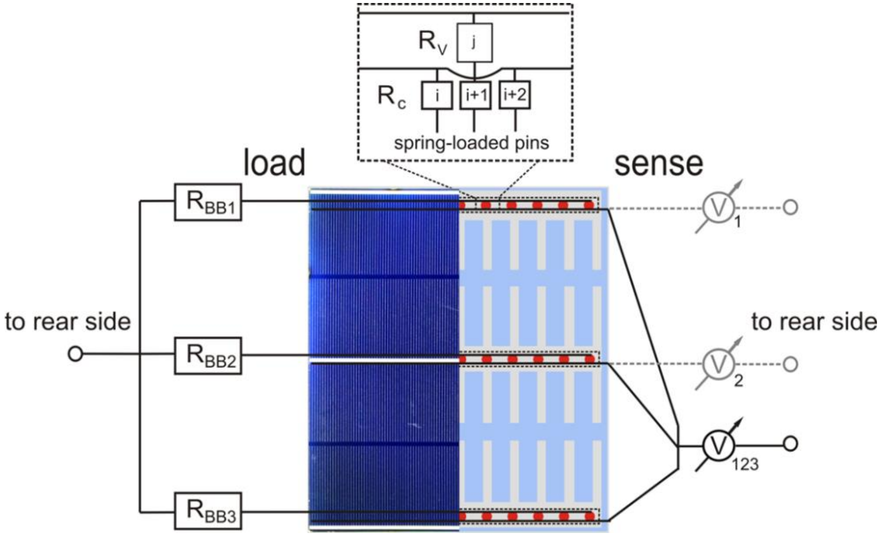


[1] R. Sinton, bifi PV workshop, Konstanz, 2012

Fraunhofer ISE

Large area back contact solar cells
Calibrated *I-V* measurements

- Balancing resistors [1]
  - Dominating contact and external circuit resistance
  - Adjusted so that voltage drop from terminal to pad/busbar is equal for all contact points
- Tested for different resistor balancing configurations and voltage sensing schemes [2]
  - cell with IBB1 = IBB3 = ½ IBB2



[1] R. Sinton, bifi PV workshop, Konstanz, 2012
[2] I. Geisemeyer et al., EUPVSEC 2014, Amsterdam

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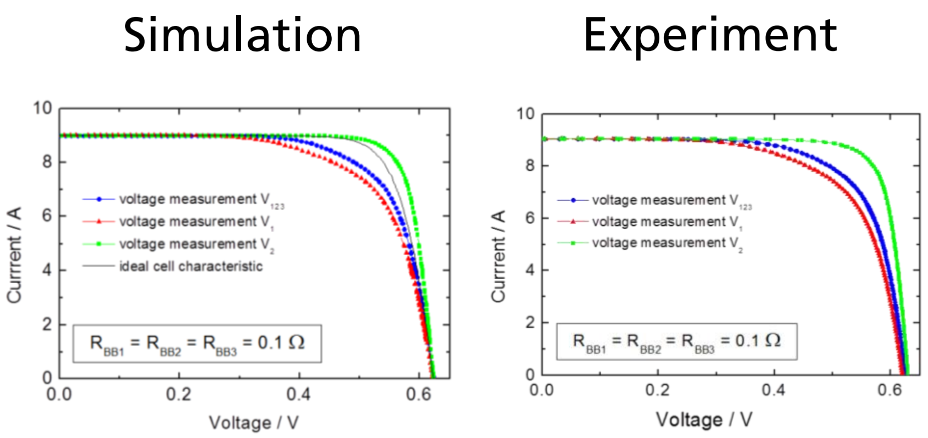
Large area back contact solar cells

Calibrated *I-V* measurements

- I-V simulations and measurements for different V sensing schemes[1]
  - Dominating but equal balancing resistors of 0.1 Ω
  - FF underestimation of 12%$_{abs}$
    overestimation of 3.5%$_{abs}$
    ➡ Cell with 25.0 % efficiency measured as 26.0%!



[1] I. Geisemeyer et al., EUPVSEC 2014, Amsterdam

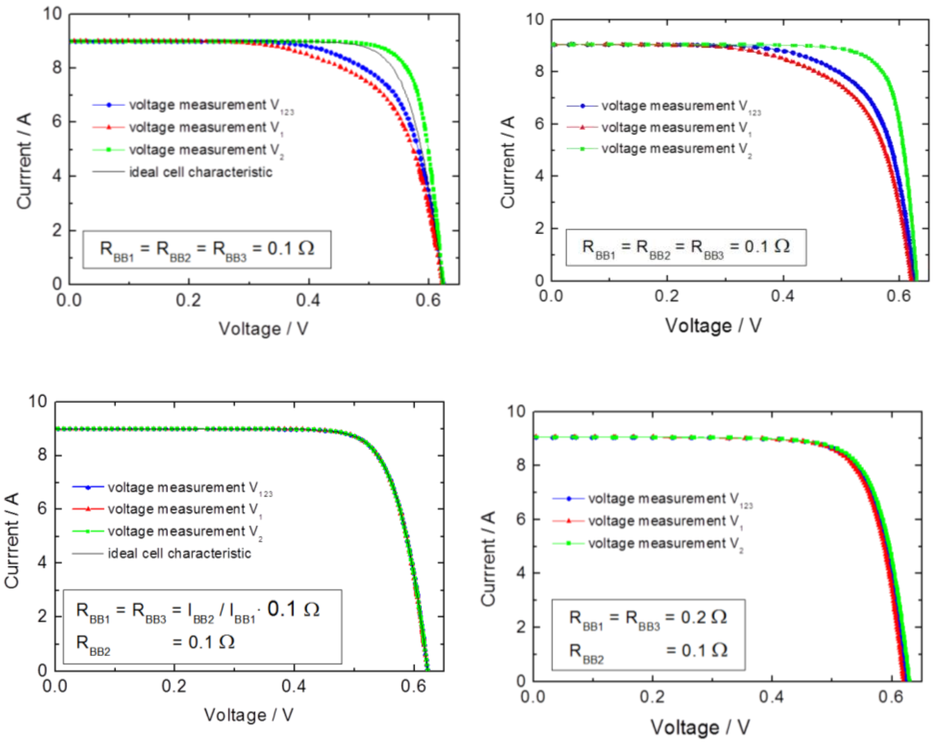
Fraunhofer ISE

Large area back contact solar cells

Calibrated *I-V* measurements

- I-V simulations and measurements for different V sensing schemes[1]
  - Dominating but equal balancing resistors of 0.1 Ω
  - FF underestimation of 12%$_{abs}$
    overestimation of 3.5%$_{abs}$
    ➡ Cell with 25.0% efficiency measured as 26.0%!
- Only with adjusted balancing resistors
  - applied voltage equal at all contacting points
  - sense contacting scheme does not influence FF

Simulation | Experiment



[1] I. Geisemeyer et al., EUPVSEC 2014, Amsterdam

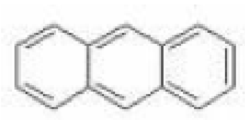
Outline

- Accurate performance measures:
  Why are they needed and how can they be realized?
- Highly efficient silicon solar cells with low complexity
  - Summary of future developments
  - Challenges for performance measurements:
    Bifaciality, contacting
- Emerging technologies and their measurement challenges
  - Perovskite cells
  - Multi-junction cells
    - III-V concentrator cells
    - Organic cells

Thin film technologies (CdTe, CIGS, a-Si…) not discussed

Organic PV Devices (OPV): Physical properties
Fundamentally different from conv. inorganic PV devices

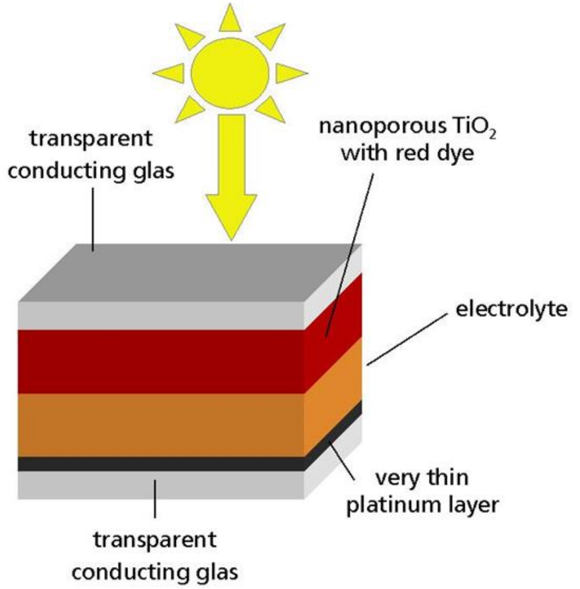
Property	Germanium	Anthracene
Atomic Weight	72.63	178.22
Melting Point (°C)	937	217
Density (g(cm³)	5.3	1.28
Density (molecules/cm³)	4.42×10^{22}	0.42×10^{22}
Crystal Strcture	Diamond	Monoclinic
Dielectric Constant	16	3.2
e-Mobility at 300K (cm²/Vs)	3800	1.06
h-Mobility at 300K (cm²/Vs)	1800	1.31
Concentration of intrinsic carriers (cm^{-3})	5.2×10^{13}	~10^{-4}
Vacuum Ionisation Energy (eV)	4.8	5.8

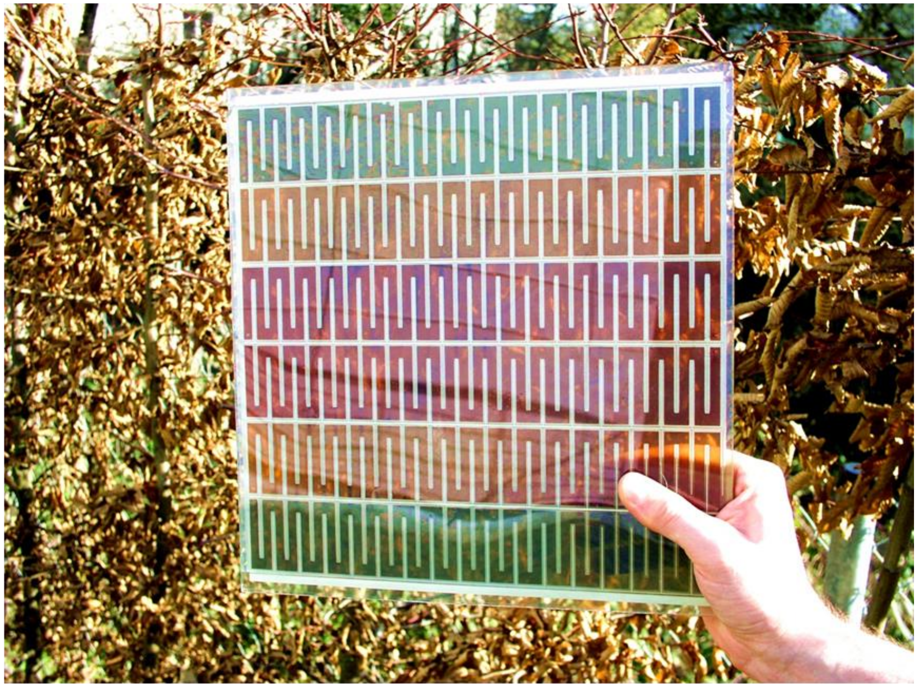


Anthacene data from W. Warta *et al.*, Phys. Rev. B 32, 1172 (1985)

Fraunhofer ISE

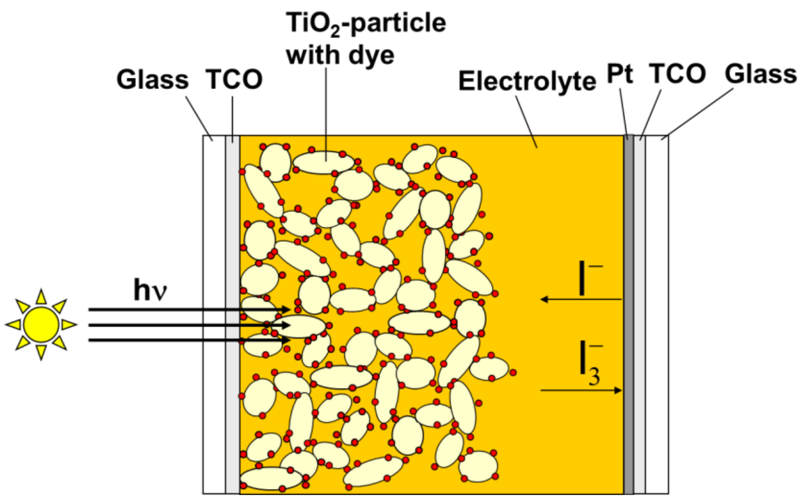
Dye Sensitized Solar Cells – Principle
Example: Conv. liquid electrolyte cell

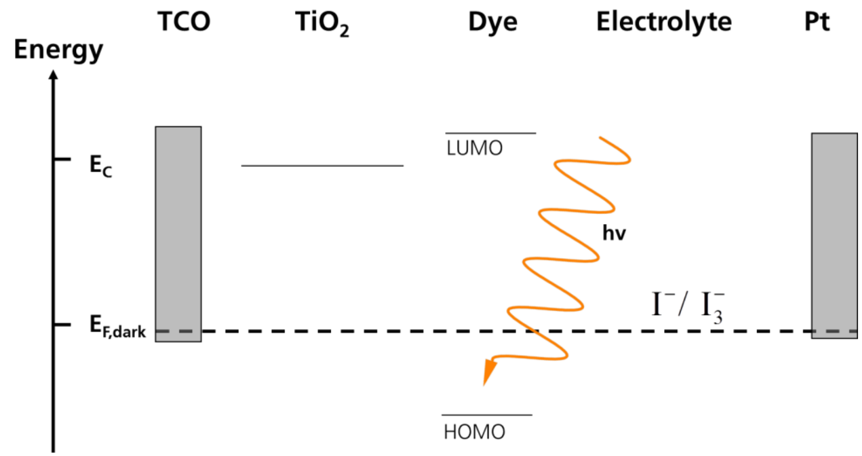




S. Glunz, IMTEC, 2013

Dye Sensitized to Perovskite Solar Cells – Principle
Mesoporous Conductor





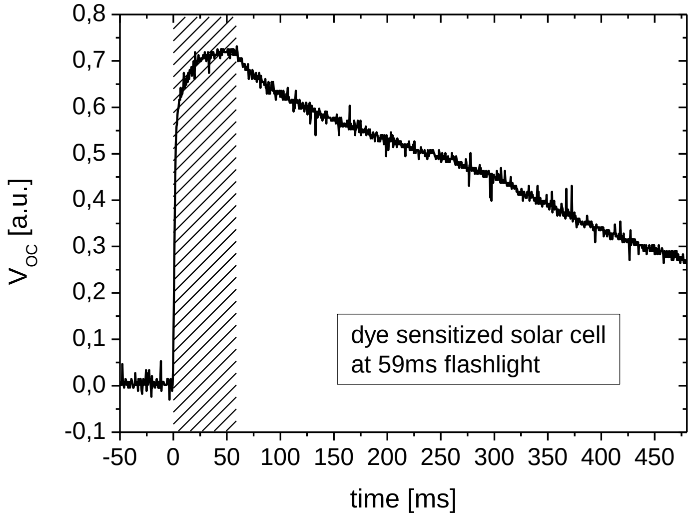
S. Glunz, IMTEC, 2013

- Strong efficiency gain with Perovskite as dye
- Perovskite cell works also with non-conducting (Al_2O_3) mesoporous and planar layer
- Key: Blocking layers to separate electron-hole pairs

Fraunhofer ISE

Time dependence effects in DSSC measurements
Hysteresis of IV measurements on Perovskite cells

- Previously: IV of DSSC correct if measured slowly
- Conv. DSSC with perovskite absorber: behaves similar (Dualeh et al. 2013)



Fraunhofer ISE

Time dependence effects in DSSC measurements
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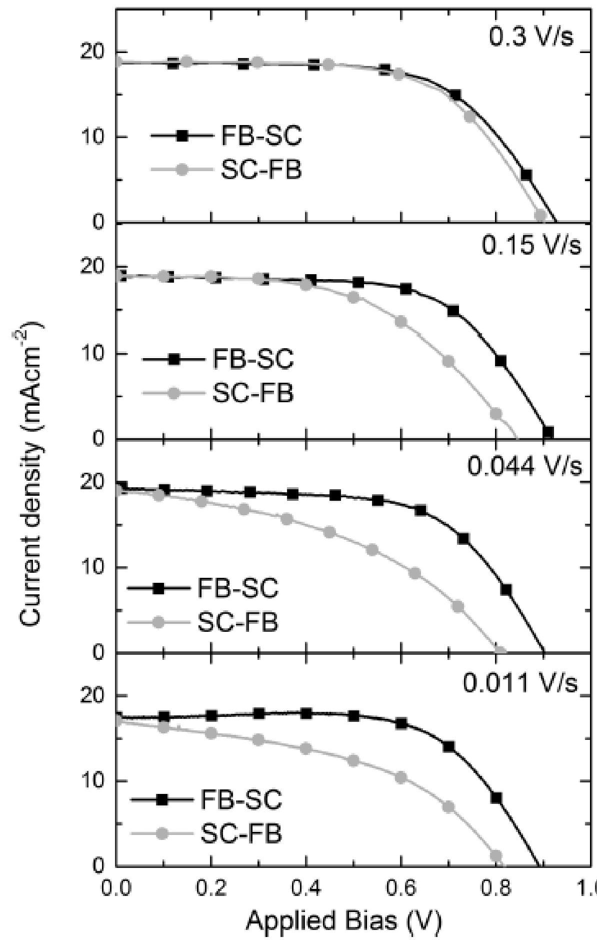

Planar structure

Snaith et al. J. Phys. Chem. Lett. 2014

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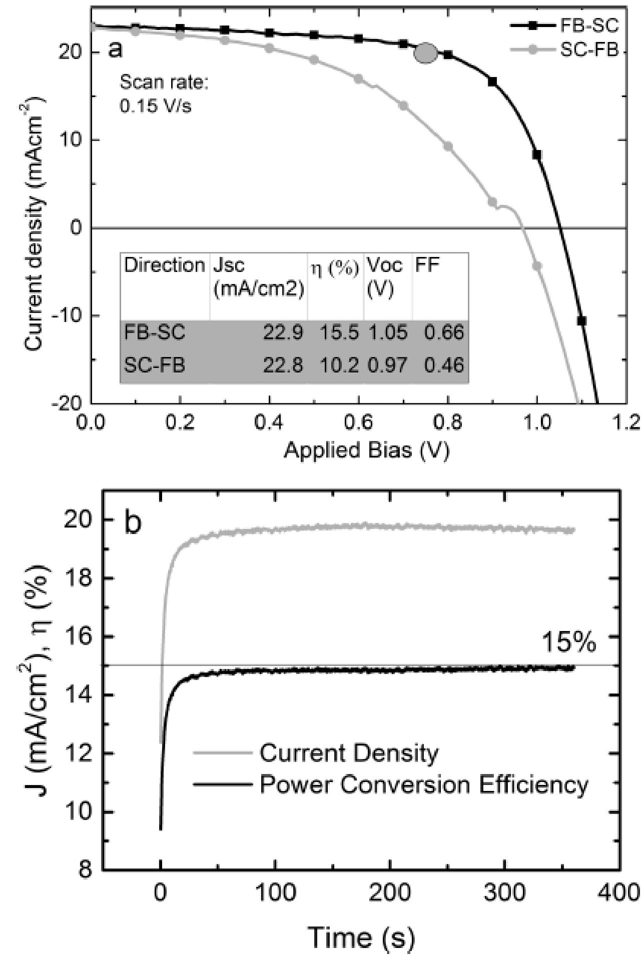
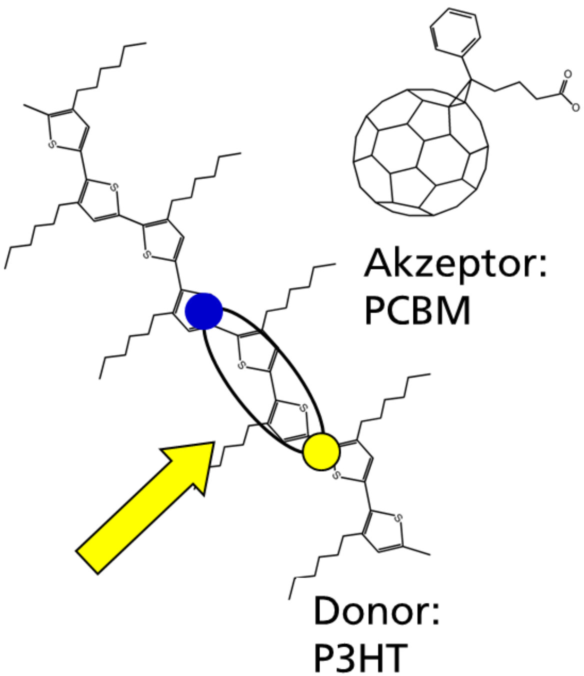
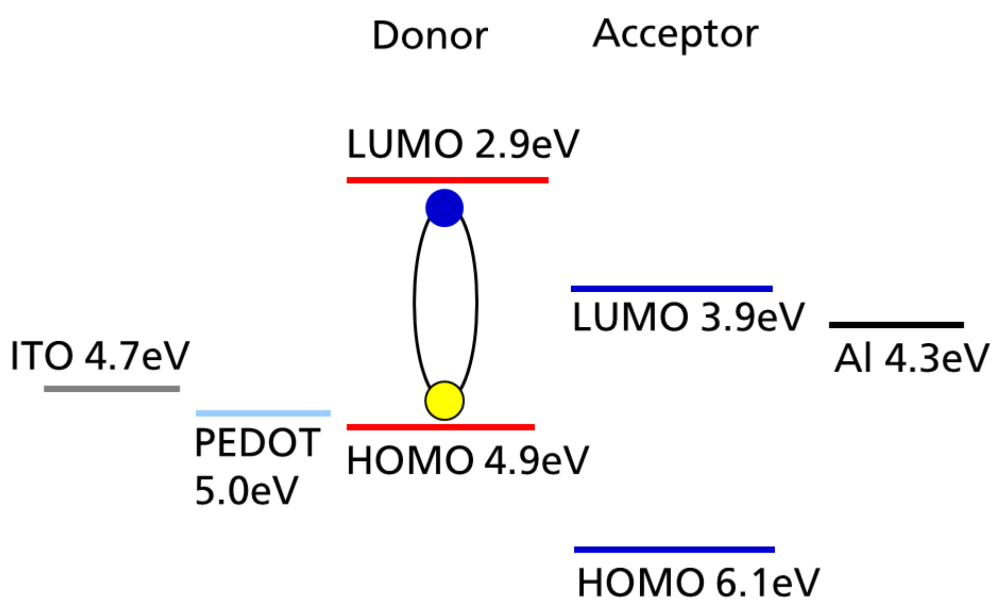


MSSC (with mesoporous Al_2O_3)
Snaith et al. J. Phys. Chem. Lett. 2014

Fraunhofer ISE

Organic PV devices (OPV): Principle
Example: Polymer Cell



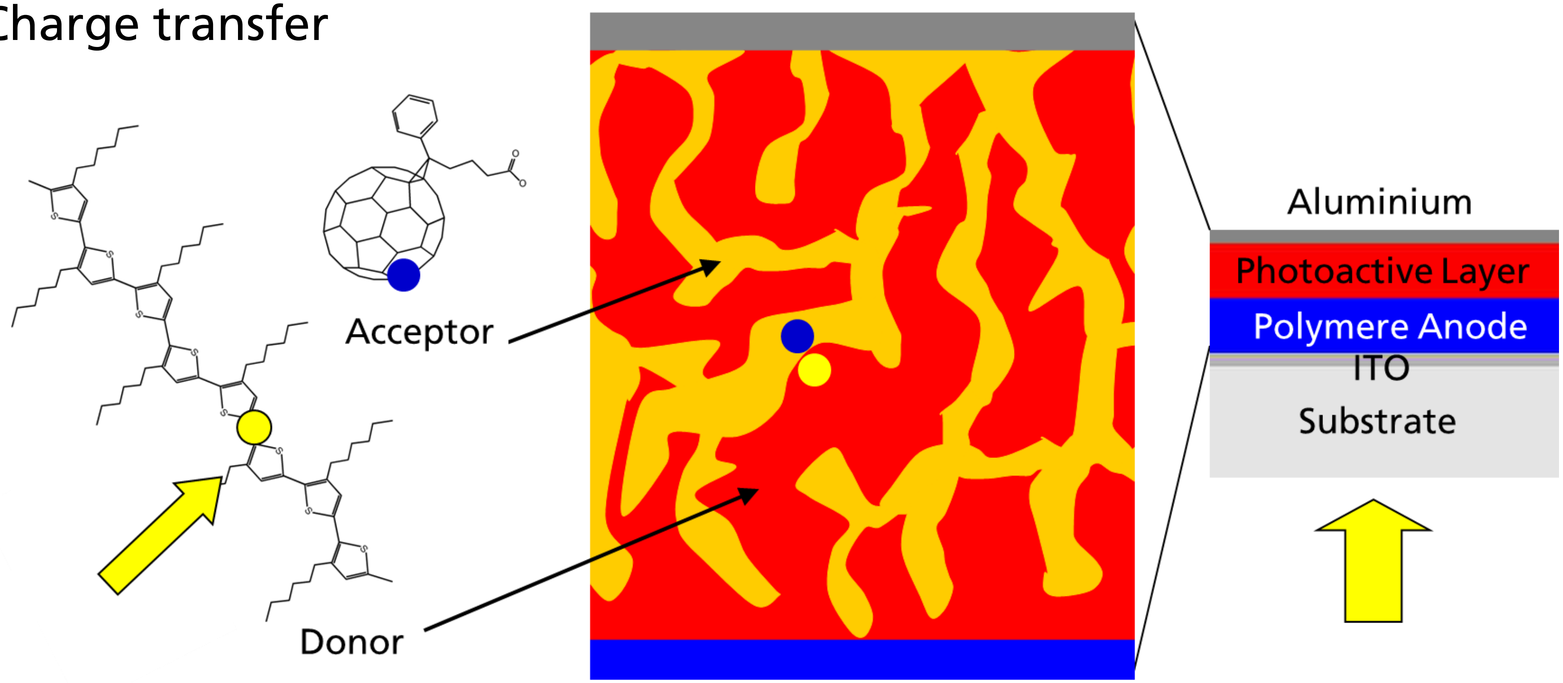


S. Glunz, IMTEC, 2013

Photon creates exciton – excitonic solar cell

Organic PV Decvices (OPV) – Principle
Example: Polymer Cell

Charge transfer

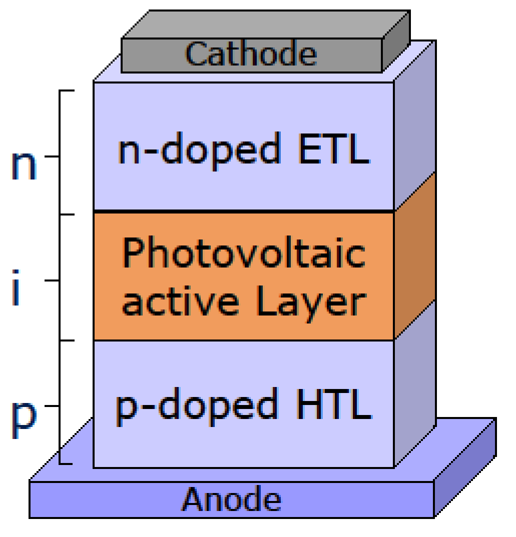


S. Glunz, IMTEC, 2013

Bulk heterojunction structure

Organic PV Devices (OPV): Principle
Variants

- Absorber polymer – solution processed, e.g. by printing
  - Room temperature process, high speed
- Absorber small molecules – vacuum sublimation
  - High purity
  - Allows complex structures

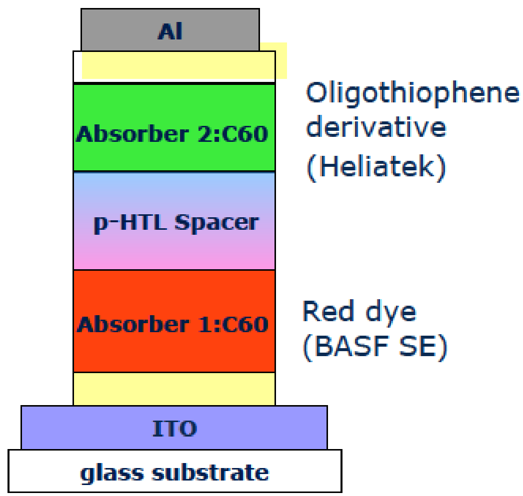


M. Riede, DPG Dresden, 2011

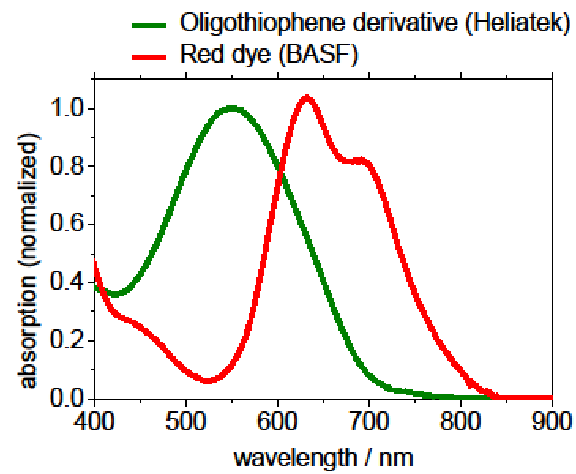
Organic solar cells: Principle
Development Directions

- Absorber polymer – solution processed, e.g. by printing
  - Room temperature process, high speed
- Absorber small molecules – vacuum sublimation
  - High purity
  - Allows complex structures
- Multi-junction cells:

  Path to competitive efficiencies



heliatek
Organic based Photovoltaics



DPG Frühjahrstagung 2011 Dresden Moritz Riede Slide 2:

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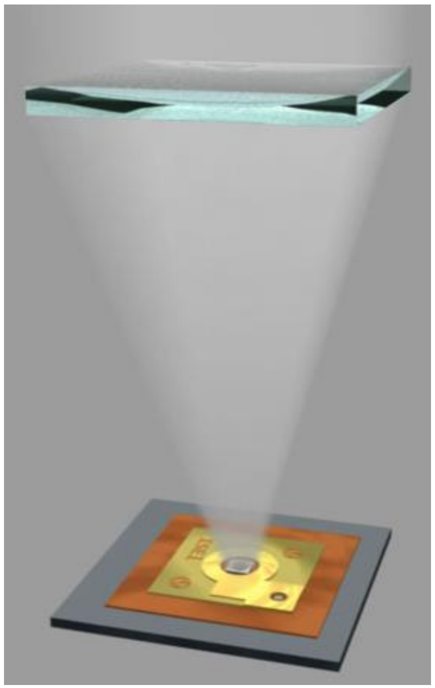
  - Multi-junction cells
    - III-V concentrator cells
    - Organic cells

Thin film technologies (CdTe, CIGS, a-Si…) not discussed

Calibration of Multi-Junction Cells
III-V (Concentrator) Devices

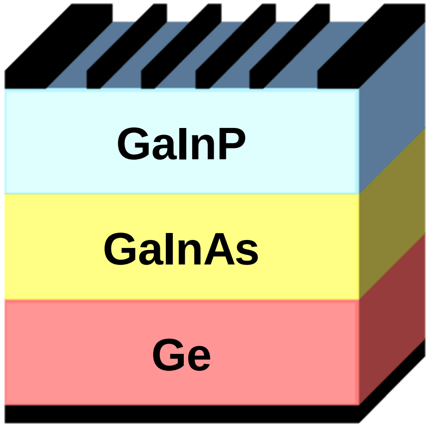
Advantage of Two-Axis Tracking in CPV: Land Use



2014: SOITEC SOLAR builds a 300 MW CPV installation, using the new 150 MW_p/yr factory near San Diego, CA!

Fraunhofer ISE

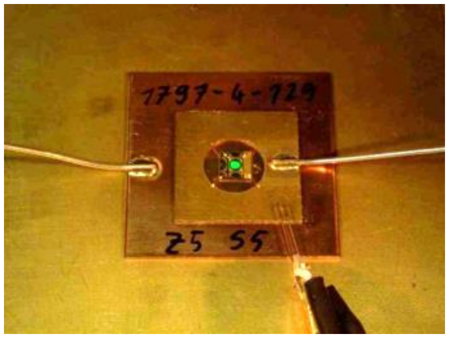
Calibration of Multi-Junction Cells
High Demand on Measurement Technique

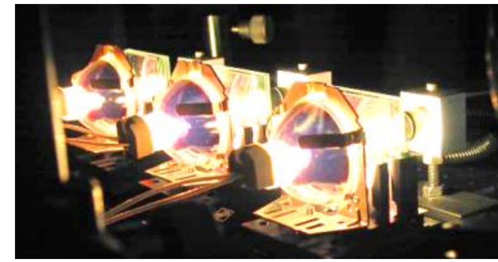


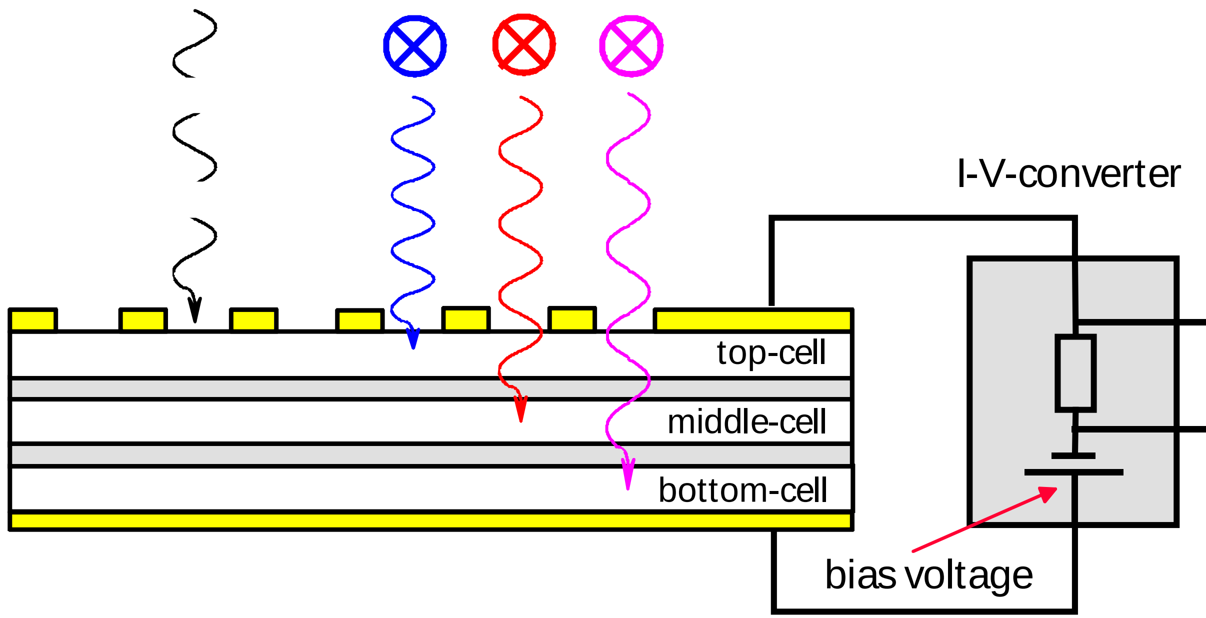
- Internal series connection
- Individual subcells not accessible directly
- Principle of current limitation:

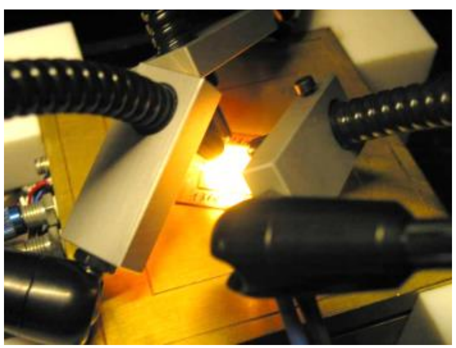
$$I_{MJ} = Min\{I_i\} \qquad V_{MJ} = \sum_i V_i$$

Calibration of Multi-Junction Cells
Spectral Response Measurement









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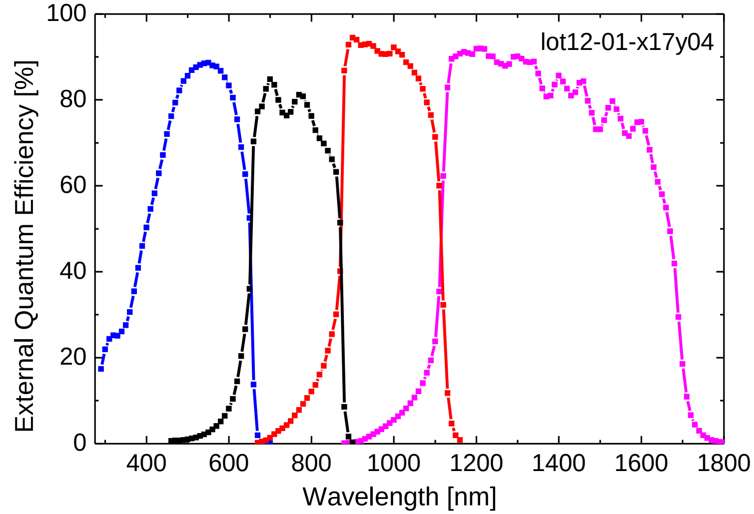
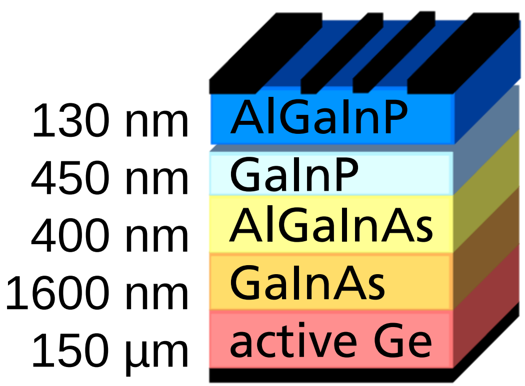
Calibration of Multi-Junction Cells

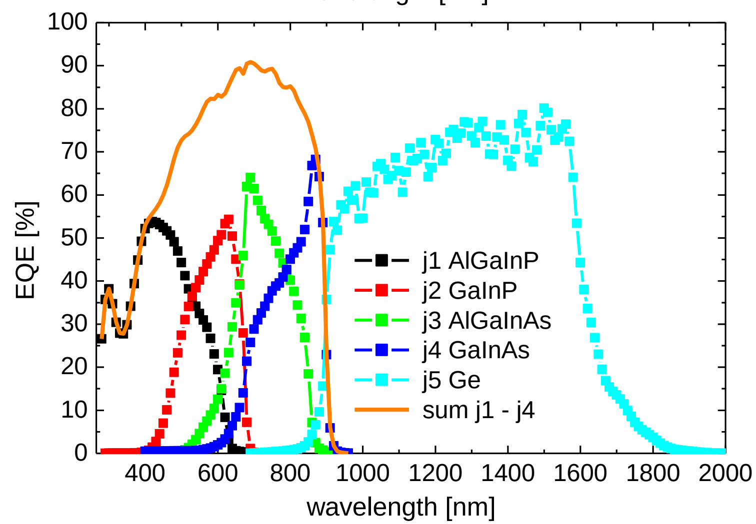
Spectral Response Measurement

Bias irradiation:
Excess generation in all cells apart from the one to be measured ➡ limiting cell





1117-quint



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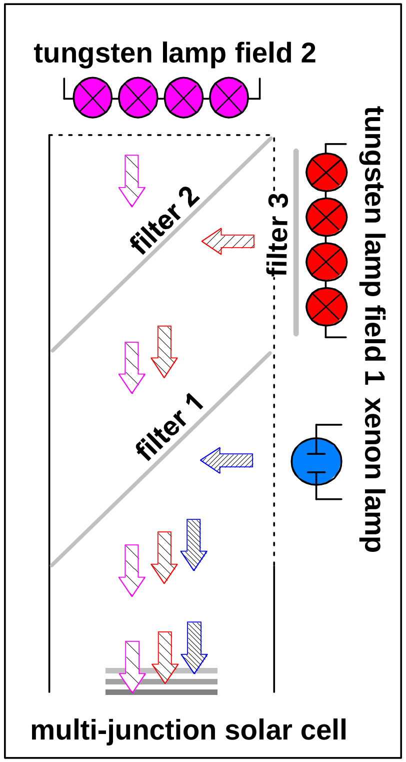
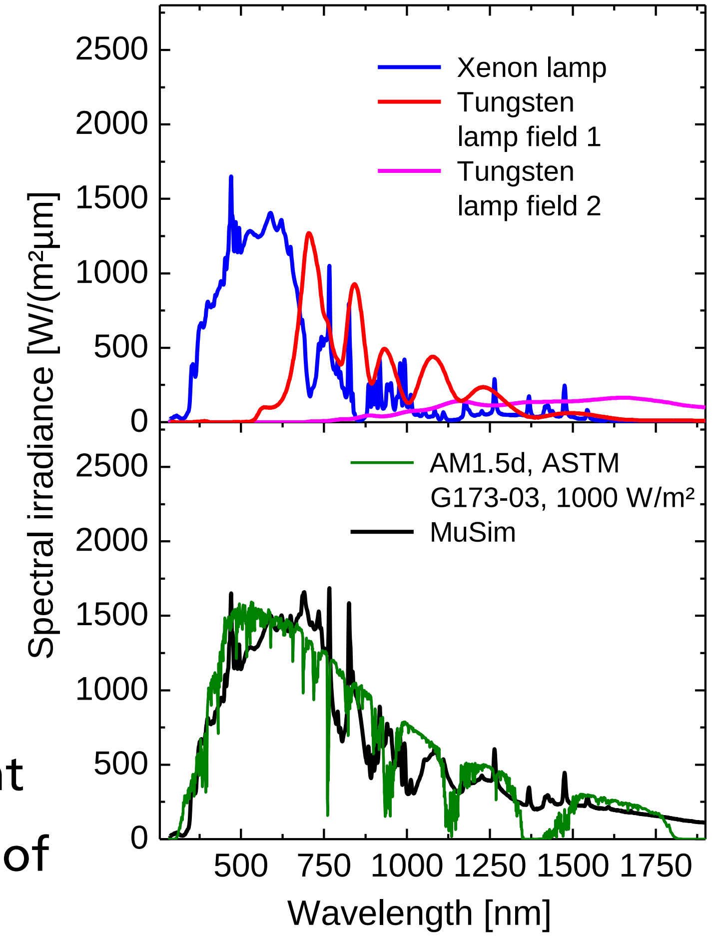
Calibration of Multi-junction devices

IV measurement at Multi-Source-Simulator (MuSim)





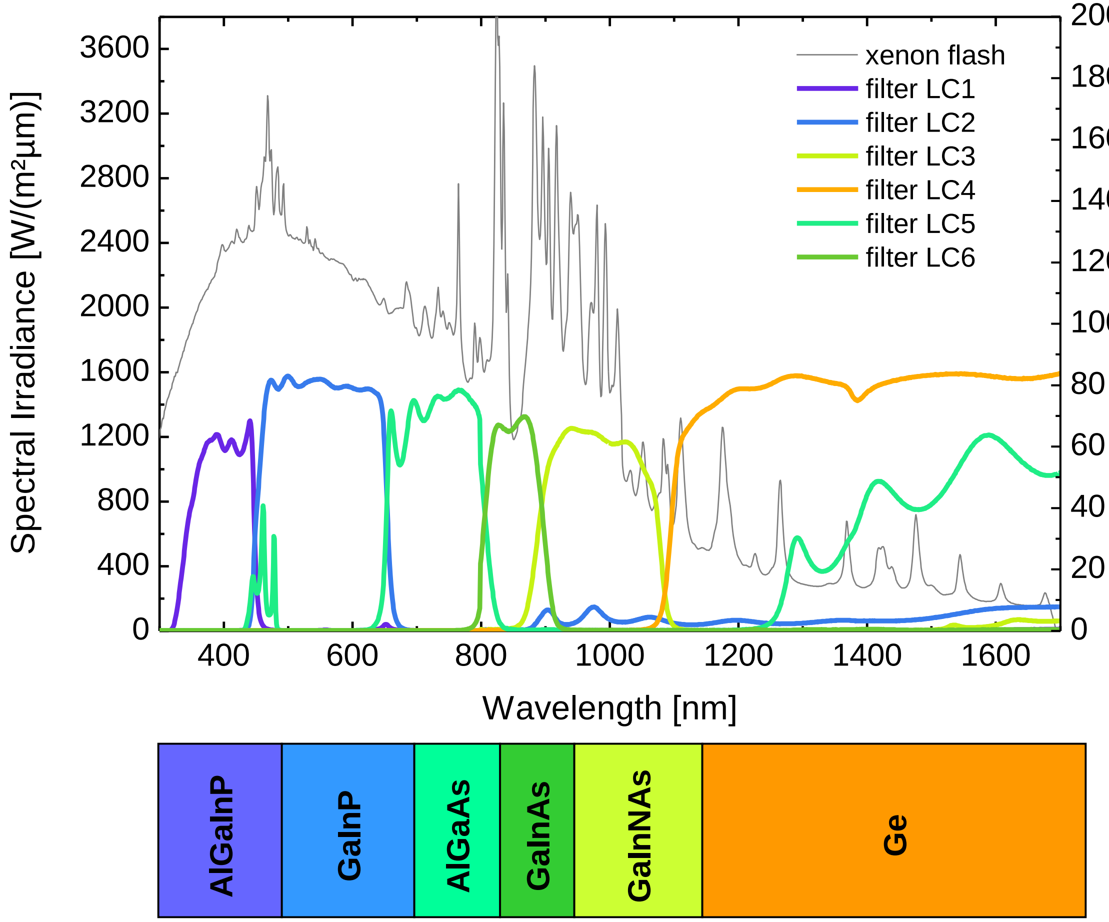
- Adjust so that each cell delivers STC-current
- Settings calculated from spectral response of each junction

Fraunhofer ISE

Six Source Sun Simulator X-Sim

Spectrum of the Light Channels

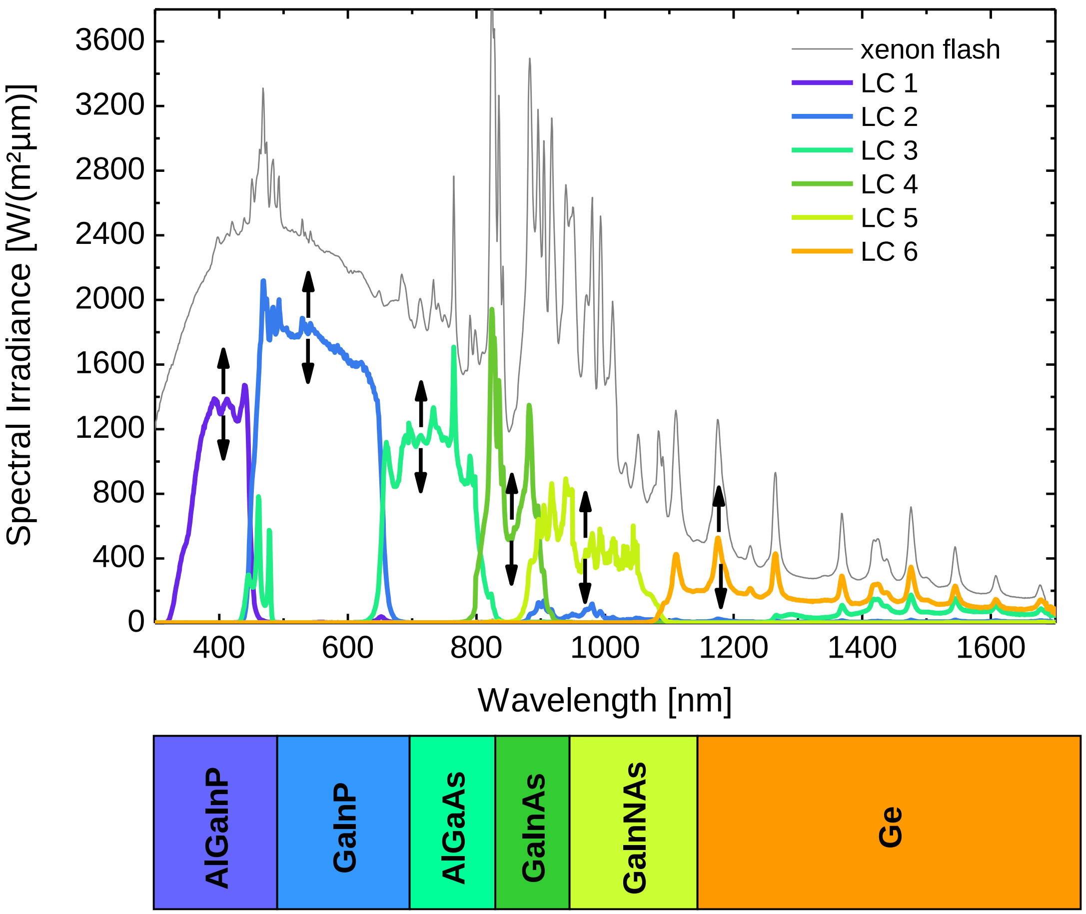
- Xenon flash tube
- Filter transmission with a sharp separation of the spectral ranges
- Spectral ranges based on the SR of a ISE 6-junction solar cell



Fraunhofer ISE

Six Source Sun Simulator X-Sim
Spectrum of the Light Channels

- Xenon flash tube
- Filter transmission with a sharp separation of the spectral ranges
- Spectral ranges based on the SR of a ISE 6-junction solar cell
- Intensity of each LC independently adjustable

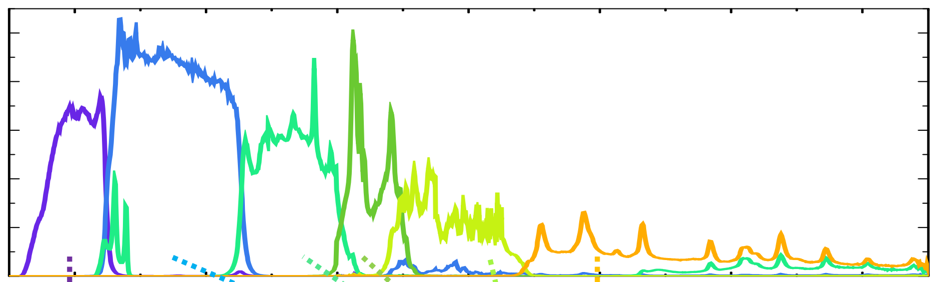


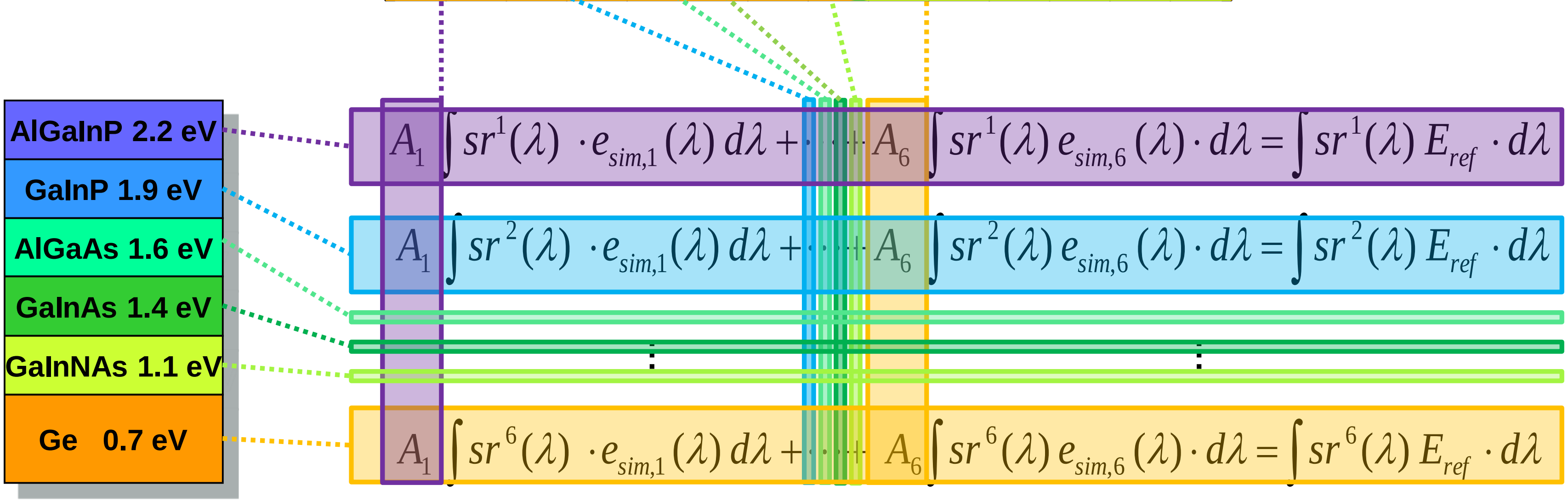
Fraunhofer ISE

Six Source Sun Simulator X-Sim

Spectral Correction

$$j_{sim}^{TC,i} = j_{ref}^{TC,i}$$





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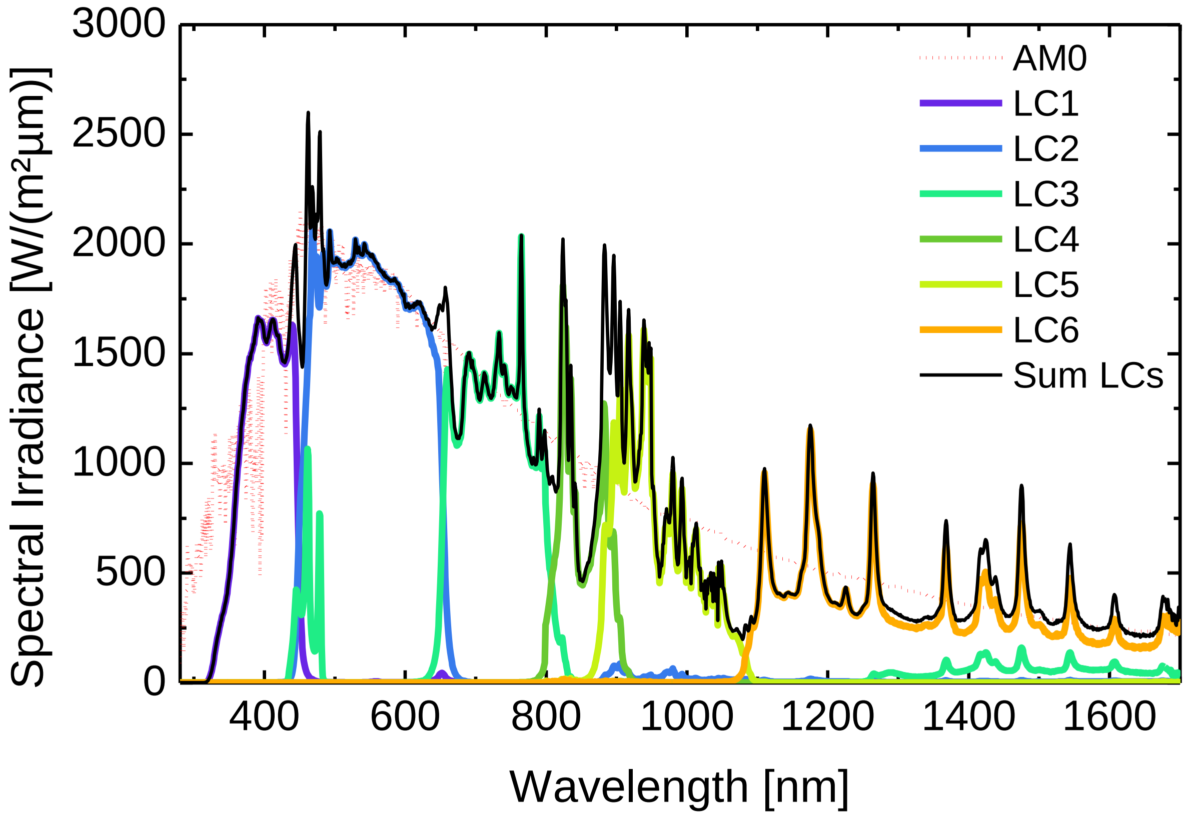
Six Source Sun Simulator X-Sim
Simulator Spectrum

- Reference spectrum AM0
- Sum of spectra of all LCs in the measurement plane



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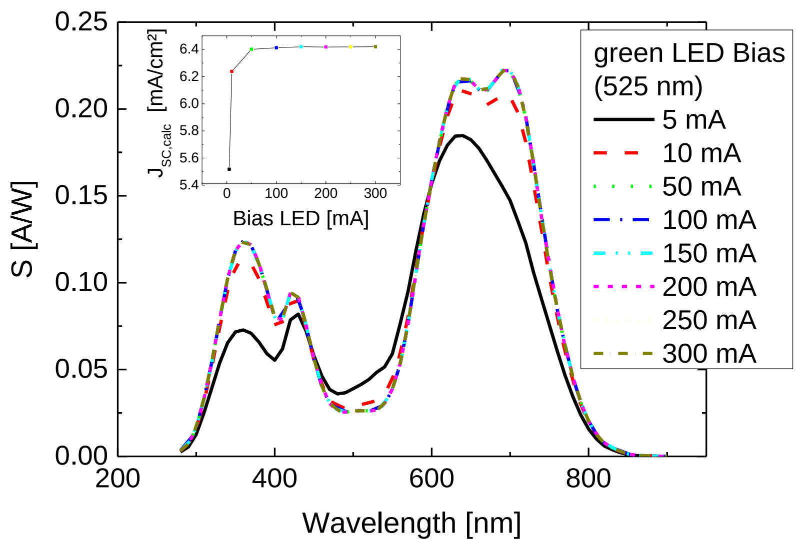
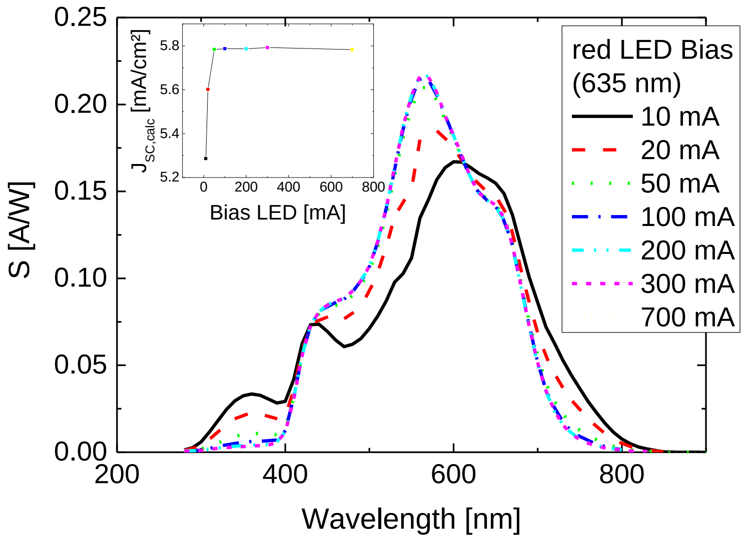
Calibration of Organic multi-junction devices
Spectral Response Measurement

- Bias irradiation dependence
  - Spectral overlap of absorbers: identification of artifacts difficult
  - Irradiation dependence of limiting cell hard to determine

  → Knowledge of corresponding single cells needed

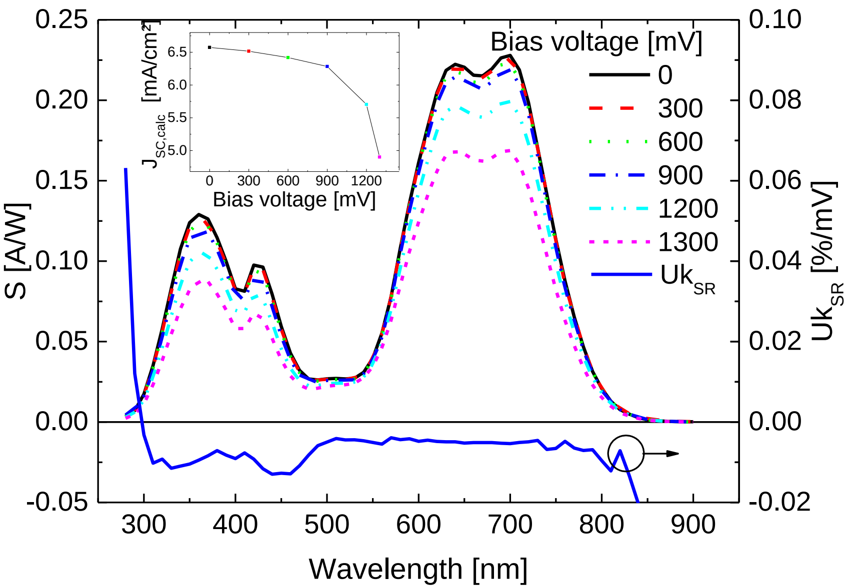


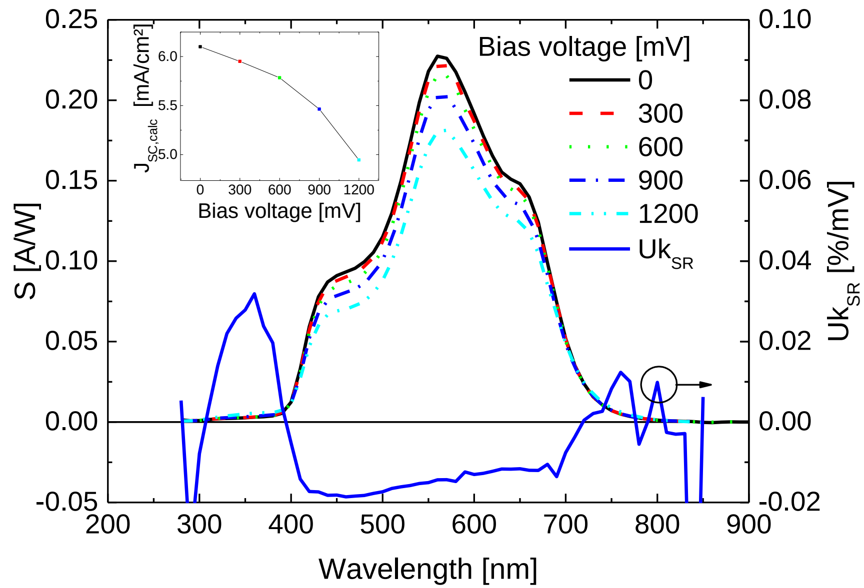


Fraunhofer ISE

Calibration of Organic Multi-Junction Devices
Spectral Response Measurement

- Bias voltage dependencies
  - Bias voltage dependence due to field assisted charge separation
  - Bias voltage variation at actual bias light conditions for uncertainty estimation





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How to Assure International Comparability?
Calibration Labs Accredited to ISO 17025

- Comparable IV-curve parameters important competition measure
- Key: Traceability to SI-units
- Assured by calibration labs accredited according to ISO 17025
  - extensive, audited uncertainty calculation
  - regular proficiency test: inter-comparison with other calibration labs (NREL, AIST, JRC, KIER?)

ilac-MRA
DAkkS Deutsche Akkreditierungsstelle D-K-11140-01-00

- Test labs can also have accreditation to ISO 17025, but
  - do not need to implement uncertainty calculations
  - do not necessarily assure traceability of measured results to SI-units and international comparability

Summary

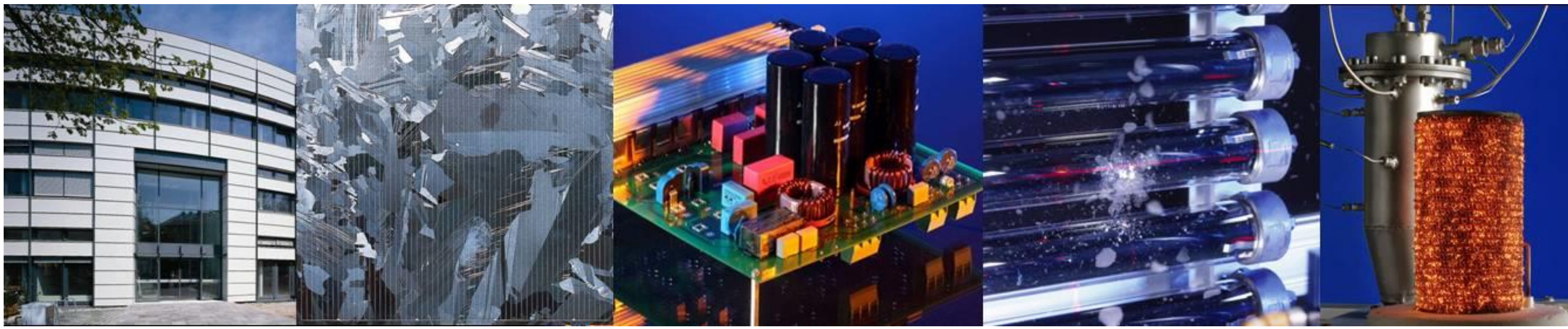
- Future prospect of silicon solar cells:
  High efficiency cells with low complexity
- Rear contacted and bifacial cells will play an increasing role
- Agreed way how to valuate the gain of bifaciality urgently needed
- Faulty contacting of rear contacted cells can lead to marked errors
- Perovskite cells: Metastability has enormous influence on IV-results
- Multi-junction cells: Strong expertise available, but challenges high especially for organic devices

Acknowledgment

Parts on high efficiency silicon solar cells and III-V-multi-junction cells courtesy of Martin Hermle and Gerald Siefer, respectively

Contributions from Holger Seifert, Jochen Hohl-Ebinger

Thank You for Your Attention!



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