New challenges and possibilities for silicon based solar cells

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Outline

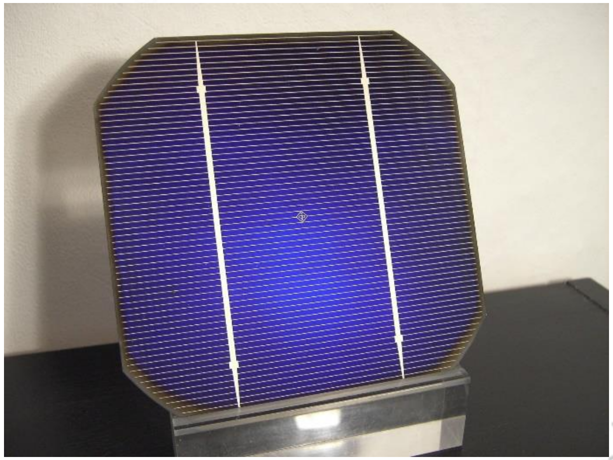
-What is a solar cell?

-How does it work?

-Silicon based solar cells manufacturing

-Challenges and Possibilities

-Concluding remarks



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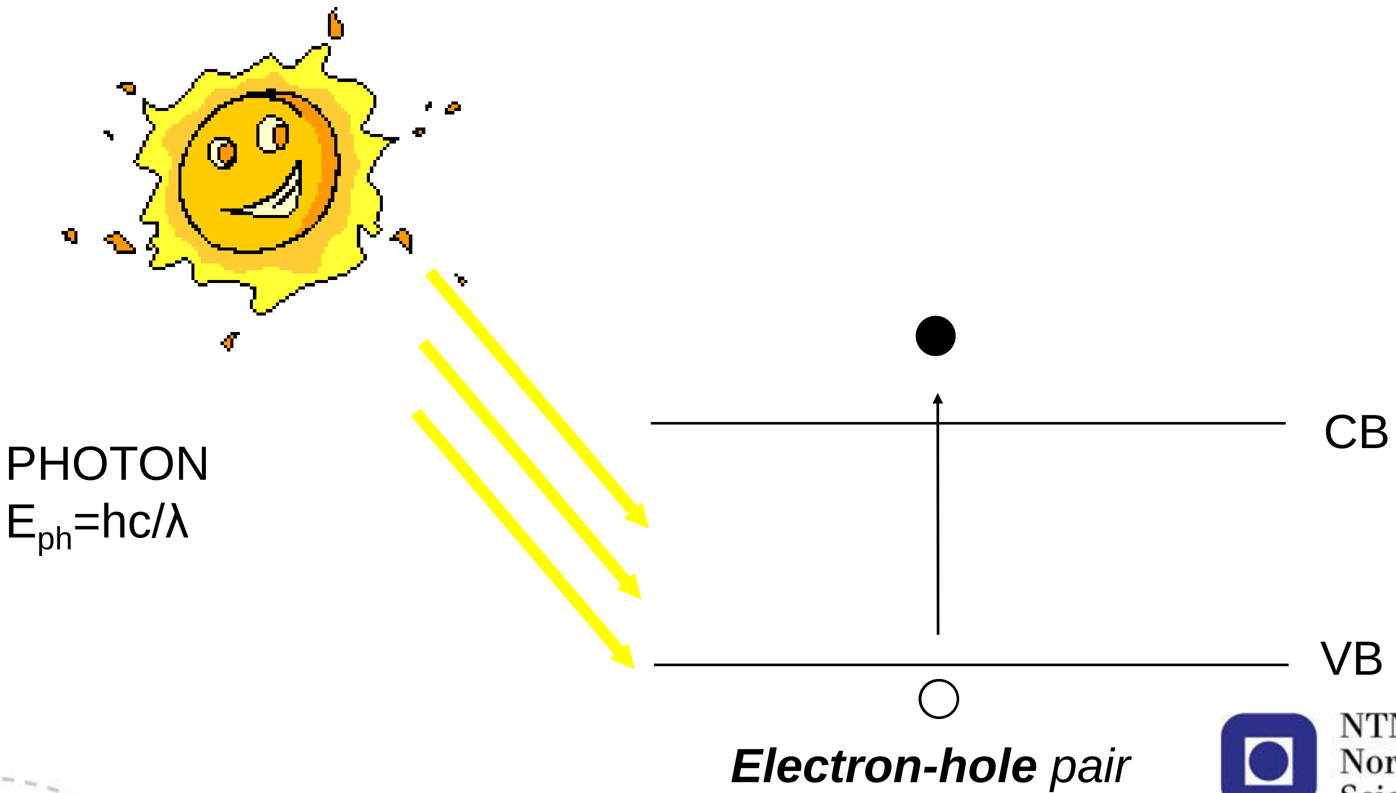
What is a solar cell?

- **It is a device that converts the energy of the sunlight directly into electricity.**



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How does a solar cell work?

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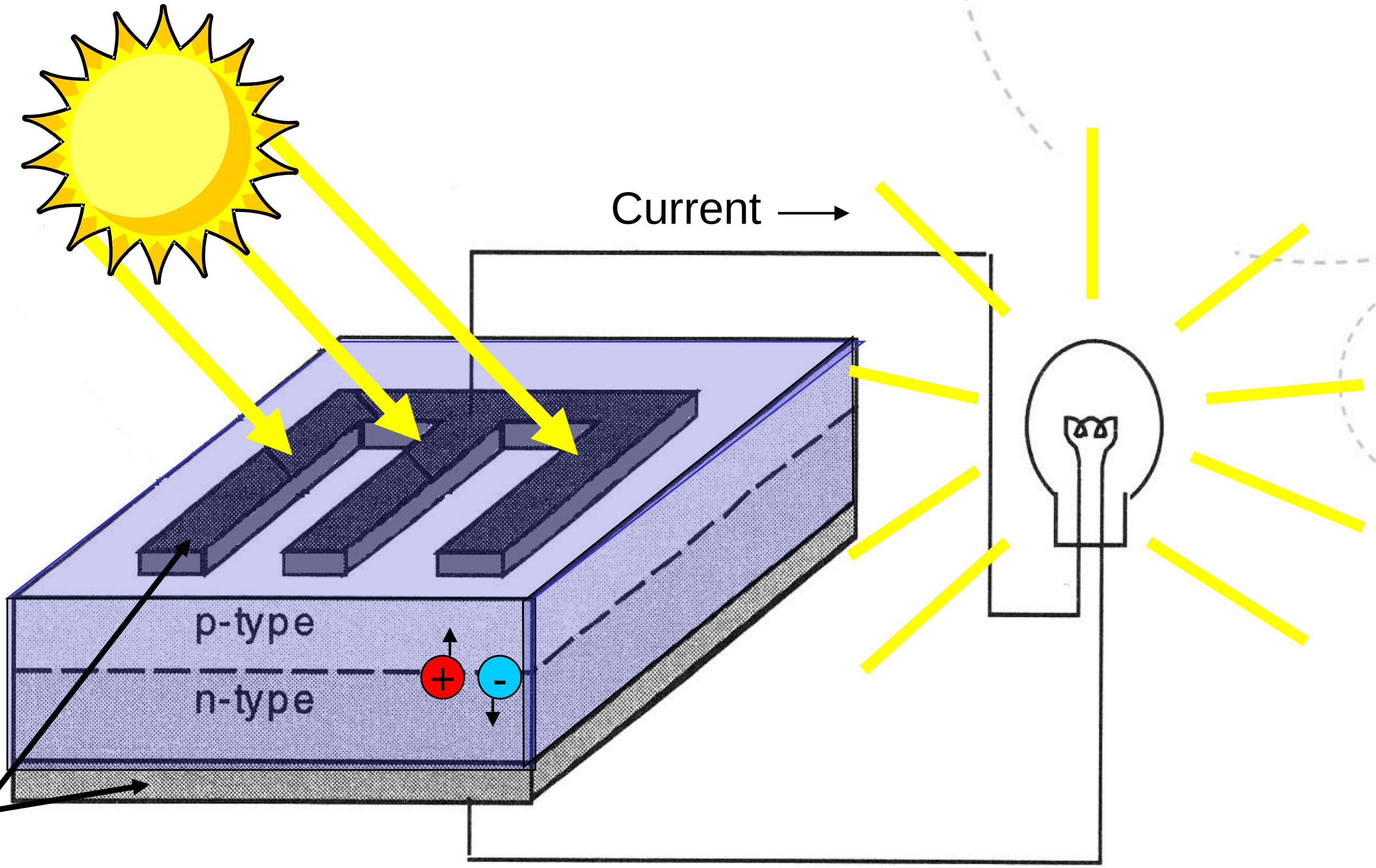
How does a solar cell work?



Semiconductor

E_g

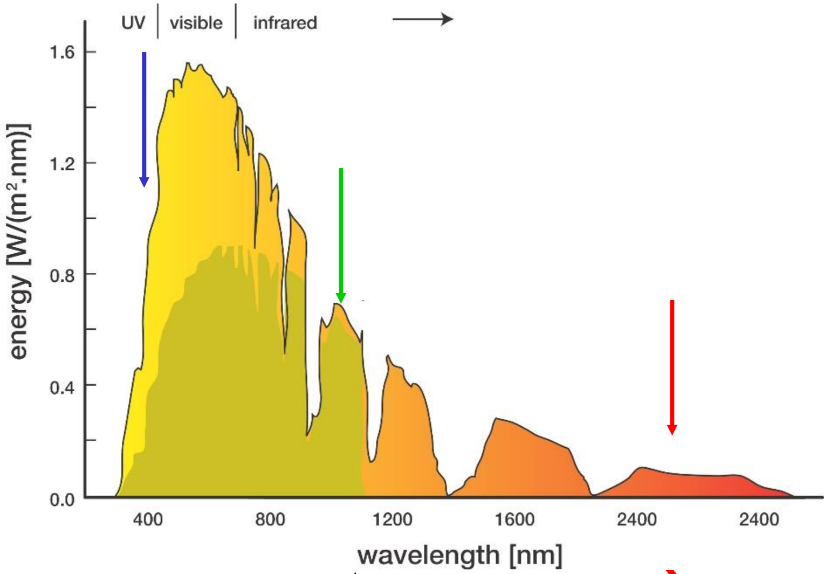
P-n junction

Metallic contacts

Turid Worren Reenaas

How does a solar cell work?

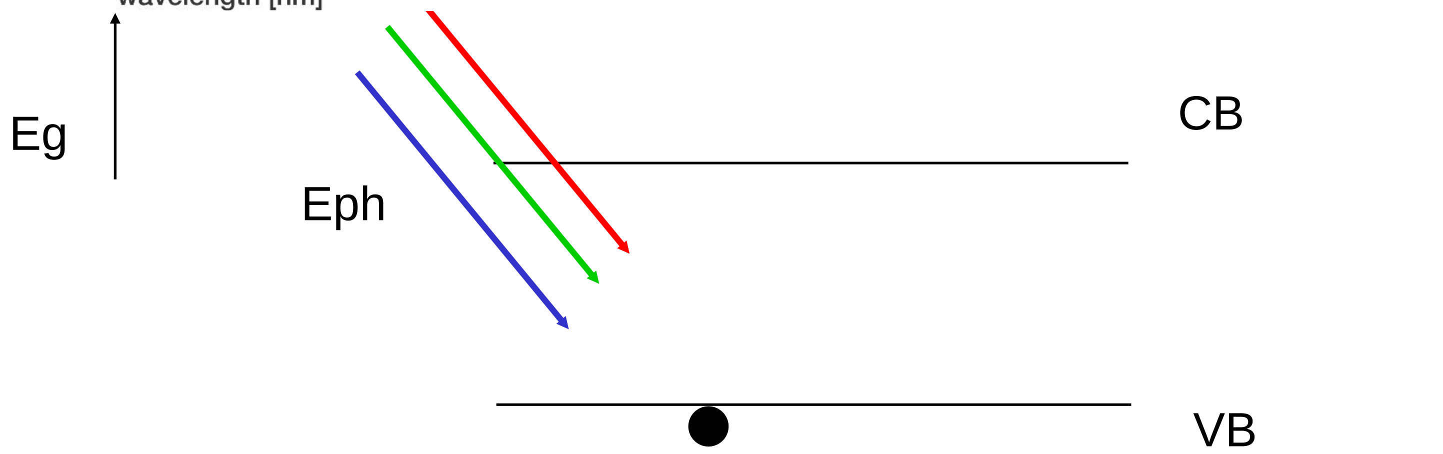
- *Charge generation (electron-hole pairs)*
- *Charge separation (electric field)*
- *Charge transport*



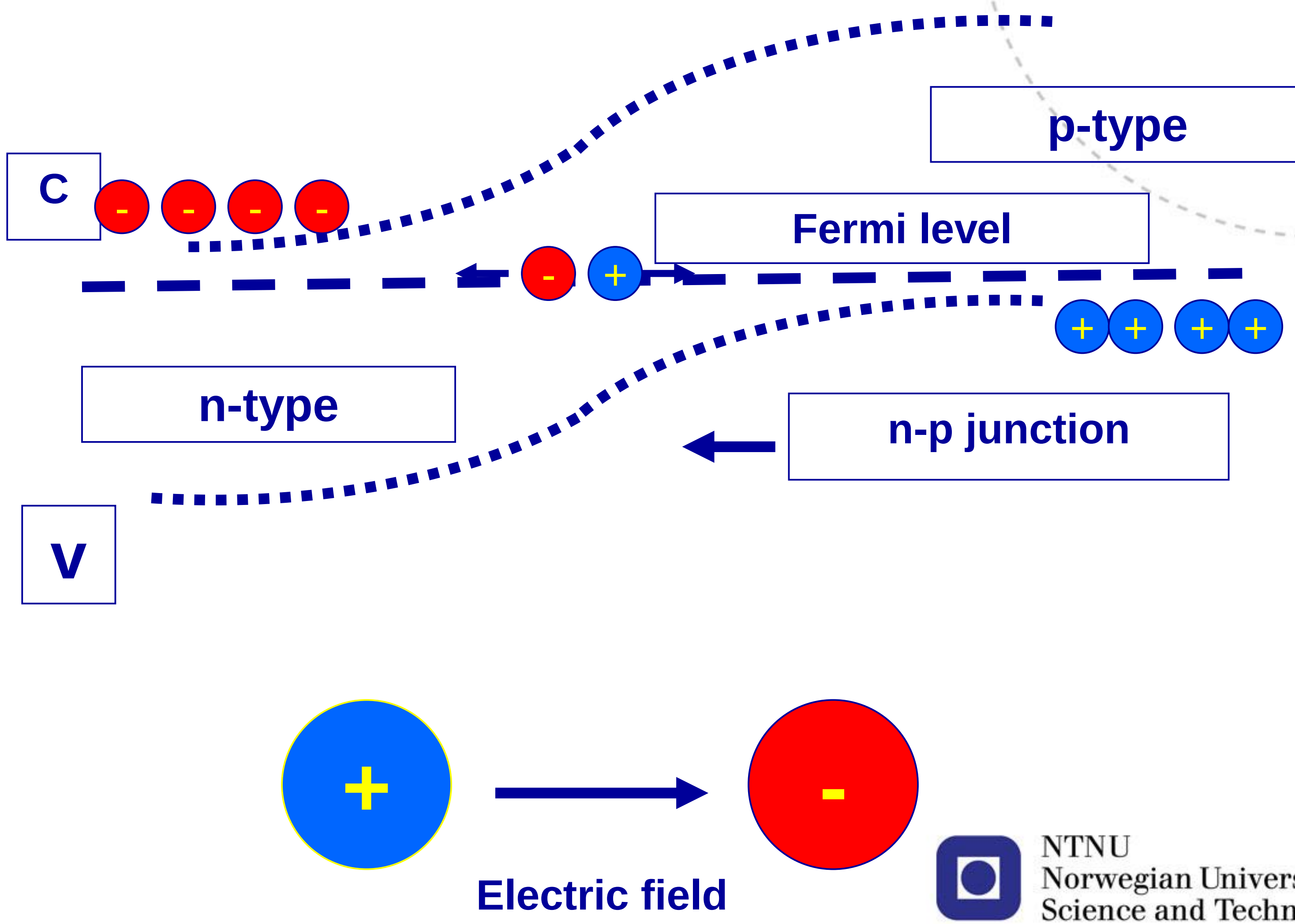
- *Charge generation (electron-hole pairs)*

- Charge separation (electric field)

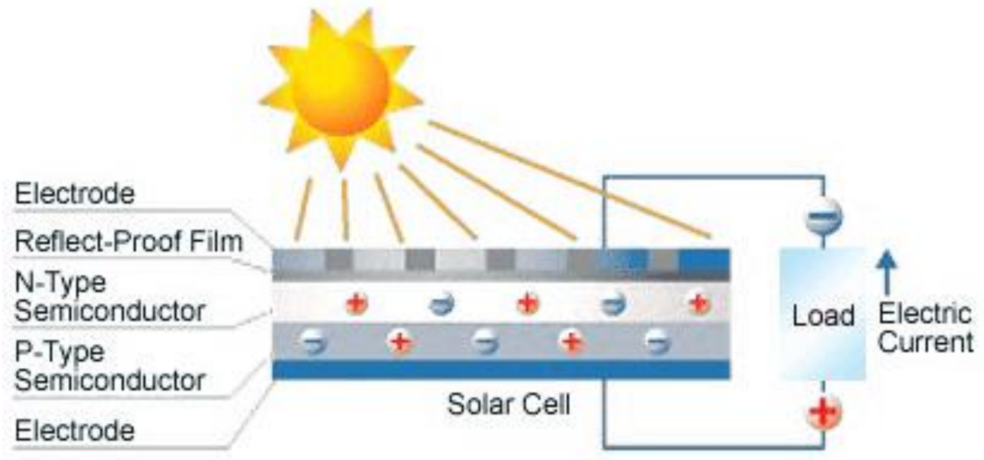
- Charge transport

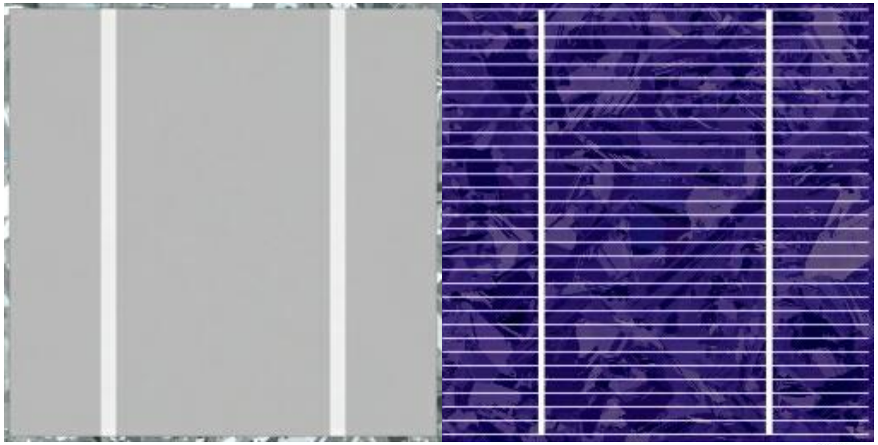


- Charge generation (electron-hole pairs)
- **Charge separation (electric field)**
- Charge transport



- *Charge generation (electron-hole pairs)*
- *Charge separation (electric field)*
- ***Charge transport***





Back and front side of a silicon solar cell

Semiconductors

Materials for solar cells

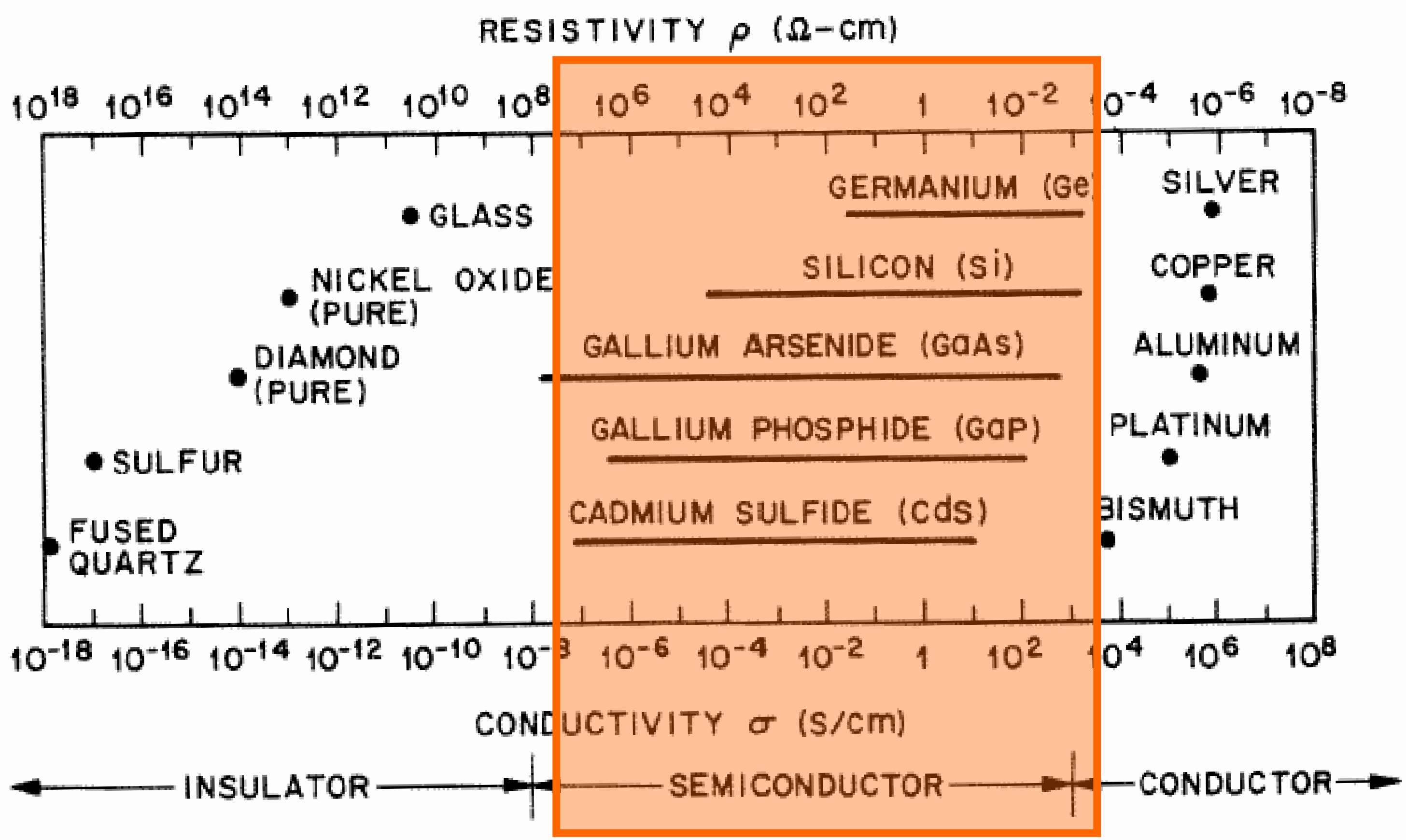
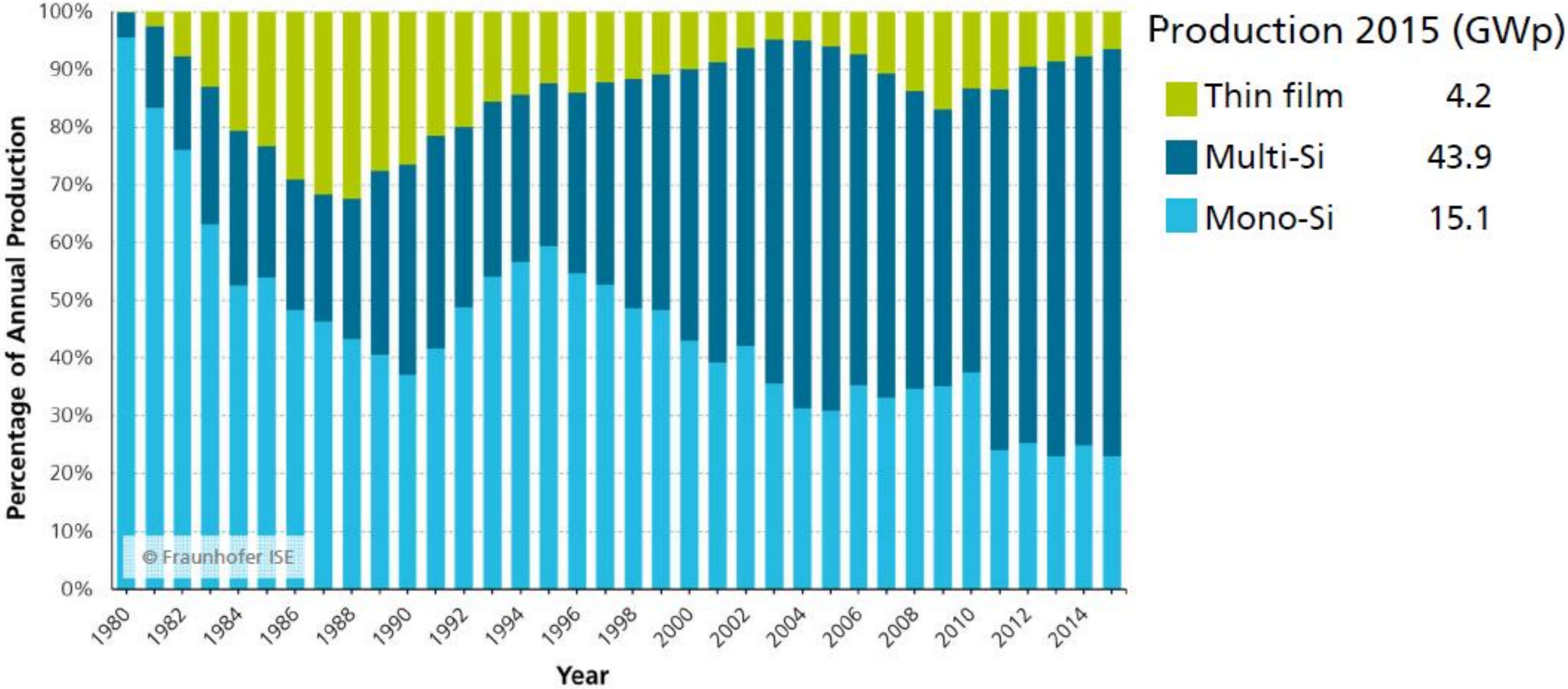


Fig. 1 Typical range of conductivities for insulators, semiconductors, and conductors.

Why Silicon?



Data: from 2000 to 2010: Navigant; from 2011: IHS (Mono-/Multi- proportion from cell production). Graph: PSE AG 2016

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Silicon: abundant, cheap, well-known technology

Silicon solar cell value chain

Silicon solar cells value chain

From sand to solar cells…

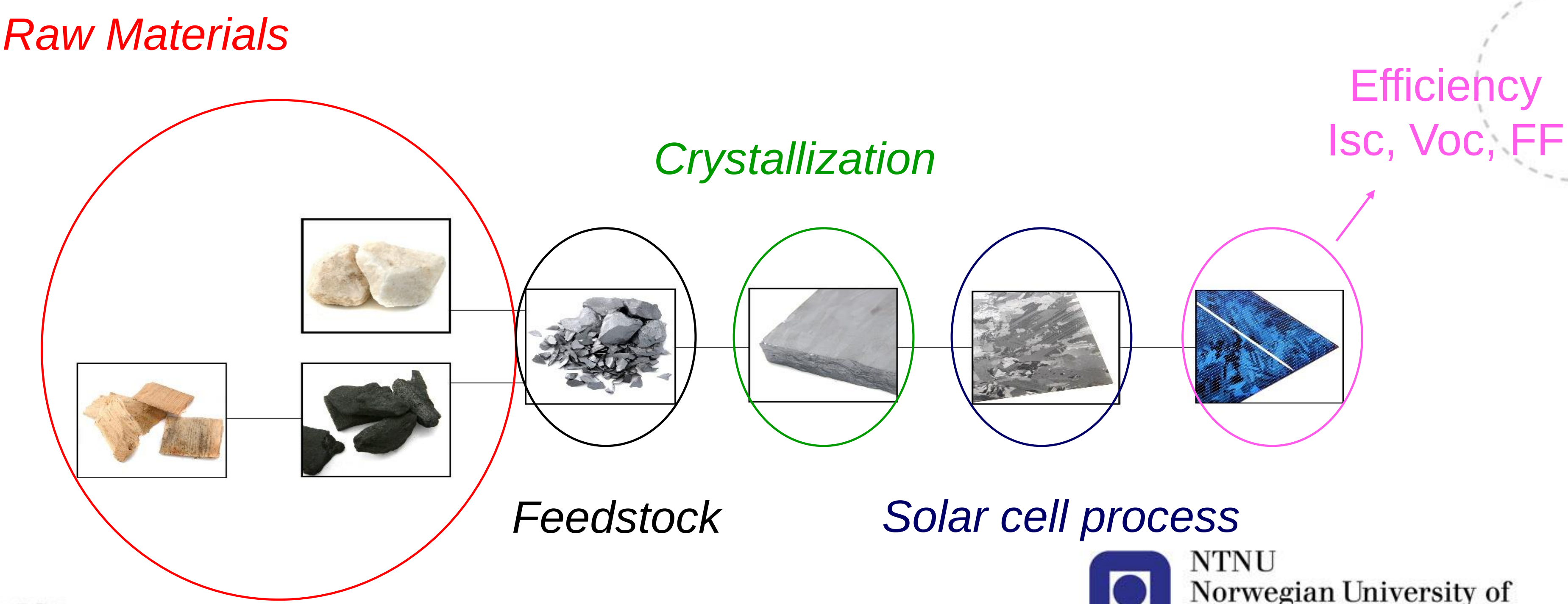

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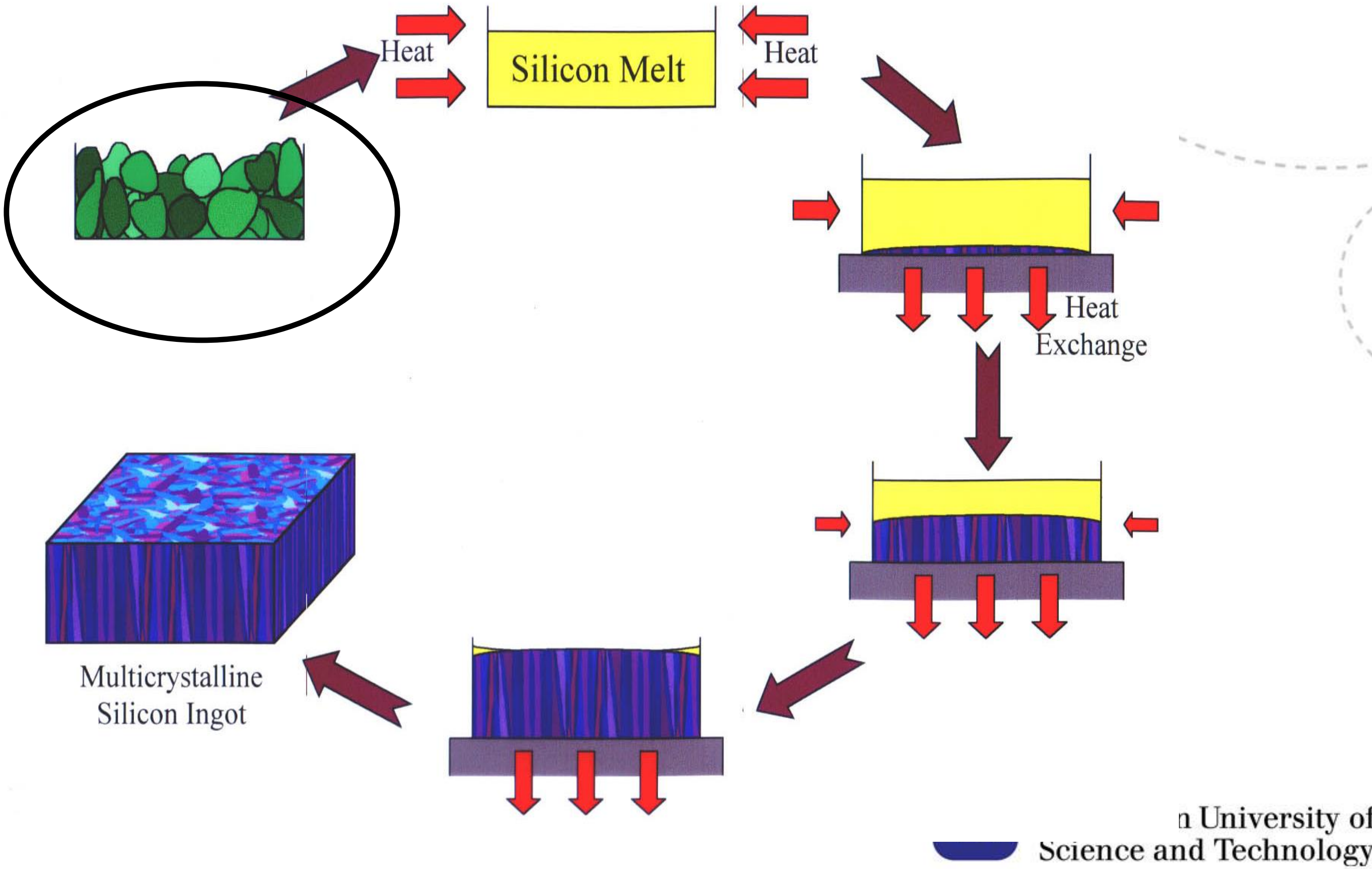
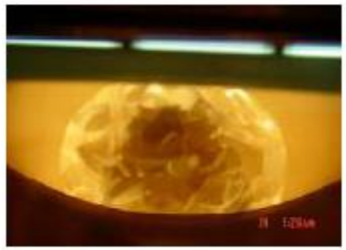
Photo: Melinda Gaal

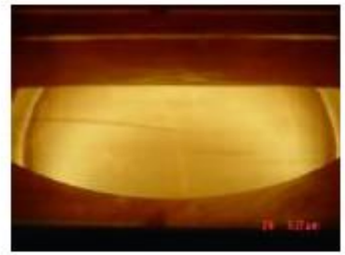
Multicrystalline silicon solar cells
Directional solidification

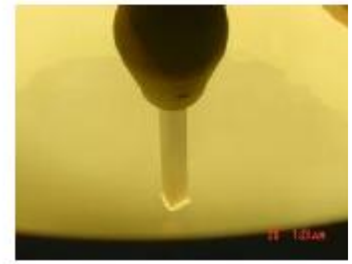


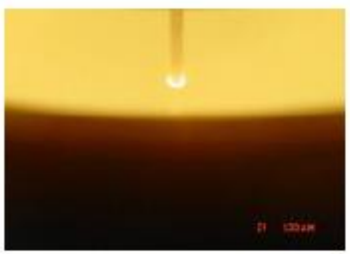
Monocrystalline silicon solar cells
Czochralski process

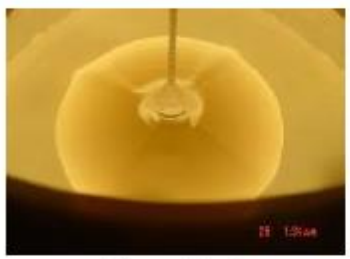

Stacking

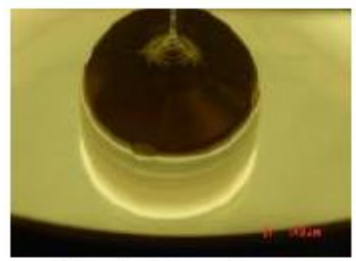

Melting

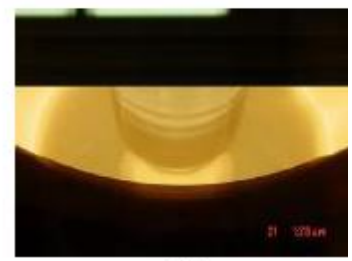

Stabilization


Dipping


Necking


Shouldering


Body Growing


Tailing

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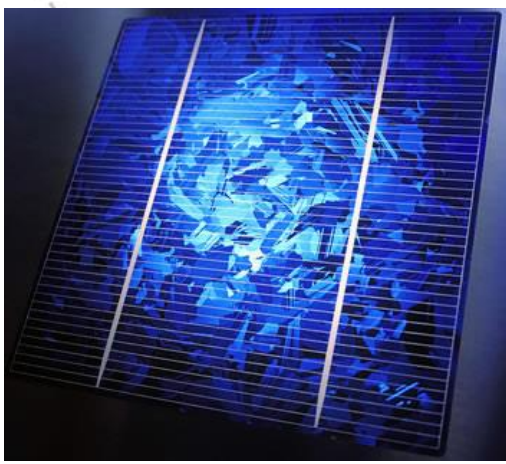
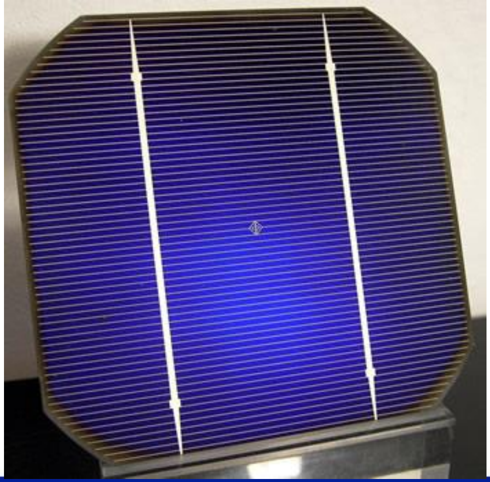
Crystallization methods for PV silicon



- **Multicrystalline silicon ingots:**
  - Lower cost than monocrystalline
  - More defects (dislocations and impurities)
- **Monocrystalline silicon ingots:**
  - Higher cost and lower yield
  - Oxygen related defects
  - Structure loss



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Czochralski PV single crystal growth

- Dominating process for single crystals
- Both p (B-doped) and n (P-doped) type crystals
- Growth rate 60 mm/h

Challenges:

•Productivity

low due to slow growth, long cycle time...

•Defects

point defects: vacancies, interstitials, oxygen defects

•Segregation

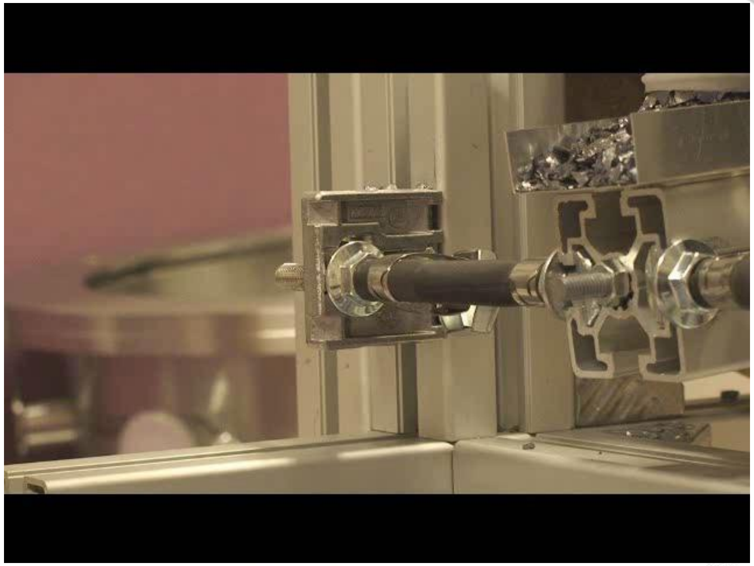
k_B=0.8 (for p-type); k_P=0.35 (for n-type)

•Oxygen

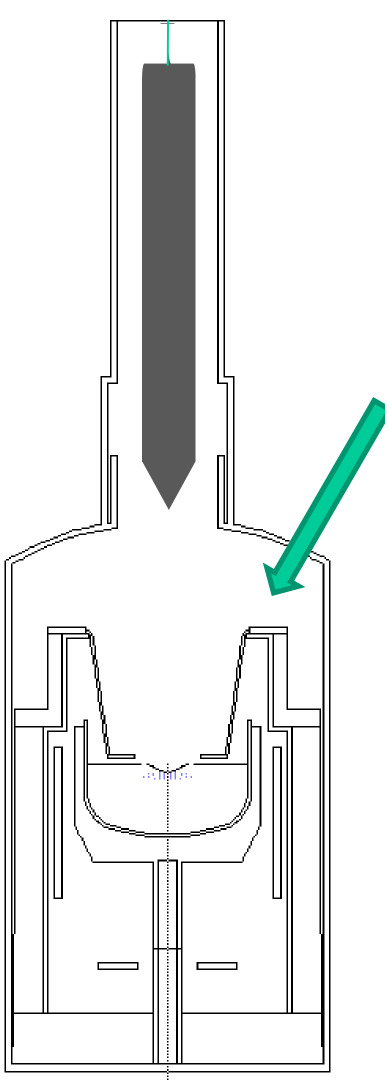
Contamination from SiO_2 crucible

Continuous feeding in Czochralski growth

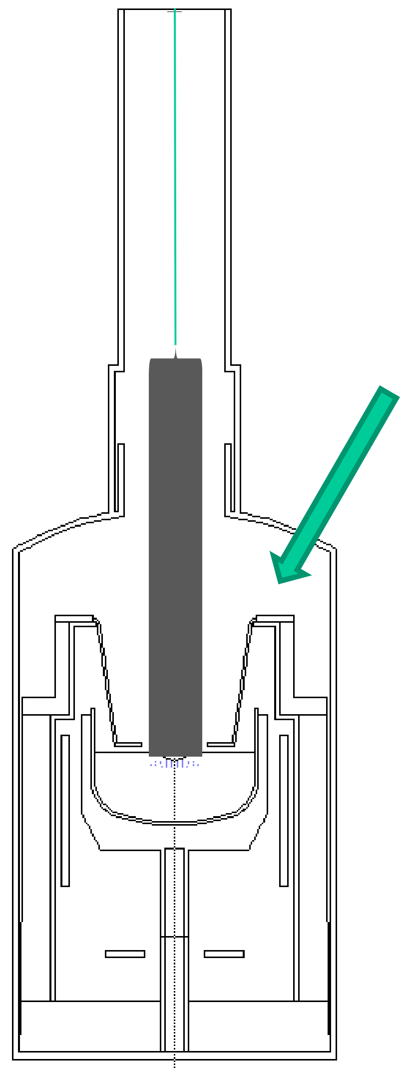
- Increase of productivity
  - -no need to cool down & recharge
- Adjust composition during growth
  - -compensate for segregation
  - -crystal of uniform composition



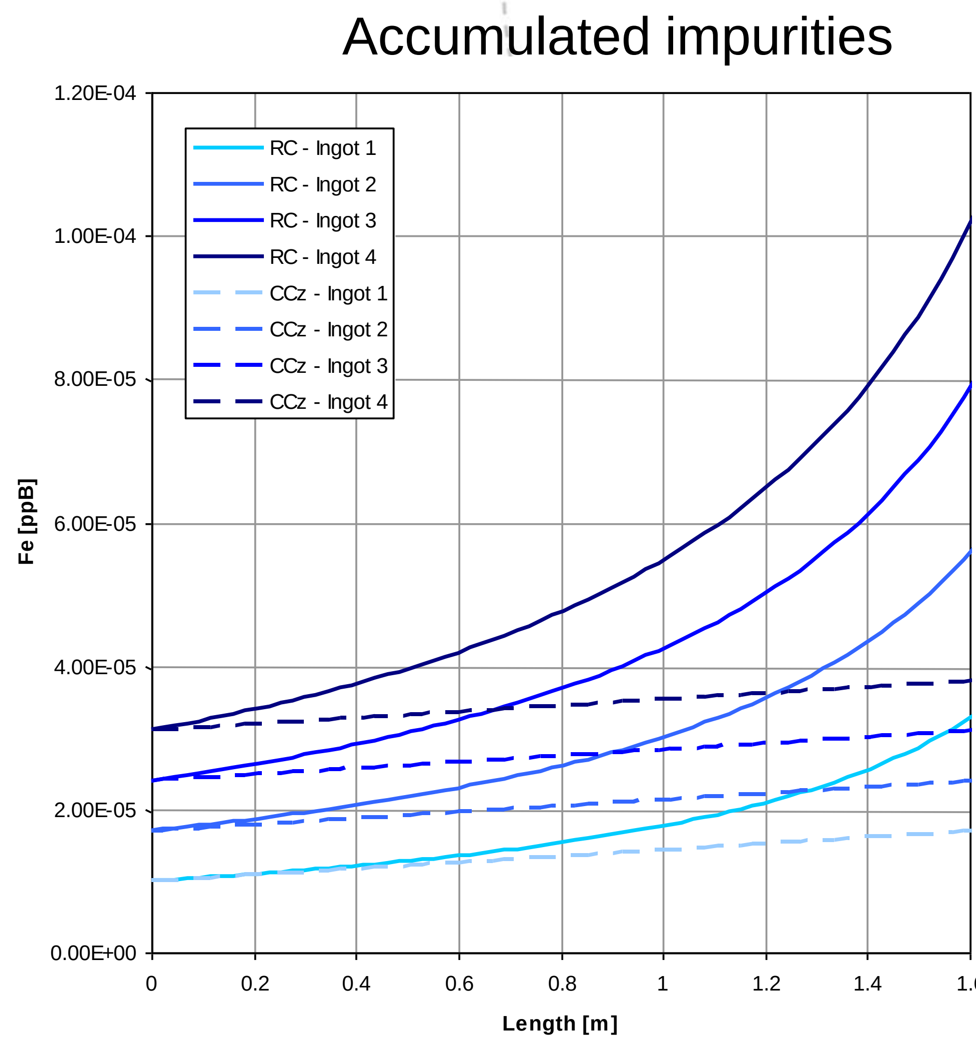
Recharging / Continuous feeding



Recharging



CCZ



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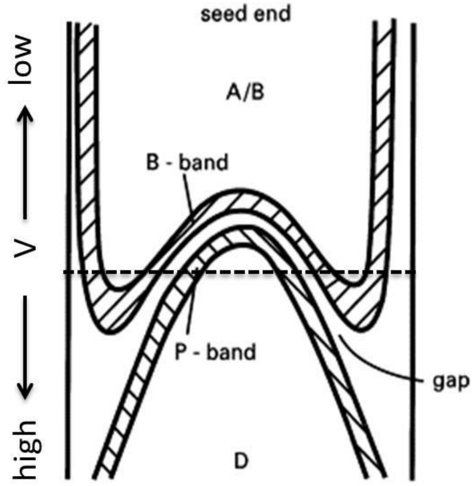
Point defects during Czochralski growth

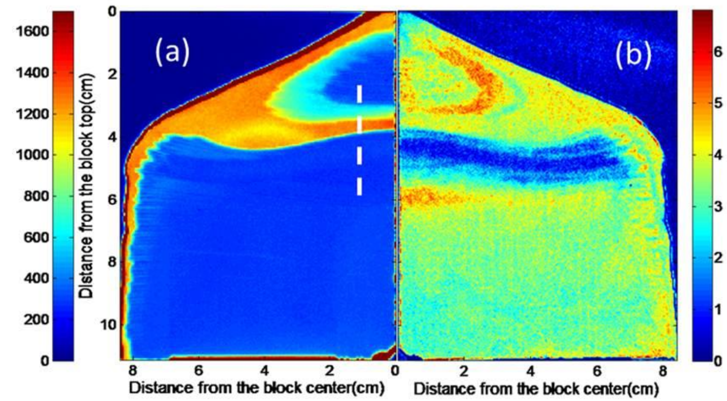


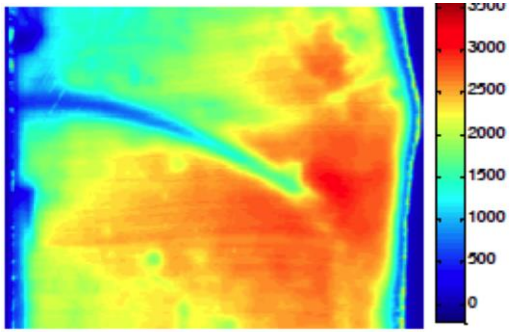
V/G low:
interstitials

V/G high:
vacancies

Sketch of grown-in microdefects distribution in an axial section of a Cz ingot

PV monocrystals are grown at high rates in vacancy mode but starts in interstitial mode. Defect zone durig transition.





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** Y. Hu, PhD Thesis at NTNU, 2012*

Directional solidification
Bridgman / Vertical Gradient Freeze (VGF)

- Dominating process for PV
- Multicrystalline ingots
- Bach size, trend towards larger ingots >800 kg
- Growth rate > 60 mm/h
- Defects deteriorate properties
  - Structural (grain boundaries, dislocations…)
  - Impurities

Challenges:

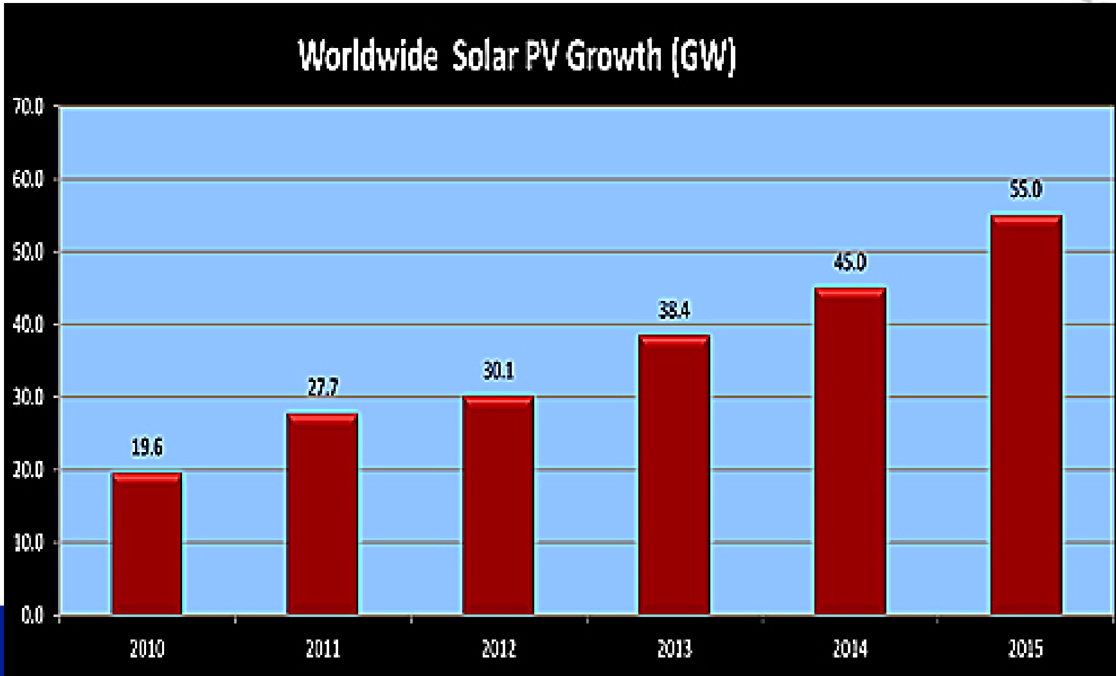
Reduce cost

- Directional solidification, VGF
  - Bridge gap between multi- and mono
- New Si materials
  - Less pure
    - Doping elements, B, P
    - Light elements, O, C, N
    - Metals, Fe, Cr, Cu, Ti

Improve efficiency

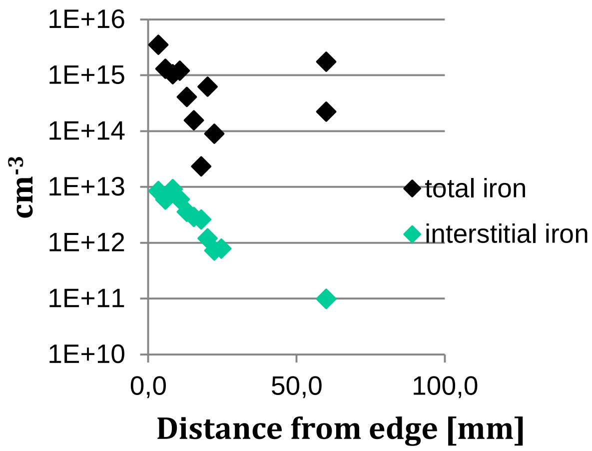
- Control structure
  - Grain size, orientation
  - Defect structure,
  - Dislocations, grain boundaries
- Control impurities

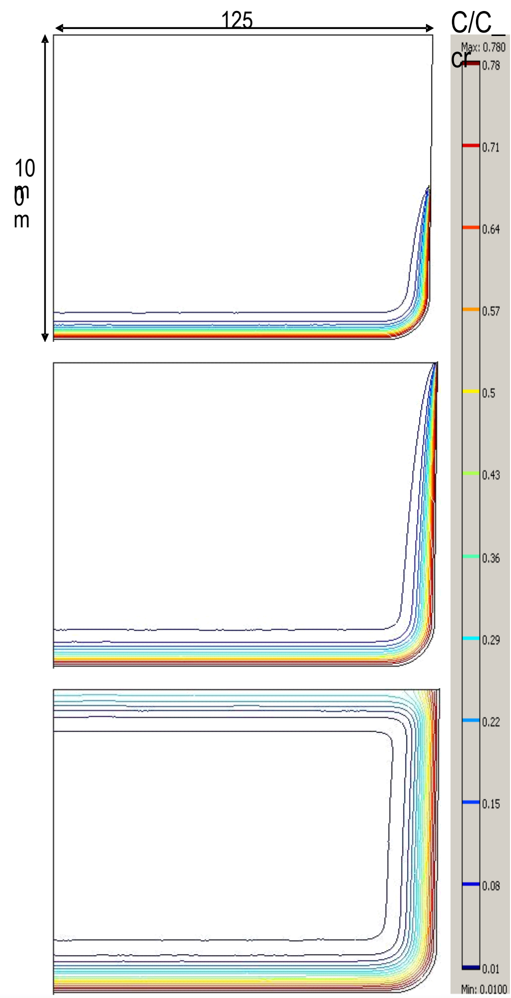
PV installation growth

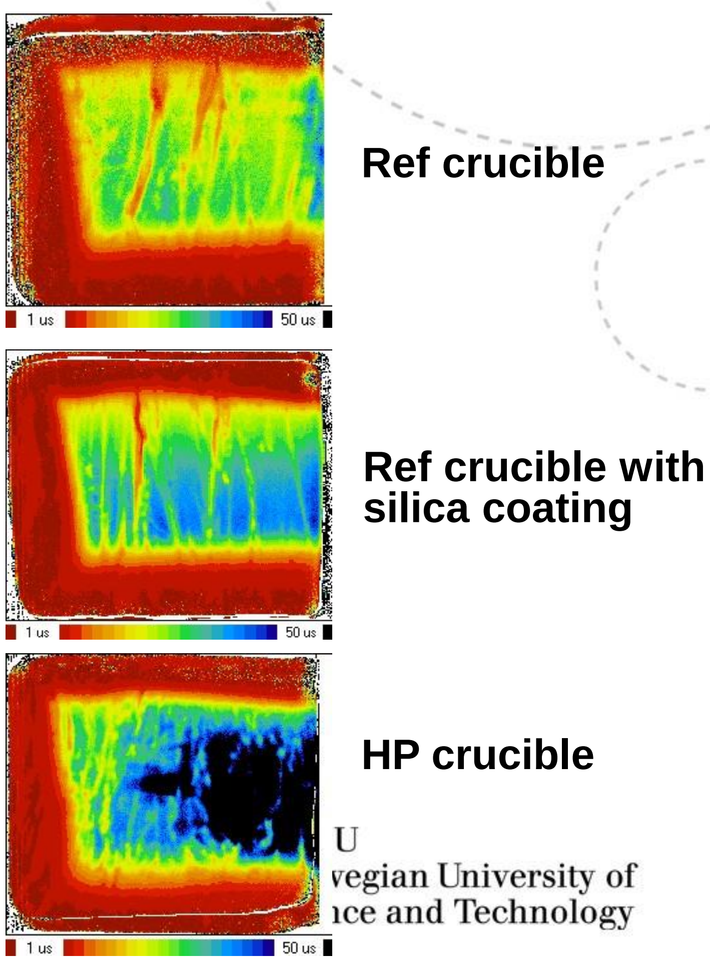


Metal contamination

Solid state difusion of iron from crucible into ingot
Low lifetime ”red zone”



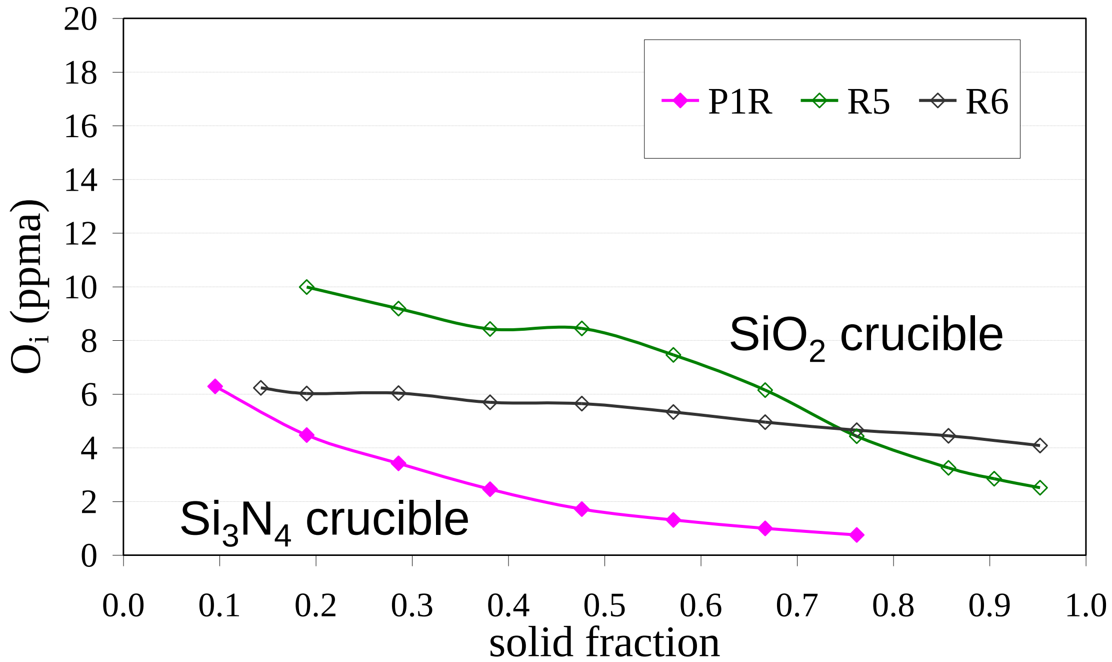


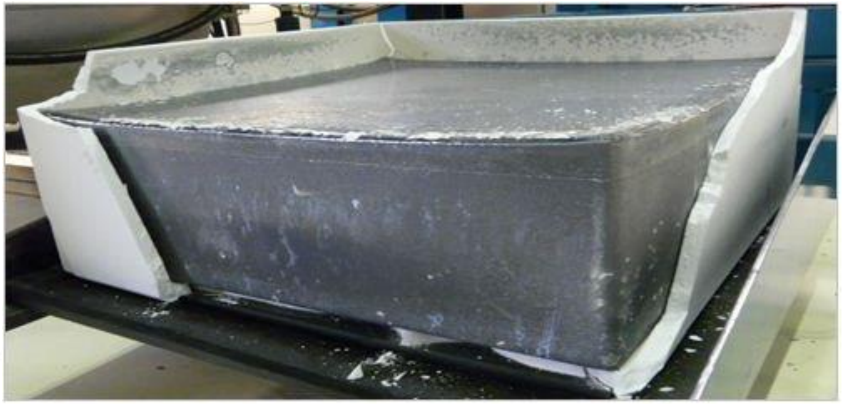


* T. Nærland, PiP, 2009
* Y. Boulfrad, PhD Thesis, 2012

Reusable Si_3N_4 crucibles for oxygen control

- Nitride crucibles allow low oxygen levels
- Can be reused several times (>5)

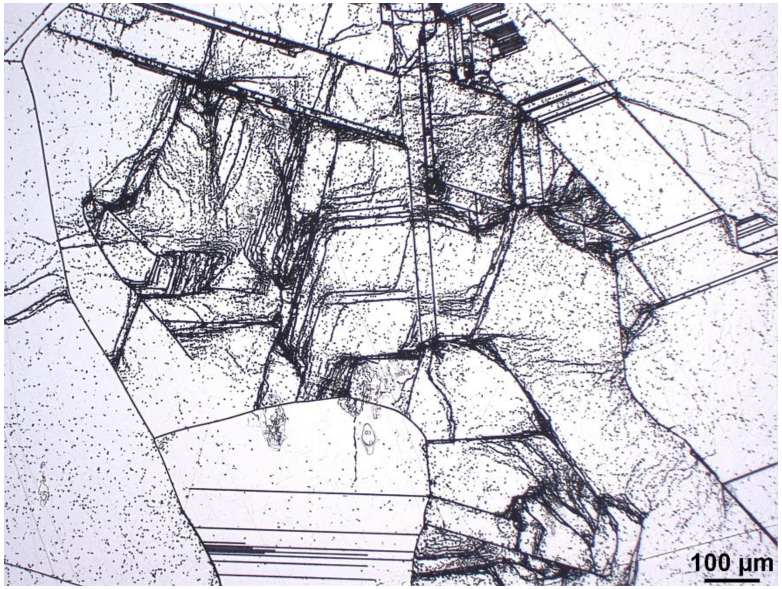




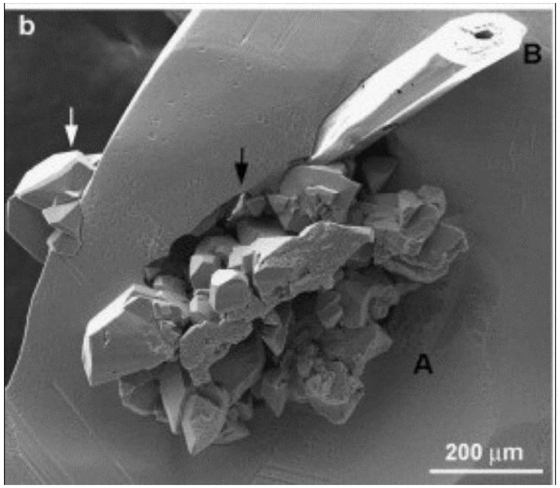
**Modanese et al, J Cryst. Gr. 354 (2012)*

Dislocation structures in mc Si

- Form during solidification, cooling and deformation
- Often associated with grain boundaries
- Interact with impurities
- Prevents gettering
- Depend on crystal orientation
- Increase with fraction solid



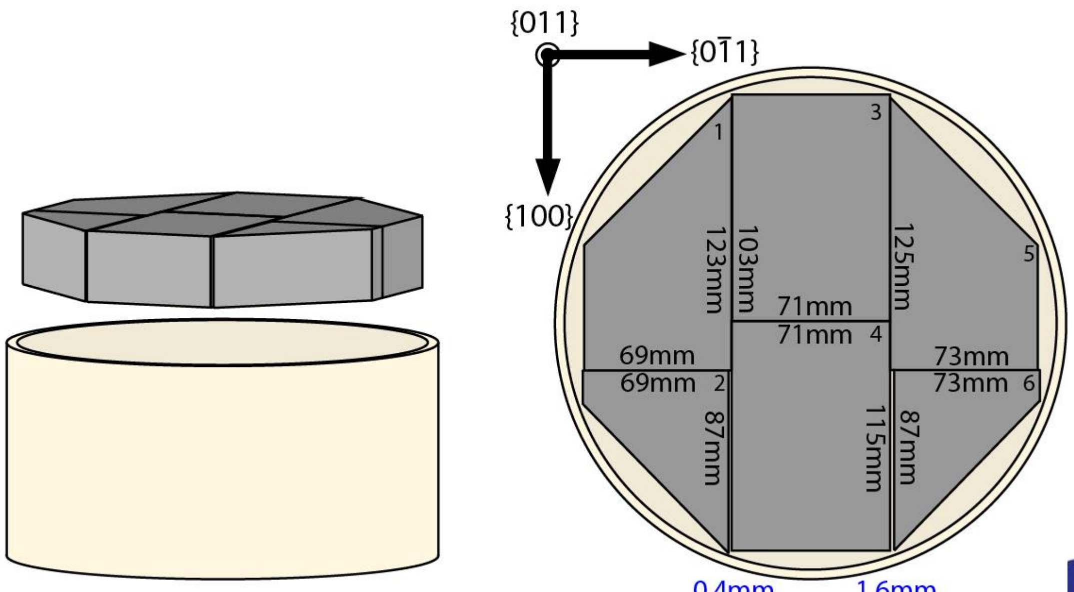
Si_3N_4 (B) and SiC (A) melt precipitates



Seed-assisted growth
Mono-like silicon ingots

Larger grains but lower cost and higher yield than CZ process

- A seed-structure consisting of six equally oriented <110>-seeds
- Grown in a pilot-scale Crystalox furnace, 12 kg



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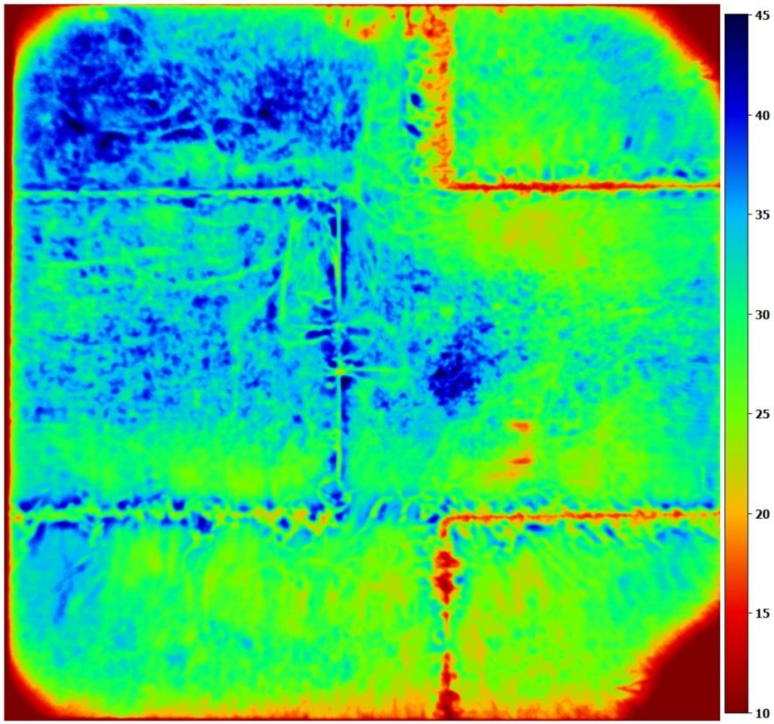
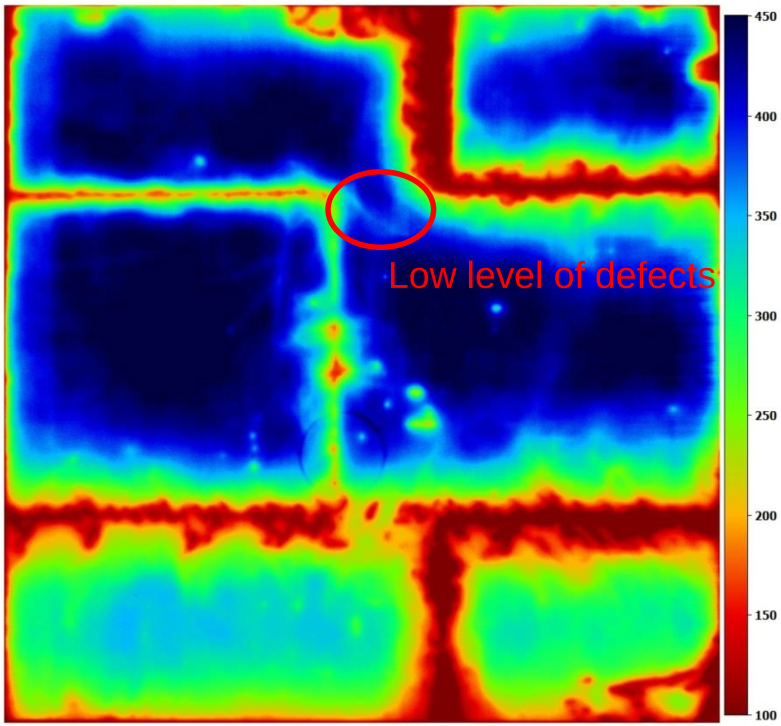
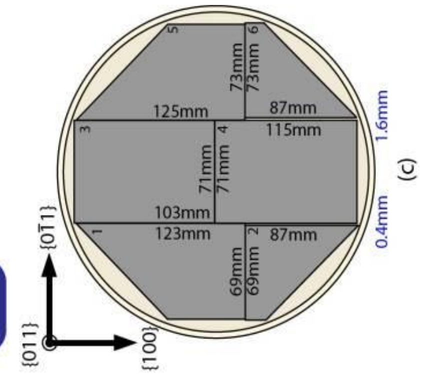
*K. E. Ekstrøm et al, CSSC7, 2013

Seed-assisted growth





- Lifetime maps before and after gettering
- Dislocations develop at seed-interfaces and also depend on seed misorientation

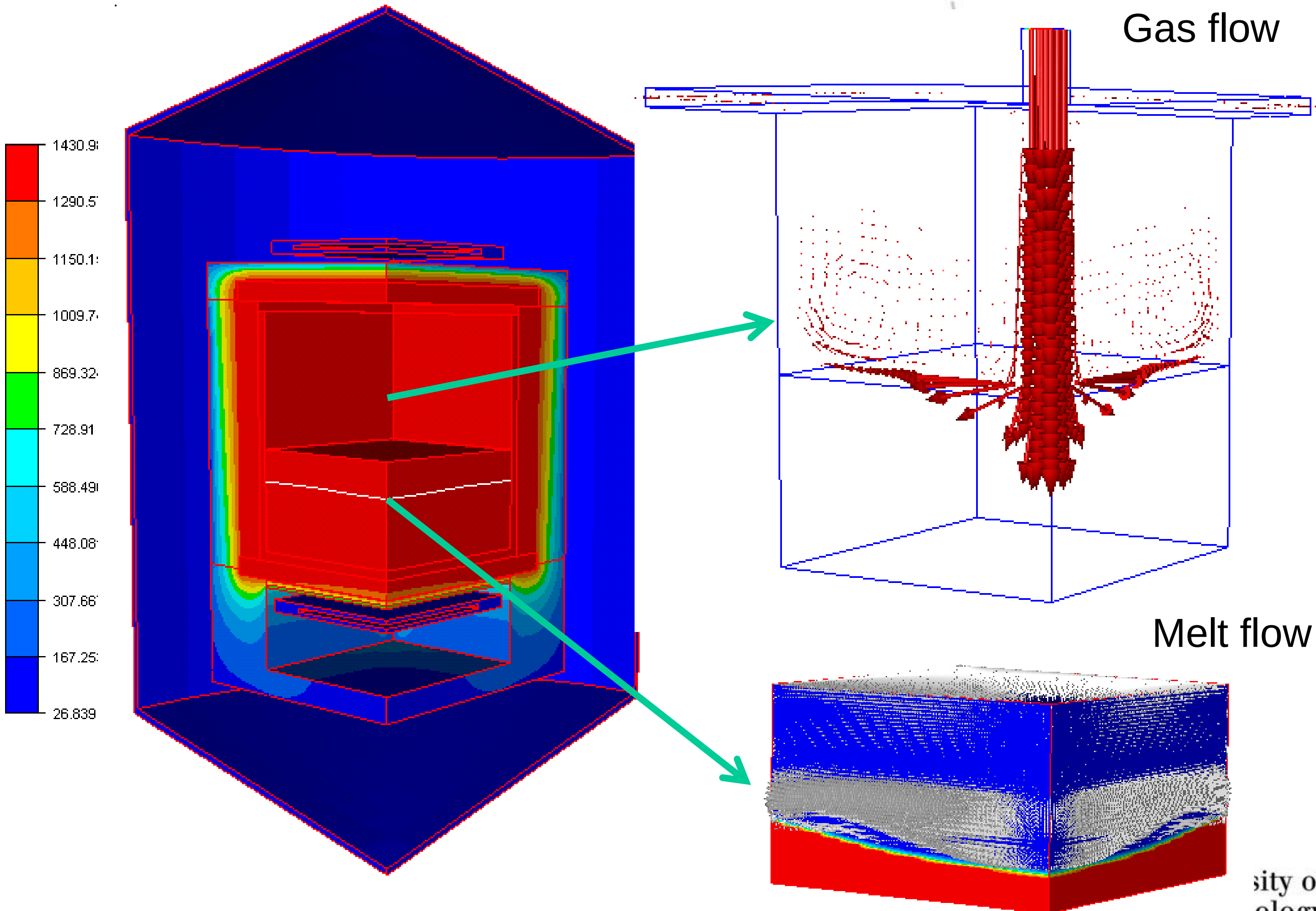


*K. E. Ekstrøm et al, CSSC7, 2013

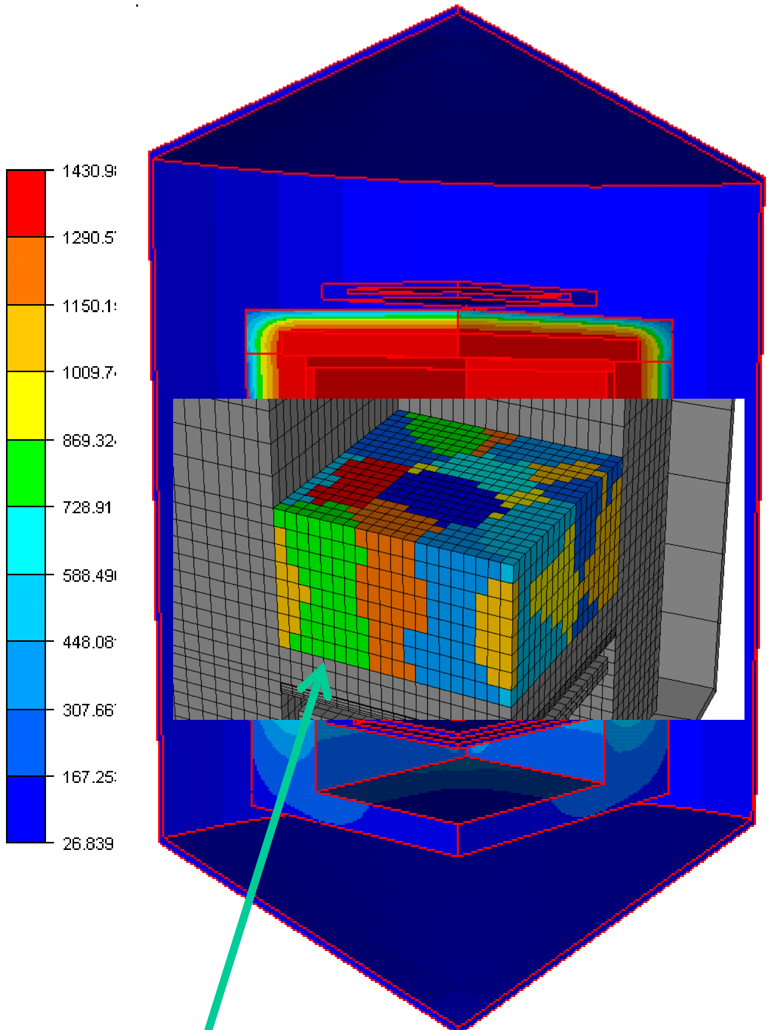
DEVELOPMENT OF NEW MODELING SOFTWARE SiSim

Task	Title	Activities
1	**SiSim software**	Software framework, releases, manuals, pre and post, user courses.
2	**SiSim numerical methods**	Implementation of numerical methods
3	**Global furnace modelling**	Furnace modelling (multi, mono) validation
4	**Impurity transport and defect formation**	Modelling impurity transport phenomena, thermodynamics and particle formation, defect formation
5	**Mechanical modelling**	Stresses and deformation in furnace components, elastic and plastic deformation, crystal plasticity
6	**Electromagnetism**	Electromagnetic field, coupling with fluid flow and consequences

Cyberstar furnace: fluid and gas flows

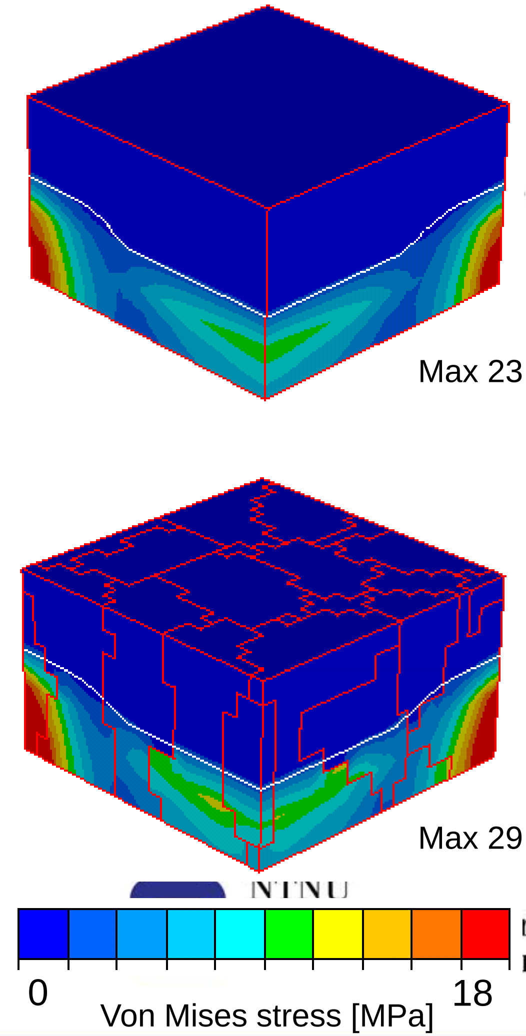


Cyberstar furnace: Stresses and strains

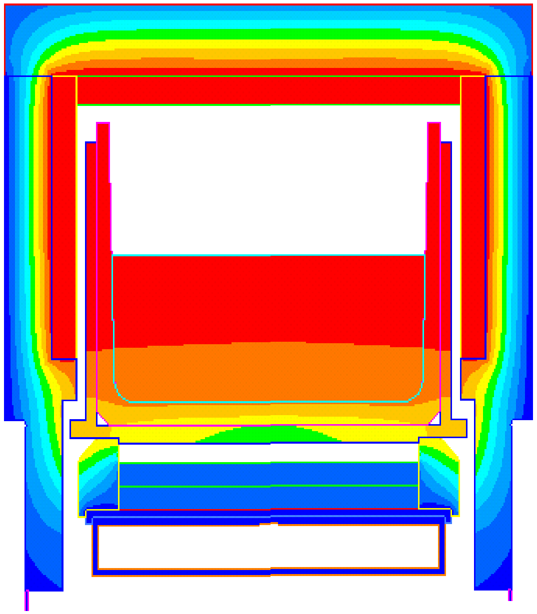


Grain structure

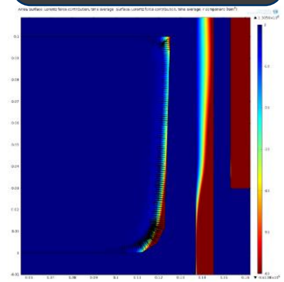
Thermo-elastic stresses



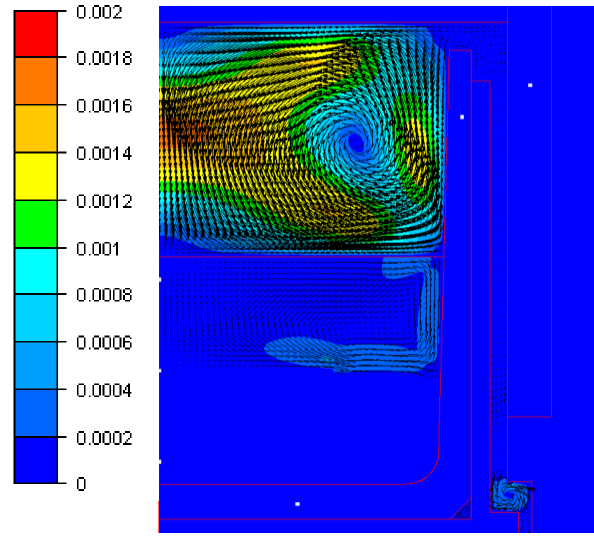
Crystallox furnace: impurities

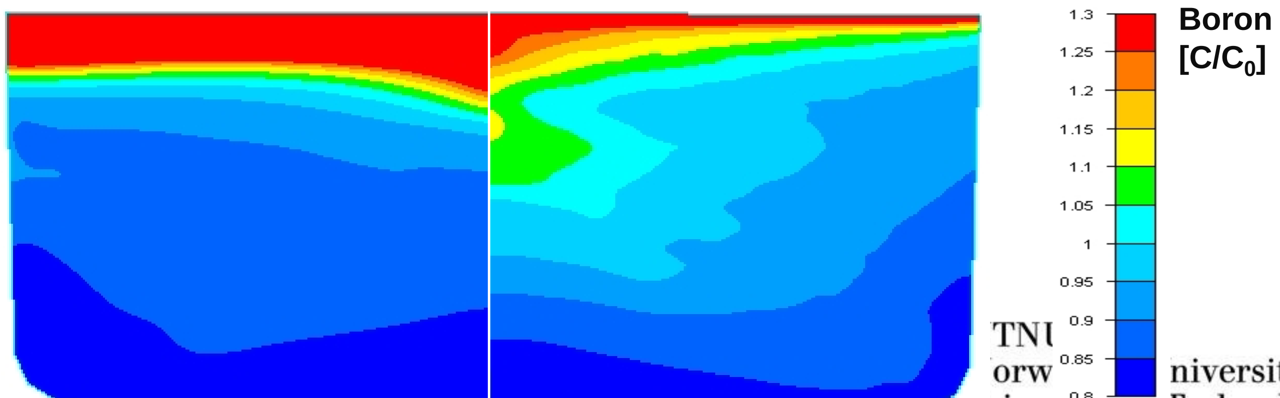


EM forces



Gas/melt flow

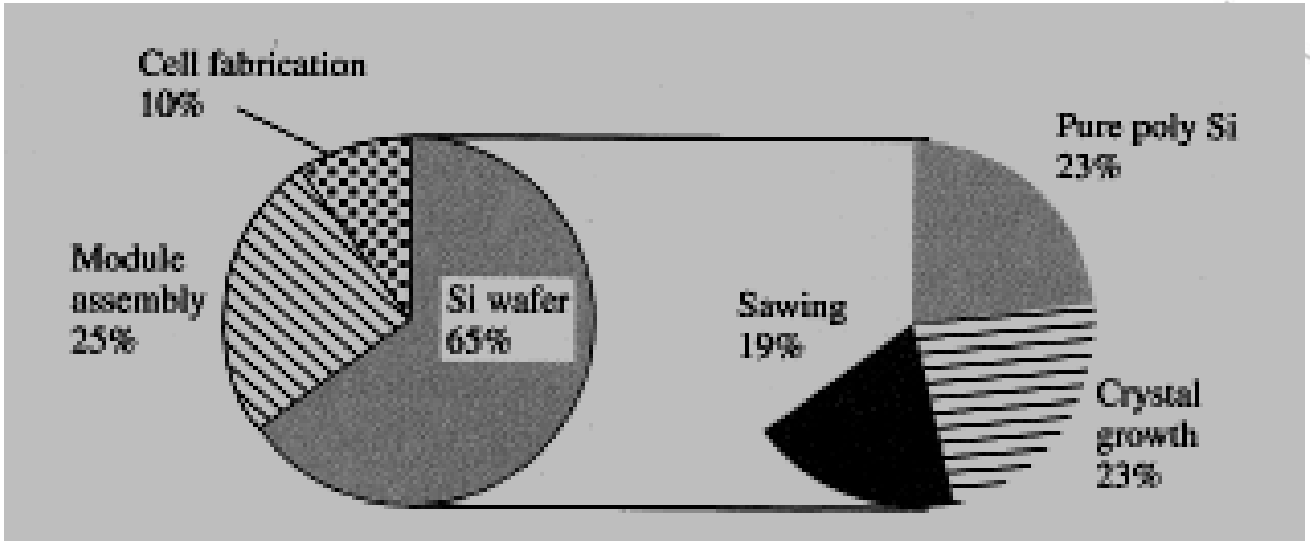




With EM

Without EM

Cost for production of solar modules



Silicon solar cells production

What happens to the wafer?

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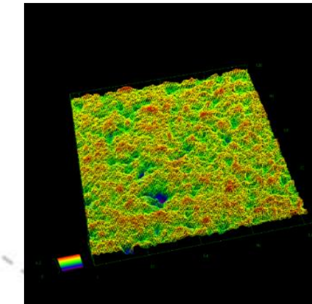
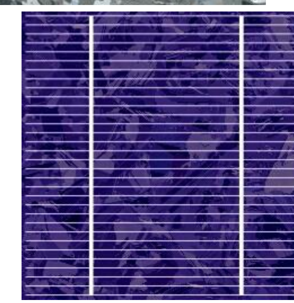
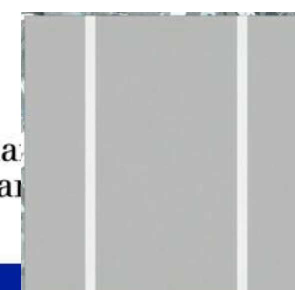
Courtesy Radovan Kopecek, ISC
and Erik Stensrud Marstein, IFE

Silicon solar cells production

- Saw-damages removal
- Texturing
- Emitter-diffusion
- Anti-reflection coating (ARC)
- Metal contacts/Screen printing
- Metal contacts/Co-firing
- Edge isolation







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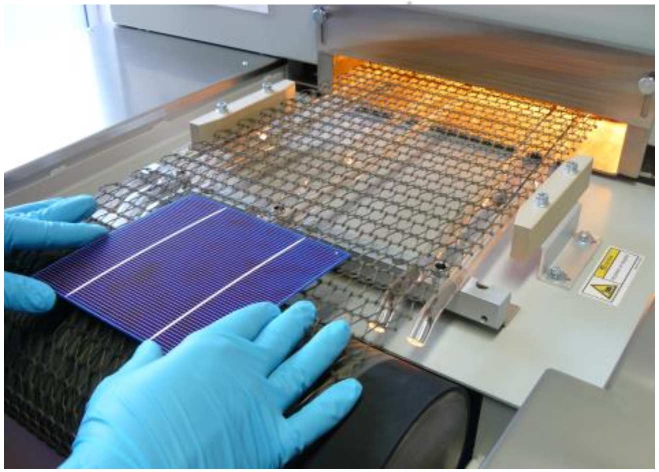

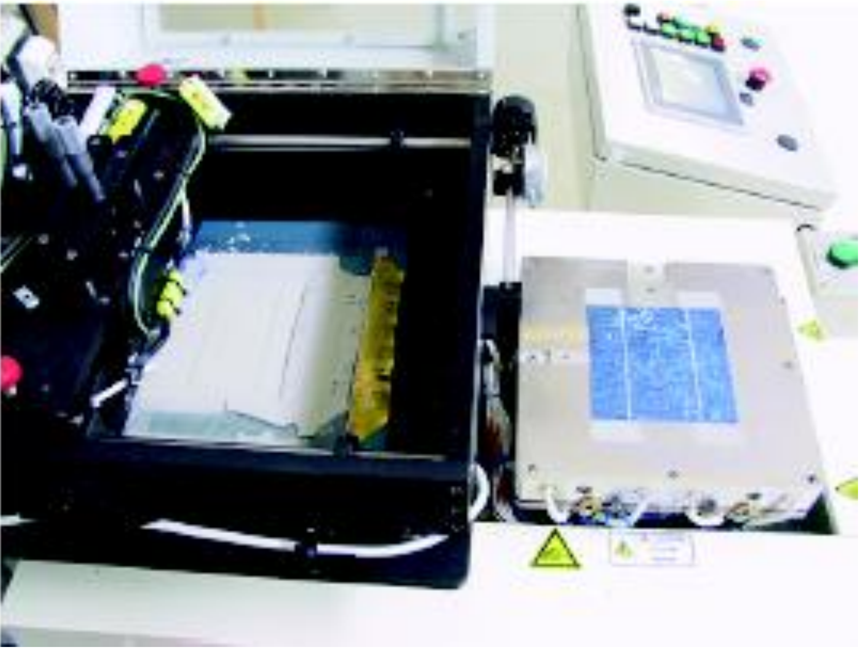

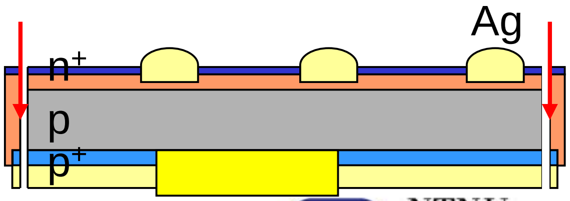

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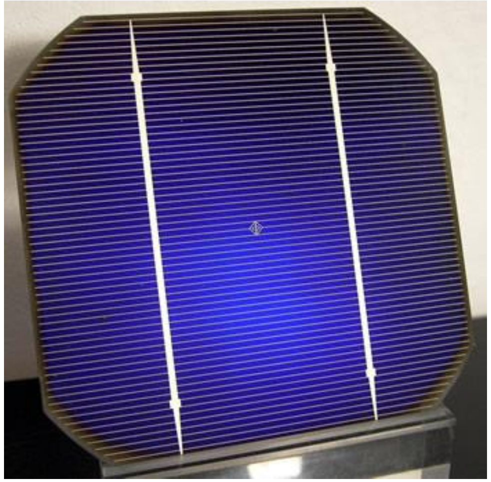
Efficiency limits

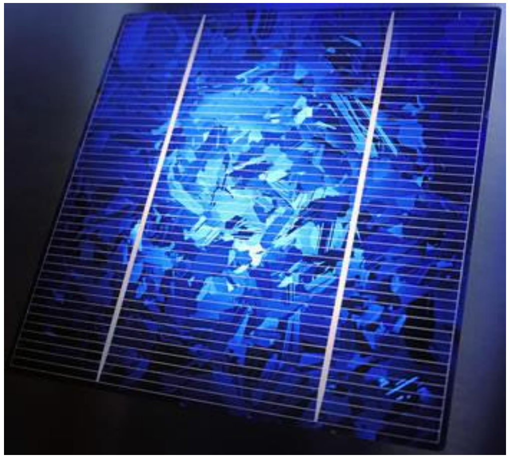
η= 33% 1 sun (E_g=1.4eV) Theoretical limit by Shockley and Queisser, 1961

Si (E_g = 1.1 eV): **η= 31%**

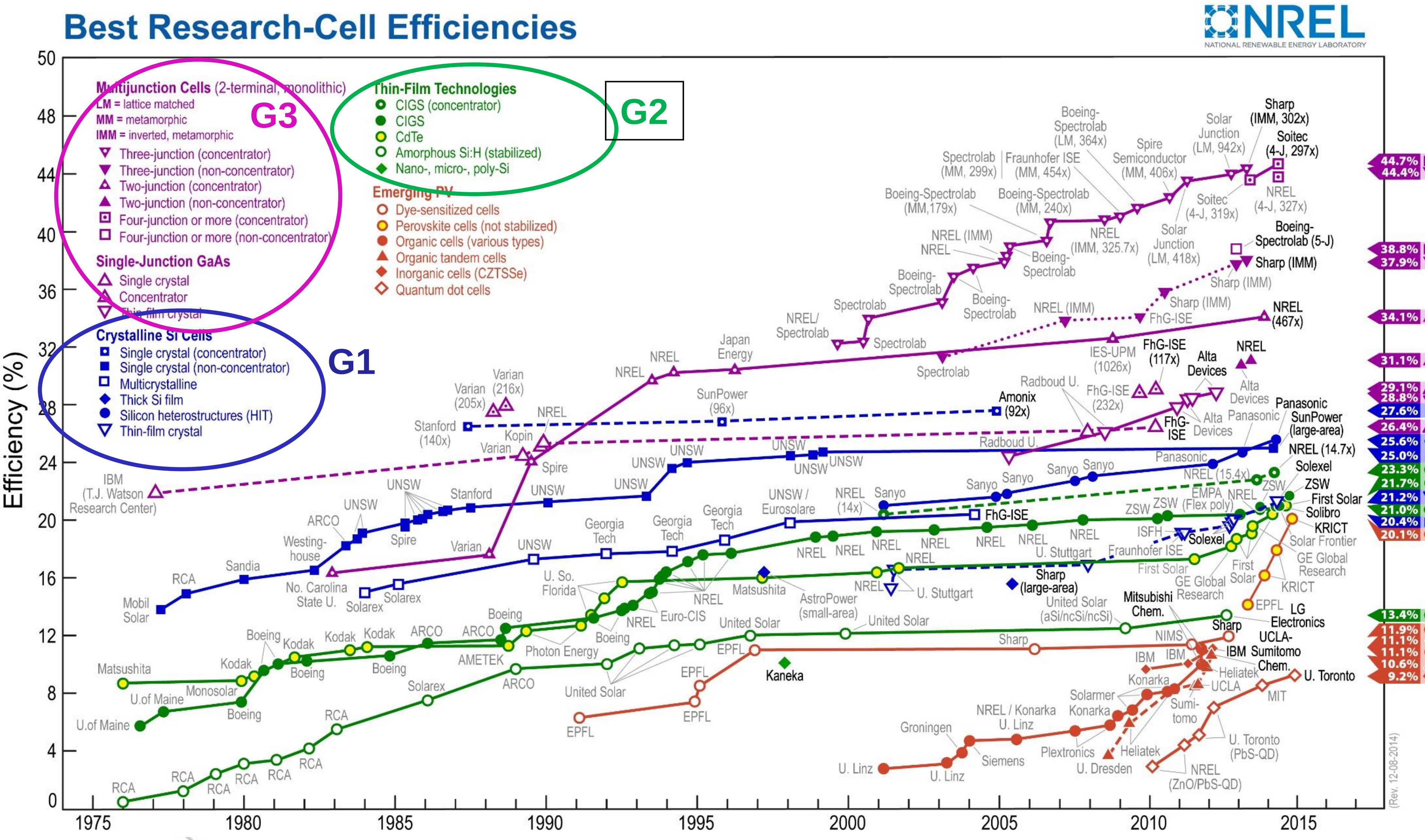
Typical values for commercial solar cells:



Sola cells Efficiency:
19-22%



Solar cells Efficiency:
16-19%



Best Research-Cell Efficiencies
NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Efficiency (%)
Multijunction Cells (2-terminal, monolithic)
LM = lattice matched
MM = metamorphic
IMM = inverted, metamorphic
Three-junction (concentrator)
Three-junction (non-concentrator)
Two-junction (concentrator)
Two-junction (non-concentrator)
Four-junction or more (concentrator)
Four-junction or more (non-concentrator)
Single-Junction GaAs
Single crystal
Concentrator
Thin-film crystal
Crystalline Si Cells
Single crystal (concentrator)
Single crystal (non-concentrator)
Multicrystalline
Thick Si film
Silicon heterostructures (HIT)
Thin-film crystal
Thin-Film Technologies
CIGS (concentrator)
CIGS
CdTe
Amorphous Si:H (stabilized)
Nano-, micro-, poly-Si
Emerging PV
Dye-sensitized cells
Perovskite cells (not stabilized)
Organic cells (various types)
Organic tandem cells
Inorganic cells (CZTSSe)
Quantum dot cells
G1
G2
G3
44.7%
44.4%
38.8%
37.9%
34.1%
31.1%
29.1%
28.8%
27.6%
26.4%
25.6%
25.0%
23.3%
21.7%
21.2%
21.0%
20.4%
20.1%
13.4%
11.9%
11.1%
11.1%
10.6%
9.2%
(Rev. 12-08-2014)

- c-Si solar cell have reached 25% (UNSW) for mono and 20% (FhG ISE) for mc-Si solar cells on small areas
- these records were lately topped on large substrates (Panasonic, sunpower, TRINA)

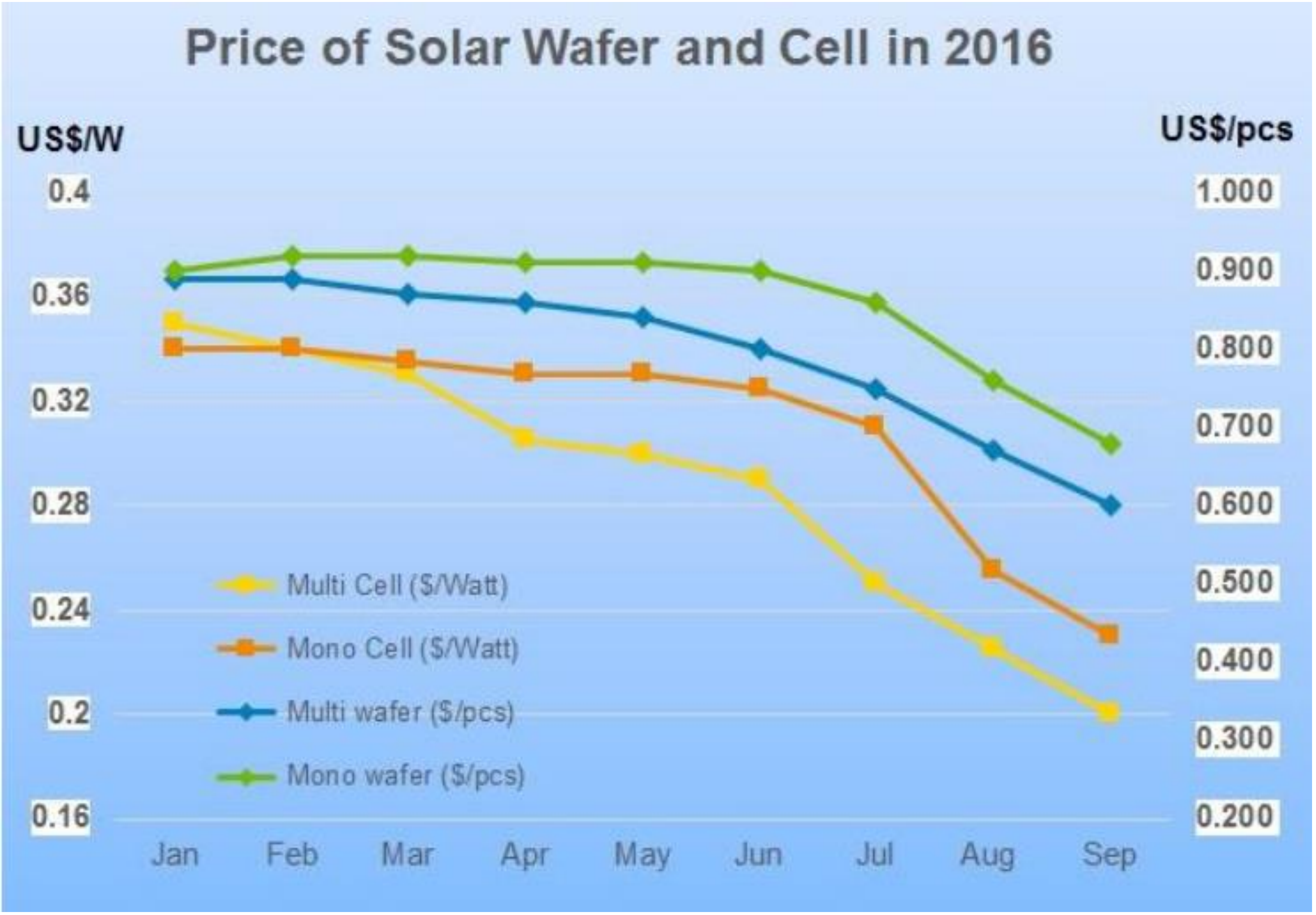
- CdTe and CIGS are at 22%, a-Si at around 14%

- organic solar cells are at around 12% (not stable)
- Perovskites have reached recently 22% (not stable)
- Quantum dot cells reached 11%

- GaAs multijunction cells have the highest efficiency of 46%

- They are mostly used in high concentration mode

- Expensive technology



- Prices for wafers and solar cells dropping
- Modules on stock
- Cell production running at low capacity
- Cell and module companies have problems again
- Machine builders soon in trouble followed by institutes

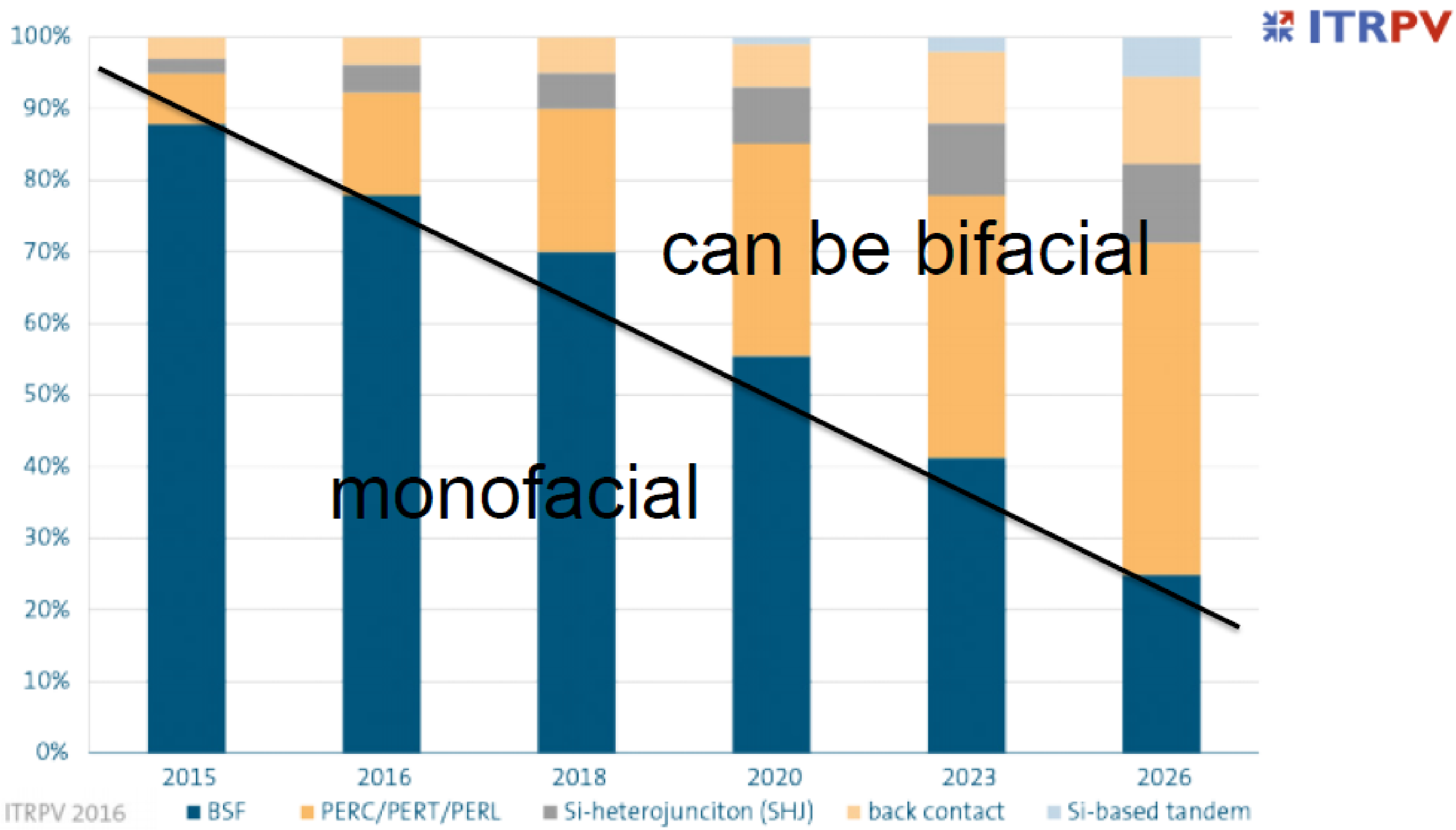
http://pvinsights.com/

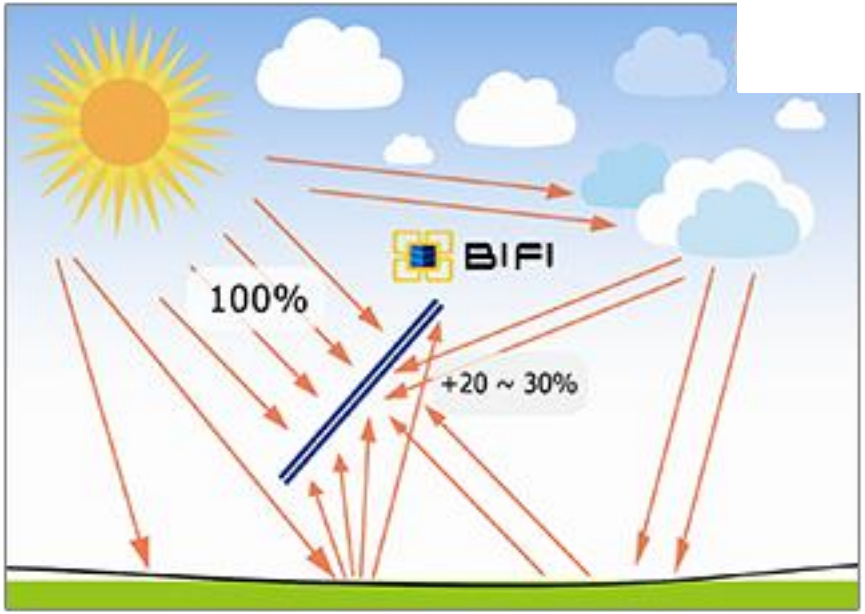
R. Kopecek, ISC, CSSC9, 2016

NTNU
Norwegian University of Science and Technology

ITRPV forecast

International Solar Energy Research Center Konstanz

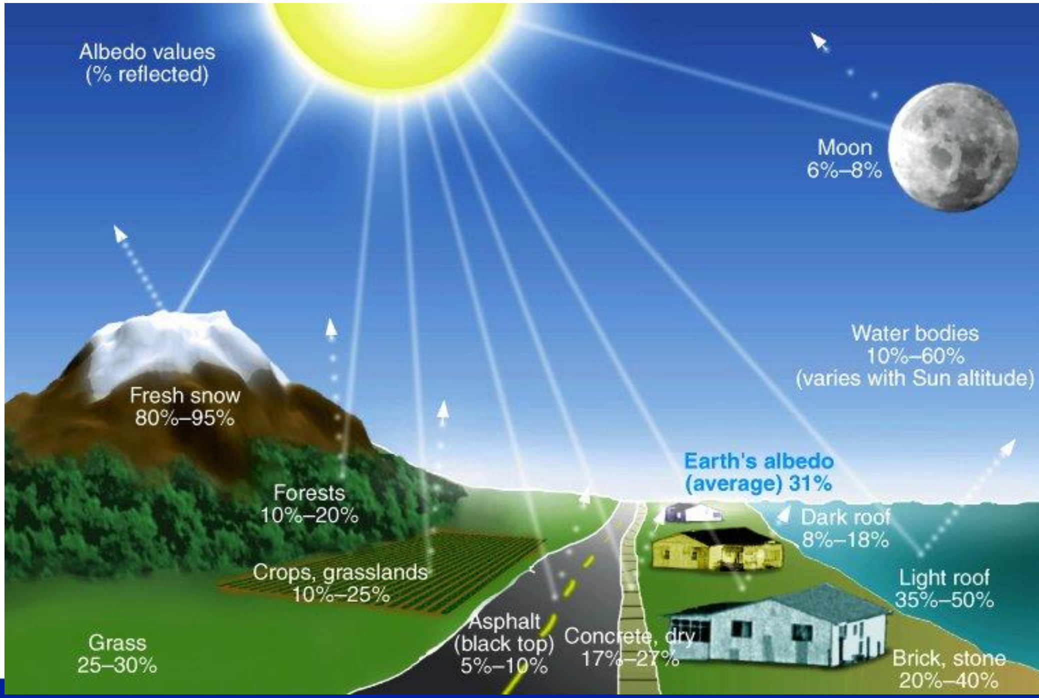




120MW total installed capacity in 2016

Global radiation on inclined surface:

$$G(\beta) = B(\beta) + D(\beta) + R(\beta)$$



Concluding Remarks

-**Silicon** based solar cells still dominating the marked

-Since 2016, prices are falling -> good for **low cost PV** but bad for **PV industry**

-Room for **innovations** (e.g. direct wafer, tandem etc) is extremely **tight**

-Material **quality** and solar cell **architectures** still key parameters

-**Bifacility** is coming! 120MW total installed capacity in 2016 and in 2017 at least doubled