Energy research Centre of the Netherlands

Crystalline Si Photovoltaics

Arthur Weeber

Outline

- Short introduction ECN
- Introduction ECN Solar Energy
- General Si solar cells
- Crystalline Si Photovoltaics
  - Feedstock
  - Wafering
  - Cell processing
  - Module technology
  - Costs and environmental
- Summary

ECN

Petten: ECN; NRG; JRC; TYCO

Targets ECN research

Transition to renewable energy supply:

efficiency improvement

development of renewable energy

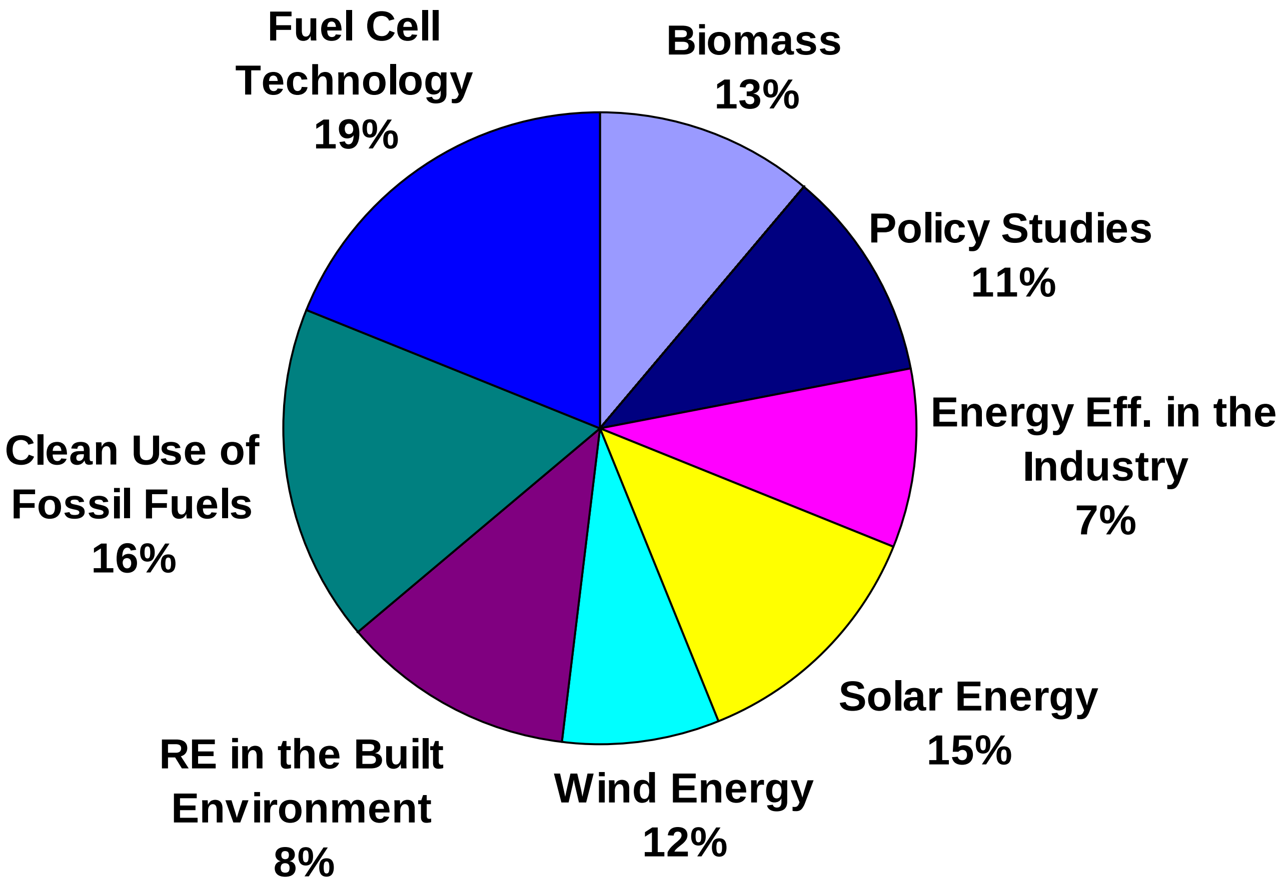
clean use of fossil fuels

maximum reliability
minimum environmental burden
optimal cost effectiveness

ECN Programme units

Strategically	**Policy Studies**
Energy savings	**Energy Efficiency in Industry** **Renewable Energy in the Built Environment**
Renewable energy	**Solar Energy** **Wind Energy** **Biomass, Coal & Environmental research**
Clean use fossil fuels	**Hydrogen & Clean fossil fuels**
Support	**Engineering & Services**

Turnover share per unit (2005)



ECN

Energy research Centre of the Netherlands

ECN Solar Energy

www.ecn.nl

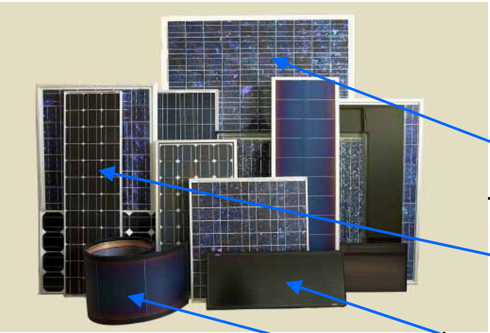
Solar Energy

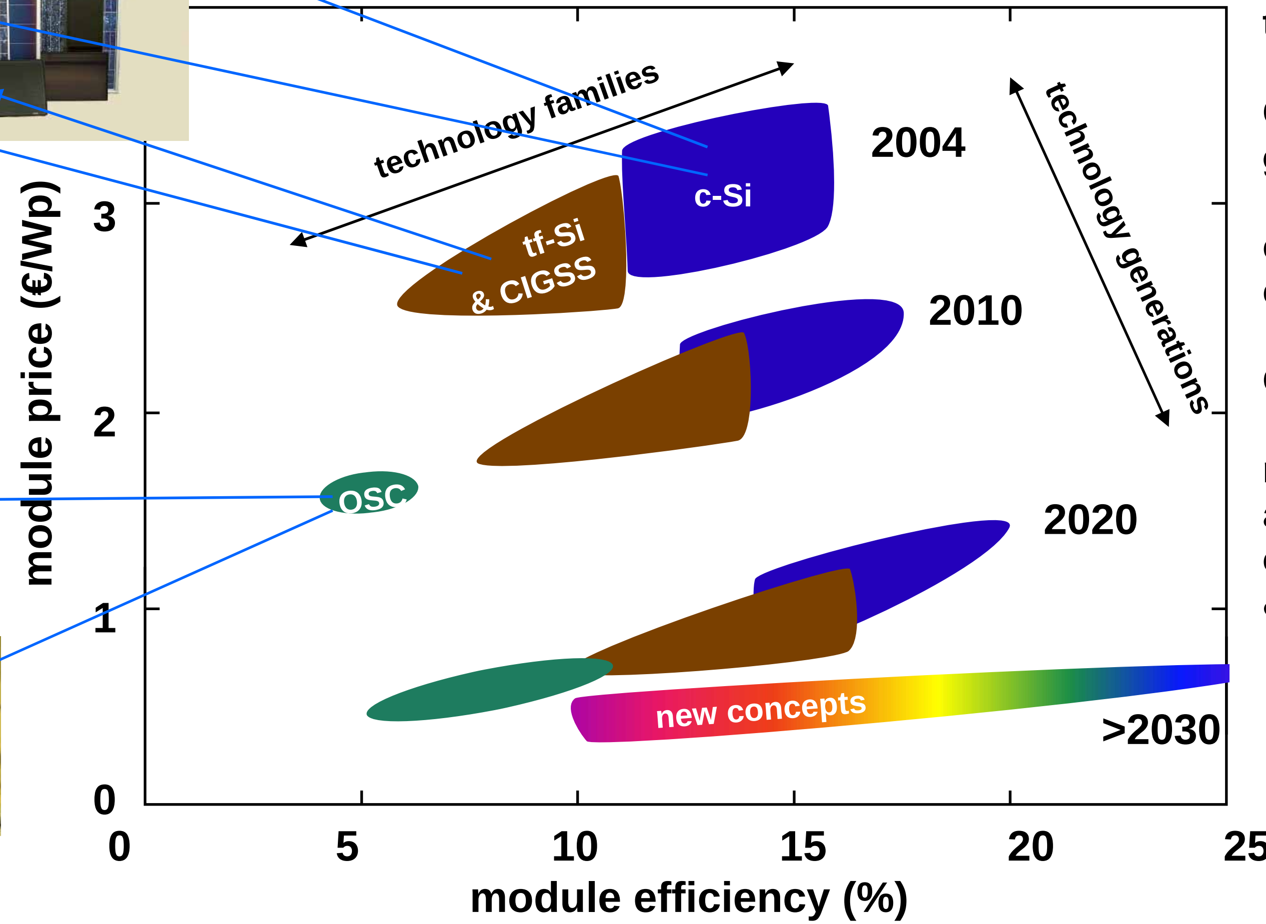
- Silicon Photovoltaics
- Thin-Film Photovoltaics
- PV Module Technology

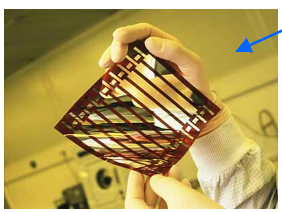
Objective:

- Price of solar electricity in 2015 the same as consumer electricity price, and after that even lower
  - High efficiency
  - Reduction of material use
  - Cost effective and environmental friendly processes and products
  - Long lifetime of the modules

PV technology development: no revolution, but evolution







tf-Si = thin-film silicon

CIGSS = copper-indium/gallium-selenium/sulfur

c-Si = wafer-type crystalline silicon

OSC = organic solar cells

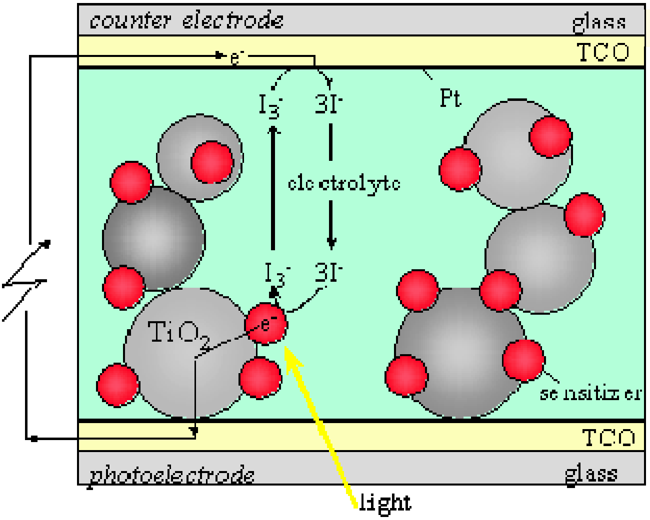
new concepts = advanced versions of existing technologies & new conversion principles

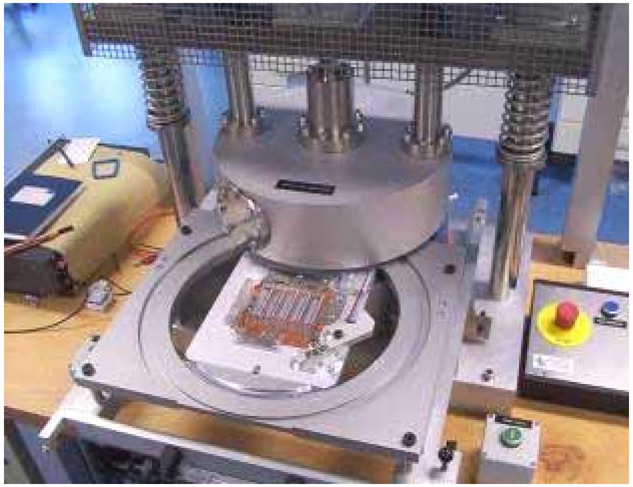
(free after W. Hoffmann)

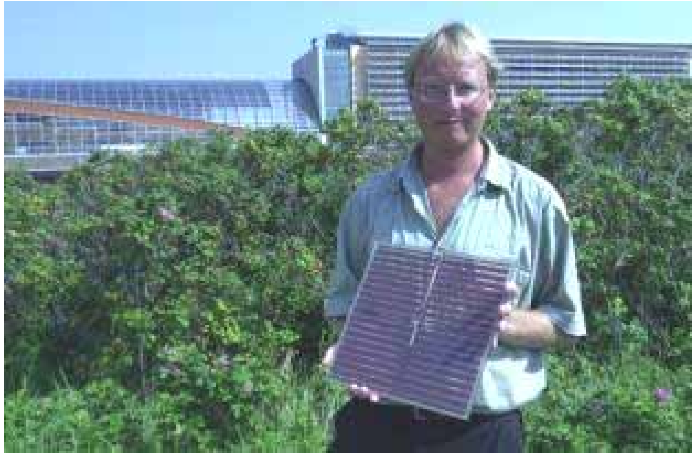
ECN Solar Energy

Thin-film photovoltaics

- Sensitised oxides
  - efficiency, stability, manufacturing technology
  - solid state version: in 2015 η=8% for 10x10 cm^2 device with >10 year outdoor stability







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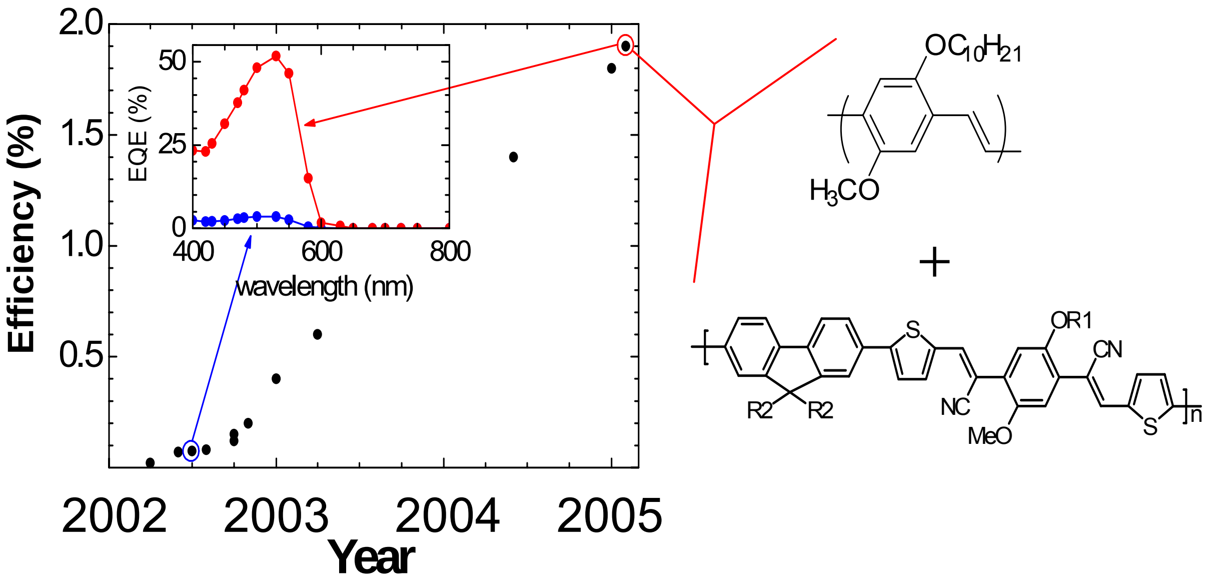
Thin-film photovoltaics

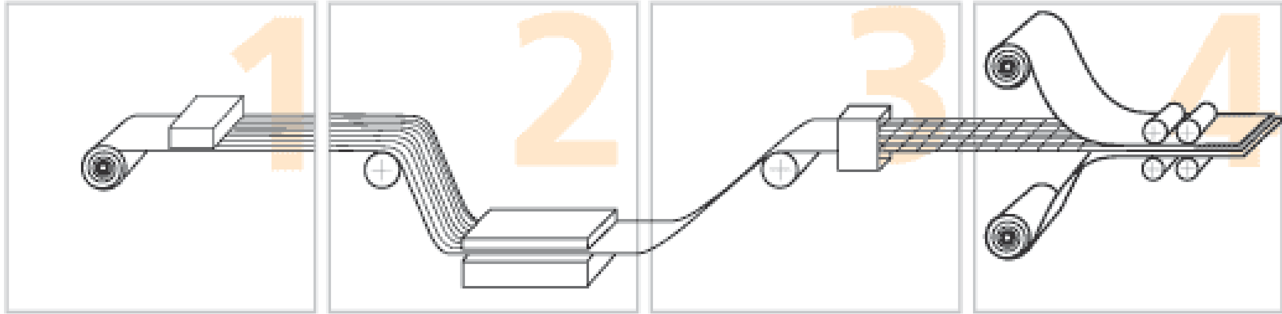
- Organic solar cells
  - device fabrication, efficiency and stability
  - in 2015 η=8% for 10x10 cm^2 device with >10 year outdoor stability



Collaboration of ECN, TNO

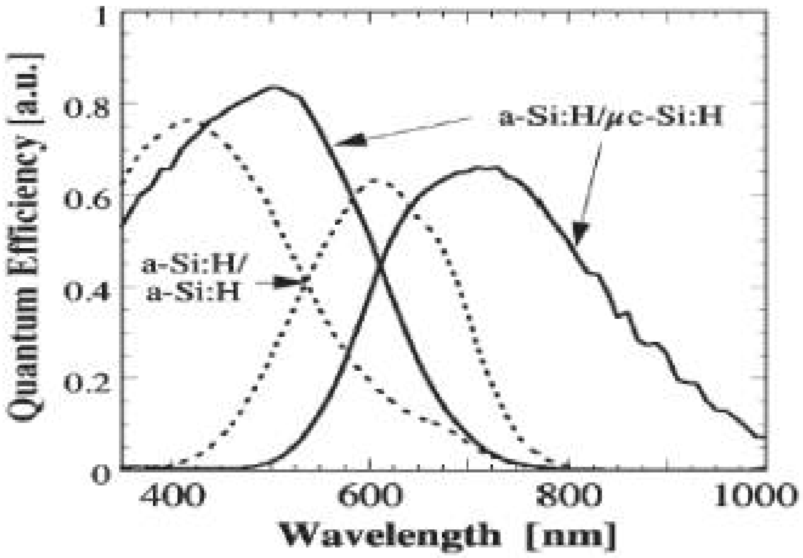
ECN

ECN Solar Energy



Thin-film photovoltaics

- Thin-film silicon
  - R-2-R deposition of (n,i,p) silicon on foils
  - Development of thin-film Si tandems
  - In 2015 a 0.3x1 m^2 PV module η=12% at 0.8€/Wp



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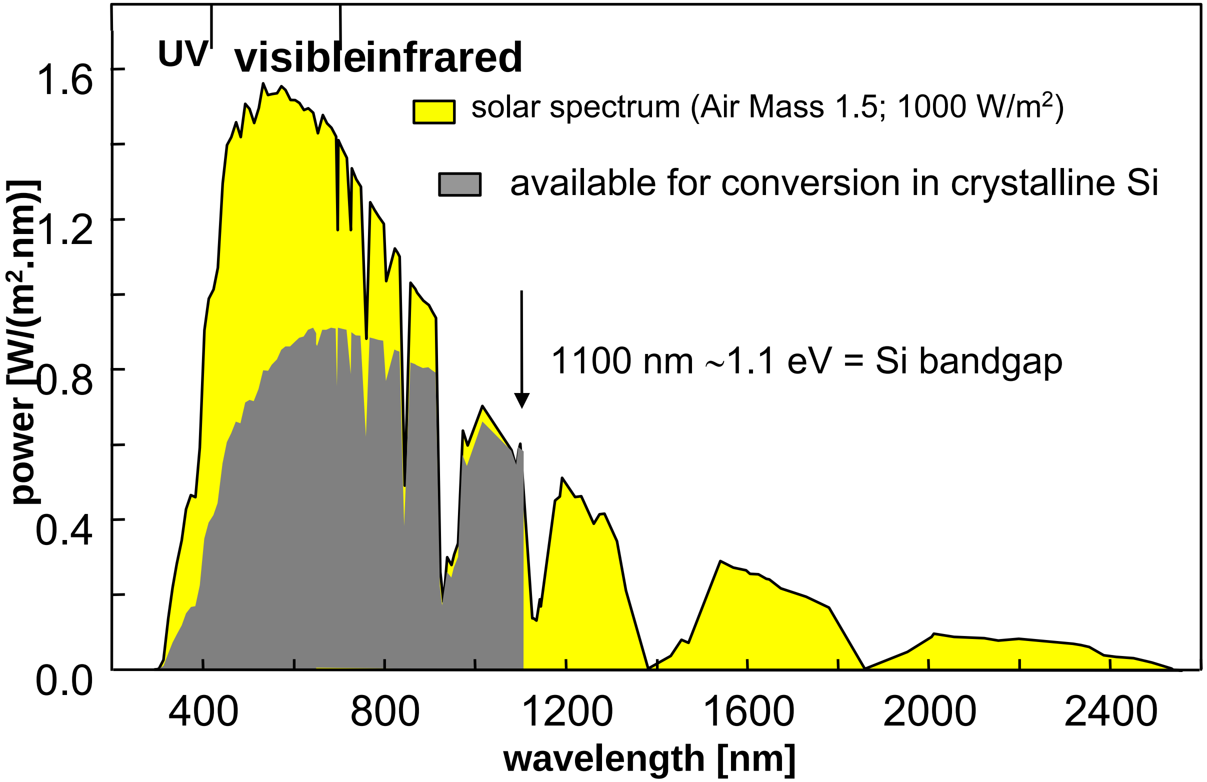
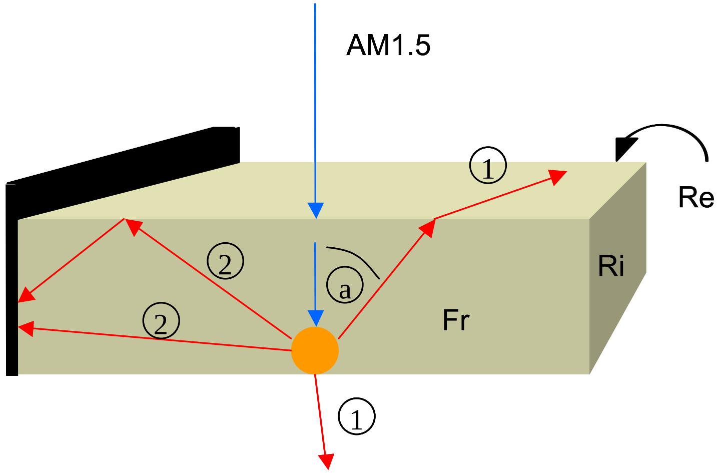
New concepts

- improved spectrum utilization
- flat plate concentrator





ECN Solar Energy

PV systems

- grid interaction
- system design & monitoring
- standards and guidelines

Crystalline Si PV technology

Objective:

- Price of solar electricity in 2015 the same as consumer electricity price, and after that even lower
  - High efficiency
    - 18% module efficiency for crystalline Si PV
  - Reduction of material usage
    - Thin wafers (<150 μm compared to current >240 μm)
  - Cost effective and environmental friendly processes and products
  - Long lifetime of the modules (>30 yr for crystalline Si)

    - Energy Pay Back Time < 1 yr

Cell structure

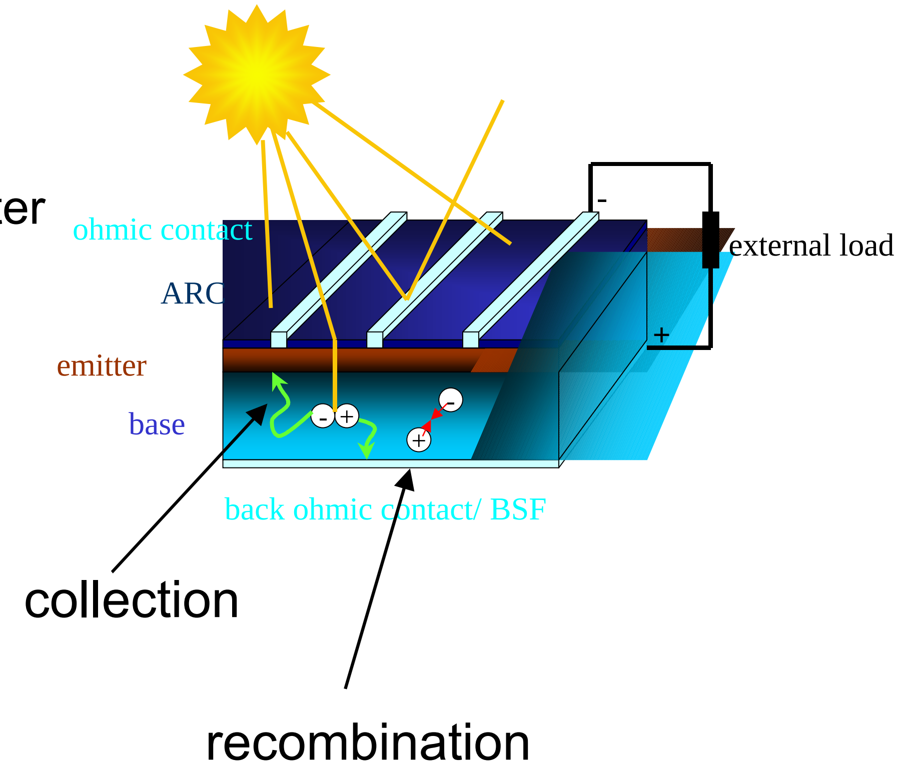
Crystalline silicon solar cell (minority carrier device)

- Base: B doped Si (p-type)
- Emitter: P doped layer (n-type)
    - Recombination losses in base and emitter
    - Voltage over pn junction

- Metallization for contacts
    - Shading losses
    - Resistance losses

- Antireflection coating to enhance current

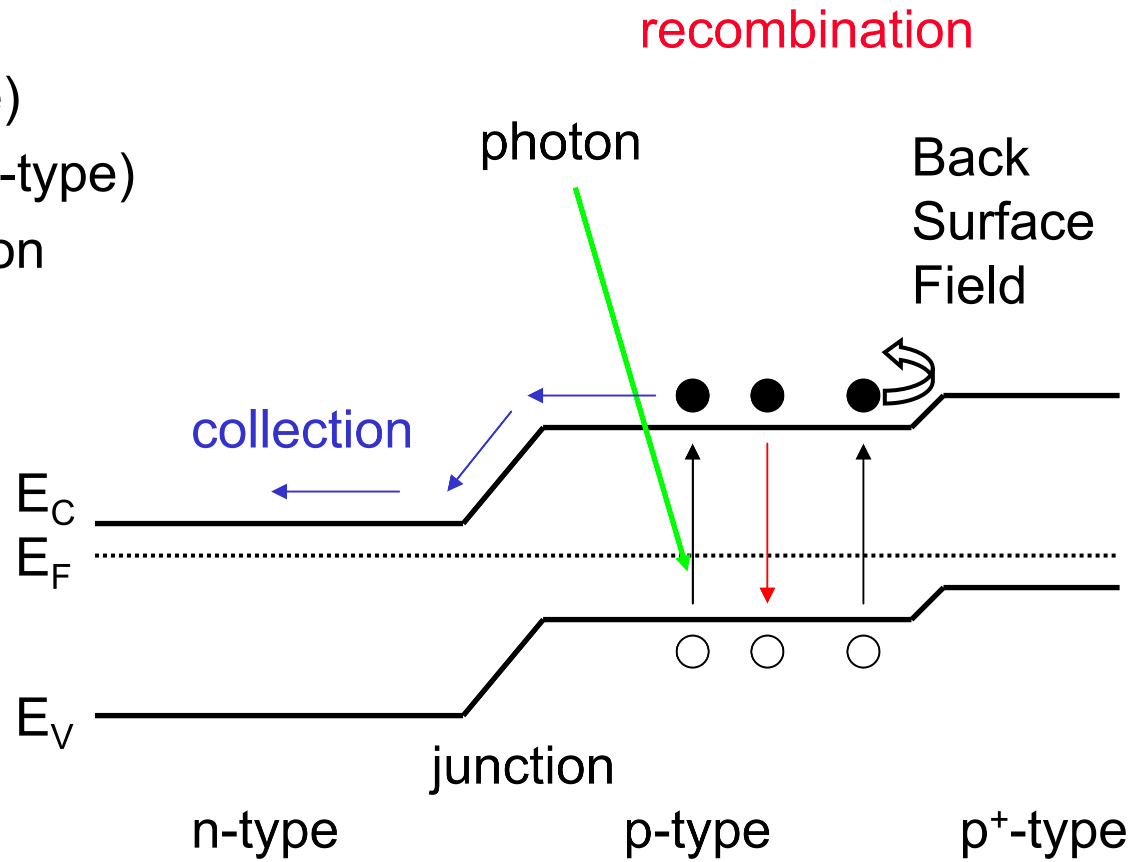
- Surfaces: recombination losses



Cell structure

Crystalline silicon solar cell

- Base: B doped Si (p-type)
- Emitter: P doped layer (n-type)
  - Voltage over pn junction
  - Recombination losses
- BSF: p^+ doped layer
  - Highly doped
  - Reduced recombination



Cell structure

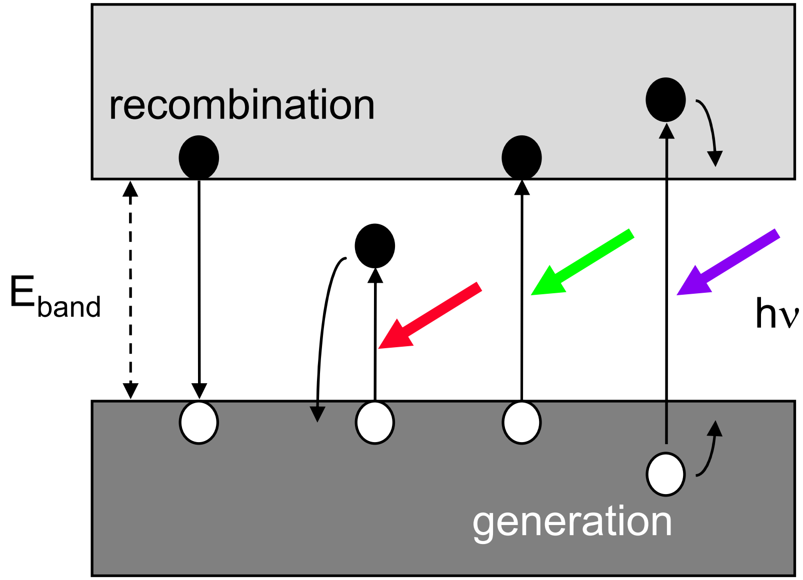
Losses in crystalline silicon solar cell

- Colour mismatch
- Fundamental recombination

} $\eta \leq 30\%$

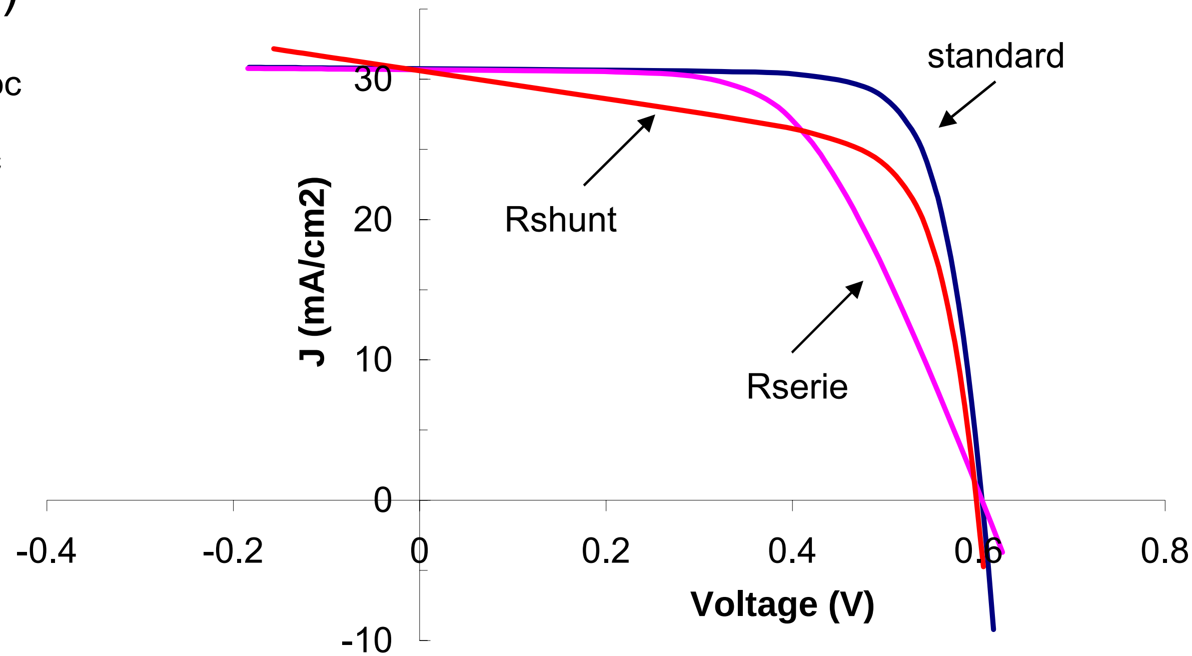
- Additional recombination
  - Impurities, defects, surfaces
- Shading
- Reflection, absorption and transmission
  - Absorption at the rear
- Resistance
- Non-ideal band gap

Crystalline Si solar cell: η=13-20%



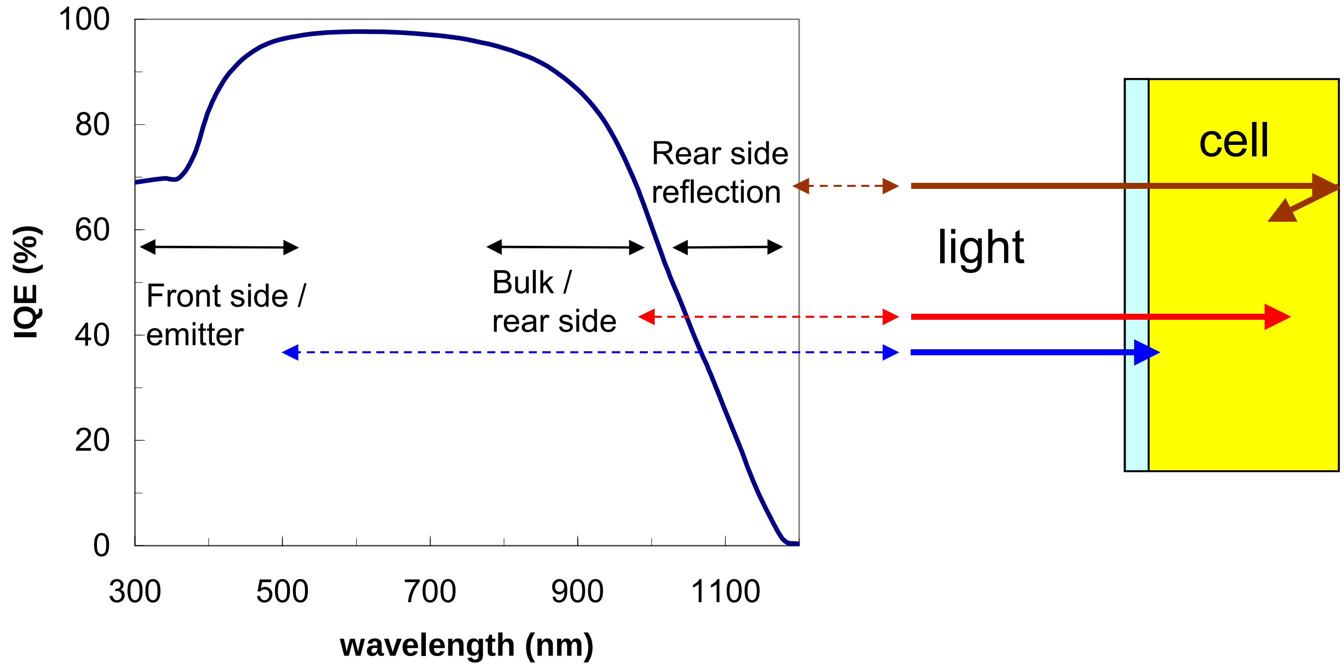
Cell characterization

- Current Voltage (IV curve)
  - Open circuit voltage V_{oc}
  - Short circuit current J_{sc}
  - Efficiency
  - Resistance losses



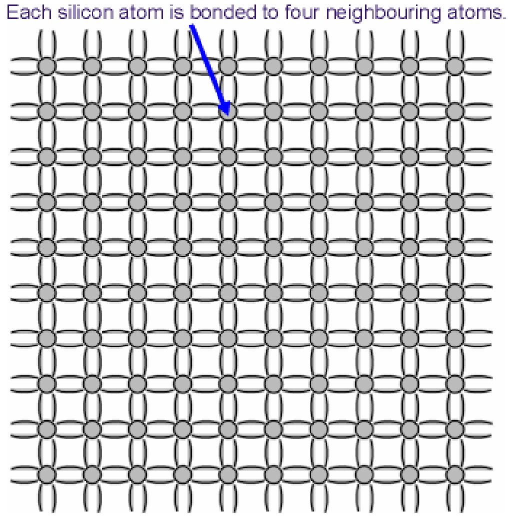
Cell characterization

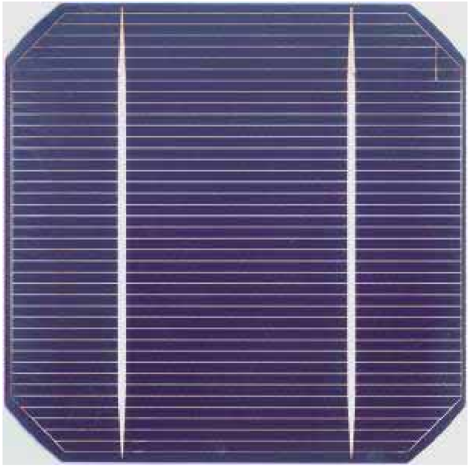
- Internal Quantum Efficiency IQE
  - IQE=collected carriers / absorbed photons
  - Depth profile cell quality



Crystalline Si PV technology

- Feedstock
  - Effect impurities on cell output
- Wafers
  - Monocrystalline Si
  - Multicrystalline Si
- Cell technology
  - High efficiency with industrial in-line processing
- Module Technology
  - Module design integrated with cell concept
  - Simple interconnection and encapsulation
- Costs and environmental aspects





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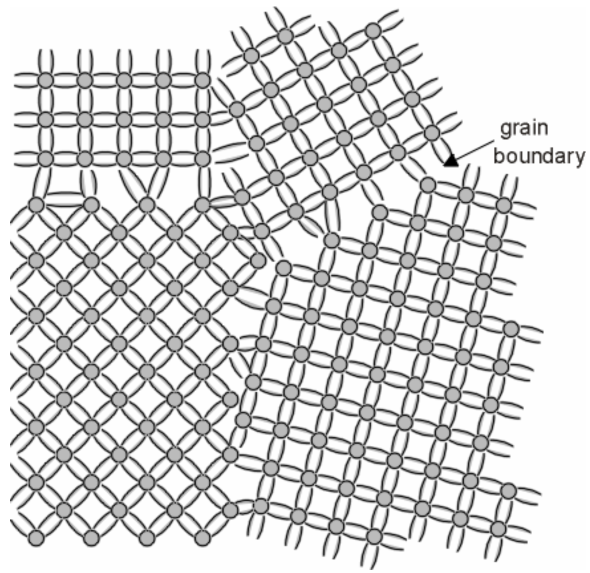
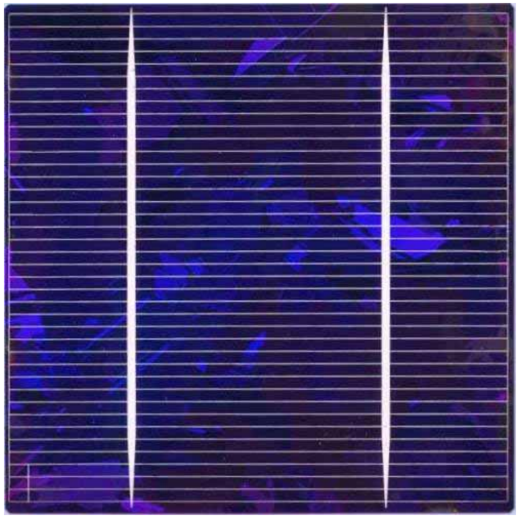
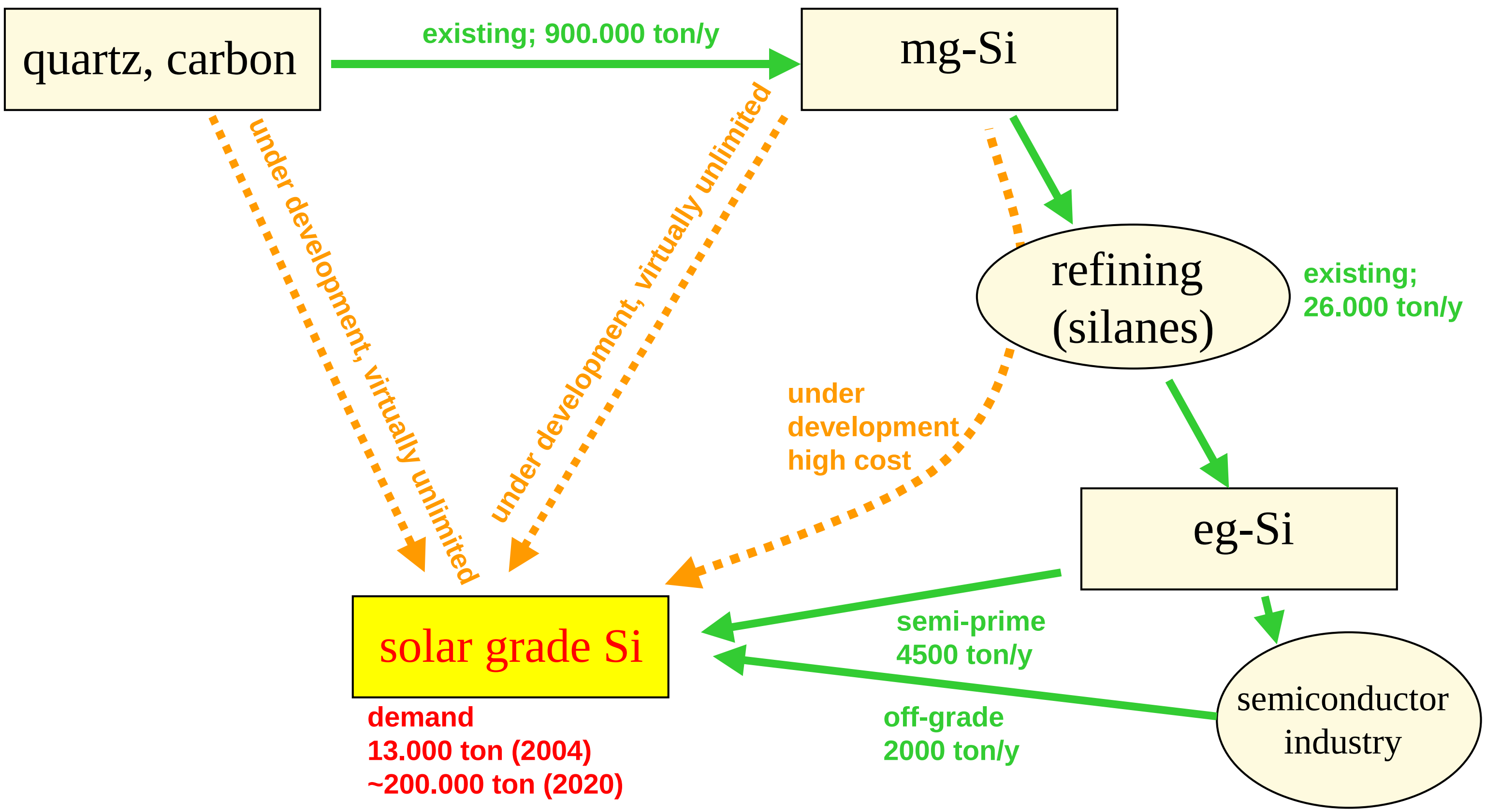




Feedstock production

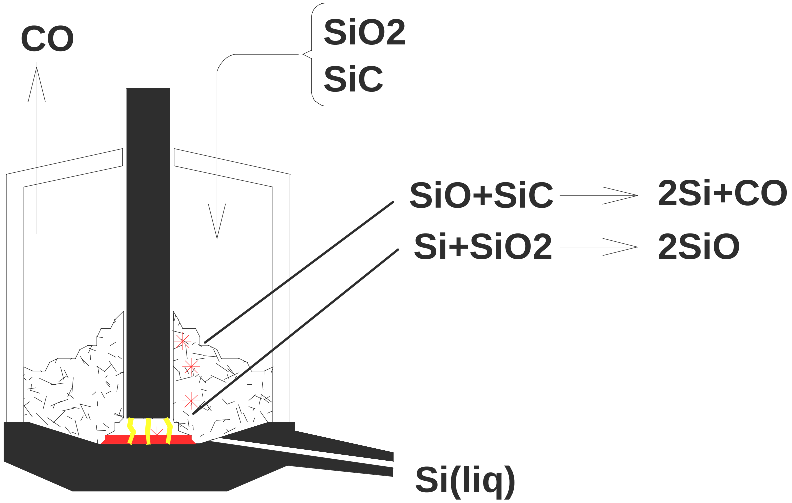


Feedstock production

- Direct route: SOLSILC process

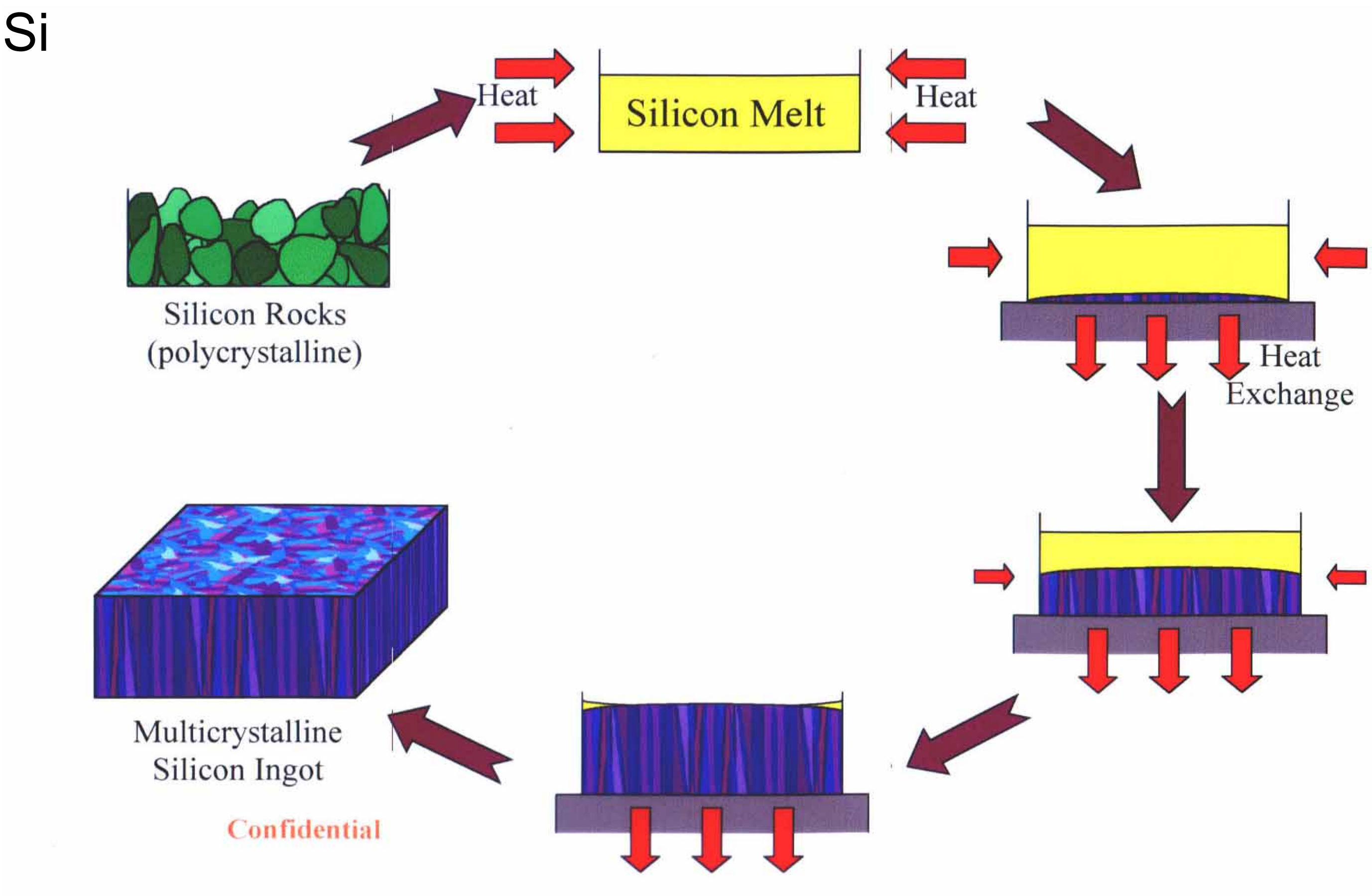
- plasma furnace: SiC from pure SiO_2 and pure C

  pellets of SiC and SiO_2 ⟶ Si(L)



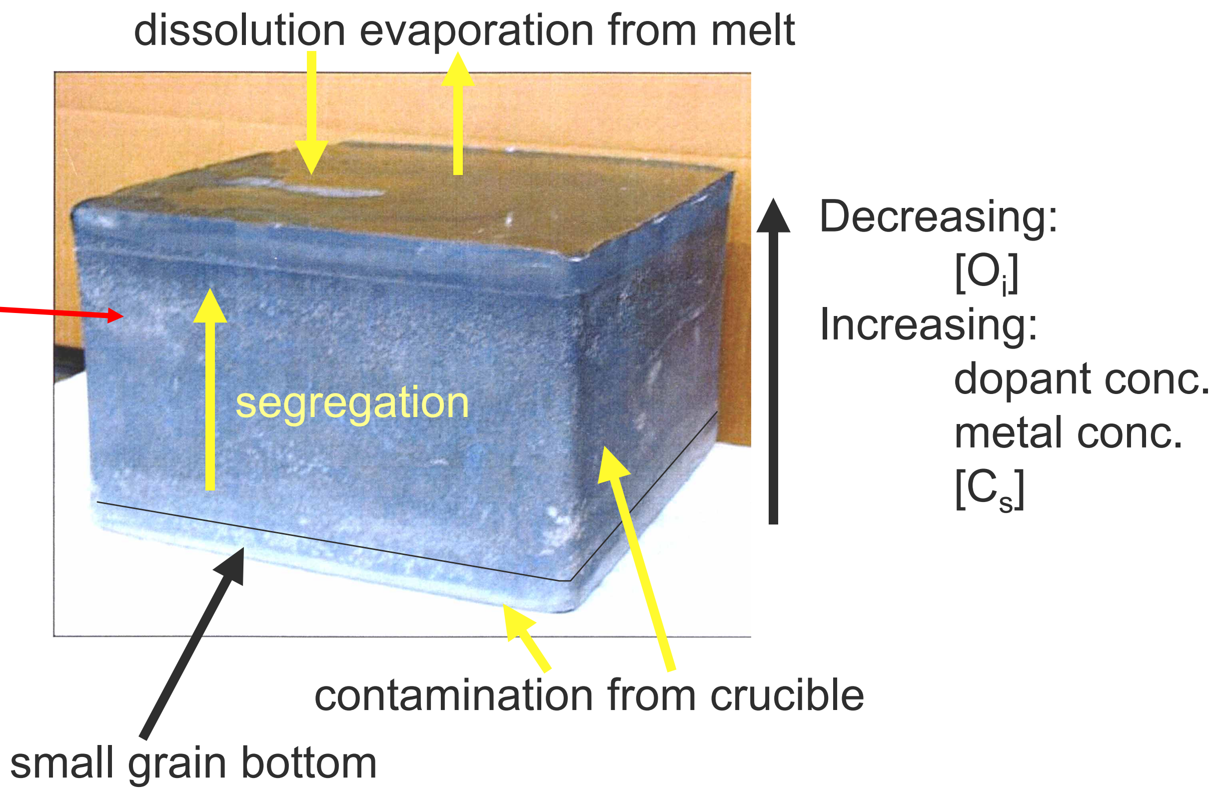
Feedstock: ingot growth

- Multicrystalline Si ingot growth



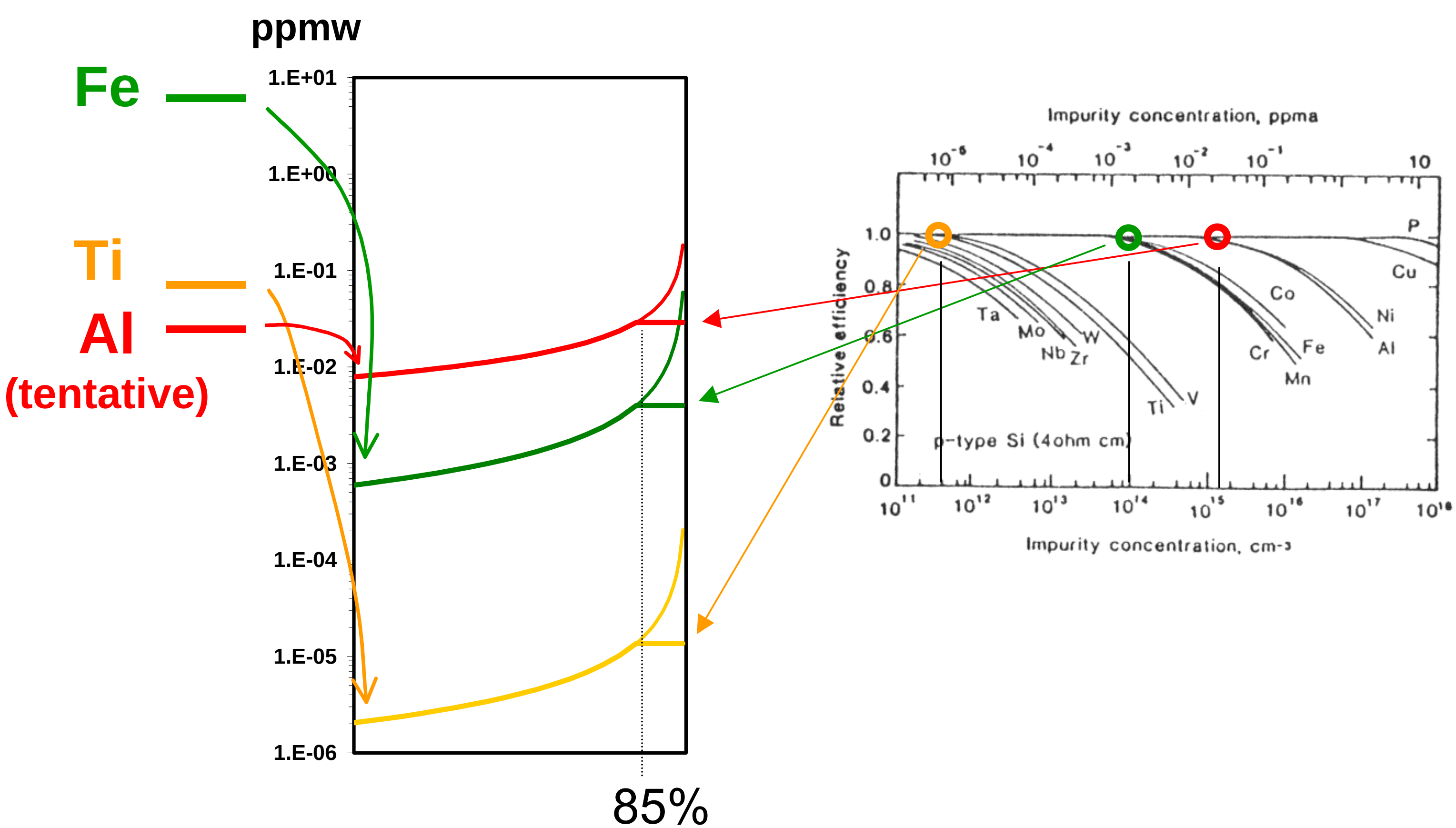
Feedstock: effect impurities

- Feedstock
  - Melting
  - Crystallization
- Ingot
  - Sawing
- Wafer



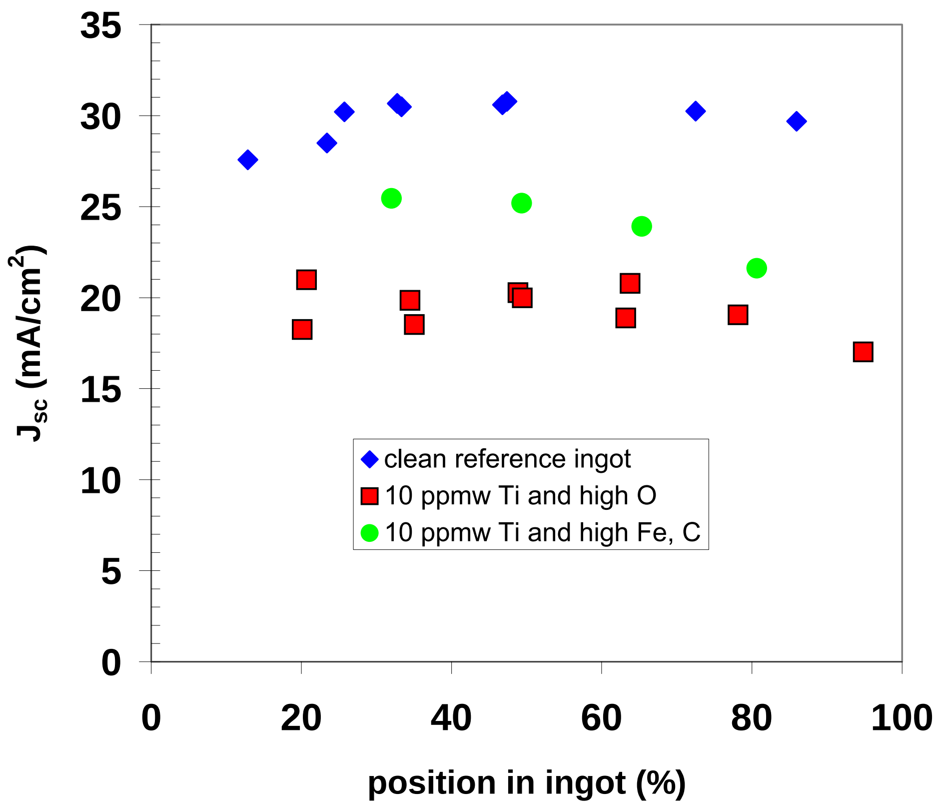
Feedstock: effect impurities

feedstock ingot wafer



Feedstock: effect impurities

Impurities added to feedstock



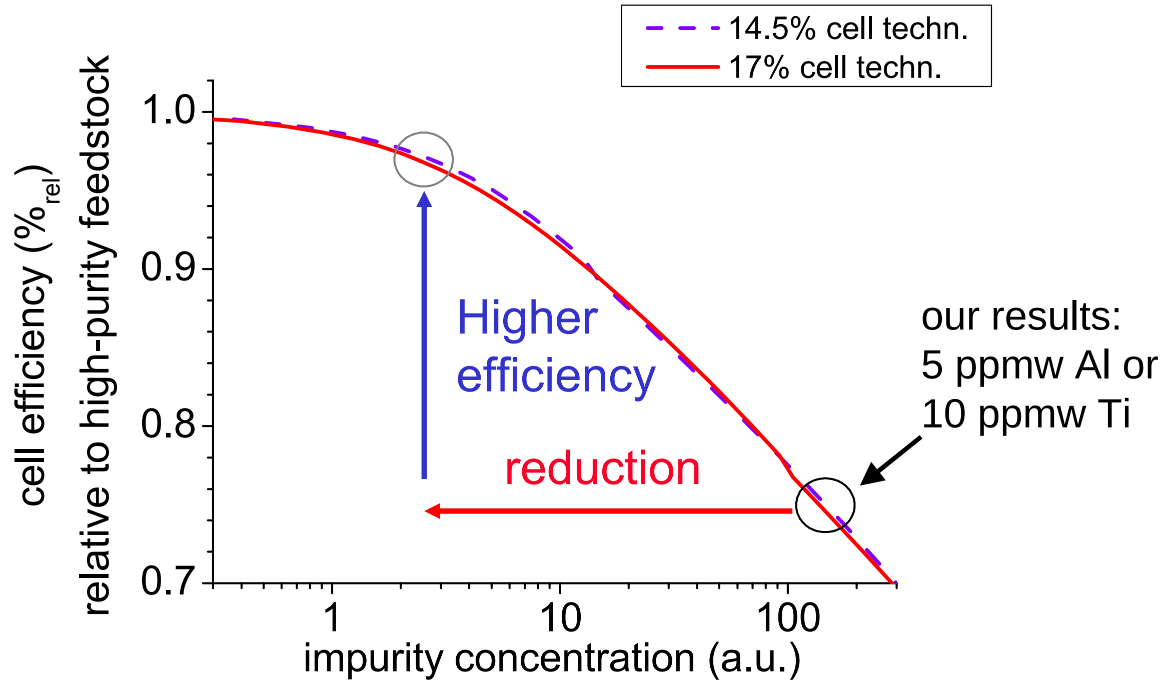
Effect Ti and O on cell output clearly visible

ECN

Feedstock: effect impurities

Impurities added to feedstock

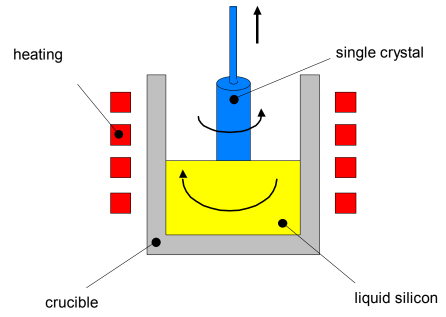
- Ingot growth
- Wafering
- Cell processing
- Characterization
- Model development
  - $1/L_{eff}^2 \propto 1/\tau \propto C_{imp}$
  - Segregation during growth
  - Solar cell modeling



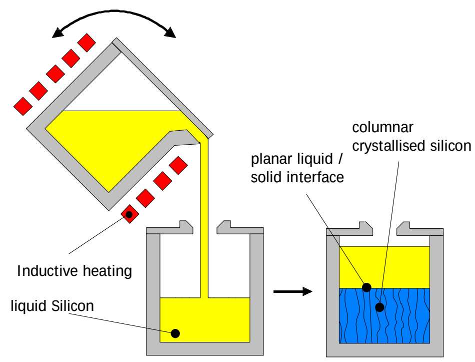
- Needed to define Solar Grade Si

Wafer technologies

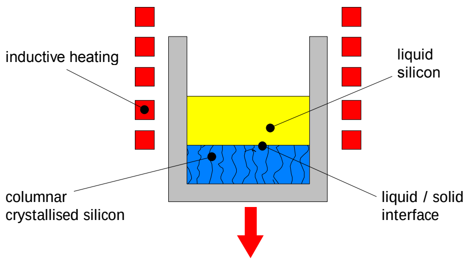
Pulling of Single Crystals (Czochralski)



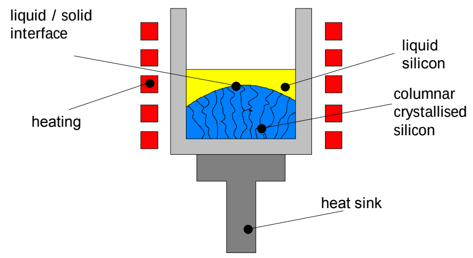
Casting of Silicon Blocks



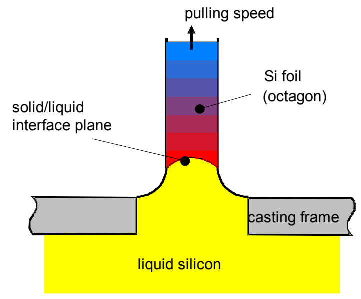
Bridgman Solidification



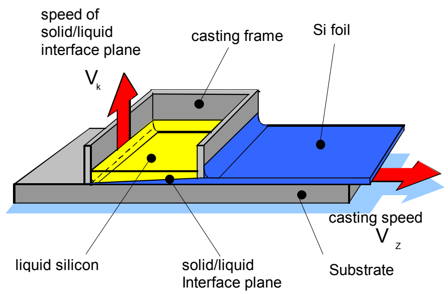
Heat Exchange Method



Edge defined Film fed Growth

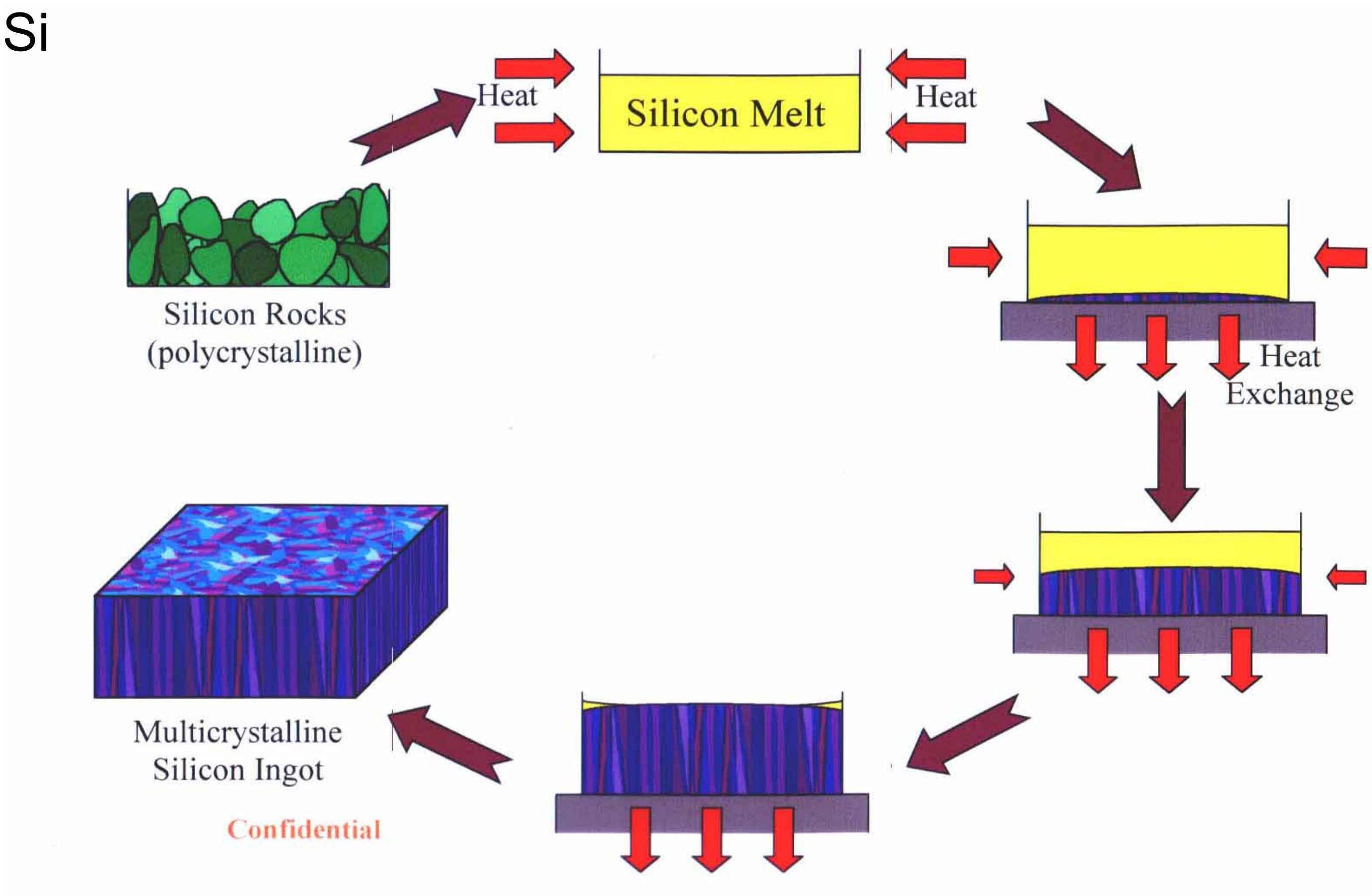


Ribbon Growth on Substrate



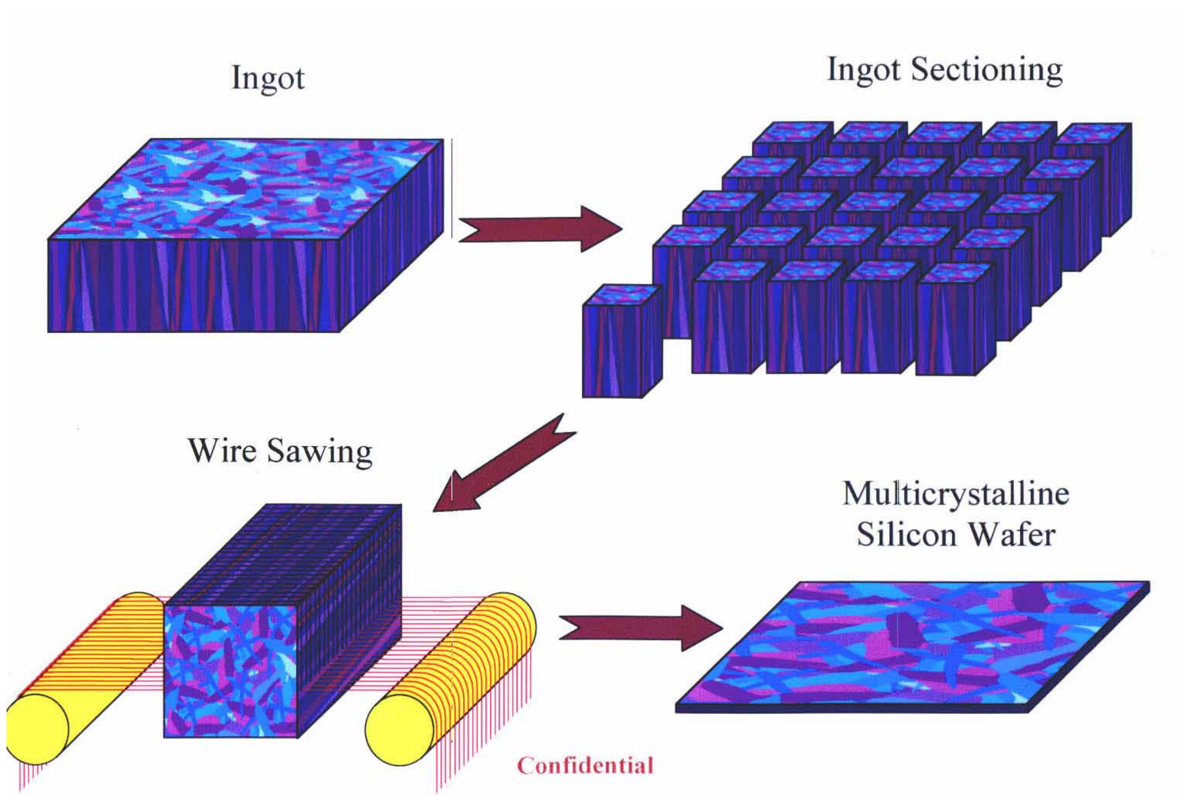
Wafer technologies

- Multicrystalline Si ingot growth



Wafer technologies

- From ingot to mc-Si wafer

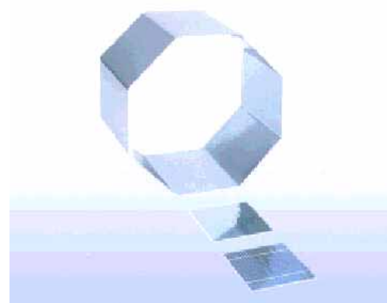


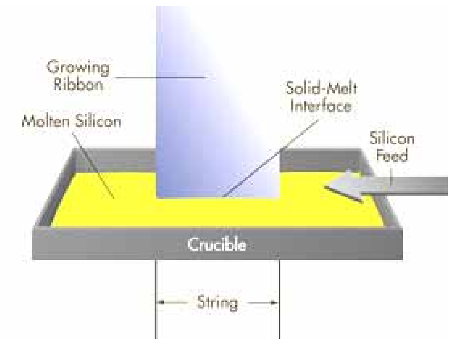
Wafer technologies

- High quality monocrystalline Si material
  - Low impurity concentration
  - Low defect concentration
  - Higher efficiency (15-17% in industry, 20% pilot)
  - Higher costs per cell
- Lower quality multicrystalline Si material (mc-Si)
  - Higher impurity concentration
  - More defects
  - Lower efficiency (13-15% in industry, >16% pilot)
  - Lower costs per cell
- For both technologies: high sawing losses (about 50%!)

Wafer technologies

- Ribbon technologies (multicrystalline Si)
- Substrate growing and crystallization in the same direction





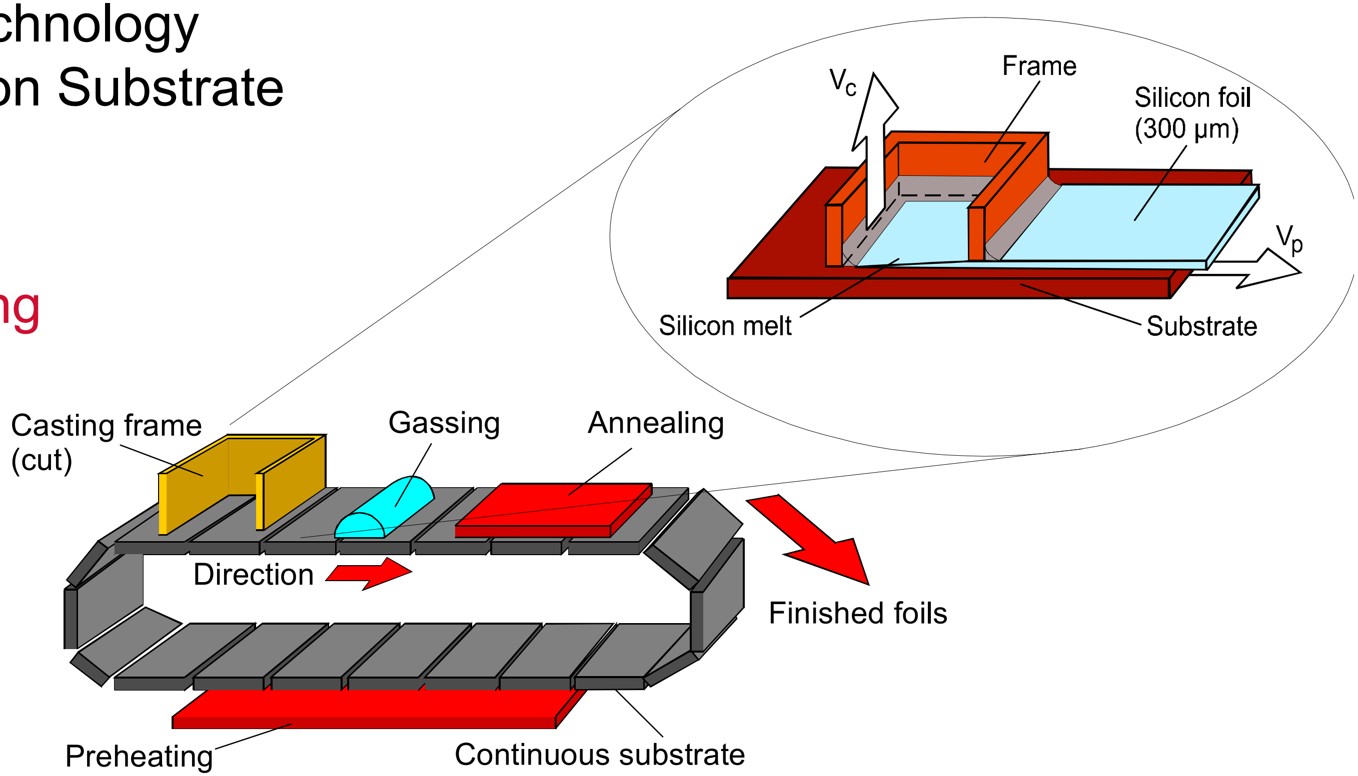
Edge defined Film-fed Growth (SCHOTT Solar)

String Ribbon

Wafer technologies

- ECN's ribbon technology
  Ribbon Growth on Substrate
  RGS

- Substrate growing perpendicular to crystallization



Wafer technologies

Ribbons:

- Better use of Si material (about factor 2)

But

- Lower initial material quality
- Lower efficiencies

- EFG/SR: about 14% (industry)
- RGS: about 13% (lab)
  - Very high throughput

Material	**Pull Speed [cm/min]**	**Through-put [cm^2/min]**	**Furnaces per 100 MW**
EFG	1.7	165	100
SR	1-2	5-16	1175
RGS	600	7500	2-3

*[J. Kalejs, E-MRS 2001 Strasbourg]

Wafer Technology

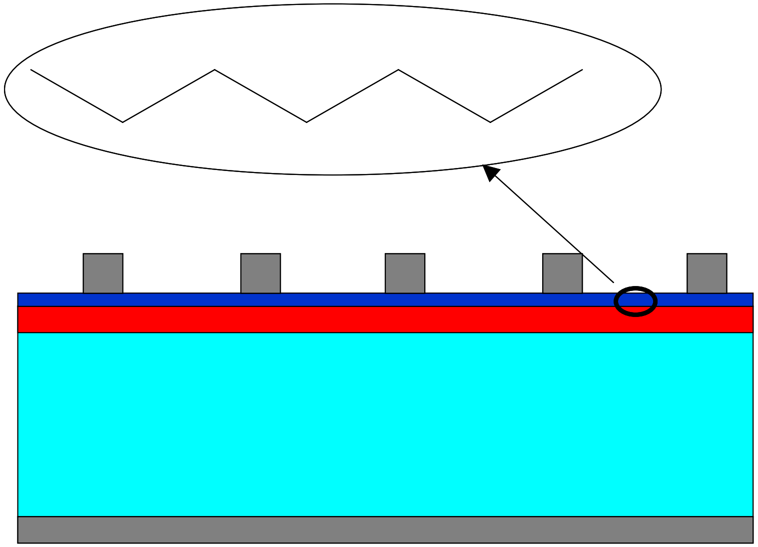
RGS cell efficiencies using industrial process

- Average efficiency 12.5%.
- Current top efficiency 13%[confirmed]
- High efficiency lab processing 14.4%[confirmed]

- ~100 µm thin RGS wafer made
    - Efficiency around 11%
    - 2.9 g Si/Wp (nowadays ~10 g Si/Wp)

Cell processing

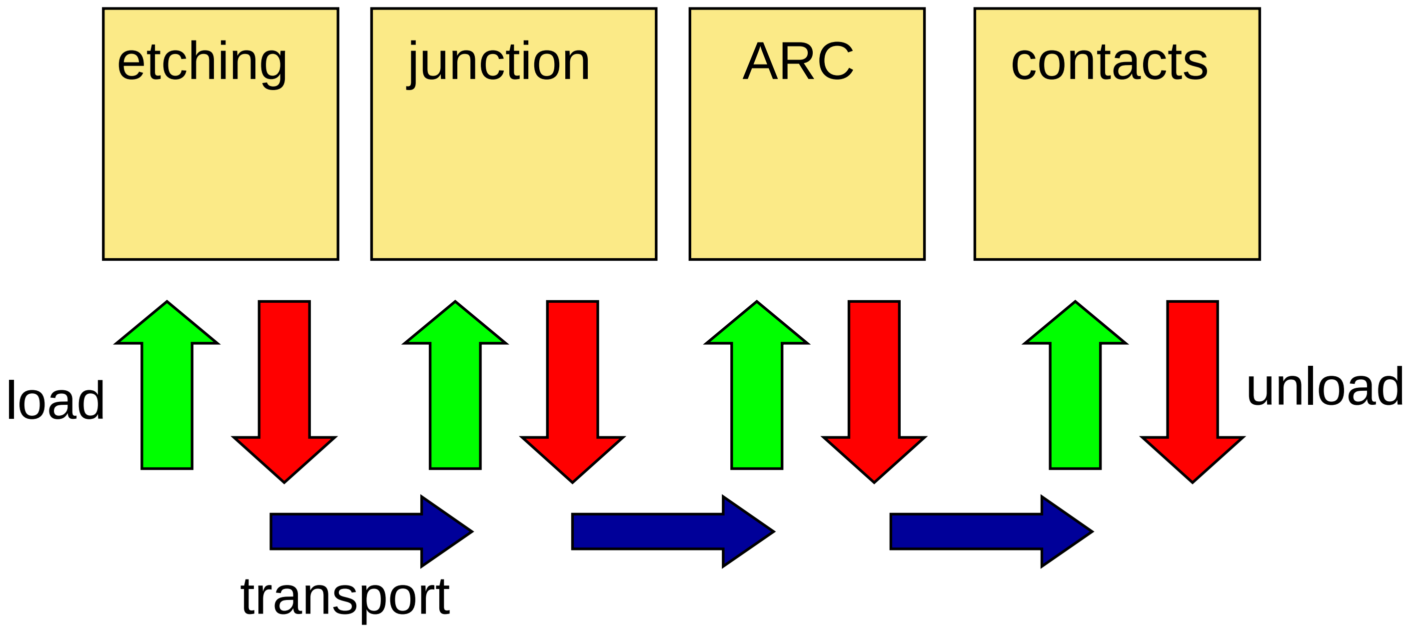
- Saw damage removal
  - Texturing for enhanced light coupling (better efficiencies)
- Emitter diffusion
  - Material improvement by gettering
- SiN_x deposition as antireflection layer
  - Material improvement by passivation
  - Reduced surface recombination (surface passivation)
- Metallization
  - Ag front side
  - Al rear side (so-called Back Surface Field)
- Sintering for contact formation

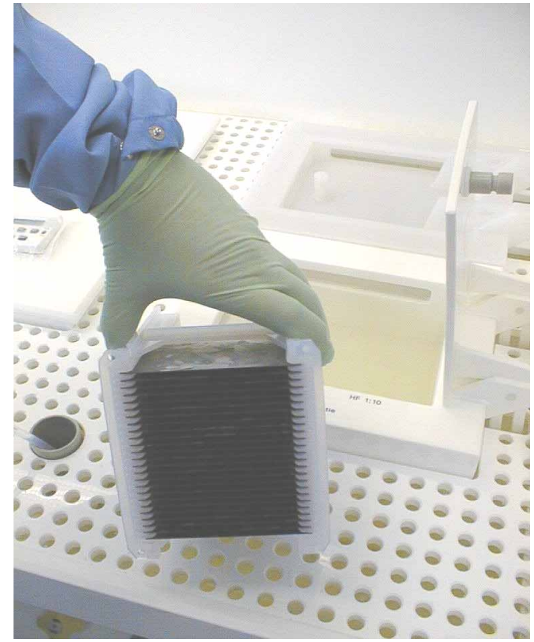


Cell processing

Batch processing

- Wafers in carriers
- Each process step well controlled
- Used for high efficiency processing



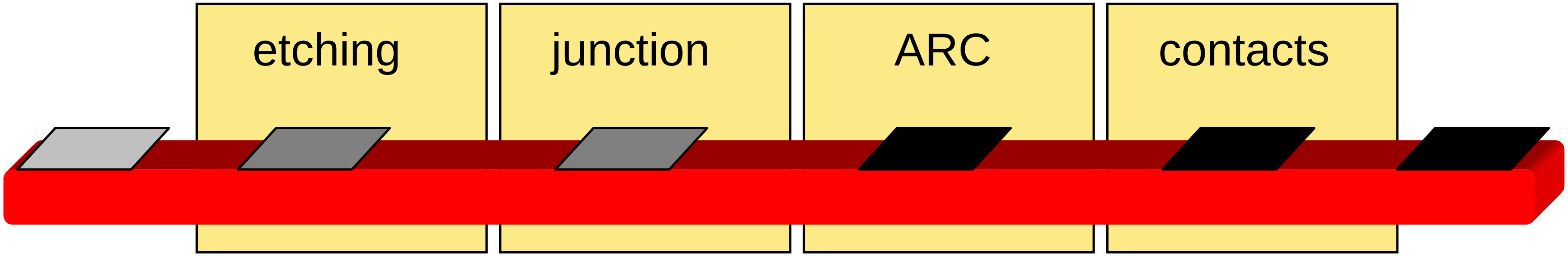


Cell processing

<u>ECN's inline processing</u>

Horizontal wafer transport on belts (wafer in; cell out)

- No wafer carriers
- Large and thin wafers easier to handle (cost reduction)



Cell processing

Examples from industry

Batch processing BP Solar

In-line processing SCHOTT Solar

Cell processing

ECN Baseline process

- Multicrystalline p-type Si
- Acidic texturing / saw damage removal
- P diffusion using belt furnace
- Deposition of SiN_x
- Metallization (Ag front, full Al rear)
- Simultaneous sintering both contacts

Results

Processing complete columns of wafers during two years

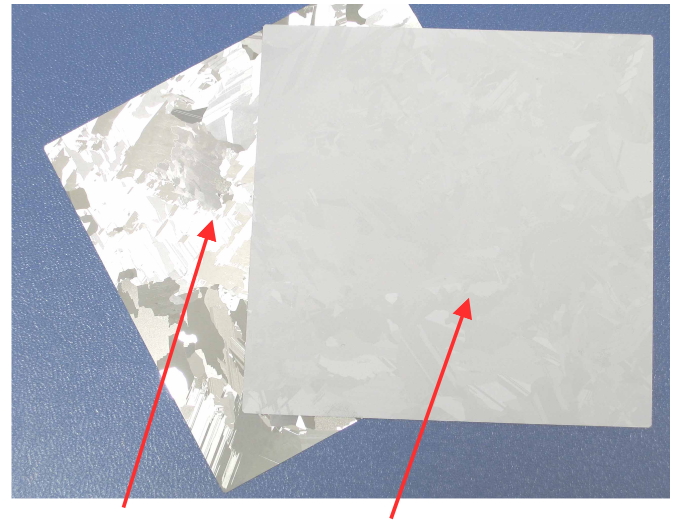
- Average 16%
- In industry about 15%

Wet chemical etching

Sintering contacts

Texturing

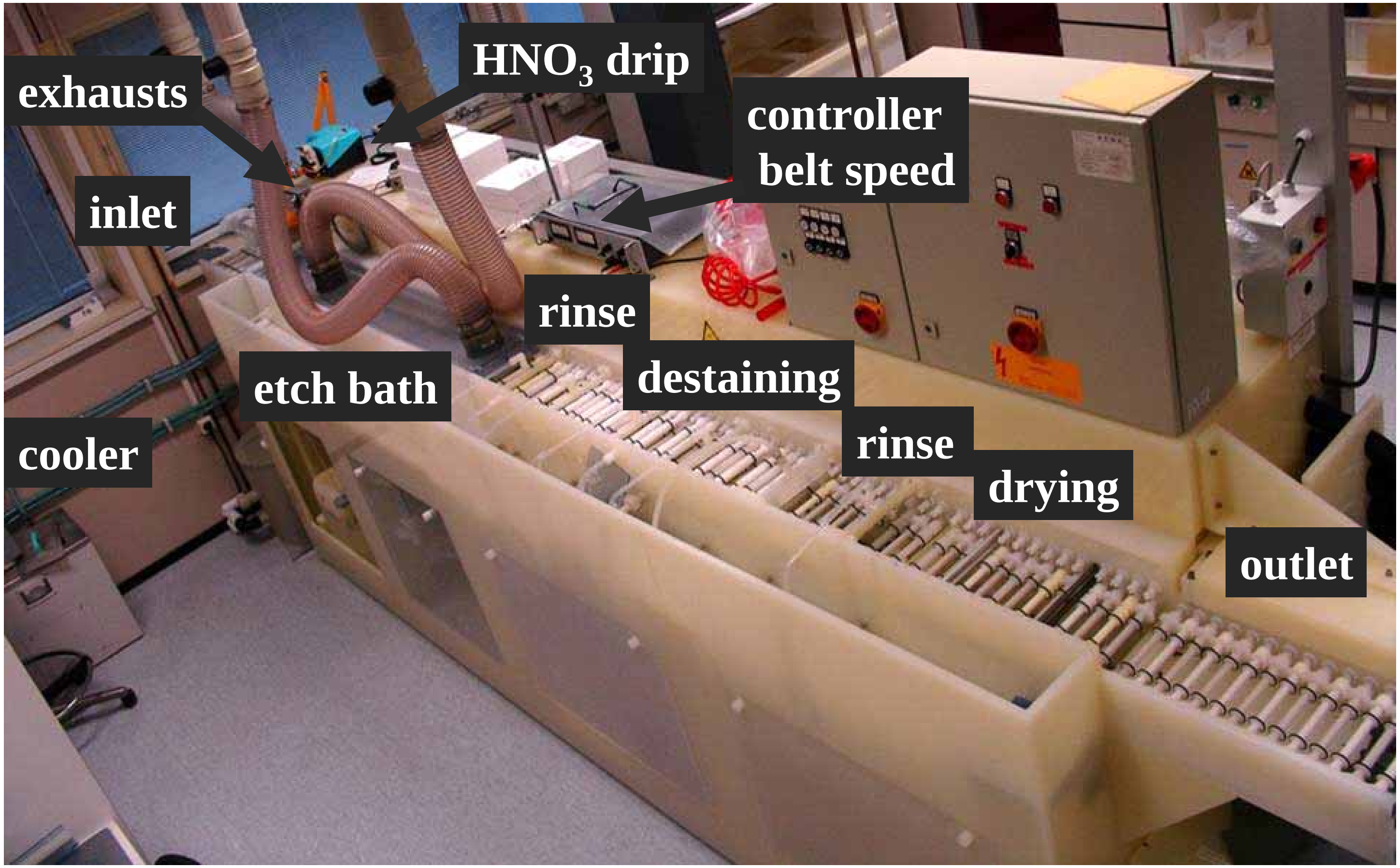
Acidic texturing of mc-Si



Alkaline and acidic etch

Texturing

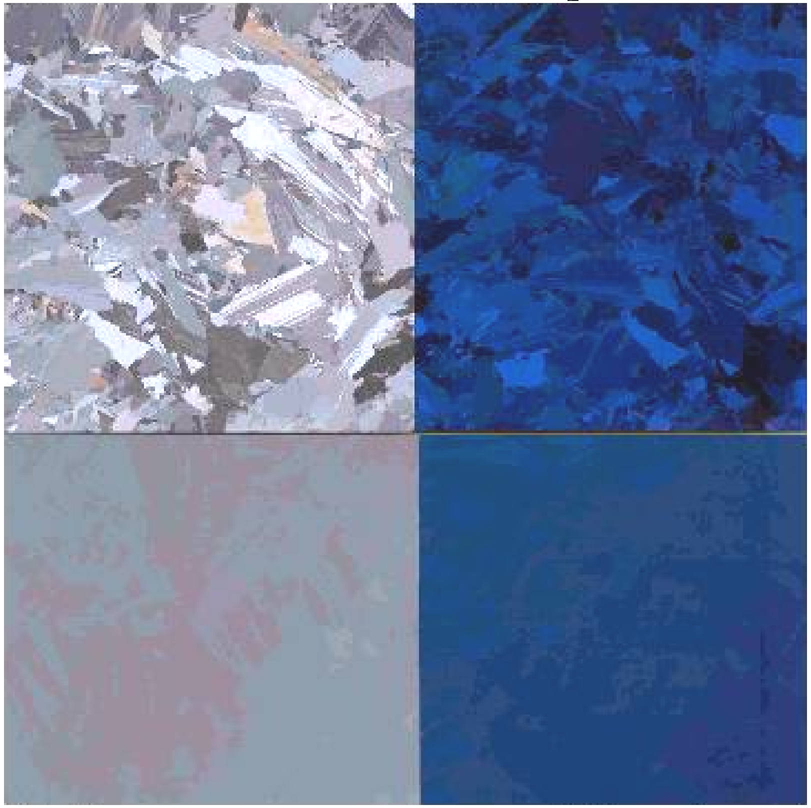
Acidic texturing of mc-Si



Texturing

Acidic texturing of mc-Si

- Lower reflection, higher efficiency
  - About 0.5% absolute
- Better appearance

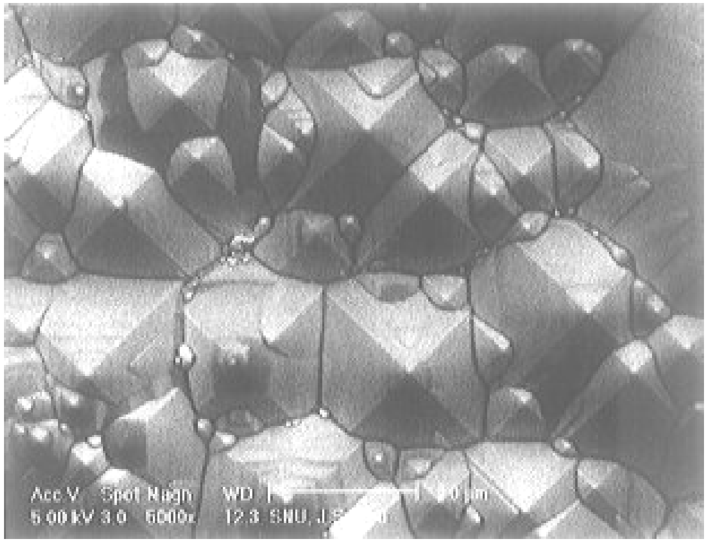


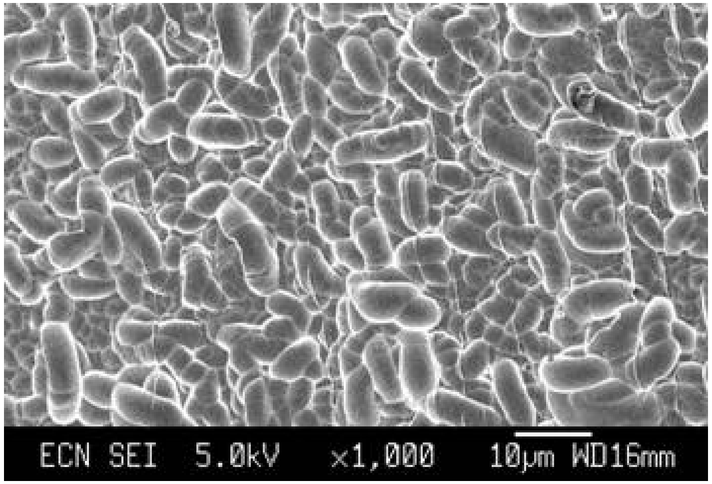
Texturing

Surface structure texturing Si

- Monocrystalline Si
  - Alkaline etching (NaOH or KOH)
  - Anisotropic etching
    - (111) planes slowest etching rate
    - Pyramids on (100) substrates

- Multicrystalline Si
  - HF/HNO_3 etching
  - Isotropic etching
    - Random structure



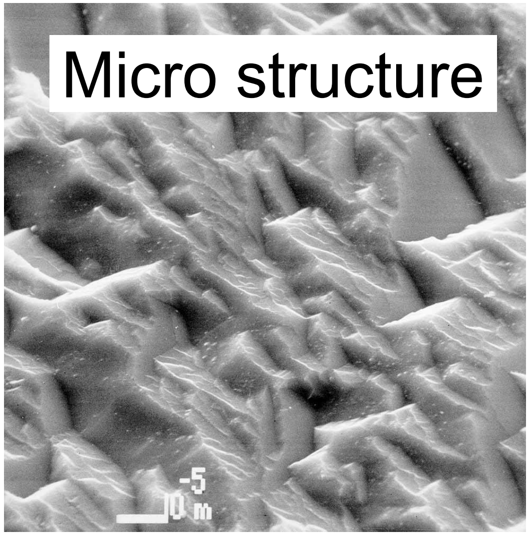


Texturing

Alkaline etching of Si

$$Si + OH^{-} + H_2O \rightarrow SiO_3^{2-} + H_{2\,gas}$$

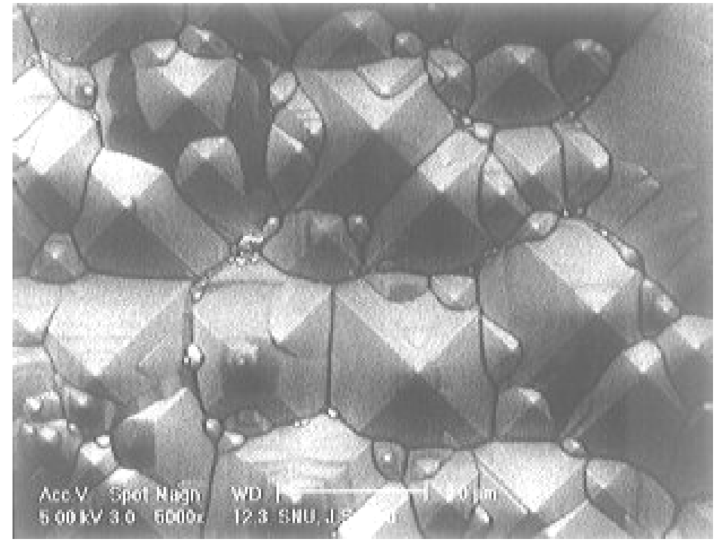
- Higher concentrations and higher *T*
  - Almost isotropic etching
  - High etching rate
  - Used to remove saw damage (5-10 μm)
  - High reflectance (~30%)

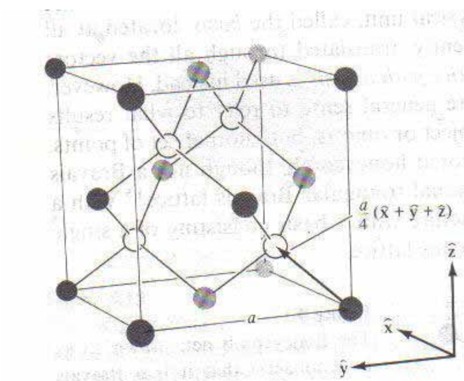


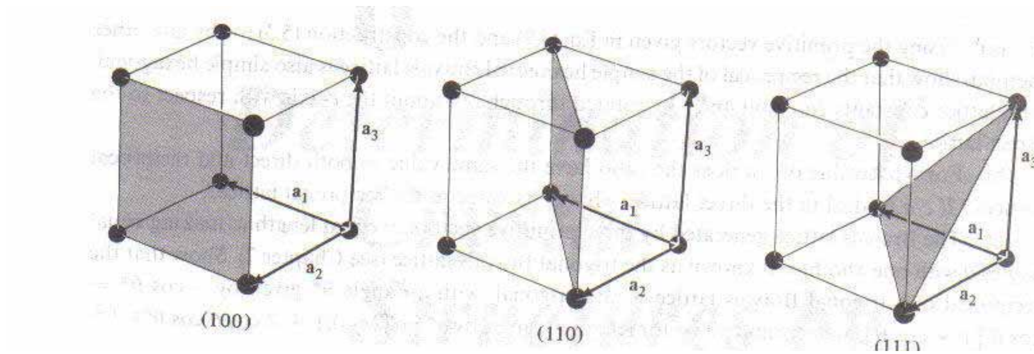
Texturing

Alkaline etching of Si

- Lower concentrations and lower *T*
  - Anisotropic etching
    - (111) planes slowest etching rate
    - Pyramids as texture on (100) substrates
    - Low reflectance (~10%)
  - But, low etching rate







Texturing

Acidic etching of Si

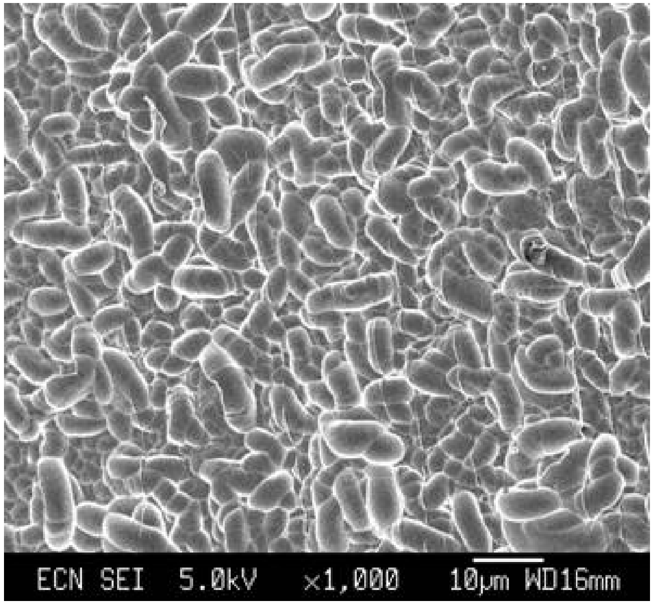
Mixture HF/HNO_3

Oxidation

$3\ Si + 4\ HNO_3 \rightarrow 3\ SiO_2 + 4\ NO_{gas} + 2\ H_2O$

Oxide removal

$SiO_2 + 4\ HF \rightarrow SiF_{4\ gas} + 2\ H_2O$



- Obtained surface morphology depends on composition
  - Polishing
  - Defect etching
  - Texturing

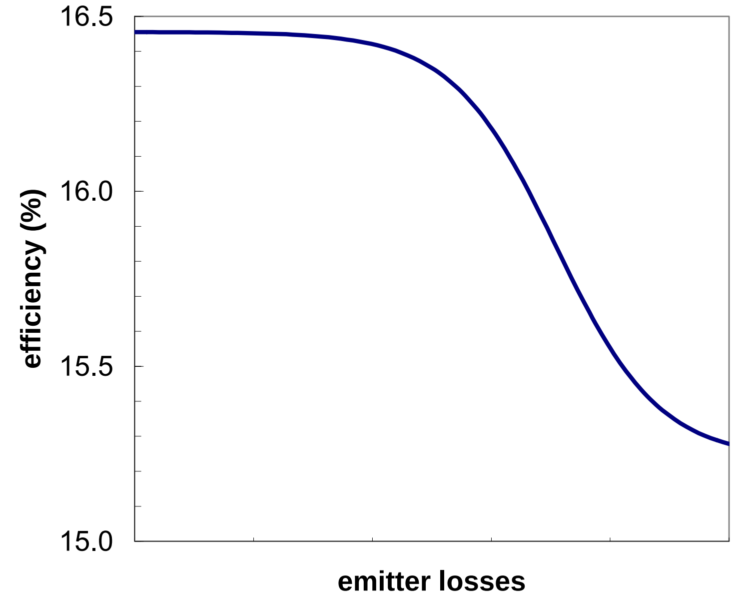
ECN

Emitter processing

Needed to form p-n junction

- Apply P source
- Diffusion at ~900 C for about 10 minutes

- Depth about 0.5 μm
- P concentration at surface: > 2×10^{20} cm^{-3}
  - Higher concentration needed for good contacting
  - However, it will result in additional recombination losses

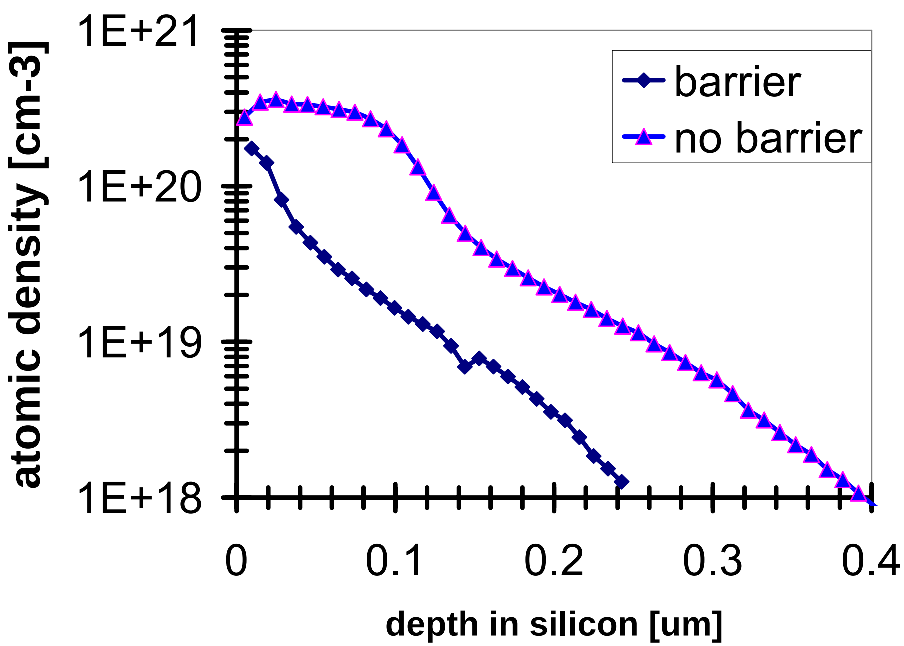


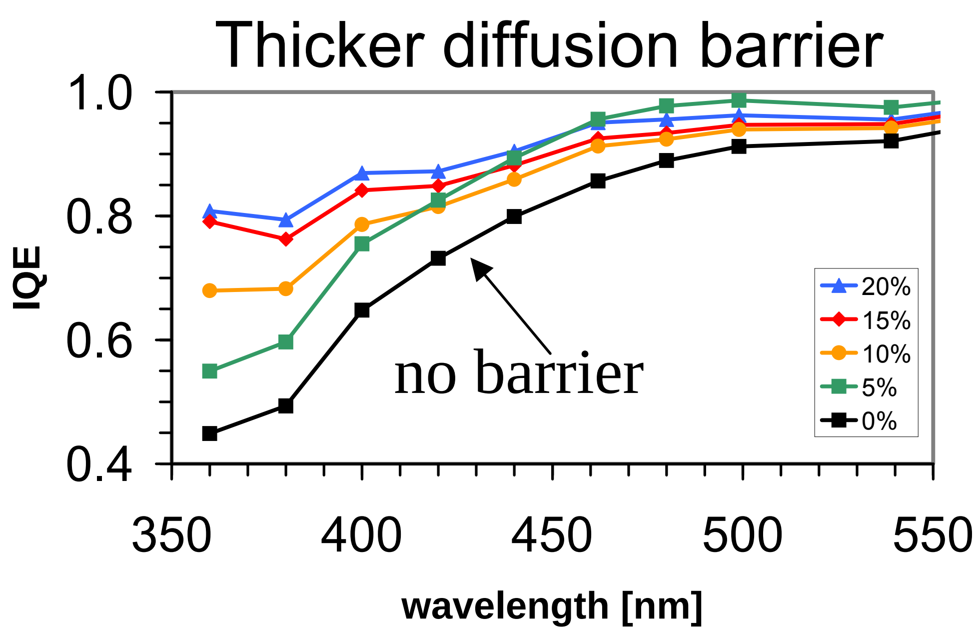
Improved emitter/front side processing can give an efficiency gain of more than 0.5% absolute

Emitter processing

Effect dopant concentration on IQE

- Improved blue response (up to 550 nm) for lower dopant concentration
- Higher V_{oc} and higher J_{sc}: higher efficiency!



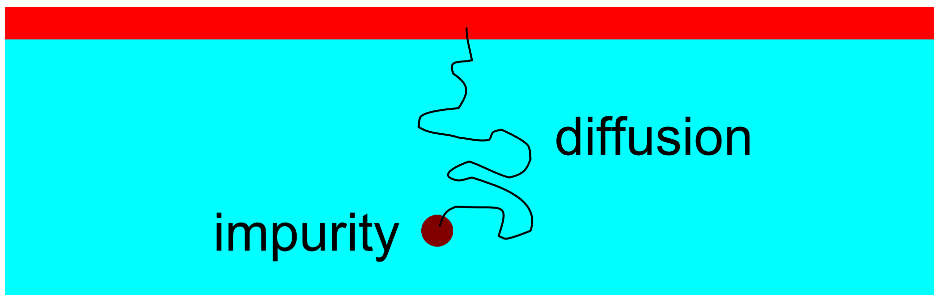


Emitter processing

Additional effect of emitter processing

- So-called gettering
  - Diffusion of impurities to P rich layers (P-gettering)
  - Impurities will not affect efficiency in those P rich layers

- Improved bulk quality and, thus, higher efficiency



SiN_x deposition

Applied using chemical vapour deposition

- Low pressure chemical vapour deposition (only surface passivation, ~700 C)
- Plasma enhanced chemical vapour deposition (different systems, ~400 C, 0.5-10 nm/s)
- Sputtering (several nm/s)

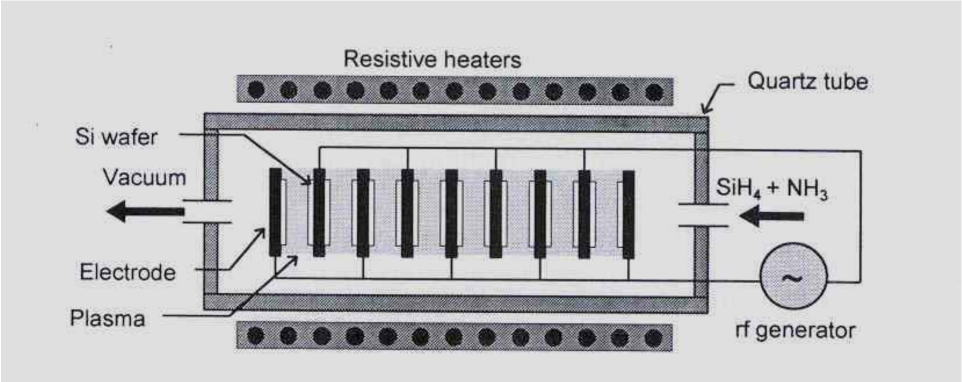
Functions SiN_x:H layer

- Antireflection coating (70-80 nm)
- Surface passivation (reduced recombination at the surface)
- Bulk passivation (improved material quality)
  - During anneal H diffuses into bulk and makes defects/impurities electrically inactive

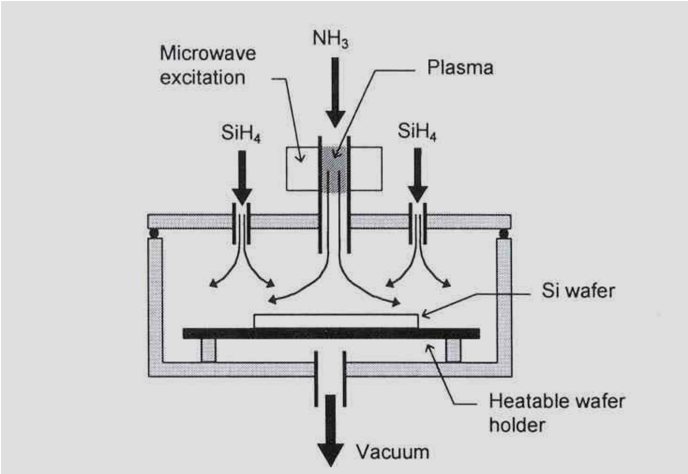
SiN_x deposition

Plasma Enhanced Chemical Vapour Deposition (PECVD)

- Parallel plate system
  Direct plasma
  - Wafers as electrodes
  - Ion bombardment dependent on plasma frequency
  - Damaged layer



- Remote PECVD
  - No ion bombardment



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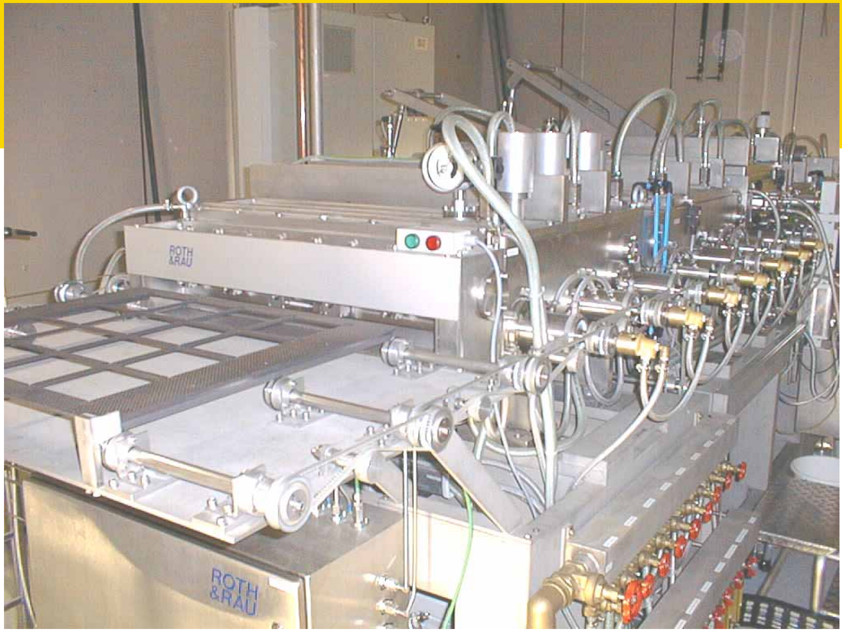
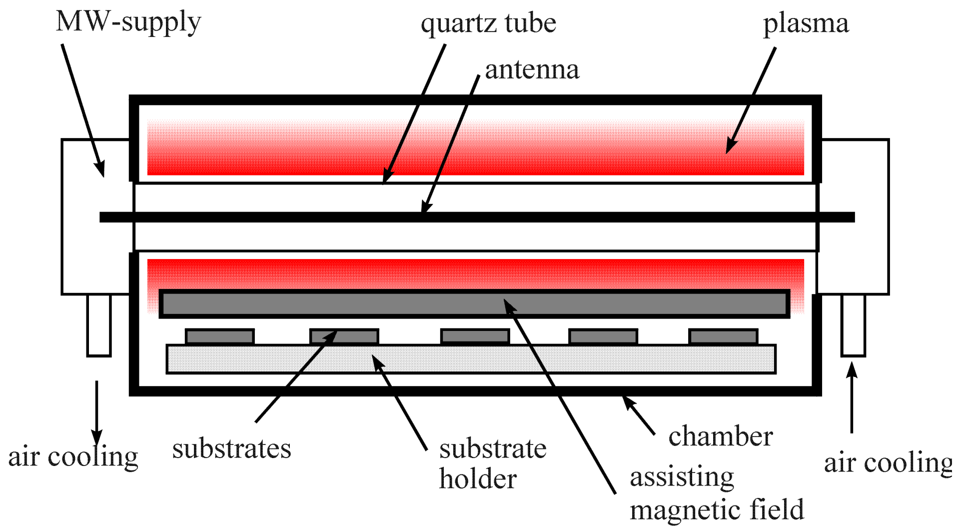
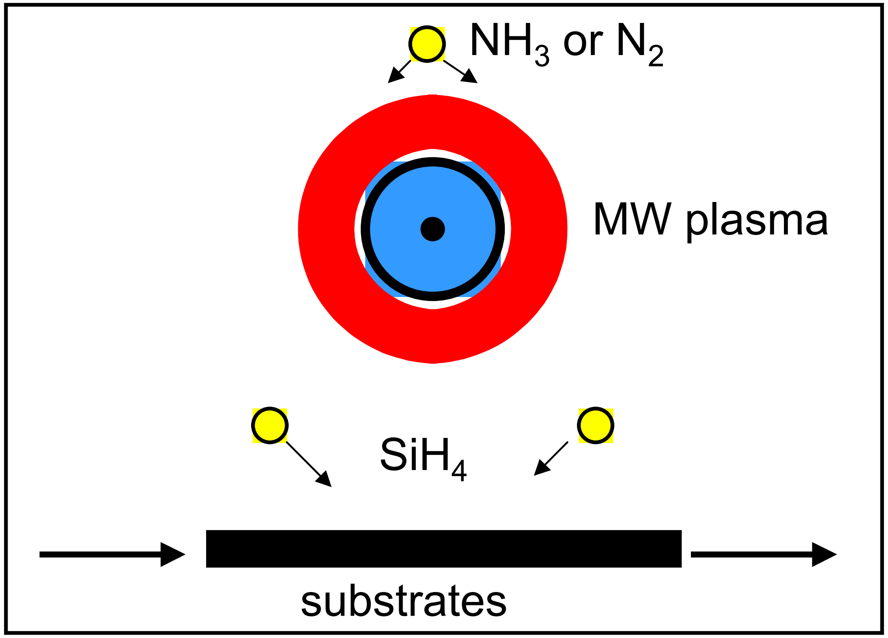
SiN_x deposition

ECN MicroWave Remote PECVD

- Deposition rate about 1 nm/s



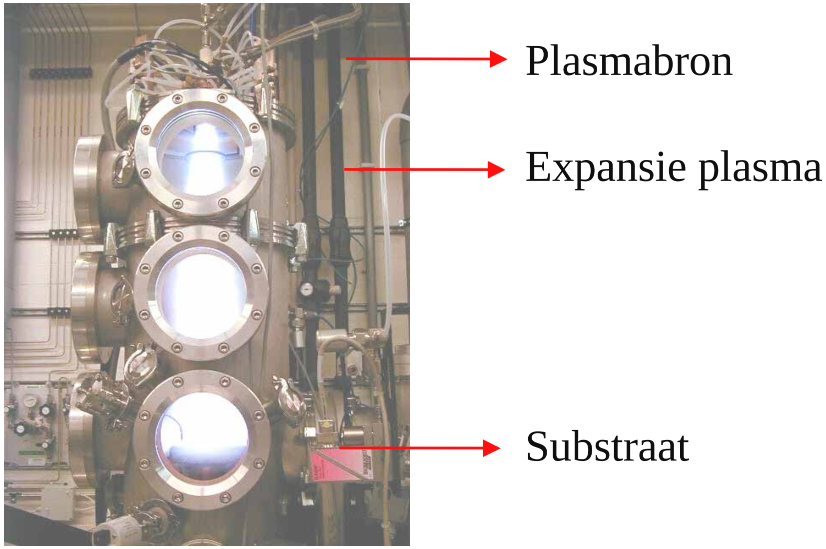


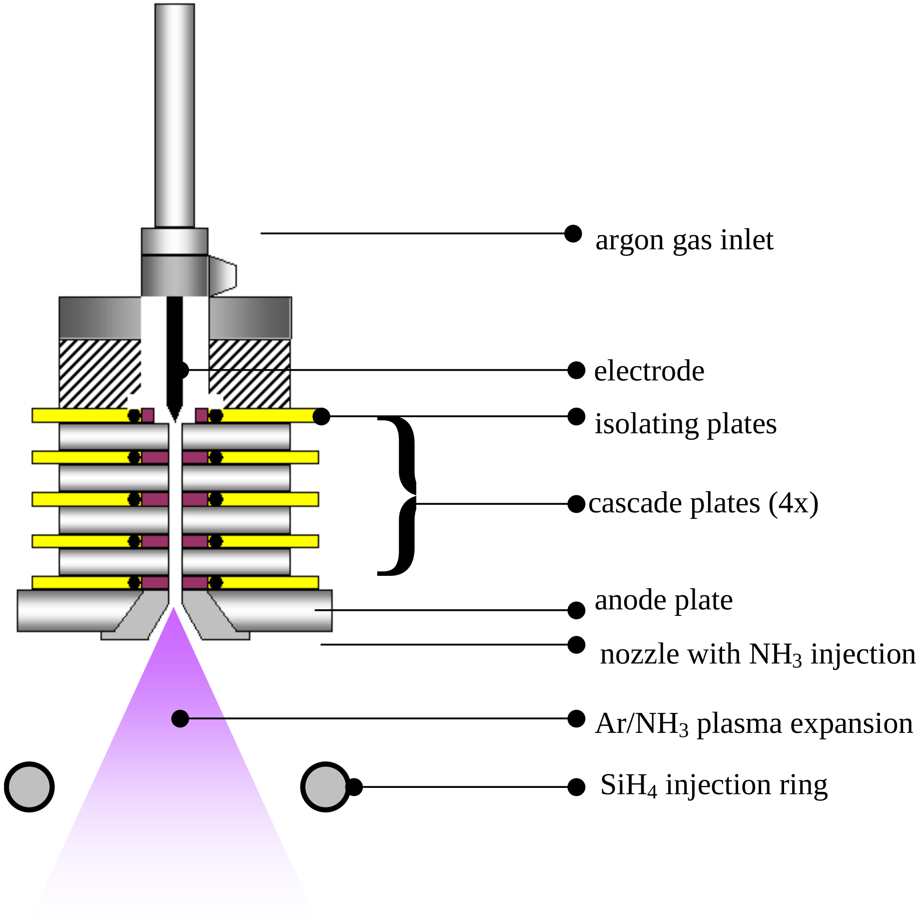


SiN_x deposition

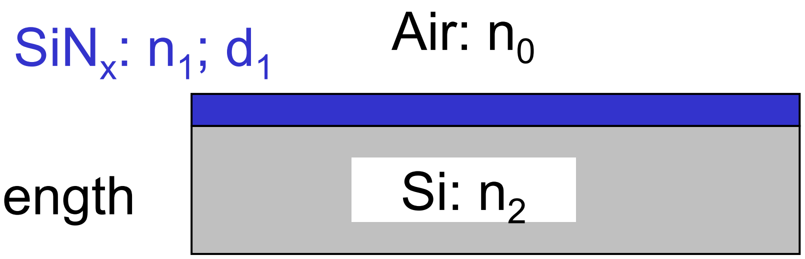
Expanding Thermal Plasma (ETP)

- Developed by TU/e
- Deposition rate 5-10 nm/s
- TU Delft: for thin film Si depositions





SiN_x deposition



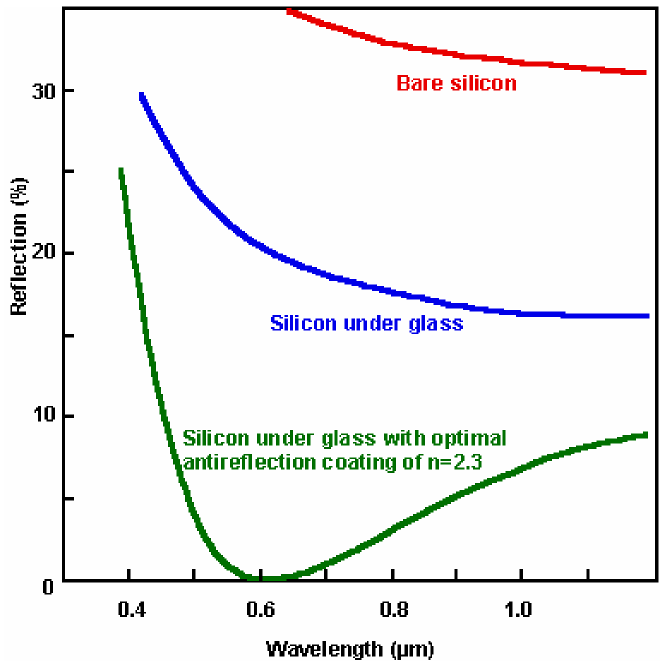
Optical specifications SiN_x:H layer

- Refractive index: *n*=2.1
  higher *n* causes absorption at lower wavelength

$$n_1 = \sqrt{n_0 n_2} \qquad d_1 = \frac{\lambda_0}{4 n_1}$$

- Ideal for air-Si: *n*=1.9; d=~80 nm
- Ideal for air-glass-Si: *n*=2.3; d=~65 nm
  (absorption SiN_x too high)

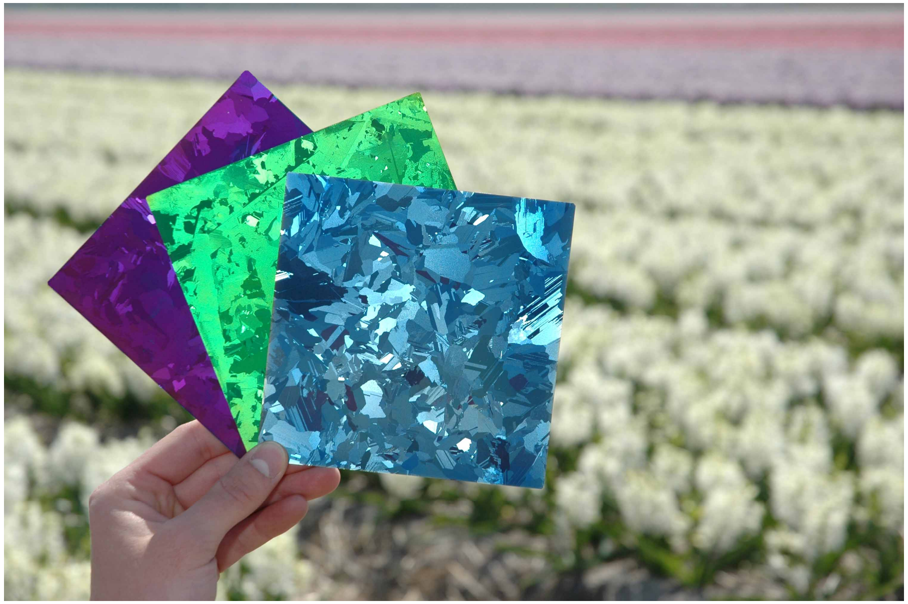
- *n* can be tuned with gas composition
- Higher *n*: more Si (SiH_4)
- Lower *n*: more N (NH_3)

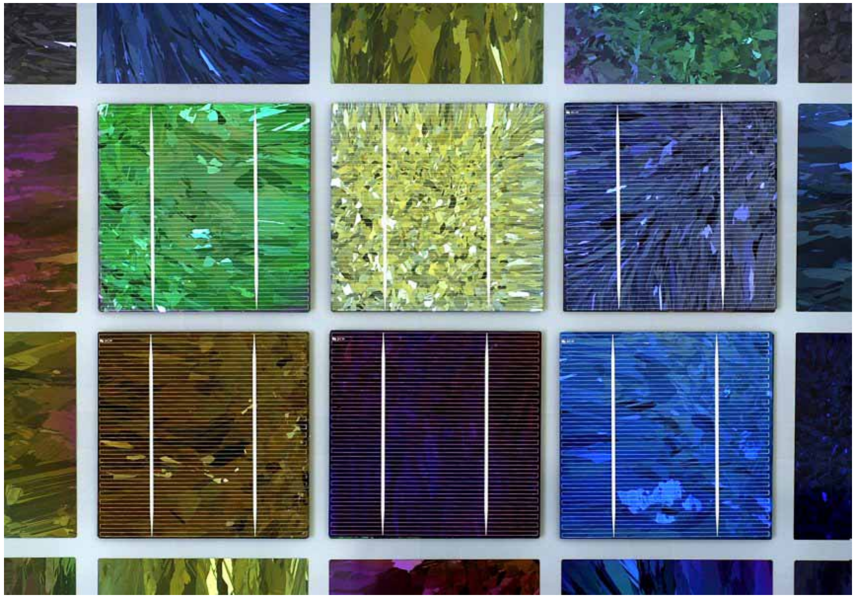


SiN_x deposition

Optical specifications SiN_x:H layer

- Different layer thickness: different colour

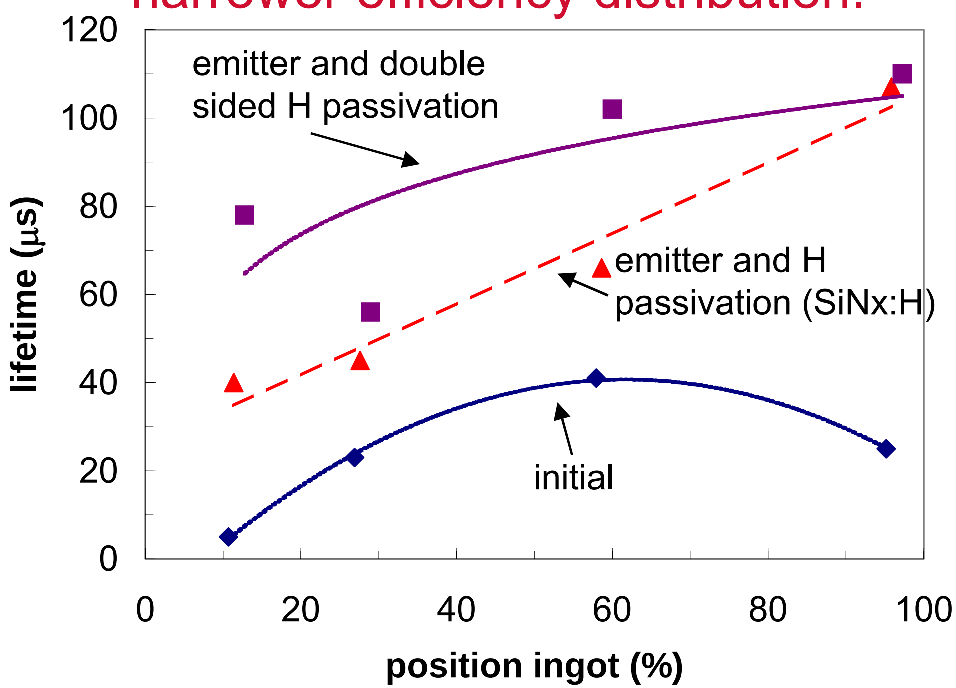


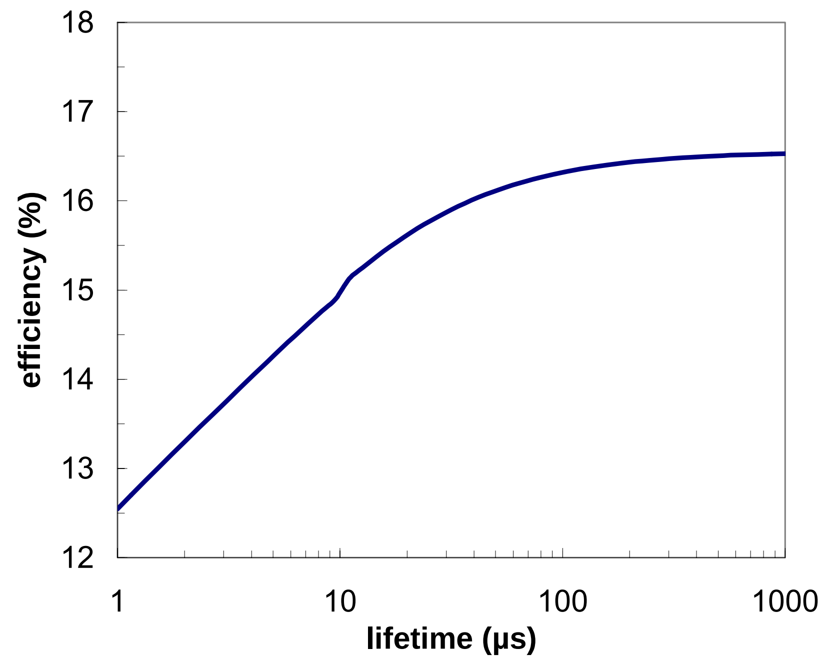


Gettering and bulk passivation (emitter and SiN_x:H)

Improved bulk quality using gettering and passivation

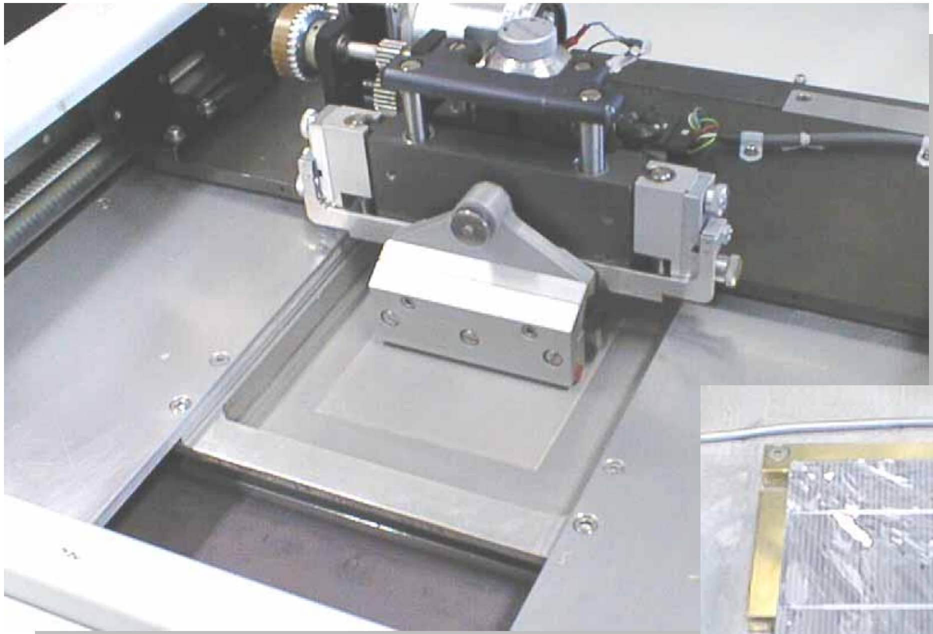
- Lifetime>100 μs will hardly affect cell efficiency (diffusion length 2 times cell thickness)
- Besides higher efficiency, gettering and passivation will result in a narrower efficiency distribution.

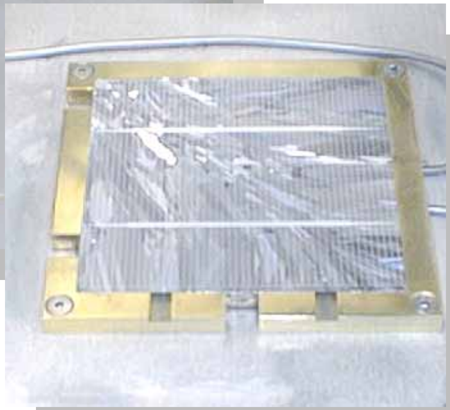




Metallization

Screen-printing process and sintering in belt furnace

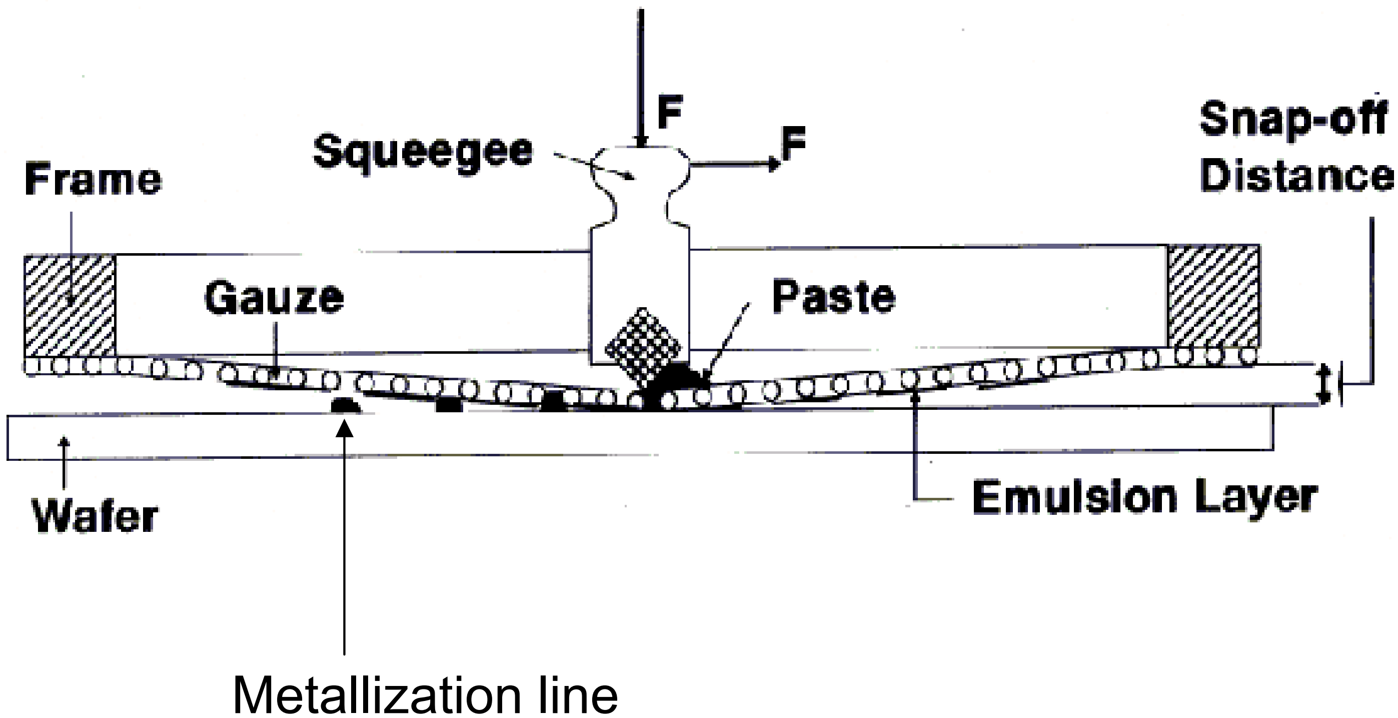




Metallization

Principle screen-printing process

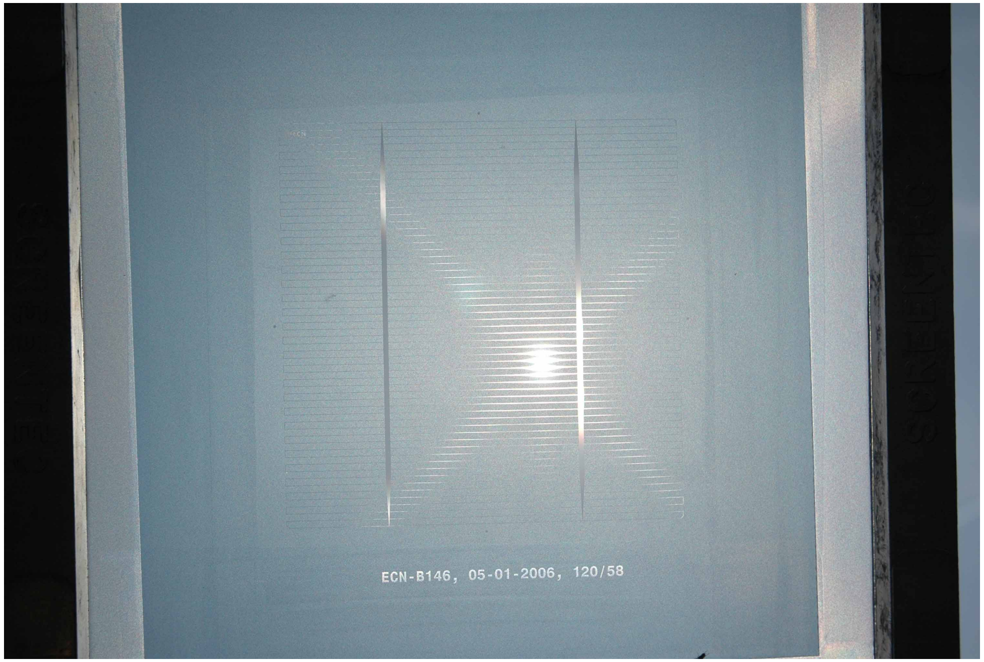
- Metallization paste is ‘pressed’ through pattern in screen
- Paste contains metal particles and oxides (etches Si at higher T)

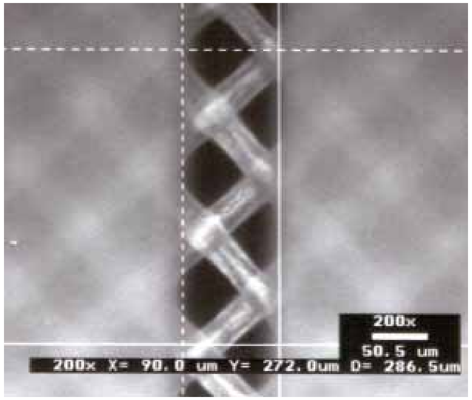


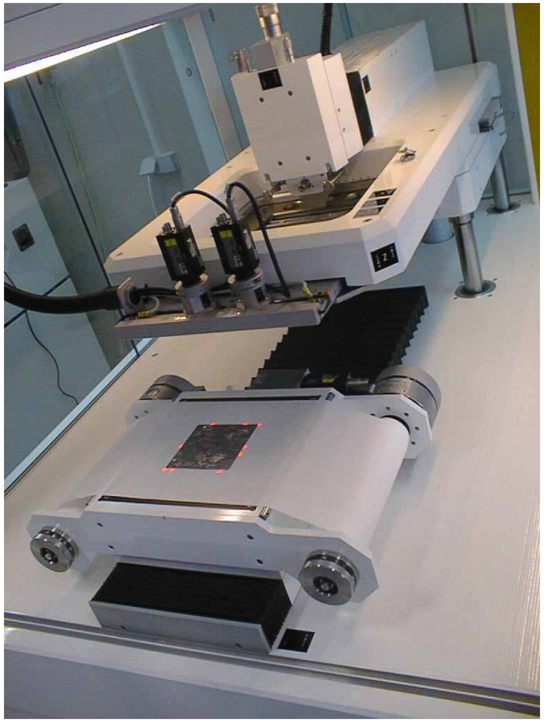
Metallization

Ag front side metallization

- Fine line metallization printed through patterned screen



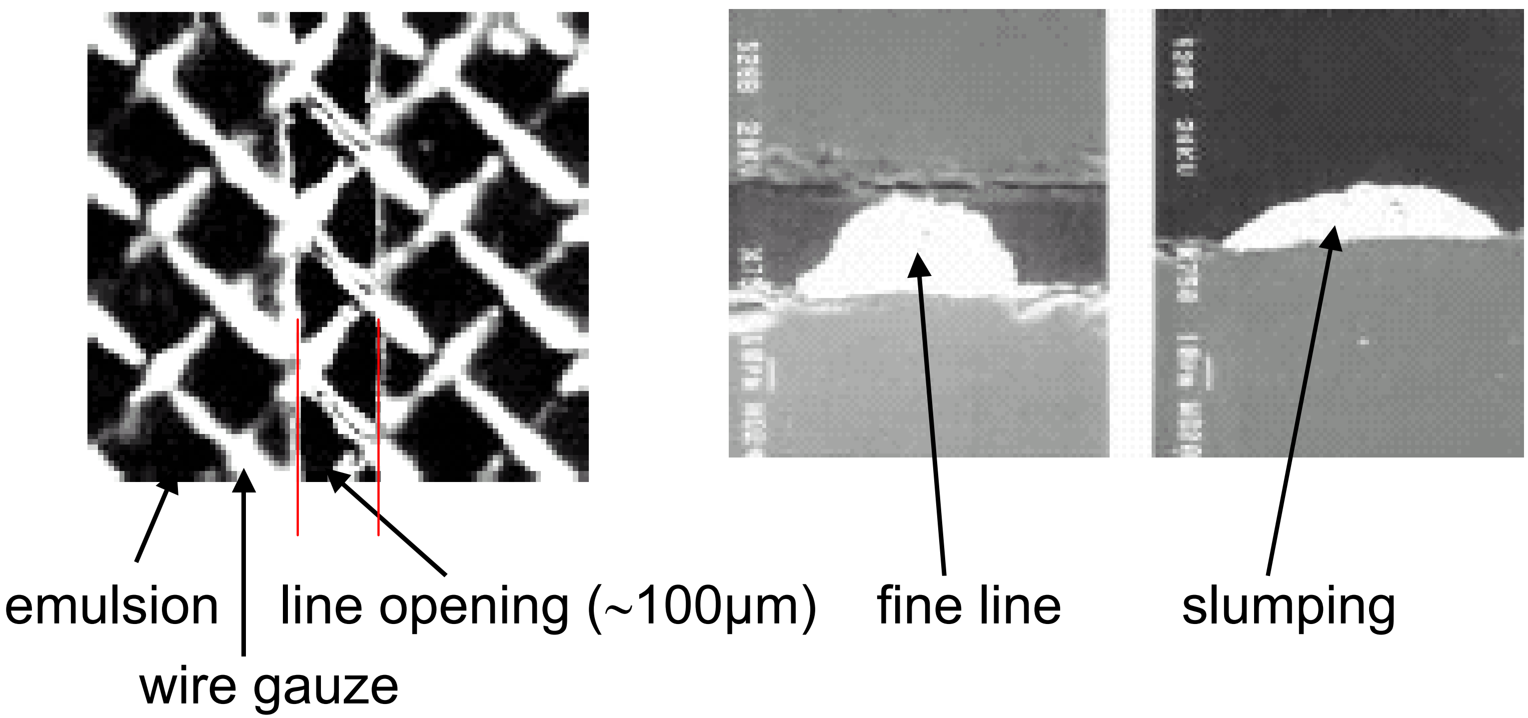




Metallization

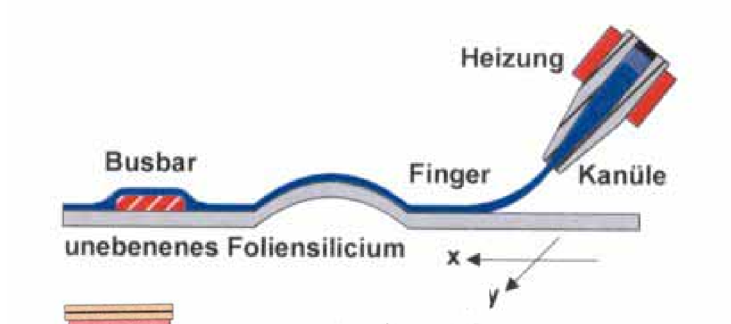
Fine line printing

- Reduced shading losses
- Contact resistance might be critical

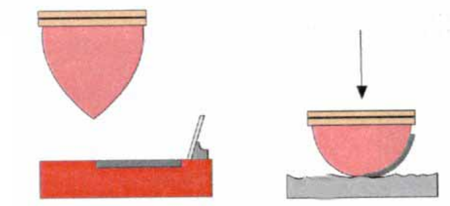


Metallization

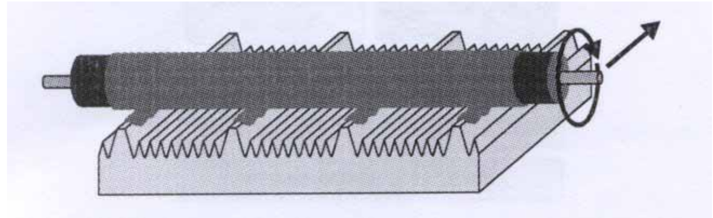
- Other techniques:
- Plating (electroless)
- Dispensing



- Pad printing



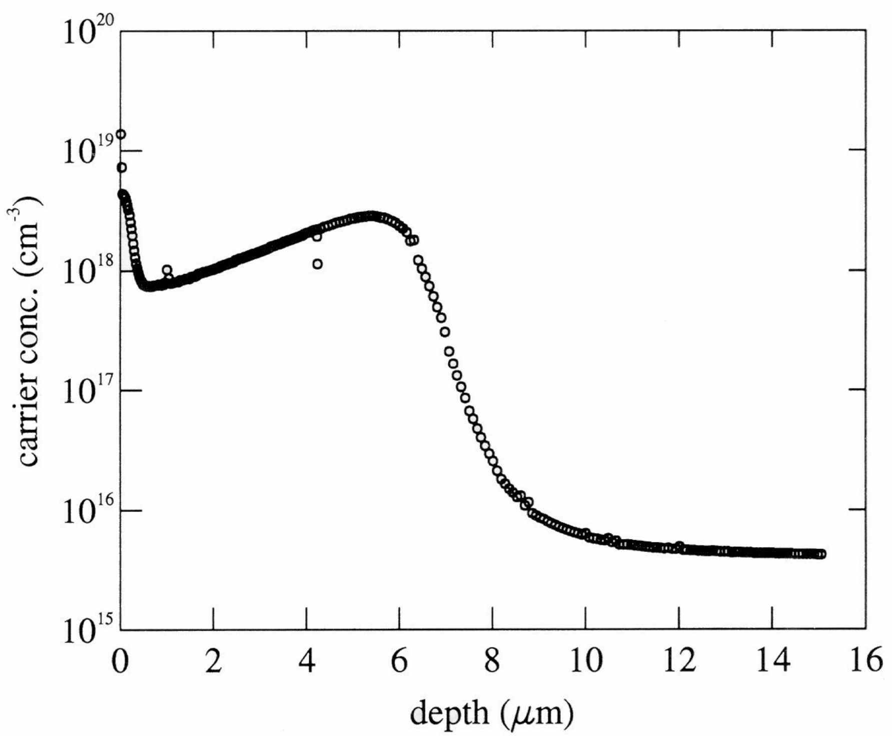
- Roller printing



Metallization

Al rear side (Back Surface Field to reduce recombination at surface)

- After sintering step (around 800 C, few seconds) highly doped layer
- Better BSF when thicker and higher doped

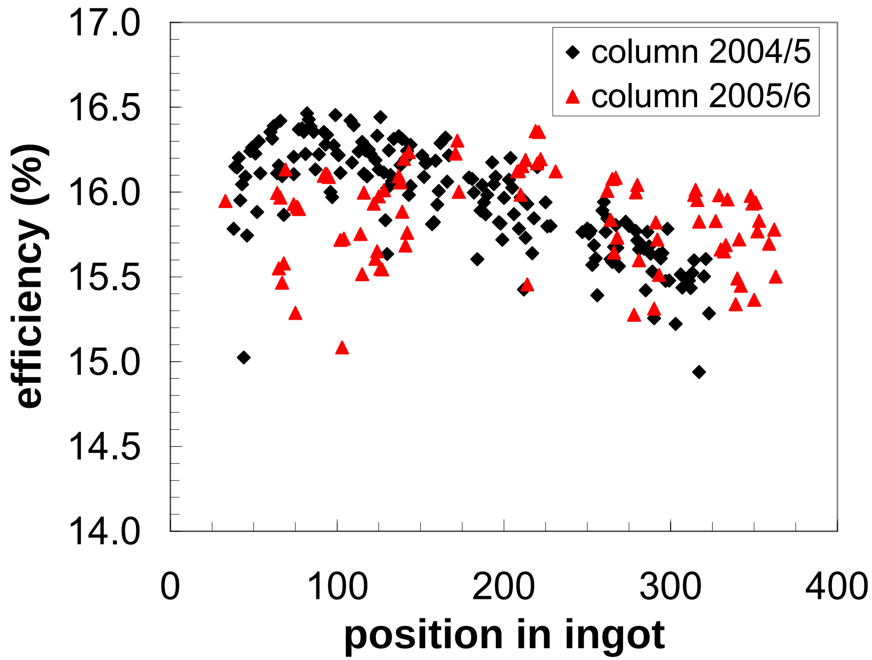


Efficiency ECN process

Results ECN Baseline process

Processing two complete columns (different ingots) of wafers during 2 years

- Average 16.0%
- In industry about 15%



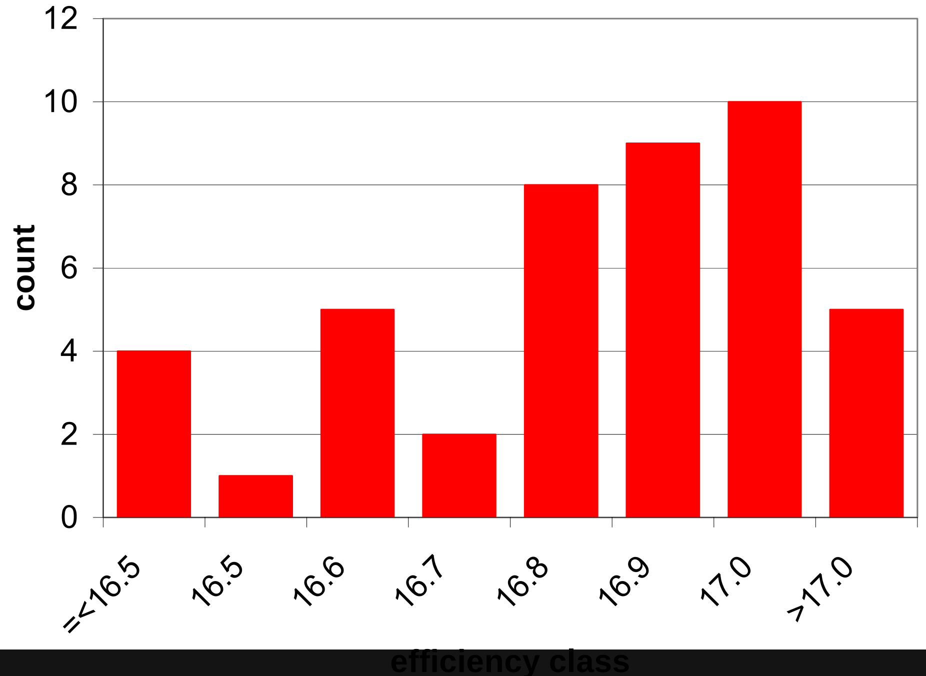
Wafer size: 125x125 mm^2

Thickness: ~300 µm

Material: p-type mc-Si

Efficiency ECN process

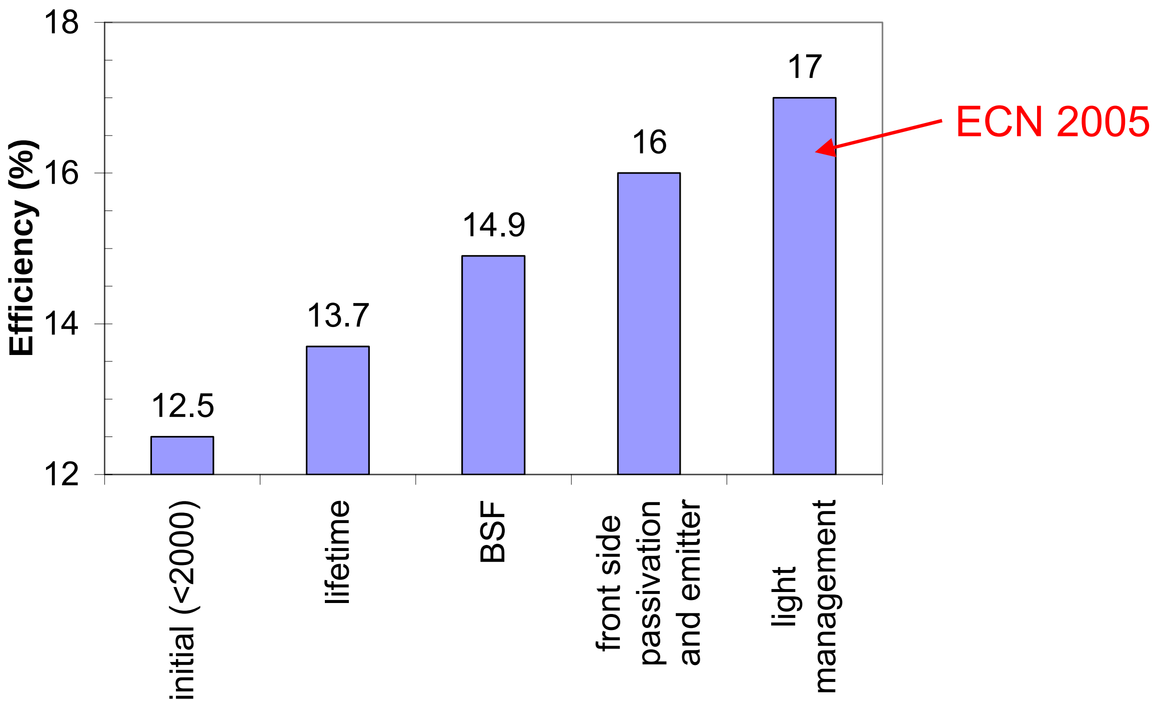
- High-efficiency (17%) in-line process (300 μm thick; 156 cm^2 mc-Si)
  - 50 cells processed (best efficiency 17.1%; average 16.8%)
  - Module made using cover glass with ARC
    Full area efficiency 14.8%; encapsulated cell eff: 16.8%

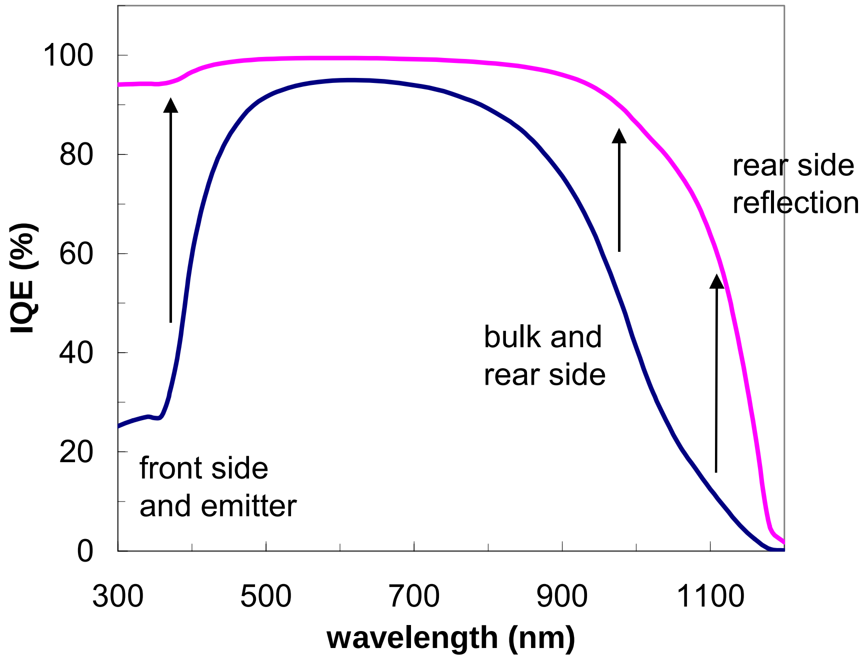


V_{OC}=22.2 V;
I_{SC}=5.76A;
FF=0.738;
P=94.3 Wp

Efficiency ECN process

- From 2000 up to now





Future improvements

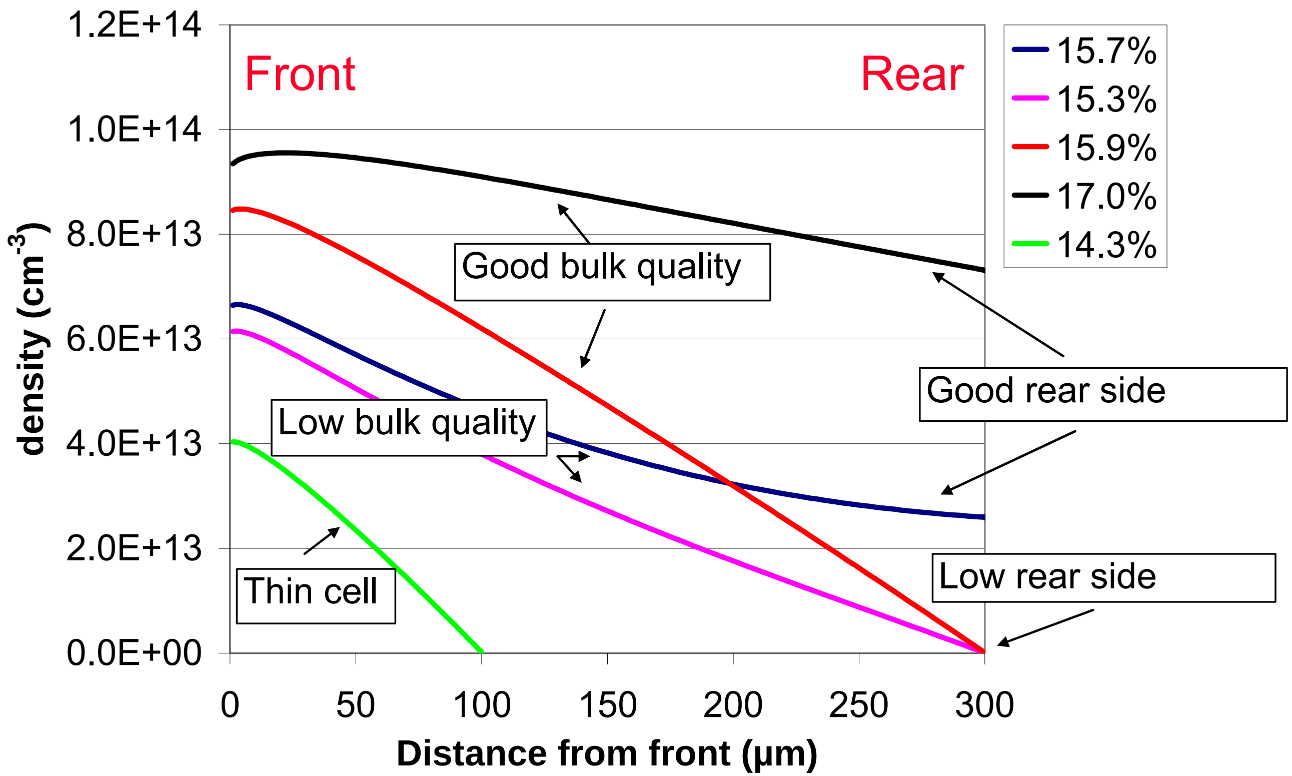
Thin wafers

- Rear side critical

Minority carrier density

- Combination of generation and recombination

17.0%: good bulk and rear
15.9%: good bulk, low rear
15.7%: low bulk, good rear
15.3%: low bulk and rear
14.3%: as 15.9%, but thin



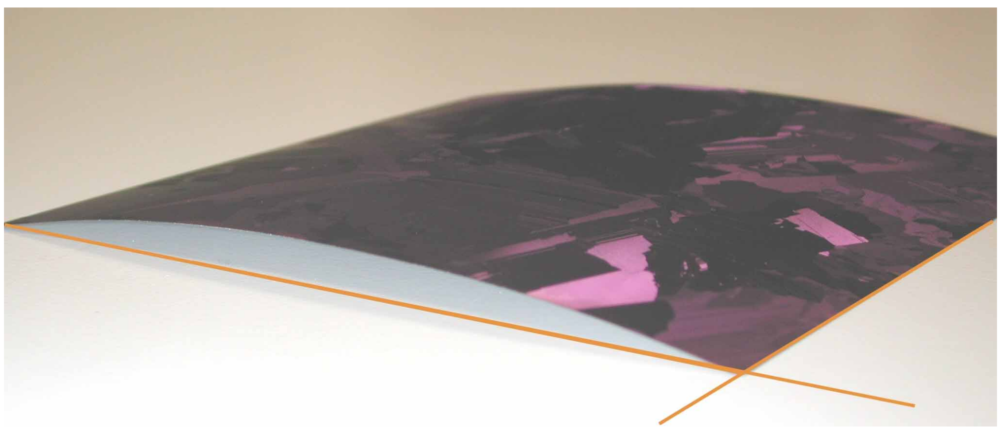
Future improvement

Al rear side (Back Surface Field to reduce recombination at surface)

- 17% reached on 300 µm thick wafers

However:

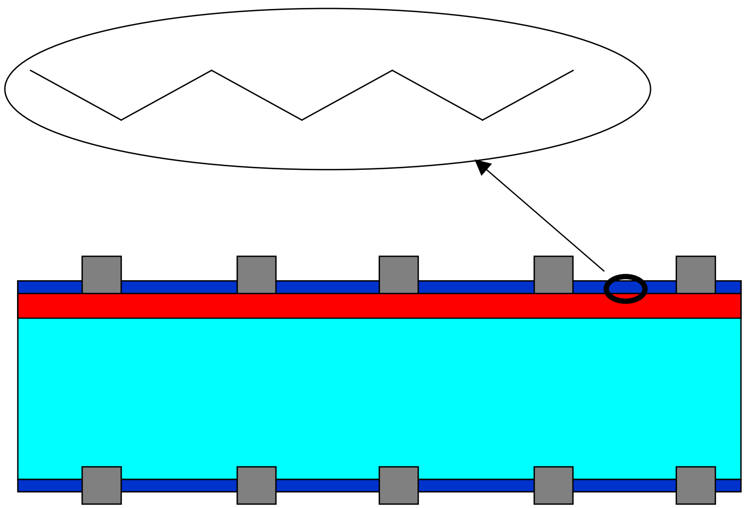
- Bowing for thinner wafers
- Recombination losses too high for high efficiencies (>18%)
- Internal reflection too low (~70%) for high efficiencies



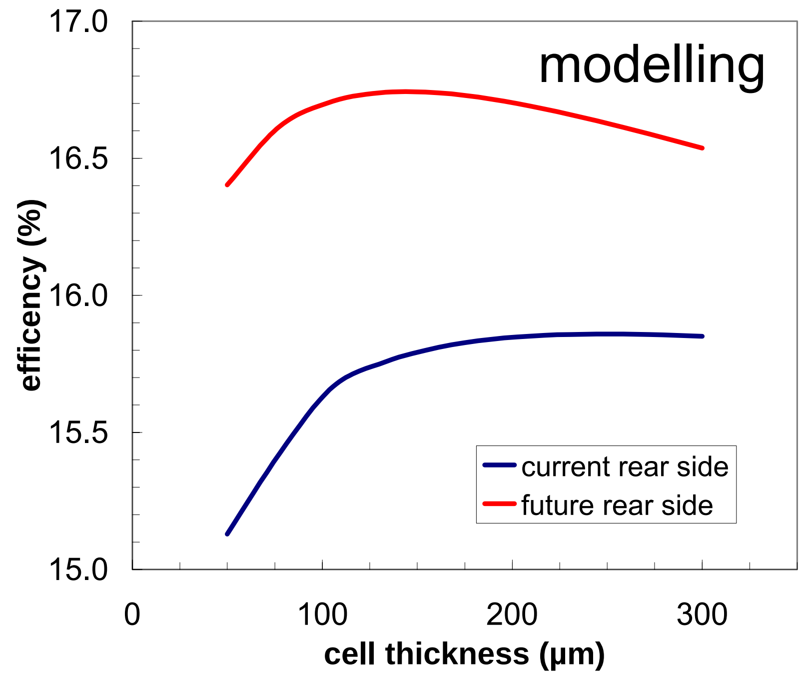
Future improvements rear side

Thin wafers

- Rear side critical (bowing, reflection, BSF)
- New rear side processing using for example SiN_x
  - Higher efficiencies for thinner wafers



SiN_x for rear side passivation
Local rear contacts / BSF



Future improvements rear side

Thin wafers

- New rear side processing using SiN_x
  - 16.4% obtained by ECN with baseline-like processing
  - About 1% absolute higher than reference with Al BSF (obtained efficiency depends on Si material quality)

Future improvements

Thin wafers (less dependent on material quality)

- Improved light management
  - Texturing
  - Light trapping
- Improved emitter (reduce losses)
- Perfect surface passivation
  - Both surfaces
- Less metallization losses
  - Series resistance (contact and line resistance)
  - Reduced shading losses

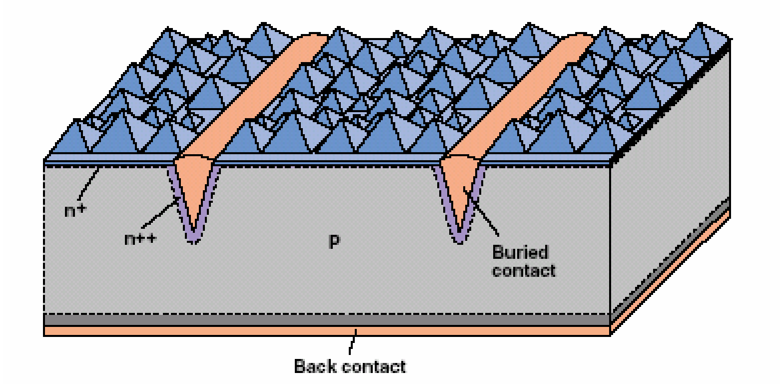
20% mc-Si cell efficiency should be possible! (long term)

Other industrial cell concepts

Laser Grooved Buried Contacts

BP Solar

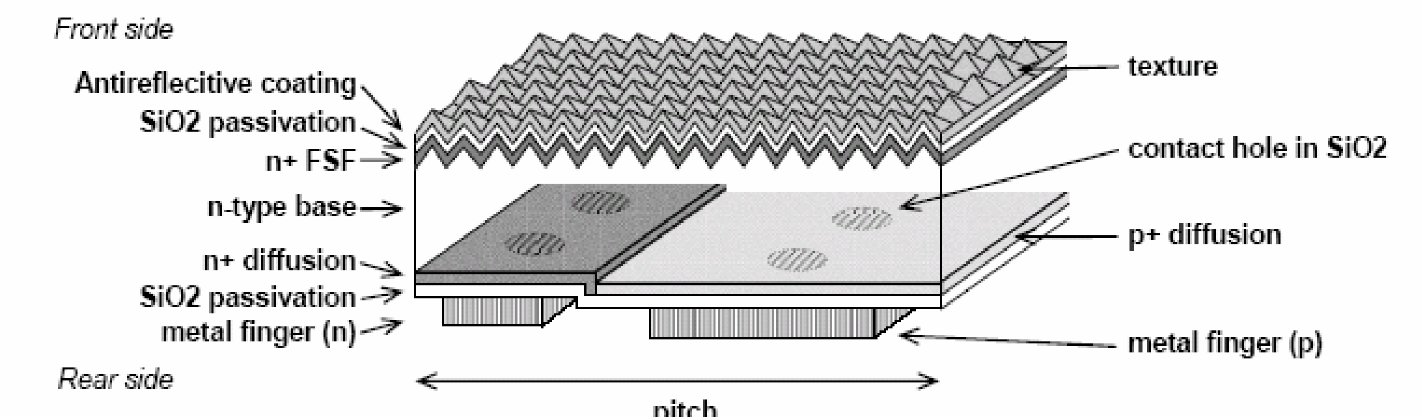
- Monocrystalline



Rear side contacted cell

SunPower

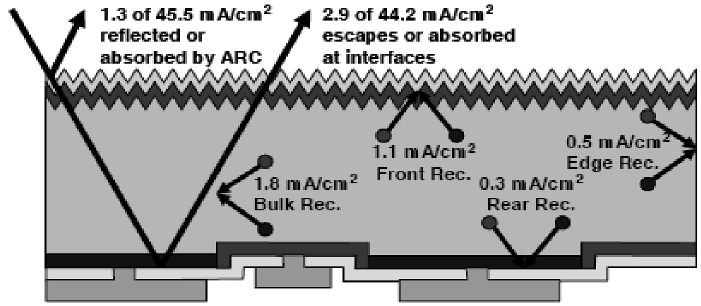
- ~20%!
- High quality and expensive material

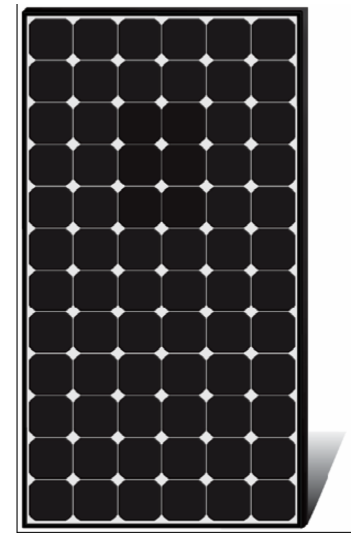


Other industrial cell concepts

SunPower

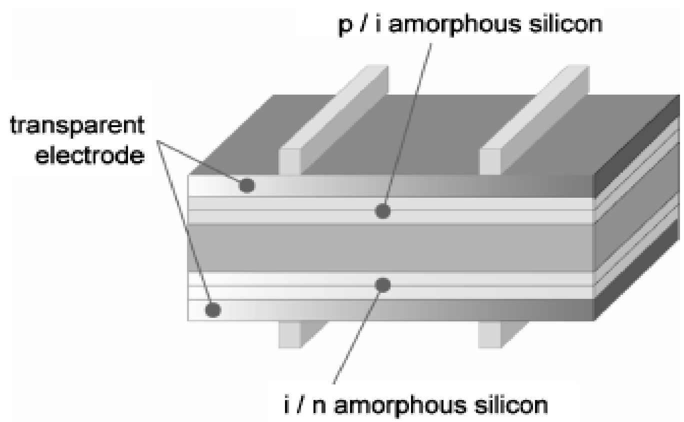
- Cell 21.8%
- n-type material
- Module: full area 18.1%





Sanyo

- HIT cell: 21.8%
- n-type material
- Emitter deposited



Record efficiencies

Monocrystalline (4 cm^2):	24.7%
Monocrystalline (149 cm^2):	21.5%
Multicrystalline (1 cm^2):	20.3%
Multicrystalline (137 cm^2):	18.1%

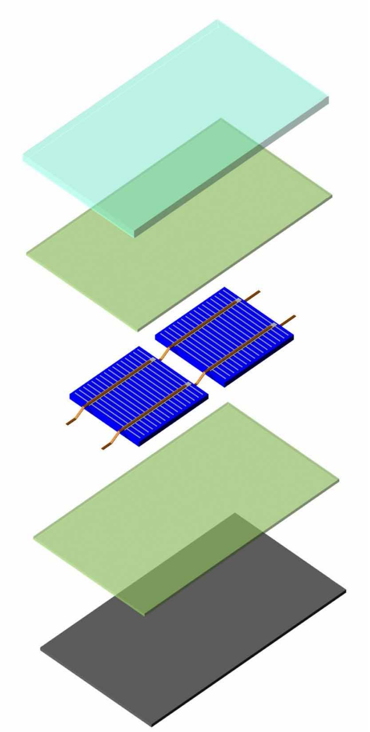
ECN multi (156 cm^2): 17.0%

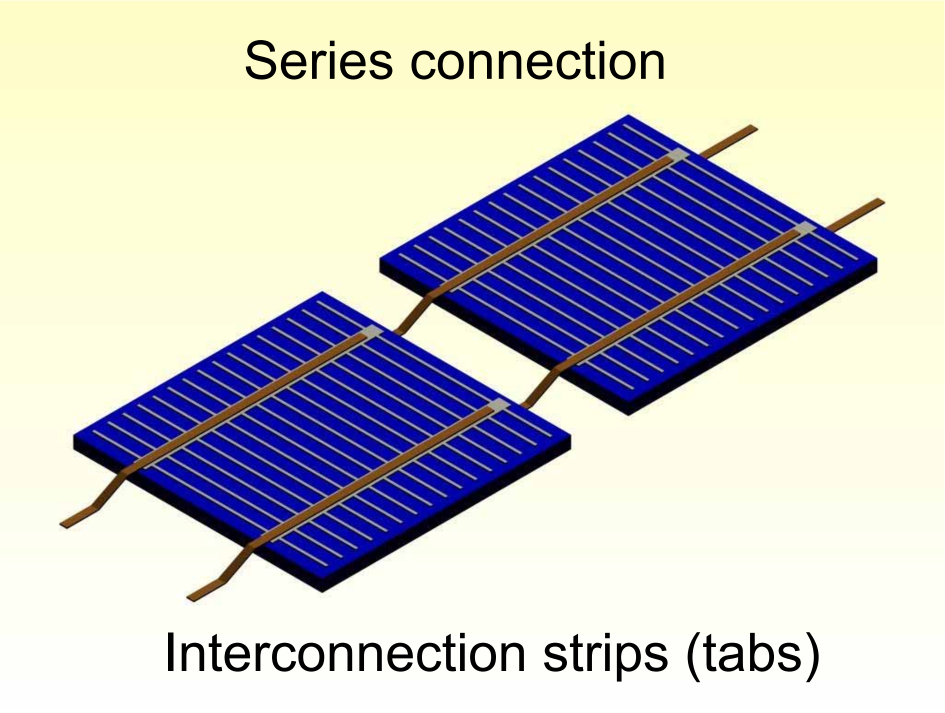
Single layer ARC; homogeneous emitter; inline processing

Highest efficiency with completely inline processing

Module technology

Conventional module technology (soldering)





Module technology

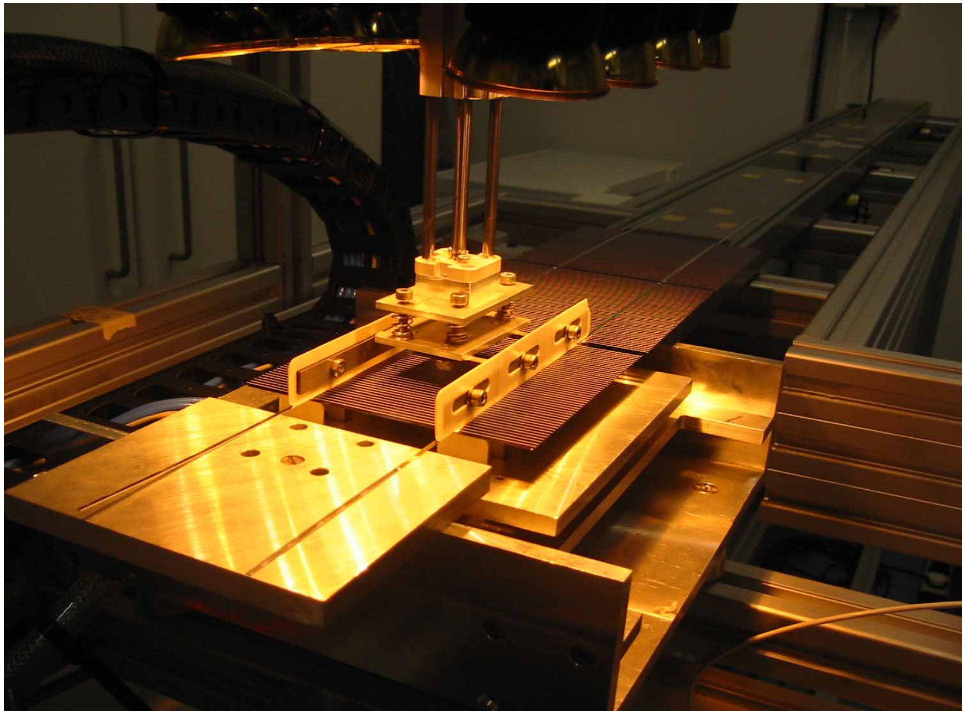
Conventional module technology

interconnection

lamination

Module technology

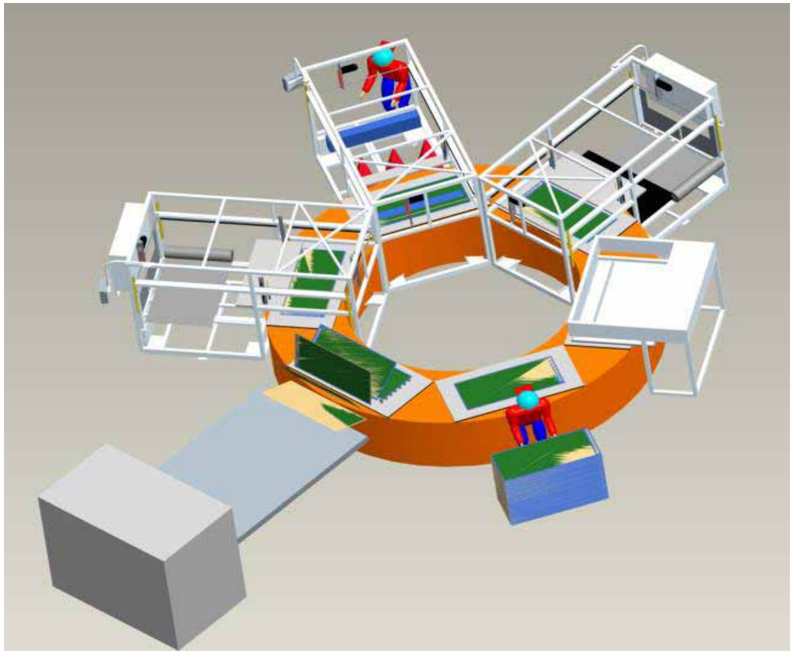
Pilot-line tabber-stringer for interconnection



Module technology

Pilot line to be built at ECN

Fully automated and realibility-tested interconnection process for back-contact cells and suitable for thin and fragile cells

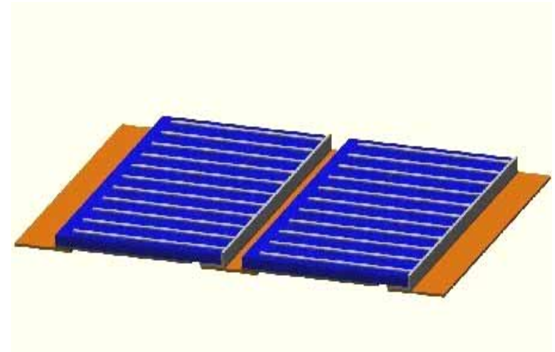


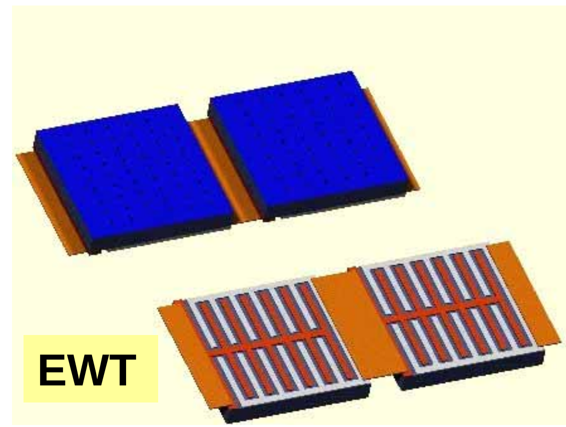
Module technology

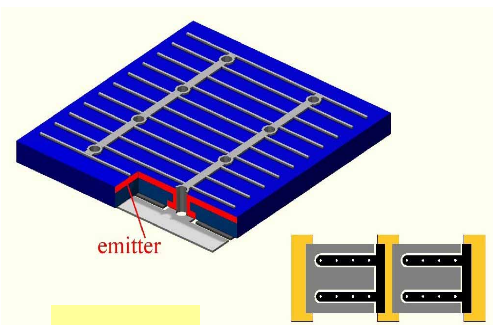
New module technology:

- New cell designs needed
  - Back contacted
  - Simple interconnection
  - Can be used for thin cells

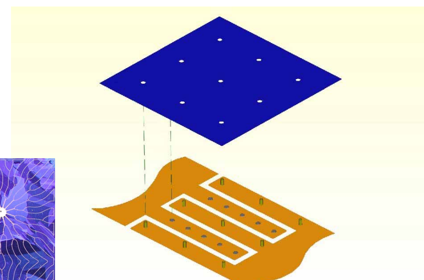
MWA



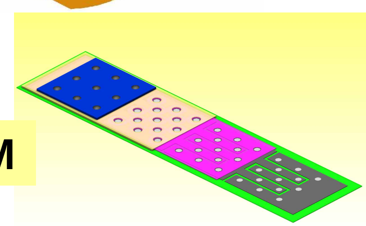




MWT



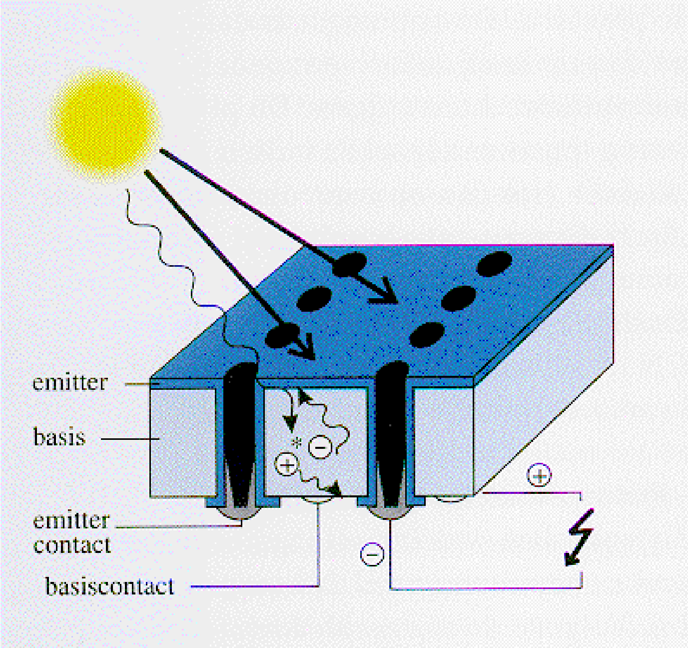
PUM

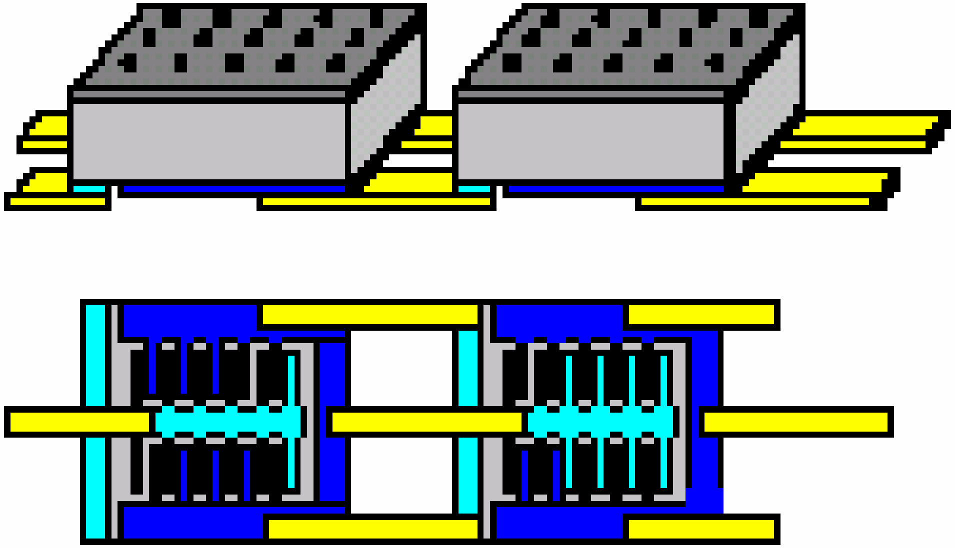


Module technology

Emitter Wrap Through:

- No metallization on the front
- Thousands of holes

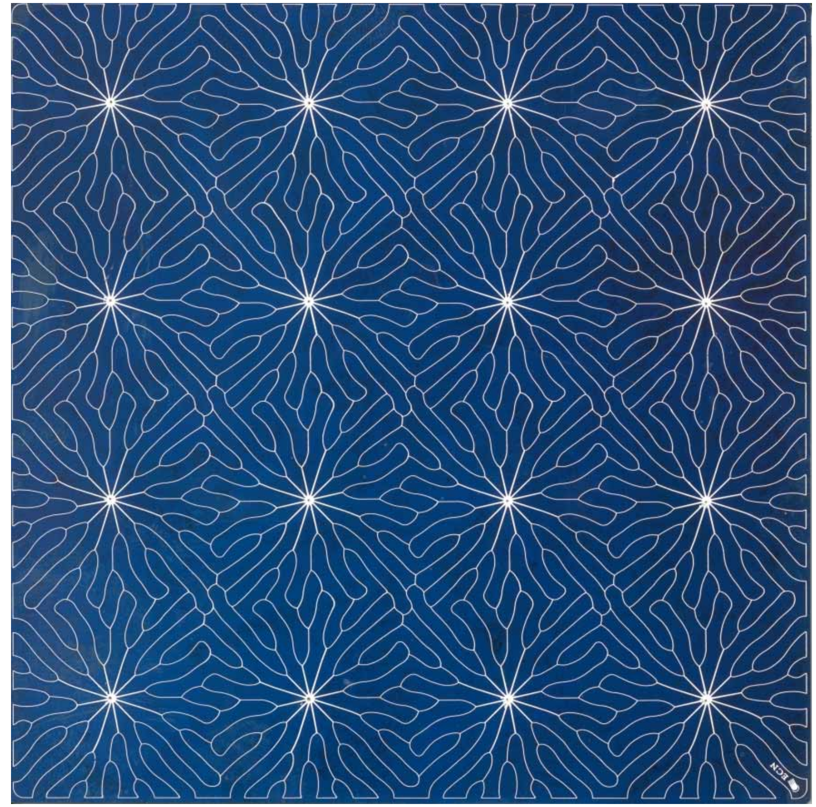




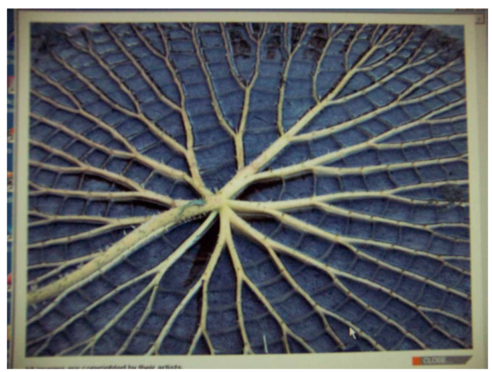
Module technology

ECN's PUM concept:

- More energy from attractive cells
- 2-3% less shading
- Resistance losses independent on cell size (only on size unit cell)
- Standard cell processing except:
  - Laser drilling holes
  - Junction isolation around holes



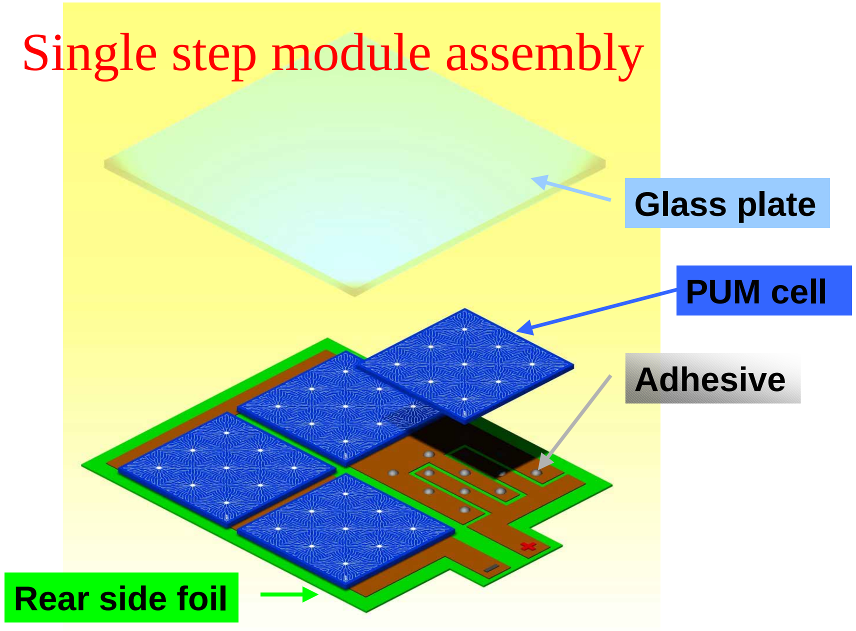
Mother Nature's water lily

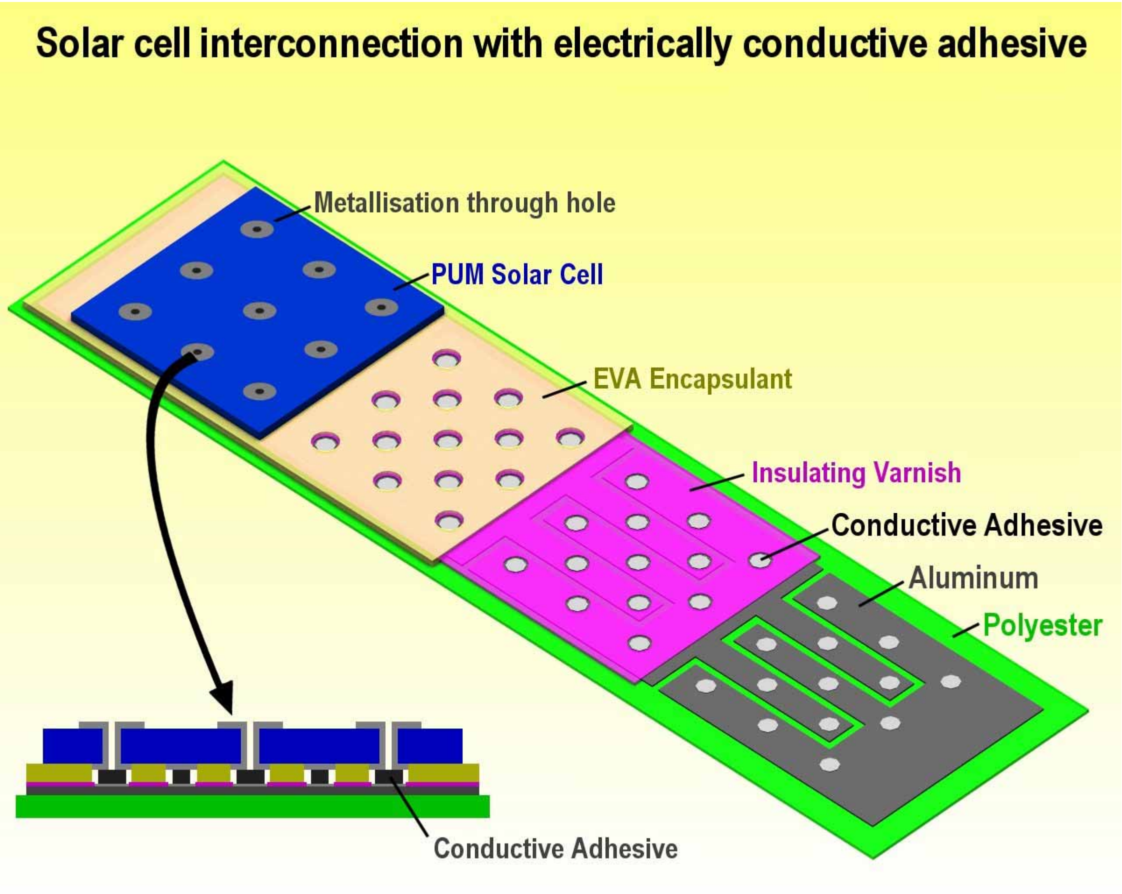


Module technology

ECN's PUM concept:

- Single shot interconnection and encapsulation

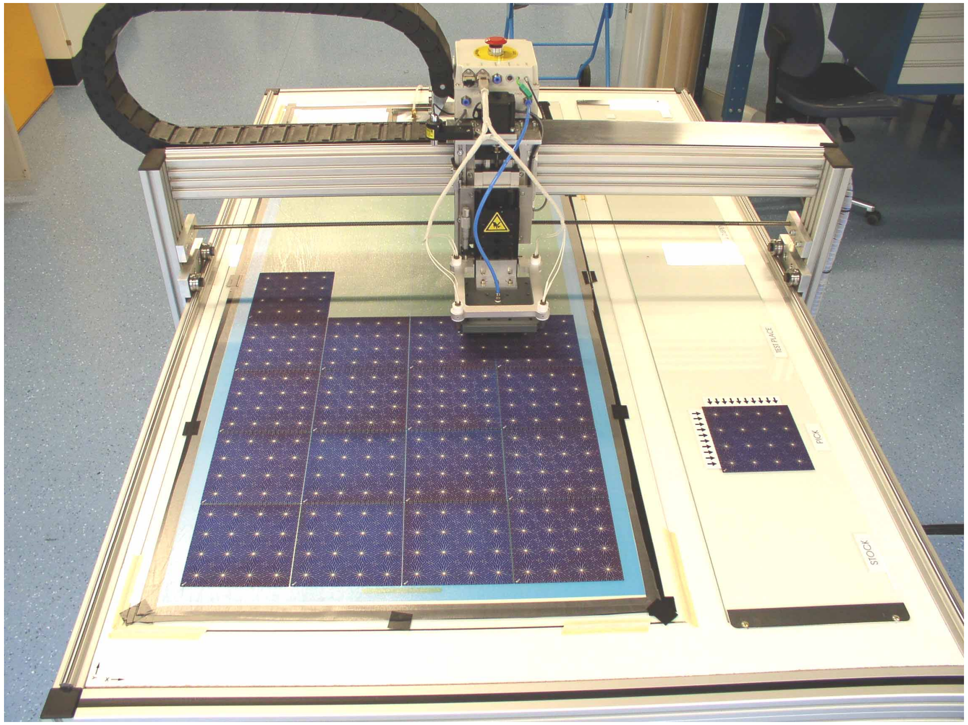




Module technology

ECN's PUM process:

- Foil preparation
- Apply conductive adhesive instead of soldering (lower stress)
- Pick and place cells
- One step curing and encapsulation



Module technology

ECN's PUM result:

- Full size module (71×147 cm^2)
- 128 Wp (15.8% encapsulated cell efficiency)
- 0.6-0.8% absolute efficiency gain

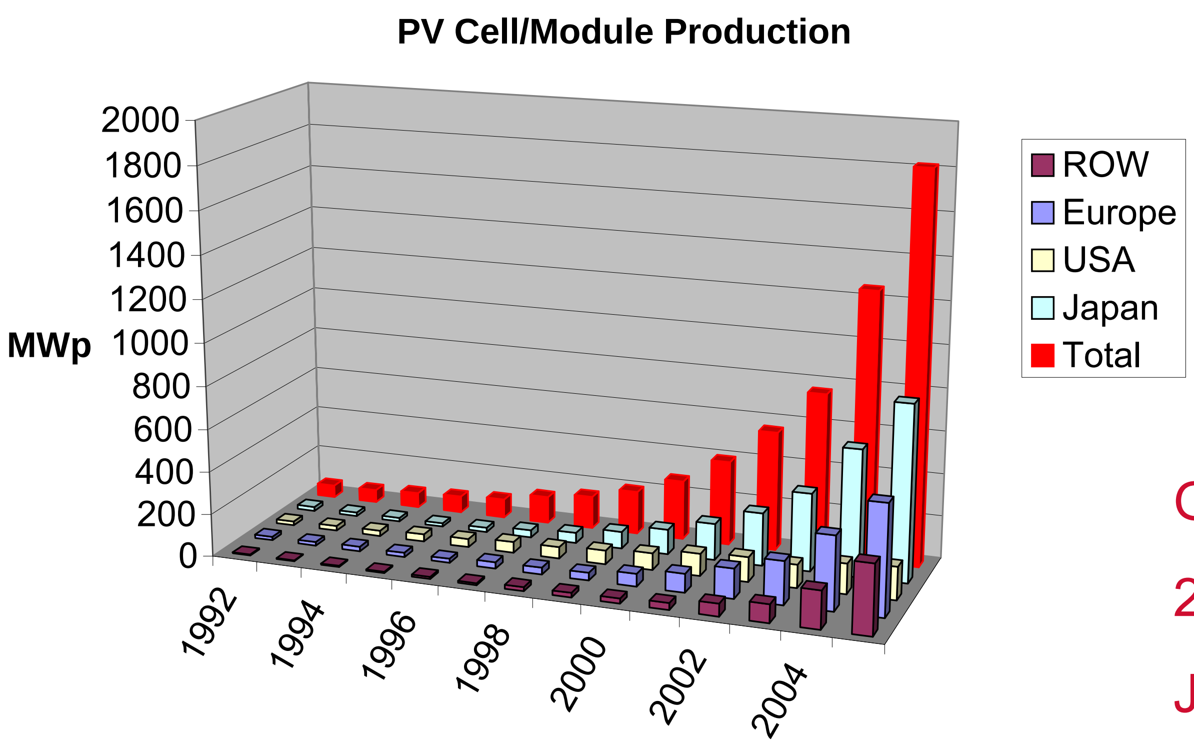
Best PUM cell result up to now:

- 16.7% (225 cm^2)

At this moment PUM is the only integrated concept for cell and module

PV market

Annual market growth more than 40%



Growth rate 2004: 67%

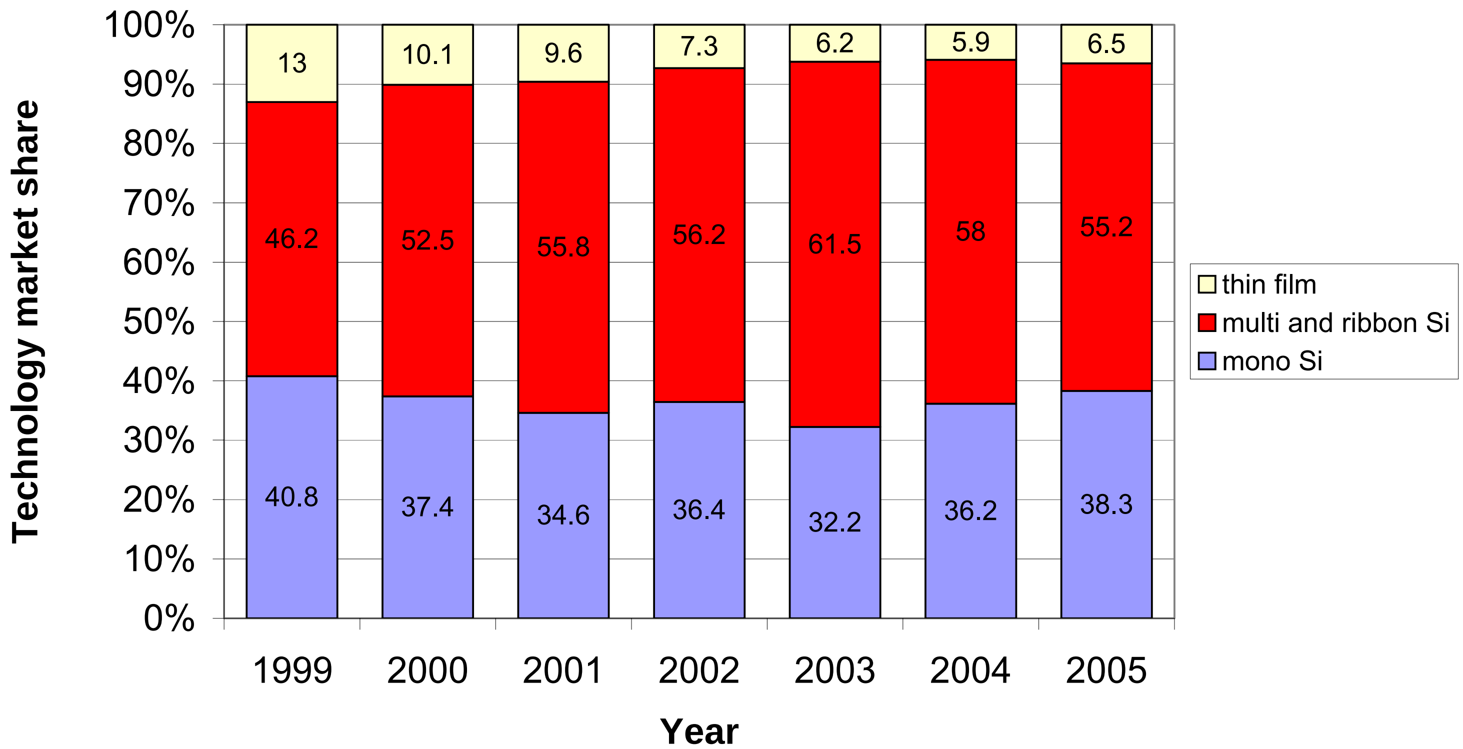
2005: 1720 MWp (+44%)

Japan: ~50% market share

Photon International, 2006

PV market

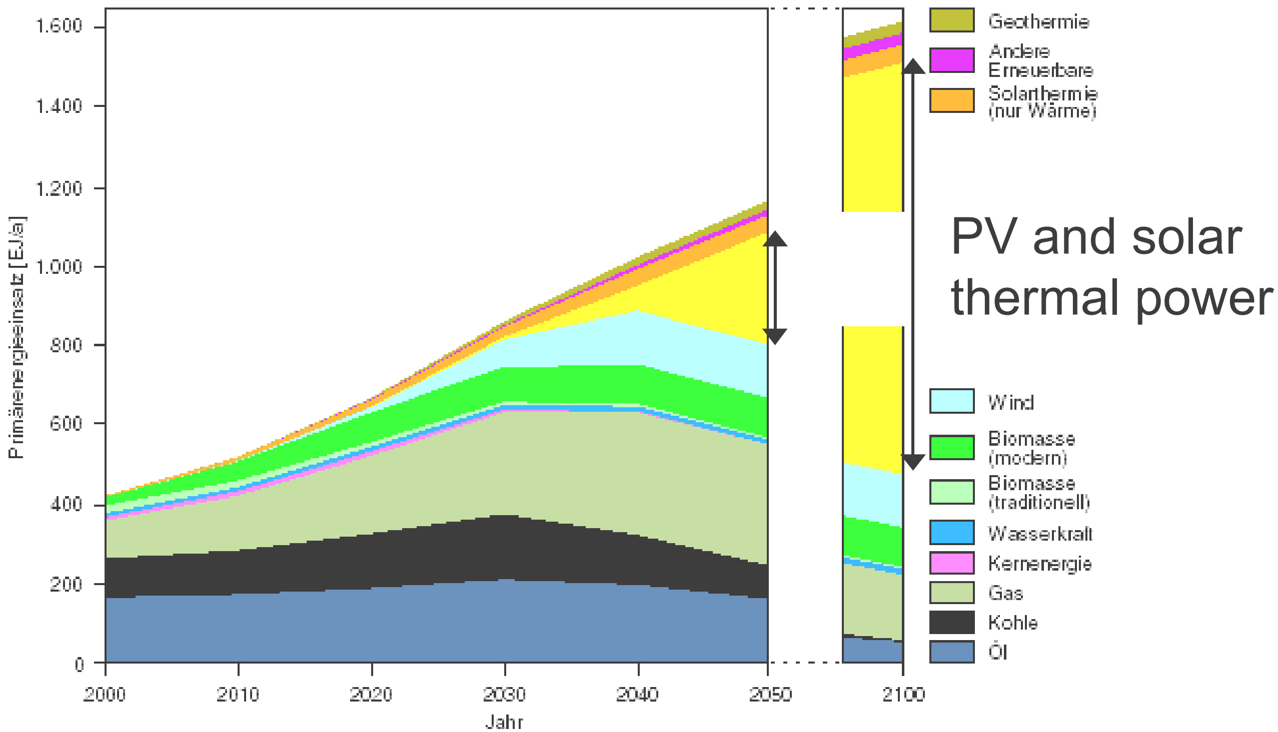
More than 90% crystalline Si technology



Photon International, 2006

PV market

Expected market: solar the most important primary energy source



Wissenschaftliche Beirat 2003

Costs PV

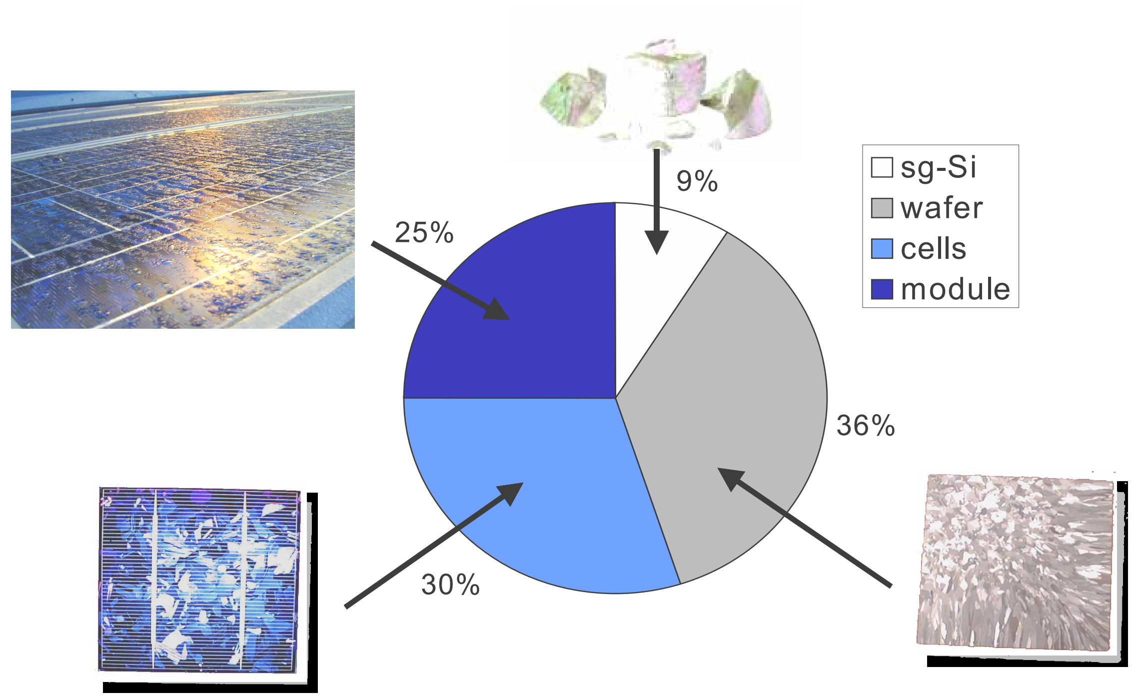
Contributes wafer is about 45%!

Thinner wafers, or better ribbons, important!

Price solar electricity:

0.20-0.50 €/kWh
(depending on location)

NL: ~0.50 €/kWh

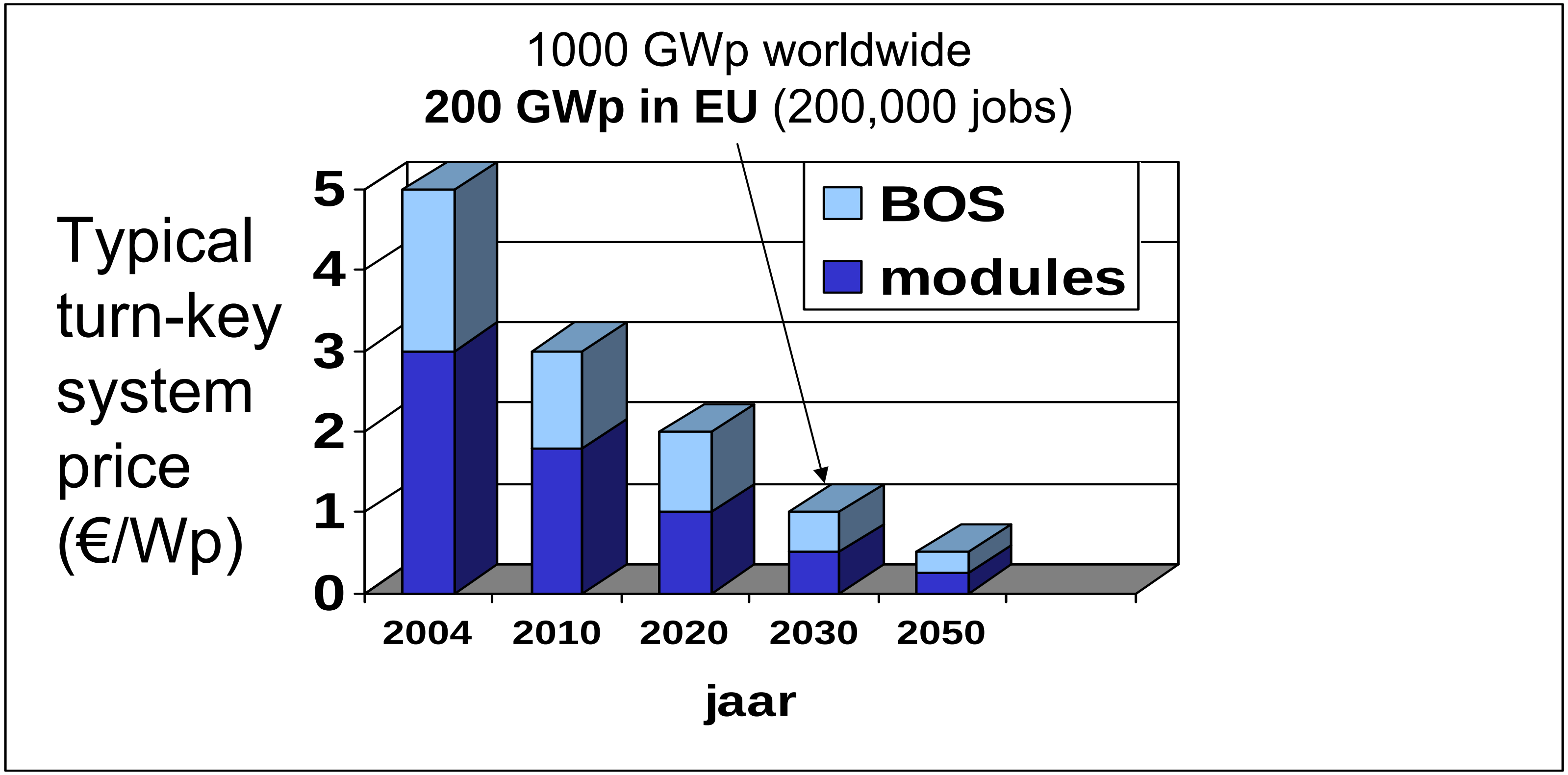


Cost reduction PV

- Less material use
  - Thin ribbons
  - Less module materials
- High efficiencies for the same process costs
  - Advanced processing
  - New cell design
- Easy manufacturing
  - Automation
  - Easy module manufacturing
- High lifetime
- Improved yearly system output

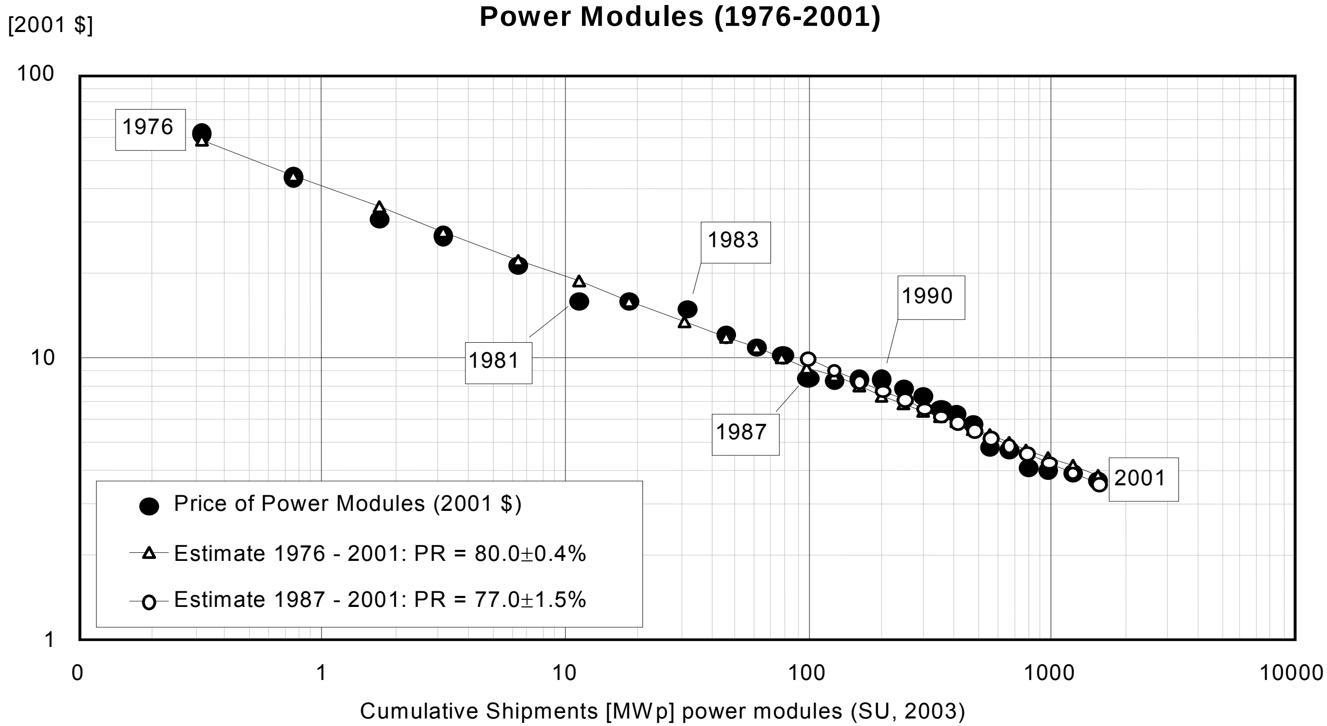
Cost reduction PV

- Expected costs



Cost reduction PV

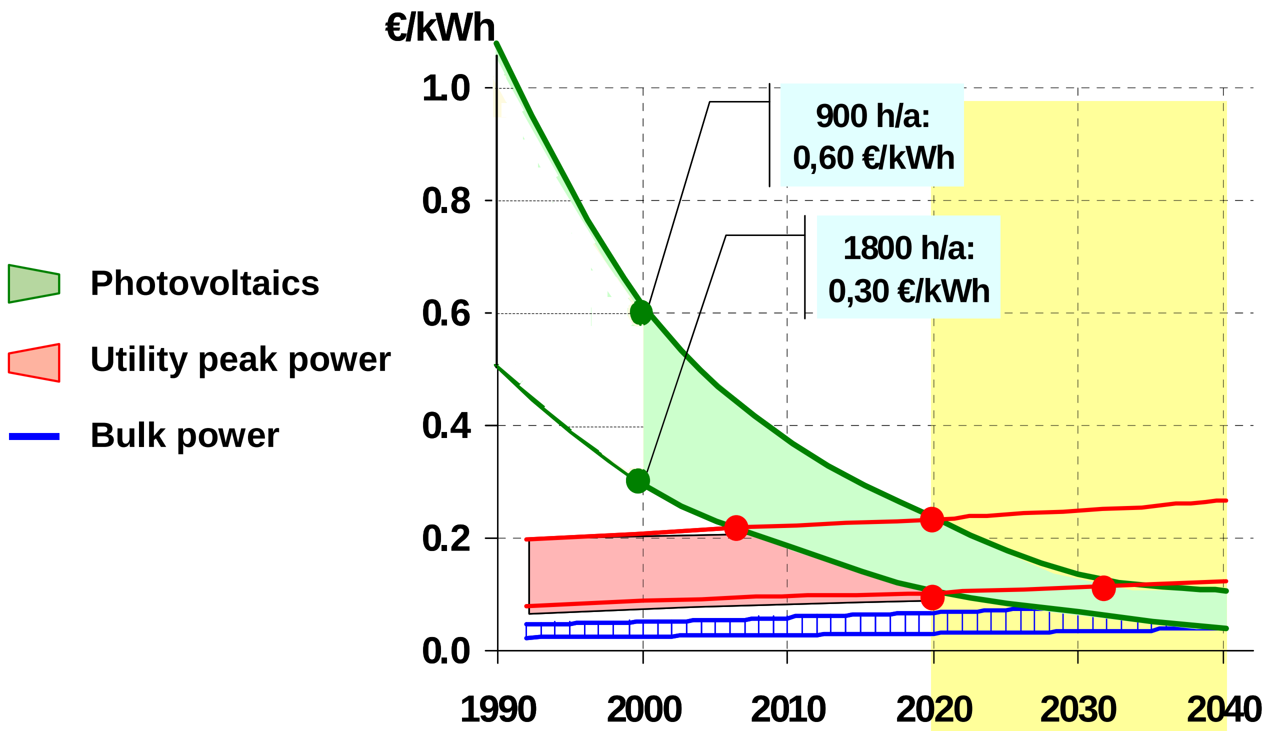
- Expected costs based on learning curves (EU project Photex)
  - Combined effect of technology development, experience, ….
  - Progress ratio PR should be around 80%



Cost reduction PV

- Expected costs

- Solar competitive between 2010-2020

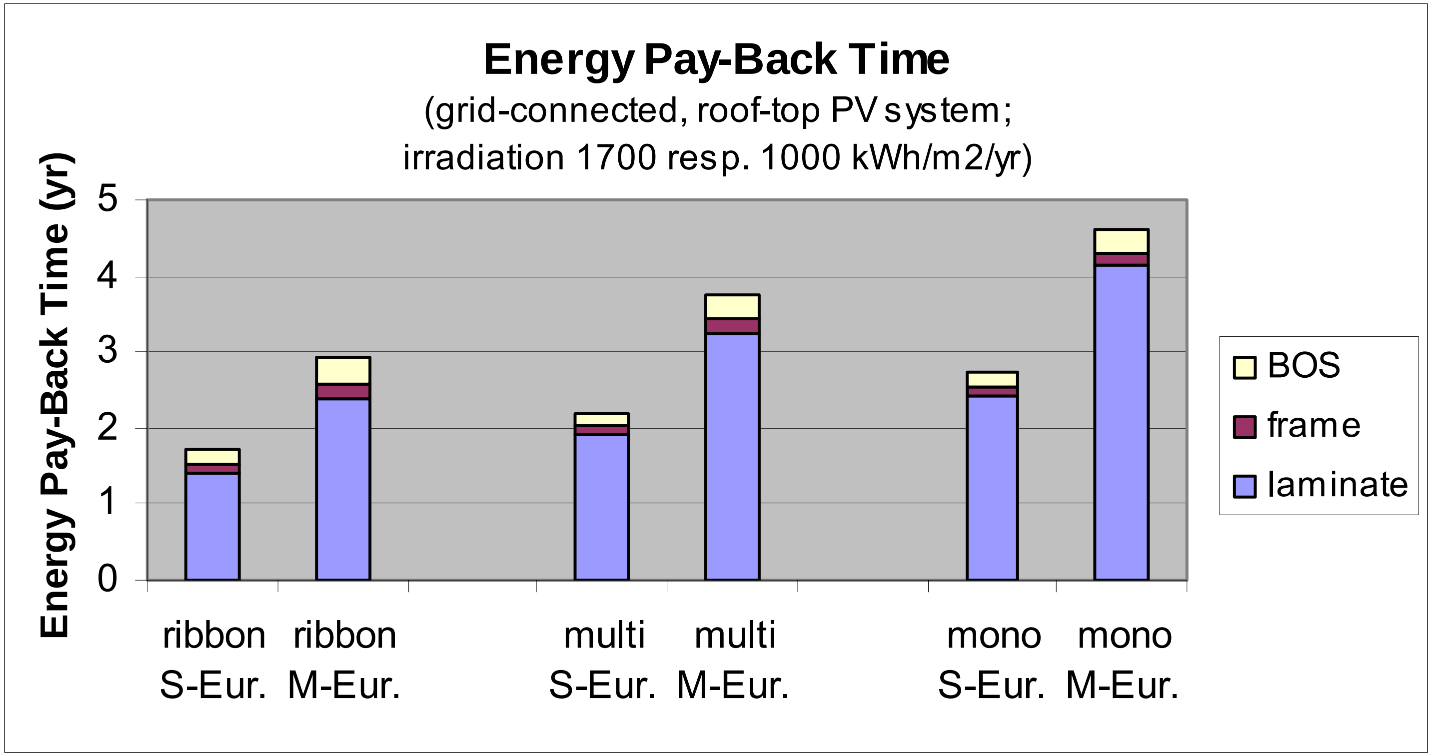


Source: RWE Energie AG and RSS GmbH

Towards an Effective European Industrial Policy for PV.ppt / 05.06.2004 / Rapp

Environmental aspects

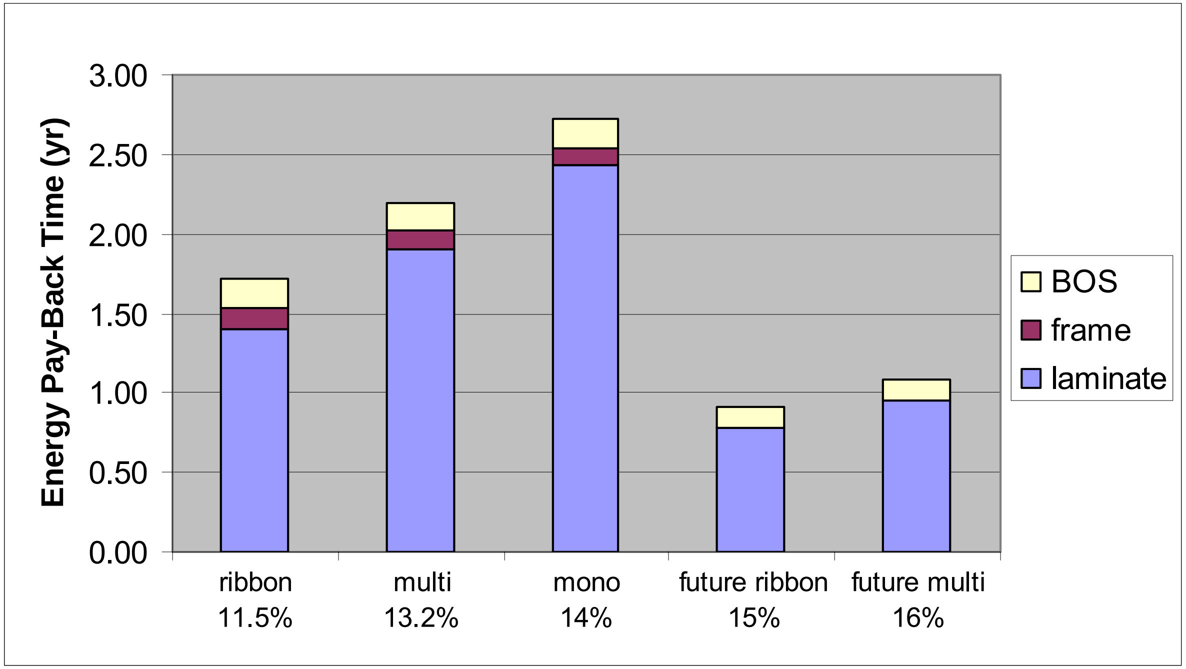
- Energy Pay Back Time 2005



Environmental aspects

Energy Pay Back Time 2005 and 2010+

- Low energy consumption especially for Solar Grade Si
- Low material use (abundance)
- High efficiency
- High lifetime modules
- Environmental friendly processes
- Recycling



Conclusions

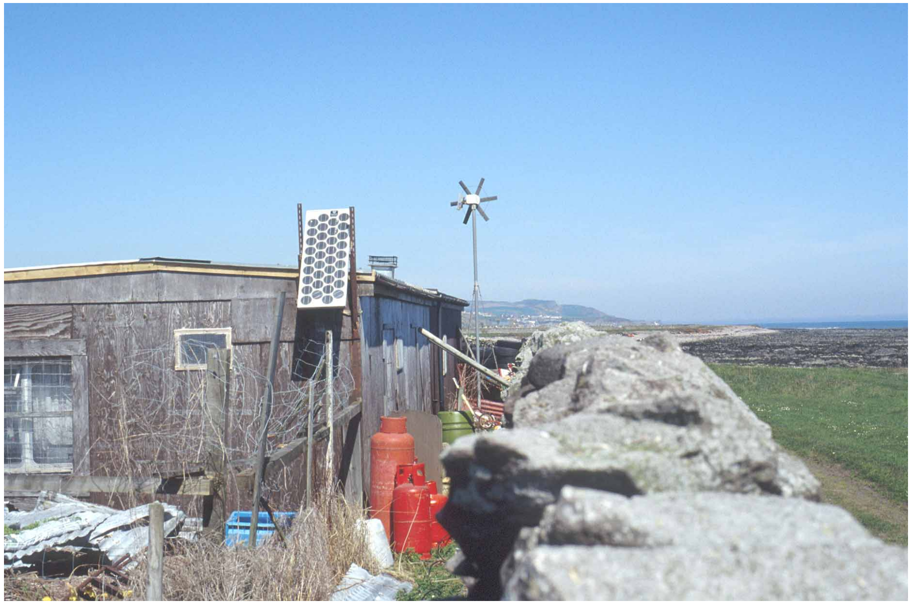
- Solar Grade Silicon needed for growing market
  - Effect of impurities on cell efficiency should be known
- Less Si use with ribbons
- Improved processing has led to 17% mc-Si efficiency using in-line processing
- New processes for thin wafers/ribbons under development
- Integrated cell and module design like PUM needed
- High module lifetime

Then

- Cost reduction possible
  - Will be competitive with bulk electricity price
- Energy Pay Back Time can be reduced to <1 year
- Solar energy will be the most important primary energy source in 2100

Applications at ECN

Applications



Thank you for your kind attention

Floriade (2.3 MWp PV)

Information / internship
www.ecn.nl
weeber@ecn.nl