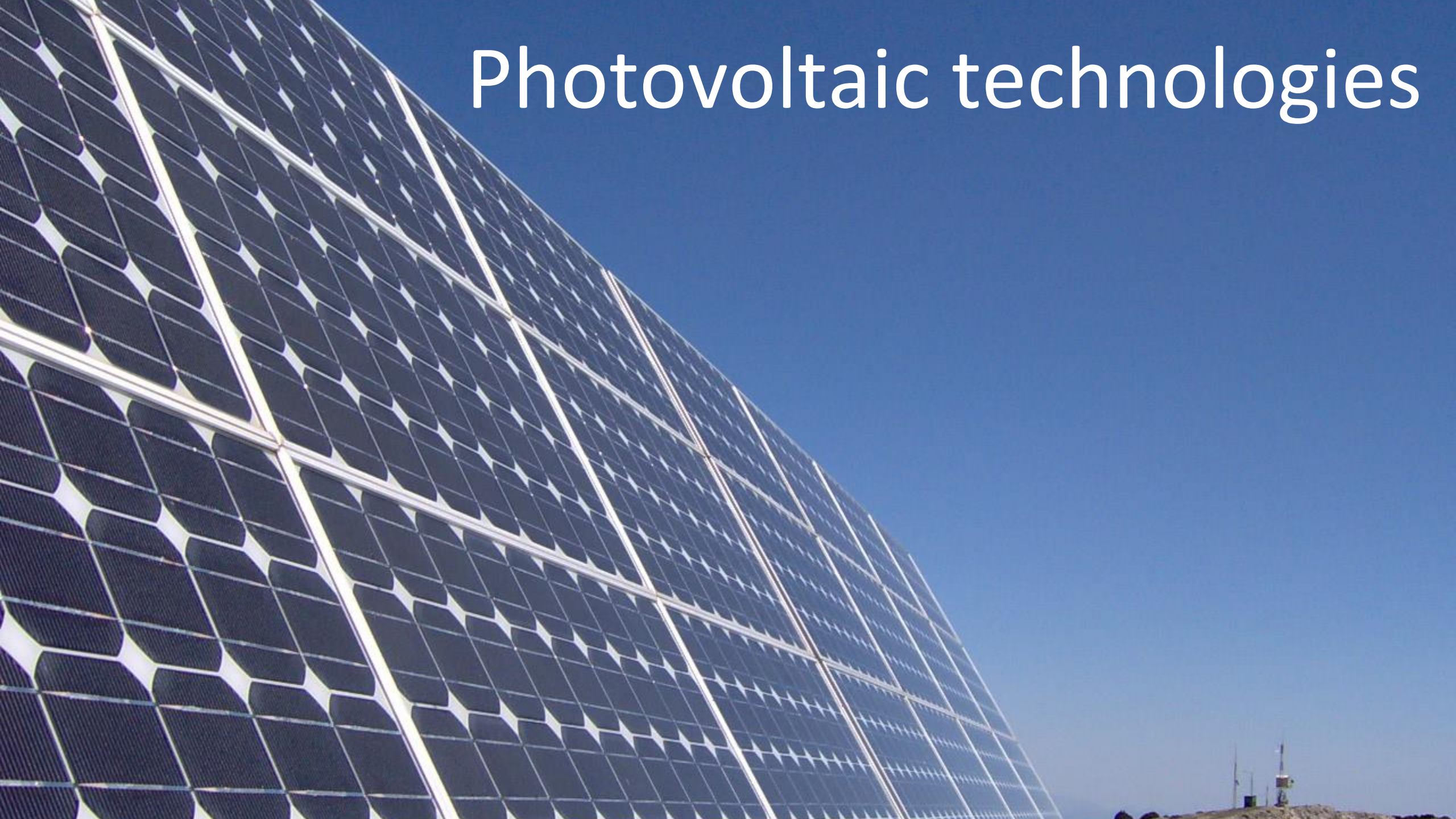


Photovoltaic technologies



Photovoltaic technologies

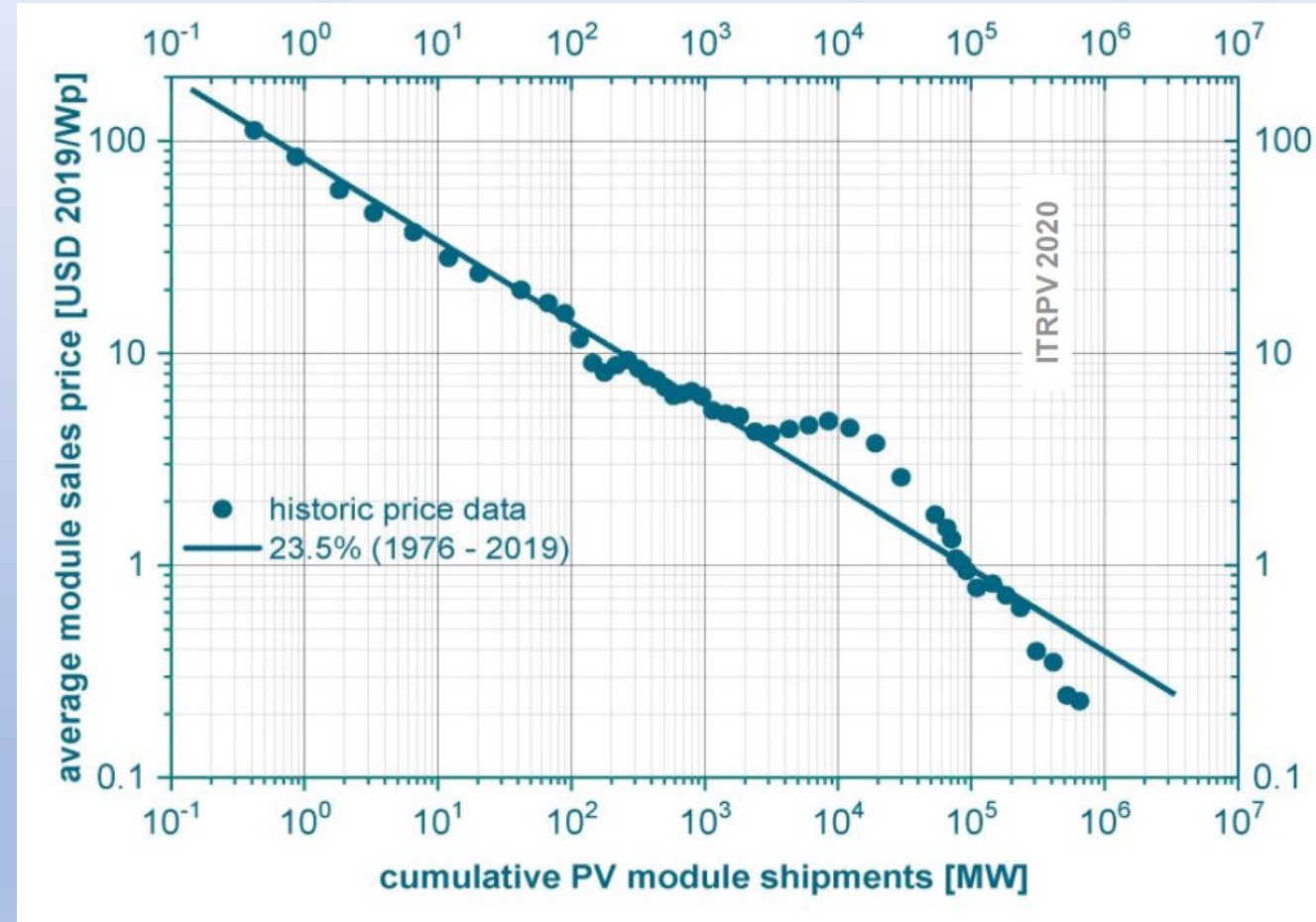
- Photovoltaic energy today
- Crystalline silicon technologies
- Limitations of crystalline silicon and monojunction solar cells
- Future PV technologies

PV energy today

Swanson law: For each duplication of the PV installed capacity the price per Wp reduces 20% - **in fact it is now 23.5%!**

Last 30 years:

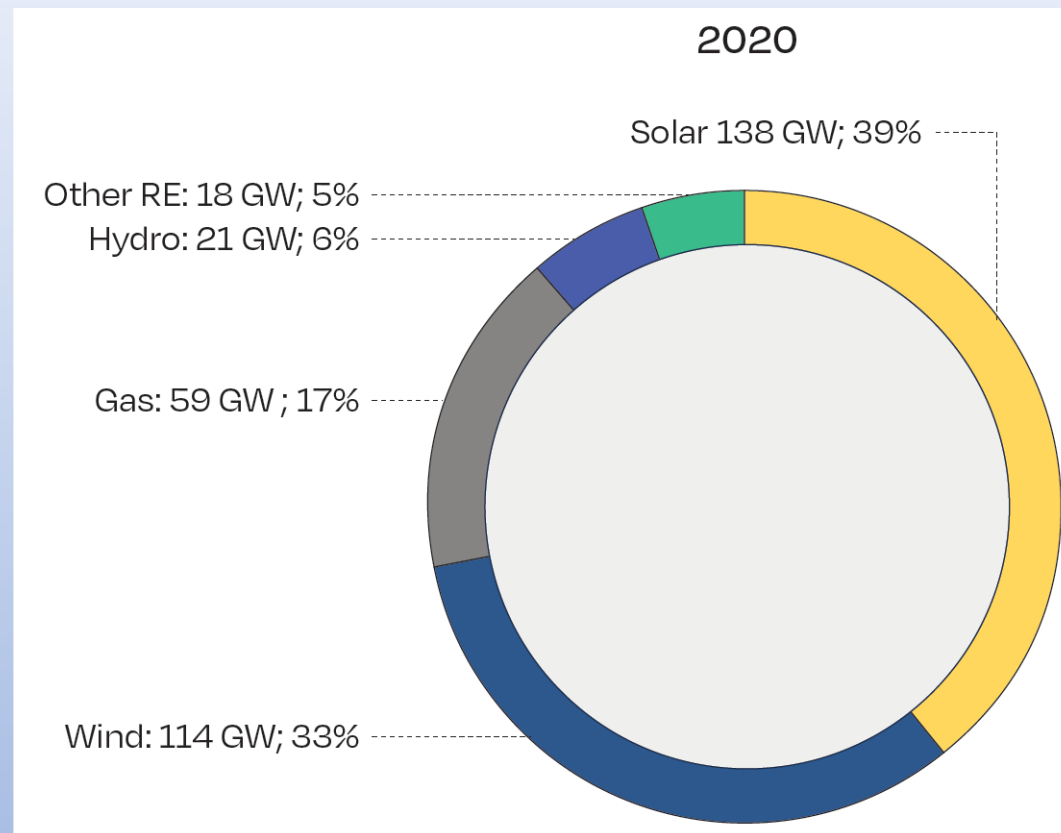
- Installed PV power increased three orders of magnitude;
- PV Energy (Wp) reduced its cost by a factor of 60.



PV energy today

PV in 2021:

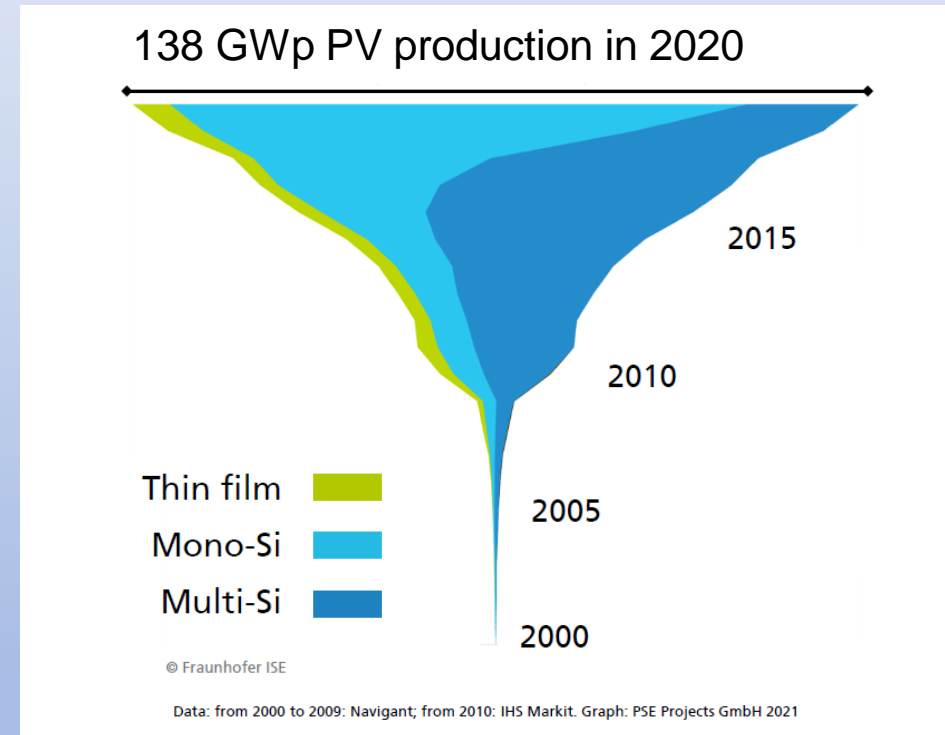
- PV was the technology with the highest capacity growth in 2020 with 138 GW installed.
- Global installed capacity > 700 GW
- PV produces ~ 3% of the world electricity.
- In several countries PV is already the cheapest way to produce electricity.



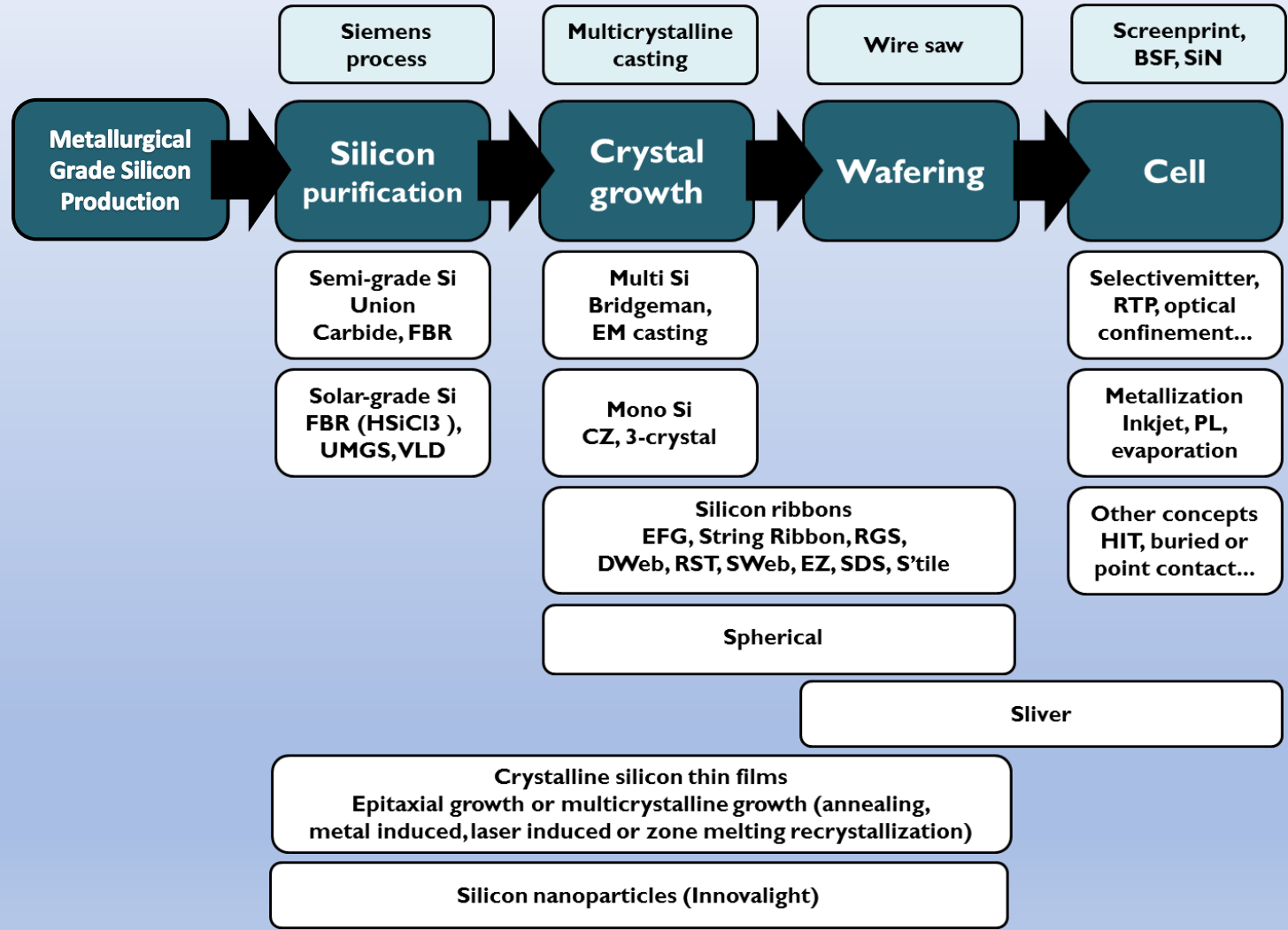
Net added power capacity by technology

Crystalline Silicon solar cell technologies

- Crystalline silicon (c-Si) has been the major driving force of PV industry.
- In the last decades c-Si accounted for more than 90% of the installed capacity.
- C-Si technologies are split between multicrystalline silicon (less expensive) and monocrystalline silicon (more efficient).
- Market share of monocrystalline silicon is increasing, in 2020 it was 84% (i.e., pursuit of high efficiency).



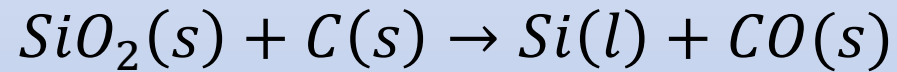
Crystalline Silicon solar cell technologies



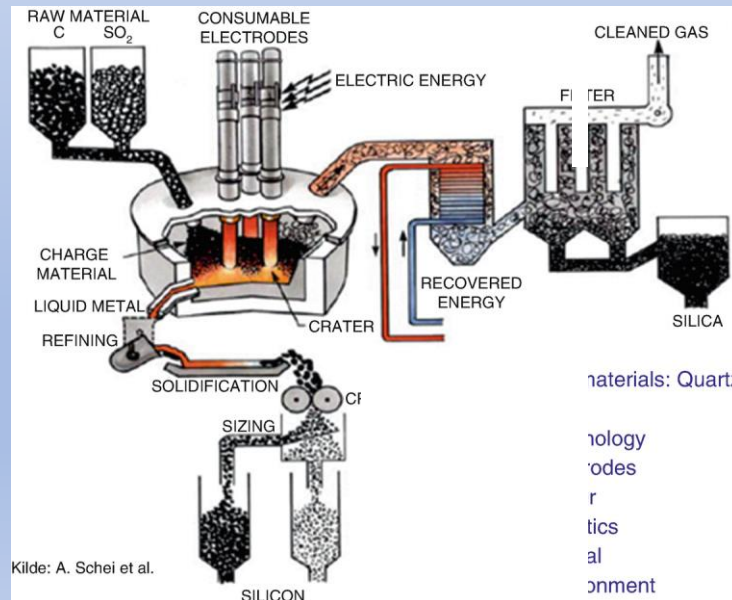
Crystalline Silicon solar cell technologies

Production of metallurgical grade silicon (MG-Si):

Reduction of silica (SiO_2) with carbon:



Process:



Quartz(silica)



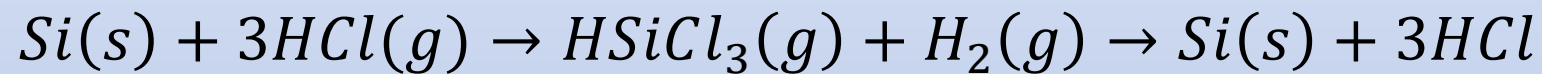
MG-Si: 98.5% purity



Crystalline Silicon solar cell technologies

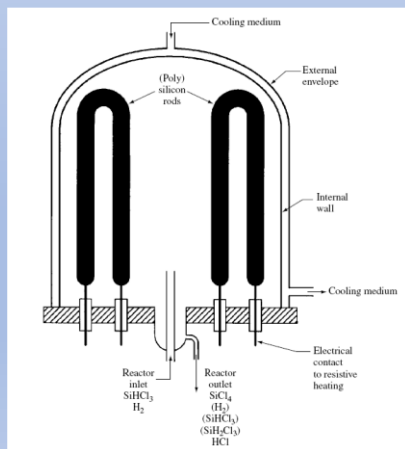
Production of pure polycrystalline silicon: PV needs a purity of 99.9999% (6N)

Purification of metallurgical grade silicon, example: Siemens' process

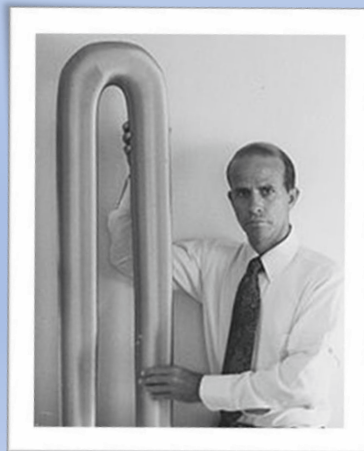


Production of $HSiCl_3$
(highly pure Si source)

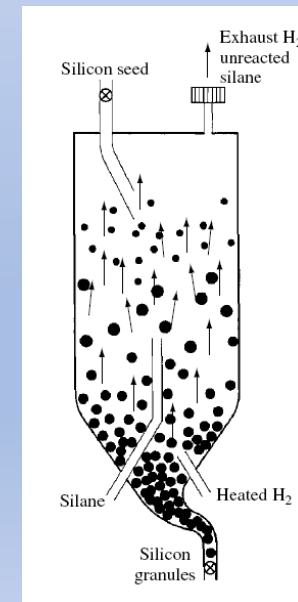
Distillation of $HSiCl_3$
→ Si CVD



Siemens' process



Alternative: Fluidized bed reactor



Crystalline Silicon solar cell technologies

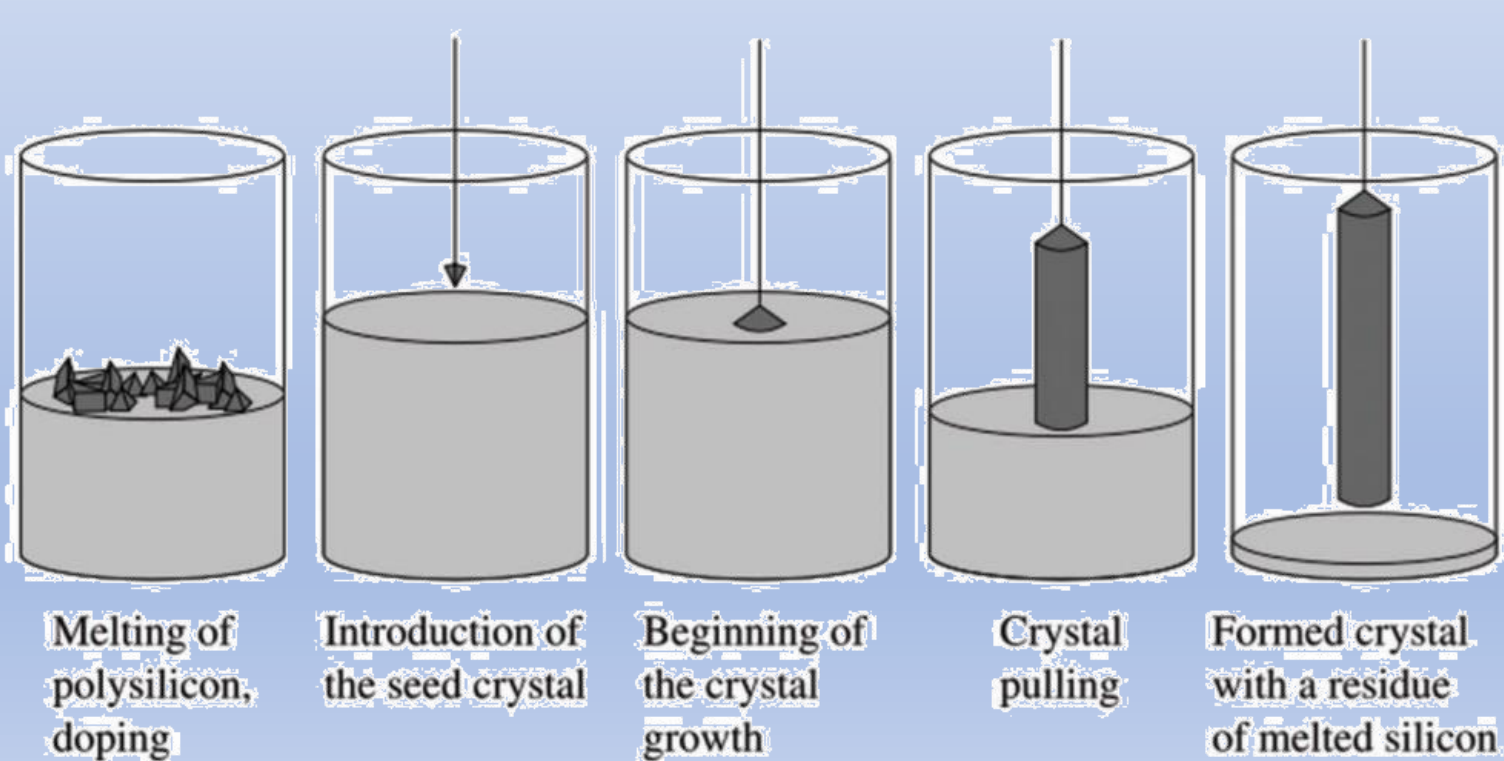
Crystalline silicon may be used in different forms

Descriptor	Symbol	Grain Size	Common Growth Techniques
Monocrystalline	sc-Si	>10cm	Czochralski (Cz) float zone (FZ)
Multicrystalline	mc-Si	1mm-10cm	Cast, sheet, ribbon
Polycrystalline	pc-Si	1 μ m-1mm	Chemical-vapour deposition
Microcrystalline	μ c-Si	<1 μ m	Plasma deposition

Crystalline Silicon solar cell technologies

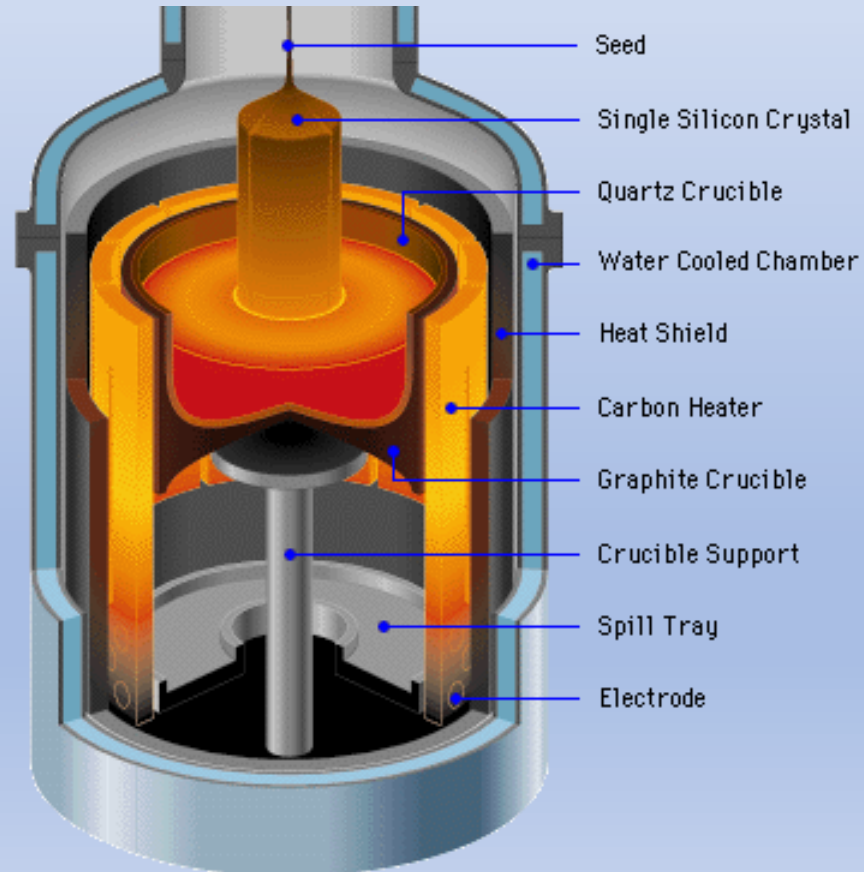
Czochralski silicon is the standard process to produce monocrystalline silicon.

- High quality material with a low contamination of oxygen and carbon.



Crystalline Silicon solar cell technologies

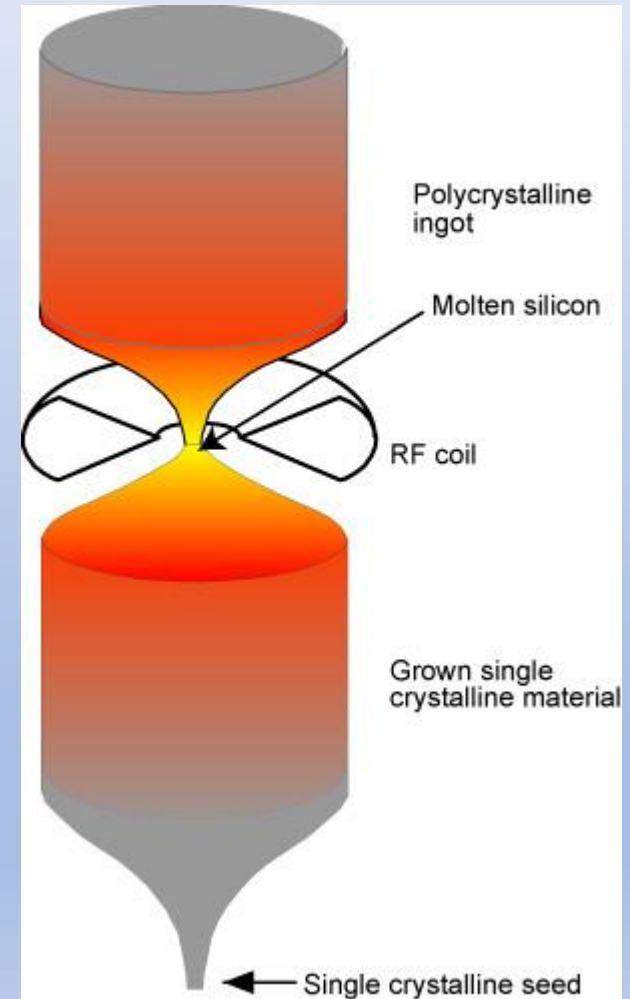
Czochralski silicon
Growth rate: 5cm/hour



Crystalline Silicon solar cell technologies

Float zone silicon is the best quality silicon

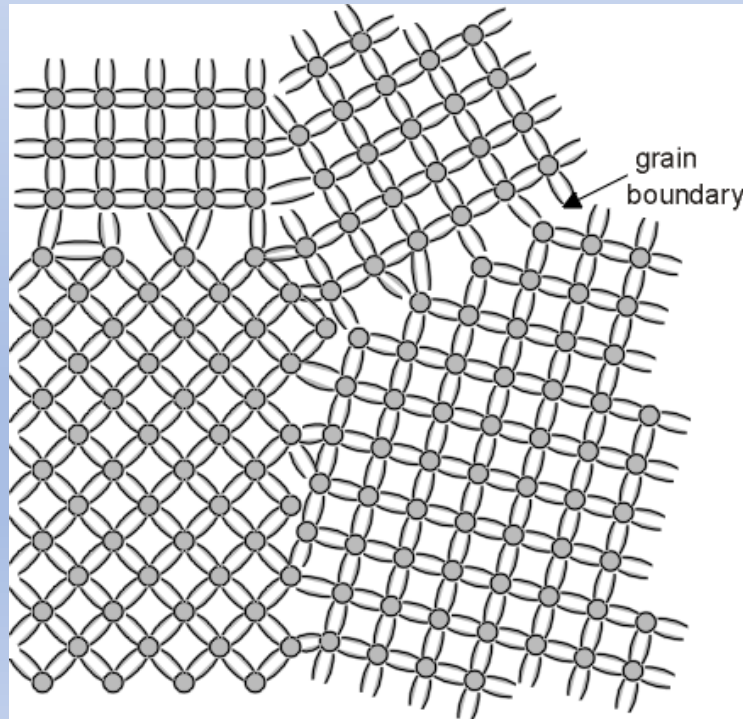
- No contamination but very expensive (i.e., slow processing).
- Only used for very demanding applications.



Crystalline Silicon solar cell technologies

Multicrystalline silicon offers acceptable quality at a lower cost

- It used to be dominant in the market (i.e., when PV was very costly).

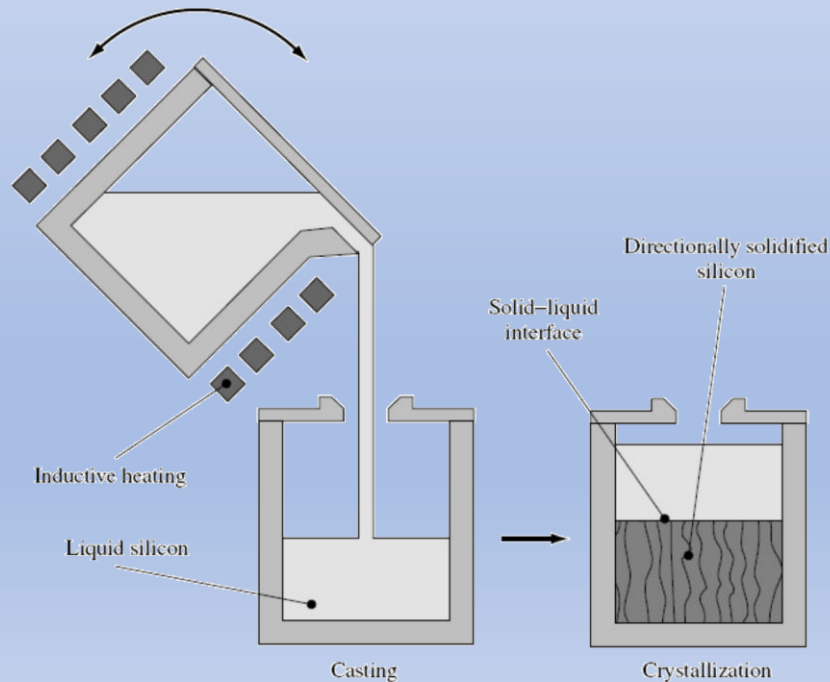


Crystalline Silicon solar cell technologies

Production of multicrystalline silicon

Process: Casting or direct solidification

- Requires careful thermal control.
- Crucible usually made of quartz or graphite, often with Si_3N_4 coating.

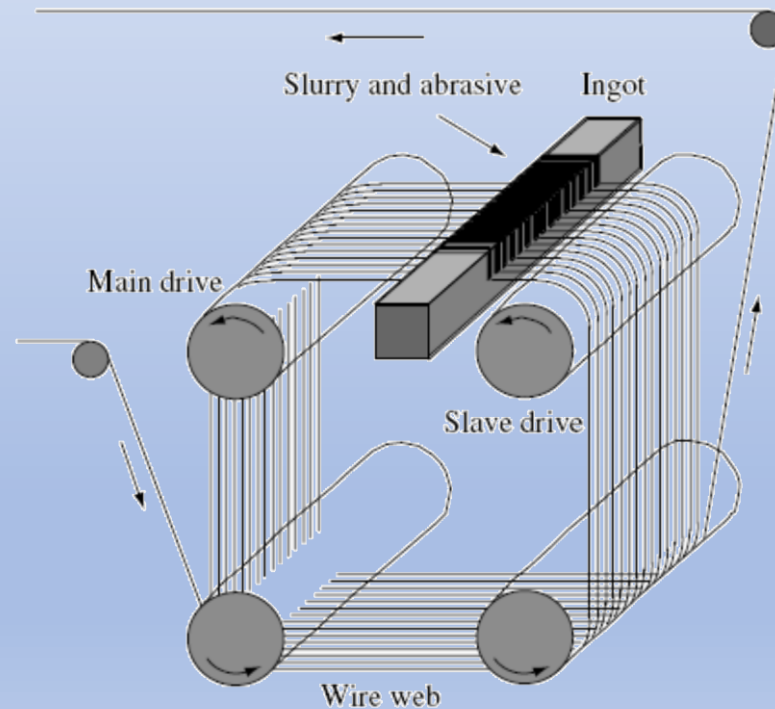


Typical casting:
240kg/56 hours

Crystalline Silicon solar cell technologies

Both mono and multicrystalline ingots require sawing

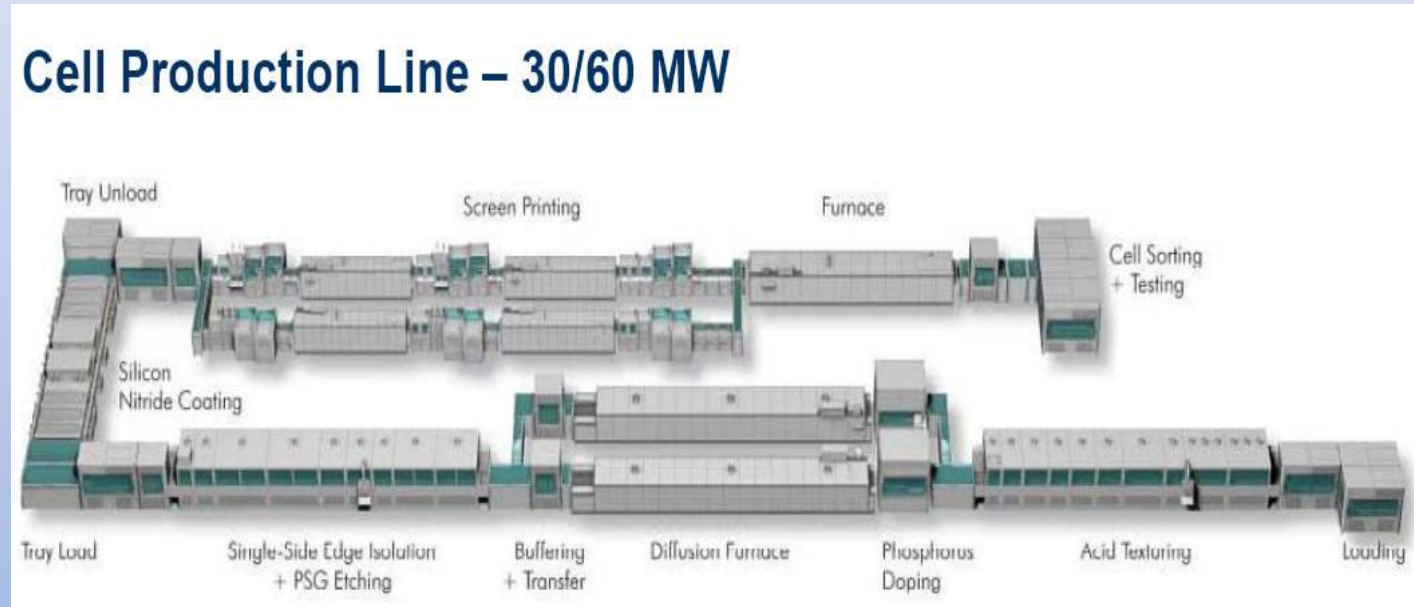
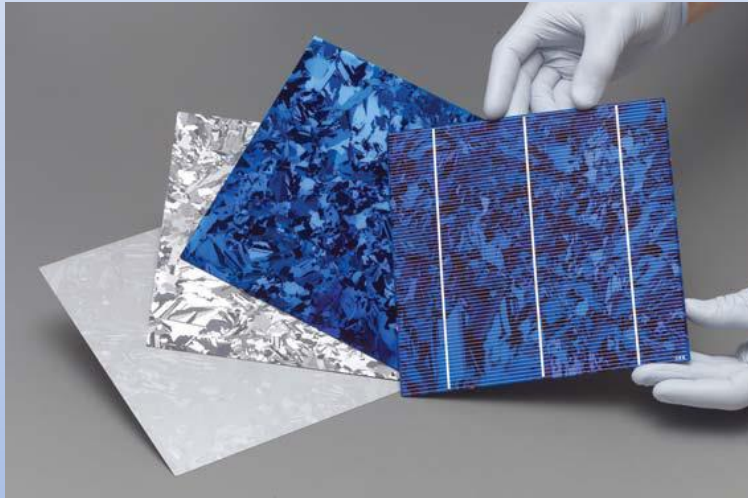
- Kerf loss and saw damage removal loss are significant (and costly).



Alternatives: Diamond and laser sawing

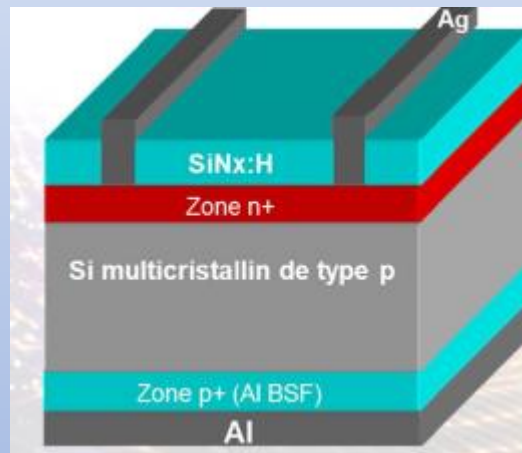
Crystalline Silicon solar cell technologies: solar cell processing

From the wafer to the solar cell:

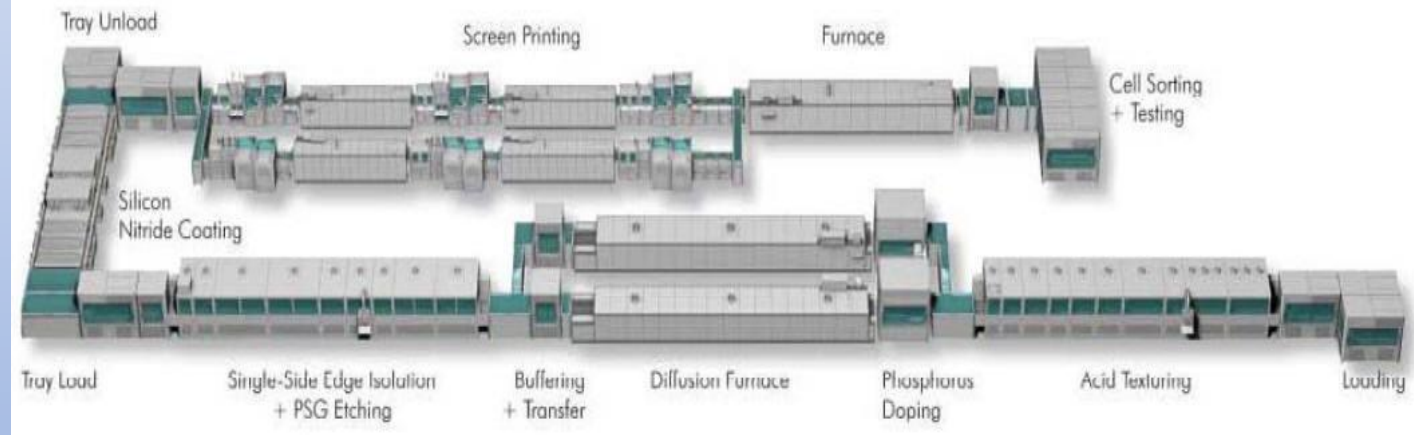


Crystalline Silicon solar cell technologies: solar cell processing

From the wafer to the solar cell:



Cell Production Line – 30/60 MW



Crystalline Silicon solar cell technologies: solar cell processing

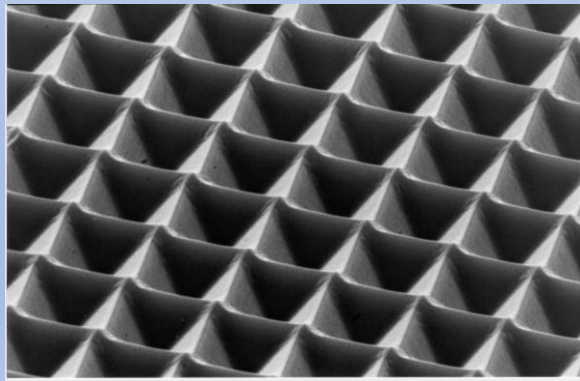
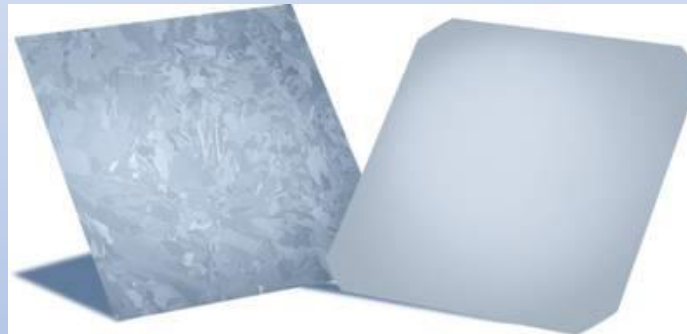
Al-BSF silicon solar cell (p-type silicon) manufacturing process

- Saw damage etch
- Texturization
- Phosphorous diffusion
- Edge isolation
- Anti reflective coating /Surface passivation
- Back contact print
- Firing
- Front contact print
- Firing
- Testing & sorting

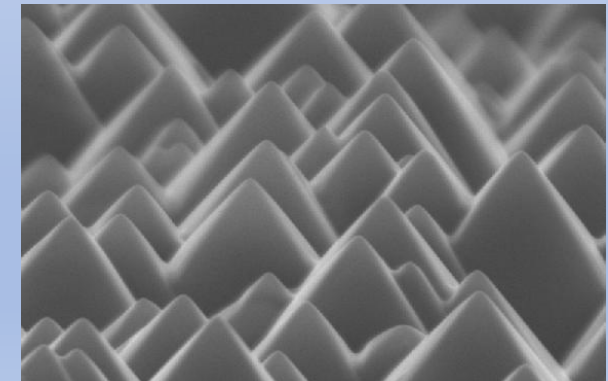
Crystalline Silicon solar cell technologies: solar cell processing

Surface Texturization:

- Chemical etching of the silicon surface: reflection of 10% instead of 35%
- Alkaline etching for monocrystalline Si and acidic etching for multicrystalline Si



Multicrystalline silicon



Monocrystalline silicon

Crystalline Silicon solar cell technologies: solar cell processing

Phosphorous diffusion:

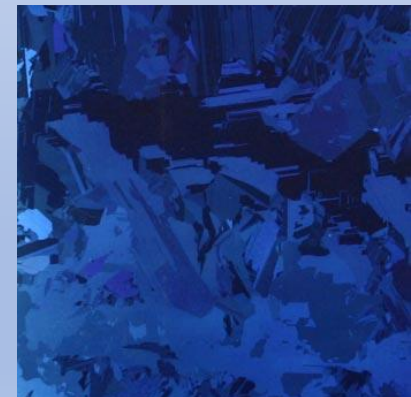
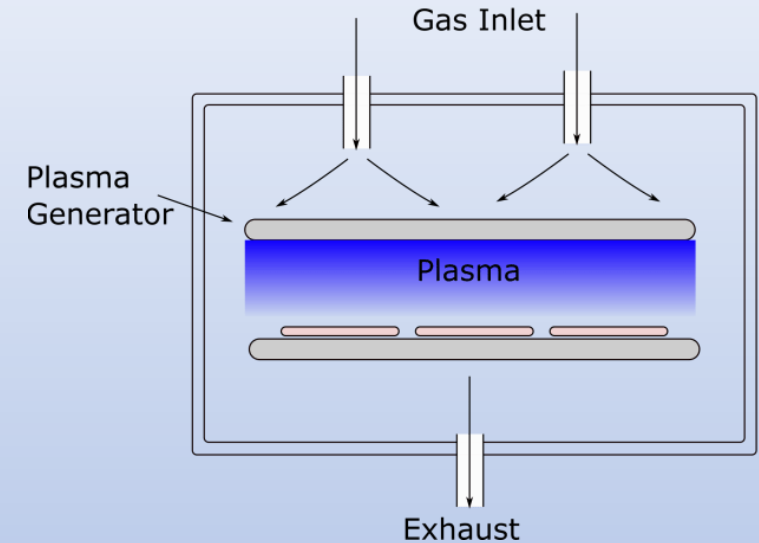
- The phosphorous forms the pn junction.
- It is performed in batch furnaces at 700°C - 800°C (t ~1h).
- Phosphorus source: Phosphorus oxychloride POCl_3 .



Crystalline Silicon solar cell technologies: solar cell processing

SiN_x:H antireflective and passivation coating

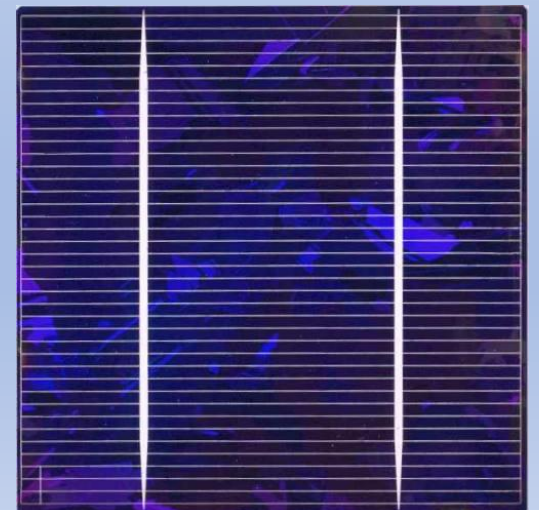
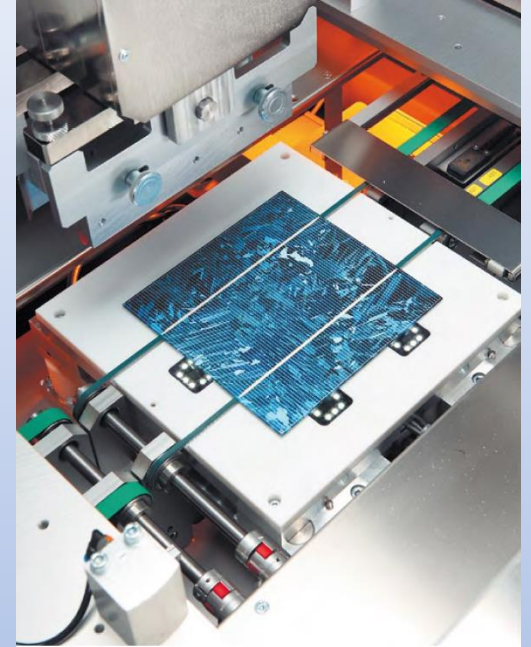
- SiN_x:H thin film is grown by PECVD (SiH₄+NH₃).
- It is performed in batch furnaces at 400°C.
- Films are 75 nm thick, and n≈2.2.
- Together with the texturization, antireflective SiN_x films reduce reflectivity to ~ 2.5%.
- SiN_x:H reduce carrier recombination in the surface and volume of the wafer are thus said to provide **passivation**.



Crystalline Silicon solar cell technologies: solar cell processing

Screen-printing:

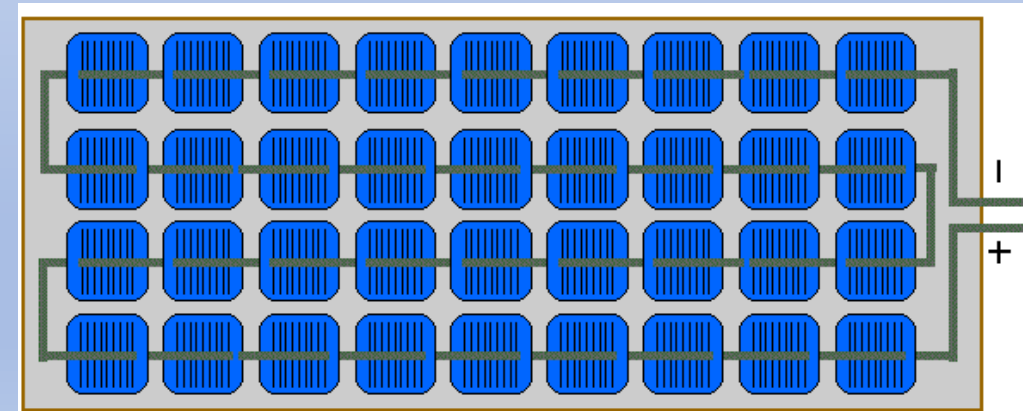
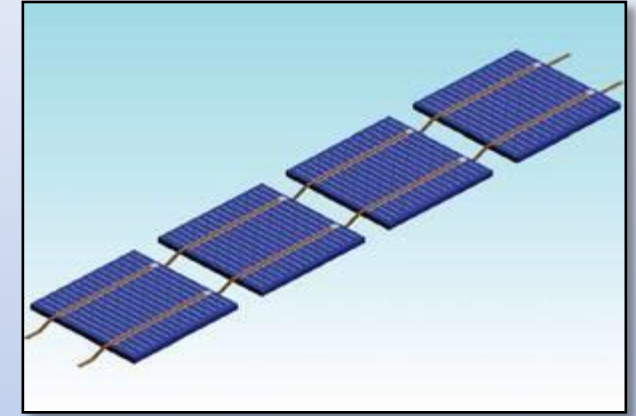
- The standard method to form the metallic contacts is imprinting metal pastes in the wafer using a screen with the design of the contacts.
- For p-type silicon solar cells a silver paste is used on the front-side and an aluminium one on the back-side (full coverage)
- After the screen-printing of the metal pastes, the samples are heated to 800°C - 900°C for a few seconds → **contact firing**
- During contact firing the aluminium diffuses to the interior of the wafer forming the **back-surface field** that reduces recombination in the back surface.



Crystalline Silicon solar cell technologies: module

Module:

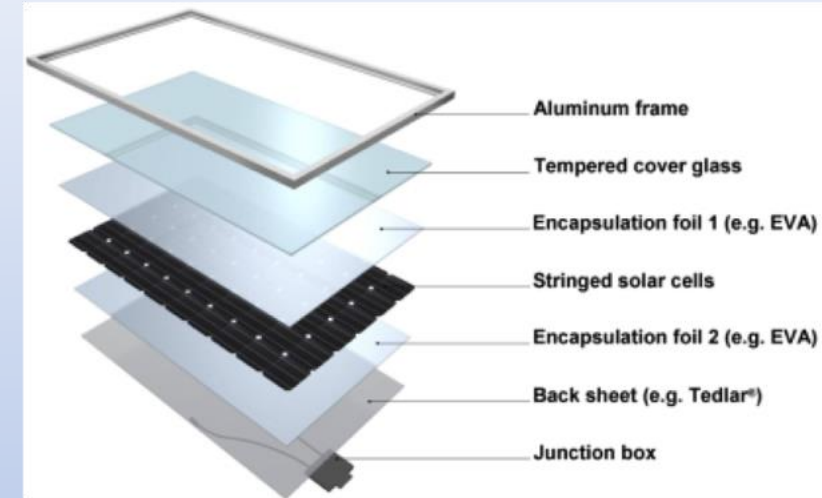
- After characterization, the solar cells are organized according to their range and used to manufacture the PV modules.
- The solar cells are connected in series. A typical PV module has 36 cells.



Crystalline Silicon solar cell technologies: module

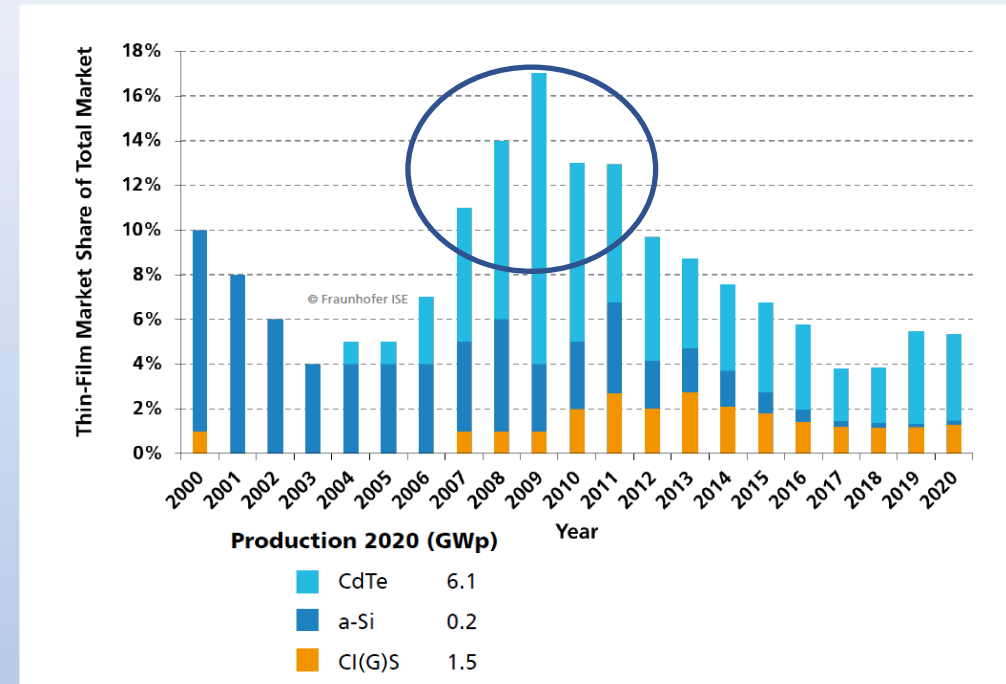
Module:

- After characterization, the solar cells are organized according to their range and used to manufacture the PV modules.
- The solar cells are connected in series. A typical PV module has 36 cells.
- The cells are then encapsulated for higher durability.
- Finally, the frame, glass cover, back-sheet protection and junction are added.



Thin film technologies

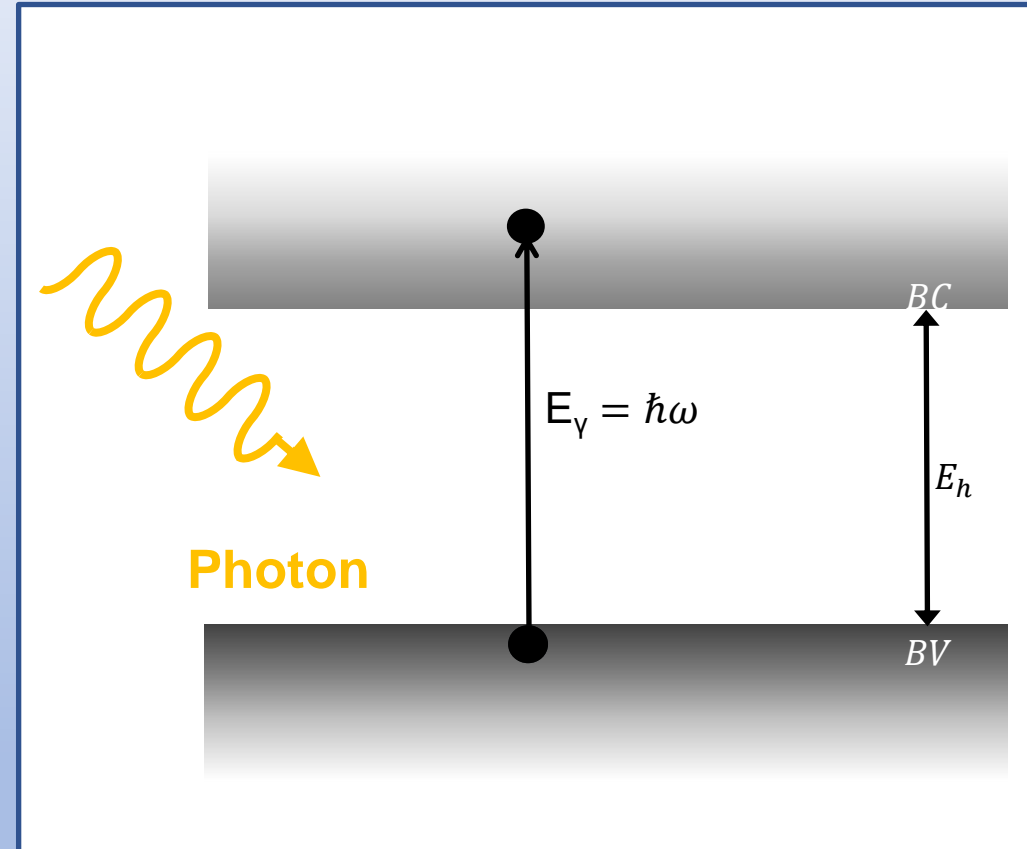
- The thin film technologies had a golden period when there was bottleneck in the polysilicon production.
- After this period, c-silicon continued its steady cost reductions and recovered market hegemony.
- It is not expected that these figures change significantly especially since the major thin film technologies are either based on the use of toxic materials (CdTe) or rare ones (CIGs – Indium).



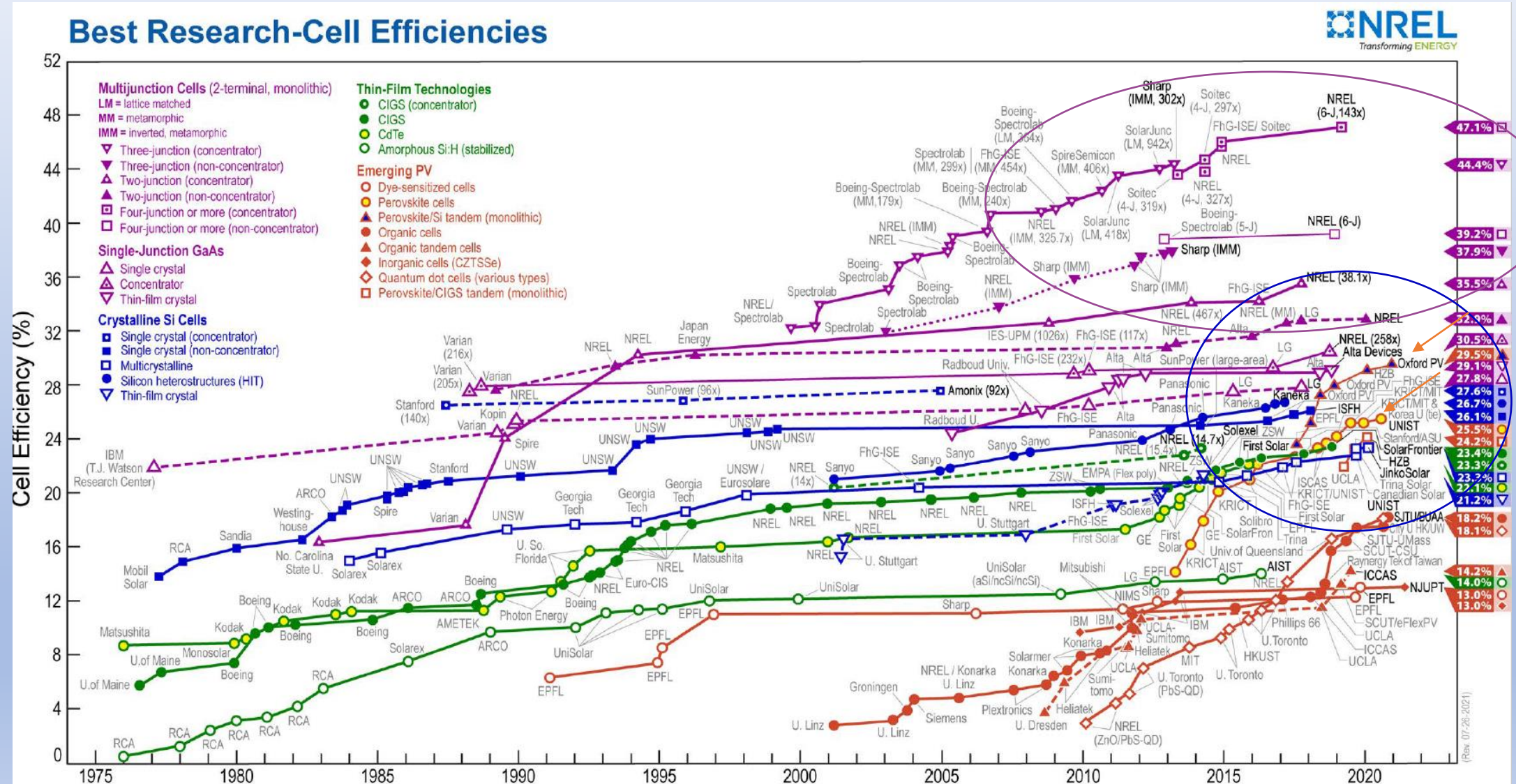
Limitations of crystalline silicon and monojunction solar cells

Efficiency limit

- Silicon solar cells are based on the absorption of photons ($E_\gamma > E_{\text{gap}}$) by the silicon atoms
→ There is a theoretical limit (Shockley-Queisser) for the conversion efficiency.
- This is true for all the solar cells based on just one semiconductor, named monojunction solar cells.
- For crystalline silicon Shockley-Queisser limit is 30%.



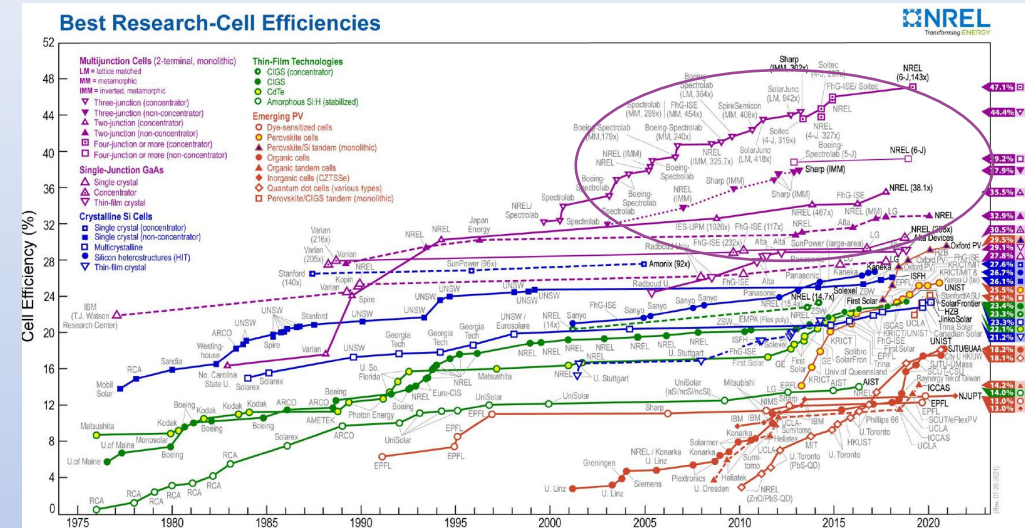
Future PV technologies



Future PV technologies

III- V groups tandem solar cells

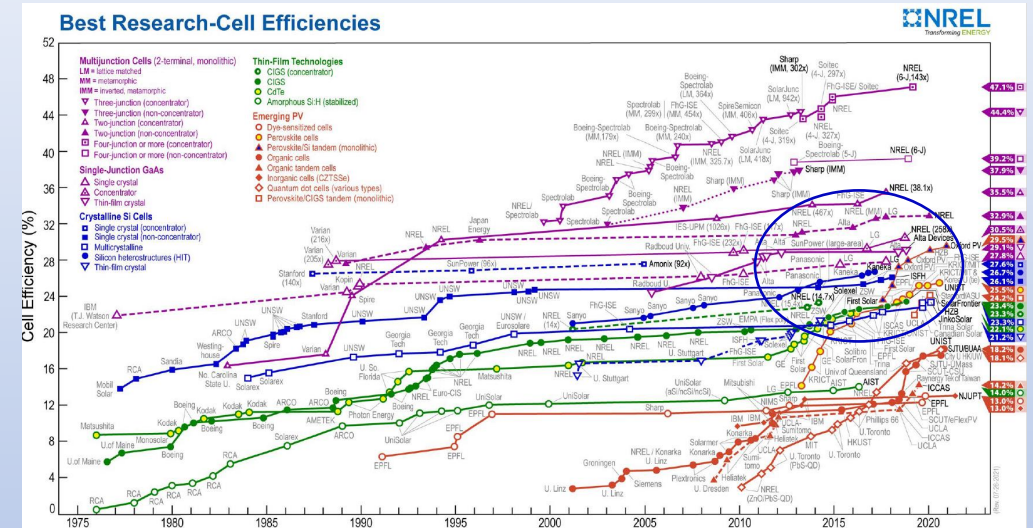
- But the technology is too expensive ($\times 100$ cost of c-Si).
- It is only used on niche markets such as space applications.
- One important trend in PV research is to make tandem solar cells, using crystalline silicon as one of the sub-cells.
- The idea is to profit from the maturity and low cost of c-Si and the high-efficiency potential of the tandem solar cells.



Future PV technologies

Crystalline silicon related technologies

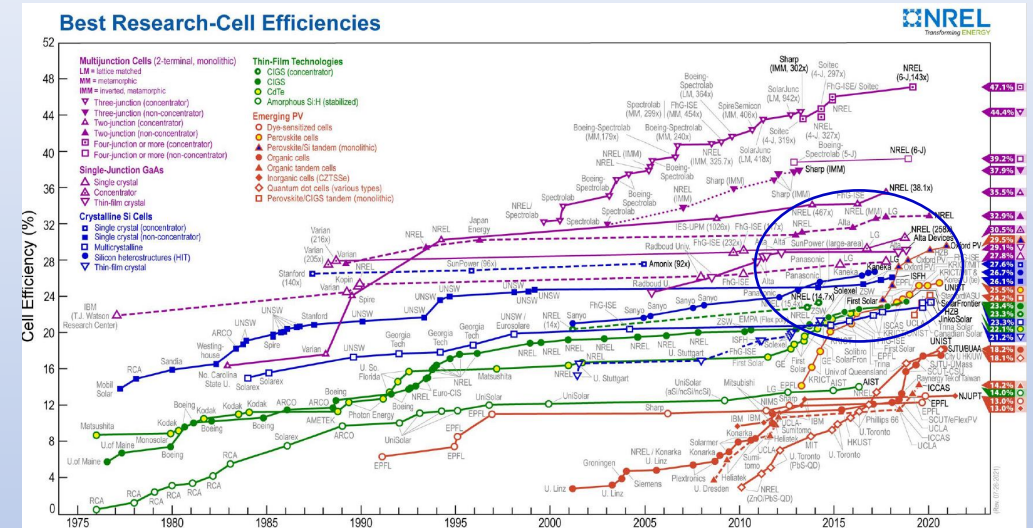
- C-Si will still dominate the market in the next decade and maintains a very dynamic research activity with a lot of high-efficiency concepts being proposed.
- The record efficiency for c-Si is 26.1% but for the heterojunction concept (c-Si/a-Si) is 26.7%.
- Most record efficiencies were obtained with n-type silicon.



Future PV technologies

Main market trends

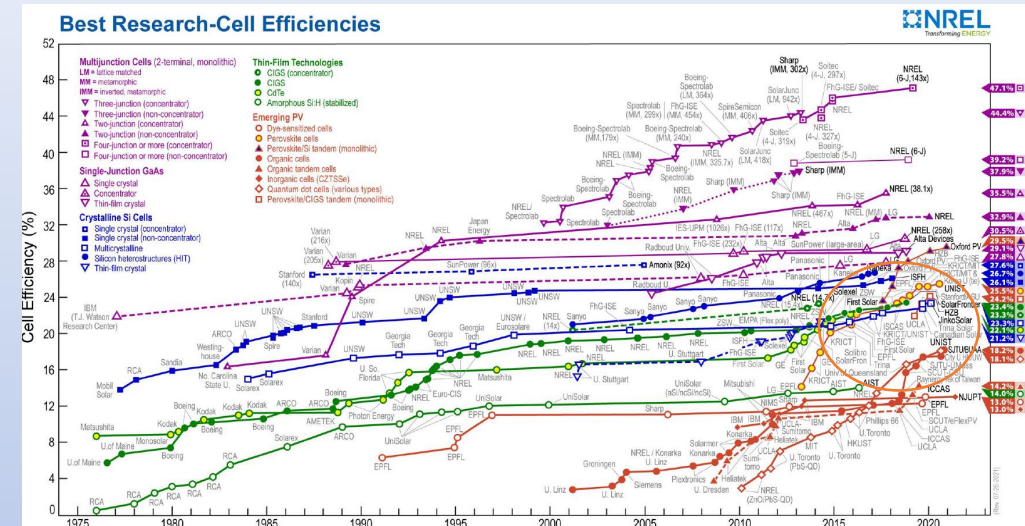
- The standard Al-BSF is being replaced by more efficient concepts as PERL, PERC, HIT, TOPCon, etc.
- N-type silicon is gaining market share to the traditional dominant p-type.
- Solar cells sizes are increasing very significantly: $156 \text{ mm}^2 \rightarrow 210 \text{ mm}^2$, and thickness is being reduced $180 \mu\text{m} \rightarrow 130 \mu\text{m}$
- Bifacial modules are becoming more common.



Future PV technologies

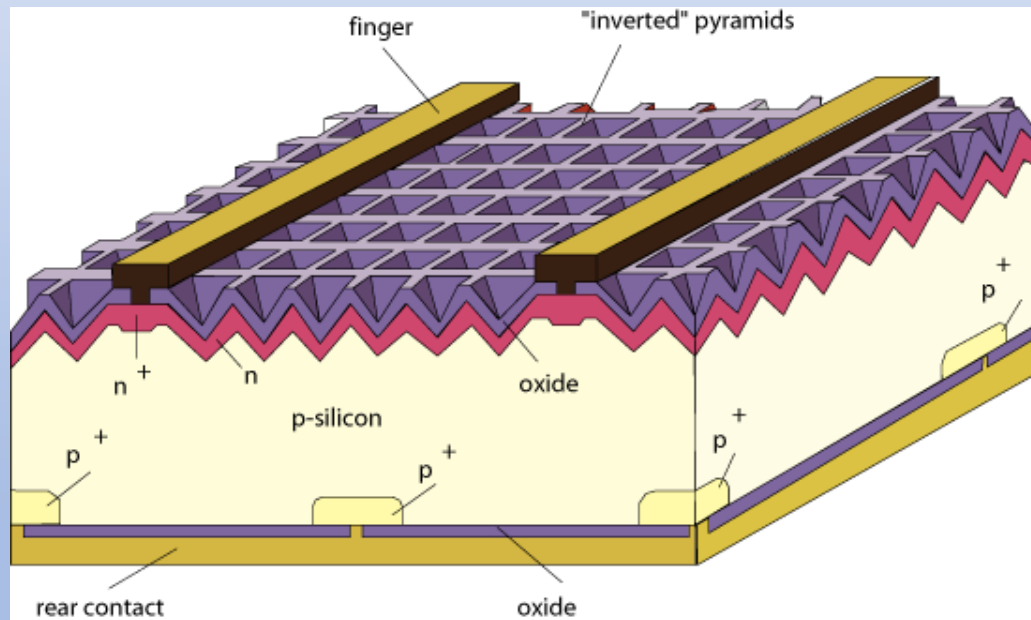
Perovskite technologies

- Emerging low-cost technology with an impressive efficiency progression (13%→25% in 8 years).
- Tandem cells c-Si/Perovskite already reached an efficiency of 29.5%.
- However, the stability of the perovskite solar cells efficiencies for a few months has not been demonstrated.
- Perovskite has a great potential for short-term PV applications such as powering IoT appliances.



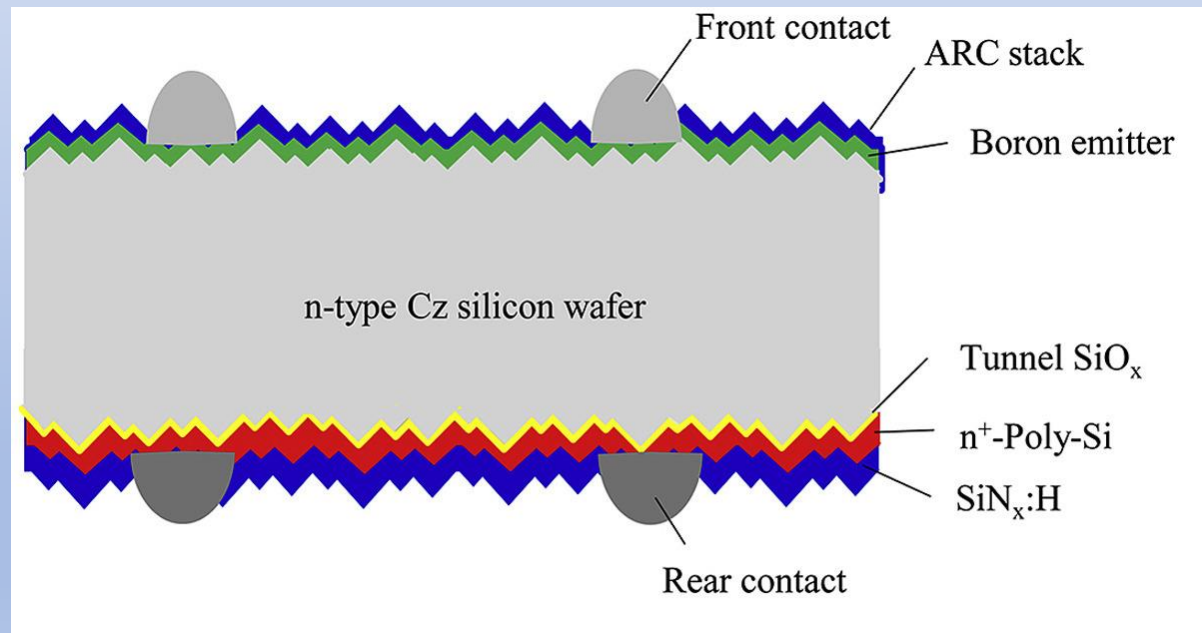
Future PV technologies

PERC solar cell



Future PV technologies

TOPCon



Future PV technologies

HIT

