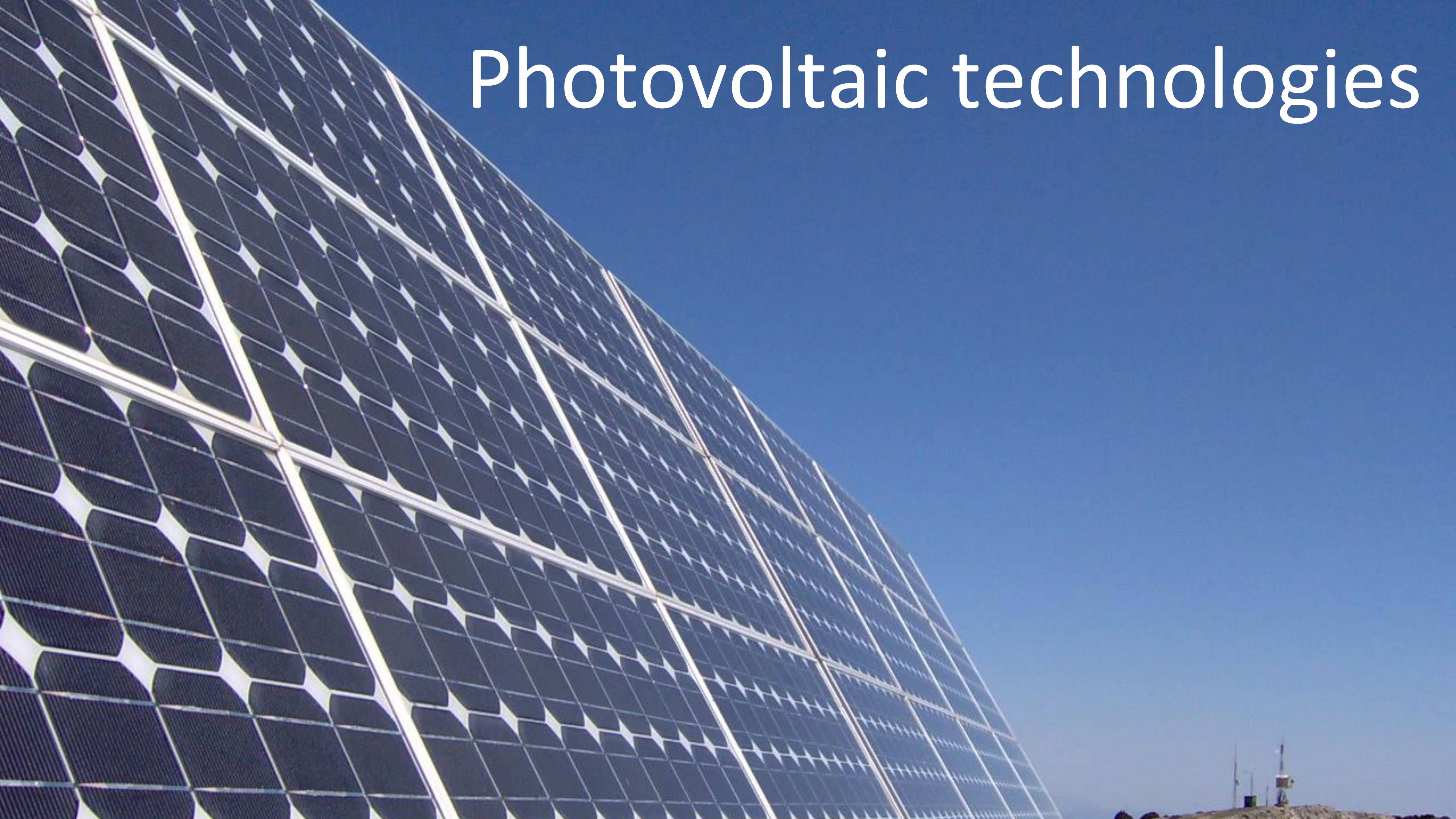
Photovoltaic technologies



Photovoltaic technologies

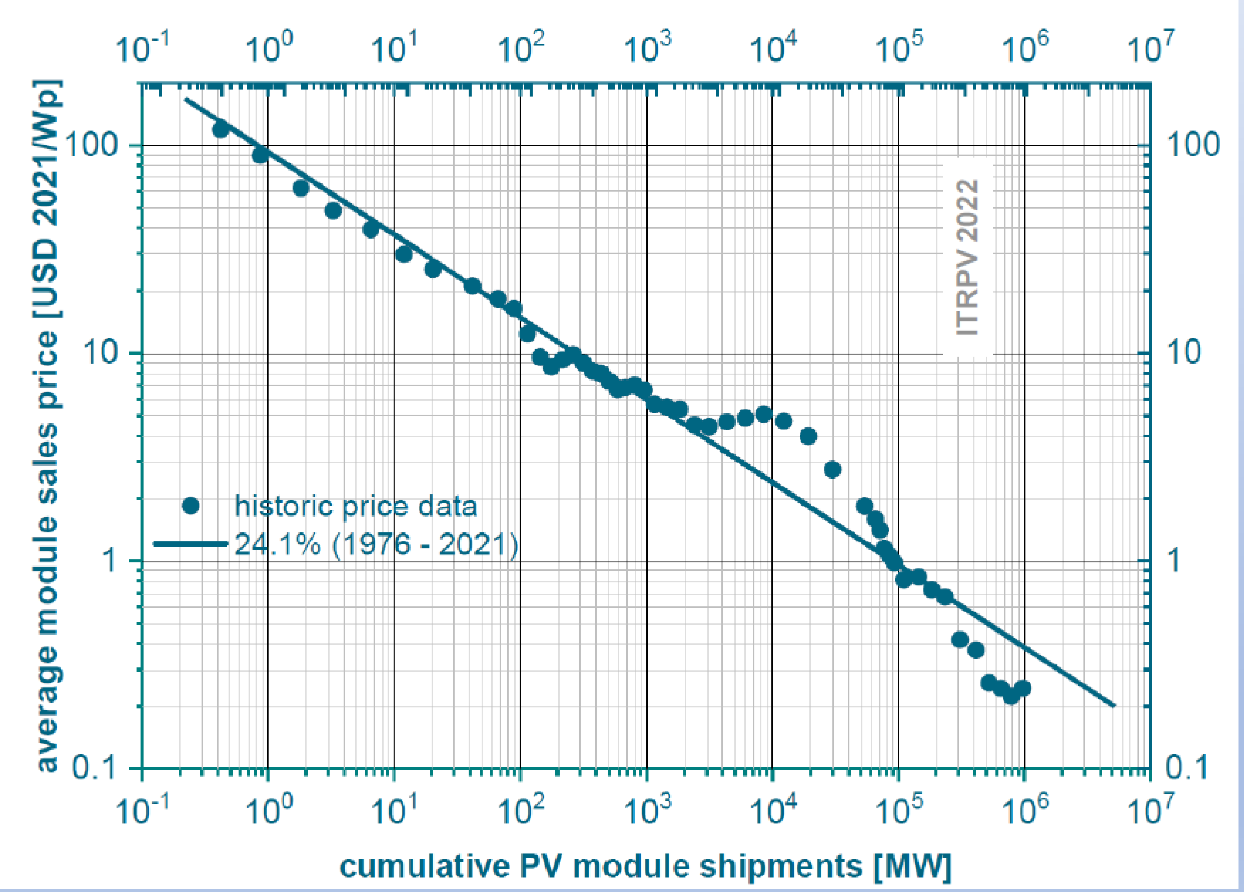
- Photovoltaic energy today
- Crystalline silicon technologies
- Limitations of crystalline silicon and monojunction solar cells
- Future PV technologies

PV energy today

Swanson law: For each duplication of the PV installed capacity the price per Wp reduces 20% - **in fact it is now 24.1%!**

Last 30 years:

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

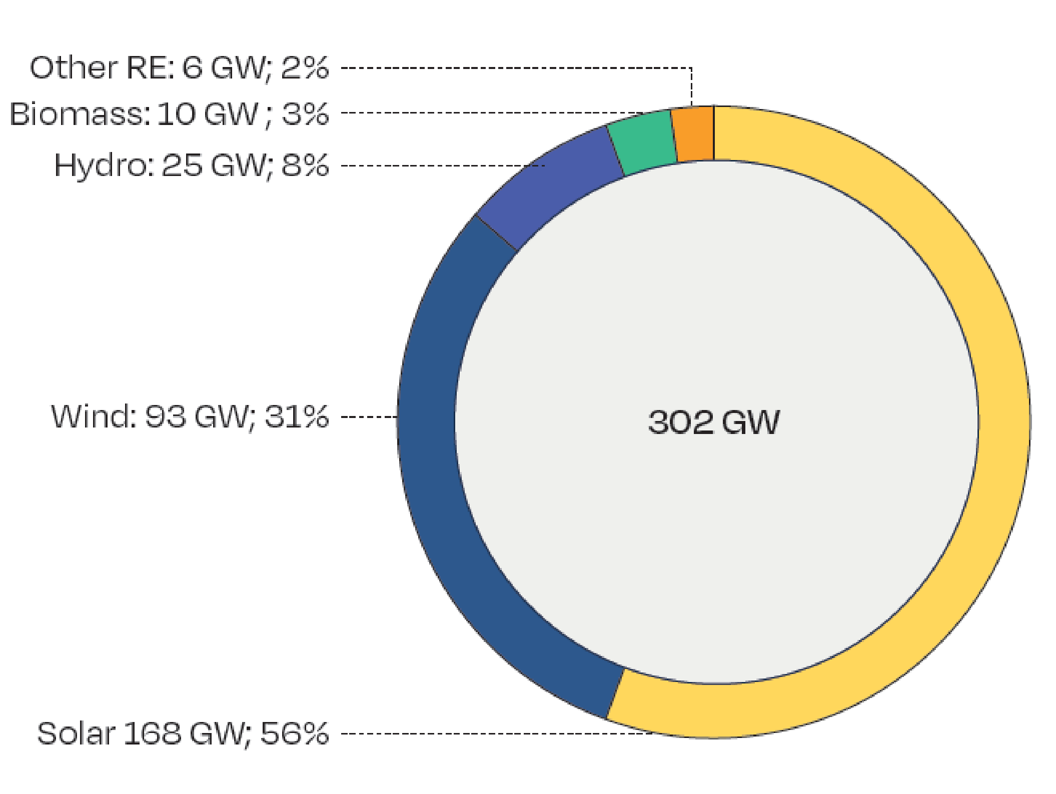


2022 International Technology Roadmap for Photovoltaic

PV energy today

PV in 2021:

- PV was the technology with the highest capacity growth in 2021 with 168 GW installed (~ 190 GW ←Fraunhofer ISE).
- Global installed capacity > 900 GW
  → **Reached 1 TW this year!!**
- PV produced 3.6% of the world electricity.
- In several countries PV is already the cheapest way to produce electricity.

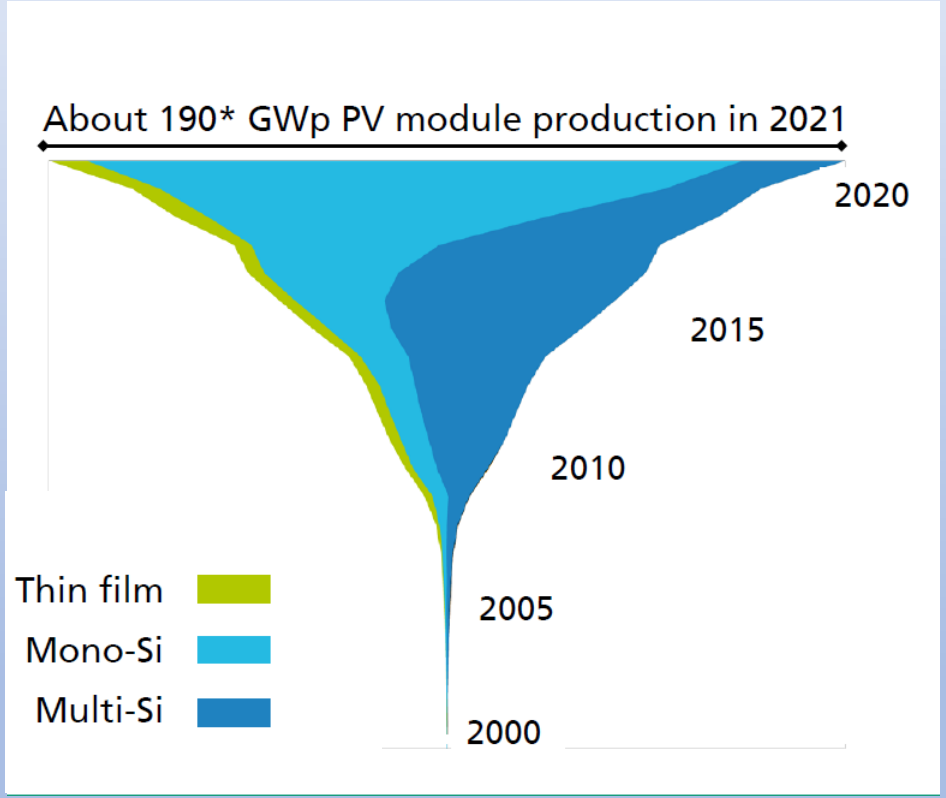


Net added power capacity by technology, 2021

IRENA/Solar Power Europe 2022

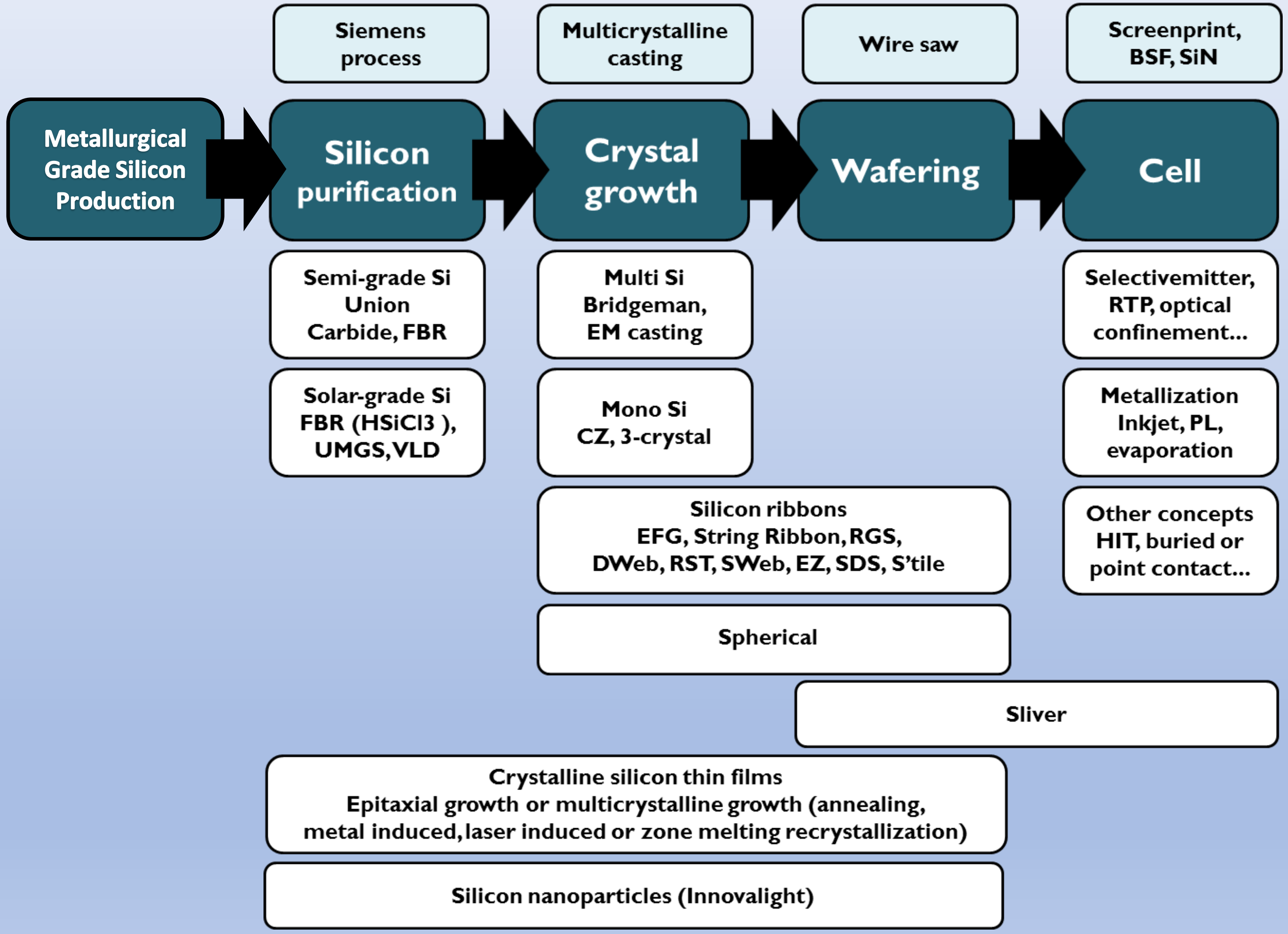
Crystalline Silicon solar cell technologies

- 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 ~ 95% in 2021.
- c-Si technologies are split between multicrystalline silicon (less expensive) and monocrystalline silicon (more efficient).
- Market share of monocrystalline silicon is increasing, in 2021 it was 84% (i.e., pursuit of high efficiency).



@Fraunhofer ISE 2022
Data: from 2000 to 2009: Navigant; from 2010: IHS Markit.
Graph PSE 2022. Date of data: Jan-2022

Crystalline Silicon solar cell technologies



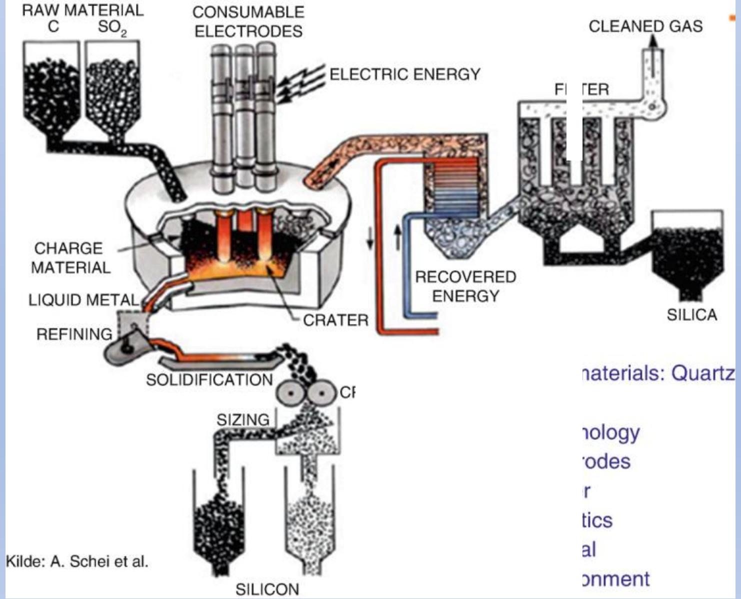
Crystalline Silicon solar cell technologies

Production of metallurgical grade silicon (MG-Si):

Reduction of silica (SiO_2) with carbon:

$$SiO_2(s) + C(s) \rightarrow Si(l) + CO(s)$$

Process:



Quartz(silica)

MG-Si: 98.5% purity

Crystalline Silicon solar cell technologies

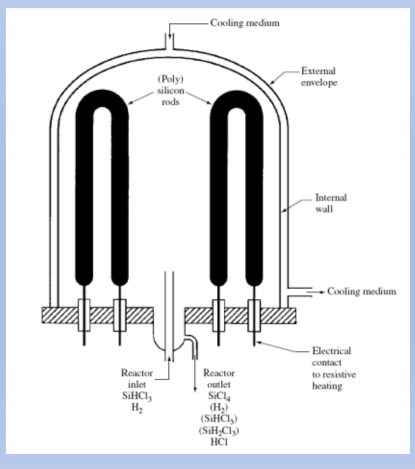
Production of pure polycrystalline silicon: PV needs a purity of 99.9999% (6N)

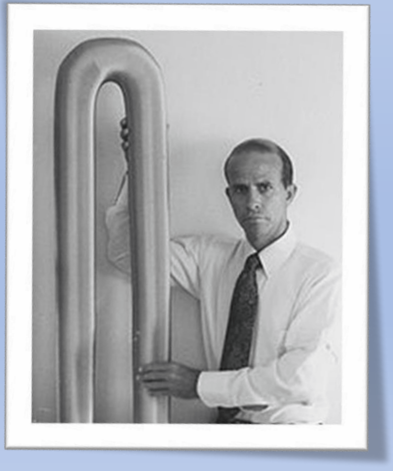
Purification of metallurgical grade silicon, example: Siemens' process

$$Si(s) + 3HCl(g) \rightarrow HSiCl_3(g) + H_2(g) \rightarrow Si(s) + 3HCl$$

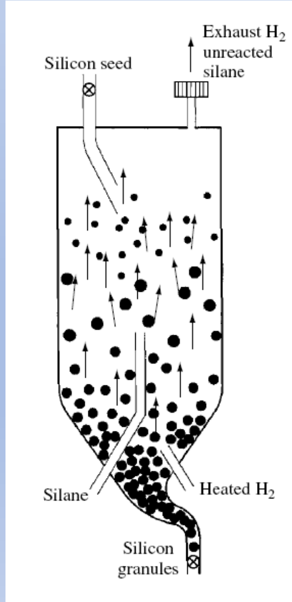
Production of $HSiCl_3$
(highly pure Si source)

Distillation of $HSiCl_3$
→ **Si CVD**





Siemens' process



Alternative: Fluidized bed reactor

Crystalline Silicon solar cell technologies

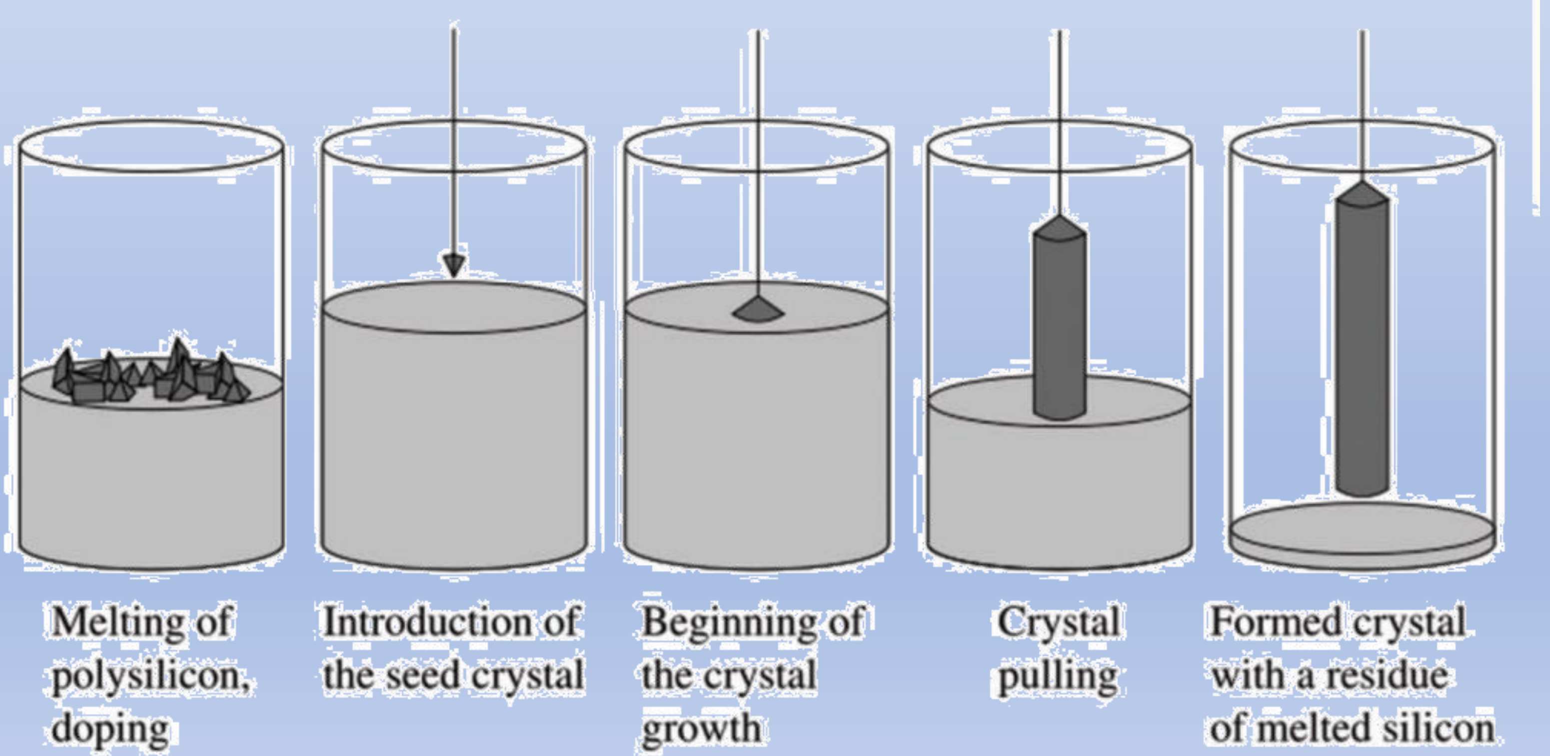
Crystalline silicon may be used in different forms

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	1µm-1mm	Chemical-vapour deposition
Microcrystalline	µc-Si	<1µm	Plasma deposition

Crystalline Silicon solar cell technologies

Czochralski silicon is the standard process to produce monocrystalline silicon.

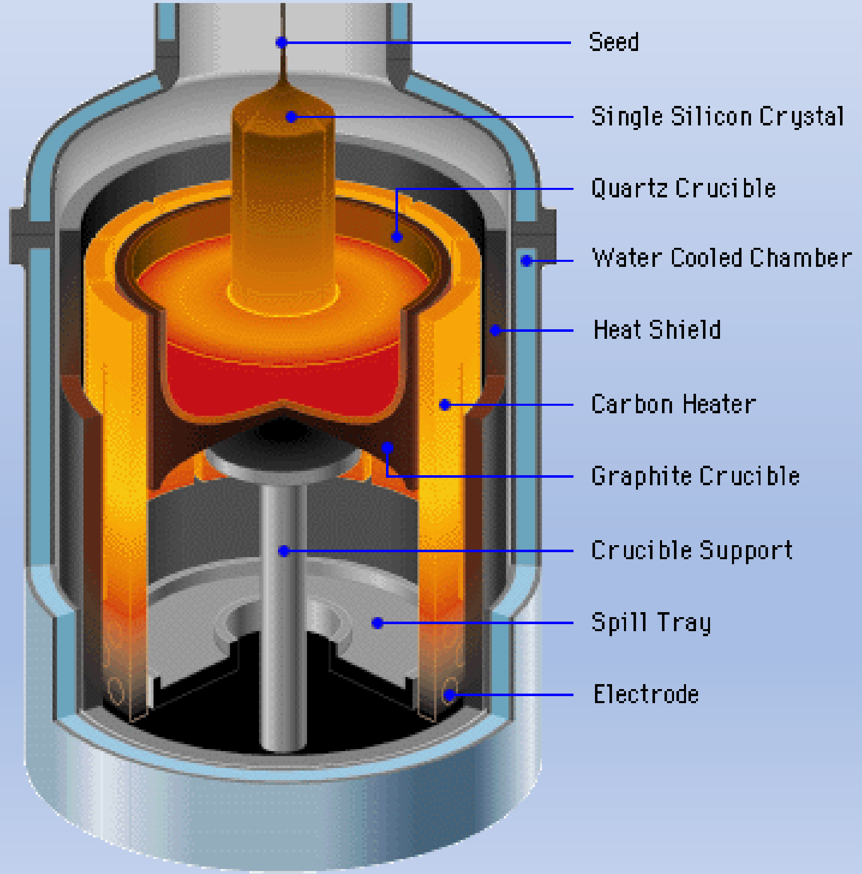
- High quality material with a low contamination of oxygen and carbon.



Crystalline Silicon solar cell technologies

Czochralski silicon

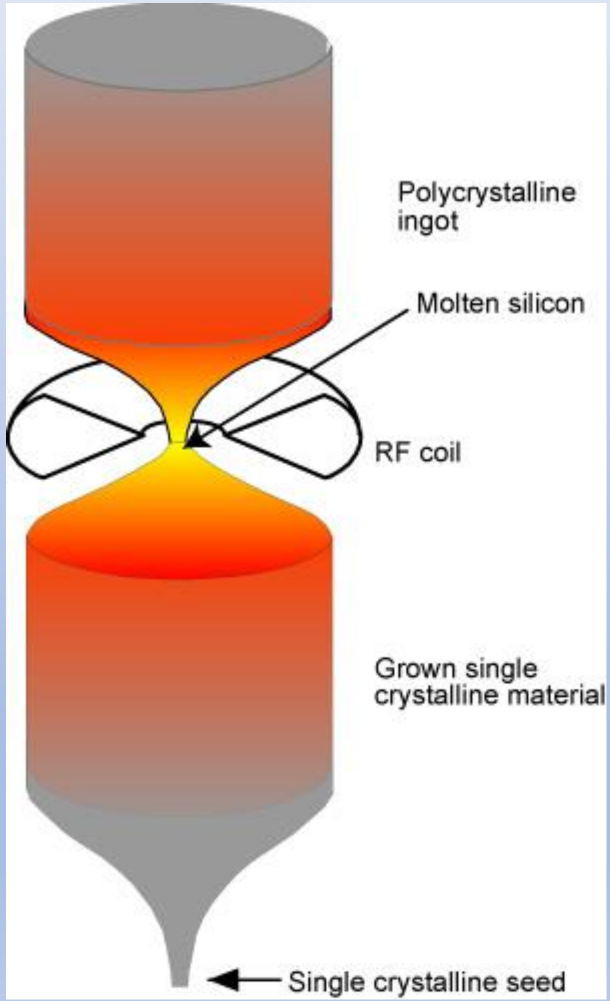
Growth rate: 5cm/hour



Crystalline Silicon solar cell technologies

Float zone silicon is the best quality silicon

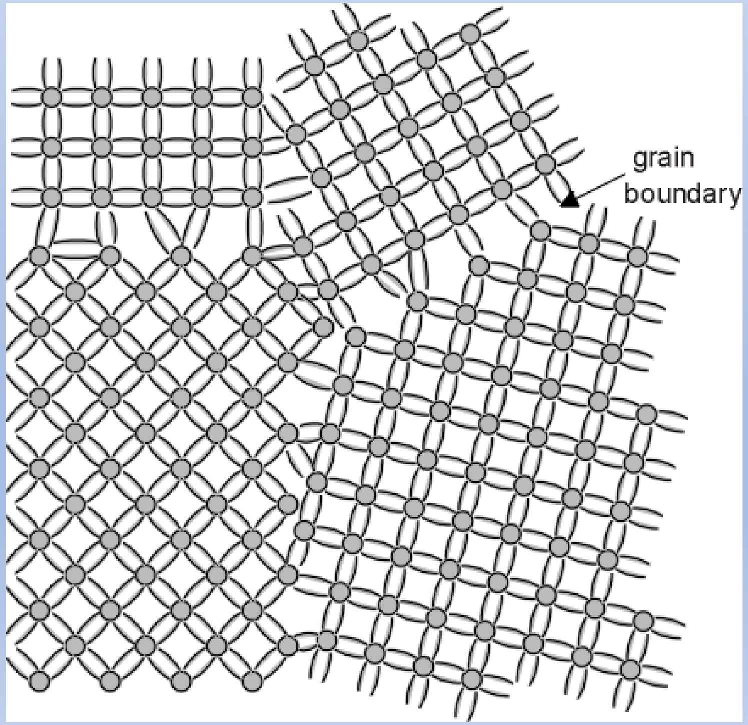
- No contamination but very expensive (i.e., slow processing).
- Only used for very demanding applications.



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).

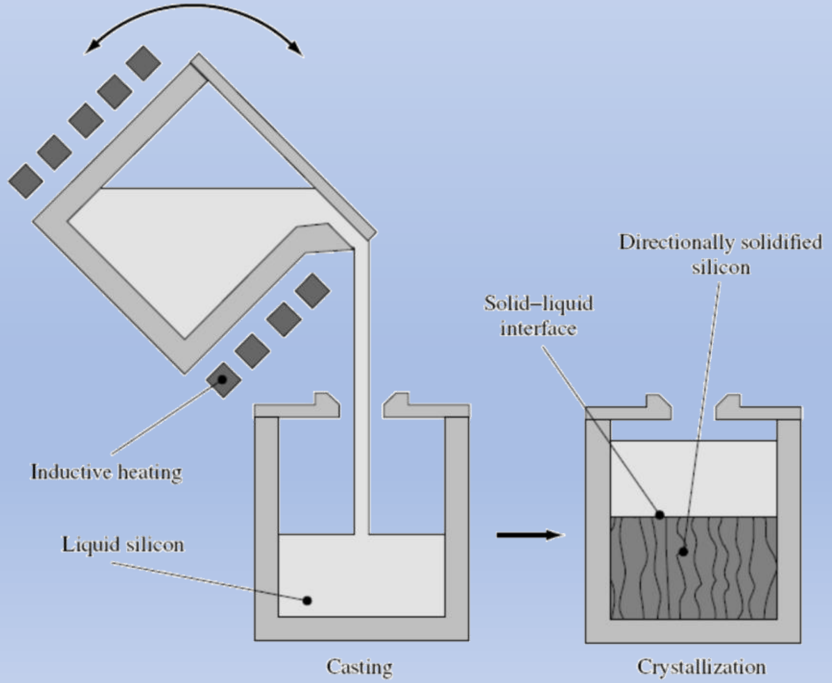


Crystalline Silicon solar cell technologies

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.

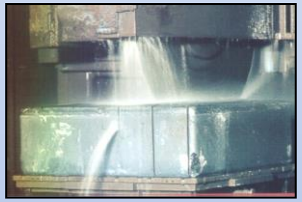


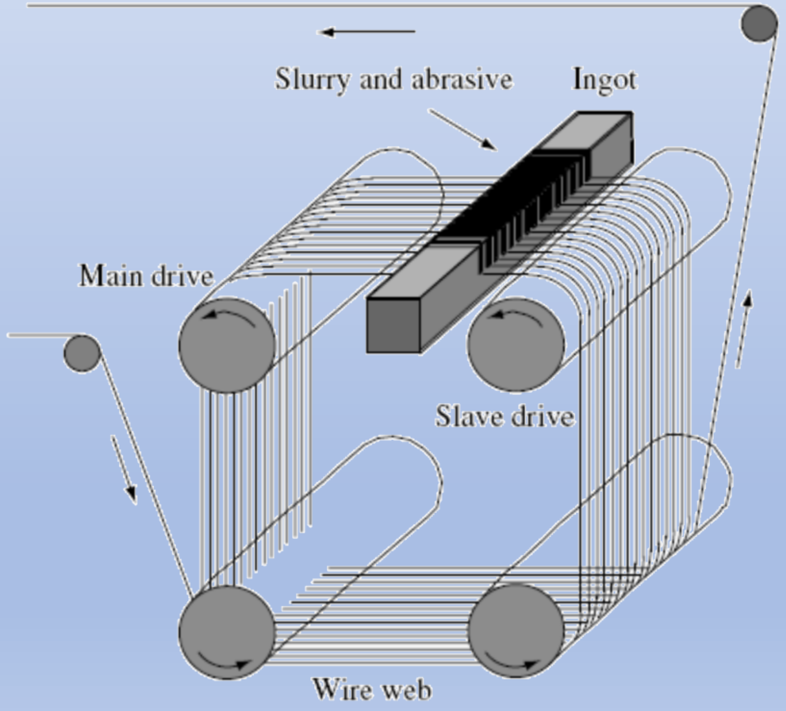
Typical casting:
240kg/56 hours

Crystalline Silicon solar cell technologies

Both mono and multicrystalline ingots require sawing

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

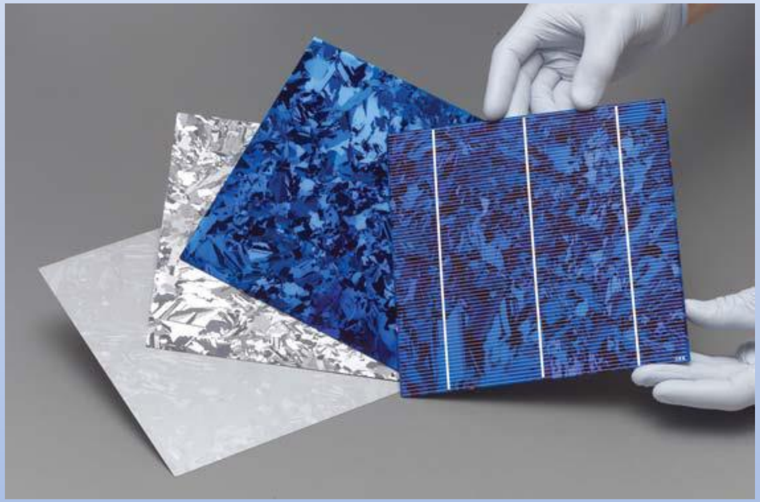


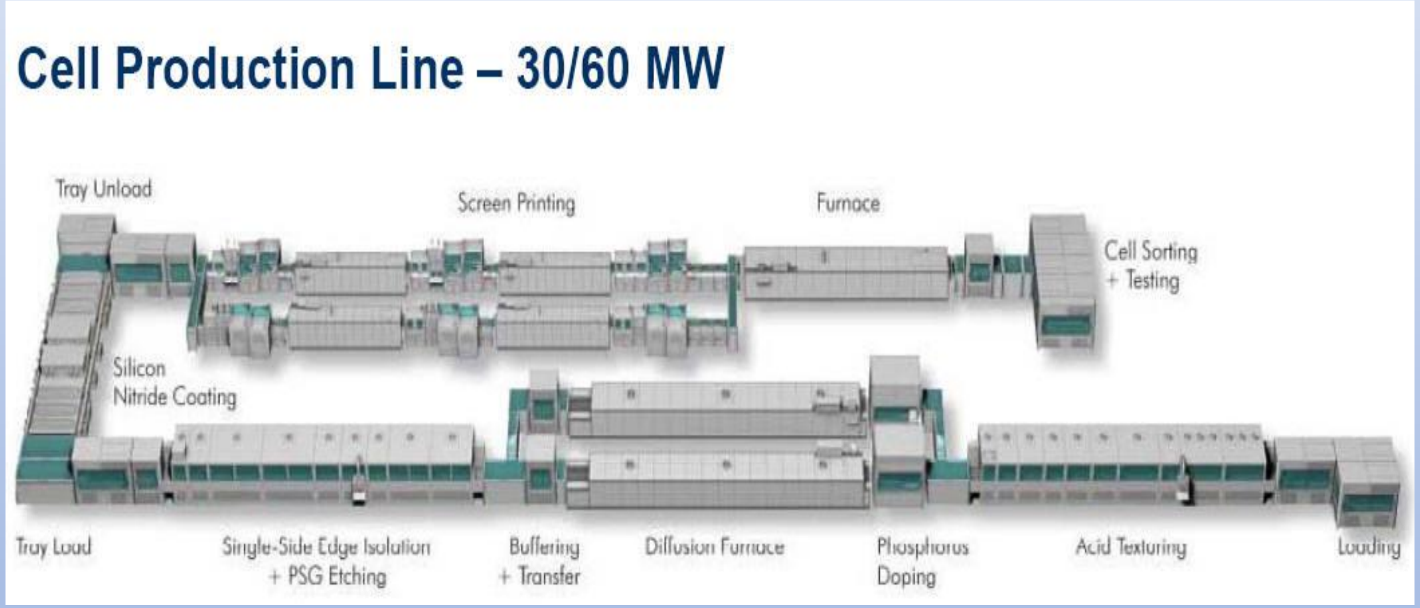


Alternatives: Diamond and laser sawing

Crystalline Silicon solar cell technologies: solar cell processing

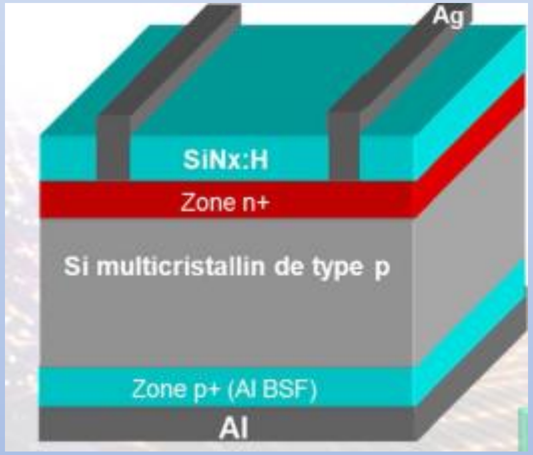
From the wafer to the solar cell:

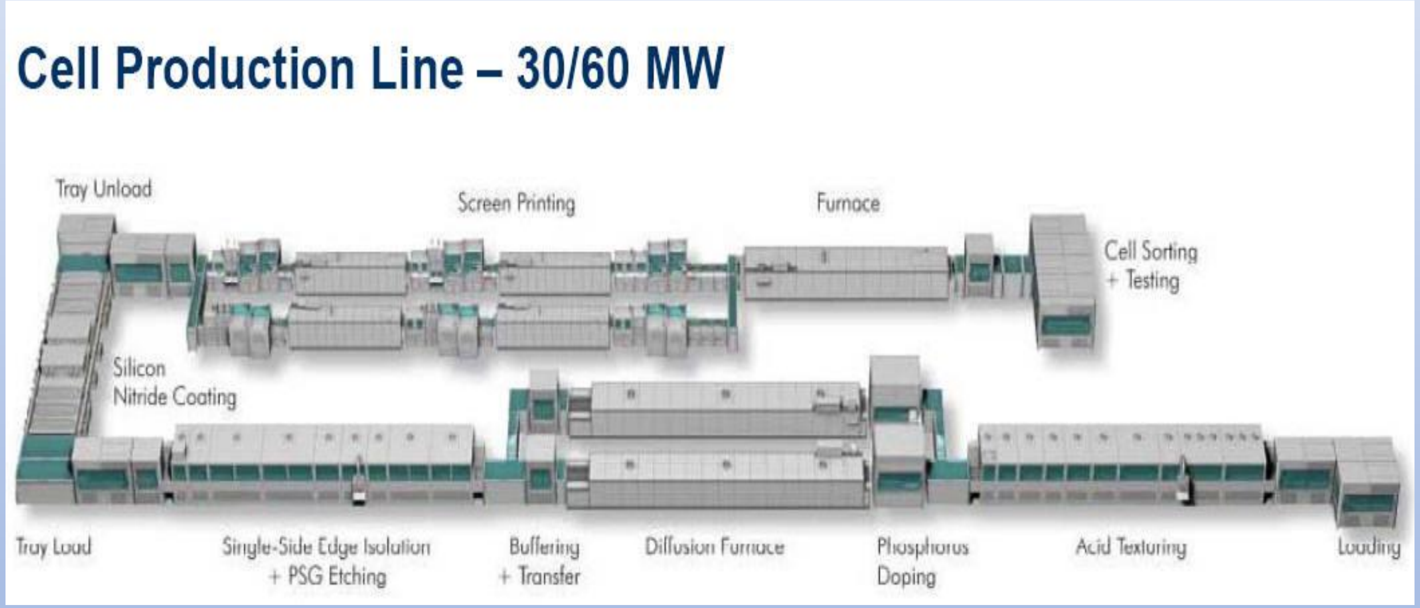




Crystalline Silicon solar cell technologies: solar cell processing

From the wafer to the solar cell:





Crystalline Silicon solar cell technologies: solar cell processing

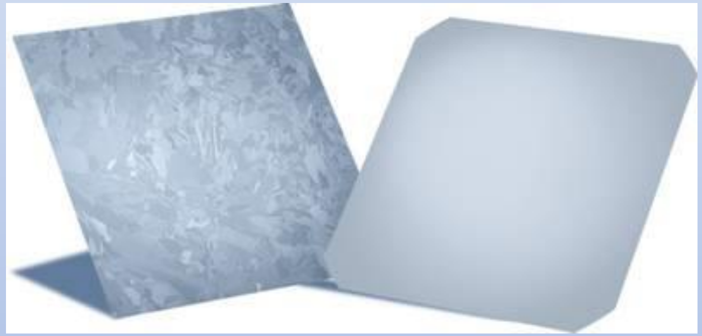
Al-BSF silicon solar cell (p-type silicon) manufacturing process

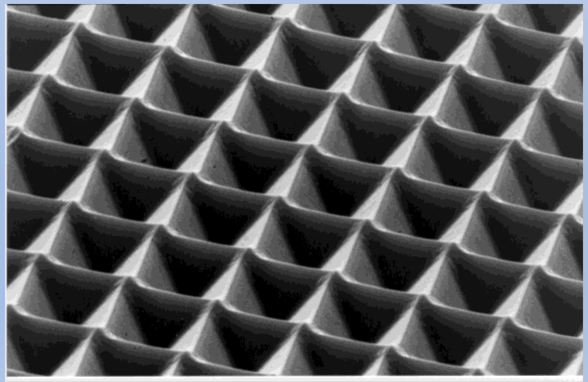
- Saw damage etch
- Texturization
- Phosphorous diffusion
- Edge isolation
- Anti reflective coating /Surface passivation
- Back contact print
- Firing
- Front contact print
- Firing
- Testing & sorting

Crystalline Silicon solar cell technologies: solar cell processing

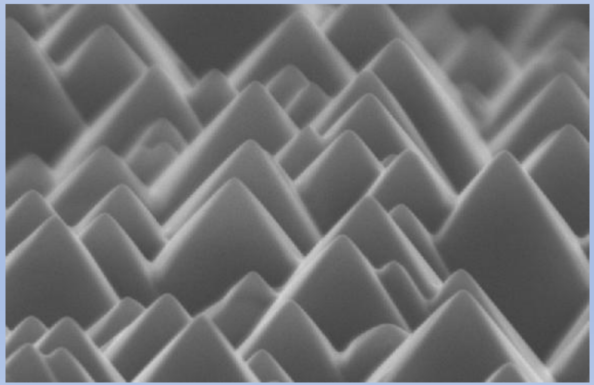
Surface Texturization:

- 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

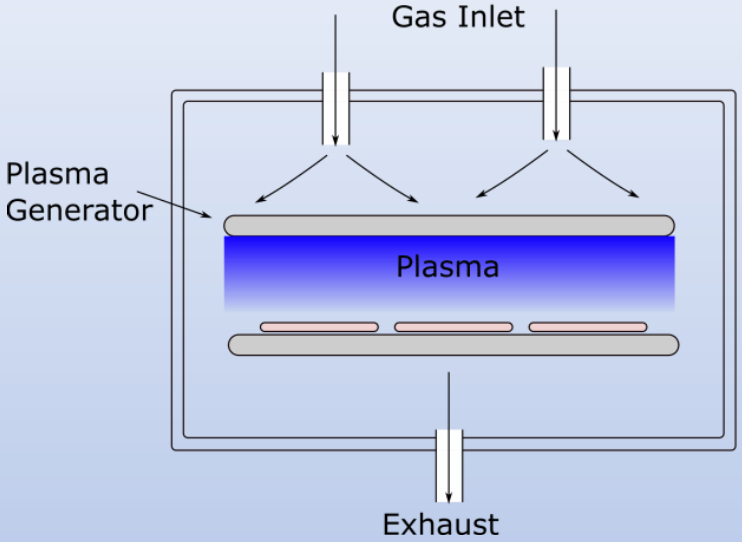
Phosphorous diffusion:

- 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

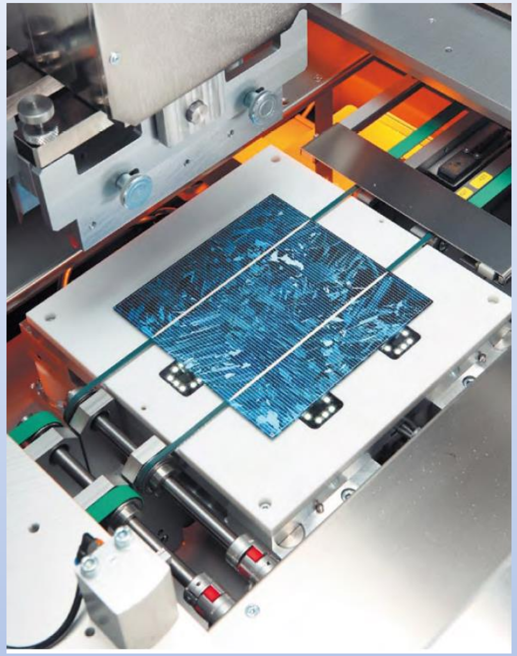
- SiN_x:H thin film is grown by PECVD (SiH_4+NH_3).
- It is performed in batch furnaces at 400°C.
- Films are 75 nm thick, and optical index, n≈2.2.
- Together with the texturization, antireflective SiN_x films reduce reflectivity to ~ 2.5%.
- SiN_x:H reduces carrier recombination in the surface and volume of the wafer it is thus said to provide **passivation.**

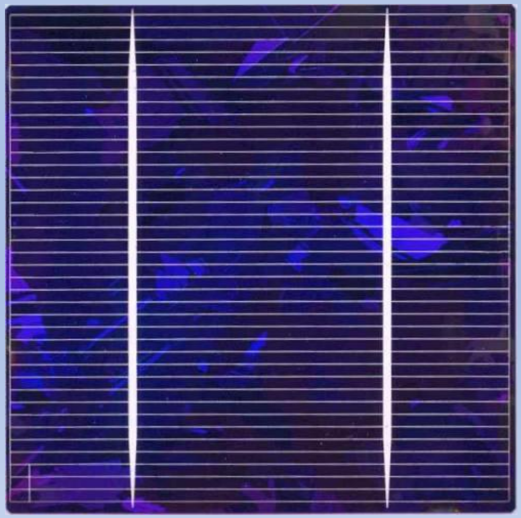


Crystalline Silicon solar cell technologies: solar cell processing

Screen-printing:

- The standard method to form the metallic contacts is imprinting metals 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.

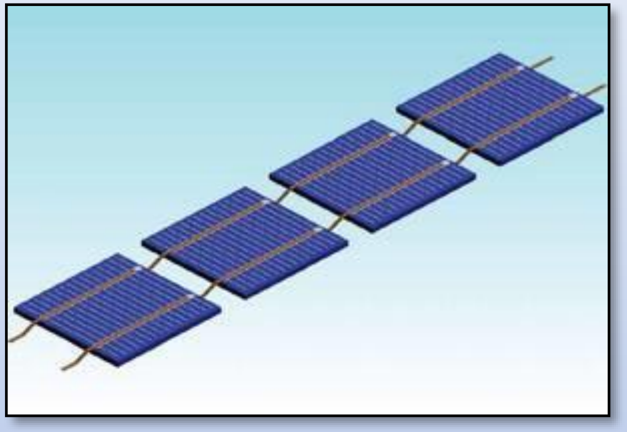


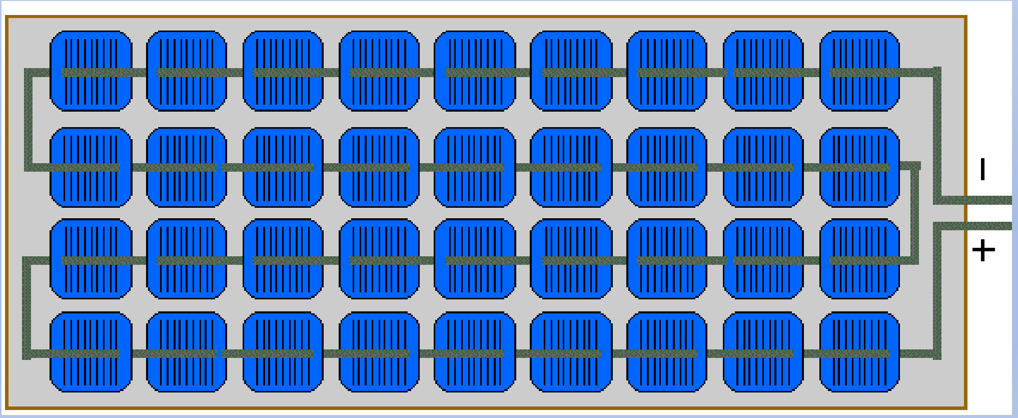


Crystalline Silicon solar cell technologies: module

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.

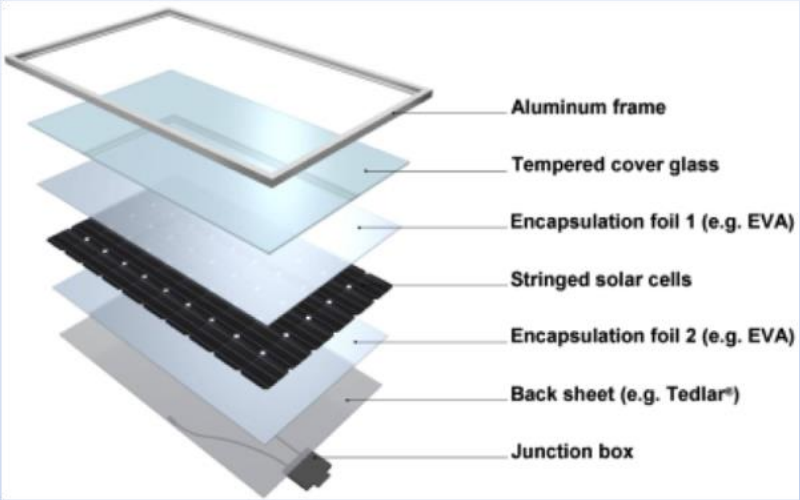




Crystalline Silicon solar cell technologies: module

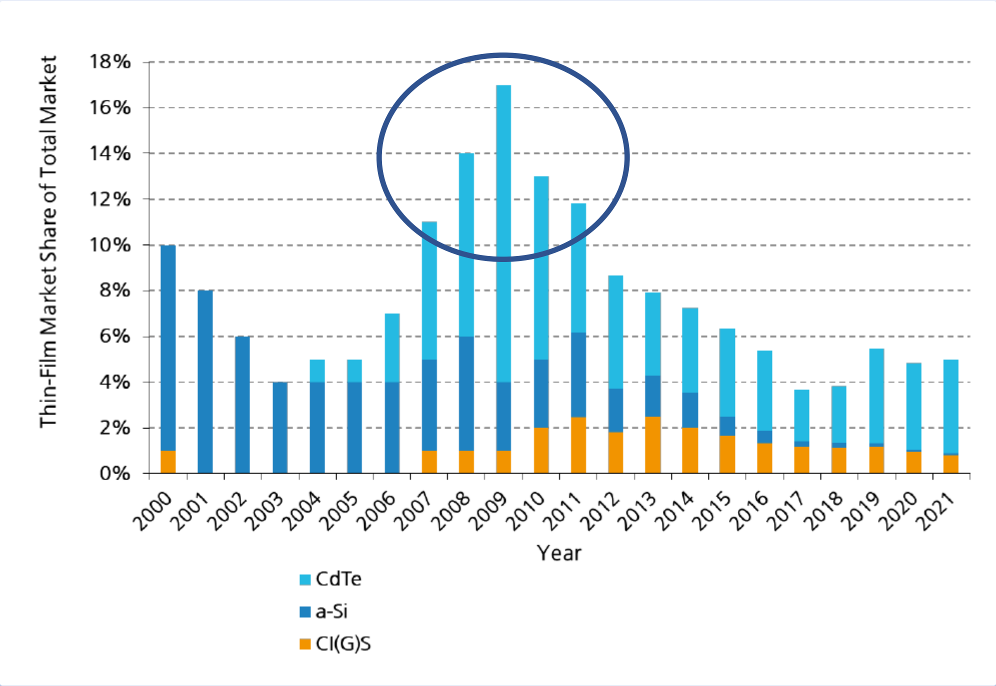
Module:

- 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.
- Its is not expect that this figures change significantly specially since the major thin film technologies are either based on the use of toxic materials (CdTe) or rare ones (CIGs – Indium).



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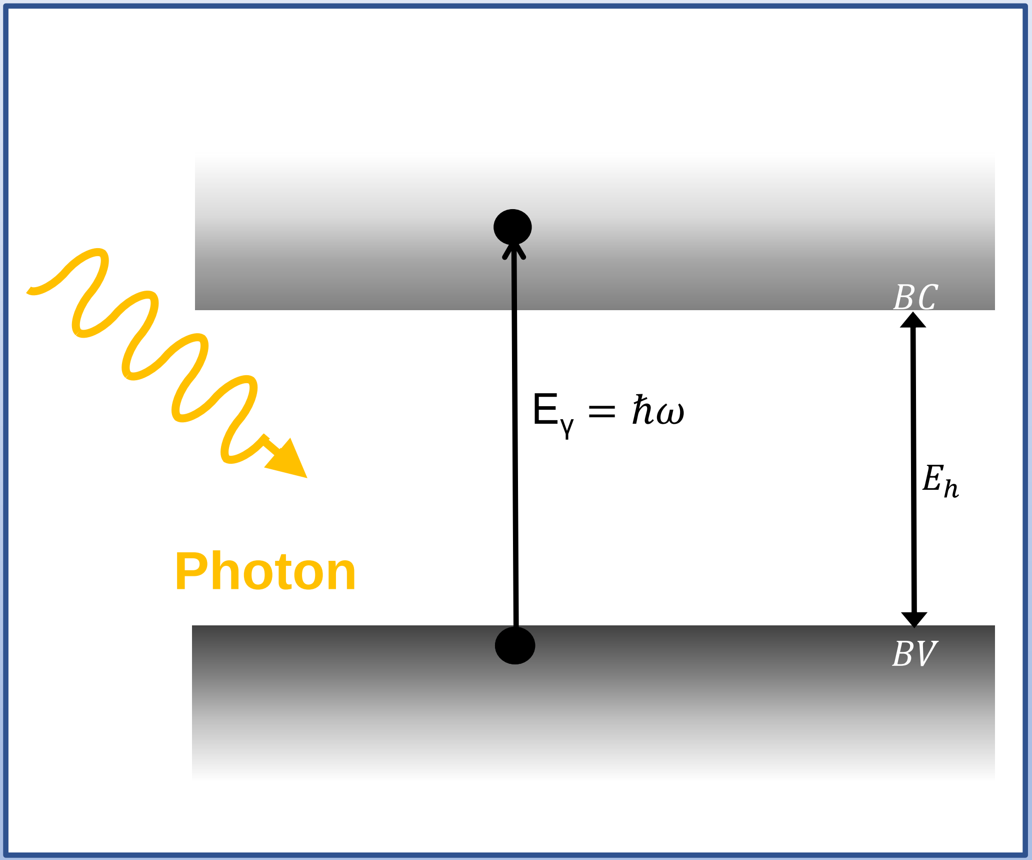
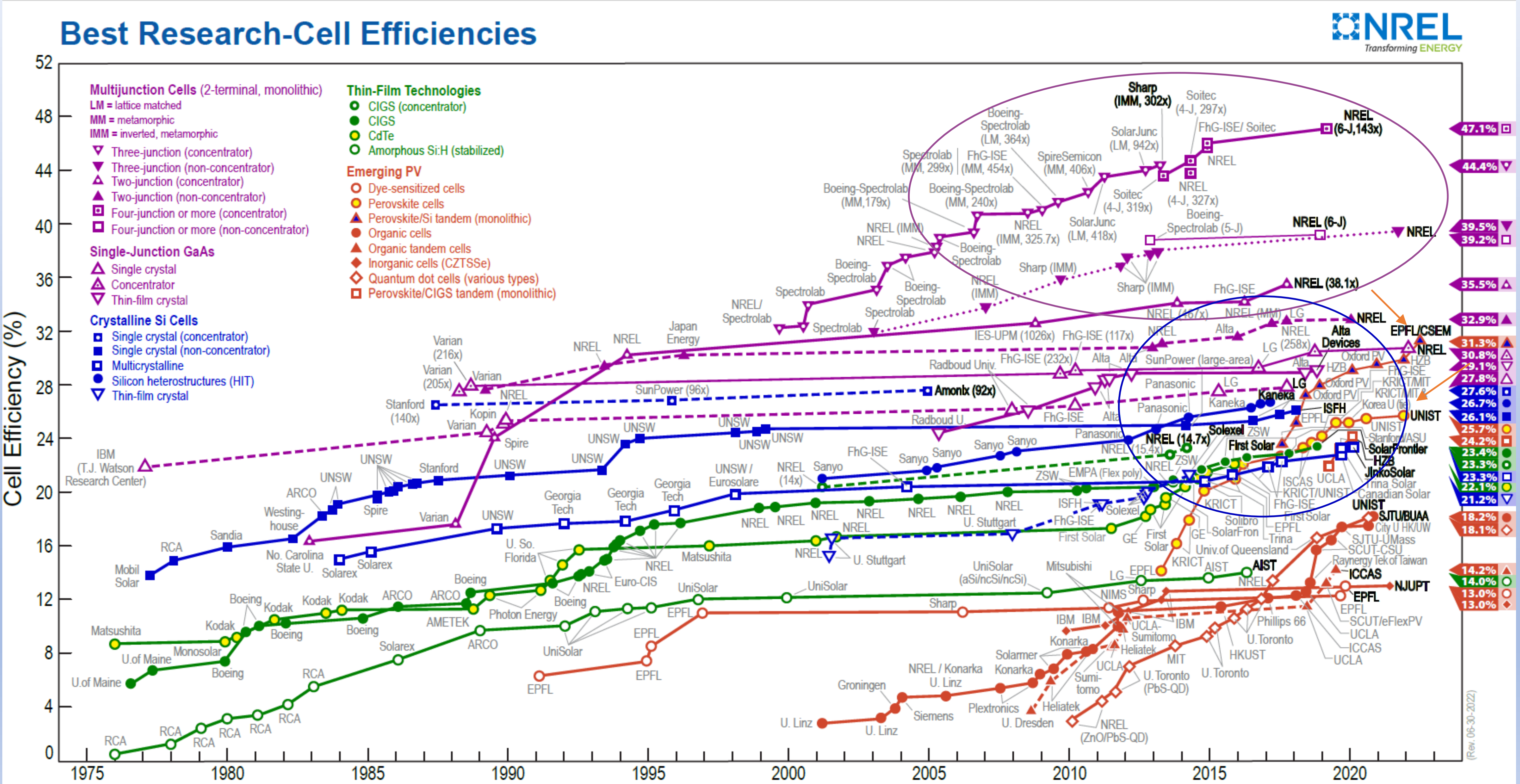
Limitations of crystalline silicon and monojunction solar cells

Efficiency limit

- Silicon solar cells are based on the absorption of photons ($E_\gamma > E_{gap}$) 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%.



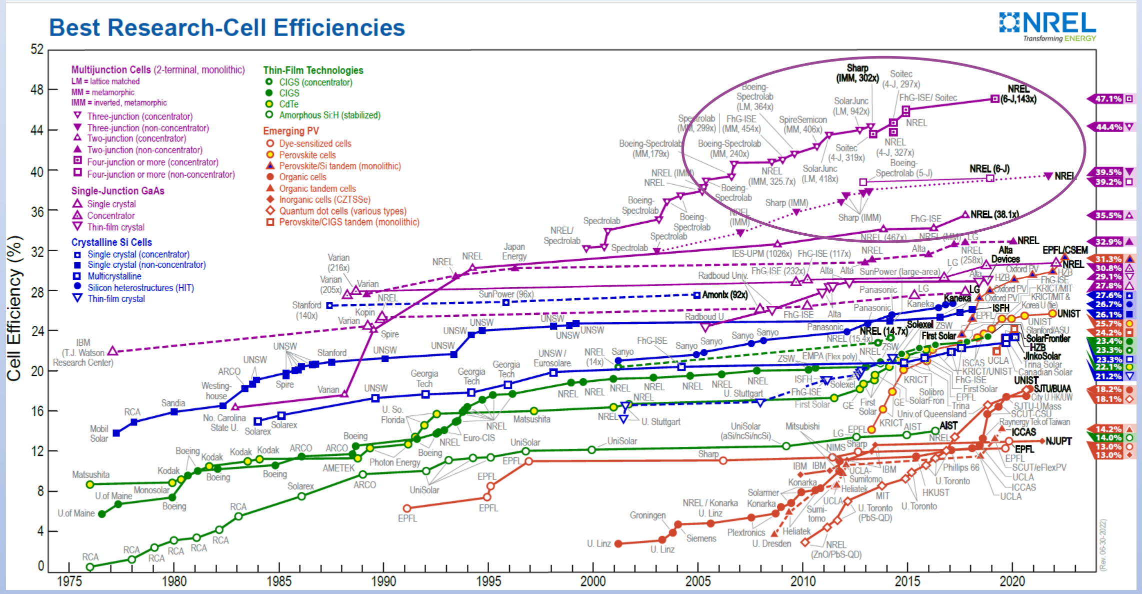
Future PV technologies



Future PV technologies

III- V groups tandem solar cells

- By far the technology the highest efficiencies: 39.5% for 1 sun, 47.1% with light concentration.
- Solar cells are formed by stacks of cells of different semiconductors, each specialized in the absorption of one part of the spectrum – avoid the Shockley-Queisser limit for monojunctions.

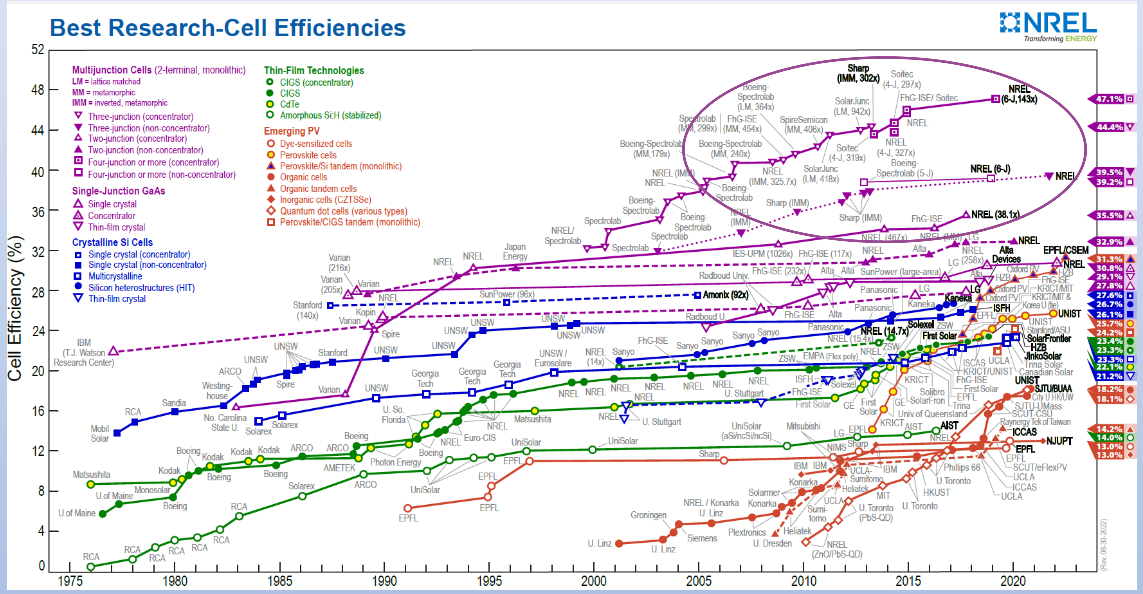


Future PV technologies

III- V groups tandem solar cells

- But the technology is too expensive (× 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.

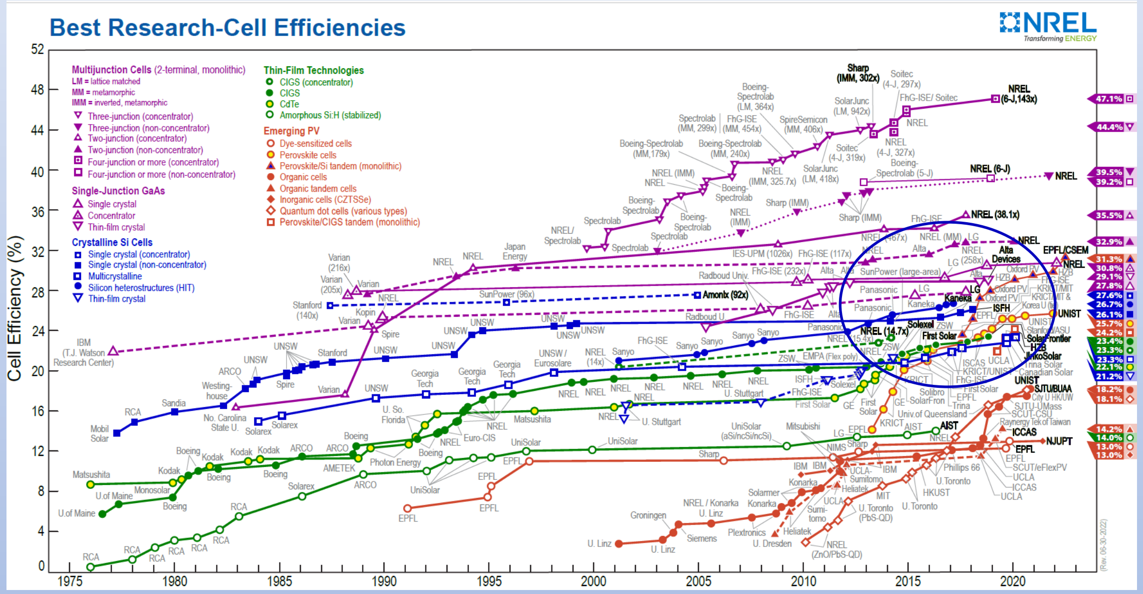
→ Profit from the maturity and low cost of c-Si and the high-efficiency potential of tandem solar cells.



Future PV technologies

Crystalline silicon related technologies

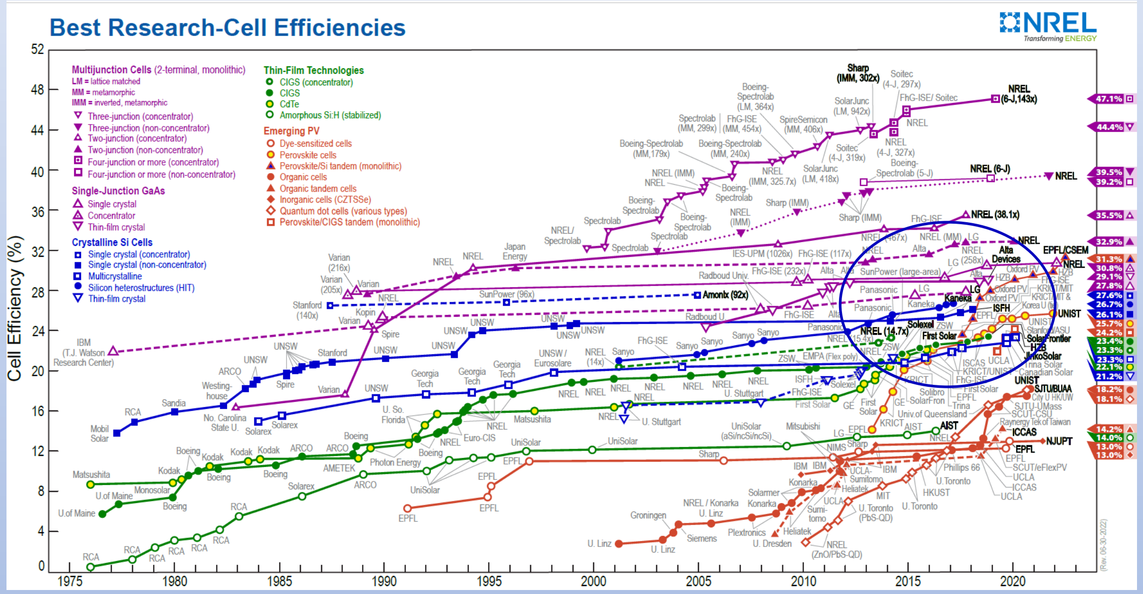
- C-Si will still dominate the market in the next decade and maintains a very dynamic research activity with a lot of high-efficiency concepts being proposed.
- The record efficiency for c-Si is 26.1% but for the heterojunction concept (c-Si/a-Si) is 26.7%.
- Most record efficiencies were obtained with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



Future PV technologies

Main market trends

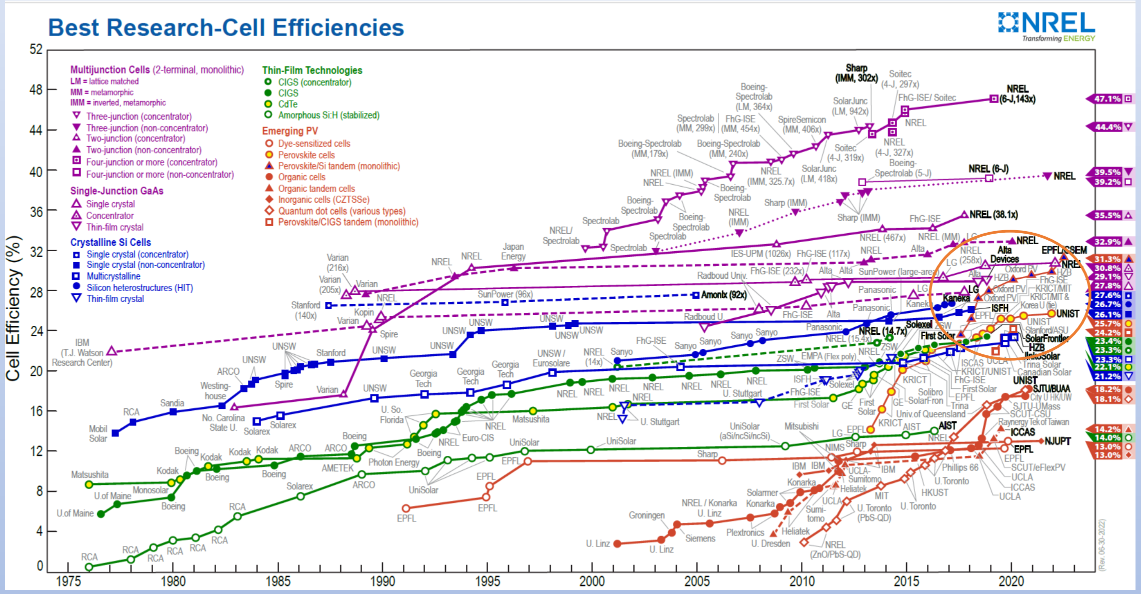
- The standard Al-BSF is being replaced by more efficient concepts as PERL, PERC, HIT, TOPCon, etc.
- N-type silicon is gaining market share to the traditional dominant p-type.
- Solar cells sizes are increasing very significantly: 156 mm^2→ 210 mm^2, and thickness is being reduced 180 µm → 130 µm
-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



Future PV technologies

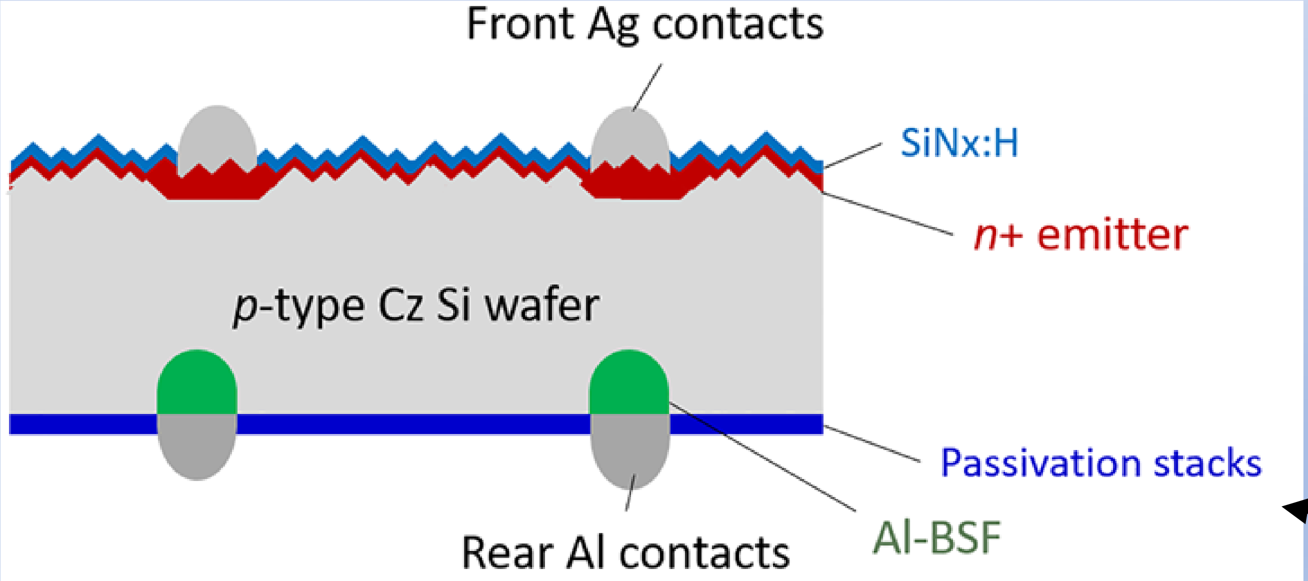
Perovskite technologies

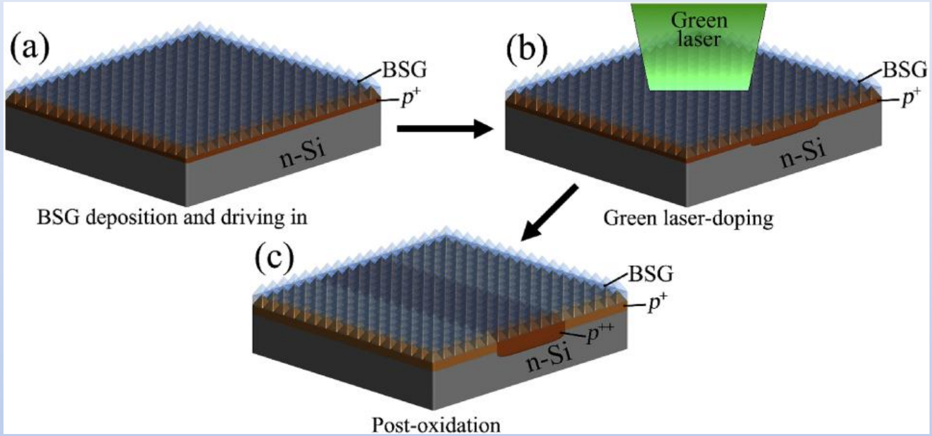
- Emerging low-cost technology with an impressive efficiency progression (13%→25.7% in 9 years).
- Tandem cells c-Si/Perovskite already reached an efficiency of 31.3%.
- However, the stability of the perovskite solar cells efficiencies for more than a few months has not been demonstrated.
- Perovskite has a great potential for short-term PV applications such as powering IoT appliances.



Future PV technologies

PERC solar cell - Bifacial





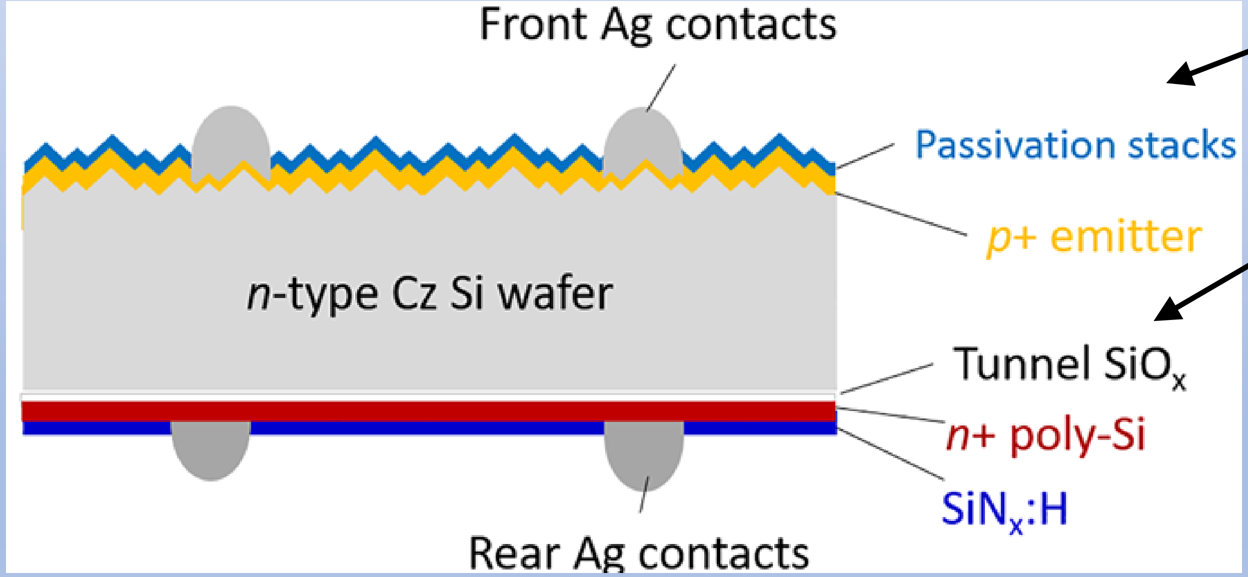
Localised doping → laser doping

SiO_x/SiN_x

Future PV technologies

TOPCon - Bifacial

Record efficiency: 26.1%

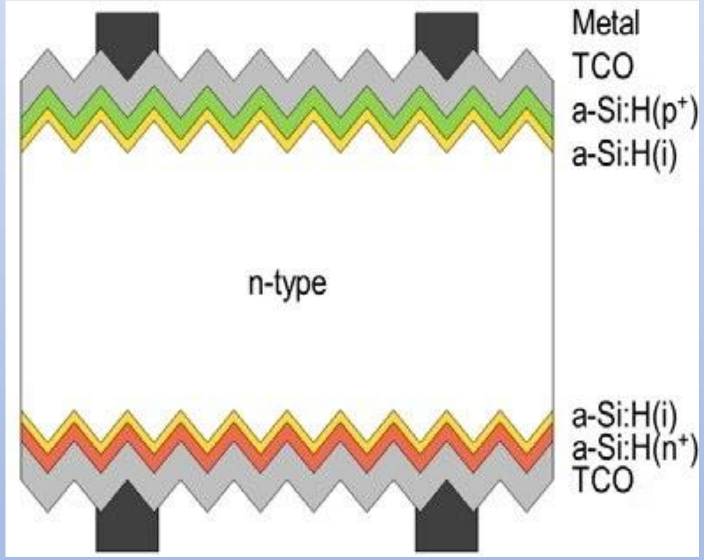


SiO_x/SiN_x

SiO_x thickness ~ 5 nm

Future PV technologies

HIT - Bifacial



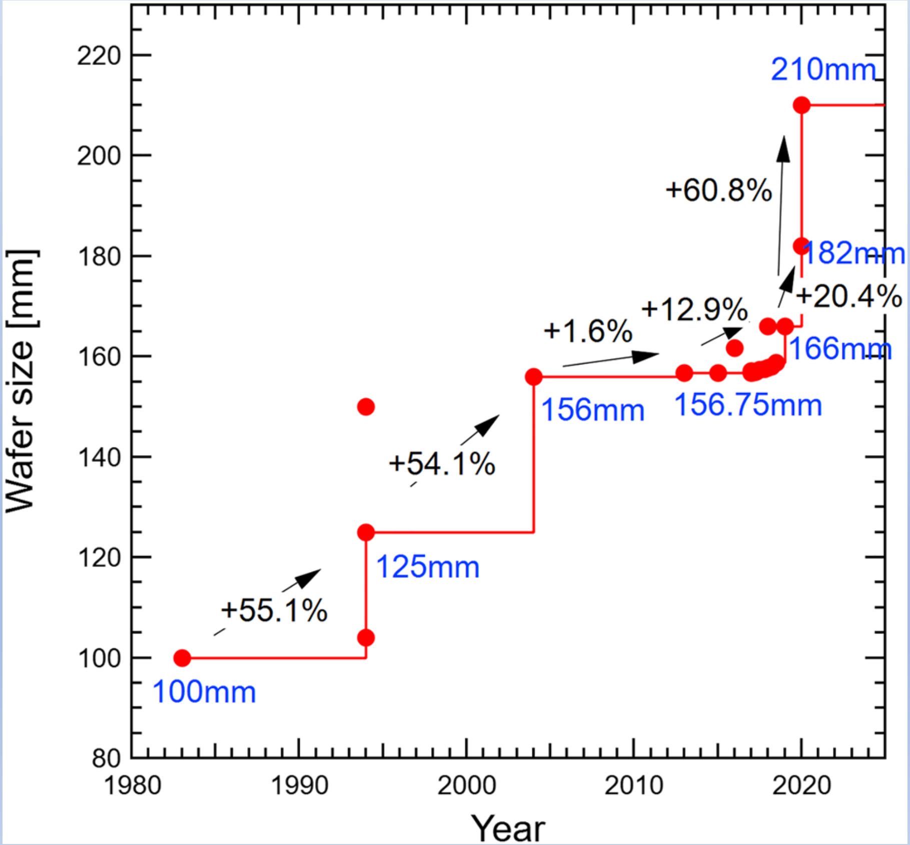
Substrate c-Si
Emitter and BSF are PECVD grown a-Si

→ Low temperature processing
→ Potencial low cost

Record efficiency: 26.7%

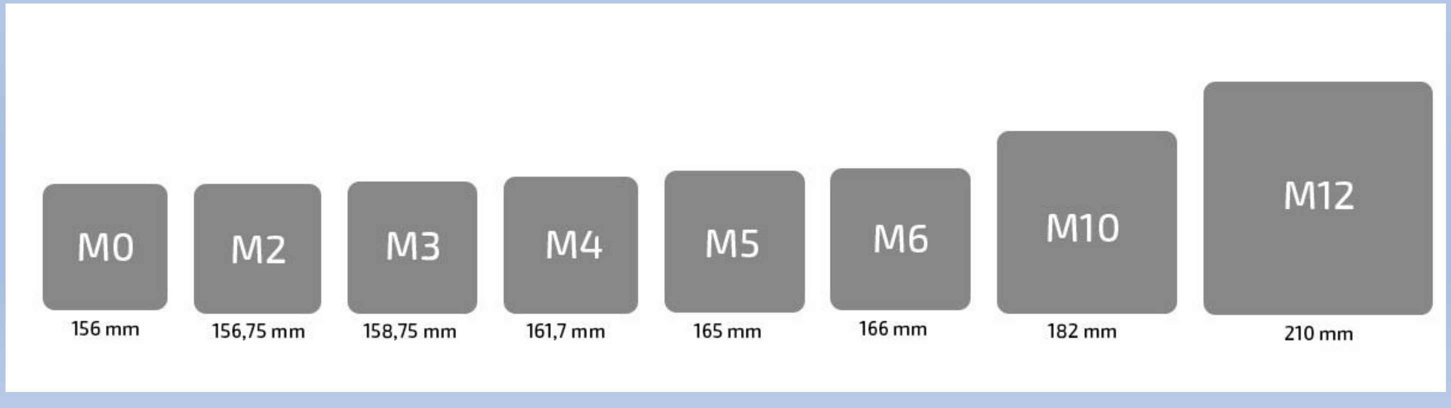
Future PV technologies

Cell dimensions evolution



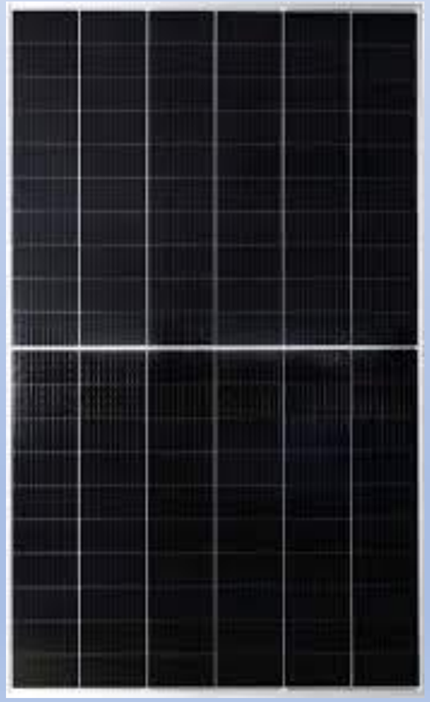
Main trends are:

- Thichness reduction
- Area increase



Future PV technologies

Half-cut cells module



- Solar cells are cut in half with a laser
- Current is halved → Resistive losses reduced
- PV panel has twice the number of cells and it is itself divided in two, that work separately
- Better performance under partial shading
- PV module voltage has twice the voltage