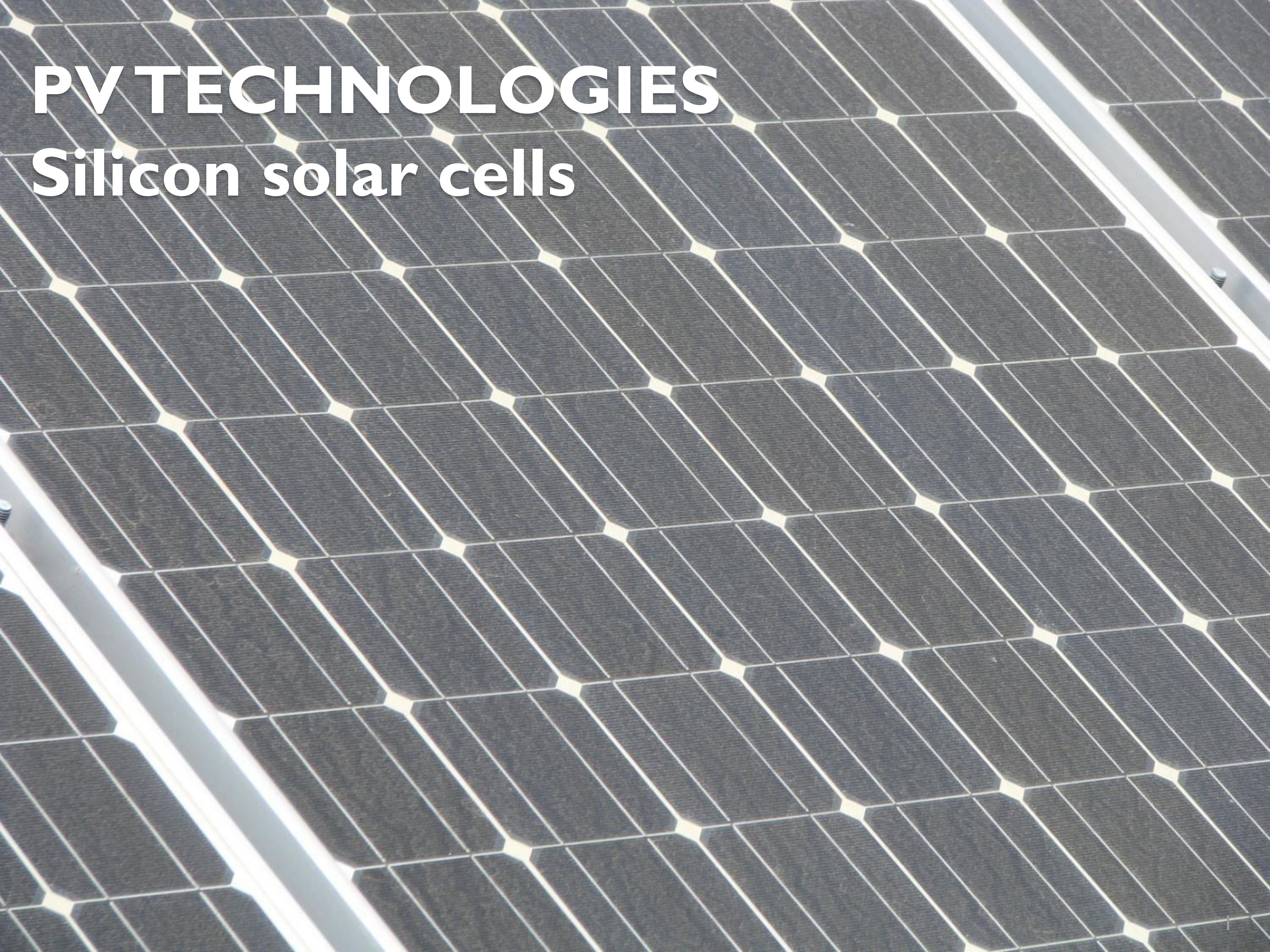
PV TECHNOLOGIES
Silicon solar cells

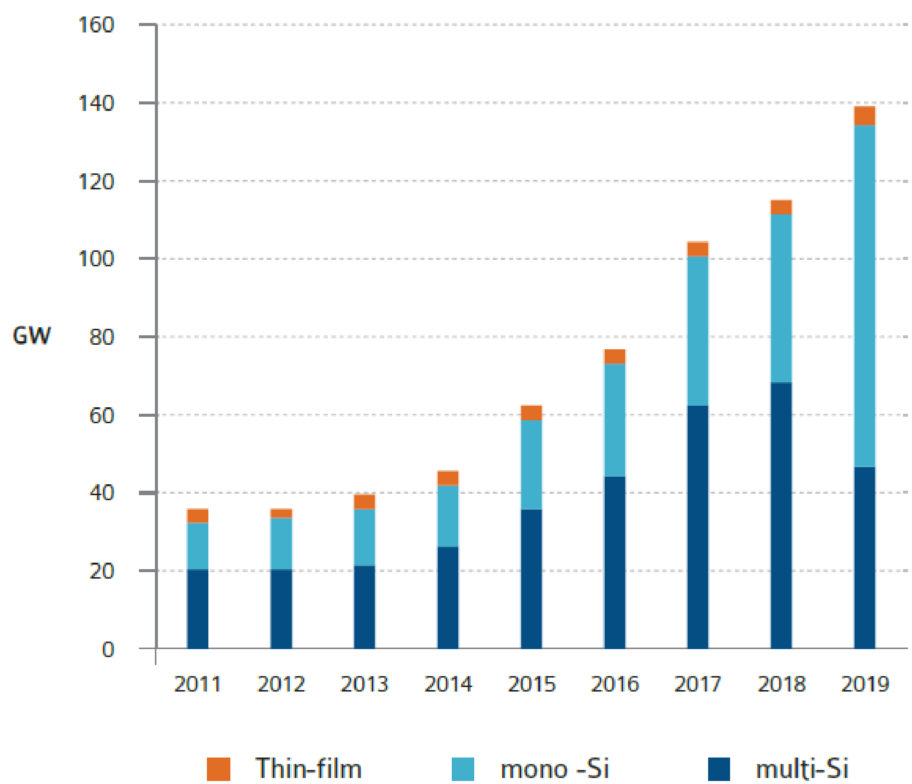


PV TECHNOLOGIES

- Is there a c-Si technology?
- Feedstock
- Wafer
- Cells
- Module
- Other silicon concepts
- Materials availability

PV TECHNOLOGIES
Silicon solar cells

FIGURE 4.6: PV MODULE PRODUCTION PER TECHNOLOGY IN 2019

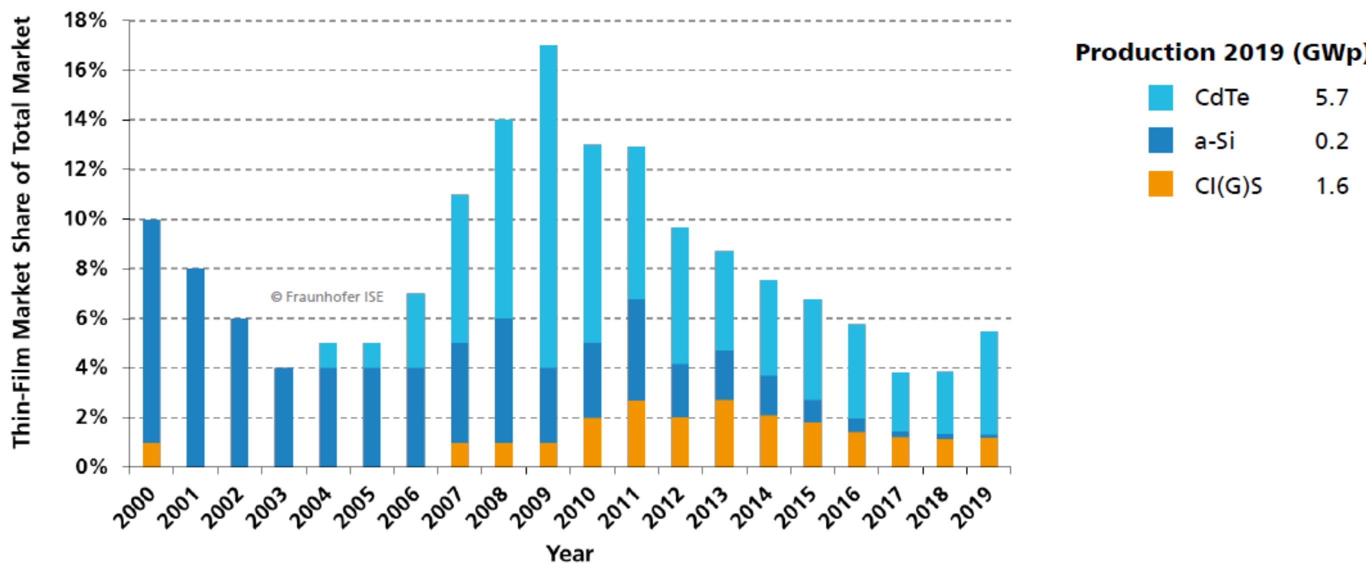


Silicon is the dominant technology

High efficiency is gaining market share

PV TECHNOLOGIES
Silicon solar cells

Market Share of Thin-Film Technologies
Percentage of Total Global PV Production

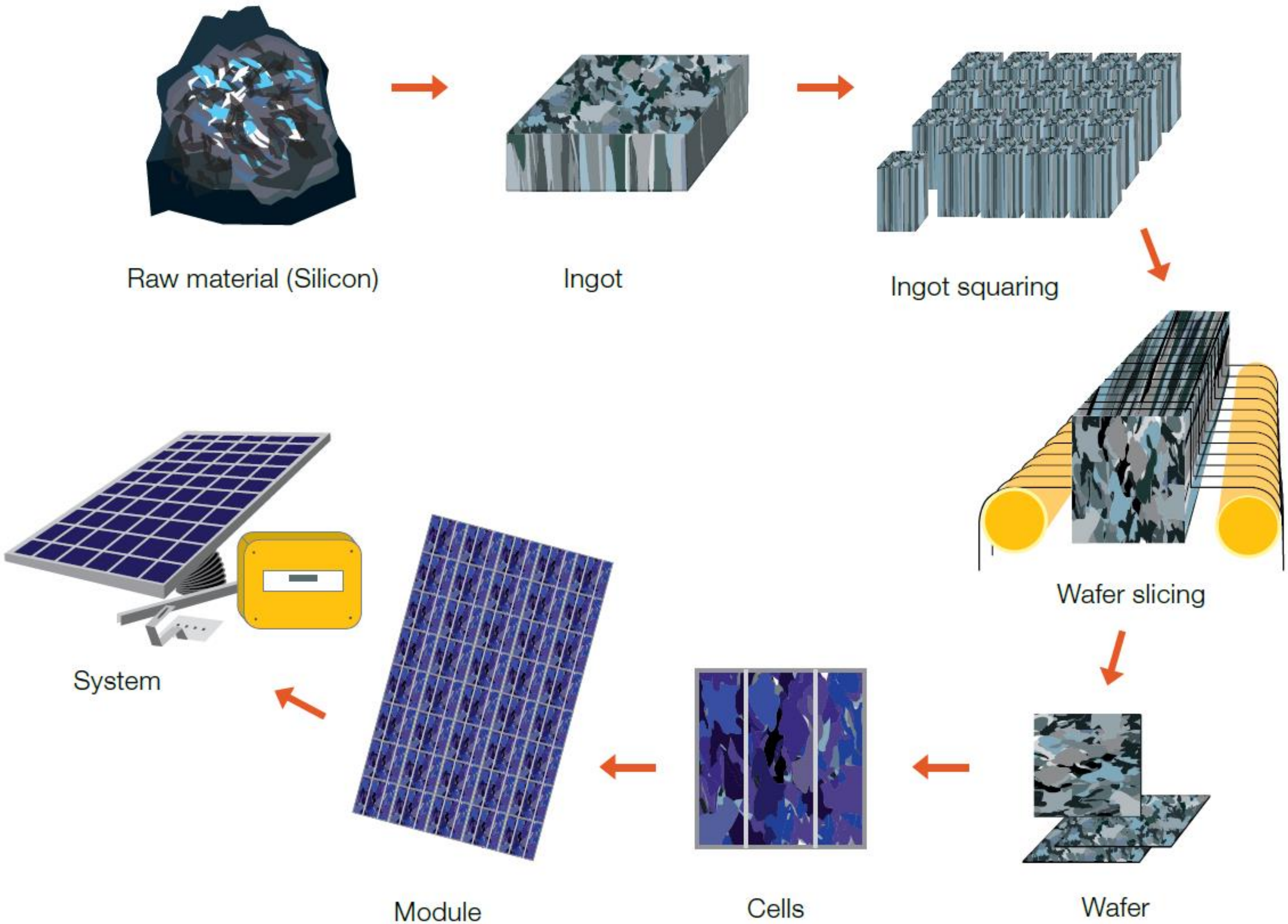


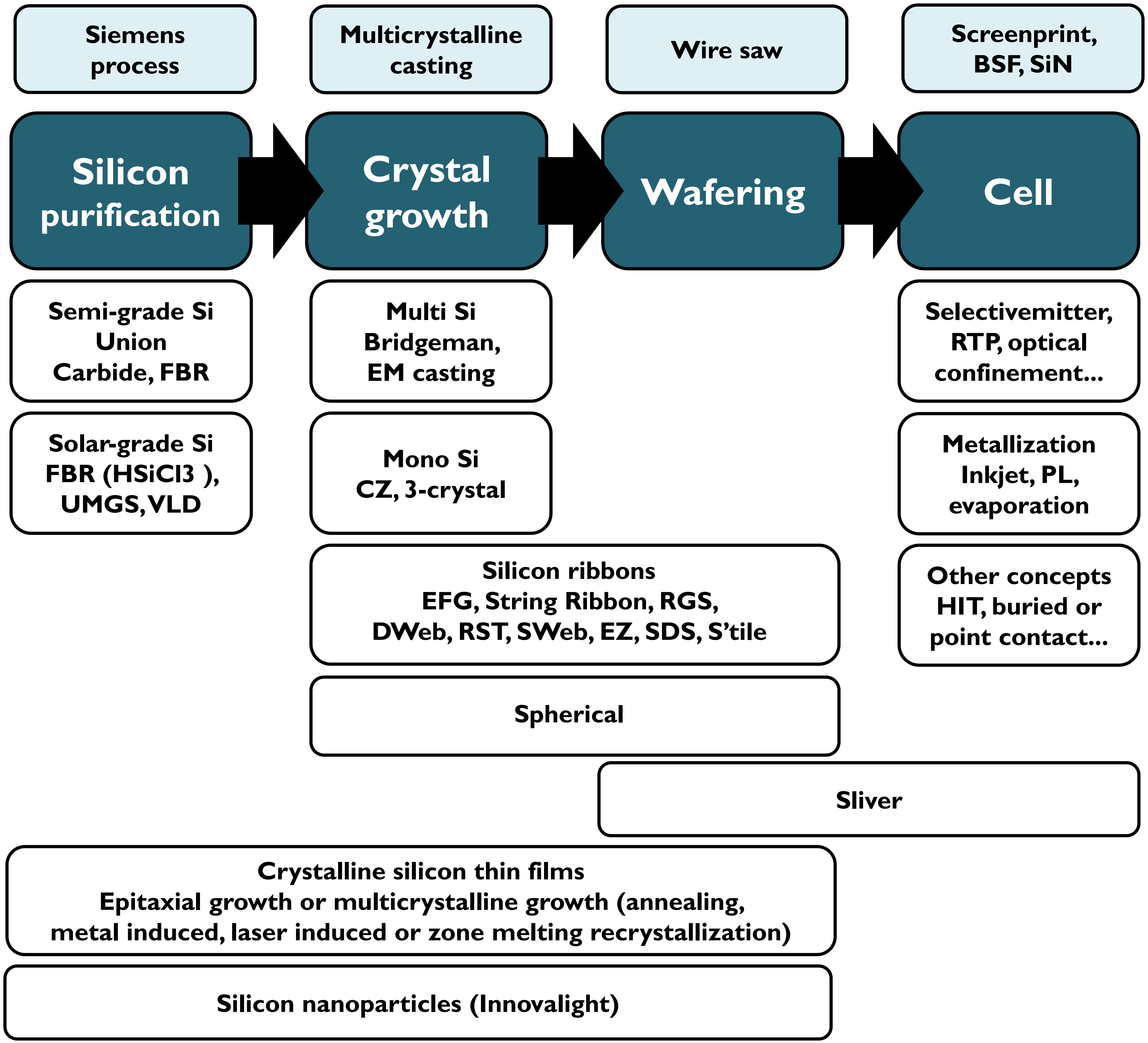
Data: from 2000 to 2009: Navigant; from 2010: IHS Markit. Graph: PSE Projects GmbH 2020

Thin films were popular when polysilicon was expensive

Amorphous silicon is disappearing

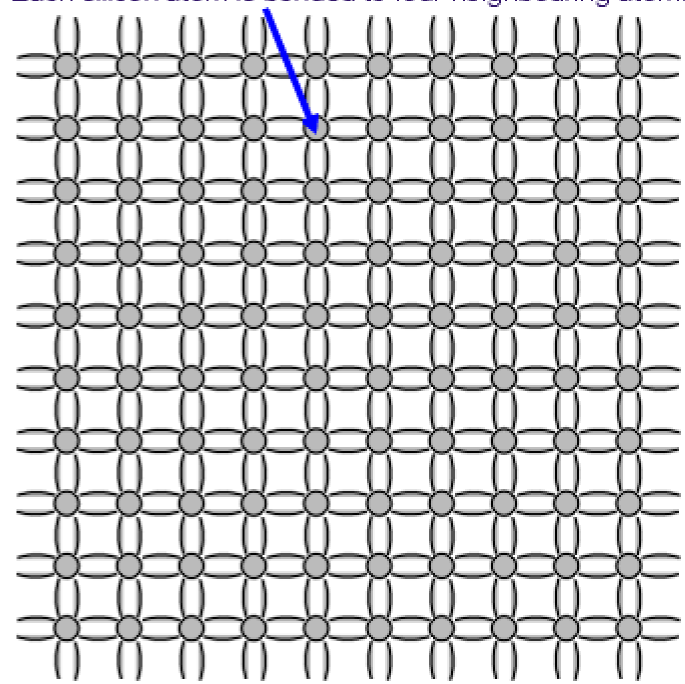
PV TECHNOLOGIES
Silicon solar cells




Siemens process
Multicrystalline casting
Wire saw
Screenprint, BSF, SiN
Silicon purification
Crystal growth
Wafering
Cell
Semi-grade Si Union Carbide, FBR
Multi Si Bridgeman, EM casting
Selectivemitter, RTP, optical confinement...
Solar-grade Si FBR (HSiCl3), UMGS, VLD
Mono Si CZ, 3-crystal
Metallization Inkjet, PL, evaporation
Silicon ribbons EFG, String Ribbon, RGS, DWeb, RST, SWeb, EZ, SDS, S'tile
Other concepts HIT, buried or point contact...
Spherical
Sliver
Crystalline silicon thin films Epitaxial growth or multicrystalline growth (annealing, metal induced, laser induced or zone melting recrystallization)
Silicon nanoparticles (Innovalight)

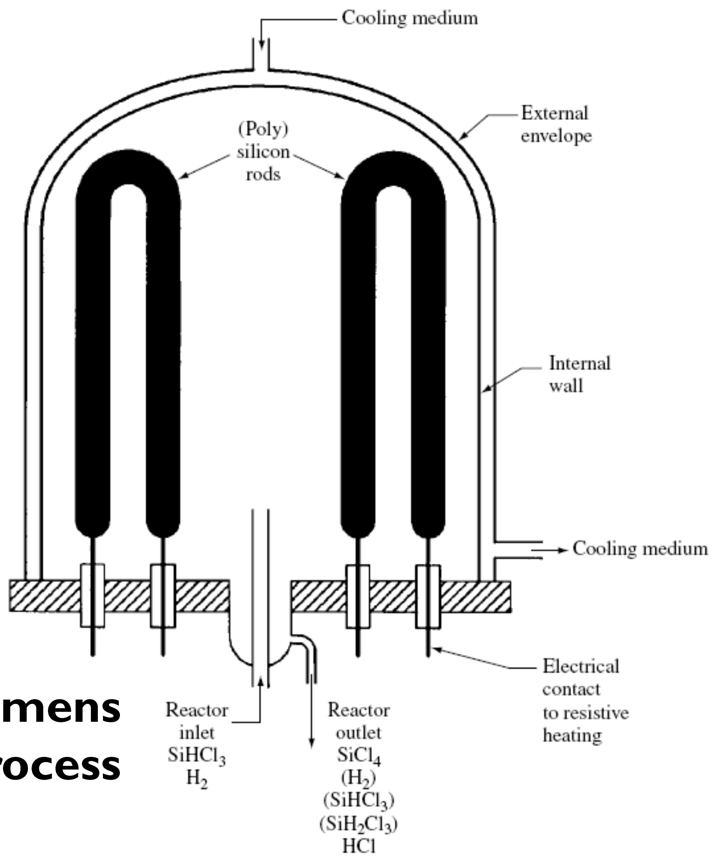
PV TECHNOLOGIES
Silicon solar cells

Silicon is the second most abundant element on Earth after oxygen (28% of the Earth's crust). Its most familiar forms are sand and quartzite (the latter one is more pure).



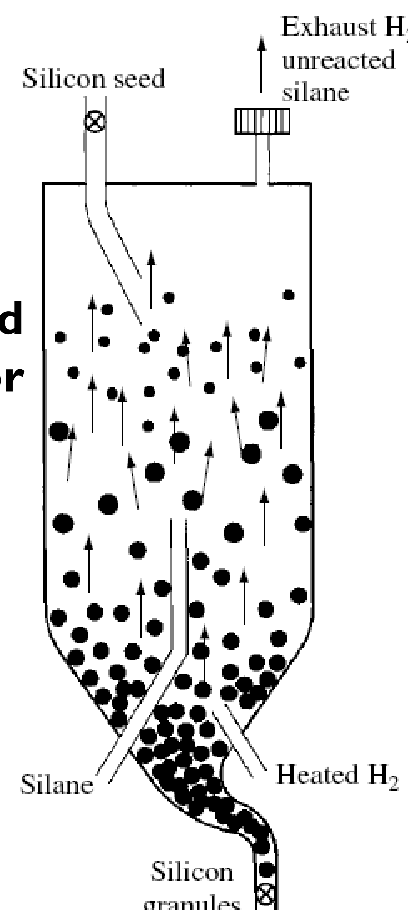
PV TECHNOLOGIES
Silicon solar cells

Feedstock: obtaining hyperpure silicon from gas phase



Siemens process

Fluidized bed reactor



PV TECHNOLOGIES
Silicon solar cells

Feedstock: obtaining hyperpure silicon from gas phase

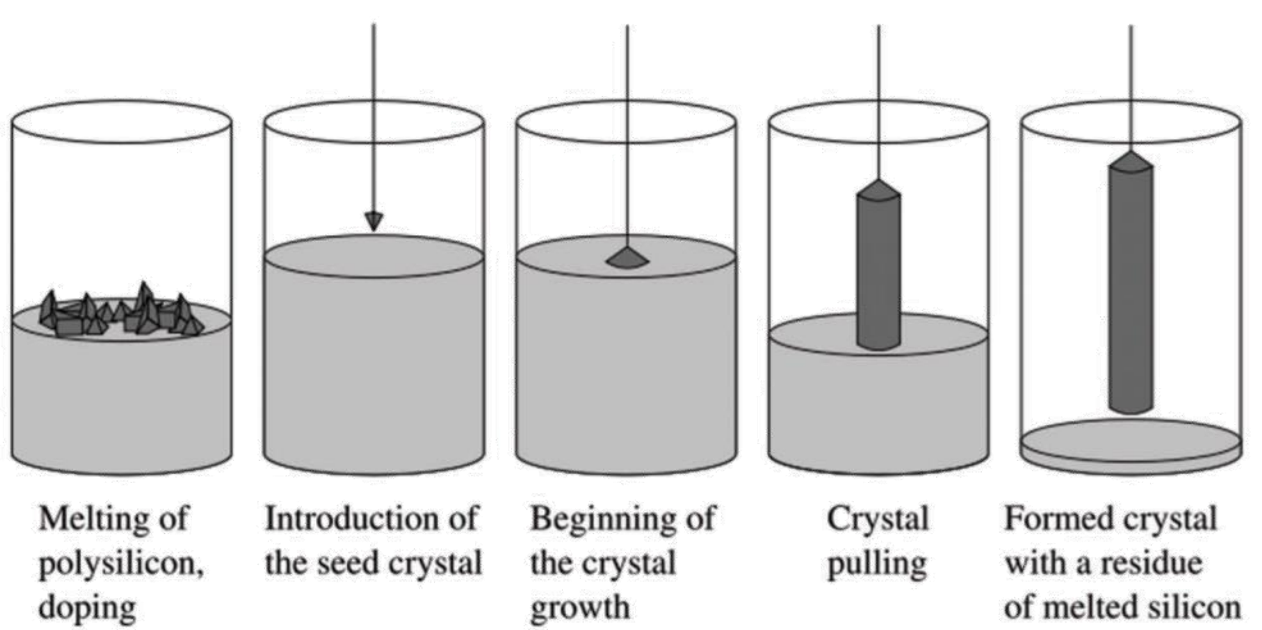
PV TECHNOLOGIES
Silicon solar cells

Crystalline silicon may be used in PV in different forms:

Descriptor	Symbol	Grain Size	Common Growth Techniques
Single crystal	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

PV TECHNOLOGIES
Silicon solar cells

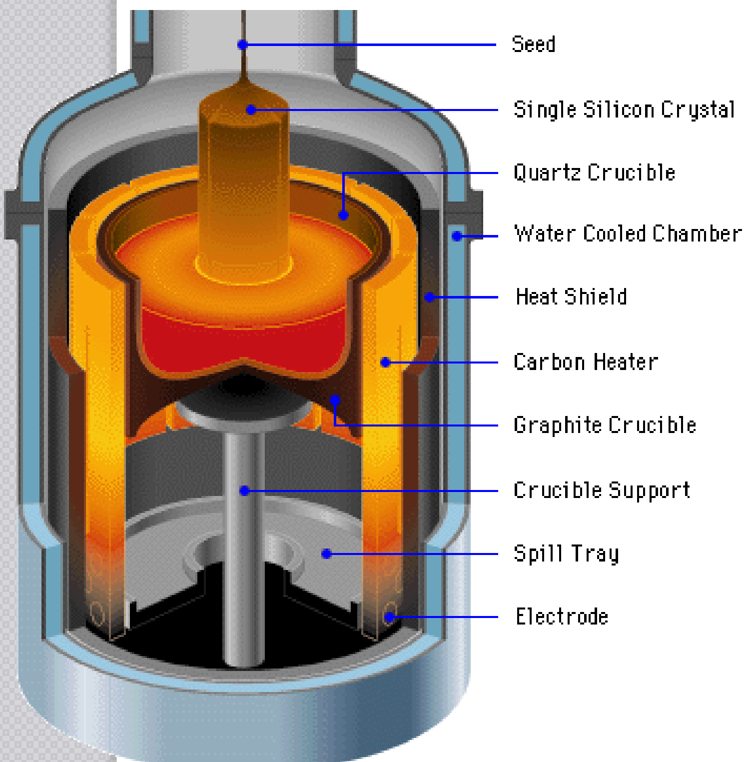
Czochralski silicon is the standard for electronics industry. High quality (mono) with contamination with oxygen and carbon into the melt.



PV TECHNOLOGIES
Silicon solar cells

Czochralski silicon

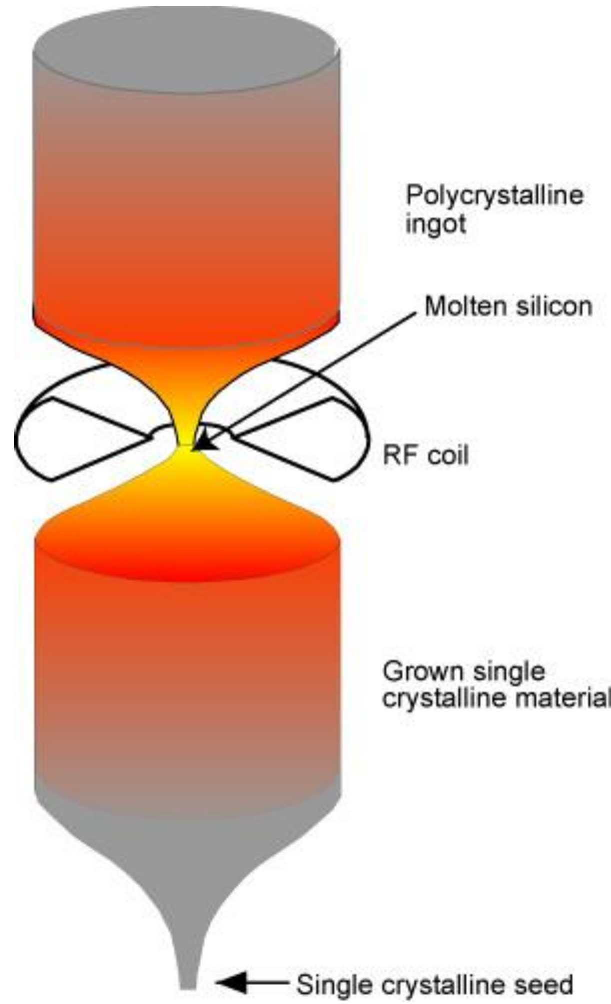
Growth rate: 5cm/hour



PV TECHNOLOGIES
Silicon solar cells

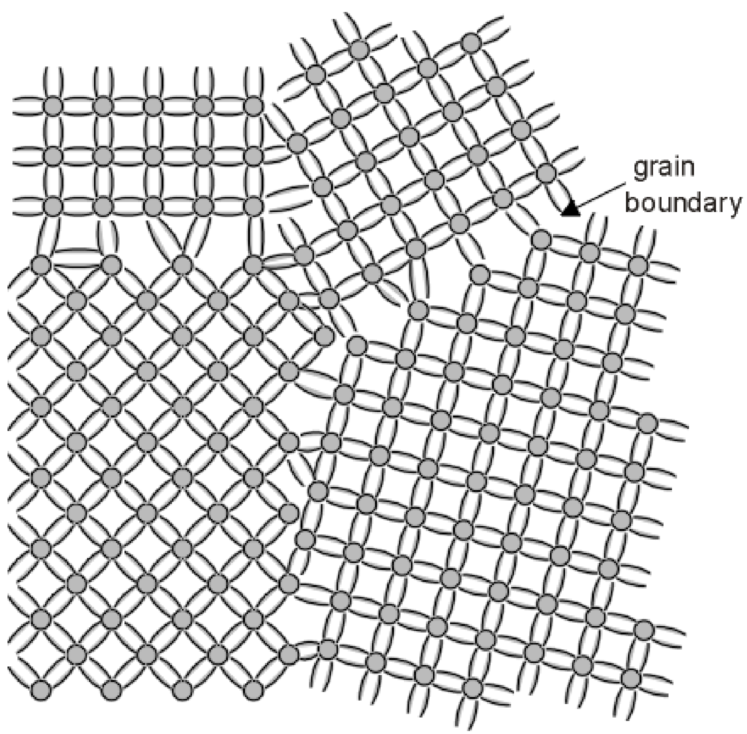
Float zone silicon is the best quality silicon

No contamination but very expensive. Only for very demanding applications.



PV TECHNOLOGIES
Silicon solar cells

Multicrystalline silicon offers acceptable quality but at lower cost



PV TECHNOLOGIES
Silicon solar cells

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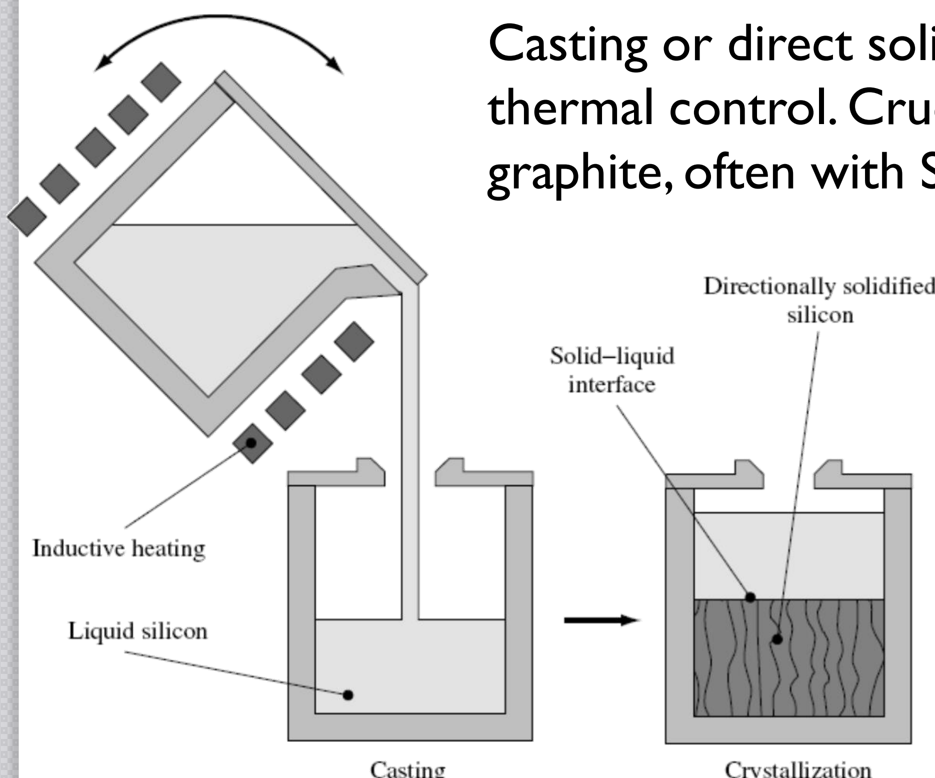


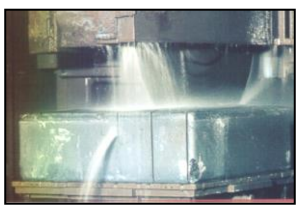
Casting or direct solidification, requires careful thermal control. Crucible usually made of quartz or graphite, often with Si_3N_4 coating.

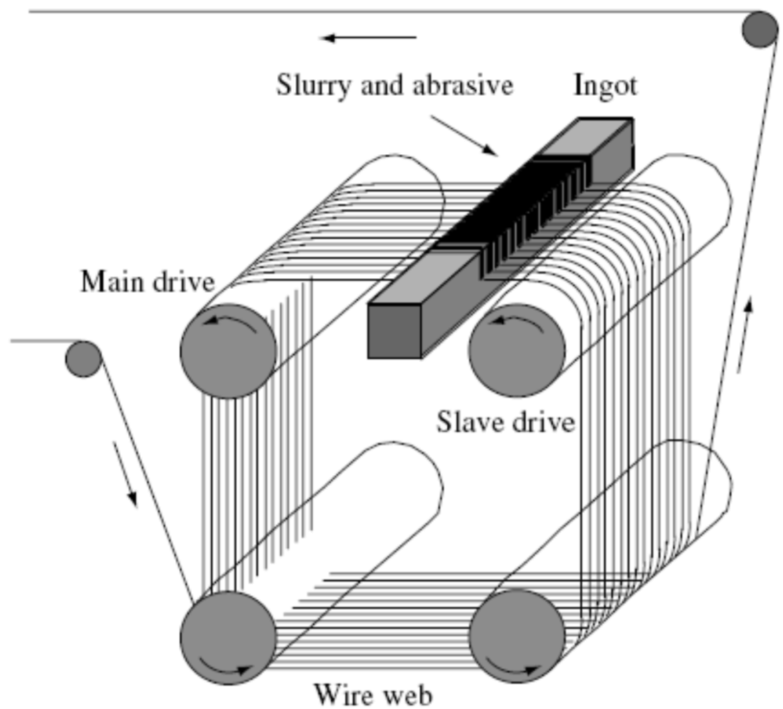
Typical casting:
240kg/56 hours

PV TECHNOLOGIES
Silicon solar cells

Multicrystalline ingots require sawing.

Kerf loss and saw damage removal is significant (and costly).

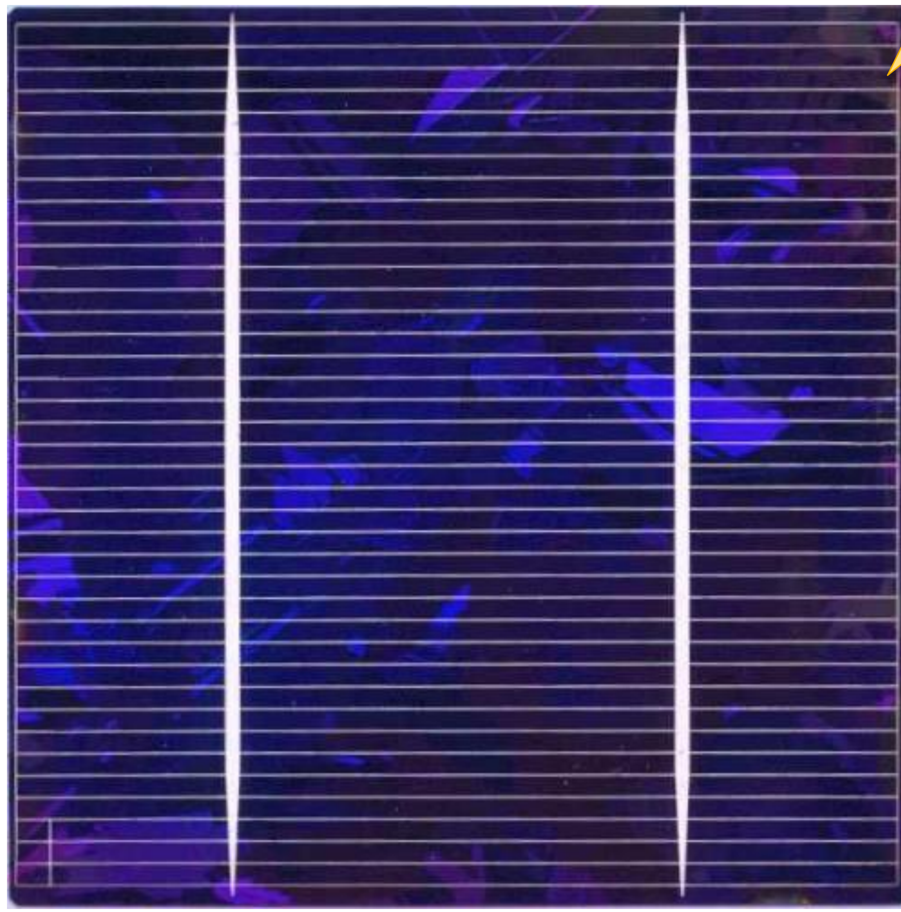




PV TECHNOLOGIES
Silicon solar cells

PV TECHNOLOGIES
Silicon solar cells

Check:
PVCDROM
Chapter 6



PV TECHNOLOGIES
Silicon solar cells

Typical screen printed silicon solar cell manufacturing process

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

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Silicon solar cells

Typical screen printed silicon solar cell manufacturing process

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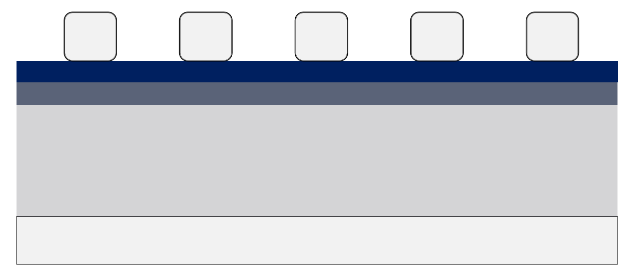

PV TECHNOLOGIES
Silicon solar cells

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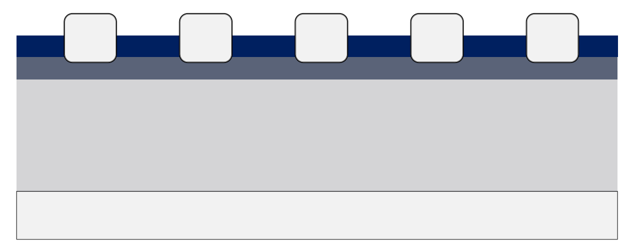


PV TECHNOLOGIES
Silicon solar cells

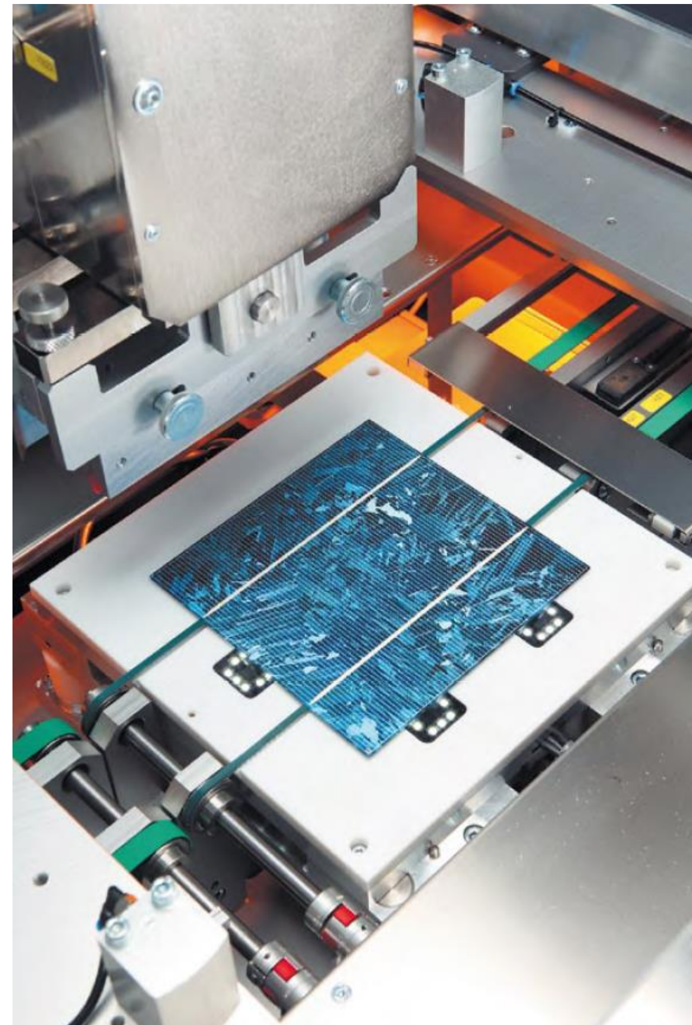
Phosphorous diffusion can be inline continuous or batch type

P source: $POCl_3$

PV TECHNOLOGIES
Silicon solar cells

Screenprinting using silver paste is standard.

Inkjet alternatives and/or other materials are fashionable research topics.



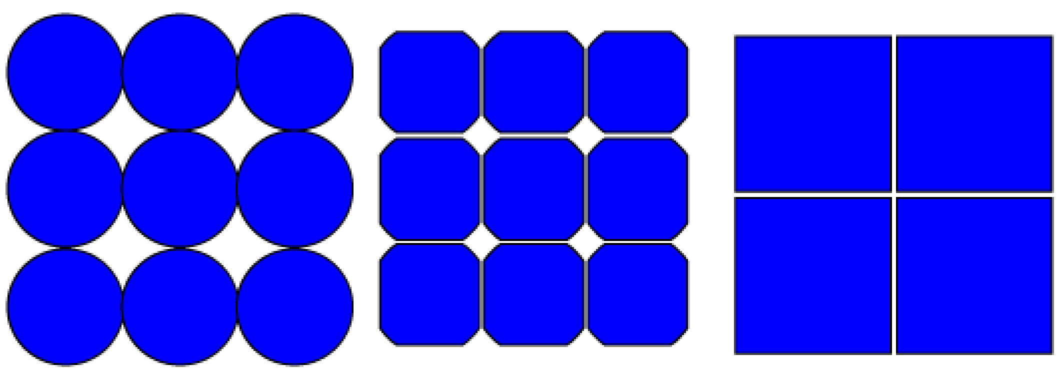
PV TECHNOLOGIES
Silicon solar cells

Handling thin wafers and keeping high yields may be challenging

PV TECHNOLOGIES
Silicon solar cells

PV silicon module

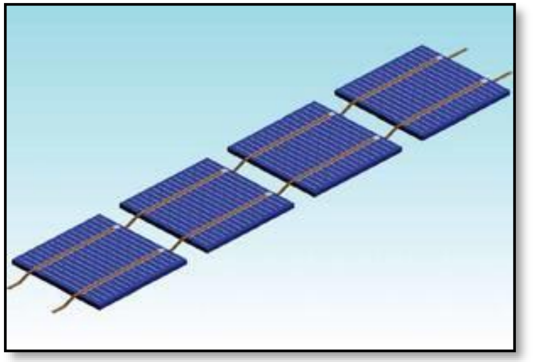
- Packing density
- Interconnection PV cells
- Encapsulation

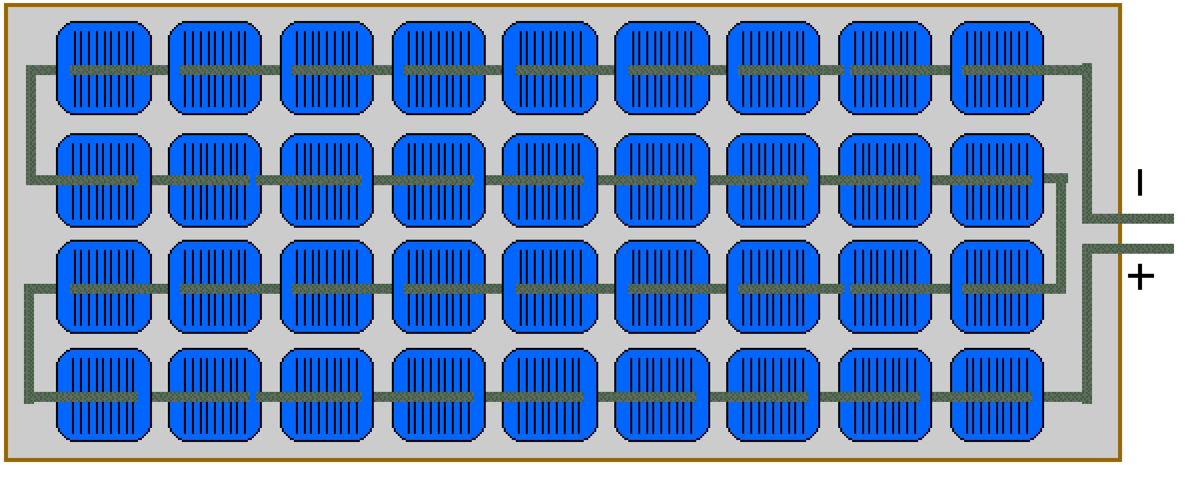


PV TECHNOLOGIES
Silicon solar cells

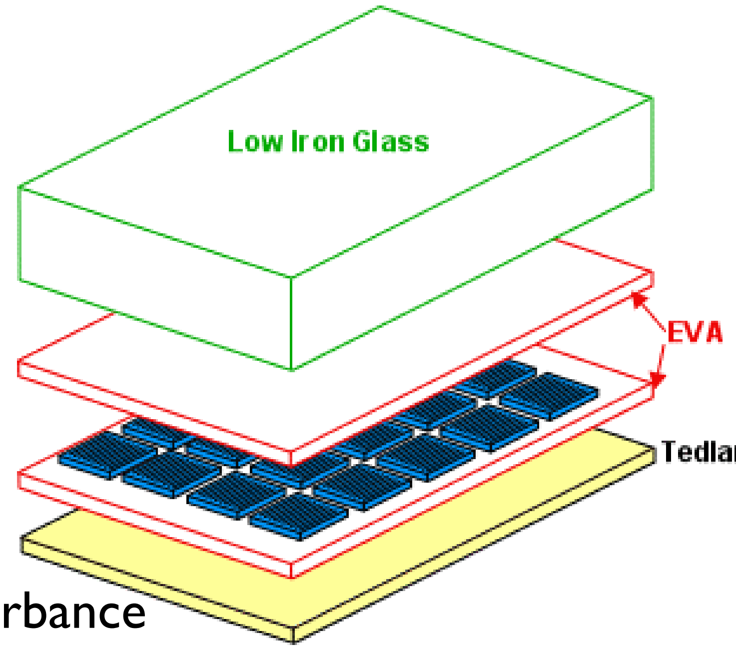
PV silicon module

- Packing density
- Interconnection PV cells
- Encapsulation



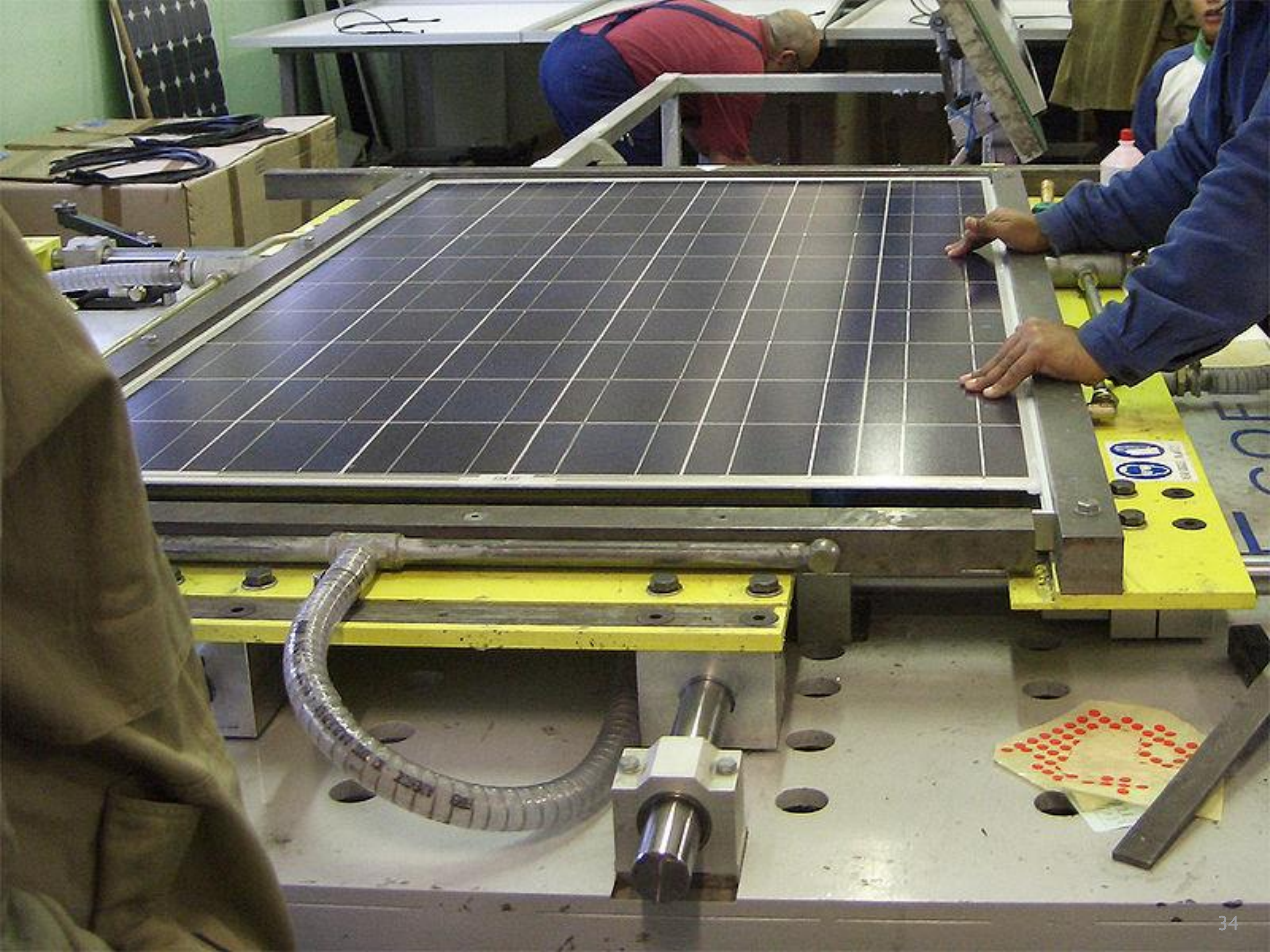


PV TECHNOLOGIES
Silicon solar cells



PV silicon module

- Packing density
- Interconnection PV cells
- Encapsulation
  - Good transmittance but UV absorbance
  - Rigidity to withstand mechanical loads
  - Protection from weather agents and humidity



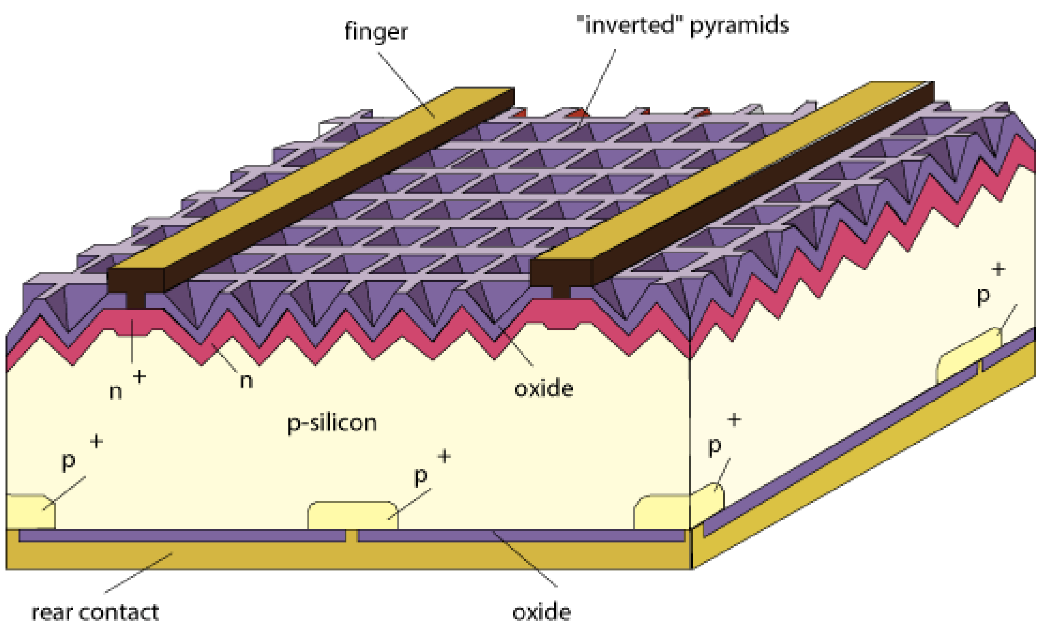
PV TECHNOLOGIES
Silicon solar cells

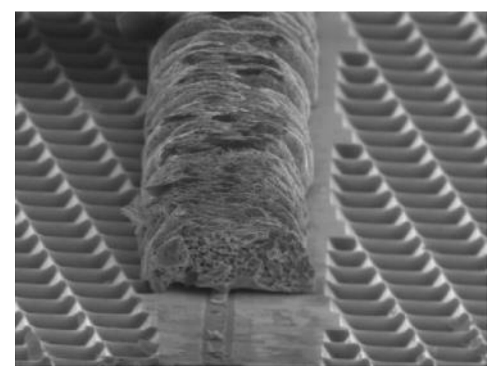
Is there a c-Si technology?

PV TECHNOLOGIES
Silicon solar cells

Is there a c-Si technology?

PERL solar cell

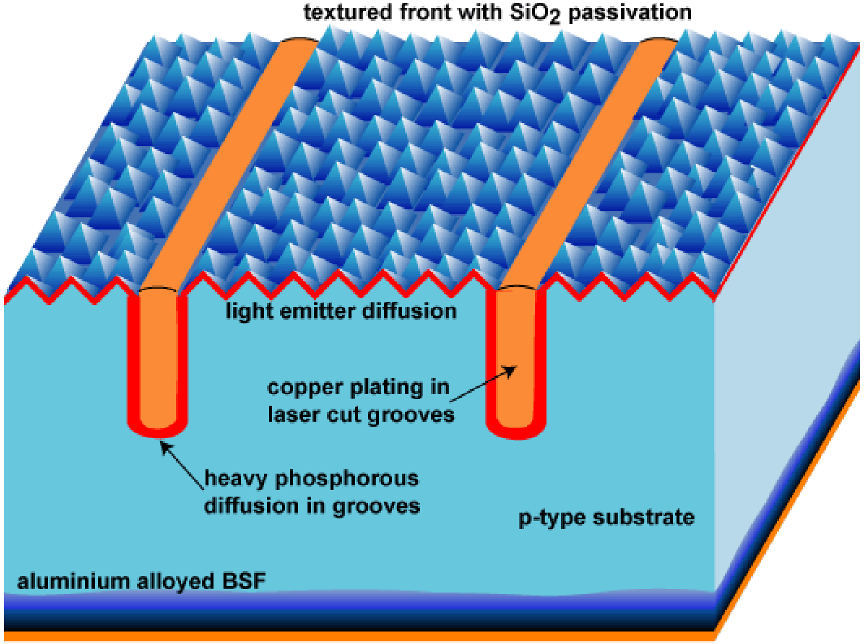


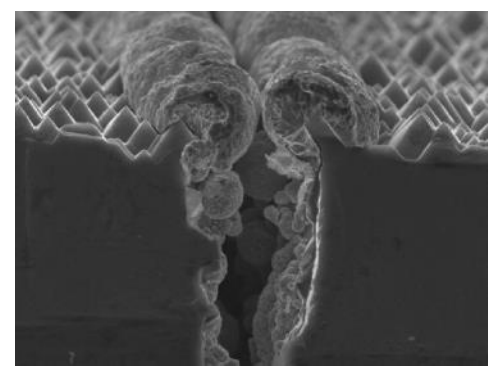


PV TECHNOLOGIES
Silicon solar cells

Is there a c-Si technology?

Buried contact solar cell

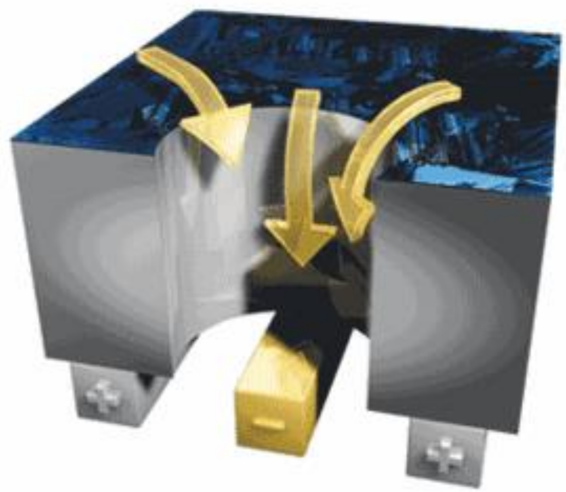


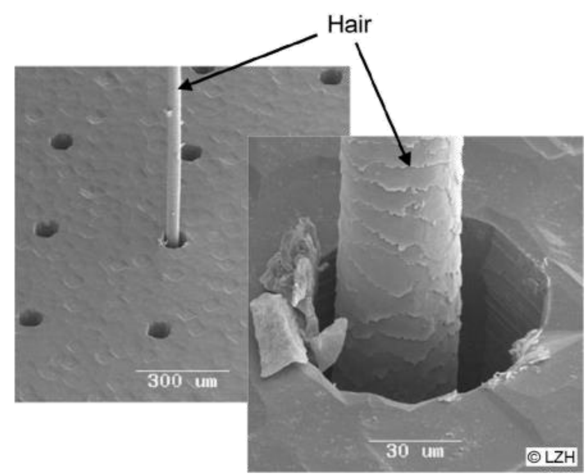


PV TECHNOLOGIES
Silicon solar cells

Is there a c-Si technology?

Rear interdigitated (RISE) solar cell

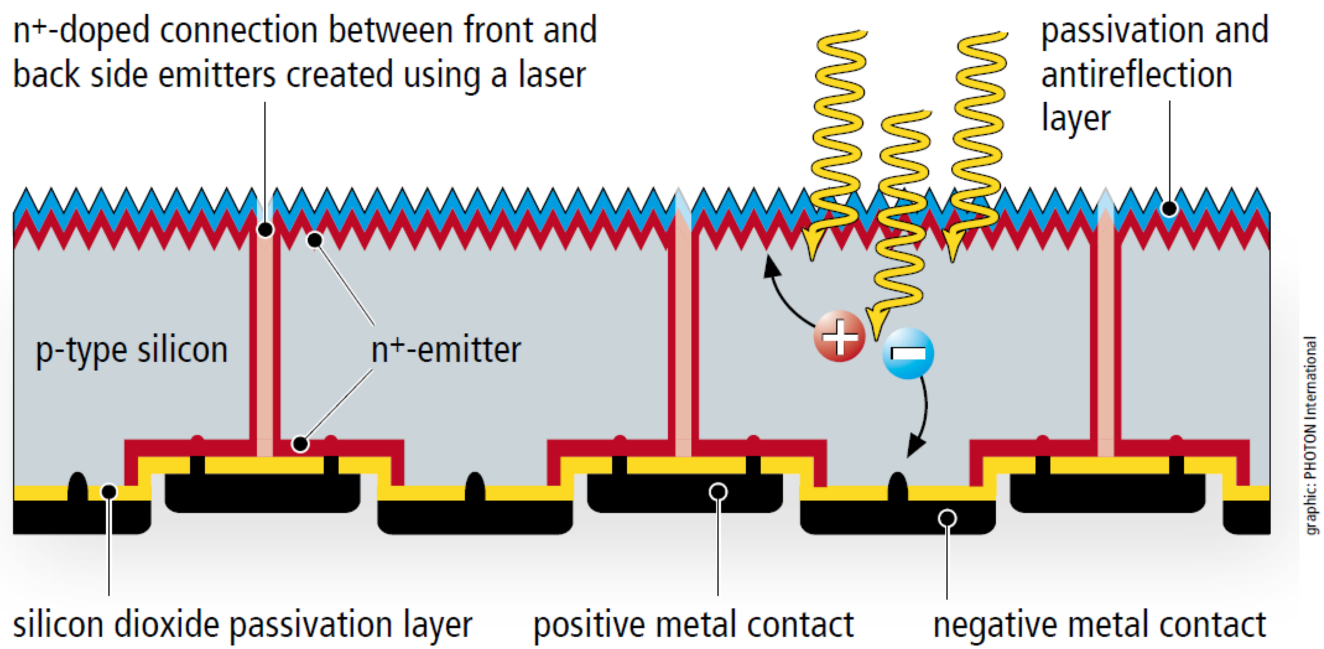




PV TECHNOLOGIES
Silicon solar cells

Is there a c-Si technology?

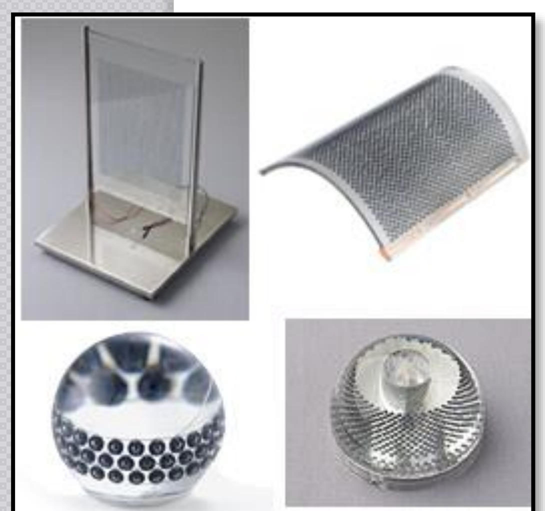
Rear interdigitated (RISE) solar cell

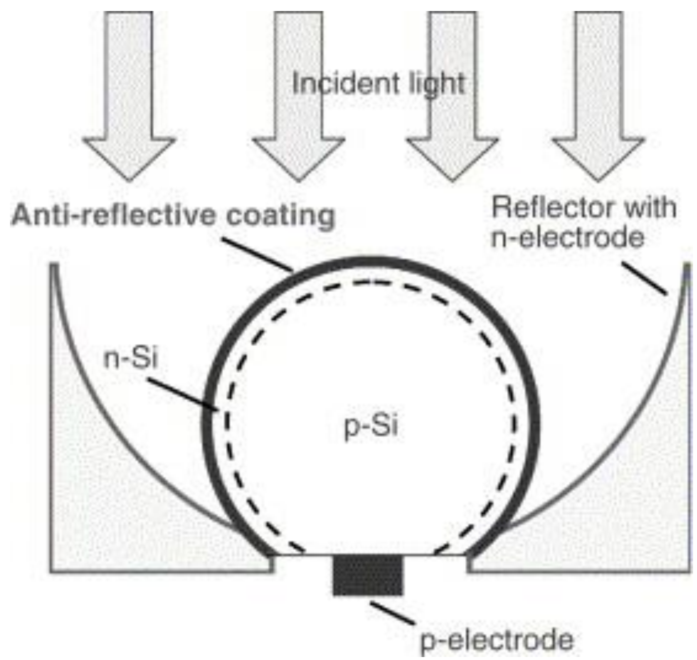


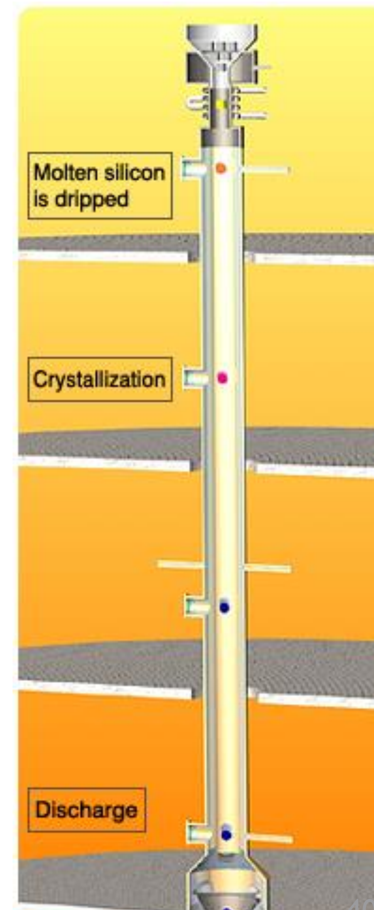
PV TECHNOLOGIES
Silicon solar cells

Is there a c-Si technology?

Spheral solar cell



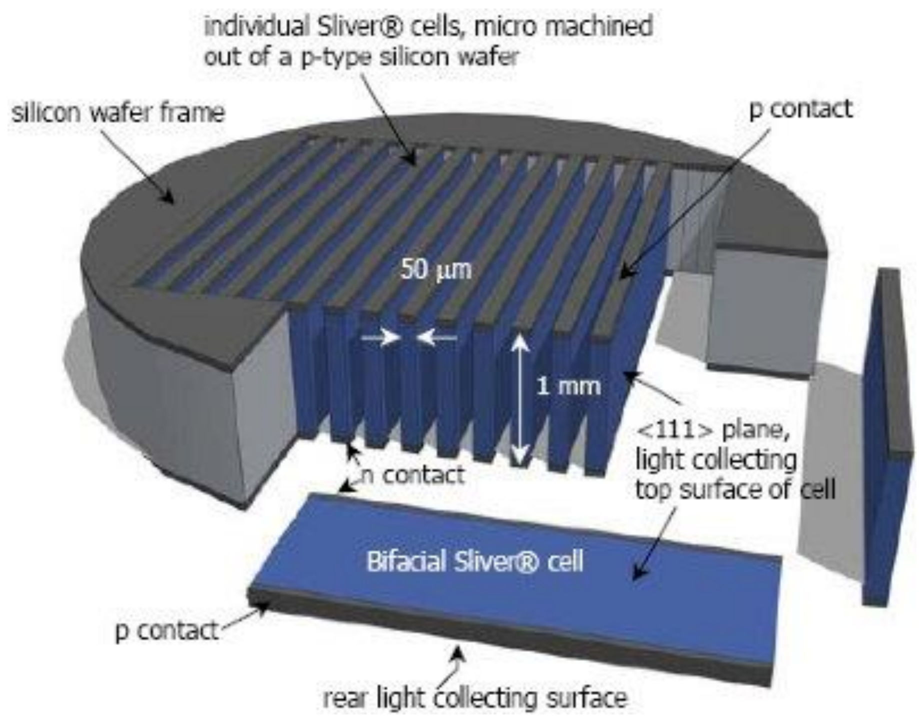




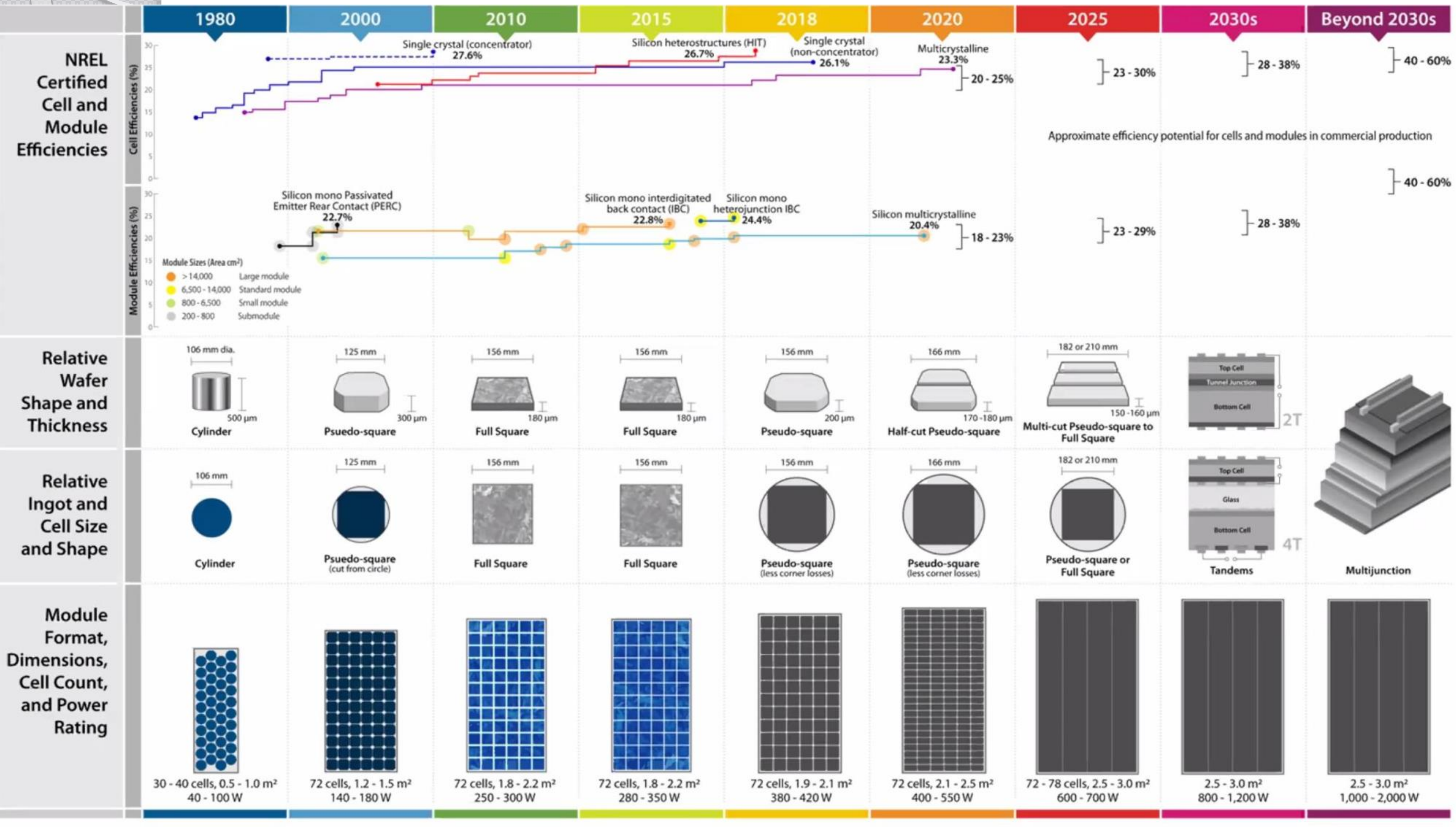
PV TECHNOLOGIES
Silicon solar cells

Is there a c-Si technology?

Sliver solar cell



PV TECHNOLOGIES
Silicon solar cells



PV TECHNOLOGIES
Silicon solar cells

Materials availability

- Silicon is **very** abundant…
- Silver paste for the contacts will be a material bottleneck
- Other (temporary) bottlenecks:
  - Module glass
  - Tedlar
  - EVA

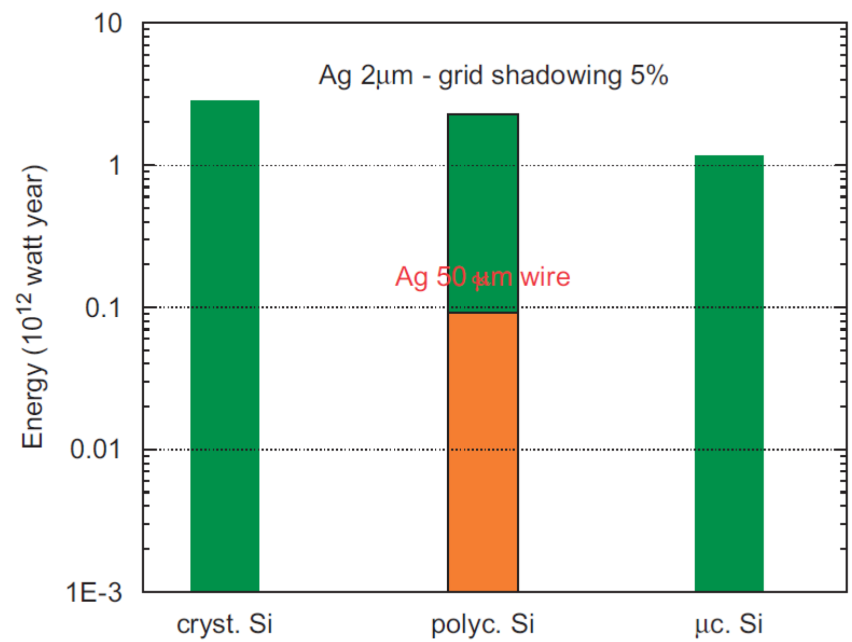


Fig. 3. Potential energy limits imposed by global silver (Ag) reserves for bulk-like silicon photovoltaic technologies. Calculations assume AM1.5 efficiencies of 24.7% (Ref. [8]) and 20.3% (Ref. [7]) for crystalline and large grain poly-crystalline solar cells. The orange shaded area represents limits reached using 50 μm-thick Ag ribbons. The green shaded area represents limits estimated using a 2 μm thick Ag electrodes and 5% grid shadowing.

PV TECHNOLOGIES
Silicon solar cells

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- Silver paste for the contacts will be a material bottleneck
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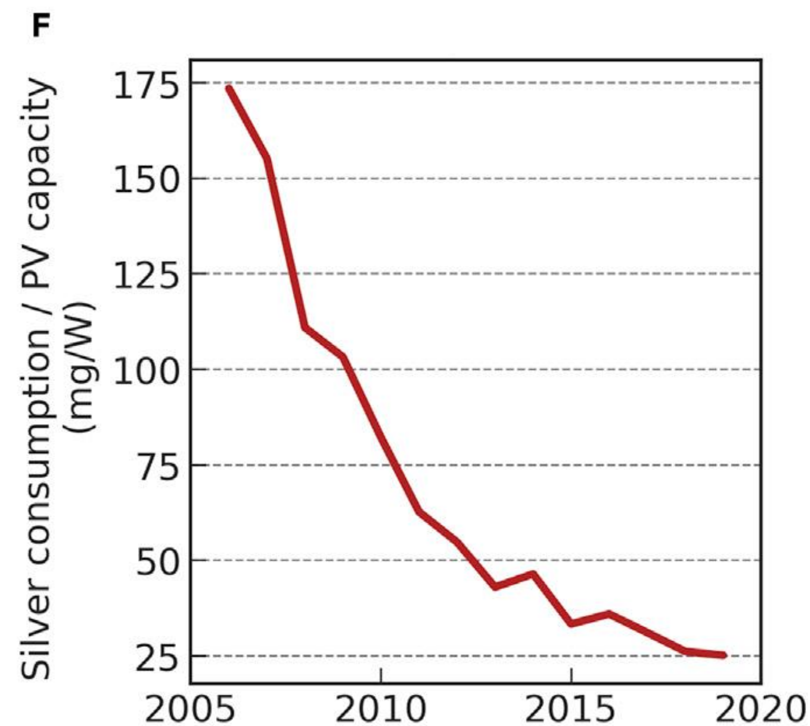
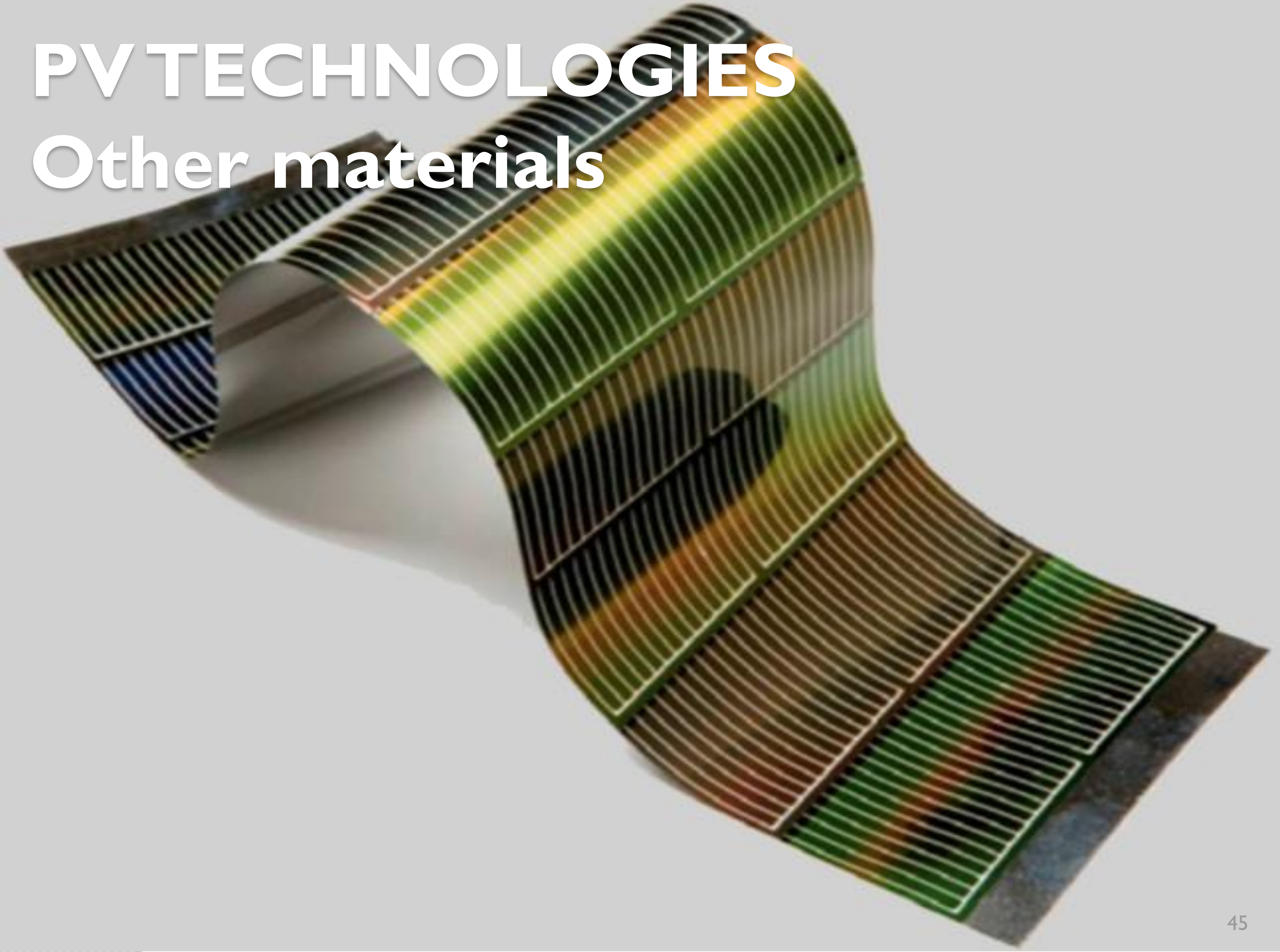


PV TECHNOLOGIES
Other materials

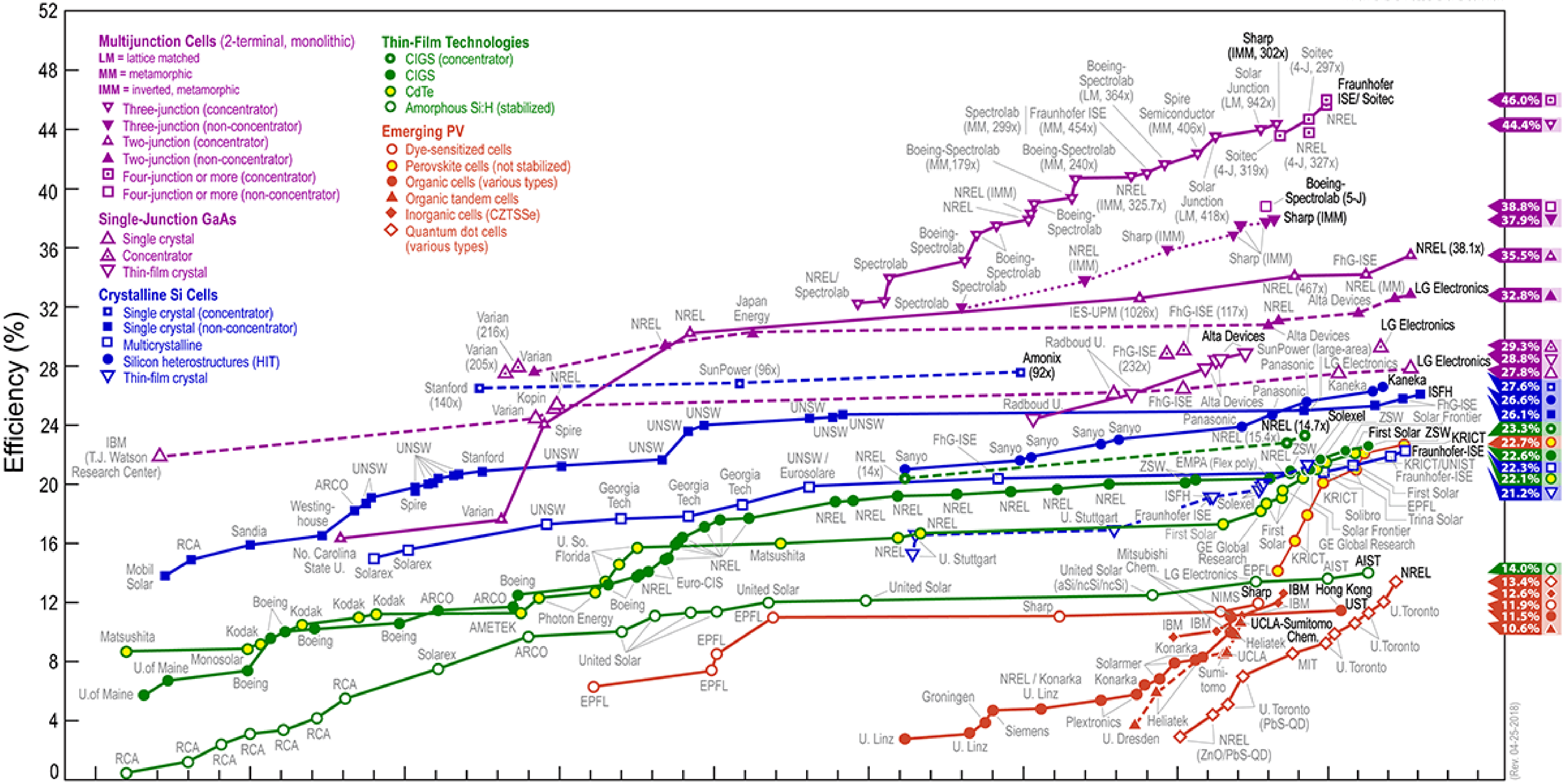


PV TECHNOLOGIES
Other technologies

- Other concepts, materials & technologies
  - a-Si
  - CIGS
  - CdTe
- It's not only about efficiency (nor cost!)

Best Research-Cell Efficiencies

NREL
NATIONAL RENEWABLE ENERGY LABORATORY



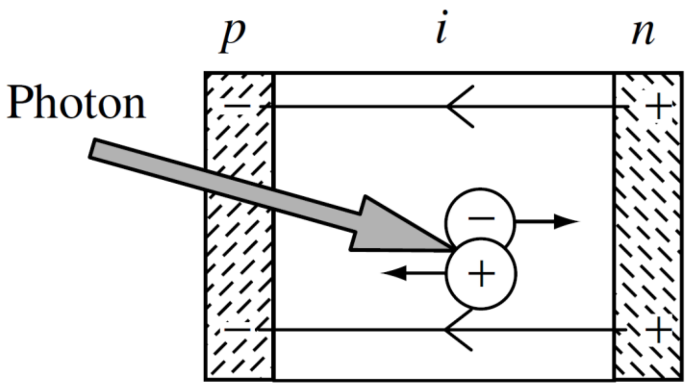
PV TECHNOLOGIES
Amorphous silicon solar cells

- Amorphous – commonly applied to noncrystalline materials prepared by deposition from gases
- First working a-Si based solar cell: Carlson D, Wronski C, *Appl. Phys. Lett.* 28, 671 (1976)
- Cheaper deposition
- Hydrogenated amorphous silicon (a-Si:H) has higher absorption coefficient than crystalline silicon – much thinner (<1 μm) solar cells are possible

PV TECHNOLOGIES
Amorphous silicon solar cells

p-i-n configuration

- Electron-hole pairs are generated in the intrinsic 'thick' layer and
- Separated by the built electric field



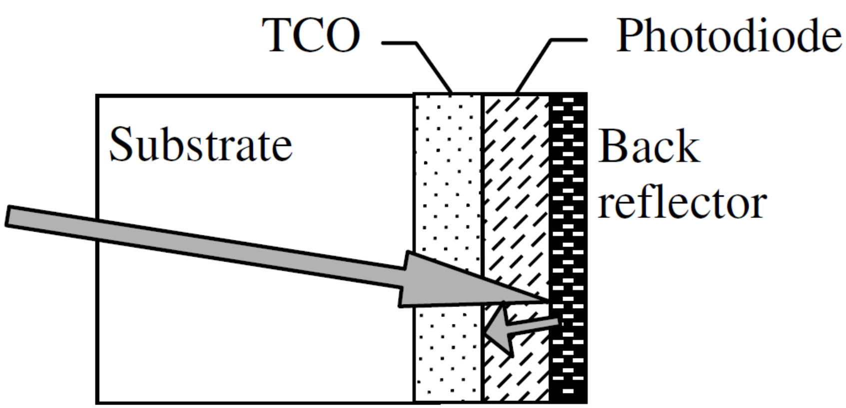
pin photodiode

Because doped layers have very little diffusion length…

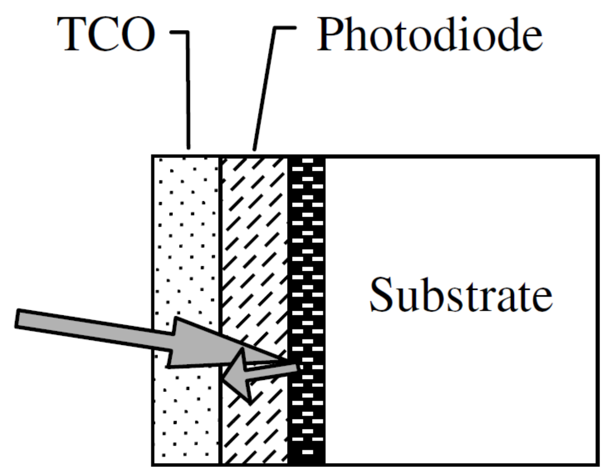
PV TECHNOLOGIES
Amorphous silicon solar cells

Very thin active layer (<1 μm) thus:

requires substrate



Superstrate



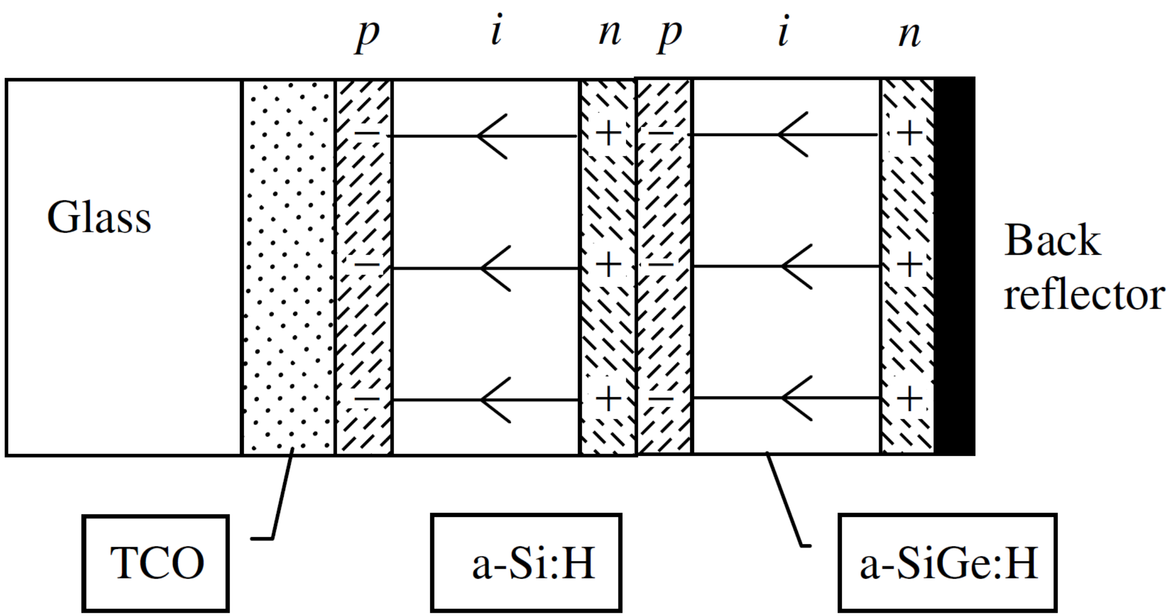
Substrate

Substrate may be glass:
useful for building **integrated** PV

Substrate may be foil:
useful for **flexible** solar cells

PV TECHNOLOGIES
Amorphous silicon solar cells

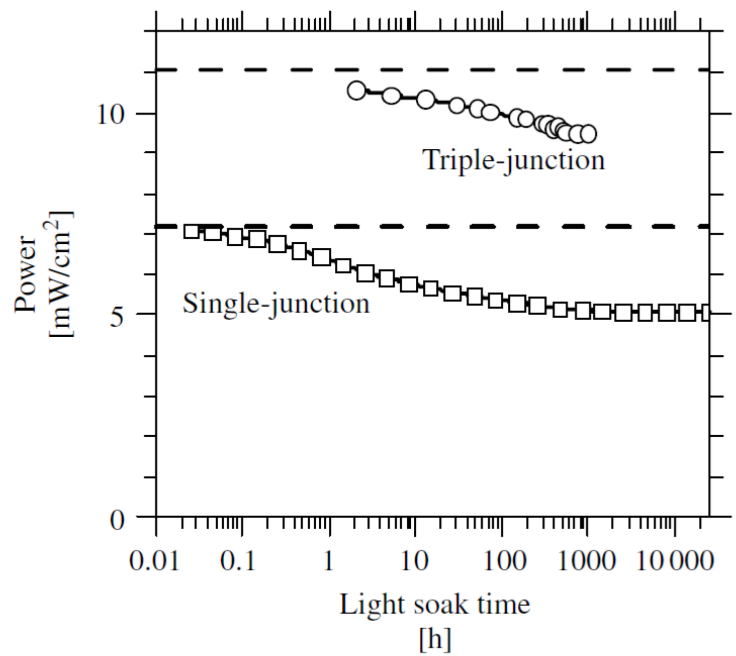
To increase efficiency, more junctions (tandem configuration) may be added



A more modern & fashionable second layer: microcrystalline silicon layer

PV TECHNOLOGIES
Amorphous silicon solar cells

Significant decline in their efficiency during their first few hundred hours of illumination: Staebler–Wronski effect



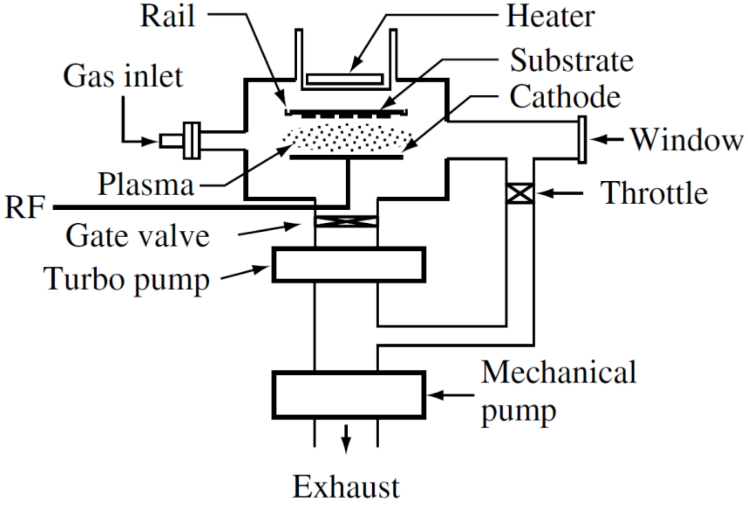
Staebler D, Wronski C, *Appl. Phys. Lett.* 31, 292 (1977).

Figure 12.5 The conversion efficiency in a-Si:H-based solar cells declines noticeably upon the first exposure to sunlight. The figure illustrates this decline under a solar simulator (100 mW/cm^2) for a single-junction cell (260-nm *i*-layer thickness) and for a triple-junction module made at United Solar Systems Corp. [14, 15]; the dashed lines indicate the initial power measured for each device

PV TECHNOLOGIES
Amorphous silicon solar cells

PECVD - Plasma enhanced chemical vapour deposition (a.k.a. RF glow discharge deposition)

- SiH_4 + H_2 into the chamber
- RF is applied and generates plasma
- plasma excites and decomposes the gas and generates radicals and ions
- that will diffuse onto the heated substrate

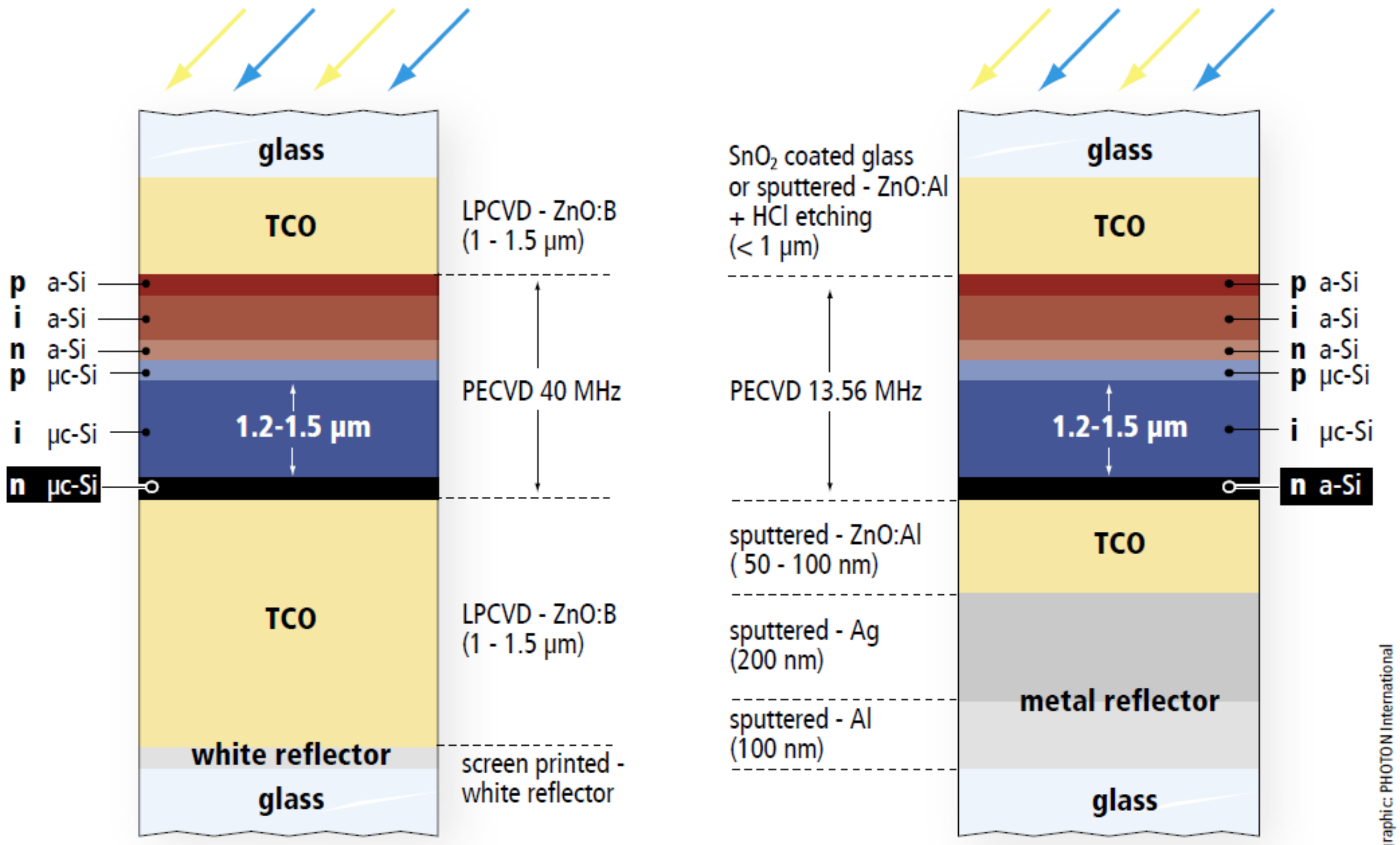


Typical growth speed: 1 angstrom/sec; Typical substrate temperature: 150-350°C

PV TECHNOLOGIES
Amorphous silicon solar cells

Oerlikon
based on process developed at the University of Neuchâtel

Applied Materials
based on process developed at Research Center Jülich (FZJ)



PV TECHNOLOGIES
Amorphous silicon solar cells

In summary:

- Low efficiency (for the same yield requires more area: module framing & encapsulation become relevant costs)
- Low cost (may be interesting if land availability is not an issue)
- Niche markets such as building integrated PV, consumer electronics (i.e. gadgets), flexible solar cells,…

PV TECHNOLOGIES
Cadmium Telluride solar cells

- CdTe has a high absorption coefficient: thus very thin active layer
- Earliest paper on CdTe solar cell:

  Loferski J, *J. Appl. Phys.* 27, 777–784 (1956)
- Most 'popular' configuration: CdTe/CdS heterojunction (p-type CdTe and n-type CdS)

Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length and should be submitted in duplicate.

High-Voltage Photovoltaic Effect*

L. PENSAK
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(Received November 25, 1957)

VACUUM evaporated films of cadmium telluride have been prepared that show unusually high photovoltages across their ends. The effect is independent of the electrode material and the voltage is proportional to the length of the film. A value of one hundred volts/cm has been obtained in sunlight. Since the photovoltage of a single junction is limited by the band gap of the material (1.45 ev), it is concluded that the films consist of large numbers of junctions (or other photovoltaic elements) whose individual voltages add to produce the observed values. Photovoltages greater than band gap have been reported for films of PbS,[1,2] but with a maximum of 3 volts and only after some post-evaporation processing. No such processing is required for the CdTe films.

The presence of the effect depends on the angle, θ, of deposition of the vapor onto the substrate as shown in Fig. 1. Lines of constant θ are found to be equipotentials for photovoltage. No photovoltage exists in material deposited with $\theta=0$. The photovoltage increases rapidly with θ up to about 10 degrees and then very slowly up to 60 degrees, above which no measurements were taken. A second requirement for the effect is that the substrate be held at a temperature between 100 and 250°C during deposition. The pressure during evaporation, $\sim 10^{-5}$ mm, is maintained by an oil diffusion pump. The rate of film formation is about 1000 A per minute. The films become photovoltaic when the thickness is sufficient to absorb some light, and the voltage increases to a maximum at approximately one micron. The effect occurs with Pyrex glass, fused quartz, and other substrate materials. The only requirement is that the substrate be more insulating than the films which, in the dark, have a resistance of the order of 10^{13} ohms per square at room temperature.

The electrical properties of the films and their response to light and temperature are reported in a following letter. Optical transmission measurements show that the fundamental absorption edge is 8300 A, the expected value for CdTe. X-ray studies by J. G. White of this Laboratory are consistent with the view that the films consist of crystallites whose size is comparable with the film thickness ($\sim 1\ \mu$). The crystallite (111) planes have a preferred orientation parallel to the substrate, regardless of the angle of deposition.

Although the effect has been found in every film made, the magnitude has not been reproducible within a factor of 10. An explicit model for the mechanism of the effect has not yet been established. An effect of comparable magnitude has been found in single-crystal zinc sulfide by another group in this laboratory. Further studies of the effect in both materials are under way.

* This work was supported by the Evans Signal Corps Laboratories.
[1] Starkiewicz, Sosnowski, and Simpson, Nature **158**, 26 (1946).
[2] Berlaga, Rusmach, and Strakhov, Zhur. Tekh. Fiz. **25**, 1878 (1955).

Properties of Photovoltaic Films of CdTe†

B. GOLDSTEIN
RCA Laboratories, Princeton, New Jersey
(Received November 25, 1957)

THIS letter describes some of the basic properties of a representative photovoltaic film of CdTe.[1] The film was deposited onto a Pyrex substrate: it was one-half cm long, one cm wide, and about one micron thick. The open-circuit voltages were measured with a

PV TECHNOLOGIES
Cadmium Telluride solar cells

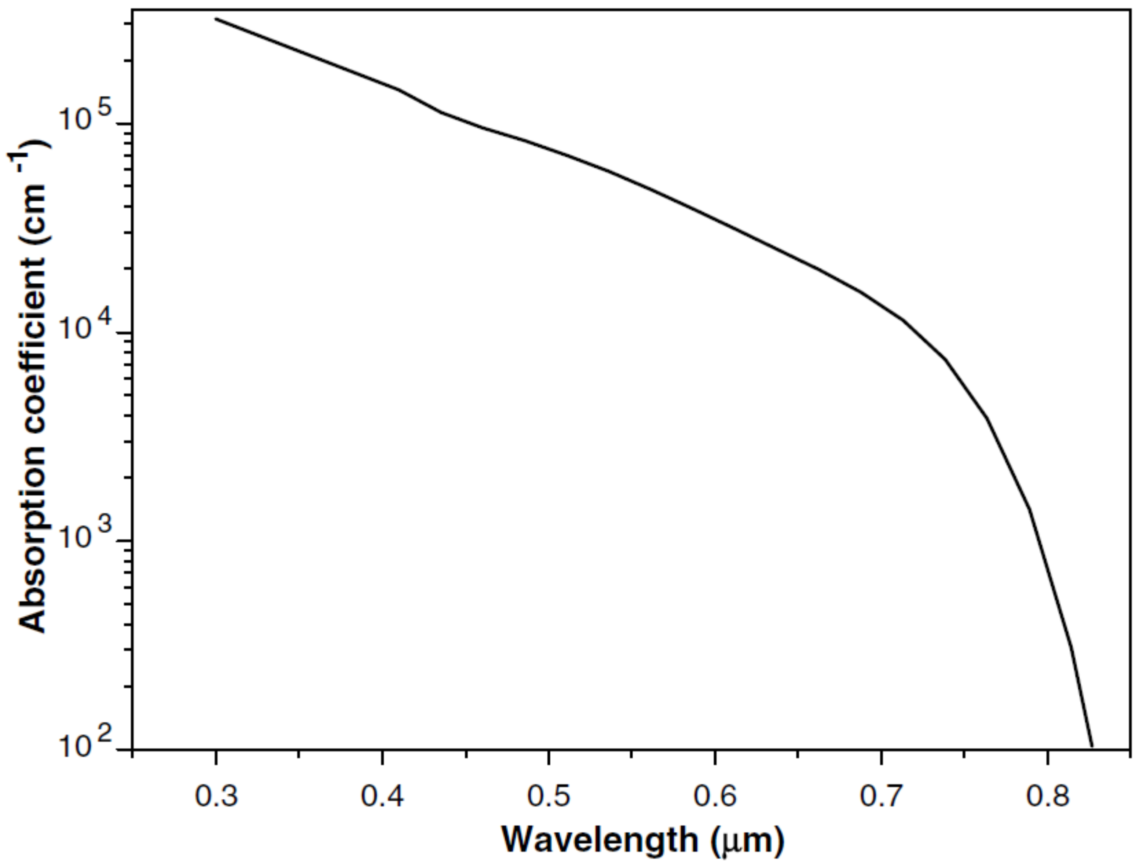


Fig. 5. CdTe absorption coefficient at room temperature.

A. Morales-Acevedo, *Thin film CdS/CdTe solar cells: Research perspectives*, Solar Energy 80 (2006) 675–681

PV TECHNOLOGIES
Cadmium Telluride solar cells

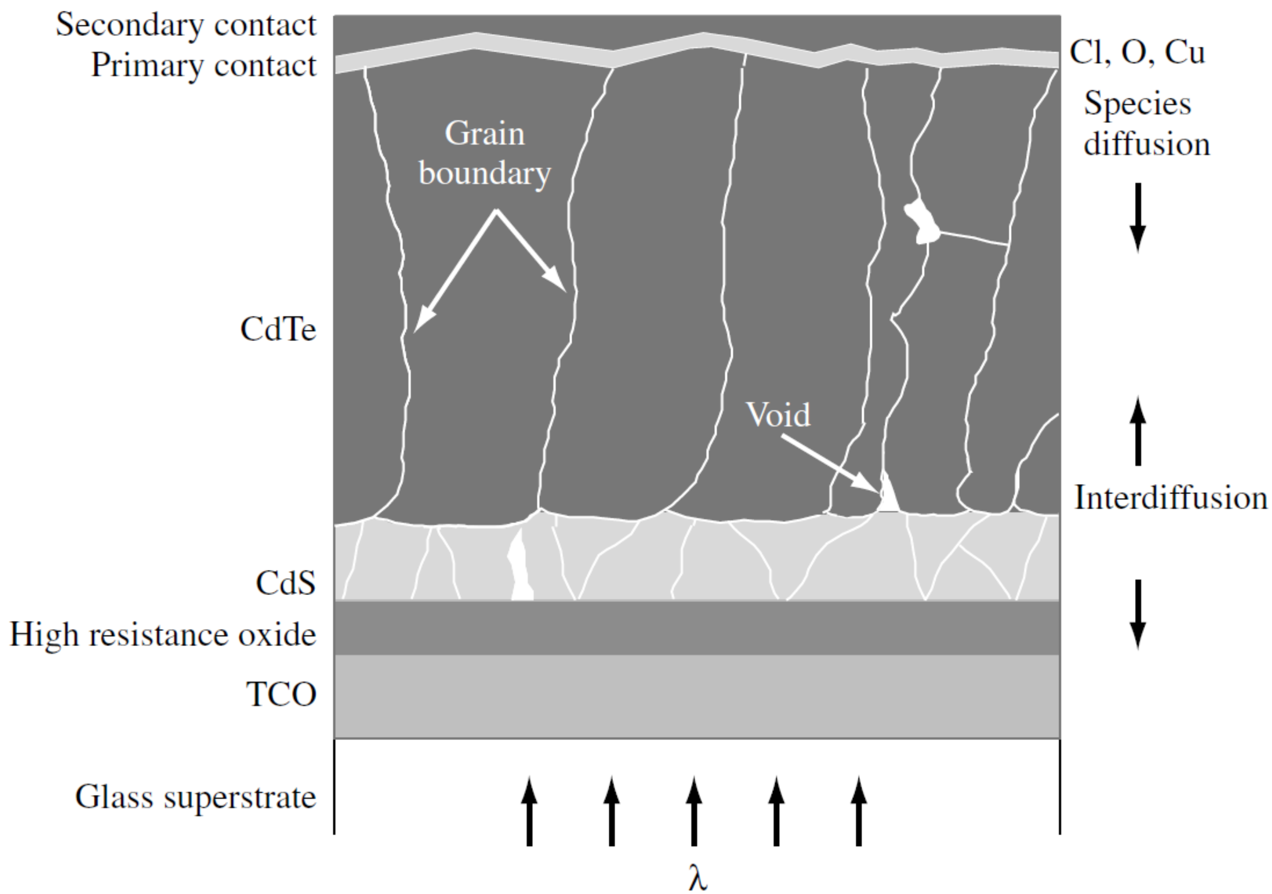
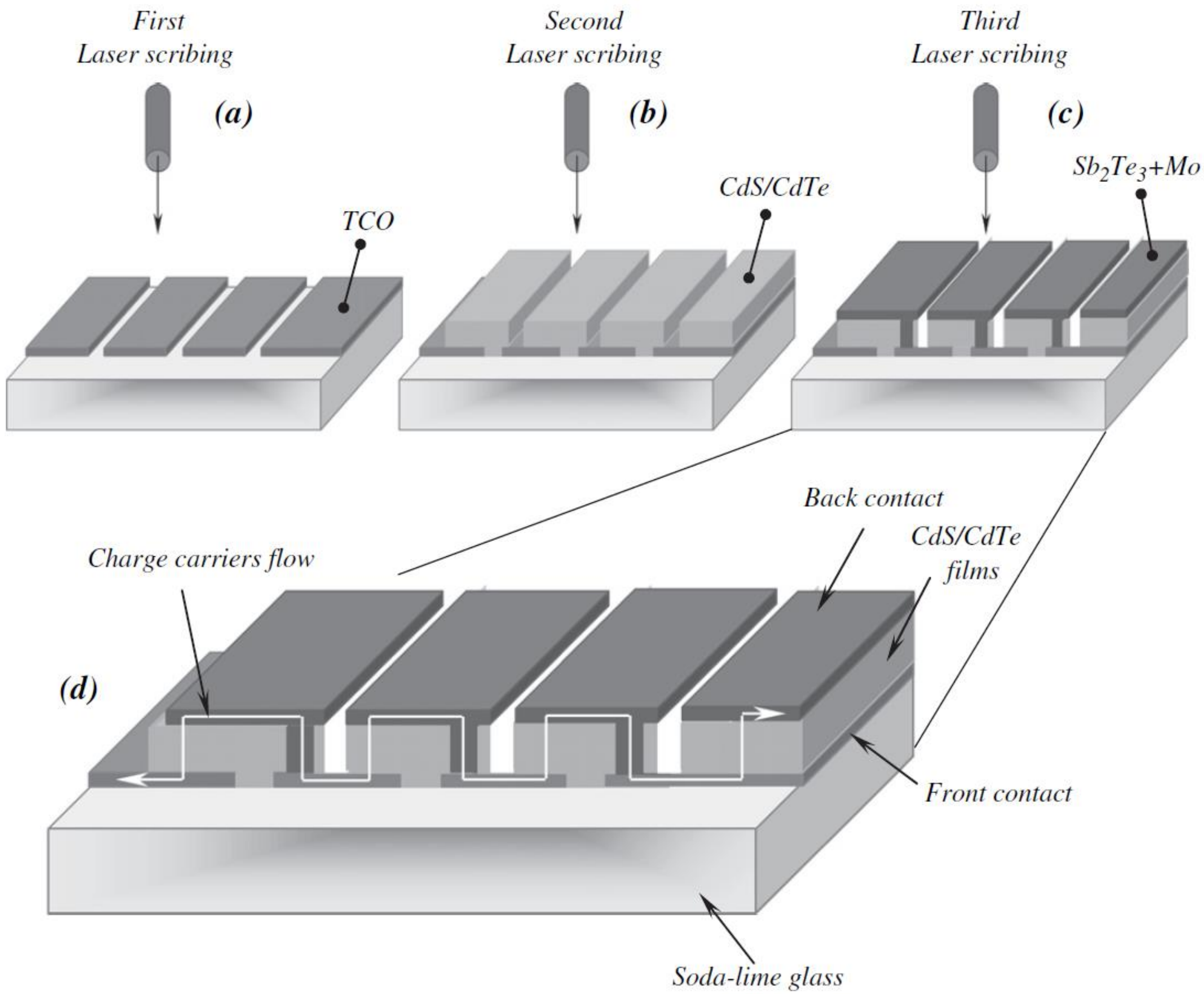


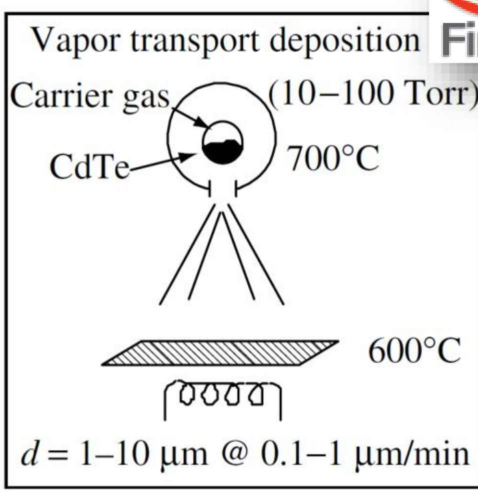
Figure 14.7 Basic CdTe solar cell structure. The polycrystalline nature of the CdS and CdTe layers are indicated schematically and are not to scale

PV TECHNOLOGIES
Cadmium Telluride solar cells



PV TECHNOLOGIES
Cadmium Telluride solar cells

- Top efficiencies:
  - Cell 16.7% (NREL);
  - Module 10.9% (BP Solarex);
  - Best seller: First Solar



Main issues:

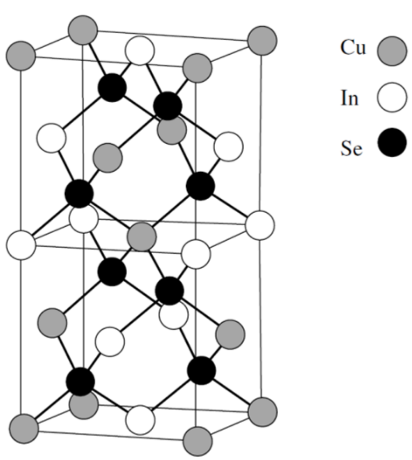
- Cheapest technology in the market (<1€/Wp)
- 'Limited' efficiency
- Reliability (lifetime)
- Materials!!
  - Toxic Cd
  - Rare Te
- Window of opportunity taken!

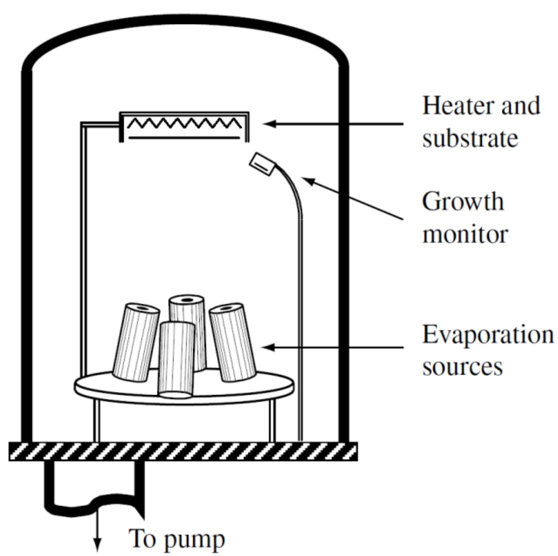
PV TECHNOLOGIES
$Cu(InGa)Se_2$ solar cells

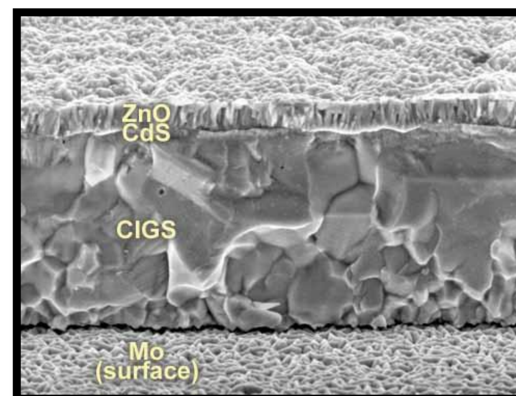
- Synthesis and characterization were first reported by Hahn H et al., Z. Anorg. Allg. Chem. 271, 153–170 (1953)
- High absorption coefficient: thin film
- Like all thin films: potential for cheap manufacturing for fabrication of monolithically interconnected modules
- Potential for relatively high efficiency: 19.4% (cell) and 13.5% (module)

PV TECHNOLOGIES
$Cu(InGa)Se_2$ solar cells

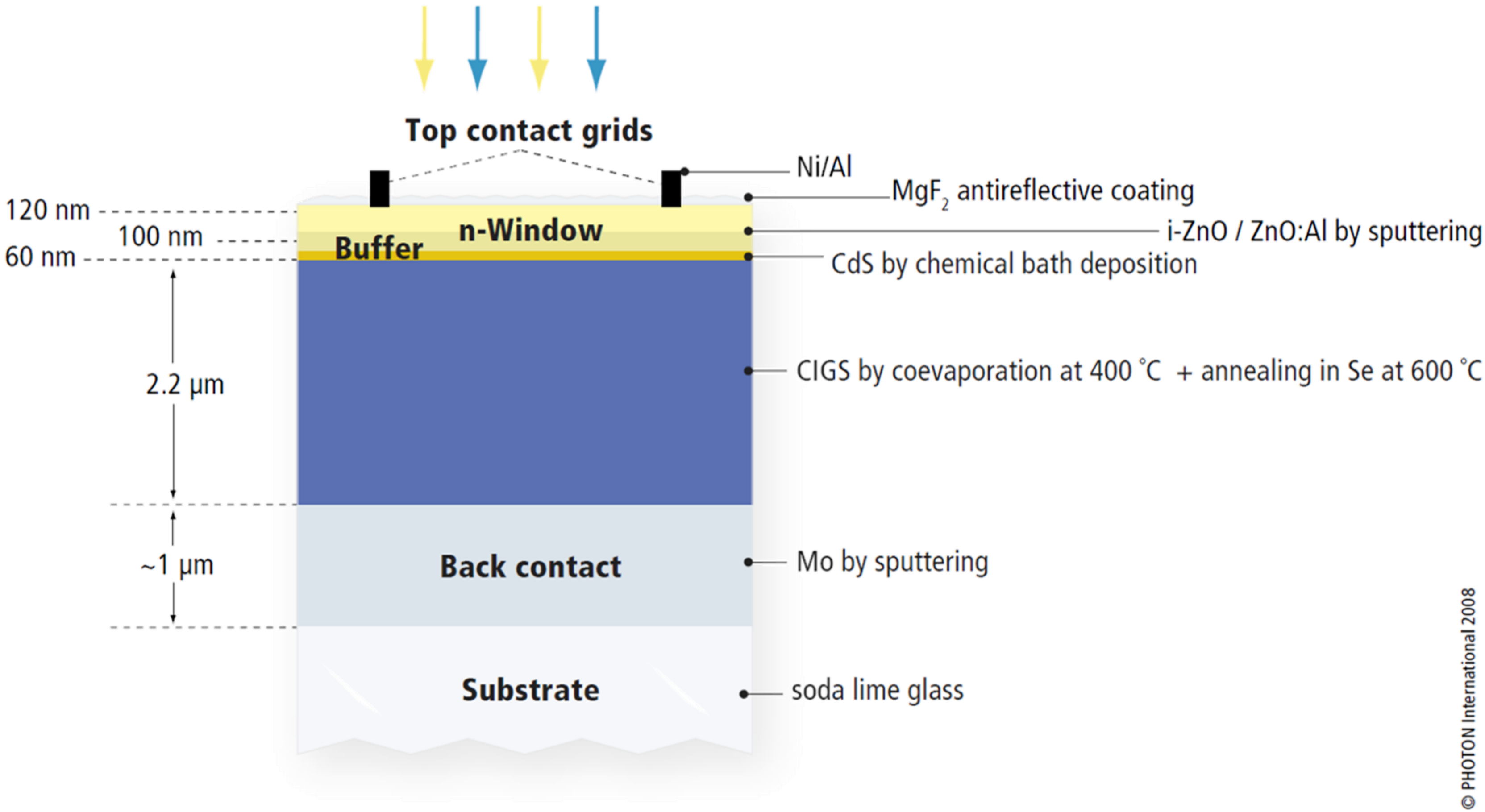
- P-type: $Cu(InGa)Se_2$
- N-type: CdS





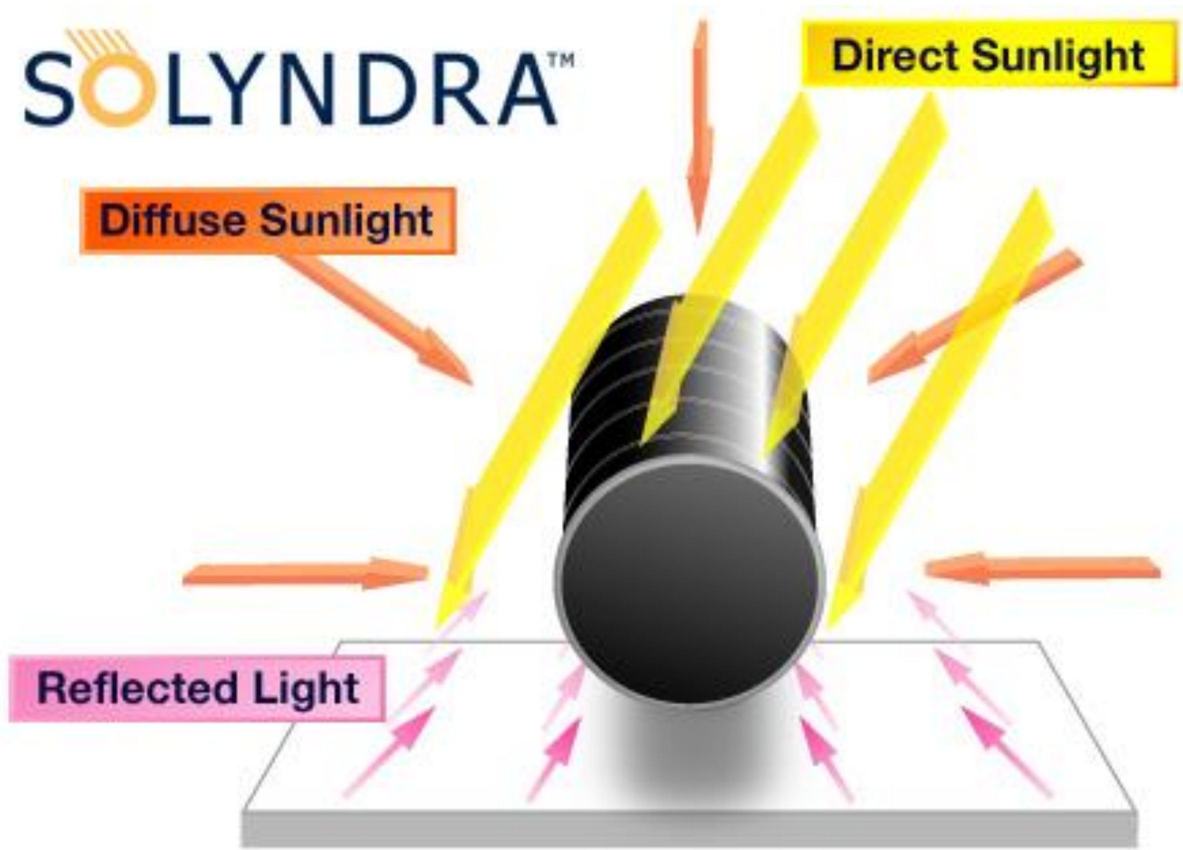


PV TECHNOLOGIES
$Cu(InGa)Se_2$ solar cells



PV TECHNOLOGIES
Cu(InGa)Se_2 solar cells

- Other different CIGS concepts…



PV TECHNOLOGIES
Other technologies

- Many other different concepts…

Polymer solar cells

CIGS nanoparticles

Dye sensitized solar cells

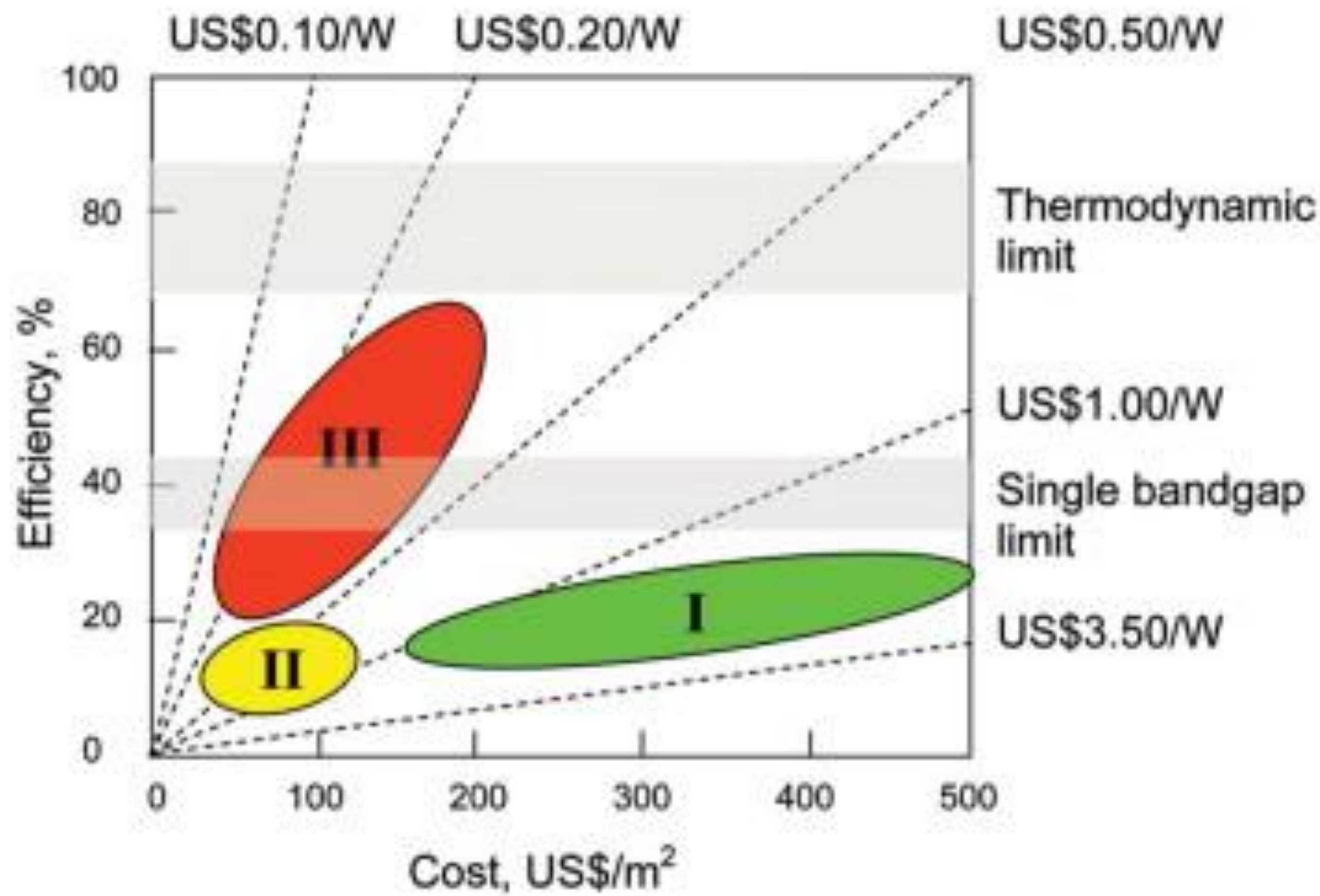
Thin silicon film

Intermediate band cells

DARPA (spectrum splitting)

Silicon nanoparticle ink

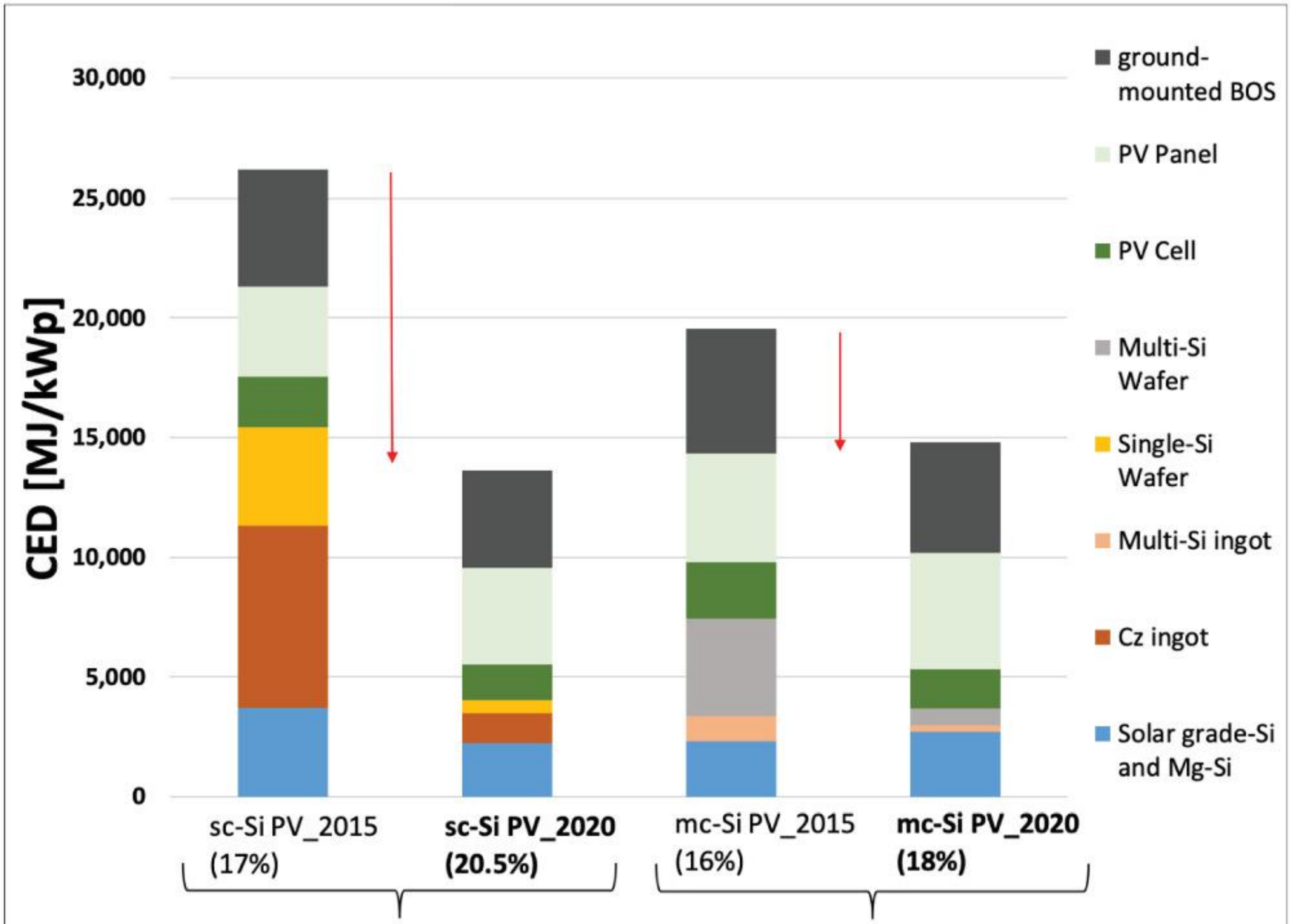
PV TECHNOLOGIES
Other technologies



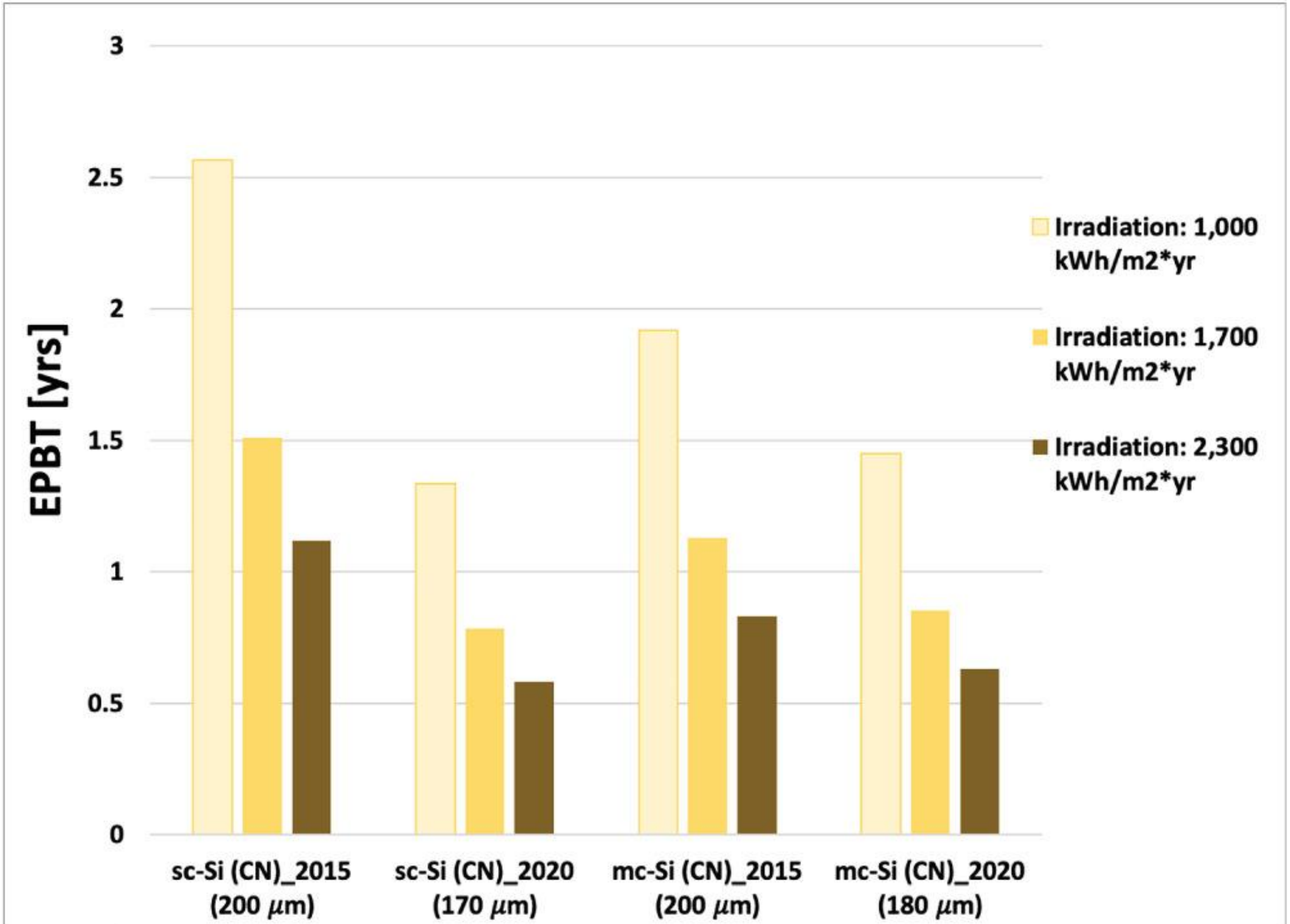
PV TECHNOLOGIES
Comparing different technologies

- Cost
- Performance/durability
- Materials availability
- Environmental issues
- Maturity
- Developers
- Market penetration potential & others

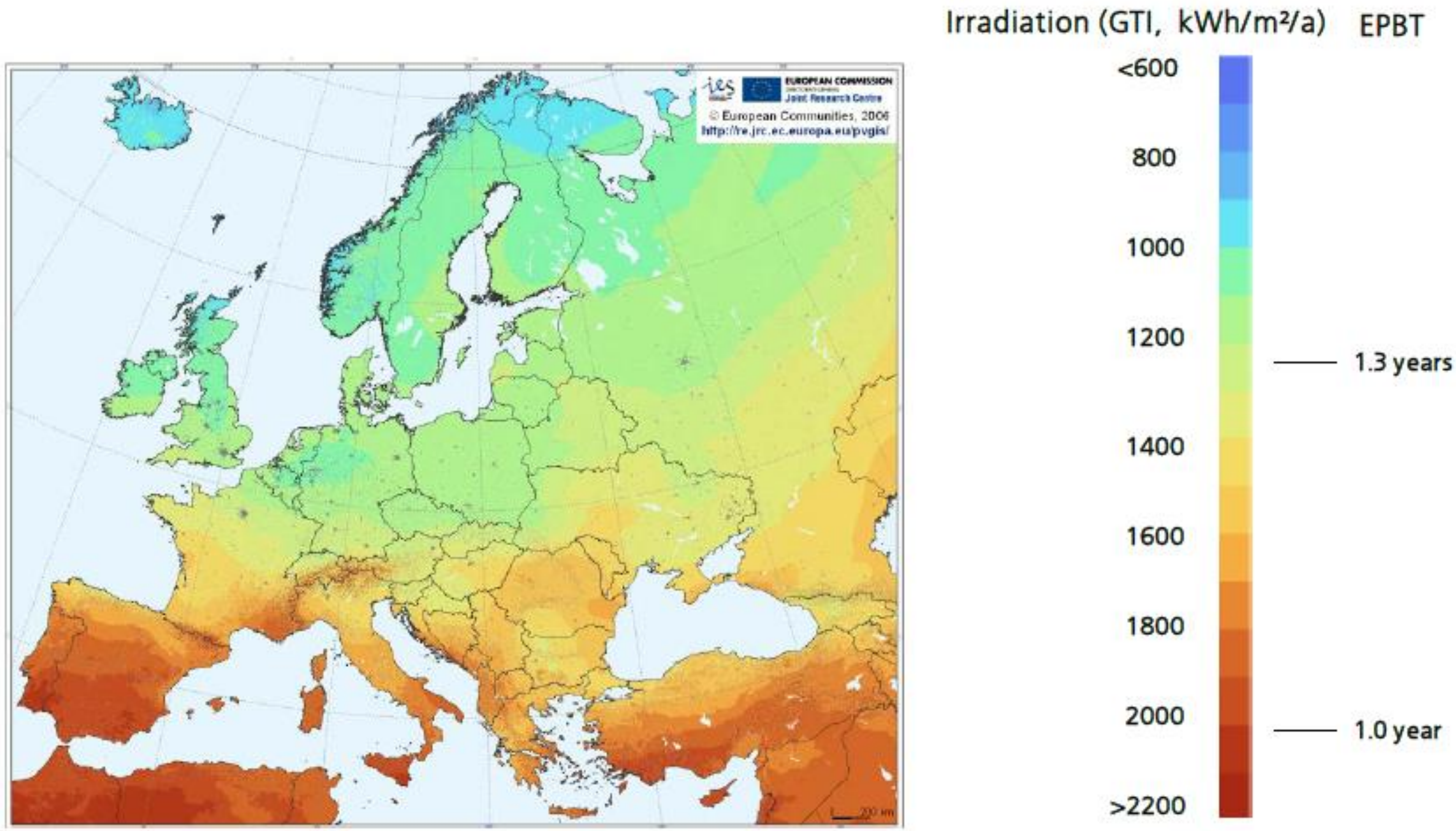
PV TECHNOLOGIES
Energy payback time



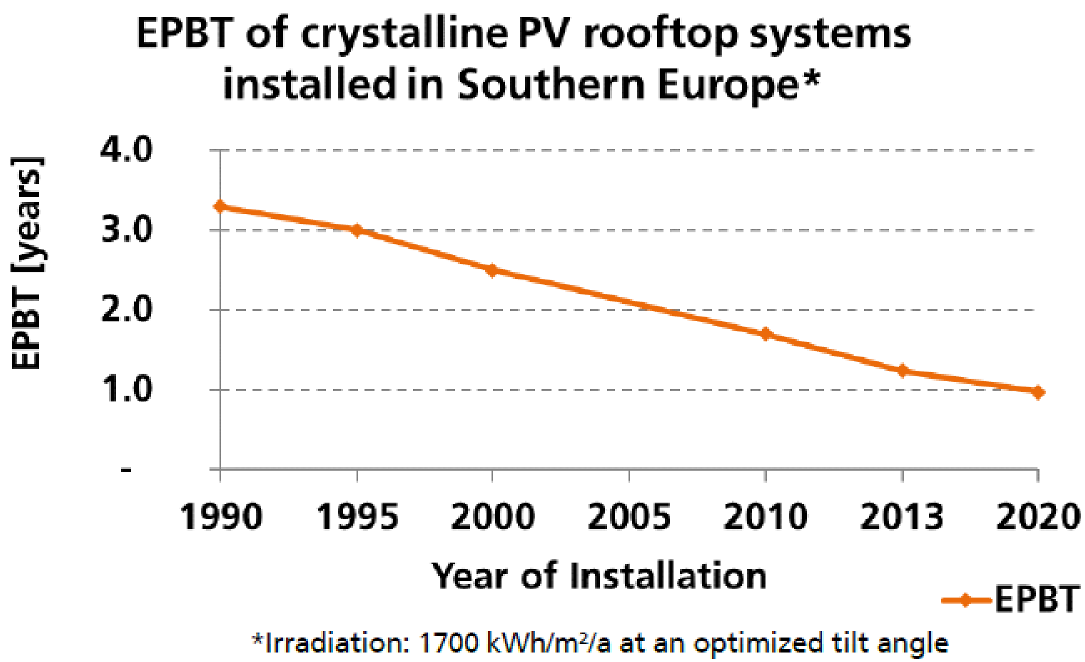
PV TECHNOLOGIES
Energy payback time



PV TECHNOLOGIES
Energy payback time

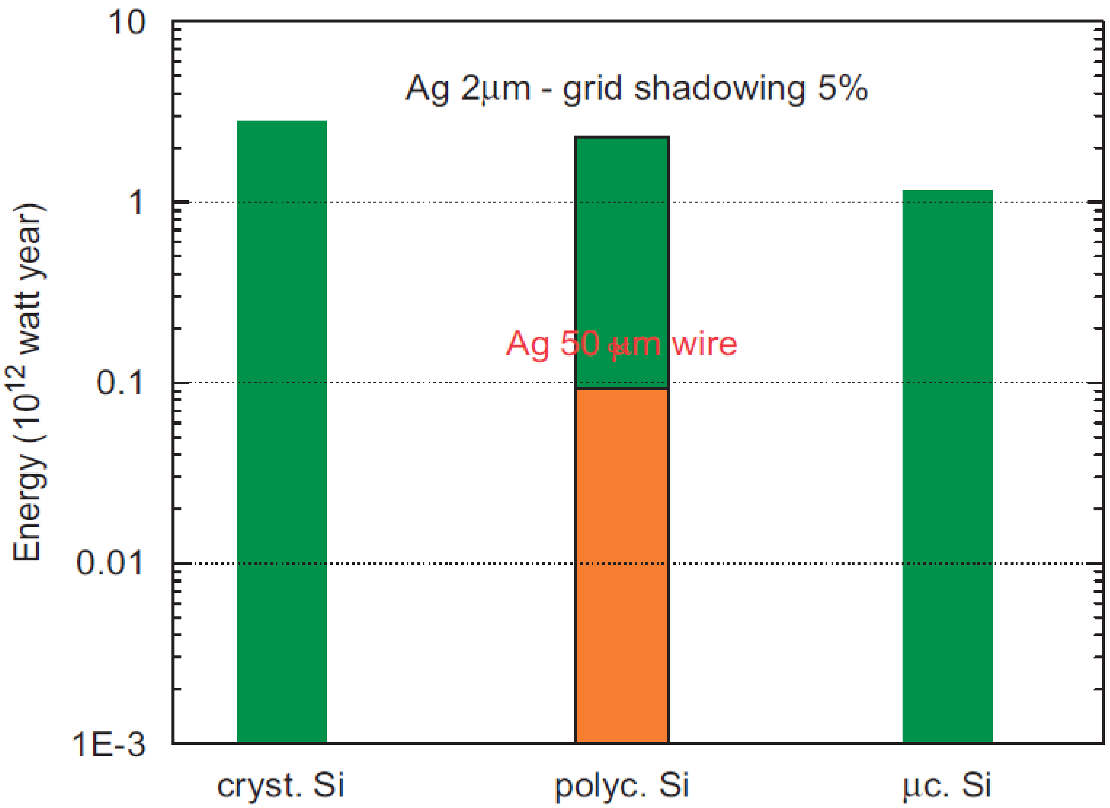


PV TECHNOLOGIES
Energy payback time



$$\text{energy yield} = \frac{\text{operational lifetime}}{\text{energy payback time}}$$

PV TECHNOLOGIES
Materials availability



Potential energy limits imposed by global silver (Ag) reserves for bulk-like silicon photovoltaic technologies. The orange shaded area represents limits reached using 50 mm-thick Ag ribbons. The green shaded area represents limits estimated using a 2 mm thick Ag electrodes and 5% grid shadowing.

A.Feltrin, A.Freundlich, *Material considerations for TW level deployment of PV,* Renewable Energy 33 (2008) 180–185

PV TECHNOLOGIES
Materials availability

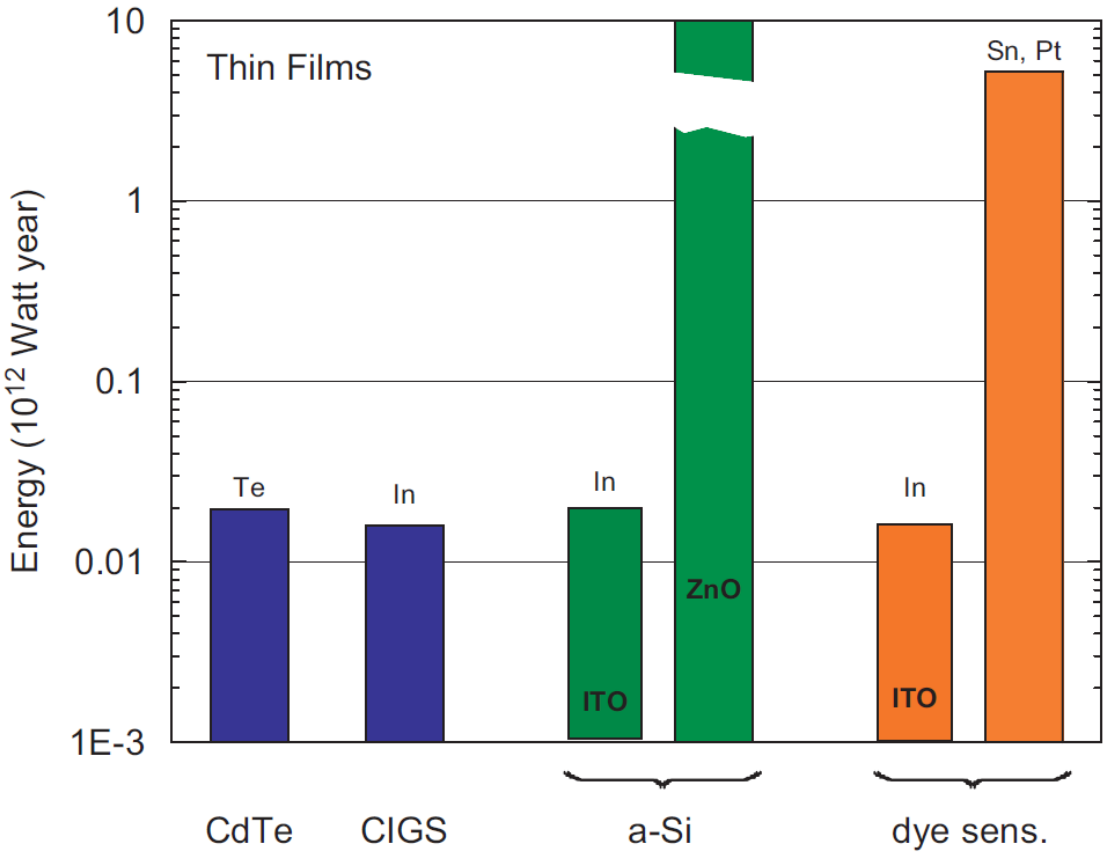


Fig. 4. Potential energy limits imposed for four different thin film photovoltaic technologies.

A.Feltrin, A.Freundlich, *Material considerations for TW level deployment of PV,* Renewable Energy 33 (2008) 180–185

PV TECHNOLOGIES
Materials availability

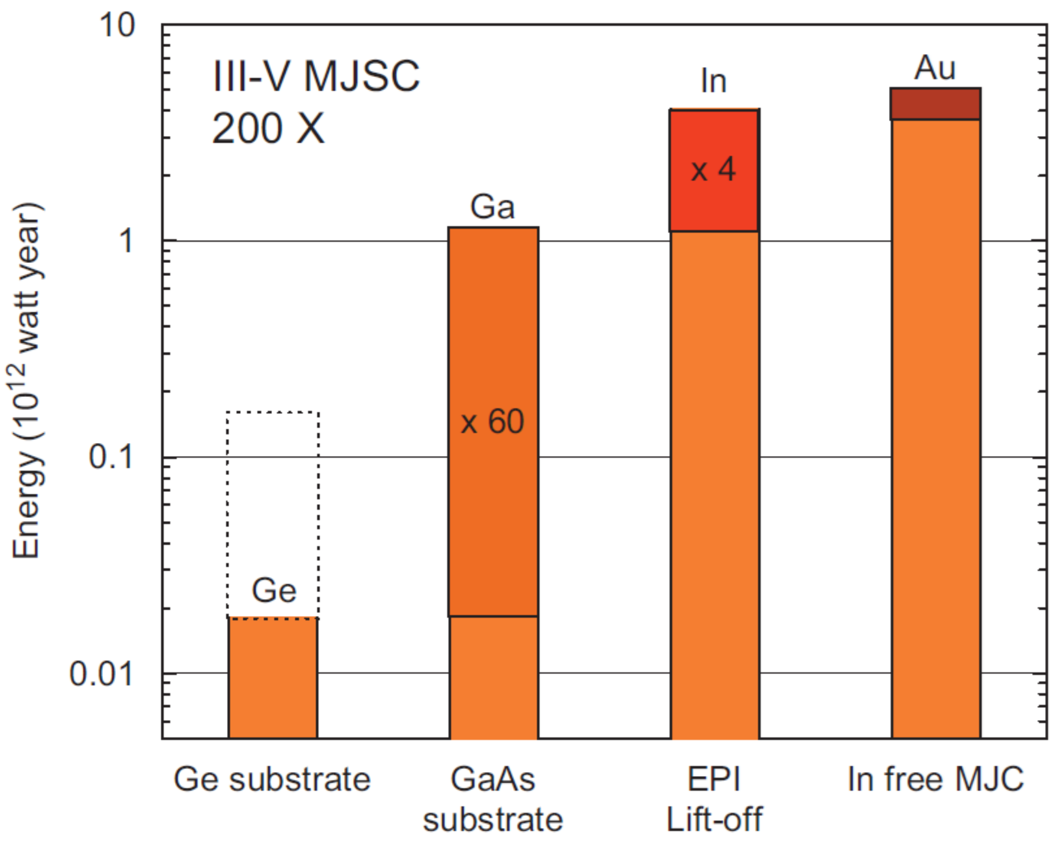


Fig. 5. Potential energy limits imposed to III–V multi-junction cells (200 sun concentrations). The third and fourth columns show the extrapolated potential of this technology if lift-off/cell exfoliation techniques are adopted.

A.Feltrin, A.Freundlich, *Material considerations for TW level deployment of PV,* Renewable Energy 33 (2008) 180–185

PV TECHNOLOGIES
Comparing different technologies

Considering all these factors…

- Silicon technologies are to dominate the market in the foreseeable future
- Opportunities for other technologies with industrial scale, in particular CdTe (e.g. First Solar)
- Niche markets are breeding ground for other ‘new’ technologies (thin films in BIPV or flexible applications, concentration for large solar power plants, etc)