Energy Conversion by Semiconductor Devices

Jun-Ho YUM
junho.yum@epfl.ch

- Solar Cells
  - 1st generation wafer based solar cells
    - Single-crystalline Si solar cells
    - Polycrystalline Si solar cells
  - 2nd generation thin film solar cells
    - Amorphous Si solar cells
    - CdTe thin film solar cells
    - CdS thin film solar cells
    - CIGS thin film solar cells
  - 3rd generation solar cells
    - Organic Photovoltaics
    - Dye-sensitized solar cells
    - Perovskite solar cells
    - Quantum dot solar cells

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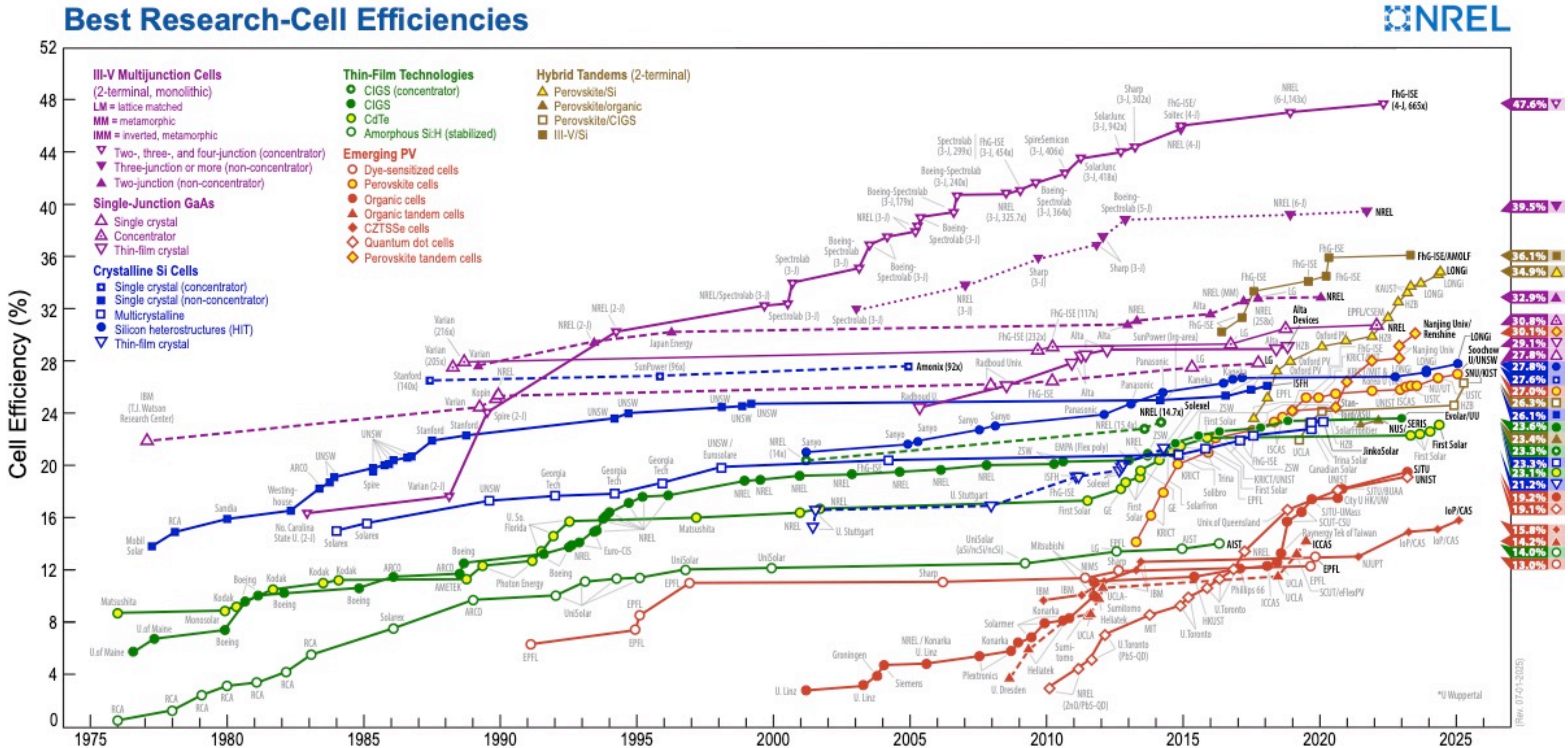
NREL Best Research-Cell Efficiencies



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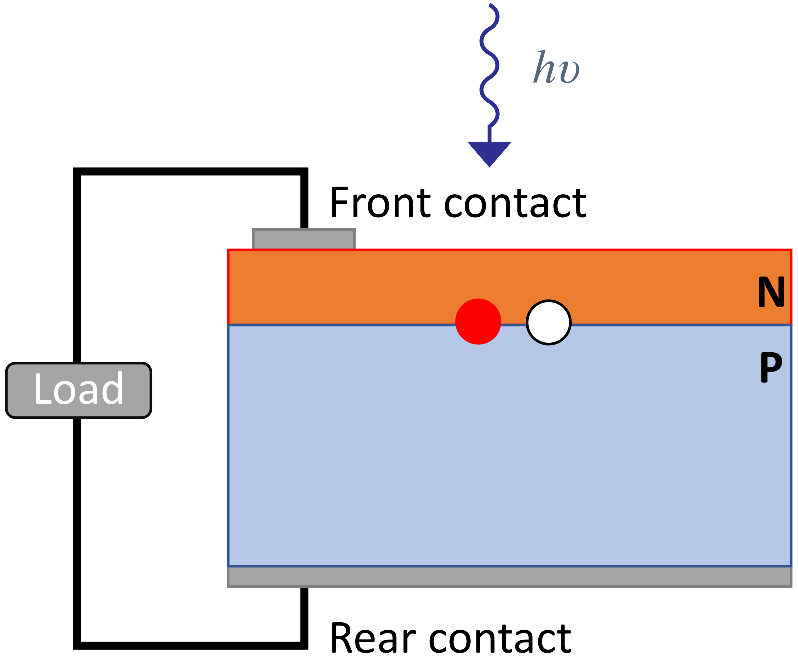
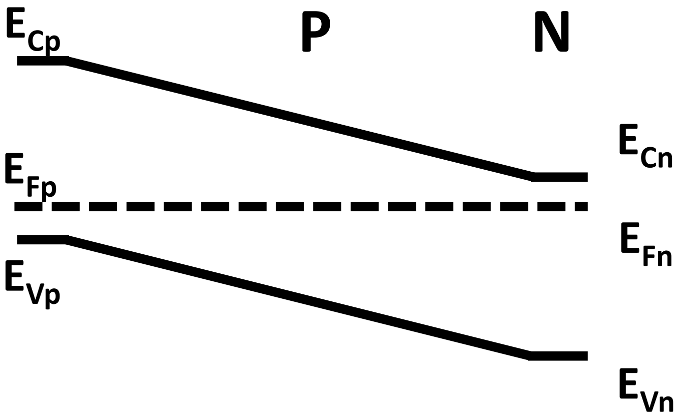
pn Junction Solar Cell

- In general, the n region is heavily doped and thin so that the light can penetrate through it easily.
- The p region is lightly doped so that most of the depletion region lies in the p side.
- Main two processes: carrier generation and carrier collection.
- Electron-hole pairs are generated by the incident photon > E_g.
- The carriers are separated by the E-field existing at the p-n junction.
- The electron-hole pairs exist, on average, for a length of time equal to the minority carrier lifetime before they recombine.





See the animation in https://www.pveducation.org/pvcdrom/solar-cell-operation/light-generated-current

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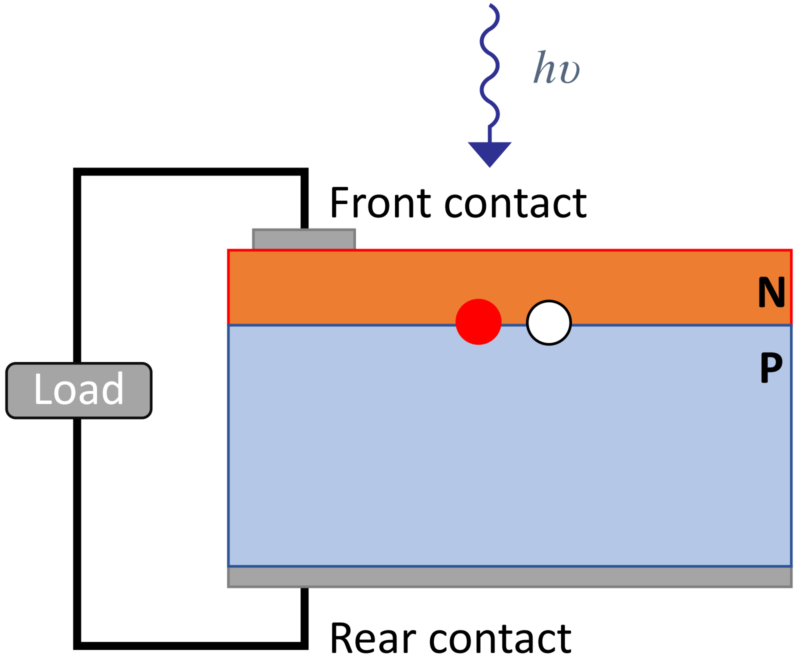

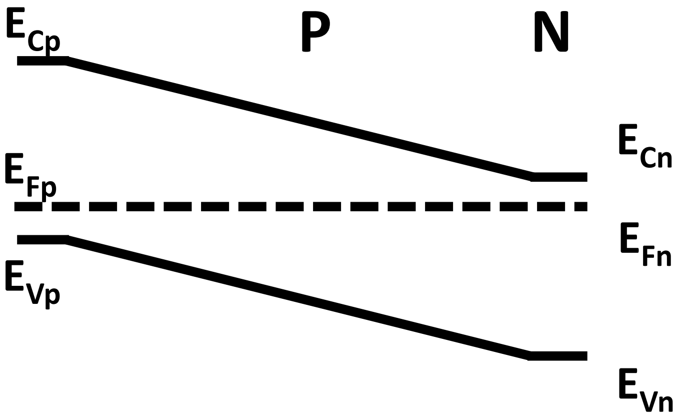

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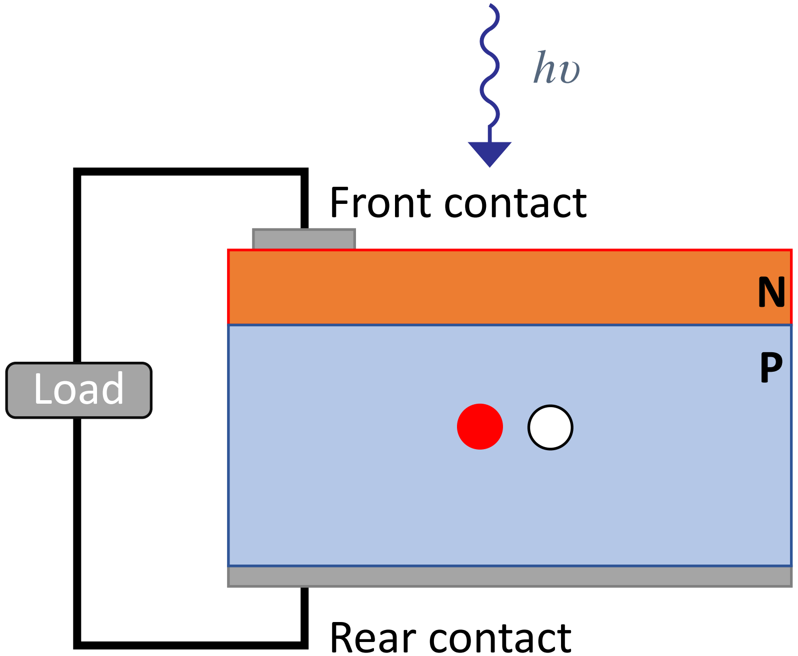

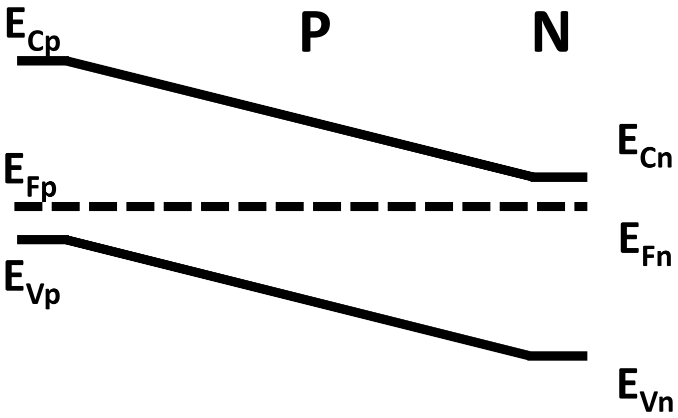

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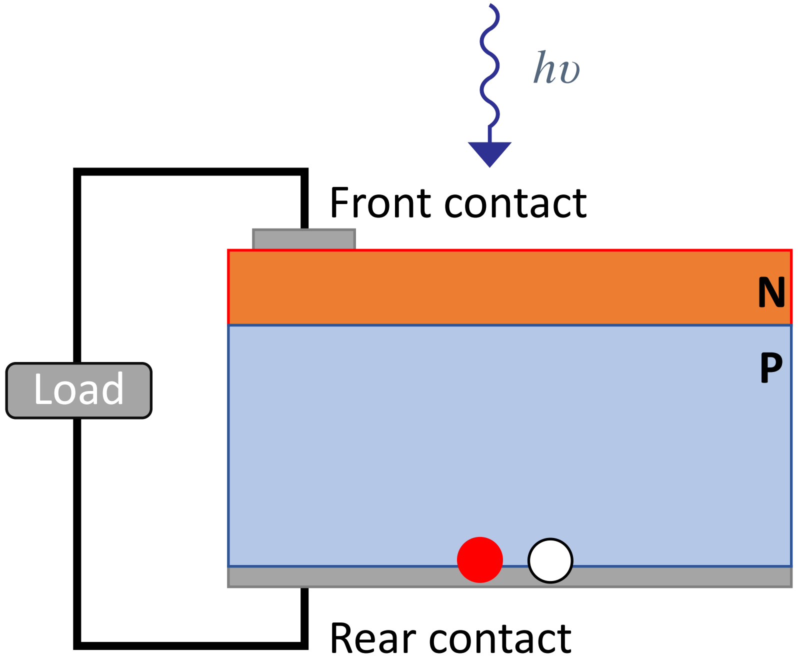

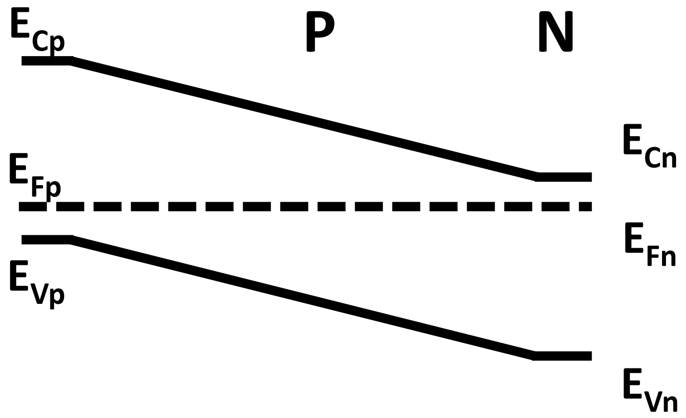

See the animation in https://www.pveducation.org/pvcdrom/solar-cell-operation/light-generated-current

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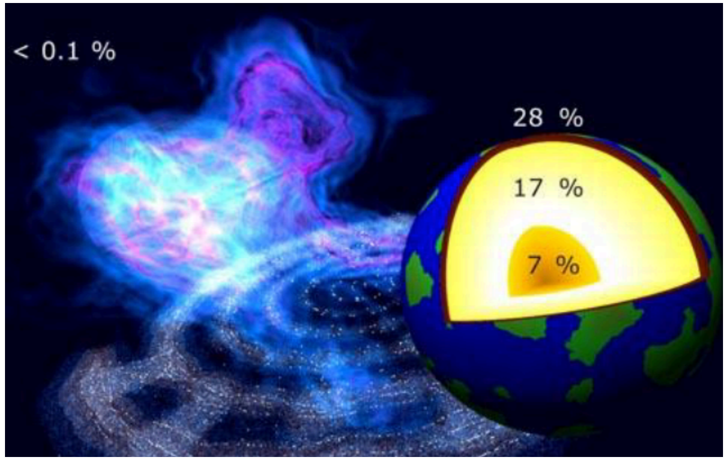
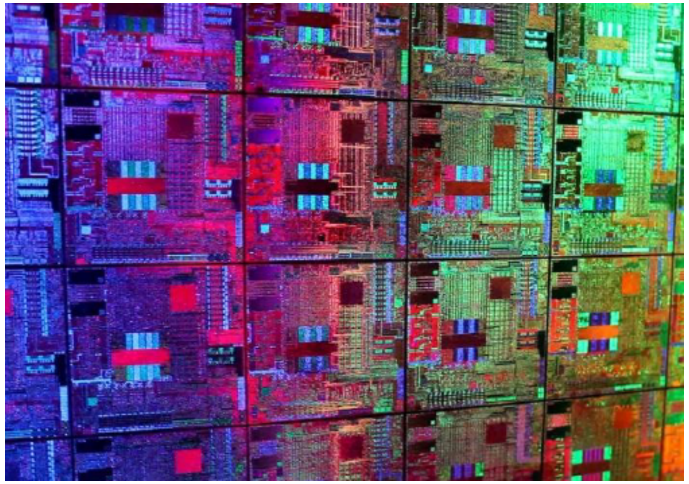
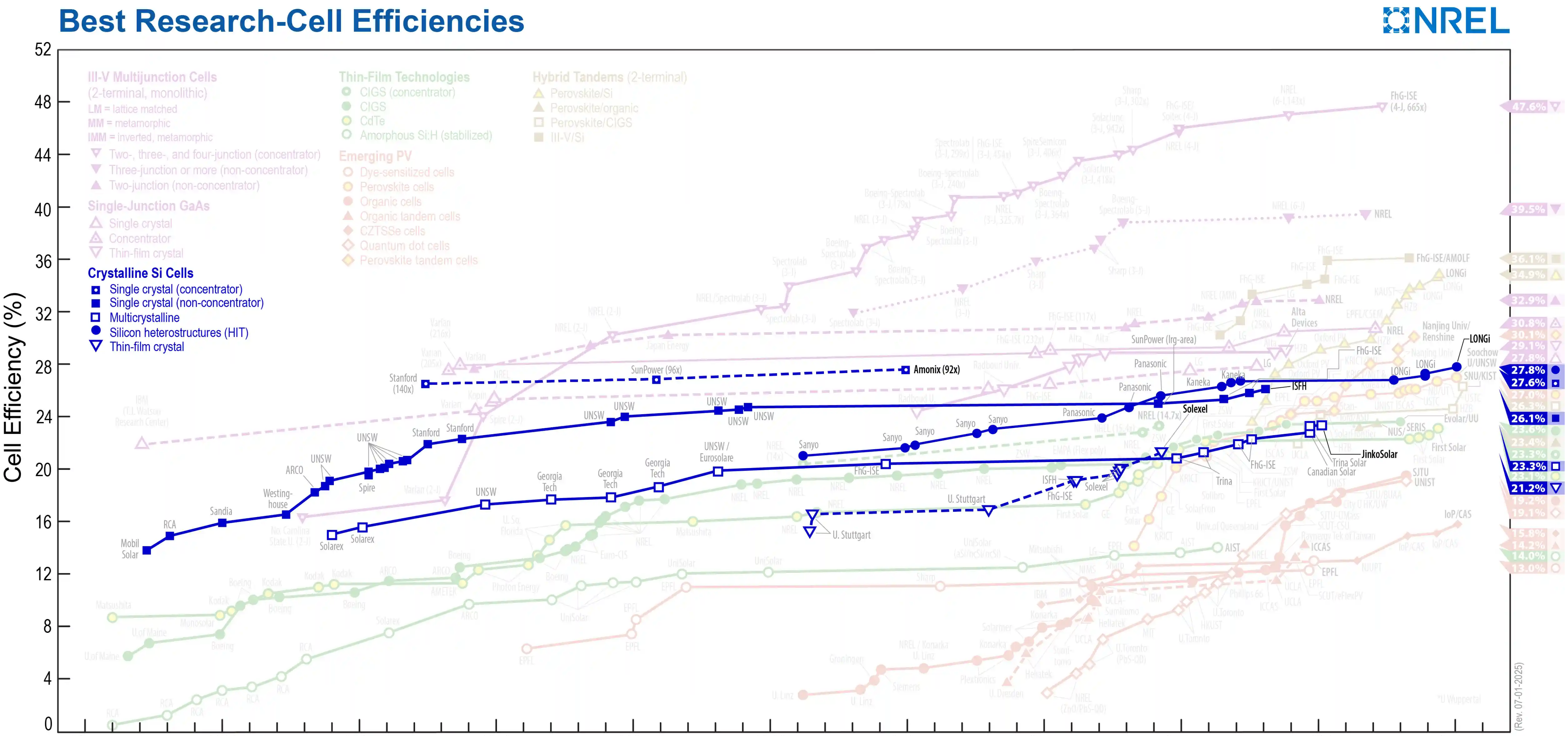
Silicon Solar Cell

Si has suitable Eg, 1.12 eV
Doing is possible
Abundant and non-toxic
Mostly used in microelectronics





Type of Silicon for Solar Cells



27.8%

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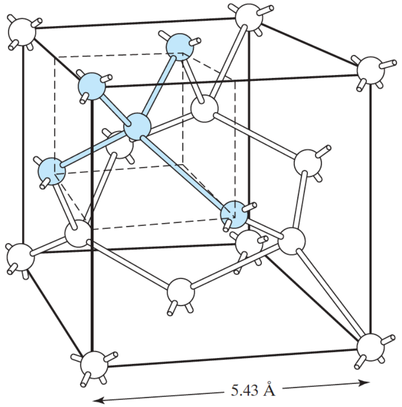
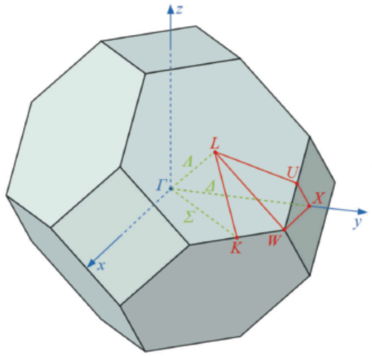
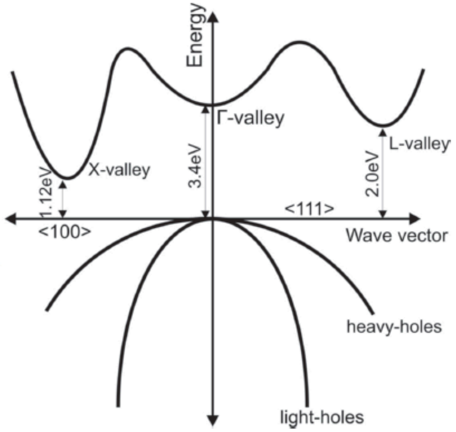
Crystalline Silicon

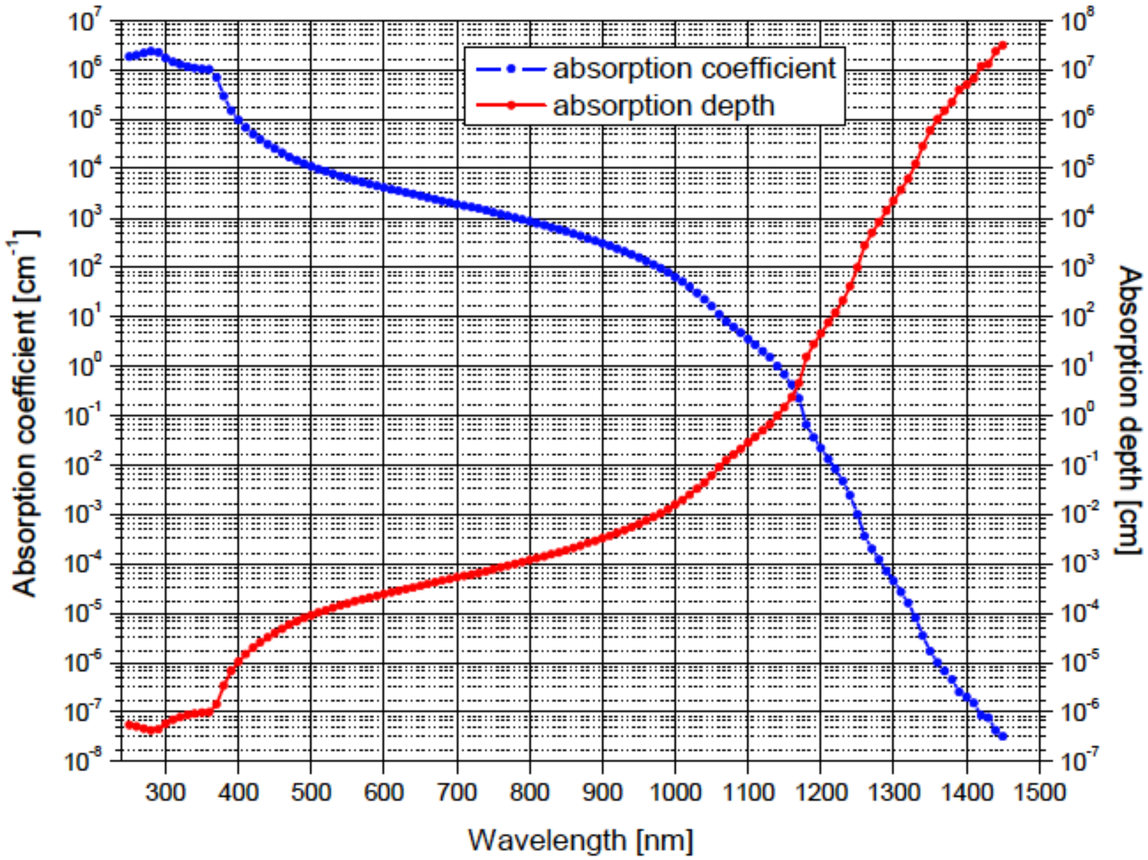
Bond angle is 109º28′ and bond length is approximately 2.35 Å.



Indirect band gap is 1.12 eV







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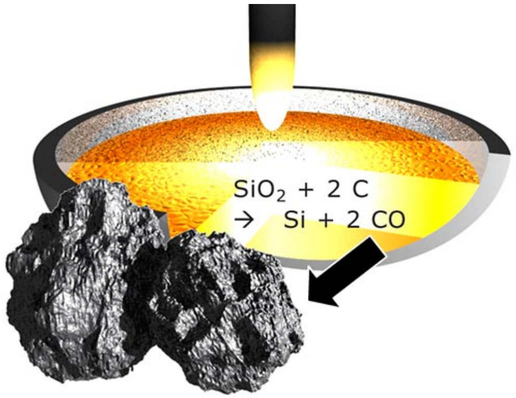
From Sand to Silicon Single Crystal

Reduction of SiO_2 with carbon to metallurgical grade silicon (>98%) in an electric arc furnace



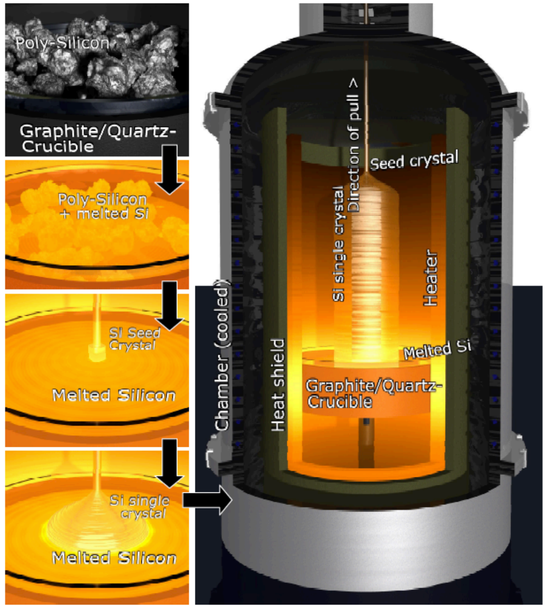
$Si + 3HCl \rightarrow HSiCl_3 + H_2$

Purification of Silicon by distillation (Siemens Process)

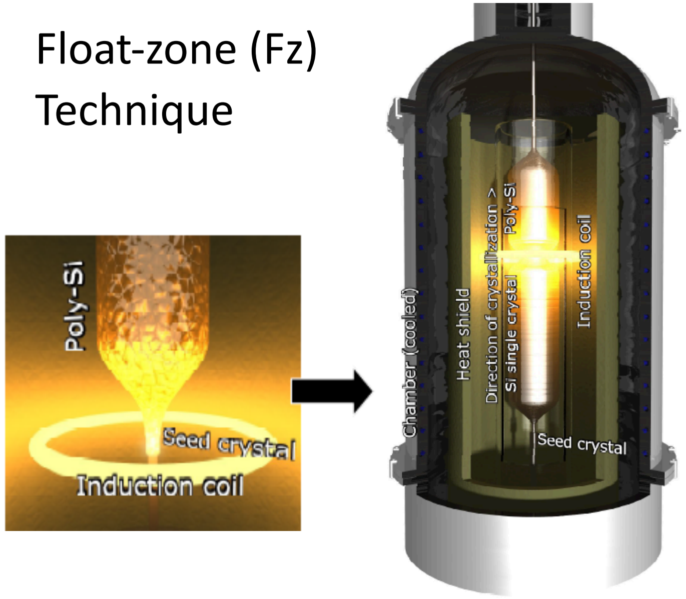
$HSiCl_3 + H_2 \rightarrow Si + 3HCl$

Electronic grade poly silicon (9N, impurities < 10^{14} cm^{-3})

Czochralski (Cz) Technique



Float-zone (Fz) Technique

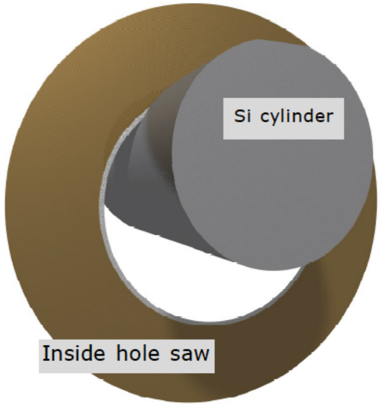


https://www.microchemicals.com/products/wafers/wafer_brochure.html

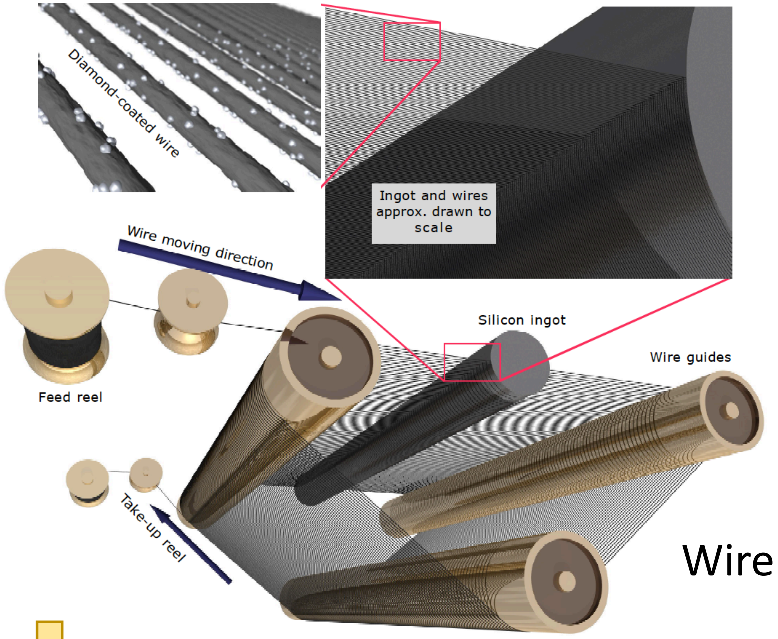
From Single Crystal to Polished Wafer

Grinding

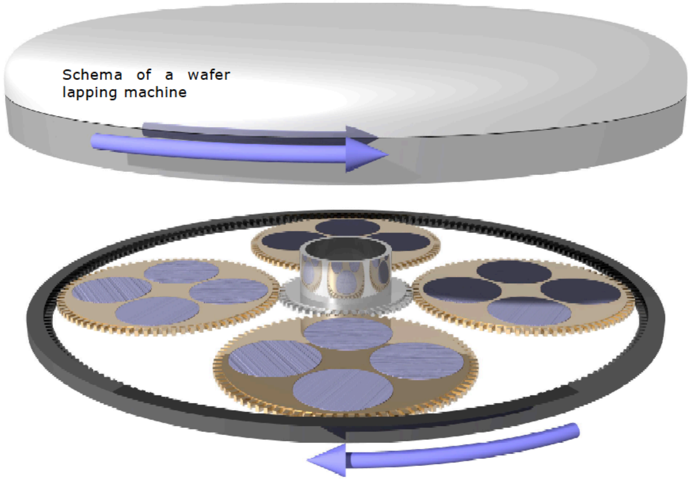
Dicing



Inside Hole Saw



Wire Saw

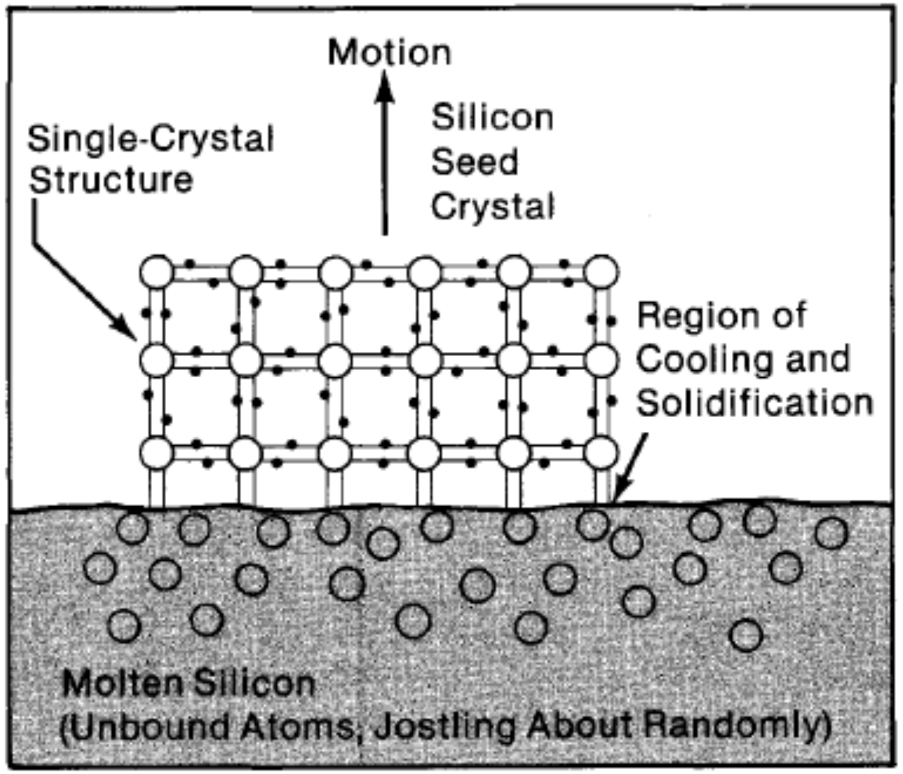


Lapping

Etching, Polishing, Cleaning

https://www.microchemicals.com/products/wafers/wafer_brochure.html

From Sand to Silicon Single Crystal



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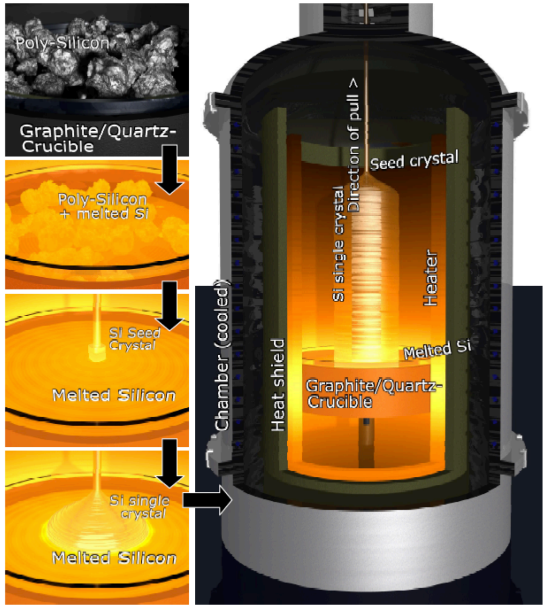

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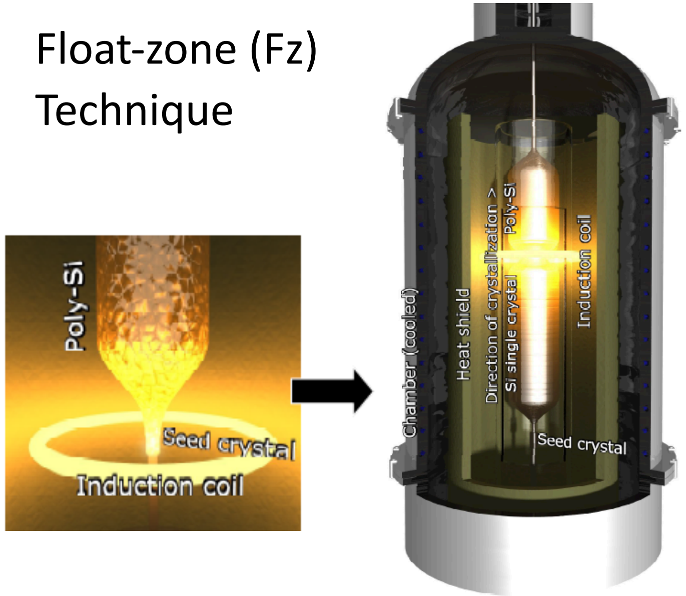

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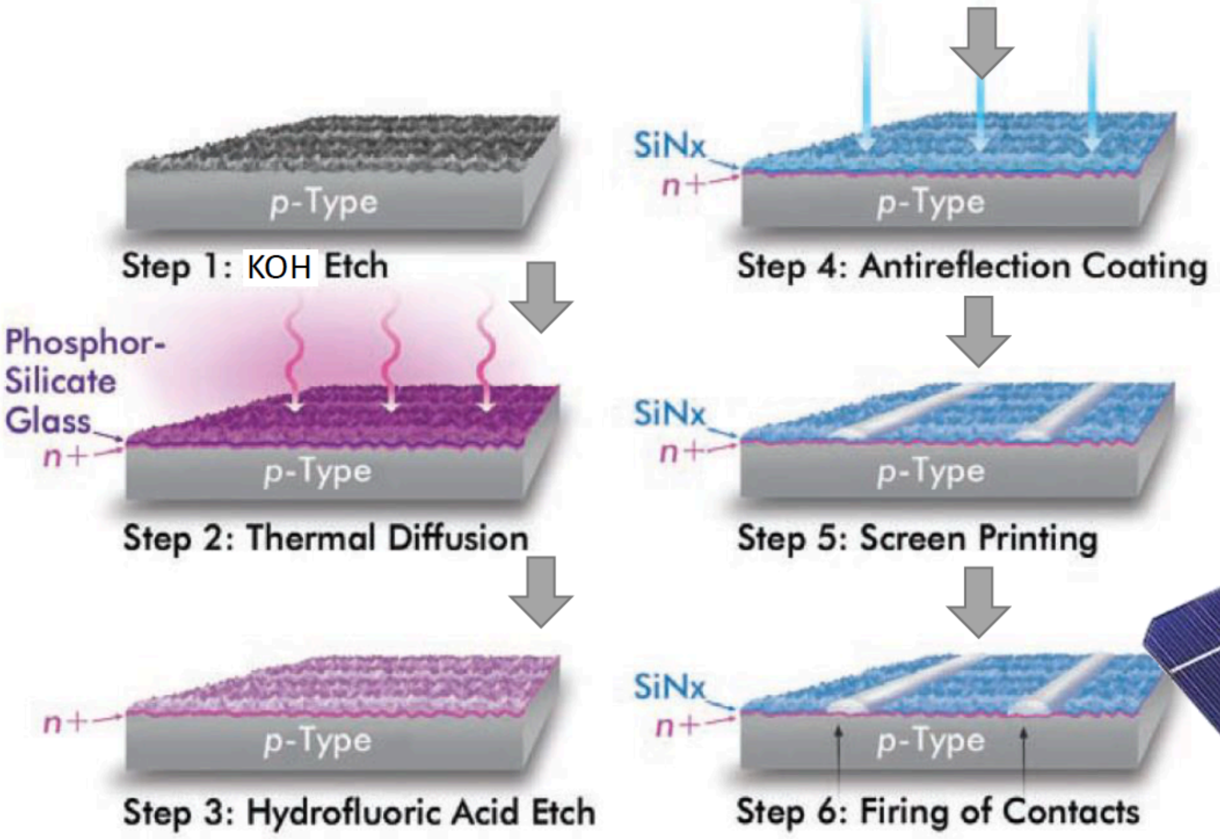
Single Crystalline Si Solar Cell Cell Fabrication Technologies

Screen Printed Solar Cells: https://www.pveducation.org/pvcdrom/manufacturing-si-cells/screen-printed-solar-cells

Buried Contact Solar Cells: https://www.pveducation.org/pvcdrom/manufacturing-si-cells/buried-contact-solar-cells

High Efficiency Solar Cells: https://www.pveducation.org/pvcdrom/manufacturing-si-cells/high-efficiency-solar-cells



Refractive index:
Air (~1)
SiN_x (~2)
Si (~3.88)

Mono-Crystalline Solar Cell

Newport Corp./Spectra-Physics

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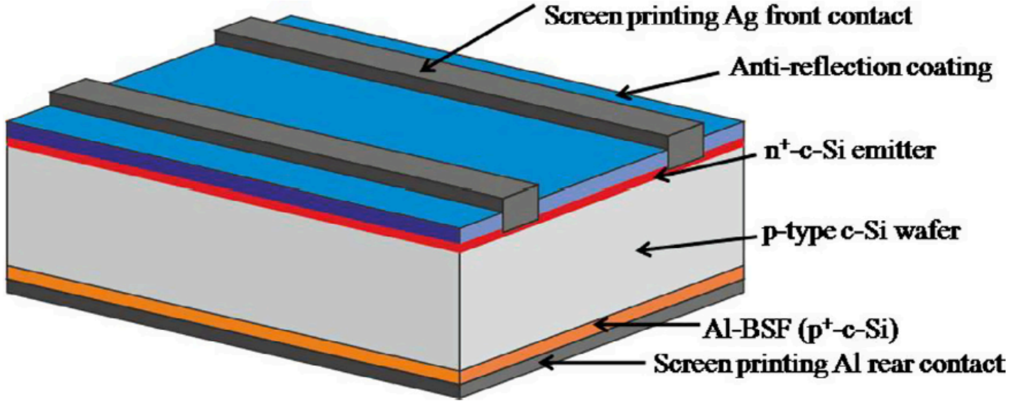
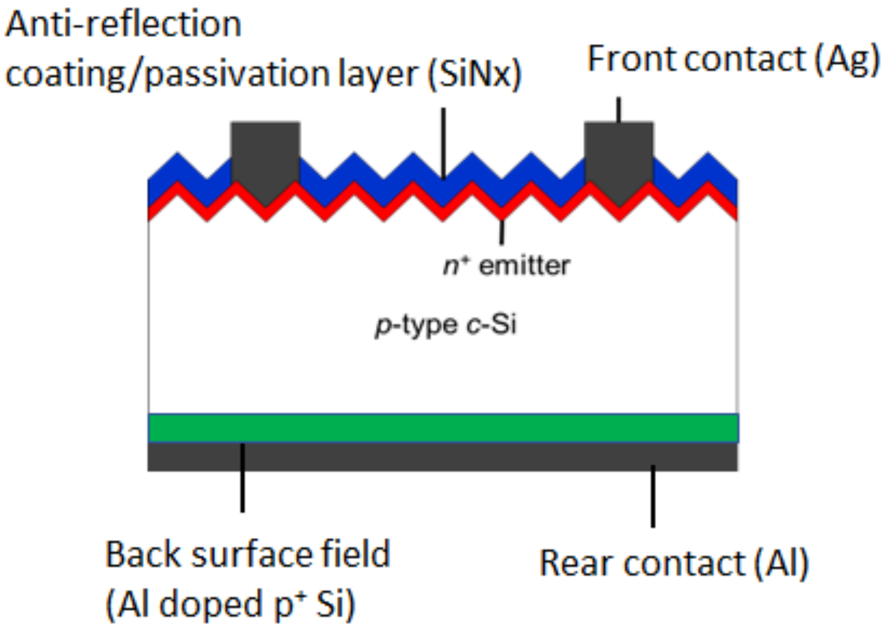
Single Crystalline Si Solar Cells Architecture

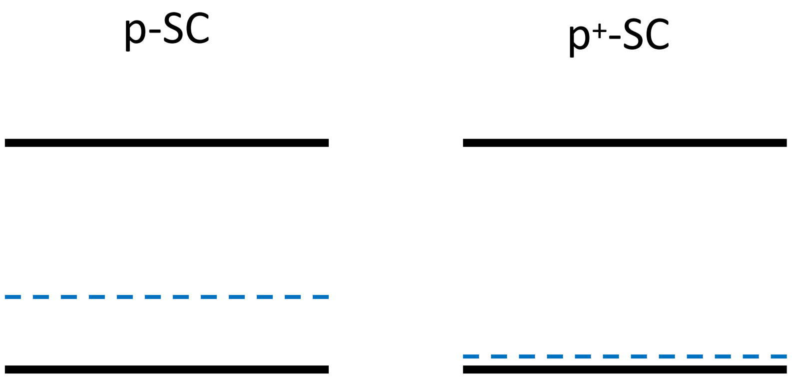
Conventional Si Solar Cell: Al-back surface field (BSF) solar cell





- At the rear side, a heavily Al-doped p^+-region in p-type c-Si forms a high-low (p^+/p) junction known as Al-BSF.
- The potential barrier at the high-low (p^+/p) junction drives electrons away from reaching the back electrode and towards the pn junction (Reduced surface recombination)

→ Increase in V_{oc} and J_{sc}.



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Single Crystalline Si Solar Cells Architecture

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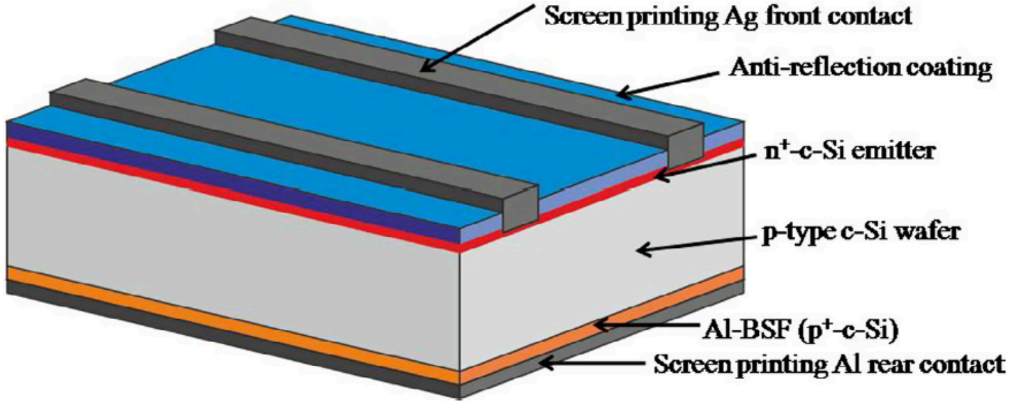

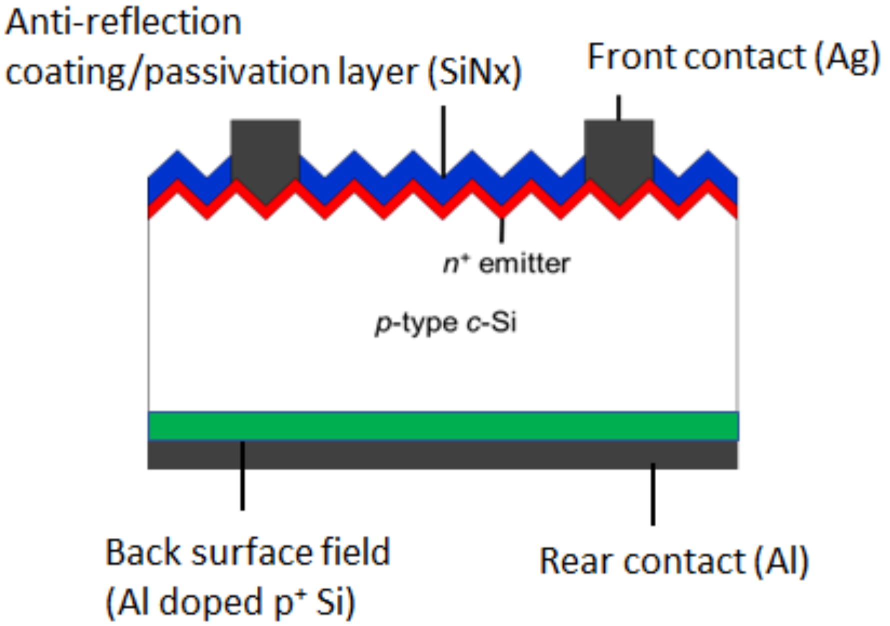

- At the rear side, a heavily Al-doped p⁺-region in p-type c-Si forms a high-low (p⁺/p) junction known as Al-BSF.
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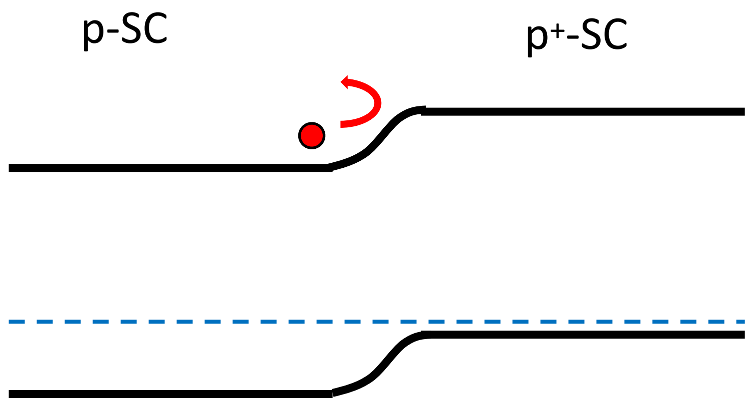

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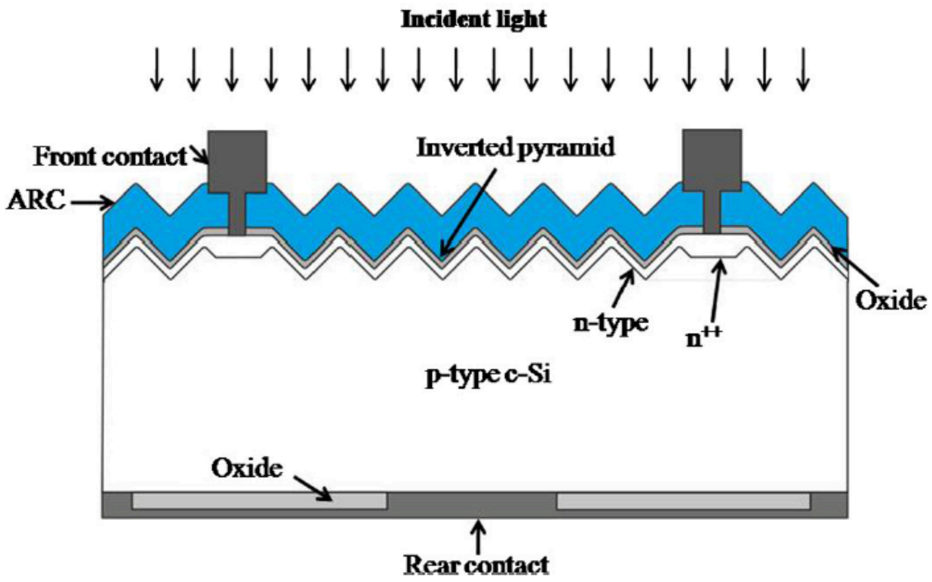
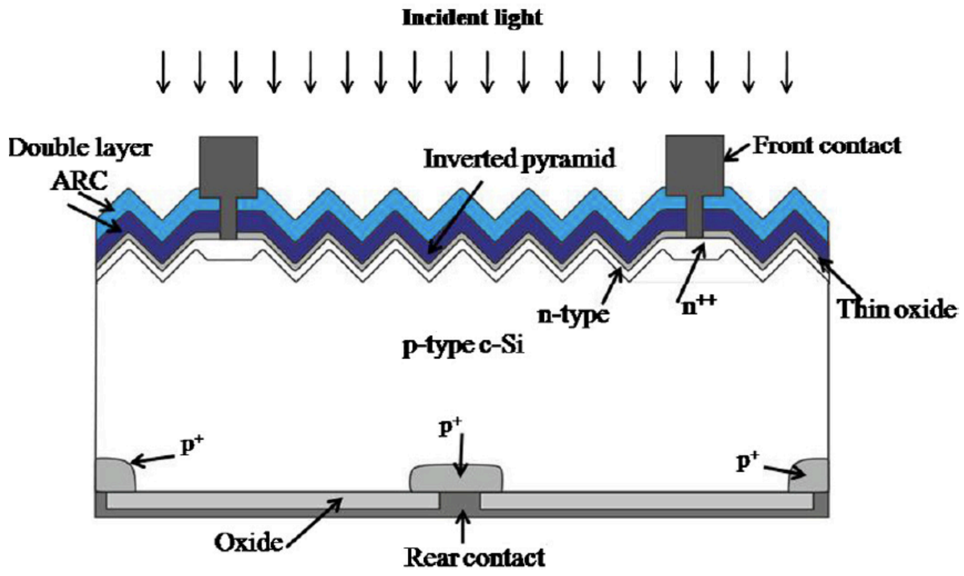
PERC and PERL Solar Cells

High Efficiency Solar Cell: passivated emitter rear contact (PERC) and passivated emitter rear locally-diffused (PERL) solar cell



Rear side dielectric passivation layer (Al_2O_3): reduced surface recombination and improved reflection.



Electric field in the BSF region between p+/p junction drives electrons away towards the pn junction and reduces surface recombination at the defective metal/c-Si interface.

21.2% with PERC and 25% with PERL

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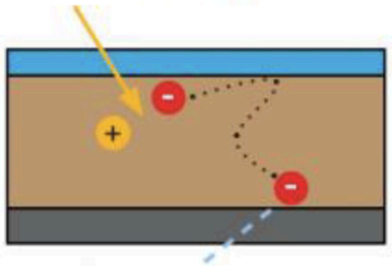
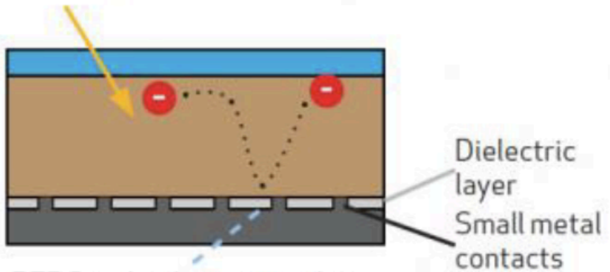
PERC and PERL Solar Cells

CONVENTIONAL CELL



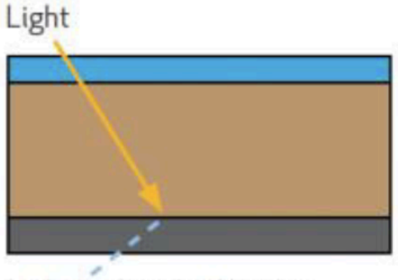
If an electron reaches the back surface, it is frequently captured and can no longer contribute to the current.

PERC CELL



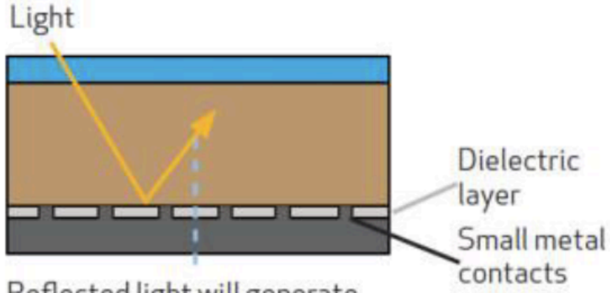
PERC technology stops the electron from being captured, and gives it a 'second chance' to reach the emitter and contribute to the current.

CONVENTIONAL CELL

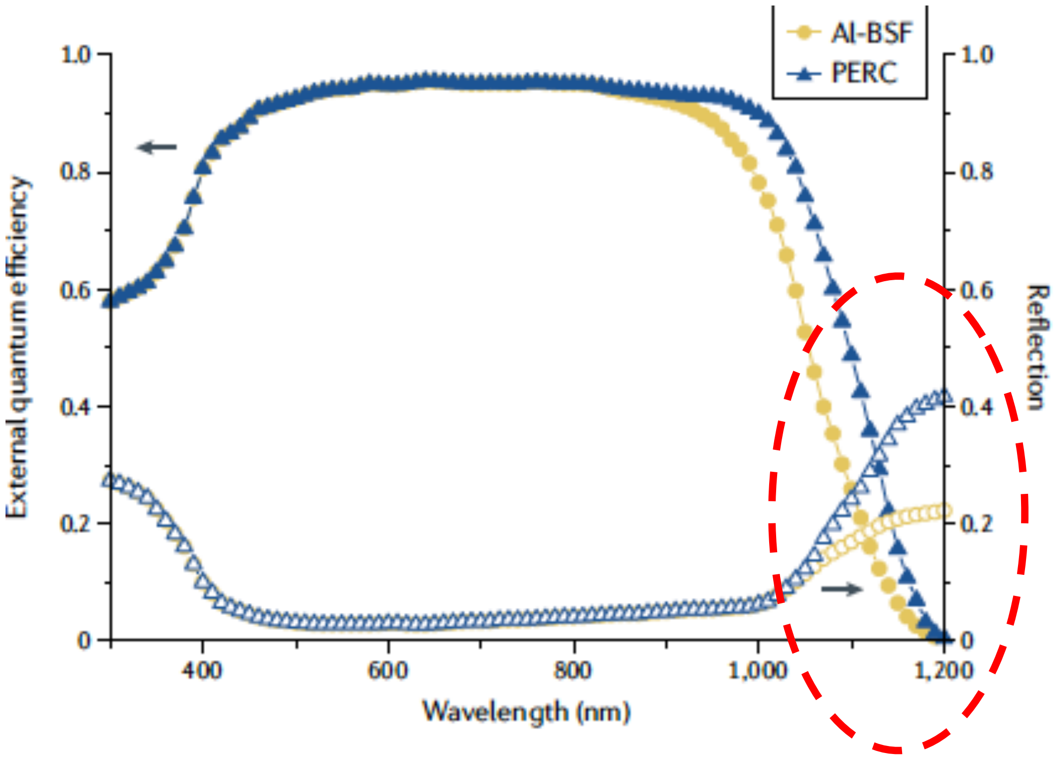


Light is absorbed by the aluminum metallization.

PERC CELL



Reflected light will generate additional current.



C. Ballif et al., *Nat. Rev. Mater.*, **7**, 597 - 616 (2022)

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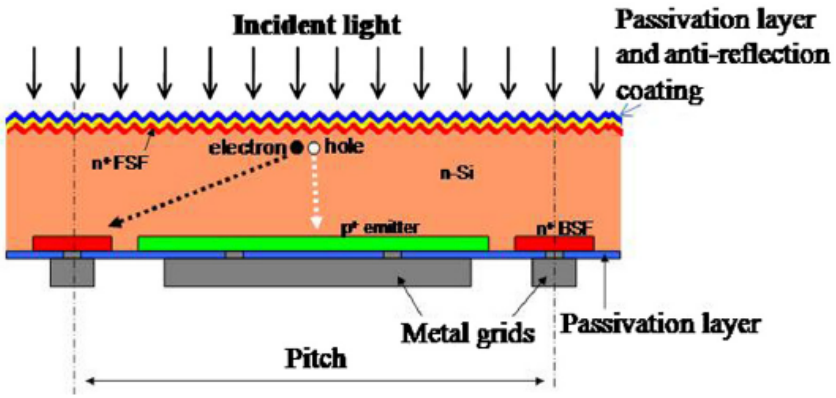
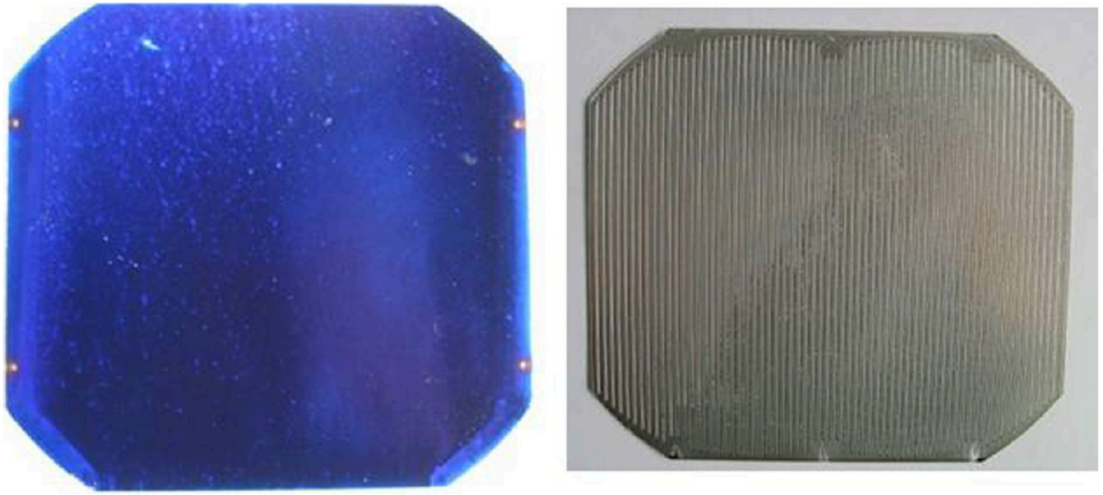
IBC c-Si Solar Cells

Interdigitated back contact (IBC) c-Si solar cells



- Major advantage: No front side metallization grid → Zero shading losses → High J_{sc}
- No limit for the width and thickness of metallization on the back side: Reduced series resistance
- Advantageous for the module manufacturing because of co-planar interconnection of the back-contact
- Passivation and light trapping properties can be optimized for the front side



Grid less front side (147.4 cm²) Rear side

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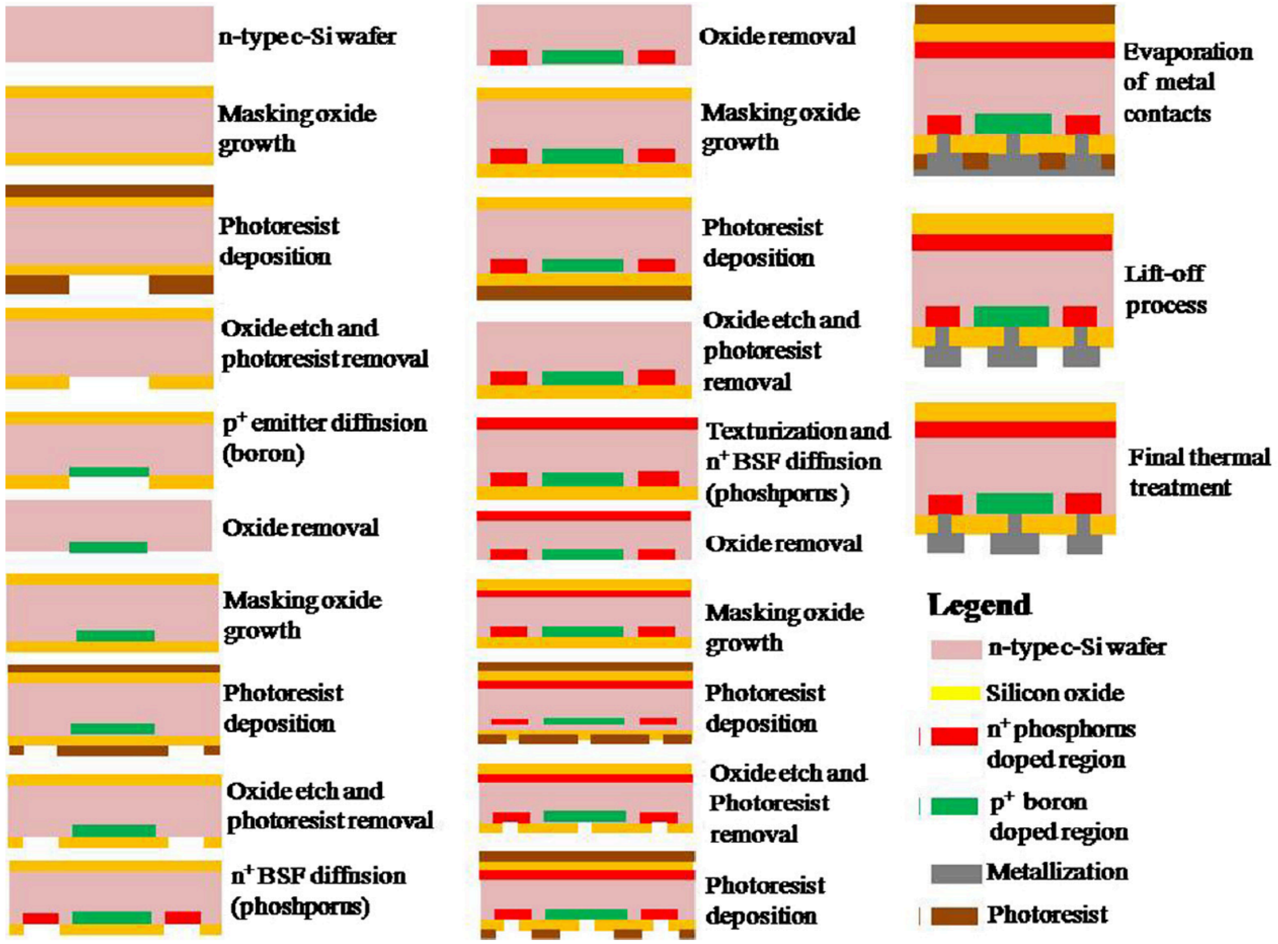
Granek F. PhD thesis. High-efficiency back-contact back-junction silicon solar cells. Verlag Dr. Hut. ISBN 978-3-86853-348-4; 2009.

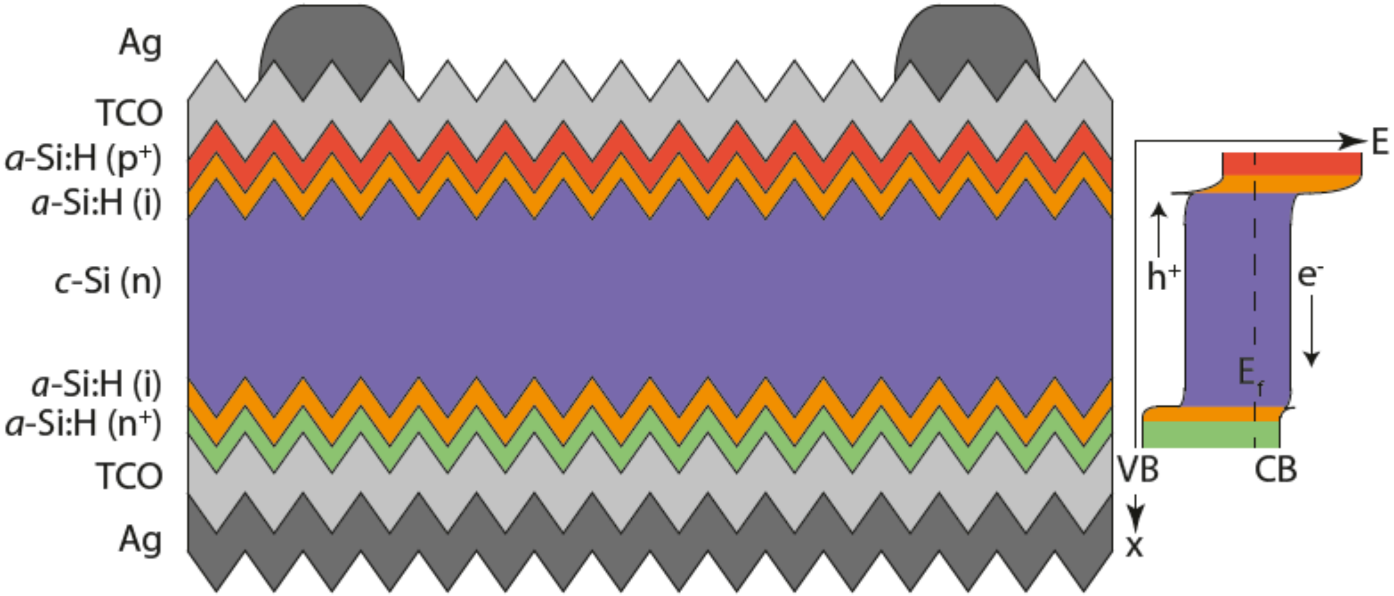
IBC c-Si Solar Cells



- The complexity of the processing technology: Example of a complex laboratory scale process flow for the IBC solar cell processing using photolithography and high-temperature diffusion processes.
- Photolithography is however not a cost-effective process for mass production in the photovoltaic industry.
- High accuracy masking steps are required to avoid shunting between p-type and n-type electrodes.
- Highly pure, lightly doped Fz c-Si wafers with diffusion length at the least four times higher than the thickness of the c-Si wafer and the lifetime of 1 – 3 ms are required.

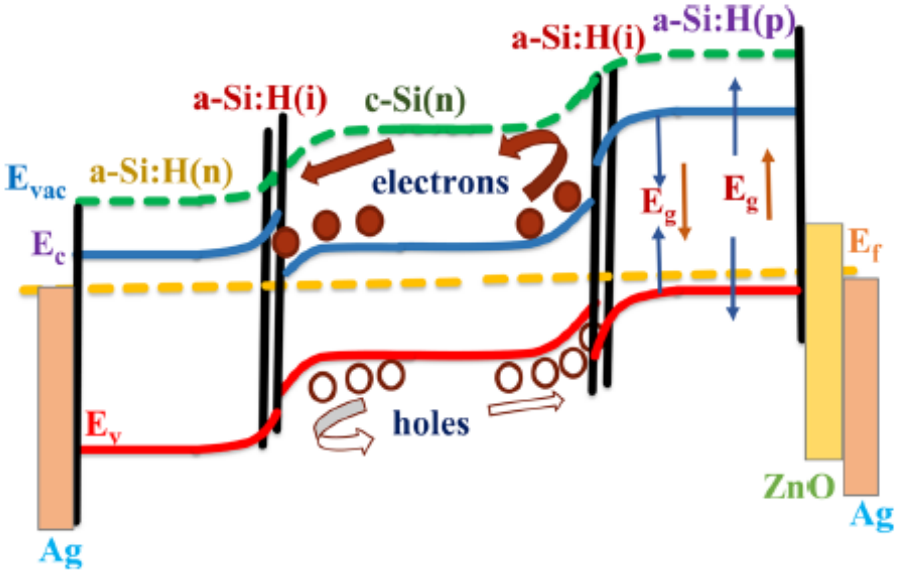
Silicon Heterojunction Solar Cell

Si Heterojunction solar cell



Wolf et al., *Green*, 2. 7 – 24 (2012)

Type I Heterojunction at c-Si and a-Si:H



V. Kanneboina, *J. Comp. Electronics*, 20:344 (2021)

- Doped (n or p) a-Si:H over-layers are used to form junctions as electron and hole collectors, allowing the fabrication of nearly recombination-free contacts.
- Long carrier lifetime by a-Si:H over-layers
- Charges trickle through the buffer layers sufficiently slowly to build up a high voltage e.g > 730 mV.

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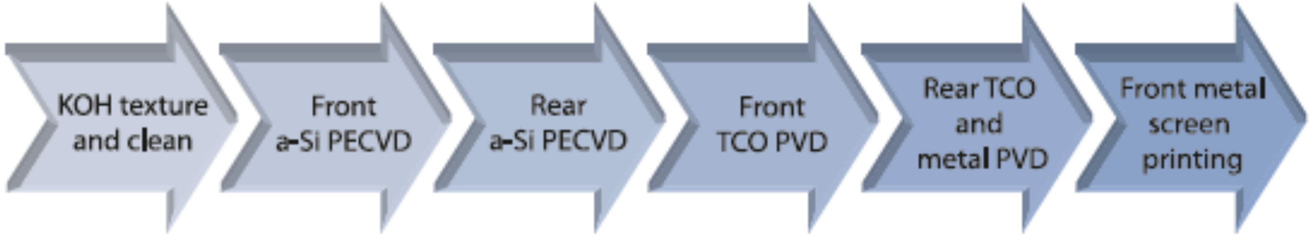
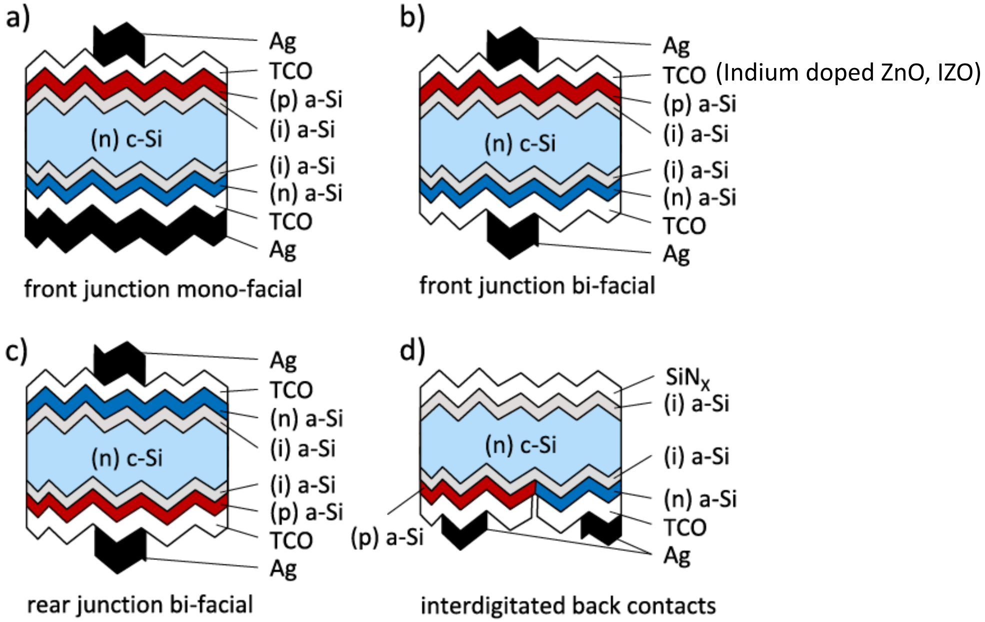
Silicon Heterojunction Solar Cells

Basic process steps for Si Heterojunction solar cell: low temperature process <200 °C



Wolf et al., *Green*, 2. 7 – 24 (2012)

Device architectures for SHJ solar cells.



a) front junction mono-facial

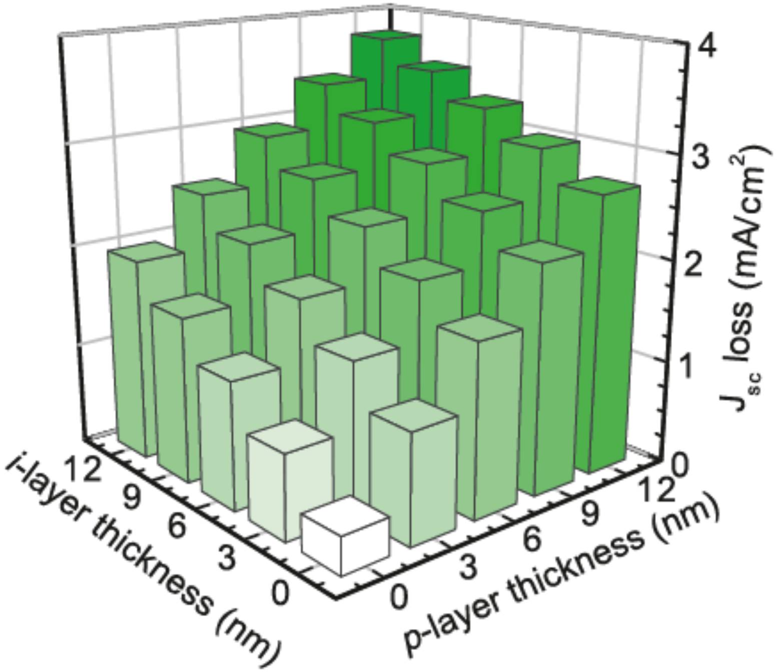
b) front junction bi-facial

c) rear junction bi-facial

d) interdigitated back contacts

Haschke et al., *Solar Energy Mater. Solar Cells*, 187. 140 – 153 (2018)

Estimate of the losses in J_{sc} below 600 nm associated with increasing intrinsic and p-type layer thicknesses: bandgap of a-Si:H (1.7–1.9 eV)



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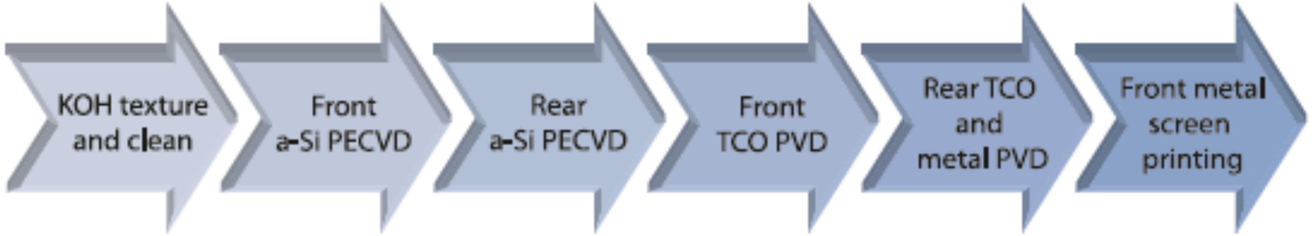

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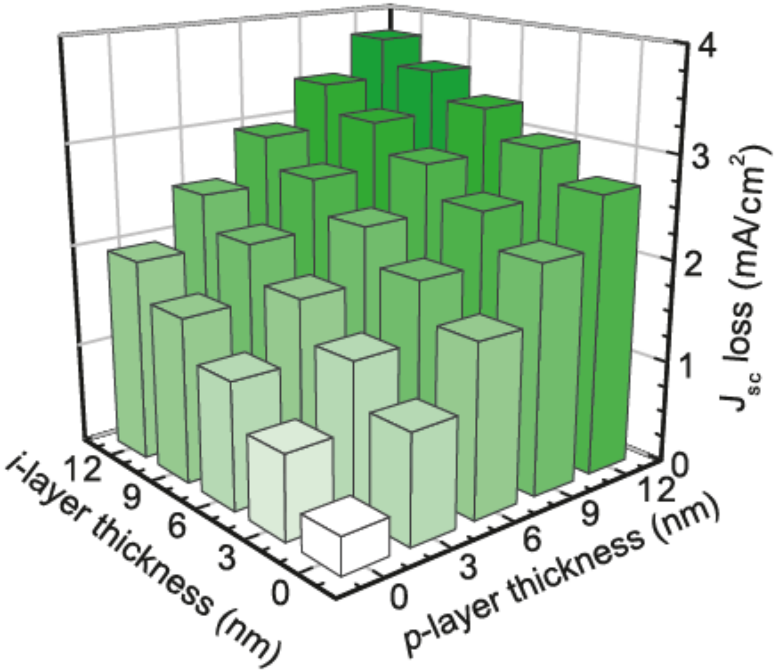


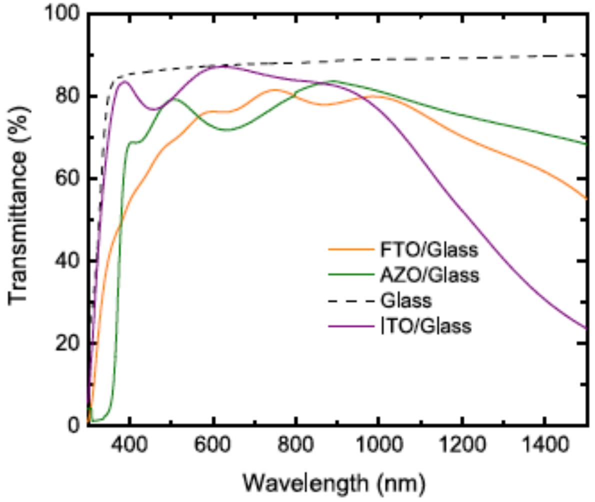
Solution!

- Improving TCO transparency.
- Replacing a-Si:H with microcrystalline Si, which has features a higher doping.
- Combination with IBC structure.
- Thinner wafer (general trend for all c-Si PV technologies) possible to further increase V_{oc}.

Transparent Conductive Oxides

- IZO (Indium doped Zinc Oxide)
- AZO (Aluminum doped Zinc Oxide)
- ITO (Indium doped Tin Oxide)
- FTO (Fluorine doped Tin Oxide)

Image from https://www.ossila.com/



Data from V. Marinova et al., Opt. Mat.: X, 22, 100330 (2024)

	IZO	AZO	ITO	FTO
Conductivity	Good (better than ITO)	Lower than ITO	Good	Lower than ITO
Transmittance	Good even in the NIR	Good	Good in the Vis	Good in the Vis
Thermal stability	Least	Lower than FTO	Lower than AZO	Good
Structure	Amorphous	Polycrystalline	Polycrystalline	Polycrystalline
Deposition method	Sputtering, Atomic Layer Deposition, CVD	Sputtering, Atomic Layer Deposition, CVD	Sputtering, Electron beam evaporation	Spray pyrolysis, Chemical vapor deposition (CVD)
Cost	High	Low	High	Low

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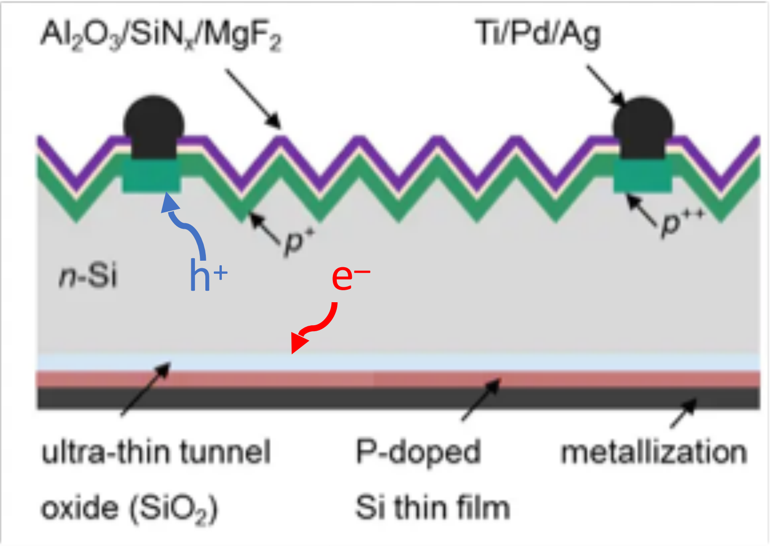
TOPCon Silicon Solar Cell

TOPCon

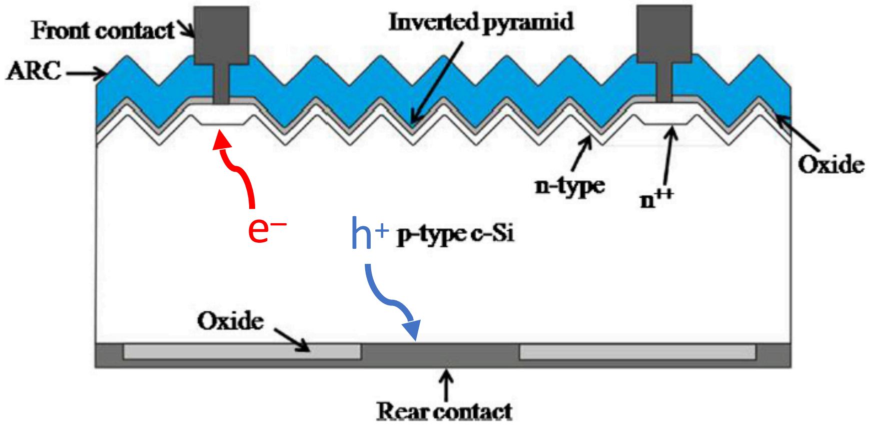


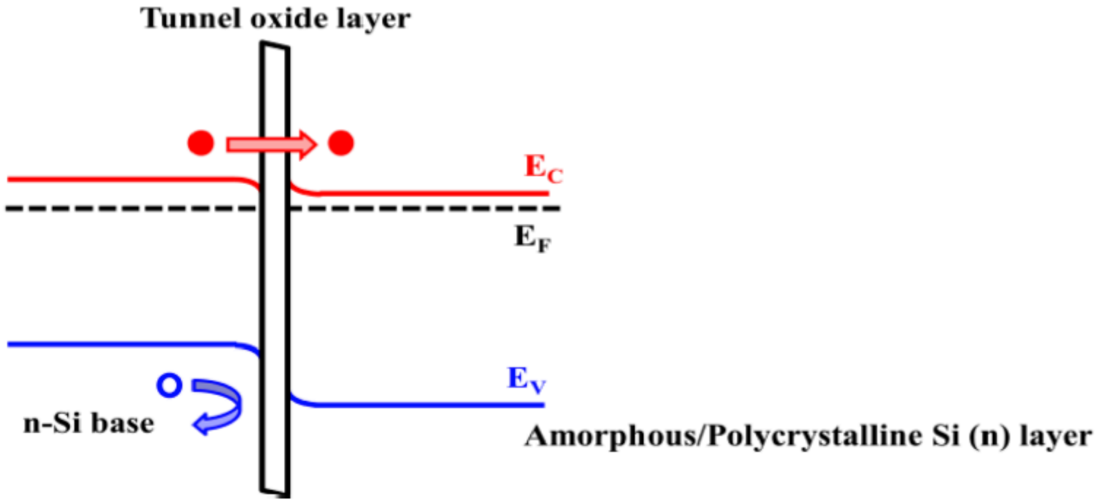
(polycrystalline)

- The term TOPCon stands for **Tunnel Oxide Passivated Contact** and the architecture was presented by researchers at the Fraunhofer Institute for Solar Energy Systems in Freiburg in 2013.
- The heavily phosphorous doped poly-Si(n) layer induces a band bending in c-Si(n) absorber .
- The thin oxide could have a slightly asymmetric tunnelling probability for electrons and holes due to differences in energy barrier heights.

$(\Delta\Phi_e < \Delta\Phi_h)$

PERC





D. K. Ghosh et al., *Surfaces and Interfaces*, 30, 101917 (2022)

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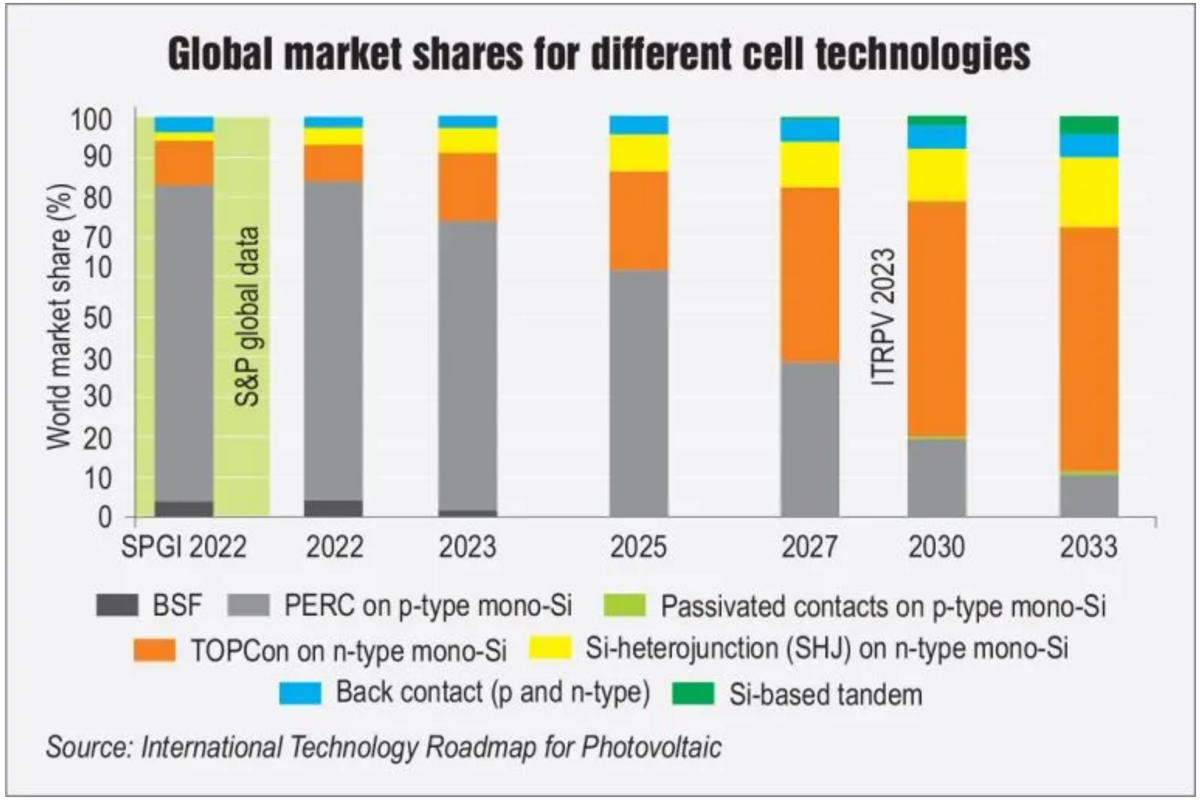
Trend for Single Crystalline Si Solar Cells



Source: International Technology Roadmap for Photovoltaic

	PERC	TOPCon	SHJ	IBC
Efficiency in mass production	23.50 %	24.80 %	25.80 %	25.00 %
Efficiency limit	24.50%	28.70%	28.70%	29.10%
Complexity on fabrication	★★	★★★	★	★★★★
Facility investment	★	★★	★★★	★★★★

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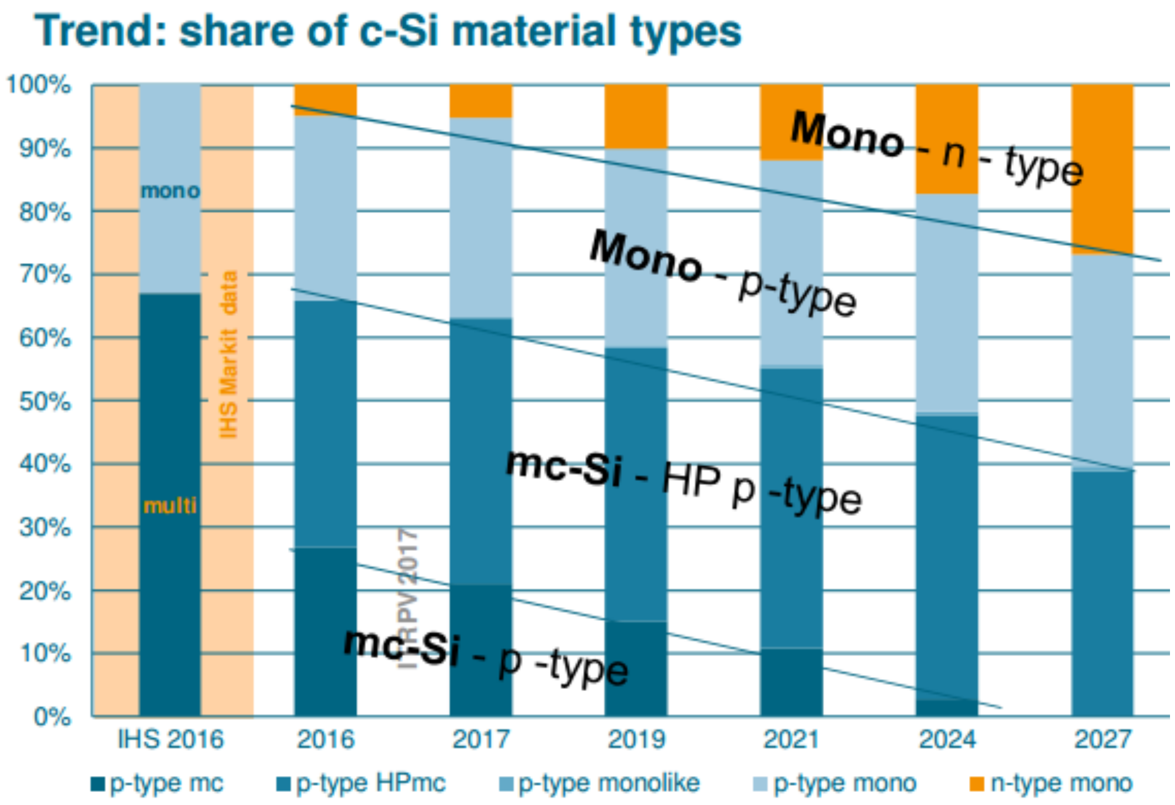
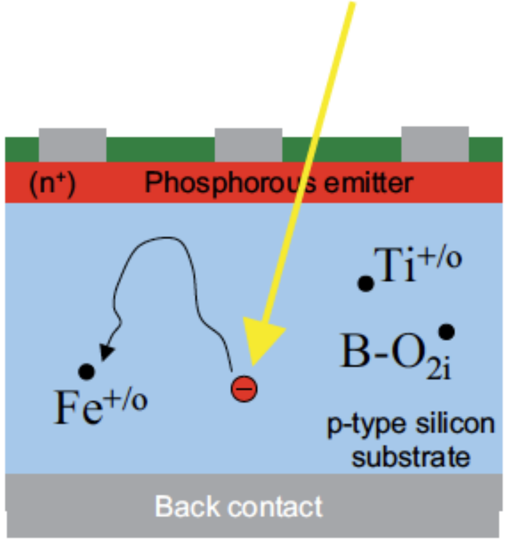
Trend for Single Crystalline Si Solar Cells



- Boron doped p-type Cz wafer: Boron (dopant) and oxygen (growth process impurity) forms a boron-oxygen related metastable defect upon illumination.

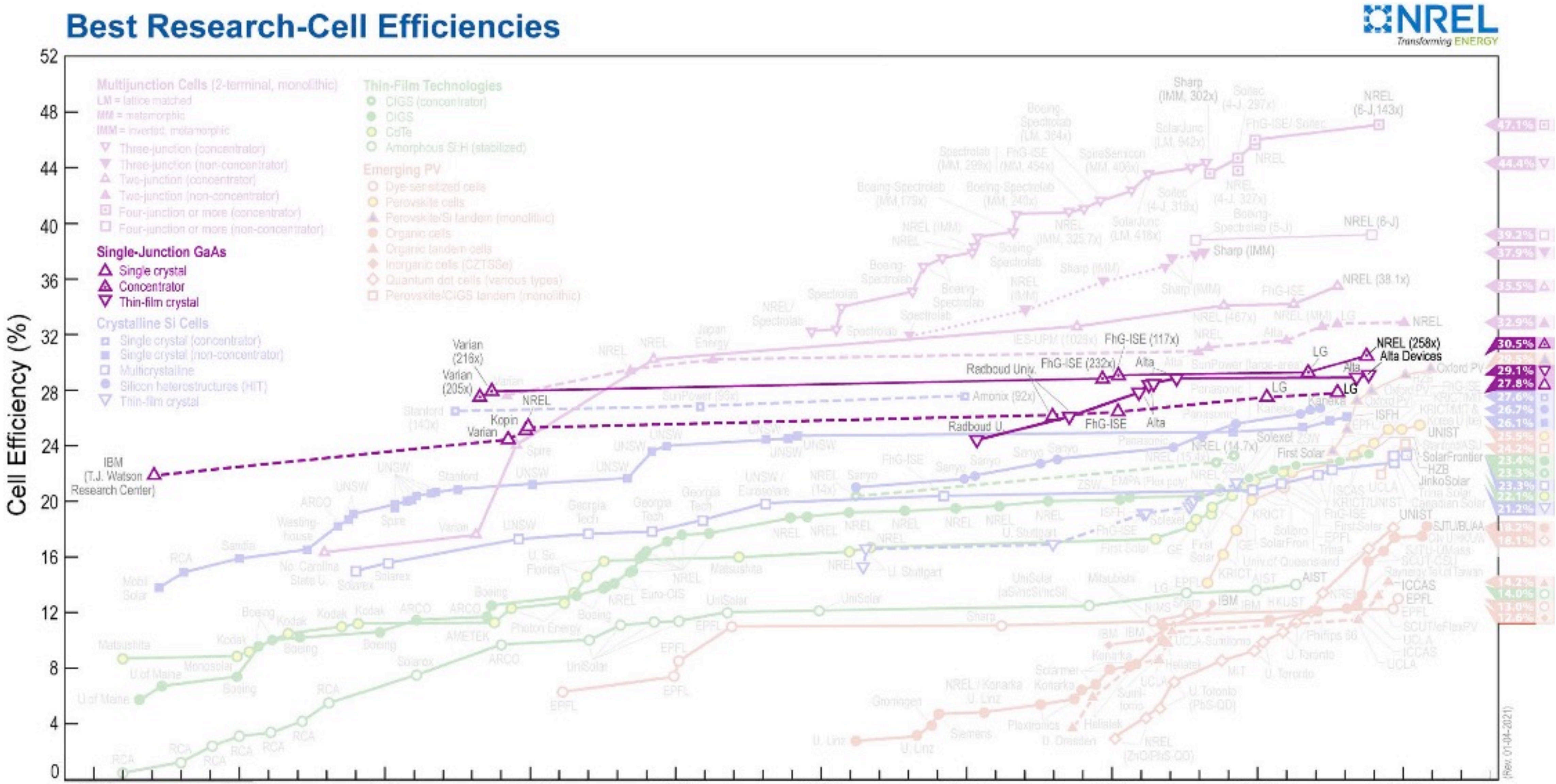
  → Solution: Boron to Gallium dopant
  FZ instead of Cz
  Regeneration process to remove the defect

- Transition metal defects, Fe in p-type wafers have an increased capture rate for minority carriers in p-type wafers (e^-).



L.J. Geerlings et al in the twelfth edition of Photovoltaics International (2011)

III-V Semiconductors: GaAs



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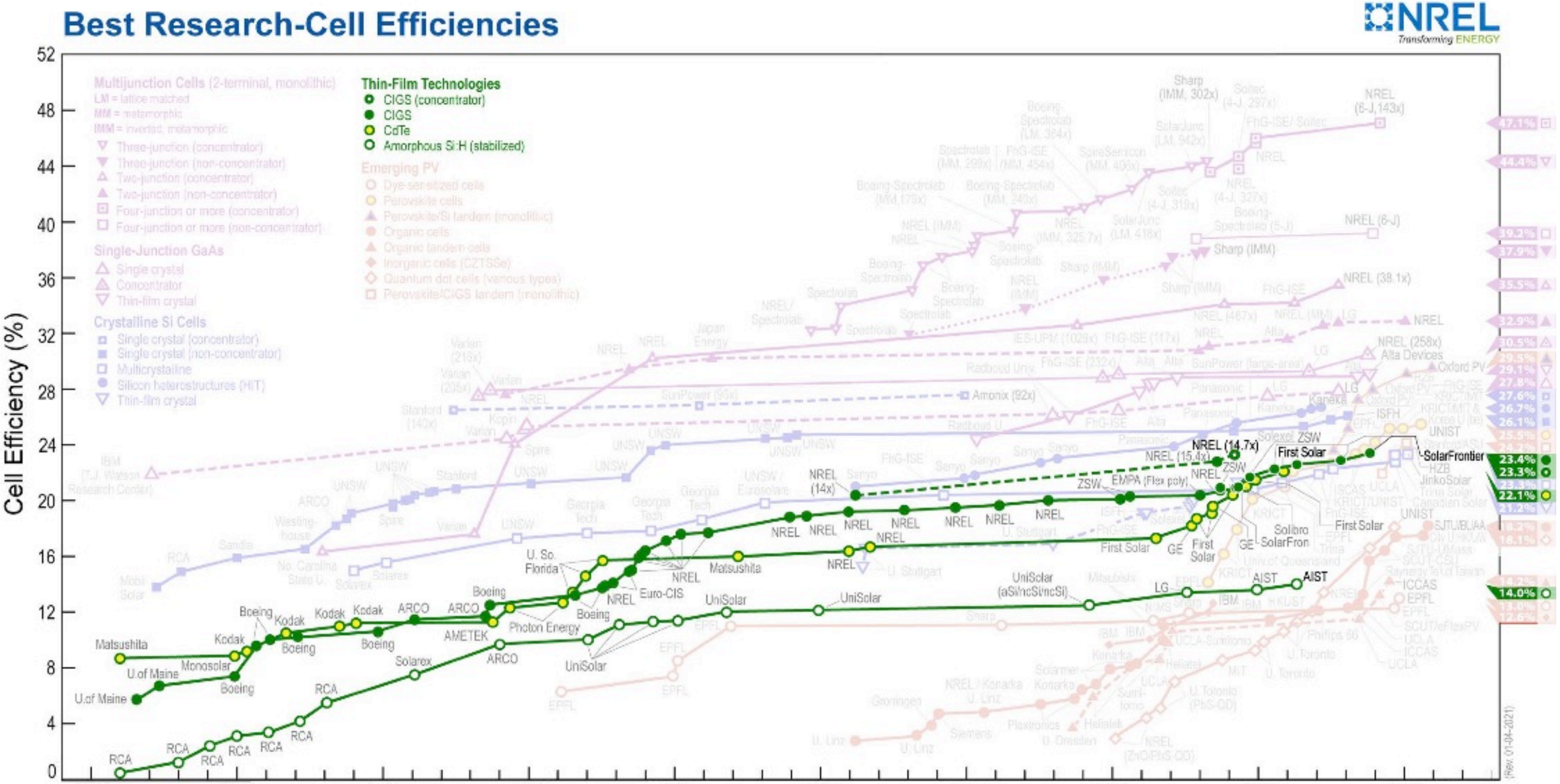
II-VI Semiconductors: CdTe



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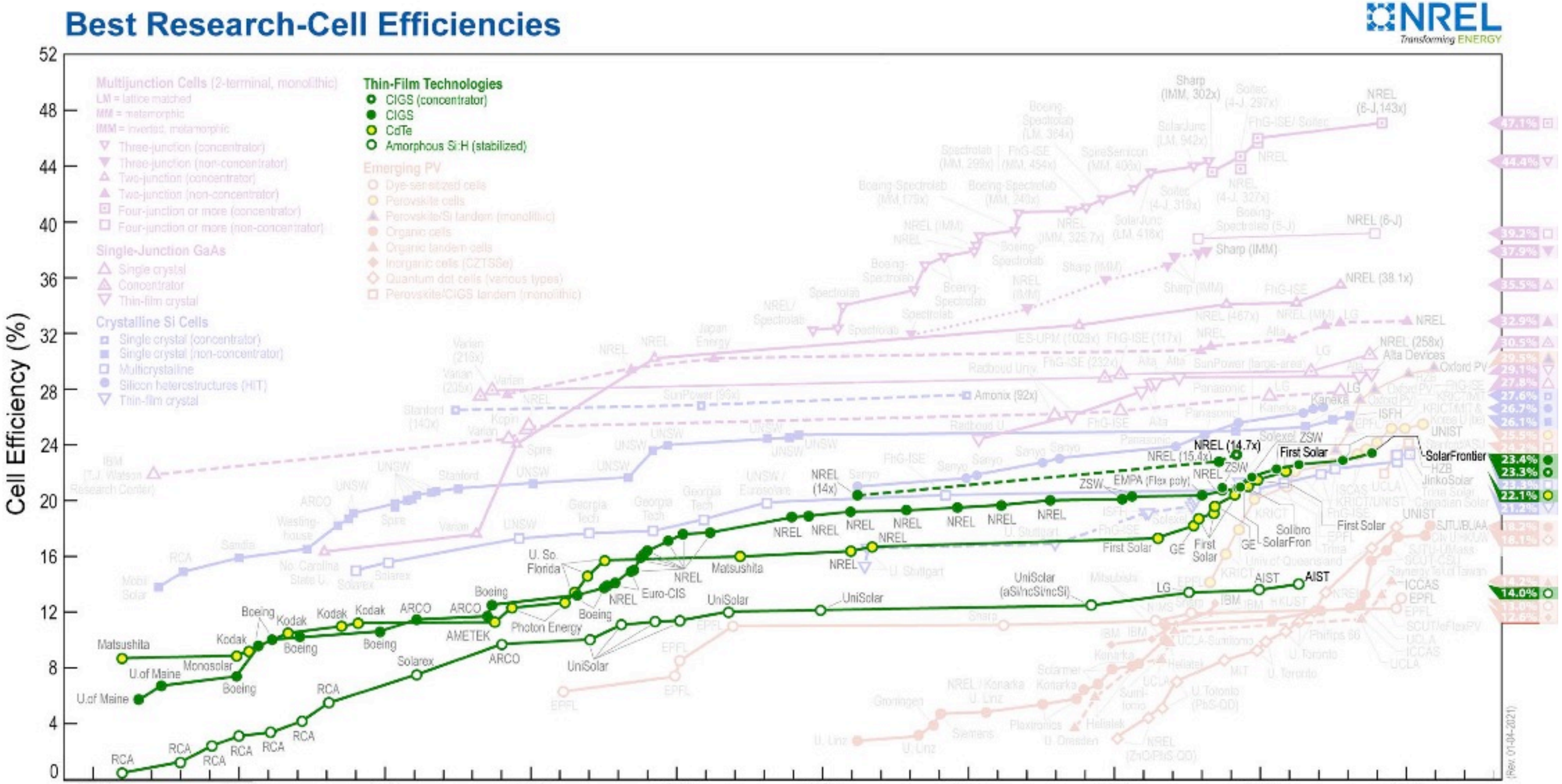
CIGS Thin Film Solar Cells



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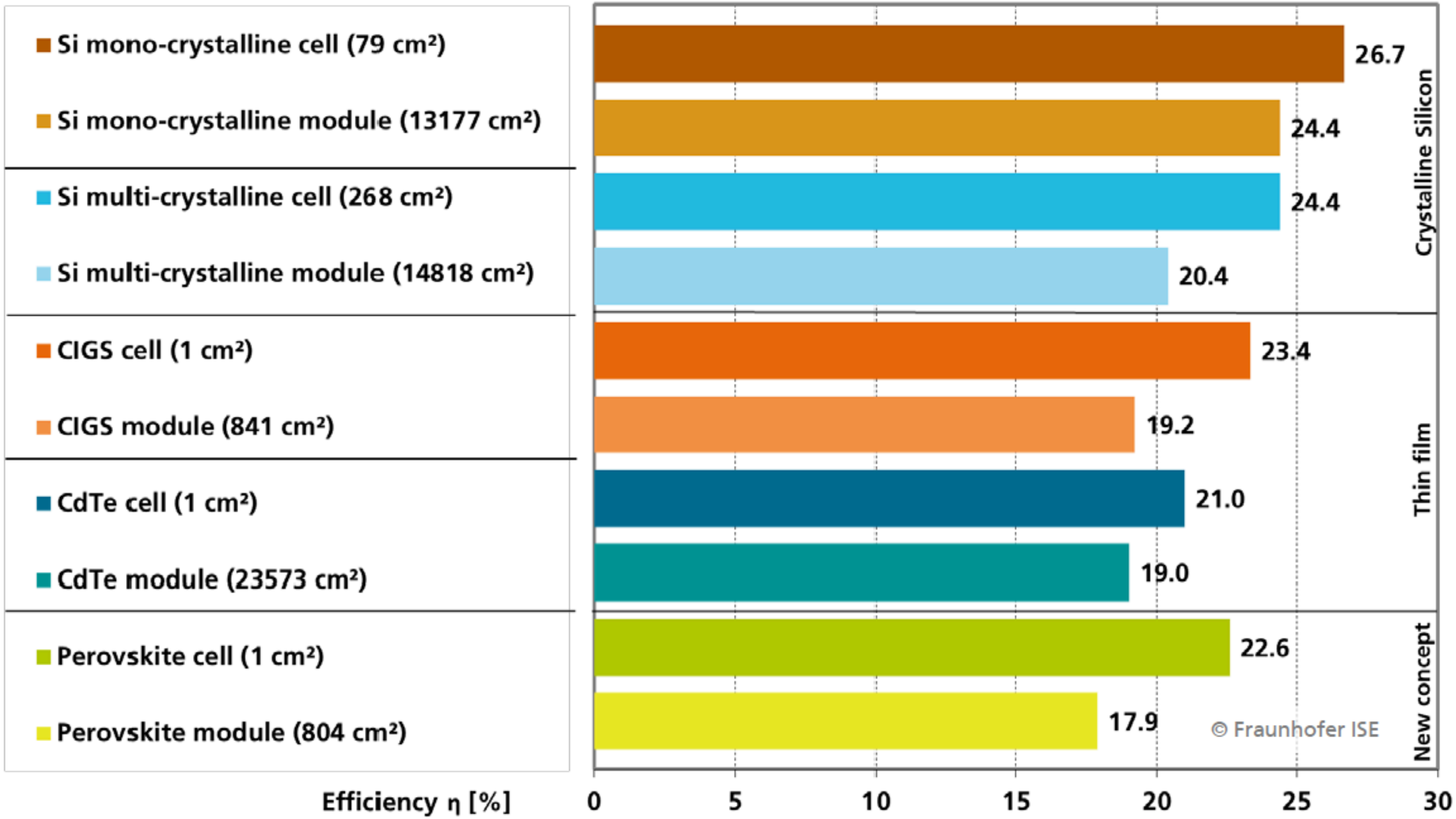
Efficiency Comparison of Technologies



Slides from Fraunhofer Institute, ISE, prepared by Dr. Simon Philipps and Werner Warmuth

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