Energy Conversion by Semiconductor Devices

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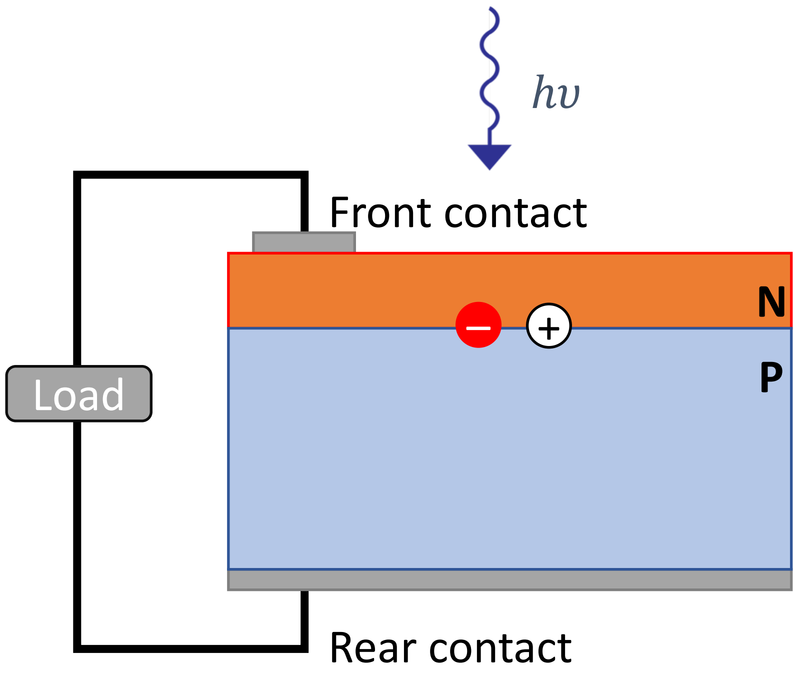
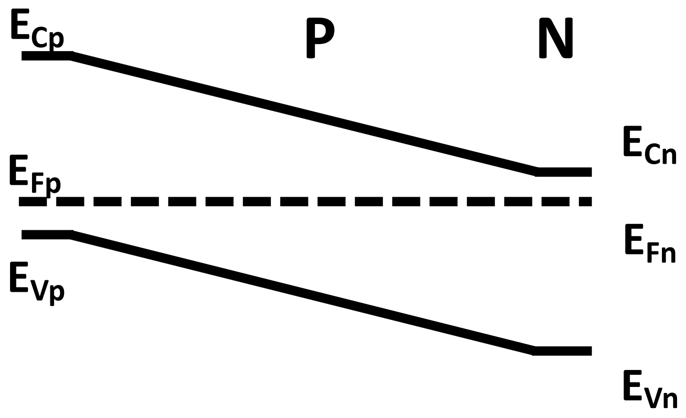
pn Junction Solar Cell

- 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 electron-hole pairs exist, on average, for a length of time equal to the minority carrier lifetime before they recombine.
- The carriers are separated by the E-field existing at the p-n junction.





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

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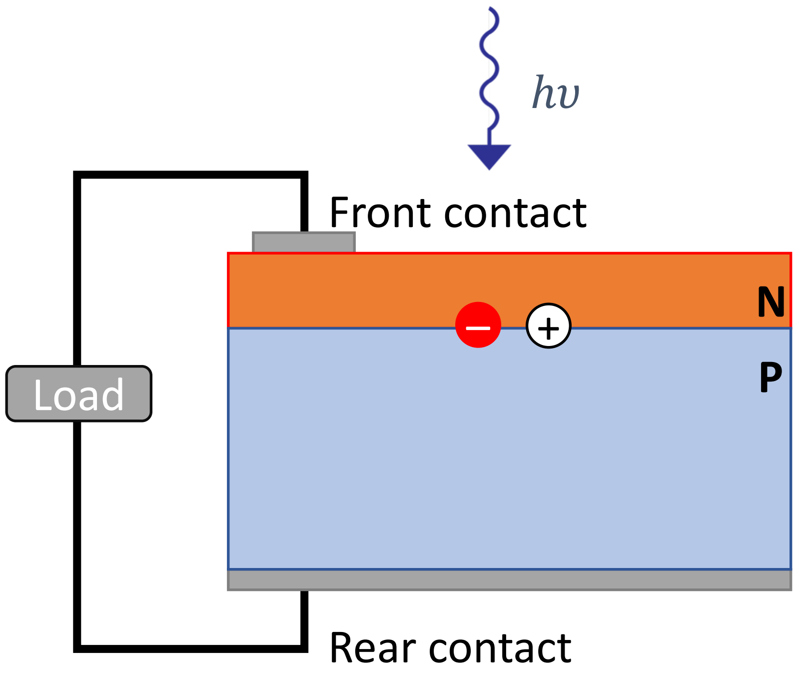

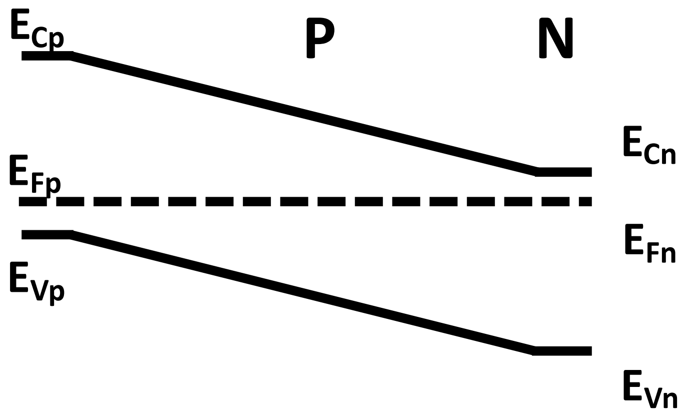

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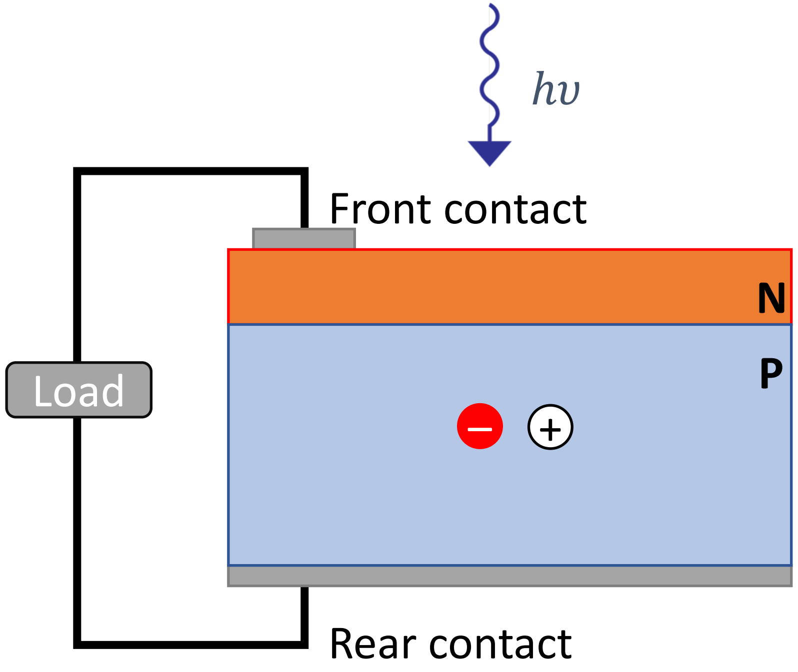

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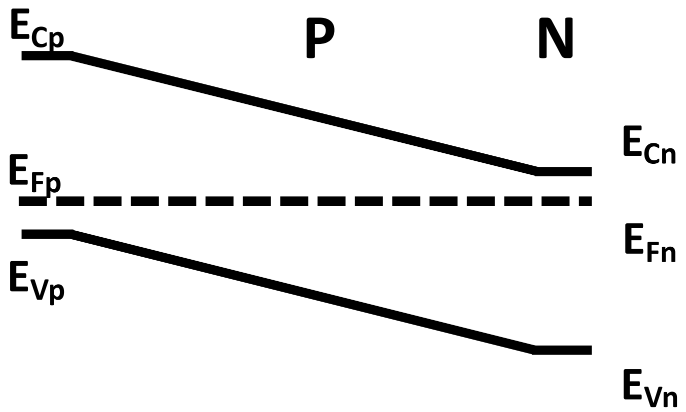

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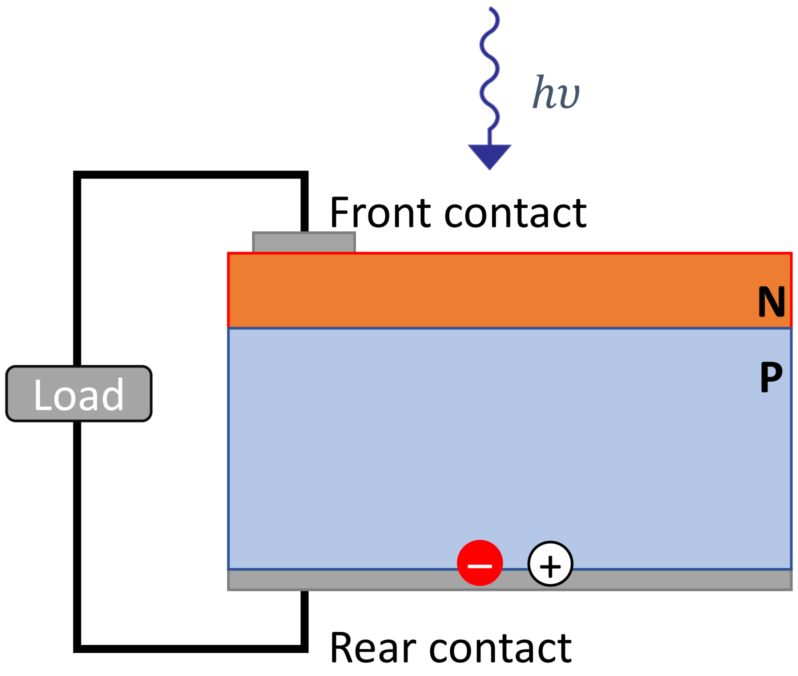

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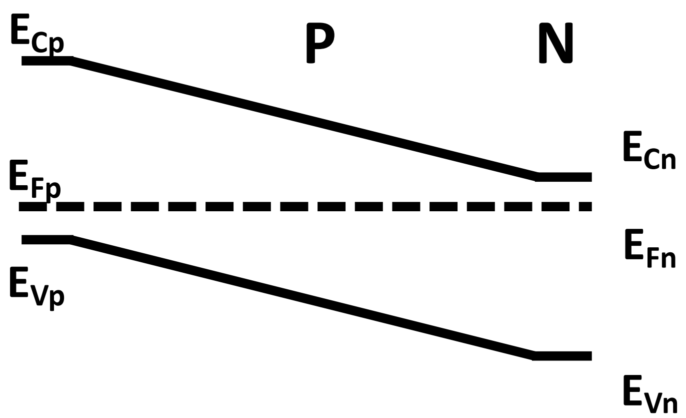
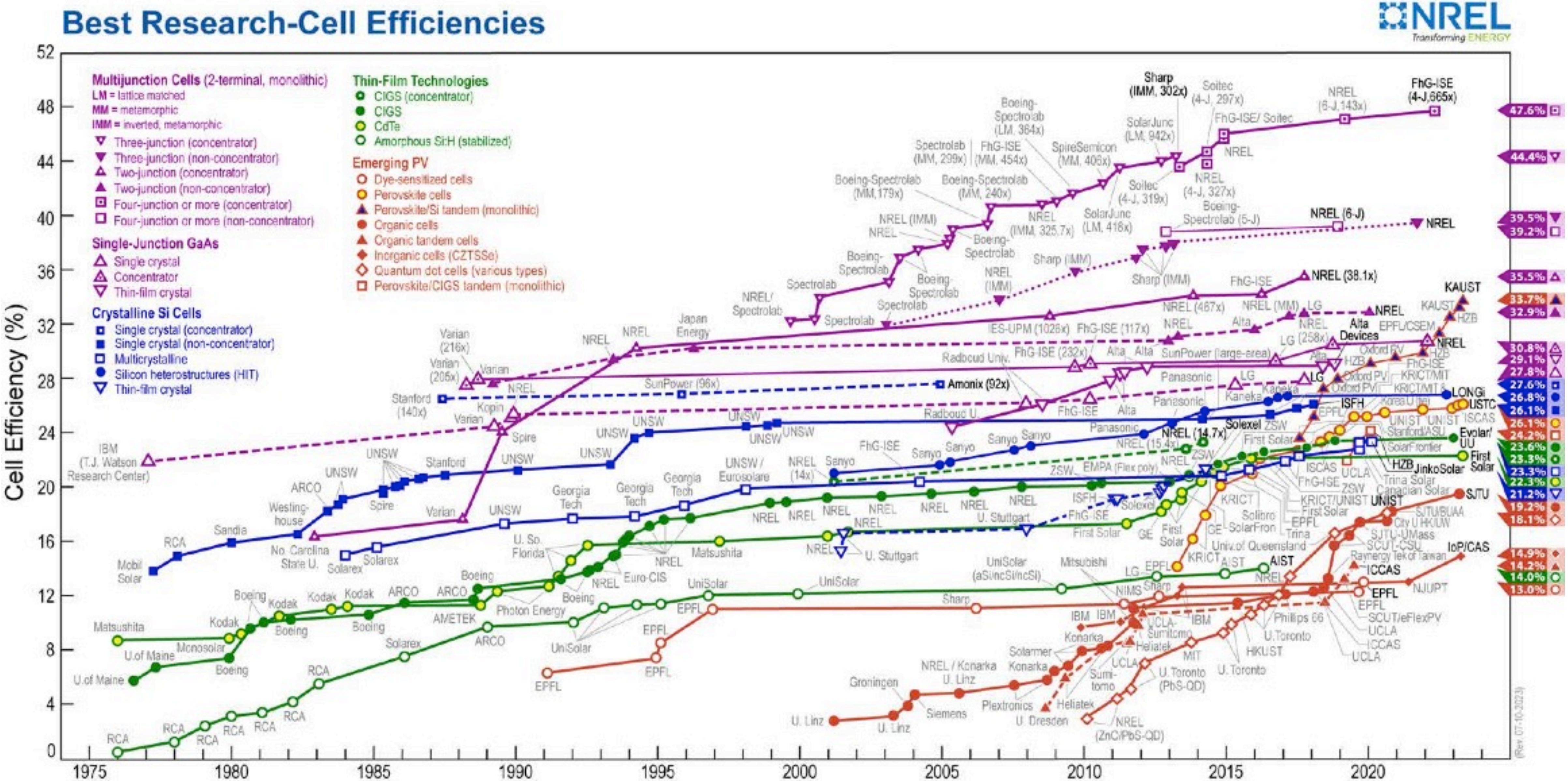


See the animation in https://www.pveducation.org/pvcdrom/solar-cell-operation/light-generated-current

NREL Best Research-Cell Efficiencies



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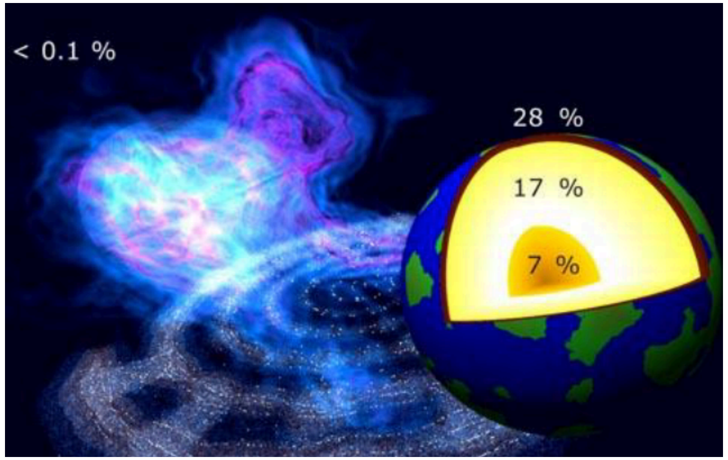
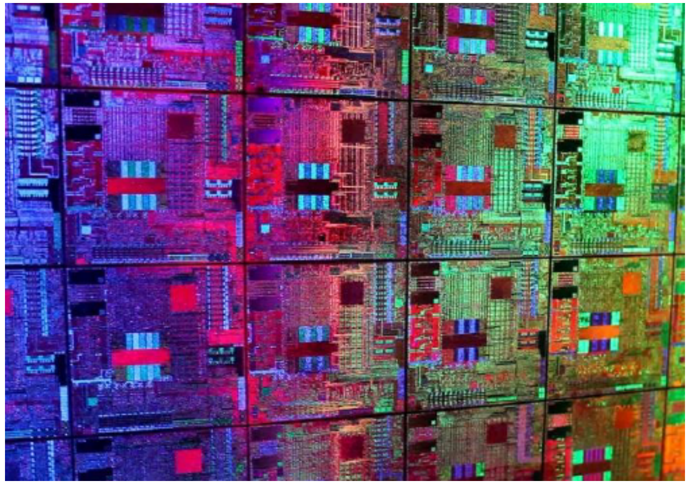
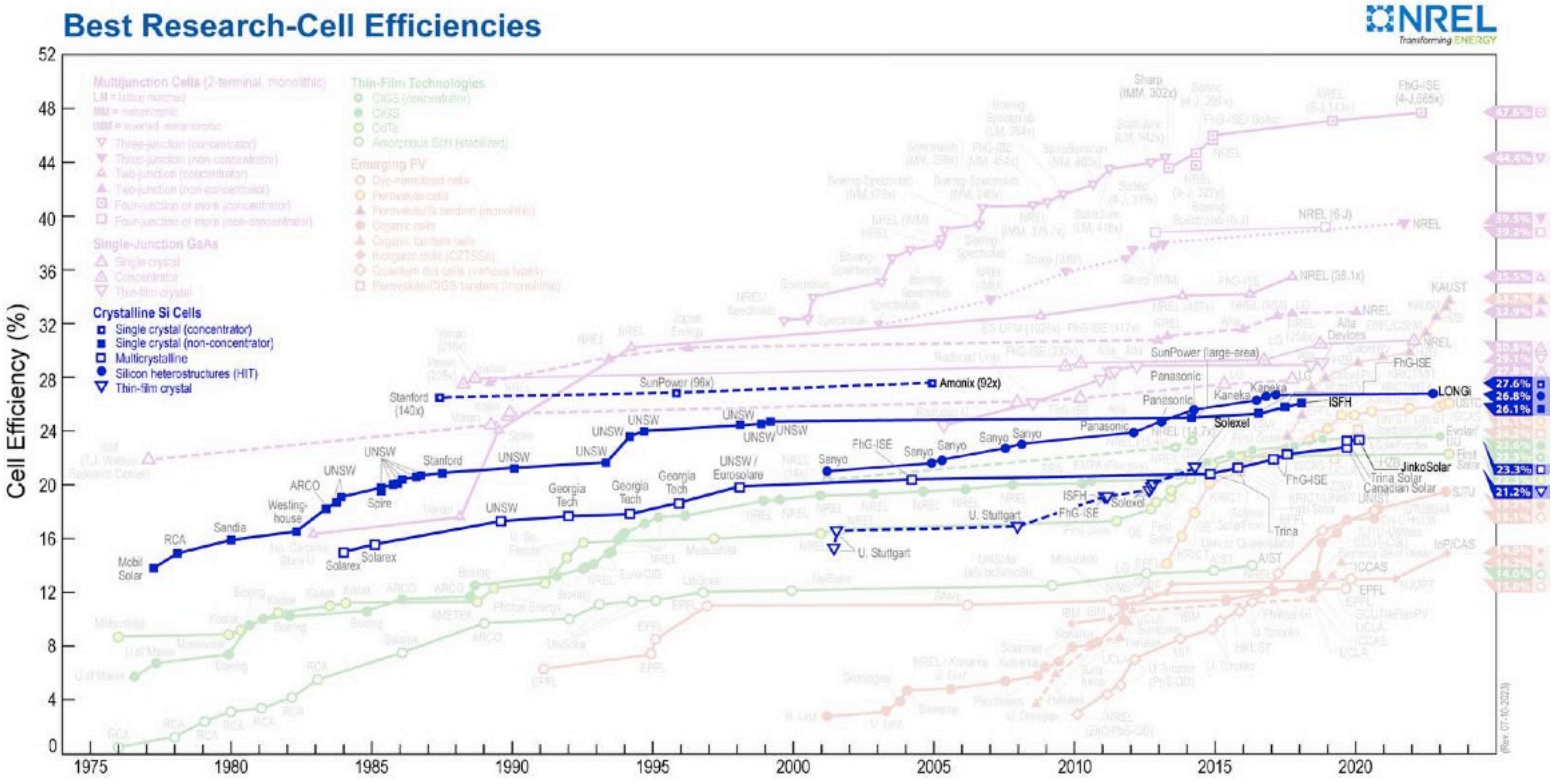
Silicon Solar Cell

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





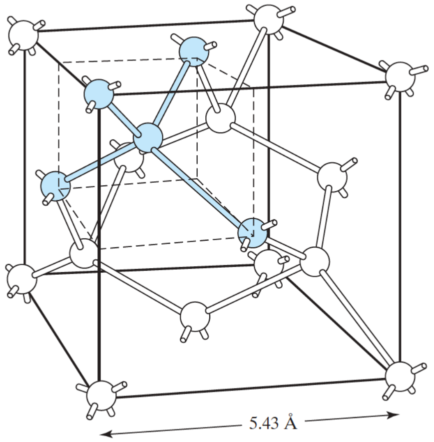
Type of Silicon for Solar Cells

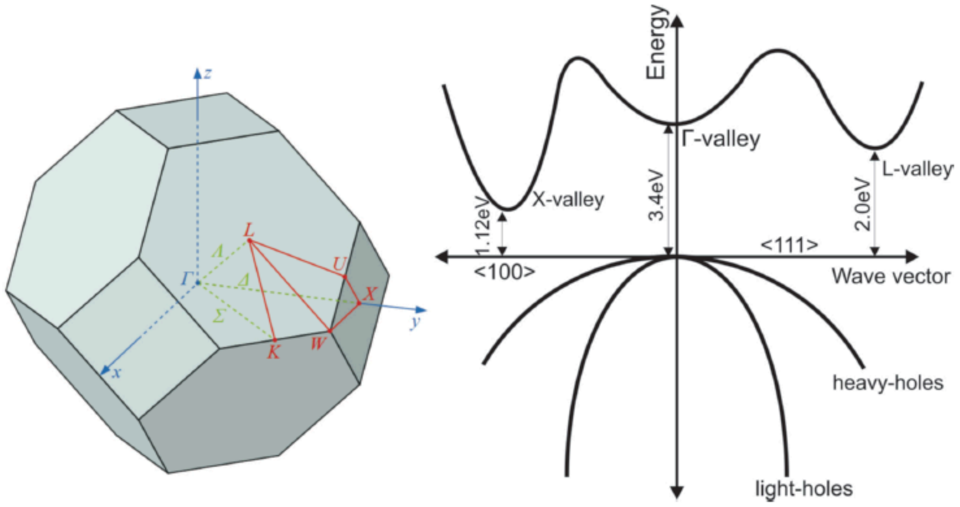


26.8%

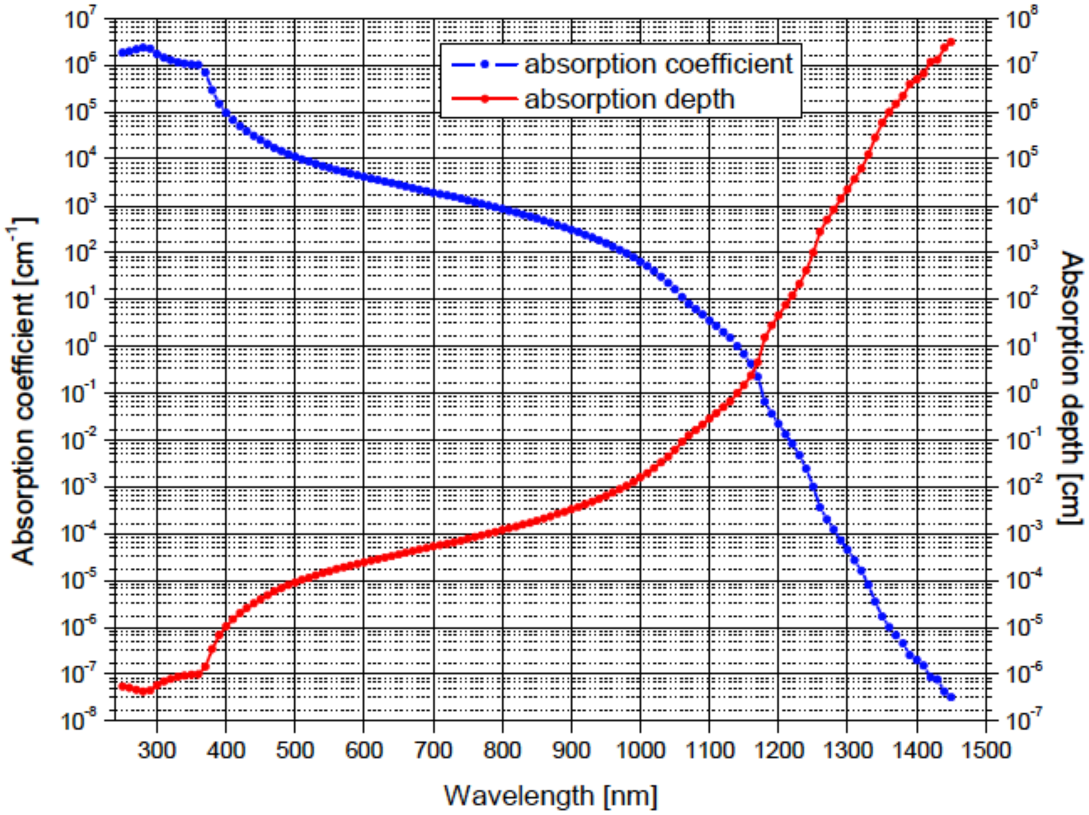
Crystalline Silicon

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



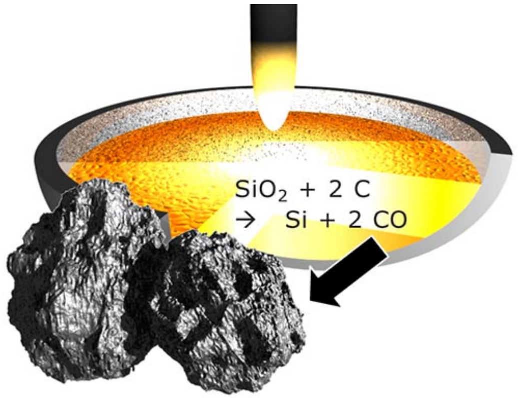


Indirect band gap is 1.12 eV



From Sand to Silicon Single Crystal

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



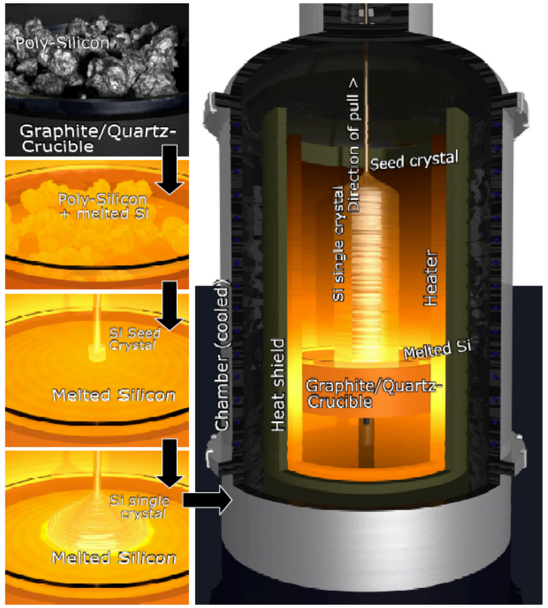
$Si + 3HCl \rightarrow HSiCl_3 + H_2$

Purification of Silicon by distillation
(Siemens Process)

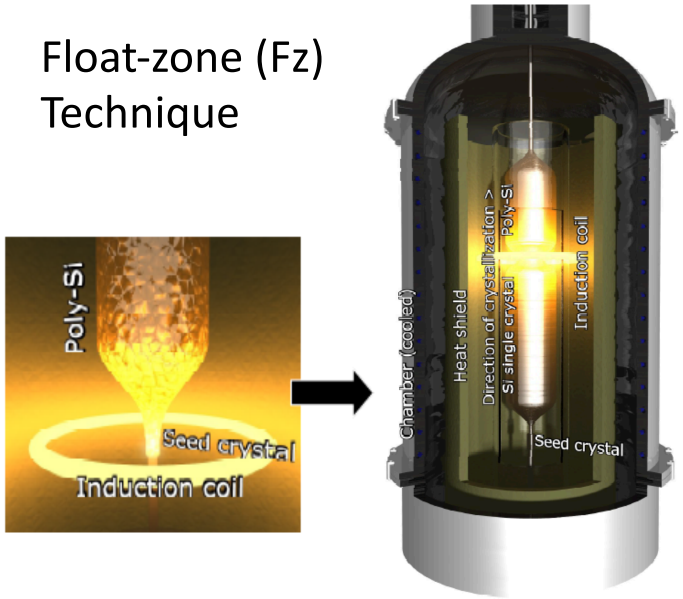
$HSiCl_3 + H_2 \rightarrow Si + 3HCl$

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

Czochralski (Cz) Technique



Float-zone (Fz) Technique



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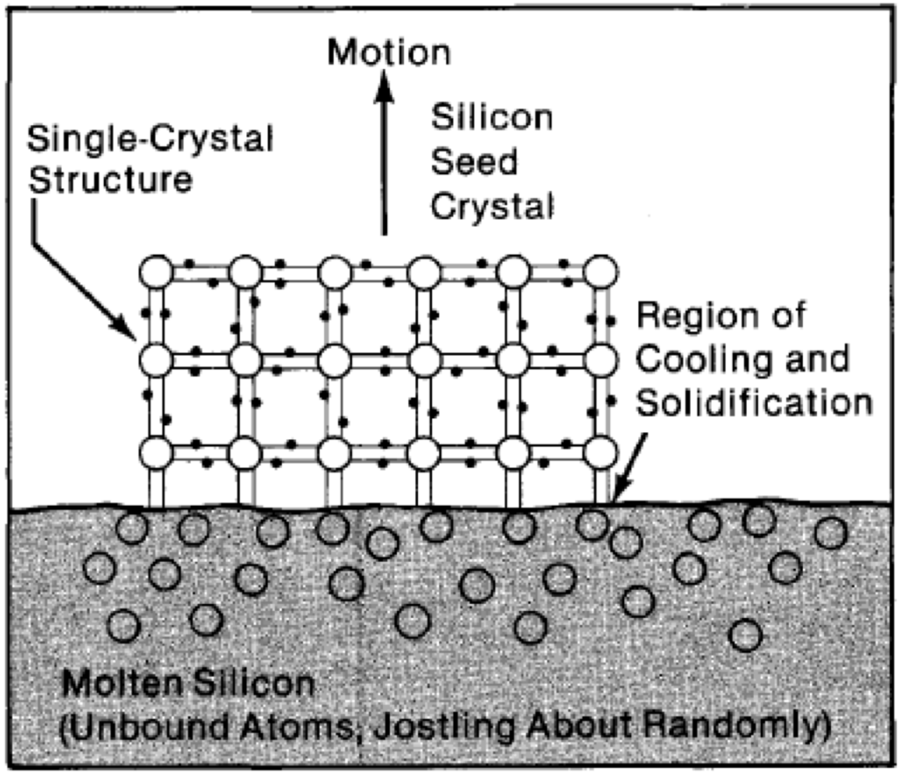
https://www.microchemicals.com/products/wafers/wafer_brochure.html

From Sand to Silicon Single Crystal



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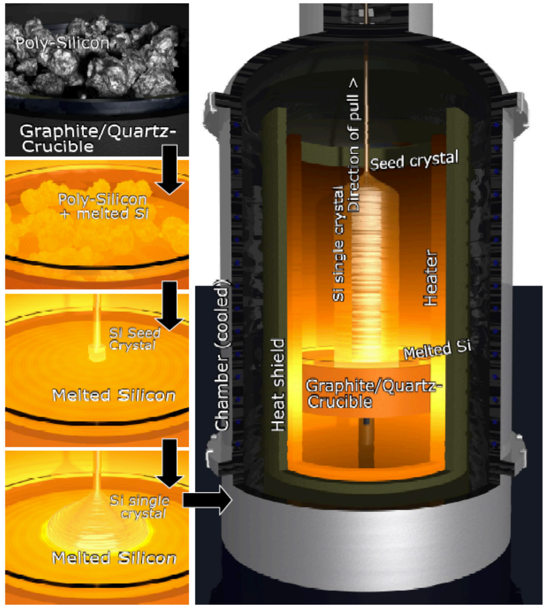

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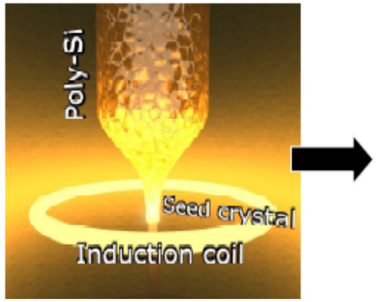
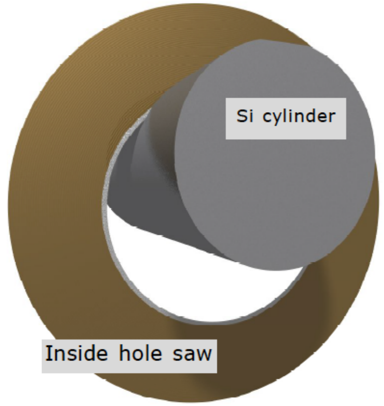


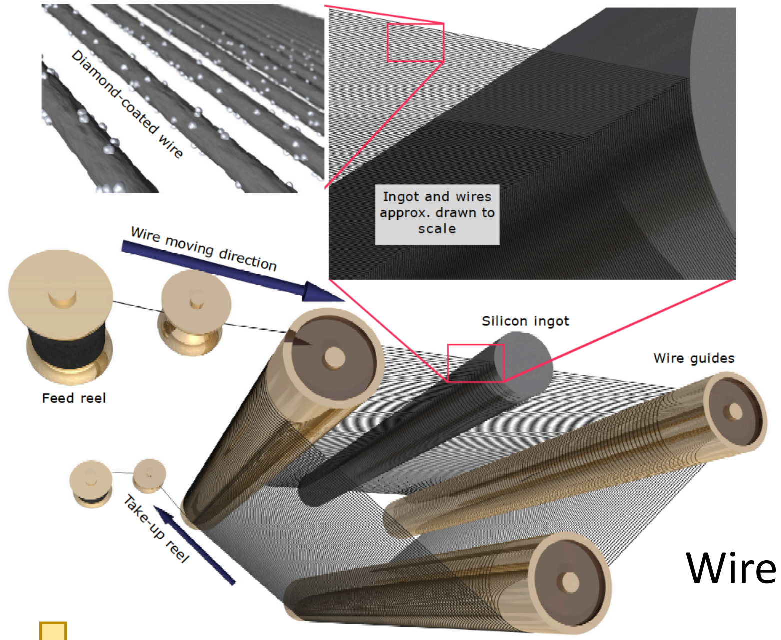
From Single Crystal to Polished Wafer

Grinding

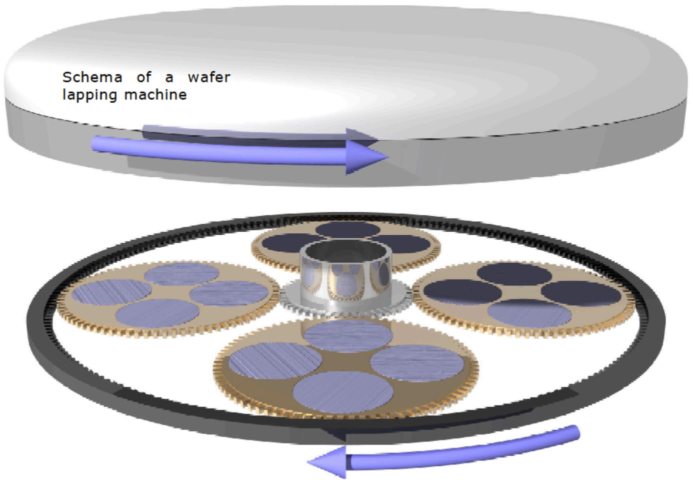


Inside Hole Saw

Dicing



Wire Saw



Lapping

Etching, Polishing, Cleaning

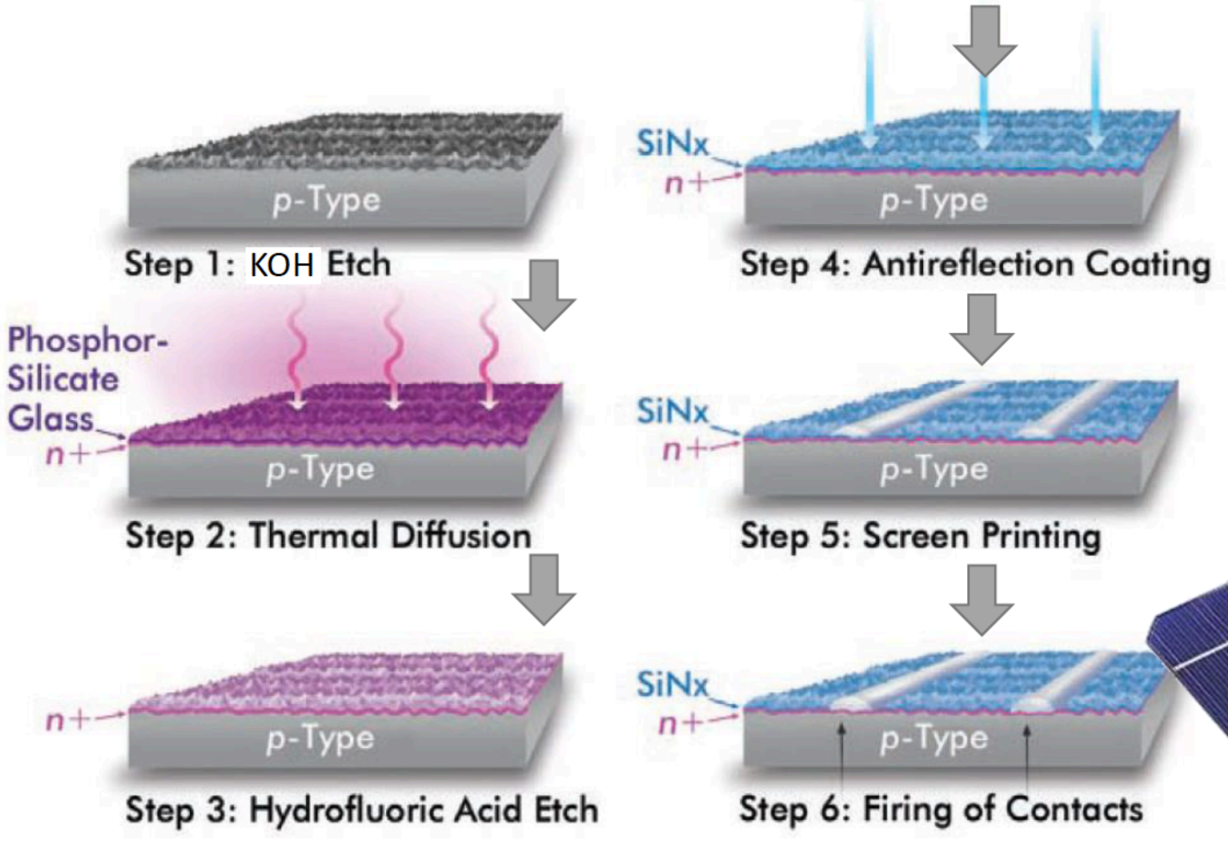
https://www.microchemicals.com/products/wafers/wafer_brochure.html

Single Crystalline Si Solar Cell Cell Fabrication Technologies

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

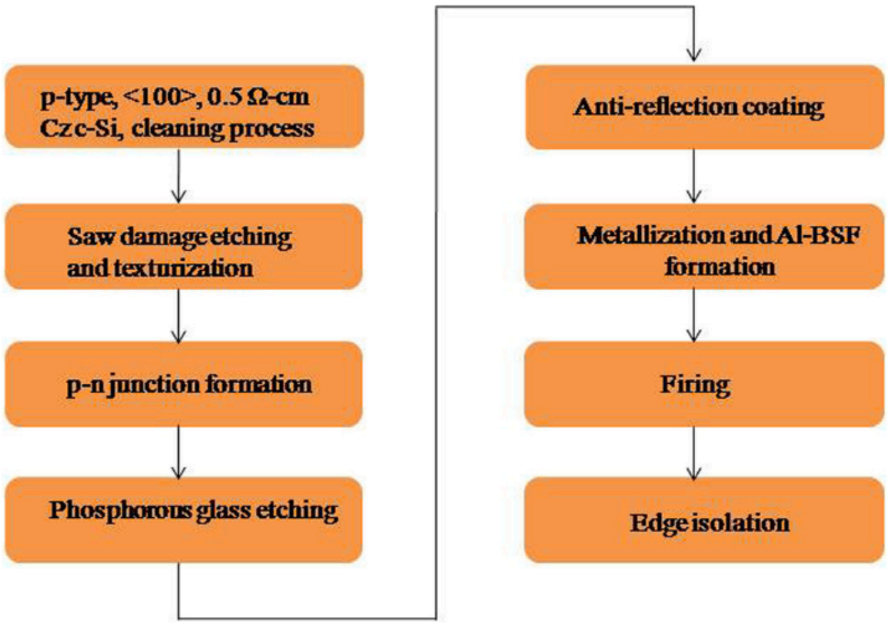
Buried Contact Solar Cells: https://www.pveducation.org/pvcdrom/manufacturing-si-cells/buried-contact-solar-cells

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



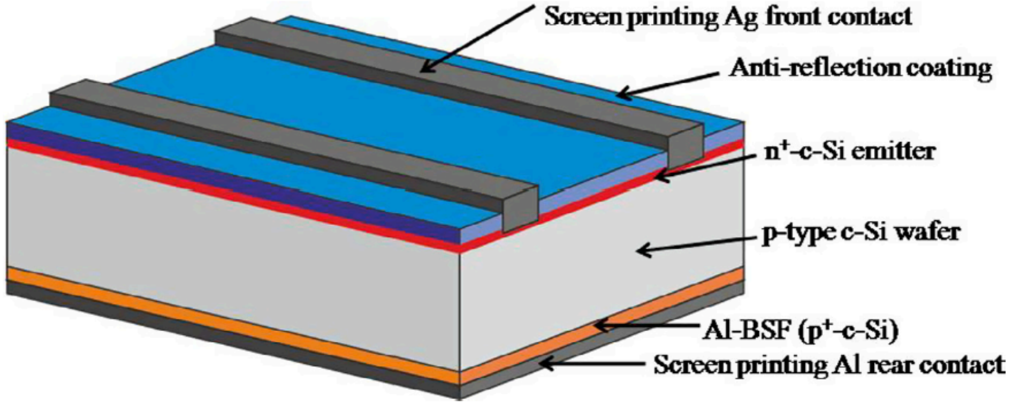
Newport Corp./Spectra-Physics

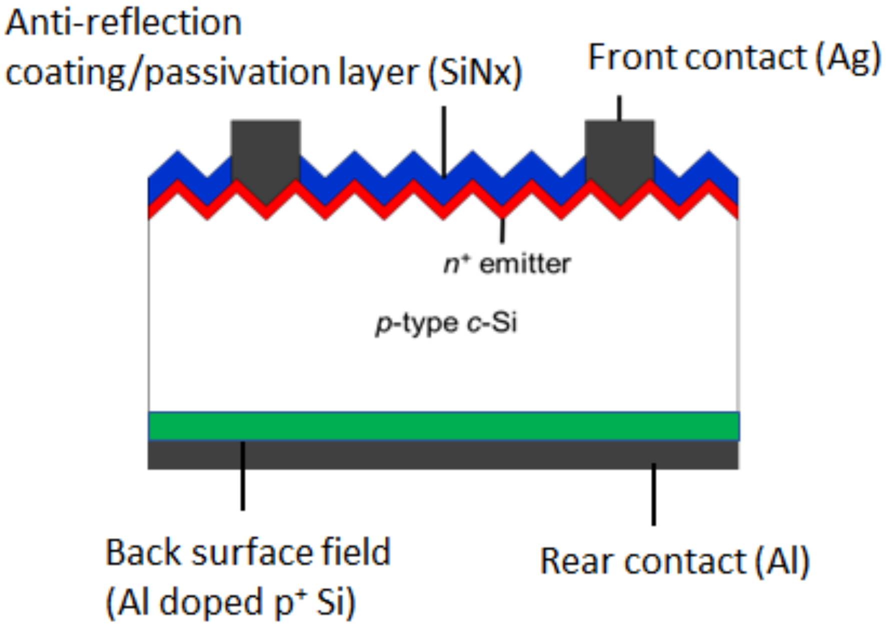
Mono-Crystalline Solar Cell



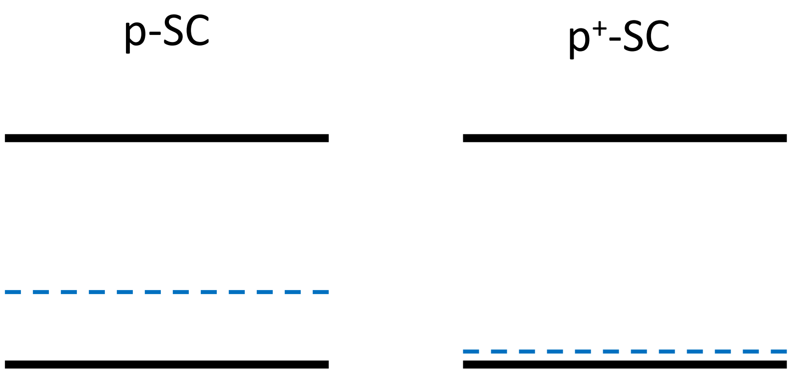
Single Crystalline Si Solar Cells Architecture

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 velocity (SRV)) → Increase in V_{oc} and J_{sc}.



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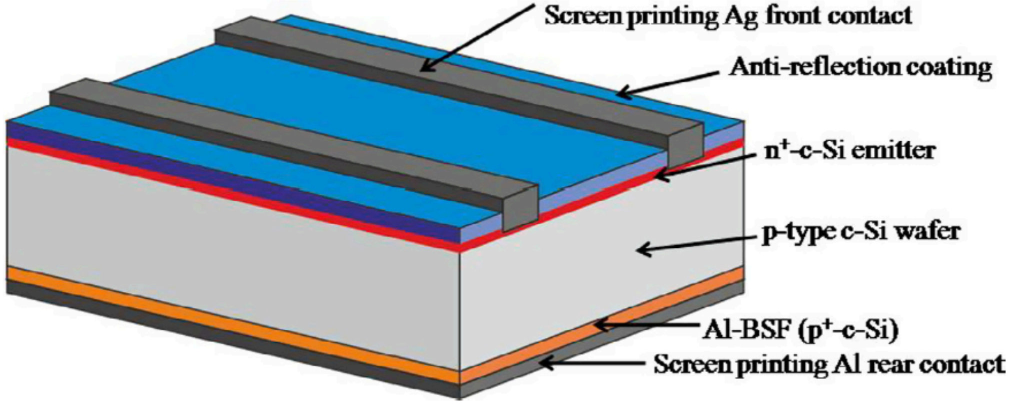

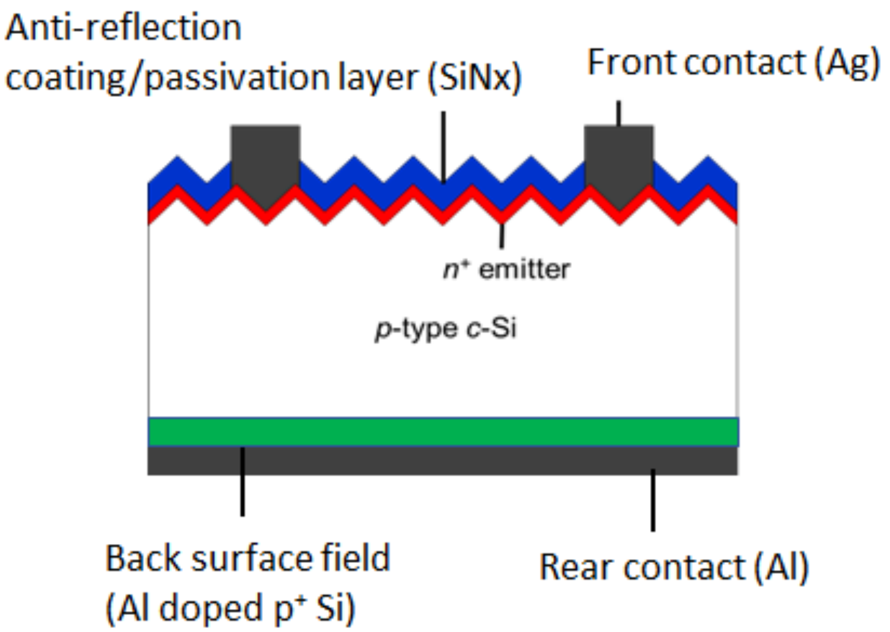

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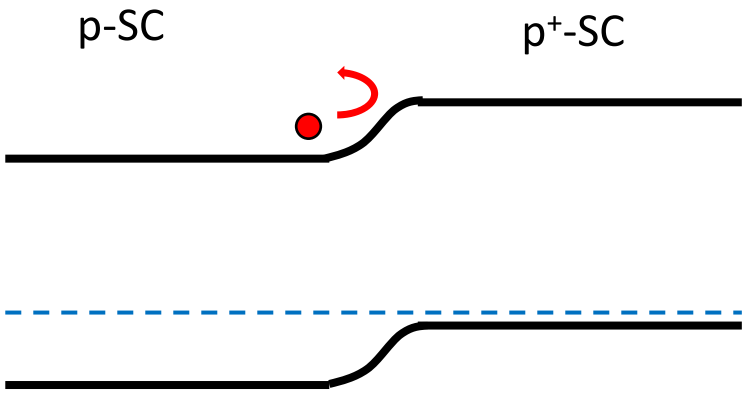
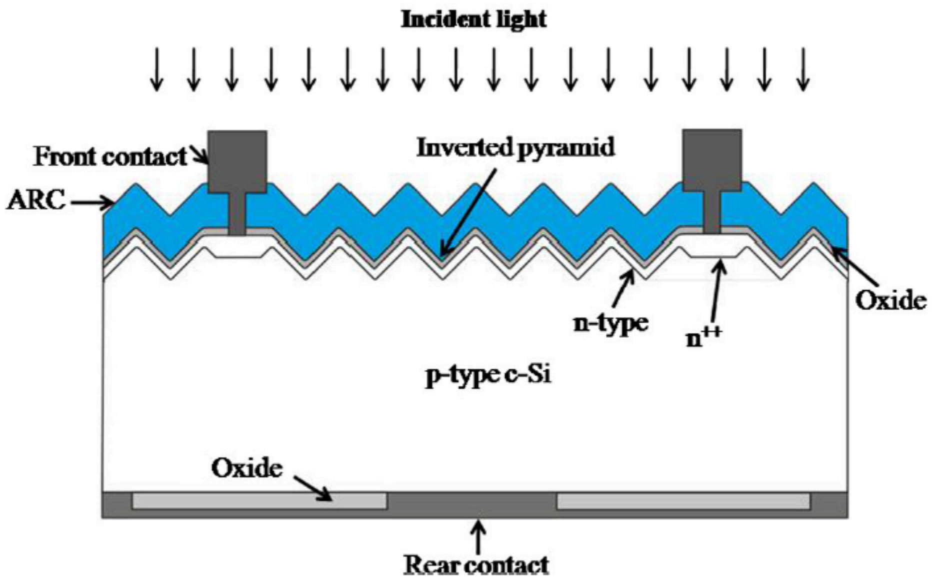
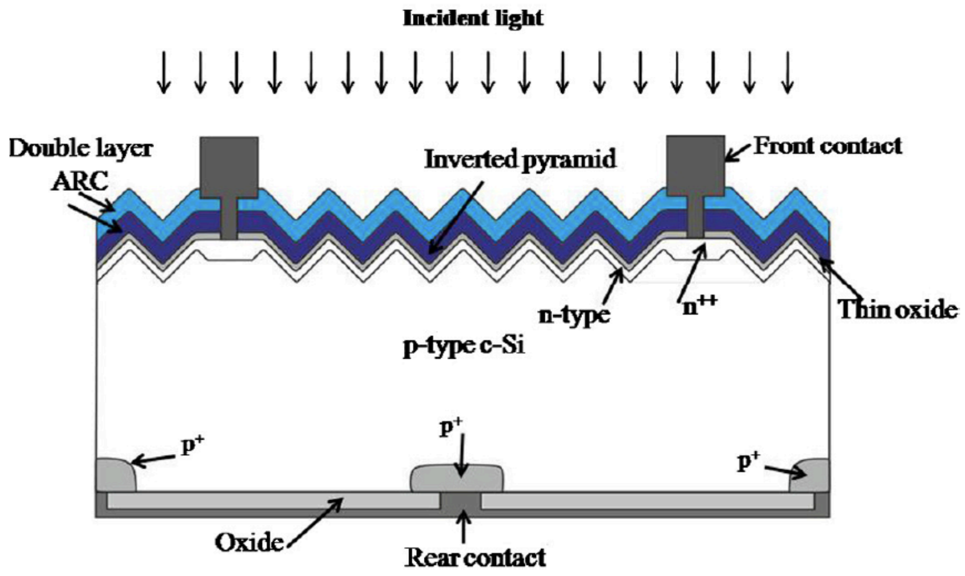


PERC and PERL Solar Cells

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



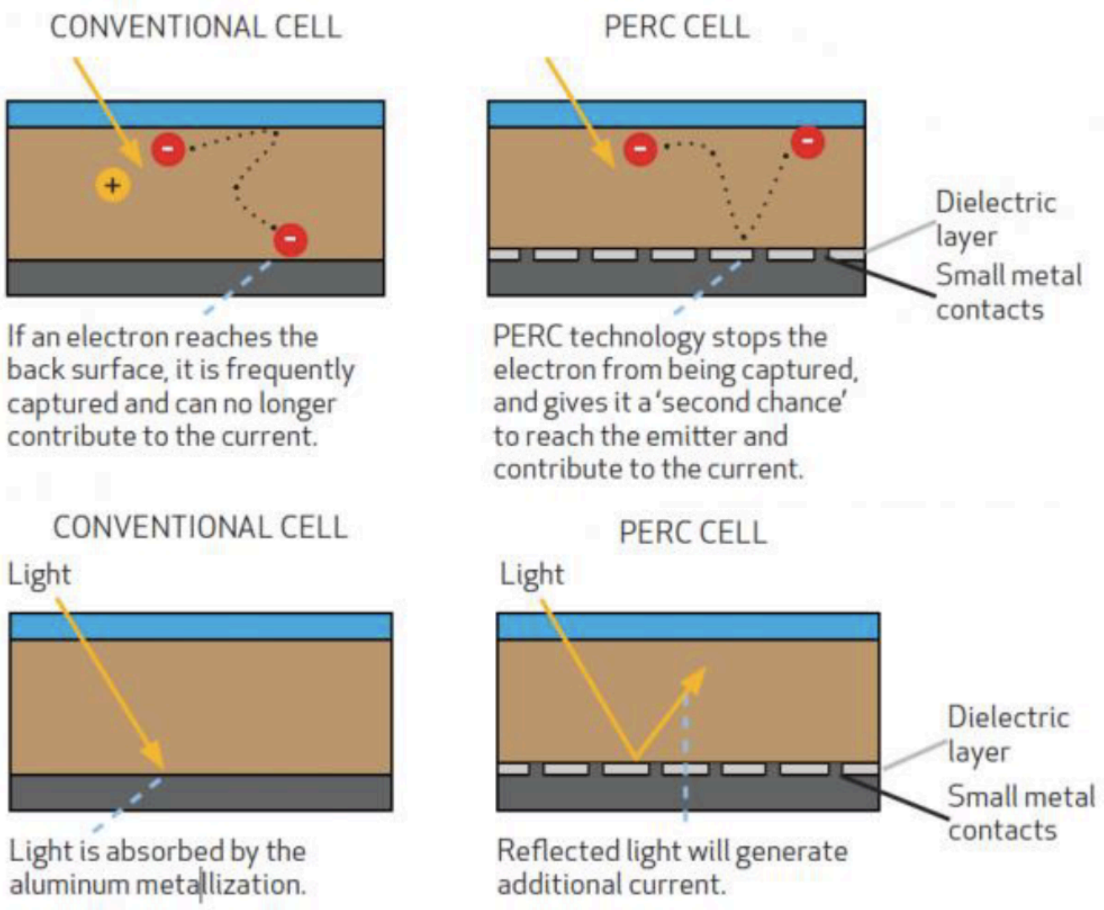
Rear side dielectric passivation layer (Al_2O_3): reduced surface recombination and improved reflection.

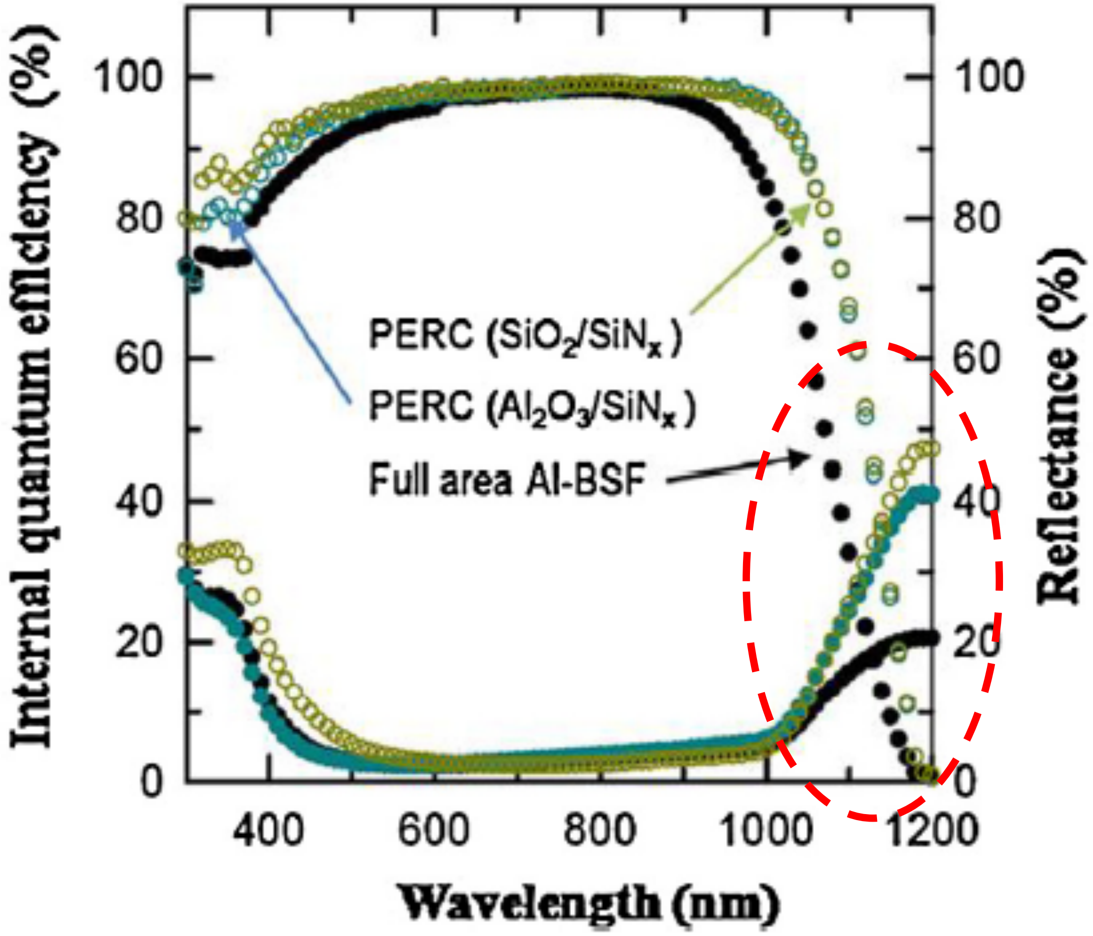


Electric field in the BSF region between p+/p junction drives electrons away towards the pn junction and reduces surface recombination at the defective metal/c-Si interface.

21.2% with PERC and 25% with PERL

PERC and PERL Solar Cells

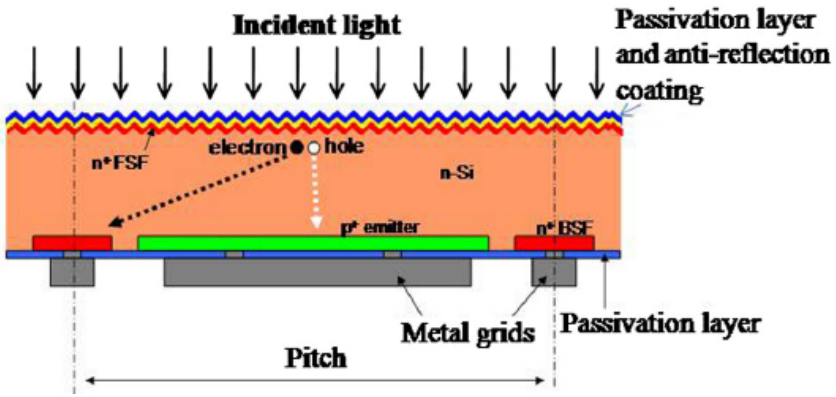




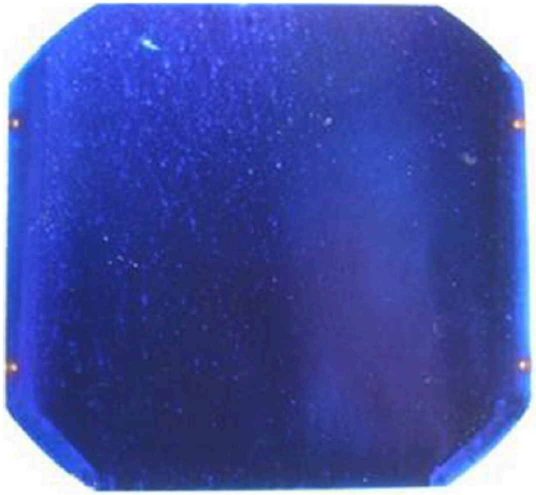
Dullweber T. et al., *Prog Photovolt: Res Appl*; 20:630–8 (2012)

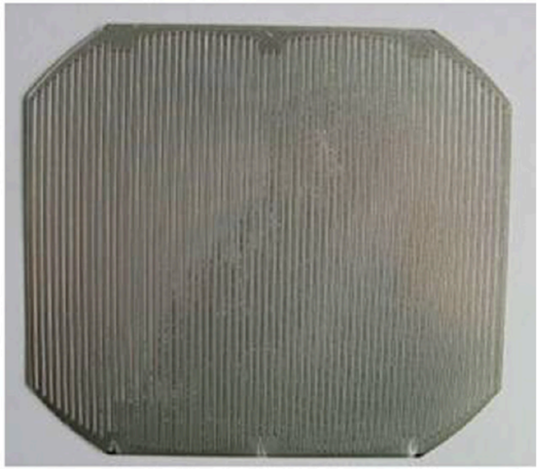
IBC c-Si Solar Cells

Interdigitated back contact (IBC) c-Si solar cells



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

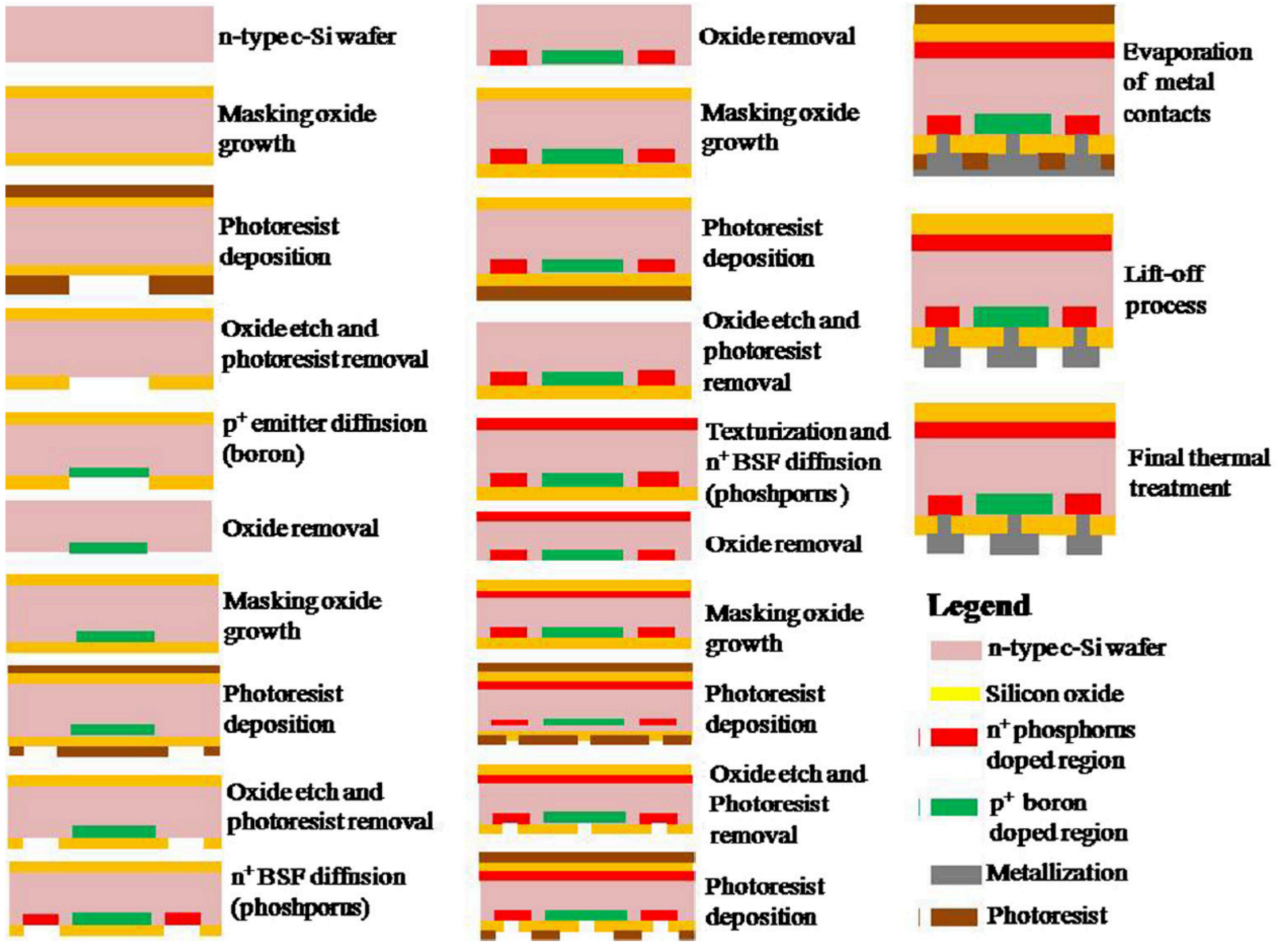




Grid less front side (147.4 cm^2) Rear side

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.

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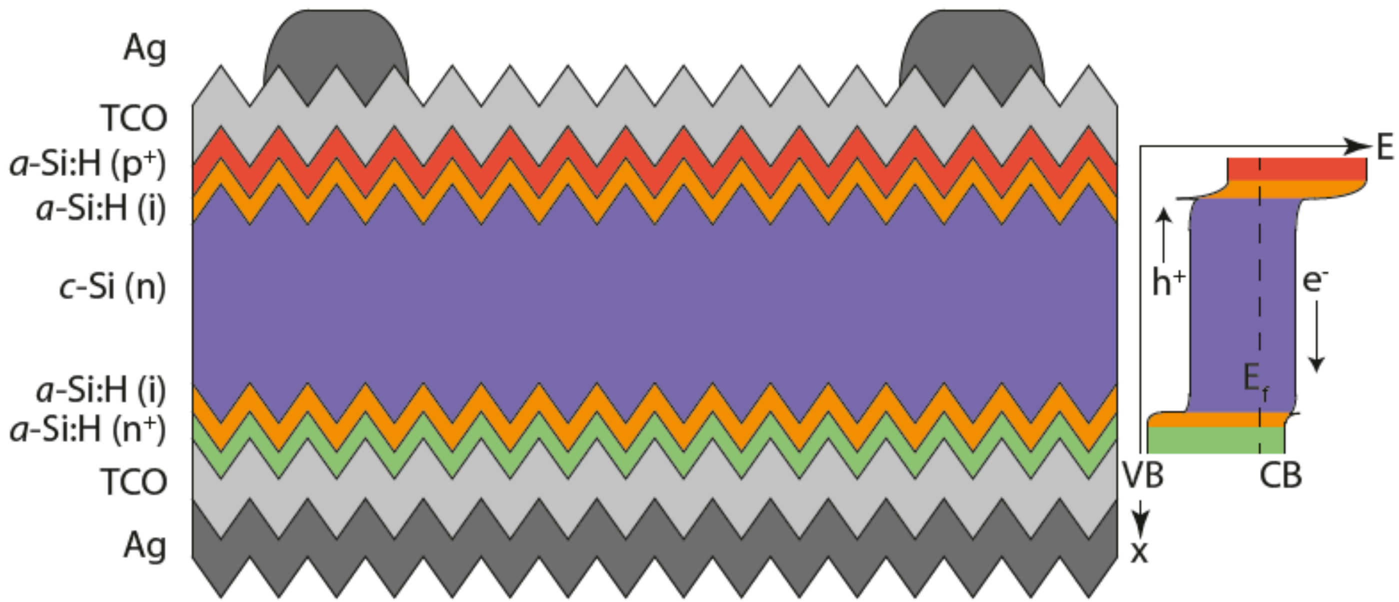
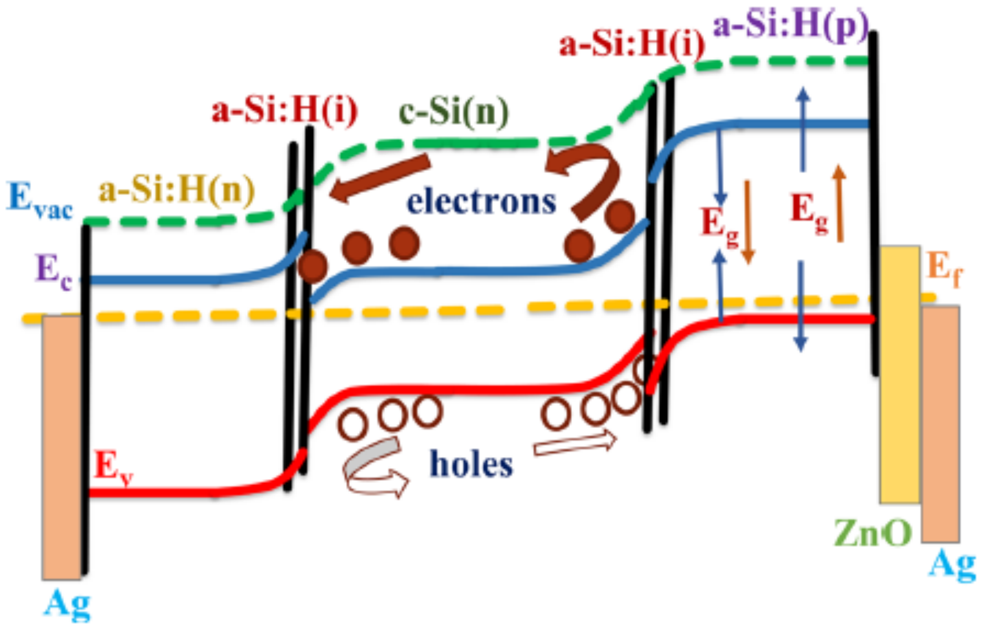
Silicon Heterojunction Solar Cell

Si Heterojunction solar cell



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

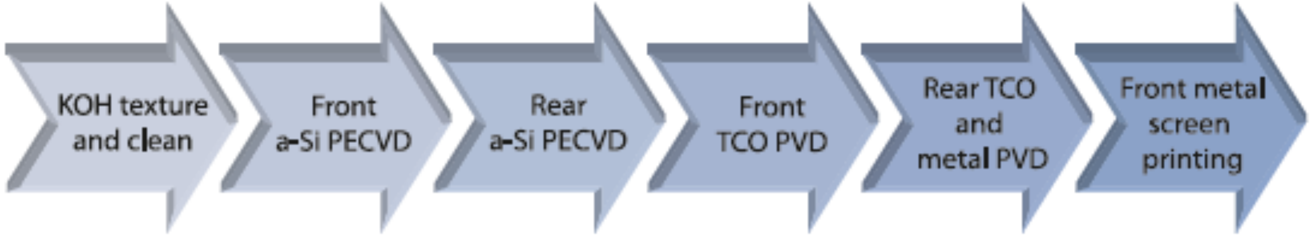


V. Kanneboina, *J. Comp. Electronics*, 20:344 (2021)

- 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.

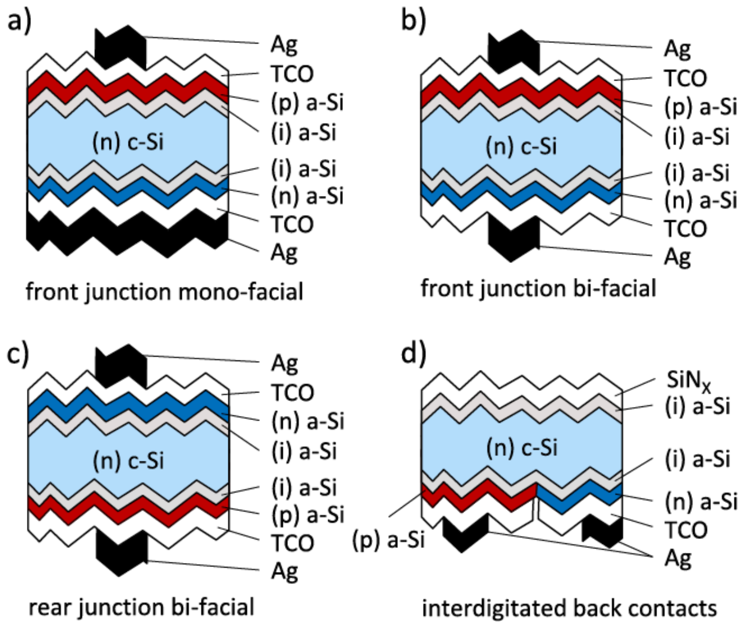
Silicon Heterojunction Solar Cells

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



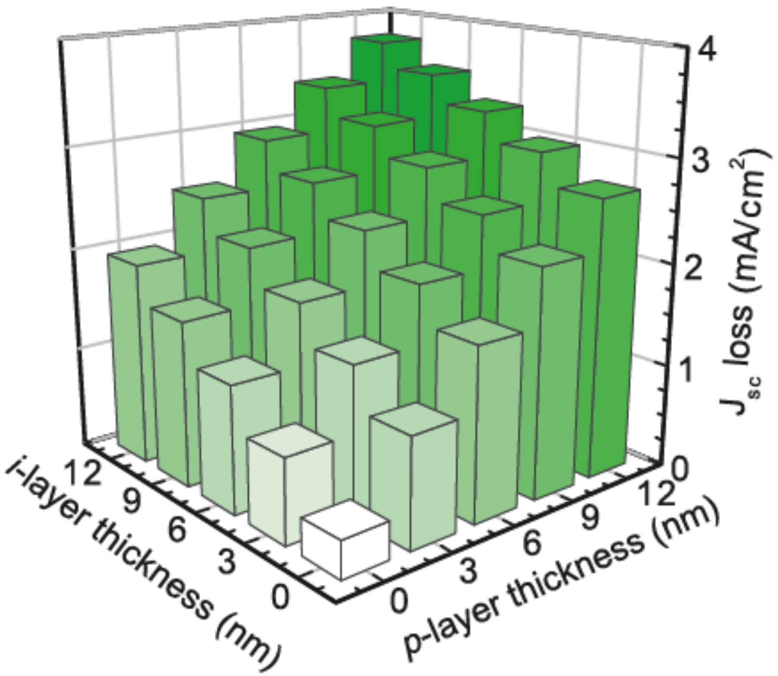
Wolf et al., *Green*, 2. 7 – 24 (2012)

Device architectures for SHJ solar cells.



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)



Silicon Heterojunction Solar Cells

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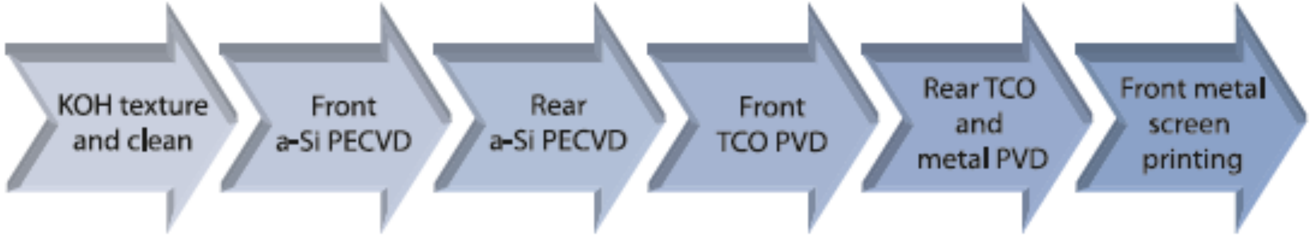

Wolf et al., *Green*, 2. 7 – 24 (2012)

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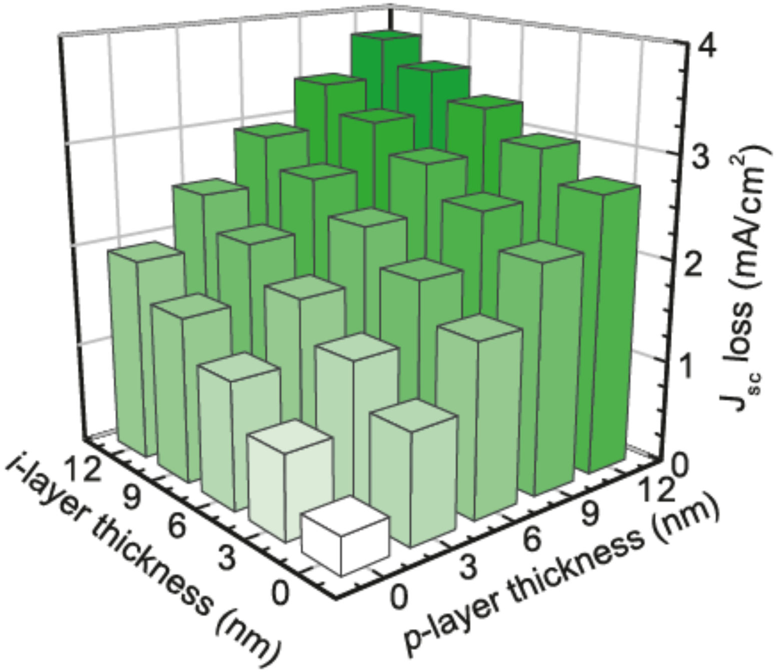


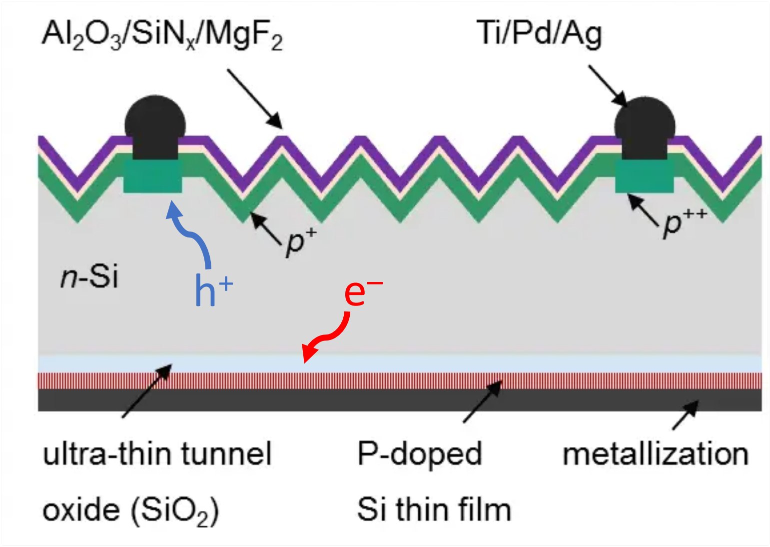
Solution!

- 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}.

EPFL

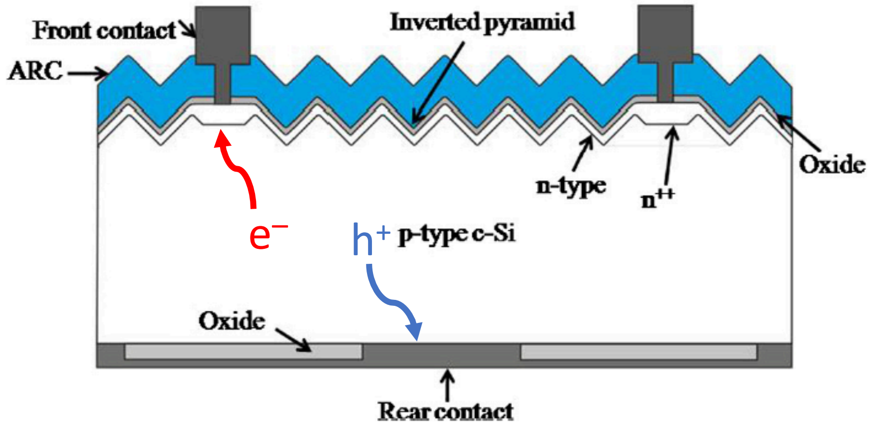
TOPCon Silicon Solar Cell

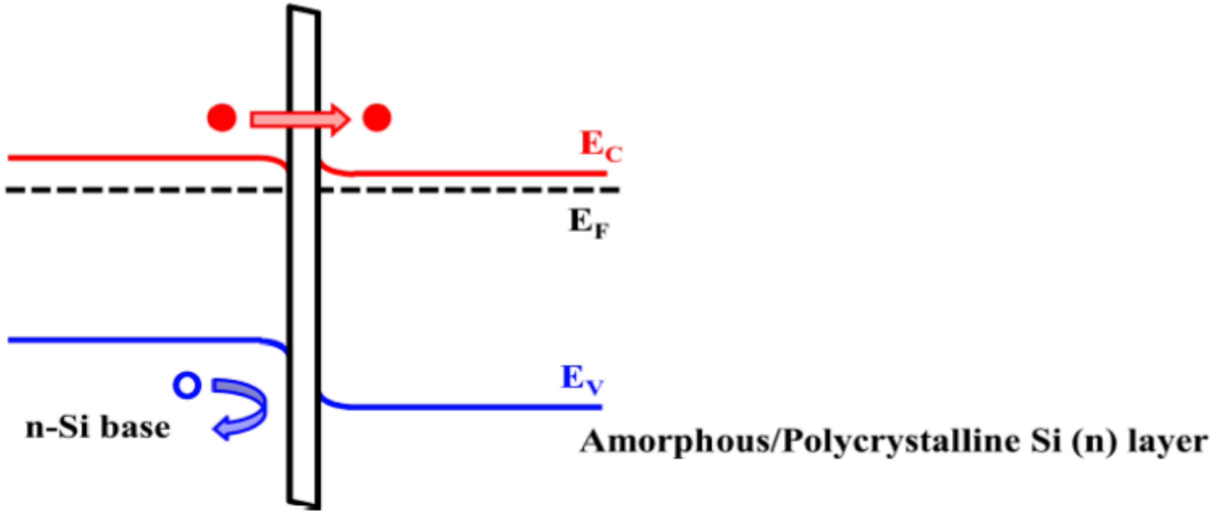
TOPCon



- 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.
- A very thin layer of silicon oxide (just a few nanometers) is applied to the surface of the solar cell and the SiO_2 layer passivates the surface, i.e. low surface recombination.
- However, the layer is so thin that the current can "tunnel through".

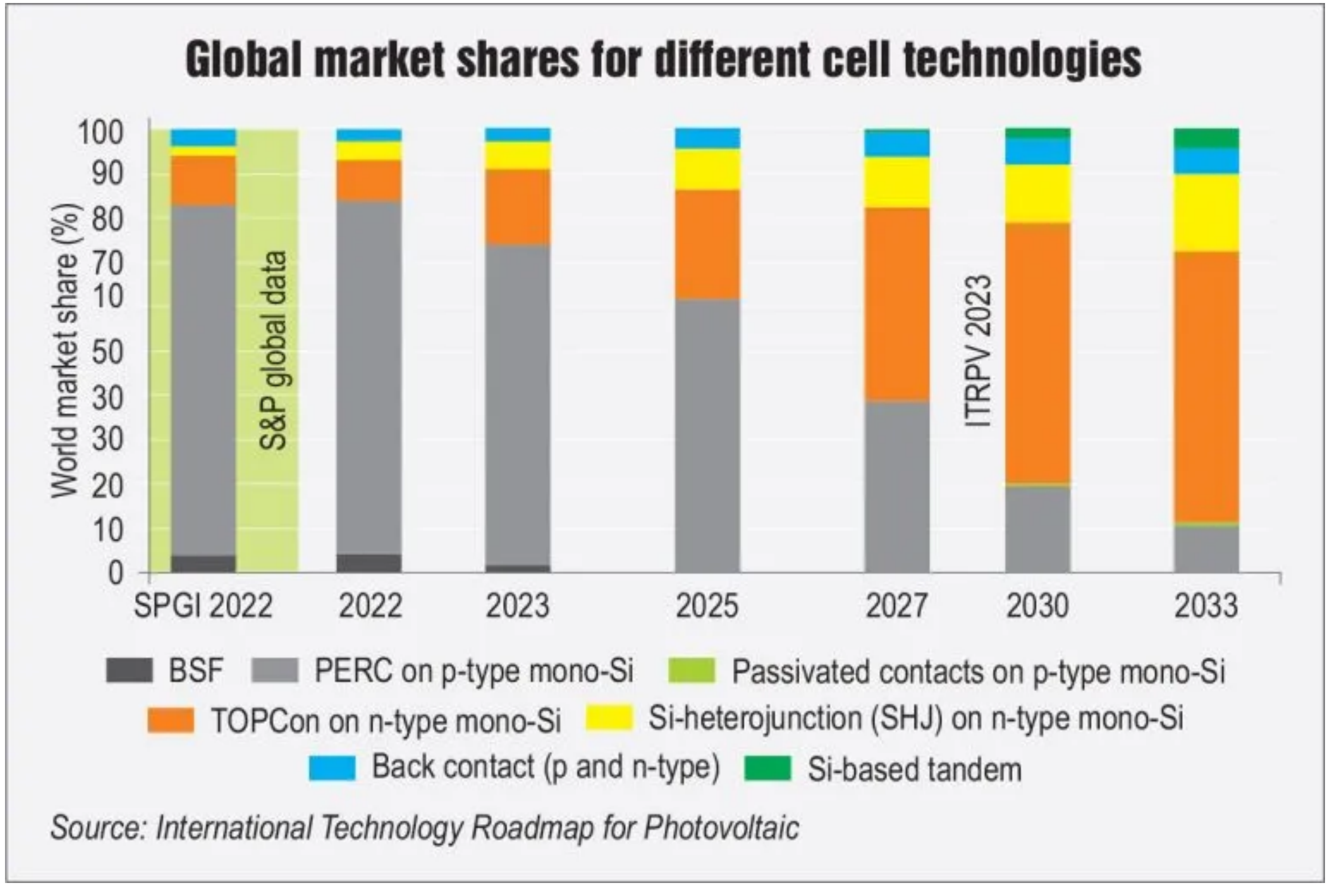
PERC





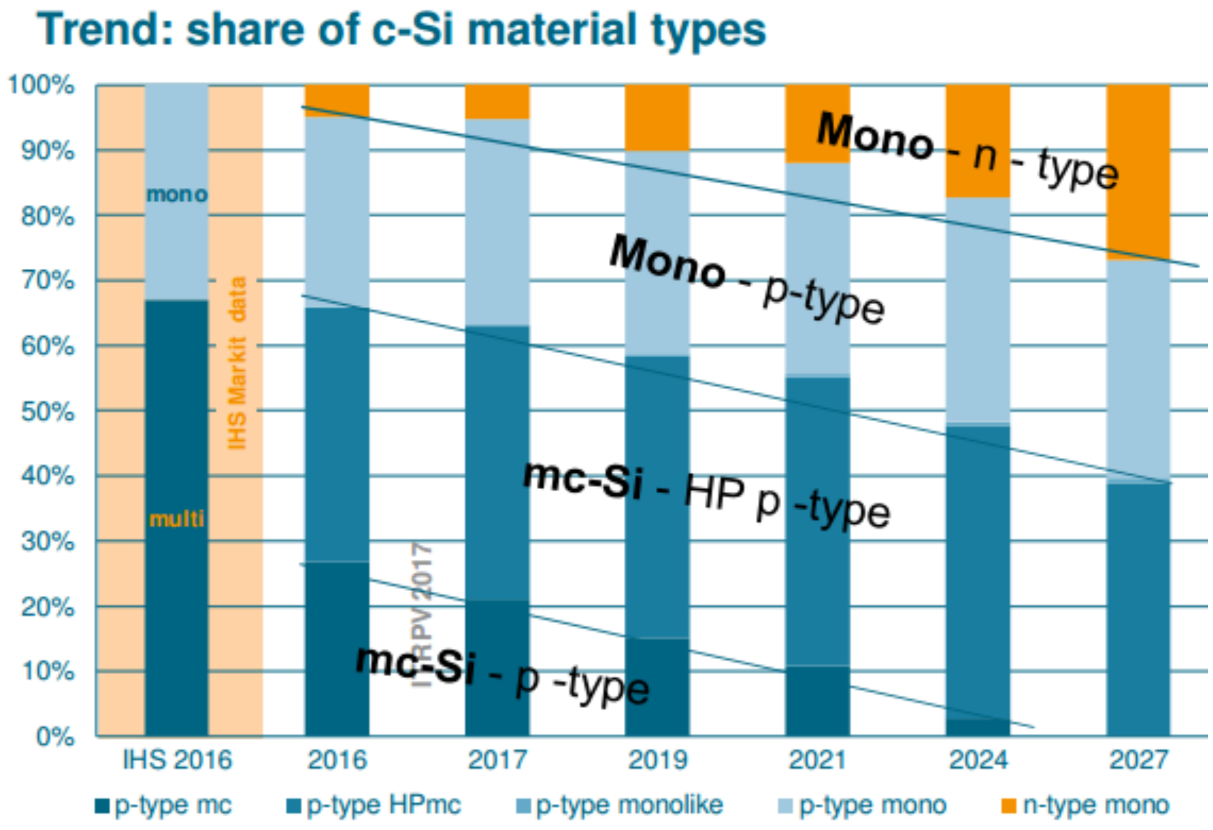
D. K. Ghosh et al., *Surfaces and Interfaces*, 30, 101917 (2022)

Trend for Single Crystalline Si Solar Cells



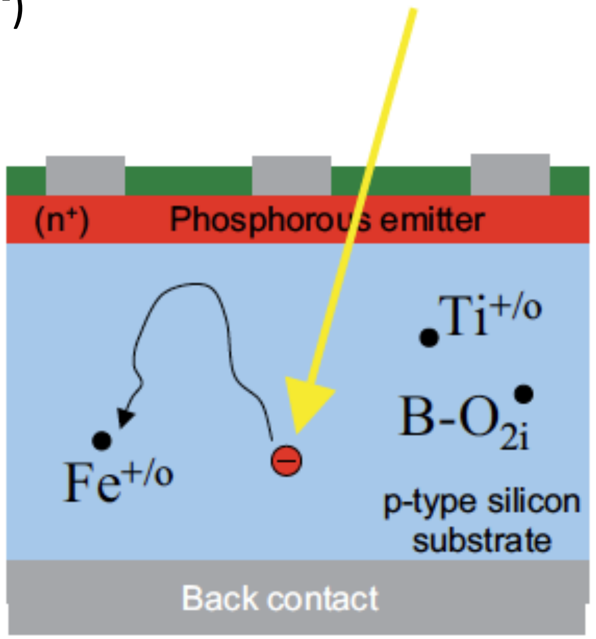
	PERC	TOPCon	HJT	IBC
Efficiency in mass production	23.50 %	24.80 %	25.80 %	25.00 %
Efficiency in lab	24.50 %	26.40 %	26.81 %	25.20 %

Trend for Single Crystalline Si Solar Cells



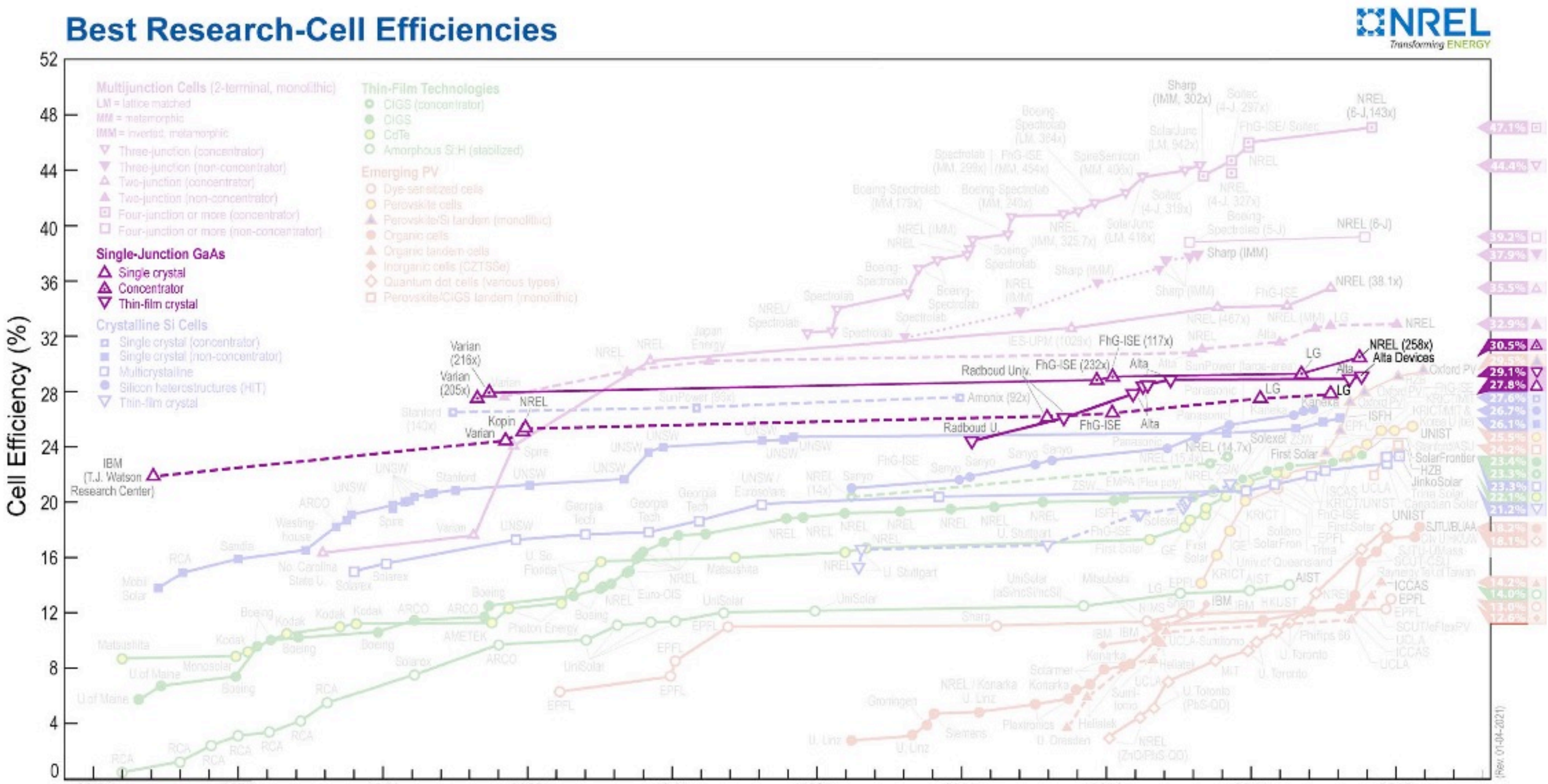
- Boron doped p-type Cz water: Boron (dopant) and oxygen (growth process impurity) forms a boron-oxygen related metastable defect upon illumination
  → Solution: Boron to Gallium dopant
  FZ instead of Cz
  Regeneration process to remove the defect

- 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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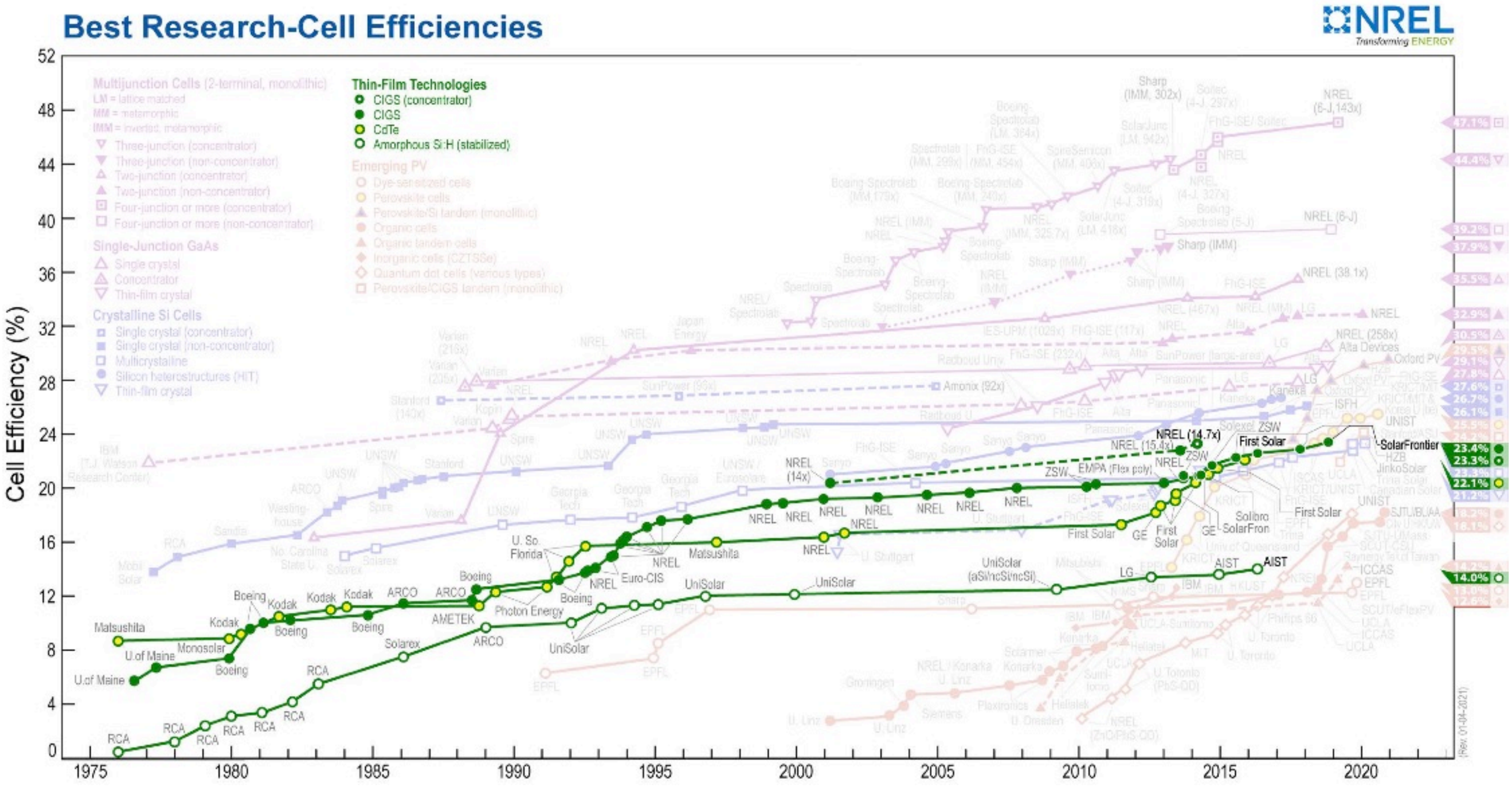
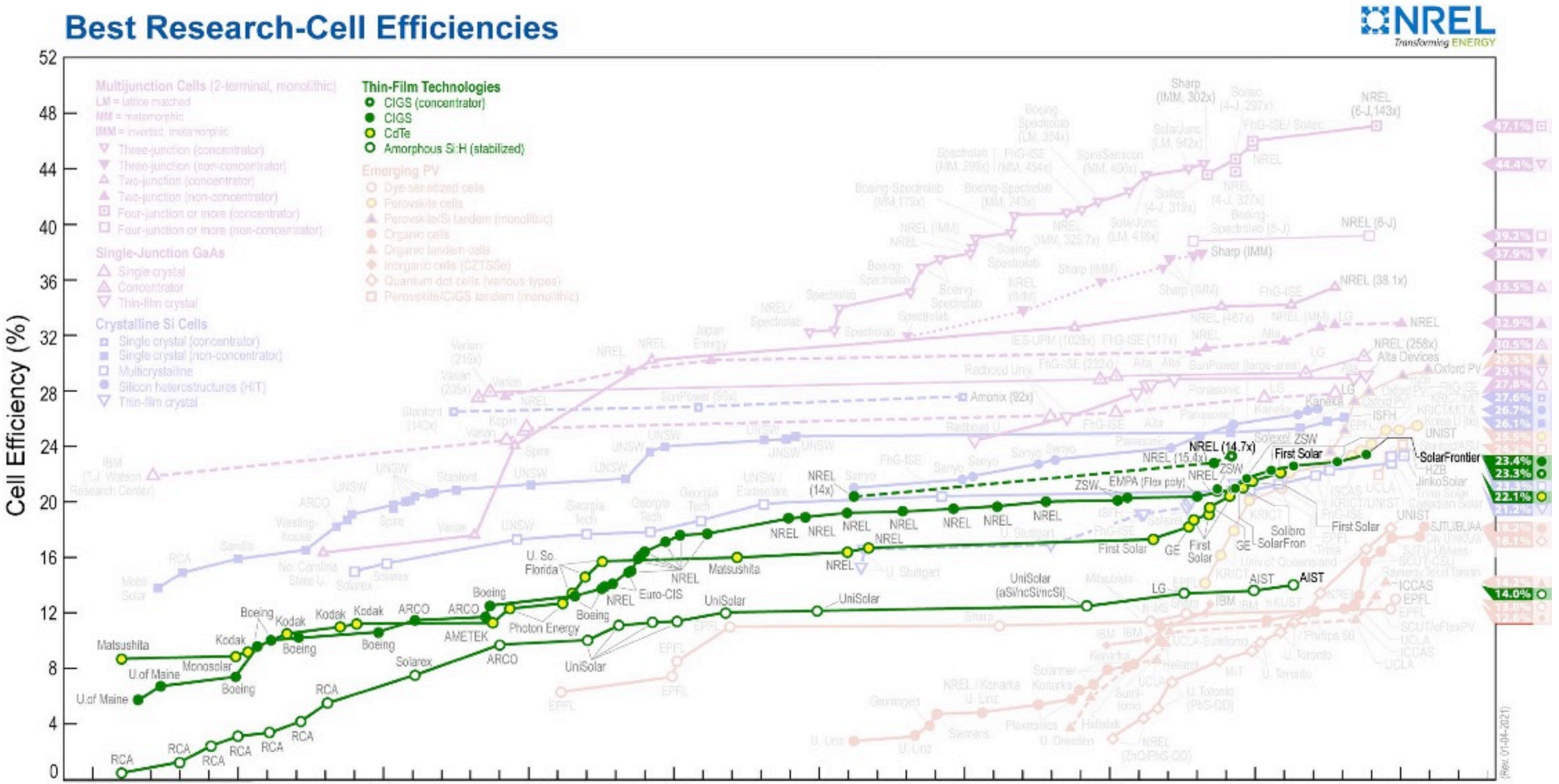
II-VI Semiconductors: CdTe



CIGS Thin Film Solar Cells



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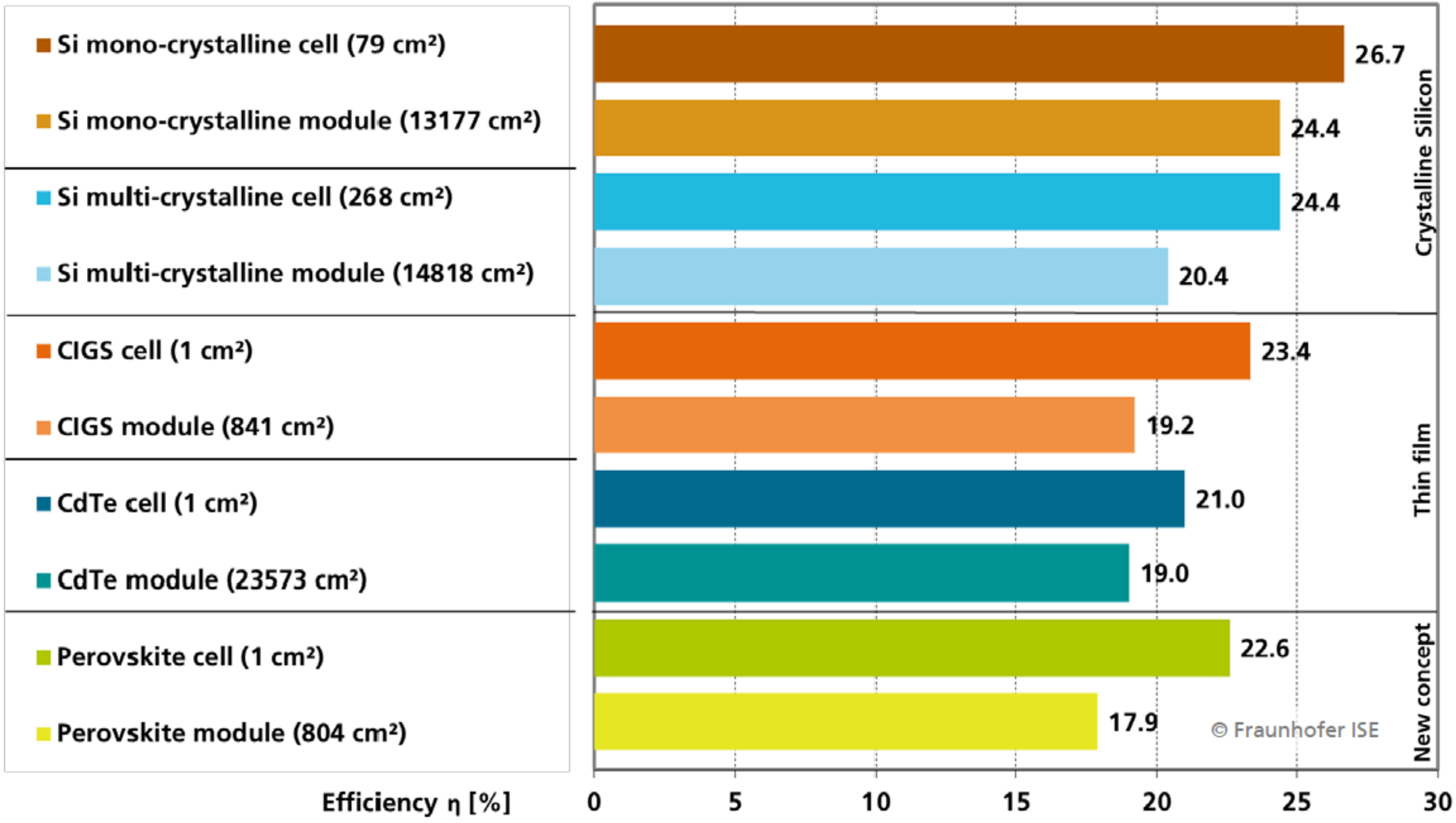
Efficiency Comparison of Technologies



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