



Solar_{PV} Energy

“Solar Park” 31 MW farm in Les Mees/France (2011)
6 solar PV plants (Eco Delta Développement, EDD)

112,000 solar modules on 70 hectares.
Inverters: low- and medium-voltage components/ DC-AC
transformers. Siemens responsible for the civil works and
substructure, performs maintenance on power plants.

Agenda

- Intro
- Solar insolation, power density, solar emission spectrum
- Utility size(solar farms) & residential PV arrays
- Silicon solar photo-voltaic (PV) technology
 - Semiconductor band structure, gap, junctions
 - Charge carriers in n-type and p-type semiconductors
 - Photocell operation, efficiency
 - Solar-PV cell design R&D
 - Silicon wafer, cell manufacture
 - Materials and emissions in construction
- Concentrated Solar power
- US installations and performance, system cost and incentives
- Solar power strategic issues



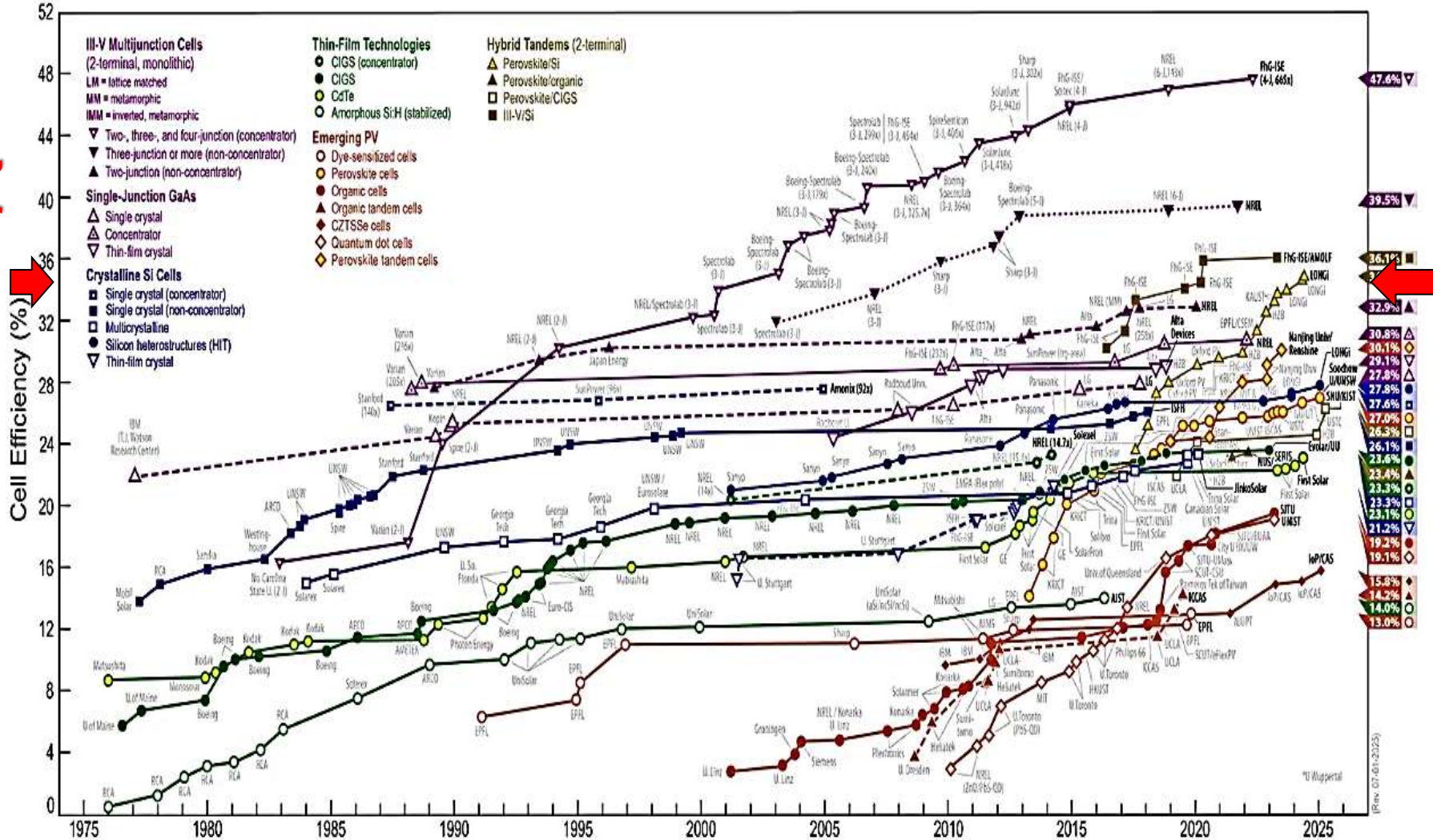
Mercedes-Benz Vision Iconic

German automaker Mercedes-Benz has unveiled the Vision Iconic prototype, the first car featuring its “solar paint” photovoltaic solution, at Shanghai Fashion Week in China. The company said the coating comprises innovative modules just 5 micrometers thick that can be applied to the car body “like a wafer-thin paste” or other substrates.

Ongoing (2025) R&D: Efficiencies of Solar Cells

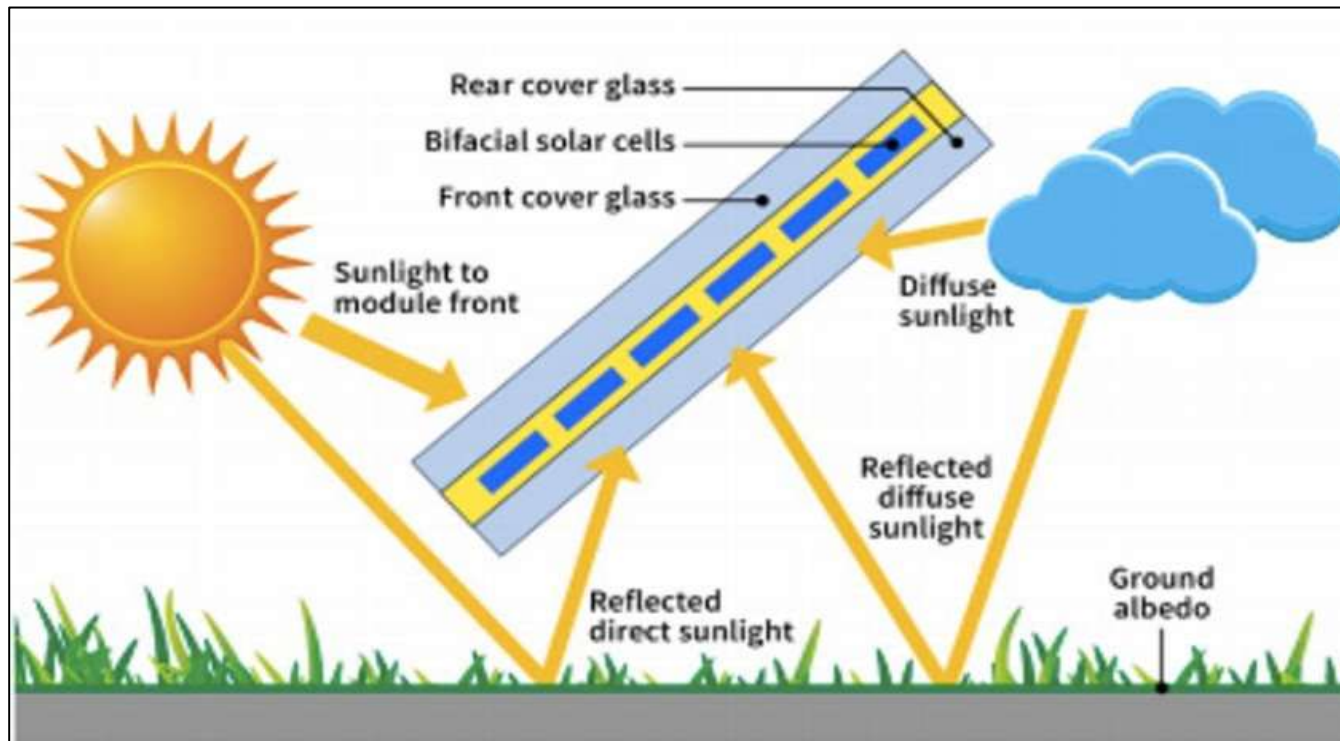
Shockley-Queisser Limit

Best Research-Cell Efficiencies



Mainstay Si cell production

New R&D: Bifacial PV Cells

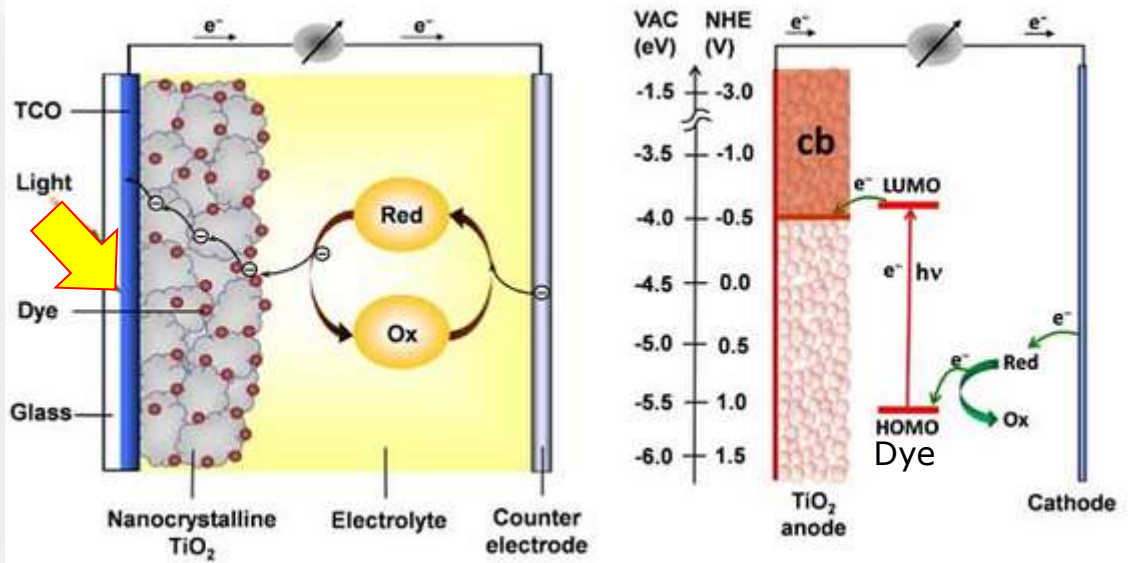


Reflected sunlight has same frequency as incoming light.

Study determined that two-sided, sun-tracking panels produce an average of 35% more energy than immobile single-panel systems and that they are 16% more cost-efficient.

That holds true even when accounting for changes in weather conditions.

Cell Designs in R&D



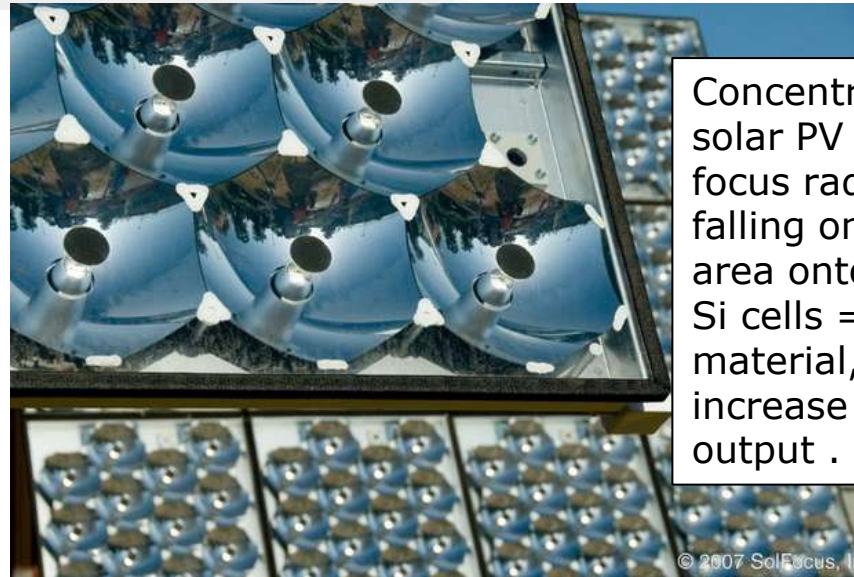
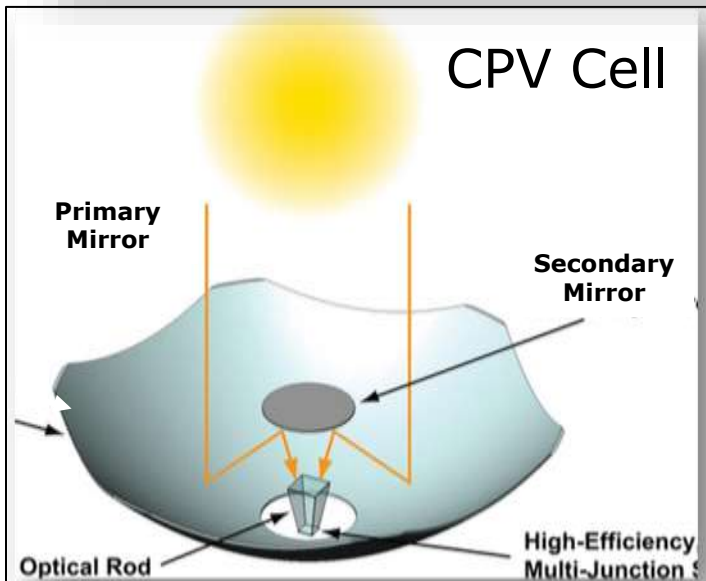
Dye sensitized solar cells:
20-nm, dye-coated TiO₂ nanoparticles in electrolyte.

$h\nu \rightarrow \text{dye} - e^- h$, $e^- \rightarrow \text{TiO}_2 \text{ CB}$

Electrolyte ion⁻ donates e^- and fills dye- h

6

ESTS 3-6-2 PV Solar Power



Concentrated solar PV cells: focus radiation falling on large area onto small Si cells = save material, increase cell output .

© 2007 SolFocus, Inc.

Thin-Film PV Solar Cells: CIGS



Nano-particles embedded in plastic sheets. Monolithic design.

The ZSW institute's building in Stuttgart-

2019: CIGS (Copper, Indium, Gallium and Selenium) p-type CuInGaSe_2 joined with n-type CdS, plus contacts. → high cell efficiencies PCE in thin-film PV technologies, (23.4% one cell, 17.5% on module).

CIGS "ultra-high efficiency" tandem cells → 30% efficiency.

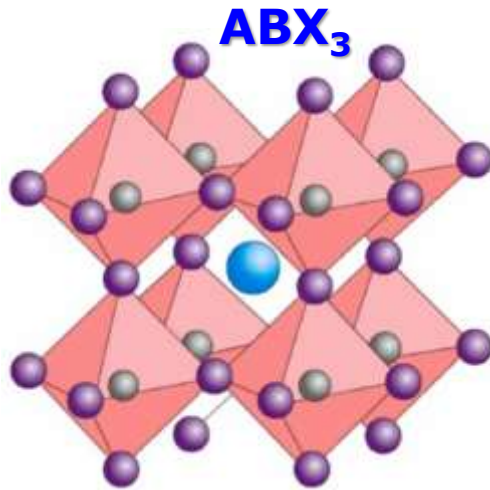
Future efficiency development via band-gap tuning: *Perovskite/CIGS* tandem

2022-24: CdTe thin-film, US First Solar (\$0.3/W),

Monolithic panel arrays → 100-200V

Perovskite Solar Cells (Heterojunction PSL)

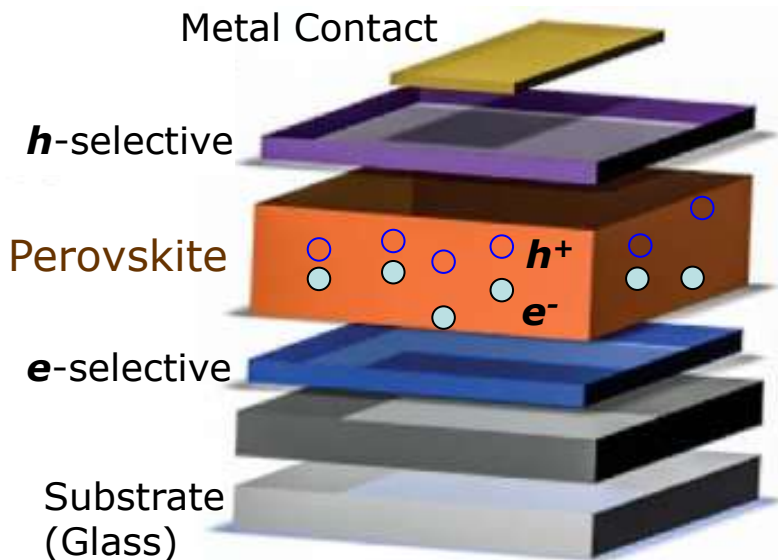
CaTiO₃ Mineral



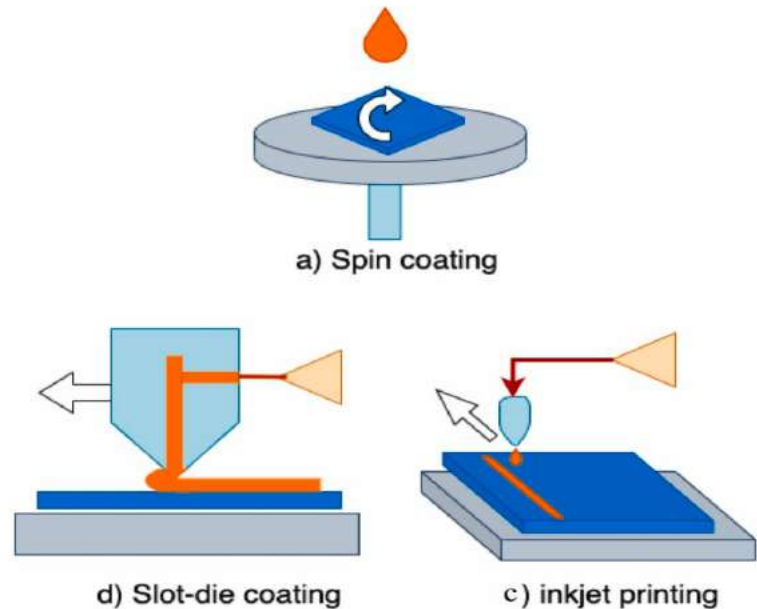
ABX₃ perovskite semiconductors:
 Cations A & B, A= Methylammonium (MA=CH₃NH₃), B= metal (Pb, Sn),
 X=Halide (Cl, Br, I) **Water-soluble (!)**

R&D priorities: Light absorbance, exciton lifetime, diffusion length, **stability**, ease of fabrication, versatility, environment, marketing.

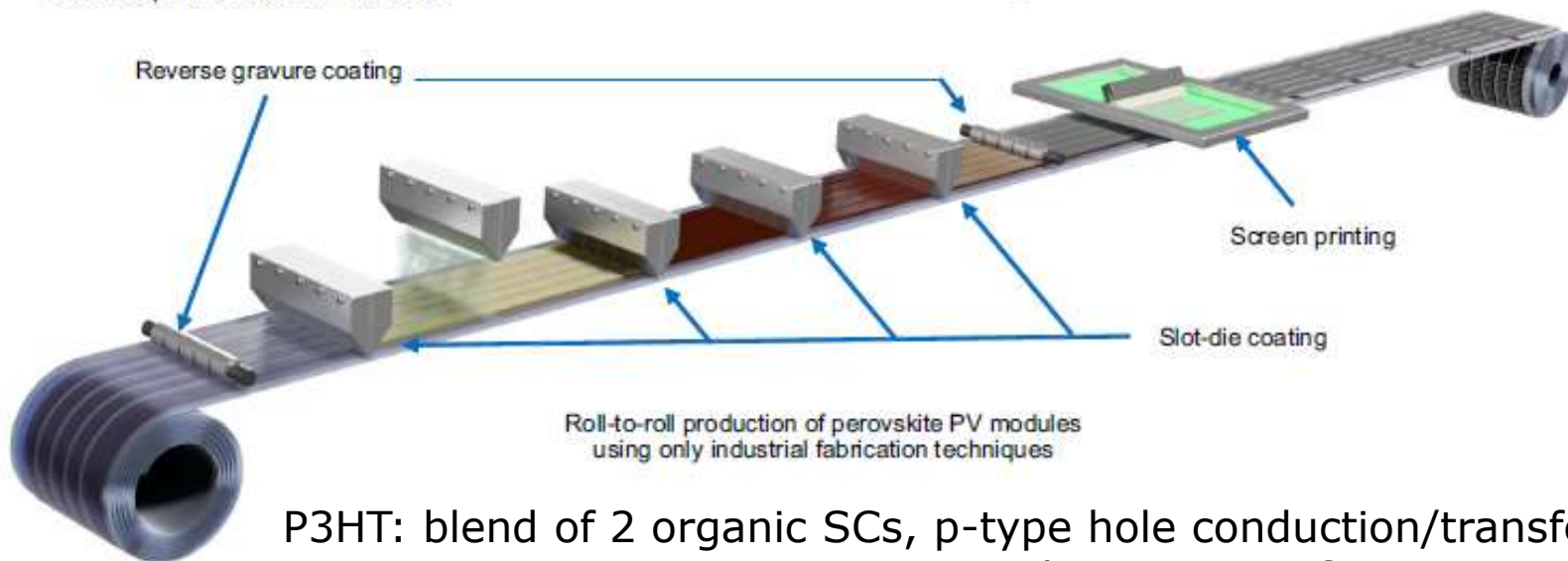
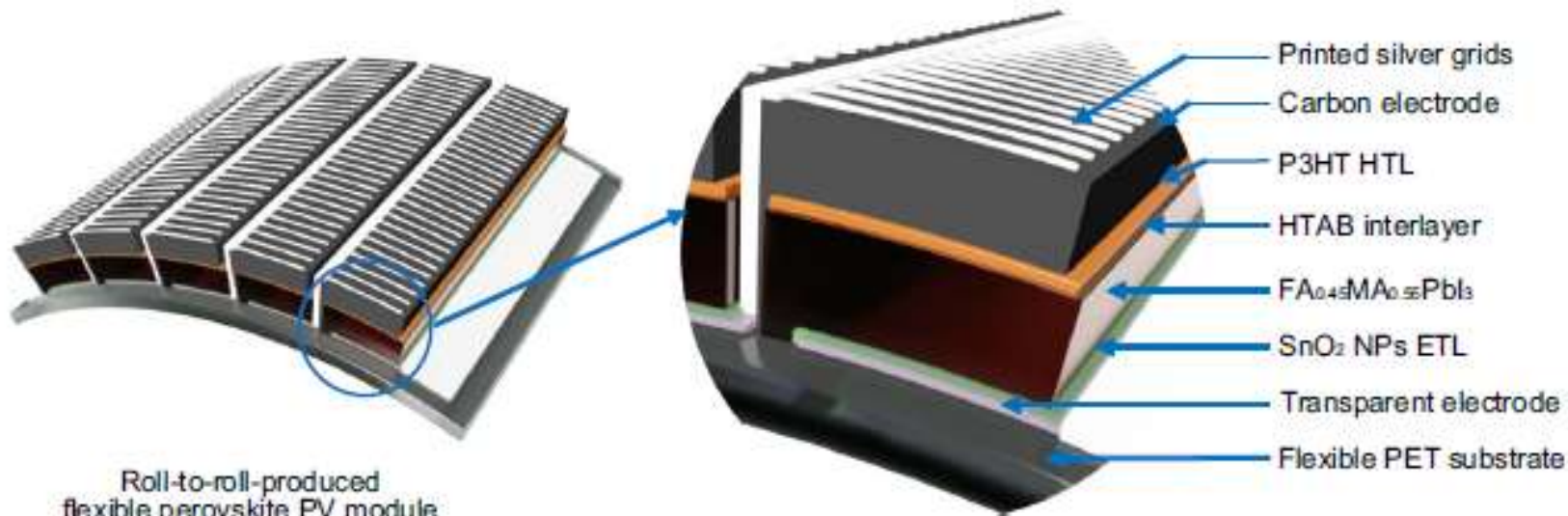
Planar heterojunction PSL



Thin-Film Fabrication Methods



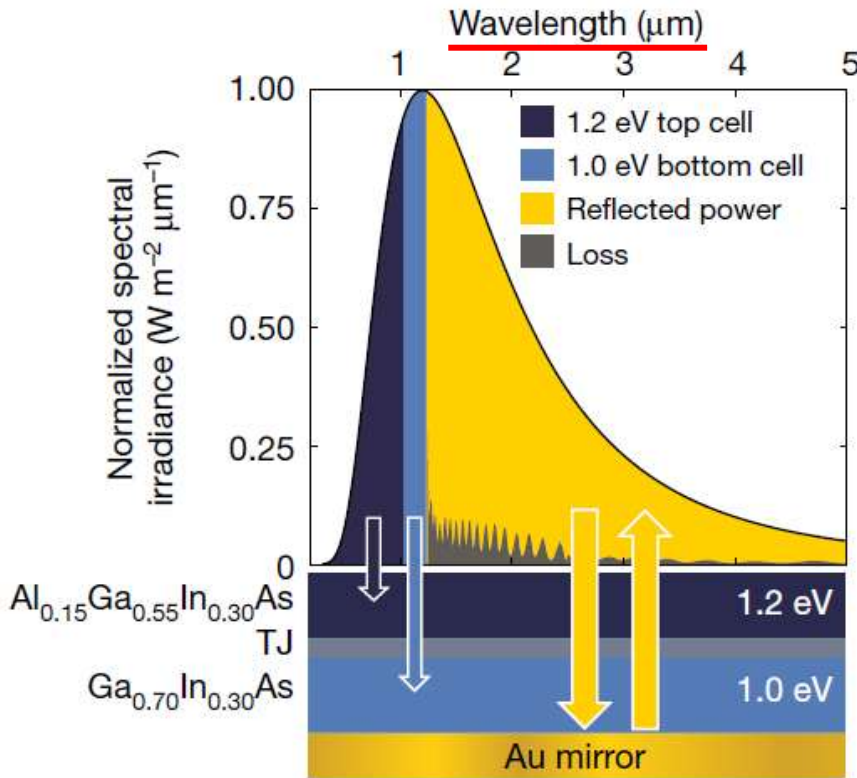
Thin-Film Multi-Junction Perovskite Solar Cells



P3HT: blend of 2 organic SCs, p-type hole conduction/transfer.
 ETL: TiO_2 , SnO_2 , or organic PCBM Electron Transfer Layer;
 HTL-Organic, Hole Transfer Layer

Hi-T Thermophotovoltaic (TPV) Cells

Application: Heat (Q_h) Conversion



TPV for high temperatures $\sim 2000^\circ\text{C}$:

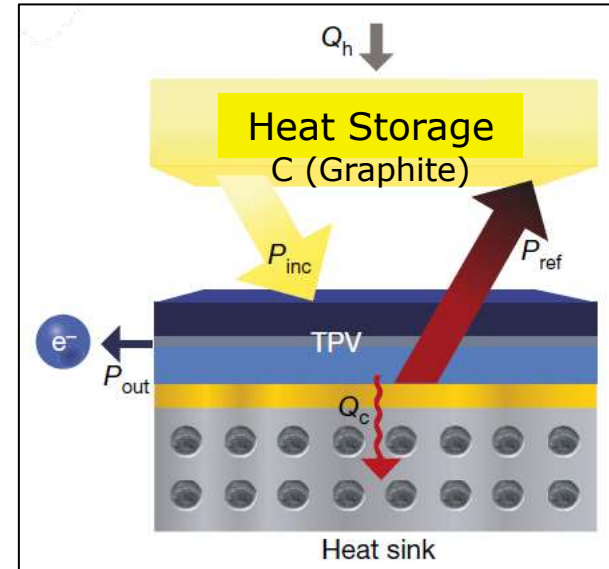
SC materials with $\varepsilon_G = (1.0 - 1.4) \text{ eV}$

Tandem of 2 SD diodes with

TJ thermal junction

Back mirror for recycling (P_{ref})

heat ($h\nu < \varepsilon_G$ back to emitter)



TPV: Incident power can be

- a) converted to electricity (P_{out}),
- b) reflected back to emitter (P_{refl})
- c) dissipated (Q_c), because of inefficiencies of cell and/or back reflector.

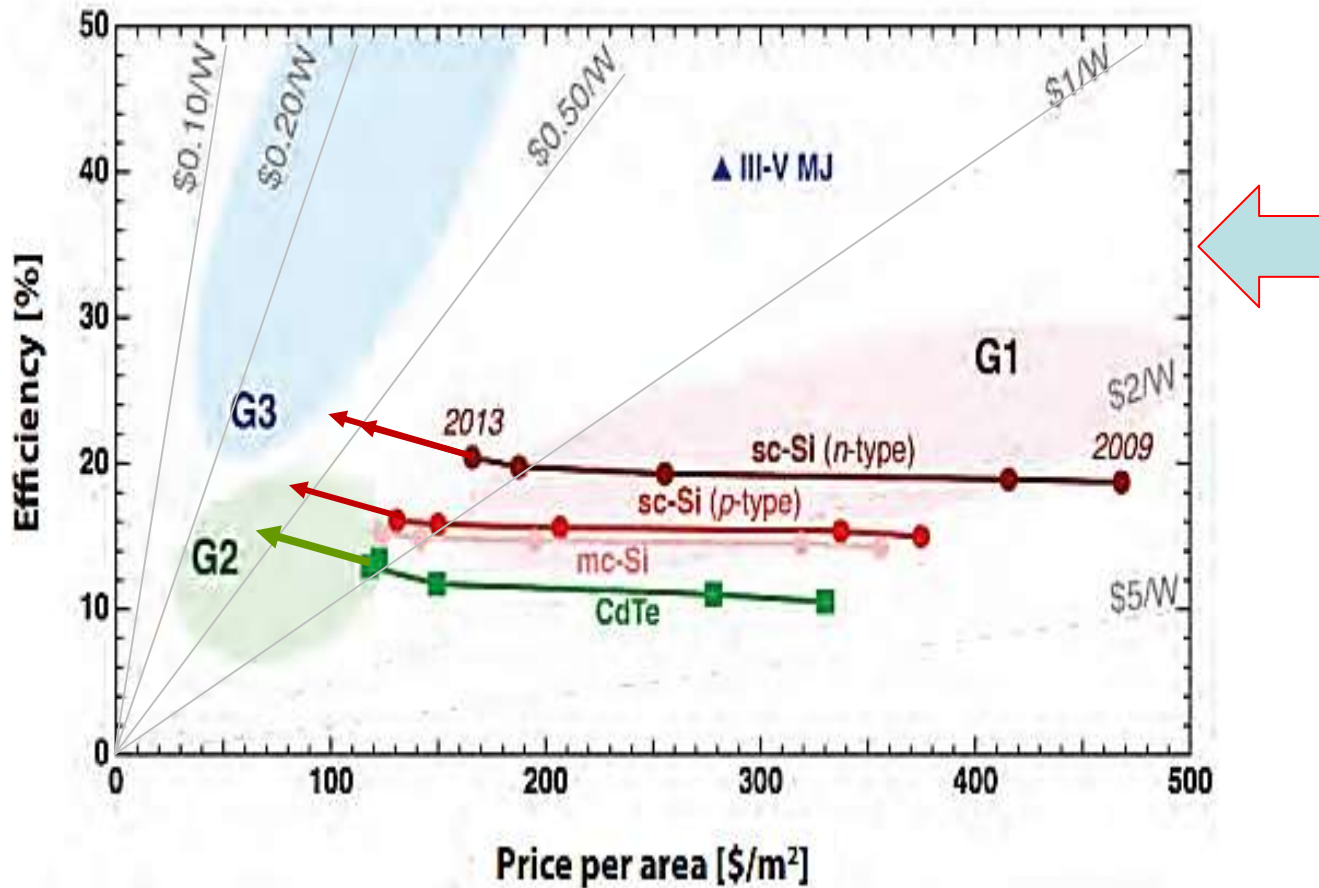
$$PCE \ \varepsilon = \frac{P_{out}}{P_{inc} - P_{refl}} \approx 39\%$$

Thermal Coefficients of Solar PV Cell Power

Thermal coefficient leads to reduction in maximum power:
 $\Delta P/P \approx \gamma_p \times (T_{\text{cell}} - 25 \text{ }^\circ\text{C}),$ Typically = 0.3%/°C

Tech	γ_p (Pmax)	Notes (Voc/Isc)	Source
CdTe (Series 7)	-0.32	Voc \approx -0.28 %/°C; Isc \approx +0.04 %/°C	5324526.app.net...
c-Si PERC (mono)	\sim -0.35	Voc \approx -0.27 %/°C; Isc \approx +0.048 %/°C	enfsolar.com
c-Si TOPCon (mono, n-type)	\sim -0.29	Voc \approx -0.23 %/°C; Isc \approx +0.05 %/°C	LONGi Solar
c-Si HJT (mono, n-type)	\sim -0.24 (-0.24 to -0.26)	Low-magnitude γ_p is a key HJT advantage	recgroup.com

Trends in Commercial PV Price/Performance



PV module efficiency and price per area (period 2009-2013), extrapolated 2025. Conventional generations: G1 in red, G2 in green, and G3 in blue.

Current G1 and G2 modules cluster near the region originally defined as G2. BUT: Need to consider electrical etc. balance of system cost.

Agenda

- Intro
- Solar insolation, power density, solar emission spectrum
- Utility size(solar farms) & residential PV arrays
- Silicon solar photo-voltaic (PV) technology
 - Semiconductor band structure, gap, junctions
 - Charge carriers in n-type and p-type semiconductors
 - Photocell operation, efficiency
 - Solar-PV cell design R&D
 - Silicon wafer, cell manufacture
 - Materials and emissions in construction
- Concentrated Solar power
- US installations and performance, system cost and incentives
- Solar power strategic issues

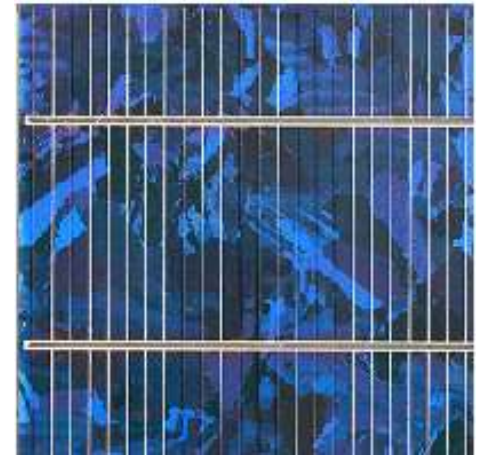
Common Commercial Solar Cells



Silicon single-crystals:

Continuous, repetitive structure.
Rare in nature, needs to be grown in lab. → expensive for large crystals.

Solar cells made from single crystal, (200-300) μ wafers. Mono-crystalline cells, most efficient, most expensive.



Multi-crystalline silicon:

Pieces made of more than one single-crystal, multiple domains.

Constituent crystals relatively small, easier to grow and cheaper.
Also less efficient, free charge carriers have to cross boundaries.

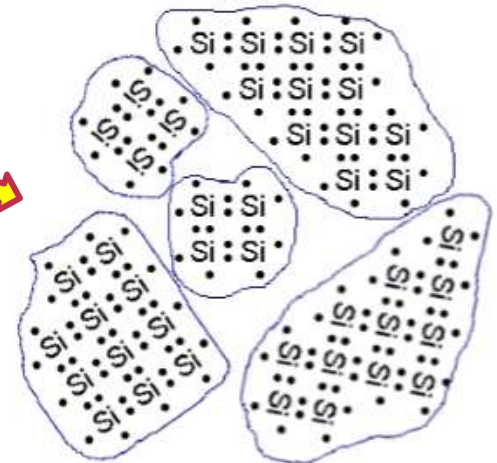
Amorphous **a-Si:H** $\langle \epsilon_G \rangle = 1.7\text{eV}$, high absorbance.

>2020: **Thin-film** cells (1 μ thick), technique saves material, stability problems.

Heterojunction cells: CdTe,..

Multi-layer cells

Organic semiconductors.



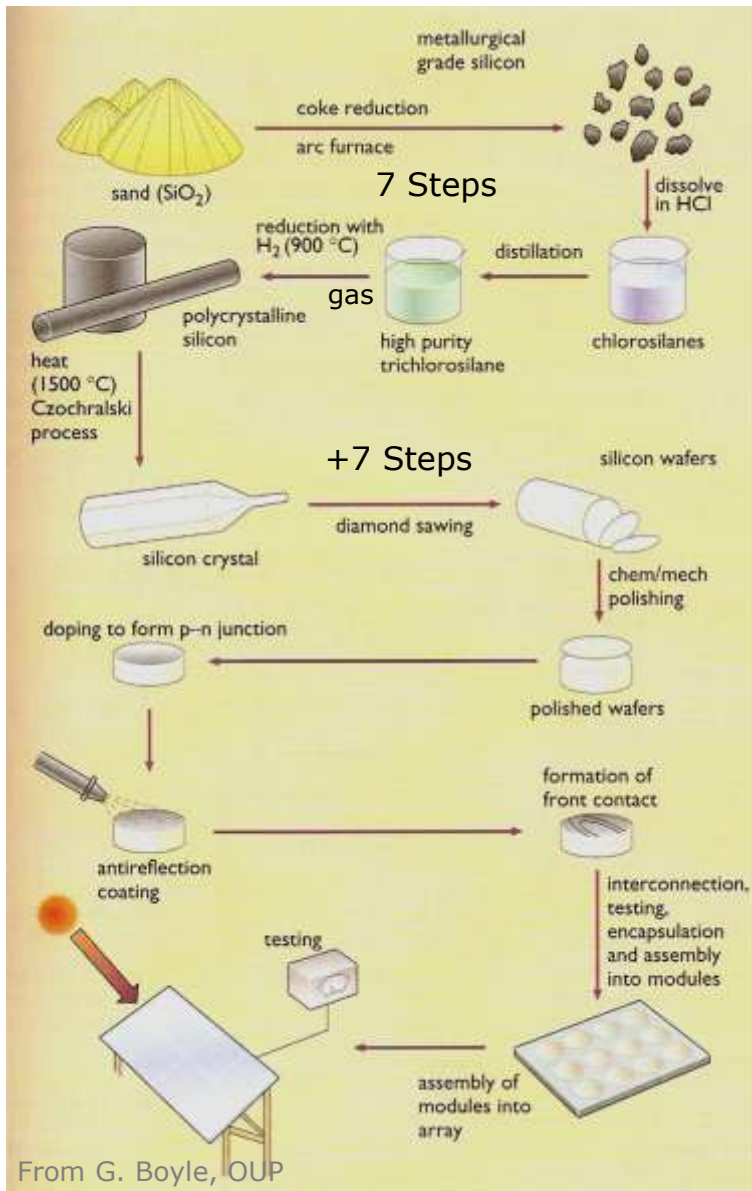
Cell Production Process

Single-crystal Si cell manufacture

Reduction of SiO_2 with coke. Chemical purification: Silicon tetrachloride (SiCl_4) and trichlorosilane (HSiCl_3) are intermediates in the industrial production of ultrapure silicon.

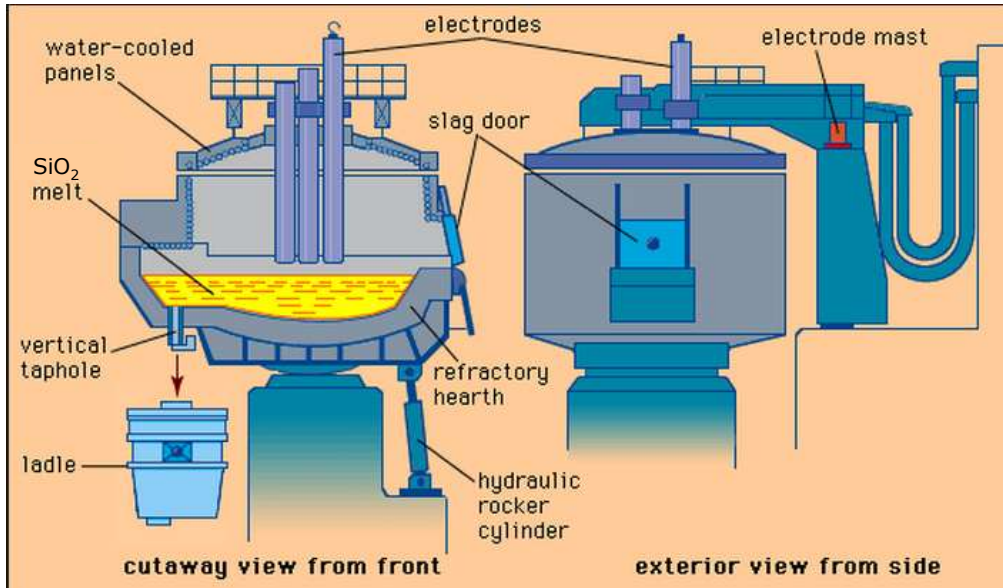
Chlorosilanes obtained from metallurgical Si
 → purified by fractional distillation
 → reduced with H_2 (900°C) →
 → Si with 99.999999999 % (10^{-11}) purity.

Czochralski process draws single-crystal ingot out of Si melt, originally developed for computer chip industry. Variations: edge defined, film fed single-crystal Si growth



From G. Boyle, OUP

Semiconductor Grade Silicon Fabrication



Steps to Obtaining Semiconductor Grade Silicon (SGS)

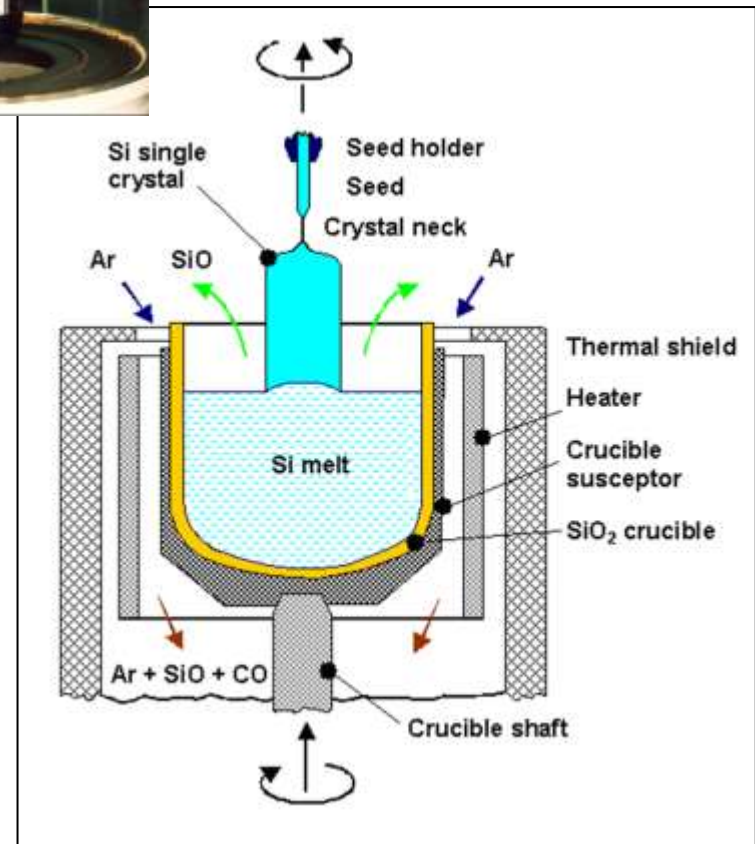
Step	Description of Process	Reaction
1	Produce metallurgical grade silicon (MGS) by heating silica with carbon	$C (s) + SiO_2 (s) \rightarrow Si (l) + SiO (g) + CO (g)$
2	Purify MG silicon through a chemical reaction to produce a silicon-bearing gas of trichlorosilane (SiHCl ₃)	$Si (s) + 3HCl (g) \rightarrow \underline{SiHCl_3 (g)} + H_2 (g) + \text{heat}$
3	SiHCl ₃ and hydrogen react in a process called Siemens to obtain pure semiconductor-grade silicon (SGS)	$2SiHCl_3 (g) + 2H_2 (g) \rightarrow 2Si (s) + 6HCl (g)$

Arc furnace for processing materials with high melt temperatures, e.g.,
 $T_{\text{fus}} = SiO_2: 1,600^\circ C.$

Czochralski Process

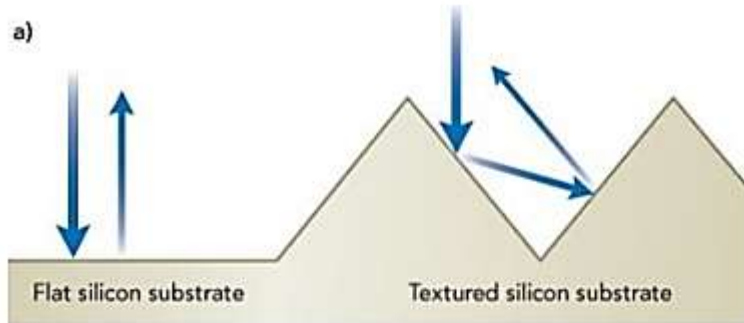


Metallurgical Si is melted in quartz crucible, seed Si crystal dipped into melt, slowly drawn while rotated. Impurities remain in melt, oxygen from crucible → Si crystal, stabilizes.

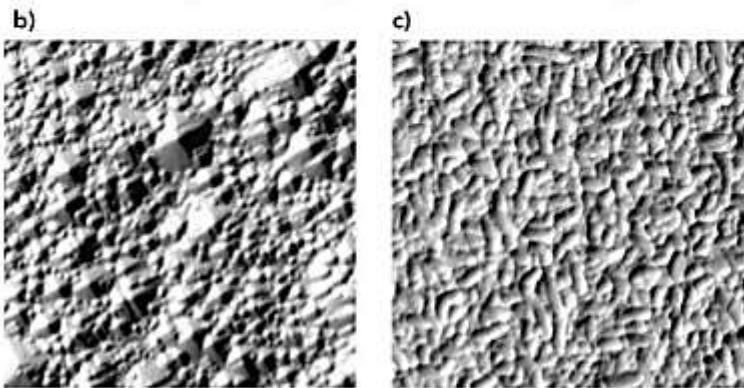


Large single-crystal suspended by thin **Si** seed crystal (inset, arrow). Seed crystal supports weight of the crystal and the torque needed to rotate crystal during its growth

Surface Treatment



Texturization results in the reflected light striking the silicon surface again, increasing the amount of absorbed light.



Random pyramids formed after alkaline texturing of monocrystalline silicon.

Worm-like structures formed after acidic texturing of multicrystalline silicon.

Surface treatment increases light trapping probability.

- 1) Anisotropic alkaline "texturing," mainly for mono-crystalline wafers: potassium hydroxide (KOH)/isopropanol (IPA) mixture → processing at (80°-90°C) for extended periods, 30 min → 8 hrs (newer methods).
- 2) Texturing multi-crystalline silicon wafers, isotropic acidic etch with (HF)/nitric acid (HNO₃) mixture, in which HNO₃ is added to oxidize the silicon surface and HF to strip the oxide.

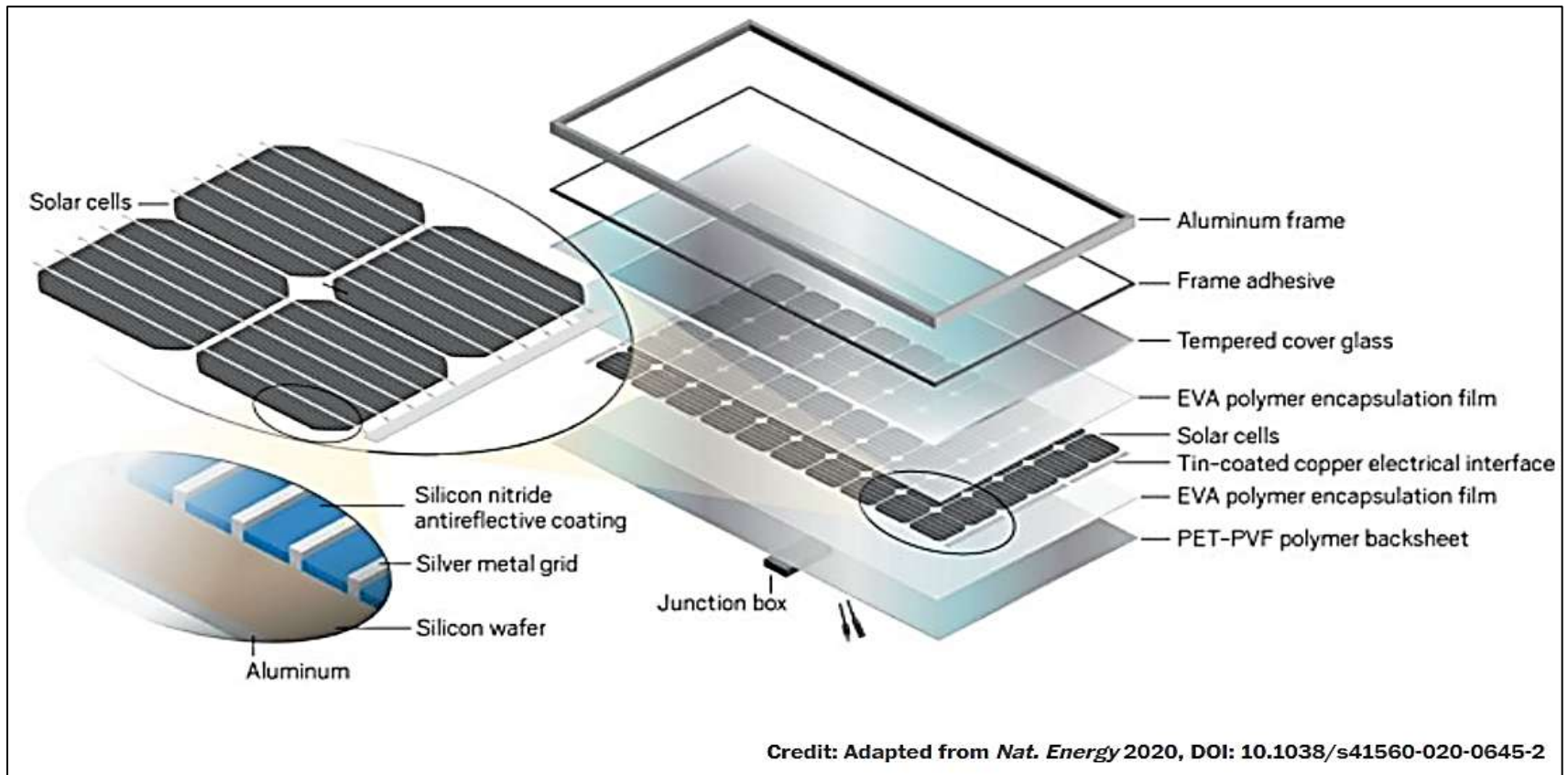
Chemicals used in doping:

p-type silicon solar cell: phosphoric acid or POCl₃, dissolved by a simple HF dip.

a) schematic representation of increase in light absorption on a textured silicon surface; b) Silicon wafer after treatment with an alkaline texturing solution; c) Silicon wafer after treatment with an acidic texturing solution.

After J. Hoogboom, S. Kuiper, P. Thomassen (Mallinckrodt Baker BV)
<http://www.renewableenergyworld.com/rea/news/article/2010/02/performance-chemicals>

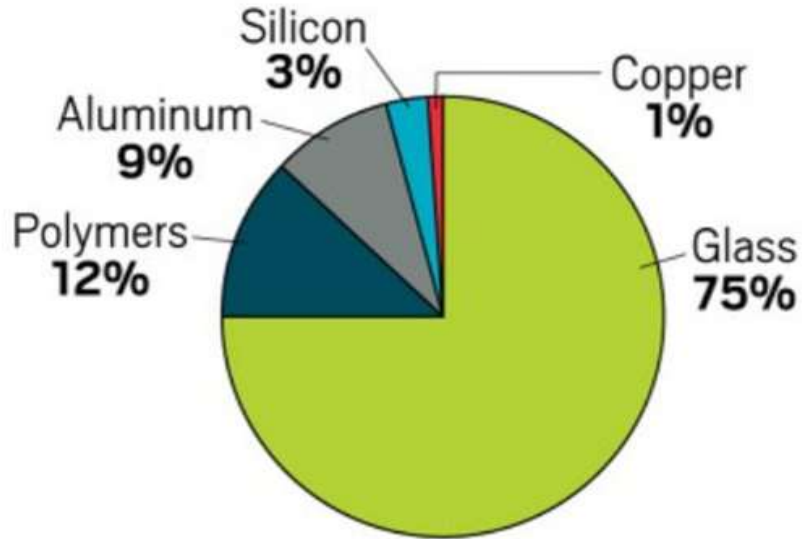
PV Solar Cell Assembly



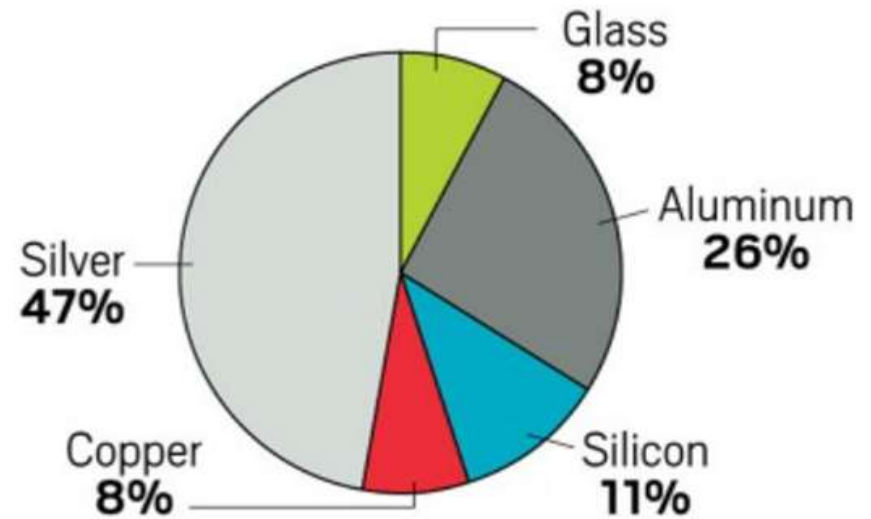
Bulk materials like glass and aluminum make up more than 80% of the mass of a silicon photovoltaic cell.

But two-thirds of the monetary value of a cell's materials is from silver, silicon, and copper—more minor components.

Si-PV Cell Materials



Distribution of materials by mass



Distribution of materials by value

Source: Martin Bellman/Icarus. **Note:** Silver is less than 1% of the mass.

Raw Materials Used in Energy Technologies

Materials (kg) needed for generating 1-GWh of electricity in various technologies, including basic resources. (1GWh = 8.7TWh)

Plant → Materials	Coal 45,5 %	Lignite 44 %	natGas 58 %	Nucl	Hydro 3 MW	Wind 1,5 MW, Off-sh	Solar therm al	Solar PV roof top
Iron	2.000	2.00	1.200	420	2.400	5.200	3.470	5.200
Bauxite	16	18	2	27	4	44	6	2.000
Copper	2	7	1	6	5	65	252	230
Limestone	7.000	20.000	6.400	800	6.000	2.490	2.100	10.000
Nickel	1,4	1,1	0,4	15,5	0,4	0,4	0,5	14
Coal	501.300	3.500	255	880	2.860	3.840	2.700	14.000
Lignite	5.180	1.017.000	300	500	2.750	5.100	745	32.900
natGas	1.160	800	185.705	1.070	730	1.560	440	5.690
Crude Oil	3.760	1.200	2.220	610	580	720	1.750	4.300
Uranium	0,34	0,2	0,003	26,5	0,007	0,02	0,03	0,92

GHG Emissions From PV Plants

Major Construction Inputs and GWE (after 20 yr) for a Photovoltaic Plant^a 4.1 GW installed, \$3.6B(1997)

MT = metric ton

construction inputs	total MT	unit cost (1992 \$/MT)	total cost (1992 \$)	GHG emissions (MT of CO ₂ equiv)			
				CO ₂	+ CH ₄	+ N ₂ O	= GWE
steel	4 600 276	385 ^b	1 772 797 382	6 957 724	4 216	35 924	6 997 865
copper	480 029	2 368 ^b	1 136 805 659	984 580	1 617	10 504	996 701
electricity (MWh)	7 556 010	36 ^c	268 780 863	2 152 447	1 077	20 407	2 173 931
aluminum	177 788	1 268 ^b	225 374 699	428 610	405	6 558	435 573
cement	2 222 356	55 ^b	121 362 849	410 263	394	15 497	426 153
glass	1 066 731	50 ^b	53 336 538	56 951	67	759	57 777
total			3 578 457 990	10 000 000	8 000	90 000	10 000 000

^a Total emissions are rounded to one significant digit. ^b Ref 40. ^c Ref 41.

S. Pacca& A. Horvath, Environ. Sci. Technol. 36, 3194 (2002))

Land purchase for construction (51 km²) not included in cost

Chemicals used in doping and surface treatments: phosphoric acid H₃PO₄, phosphoryl chloride (phosphorus oxychloride, POCl₃), potassium hydroxide (KOH), isopropanol (IPA), hydro-fluoric acid (HF), nitric acid (HNO₃).