Modern photovoltaic technologies
PHYS-609

Part 1.2 Crystalline Si solar cells*
* c-Si will be continued and extended further in Franz Haug`s lecture on Wednesday

- Material & fabrication
- Conventional c-Si solar cells
- PV modules

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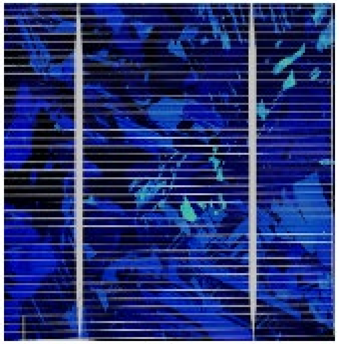
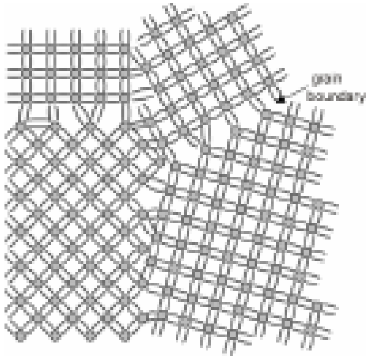
Materials Science and Technology

Si wafer based solar cells and modules

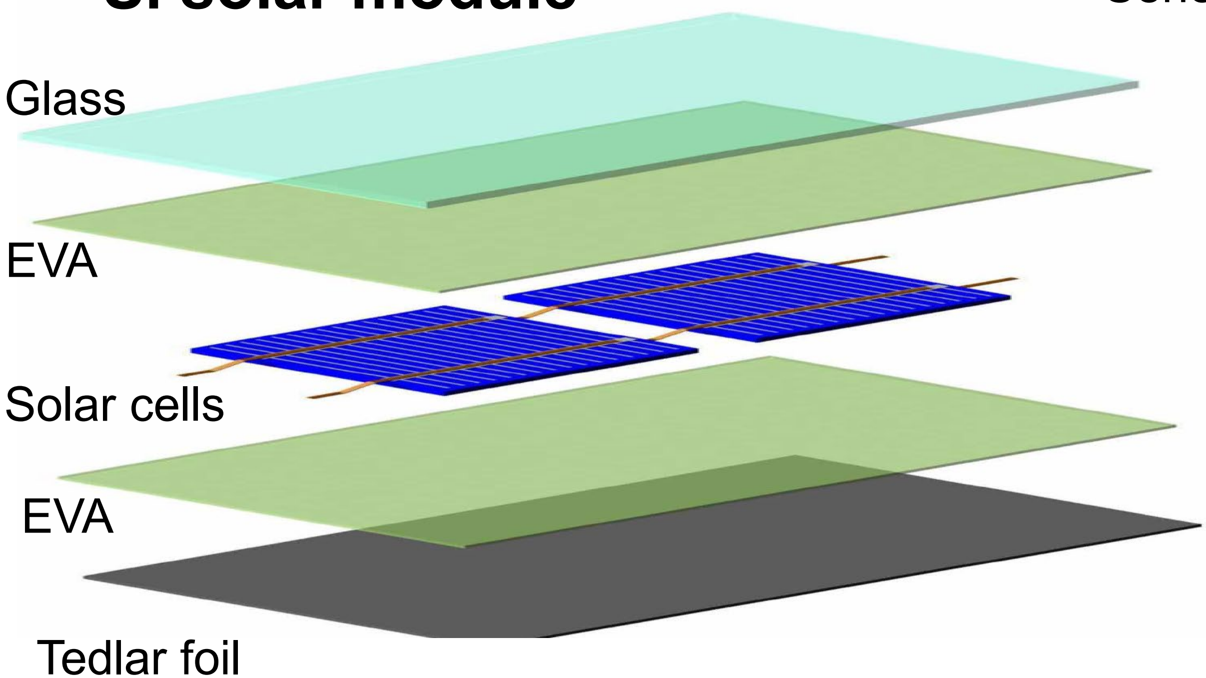
Single crystal

Polycrystalline

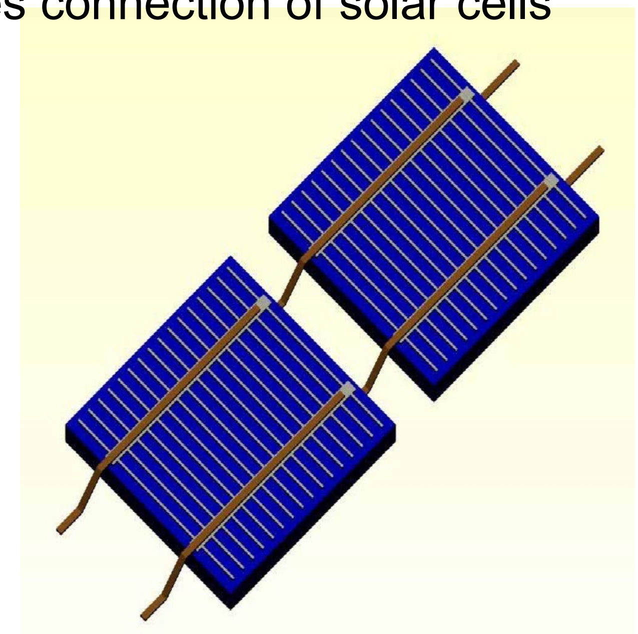




Si solar module



Series connection of solar cells

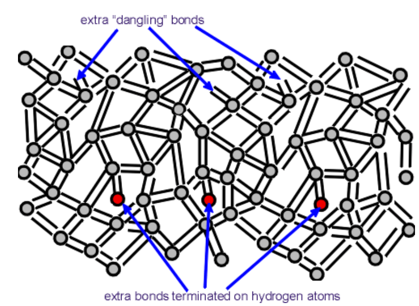


Tabs: Interconnection strips

Properties of Si as semiconductor

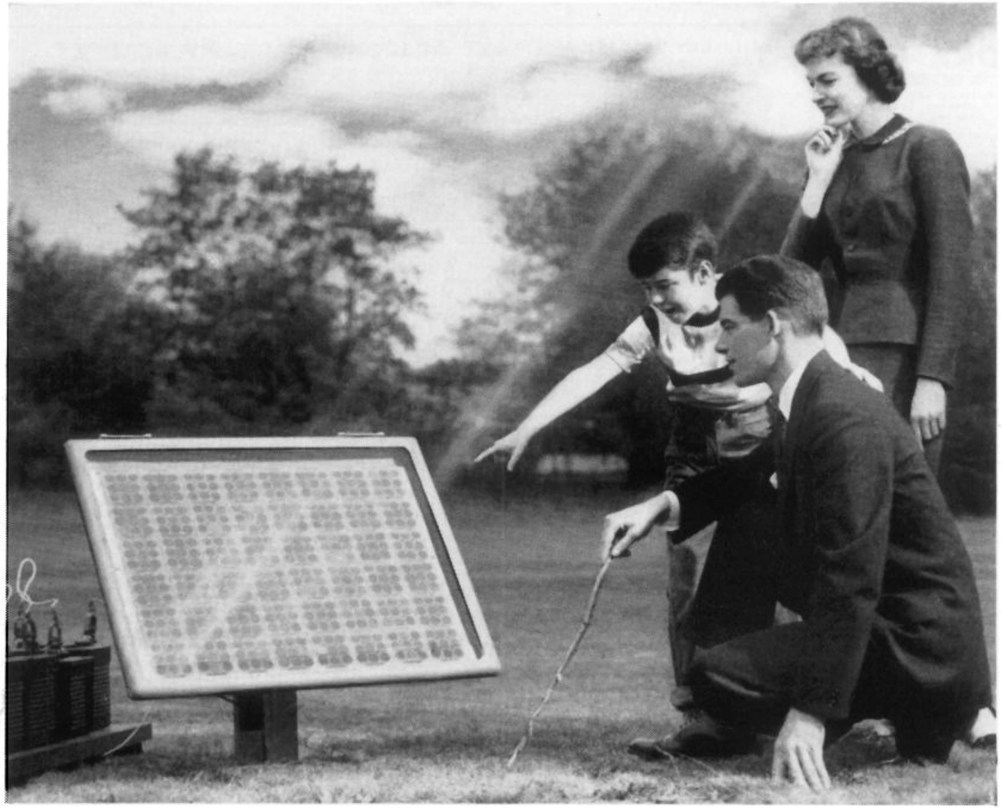
Property	**Value**
Atomic Density	5×10^{22} cm^{-3}
Atomic Weight	28.09
Density (ρ)	2.328 g cm^{-3}
Bandgap energy at 300 K	1.12 eV **(indirect)**
Intrinsic Carrier Concentration (n_i) at 300K	1×10^{10} cm^{-3}
Lattice Constant	0.543095 nm
Melting Point	1415 °C
Thermal Conductivity	1.5 Wcm^{-1}K^{-1}
Thermal Expansion Coefficient	2.6×10^{-6} K^{-1}
Effective Density of States in the Conduction Band (N_C)	3×10^{19} cm^{-3}
Effective Density of States in the Conduction Band (N_V)	1×10^{19} cm^{-3}

Types of silicon

Name	Symbol	Grain Size	Growth Techniques
Single crystal (mono-Si)	sc-Si	>10cm	Czochralski (CZ) Float zone (FZ) 
Multicrystalline (poly-Si)	mc-Si	1µm-10 cm	Directional solidification (DS) 
Microcrystalline	µc-Si	<1µm	Chemical vapor deposition (CVD) 
Amorphous (a-Si)	a-Si	1..10 nm	

History of Si solar cells

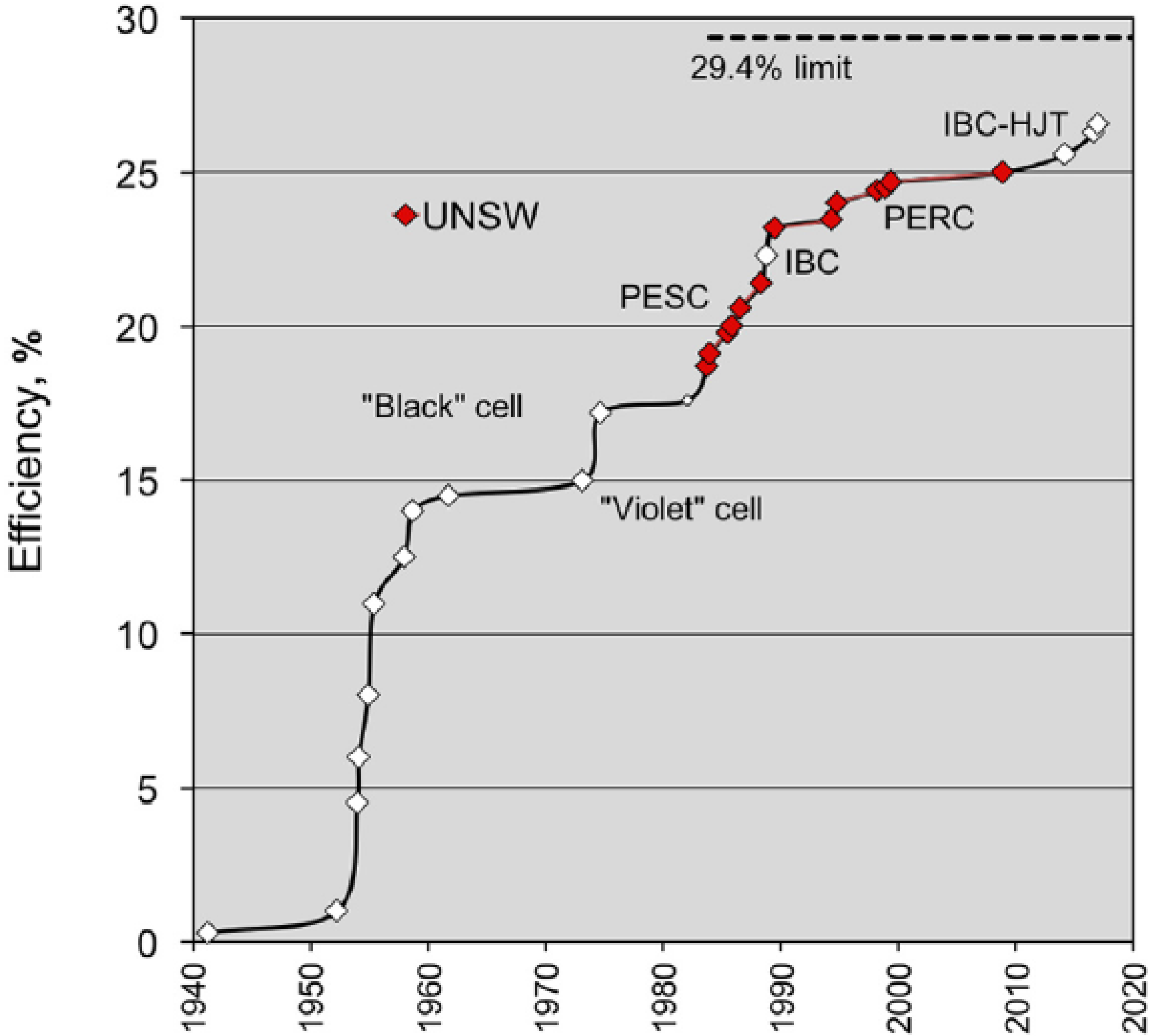
Thomson gave name «silicon» in 1817
Berzellius obtained pure Si in 1823
Deville obtained crystalline Si in 1854
Bell Labs (USA) make the first Si solar cell with efficiency 5% in 1954



Something New Under the Sun. It's the Bell Solar Battery, made of thin discs of specially treated silicon, an ingredient of common sand. It converts the sun's rays directly into usable amounts of electricity. Simple and trouble-free. (The storage batteries beside the solar battery store up its electricity for night use.)

Bell System Solar Battery Converts Sun's Rays into Electricity!

Evolution of Si solar cell efficiency

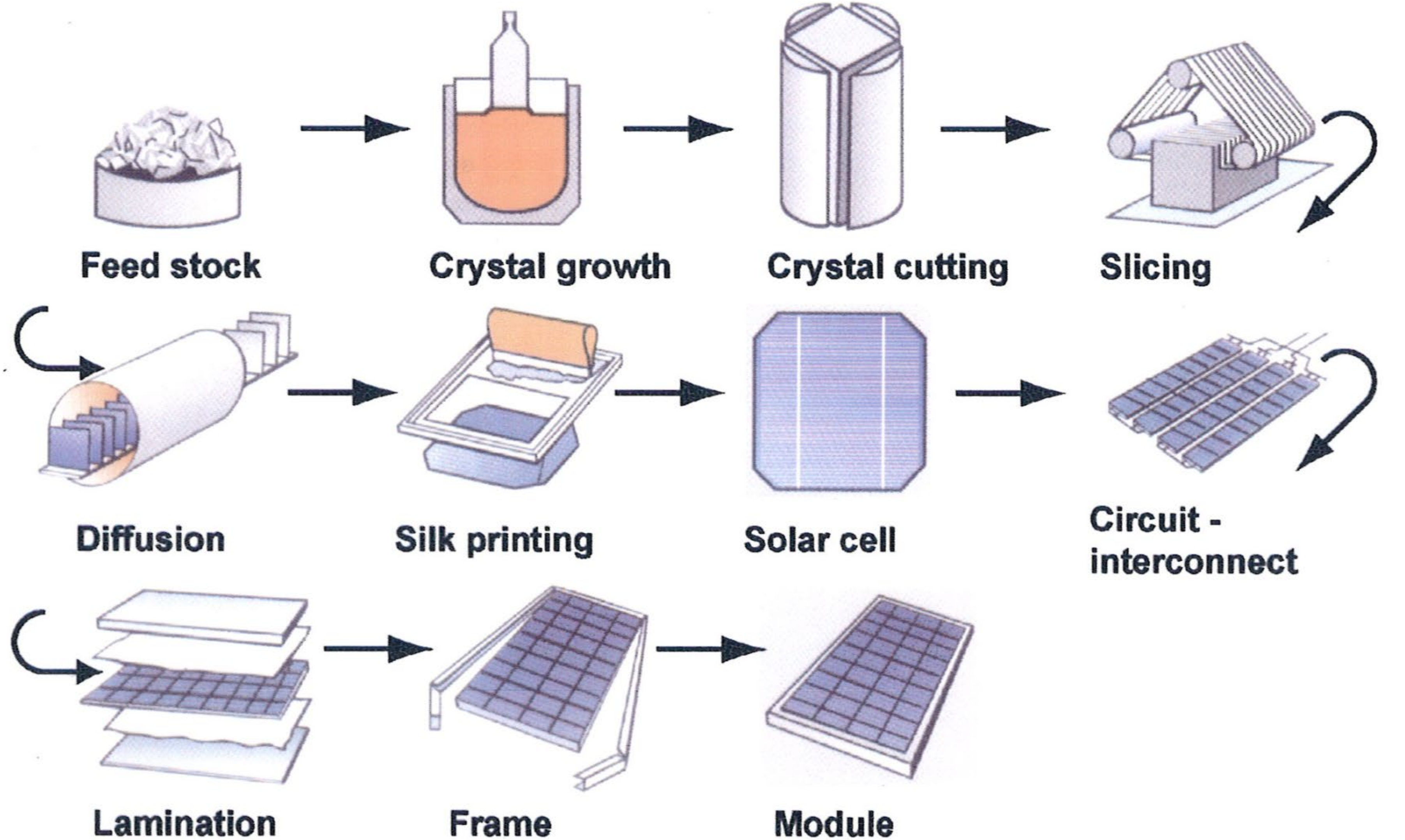


26.7% (Kaneka)

Image: UNSW (University of South Wales)

Materials

Fabrication sequence

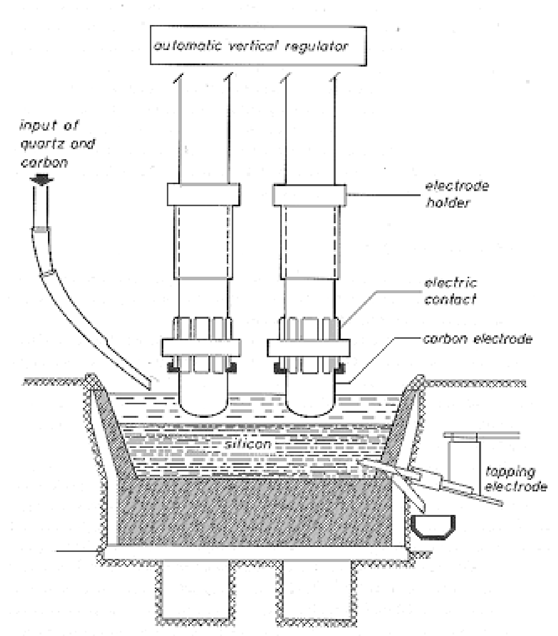


Metallurgical grade Si

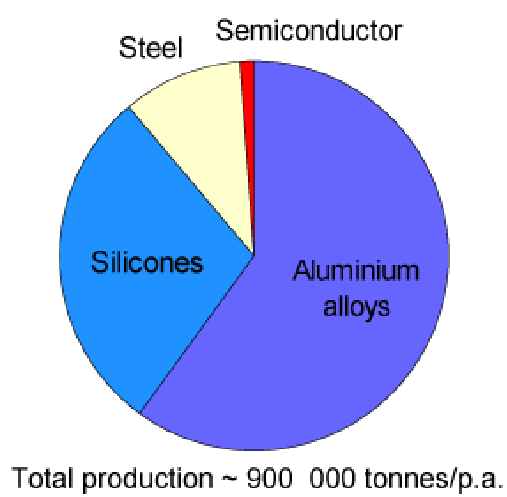
- Si is the second most abundant material
- Sand or typically its crystalline mineral quartzite is used as starting material
- Reduction in arc furnace by Carbon (mixture of wood, coal, etc.) at about 2000 K.

$$SiO_2 + 2C \Rightarrow Si + 2CO$$

- Process is repeated for purification up to 98 %



Arc furnace lined with **C** and SiC, and large graphite electrodes inside (carrying a few **10.000 A** of current).



Element	Concentration (ppma)
Al	1200-4000
B	37-45
P	27-30
Ca	590
Cr	50-140
Cu	24-90
Fe	1600-3000
Mn	70-80
Mo	<10
Ni	40-80
Ti	150-200
V	100-200
Zr	30

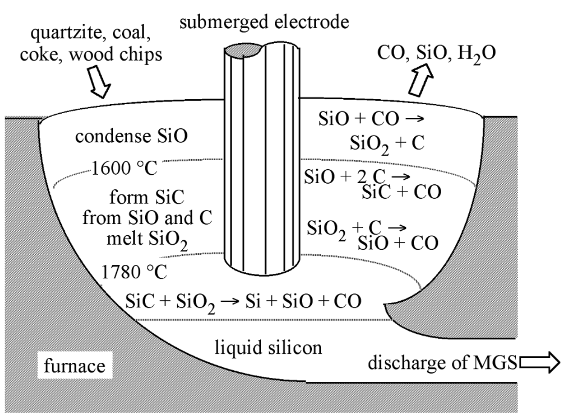


Image: Wikipedia

Image: Handbook of Photovoltaic Science and Engineering, 2011

Semiconductor grade (SG) Si

Microelectronics and PV industries require a very high purity Si, up to 99.9999999 (nine "nines"), called semiconductor-grade (SG) Si

Siemens process to obtain SG-Si by purification of MG-Si:

1) Si is converted to trichlorosilane (**$SiHCl_3$**) at **300°C** above a catalyst:

$$\mathbf{Si + 3HCl \Rightarrow SiHCl_3 + H_2}$$

$SiHCl_3$ is a liquid with a boiling point of **31.8°C.** It is much purer than **MG Si**

2) Fractional distillation to obtain extremely pure **$SiHCl_3$**

3) High-purity Si chunk is produced by **Chemical Vapor Deposition (CVD)**

$$\mathbf{SiHCl_3 + H_2 \Rightarrow Si + 3HCl}$$

Czochralski (CZ) growth of single crystals

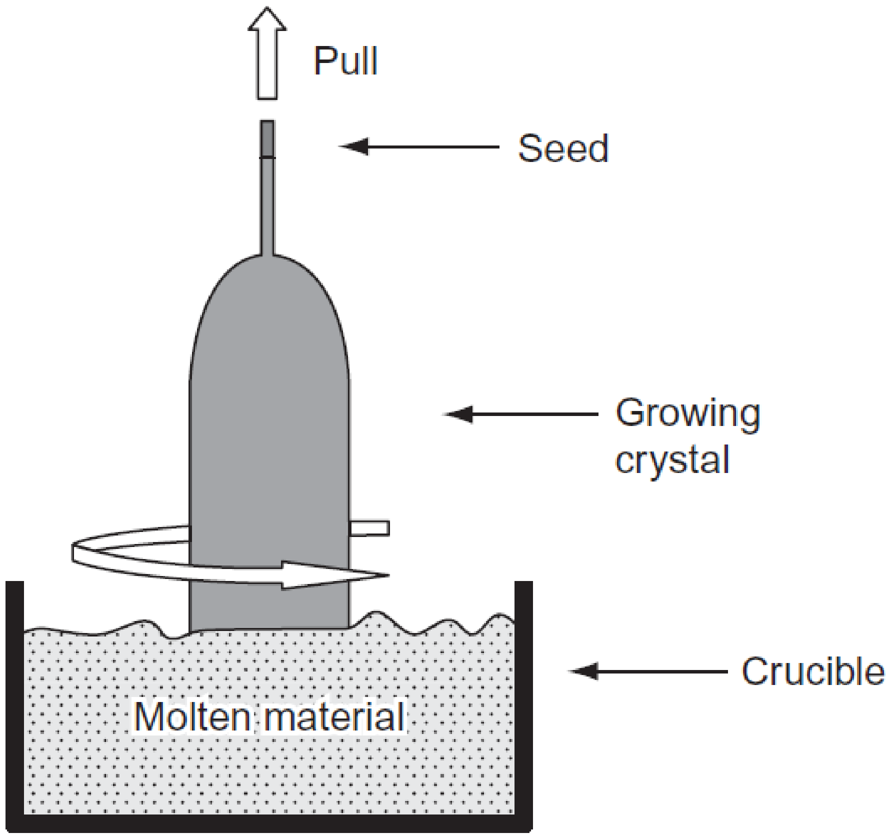


Image: McEvoy`s Handbook of Photovoltaics, 2017

Invented by J. Czochralski_in **1916**

Source: http://www.tf.uni-kiel.de

- The "last drop" contains all the impurities not incorporated because of their small segregation coefficients.

- **Seed crystal** supports the weight of the crystal during rotation and determines the growth direction.

Directional solidification (DS) process

- Si casting into graphite or quartz coated with Si_3N_4 or other compounds (to discourage sticking or enable reuse) as an alternative to CZ growth for PV applications was developed in 1976.

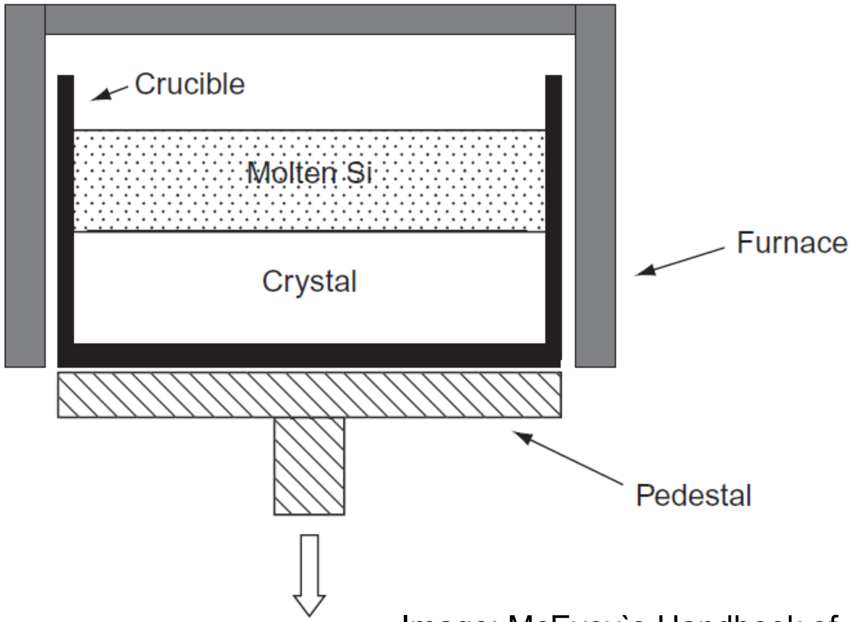


Image: McEvoy`s Handbook of Photovoltaics, 2017

PVeducation.org

- Multi-crystalline ingots weighing as much as 1000 kg are obtained in cycle times of 56 hours.

poly-Si vs mono-Si

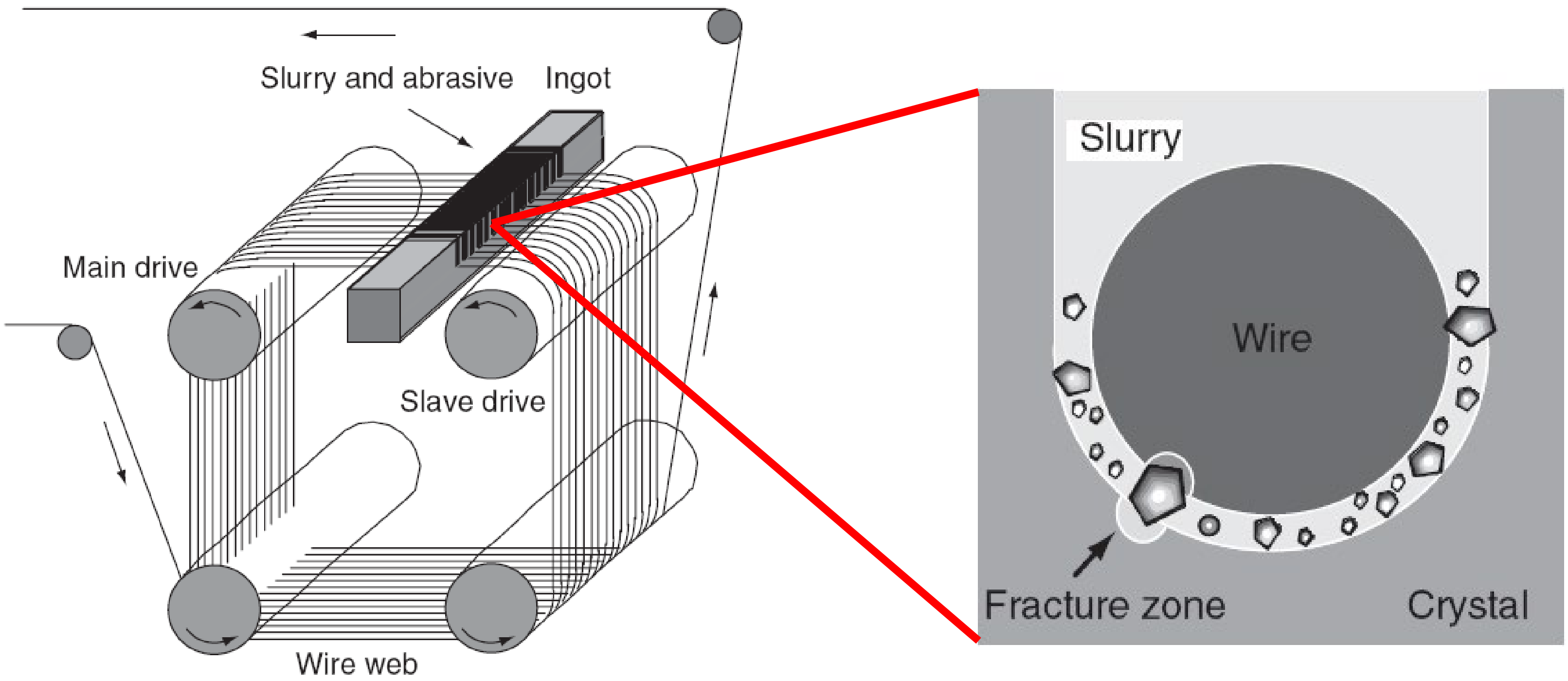
- Multi-crystalline DS ingots are produced in larger size than CZ Si (1000 kg vs 200 kg)
- The energy consumption for DS (8-15 kWh/kg) is lower
- DS is a simpler process requiring less sophisticated equipment than CZ growth

⇒ **DS is a lower cost process than CZ**

- Multi-crystalline structure has numerous crystal defects (grain boundaries and dislocations)
- Impurity contents in DS Si can be higher depending on the crucibles used

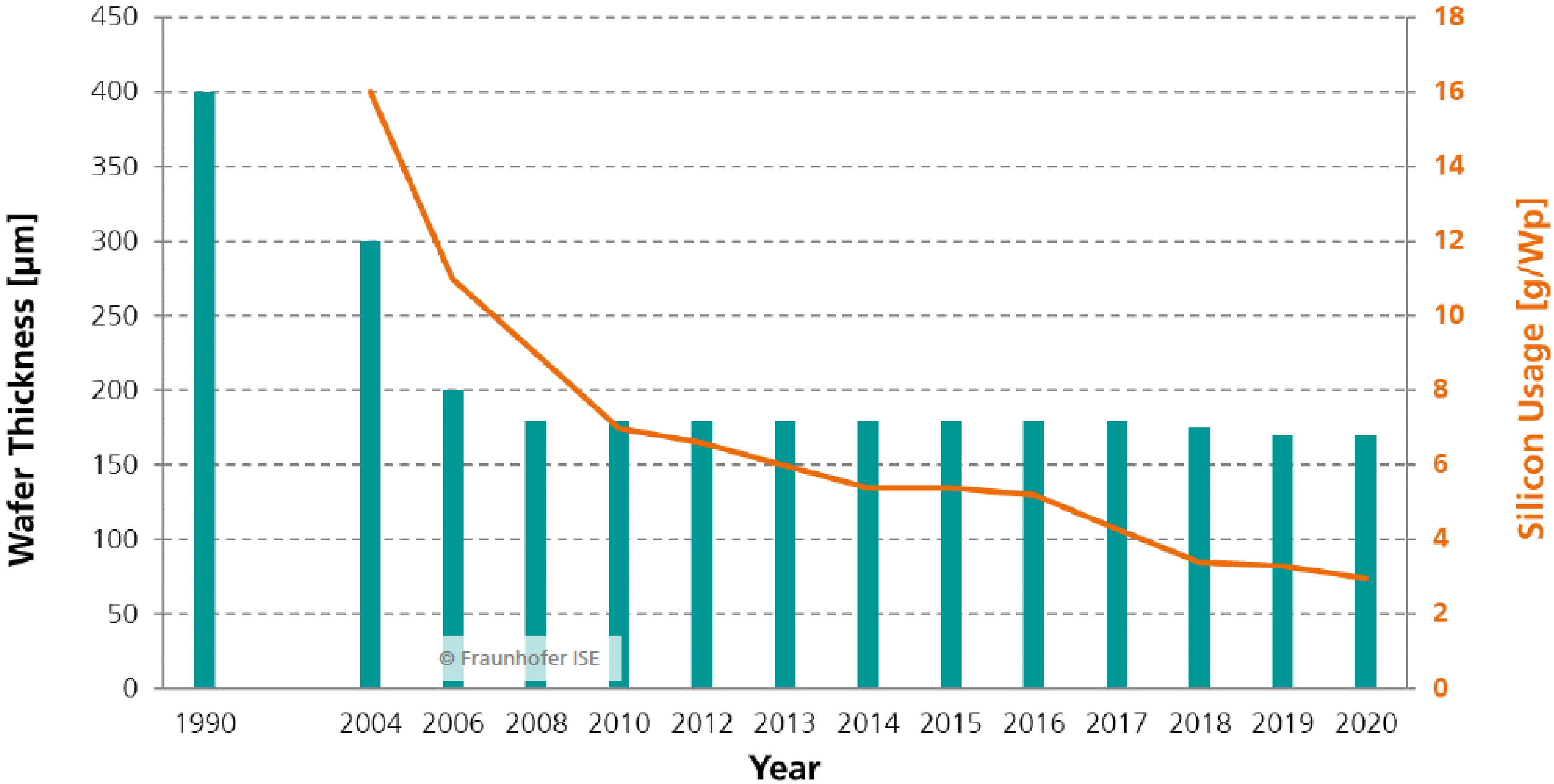
⇒ **Poly-Si solar cells are about 10% (relative) less efficient than mono-Si**

Si wafer cutting



- Cutting is done with an abrasive slurry – typically SiC in polyethylene glycol
- Cutting induces defects and rough surface – polishing is needed to remove the saw damage

Wafer thickness & silicon usage



Photovoltaics report, Fraunhofer Institute ISE, Feb 2022

Fabrication of Si solar cells

Si solar cell processing

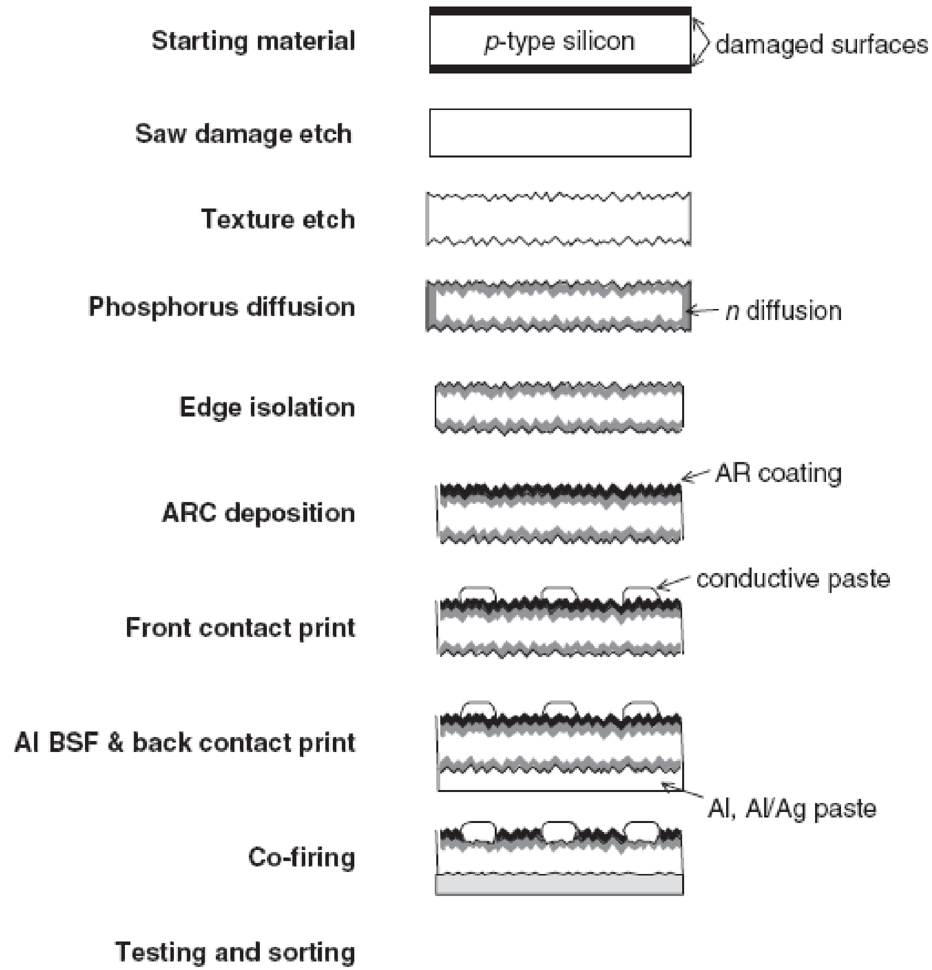
p-type, B-doped Si (100) wafers

Texturing with wet chemical etching

N-type emitter region is formed by diffusion of phosphorous (n-type dopant)

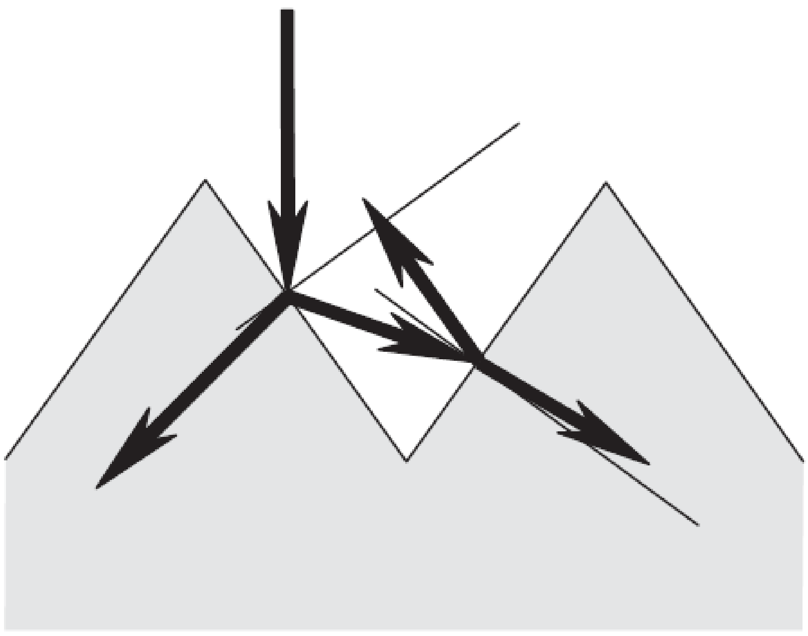
Anti-reflection coating and passivation with SiO_x, $SiON_x$, *a*-Si, or Al_2O_3

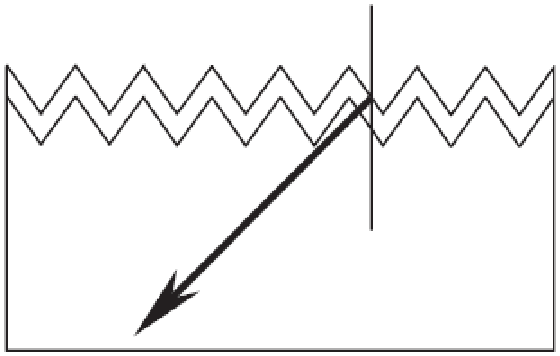
Back and front Al electrodes deposited by screen printing and firing afterwards



Handbook of Photovoltaic Science and Engineering, 2011

Texturing



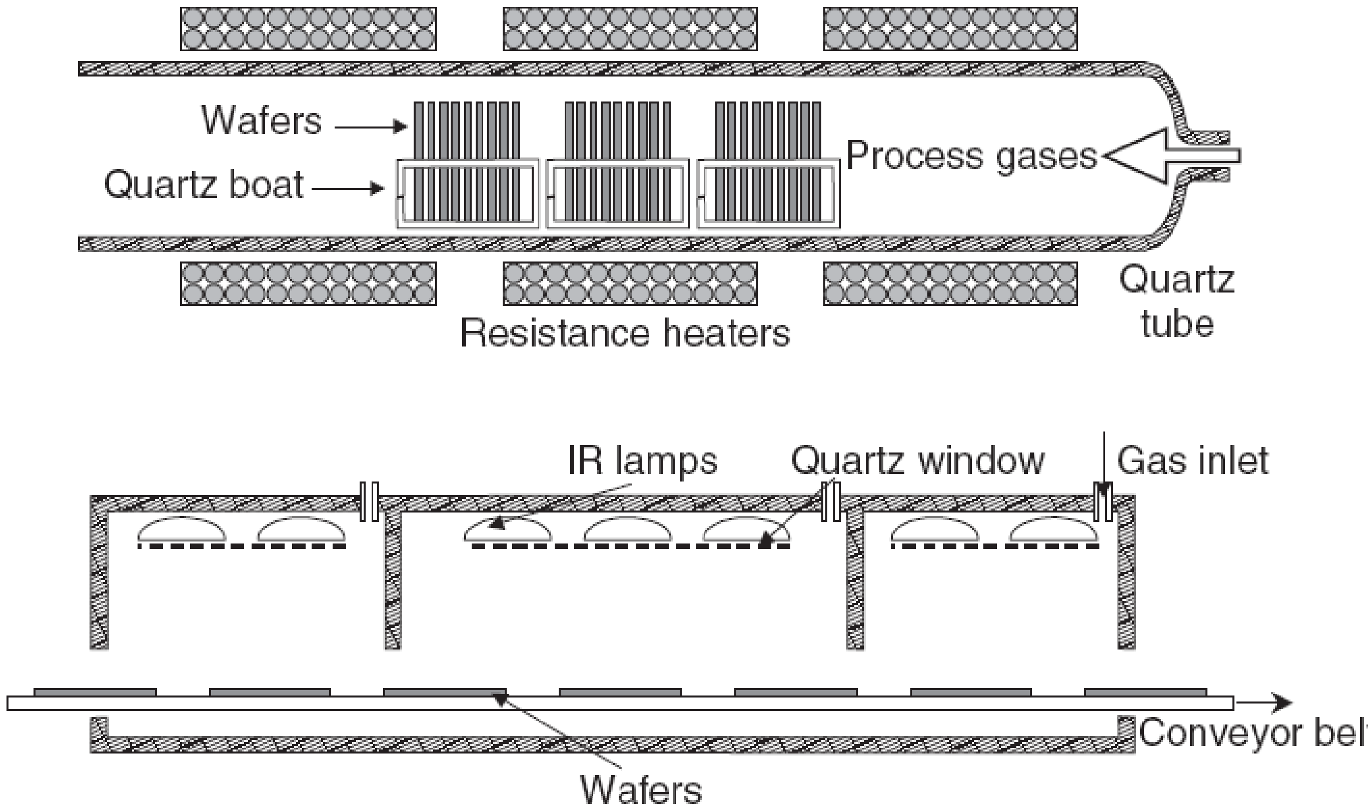


- Decreased reflection because reflected beam can hit another pyramid and still enter Si absorber

- Increased photogeneration due to a longer optical path:

- Important for materials with low absorption coefficient like indirect bandgap Si

Phosphorus diffusion

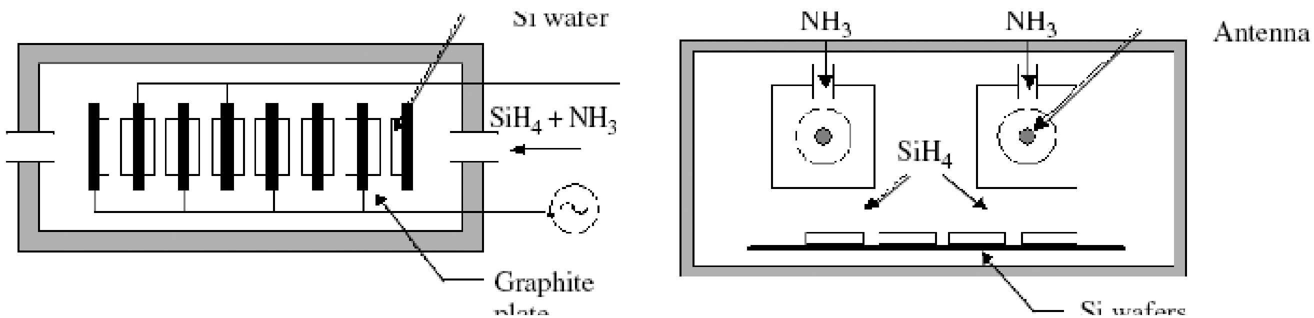


- Doping with P creates n-type region, ca. 200 nm deep, resistance 50…100 Ω

Handbook of Photovoltaic Science and Engineering, 2011

Antireflection and passivation coatings

- AlOx or SiNx:H are deposited by CVD method
- Combines the function of AR coating and passivation of electronic defects
- Different colors are possible



Industrial PECVD reactors: (a) direct-plasma reactor; and (b) remote-plasma system

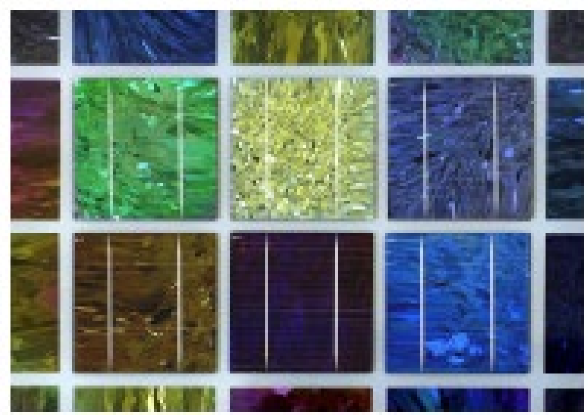
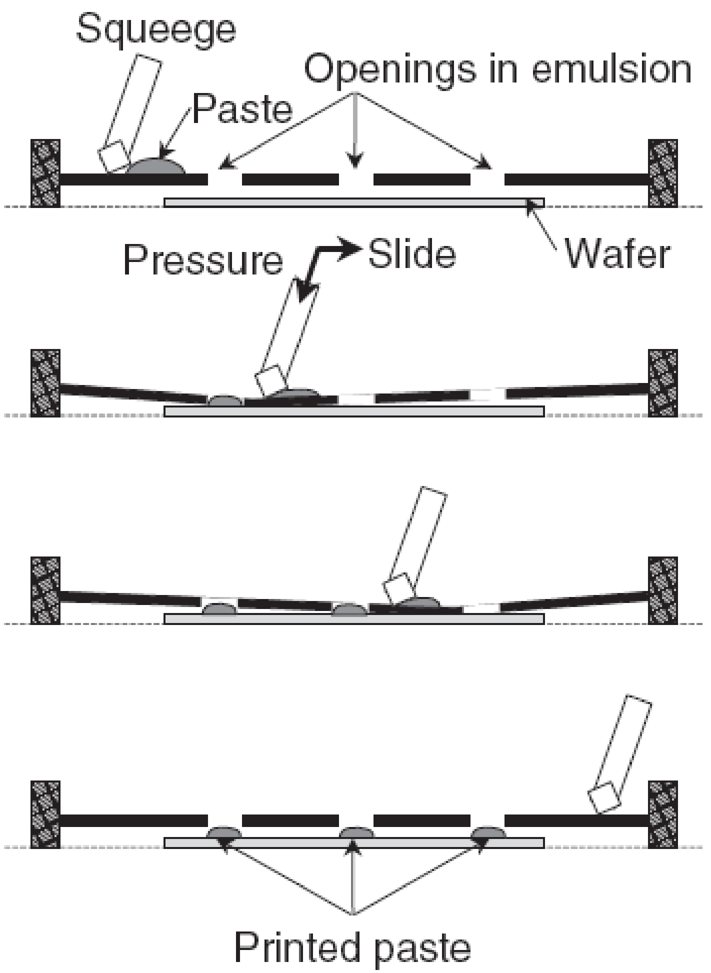
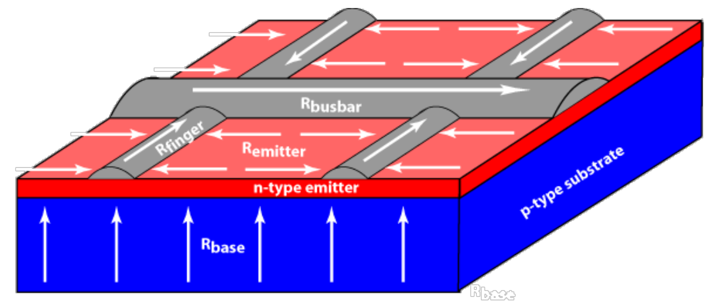
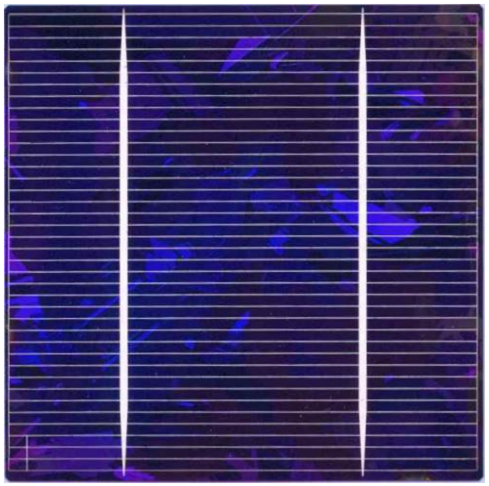


Image: Arthur Weber, ECN, http://ocw.tudelft.nl/fileadmin/ocw/courses/SolarCells/.pdf

Metal grid by screen printing



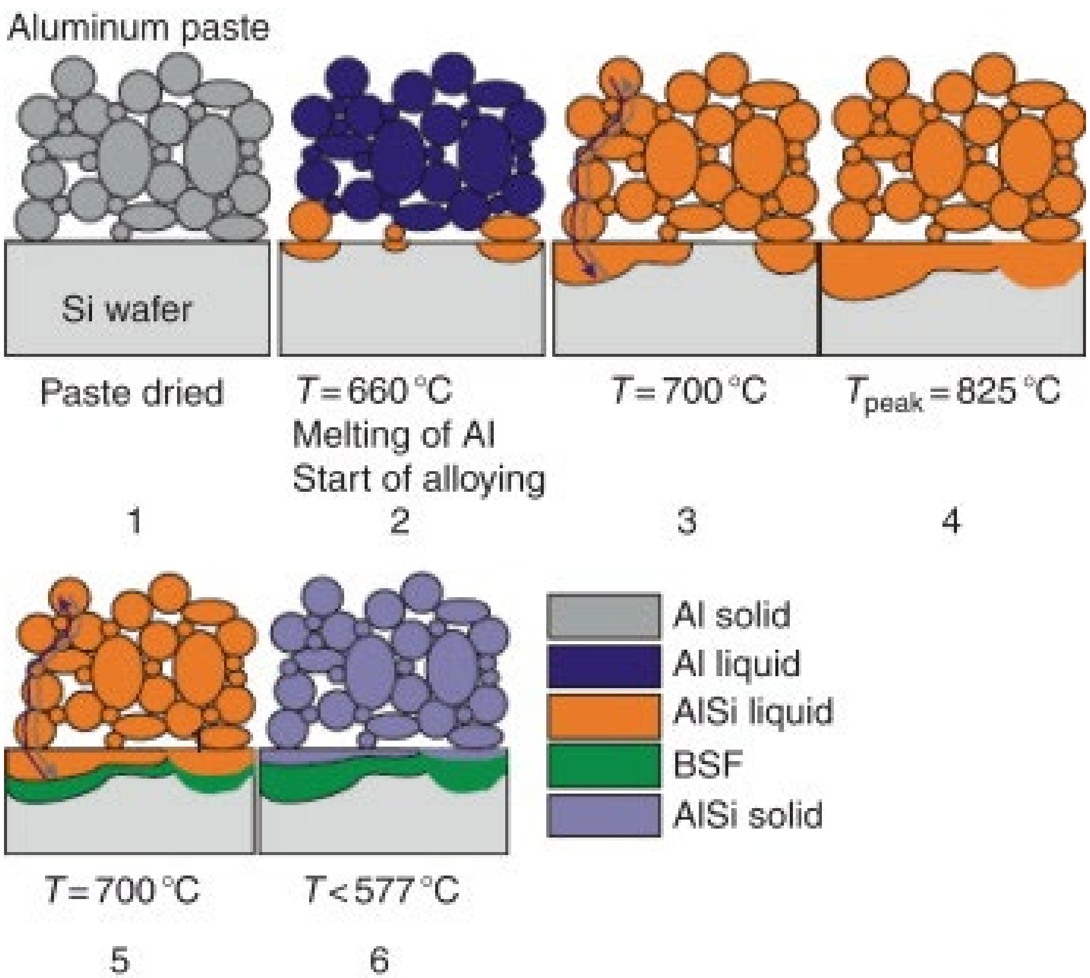




Handbook of Photovoltaic Science and Engineering, 2011

- Silver (Ag) consumption: ~90 mg/cell

Back-contact metallization



(1) paste after drying;

(2) at 660 °C, melting of aluminum occurs and silicon dissolves in a mixed phase;

(3) at 700 °C, all the aluminum is completely molten and substantial incorporation of silicon occurs;

(4) the liquid phase has its maximum thickness;

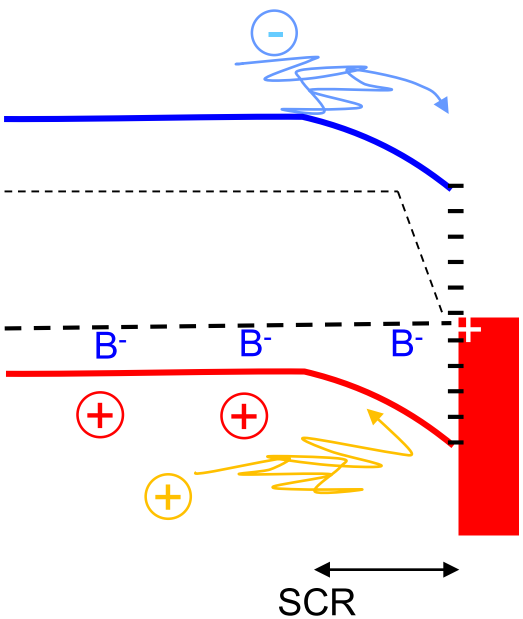
(5) the silicon recrystallizes with incorporation of aluminum,

(1) at the eutectic temperature of 577 °C, the mixed phase of aluminum and silicon solidifies.

S.W. Glunz et al, Comprehensive Renewable Energy, 2012, Ch. 1.16

Back surface field (BSF)

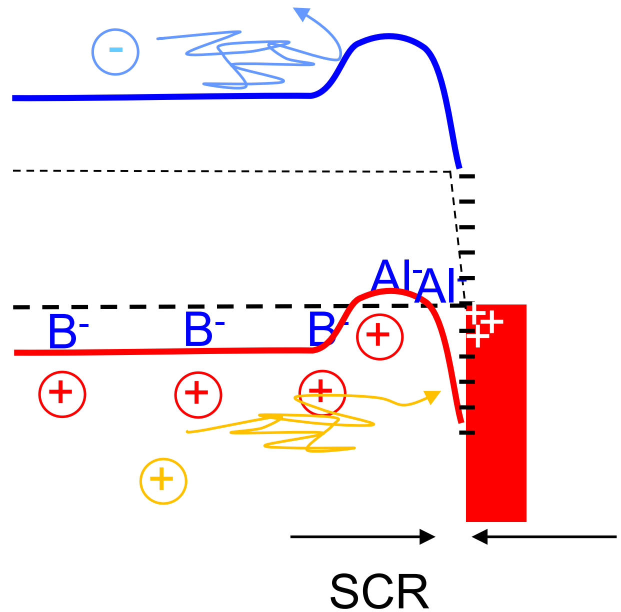
Regular Si-metal contact



- barrier for holes (majority carriers)

- electrons (minority) can recombine via interface states

Solution: introduce strongly doped p+ region to create **back surface field (BSF)**

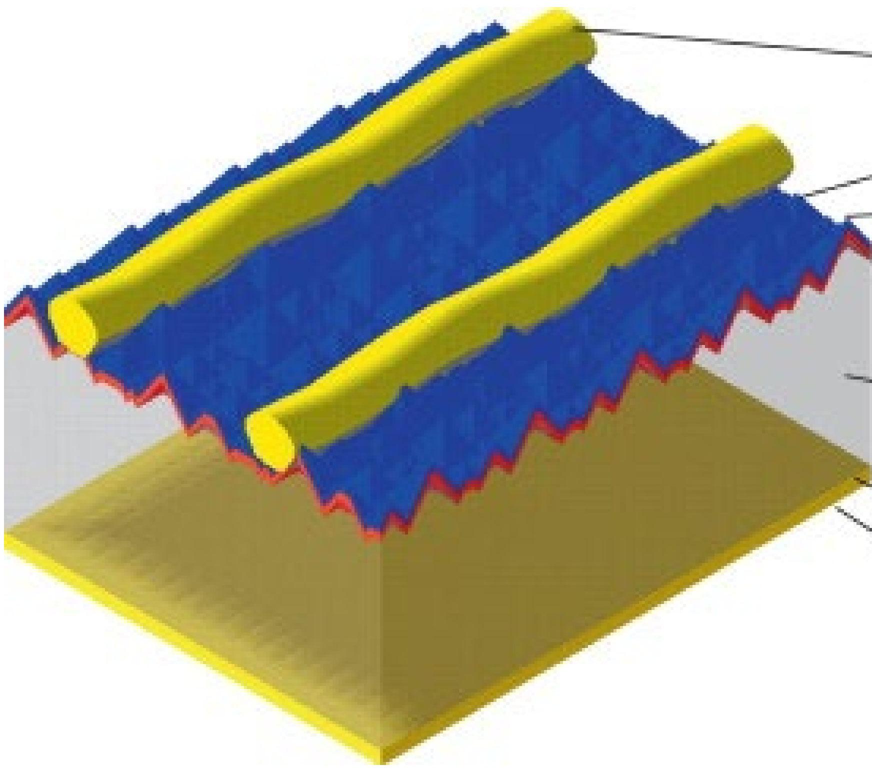


+ holes tunnel through narrow barrier

+ electrons are repelled

Courtesy: F.-J. Haug, EPFL

Typical screen-printed grid Al-BSF Si cell

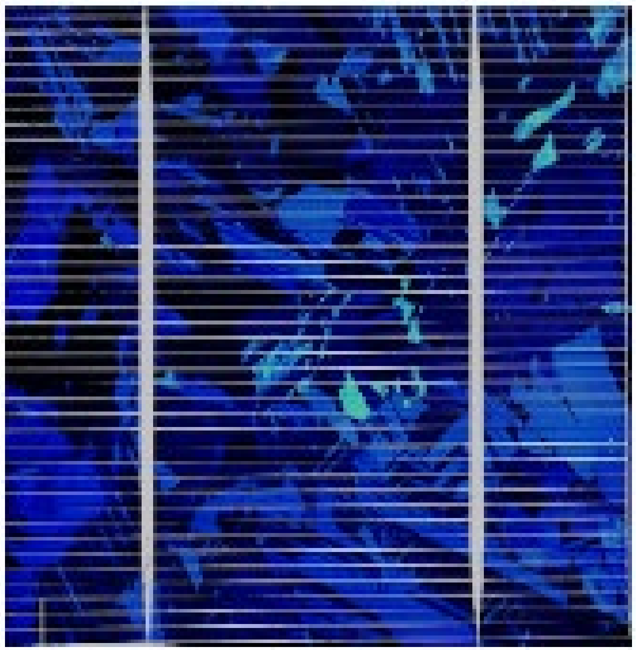


S.W. Glunz et al, Comprehensive Renewable Energy, 2012, Chapter 1.16

Different Si solar cells

Monocrystalline mono-Si
(also called single crystal sc-Si)

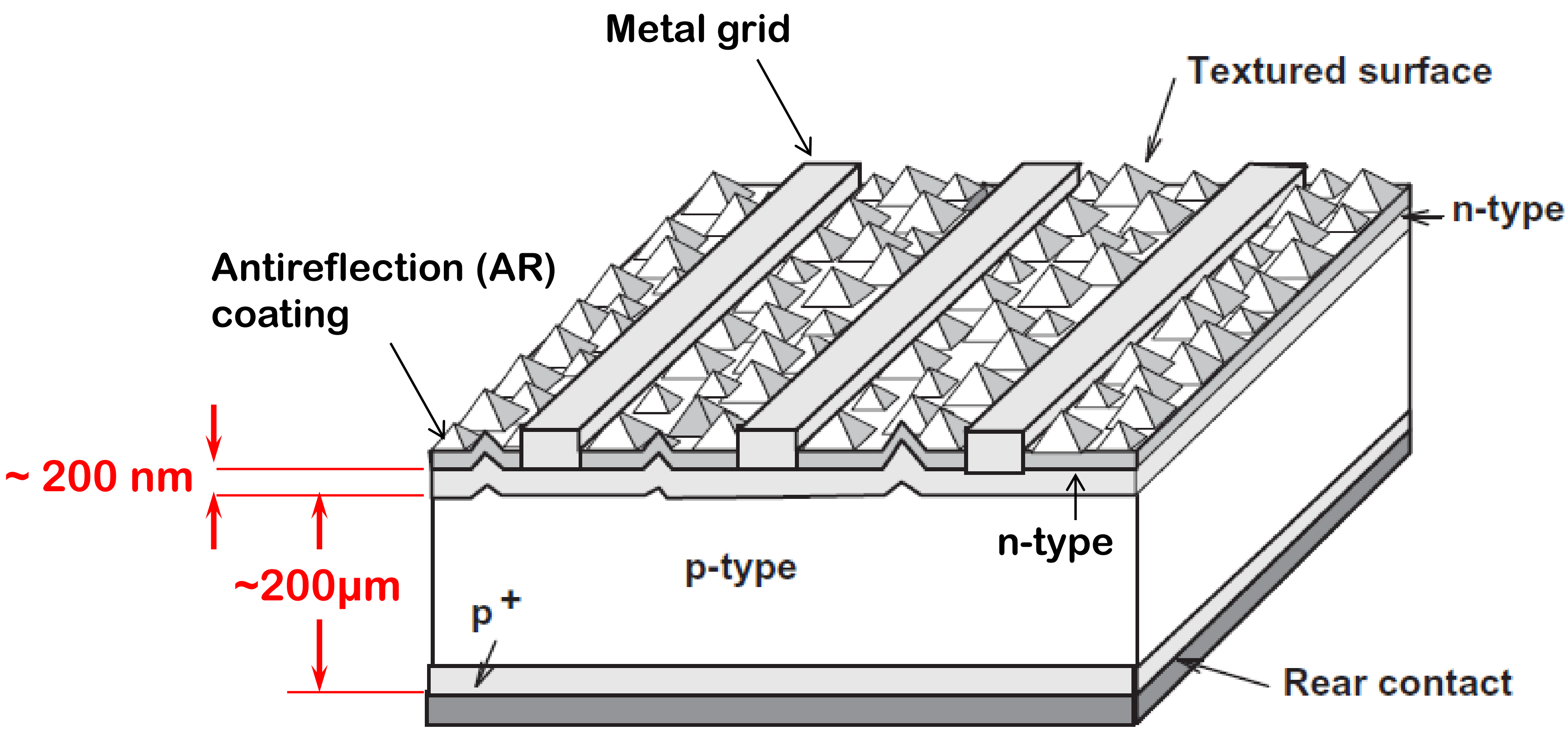
Polycrystalline – poly-Si
(also called multicrystalline – mc-Si)



- Wafer size: 158 x 158 mm => 166x166 mm from 2015
- Thickness: 180 μm

Si solar cell operation

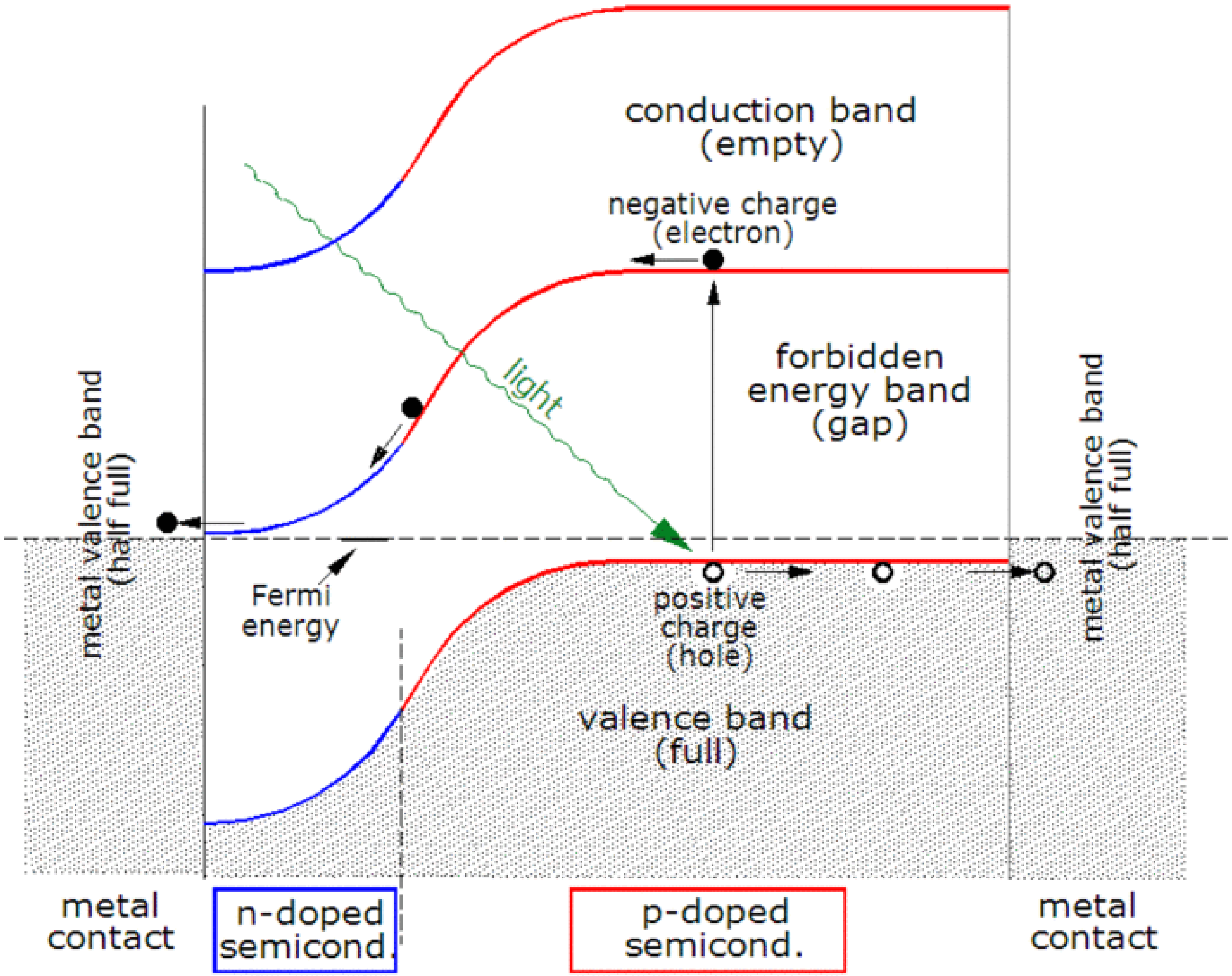
Structure



McEvoy`s Handbook of Photovoltaics, Chapter 1-2-B, Elsevier, 2018

- n-type region is much thinner than p-type wafer (200 nm vs 200 μm)
- Screen printed Al-BSF cell is also “black cell” on the efficiency chart (slide 6)

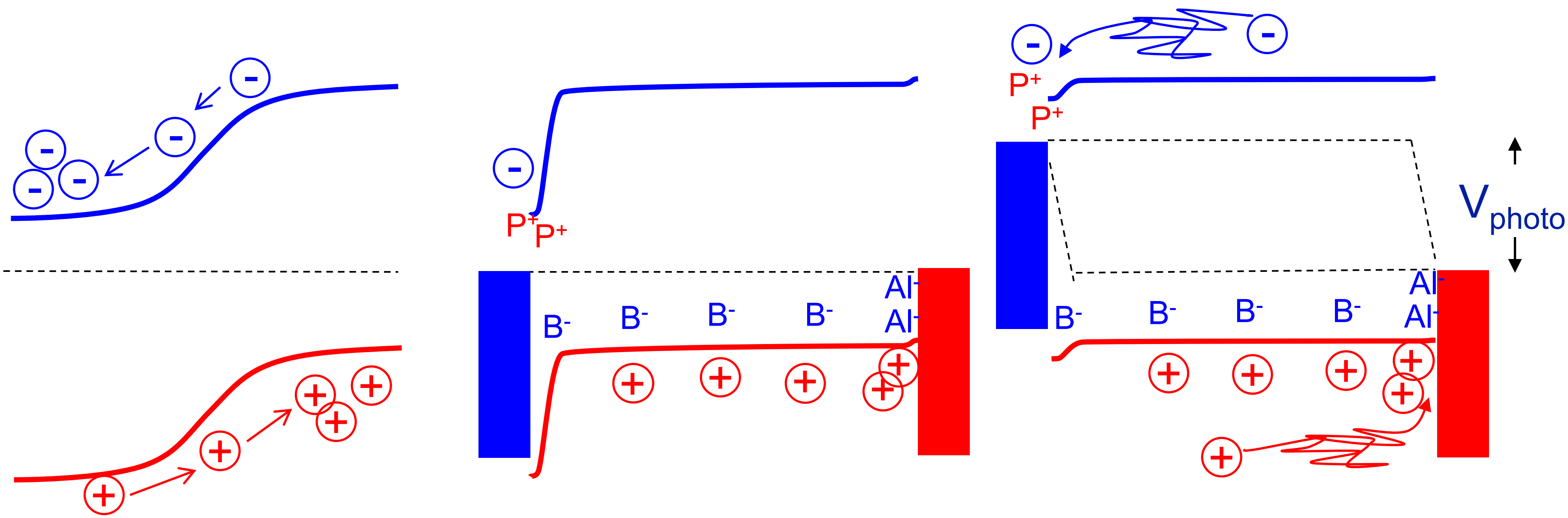
Band diagram (idealized)



www.wikipedia.com

Band diagram (more realistic)

What you often see… how it looks in dark how it works under light



the p-n junction field is <1µm, most of the 200 µm wafer is neutral

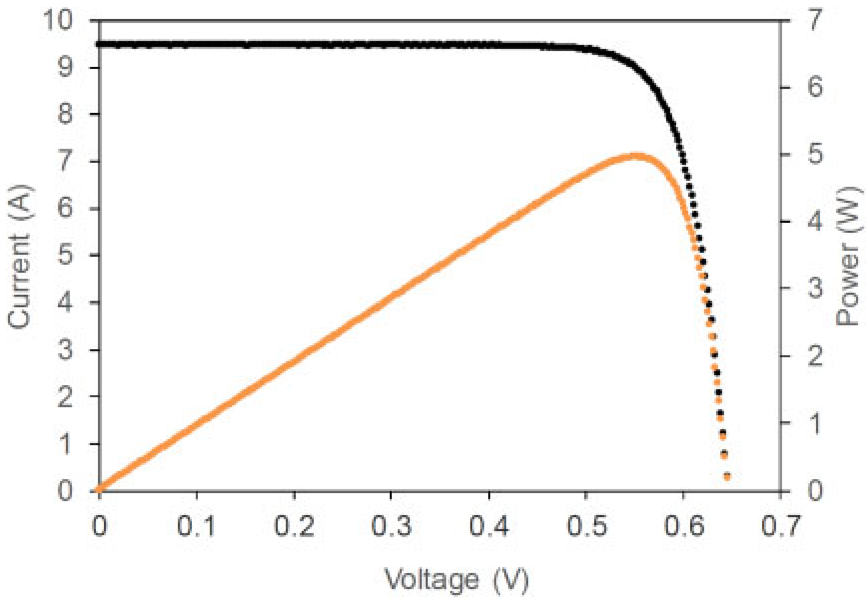
charges diffuse randomly until they "see" a contact region

⇒ **Si cell is diffusion-controlled device, which requires high-quality crystal**

Courtesy: Dr. F.-J. Haug, EPFL

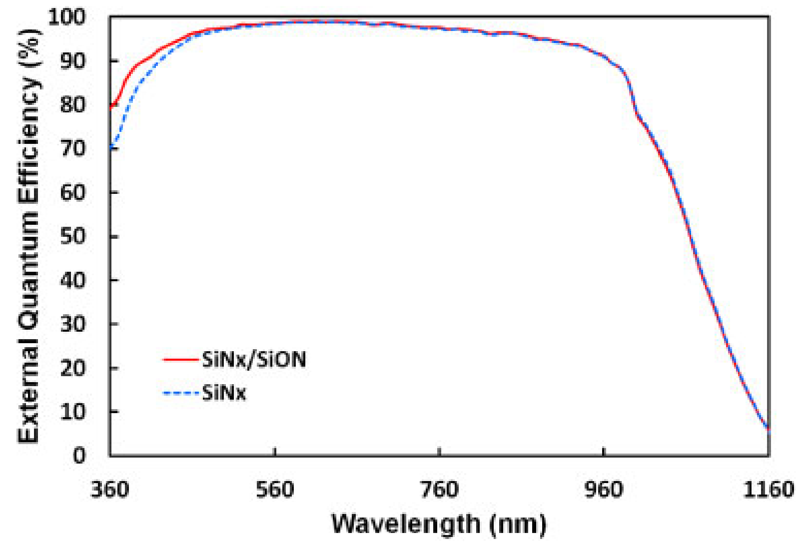
Solar cell characteristics

I-V and power curves of best Al-BSF cell



Voc = 647 mV
Jsc = 38.76 mA/cm2
FF = 80.92%
Eff = 20.29% (current record)

QE of best Al-BSF cell

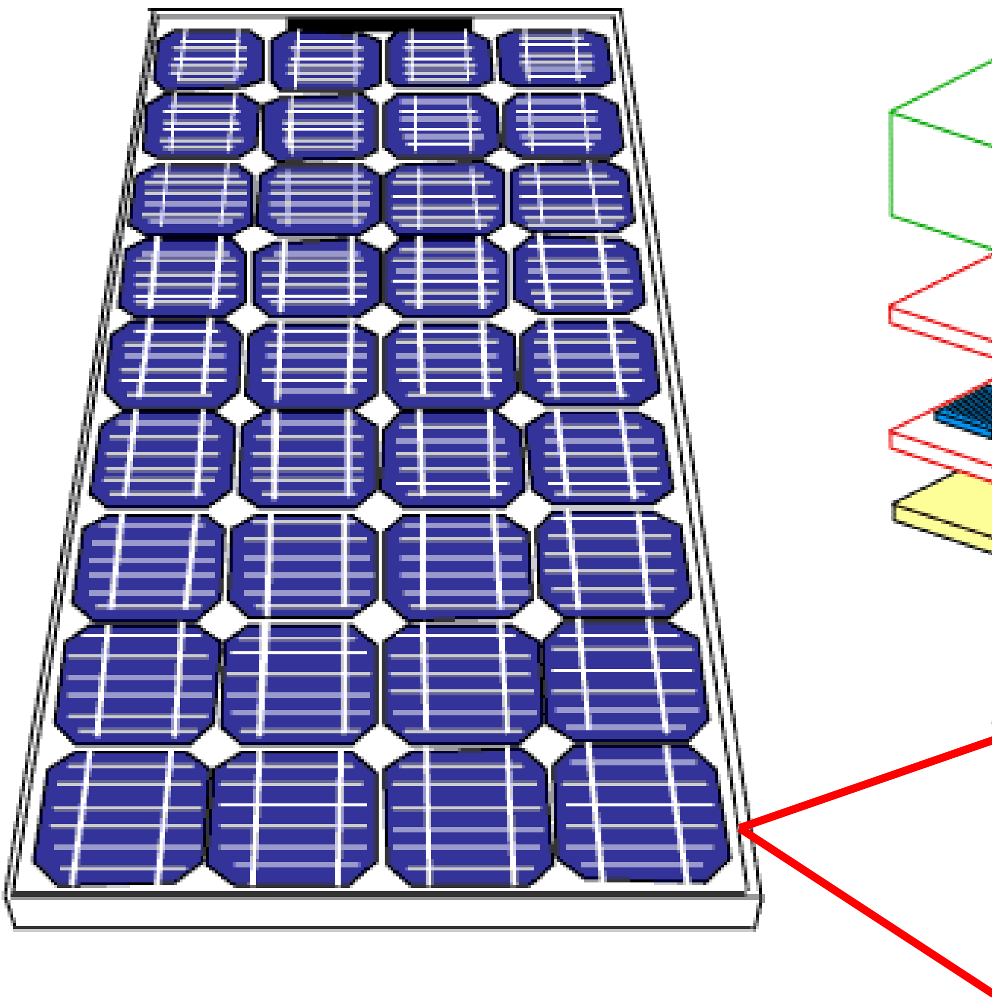


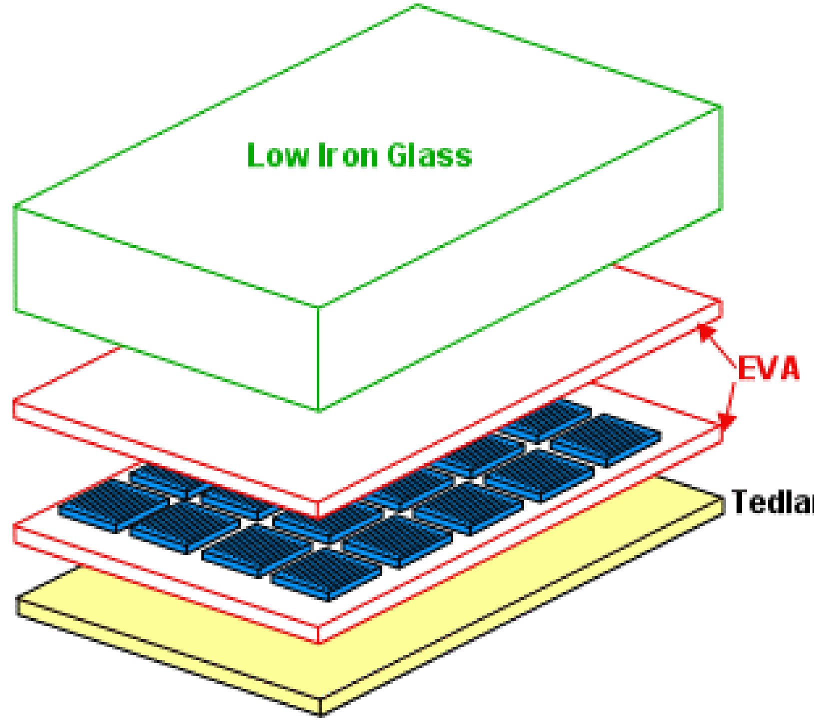
- QE > 95% in the visible range
- IR response is not perfect due to indirect bandgap nature of Si

Shinsung Solar Energy, Jpn. J. Appl. Phys. 56 (2017) 08MB25

Si PV modules

Module structure





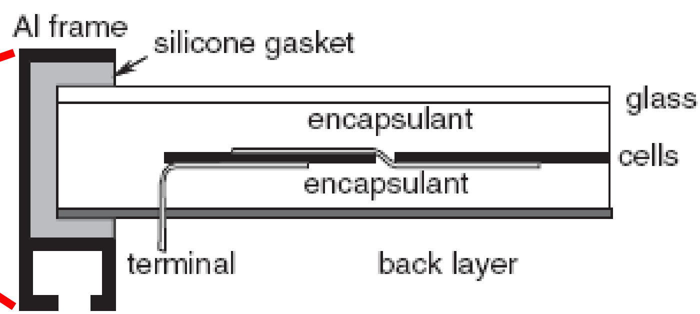
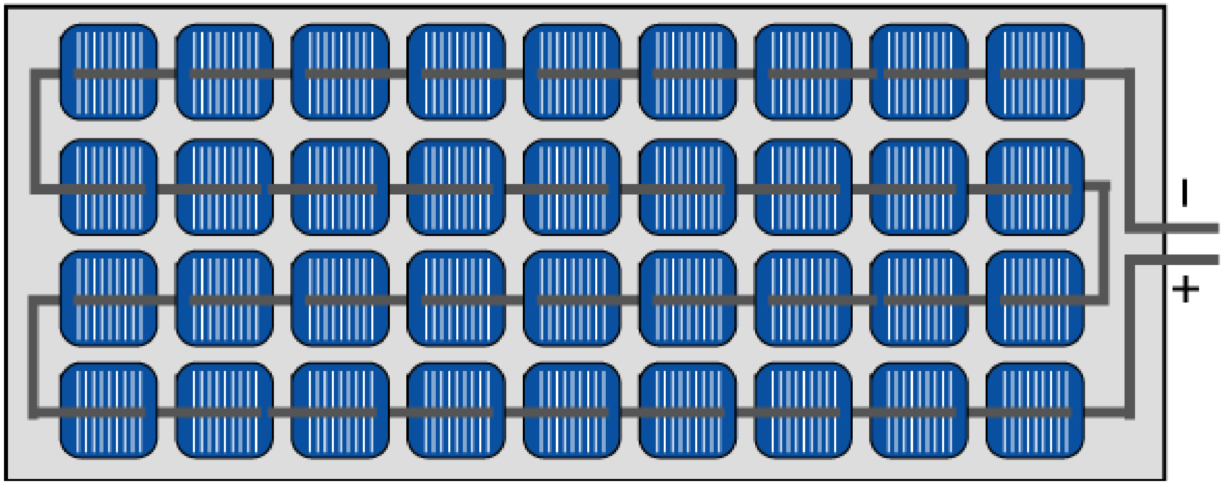


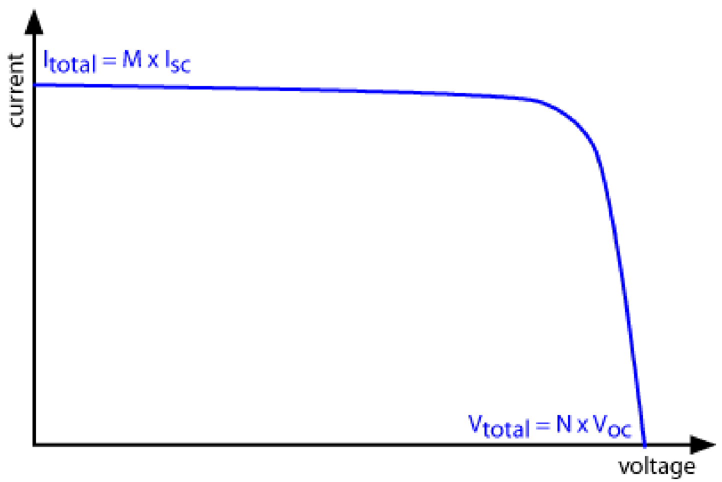
Figure 7.19 Cross- section of a standard module

www.pveducation.org

Handbook of Photovoltaic Science and Engineering, 2011

Si photovoltaic module

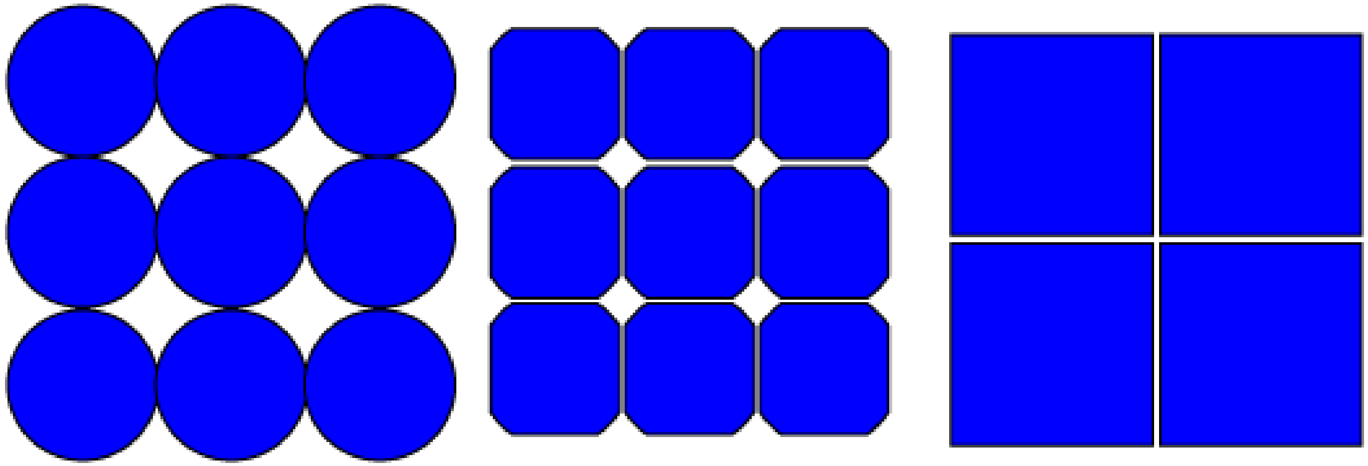




M – number of cells connected in parallel
N – number of cells connected in series

- Old PV modules had 36 cells:
  - Current: 7-8 A (assuming 30…35 mA/cm^2 for one wafer)
  - Voltage: 21 V (0.6 V/wafer)
  - Power: 140-160 W
- Modern PV modules have 60 / 72 cells
  - Power up to 300 W
  - Efficiency 15…19%

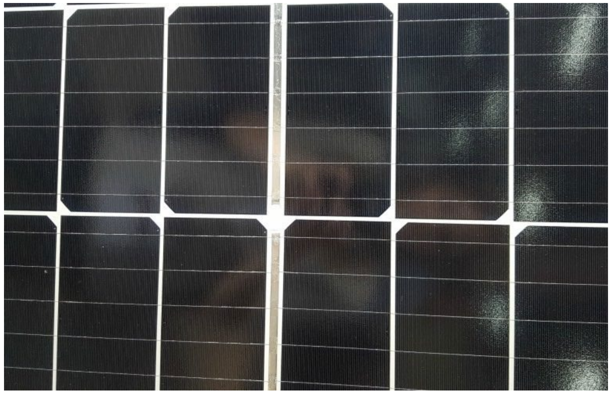
Packing of Si cells in modules



- The round ingots of Cz material gives a low packing density so the edges are cut off to produce semi-square cells for higher packing density.

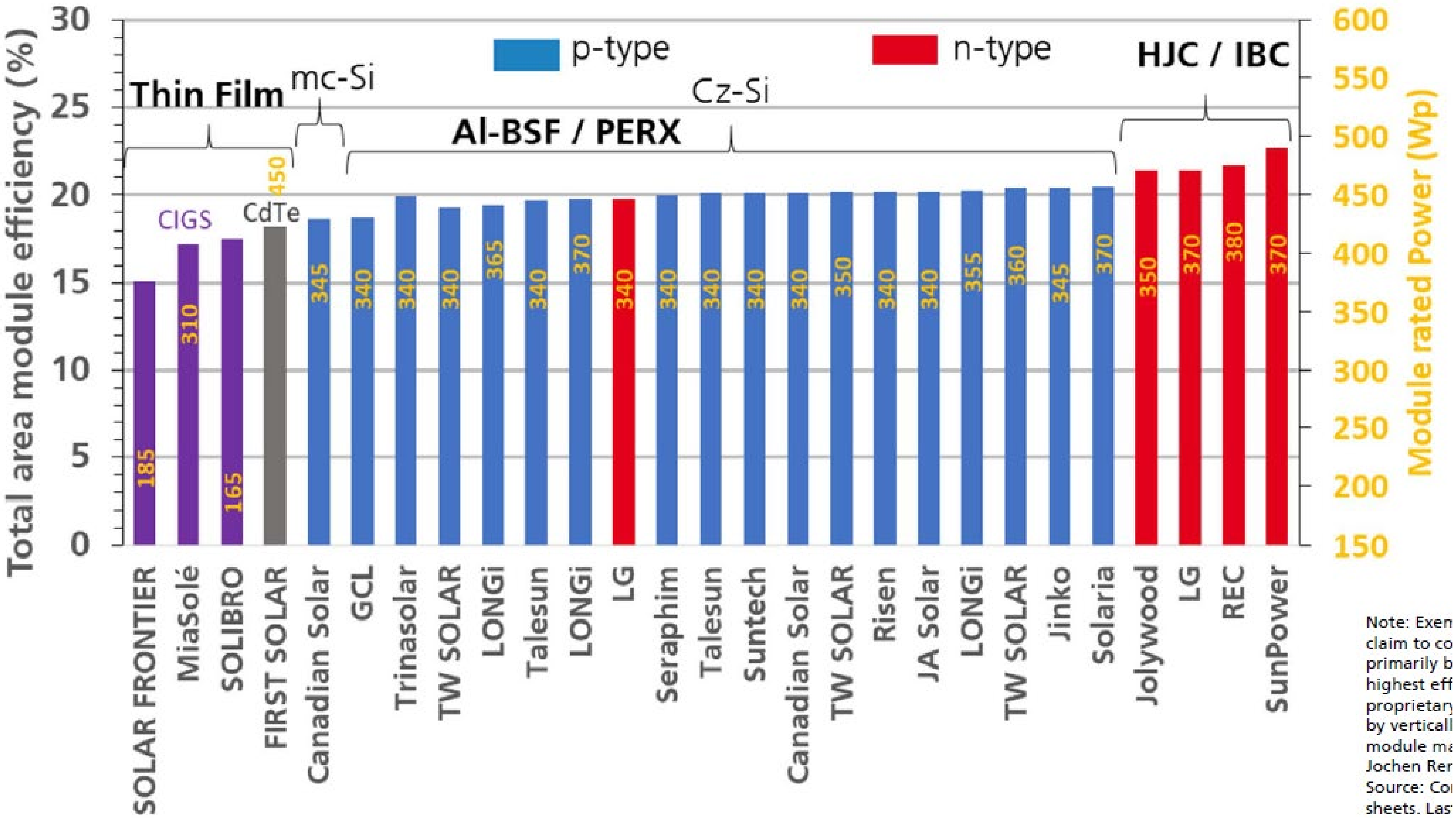
- Multicrystalline material is cut in squares, enabling a high packing density.

- From 2015:
  - half-cell modules because of 1-2% higher power (due to lower resistive losses)
  - larger wafers of 166 mm



Current Efficiencies and Power of Selected Commercial PV Modules

Sorted by Bulk Material, Cell Concept and Efficiency



Source: Photovoltaics report, Fraunhofer Institute, Sept 2020