“Solar Energy” WS 2021/2022

PV Technology:

Lecture 7: Crystalline Silicon (c-Si) Solar Cells

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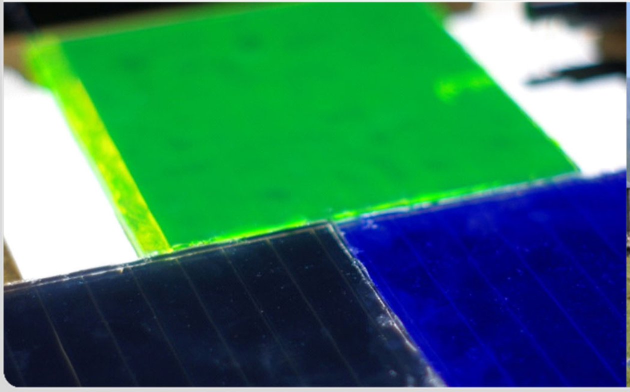
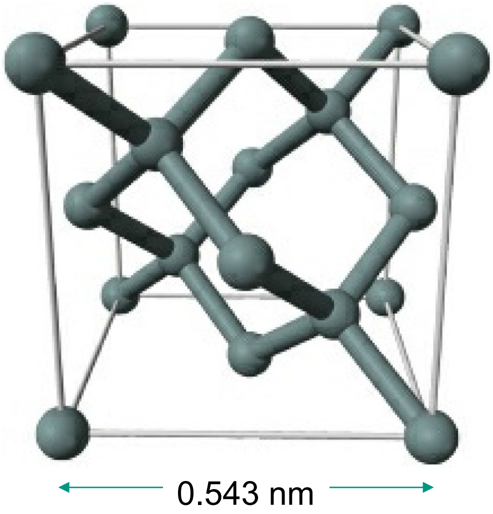


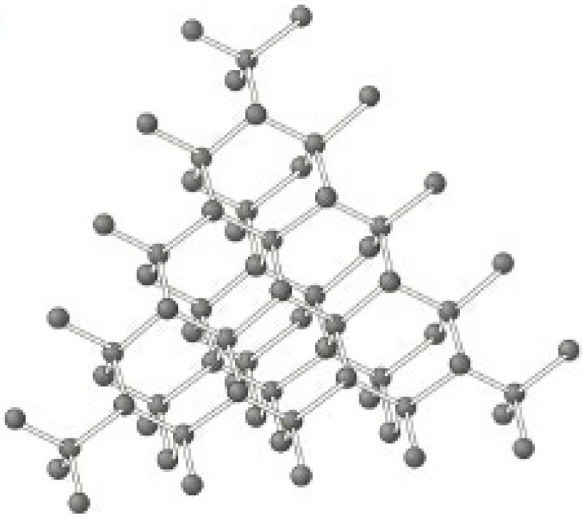
Properties of c-Si

Crystal lattice of c-Si
⇒ atoms arranged in certain repeating pattern (diamond cubic crystal)
⇒ lattice exhibits long-range order and symmetry

One unit cell



Larger crystal

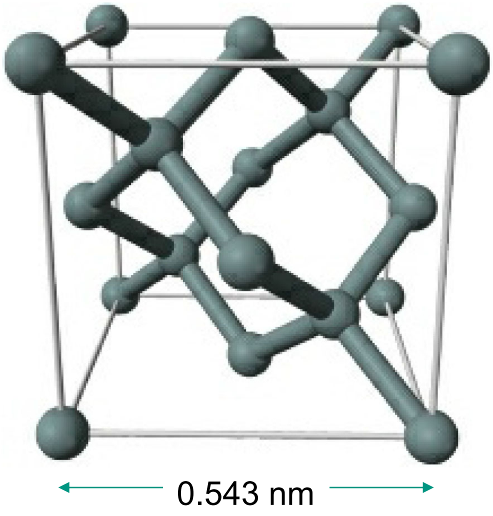


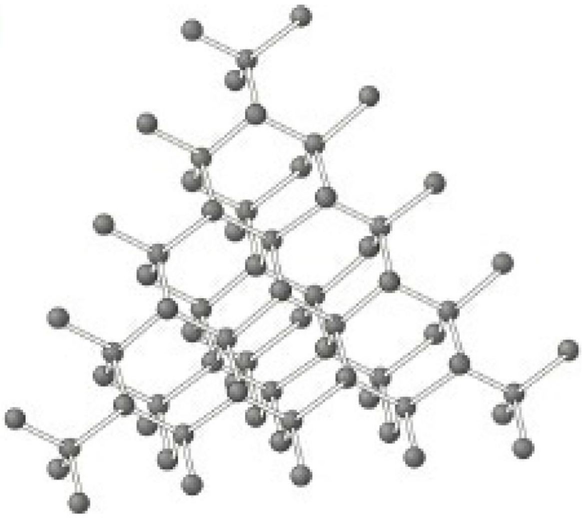
Source: textbook

Properties of c-Si

Crystal lattice is not the same in every direction

e.g. if we make large cuts through the lattice, the various planes would not look the same





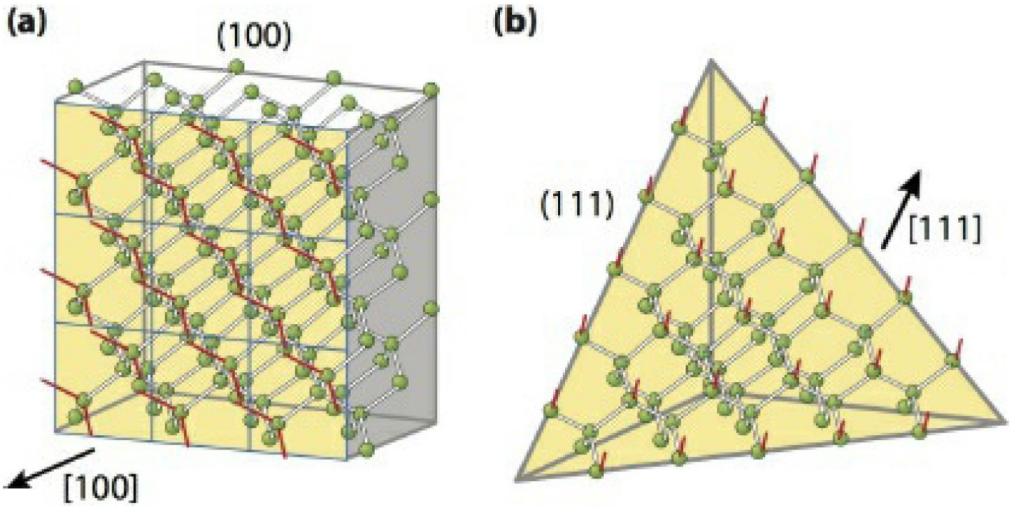
Source: textbook

Properties of c-Si

e.g. figure below shows a 3 × 3 × 3 unit cell cut along:

(a) the (100) surface, i.e. surface normal to [111] direct
⇒ each Si atom has two e^- looking to bond

(b) the (111) surface, where every Si atom has one e^- looking to bond



Source: textbook

Properties of c-Si

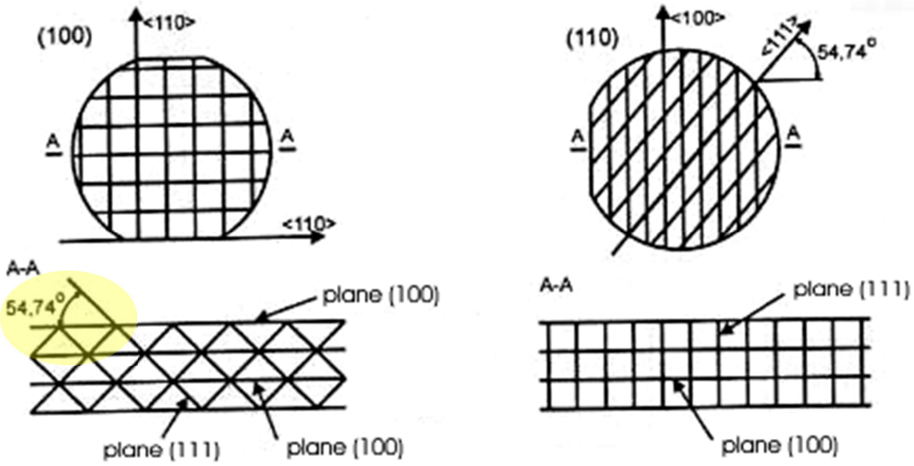
(100) c-Si wafers normally used making solar cells – three advantages:

i) Lowest density of surface atoms ($6.8\times10^{14}/cm^2$) compared to other planes

ii) Interface between (100) Si and SiO_2 demonstrated to have lowest <u>defect density</u> ⇒ less recombination ⇒ lower J_0 ⇒ higher V_{oc}

iii) The surface can be chemically <u>textured</u> to reduce reflection losses

(note the 54.7° angle – will revisit later in lecture)



Source: https://www.el-cat.com/silicon-properties.htm

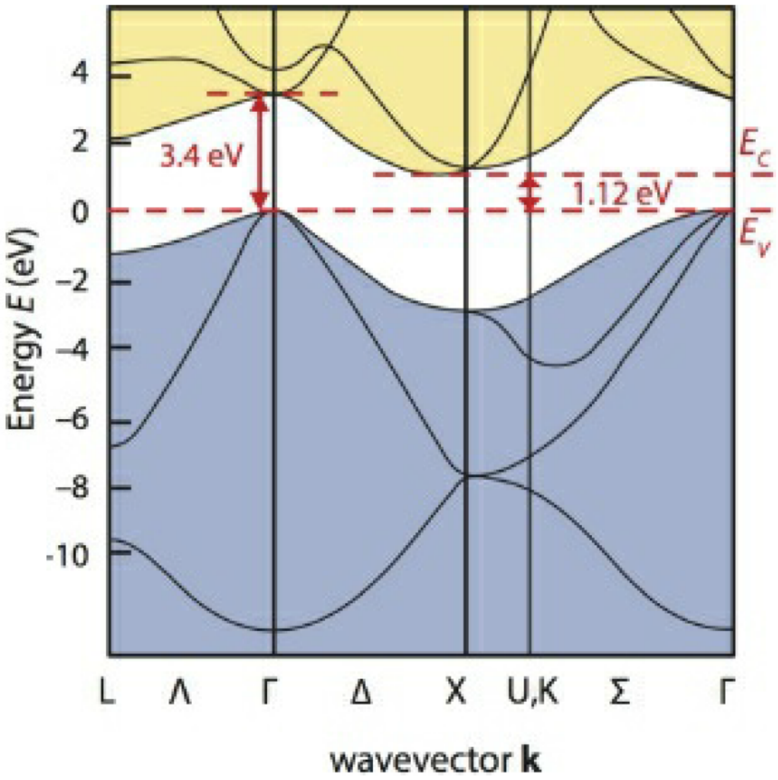
Properties of c-Si

c-Si has bandgap energy $E_g \sim 1.12$eV ($\lambda\sim1100$ nm)

This bandgap is <u>indirect</u> is ⇒ i.e. energy as well as momentum required to excite charge carriers from valence band to conduction band

c-Si has direct transitions too, but these are in UV, e.g $E_{g\text{-}direct} = 3.4$ eV ($\lambda = 364$ nm)

Additional momentum given to charge carriers via <u>phonons</u> (lattice vibrations)



Source: textbook

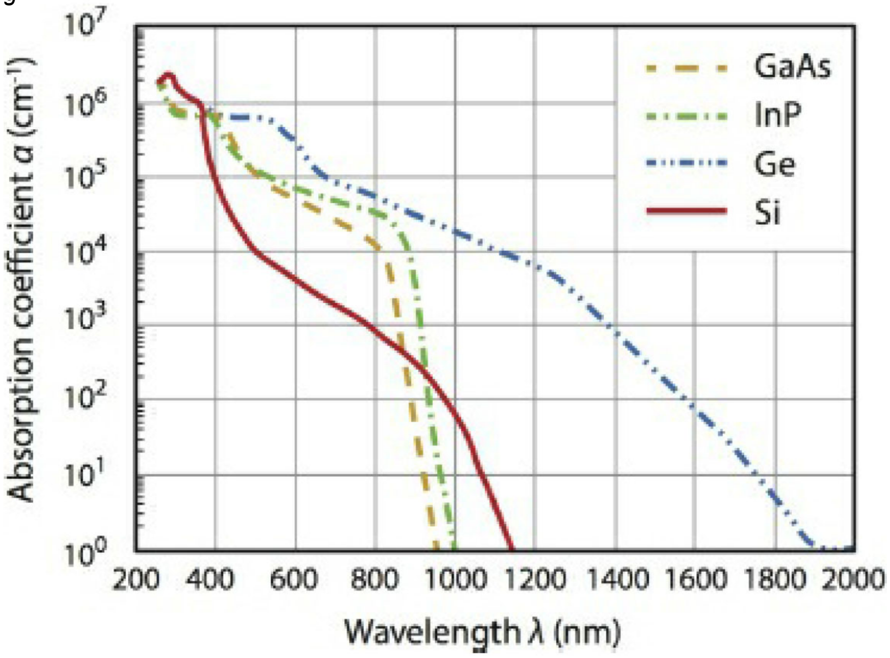
Properties of c-Si

Due to required change in momentum ⇒ indirect bandgap material less likely to absorb photon with energy > E_g ⇒ e.g. compared to direct bandgap materials with similar E_g, gallium arsenide (GaAs), indium phosphide (InP)

∴ absorption coefficient α of c-Si is lower in visible region

GaAs and InP have steeper slopes near E_g

Germanium (Ge) is also an indirect bandgap material (E_g ~ 0.67 eV)



Source: textbook

Properties of c-Si

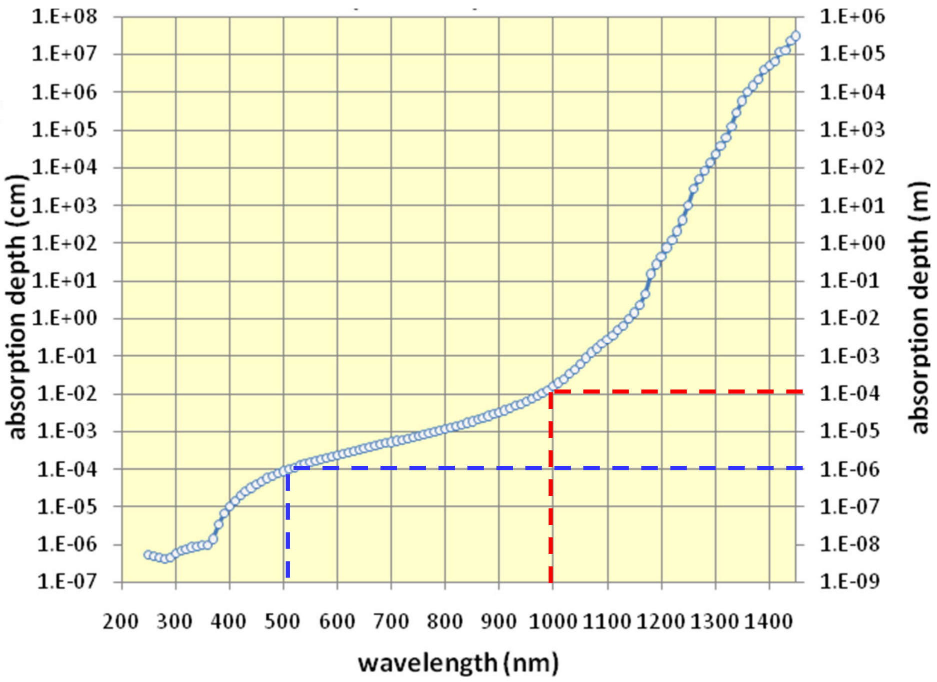
Can also consider the absorption depth α^{-1} (a.k.a. penetration depth)

Calculate fraction of light absorbed: Lambert-Beer Law:

$$I = I_0\, e^{-\alpha x}$$

Absorption depth of 1 μm for 500nm light ⇒ light intensity fallen to 1/e (36%) of its original value

For 1000 nm light ⇒ more like 100 μm



Source: https://www.pveducation.org/pvcdrom/materials/optical-properties-of-silicon

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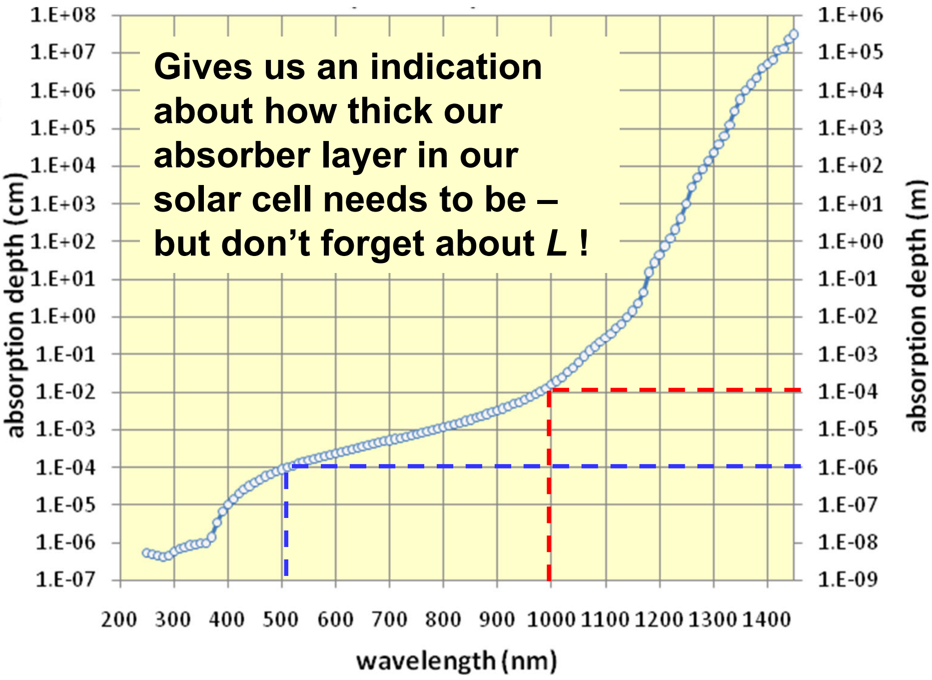

Gives us an indication about how thick our absorber layer in our solar cell needs to be – but don't forget about *L* !

Source: https://www.pveducation.org/pvcdrom/materials/optical-properties-of-silicon

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Properties of c-Si

Refractive index (n) and extinction coefficient (k) of silicon

α related to k by:

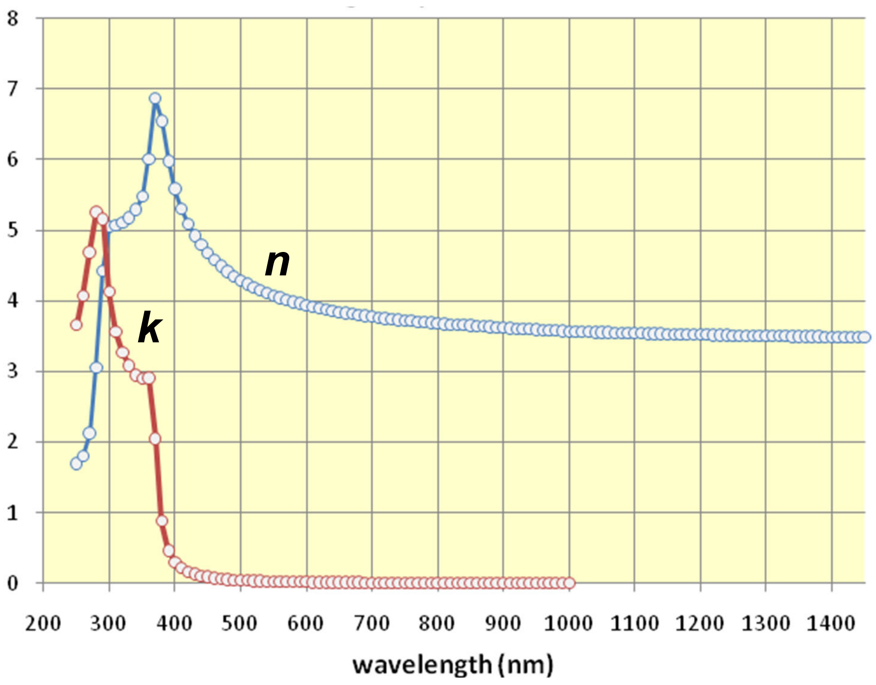
$$\alpha = \frac{4\pi k}{\lambda}$$

Units:

α typically in cm^{-1}
(thus λ also in cm)

k is dimensionless

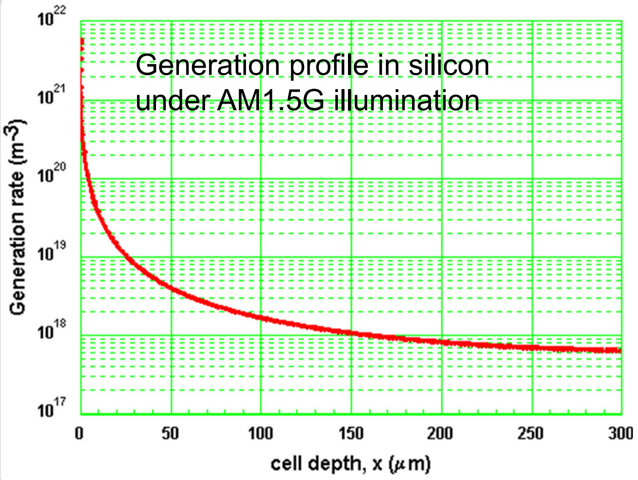
n also dimensionless

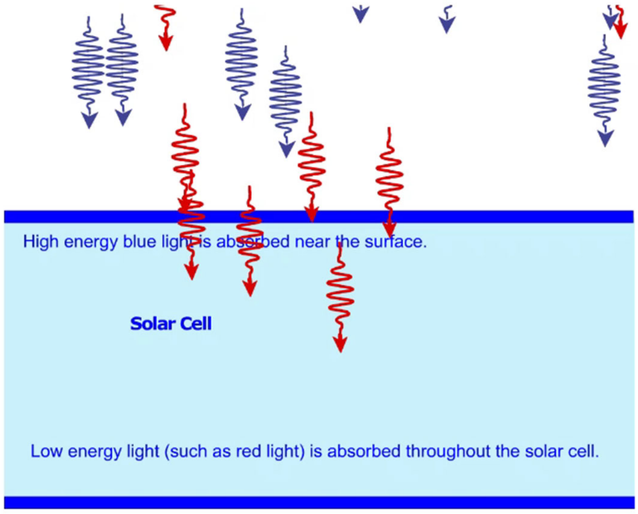


Source: https://www.pveducation.org/pvcdrom/materials/optical-properties-of-silicon

Properties of c-Si

Reminder of generation rate (vast majority of carriers generated near front surface):





Source: https://www.pveducation.org/pvcdrom/pn-junctions/absorption-depth

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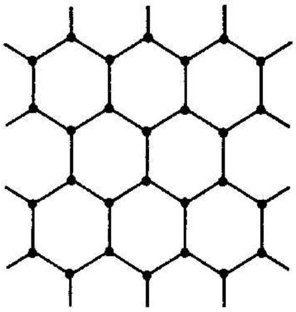
Properties of c-Si

Further impact of indirect nature of c-Si bandgap ⇒ radiative recombination can be neglected ⇒ thus Auger recombination and Shockley–Read–Hall (SRH) recombination dominate

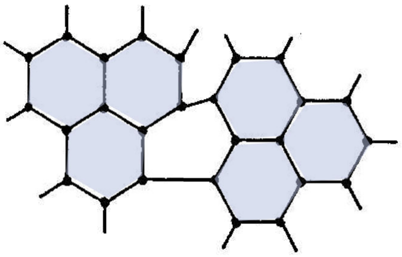
Monocrystalline silicon (a.k.a. single-crystalline silicon) ⇒ crystalline solid in where crystal lattice is continuous and unbroken

Multicrystalline (mc-Si – a.k.a. polycrystalline silicon) ⇒ material consists of many small crystalline grains with random orientations. Between each grain are "grain boundaries"

Results in shorter charge carrier lifetime (i.e shorter *L*) as SRH recombination rate increased (related to e^- trapped at defect states)



c-Si

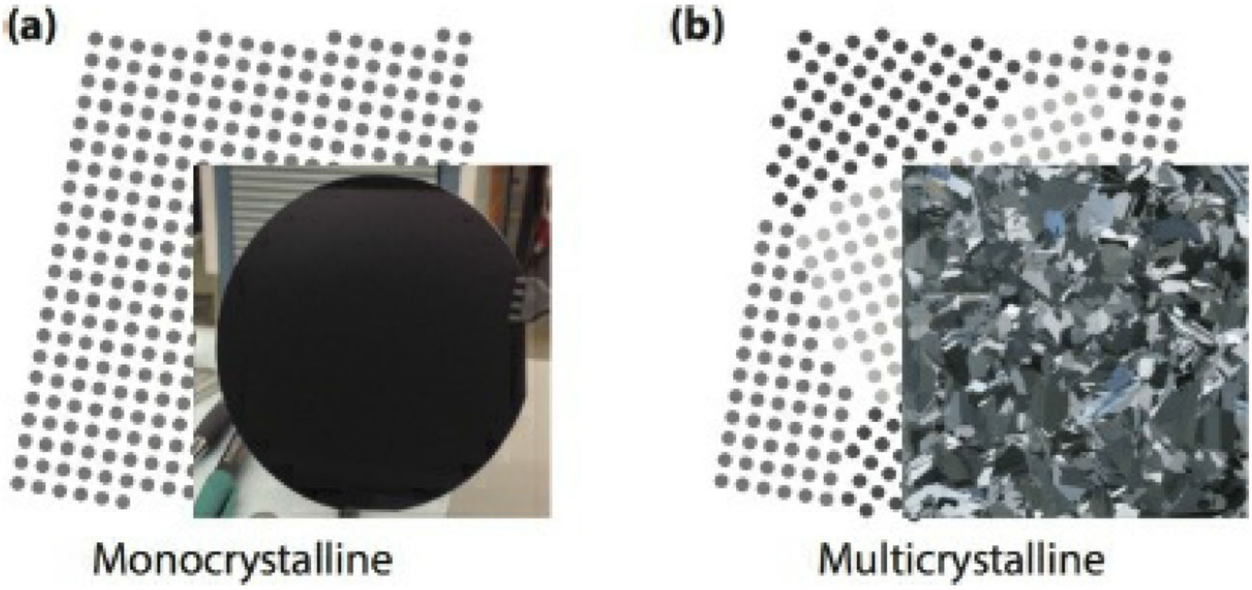


mc-Si

Source: adapted from Wolfe, Holonyak, Stillman, Physical Properties of Semiconductors, 1989

Properties of c-Si

With mc-Si, the differently-oriented grains (crystals) are relatively large (mm^2 – cm^2) and clearly visible



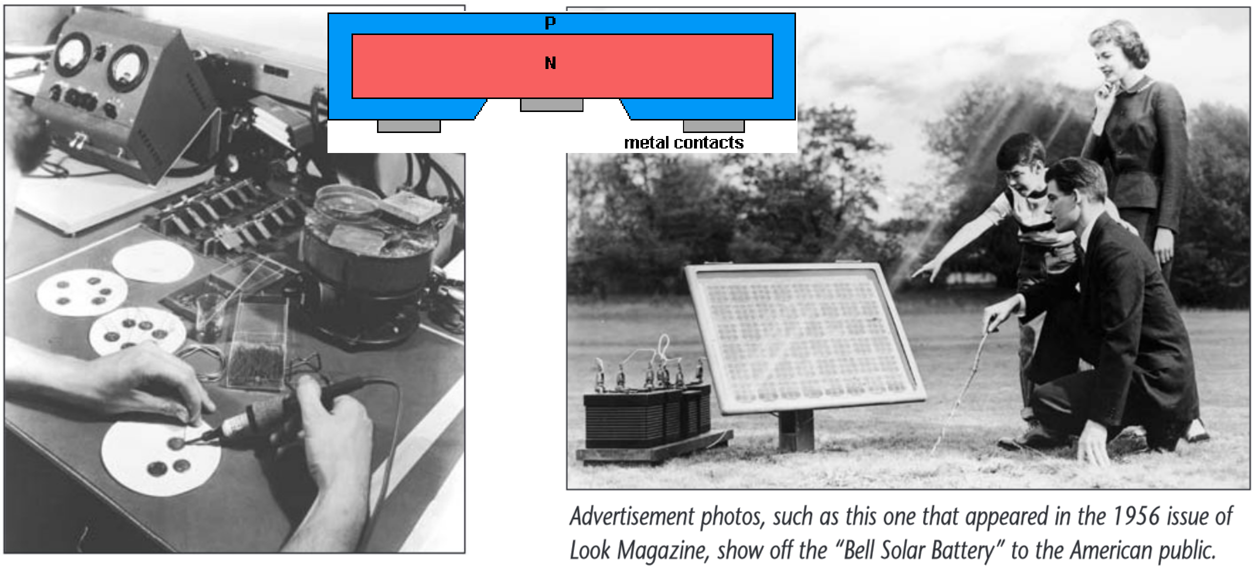
Monocrystalline

Multicrystalline

Source: textbook

Silicon – Long History

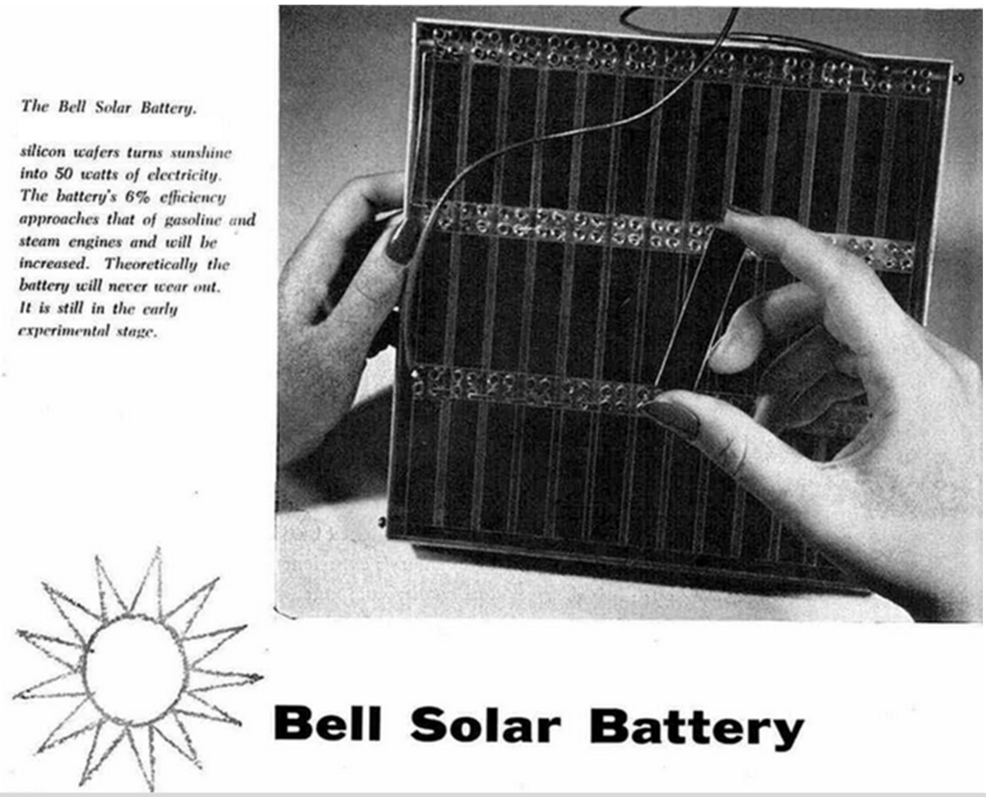
Forefather of today's Si solar cell date to 1954 by researchers at Bell Laboratories (USA). Cells had a diffused junction and both *n*- and *p*-type contacts on the rear ⇒ η = 6% (15x that of earlier devices). First application for space ⇒ remained major market until early 1970's



Advertisement photos, such as this one that appeared in the 1956 issue of Look Magazine, show off the "Bell Solar Battery" to the American public.

Sources: http://www.pveducation.org/pvcdrom/manufacturing/early-silicon-solar-cells
http://www.nrel.gov/education/pdfs/educational_resources/high_school/solar_cell_history.pdf

Silicon – Long History



The Bell Solar Battery.

silicon wafers turns sunshine into 50 watts of electricity. The battery's 6% efficiency approaches that of gasoline and steam engines and will be increased. Theoretically the battery will never wear out. It is still in the early experimental stage.

Bell Solar Battery

Source: http://www.radiomuseum.org/forumdata/users/6435/Cxt/07_cell.jpg

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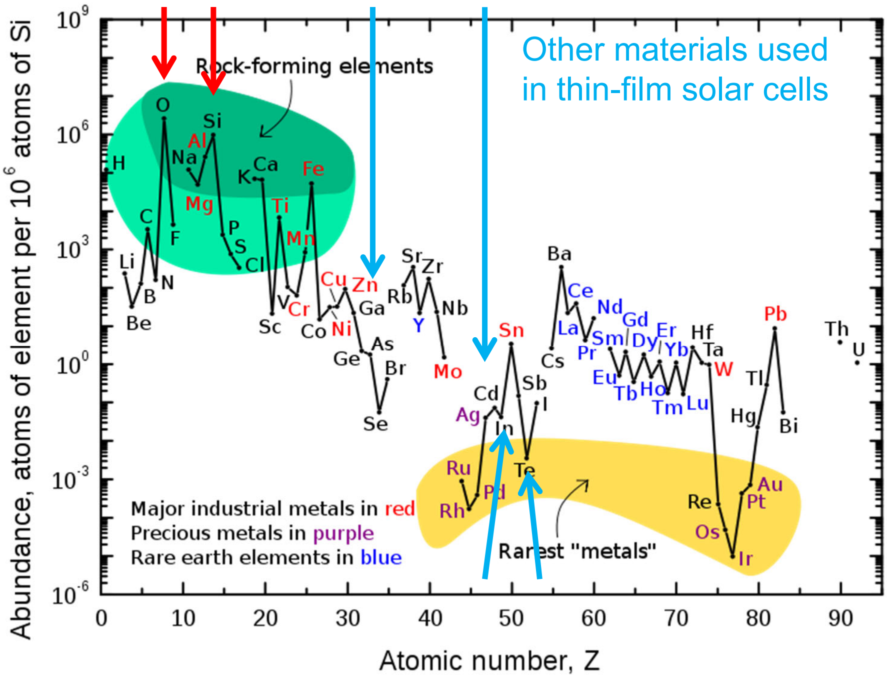
Refining Silicon

Silicon dioxide (SiO_2) ⇒ **most abundant mineral in earth's crust**
⇒ used to manufacture pure silicon in two stages

1. Oxygen is removed to produce metallurgical grade silicon
2. Further refined to produce electronic grade silicon

An intermediate grade with impurity levels between 1) and 2) above is often termed solar grade silicon



Source: http://en.wikipedia.org/wiki/Abundance_of_the_chemical_elements

Metallurgical Grade Silicon

Silica (SiO_2) occurs naturally as quartz.

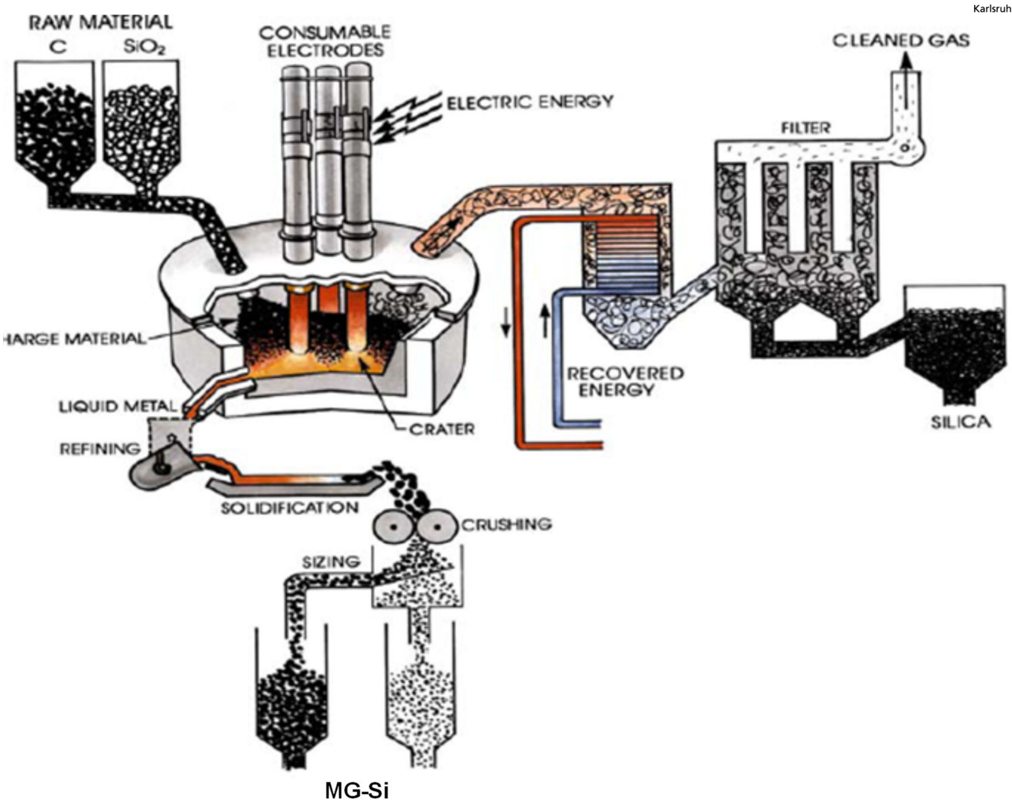
High purity quartz rock is most common raw material for making electronic grade Si, but could also use beach sand. Ideally, silica has low concentrations of Fe, Al and other metals.

Silica is reduced (O_2 removed) via reaction with carbon (coal, charcoal) and heating to 1500-2000 °C in an electric furnace

$$SiO_2 + C \rightarrow Si + CO_2$$

Result is metallurgical grade silicon (MG-Si)
⇒ 98% pure and used extensively in the metallurgical industry (e.g. ~1% Si used for making some Al alloys)

Metallurgical Grade Silicon



Source: Handbook of PV Science & Engeneering, A. Luque, Wiley, 1998

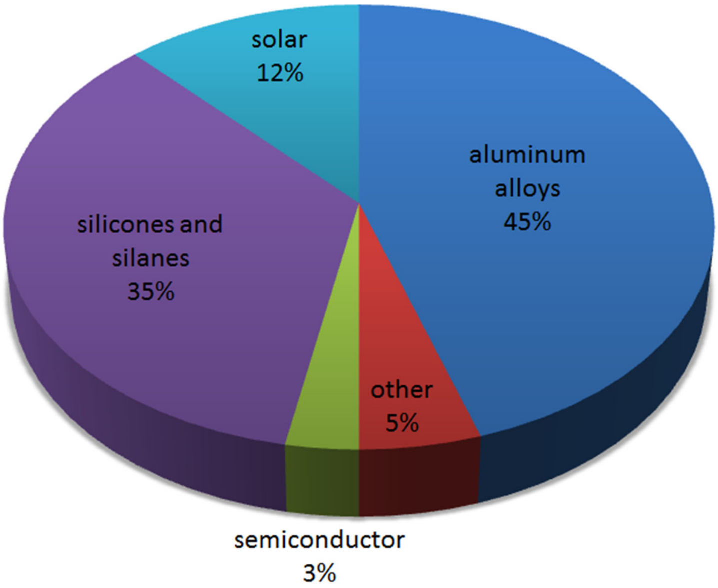
Metallurgical Grade Silicon

Total production of silicon is ~7.6 million tonnes p.a.

Low cost (few $/kg)

Energy content of ~15 kWh/kg

N.B. Solar industry consumes 4x as much as silicon as remainder of semiconductor industry!



Source: https://www.pveducation.org/pvcdrom/manufacturing-si-cells/refining-silicon

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Metallurgical Grade Silicon

2% impurities are mainly carbon, alkali-earth and transition metals and hundreds of ppm of B and P

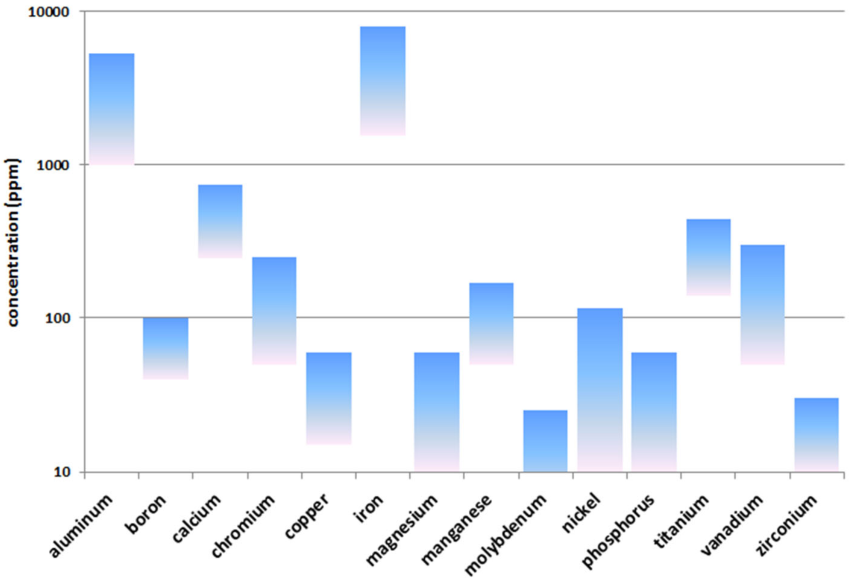
Transition metals in silicon result in deep levels (defects) within bandgap

⇒ high recombination activity

⇒ MG-Si unsuitable for use in electronics

Also, while B and P sounds relevant, the dopant concentrations are way too high

⇒ we need ppb!

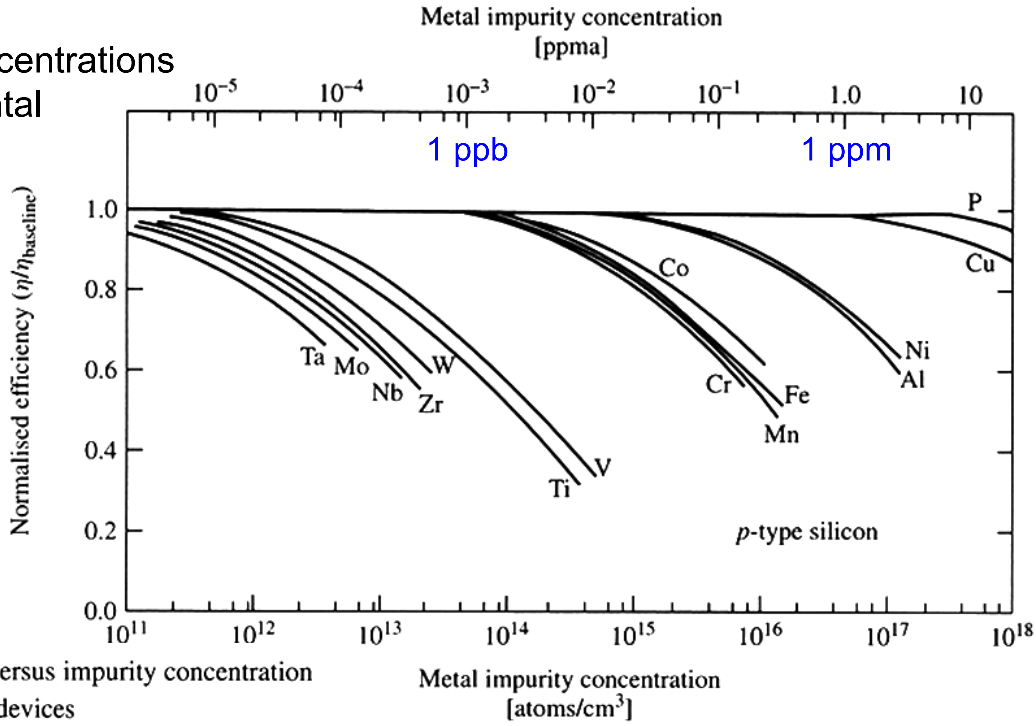


Source: https://www.pveducation.org/pvcdrom/manufacturing-si-cells/refining-silicon

Metallurgical Grade Silicon

Research in ‘80s determining effect of impurities on solar cell efficiency

Even ppb concentrations have detrimental effect!



Solar cell efficiency versus impurity concentration for 4 ohm cm p-base devices

Source: Davis et al. IEEE Trnas Electron Dev, 1980

Electronic Grade Silicon

Thus, MG-Si needs to be further refined for semiconductor applications

Powdered MG-Si reacted with hydrochloric acid (HCl) at 300°C in a fluidized bed reactor to form trichlorosilane (TCS, $SiHCl_3$)

$$Si + 3HCl \rightarrow SiHCl_3 + H_2$$

Why? Impurities such as Fe, Al, and B react to form halides (e.g. $FeCl_3$, $AlCl_3$,…) and $SiHCl_3$ has low boiling point of 32°C (c.f. 180-300 °C for $FeCl_3$, $AlCl_3$)

$\Rightarrow$ distillation used to purify and separate $SiHCl_3$ from impurity halides
$\Rightarrow$ now has < 1 ppb of electrically active impurities

Finally, pure $SiHCl_3$ is reacted with hydrogen at 1100°C for ~200 – 300 hours to produce a very pure silicon

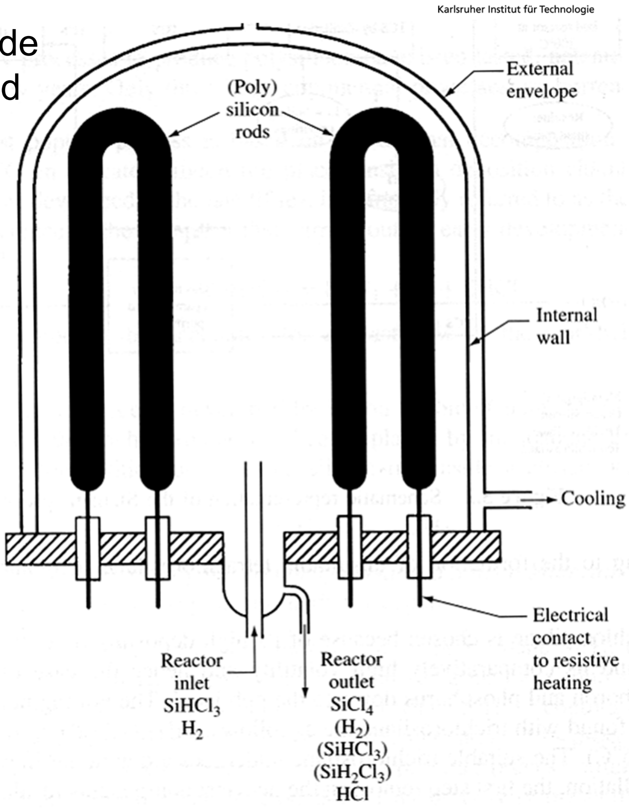
$$SiHCl_3 + H_2 \rightarrow Si + 3\ HCl$$

Electronic Grade Silicon (EG-Si)

Reaction of $SiHCl_3 + H_2$ takes place inside large vacuum chambers ⇒ Si deposited onto thin polysilicon rods to produce high-purity polysilicon (~Ø20cm)
⇒ “Siemens process” (1960’s)

Rods of EG-Si then broken ⇒ form feedstock for crystallisation process

Production requires a lot of energy



Source: *Handbook of PV Science and Engeneering, A. Luque, Wiley, 1998*

Single Crystal Silicon

Once we have EG-Si, the Czochralski (Cz) process is most common way to produce single crystal ingots

The use of quartz crucibles (see next slide) in manufacture of Cz Si results in
⇒ incorporation of ppm (10^{18} cm^{-3}) of O into Si ingot
⇒ creation of B-O defect that can degrade *L* over time (does not happen in *n*-type ingots fabricated with phosphorus)

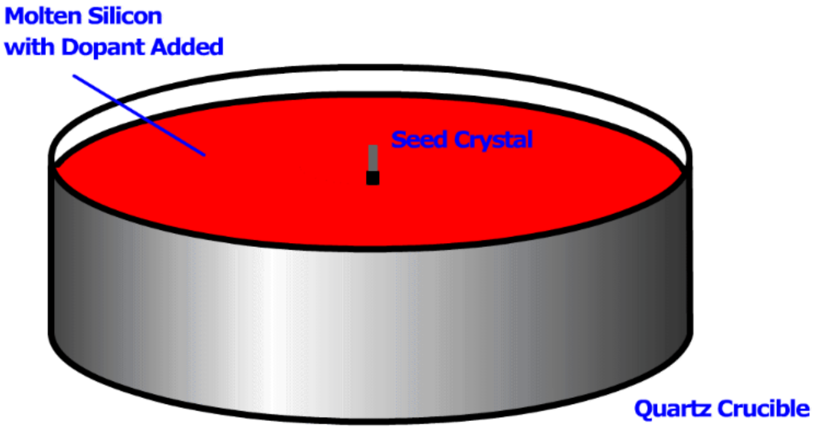
Energy content of Cz c-Si ~210 kWh per kg of EG-Si

Source: *http://www.pveducation.org/pvcdrom/manufacturing/czochralski-silicon*

Single Crystal Silicon

A seed crystal is palced in a pool of silicon just above its melting point.

Click to Start

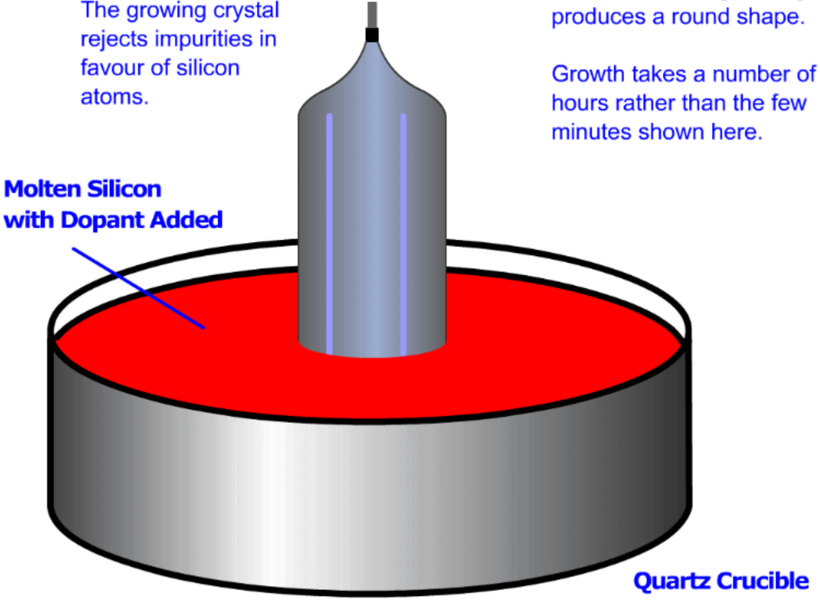


See animation at: *https://www.pveducation.org/pvcdrom/manufacturing-si-cells/czochralski-silicon*

Single Crystal Silicon

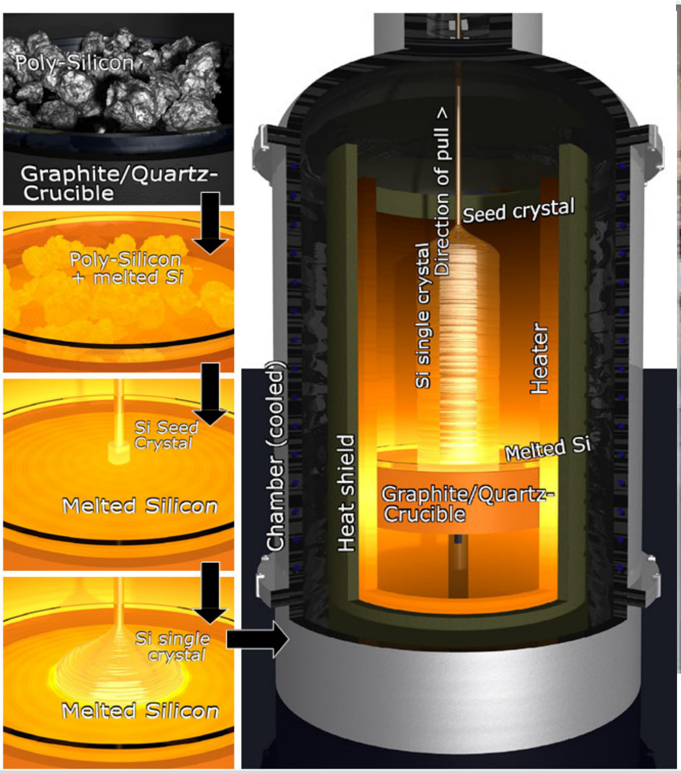
By carefully conrolling the temperature and the rate of pull it is possible to grow large ingots of single crystal material. Rotating the ingot produces a round shape.

Growth takes a number of hours rather than the few minutes shown here.


The growing crystal rejects impurities in favour of silicon atoms.

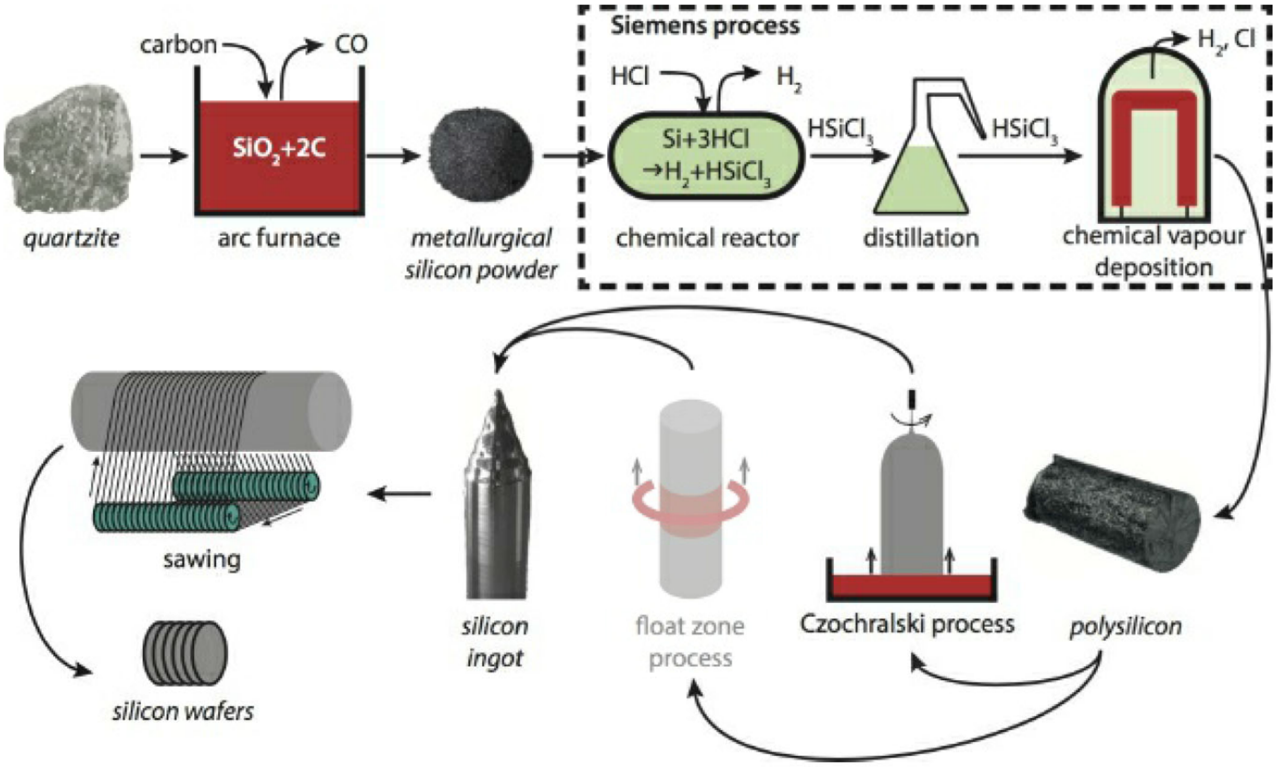
Source: https://www.pveducation.org/pvcdrom/manufacturing-si-cells/czochralski-silicon

Single Crystal Silicon



Source: http://www.waferpro.com/about-silicon-wafers/

Single Crystal Silicon



Source: textbook

Multi-Crystalline Silicon

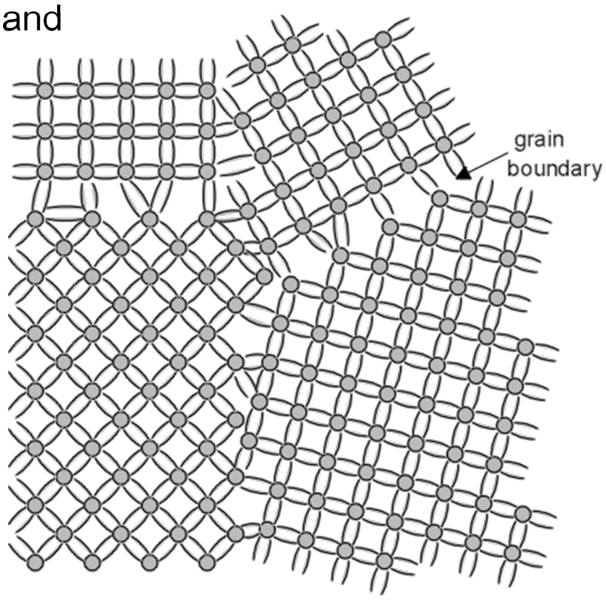
Can instead produce mc-Si ⇒ ingots are grown in a large square ceramic crucible:

☑ simpler,
☑ less energy intensive (8-15 kWh/kg), and
☑ cheaper, but…

☒ … lower quality material due to presence of grain boundaries

Grain boundaries introduce

- high localised regions of recombination due to introduction of extra defect energy levels into bandgap ⇒ reduces *L*
- Barriers to flow of carriers and providing shunting paths for current flow across *p-n* junction



Source: https://www.pveducation.org/pvcdrom/manufacturing-si-cells/multi-crystalline-silicon

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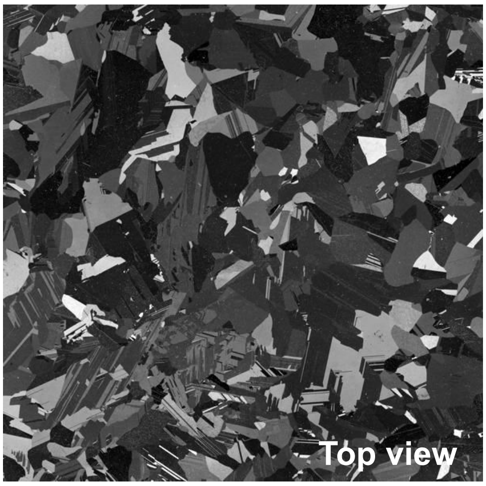
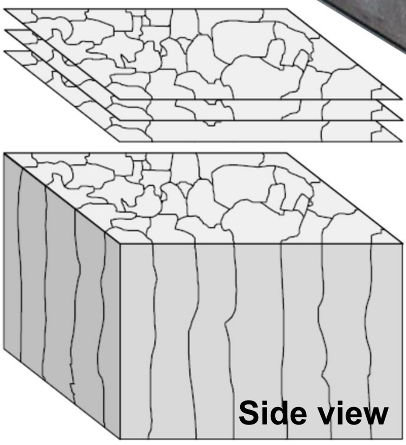
Multi-Crystalline Silicon

To avoid significant recombination losses need grain sizes of mm^2 – cm^2 ⇒ also allows single grains to extend from front to back of the cell, providing less resistance to carrier flow



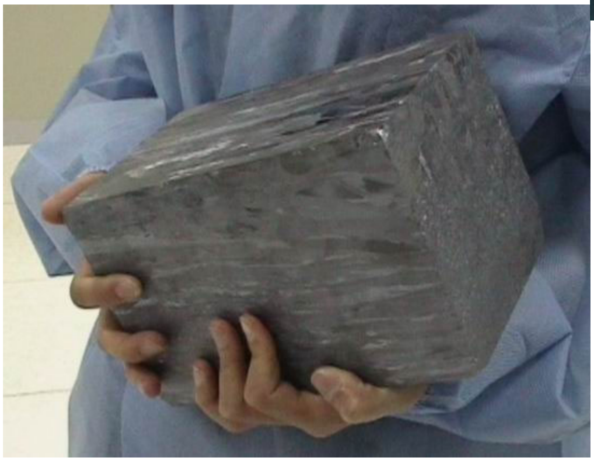


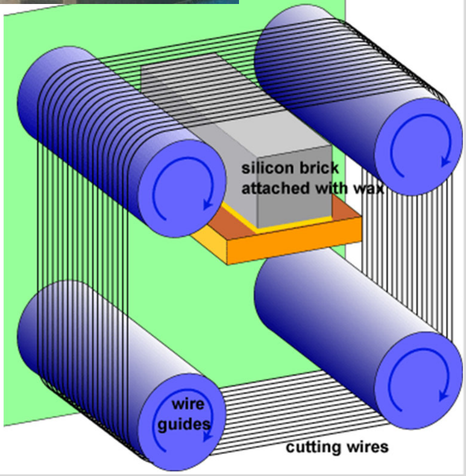
Source: https://www.pveducation.org/pvcdrom/manufacturing-si-cells/multi-crystalline-silicon

Wafer Slicing

Ingot then sliced up into **wafers**

For mc-Si, large slabs are then sliced up first into smaller **bricks** using diamond saw. Wafers then realised using a wire saw with SiC slurry





Source: https://www.pveducation.org/pvcdrom/manufacturing-si-cells/wafer-slicing

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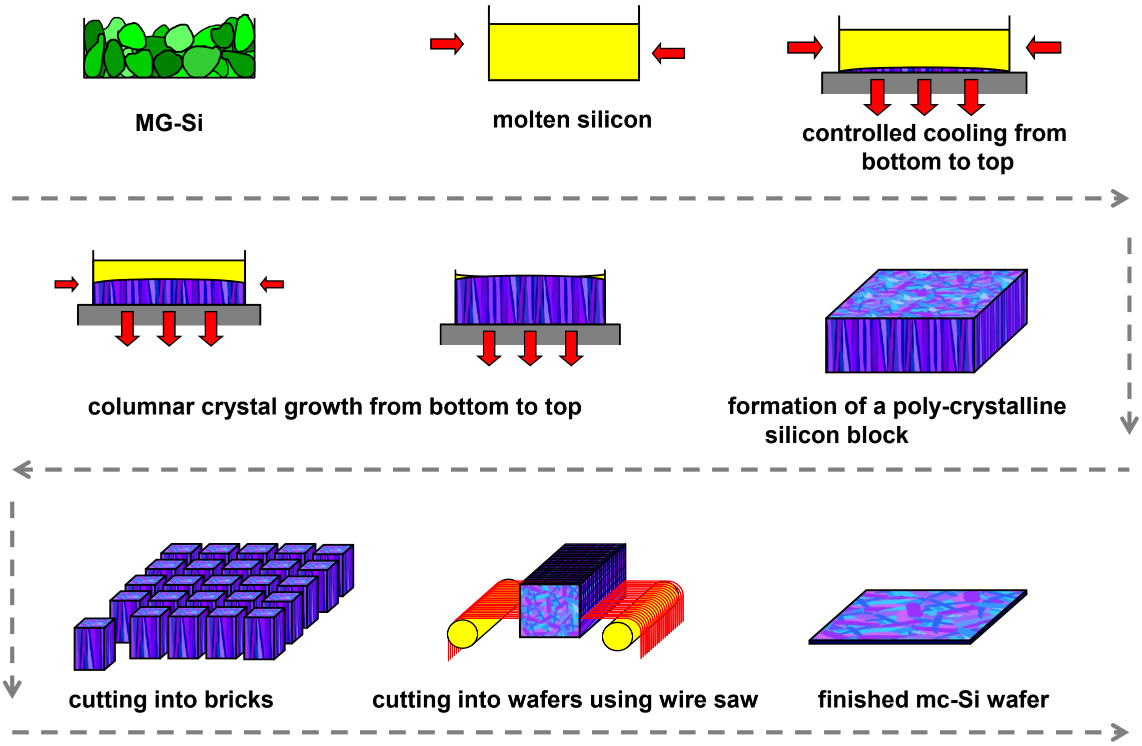
Production of mc-Si Wafers



MG-Si

molten silicon

controlled cooling from bottom to top

columnar crystal growth from bottom to top

formation of a poly-crystalline silicon block

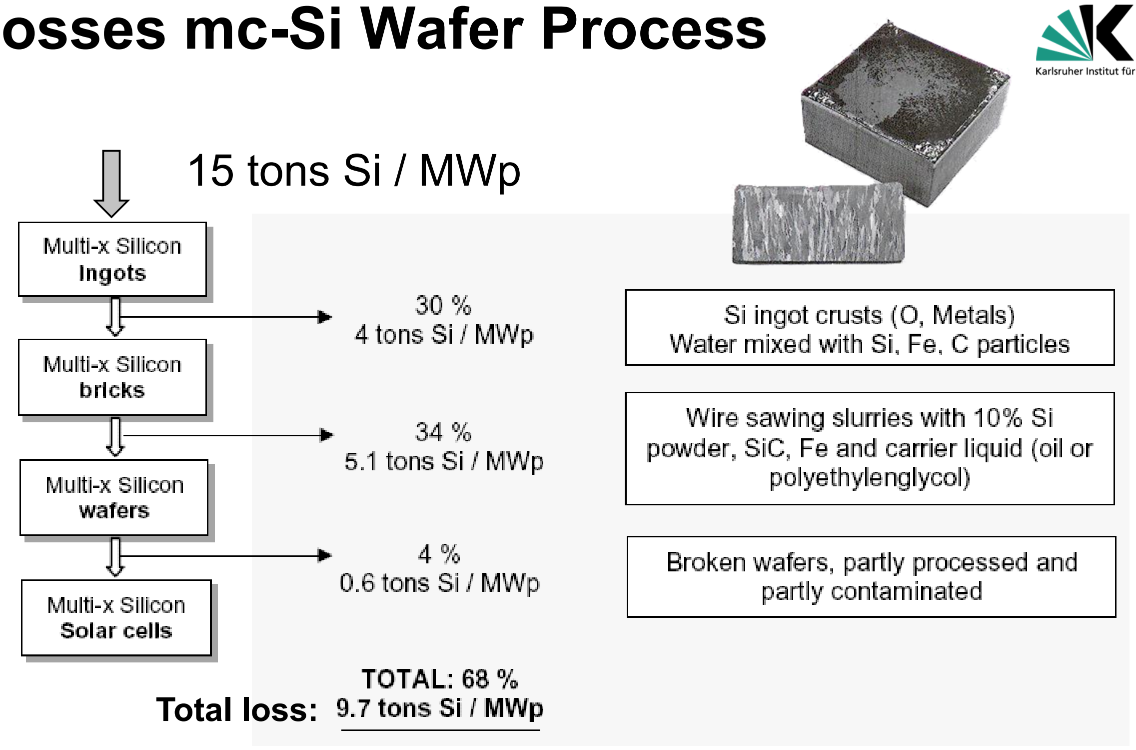
cutting into bricks

cutting into wafers using wire saw

finished mc-Si wafer

Source: Gerhards, Dissertation, Konstanz 2002, U.Kindereit, Studienarbeit, Berlin 2004)

Losses mc-Si Wafer Process



15 tons Si / MWp

Multi-x Silicon Ingots → 30 % 4 tons Si / MWp — Si ingot crusts (O, Metals) Water mixed with Si, Fe, C particles

Multi-x Silicon bricks → 34 % 5.1 tons Si / MWp — Wire sawing slurries with 10% Si powder, SiC, Fe and carrier liquid (oil or polyethylenglycol)

Multi-x Silicon wafers → 4 % 0.6 tons Si / MWp — Broken wafers, partly processed and partly contaminated

Multi-x Silicon Solar cells

Total loss: **TOTAL: 68 %** **9.7 tons Si / MWp**

Remaining 5.3 tons (32%) used to make solar cells

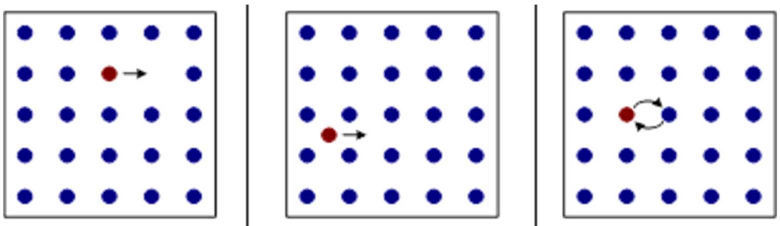
Source: D. Sarti and R. Einhaus, Photowatt (2002)

Solid State Diffusion

Solid state diffusion: net transport of atoms from a region of higher concentration to one of lower concentration by random molecular motion
⇒ results in a gradual mixing of materials

e.g. drop of ink in glass of water is evenly distributed after a certain amount of time

In Si crystal, there is a solid lattice of atoms through which the dopant atom has to move. This can be done in different ways:



Dopants ● fill empty places in the lattice

Dopants move in-between atoms

Dopants exchange places with silicon atoms

In Si solar cells, typically start with a uniformly doped *p*-type wafer (the “base”) – the *n*-type “emitter” layer is formed via phosphorus doping

Source: https://www.easybiologyclass.com/difference-between-diffusion-and-osmosis-a-comparison-table/ https://www.halbleiter.org/en/waferfabrication/doping/

Solid State Diffusion

Reminder – diffusion process follows Fick's law:

$$j = -D\frac{\partial N}{\partial x}$$

where

j = flux density (atoms/cm^2),
D = diffusion coefficient (cm^2 /s) at a given temperature, T
N = concentration volume (atoms/cm)
x = distance (cm)

Typically, the diffusion of atoms into Si wafer is a 2-step process:

1) wafer first placed in a furnace with unlimited source (e.g. full of phosphorus gas)
2) then turning off the dopant source (limited source) and driving the phosphorus atoms further into the wafer

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Solid State Diffusion

1) Diffusion from an unlimited source: produces a shallow junction with a very high surface concentration of P atoms

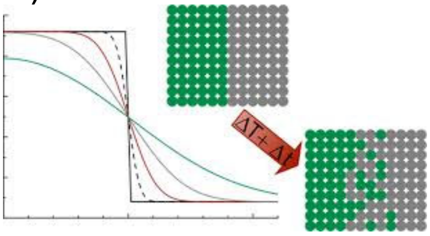
Best described by complementary error function (erfc)

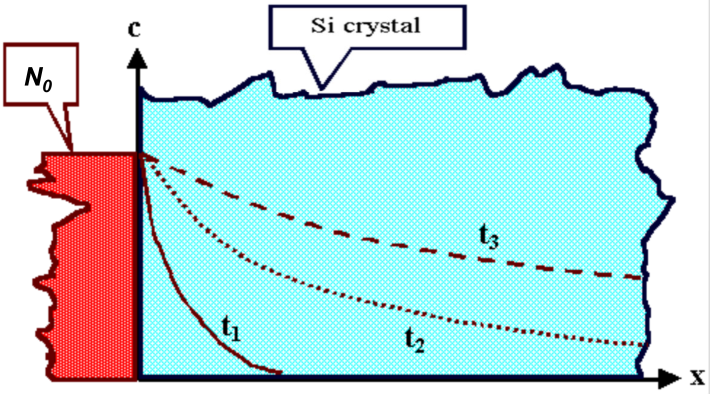
$$N(x,t) = N_0 erfc\frac{x}{2\sqrt{Dt}}$$

where

N_0 = impurity concentration at surface (atoms cm^{-3})
t = time (sec)

Often called a “pre-deposition” step





Source: Strauß et al. The Journal of Physical Chemistry C 122.12 (2018): 6508-6513

Solid State Diffusion

2) <u>Diffusion from a Limited Source</u>: consists of two-step process

i. a short <u>pre-deposition</u> as outlined in 1) above, followed by

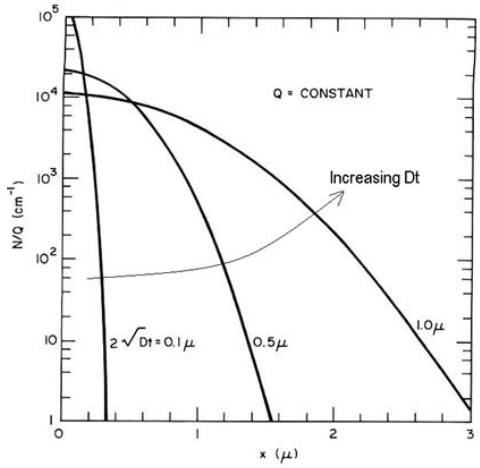
ii. a longer <u>drive-in</u> at a higher temperature (with dopant source removed) to provide a deeper and more lightly-doped emitter

The drive-in is usually at a higher temperature ⇒ now the final dopant profile is described by a Gaussian:

$$N(x,t) = \frac{Q_0}{\sqrt{\pi D t}} e^{-\left(\frac{x}{2}\sqrt{Dt}\right)^2}$$

where

Q_0 = is atoms introduced in the pre-deposition (atoms cm^{-2})



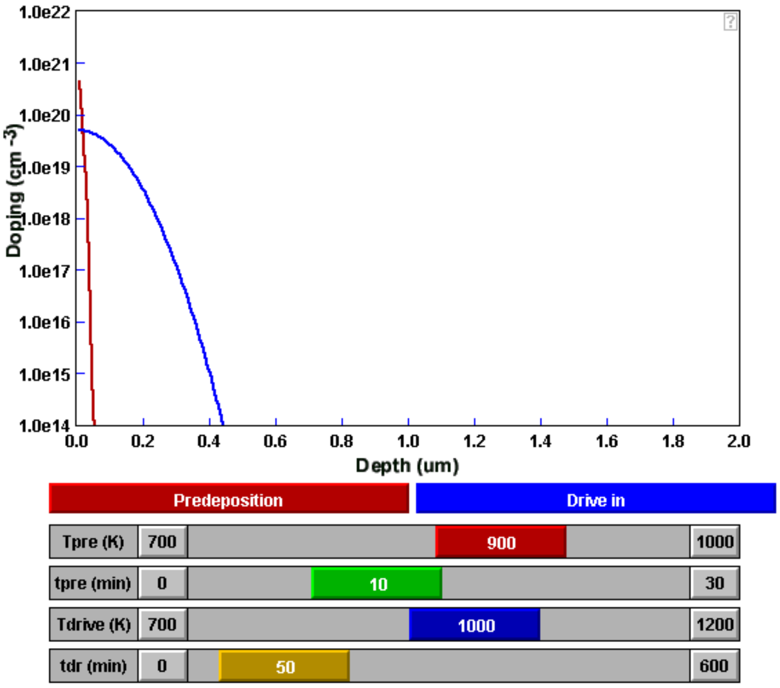
Gaussian impurity profile.

Solid State Diffusion

Diffusion of an n-type dopant, phosphorus (P), to create a *pn* junction in a p-type (boron, B) base

Pre-dep: 900°C for 10min

Drive-in: 1000°C for 50min



Tpre (K) 700 900 1000

tpre (min) 0 10 30

Tdrive (K) 700 1000 1200

tdr (min) 0 50 600

Source: https://www.pveducation.org/pvcdrom/manufacturing-si-cells/solid-state-diffusion

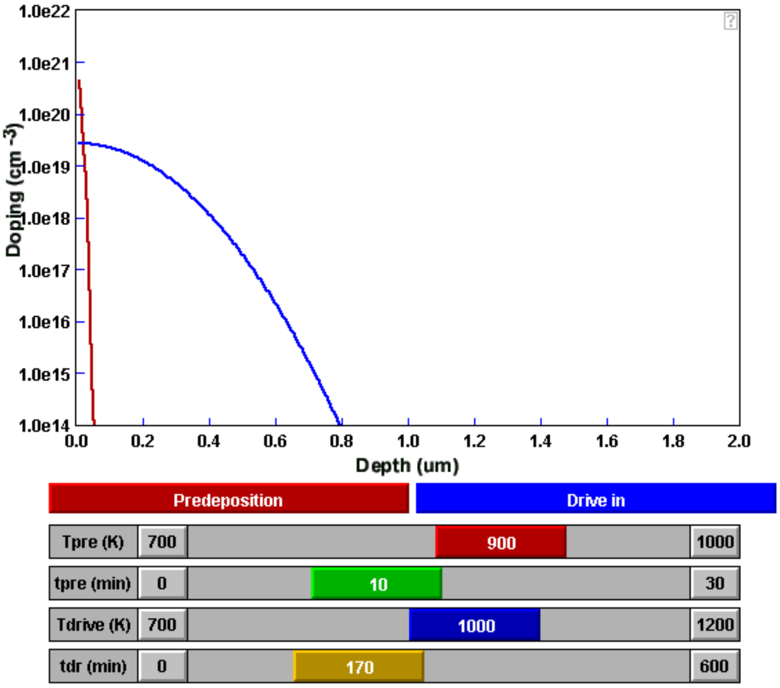
Solid State Diffusion

Pre-dep: 900°C for 10min
Drive-in: 1000°C for 170min

Achieves:

i) Lower surface concentration of P ions

ii) Deeper junction – further away from front surface



Tpre (K) 700 — 900 — 1000
tpre (min) 0 — 10 — 30
Tdrive (K) 700 — 1000 — 1200
tdr (min) 0 — 170 — 600

Source: https://www.pveducation.org/pvcdrom/manufacturing-si-cells/solid-state-diffusion

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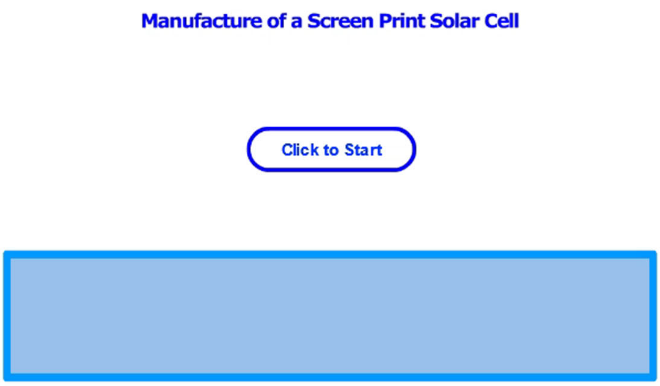
Screen Printed Solar Cells

Screen-printed (SP) solar cells first developed in 1970's
⇒ remains most mature solar cell fabrication technology
⇒ Still in production today (although higher efficiency devices becoming more common in production in last 2-3 years)

Key advantages of SP process are:
i) simplicity and
ii) robustness

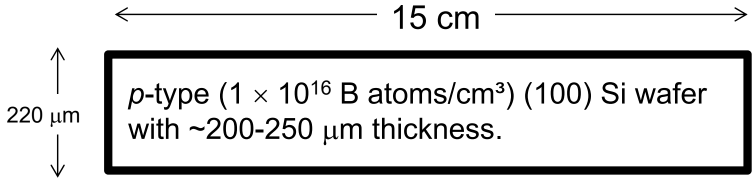


Source: https://www.pveducation.org/pvcdrom/manufacturing-si-cells/screen-printed-solar-cells

Screen Printed Solar Cells

Fabrication sequence:

1. Sawing
   of monocrystalline or mc-Si ingots to produce wafers



p-type (1×10^{16} B atoms/cm³) (100) Si wafer with ~200-250 μm thickness.

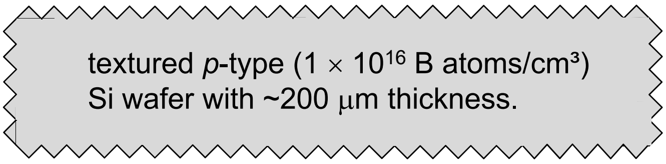
2. Etching
   to remove saw damage (10-20μm from either side of wafer etched off)

Etching away the saw damage

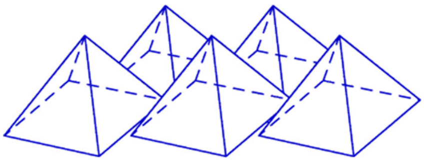
Screen Printed Solar Cells

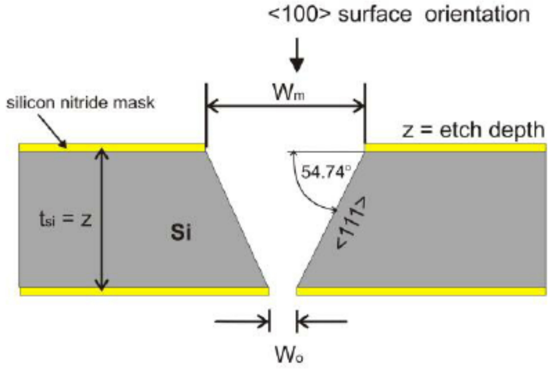
Fabrication sequence:

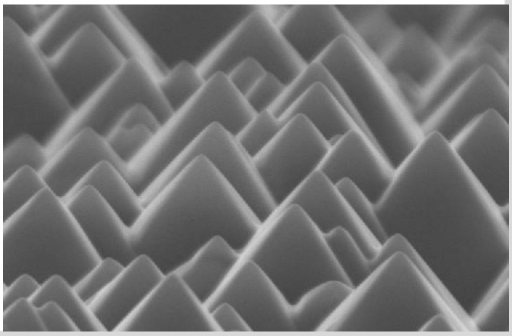
3. Texturing (only for monocrystalline Si wafers)
   <100> oriented Si wafers are textured ⇒ results in exposing <111> crystal planes using potassium hydroxide (KOH) or sodium hydroxide (NaOH) based anisotropic etch ⇒ 1-10μm high pyramids



textured *p*-type (1×10^{16} B atoms/cm³) Si wafer with ~200 μm thickness.







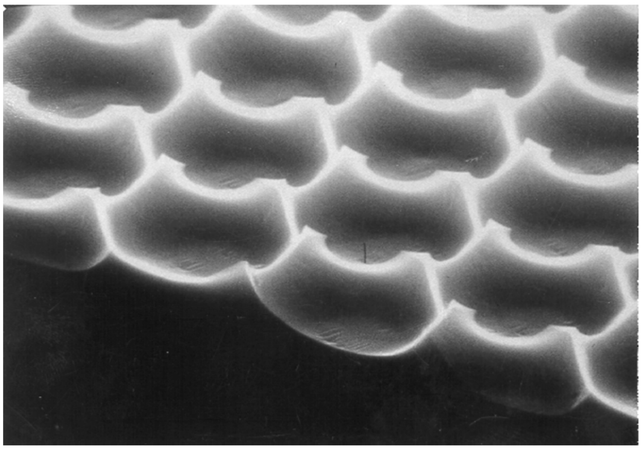
Source: www.pveducation.org/pvcdrom/light-trapping
Abidin *et al.*, *Jurnal Teknologi* 74. (2015) 10

Screen Printed Solar Cells

Surface Texturing to Reduce Reflection:
While monocrystalline Si wafers are easily textured using alkaline etch to from pyramids and reduce reflection, same process is only marginally effective on the randomly orientated grains of mc-Si

Various schemes have been proposed to texture mc-Si material:

- mechanical texturing of wafer surface with dicing saws or lasers
- plasma etching
- isotropic chemical etching in combination with a photolithographic mask →



But, standard practice in industry is to still perform alkaline etching – even though not very beneficial (high throughput, low cost)

Source: https://www.pveducation.org/pvcdrom/design-of-silicon-cells/surface-texturing

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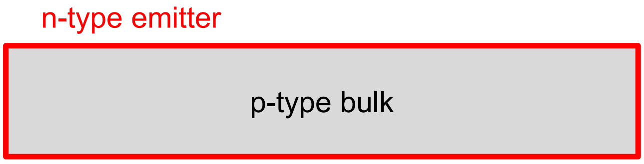
Screen Printed Solar Cells

Fabrication sequence:

4. Emitter diffusion
   phosphorus diffusion required to form *n*-type emitter on a *p*-type (boron-doped) substrate. Conducted in tube furnace at ~900°C containing phosphorus trioxychloride ($POCl_3$) ⇒ deposits a phosphorus glass (P_2O_5) layer on top of Si wafer ⇒ acts as a diffusion source for P atoms



Screen Printed Solar Cells

Phosphorus Diffusion: *p-n* junction formation

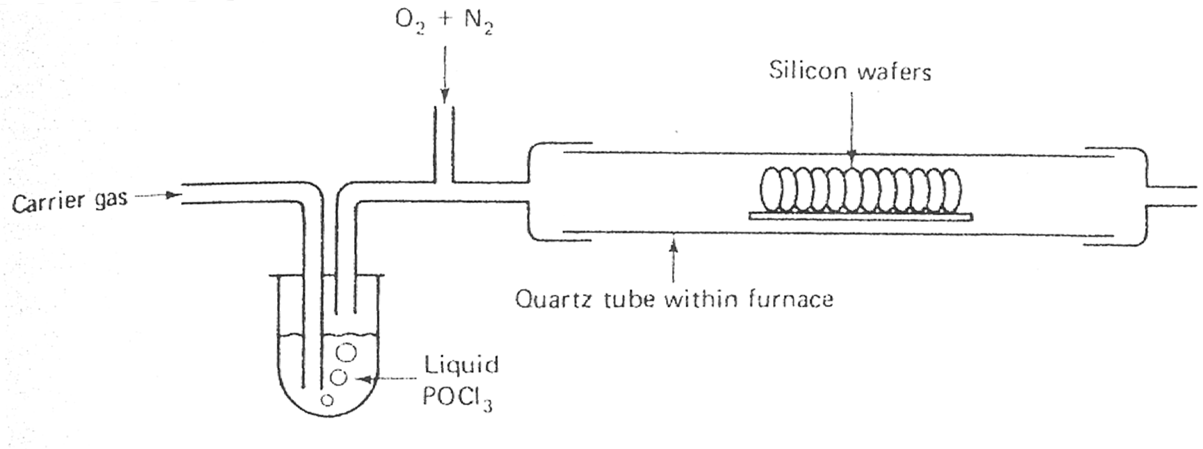


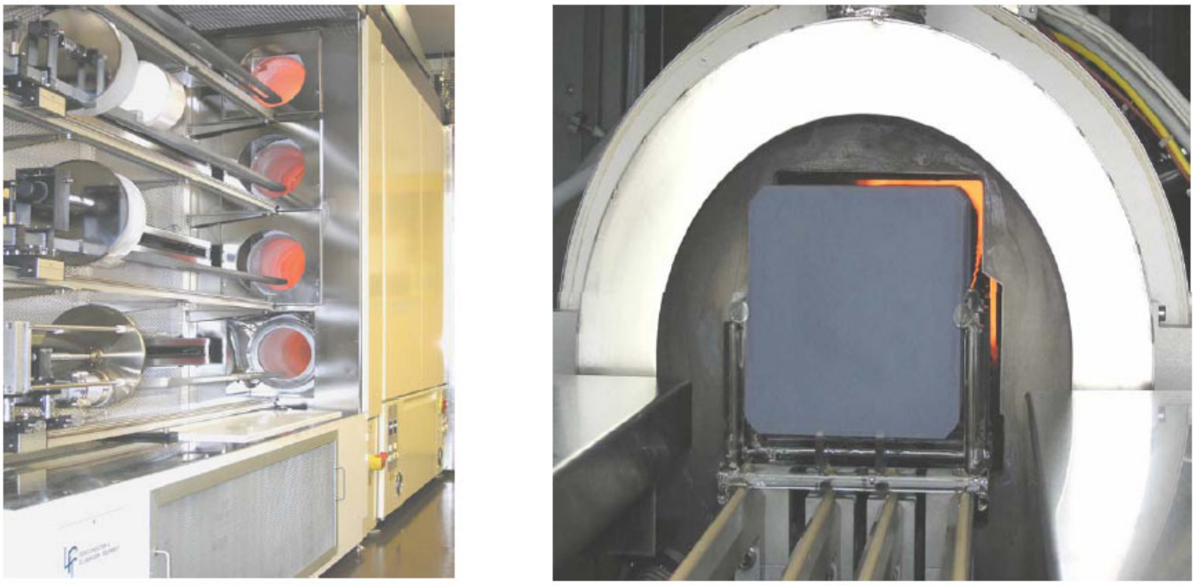
Figure 6.4. Phosphorus diffusion process.

- Evaporation of liquid $POCl_3$
- Transported via a carrier gas (N_2)
- Deposited as a P-doped glass layer (P_2O_5) onto Si wafer
- P_2O_5 is the diffusion source for P at high T ~900°C

Source: M.A. Green "Solar Cells", Prentice Hall

Screen Printed Solar Cells

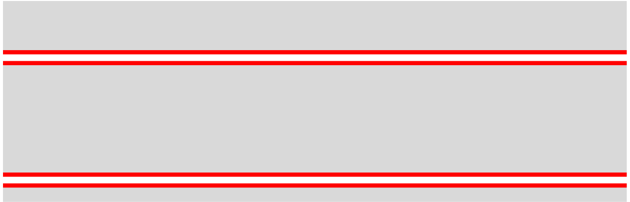
Phosphorus Diffusion: *p-n* junction formation



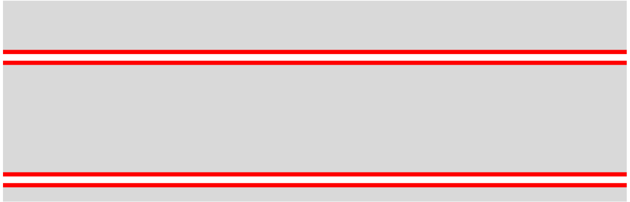
Screen Printed Solar Cells

Fabrication sequence:

5. Edge isolation
   plasma etching used to remove unwanted junction from edge of wafers



Cells stacked on top of each other for edge isolation (via plasma etching)



Remaining P_2O_5 layer on front/rear also removed via an acid-based etch

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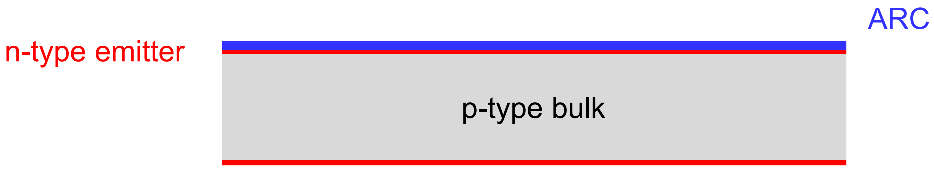
Screen Printed Solar Cells

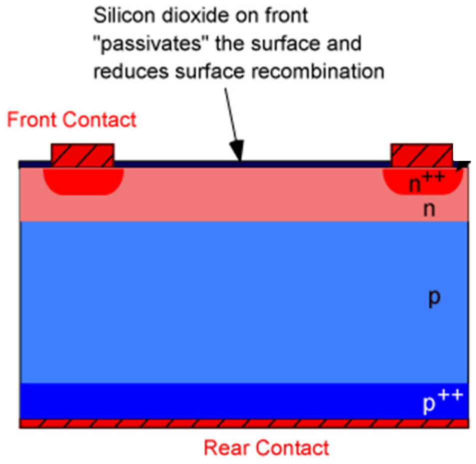
6. Passivation and antireflection coating (ARC)
   the most common ARC material is silicon nitride (a-SiN_x:H)
   - refractive index $n \sim 2.2$
   - not only chosen for its optimal refractive index
     (e.g. in that regard TiO_2 is also good)
   - but also because a-SiN_x:H affords some passivation of surface and
     bulk defects (via hydrogen)



Screen Printed Solar Cells

High recombination rates at top surface have particularly detrimental impact on I_{sc} (remember highest generation region of carriers occurs at top surface)

Reducing high front surface recombination is typically accomplished by reducing the number of dangling silicon bonds at the top surface by using <u>surface passivation layer</u>, e.g. thermally grown silicon dioxide (SiO_2) or hydrogenated silicon nitride (a-SiN:H) layers to passivate the surface and reduce defect states at interface



Silicon dioxide on front "passivates" the surface and reduces surface recombination

Source: http://www.pveducation.org/pvcdrom/design/current-losses-due-to-recombination

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Screen Printed Solar Cells

7. <u>Rear side – Metallisation</u>:

Metal pastes made of three components:

(a) powdered metal particles ⇒ provides good conductivity

(b) glass frit ⇒ a binder that helps the silver to adhere to Si substrate and ensure good contact formation

(c) an organic medium ⇒ disperses the metal powder and glass frit ⇒ e.g. optimised (e.g. viscosity) to be i) printable and ii) obtain a good aspect ratio of finger grids

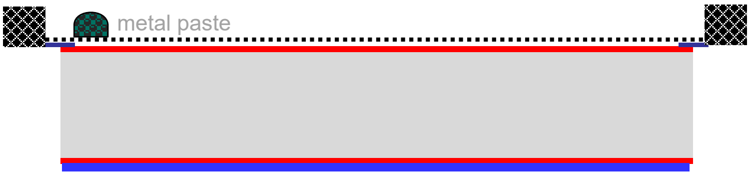
Disadvantages of screen printing:
- Front contacts can not be finer in width than ~100µm
- Particle nature of metal limits conductivity (e.g. to around 1/3 of that of the bulk metal)

⇒ but screen-printing is still the standard process in industry

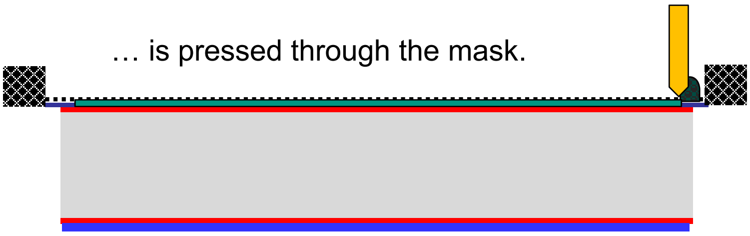
Screen Printed Solar Cells

7. Rear side – Metallisation:

Screen printing of rear contact
A mask is laid on top of the wafer and
an Al (sometimes with Ag) paste …



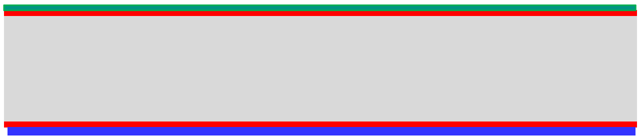
… is pressed through the mask.



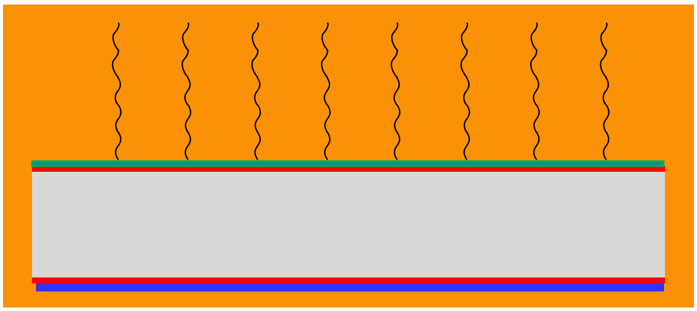
Screen Printed Solar Cells

8. Rear side – Firing:
   of pastes at high T

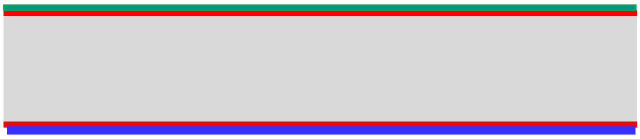
The mask is removed and the remaining
wet metal paste is dried in an furnace.



The organic binding material is
evaporated off



At higher temperatures, contact
between the metal and silicon is made
(diffusion of Al)



This converts the rear *n*-type layer to *p*-type!
Creates “back surface field”

The cell is now flipped over

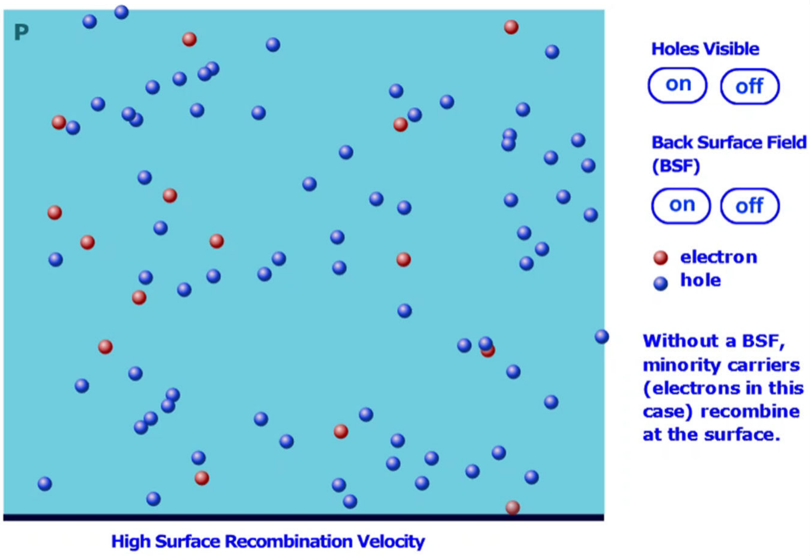
Screen Printed Solar Cells

A "back surface field" (BSF) consists of a higher-doped region at rear surface of solar cell. Interface between high- and low-doped region behaves like a *p*-*n* junction

⇒ forms electric field at interface

⇒ introduces a barrier to minority carrier flow to rear surface by “steering” carriers away from rear surface

Thus, minority carrier concentration is maintained at higher levels in the bulk of the device ⇒ BSF has net effect of passivating rear surface



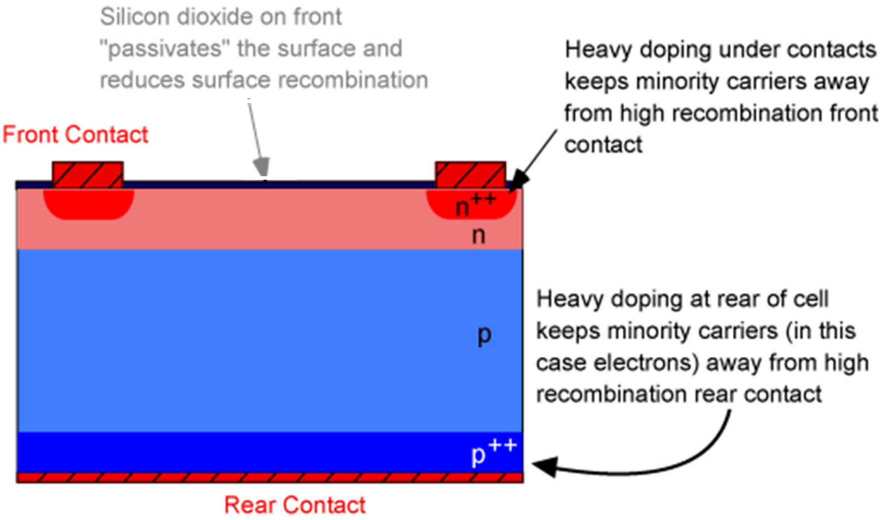
Without a BSF, minority carriers (electrons in this case) recombine at the surface.

Source: *https://www.pveducation.org/pvcdrom/design-of-silicon-cells/surface-recombination*

Screen Printed Solar Cells

Surface passivation via a dielectric (SiO_2 or a-SiN:H) obviously does not work under an metal contact

Instead, recombination effect minimised by increasing doping (similar approach to BSF) ⇒ high doping severely degrades *L*, but no carrier generation under the contacts



Silicon dioxide on front "passivates" the surface and reduces surface recombination

Heavy doping under contacts keeps minority carriers away from high recombination front contact

Heavy doping at rear of cell keeps minority carriers (in this case electrons) away from high recombination rear contact

Source: http://www.pveducation.org/pvcdrom/design/current-losses-due-to-recombination

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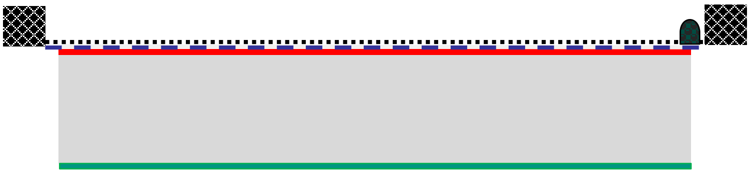
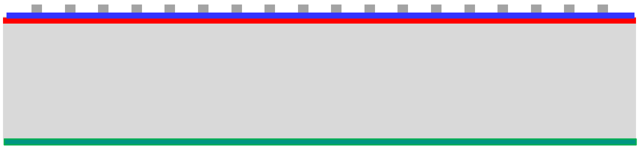
Screen Printed Solar Cells

8. Front side – Printing
9. Front side – Firing

Front contact is produced in a similar way to the rear, but with a different mask that specifies the desired grid contact



Hopefully low shading is achieved and this grid pattern is now fired



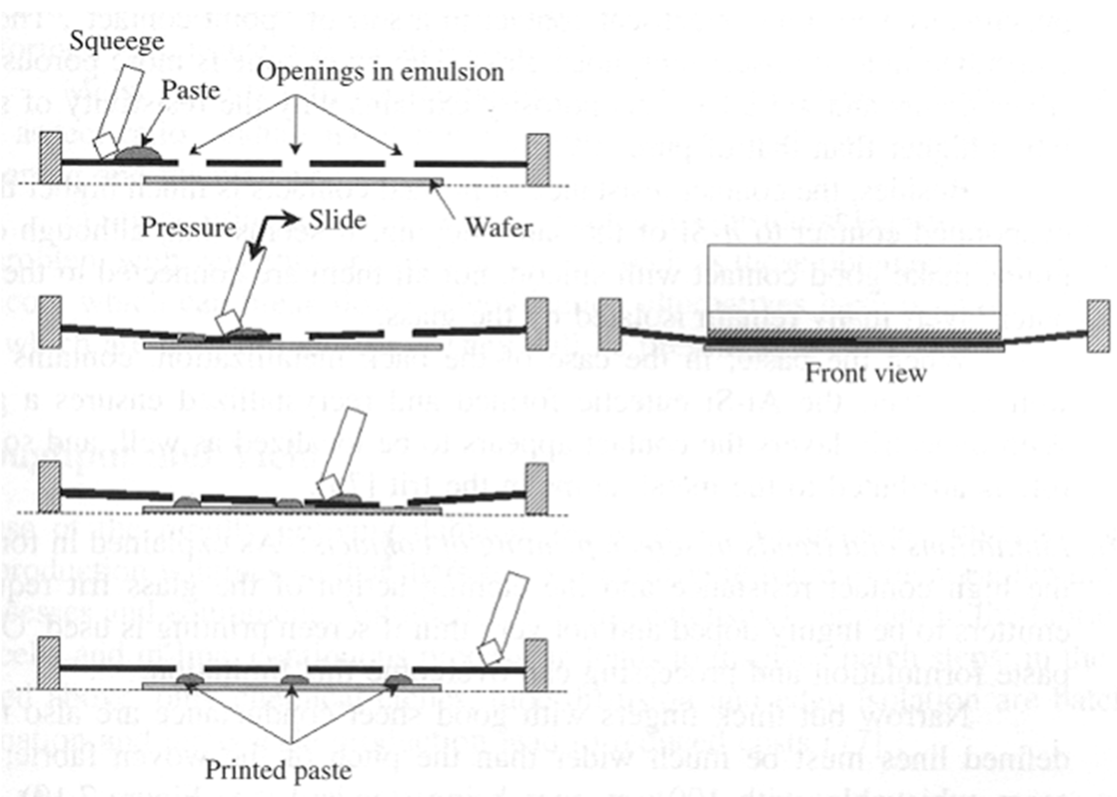
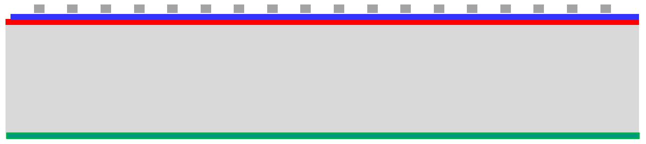


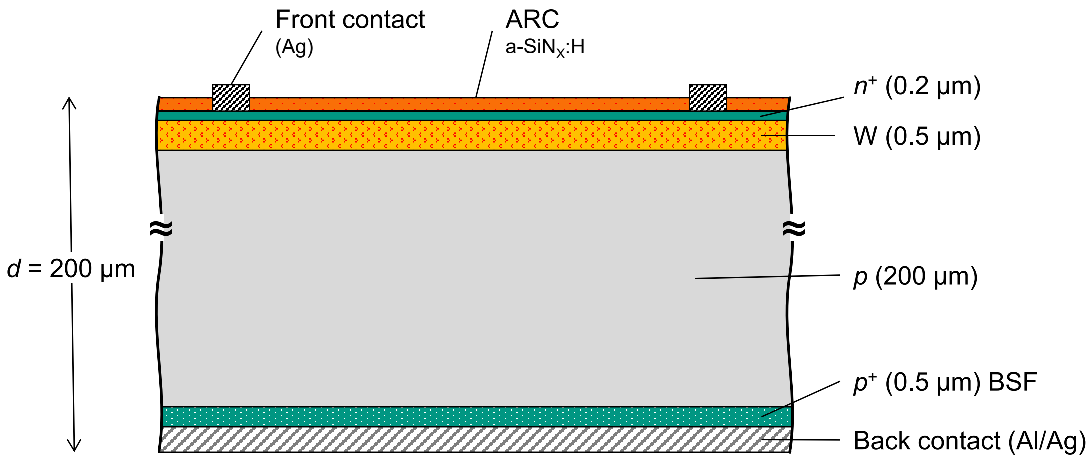
Illustration of a printing sequence

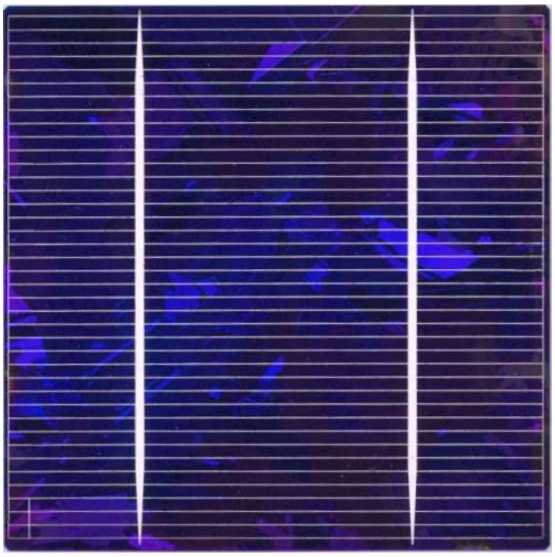
Source: *Handbook of PV Science and Engineering, Luque, Wiley*

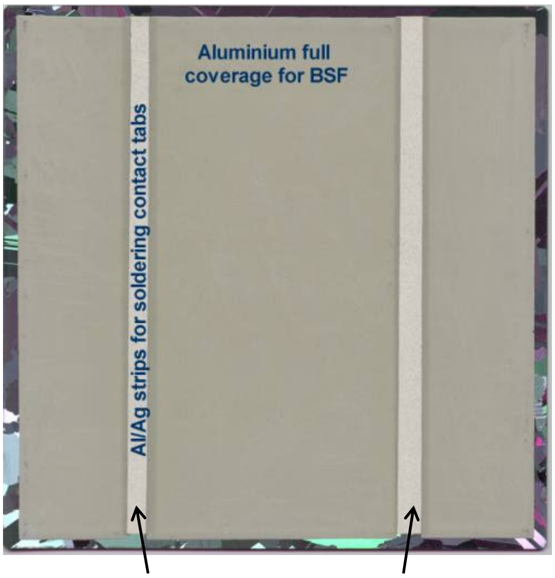
Screen Printed Solar Cells

We now have a finished solar cell









Second Al/Ag SP stripes needed to solder tabbing onto!

Screen Printed Solar Cells

10. <u>Measurement</u>: under “solar simulator” and sorting into different efficiencies

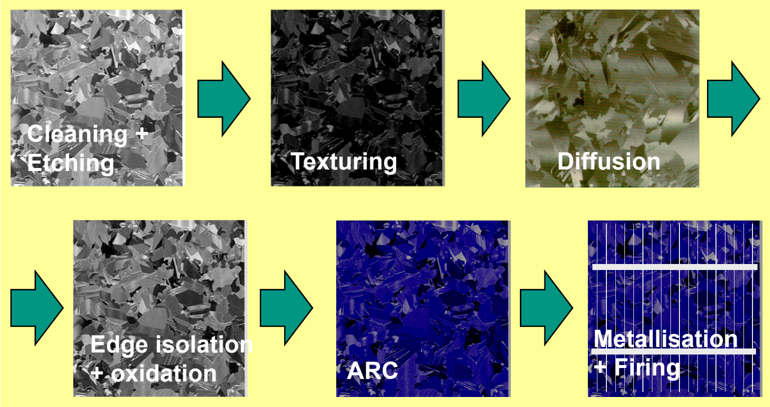
Source: https://www.pveducation.org/pvcdrom/manufacturing/testing

Screen Printed Solar Cells

Overview Production – Main Processes

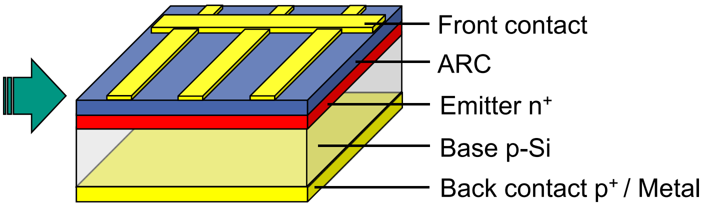
Starting material:

- mc-Si (or Cz) Wafer
- 125 x 125 mm² or 150 x 150 mm²
- ~200 µm thick



Solar Cells:

- ~18% efficiency

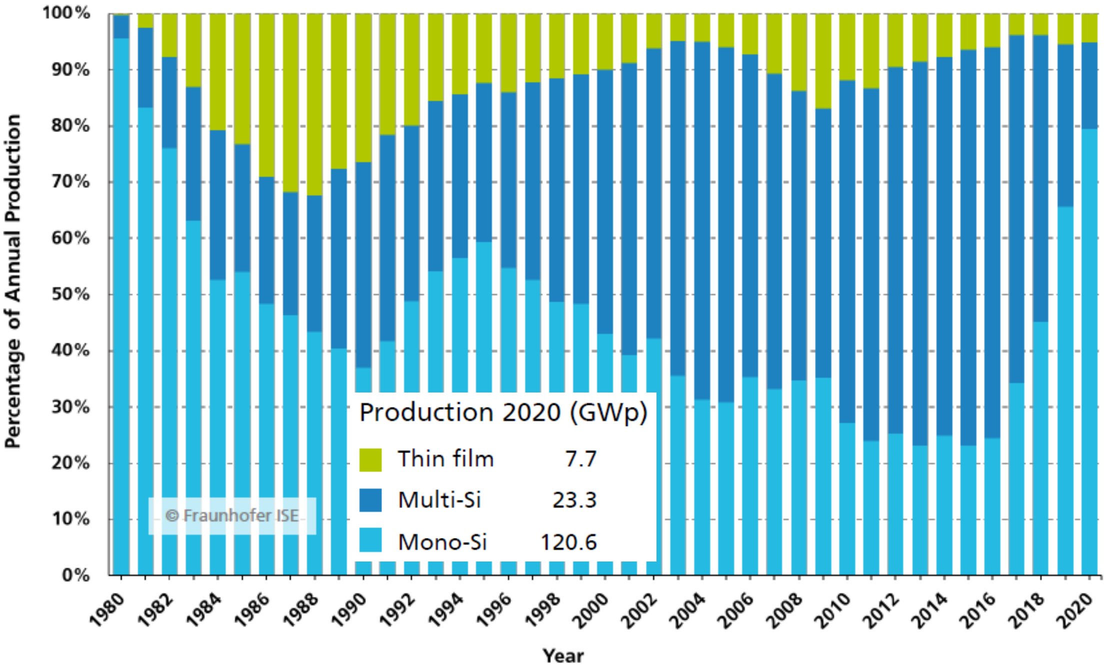


High-Efficiency c-Si Solar Cells

- Several high-efficiency c-Si solar cells exist $\Rightarrow$ η in 22-26% range
- All are based on monocrystalline Si wafers due to lower recombination
- Simple homogeneous (one-step) emitter diffusion for SP solar cells $\Rightarrow$ doping is same beneath metal contacts and in-between fingers
- Trade-off:
  a) high surface concentration of P is required below the front metal contact to maintain low contact resistance (R_s); vs.
  b) <u>but</u> too high a P surface concentration produces a “<u>dead layer</u>” $\Rightarrow$ which reduces EQE of solar cell in the UV/blue region over entire front surface of solar cell
- Thus, most high efficiency approaches seek to reduce R_s and as well improved the blue response of the solar cell
- Can be realized via “selective emitter” $\Rightarrow$ a lower doped emitter that then possess much higher doping below the metal contacts $\Rightarrow$ more complicated as it involves an alignment step

Si PV Market Today

- mc-Si and c-Si wafer-based PV modules represent ~95% of global annual production



Source: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf

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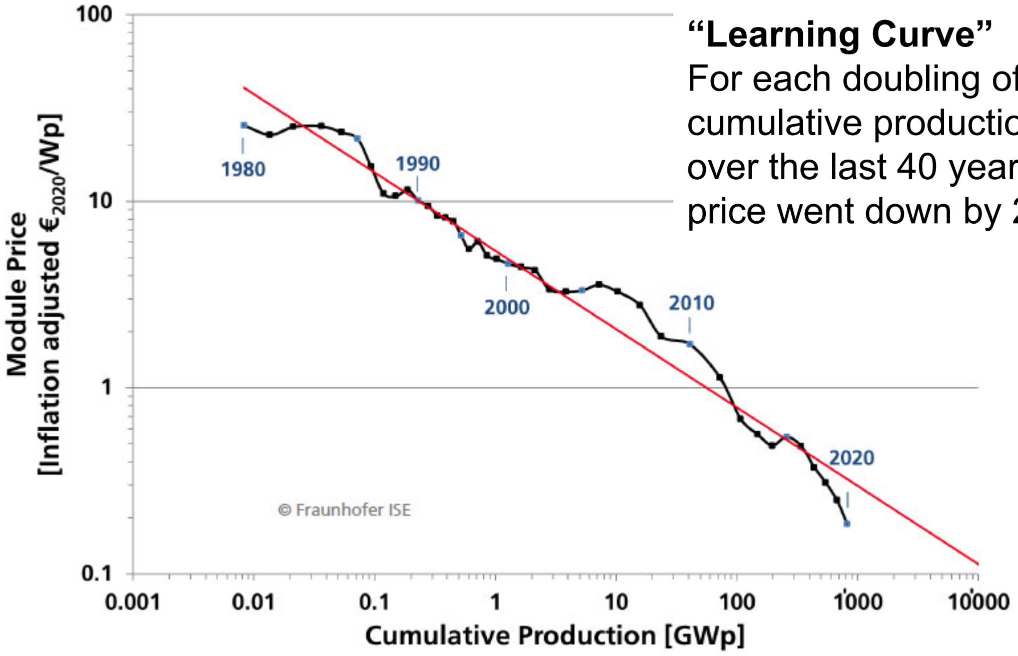
Learning Curve

- Wafer-based Si PV is constantly decreasing costs and increasing η ($/$W_p$ decreasing)



“Learning Curve”
For each doubling of cumulative production over the last 40 years, the price went down by 25%

Source: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf

Summary

- Simple and robust fabrication process for screen-printed PV
- High energy intensity of crystalline silicon… but still cheap?
- mc-Si and c-Si solar cells remain dominant technology
- Si is constantly decreasing costs and increasing η
- Today's Si PV technology expected to dominate for at least another decade!
- Hence, wafer-based Si presents all other PV technologies (e.g. thin-film and concentrating PV) with a "moving goal post"

Quick Test

- Why is silicon a good choice as a semiconductor for PV?
- What is the difference between: i) silicon; ii) silica; iii) silicone?
- Why can't MG-Si be used to make a working solar cell?
- What are the advantages of mc-Si compared to CZ-Si?
- What trade-offs are there when choosing the dopant profile of the emitter?
- How is the diffusion of P into Si typically realised?
- Why can mc-Si not be effectively etched using the standard alkaline (KOH/NaOH-based) etches for c-Si?
- What technique can we tell whether we have a "dead layer" at the top surface of our solar cell?

Questions

?