EE 446/646
Photovoltaic Devices IV

Y. Baghzouz

Fabrication of Si cells

- Silicon is one most abundant elements on earth (≈ 20% of the earth's crust. Pure silicon forms a layer of SiO_2 on its surface when exposed to air.
- Steps involved in refining silicon:
  - The oxygen is removed through a reaction with carbon in an electrode arc furnace:

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

  - It is then transformed to a liquid,

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

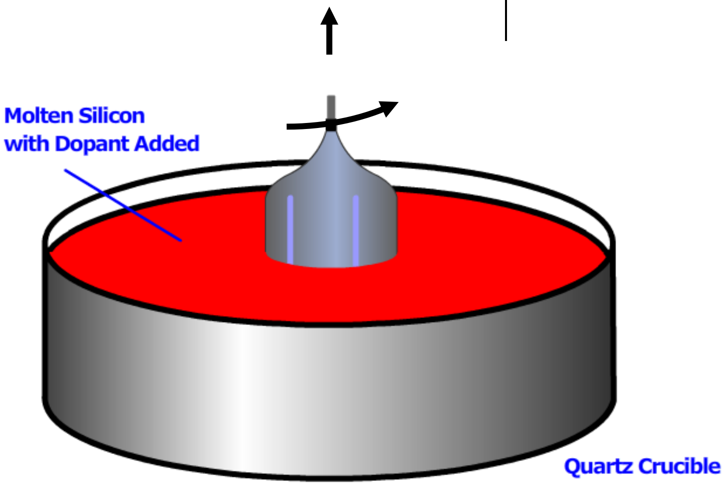
  - The final step forms extremely pure silicon:

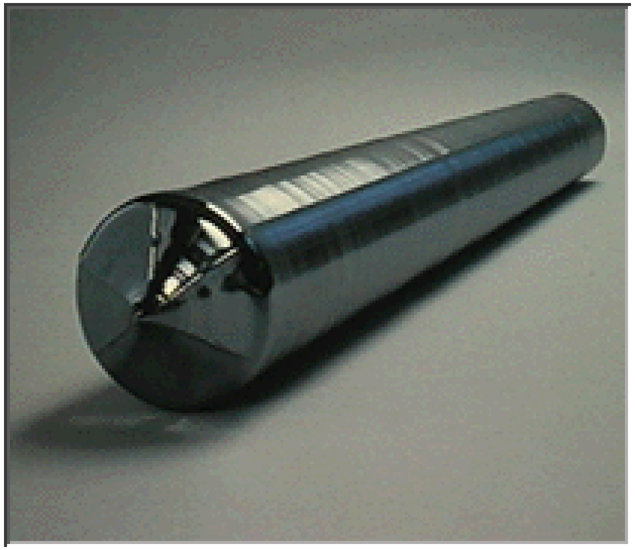
$$SiHCl_3 + H_2 + heat \rightarrow Si + 3HCl$$

- The result is 99.9999% pure silicon. When heated to over 1400^{o}C, it is melted in a quartz crucible to form a molten vat of silicon.

Single crystalline silicon

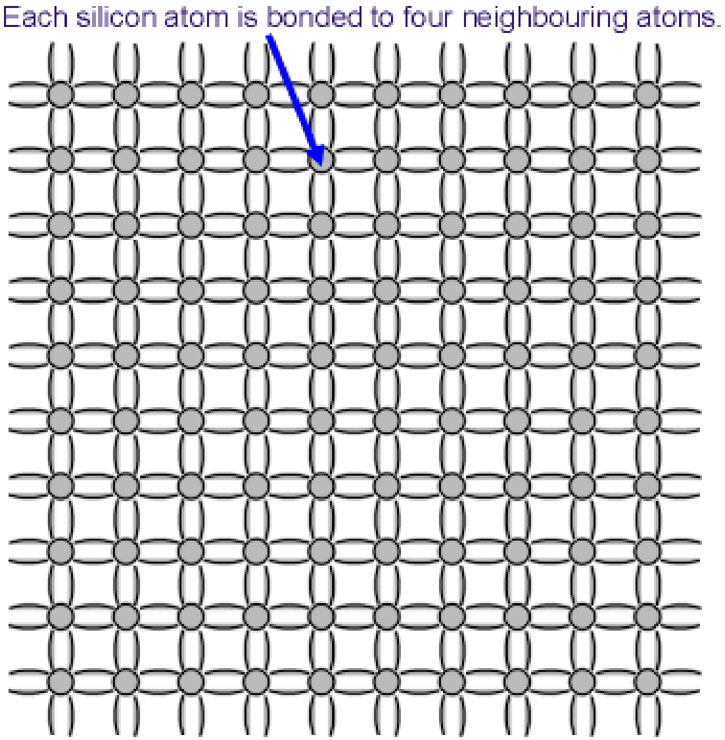
- The most commonly used technique to form a single-crystal Si from the crucible of molten silicon is the Czochralski method:
  - A seed is placed in a pool of Si just above its melting point.
  - By carefully controlling the pull and temperature, it is possible to grow large ingots of single crystal.
  - Rotating the ingot produces a round shape.
  - The ingot may be as large as 30 cm in diameter and as long as 2 m in length.
  - By adding proper amounts of a dopant to the melt, the resulting ingot can be fabricated as an n-or p-type material.

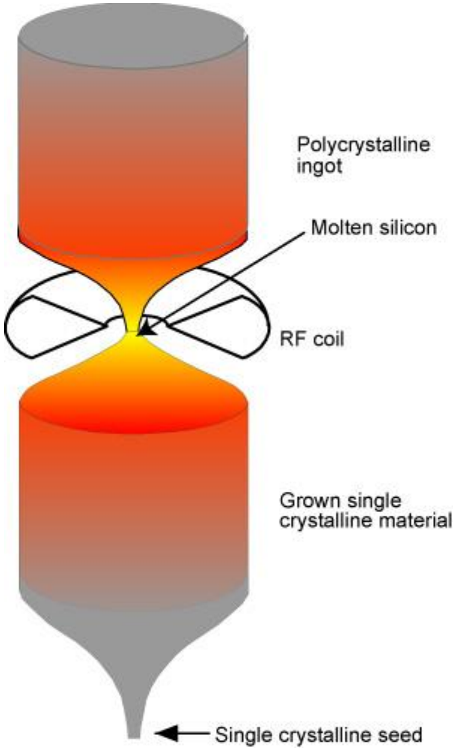




Single crystalline silicon

- An alternative to the Czochralski method is the float-zone process, where an ingot of silicon is locally melted and then solidified by an RF coil that passes slowly along the ingot.
- Crystalline silicon has an ordered crystal structure, with each atom ideally lying in a pre-determined position, thus exhibiting a predictable and uniform behavior

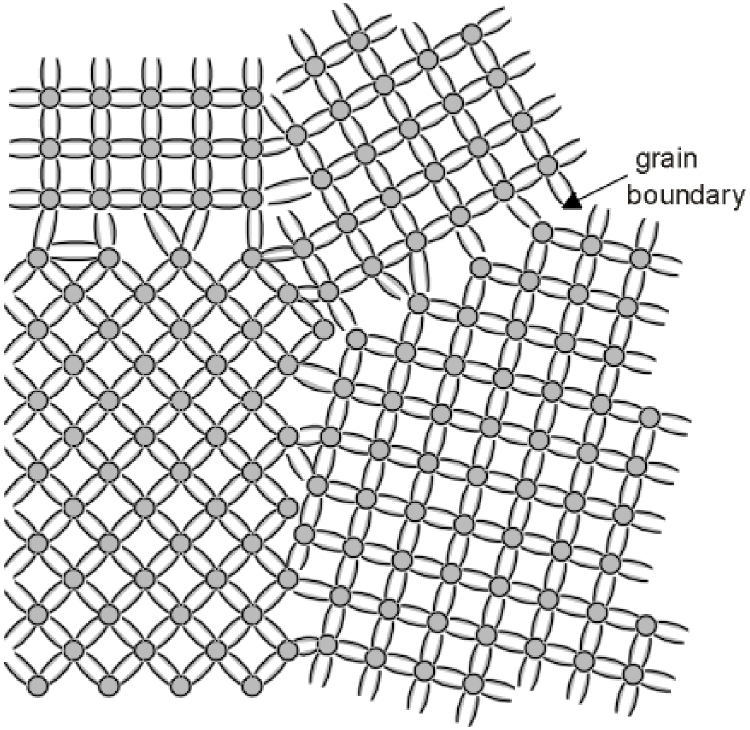




Multi-crystalline Silicon

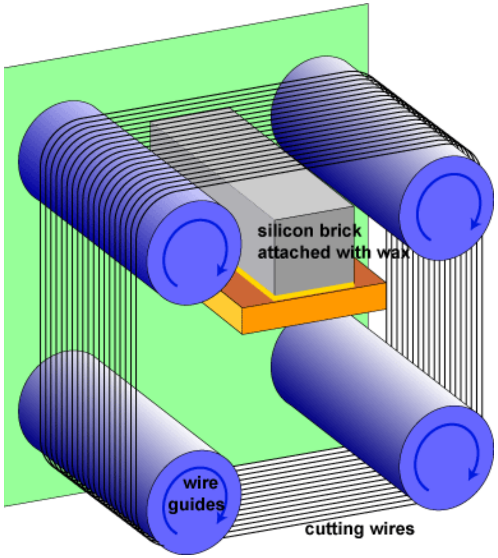
- Techniques for the production of multi-crystalline silicon are simpler and cheaper than those required for single crystal material. However, the quality is lower due to the presence of grain boundaries.
- Grain boundaries introduce localized regions of recombination and reduce current flow.

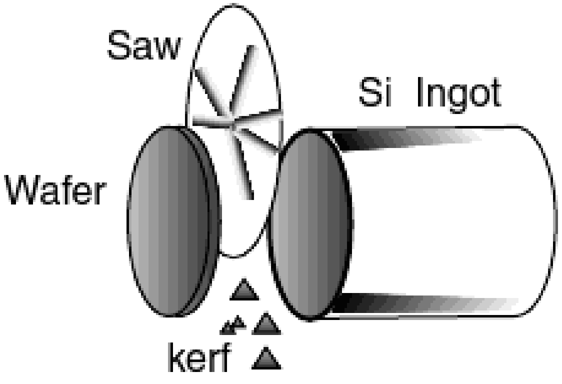
Slab of multi-crystalline silicon after growth.



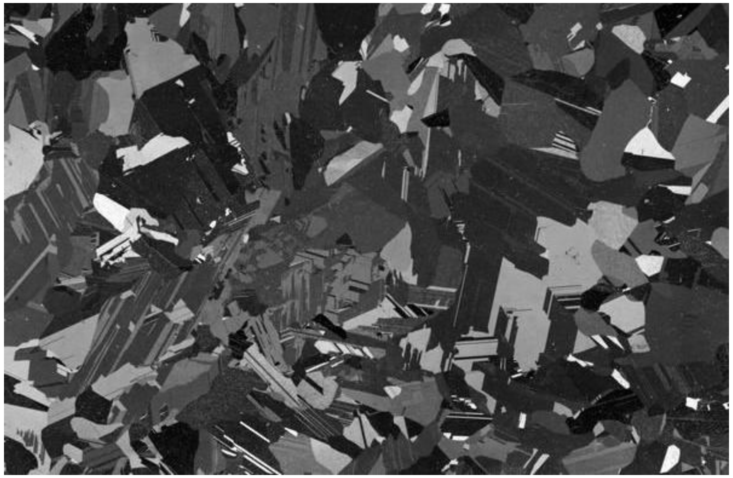
Making Wafers

- Bricks or ingots are sliced into wafers. In a multi-crystalline wafer, grains of different orientations show up as light and dark.
- The wafers are then etched to remove some of the surface damage and to expose the microscopic crystalline structure at the top of the cell.
- The wafers are then placed in tubes of silica glass for the diffusion process.



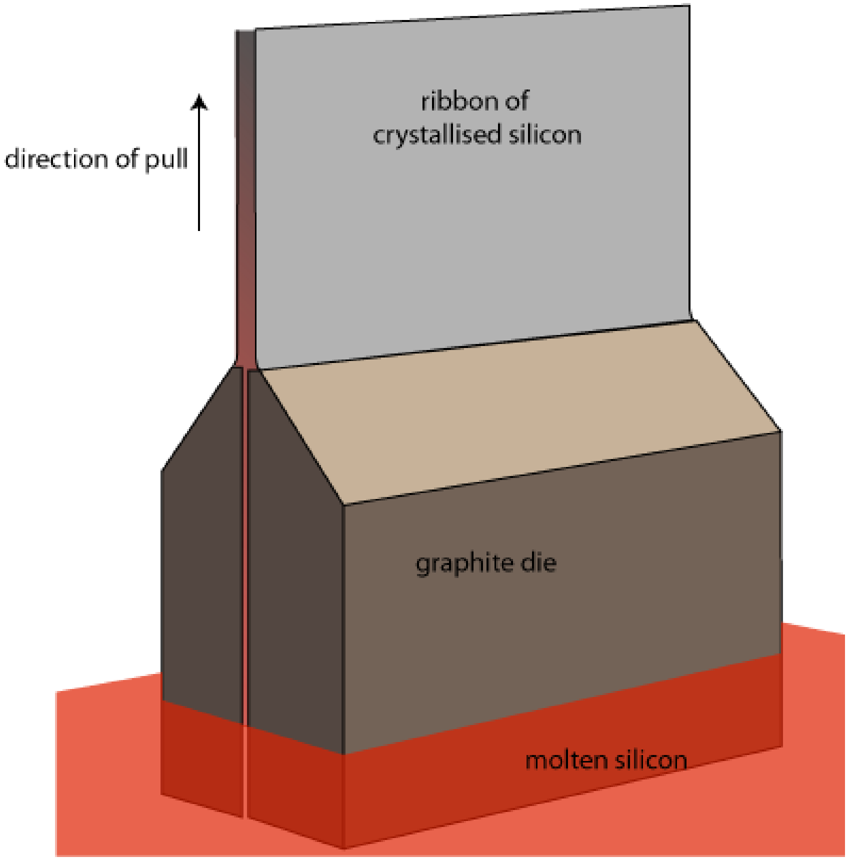


Slicing into wafers



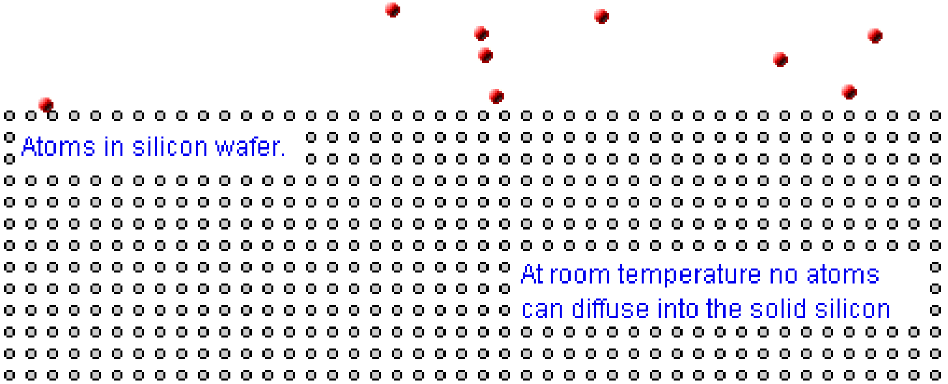
Direct wafering (ribbon) technologies

- There are a number of techniques that try to grow wafers from the outset, thus avoiding the cutting process.
- One of these is the edge defined film fed growth technique that uses a die to define the thickness of a sheet of silicon.
- Careful adjustment of the temperature profile of the graphite die causes the sheets of silicon to crystallize with large grains.



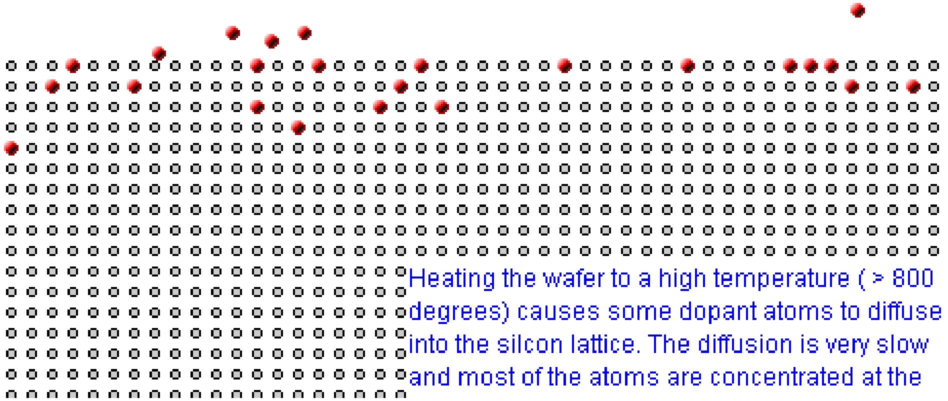
Solid State Diffusion

- Solid state diffusion is a process of introducing dopant atoms into semiconductors.
- Silicon solar cells are uniformly doped with
  - ❖ boron giving a p-type base, and
  - ❖ Phosphorous giving the n-type emitter.

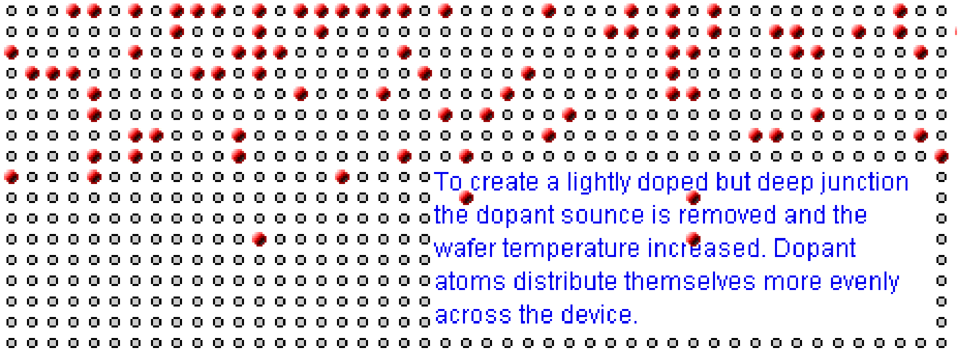


Atoms in silicon wafer.

At room temperature no atoms can diffuse into the solid silicon



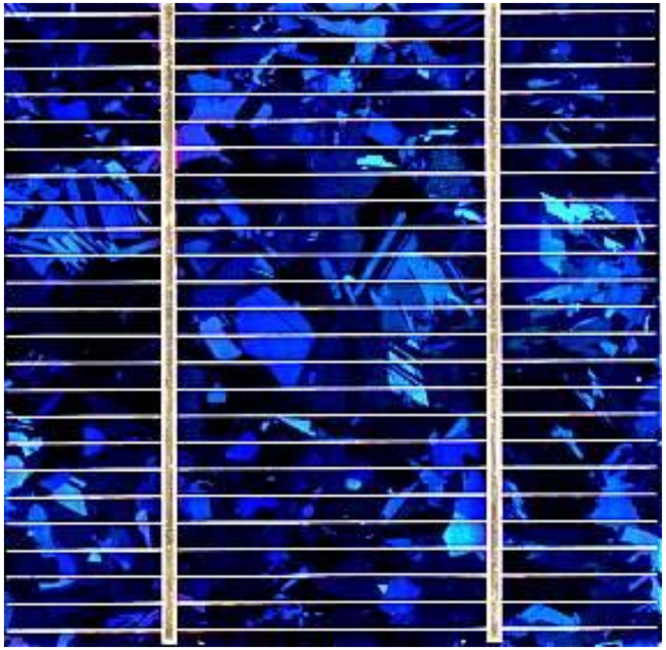
Heating the wafer to a high temperature (> 800 degrees) causes some dopant atoms to diffuse into the silcon lattice. The diffusion is very slow and most of the atoms are concentrated at the



To create a lightly doped but deep junction the dopant source is removed and the wafer temperature increased. Dopant atoms distribute themselves more evenly across the device.

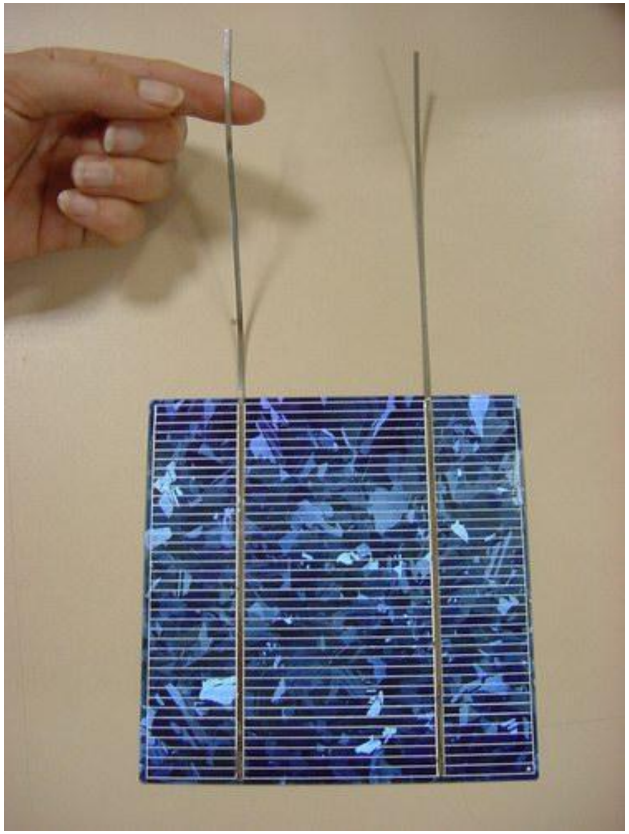
Front surface treatment

- Since silicon is naturally quite reflective to solar wavelengths, some sort of surface treatment is required to reduce those losses. An antireflection (AR) coating of some transparent material such as tin oxide is applied.
- See next slides.



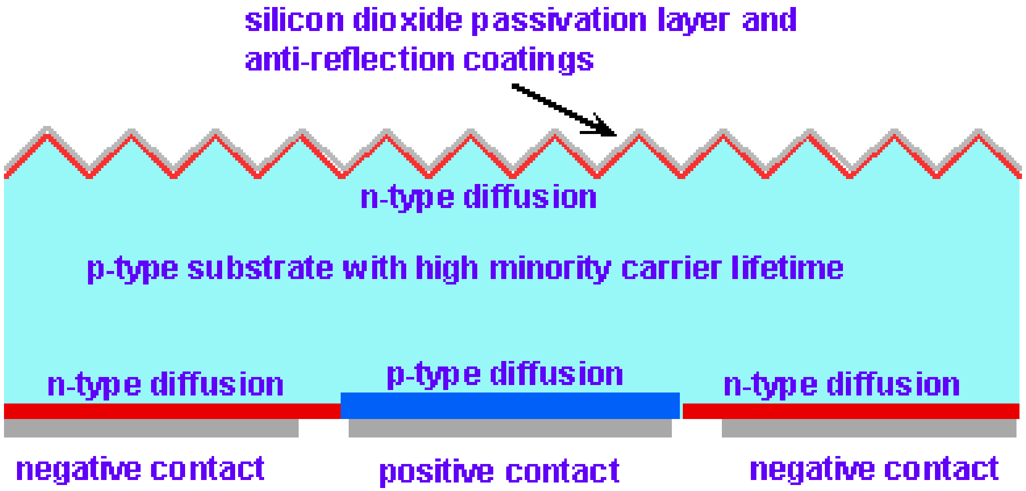
Electrical contacts

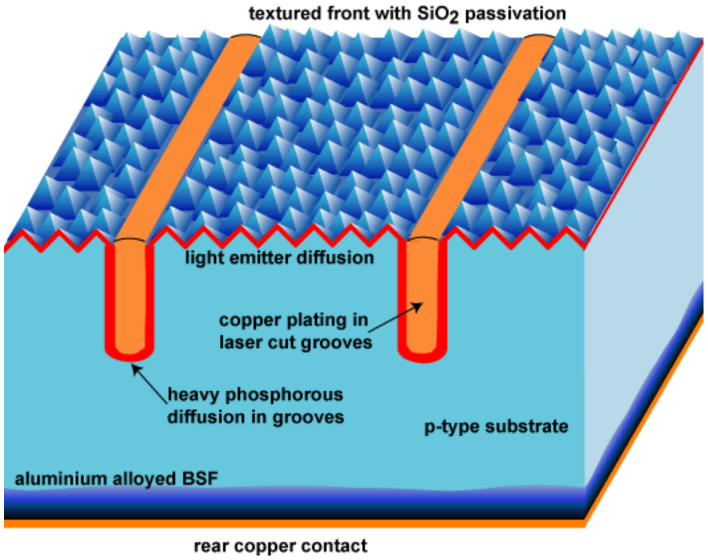
- The bottom contacts are formed by vacuum deposition of a layer of aluminum that covered the back side of the cell. Aluminum also contributes to the concentration of holes in the bottom (p+ layer).
- The front-surface contacts in most cells have been formed by depositing a grid of metal conductors that covers on the order of 5 – 10% of the total area.



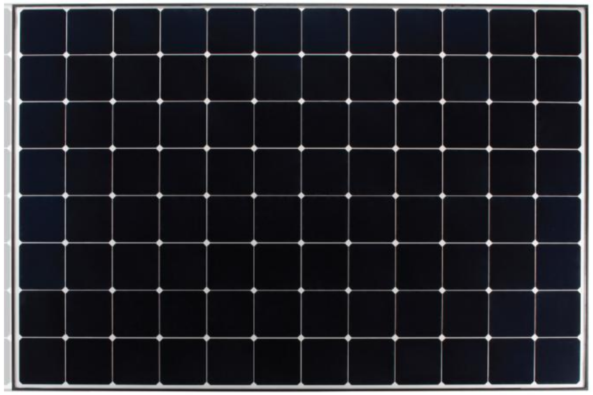
Electrical contacts

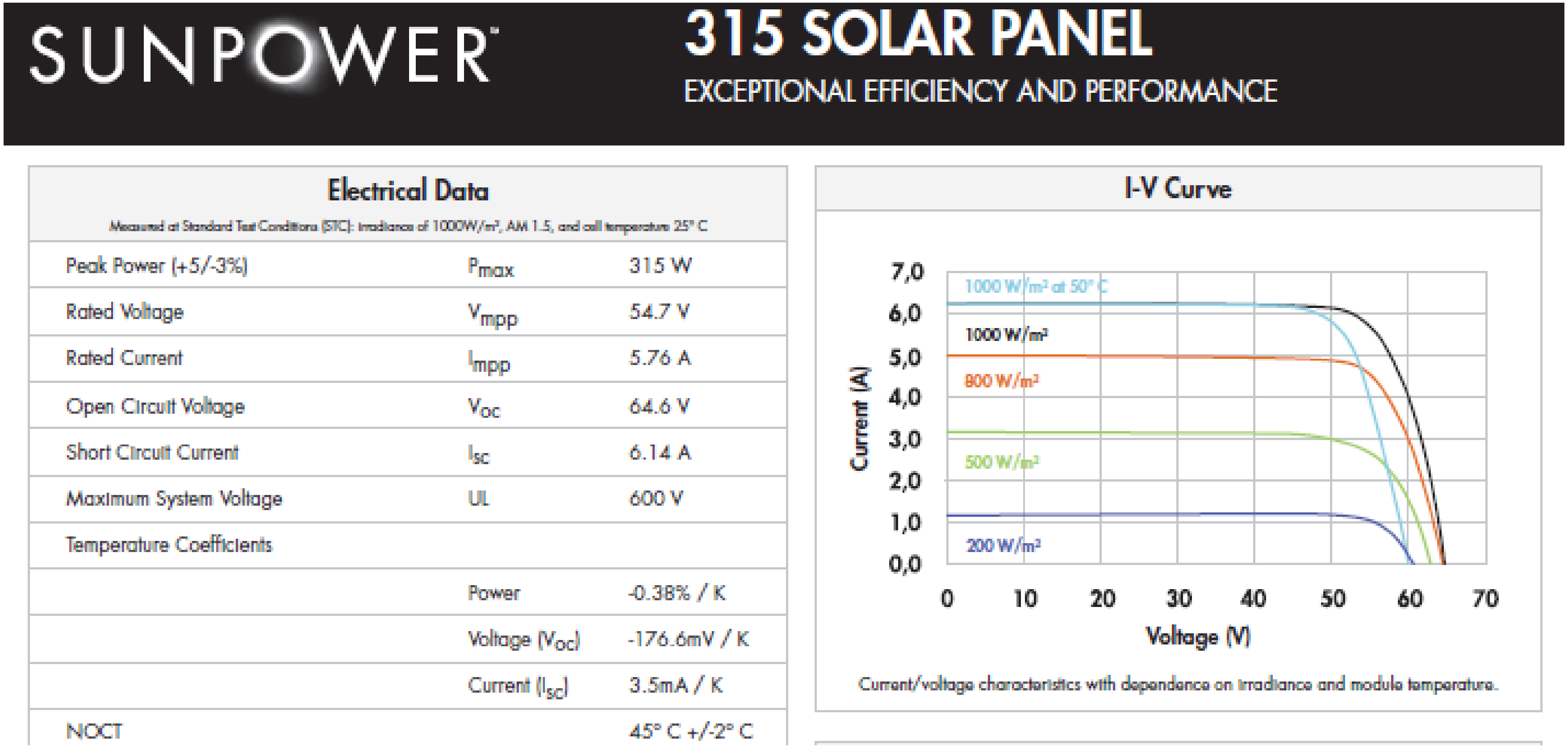
- Some newer cells, called back-point contact cells, put both contacts on the bottom to avoid the shading effect.
- Another approach involves use of lasers to dig deep, narrow grooves into the cell.





SunPower back-contact solar cells





SUNPOWER

315 SOLAR PANEL

EXCEPTIONAL EFFICIENCY AND PERFORMANCE

Electrical Data

Measured at Standard Test Conditions (STC): irradiance of 1000W/m², AM 1.5, and cell temperature 25° C

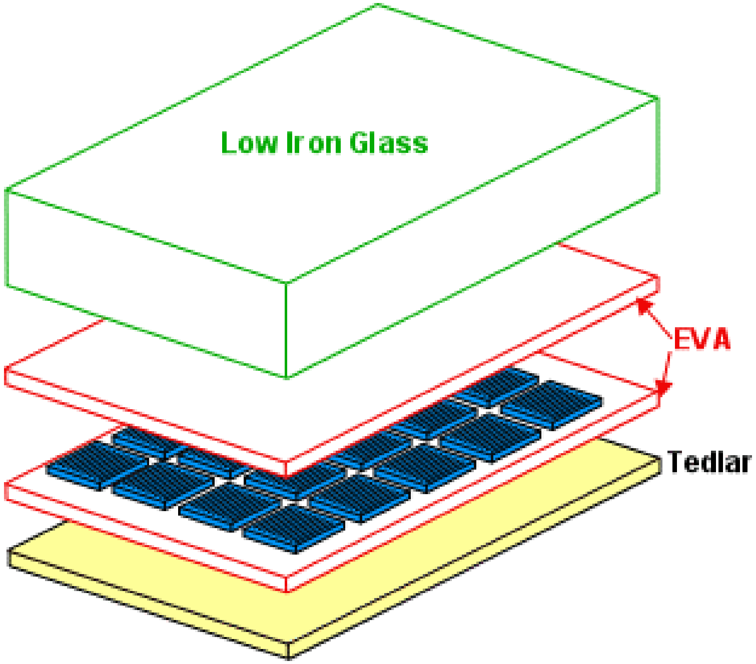
Peak Power (+5/-3%)	P_{max}	315 W
Rated Voltage	V_{mpp}	54.7 V
Rated Current	I_{mpp}	5.76 A
Open Circuit Voltage	V_{oc}	64.6 V
Short Circuit Current	I_{sc}	6.14 A
Maximum System Voltage	UL	600 V
Temperature Coefficients		
	Power	-0.38% / K
	Voltage (V_{oc})	-176.6mV / K
	Current (I_{sc})	3.5mA / K
NOCT		45° C +/-2° C

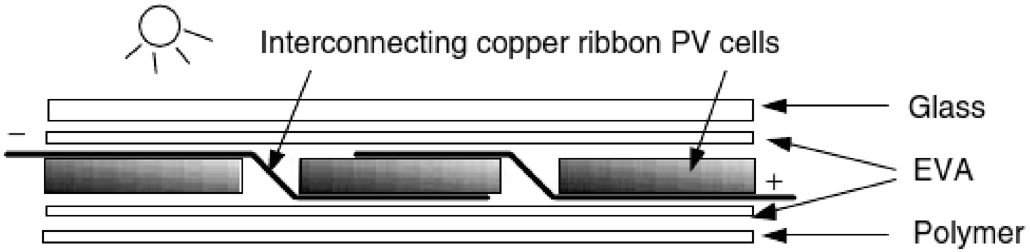
I-V Curve

Current/voltage characteristics with dependence on irradiance and module temperature.

Module Materials

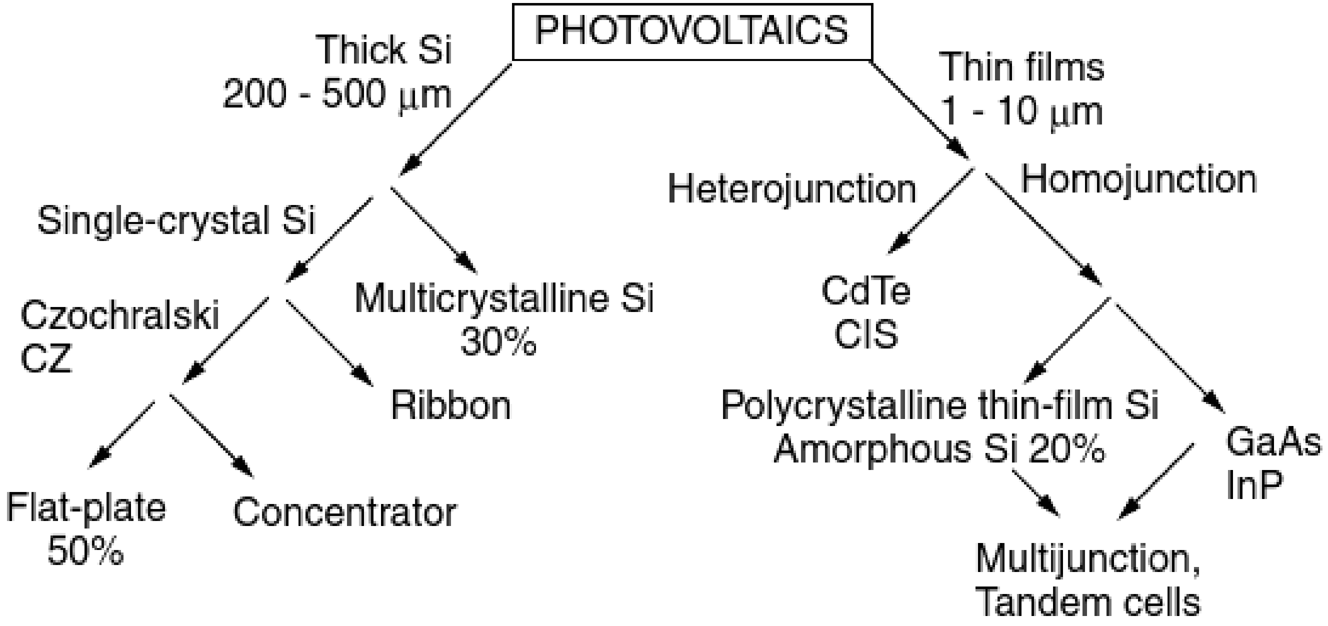
- The cells are connected in series (front of one cell connected to the back of the next), then sandwiched in materials that offer structural support as well as weather protection.
- The upper surface is tempered glass, and the cells are encapsulated in two layers of ethylene vinyl acetate (EVA). Finally, the back is covered with sheets of polymer (Tedlar) that prevent moisture penetration.





Classification of solar cells

- There are a number of ways to categorize photovoltaics: One way is by their thickness;
  - *Thick silicon cells* — on the order of 200 to 500 µm. These cells currently dominate the market.
  - *Thin film cells* – on the order of 1 to 10 µm. These require much less semiconductor material and are easier to manufacture.



Classification of solar cells

- Photovoltaic technologies can be categorized by the extent to which atoms bond with each other in individual crystals:
  - *Single crystalline*, the cell is made up of a single crystal. Common growth technique: Czochralski Float zone.
  - *Multi-crystallin*e, in which the cell is made up of a number of relatively large areas of single crystal grains, each on the order of 1 mm to 10 cm in size, e.g., mc-Si. Common growth technique: Cast, sheet, ribbon
  - *Poly-crystalline*, with many grains having dimensions on the order of 1 µm to 1 mm, e.g., cadmium telluride cells, copper indium, and thin-film silicon. Common growth technique: Chemical-vapor deposition
  - *Amorphous*, in which there are no single-crystal regions, as in amorphous silicon (a-Si).

Classification of solar cells

- Another way to categorize photovoltaic materials is based on whether the p and n regions of the semiconductor are made of the same material or different materials.
  - Those with the same material are called **homo-junction** *p*hotovoltaics (e.g., silicon cells).
  - When the p –n junction is formed between two different semiconductors, they are called **hetero-junction** PVs (e.g., cadmium sulfide (CdS) for the n-type layer and copper indium diselenide (CIS) for the p-type layer).
- Other distinctions include **multi-junction** solar cells (also known as cascade or tandem cells) made up of a stack of p –n junctions with each junction designed to capture a different portion of the solar spectrum.
- Finally, some cells are specifically designed to work best with **concentrating** sunlight while others are used in **non-concentrating** flat-plate systems.

Thin film photovoltaics

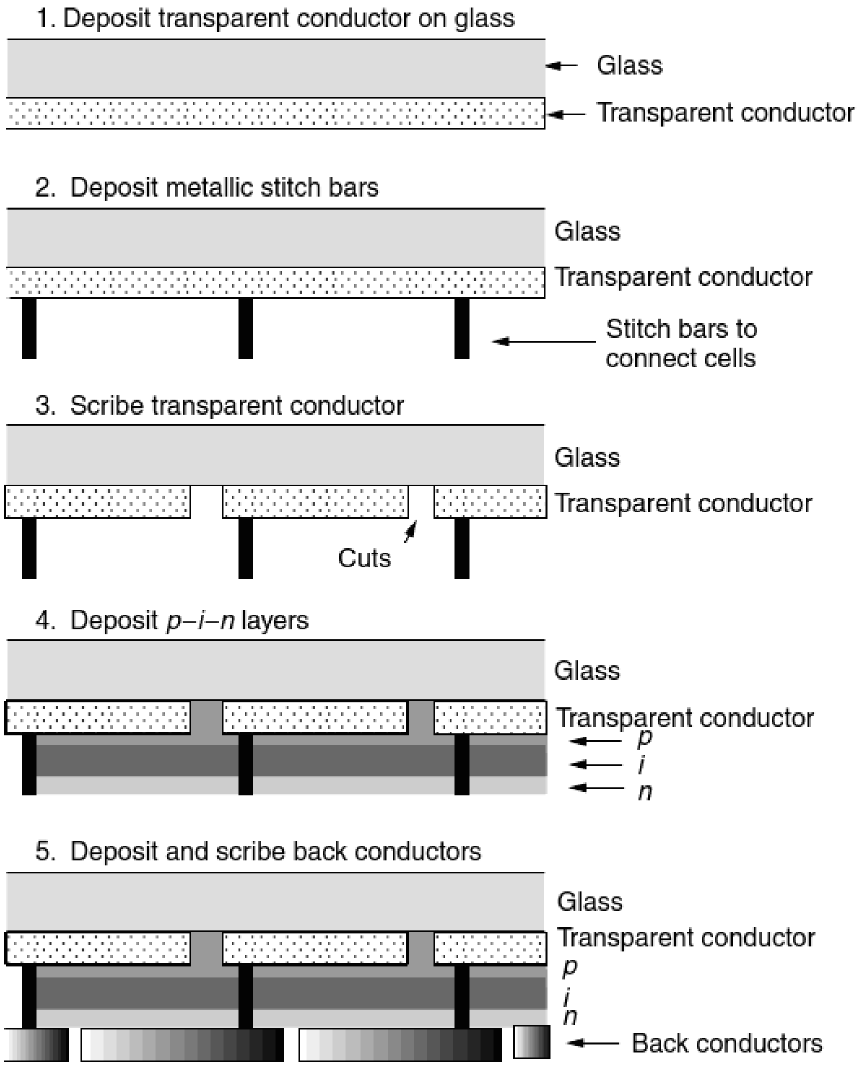
- Conventional crystalline silicon technologies require a lot of effort, and numerous complex processing steps.
- Competing technologies, are based on depositing extremely thin films (microns) of photovoltaic materials onto glass or metal substrates, they do not require the complexity of cell interconnections, and they are particularly well suited to mass-production techniques.
- Their thinness allows photons that aren’t absorbed to pass completely through the photovoltaic material thus offering two opportunities:
  - They can be deposited onto windows, making building glass a provider of both light and electricity.
  - They lend themselves to multiple-junction, tandem cells in which photons of different wavelengths are absorbed in different layers of the device.

Amorphous Silicon

- Almost all of today’s thin-film technology is based on amorphous silicon (a-Si)—that is, silicon in which there is very little order to the arrangement of atoms. Since it is not crystalline, the organized tetrahedral structure does not apply.
- While almost all of the atoms do form bonds with four other silicon atoms, there remain numerous “dangling bonds” where nothing attaches to one of the valence electrons.
  - These dangling-bond defects act as recombination centers so that photo-generated electrons recombine with holes before they can travel very far.
- The key to making a-Si into a decent photovoltaic material is by alloying amorphous silicon with hydrogen (a-Si:H) between the p-layer and the n-layer. Concentration: 1 in 10. This reduces the concentration of defects by about three orders of magnitude.

Amorphous Silicon (a-Si or a-Si:H)

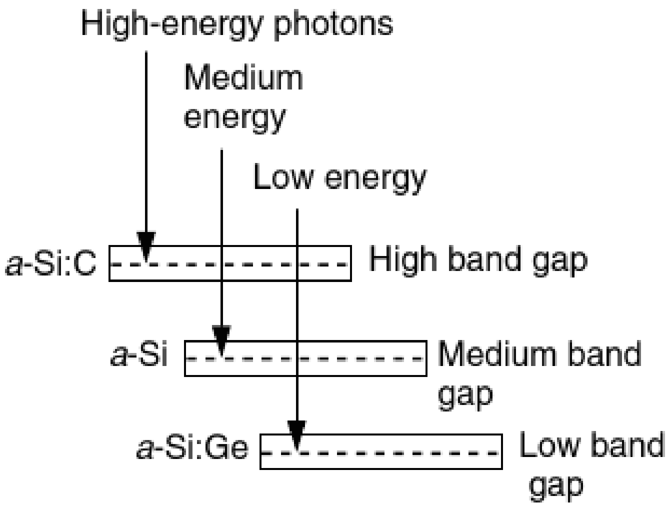
An important advantage of thin-film photovoltaics over conventional crystalline silicon is the ease with which they can be manufactured.

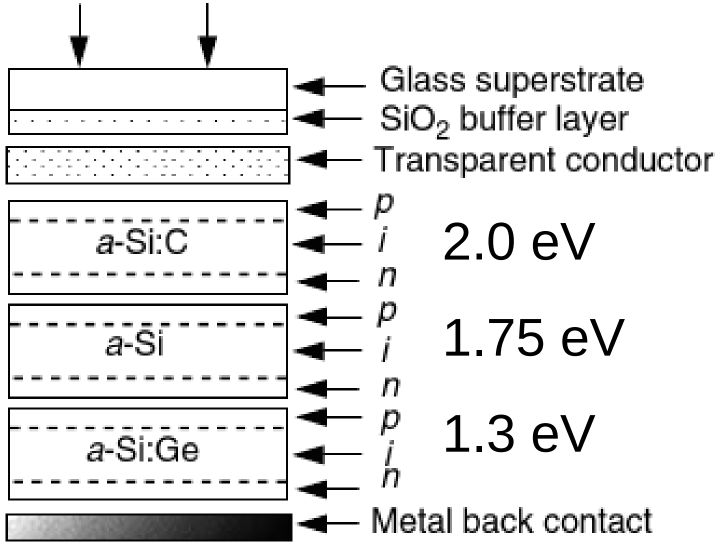


Band gap: 1.75 eV

Multi-junction or Tandem a-Si

- The idea behind a multi-junction cell is to create junctions with decreasing band gaps as photons penetrate deeper and deeper into the cell.
- the top junction should capture the most energetic photons while allowing photons with less energy to pass through to the next junction below, and so forth.
- The theoretical maximum efficiency of an ideal multijunction a-Si:H cell is 42%, and some estimate a practically achievable efficiency of about 24%.



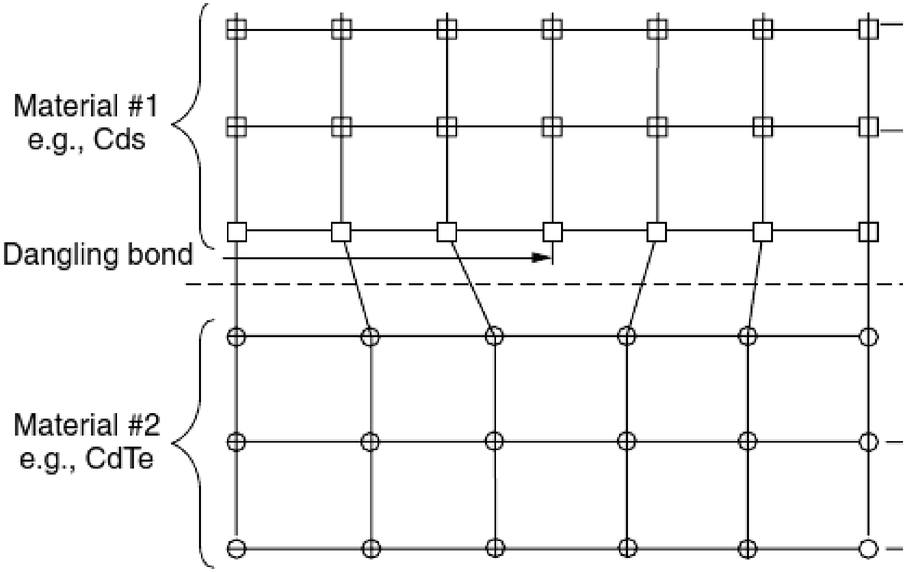


Gallium Arsenide (GaAs) cells

- The emerging competition from thin films made of compounds of two or more element is gallium arsenide (GaAs)
- The GaAs band gap of 1.43 eV is very near the optimum value of 1.4 eV. Therefore, GaAs cells are among the most efficient single-junction solar cells around. The maximum efficiency of single-junction GaAs solar cells is 29% (w/o solar concentration) and 43% (with solar concentration).
- The efficiency of GaAs is relatively insensitive to increasing temperature, which helps them perform better under concentrated sunlight. They are also less affected by cosmic radiation, and as thin films they are lightweight, which gives them an advantage in space applications.
- On the other hand, gallium is much less abundant in the earth’s crust and it is a very expensive material. When coupled with the much more difficult processing required to fabricate GaAs cells, they have been too expensive for all but space applications and, potentially, for concentrator systems.

Cadmium Telluride

- Cadmium telluride (CdTe) is an example of a the Group II - Group VI photovoltaic compound. It is often used as the p-layer in heterojunction solar cells.
- One difficulty associated with heterojunctions is the mismatch between the size of the crystalline lattice of the two materials, which leads to dangling bonds.
- One compound that is often used for the n-layer is cadmium sulfide CdS, (lattice mismatch with CdTe of nearly 10%). The band gap for CdTe is 1.44 eV - very close to the optimum for terrestrial cells.

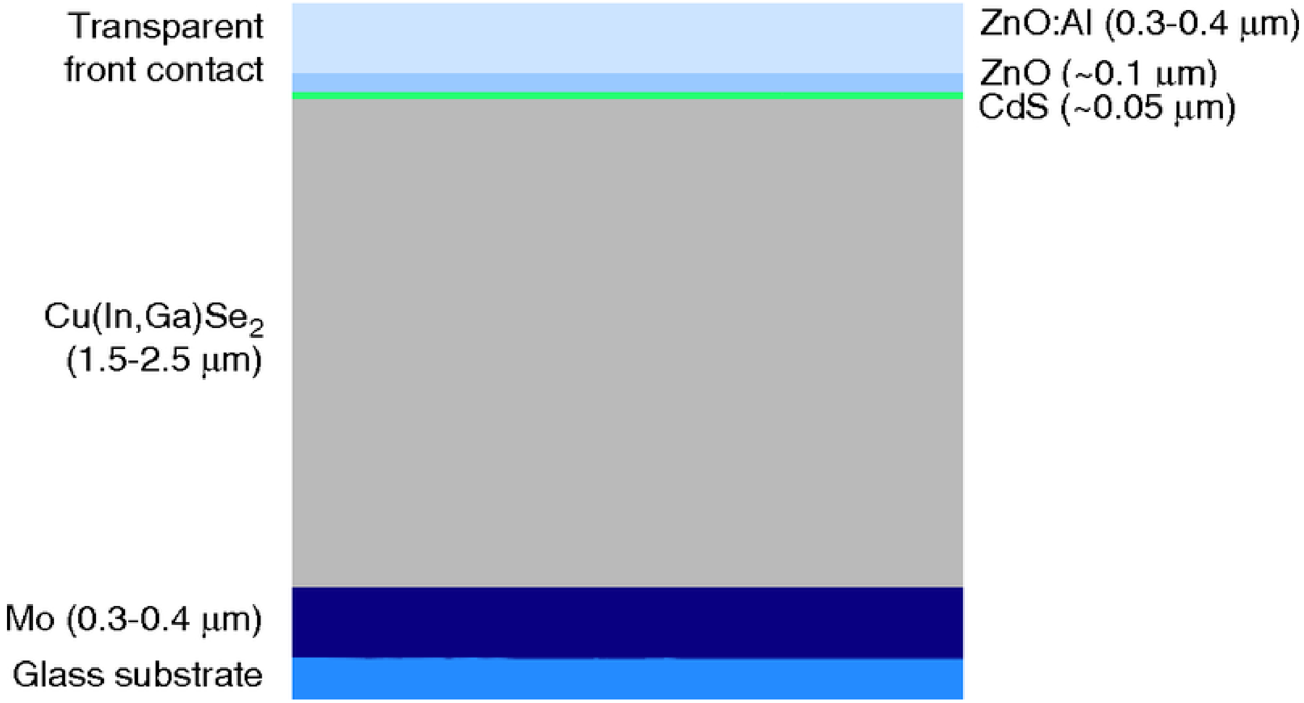


Cadmium Telluride

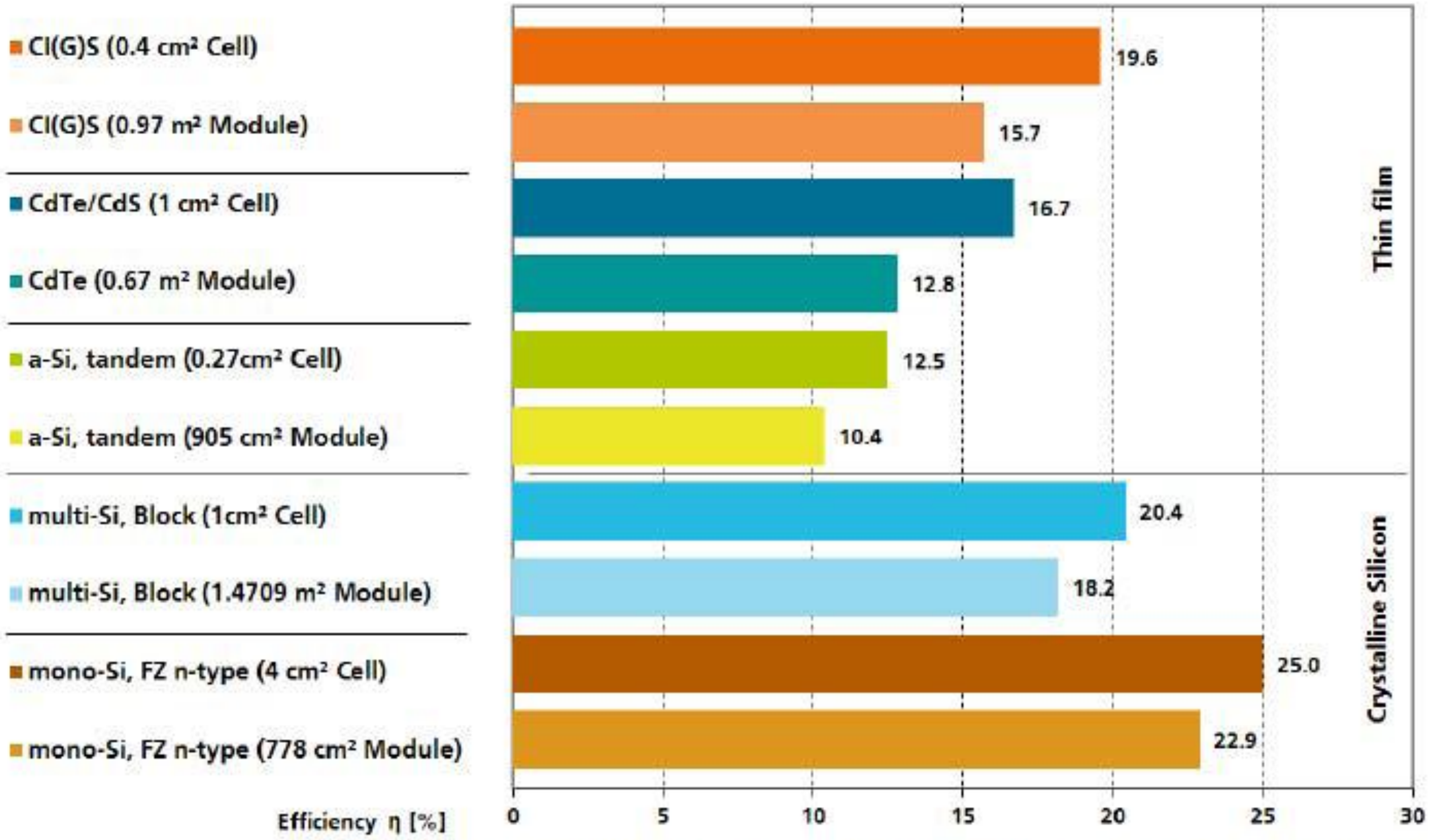
- Thin-film prototype modules using the n-CdS/p-CdTe heterojunction have efficiencies approaching 17%.
- The equipment needed to manufacture these cells is orders of magnitude cheaper than that required for x-Si, and their relatively high efficiency makes them attractive candidates for mass production.
- One aspect of CdS/CdTe cells is the potential hazard to human health and the environment associated with cadmium. Cadmium is a very toxic substance. Waste cadmium produced during the manufacturing process needs to be kept out of the environment.
- CdS/CdTe modules contain about 6 g of cadmium per square meter of surface area, but it is completely sealed inside of the module so it should pose no risk under normal circumstances.

Copper Indium Gallium Selenide (CIGS)

- The heterojunction is formed between the semiconductors CIGS and ZnO:Al, separated by a thin layer of CdS and a layer of intrinsic ZnO.
- The CIGS is doped p-type, while the ZnO is doped n-type.
- Laboratory CIGS cells had achieved efficiencies of almost 20%.

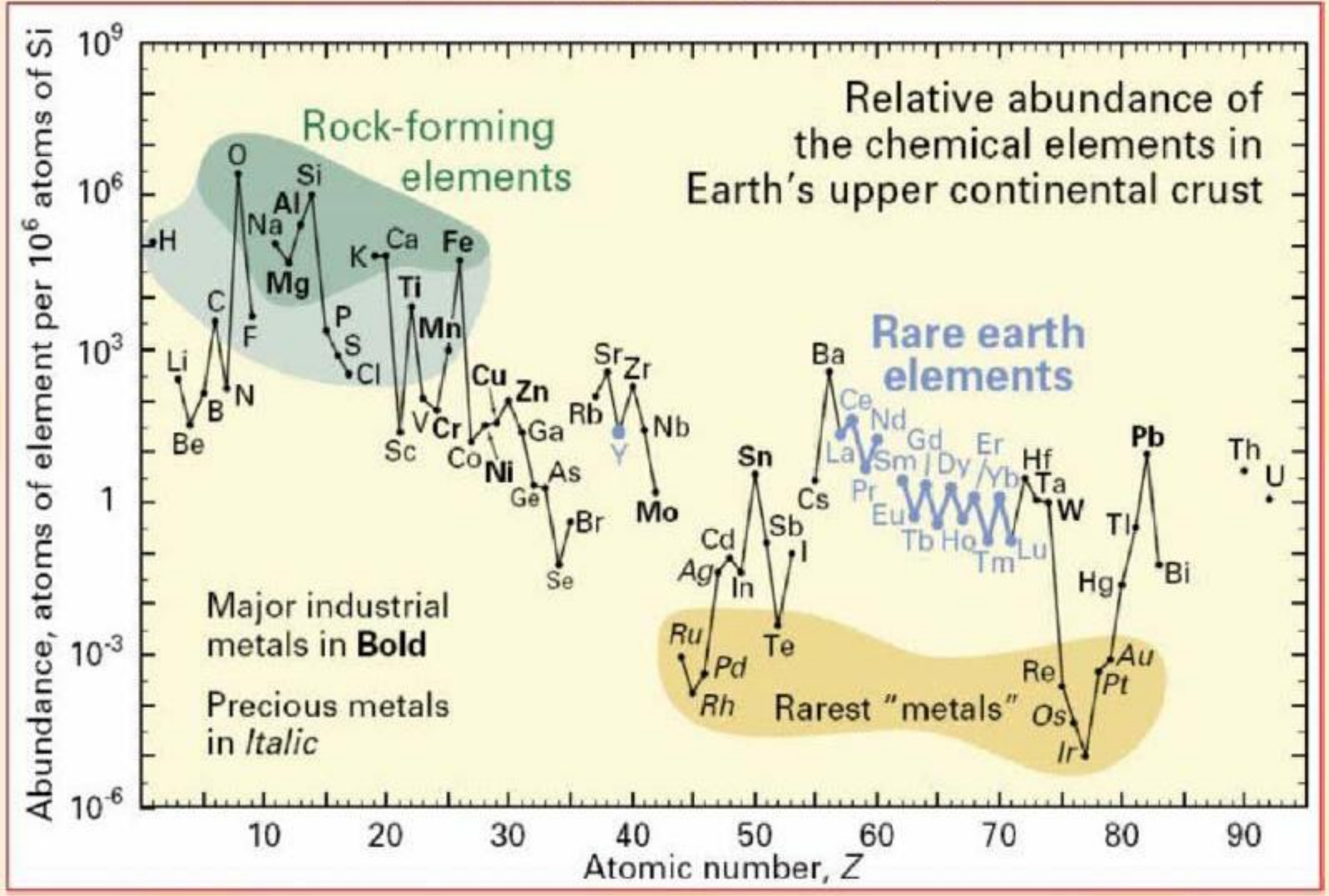


Efficiency Comparison for PV Technologies now in Production: Best Lab Cells and Best Lab Modules



Data: Green et al.: Solar Cell Efficiency Tables,(Version 1-40), Progress in PV: Research and Applications 2012, Graph: PSE AG 2012

Availability of the elements - Tellurium (Te) is as rare as gold (Au).



P.H. Stauffer et al, Rare Earth Elements - Critical Resources for High Technology, USGS (2002)