EE 495/695 Semiconductors II

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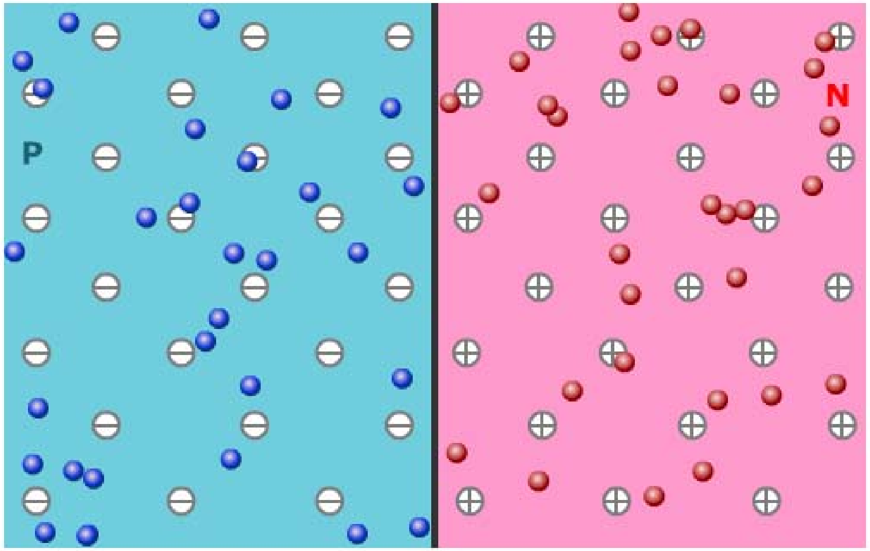
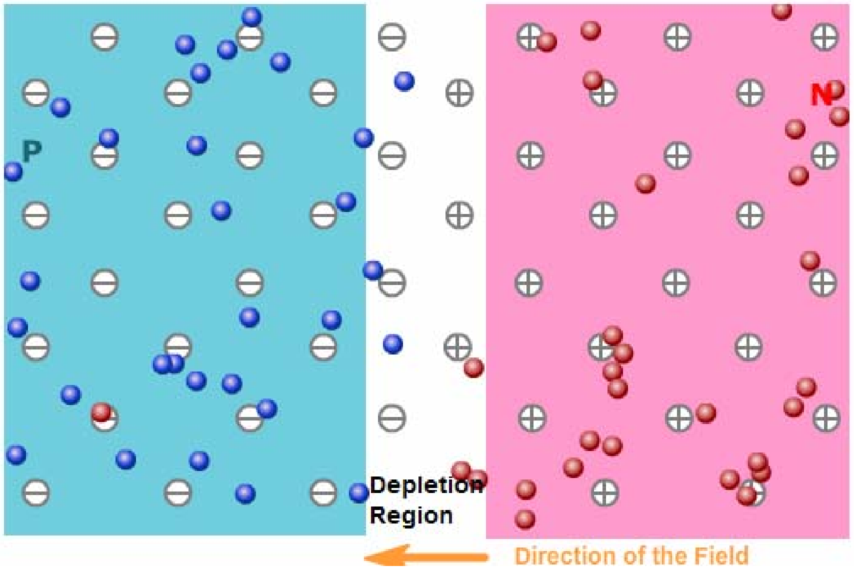
Formation of P-N Junction

- *P-n* junctions are formed by joining *n*-type and *p*-type semiconductor materials, as shown to the right.
  - Since the *n*-type region has a high electron concentration and the *p*-type a high hole concentration.
  - electrons diffuse from the *n*-type side to the *p*-type side. Similarly, holes flow by diffusion from the *p*-type side to the *n*-type side (like when two gasses come into contact with each other).



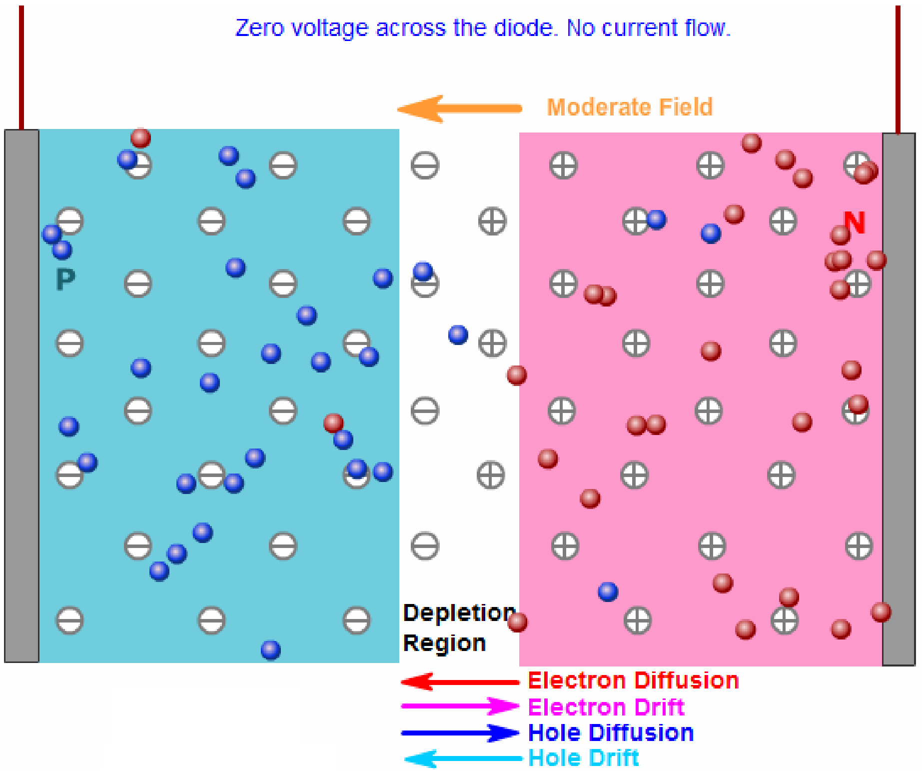
Formation of P-N Junction

- However, in a *p-n* junction, when the electrons and holes move to the other side of the junction, they leave behind exposed charges which are fixed in the crystal lattice: On the *n*-type side, positive ions are exposed, and on the *p*-type side, negative ions are exposed.
- → An electric field E forms between the the *n*-type material and the *p*-type material.
- This region is called the "**depletion region**" since the electric field quickly sweeps free carriers out, hence the region is depleted of free carriers.
- → A "built in" potential V due to E is formed at the junction.



Carrier Movement in Equilibrium

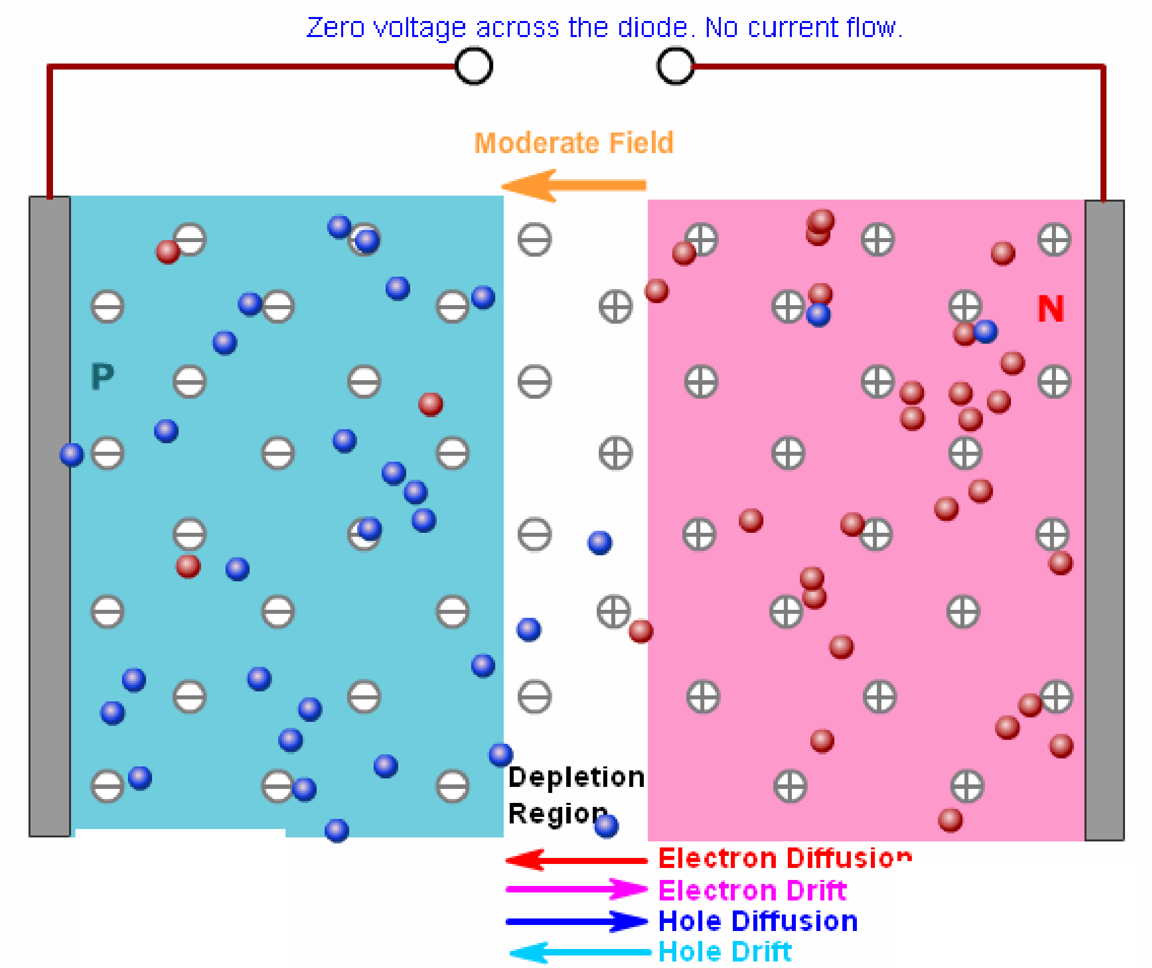
- A p-n junction with no external inputs represents an equilibrium between carrier generation, recombination, diffusion and drift in the presence of the electric field in the depletion region.
- Despite the presence of the electric field, which creates an impediment to the diffusion of carriers across the electric field, some carriers still cross the junction by diffusion.
  - Most majority carriers which enter the depletion region move back towards the region from which they originated.
  - However, statistically some carriers will have a high velocity and travel in a sufficient net direction such that they cross the junction.



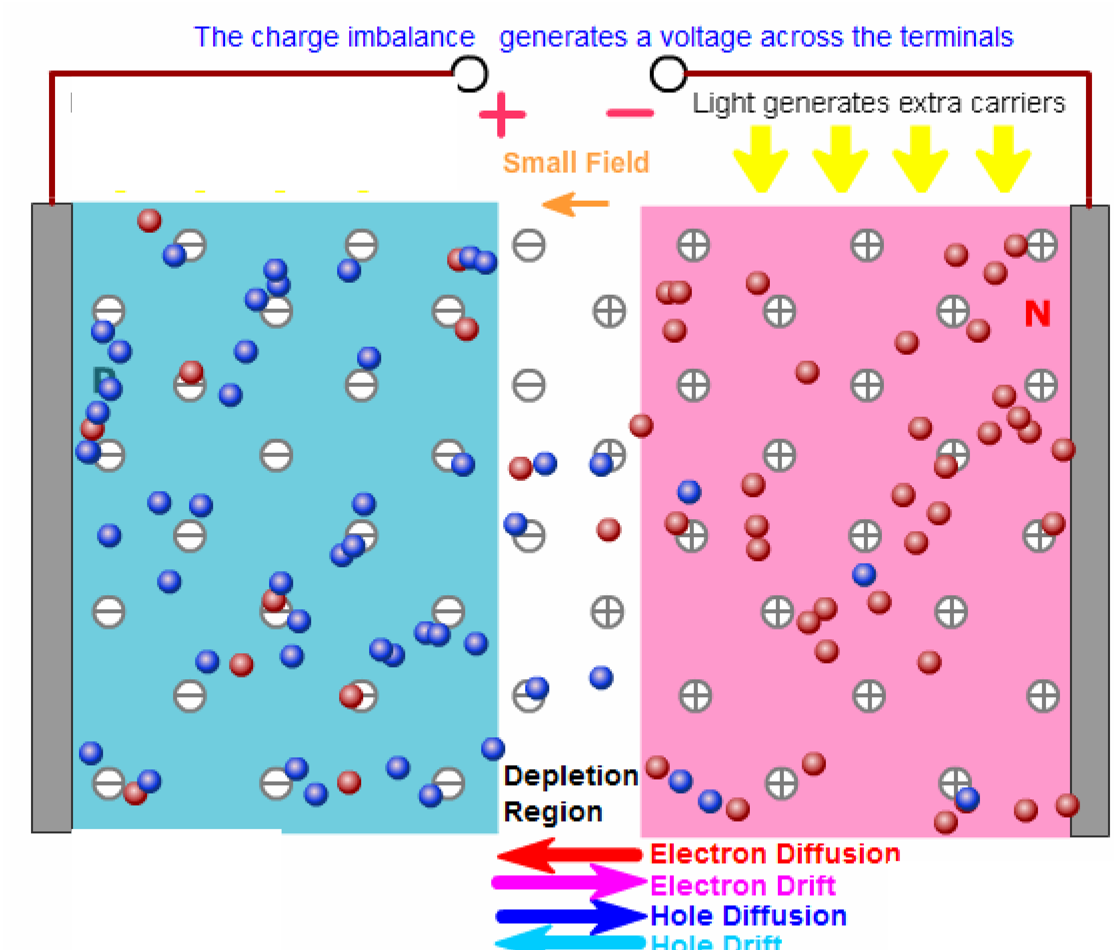
Carrier Movement in Equilibrium

- Once a majority carrier crosses the junction, it becomes a minority carrier. It will continue to diffuse away from the junction before it recombines.
- The current caused by the diffusion of carriers across the junction is called the **diffusion current**.
- Minority carriers which reach the edge of the diffusion region are swept across it by the electric field in the depletion region. This current is called the **drift current**.
- In equilibrium,
  - the net current from the device is zero. The electron drift current and the electron diffusion current exactly balance out.
  - Similarly, the hole drift current and the hole diffusion current also balance each other out

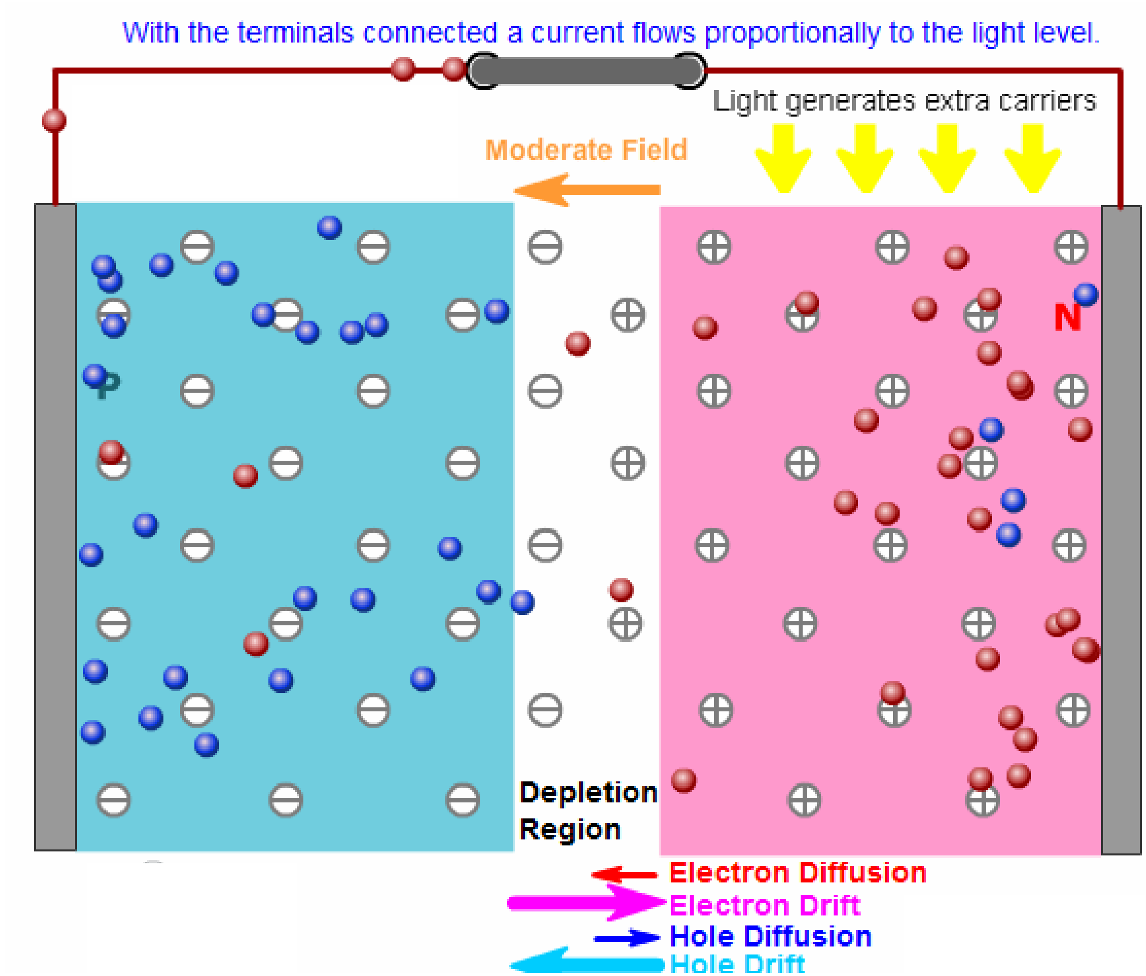
- In equilibrium (i.e. in the dark) both the diffusion and drift current are small.



- Under open circuit conditions, the light-generated carriers forward bias the junction, thus increasing the diffusion current. Since the drift and diffusion current are in opposite direction, there is no net current from the solar cell at open circuit.



- Under short circuit conditions, the minority carrier concentration on either side of the junction is increased and the drift current, which depends on the number of minority carriers, is increased.



Manufacturing of Silicon Cells

Refining Silicon

- Silicon dioxide (SiO_2) is the most abundant mineral in the earth's crust.
- The oxygen is removed through a reaction with carbon in an electrode arc furnace.

$$SiO_2 + C \Rightarrow Si + CO_2$$

- The resulting silicon is metallurgical grade silicon (MG-Si). It is 98% pure and is used extensively in the metallurgical industry.
- MG-Si is further refined for the semiconductor industry.

$$Si + 3HCl \Rightarrow SiHCl_3 + H_2$$ (to remove impurities)

$$SiHCl_3 + H_2 \Rightarrow Si + 3HCl$$ (In vacuum chamber at 1,100^{o} C for 1-2 weeks)

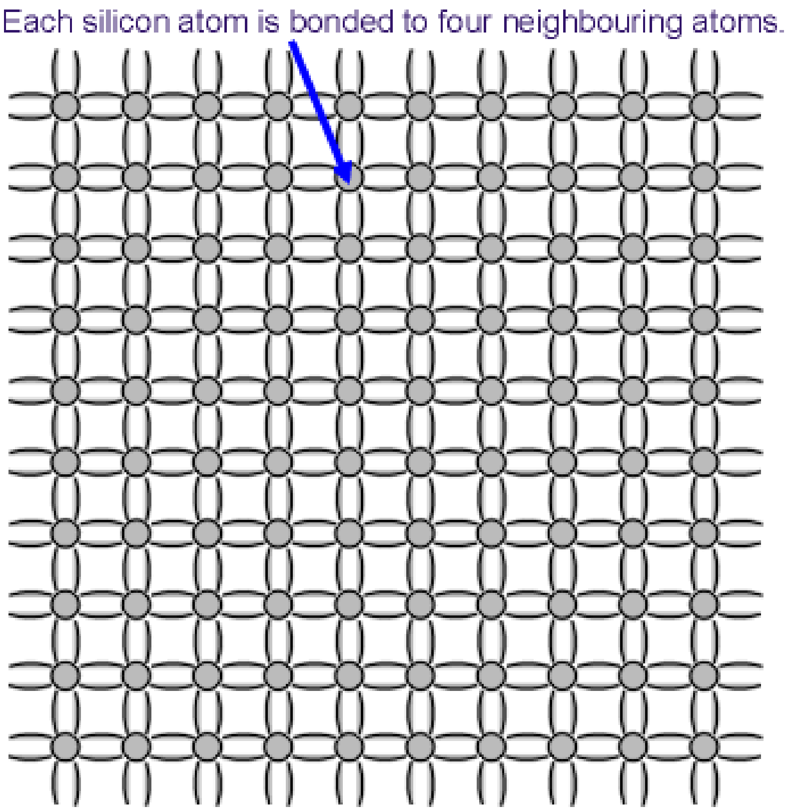
Types of Silicon

- Silicon used for solar cells can be single crystalline, multi-crystalline, polycrystalline (or amorphous).
- The key difference between these materials is degree to which the semiconductor has a regular, perfectly ordered crystal structure.

Descriptor	Symbol	Grain Size	Common Growth Techniques
Single crystal	sc-Si	>10cm	Czochralski (CZ) Float zone (FZ)
Multicrystalline	mc-Si	1mm-10cm	Cast, sheet, ribbon
Polycrystalline	pc-Si of a-Si	1µm-1mm	Chemical-vapour deposition

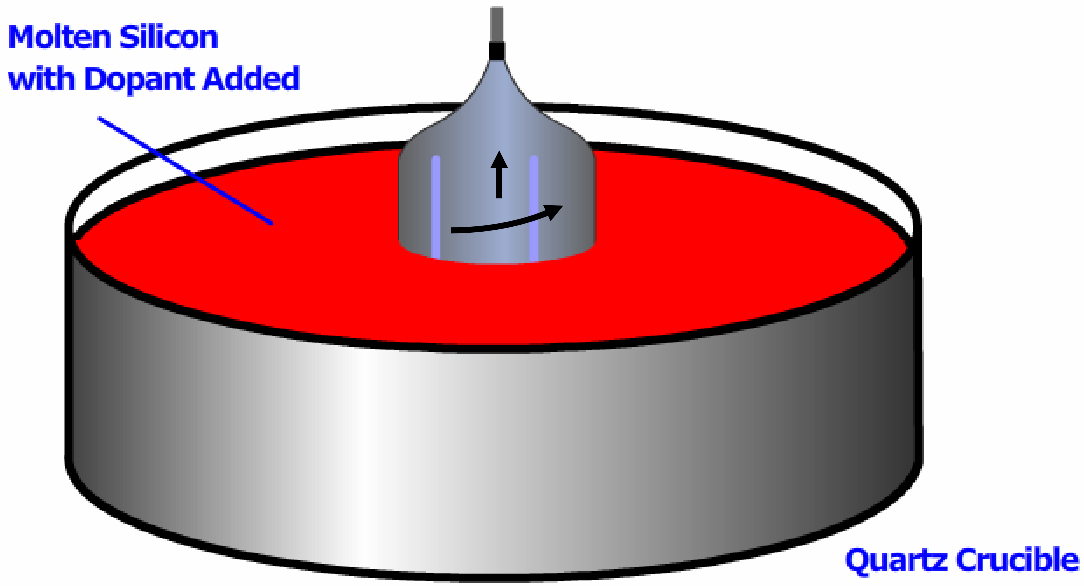
Single Crystalline Si

- Crystalline silicon has an ordered crystal structure, with each atom ideally lying in a pre-determined position.
- Crystalline silicon exhibits predictable and uniform behavior, but because of the careful and slow manufacturing processes required, it is also the most expensive type of silicon.



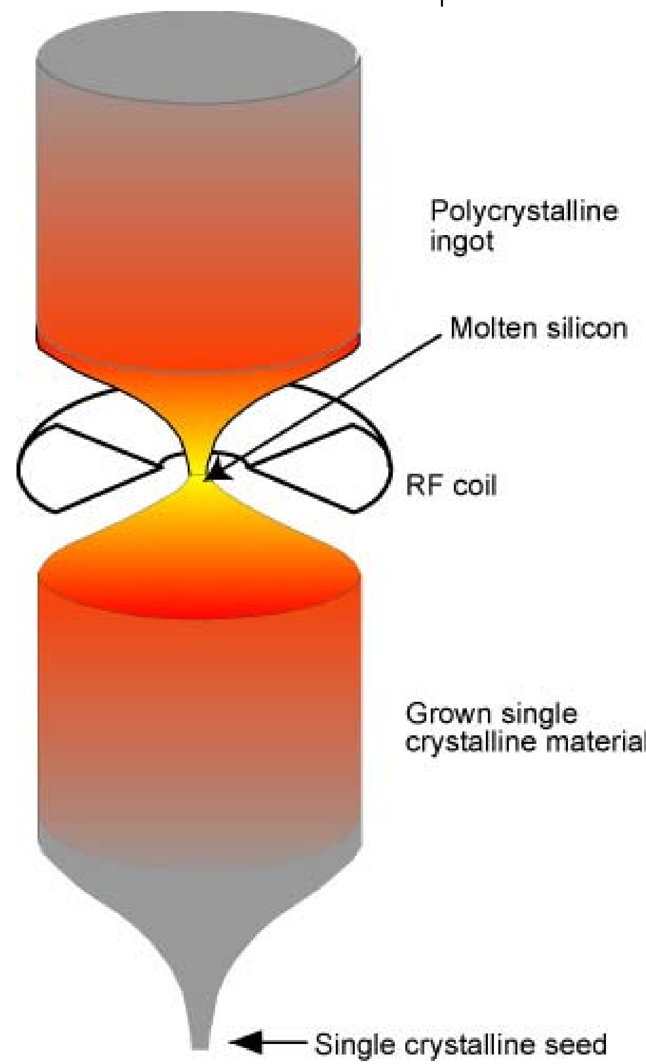
Making a large single crystalline silicon ingot by the Czochralski method

- 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.



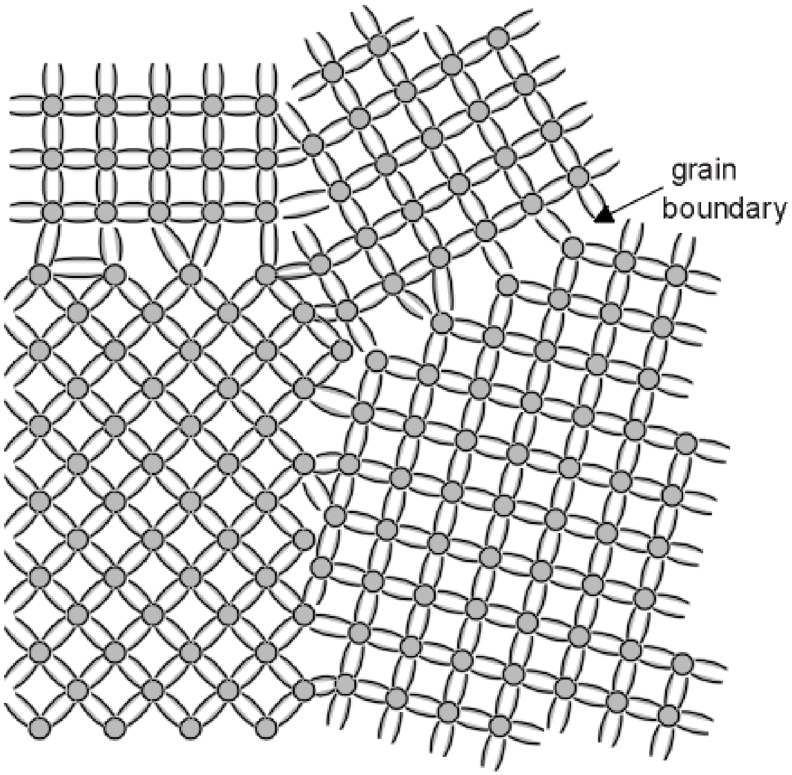
Making a large single crystalline silicon ingot by the Float Zone method

- A molten region is slowly passed along a rod or bar of silicon.
- Impurities in the molten region tend stay in the molten region rather than be incorporated into the solidified region, thus allowing a very pure single crystal region to be left after the molten region has passed.



Multi-crystalline Silicon

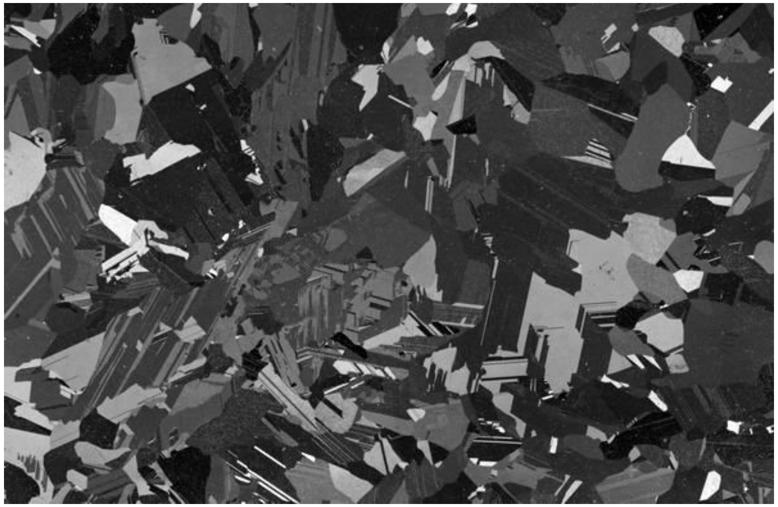
- Techniques for the production of multi-crystalline silicon are more simple, and therefore cheaper, than those required for single crystal material.
- However, the quality of multi-crystalline material is lower than that of single crystalline material due to the presence of grain boundaries.
- Grain boundaries introduce high localized regions of recombination due to the introduction of extra defect energy levels into the band gap.



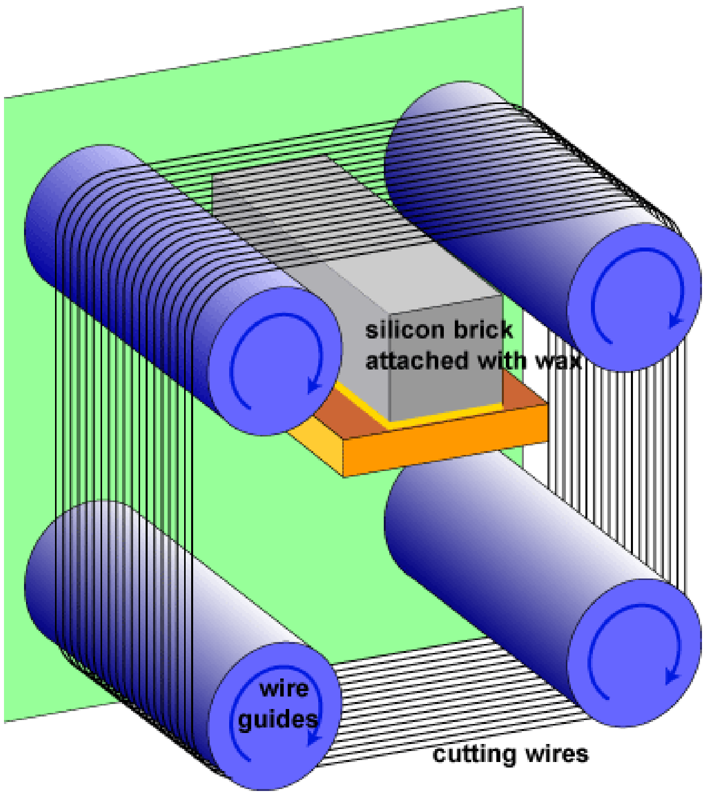
Multi-crystalline silicon

- Slab of multi-crystalline silicon after growth. The slab is further cut up into bricks and then the bricks are sliced into wafers.

- In a multi-crystalline wafer, grains of different orientations show up as light and dark.

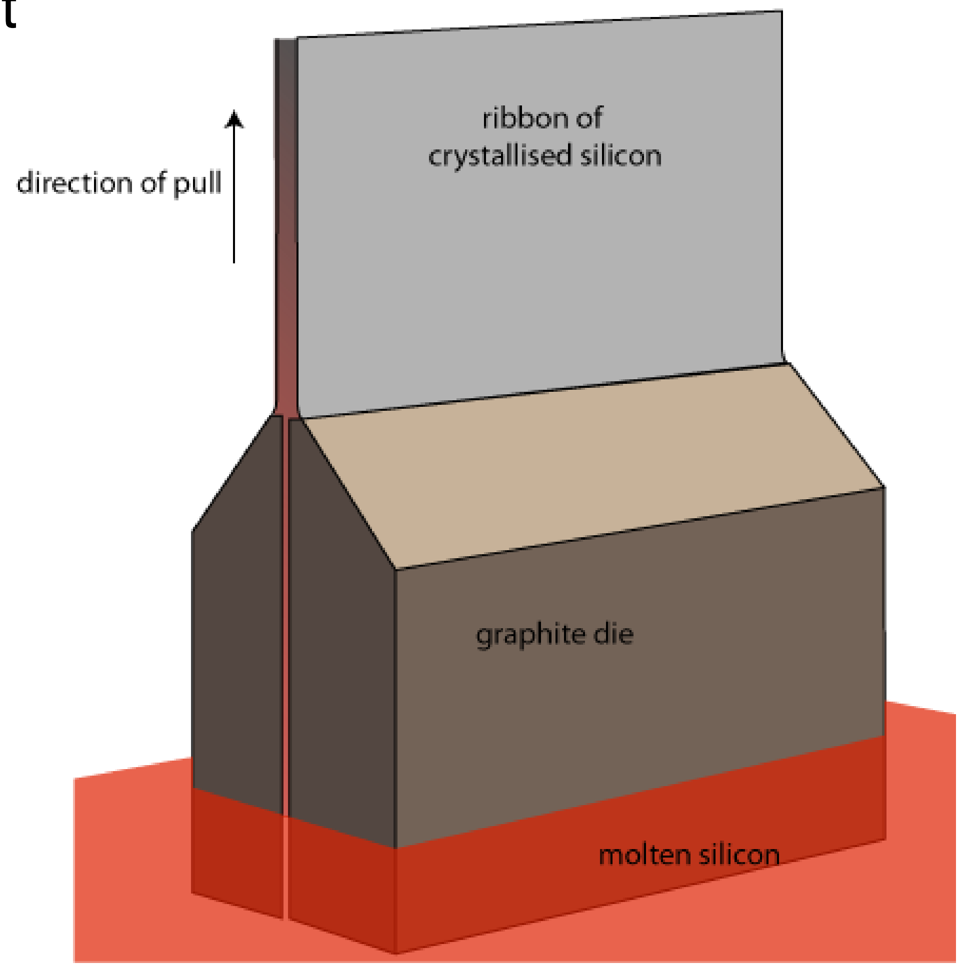


Wafer Slicing: Bricks or Ingots are Sliced into Wafers



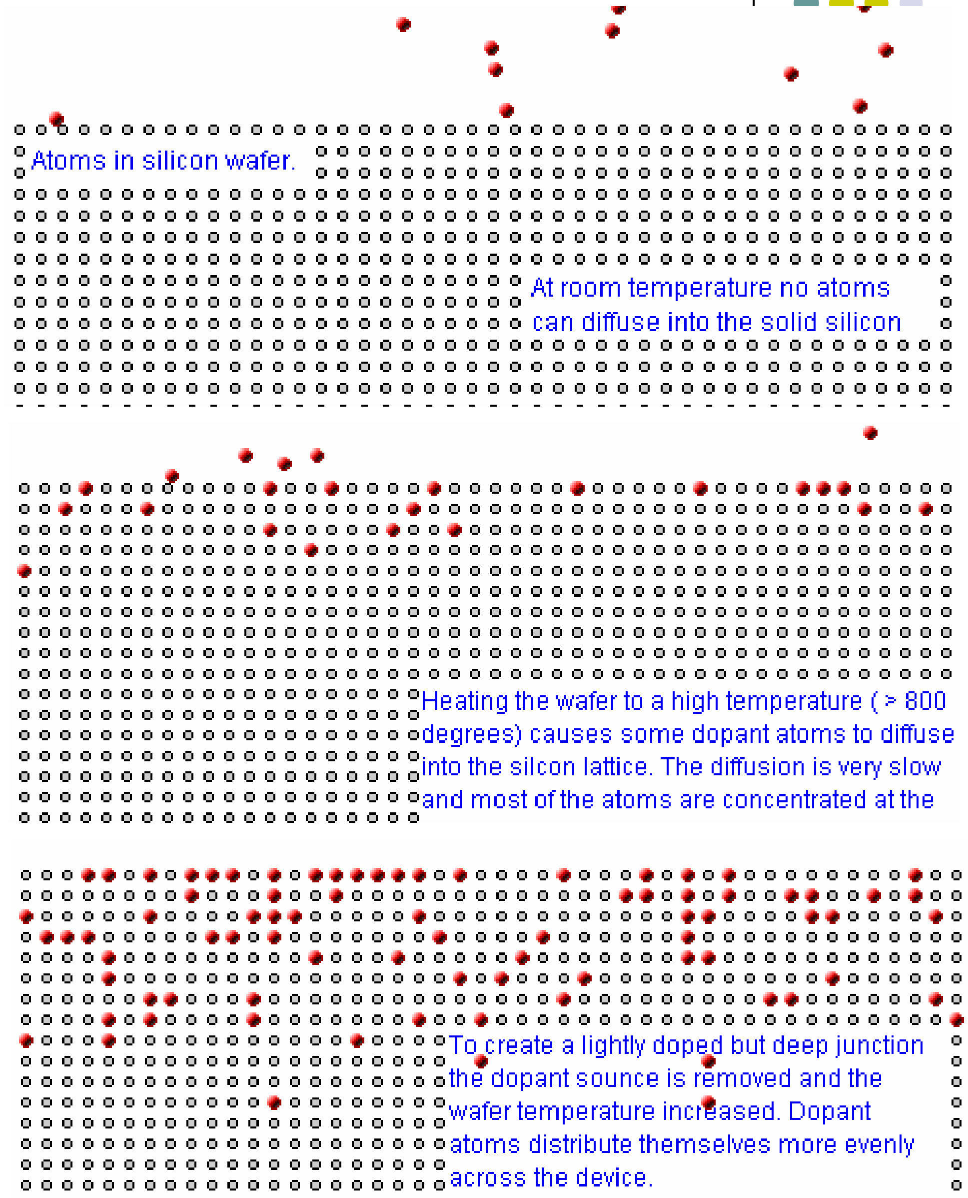
Direct Wafering Technique: Edge Defined Film Fed Growth (EFG)

- There are many processes that try to grow wafers from the outset, thus avoiding the cutting process.
- The edge defined film fed growth technique 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.



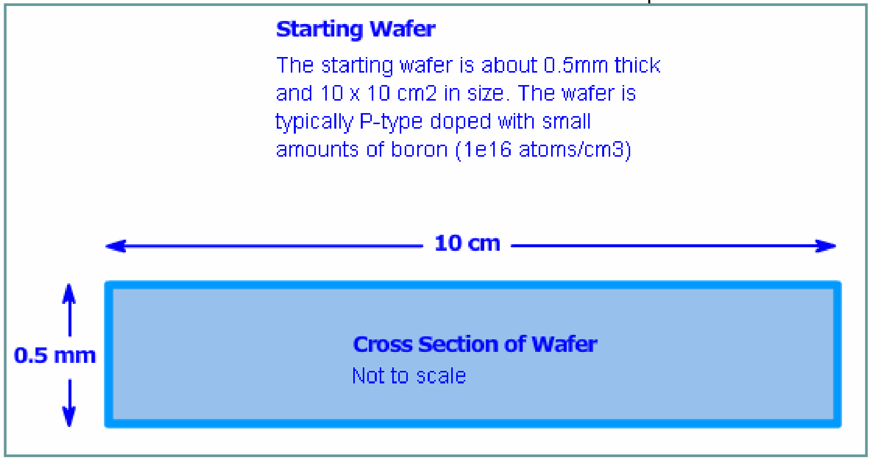
Solid State Diffusion

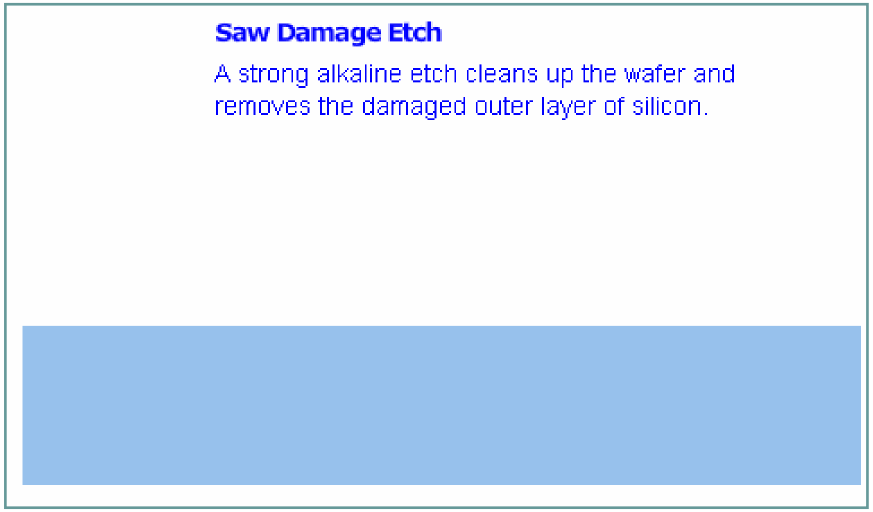
- Solid state diffusion is a process of introducing dopant atoms into semiconductors.
- Silicon solar cells are uniformly doped with
  - boron giving a p-type base, and
  - Phosphorous giving the n-type emitter.



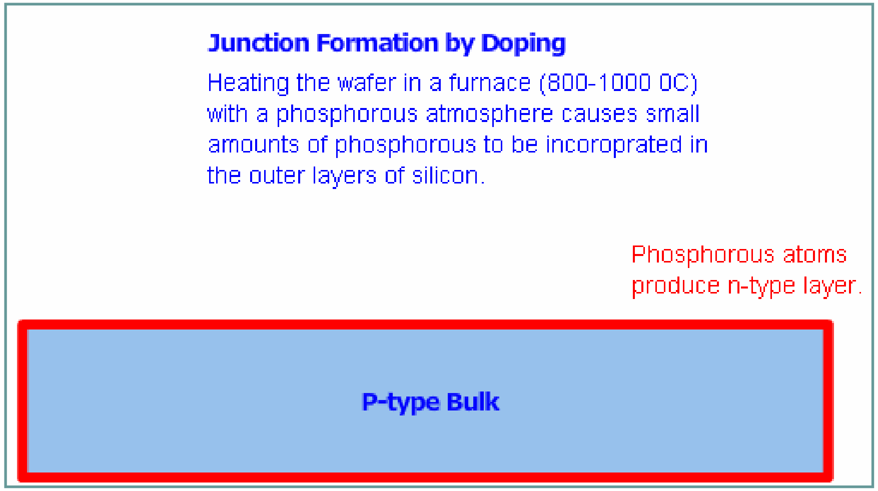
Screen Printed Solar Cells

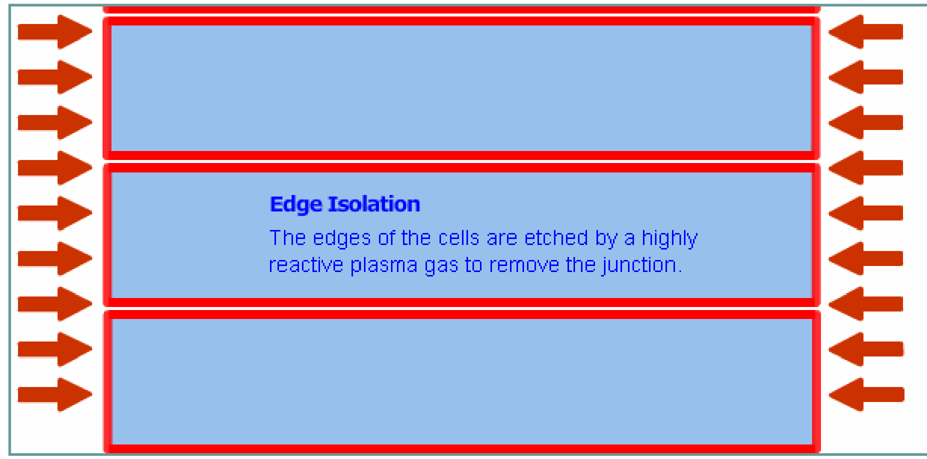
- Screen-printed solar cells are the best established, most mature solar cell fabrication technology, and currently dominate the market for photovoltaic modules.
- The key advantage of screen-printing is the relative simplicity of the process.
- There are a variety of processes for manufacturing screen-printed solar cells. The following production technique is one of the simplest techniques.

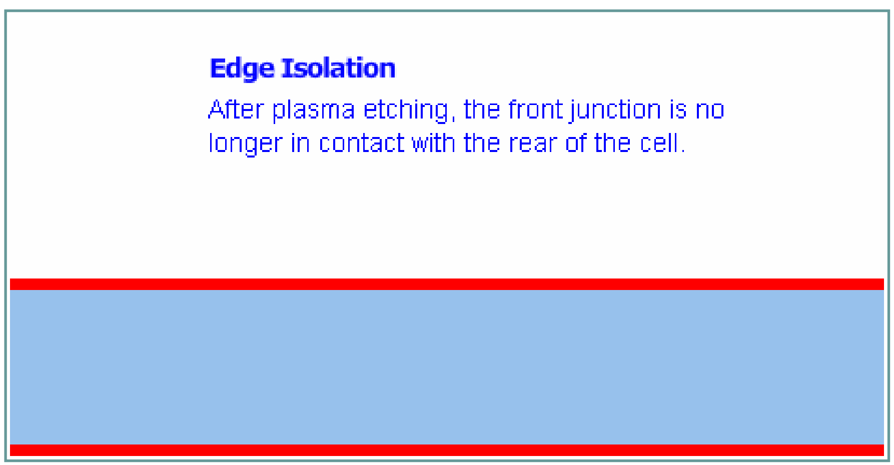


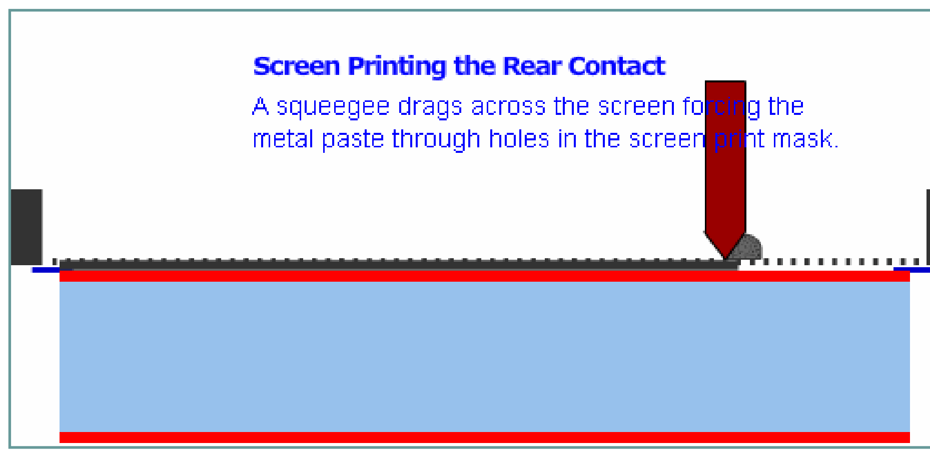


Screen Printed Solar Cells

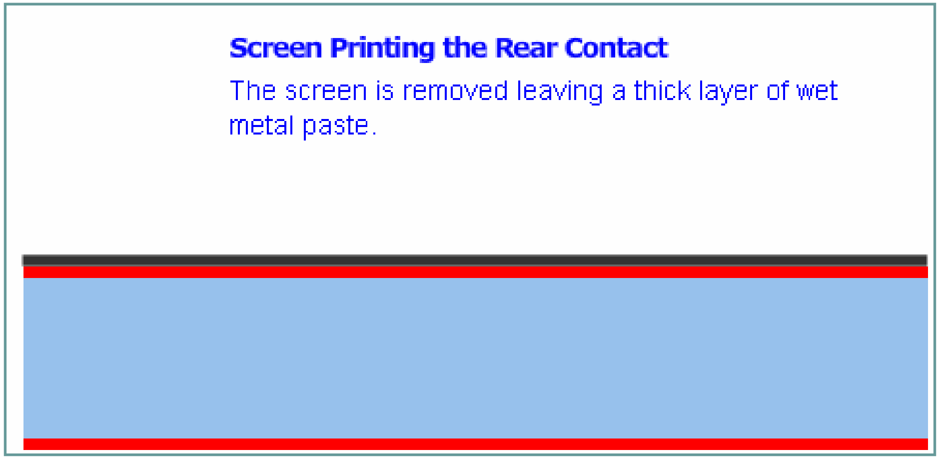


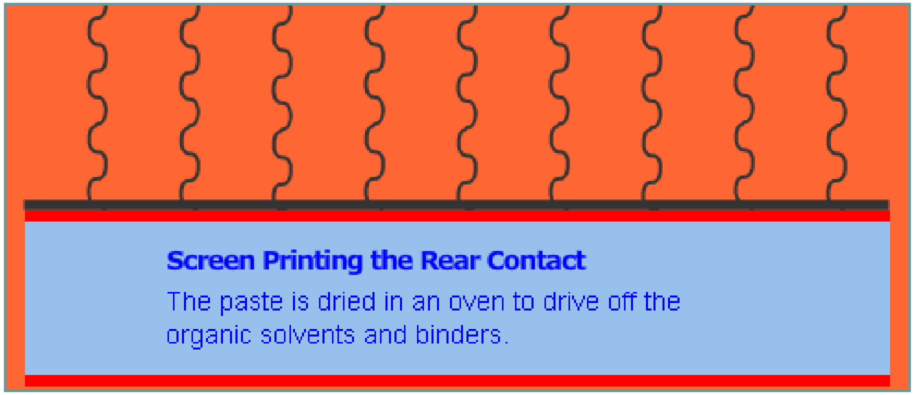


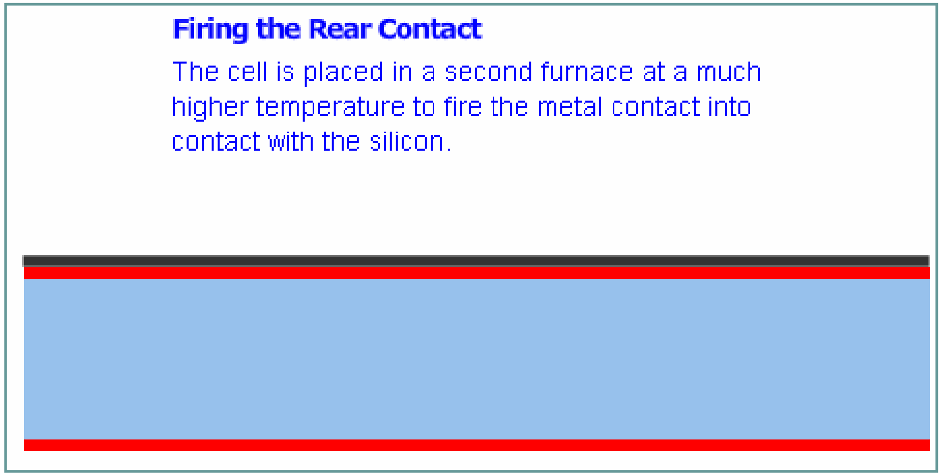


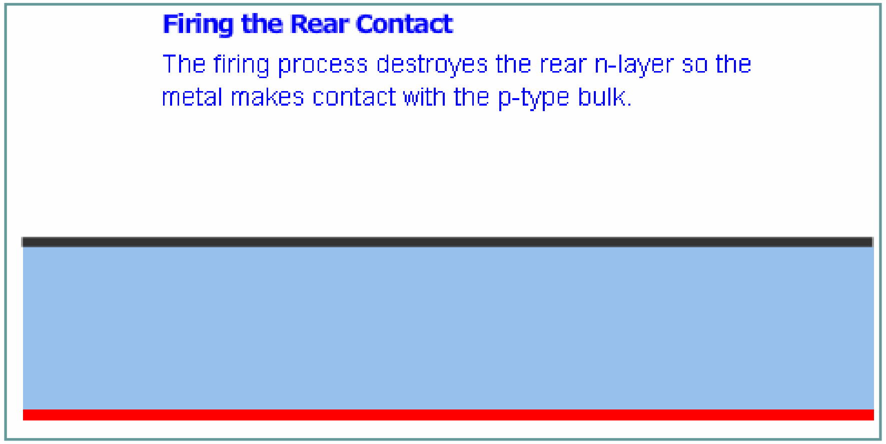


Screen Printed Solar Cells

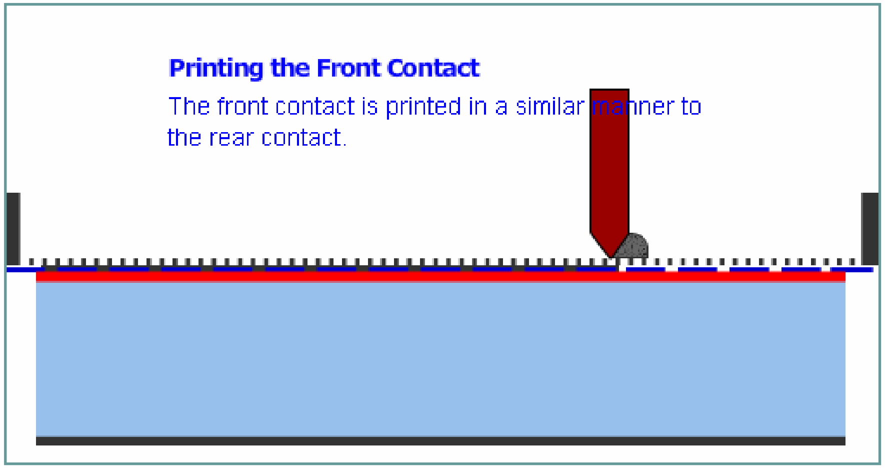


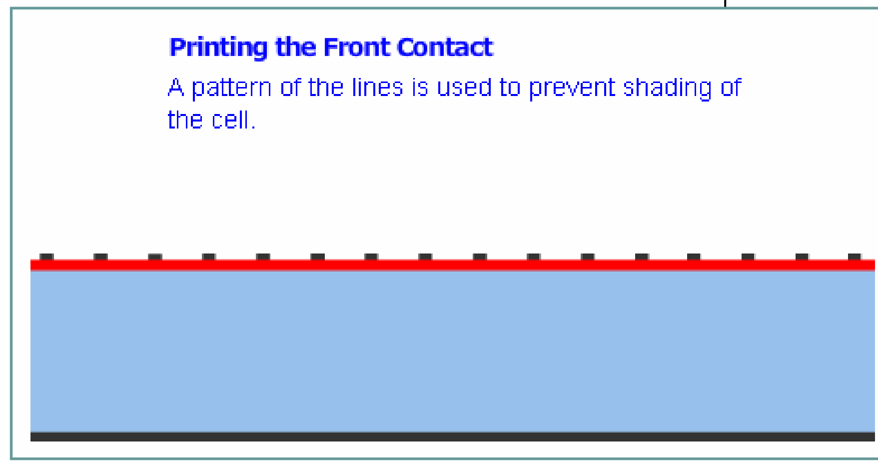


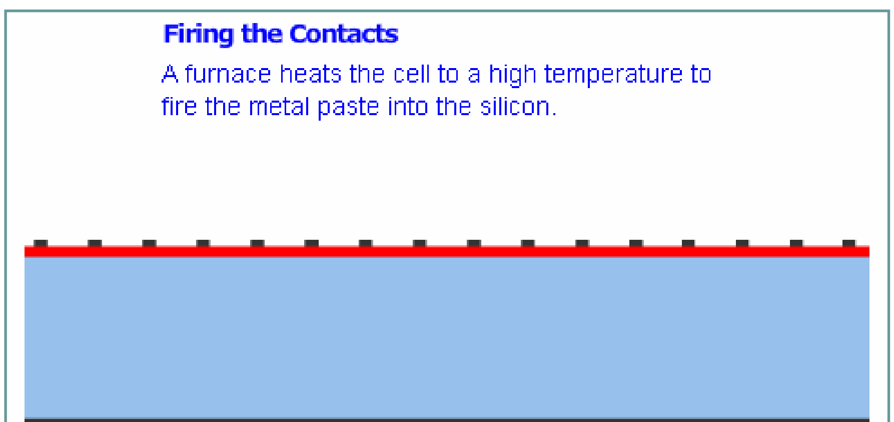


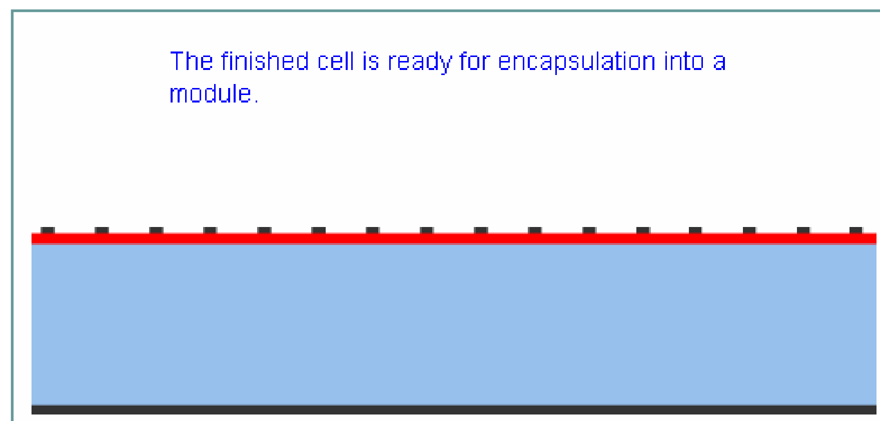


Screen Printed Solar Cells



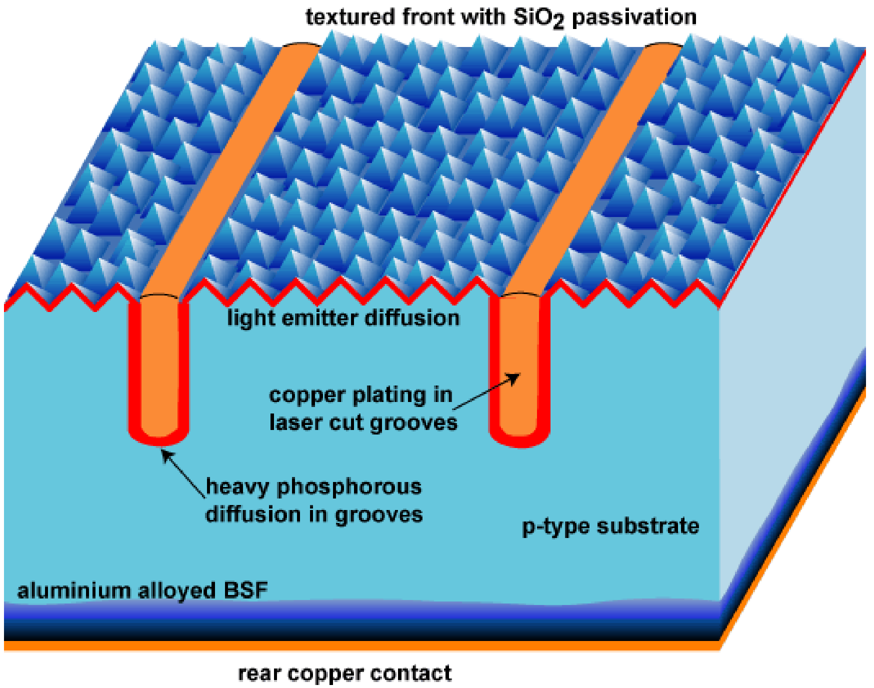






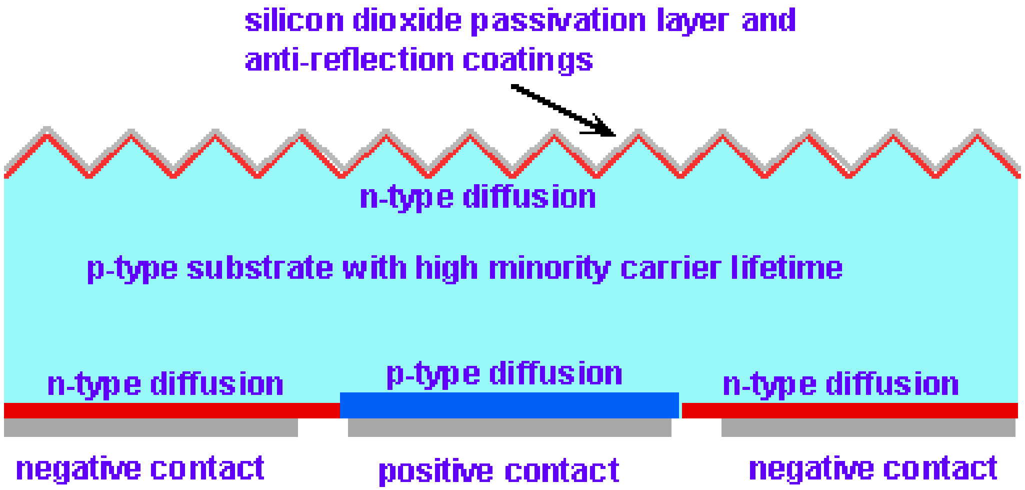
Buried contact solar cells

- The buried contact solar cell is a high efficiency commercial solar cell technology based on a plated metal contact inside laser-formed grooves.
- The buried contact technology overcomes many of the disadvantages associated with screen-printed contacts and this allows buried contact solar cell to have performance up to 25% better than commercial screen-printed solar cells.
- In addition to good reflection properties, the buried contact technology also allows low parasitic resistance losses.



Rear contact solar cells

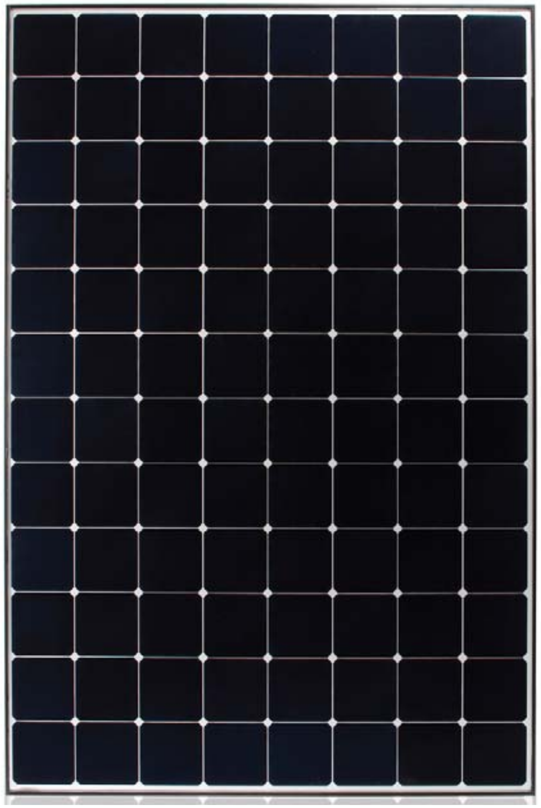
- Rear contact solar cells eliminate shading losses altogether by putting both contacts on the rear of the cell.
- By using a thin solar cell made from high quality material, electron-hole pairs generated by light that is absorbed at the front surface can still be collected at the rear of the cell.
- Such cells are especially useful in concentrator applications where the effect of cell series resistance is greater.
- (See SunPower cells)



SunPower back-contact solar cells

SunPower's High Efficiency Advantage - Up to Twice the Power

	Thin Film	Conventional	SunPower
Peak Watts / Panel	65	215	315
Efficiency	9.0%	12.8%	19.3%
Peak Watts / ft² (m²)	**8 (90)**	**12 (128)**	**18 (193)**



SUNPOWER

315 SOLAR PANEL

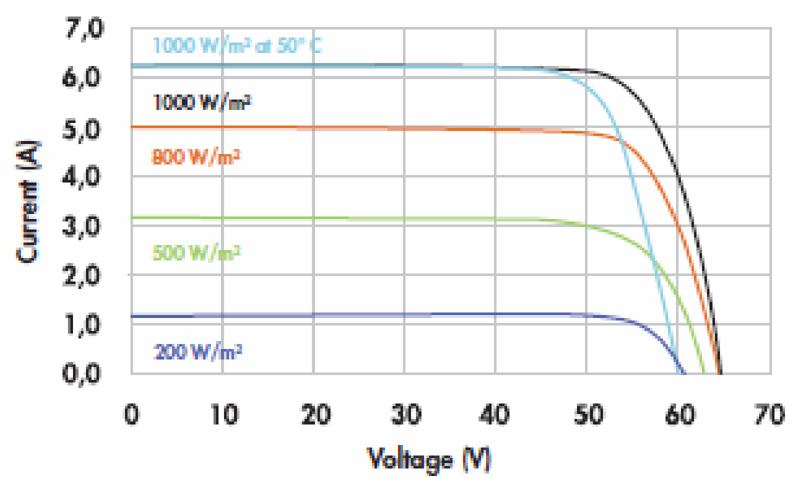
EXCEPTIONAL EFFICIENCY AND PERFORMANCE

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

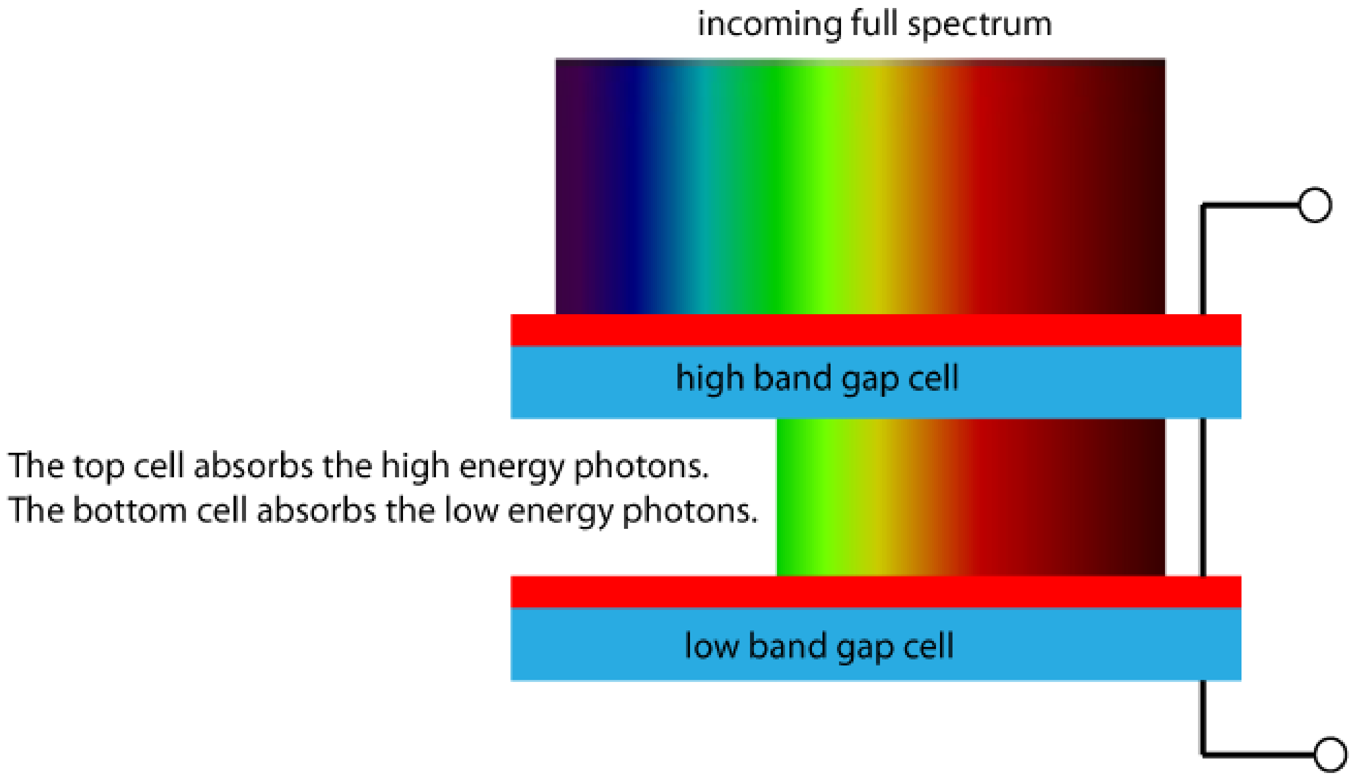
I-V Curve



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

Tandem Cells

- One method to increase the efficiency of a solar cell is to split the sun spectrum and use a solar cell that is optimized to each section of the spectrum.
- The most common arrangement for tandem cells is to grow them monolithically so that all the cells are grown as layers on the on substrate and tunnel junctions connect the individual cells.



Trend in Cell Efficiencies