EE580 – Solar Cells
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- Lecture 06
- Solar Cell Materials & Structures

Solar Cell Technologies

- A) Crystalline Silicon
- B) Thin Film
- C) Group III-IV Cells

A) Crystalline Silicon

- Most common for commercial applications
- Advantages
  - Well known standard processing
  - Silicon is very abundant
- Disadvantages
  - Requires expensive highly pure silicon
  - Competes for silicon with electronics industry

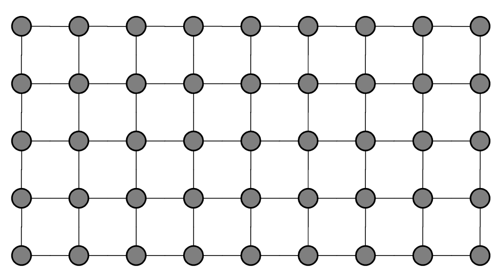
Types of Crystalline Silicon

- Carefully made Silicon forms crystals. Different levels of crystal structure may exist ranging from single crystal to totally non-crystalline
  - Single crystal silicon
  - Multi-crystal silicon
  - Polycrystalline
  - Ribbon silicon
  - Amorphous silicon
- The main difference between each is the crystal grain size and their growth technique

Different Forms of Silicon

Crystal Type	**Symbol**	**Crystal Grain Size**	**Common Growth Techniques**
Single-crystal	sc-Si	> 10 cm	Czochralski (Cz), Float-Zone (FZ)
Multicrystalline	mc-Si	10cm	Cast, Spheral, Sheet, ribbon
Polycrystalline	pc-Si	1μm – 1mm	Evaporation , CVD, sputtering

Single Crystal Silicon



All atoms arranged in pattern, one single crystal of silicon

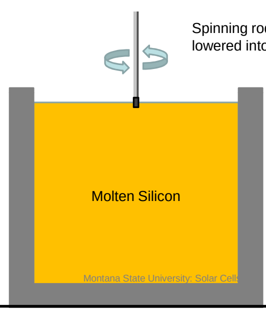
Single Crystal Growth Techniques

- Czochralski Growth (Cz)
  - Most single crystal silicon made this way
  - Lower quality silicon than FZ with Carbon and Oxygen present
  - Cheaper production than FZ
  - Produces cylinders and circular wafers
- Float Zone (FZ)
  - Better Quality than Cz
  - More Expensive than Cz
  - Produces cylinders and circular wafers

Czochralski Method

- Pure Silicon is melted in a quartz crucible under vacuum or inert gas and a seed crystal is dipped into the melt
- The seed crystal is slowly withdrawn and slowly rotated so that the molten silicon crystallizes to the seed (Rock Candy)
- The melt temperature, rotation rate and pull rate are controlled to create a ingot of a certain diameter

Czocharlski Technique



Spinning rod with “Seed” Crystal lowered into the molten silicon

Slowly pulled up to allow silicon to crystallize on the seed layer

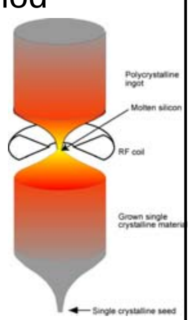
Once to the size desired, the crystal is pulled faster to maintain the needed diameter

Czochralski Growth

- Entire ingots of silicon produced as one big crystal
- Very high quality material with few defects
- No boundaries between crystals because it is one crystal in one orientation
- Si crystal inevitably contains oxygen impurities dissolved from the quartz crucible holding the molten silicon

Float Zone Method

- Produced by cylindrical polysilicon rod that already has a seed crystal in its lower end
- An encircling inductive heating coil melts the silicon material
- The coil heater starts from the bottom and is raised pulling up the molten zone
- A solidified single crystal ingot forms below
- Impurities prefer to remain in the molten silicon so very few defects and impurities remain in the forming crystal



Slicing into Wafers

- Ingots are cut into thin wafers for solar cells (300 μm)
- Two Techniques
  - Wire sawing
  - Diamond blade sawing
- Both results in loss of silicon from “kerf losses” → silicon saw dust
- Time consuming
- Water Cooled, Dirty

Single Crystal Silicon

- What we are using
- Currently supplies a significant but declining solar cell market share
- Advantages
  - Produced for electronics industry
  - Allows for higher efficiency solar cells
- Disadvantages
  - Requires higher quality of feed stock
  - More expensive and slower to produce
  - Circular shape leads to lower packing density in panels or larger waste of silicon

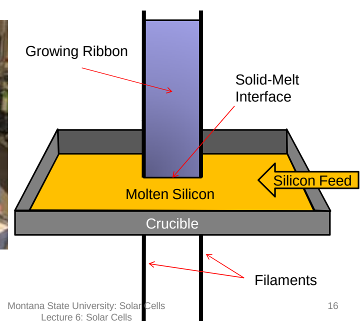
Ribbon Silicon

- Ribbon silicon is a technique used to grow multi-crystalline silicon
- Two graphite filaments are placed in a crucible of molten silicon
- The molten silicon is grown horizontally through capillary action along the filaments
- Produces a ribbon-like sheet of multi-crystalline silicon which is already a long wafer → no kerf losses

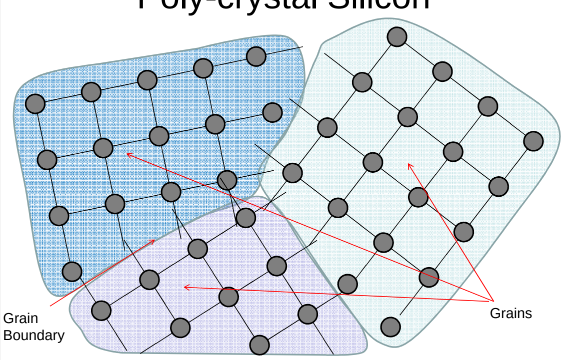
Ribbon Silicon (+/-)

- Advantages
  - Thickness can be varied by the filament width & the pull speed
  - Cheaper - less wasted silicon due to sawing wafers
- Disadvantages
  - Lower Solar Cell Efficiencies due to more defects
  - Irregular surface characteristics leading to poorer cell performance

Ribbon Silicon Method



Poly-crystal Silicon

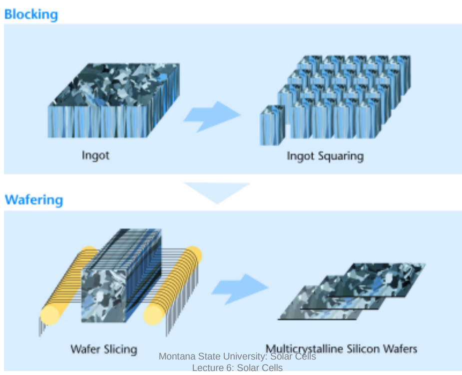


Regions of single crystalline silicon separated by grain boundaries with irregular bonds

Poly& Multi-Silicon Method

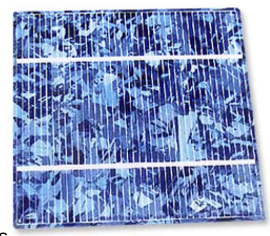
- Produced by melting silicon source material in a large rectangular crucible
- The material is slowly directionally cooled
- Impurities drift to the edges which cool last
- These edges are sawn or acid etched off
- These blocks are sawn into smaller blocks and then sawn into thin wafers

Multicrystalline Silicon Wafer Fabrication



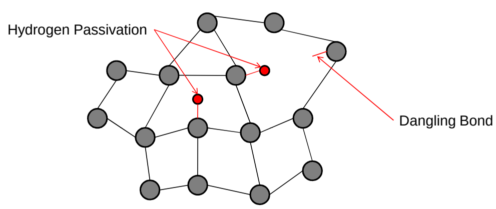
Multi-crystalline

- Significant differences in the size of crystal grains
- Advantages
  – Cheaper
  – Faster Processing
- Disadvantages
  – Less efficient than single crystal due to grain boundaries where electrical losses occur



Clearly shows different crystals formed during the casting process

Amorphous Silicon



Less regular arrangement of atoms leading to dangling bonds and passivation by hydrogen

B) Thin Film

- Thin film of semiconductor 1-10 microns compared to 200-300 microns
- Created by depositing a thin expensive semiconductor on a cheaper glass substrate
- Advantages
  – Requires little semiconductor material
  – Cheaper to produce:
    - glass is cheap
    - semiconductor expensive
- Disadvantages
  – Difficult to manufacture good films
  – Lower efficiencies

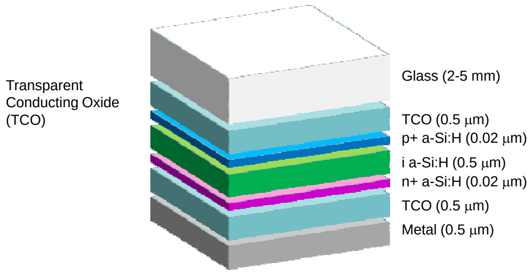
Three Main Thin Films

- Amorphous Silicon (a-Si)
- Cadmium Telluride (CdTe)
- Copper Indium Gallium Diselenide (CIGS)

Amorphous Silicon (a-Si)

- Made by evaporating silicon onto a glass base
- More random orientation than crystalline
- More electrons not bound to SI atoms
- Unbounded electrons attract impurities and degrade the electrical performance of the cell
- Hydrogen is often added to the material to de-activate the dangling bonds

a-Si Cross-Section



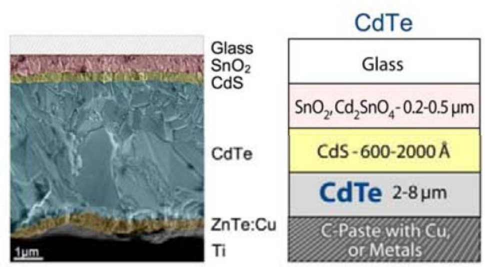
Amorphous Silicon (+/-)

- Advantages
  - Absorbs low and high intensity light
  - Less Semiconductor needed→ Lower Cost
  - High temperatures do not significantly reduce performance
- Disadvantages
  - Lower Efficiency (lower grade Si)
  - Long term degradation of material under sunlight
  - Production requires hazardous gases

Cadmium Telluride (CdTe)

- p-type made from Cadmium and Telluride
- n-type from Cadmium Sulfide
- Advantages
  - High Efficiencies compared to a-Si (over 16%)
- Disadvantages
  - Requires high processing temperatures
  - CdTe is unstable and will degrade
  - Cadmium is toxic and costly to dispose of
  - Sensitive to water ingress and cell degradation

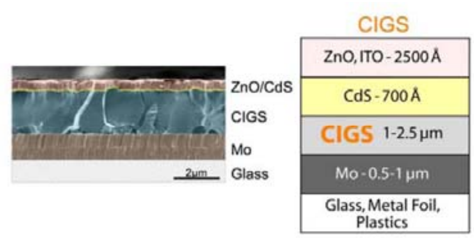
CdTe Cross-Section



Copper Indium Gallium Diselenide (CIGS)

- Extremely good light absorption (99% of light absorbed in the first micron)
  - → an optimal and effective PV material
- The addition of gallium boosts its light absorption band gap for the solar spectrum
- No performance degradation over time
- Much higher efficiencies than other thin films (19%)

CIGS Cross-Section



CIGS (+/-)

- Advantages
  - Highest efficiency for thin film cells
  - Clear pathways to improve performance and efficiencies
- Disadvantages
  - Gallium and Indium are scarce materials
  - Requires expensive vacuum processing

C) Group III-V

- Compounds of Group III and V on periodic table
- Compound is a material that combines multiple elements in a single structure (not just a mixture)
- Used extensively in the electronics and optoelectronics industries as well as space satellites
- Makes excellent but very expensive solar cells
- Can create multi-junction cells for higher efficiency

Single Junction III-V Cells

- Made from combination of two materials
  - Gallium Arsenide (GaAs)
  - Indium Phosphide (InP)
- Best efficiency is at 27.6%
  - 1000 W/m^2 of sunlight produces 276 Watts of usable power

Single Junction III-V Cells (+/-)

- Advantages
  - Very high efficiencies
  - Low weight
  - Resistant to damage from cosmic radiation
- Disadvantages
  - Expensive
  - Required materials are not abundant

Multi-Junction III-V Cells

- Stacked p-n junctions on top of each other
- Each junction has a different band gap energy so each will respond to a different part of the solar spectrum
- Very high efficiencies, but more expensive
- Each junction absorbs what it can and lets the remaining light pass onto the next junction
- Widely used for space applications because they are very expensive
- Overall record for electrical efficiency is 35.2%

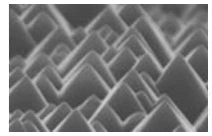
Solar Cell Features

Top Surface Features

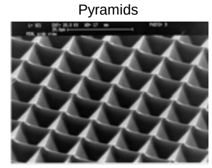
- Light striking the surface
  - Absorbed - Converted into electricity (GOOD)
  - Reflected – Optical loss (BAD)
  - Transmitted – Optical loss if escapes
- Bare silicon is highly reflective
- Top of PV cell is designed to improve the light trapping (reduce reflection & confine transmitted)
  - Texturing
  - Anti-Reflection Coating (AR coating)

Texturing

- Reduce the reflectivity of the surface of wafers by forming microscopic structures
- Works mainly for single crystal surfaces



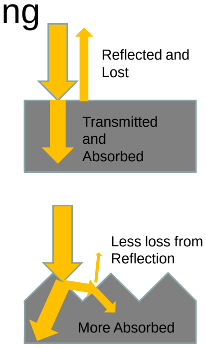
Pyramids



Inverted Pyramids

Texturing

- Formed by Anisotropic etching different crystal planes etch at different rates
- Reduces total reflection by reflecting light into another pyramid instead of away
- Increases the chances of absorbing the light
- 30% reflection from polished Si reduced to 10% for textured Si

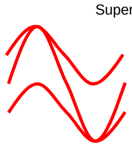


Anti-reflection (AR) Coatings

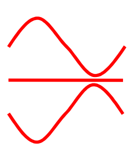
- Finished PV cell is coated with a material to reduce the amount of reflected light (just like eye glasses)
- Usually used on cells unsuitable for texturing
- Can reduce reflection to 5%
- AR Coating Materials
  - Silicon nitride
  - Silicon dioxide
  - Zinc oxide

AR mechanism

Superposition of two waves:



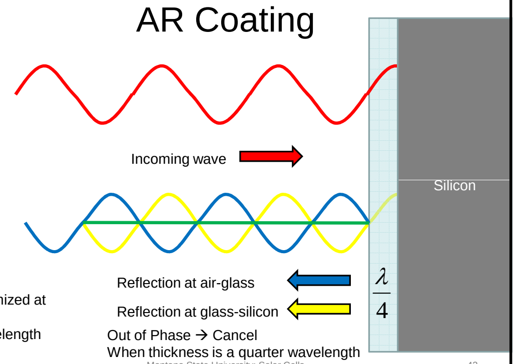
Constructive Interference
Waves in phase add



Destructive Interference
Waves out of phase cancel

This destructive interference is created by AR coatings

AR Coating



Only optimized at one wavelength

Out of Phase → Cancel
When thickness is a quarter wavelength

Front Metal Contacts

- Grid of metal contacts are used to collect the current from the p-n junction (blocks sunlight to silicon)
- Silver is mainly used: Highest conductivity but very expensive (we use aluminum…cheaper)
- High conductivity reduces the resistance the traveling electrons experience so they lose less energy as they move
- There will be some additional resistance provide by the alloying of the metal and silicon (contact resistance)
- A well formed bond minimizes this resistance by allowing electrons to flow between the materials with out any edge effects, barriers or opposing voltages

Front Metal Contacts Process

- The main process used by industry is silk-screening because it is quick and cheap
  – Silver paste is squeezed through a mesh with a pattern onto the cell's top surface
- Other Processes
  – Evaporation (our method)
  – Laser Grooving and Electroplating
    - Slower and more expensive but gives good efficient cells
  – Inkjet Printing
    - Fast and cheap in theory
    - Yet to achieve improved performance

Rear Metal Contacts

- Does not need to let sunlight through usually covers the entire back surface
- This reduces the back surface contact resistance
- Aluminum is usually used for the rear metal contact because a lot is used
- Aluminum is a good conductor (not as good as silver) but much less expensive
- Made thicker to compensate for lower conductivity

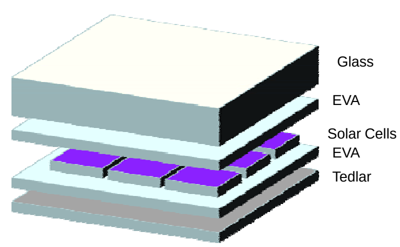
Encapsulation

- Solar cells are thin & brittle and need to be exposed to outdoor conditions for 25-30 years
- A physical casing (encapsulation) protects the PV cells and provide structural strength
- Accomplishes
  – Electrically isolate cells and make contacts
  – Protect from water and oxygen ingress
  – Withstand heavy winds, hail & installation
  – Maintain protection for decades
  – Allow modules to attach to each other

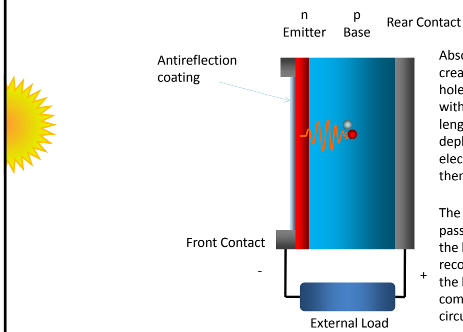
Materials

- Glass(low Iron):
  – Used for the transparent top surface.
  – Needs to be highly transparent, scratch-resistant & rain, wind, hail, human… proof.
- Tedlar
  – Typical back layer because it is strong material
  – Gives structural support
  – Removes excess heat that reduces efficiency
- Ethylene Vinyl Acetate (EVA)
  – Transparent encapsulant
  – Fills all the spaces between the front, rear edges and between layers

Module Structure



Solar Cell Operation



Absorption of photon creates an electron hole pair. If they are within a diffusion length of the depletion region the electric field separates them.

The electron after passing through the load recombines with the hole completing the circuit