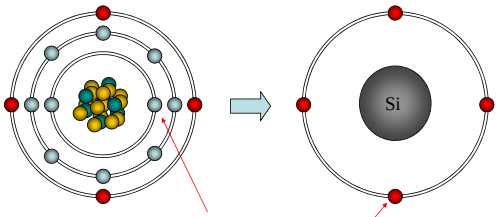
EE580 – Solar Cells
Todd J. Kaiser

- Lecture 04
- Semiconductor Materials
- Chapter 1

Semiconductor Bond Model

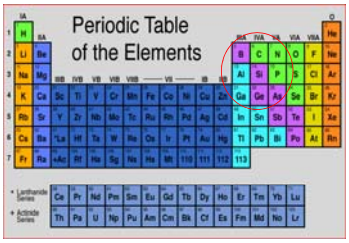
- Bohr's Atomic Model
  - Atoms are the building block of all matter
  - Atoms are made of a dense nucleus with orbiting electrons (mostly open space)
  - Groups of electrons occupy shells at a particular distance from the nucleus
  - The outermost orbit is the valence band where electrons interact to form bonds

Silicon Atom – 14 electrons with 4 valence



Filled orbitals do not interact

The four outer valence electrons interact

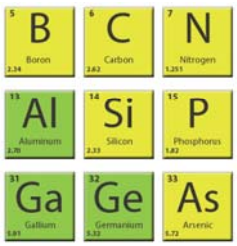


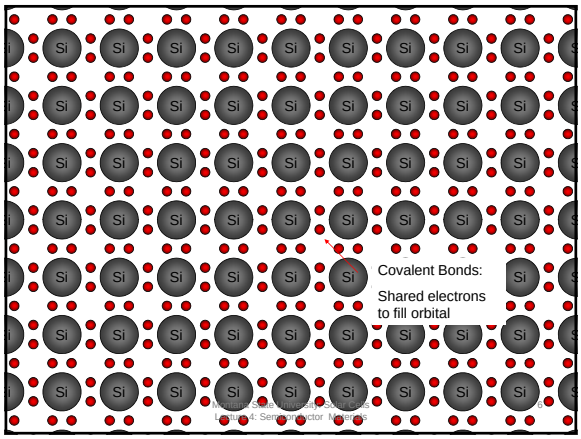
- Each block is an element with its own abbreviation, (Chemical Symbol)
- Each element has its own number of electrons and protons (Atomic Number)

- Silicon (Si) is in the IVA Column (4 valence electrons)
- Boron (B) is in the IIIA Column (3 valence electrons)
- Phosphorus (P) is in the VA Column (5 valence electrons)

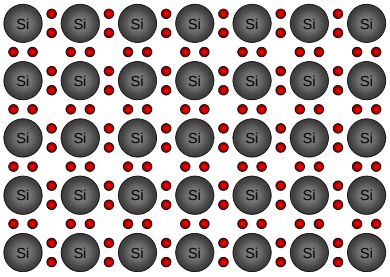
Elements around Silicon

III IV V





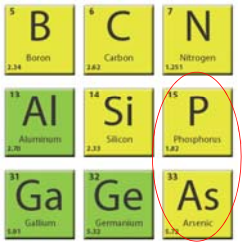
Intrinsic Silicon



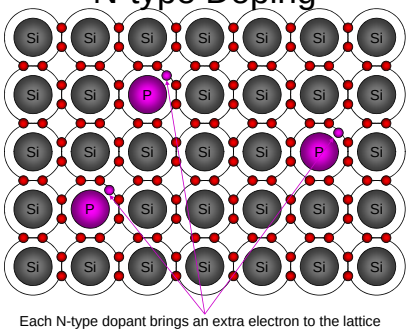
Poor conductor: No free electrons to carry current
Need to engineer electrical properties (conduction)

Valence V: n-type doping

III IV V



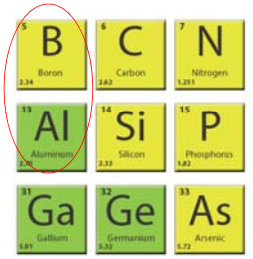
N-type Doping



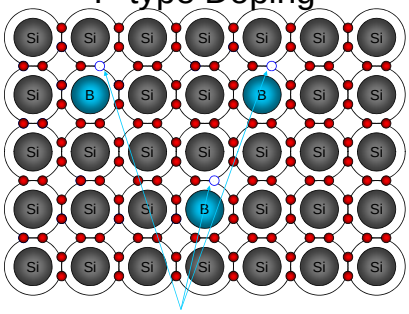
Each N-type dopant brings an extra electron to the lattice

Valence III: p-type doping

III IV V



P-type Doping



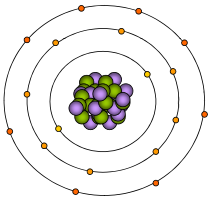
Each P-type dopant is short an electron, creating a hole in the lattice

Band Model

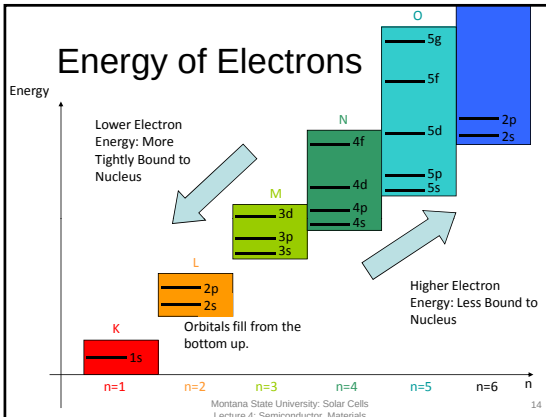
Energy vs Position

Orbital Shells

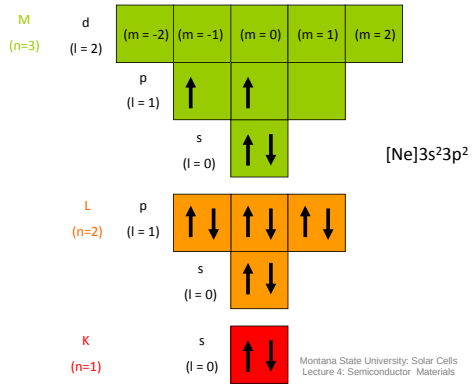
- The positions of the electrons around the nucleus are quantized to specific energy levels or Shells
- The electron orbital determines the size of the atom



Energy of Electrons



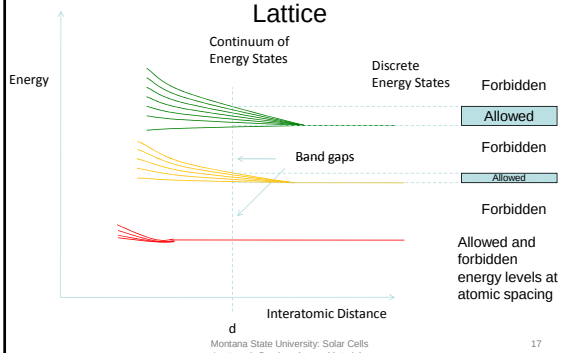
Silicon Electron Configuration



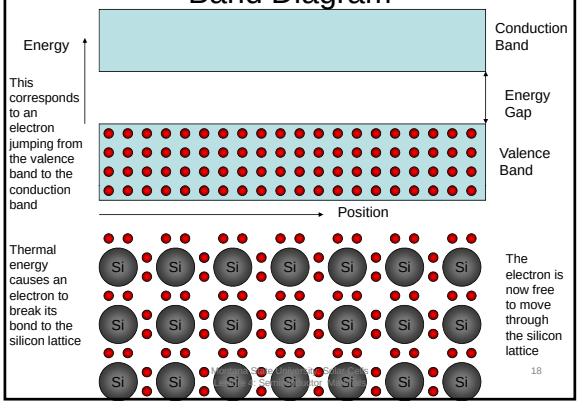
Coupling of Energy

- Swing Set Analogy
  - Isolated Swings can move at there own frequency (Energy)
  - When they get close enough to interact the modes couple
  - Two stable modes
    - Move together
    - Move against each other
  - More Swings more modes

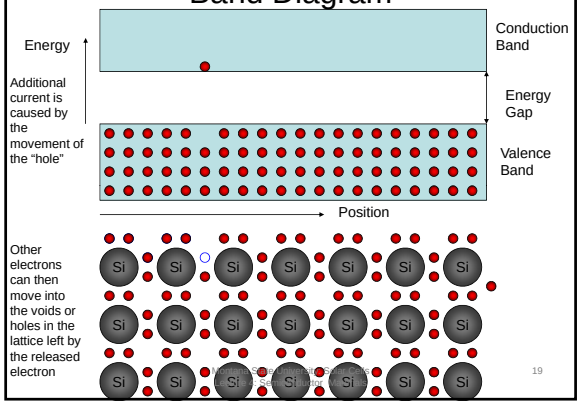
Splitting of Energy Levels in a Crystalline Lattice



Band Diagram



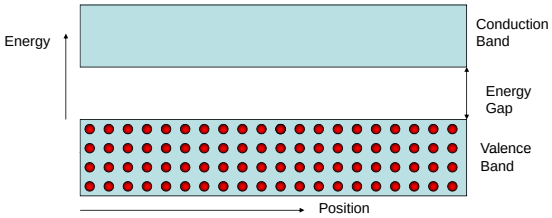
Band Diagram



Additional current is caused by the movement of the "hole"

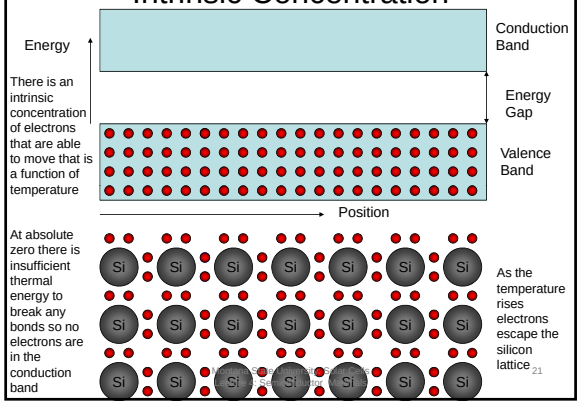
Other electrons can then move into the voids or holes in the lattice left by the released electron

Band Diagram



It is easier to think of a positive hole moving in the valence band with a lower mobility than a electron in the conduction

Intrinsic Concentration



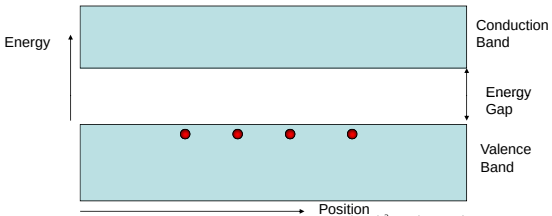
There is an intrinsic concentration of electrons that are able to move that is a function of temperature

At absolute zero there is insufficient thermal energy to break any bonds so no electrons are in the conduction band

As the temperature rises electrons escape the silicon lattice

Intrinsic Concentration

As the temperature rises more and more electrons are excited into the conduction band and the silicon becomes more conductive with an equal concentration of electrons in the valence band and holes in the conduction band



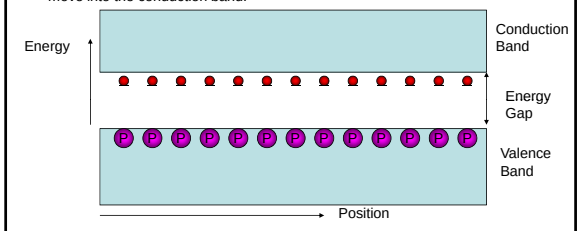
Empirical equation for near room temperature

$$n_i(T = 275K - 375K) = 9.38\times10^{19}\left(\frac{T}{300}\right)^2 \exp\left(-\frac{6884}{T}\right)$$

$$n_i(T = 300K) = 1\times10^{10}\left(/\,cm^3\right)$$

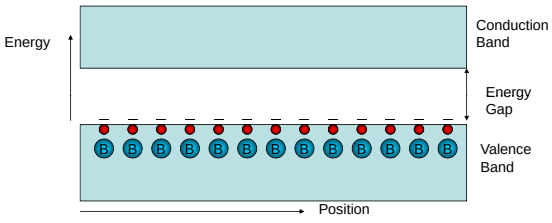
N-Type Doping

Doping the silicon lattice with atoms with 5 valence electrons (V) create sites in the band diagram that require little energy to break the bond to the dopant atom and become free to move in the lattice or in other words move into the conduction band.



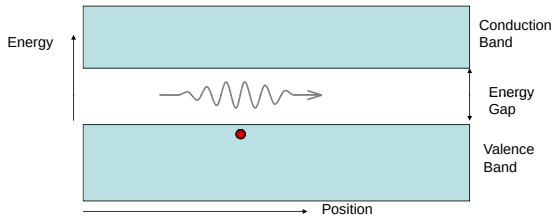
P-Type Doping

Doping the silicon lattice with atoms with 3 valence electrons (III) create sites in the band diagram that require little energy to trap an electron into the dopant atom. Holes are created in the valence band that are free to move.



Absorption of Light

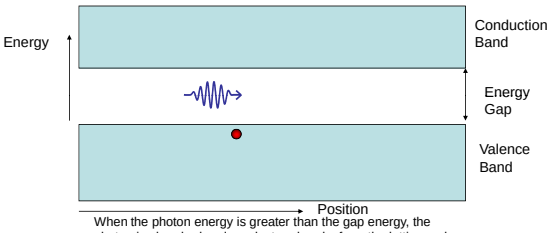
$E_{ph}<E_G$



When the photon energy is less than the gap energy, the photon is not absorbed and the photon passes straight through the semiconductor

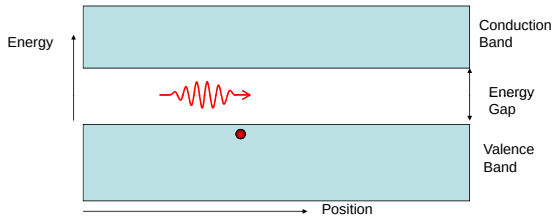
$E_{ph}>E_g$

The electron looses thermal energy to the lattice by collisions and moves to the edge of the conduction band



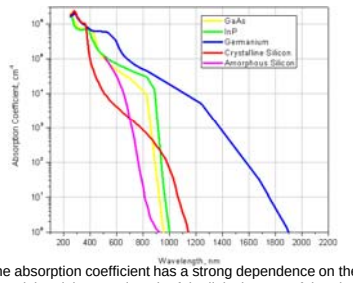
When the photon energy is greater than the gap energy, the photon is absorbed and an electron breaks from the lattice and moves from the valence band into the conduction band.

$E_{ph}=E_G$



When the photon energy is equal to the gap energy, the photon is again absorbed but no thermal energy is generated.

Absorption Coefficient (α)



The absorption coefficient has a strong dependence on the material and the wavelength of the light (energy of the photon).

Photoelectric Effect

- Each photon with an energy greater than the band gap creates ONE electron hole pair (EHP) when the photon is absorbed.

Solar Cell Materials

- Generally Group IV elements in periodic table
- The main difference between semiconductors is
  - Band gap energy
  - Band gap type
- Band Gap Energy: The energy needed to allow an electron in an atom's shell to break way from the atom and flow freely in the material

Band Gap of Cell Materials

- The higher the band gap energy the higher the energy of light required to release a electron and allow it to conduct current
  - Too high:Few photons have enough energy results in low current → low power
  - Too low: All photons produce the same low voltage → low power

Material	Gap Type	Gap Energy
Silicon (Si)	Indirect	1.1 eV
Germanium (Ge)	Indirect	0.66 eV
Cadmium Telluride (CdTe)	Direct	1.56 eV
Gallium Arsenide (GaAs)	Direct	1.42 eV
Copper Indium Diselenide (CIS)	Direct	2.4 eV
Copper Indium Gallium Selenide (CIGS)	Direct	1.5 eV

Band Gap Type

- Direct Band Gap
  - Only a photon required to release a electron
  - Higher efficiency in creating free electrons
  - Thinner materials needed
- Indirect Band Gap
  - Requires a little kinetic energy that cannot come from a photon
  - Energy comes from momentum of other particles
  - Less efficient so thicker materials needed
  - Silicon is indirect, but is much cheaper than other elements

Silicon

- 2nd most abundant element in Earth's crust
- Non-toxic (except for processing chemicals)
- Links well with the energy of visible sunlight
- Abundant, much cheaper than other semiconductors used
- Comes from sand (silicon dioxide) can be oxidized to make insulator
- The dominate material used for solar cells and likely to remain so

Silicon (+/-)

- Advantages
  - Second most abundant element on earth's surface
  - Non-toxic
  - Used in electronics and well studied and understood
  - Cheap to process
  - Can oxidize to make insulator
- Disadvantages
  - Indirect band gap → weak absorber of light
  - Band gap lower than ideal for solar spectrum

Germanium

- Widely used in electronics
- Dominate the early PV market for use in outerspace until the mid 1960's then silicon took over
- Band gap is low → lower voltages
- Now being used in combination with silicon to develop the highest efficiency cells

Germanium (+/-)

- Advantages
  - Low impurities that can reduce cell output
  - Able to be used in amorphous and various crystalline forms
- Disadvantages
  - Poor semiconductor property of indirect band gap
  - Band gap too small for high efficiency cells

Gallium Arsenide (+/-)

- Advantages
  - Electrons have longer lifetime and generates current easier
  - More efficient due to direct band gap
- Disadvantages
  - No natural insulating layer to prevent impurities from shorting cell
  - Expensive

Selenium

- Early discoveries in photovoltaics were made using Selenium as the semiconductor
- It is expensive and difficult to obtain (too expensive for commercial use)
- Well suited to solar spectrum (most photons have sufficient energy and few have too much)

Copper Indium Diselenide (CIS) (+/-)

- Advantages
  - Extremely high absorption of light
  - Effective photovoltaic material
- Disadvantages
  - Expensive to process
  - Indium is scarce

Copper Indium Gallium Selenide (CIGS) (+/-)

- Advantages
  - Adding Gallium boosts absorption even more
  - Well matched to solar spectrum
  - High Efficiencies
- Disadvantages
  - Processing is expensive
  - Gallium and Indium are scarce

Copper Sulfide (CuS)

- Used in the 1930's as a semiconductor material, not used much now
- Copper and Sulfur are very common and abundant
- Does not produce very efficient cells

Cadmium Telluride (+/-)

- Advantages
  - Cheaper than silicon
- Disadvantages
  - Cadmium is toxic
  - Not as efficient as other materials