EE113FZ
Solid State Electronics
Lecture 5: Electronic Materials

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What is to be Discussed Today?

- Characteristics that are important for electronic materials.
- Definition of:
  - Insulators;
  - Conductors;
  - Semiconductors.
- Bonding types.
- Energy band diagrams.

Characteristics of Electronic Materials

- We need materials to be transporters (or not) of something that we consider useful:
  - Movement of charge or other energy forms;
  - Storage of charge or other energy forms;
  - Blockage of charge or other energy forms.

- We will next look at 3 main different types of materials that are important in electronic engineering.
- Combinations of these materials give rise to different effects.

Insulators

- Definition:

  to cover, line, or separate with a material that prevents or reduces the passage, transfer, or leakage of heat, electricity, or sound.

  http://dictionary.reference.com/browse/insulate

- Physical properties:
  - Large resistance to the flow of
    - Charge (Current);
    - Heat;
    - Other electromagnetic parameters such as RF absorption.

Insulators

- Generally not able to control any of these properties if the material is naturally formed;
- Materials that have a measured electrical resistivity of 1×10^{11} ohm·m are classified as electric insulators;
- One can manufacture very resistive materials. We will see what they look like a bit later.

Don't take the resistivity range too seriously. Insulators have very high resistivity. However, the number that is given is only an indication of how high this resistivity may be. Often there is not a clear cut.

Examples of Insulators

- Glass has very high resistance to current. Its resistivity is at approx. 1×10^{13} ohm·m.
- It is not so great at stopping heat. It is easier to heat up than water, for instance.
- It lets most EM wavelengths go through.

- Does it?
- Which one does it stop then?

Examples of Insulators

- Rubber: not good at letting current flow.

- Very good at letting heat through: hot water for cleaning dishes and rubber gloves do not equal safe hands!
- Good at stopping most EM wavelengths.

Examples of Insulators

- These are specially manufactured insulators used on high-voltage power lines.

https://www.elecmit.com/bus-bar-support/high-voltage-insulator.html

Conductors

- Definition:

  A substance, body, or device that easily conducts heat, electricity, or sound, etc.

  http://dictionary.reference.com/browse/conductor

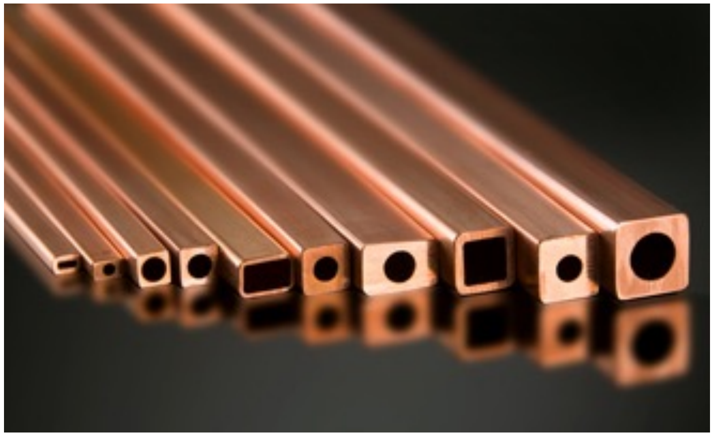
- Physical properties:
  - Ease of flow of:
    - Charge (Current);
    - Heat;
    - Transmission of EM;
- Good conductors are normally metallic.

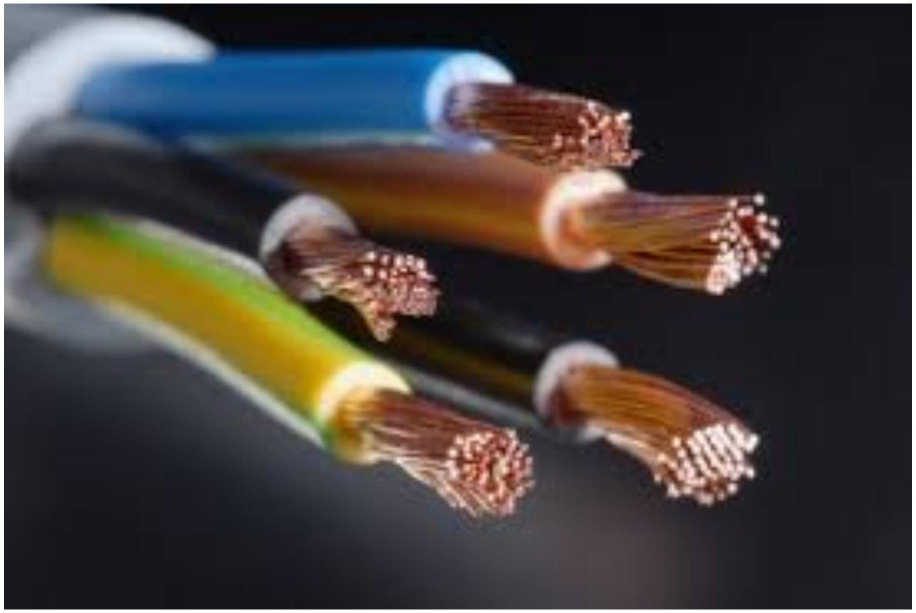
Conductors

- We generally are not able to control any of these properties (charge conduction, thermal conduction, or EM wave transmission) for naturally occurring materials;
- Materials that have a measured electrical resistivity of 1×10^{-6} ohm·m or lower are classified as conductors.

Examples of Conductors

- Good at letting current and heat flow.
- Good at conducting most parts of the EM spectrum.





Notes on Conductors

- Electrical conductivity and thermal conductivity are usually strongly correlated;
- It is very difficult to find a good electrical conductor and at the same time, a good thermal insulator;
- On the other hand, some good thermal conductors may be electrically insulating (e.g., diamond);
- You may want to consider these factors while carrying out electrical designs.

Semiconductors

- Definition:

  A substance, as silicon or germanium, with electrical conductivity intermediate between that of an insulator and a conductor; a basic component of various kinds of electronic circuit elements.

  http://dictionary.reference.com/browse/semiconductor?s=t

- Physical properties:
  - Resistivity that is somewhere between an insulator and a conductor;
  - Under certain circumstance it is good at conducting charge (current);
  - Not so good at conducting heat or most EM wavelengths;
  - Conductivity is controllable.

Semiconductors

- Materials that have a measured electrical resistivity of between 1×10^{-6} ohm·m and 1×10^{11} ohm·m are classified as semiconductors;
- These are manufactured and never found in nature.

Again, don’t take the resistivity range too seriously. Semiconductors are materials with their resistivity between conductors and insulators. However, where the cut-off points should be placed is often not a clear cut. For example, an intrinsic semiconductor at very low temperatures would behave much more like an insulator rather than a semiconductor.

Why are These Materials so Different?

- Due to bonding types:
  - Insulators usually have either covalent bonds or ionic bonds;
  - Conductors have metallic bonds;
  - Semiconductors often have covalent bonds (bonds in some semiconductors may have an ionic nature, e.g., GaAs).
- Due to energy levels and band gaps.
- Will now have a closer look at the different bonding types.
- Semiconductors are artificially created due to our understanding of the above.

Bonding

- There are 3 different types of bonding mechanisms found in materials:
  - Primary – Ionic and Covalent
  - Secondary – Intermolecular forces
    - Hydrogen bonding;
    - Dipole-dipole;
    - Dipole-induced dipole;
    - London Dispersion forces;
    - van der Waals forces.

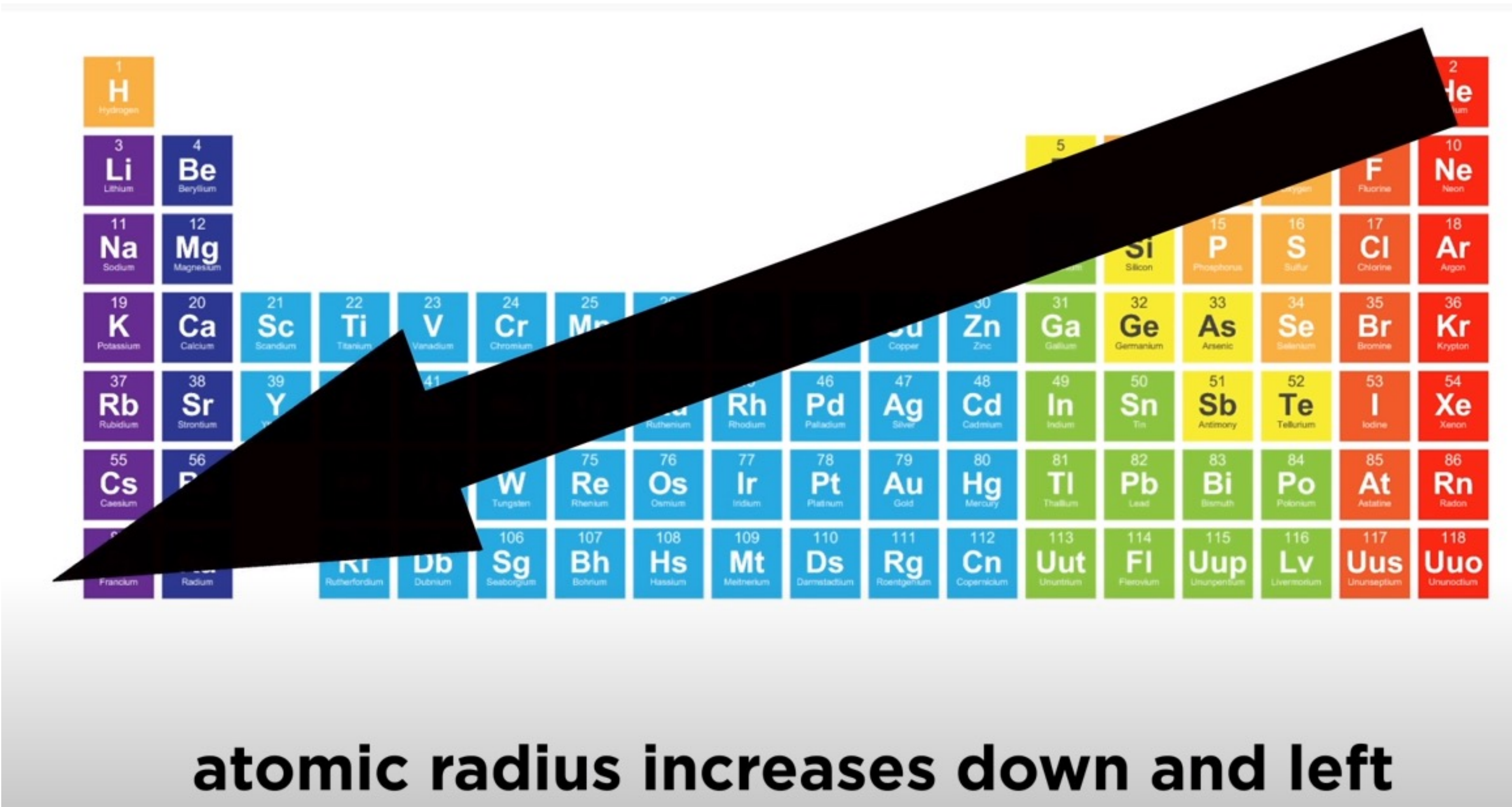
—Metallic Bonding

Strongest

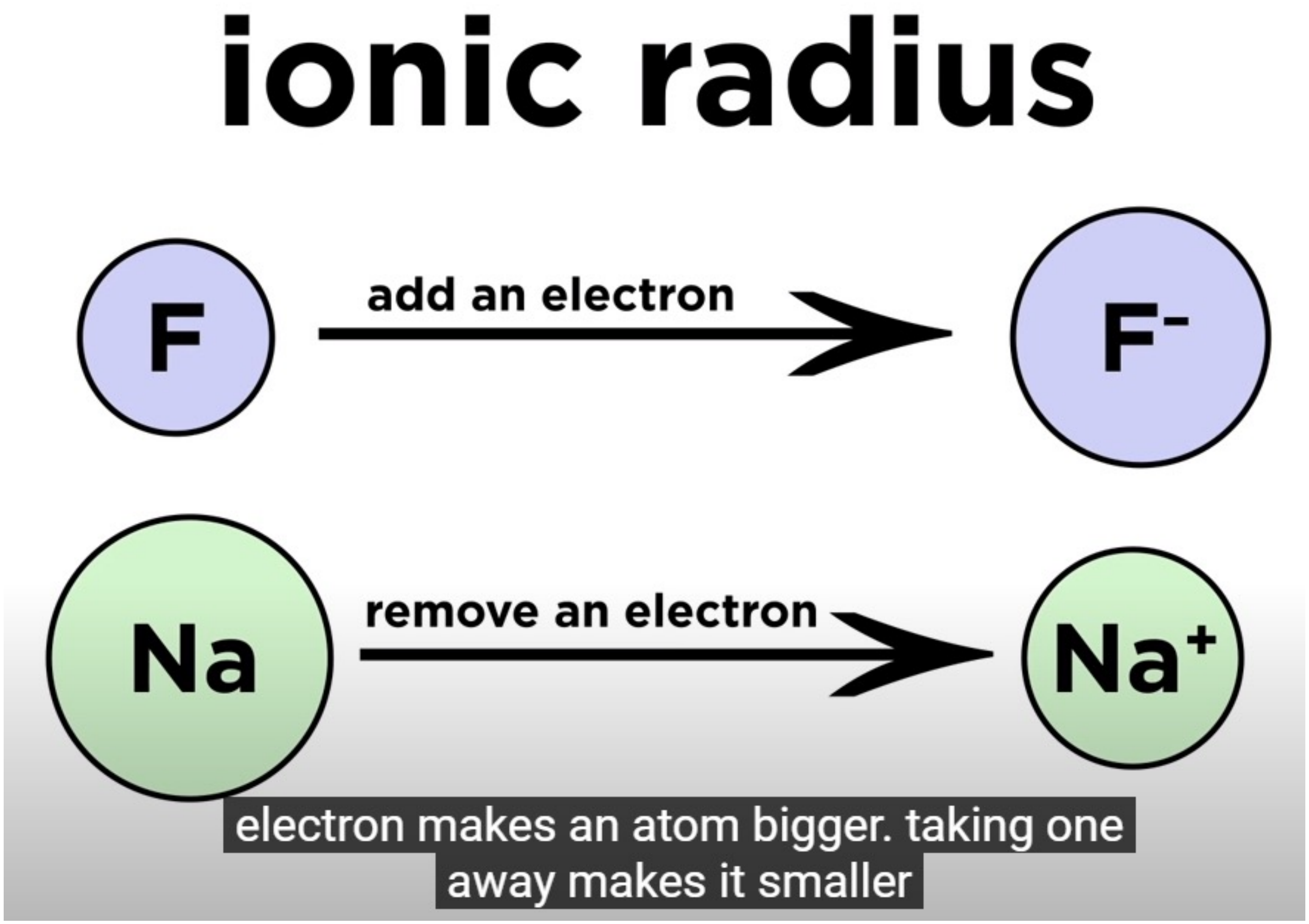
Weakest

Different

Atomic Radius

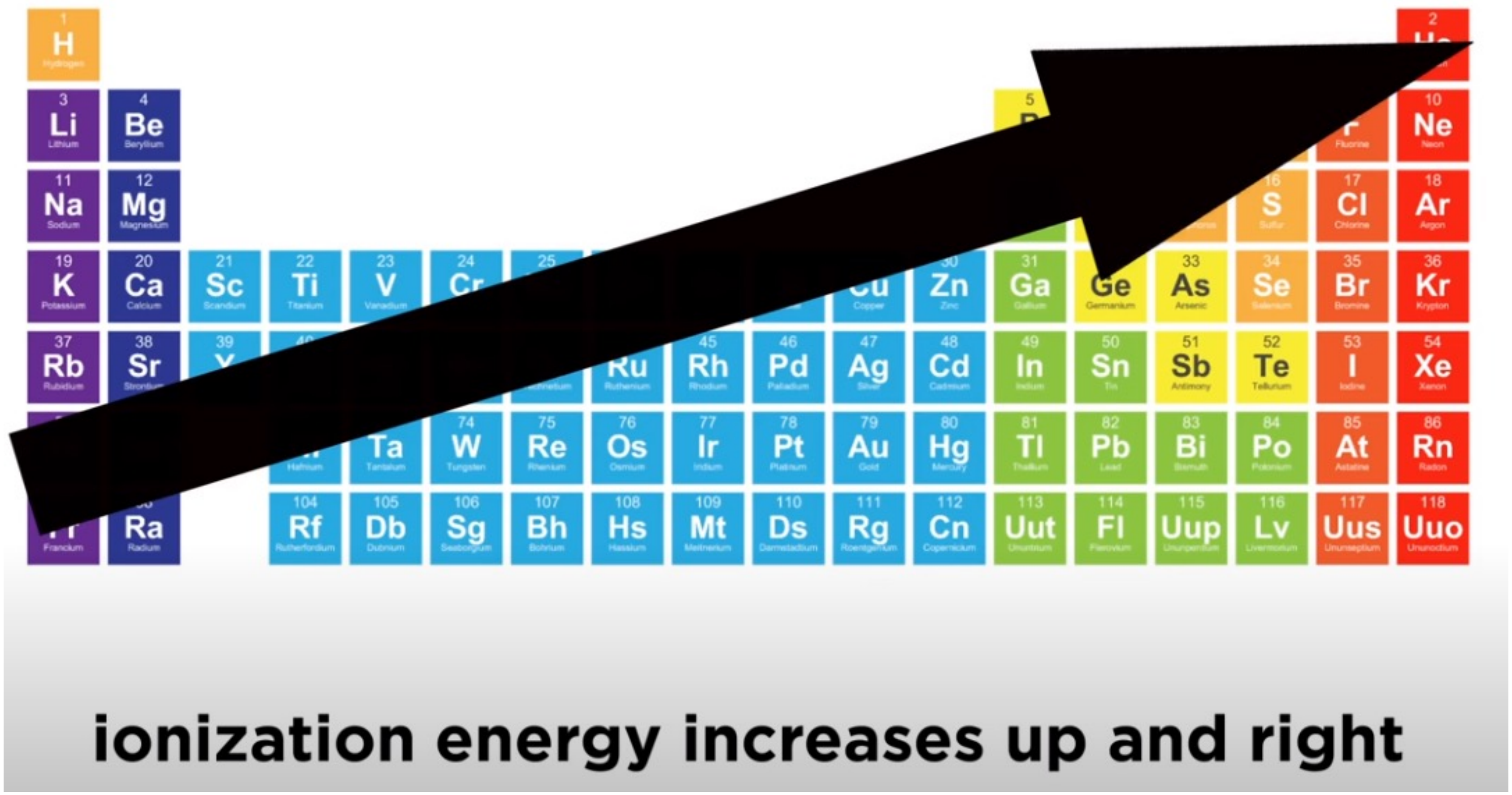


Ionic Radius



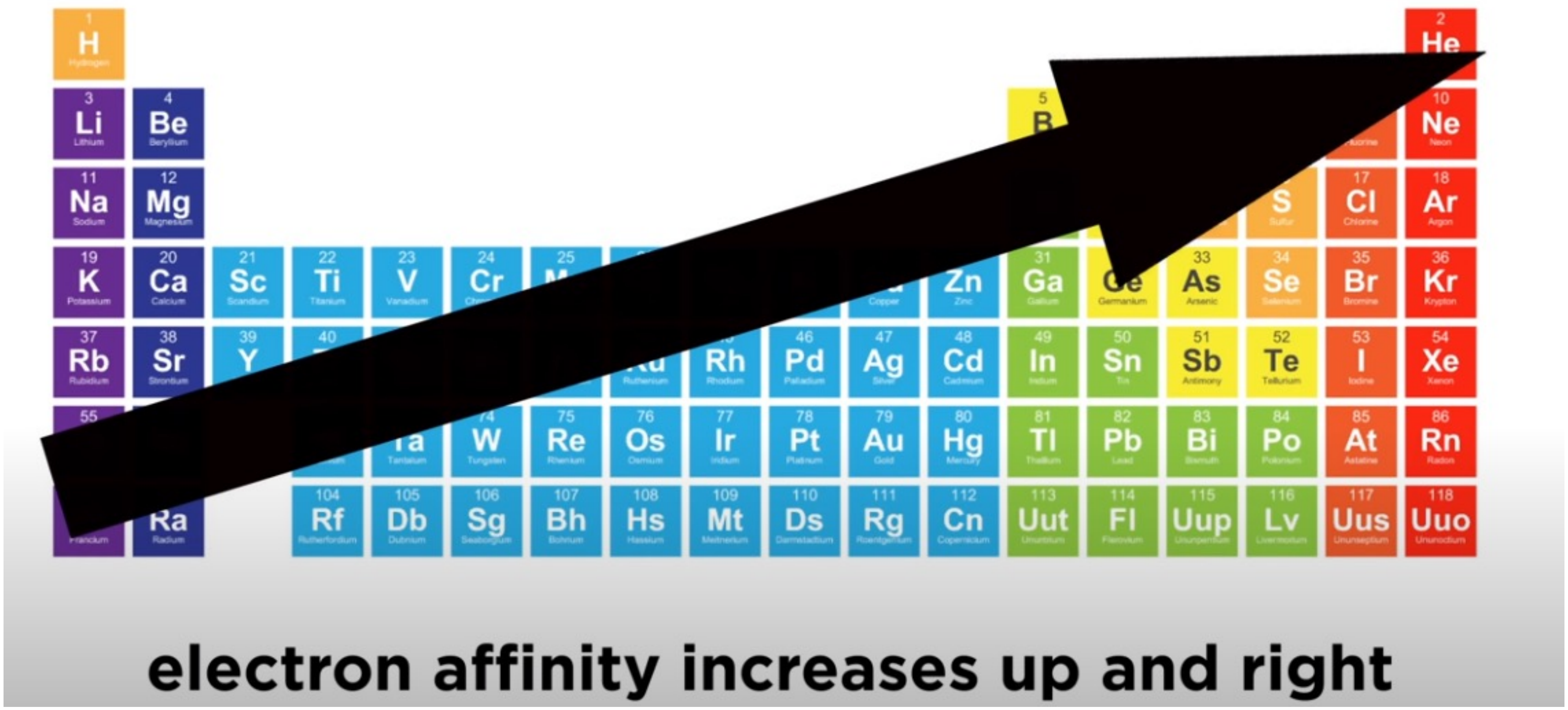
Ionisation Energy

- Ionisation energy: the energy required to remove an electron from an atom.



Electron Affinity

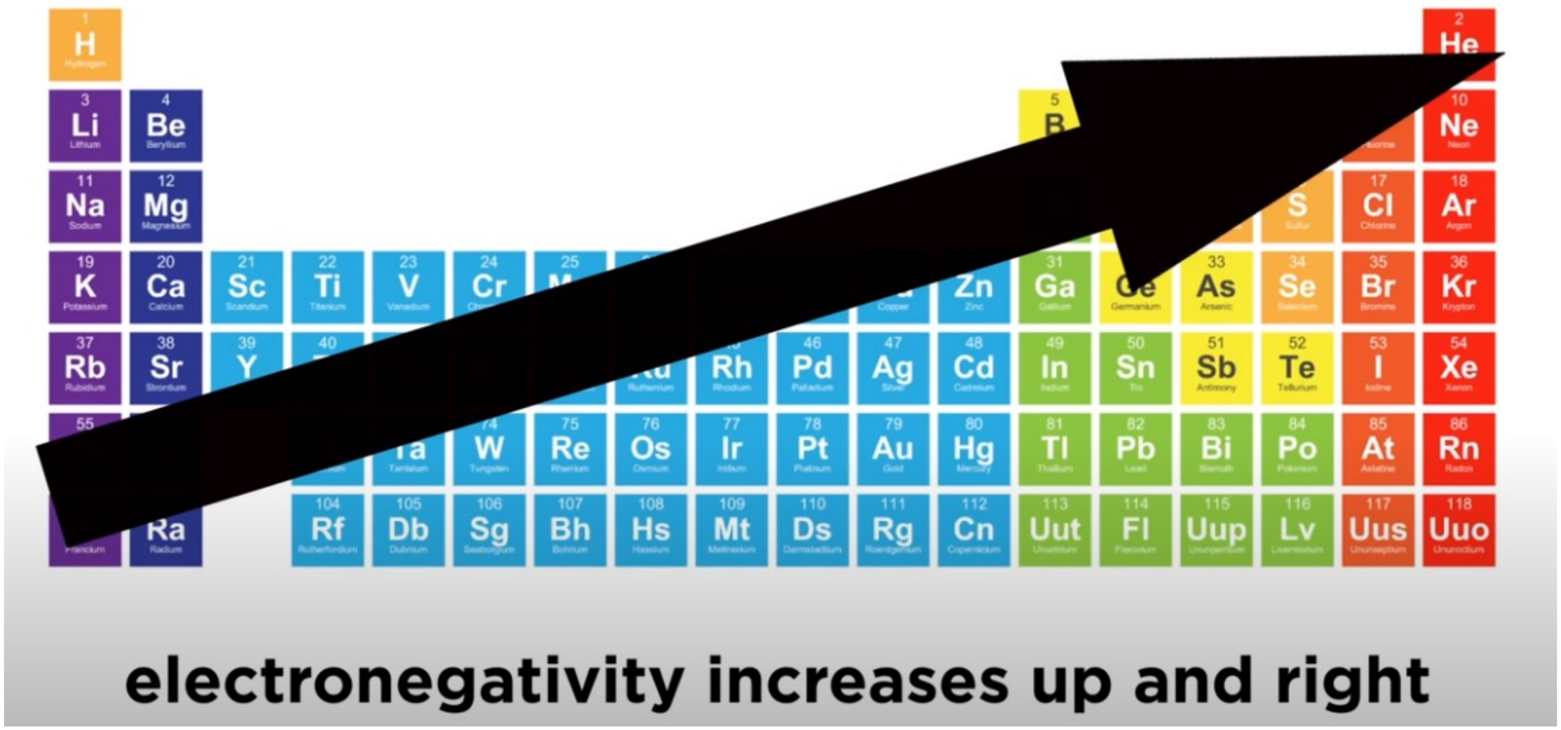
- Electron affinity: how much an atom wants to gain an electron.



Watch out! This excludes noble gases which do not want to gain or lose electrons.

Electronegativity

- Electronegativity: the ability of an atom to hold electrons tightly (an average of electron affinity and ionisation energy according to the Mulliken scale).

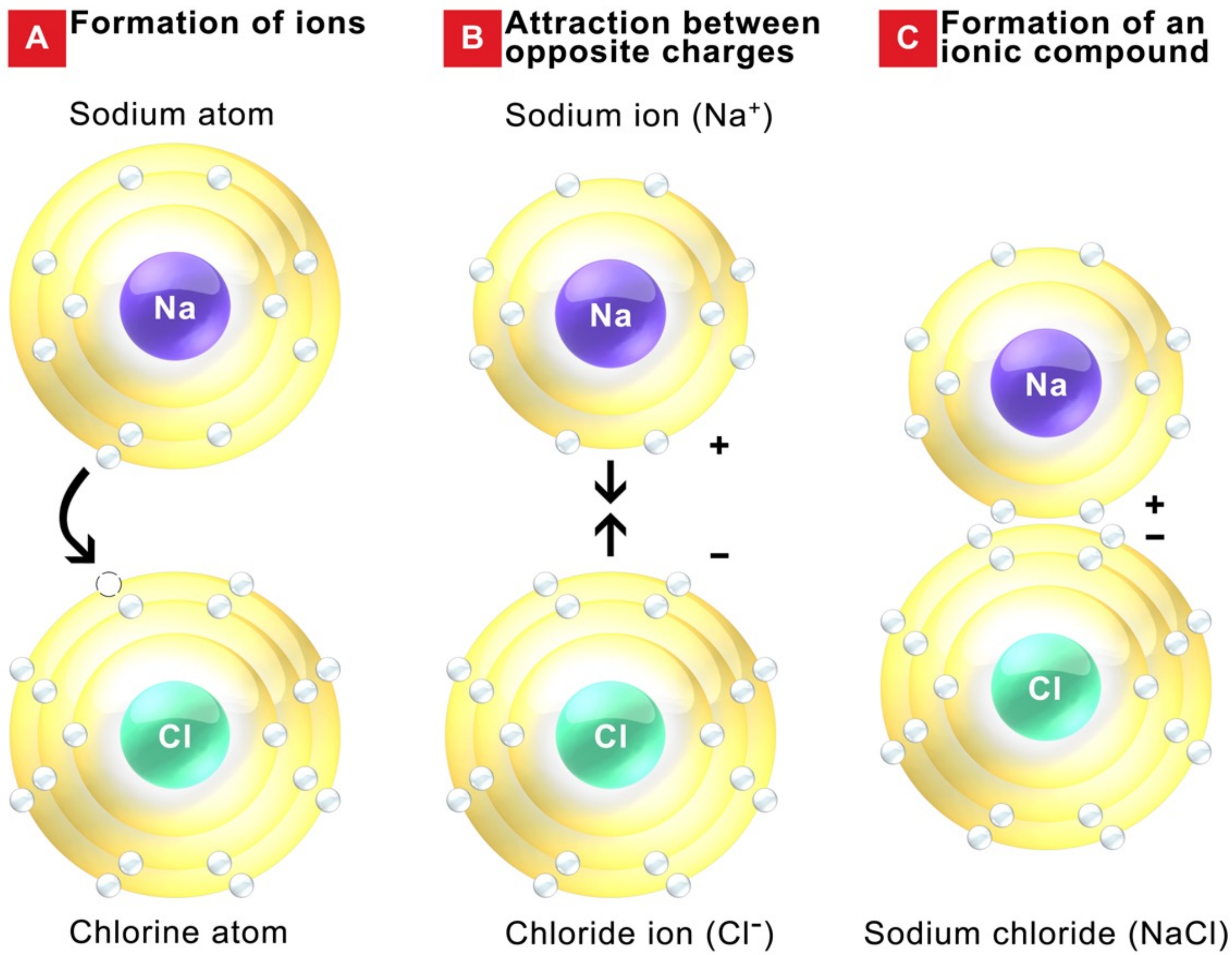


Watch out! This excludes noble gases which do not want to gain or lose electrons.

Ionic Bonds

- Occurs between oppositely charged ions;
- Bond is an electrostatic force;
- Forms crystalline solids;
- High melting and boiling points;
- Conduct electricity when in liquid form;
- Typically formed with elements at the opposite sides of the periodic table;
- One atom loses an electron while the other gains an electron.

Ionic Bonds

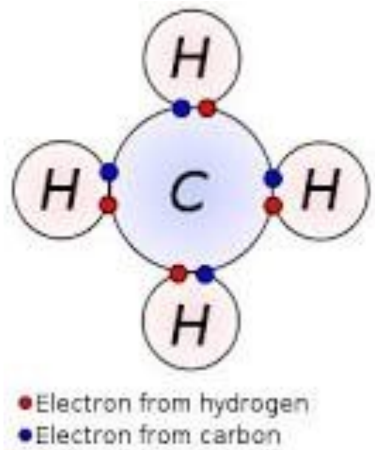


Formation of an Ionic Bond

Covalent Bonds

- Electrons are shared!
- Can be either gas, liquid or solid at RT;
- Can have either high melting and boiling points (covalently bonded network) or low melting and boiling points (discrete covalent molecules);
- Poor at conducting electricity in any state (with very few exceptions, e.g., graphite).

For interested folks, here is a great video:
https://youtu.be/LkAykOv1foc



Metallic Bonds

- Bonding within metals;
- Forces between delocalised electrons (conduction electrons) and positively charged metal ions;
- Strength due to electrostatic attraction of electrons and protons;
- Responsible for the physical properties of metals (thermal and electrical resistivity, strength, ductility, and opacity, etc).

Energy Band

- Electrons in single, isolated atoms occupy atomic orbitals which have discrete energy levels;
- When N atoms ($N \approx 10^{22}$) come together to form solids, each of their atomic orbitals splits into N discrete (molecular) orbitals whose energy levels are very closely spaced -> energy band.
- Energy band forms due to the Pauli exclusion principle (no two electrons in the solid can have exactly the same quantum numbers).

Energy Band: Quick Explanations

- Conduction band:

  Where you are most likely to find free electrons as charge carriers.

- Valence band:

  Where you are most likely to find holes as charge carriers.

- Fermi level:

  The point at which it is equally likely to find an electron or a hole as a charge carrier. We'll look at this in detail in coming lectures.

- Bandgap:

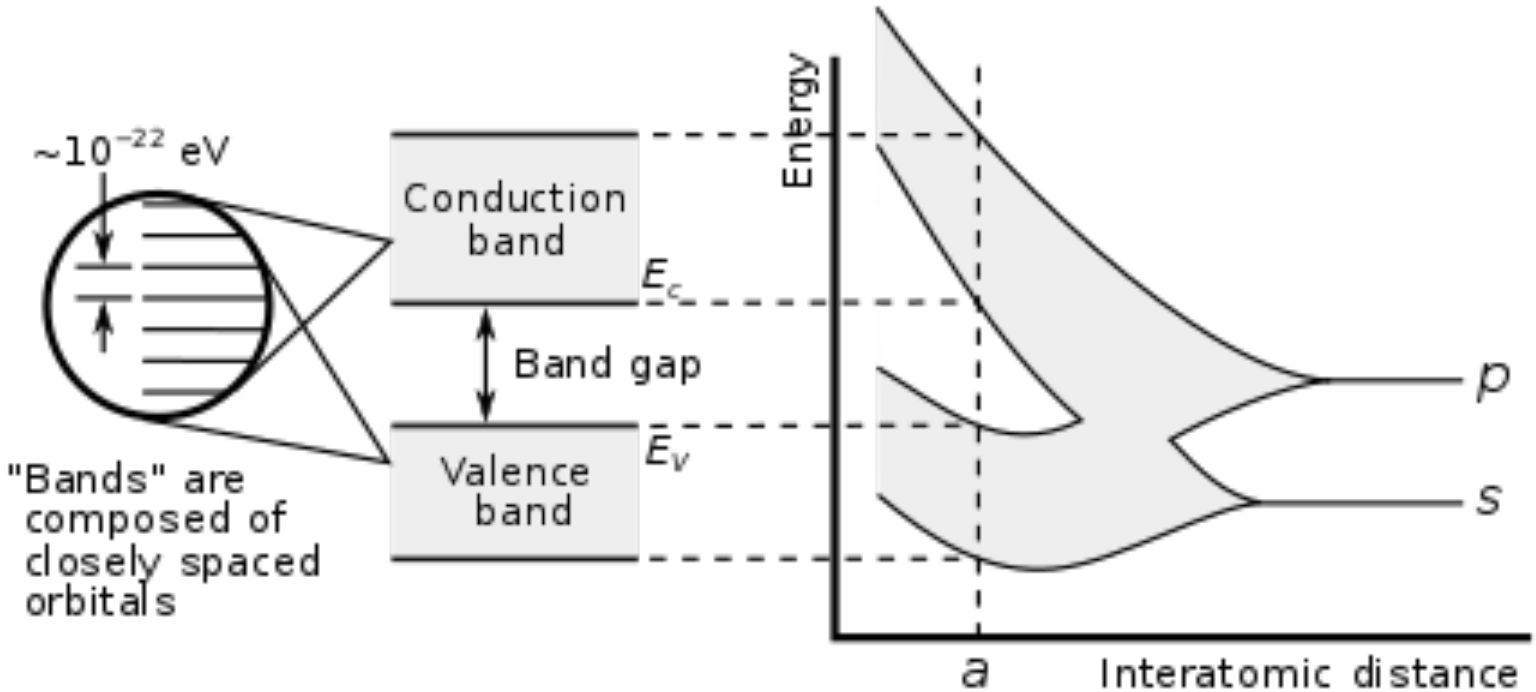
  The energy gap between the valence and conduction bands. Normally expressed in eV (electron volts, 1 eV = 1.602×10^{-19} J). Dependent on the base material used and the dopant added. More on this later.

Energy Diagrams & Bandgaps

- For conduction to take place there must be a net movement of charge;
- When a charge is accelerated, its kinetic energy increases. Thus, it has a higher total energy;
- An allowed energy level has to exist to accommodate this accelerated charge. Hence, fully filled bands cannot conduct;
- Energy bands that are of interest to our discussion are:
  - Valence band;
  - Conduction band.
- The energy difference between these bands is called the bandgap.

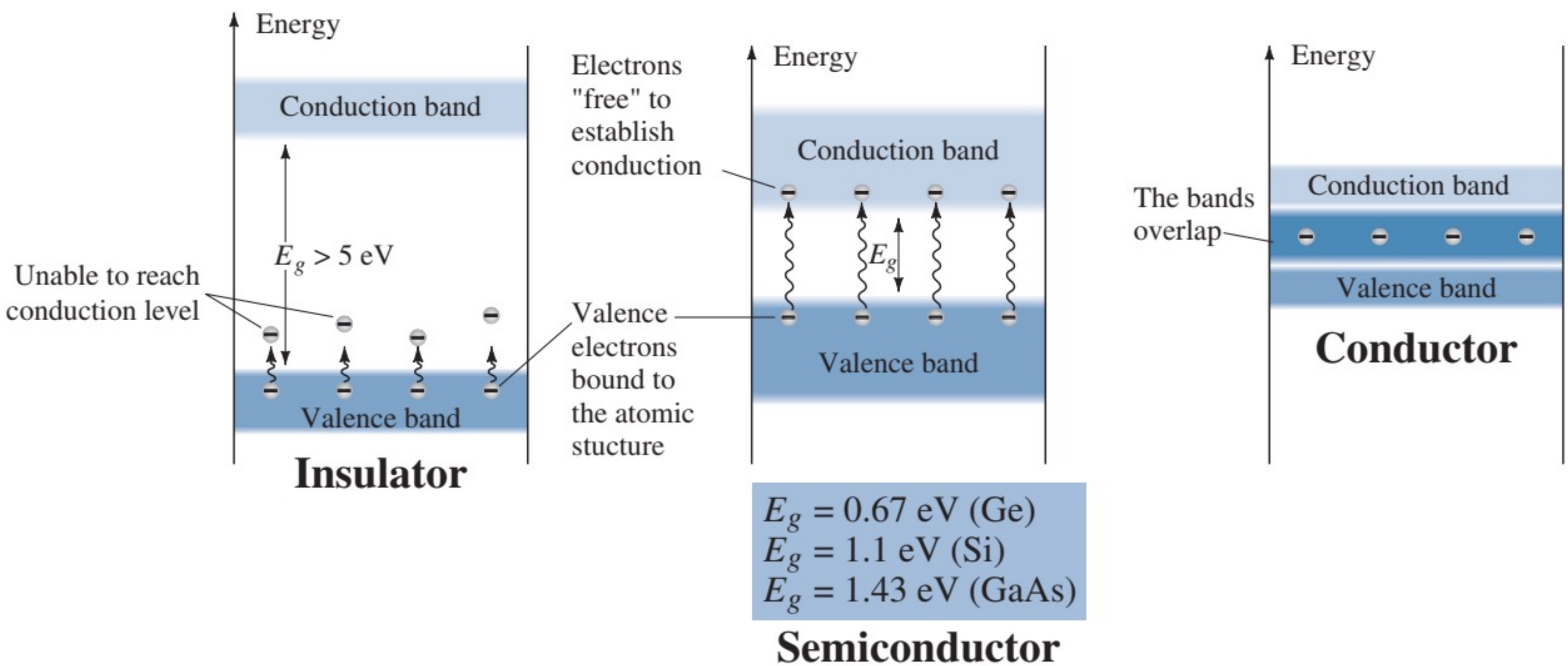
Bandgaps

- Bandgap is a range of energy in a solid where no electronic states can exist.

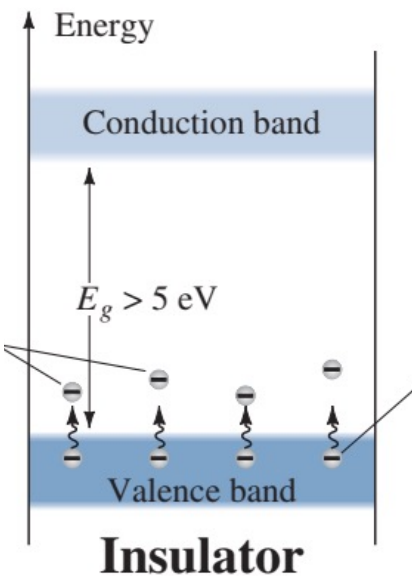


https://en.wikipedia.org/wiki/Electronic_band_structure

Bandgaps of Electronic Materials



Bandgaps: Insulators



Remember that we spoke of quantisation in an earlier lecture?

There are only discrete energy levels where electrons can exist and electron shells that need to be filled.

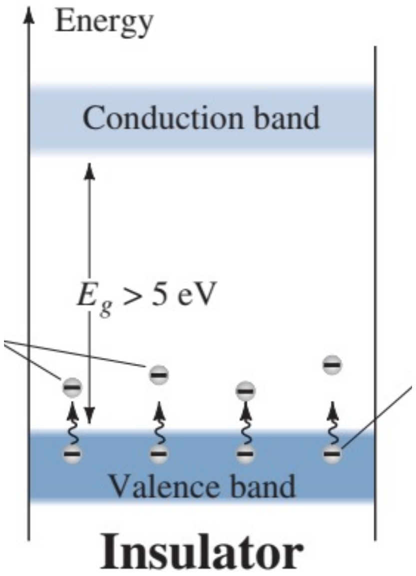
All of the available energy levels are filled in the valence band.

So in order for charge to flow, a charge carrier, let's say an electron, needs to move from the valence to the conduction band.

An electron must some how gain enough energy to move across the 'space' between the valence and conduction bands across the bandgap.

This movement is very difficult at RT!!

Bandgaps: Insulators



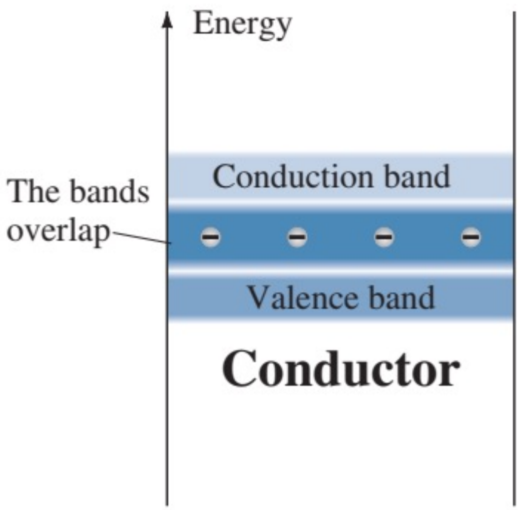
Why can't we get enough energy to cross the bandgap?

Simple answer – we can. ☺

But this is what happens – destruction of the insulator.

Not a useful effect for us.

Bandgaps: Conductors



No bandgap here.

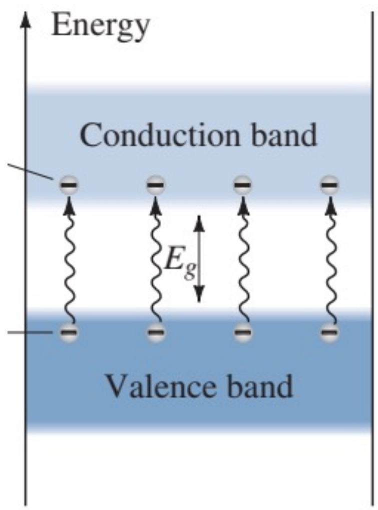
In fact there is an overlap of the conduction and valence bands.

No need to move charge carriers from the valence to the conduction bands!

Essentially free movement of charge, and everything else, too.

This can cause other issues but we don't care about this at the moment.

Bandgaps: Semiconductors



$E_g = 0.67$ eV (Ge)
$E_g = 1.1$ eV (Si)
$E_g = 1.43$ eV (GaAs)

Semiconductor

The valence and conduction bands are separated but by a smaller bandgap than that in an insulator.

There’s that Fermi level again – more on that soon.

Bandgap is tunable, to a reasonable level, but small enough to be useable without destroying the material.

In other words, we can control, to a reasonable degree the amount of movement of charge carriers.

We will be looking at semiconductors in more detail and doing calculations in relation to bandgaps in upcoming classes.