

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.



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;

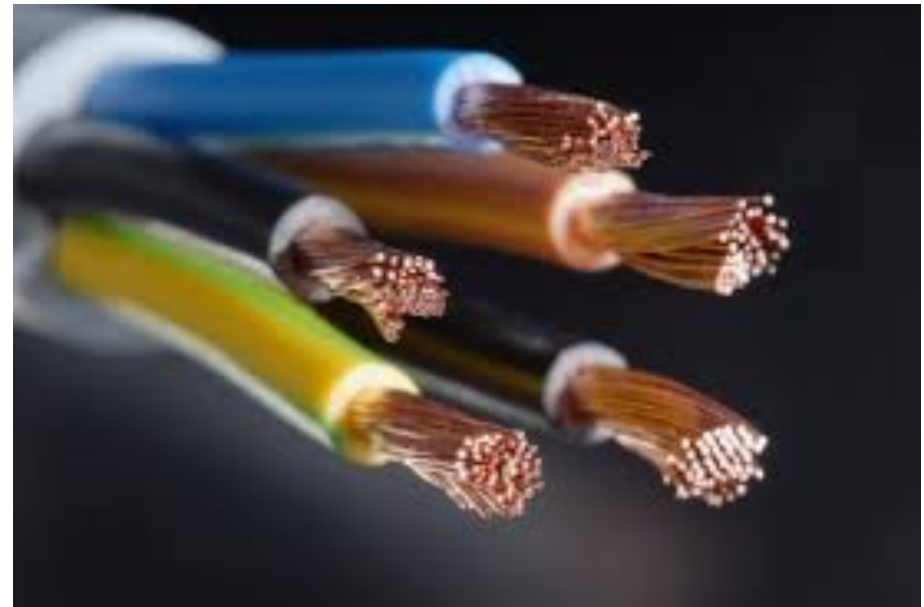
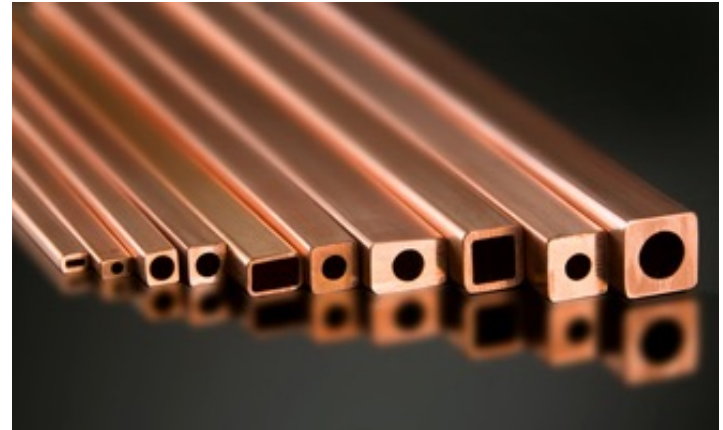
- Good conductors are normally metallic.

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 $1 \times 10^{-6} \text{ ohm}\cdot\text{m}$ and $1 \times 10^{11} \text{ ohm}\cdot\text{m}$ 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?

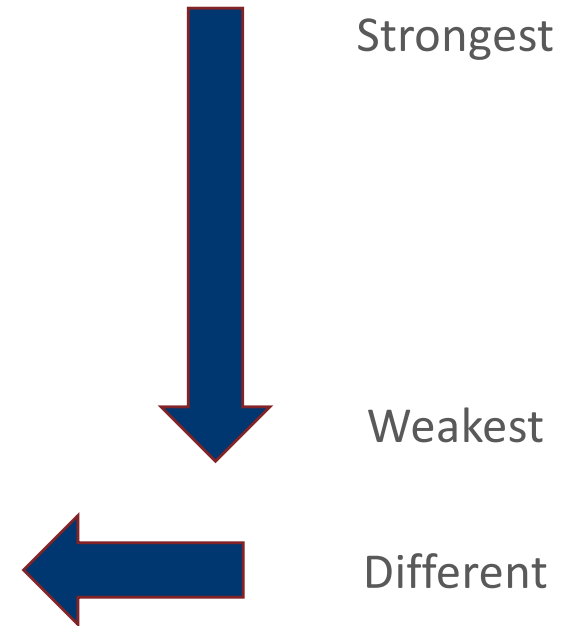
- Due to bonding types:
 - Insulators usually have either covalent bonds or ionic bonds;
 - Conductors have metallic bonds;
 - Semiconductors often have covalent bonds (bonds in some semiconductors may have an ionic nature, e.g., GaAs).
- Due to energy levels and band gaps.
- Will now have a closer look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

Bonding

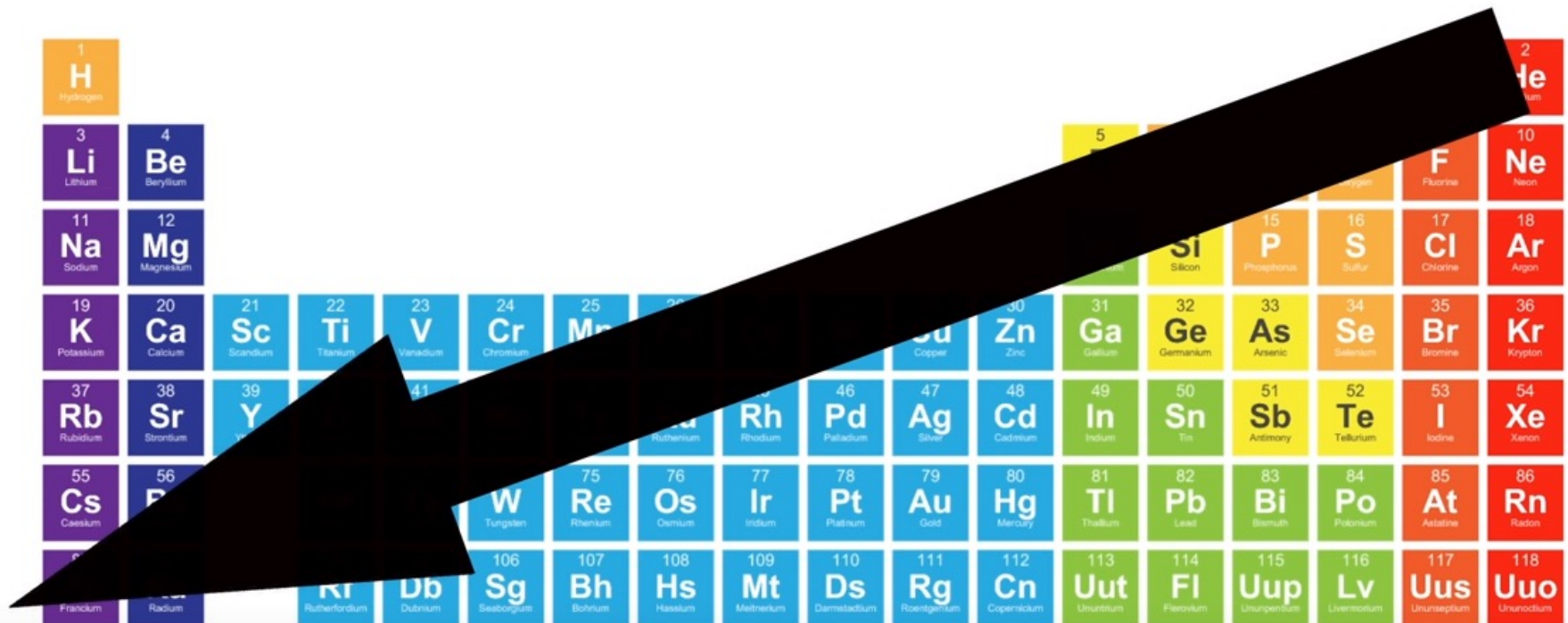
- There are 3 different types of bonding mechanisms found in materials:

- Primary – Ionic and Covalent
- Secondary – Intermolecular forces
 - Hydrogen bonding;
 - Dipole-dipole;
 - Dipole-induced dipole;
 - London Dispersion forces;
 - van der Waals forces.

—Metallic Bonding



Atomic Radius



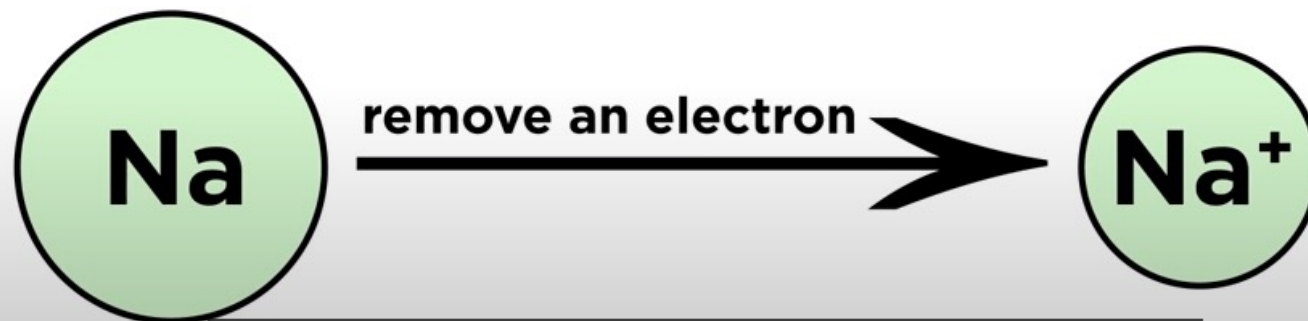
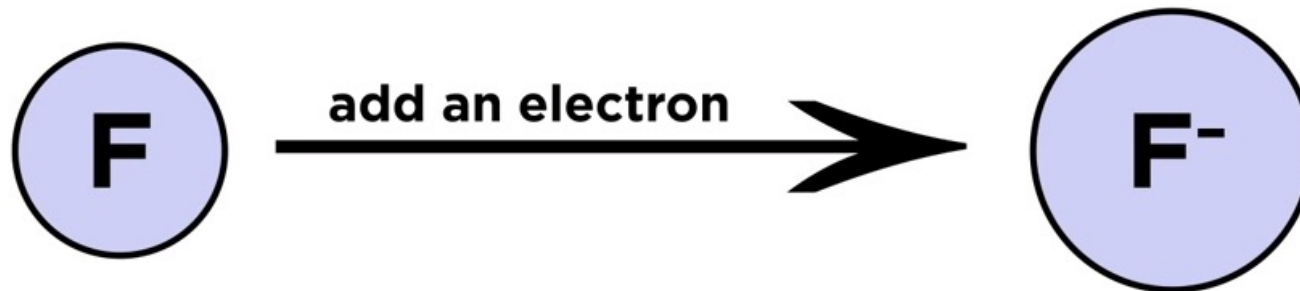
A periodic table of elements is shown, with a large black arrow pointing from the top right towards the bottom left. The arrow indicates the direction in which atomic radius increases. The elements are arranged in rows and columns, with their atomic numbers and names displayed. The colors of the elements are: Hydrogen (orange), Helium (red), Lithium (purple), Beryllium (blue), Boron (green), Carbon (yellow), Nitrogen (orange), Oxygen (red), Fluorine (red), Neon (red), Sodium (purple), Magnesium (blue), Aluminum (green), Silicon (yellow), Phosphorus (orange), Sulfur (red), Chlorine (red), Argon (red), Potassium (purple), Calcium (blue), Scandium (blue), Titanium (blue), Vanadium (blue), Chromium (blue), Manganese (blue), Iron (blue), Cobalt (blue), Nickel (blue), Copper (blue), Zinc (blue), Gallium (green), Germanium (yellow), Arsenic (orange), Selenium (red), Bromine (red), Krypton (red), Rubidium (purple), Strontium (blue), Yttrium (blue), Zirconium (blue), Niobium (blue), Molybdenum (blue), Technetium (blue), Ruthenium (blue), Rhodium (blue), Palladium (blue), Silver (blue), Cadmium (blue), Indium (green), Tin (yellow), Antimony (orange), Tellurium (red), Iodine (red), Xenon (red), Cesium (purple), Barium (blue), Lanthanum (blue), Cerium (blue), Praseodymium (blue), Neodymium (blue), Promethium (blue), Samarium (blue), Europium (blue), Gadolinium (blue), Terbium (blue), Dysprosium (blue), Holmium (blue), Erbium (blue), Thulium (blue), Ytterbium (blue), Lutetium (blue), Hafnium (blue), Tantalum (blue), Tungsten (blue), Rhenium (blue), Osmium (blue), Iridium (blue), Platinum (blue), Gold (blue), Mercury (blue), Thallium (green), Lead (green), Bismuth (green), Polonium (red), Astatine (red), Radon (red), Francium (purple), Radium (blue), Actinium (blue), Thorium (blue), Protactinium (blue), Uranium (blue), Neptunium (blue), Plutonium (blue), Americium (blue), Curium (blue), Bk (blue), Cf (blue), Es (blue), Fm (blue), Md (blue), No (blue), Lr (blue), Rf (blue), Db (blue), Sg (blue), Bh (blue), Hs (blue), Mt (blue), Ds (blue), Rg (blue), Cn (blue), Uut (green), Fl (green), Uup (green), Lv (green), Uus (red), Uuo (red).

1 H Hydrogen																		2 He Helium													
3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon														
11 Na Sodium	12 Mg Magnesium											13 Al Aluminum	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon														
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton														
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon														
55 Cs Caesium	56 Ba Barium	57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Cn Copernicium	113 Uut Ununtrium	114 Fl Flerovium	115 Uup Ununpentium	116 Lv Livermorium	117 Uus Ununseptium	118 Uuo Ununoctium

atomic radius increases down and left

Ionic Radius

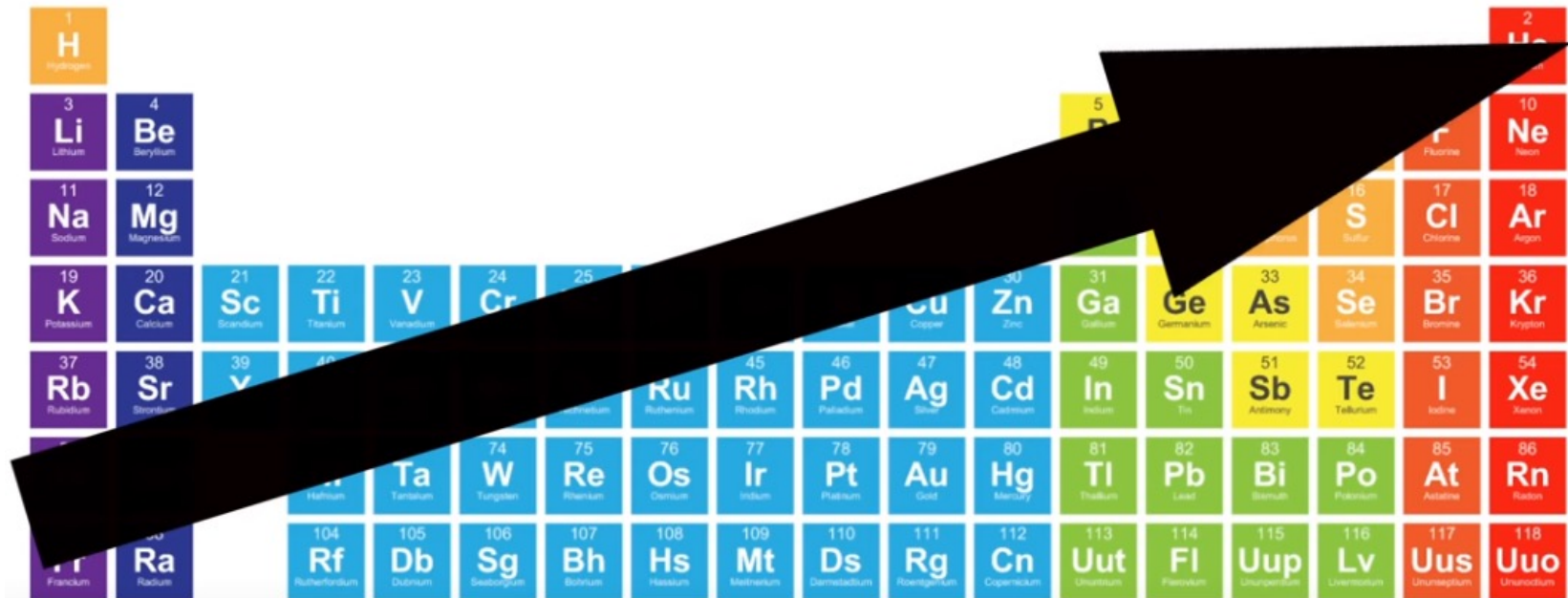
ionic radius



electron makes an atom bigger. taking one
away makes it smaller

Ionisation Energy

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

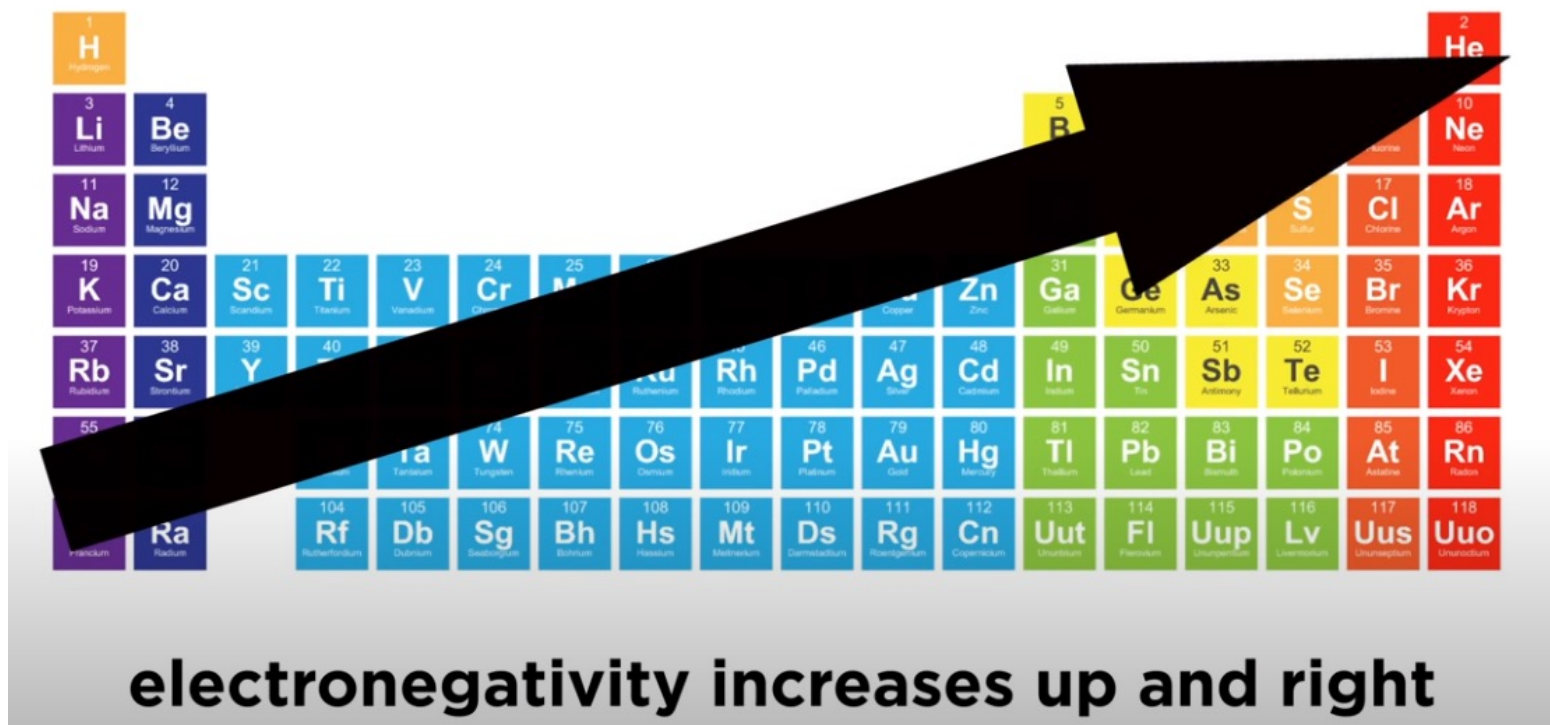


ionization energy increases up and right



Electronegativity

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



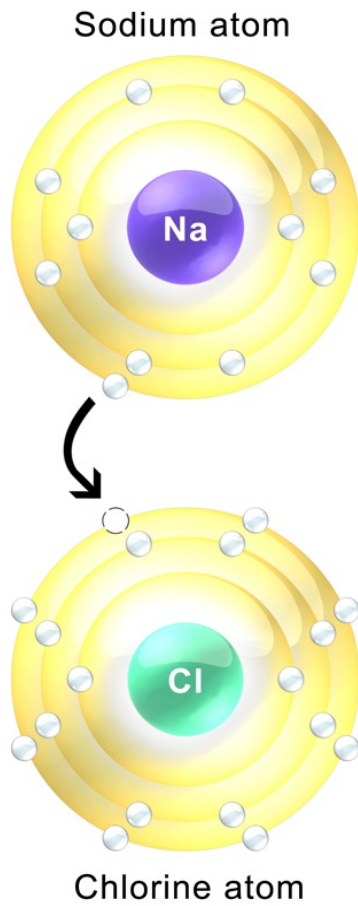
Watch out! This excludes noble gases which do not want to gain or lose electrons. 21

Ionic Bonds

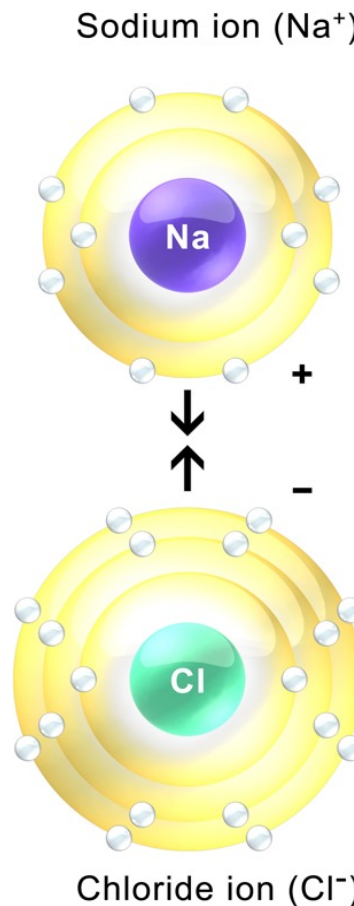
- Occurs between oppositely charged ions;
- Bond is an electrostatic force;
- Forms crystalline solids;
- High melting and boiling points;
- Conduct electricity when in liquid form;
- Typically formed with elements at the opposite sides of the periodic table;
- One atom loses an electron while the other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

Ionic Bonds

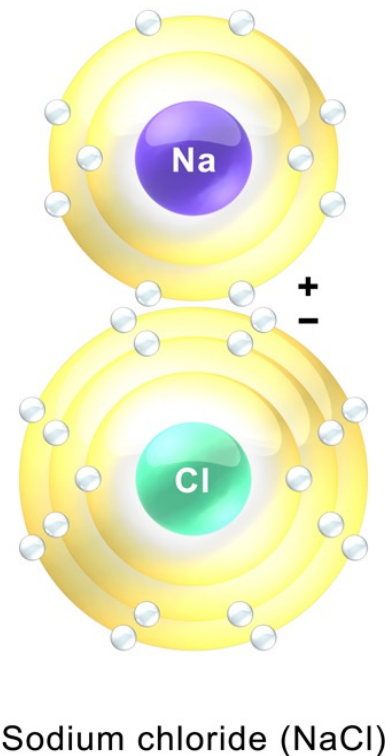
A Formation of ions



B Attraction between opposite charges



C Formation of an ionic compound

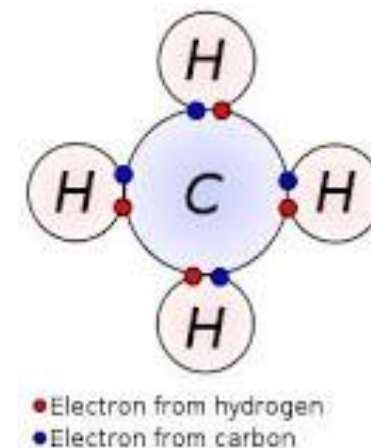


Formation of an Ionic Bond

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:**

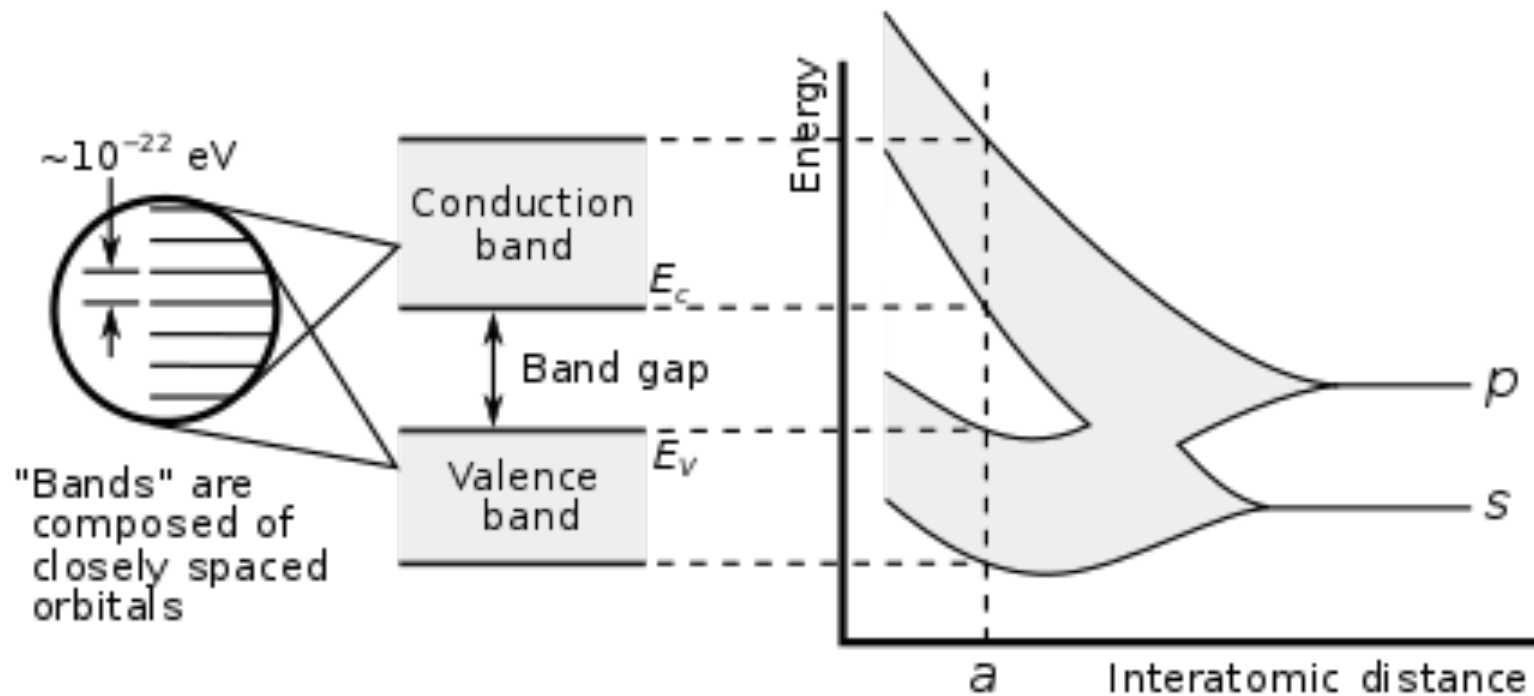
The energy gap between the valence and conduction bands. Normally expressed in eV (electron volts, $1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$). Dependent on the base material used and the dopant added. More on this later.

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**.

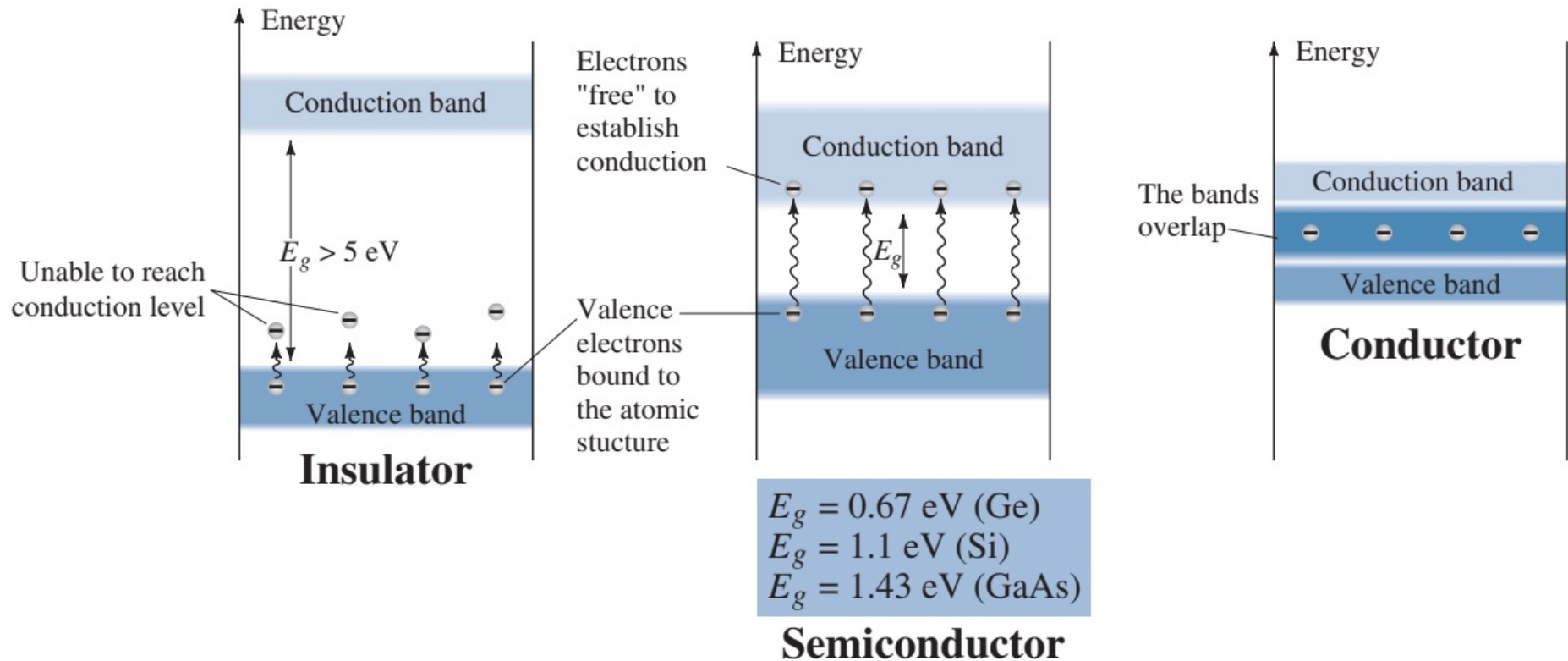
Bandgaps

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

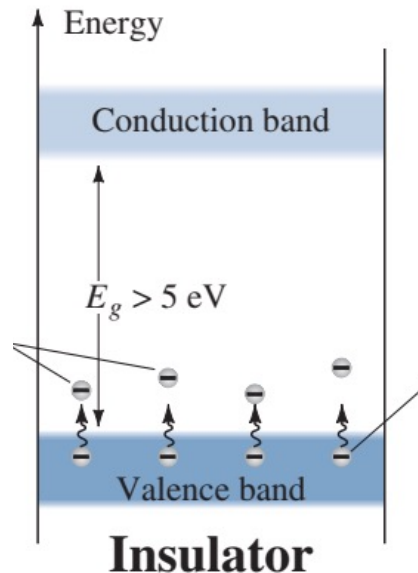


https://en.wikipedia.org/wiki/Electronic_band_structure

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.

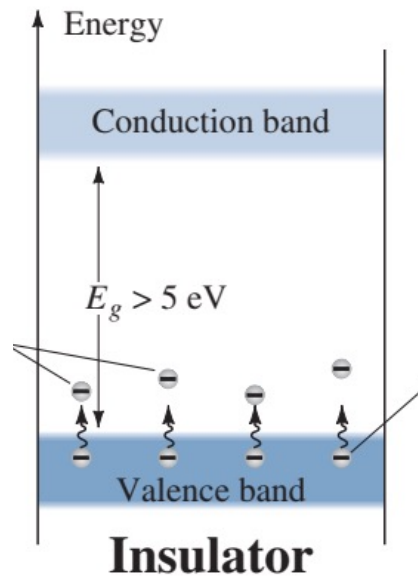
All of the available energy levels are filled in the valence band.

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 somehow 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?

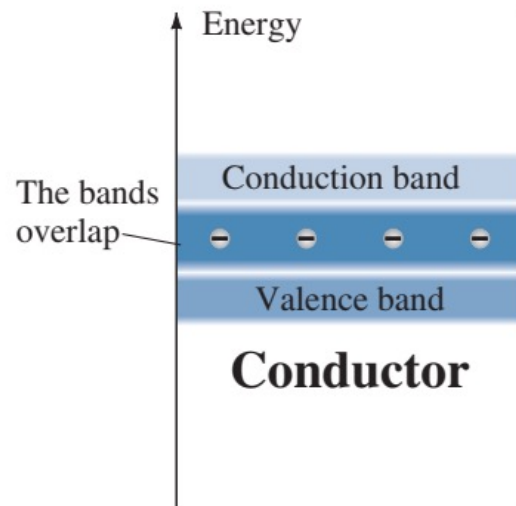
Simple answer – we can. 😊

But this is what happens – destruction of the insulator.

Not a useful effect for us.



Bandgaps: Conductors



No bandgap here.

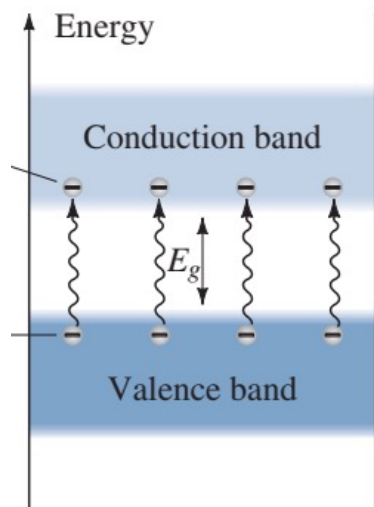
In fact there is an overlap of the conduction and valence bands.

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



$E_g = 0.67 \text{ eV (Ge)}$
 $E_g = 1.1 \text{ eV (Si)}$
 $E_g = 1.43 \text{ eV (GaAs)}$

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.