XMUT204 Electronic Design

Note 1a: Introduction to Semiconductors

1. Introduction

In the other introductory to electronics related courses, we often learn the basic properties and characteristics of circuits. In doing so, we have treated the circuit essentially as a “black box”, i.e. we did not take any notice of the components from which a circuit is constructed, but were only concerned with the signals going in and coming out of the circuit. In the second part of the course, we will now start looking at the components (diodes and transistors) that make up the basic building blocks of circuits or other integrated circuits.

In order to understand the operation of devices such as diodes, transistors or solar cells, it is essential to also have a basic understanding of the characteristics and the properties of the semiconductor materials that these devices are made from. In this first chapter, we will look at the fundamental properties of semiconductors, with focus on the silicon (Si), the most commonly used semiconductor material.

Our first exploration of semiconductors will be a relatively simplistic one, we will simply look at the bonding between Si atoms and how the substitution of some Si atoms with selected impurity atoms will produce free electrical carriers which can be positive or negative in charge. It is the controlled presence of these free charge carriers that gives semiconductors their properties that can be so effectively utilised in the many different types of electronic devices.

However, this approach of looking at semiconductor properties largely ignore the important concept of carrier energies which is essential for a more complete understanding of device operation and we will return to this topic in a more advanced course (ECEN 330).

2. Insulators – Semiconductors – Conductors

Probably the most important classification of materials to the electronic engineer is the classification of the ability to conduct electricity. Using this classification scheme, we can classify all materials into one the three groups of insulators, semiconductors or conductors.

According to Ohm’s law, the electrical resistance of a material (R) is described by the ratio of the applied potential difference (V) between two points and the electrical current (I) that flows due to this applied voltage.

$$R = \frac{V}{I}$$

The resistance of a piece of wire with a cross sectional area A and a length L can also be written in terms of the electrical resistivity ρ of the material as:

$$R = \frac{\rho L}{A} \qquad \text{or} \qquad \rho = \frac{RA}{L}$$

Where: ρ is the so called electrical resistivity (units = Ω.m). This property is a characteristic of a particular material and the value of this property will thus determine the electrical resistance of the material, with a high value of resistivity then producing a high electrical resistance and vice versa.

It is sometimes easier to work with electrical conductivity rather resistivity and the electrical conductivity σ (units = $(\Omega.m)^{-1}$) is simply the inverse of resistivity, so that:

$$\sigma = \frac{1}{\rho} = \frac{L}{RA}$$

The greater the value of the conductivity then, the greater the ability of the material to conduct electricity. In Figure 1, the electrical conductivity is shown for different materials, indicating the somewhat arbitrary boundaries between conductors, semiconductors and insulators.

The first point that is evident in this figure is the huge range of values that the resistivity or conductivity can span; with conductivity values ranging from 10^{-18} $(\Omega.m)^{-1}$ for insulators to 10^{12} $(\Omega.m)^{-1}$ for superconductors, thus spanning approximately 30 orders of magnitude!

Even if we just look at the grouping of materials classified as semiconductors we see that the values of conductivity range from ~ 10^{-8} $(\Omega.m)^{-1}$ to ~ 10^{2} $(\Omega.m)^{-1}$ – still a variation of ten orders of magnitude!

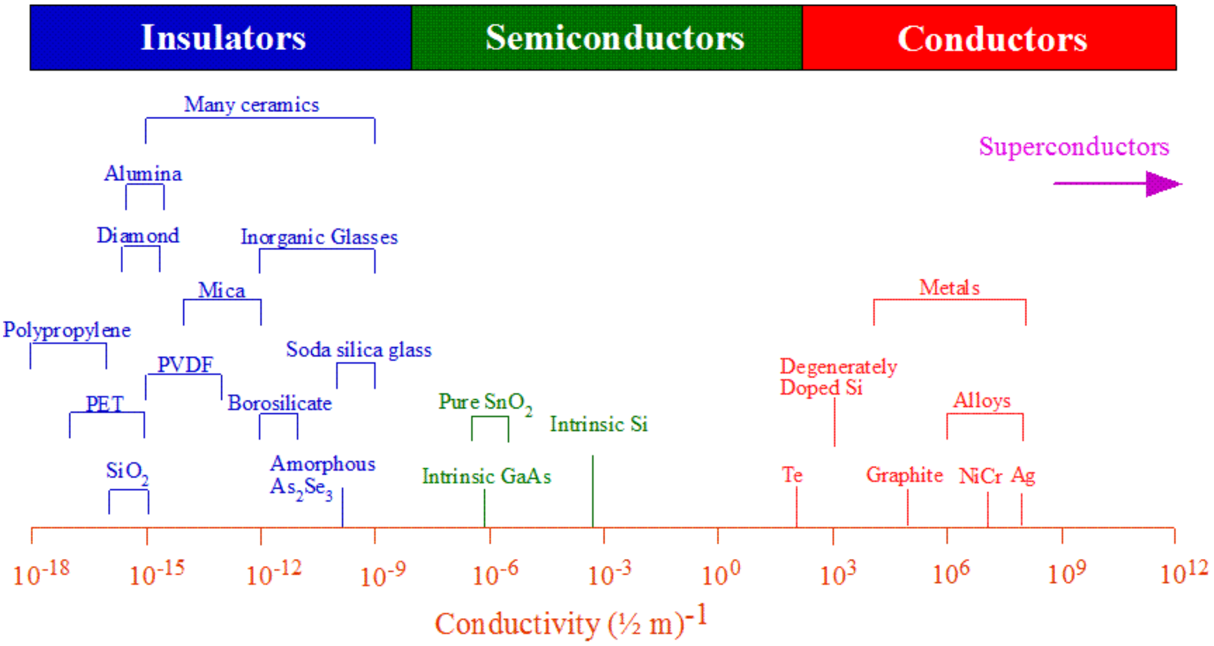


Figure 1: The conductivities of various materials.

An expression for the electrical conductivity of a material is given by:

$$\sigma = ne\mu$$

where: *n* is the density of mobile charge carriers, *e* is the electrical charge on a charge carrier and *μ* is the so-called mobility, a measure of the ease with which a charge carrier can move in an applied electric field. Of these three factors, it is the value of *n* (the number of charge carriers per unit volume) that is the most important in determining the value of the conductivity.

Table 1: Resistivity and conductivity of various materials

Material	Resistivity	Conductivity
C (Graphite)	1.0×10^{-8}	1.0×10^{8}
Ag	1.6×10^{-8}	6.3×10^{7}
Cu	1.7×10^{-8}	5.9×10^{7}
Au	2.4×10^{-8}	4.2×10^{7}
Al	2.7×10^{-8}	3.7×10^{7}
Fe	9.7×10^{-8}	1.0×10^{7}
C (Amorphous)	5.0×10^{-4}	2.0×10^{3}
Si (Pure)	6.4×10^{2}	1.6×10^{3}
Glass (Silica)	1.0×10^{11}	1.0×10^{-11}
C (Diamond)	1.0×10^{12}	1.0×10^{-12}
Teflon	1.0×10^{24}	1.0×10^{-24}

Example for Tutorial 1:

1. What is the resistance of an Aluminium wire that has diameter of 2 mm and length of 10 m? Note that an Aluminium has resistivity coefficient, $\rho = 2.65 \times 10^{-8}\ \Omega\text{m}$.

[2.5 marks]

Answer:

Resistance of the material, R is calculated from:

$$R = \frac{\rho L}{A} = \frac{L}{\sigma A}$$

Cross sectional area of the round wire (A) with a radius of r is calculated from:

$$A = \pi(r)^2$$

Putting in the values to the equation: (2.5)

$$R = \frac{(2.65 \times 10^{-8})(10)}{\pi(1 \times 10^{-3})^2} = 8.44 \times 10^{-2}\ \Omega/\mathrm{m}$$

2. Calculate the electrical conductivity of the material of a conductor of length 3 m, area of cross section 0.02 mm^2 having a resistance of 20 Ω. [2.5 marks]

Answer

For the given conductor, its resistance is calculated from:

$$R = \frac{\rho l}{A}$$

Rearrange the equation above, the resistivity of the conductor is:

$$\rho = \frac{RA}{l} = \frac{(20)(2 \times 10^{-5})}{3} = 13.33 \times 10^{-5}\ \Omega\mathrm{m}$$

Since resistivity of the conductor ρ is 13.33×10^{-5} Ωm, the electrical conductivity of the conductor is:

$$\sigma = \frac{1}{\rho} = \frac{1}{13.33 \times 10^{-5}} = 0.075\ \mathrm{S/m}$$

In the next section, we will now look at the classification of materials into three broad classes based on the number of available electrical charge carriers.

3. The band structure of materials

The above classification of materials into three broad groups depending on their electrical conductivity can be explained by a brief introduction to the concepts of energy bands of a material. The energy band model of solids is based on quantum mechanical concepts and considers the interaction of the atomic orbitals when individual atoms are brought together to form a solid. As the atoms approach each other, the individual orbitals interact and spilt into energy bands, with individual bands separated by a forbidden energy region – an energy gap.

Within each of the allowed energy bands, an electron can take on a near-continuous distribution of energies. It is the structure of the outer two (highest energy) bands and how they are filled by electrons that are crucial in determining the electrical conductivity of a solid. In Figure 2, the energy band structure of insulators, semiconductors and conductors are explained by looking at the two outer energy bands at 0° K (absolute zero of temperature).

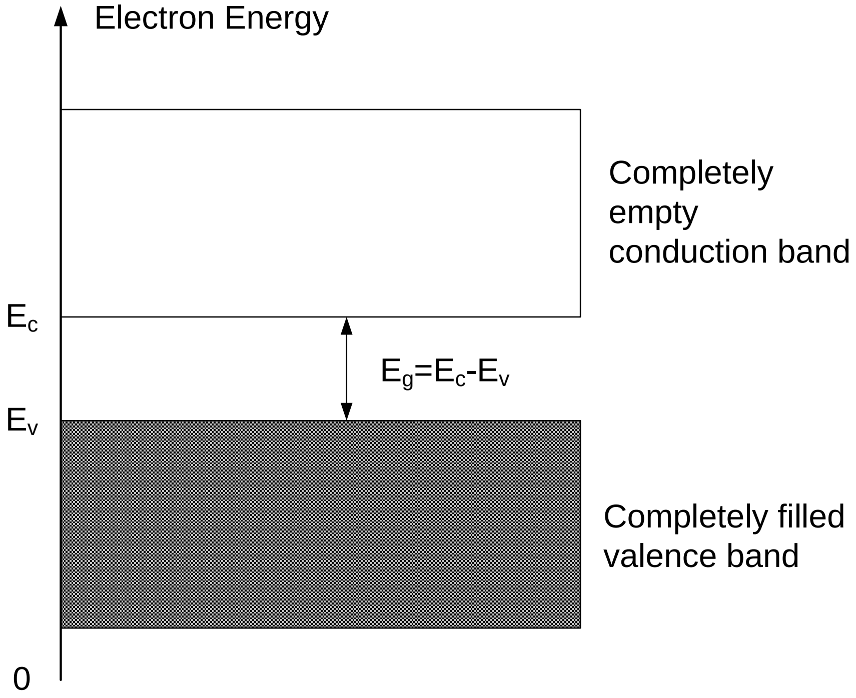


Figure 2: The electron energy band structure of a solid material, showing a completely filled valence band and a completely empty conduction band at low temperatures (~ 0° K). The conduction band is separated from the valence band by a forbidden energy gap Eg.

From this figure, we have the following observations:

- At 0° K the highest completely filled band is termed the valence band and the top of the valence band is denoted by energy E_v. Electrons occupying this energy band cannot take part in electrical conduction as they are strong bound to the host atoms. Perhaps another way of thinking about this is that this band is completely filled, thus no room for electrons to move and thus no electrical conductivity from this band.

- The next energy level up (higher in energy) is termed the conduction band and the energy of the bottom of the conduction band is denoted as E_c. This band can be either empty or partially filled and any electrons in this band will be loosely bound to the host atoms and as a result are free to move and participate in electrical conduction.

- The energy region between the top of the valence band and the bottom of the conduction band is a forbidden energy region and an electron will never be found in this region. This is called the energy gap and denoted by E_g. The value of E_g is a fundamental property of a material and is the key factor in our classification of materials into insulators, semiconductors and conductors.

If we now consider the energy band structure of each of these three groups of materials, we can make the following observations:

Insulators: The valence band is completely filled and the conduction band is completely empty, with a large gap between E_g separating the top of the valence band and the bottom of the conduction band. This gap is too large for electrons in the valence band to be thermally excited (due to ambient temperature) across the energy gap from valence band to conduction band. The (nearly) empty conduction band thus provides no or very few mobile electrons and the material is essentially a non-conductor.

Semiconductor: A similar situation as for insulators, but the value of the energy gap is now considerable smaller. This makes the thermal excitation of electrons from valence to conduction band a highly probable process and leaves enough electrons in the conduction band to result in measureable (relatively poor!) electrical conduction. As the temperature of the material is increased, more electrons will be excited into the conduction band and the conductivity will increase.

Conductors: The energy gap E_g is now negative, so that the bottom of the conduction band is below the top of the valence band and we have an overlap between the two bands. This will ensure that we will always have large numbers of electrons in the conduction band and produce a good electrical conductor.

The following diagram illustrates the differences between these three types of materials.

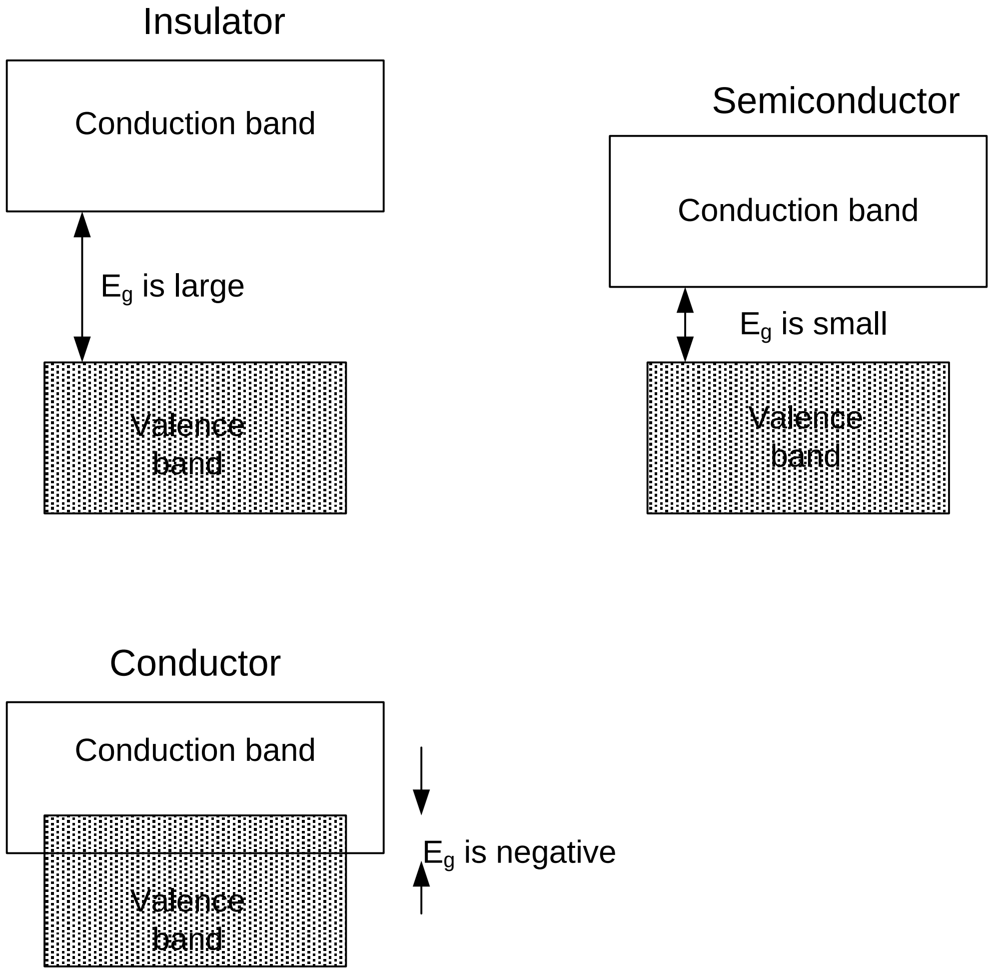


Figure 3: Classification of conductors, semiconductors and insulators based on the structure of the bandgaps.

4. The energy gap in different materials

The previous section has indicated that it is essentially the magnitude of the energy gap that determines the number of number of electrons that can make the transition from valence to conduction band at a given temperature. If we assume that we are operating at room temperature or close to, it is then this value of E_g that determines the electrical conductivity of a pure material. So, what is this value of E_g for our three classes of materials? Let’s look at the elements in Group 14 of the periodic table:

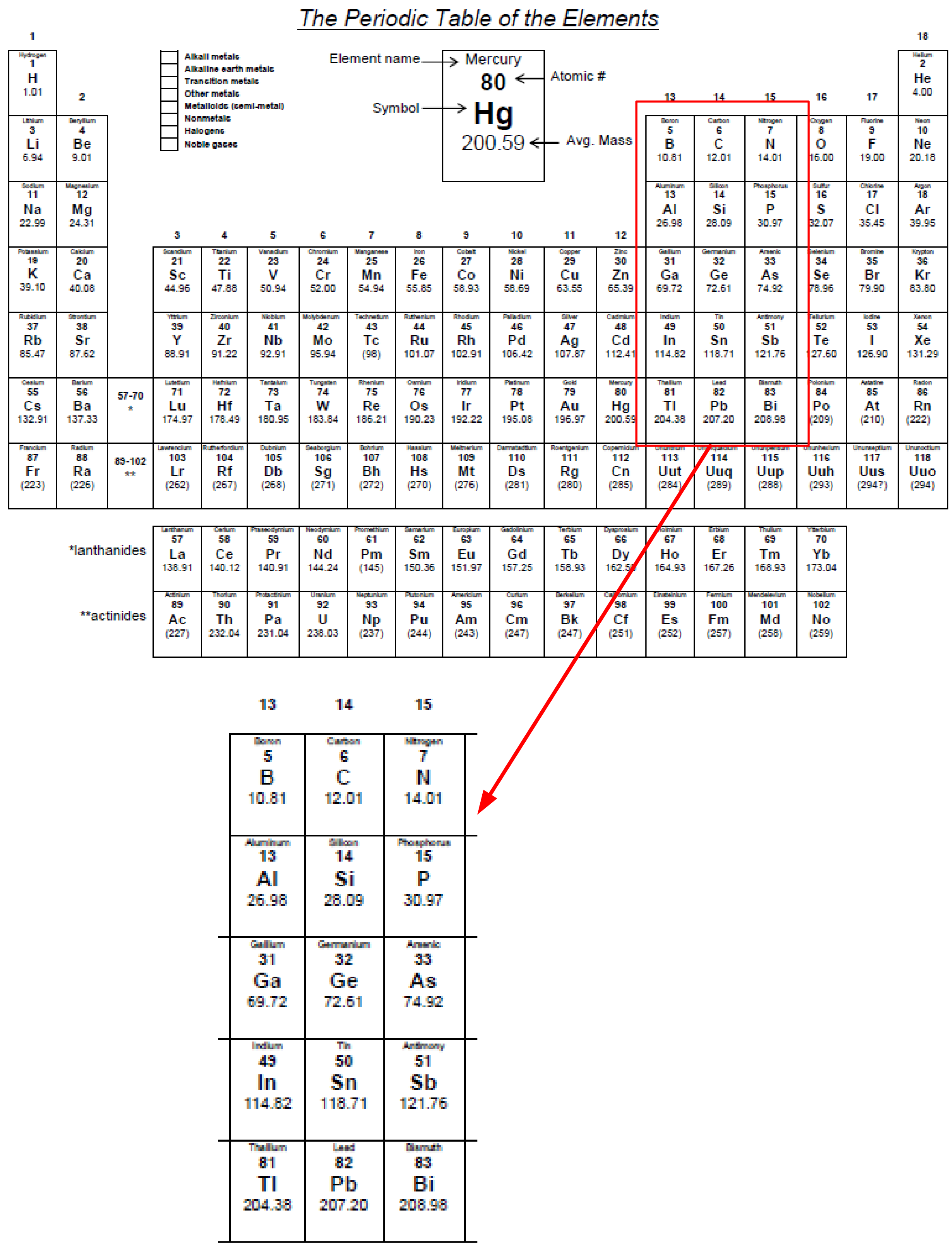


Figure 4: The periodic table, with more detail of the elements in groups 13, 14 and 15 which are of particular importance to electronic devices.

Table 2: The first five elements down Group 14 of the periodic table.

Element	Atomic Number	E_g (eV)	Classification	Bonding
C (Diamond)	6	5.5	Insulator	Covalent
Si	14	1.1	Semiconductor	Covalent
Ge	32	0.7	Semiconductor	Covalent
Sn	50	0 (-)	Conductor	Metallic
Pb	82	0 (-)	Conductor	Metallic

Note that the value of E_g represents an energy difference to be measured in Joule. However, due to the small values of the energy involved, it is more practical to use the eV unit, where 1 eV = 1.6×10^{-19} Joule. It would then appear that conductors have a very small or negative bandgap, semiconductors gave a medium bandgap (~ 1 eV) and insulators have a large (> 3 eV?) bandgap. It is clear that these boundaries are somewhat arbitrary, particularly the semiconductor-insulator boundary and a material such as gallium nitride (GaN) with a bandgaps of ~ 3.4 eV is still classified as a semiconductor.

5. Electrons and holes

If we have an electron making the transition from valence band to conduction band, we will leave a hole (the absence of an electron) in the valence band, forming an electron-hole pair. In a pure (intrinsic) material, we can then expect the number of electrons to equal the number of holes, as both are generated by the same process. This hole can be seen as a positive charge carrier and will participate in the electrical conduction process just as an electron would, with the total electrical current then made up as the sum of electron and hole currents.

It is also possible that the excited electron can recombine with a hole when the two are in close proximity (process called recombination), and both electron and hole will be annihilated. The excess energy of the electron will then be released as light or heat. Under equilibrium conditions, we will then have a constant generation of electron-hole pairs that will be balanced by a constant recombination of electrons and holes, leading to an equilibrium carrier density at that temperature. The following diagram shows the processes taking place in the recombination of electron and hole.

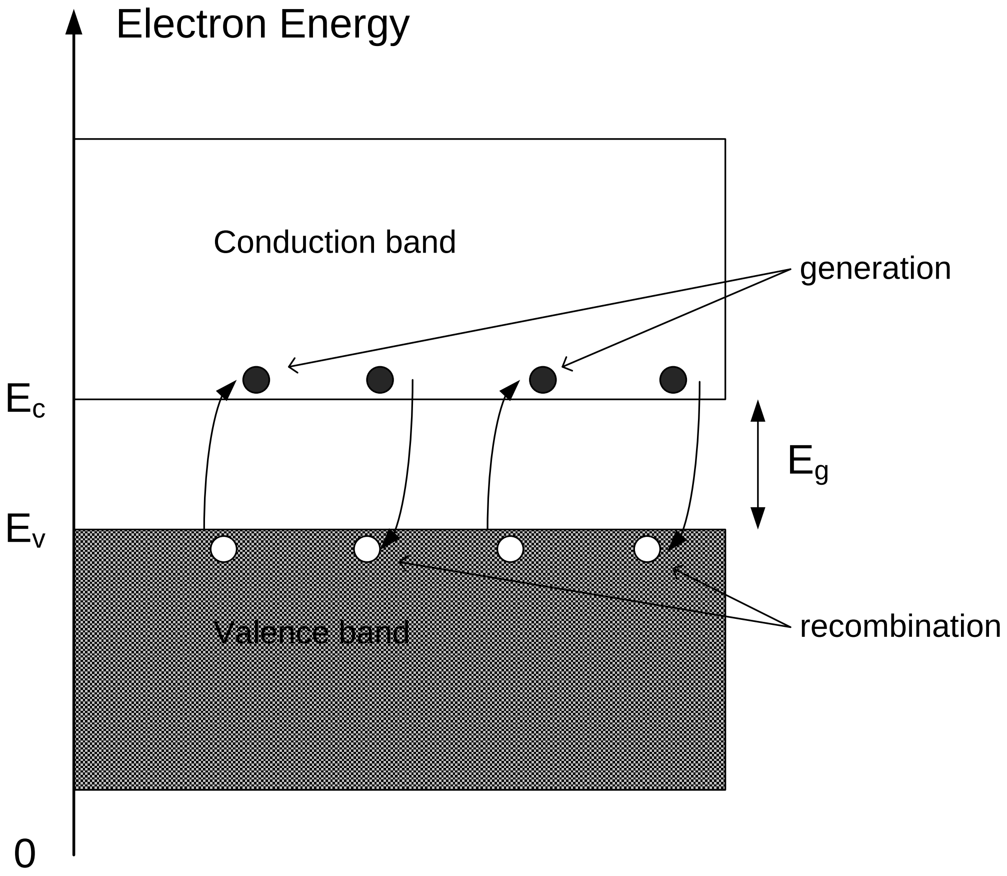


Figure 4: Electron – hole generation and recombination

6. Structure and properties of silicon

Silicon is the material that has made possible the electronics revolution of the past decades and although many other semiconductor materials are now used for many different specialised applications, Si is still the material of choice for most electronic devices. Apart from its ideal bandgap, several other properties of Si has helped it to this position of dominance:

- It forms a strong covalent bond with a relatively high melting point (~1400° C) which makes it thermally quite stable. In fact, the first commercial transistors were made from Ge, but it had poor thermal stability compared to Si.

- It is very abundant in the earth's crust as the compound SiO_2, and very pure Si can be refined relatively easily from SiO_2 (although a very energy intensive process!).

- It is mechanically hard and stable which makes it easy to handle during many different fabrication steps.

- Once we have a pure Si wafer, it is relatively easy to form a stable electrically insulating oxide SiO_2 layer on the Si surface. This layer not only protects the silicon, but forms an integral part of many device structures.

Silicon has four valence electrons and these electrons are shared with four neighbouring Si atoms to create a very strong covalent bond with tetragonal symmetry. A 3D representation of the crystal structure is shown in Figure 5. This structure, called the diamond structure, is also the crystal structure of diamond itself and of Ge.

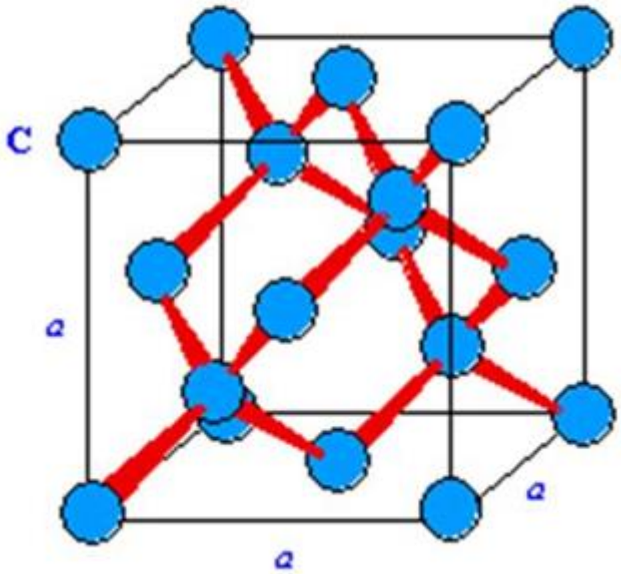
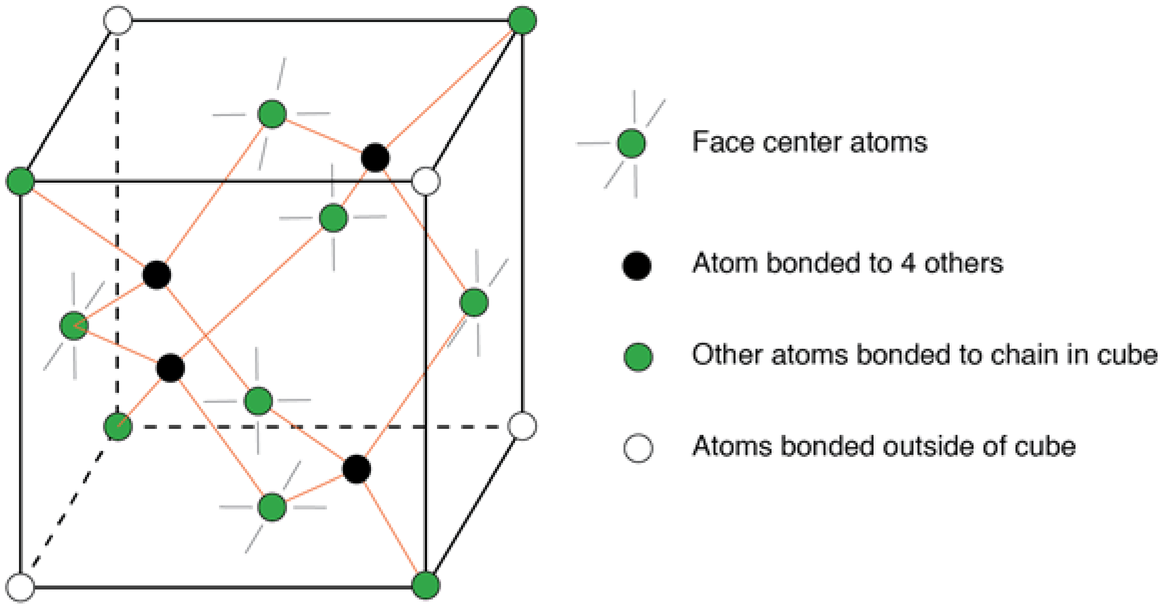


Figure 5: A single unit cell of the silicon crystal structure, often called a diamond structure as diamond takes on the same crystal structure. Note the four nearest neighbours of each Si atom and the tetragonal bonding symmetry.

To calculate:

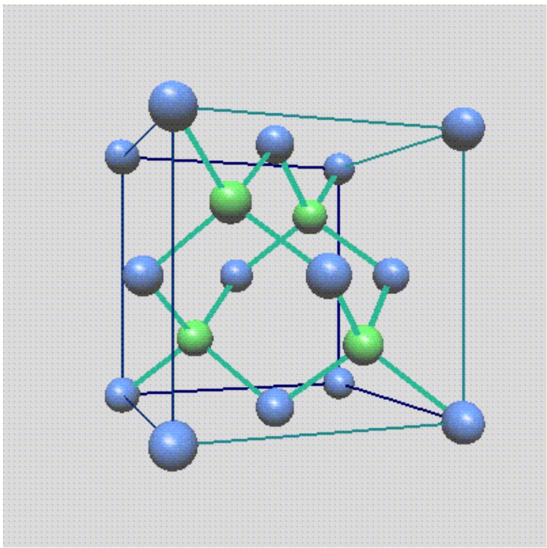


(a) Calculate the number of atoms in the silicon unit cell. Keep in mind that an atom at a corner of the cell will be shared by eight unit cells, while an atom on the face of a cell will be shared by two unit cells. Notice there are also four whole silicon atoms in the crystal.

(b) It is now given that the length of a Si unit cell, the so-called lattice parameter a = 0.54 nm. Calculate the number of Si atoms in 1 m^3 and 1 cm^3 of Si.

Example for Tutorial 2:

1. Determine the number of atoms in a unit cell of GaAs crystal as shown below. Calculate the number of Ga and As atoms in the lattice for 1 cm^3 of material (note that length of each side of the unit cell is 1.2 nm). [10 marks]



Answer:

Number of Ga and As atoms in the lattice: (5)

- Ga Atoms = 8 x 1/8 atoms (in the corners of the lattice) + 6 x ½ atoms (on the face/side of the lattice) = 4 Ga atoms/lattice.
- As atoms = 4 x 1 atom (inside the lattice) = 4 As atoms/lattice.

For 1 cm^3 of GaAs crystal, the number of atoms in the crystal is: (2.5)

$$\text{No of atoms in crystal} = \frac{1}{(\text{length})^3} = \frac{1}{(1.2 \times 10^{-7})^3} = 5.79 \times 10^{22}\ \text{atoms/cell}$$

Number of Ga and As atoms in the 1 cm^3 of GaAs crystal is: (2.5)

$$\text{No of Ga and As atoms} = (\text{Ga atoms} + \text{As atoms}) \times \text{No of atoms in crystal}$$

$$= (4 + 4)(5.79 \times 10^{22}) = 4.63 \times 10^{23} \text{ atoms}$$

As it is far more convenient and easier way to sketch the Si structure in 2D, it is more often sketched as shown in Figure 6. What is important to note is that the four nearest neighbours equally sharing the four valence electrons from each Si atom is still correctly shown in this simplified representation.

If we calculate the electrical conductivity of Si (see later the relevant topic in ECEN330), we find that at room temperature we have excited approximately 1 x 10^{10} electrons/cm^3 from valence band to conduction band. The presence of this number of free carriers produce a conductivity of approximately 2.9 x 10^5 (Ω.cm)$^{-1}$ in the material, placing it in the middle of the region we identified as semiconducting behaviour.

However, the simple property for a material to have an electrical conductivity in the semiconducting region is not enough to be able to produce useful electronic devices from this material.

What is more important about semiconductors is the fact that it is possible the dramatically vary the density of charge carriers as well as their type (positive or negative) and in this way create regions with different carrier concentrations and types that can be used to fabricate device structures.

This can be achieved by the controlled addition of impurities into the pure semiconductor in a process called doping and the effect of doping on the electrical conductivity will be considered in the next section.

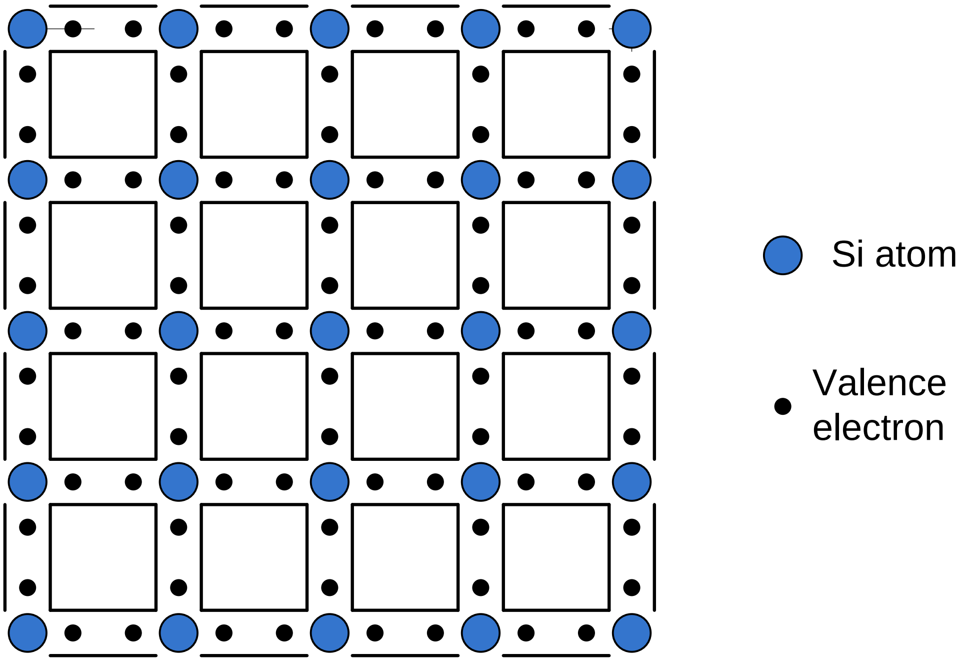


Figure 6: A 2D representation of the Si structure.

7. Doping of semiconductors

Up to now we have just discussed intrinsic material, i.e. a material with no (or extremely low levels of) impurities present. We will now look at doping and the formation of extrinsic semiconductors, i.e. semiconductors where the electrical properties are determined by the presence of foreign impurity atoms. In practice, the doping is about accelerating and depositing other material (dopant) on to the semiconductor material.

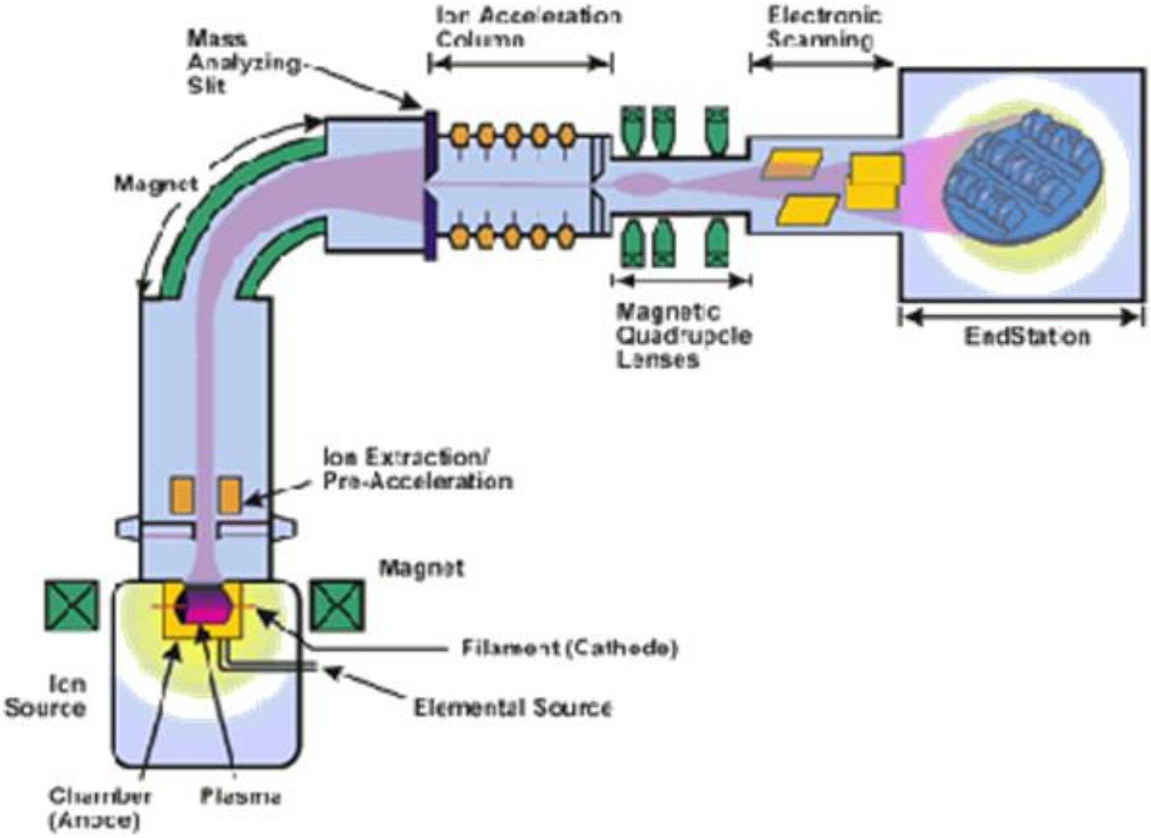


Figure 7: Electron deposition equipment for semiconductor doping

Consider the pure Si crystal of before where we have seen that at room temperature approximately 1 x 10^{10} cm^{-3} electrons are in the conduction band. It is also interesting to note that we have approximately 5 x 10^{22} Si atoms cm^{-3} in the crystal lattice. If we now selectively replace some of the Si atoms with an element such as Phosphorous (P) from Group 15 of the periodic table, these new dopant atoms will have an extra valence electron (valence = 5) which will not be required in the standard covalent in the crystal (see Figure 8).

This foreign atom thus brings with it an extra electron which will not be strongly bound to the crystal lattice and needs only a very small amount of thermal energy to put it in the conduction band. In fact, we can assume that at all temperatures more than a few degrees above absolute zero that all these extra electrons are in the conduction band and can participate in electrical conduction.

The foreign atoms have then increased the electron concentration in the conduction band and we refer to this as **n-type doping**. As the dopant (foreign) atom is donating an electron to the conduction process, this type of impurity is called a **donor** impurity.

It is also important to note that the number of electrons is now not equal to the number of holes any more as was the case for intrinsic (undoped) semiconductors, but the electrons are now the majority carriers and the holes are the minority carriers.

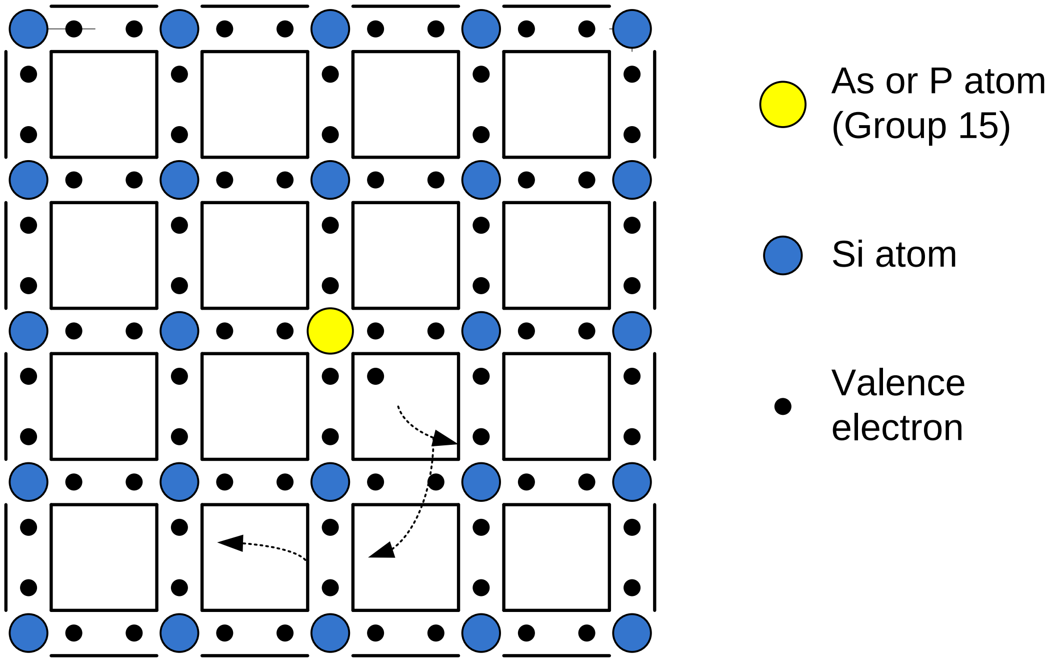


Figure 8: A 2D representation of the Si lattice containing n –type dopant (As or P)

The donor impurities also change the energy band structure compared to that of the undoped (intrinsic) material. The presence of the donor impurities lead to donor states in the forbidden bandgap as shown in Figure 9.

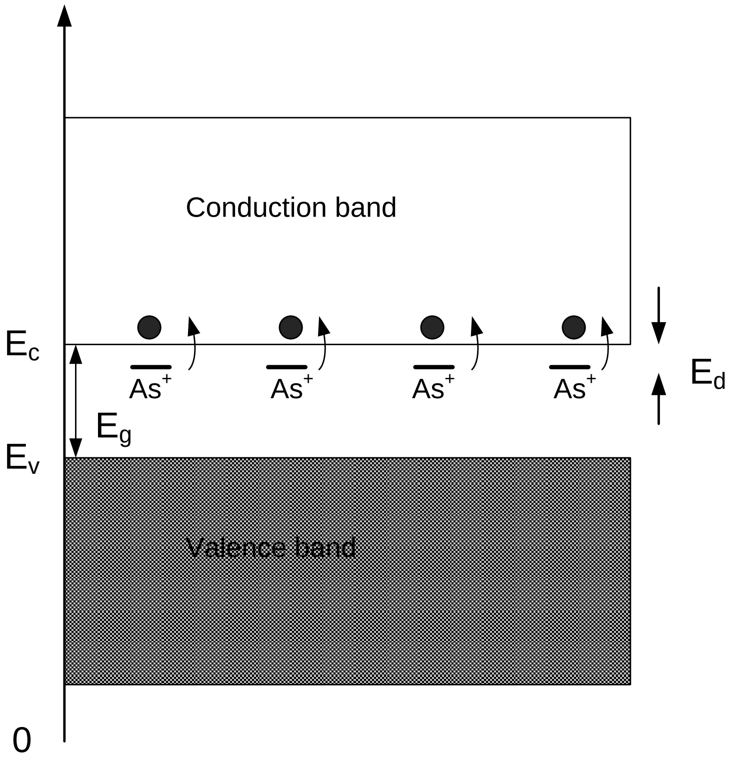


Figure 9: Energy band diagram of n-doped silicon

It is interesting to note how many foreign atoms we need to have in the crystal before we will notice a difference in the electrical conductivity. Keeping in mind that the case of pure (intrinsic) Si we should have, approximately 1 x 10^{10} cm^{-3} electrons are in the conduction band.

If we thus replace 1 x 10^{11} Si atoms in every cm^3 with a P atom which contributes its extra electron to the conduction band, we should in theory have increased the number of free electrons and the conductivity by one order of magnitude. Approximating the number of Si atoms in the crystal lattice as 10^{22} cm^{-3}, it is clear that we only need to replace 1 in 10^{11} Si atoms with a P atom in order to see an order of magnitude change in conductivity!

However, such very low doping levels (1 x 10^{11} cm^{-3}) are not often encountered in practice and more typical doping levels range from ~10^{14} to 10^{18} cm^{-3}. If we consider a typical mid-range doping level 1 x 10^{16} dopants cm^{-3} (replace 1 in a million Si atoms with a P atom), we find that it will increase the density of conduction electrons by six orders of magnitude!

We can similarly achieve **p-type doping** by replacing some of the Si atoms with an atom from group 13 such as In or Ga. The dopant atom will now only have three valence electrons, leading to a ”missing” electron for the standard covalent bonding process. This missing electron can also be seen as a hole in the conduction band and can participate in the electrical conduction process as a positive charge carrier. Just as the extra electron from the n-type dopant is free to drift in the conduction band, in the same way the missing electron or hole is now free to drift in the valence band.

In the case of a p-type material, we now have the holes as the majority carriers and the electrons as minority carriers. In this case, the impurity atoms appear to accept an electron in order to create a free hole and this type of impurity is then termed an **acceptor** impurity.

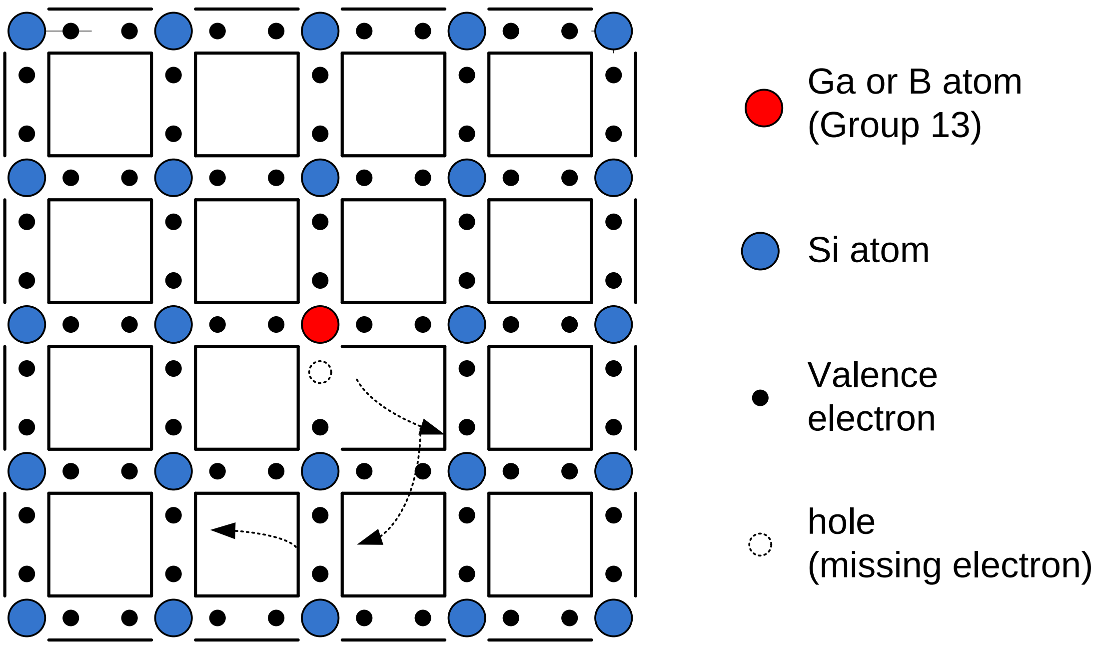


Figure 10: The effect of an element from Group 13 in the Si lattice, leading to a missing valence electron and the formation of a mobile hole.

If we look at the energy band diagram of a p-type material, we can see that the presence of the acceptor impurity has lead to the presence of so-called acceptor levels within the forbidden region of the energy band. These acceptor levels are situated just above the top of the valence band and at room will all be ionised (filled with electrons from the valence band, leaving a mobile hole in the valence band). All the acceptor impurities will thus be contributing to the electrical conduction process.

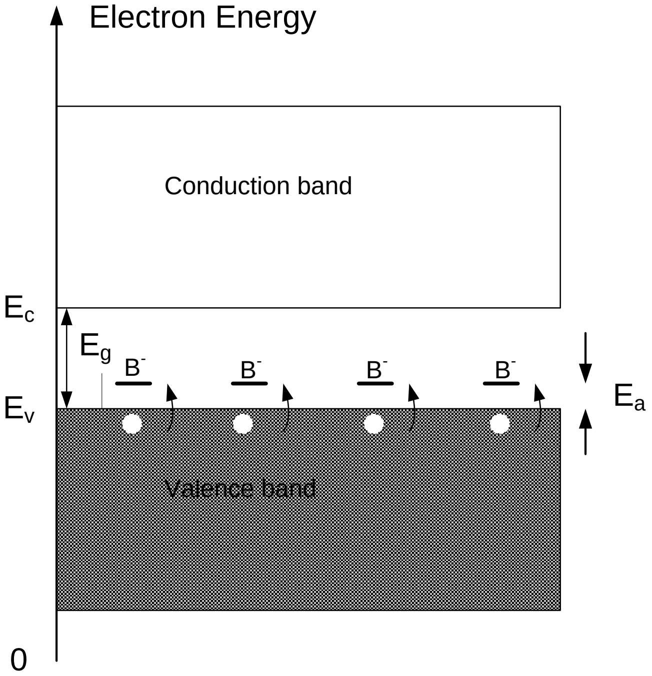


Figure 11: Energy band diagram of p-doped silicon

It is very important to keep in mind that the addition of n-type dopants does not produce Si with an effective negative charge and in the same way the addition of positive charge does not produce material with an effective positive charge. In each case, the charge is balanced and the material is still electrically neutral as it will still contain the same number of protons and electrons.

An n-type material should rather be viewed as containing some positively charged ions (the dopant atoms) and a number of mobile negatively charged carriers. Similarly, a p-type material should be viewed as containing a number of negative ions (the dopant atoms) and a number of mobile positive charge carriers.

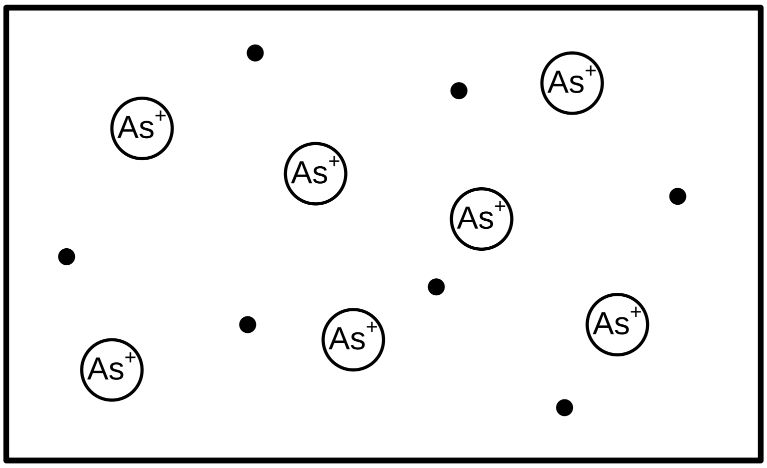


Figure 12: Representation of a silicon lattice containing a n-type dopant, showing only the ionised impurity atoms and the electrons.

These views of doped semiconductors are illustrated in Figures 12 and 13. It is important to understand this representation of a doped silicon structure, as we will use it further in the next chapter to explain device structures and operation.

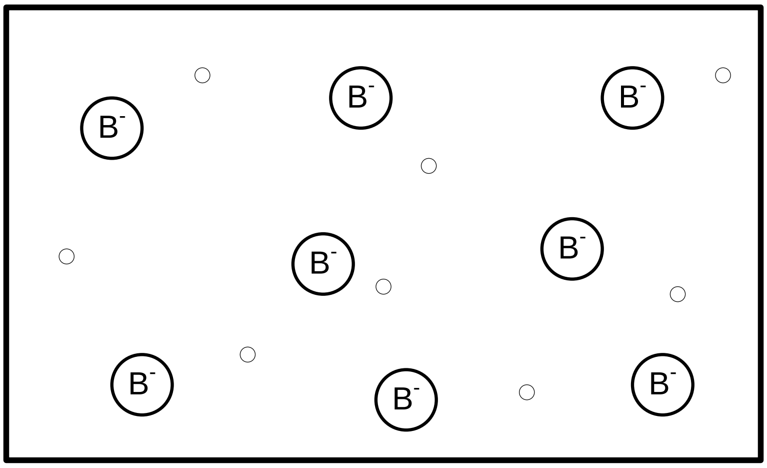


Figure 13: Representation of a silicon lattice containing a p-type dopant, showing only the ionised impurity atoms and the holes.

8. Majority and minority carriers

In the case of an undoped semiconductor, we would refer to the behaviour as **intrinsic** or use the term an intrinsic semiconductor. This would mean that the electrical conductivity is purely caused by the intrinsic semiconductor properties. In the ideal case, this will simply be determined by the number of electrons and holes that are generated by thermal excitation across the energy gap. Of course, we would also expect the number of intrinsic electrons to be exactly equal to the number of intrinsic holes (~ 10^{10} cm^{-3} for Si at 300° K).

If the semiconductor is doped so that the electrical properties is determined by the presence of these doping impurities, the behaviour is referred to **extrinsic** or we use the term an extrinsic semiconductor. The density of doping atoms is typically of the order of 10^{14} to 10^{17} cm^{-3}, thus much greater than the intrinsic levels, so that these extrinsic carriers dominate the electrical properties.

Assume that we have a piece of n-type Si which was doped with As to a level of 10^{16} cm^{-3}. This material should thus contain:

- ~ 10^{16} electrons cm^{-3} due to the impurities.
- ~ 10^{10} electrons cm^{-3} due to thermal (intrinsic) excitation.
- ~ 10^{10} holes cm^{-3} due to thermal (intrinsic) excitation.

However, we find that this number of holes is actually considerably reduced due to the excess of electrons (more recombination taking place) and the typical number of holes will be ~ 10^7 cm^{-3}.

The important point of the above observation is the fact that we still have both types of carriers (electrons and holes) present in the n-type material. The density of electrons will be ~ 10^{16} cm^{-3} as determined by the doping concentration and the electrons are referred to as the majority carriers. However, we will still have a concentration of ~ 10^7 holes cm^{-3} in the material, and these will then be the **minority carriers** in the n-type material.

In exactly the same way, we can show that for p-type material we will have holes as the majority carrier and electrons as the minority carrier. In order to accommodate the influence of both types of carriers on the conductivity, we should write our expression for conductivity as:

$$\sigma = ne\mu_e + pe\mu_h$$

where: n is the electron density, e is the electrical charge on an electron or a hole (1.6 x 10^{-19} C), μ_e is the electron mobility, p is the hole density and μ_h is the hole mobility.

Both types of carriers thus contribute to the conductivity and both types of carriers will contribute to the current that flow (note: the electron and hole current do not cancel each other out but they add to the total current observed!).

Although the value of the conductivity will be largely determined by the majority carrier term, there will still be a small contribution from minority carriers. This minority carrier contribution should never be neglected, as in many electronic devices it is the behaviour of the minority carriers that actually determine the device operation.

Example for Tutorial 3:

1. Calculate the conductivity of a Silicon material if it has intrinsic carrier concentration 1.5 x 10^{16} per m^3 and the mobilities of the electron and hole are 0.15 m^2/Vs and 0.05 m^2/Vs respectively. [2.5 marks]

   Answer:

   Conductivity of the material, σ is calculated from:

   $$\sigma = ne\mu$$

   Assuming the mobility of the particles in the materials are due to electrons and holes, then the overall mobility is:

   $$\mu = \mu_e + \mu_h$$

   Putting in the values into the equation: (2.5)

   $$\sigma = (1.5 \times 10^{16})(1.602 \times 10^{-19})(0.15 + 0.05) = 4.81 \times 10^{-4}\ \mathrm{S/m}$$

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