EEE105 - Electronic Devices
Lecture 7

The Semiconductor Diode

(CAL: semic(a) ,semic(b), semic(c), semic(d), semic(e))

The diode is basically a p-n junction. There are a number of things that we need to know if we are to be able to understand its operation:

1. What is meant by n- and p-material (or n-type and p-type material)
2. What is a hole (assuming that we all already understand what is meant by a (free) electron)
3. What happens when electrons and holes meet.
4. What happens when n-type and p-type materials are joined together.

Semiconductor Materials

Semiconductors are generally covalently bonded materials. Silicon (Si) is the most common. Others include Germanium (Ge) and Gallium Arsenide (GaAs). We will consider Si in this example. Silicon has 4 outer electrons (it is in Group IV of the periodic table). These four electrons share with one electron each from four neighbouring Si atoms to create four bonds

The bonds form as far away from each other as they can in a structure called the Diamond Crystal Structure (as it is the same way that the carbon bonds are arranged in a diamond.).

Most semiconductors form in a structure like this. In compound semiconductors, such as gallium arsenide (GaAs) the bonds form in the same way but each Ga atom has four As atoms as nearest neighbours and vice-versa.

This structure is clearly a three dimensional crystal, but for the discussions that follow we shall use a simpler representation of the bonds in two-dimensions (2-D)

Conduction Mechanisms

In a semiconductor at a temperature of absolute zero (0 K) all the atoms will be tied up in the bonds and the material will be an insulator. However heat, or radiation, will free some of the electrons by breaking the bonds:

The free electrons that are out of the bonds (or in an “excited” state in the semiconductor material) can take part in conduction as they can move around the crystal.

The number of free electrons will equal the number of bonds that are broken due to the (heat) energy. This is given by

$$n_i \propto T^{3/2} \exp\left(-\frac{W_g}{2kT}\right) \text{ (the units are in m}^{-3}\text{)}$$

Where T is the absolute temperature <u>in Kelvin</u>, W_g is the energy required to break a bond (ionisation energy), and k is the Boltzmann Constant.

Note that in the above relationship as T increases then n_i increases, so the conductivity increase as there is more energy to break the bonds.

Holes

Above we have come across the concept of an electron becoming free by breaking out of its bond. This negative charge is then able to wander around the lattice, behaving as an negatively charged free particle with a mass that has been modified by the crystal structure (the so called effective mass).

However the overall charge on the material is neutral. This means that if the negatively charged electron is wandering around the material, the broken bond that it leaves behind must be positively charged. (i.e. its charge is $+q$).

This broken bond can also move around the lattice.

Consider an electron from a neighbouring bond. It can move into the broken bond (or ***"hole"***) moving the broken bond (or ***"hole"***) to the neighbouring bond from where the electron came.

This motion is the equivalent of a positively charged particle, called a hole, moving in the opposite direction to the electron.

These holes can move in E-fields in the same way electrons can.

Rather than considering a large number of bonded electrons moving it is simpler to consider one ***hole*** (or broken bond) moving around the crystal instead.

This treatment is very convenient as mathematically we can show that the hole behaves as a positively charged particle with a mobility, and an effective mass in the crystal, in other words it behaves like a positively charged free electron.

Note that if a free electron encounters a hole then the electron and hole can ***RECOMBINE*** to form a complete bond. This process effectively involves the electron in its "excited state" falling down in energy into the bonding state, thus energy is released. This energy can be emitted in the form of light for example.

NOTE the electron has to absorb energy from the heat in the crystal to leave its bond and will release the energy back when it falls back into a broken bond (or hole) to make the bond complete again.

Intrinsic Semiconductors

In a pure semiconductor every time a bond is broken we produce one free electron and one hole. Hence $n = p = n_i$ (where n is the density of free electrons and p is the density of holes in the material.)

NOTE that in this pure (or intrinsic) semiconductor the total density of free carriers will be $n_i + p_i = 2n_i$ and that the conductivity of the material must take into account the current carried ***both*** by the free electrons ***and*** by the holes. Thus the equation for conductivity in our intrinsic semiconductor will be:

$$\sigma = n_i q \mu_e + p_i q \mu_h = n_i q(\mu_e + \mu_h)$$

This intrinsic conduction arises from current from both thermally generated electrons and holes.

However in most semiconductors the density of intrinsic carriers is very low. This means that intrinsic semiconducting material can actually be fairly insulating.

We need a way to increase this conductivity:

Extrinsic Semiconductors

In extrinsic semiconductors we deliberately introduce some impurities into the lattice. This process is called

This relies on very small quantities of impurity making a huge change in the material's conductivity.

We can increase either the number of free electrons or free holes in the material depending on the impurity we add, and we will consider each of these cases separately.

n-type Doping (Impurities to add Extra Electrons)

In Si each atom has four outer electrons that make the bonds with neighbouring atoms. So let us add an impurity with five outer electrons (from group V of the the periodic table) to the Si material we make our crystal out of. The impurity will use four of its outer electrons for bonding and there is ***one extra electron*** which was not needed to make up the crystal bonds in the Si.

This extra electron is only ***weakly*** bound to the impurity atom.

This means that ***thermal vibrations*** (or phonons) at room temperature can release this extra electron from the impurity atom so that it becomes a free electron, able to wander around the crystal material.

Let us consider the situation where we introduce (or ***dope***) 1 part per million of group V impurities into the crystal:

There are 5×10^{28} m^{-3} atoms in a Si lattice.

Therefore at one part per million, there will be 5×10^{22} m^{-3} group V impurities in the lattice.

Each impurity gives us one free electron therefore our free electron density will also be 5×10^{22} m^{-3}.

So how does this compare to intrinsic Si?

In intrinsic (or pure) Si we need to use the equation: $n_i = const \times T^{3/2} \exp\left(-\frac{W_g}{2kT}\right)$

Now the ionisation energy, W_g is 1.11eV and the temperature, T is 300 K. Substituting in for these values and for the constant, we will get a value of $\boxed{n_i \approx 10^{16}\ \text{m}^{-3}}$.

Thus our material doped with the group V impurity will have many more free electrons in it and hence a much higher conductivity

So how does this compare to a metal?

In a metal typically there is one free electron per atom in the material, thus $\boxed{n_i \approx 10^{29}\ \text{m}^{-3}}$.

Common Terms used to describe n-type doping:

Group V impurities are called ***donors*** as they *donate* free electrons to the material.

The material is called ***n-type*** material as ***n***egative electrons are the charge carriers.

Typical n-type dopants are:

Extra Notes: (These points are both important to remember)

1. When an electron moves away, the donor atom left behind is positively charged. However the atom (or ion) cannot move in an electric field as it is fixed in the crystal lattice.
2. At room temperature all the donor atoms are ionized (i.e. the donor electrons are free from the donor atoms to move around the crystal). This means that the free electron concentration is constant for temperature variations around room temperature.

Key Points to Remember:

1. In a semiconductor the atoms are bonded together in a regular array (or crystal)
   a. Each atom will have four nearest neighbours.
2. Bonds can be broken by heat (or radiation)
   a. Broken bonds give an electron that is free to move around the crystal
   b. The broken bond can also move around the material
3. A hole is a "broken bond". It behaves as a positively charged particle that can move in the same way as a free electron can move.
   a. Holes have a separate mobility and effective mass than that for electrons in the material.
4. A pure semiconductors is called an intrinsic semiconductor
   a. At room temperature there will be a low density of ***both*** electrons and holes that can conduct electricity.
5. We can dope a semiconductor by adding impurities
6. Adding an impurity with five outer electrons means that there will be one extra electron not needed for the crystal bonds
   a. Small amounts of thermal energy can make the extra electron free to move around the crystal
   b. The group V impurity atoms are called donor atoms as they donate free electrons.
   c. The material is n-type as the charge carriers are negatively charged.