

## Unit 22 Semiconductor materials

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- Substances can be divided into three groups according to their electrical properties: conductors, semiconductors and insulators.
  - The principal semiconductor materials used in electronics are the indirect band gap materials, silicon (Si) and germanium (Ge).
  - The principal semiconductor materials used in optoelectronics and in very fast electronics are the direct band gap III–V semiconductors such as gallium arsenide (GaAs) and indium phosphide (InP).
  - Intrinsic semiconductors are pure semiconductors in which the number of holes is equal to the number of mobile electrons.
  - Extrinsic semiconductors have been doped to make either p-type material (in which the positive holes are the majority carriers and the electrons are minority carriers) or n-type material (in which the negative electrons are the majority carriers and the holes are minority carriers).
  - Semiconductor equation:  $n \times p = n_i^2 = \text{constant}$  for constant  $T$ . If the concentration of holes,  $p$ , increases then the concentration of electrons,  $n$ , decreases in proportion.
  - Metallic conductors: resistance increases with increasing temperature.
  - Semiconductors: resistance decreases with increasing temperature.
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Consider the vibration of a stretched string such as a violin string. The string is constrained so that it is fixed at each end. The possible waves which can be present on the string correspond to an integral number of half wavelengths as shown in Figure 22.1.

In quantum mechanics, a particle such as an electron is described by a wave function. When an electron is constrained to a one dimensional box with rigid ends, the Schrödinger equation which describes the system has a similar mathematical form to the differential equation which describes the vibration of a string and which leads to discrete vibrational modes.

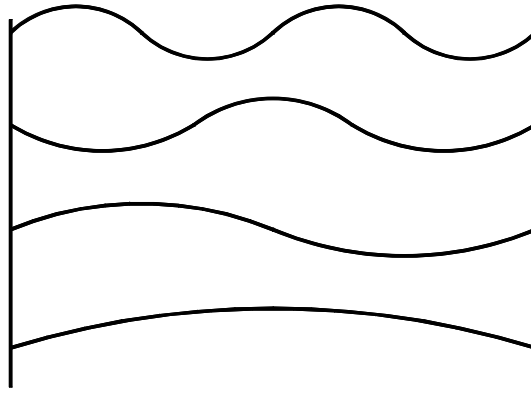


Figure 22.1: Vibrational modes on a stretched string.

However, the one significant difference is that the vibrational modes of the string can have any energy whereas a particular mode for a particle in a box has an energy which is given by  $E_j = E_1 j^2$  where  $j$  is an integer,  $E_1$  is the energy of the lowest energy mode and  $E_j$  is the energy of the  $j$ th mode. We can therefore plot the electron energy as a function of the mode number as shown in Figure 22.2 where the discrete modes lie on the parabola,  $E_j = E_1 j^2$ , and are indicated by circles.

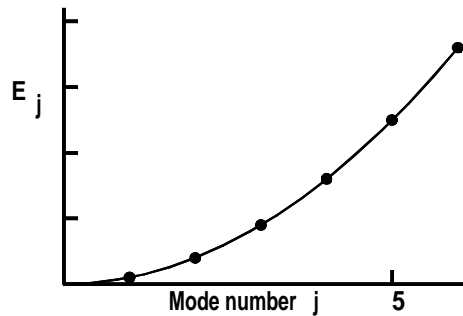


Figure 22.2: Plot of energy versus mode number.

Returning to the waves on a string, if we loosely constrain the string at the centre, then the large amplitude vibrations of the odd numbered modes, for which  $j = 1$ ,  $j = 3$ ,  $j = 5$  etc., are inhibited. This is illustrated in Figure 22.3. The constraint acts to ‘forbid’ a mode. Placing the constraint in different positions causes a different set of modes to be ‘forbidden’.

Now consider the electron in a one dimensional box. When atoms are placed at regular intervals in the box to form a one dimensional crystal, some of the solutions or modes obtained for Schrödinger’s equation will be

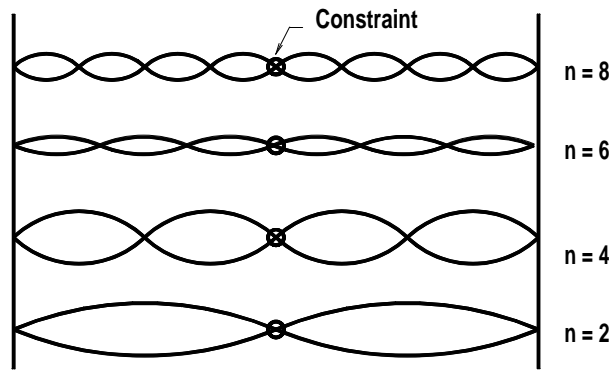


Figure 22.3: Effect of constraint in 'forbidding' modes.

forbidden. Essentially the box is sectioned by the atoms and within the crystal only electrons with certain wave vector values,  $k$ , can propagate through the crystal without being scattered by the atoms.

In a crystal, the quantized wave vector specifies the electron momentum,  $k$ , and the energy is given by  $E(k) = \frac{\hbar^2 k^2}{4\pi^2 2m^*}$  where  $\hbar$  is Planck's constant and  $m^*$  is the effective electron mass. Also since waves propagate in both directions, both positive and negative values of  $k$  must be considered. The number of distinct modes or values of  $k$  is  $N$  where  $N = \frac{l}{a}$ ,  $a$  is the lattice size (lattice constant) and  $l$  is the length of the crystal. The set of distinct modes is called a Brillouin zone.

When  $k$  exceeds the value of  $\frac{\pi}{a}$ , set by the size of the crystal lattice, the momentum values differ by multiples of  $\frac{2\pi}{a}$  but are indistinguishable within the crystal due to interchanges of momentum between electrons and phonons (vibrational modes of the crystal lattice). However, the energy continues to increase along the parabolic curve and moves into a new Brillouin zone. Thus it is possible to have electrons which have the same momentum within the crystal but have significantly different energies. At the transition from one Brillouin zone to the next there is a significant deviation from the parabolic shape of the curve (a localized bending of the  $E-k$  curve) which leaves a band gap where there are no energy states and which results in a forbidden band. The resulting band structure is shown in Figure 22.4.

We have only considered a one dimensional crystal. In a real three dimensional crystal the electron wave functions can propagate along each of the principal axes of the crystal in the  $[100]$ ,  $[010]$  and  $[001]$  directions. There is also propagation in diagonal directions through the crystal shown as  $[110]$  and  $[210]$  directions in the two dimensional projection in Figure 22.5 or, for example, in the fully diagonal  $[111]$  direction in the 3D crystal. The spacing between the planes in the crystal is different for these diagonal directions,

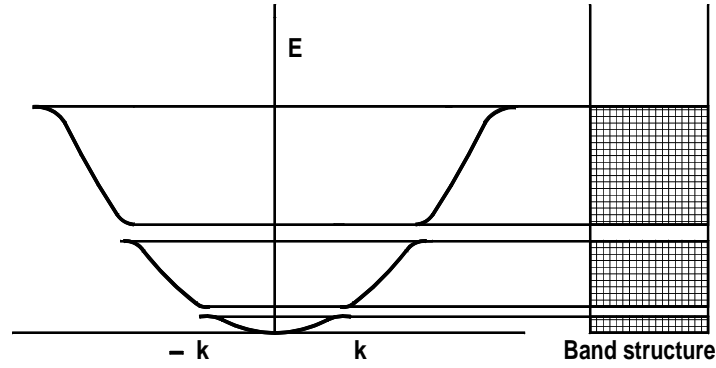


Figure 22.4: Energy levels and band structure.

leading to different and distinct  $E$ - $k$  curves.

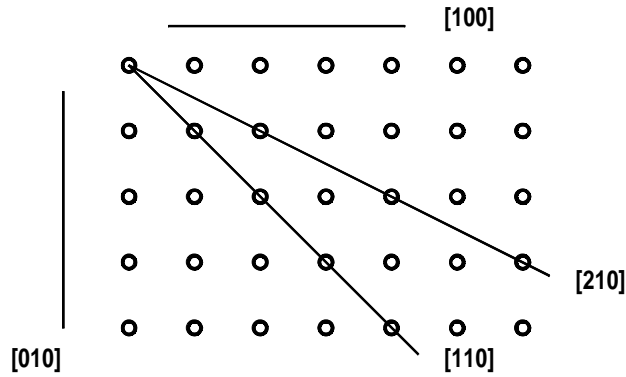


Figure 22.5: Directions in the crystal.

In a real crystal, the electrons in the lower atomic orbitals remain tightly bound to the individual atoms. However, the outer shell valence electrons, which interact with adjacent atoms, can no longer be considered to be attached to individual atoms but rather must be considered to be delocalized throughout the crystal with a distribution corresponding to the amplitudes of the wave functions which we have just discussed.

Since electrons are fermions, the Pauli exclusion principle applies and no two electrons can have the same set of quantum numbers so the available states fill up from the lowest energy states to a level called the Fermi level,  $E_F$ . At  $T = 0\text{ K}$  the distribution of electrons at the Fermi level cuts off sharply but at any higher temperature there is some rounding off of the electron distribution around the Fermi level due to thermal excitation and the probability of an electron having an energy  $E$  is then given by:

$$P(E) = \frac{1}{1 + e^{\frac{(E - E_F)}{kT}}}$$

We can now see how this band theory can be applied to explain the electrical properties of solids.

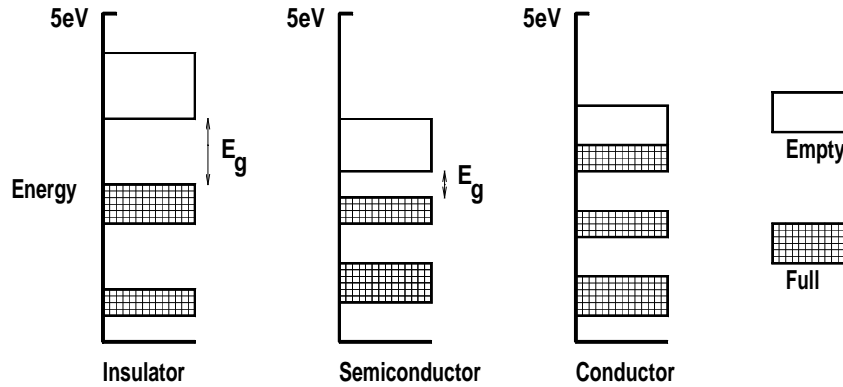


Figure 22.6: Band structure in insulators, semiconductors and conductors.

In insulators, as shown in Figure 22.6, the available electrons have filled the lower valence bands completely and there are no electrons in the next band up in energy. The energy gap or band gap between the highest full band and the lowest empty band is large, usually greater than 3 eV, and there is no mechanism for exciting significant numbers of electrons into the upper band where they could move between empty states and give electrical conduction through the crystal. The crystal is therefore an insulator because of the large energy gap.

In semiconductors, this energy gap between the top of the full valence band and the bottom of the empty conduction band is smaller, of the order of 1 eV. The thermal vibrational modes or phonons of the crystal have energies of  $kT$ . At room temperature, 293 K, we calculate:

$$kT = 1.38 \times 10^{-23} \times 293 = 4.04 \times 10^{-21} \text{ joules} = \frac{4.04 \times 10^{-21}}{1.6 \times 10^{-19}} = 0.025 \text{ eV}$$

The crystal vibrational modes can transfer energy to the electrons and excite the electrons across the energy band gap. However, only phonons at the extreme tail of the thermal phonon distribution are energetic enough to excite an electron across the band gap. Therefore the fraction of electrons excited to the conduction band is small. This small fraction multiplied by the large number of valence electrons in the crystal does give enough electrons in the conduction band to give significant electrical conduction. A small increase in the temperature gives a large increase in the fraction of electrons excited into the conduction band and therefore causes a large decrease in the resistivity of a semiconductor with increasing temperature—a negative temperature coefficient of resistance.

It should also be noted that the only difference between the insulators and the semiconductors is the size of the band gap energy and the consequent much lower probability of thermal excitation of electrons from the valence to the conduction band for insulators.

In the case of conductors, usually metals, as shown in Figure 22.6, there are only enough electrons to fill the upper band partially. This means that very little extra energy is required to move an electron up into a different energy state within the band so that the electron can move freely through the crystal and give a high conductivity and a low resistivity.

In conductors, the number of mobile electrons does not change significantly with temperature. When an electric field is applied across the crystal, the electrons accelerate and move through the crystal. The electrons also collide with the vibrating atoms of the crystal via electron-phonon interactions. These collisions randomize the imposed velocity due to the external electric field. The higher the temperature, the more phonons are present, the more frequent are the collisions and the more rapidly the electron velocities are randomized. This reduces the conductivity and increases the resistivity. Metallic conductors therefore have a positive temperature coefficient of resistance (TC of R). The sign of the temperature coefficient of resistance is one of the more important differences between semiconductors and metallic conductors.

The table shows the relative values for the resistivities of a number of representative materials. There is a factor of  $\approx 10^9$  change in the resistivity in going from one group to the next.

Material	Resistivity, $\rho$ , $\Omega$ m	Sign of TC of R
Glass	$10^{10}$	—
Silicon	2000	
Germanium	0.5	
Copper	$1.7 \times 10^{-8}$	

In a pure or intrinsic semiconductor material, if an electron is excited up into the conduction band, there will be electrical conduction due to this movable electron. However, in semiconductors there is also another mechanism for conduction. The hole left in the valence band by the excited electron can be considered as a positive charge carrier since an adjacent valence electron can hop into the hole to give an effective movement of the hole in a direction opposite to the direction of movement of the electron which hopped. Therefore, we have p-type carriers or holes which can also move through the lattice.

Electrons and holes behave similarly and their behaviour is modelled using Fermi-Dirac statistics. The consequence is that the probability that a

particular energy level,  $E$ , is occupied is given by the Fermi-Dirac distribution function:

$$P(E) = \frac{1}{1 + e^{\frac{(E-E_F)}{kT}}}$$

where  $E_F$  is the Fermi level energy. This exponential function leads to similar exponential functions appearing in the equation which describes variation of current as a function of applied voltage in a diode.

Extrinsic semiconductors result when silicon or germanium, which are Group IV elements in the Periodic Table, are doped with small quantities of either Group III elements such as boron atoms which act as acceptors for electrons to reduce the free electron concentration and give p-type semiconductor material, or Group V elements such as phosphorous atoms which act as donors of electrons to increase the free electron concentration and give n-type semiconductor material.

If  $n$  is the electron concentration,  $p$  is the hole concentration and  $n_i$  is the carrier concentration in the intrinsic material then it can be shown that:

$$n \times p = n_i^2 \quad (\text{The semiconductor equation})$$

at a constant temperature and after thermal equilibrium has been reached. Therefore when n-type semiconductor is formed by doping, the semiconductor equation shows that the concentration of p-type carriers in the n-type material is reduced below that which is found in intrinsic material. In n-type material, n-type carriers (electrons) are the majority carriers and p-type carriers (holes) are the minority carriers and conversely for p-type material.

It is possible to obtain concentrations other than those predicted by  $n \times p = n_i^2$  over a local region by injecting, say, large numbers of p-type holes into an n-type region by applying appropriate voltages to some fabricated structure in the semiconductor crystal such as the base region in a transistor. If the injection process is stopped then the system returns to thermal equilibrium and  $n \times p = n_i^2$  applies once more.

## 22.1 Problems

22.1 A thermistor is a semiconductor resistive device used for temperature sensing and measurement. The resistance  $R_2$  at temperature  $t_2$  K is given by the formula:

$$R_2 = R_1 e^{\left(\frac{B}{t_2} - \frac{B}{t_1}\right)}$$

where  $R_1$  is the resistance at a reference temperature  $t_1$  K and  $B$  is a constant for the particular type of thermistor.

A GM103 type thermistor has resistance  $10\text{ k}\Omega$  at  $25^\circ\text{C}$  and  $B = 3555\text{ K}$ .

Calculate the resistance of a GM103 at each of these temperatures:  $-6^\circ\text{C}$ ,  $30^\circ\text{C}$ ,  $50^\circ\text{C}$  and  $120^\circ\text{C}$ .

- 22.2 A constant **voltage** is applied along a resistive track formed on a silicon wafer. The resistance of the track at  $20^\circ\text{C}$  is  $R_s$ .

What is the formula for the power which is dissipated in the resistive track?

Will the temperature of the silicon increase or decrease?

Will the resistance of the resistive track increase or decrease?

Will the power dissipation increase or decrease?

Is the system thermally stable or is it subject to thermal runaway?

- 22.3 A constant **current** is driven through a resistive track formed on a silicon wafer. The resistance of the track at  $20^\circ\text{C}$  is  $R_s$ .

What is the formula for the power which is dissipated in the resistive track?

Will the temperature of the silicon increase or decrease?

Will the resistance of the resistive track increase or decrease?

Will the power dissipation increase or decrease?

Is the system thermally stable or is it subject to thermal runaway?

- 22.4 The concentration of p-type carriers in a silicon wafer is increased by doping to a value 100 times that in intrinsic silicon. Calculate the ratio of p-type to n-type carrier concentrations in the doped semiconductor.

If the conductivity is proportional to the concentration of mobile carriers present, calculate the ratio of conductivity of the doped material to that of intrinsic material  $\left(\text{conductivity} = \frac{1}{\text{resistivity}}\right)$ .

- 22.5 Use the expression for the probability of an electron having an energy  $E$ , given on page 97, to calculate the probabilities of an electron in a crystal having energies of 2, 10, 50 and 100 times  $0.025\text{ eV}$  in excess of the Fermi energy. Compare these energies to the band gap energy for silicon.