Temperature Dependence of Semiconductor Conductivity
(Originally contributed by Professor E.D.H. Green)

4.0 Theory

4.1 Band Structure of a Semiconductor

The band structure of semiconductors is such that the outermost band of electrons, the valence band, is completely full. If a voltage is applied, there is no conduction of electrons because there are no empty spaces to allow the electrons to move around. In order for conduction to occur, electrons must be excited to the next highest band, known as the conduction band. The conduction band is normally empty but is separated from the valence band by only a small amount of energy. (See Callister Figure 19.4.) Valence electrons can surmount this barrier by absorbing a small amount of energy from heat or light. This then creates a free electron in the conduction band and a hole (missing electron) in the valence band, Callister Figure 9.6.

Doping (replacing Si atoms with atoms of another element) is frequently used instead of temperature to control conductivity. Doping can be localized to certain areas whereas the affect of temperature is a less localized influence. If Si is replaced by elements from Column V of the periodic table such as phosphorous, there will be one extra electron in the valence band, Callister Figures 19.11 and 19.12. This electron is easily broken loose to create a free electron. Silicon doped with Column V elements in known as p-type and the dopants are called donors. Replacing Si with an element from Column III (such as boron) creates a hole in the valence band. (See Callister Figures 19.13 and 19.14). The silicon is known as n-type and the dopants are called acceptors.

4.2 Conductivity of a Semiconductor

The conductivity of a semiconductor is given by:

$$\sigma = q(\mu_n n + \mu_p p) \qquad (1)$$

where μ_n and μ_p refer to the mobilities of the electrons and holes, and n and p refer to the density of electrons and holes, respectively. A *doped* semiconductor, majority carriers greatly outnumber minority carriers, so that Equation 1 can be reduced to a single term involving the majority carrier.

4.3 Effects of Temperature and Doping on Mobility of a Semiconductor

Conductivity of a material is determined by two factors: the concentration of free carriers available to conduct current and their mobility (or freedom to move). In a semiconductor, both mobility and carrier concentration are temperature dependent. Thus, it is important to view the conductivity as a function of temperature which is expressed by:

$$\sigma = q\left[\mu_n(T)n(T) + \mu_p(T)p(T)\right] \qquad (2)$$

There are two basic types of scattering mechanisms that influence the mobility of electrons and holes: lattice scattering and impurity scattering. We have already discussed lattice scattering in the context of metals; we know that lattice vibrations cause the mobility to decrease with increasing temperature.

However, the mobility of the carriers in a semiconductor is also influenced by the presence of *charged impurities*. Impurity scattering is caused by crystal defects such as ionized impurities. At lower temperatures, carriers move more slowly, so there is more time for them to interact with charged impurities. As a result, as the temperature decreases, impurity scattering *increases*, and the mobility *decreases.* This is just the opposite of the effect of lattice scattering.

The total mobility then is the sum of the lattice-scattering mobility and the impurity-scattering mobility. Figure 1 shows how the total mobility has a temperature at which it is a maximum. The approximate temperature dependence of mobility due to lattice scattering is $T^{-3/2}$, while the temperature dependence of mobility due to impurity scattering is $T^{+3/2}$ (see Figure 1). In practice, impurity scattering is typically only seen at very low temperatures. In the temperature range we will measure, only the influence of lattice scattering will be expected.
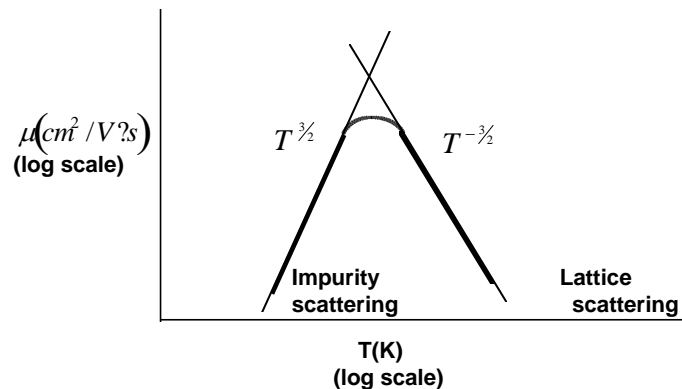

Figure1. Approximate temperature dependence of mobility with both lattice and impurity scattering

4.4 Temperature Dependence of Carrier Concentration

The carrier concentration in a semiconductor is also affected by temperature. The intrinsic carrier concentration is governed by:

$$n_i(T) = 2\left[\frac{2\pi kT}{h^2}\right]^{\frac{3}{2}} \left(m_n^* m_p^*\right)^{\frac{3}{4}} \exp\left[\frac{-E_g}{2kT}\right] \qquad (3)$$

where the exponential temperature dependence dominates $n_i(T)$. To determine the total carrier concentration, we must also consider space-charge neutrality:

$$n(T) = N_D^+(T) - N_A^- + \frac{n_i^2(T)}{n(T)} \qquad \textbf{and:} \qquad p(T) = N_A^-(T) - N_D^+(T) + \frac{n_i^2(T)}{p(T)} \qquad (4)$$

For a doped semiconductor, the temperature dependence of electron concentration can be seen in Figure 2. At very low temperatures (large $1/T$), negligible intrinsic electron-hole-pairs (EHPs) exist (n_i is very small), and the donor electrons are bound to the donor atoms. This is known as the *ionization* (or *freeze-out*) region. As the temperature is raised, increased ionization occurs and at about 100K all of the donor atoms are ionized, at which point the carrier concentration is determined by doping. The region where every available dopant has been ionized is called the *extrinsic* (or *saturation)* region. In this region, an increase in temperature produces no increase in carrier concentration. Referring to Equation 4, this is the region where $N_D^+(T) = N_D$,

$N_A^-(T) = N_A$, and $n_i(T) << |N_D - N_A|$. At high temperatures, the thermally generated intrinsic carriers outnumber the dopants ($n_i > |N_D - N_A|$). In this *intrinsic* region, carrier concentration increases with temperature as shown in Equation 3 because n_i has become the dominant term of Equation 4.
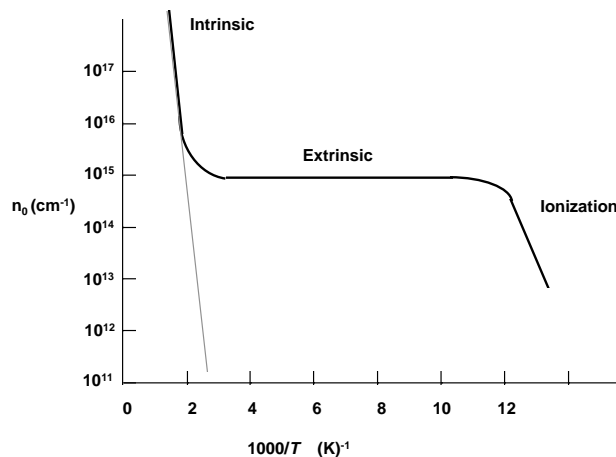

Figure 2. Carrier concentration vs. reciprocal temperature for silicon doped with 10^{15} donors/cm^3

4.5 Temperature Dependence of Conductivity for a Semiconductor

Remember that Equation 1 showed that conductivity depends on both carrier concentration and mobility, so there are a variety of possible temperature dependencies for conductivity. For

instance, at fairly low temperatures (less than 200K), the dominant scattering mechanism might be impurity scattering ($\mu \propto T^{3/2}$) while the carrier concentration is determined by extrinsic doping ($n = N_D^+$), therefore, conductivity would be seen to increase with temperature ($\sigma \propto T^{3/2}$). Other possibilities, depending on the material, doping, and temperature will show different temperature dependence of conductivity. One particularly interesting case occurs at high temperatures (above 400K or higher) when carrier concentration is intrinsic (Equation 4) and mobility is dominated by lattice scattering ($\mu \propto T^{-3/2}$). In such cases, the conductivity can easily be shown to vary with temperature as:

$$\sigma \propto \exp\left(\frac{-E_g}{2kT}\right) \qquad (5)$$

In this case, conductivity depends only on the semiconductor bandgap and the temperature. In this temperature range, measured conductivity data can be used to determine the semiconductor bandgap energy, E_g.

Reference:

Callister, Materials Science and Engineering: An Introduction, Chapter 19.6-19.12