Doping of semiconductors

**n doping** This involves substituting Si by neighboring elements that contribute excess electrons. For example, small amounts of P or As can substitute Si. Since P/As have 5 valence electrons, they behave like Si plus an extra electron. This extra electron contributes to electrical conductivity, and with a sufficiently large number of such dopant atoms, the material can display metallic conductivity. With smaller amounts, one has *extrinsic* n-type semiconduction.

Rather than n and p being equal, the n electrons from the donor usually totally outweigh the intrinsic n and p type carriers so that:

\[ \sigma \sim n|e|\mu_e \]

The donor levels created by substituting Si by P or As lie just below the bottom of the conduction band. Thermal energy is usually sufficient to promote the donor electrons into the conduction band.

**p doping** This involves substituting Si by neighboring atom that has one less electron than Si, for example, by B or Al. The substituent atom then creates a “hole” around it, that can hop from one site to another. The hopping of a hole in one direction corresponds to the hopping of an electron in the opposite direction. Once again, the dominant conduction process is because of the dopant.

\[ \sigma \sim p|e|\mu_h \]

**T dependence of the carrier concentration** The expression:
\[ \rho = \rho_0 \exp\left(\frac{E_g}{2k_B T}\right) \]

can inverted and written in terms of the conductivity

\[ \sigma = \sigma_0 \exp\left(-\frac{E_g}{2k_B T}\right) \]

Now \( \sigma = n|e|\mu_e \) or \( \sigma = p|e|\mu_h \). It is known that the mobility \( \mu \) is effectively temperature-independent so we can express the carrier concentration in terms of temperature:

\[ n = n_0 \exp\left(-\frac{E_g}{2k_B T}\right) \quad \text{or} \quad \log n = \log n_0 - \frac{E_g}{2k_B T} \]

for an electron doped semiconductor and for a hole-doped semiconductor:

\[ p = p_0 \exp\left(-\frac{E_g}{2k_B T}\right) \quad \text{or} \quad \log p = \log p_0 - \frac{E_g}{2k_B T} \]

The plot above shows typical variation of the logarithm of the carrier concentration with inverse temperature. At high temperatures (small \( 1/T \)) the data follows usual activated behavior of an intrinsic semiconductor. At lower temperatures (larger \( 1/T \)) extrinsic behavior dominates.
Initially, lowering the temperature results in saturation of the acceptor levels or exhaustion of the donor levels. Only at still lower temperatures does the extrinsic behavior take over.

**Semiconductor devices**

The $p-n$ junction is formed when the two different sides of semiconductor are doped, respectively with holes (for example, Al for Si) and electrons (for example, P for Si). One of the properties of the $p-n$ junction is that it rectifies — it allows an electric current to pass only in one direction.
The junction transistor

forward bias  reverse bias