Ram Seshadri MRL 2031, x6129

seshadri@mrl.ucsb.edu; http://www.mrl.ucsb.edu/∼seshadri/teach.html

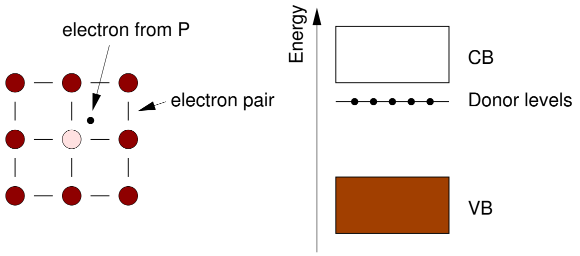
Doping of semiconductors

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 displays 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:

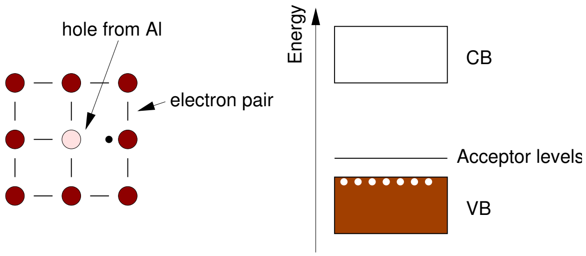
$$\sigma \sim n|e|\mu_e$$

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:

$$\rho = \rho_0 \exp(\frac{E_g}{2k_{\mathrm{B}}T})$$

can inverted and written in terms of the conductivity

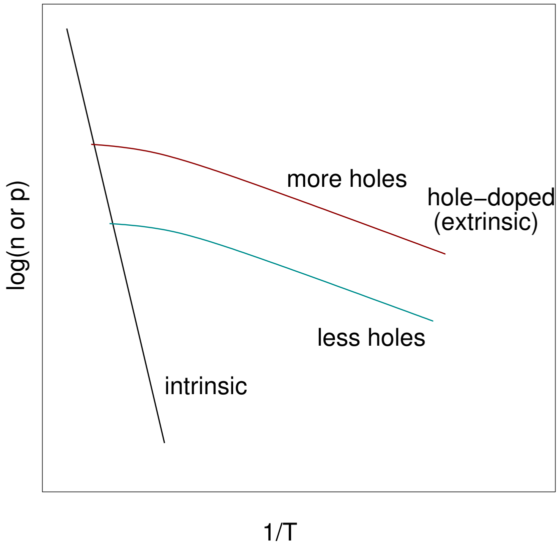
$$\sigma = \sigma_0 \exp(\frac{-E_g}{2k_{\mathrm{B}}T})$$

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

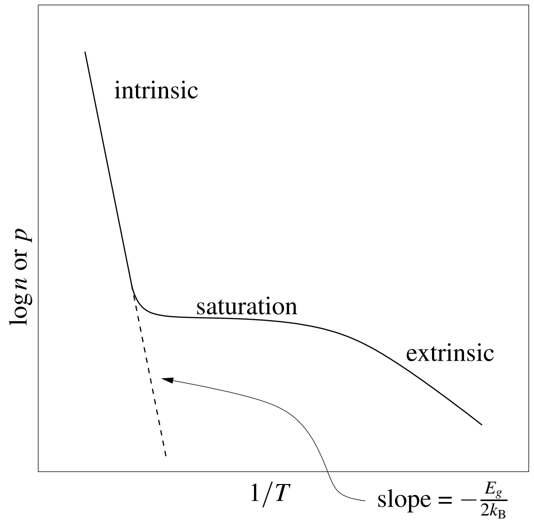
$$n = n_0 \exp(\frac{-E_g}{2k_{\mathrm{B}}T}) \quad \text{or} \quad \log n = \log n_0 - \frac{-E_g}{2k_{\mathrm{B}}T}$$

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

$$p = p_0 \exp(\frac{-E_g}{2k_{\mathrm{B}}T}) \quad \text{or} \quad \log p = \log p_0 - \frac{-E_g}{2k_{\mathrm{B}}T}$$



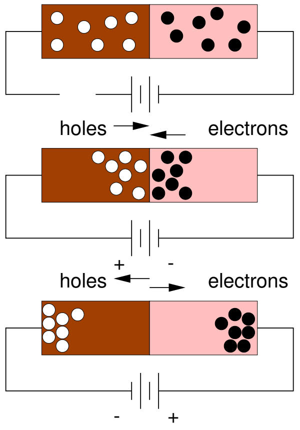
The plot above shows typical variation of the logarithm of the carrier concentration with inverse temperature. At high temperatures (small $1/T$) the data follows usual activated behavior of an intrinsic semiconductor. At lower temperatures (larger $1/T$) extrinsic behavior dominates.

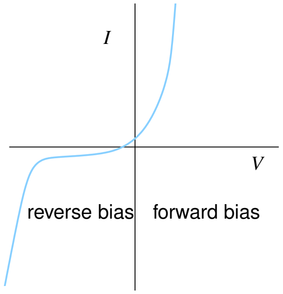


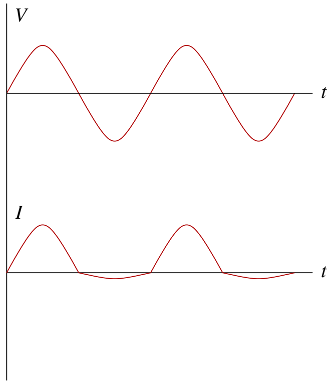
Initially, lowering the temperature results in *saturation* of the acceptor levels or *exhaustion* of the donor levels. Only at still lower temperatures does the extrinsic behavior take over.

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