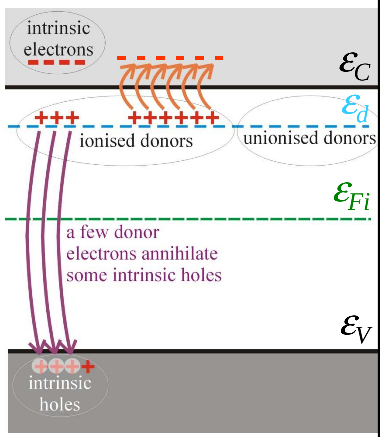
Redistribution of charge carriers

- Note that as donors atoms and corresponding donor electrons are added, there is a redistribution of electrons among the available energy states.

- A few of the donor electrons will fall into empty states in the valence band and annihilate some of the intrinsic holes.

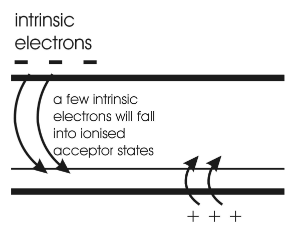
- The minority carrier hole concentration will therefore fall (see example on slide 11.9).



- Note: because of this redistribution, the number of electrons in the conduction band is **not** simply equal to donor concentration plus intrinsic electron concentration.

Redistribution of charge carriers

Similarly for acceptor impurities → reducing the concentration of intrinsic electrons:



Example: As last example, but germanium with $N_d = 5\times10^{13}$ cm^{-3} and $N_a = 0$. Assume $n_i = 2.4\times10^{13}$ cm^{-3}

Answer:

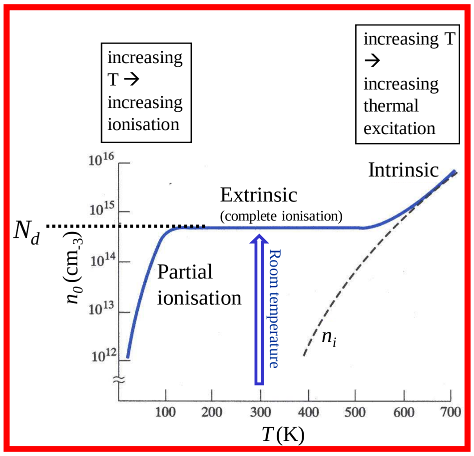
- Notice that if donor impurity concentration is not too different from intrinsic carrier concentration then the thermal equilibrium majority carrier electron concentration is influenced by the intrinsic concentration.

Electron concentration versus temperature

- The intrinsic carrier concentration (n_i) is a strong function of temperature (slide 8.9), so as T rises, n_i will begin to dominate (see equation opposite from slide 11.8)

→ **The semiconductor will eventually loose its extrinsic characteristics**.

$$n_0 = \frac{(N_d - N_a)}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2}$$



- *e.g.* (opposite) Si doped with $N_d = 5\times10^{14}$ cm^{-3}.
- At room temperature, all the impurities are ionised, hence $n_0 = N_d$
- Notice onset of freeze-out at low T when none of the impurities are ionised *i.e.*, $n_d = N_d$ - that is the concentration of electrons in the impurity band equals the concentration of impurities.

Compensated Semiconductors

- *Another Example:* Calculate the thermal-equilibrium electron and hole concentrations in a compensated semiconductor. Consider silicon at T=300 K, with $N_d = 10^{16}$ cm^{-3} and $N_a = 3\times10^{15}$ cm^{-3}. Assume $n_i = 1.5\times10^{10}$cm^{-3}.
- *Answer:*

- **If we assume complete ionisation, and if ($N_d - N_a$) >> n_i, then the majority carrier electron concentration is approximately the difference between the acceptor and donor concentrations and hence**

$$p_0 = \frac{n_i^2}{n_0} = \frac{n_i^2}{(N_d - N_a)}$$

- <u>Important note:</u> Always calculate *minority* carrier concentration from $n_0 p_0 = n_i^2$ once the majority carrier concentration has been determined (otherwise, for example, two numbers ~10^{16} would be subtracted to obtain a number of order 10^4.)

Position of Fermi Level

- We know that the electron and hole concentrations change as Fermi Energy level moves across bandgap. Also, we know how the electron and holes concentrations depend on impurity concentrations. So we can determine the Fermi Energy level as a function of doping concentration and temperature.
- If we assume the Boltzmann approx is valid, then we can rearrange the equation for n0 (slide 8.6/10.5)

$$\varepsilon_C - \varepsilon_F = k_B T \ln\left(\frac{N_C}{n_0}\right)$$

- For an *n*-type semiconductor at room temperature (complete ionisation) which is doped with $N_d >> n_i$, then $n_0 \approx N_d$:

$$\varepsilon_C - \varepsilon_F = k_B T \ln\left(\frac{N_C}{N_d}\right)$$

- *i.e.* as donor concentration increases, the Fermi level moves closer to conduction band and hence the electron concentration in the CB increases.

Position of Fermi Level

- Note, that if the semiconductor is compensated, then replace N_d with the **net** effective donor concentration, $N_d - N_a$
- *Example:* Calculate position of Fermi Energy level with respect to the bottom of the conduction band in an n-type semiconductor. Consider silicon at room temperature with $N_d = 10^{16}$ cm^{-3}, $N_a = 0$ and $n_i = 1.5\times10^{10}$cm^{-3}
- *Answer:*
- We also know that $n_0 = n_i \exp[(\varepsilon_F - \varepsilon_{Fi})/k_BT]$ from slide 10.6, so we can also write

$$\varepsilon_F - \varepsilon_{Fi} = k_B T \ln\left(\frac{n_0}{n_i}\right)$$

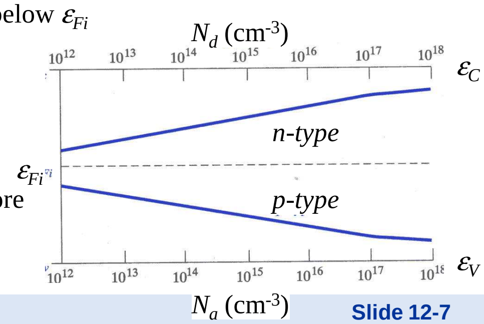
- This equation can be used specifically for an n-type semiconductor where n_0 is given by $n_0 = \frac{(N_d - N_a)}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2}$ from slide 11.8.
- Note: if the net effective donor concentration is zero $(N_d - N_a) = 0$, then $n_0 = n_i$ and $\varepsilon_F = \varepsilon_{Fi}$ *i.e.* a completely compensated material has the properties of an intrinsic material.

Position of Fermi Level

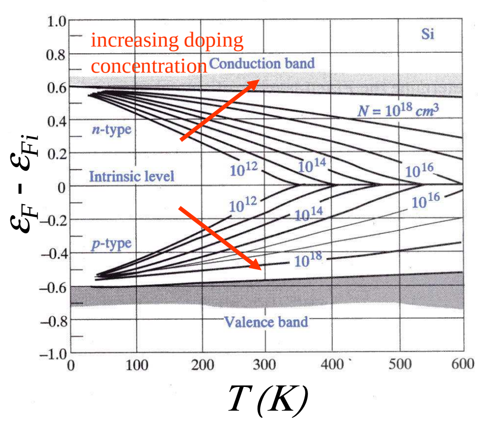
- Similarly for a p-type semiconductor,

$$\varepsilon_F - \varepsilon_V = k_B T \ln\left(\frac{N_V}{p_0}\right) \xrightarrow[N_a >> n_i]{\text{Assuming 300K and}} \varepsilon_F - \varepsilon_V = k_B T \ln\left(\frac{N_V}{N_a}\right)$$

- And in the same way as before, we derive an expression in terms if the intrinsic Fermi energy level: $\varepsilon_{Fi} - \varepsilon_F = k_B T \ln\left(\frac{p_0}{n_i}\right)$
- *i.e.* for a n-type material, $n_0 > n_i$ and the Fermi level is above ε_{Fi}, and for a p-type material, $p_0 > n_i$ and the Fermi level is below ε_{Fi}
- We can plot the position of the Fermi level as a function of doping concentration: (Si at T = 300K)
- the intrinsic carrier concentration is a strong function of temperature – therefore so is the Fermi energy level.



Position of Fermi Level



- As the temperature increases, n_i increases, and ε_F moves closer to the intrinsic level.
- At high temperatures, the semiconductor becomes more intrinsic-like.
- At very low temperatures, freeze-out occurs, the Fermi level goes above the donor level for n-types, and below the acceptor level in p-types – the Boltzmann approximation is no longer valid, and the some of the equations we've derived will no longer apply.