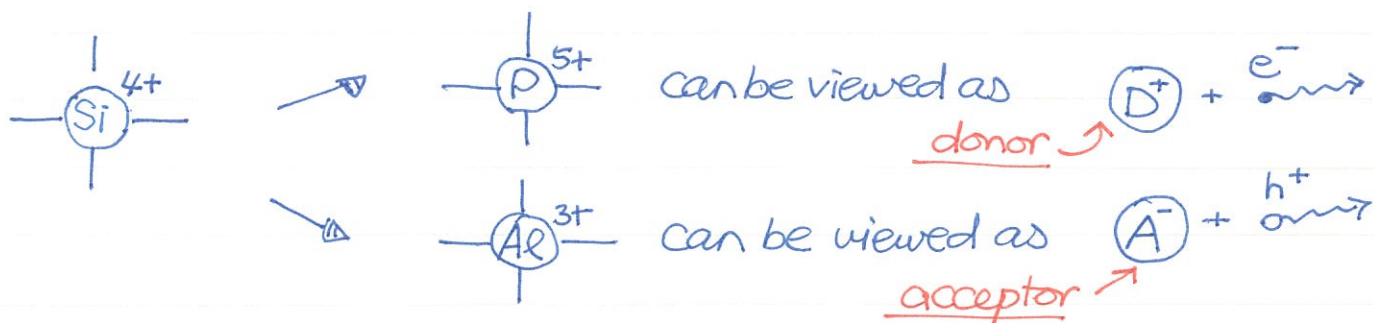


# HH0041 p-type and n-type Semiconductors

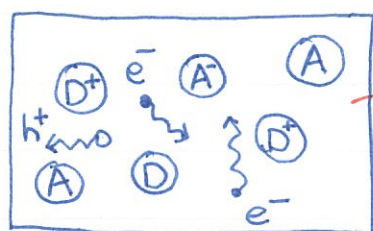
The true usage of a semiconductor is to dope different impurity atoms into the regular lattice. Take Si as an example —



In short, an ionized donor contributes extra electrons into the system. On the other hand, an ionized acceptor contribute extra holes.

① **Charge neutrality**: Because the system is charge neutral,  $n^+ = n^-$ . The positive charges come from holes and ionized donors  $n^+ = n_h + n_d^+$ . Similarly,  $n^- = n_e + n_a^-$ .

Introduce  $\Delta n \equiv n_e - n_h$ . According to charge neutrality,  $\Delta n = n_d^+ - n_a^-$ . Note that for intrinsic semiconductors  $\Delta n = 0$ !



$$n_h + n_d^+ = n_e + n_a^-$$

From mass action law,  $n_e \cdot n_h = n_i^2 \rightarrow n_e(n_e - \Delta n) = n_i^2$

One can solve for  $n_e, n_h$ .

$$n_e = \frac{1}{2} \sqrt{(\Delta n)^2 + 4n_i^2} + \frac{1}{2} \Delta n$$

$$n_h = \frac{1}{2} \sqrt{(\Delta n)^2 + 4n_i^2} - \frac{1}{2} \Delta n$$

In an extrinsic n-type semiconductor  $\Delta n > 0$  and  $\Delta n \gg n_i$

$$n_e \approx \Delta n, n_h \approx n_i^2 / \Delta n$$

In an extrinsic p-type semiconductor  $\Delta n < 0$  and  $|\Delta n| \gg n_i$ . The electron

$$n_h \approx |\Delta n|, n_e \approx n_i^2 / |\Delta n|$$

and hole concentrations are

It is important to emphasize that  $\Delta n = n_d^+ - n_a^- \neq n_d - n_a$

← not all donors/acceptors are ionized ☹



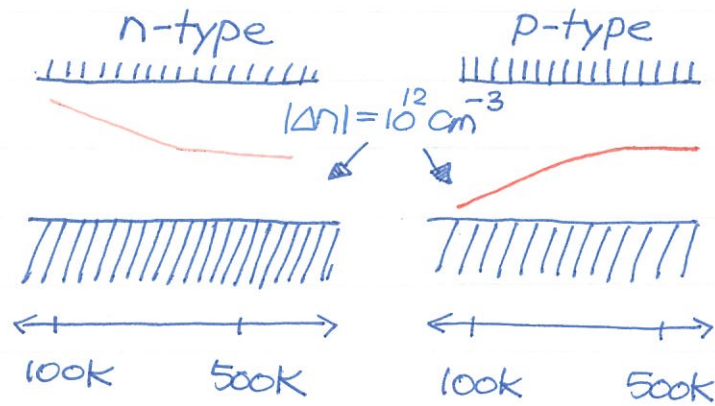
The chemical potential can be expressed in the "ideal-gas" form:

$$\begin{aligned} \mu &= \epsilon_c - \tau \log(n_c/n_e) \\ &= \epsilon_v + \tau \log(n_v/n_h) \end{aligned}$$

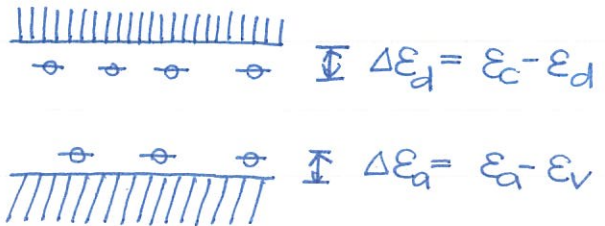
For n-type,  $\mu \approx \epsilon_c - \tau \log(n_c/n_n)$

For p-type,  $\mu \approx \epsilon_v + \tau \log(n_v/n_p)$

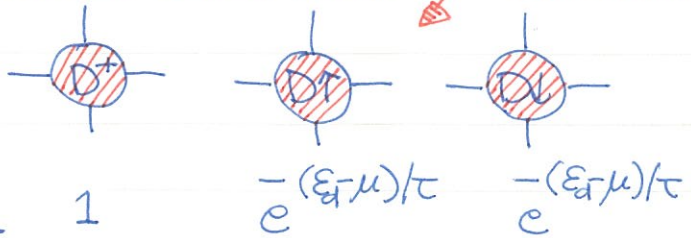
At lower temperature, the chemical potential  $\mu \lesssim \epsilon_c$  slightly below the conduction band in n-type S-C. But, in p-type S-C,  $\mu \gtrsim \epsilon_v$ , slightly above the valence band.



**Impurity levels.** The addition of impurities to a semiconductor moves some orbitals from the conduction or valence band into the energy gap, where the shifted orbitals are localized bound states to the donor or acceptor.



Let's consider the occupation of a donor level first. **THREE conf.**



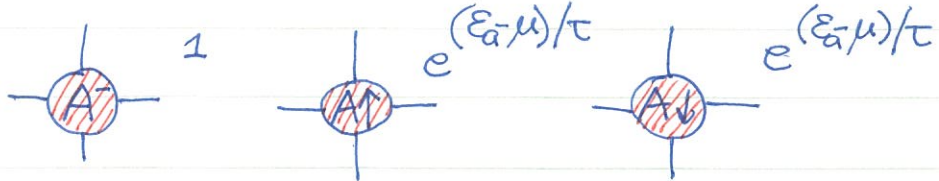
Adding the factors to obtain Gibbs sum.  $Z_G = 1 + 2 e^{(\mu - \epsilon_d)/\tau}$

Thus, the probability to find

an ionized donor is  $f(D^+) = \frac{1}{Z_G} = \frac{1}{1 + 2 e^{(\mu - \epsilon_d)/\tau}}$

The occupation of an acceptor level is more tricky. One can follow Kittel's argument. OR, one can make good use of the notion of "holes".

Again, three configurations





The trick for holes is to reverse the signs of  $\epsilon_a$  and  $\mu$ . In consequence, the Gibbs sum is  $Z_G = 1 + 2 e^{(\epsilon_a - \mu)/\tau}$

The probability to find an ionized acceptor is

$$f(A^-) = \frac{1}{1 + 2 e^{(\epsilon_a - \mu)/\tau}}$$

The concentrations of ionized dopants  $D^+$  and  $A^-$  are

$$n_d^+ = n_d f(D^+) = \frac{n_d}{1 + 2 e^{(\mu - \epsilon_d)/\tau}}$$

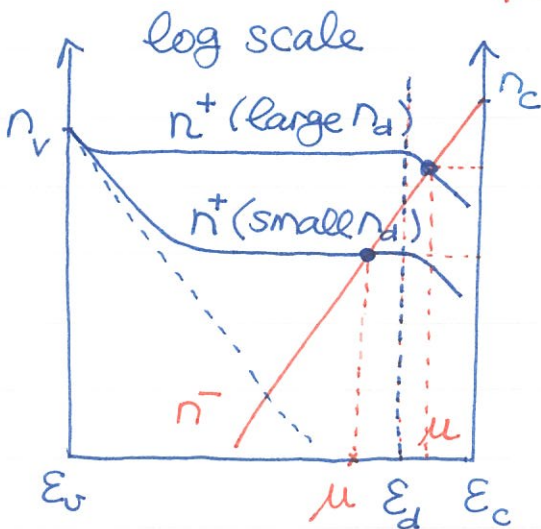
$$n_a^- = n_a f(A^-) = \frac{n_a}{1 + 2 e^{(\epsilon_a - \mu)/\tau}}$$

$n_d^+ \approx n_d$  if  $(\mu - \epsilon_d)/\tau \ll 0$

$n_a^- \approx n_a$  if  $(\mu - \epsilon_a)/\tau \gg 0$

Charge neutrality requires  $n^- = n^+$ , i.e.  $n_e + n_a^- = n_h + n_d^+$

To make life easier, let's consider the n-type first. The relation simplifies  $n_e = n_h + n_d^+$  because  $n_a = 0 = n_a^-$ .



One can solve the relation by the log plot on the left.

$$n_e = n_c e^{-(\epsilon_c - \mu)/\tau}$$

straight line with slope  $1/\tau$  in log plot.

The  $n^+$  curve contains two parts

$$n_h = n_v e^{-(\mu - \epsilon_v)/\tau}$$

straight line with slope  $-1/\tau$

$$n_d^+ = n_d \cdot \frac{1}{1 + 2 e^{(\mu - \epsilon_d)/\tau}}$$

plateau + a bend-down line.

(1) For small donor concentration  $n_d$ ,

the intersection of  $n_+$ ,  $n_-$  curves happens on the plateau of  $n^+$  curve  $\rightarrow$   $n^+ \approx n_d \approx n_d^+$  most donors are ionized.

The chemical potential  $\mu < \epsilon_d$  so that the donor levels are almost empty, indicating strong ionization.

(2) For large donor concentration  $n_d$ ,  $n_+$ ,  $n_-$  curves intersect at the bend-down line.  $n^+ = n_h + n_d^+ \approx n_d^+$ . But,  $n_d^+$  is smaller than  $n_d$ , meaning the ionization is weaker. In this case, the chemical potential  $\mu > \epsilon_d$  so that the donor levels are partially filled.

The p-type acceptor can be understood in a similar way and I shall skip the details. Going back to the n-type. We can make the calculations precise  $\ddot{\circ}$

$$n_e = n_c e^{-(\epsilon_c - \mu)/\tau} \quad \text{and} \quad n_h = \frac{n_i^2}{n_e}$$

charge neutrality  
 $n_e = n_h + n_d^+$

$$n_d^+ = \frac{n_d}{1 + 2 e^{(\mu - \epsilon_d)/\tau}} = \frac{n_d}{1 + 2 (n_e/n_c) e^{\Delta\epsilon_d/\tau}}$$

solve for  $n_e$  !!

$$\rightarrow \boxed{n_e = \frac{n_i^2}{n_e} + n_d \frac{1}{1 + 2 (n_e/n_c) e^{\Delta\epsilon_d/\tau}}}$$

a bit messy but easy to solve  $\ddot{\circ}$

In strong ionization limit with extrinsic doping,  $n_h$  is small and  $n_e \approx n_d$ .

$$n_e \approx n_d \frac{1}{1 + 2 (n_e/n_c) e^{\Delta\epsilon_d/\tau}} \approx n_d \left( 1 - 2 \frac{n_e}{n_c} e^{\Delta\epsilon_d/\tau} \right)$$

Making use of  $n_e \approx n_d$ , the electron concentration is

$$\boxed{n_e \approx n_d \left( 1 - \frac{2n_d}{n_c} e^{\Delta\epsilon_d/\tau} \right)}$$

For P in Si @  $\tau = 300\text{K}$

$$\underline{\Delta\epsilon_d = 1.74\tau} \quad \text{comparable!}$$

$$e^{\Delta\epsilon_d/\tau} \approx 5.7. \quad \text{Given } n_d = 0.01 n_c \rightarrow n_e/n_d \approx 89\%$$

**STRONG ionization.**



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