

Recitation 2: Equilibrium Electron and Hole Concentration from Doping

Here is a list of new things we learned yesterday:

1. Electrons and Holes
2. Generation and Recombination
3. Thermal Equilibrium
4. Law of Mass Action
5. Doping - (donors and acceptors) and charge neutrality
6. Intrinsic Semiconductor vs. Extrinsic Semiconductor
7. Majority and Minority carriers

1 Electrons and Holes

This refers to the “free” electrons and holes. They carry charges (electron -ve and hole +ve), and are responsible for electrical current in the semiconductor. Concentration of electron ($= n$) and hole ($= p$) is measured in the unit of $/\text{cm}^3$ or cm^{-3} (per cubic centimeter). Remember in Si the atomic density is $5 \times 10^{22} \text{cm}^{-3}$, very useful number

2 Generation and Recombination

Generation is one way to obtain “free” e & h in semiconductors. 1 electron-hole pair (1e + 1h) is generated by breaking a bond. Recombination is the reverse process.

3 Thermal Equilibrium

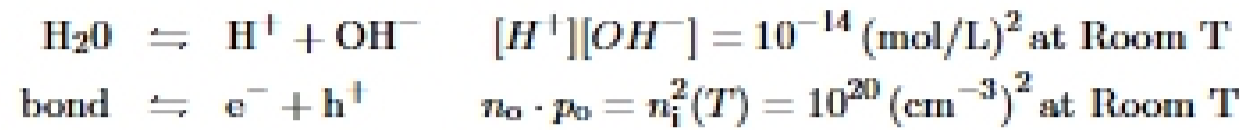
A concept which will be used very often. Thermal equilibrium is defined as steady state + no extra energy source. Note that we have generation or recombination under thermal equilibrium. It is just that the two rates are equal and cancel each other, so the concentrations of e & h do not change. n_0 and p_0 refer to concentrations in thermal equilibrium.

4 Law of Mass Action

At each temperature T , under thermal equilibrium:

$$\begin{aligned}n_0 \cdot p_0 &= \text{constant} = f(T) \quad (\text{only depends on temperature}) \\n_0 \cdot p_0 &= n_i^2(T) \quad (n_i \equiv \text{intrinsic carrier concentration})\end{aligned}$$

This is like a chemical reaction:



Note n_i has a temperature dependence:

$$n_i = A \cdot (T)^{3/2} e^{-\frac{E_G}{2k_B T}}$$

A is a constant, T is in Kelvin, $T(\text{K}) = 273 + T(^{\circ}\text{C})$, and $k_B = 8.62 \times 10^{-5} \text{ eV/K}$. E_G is the “Bandgap” energy of the semiconductor - it also corresponds to the case of bond breakage. For Si, $E_G = 1.12 \text{ eV}$.

Example 1

At room temperature, $T = 300 \text{ K}$, $n_i(300 \text{ K}) = 1 \times 10^{10} \text{ cm}^{-3}$. What is $n_i(500^{\circ}\text{C})$?

$$\begin{aligned} n_i(500^{\circ}\text{C}) &= n_i(773 \text{ K}) \\ \frac{n_i(773 \text{ K})}{n_i(300 \text{ K})} &= \left(\frac{773}{300}\right)^{3/2} \times \frac{e^{-\frac{E_G}{2k_B(773)}}}{e^{-\frac{E_G}{2k_B(300)}}} = 4.14 \times \frac{e^{-8.4}}{e^{-21.65}} = 3.5 \times 10^6 \end{aligned}$$

Therefore, $n_i(773 \text{ K}) = 3.5 \times 10^6 \times n_i(300 \text{ K}) = 3.5 \times 10^6 \times 10^{10} \text{ cm}^{-3} = 3.5 \times 10^{16} \text{ cm}^{-3}$

Something to observe:

At room temperature, $n_o = p_o = 10^{10} \text{ cm}^{-3}$ for Si. Atomic density is $5 \times 10^{22} \text{ cm}^{-3}$. Therefore, only a tiny fraction of atoms ($\frac{10^{10}}{5 \times 10^{22}} = \frac{1}{5 \times 10^{12}} = 2 \times 10^{-11}\%$) lose an electron in one of their 4 bonds. By heating up to 500°C , the concentration of free carriers goes up $\sim 10^6$ (1 million) times, but the percentage is still quite low.

5 Doping and Charge Neutrality

Doping

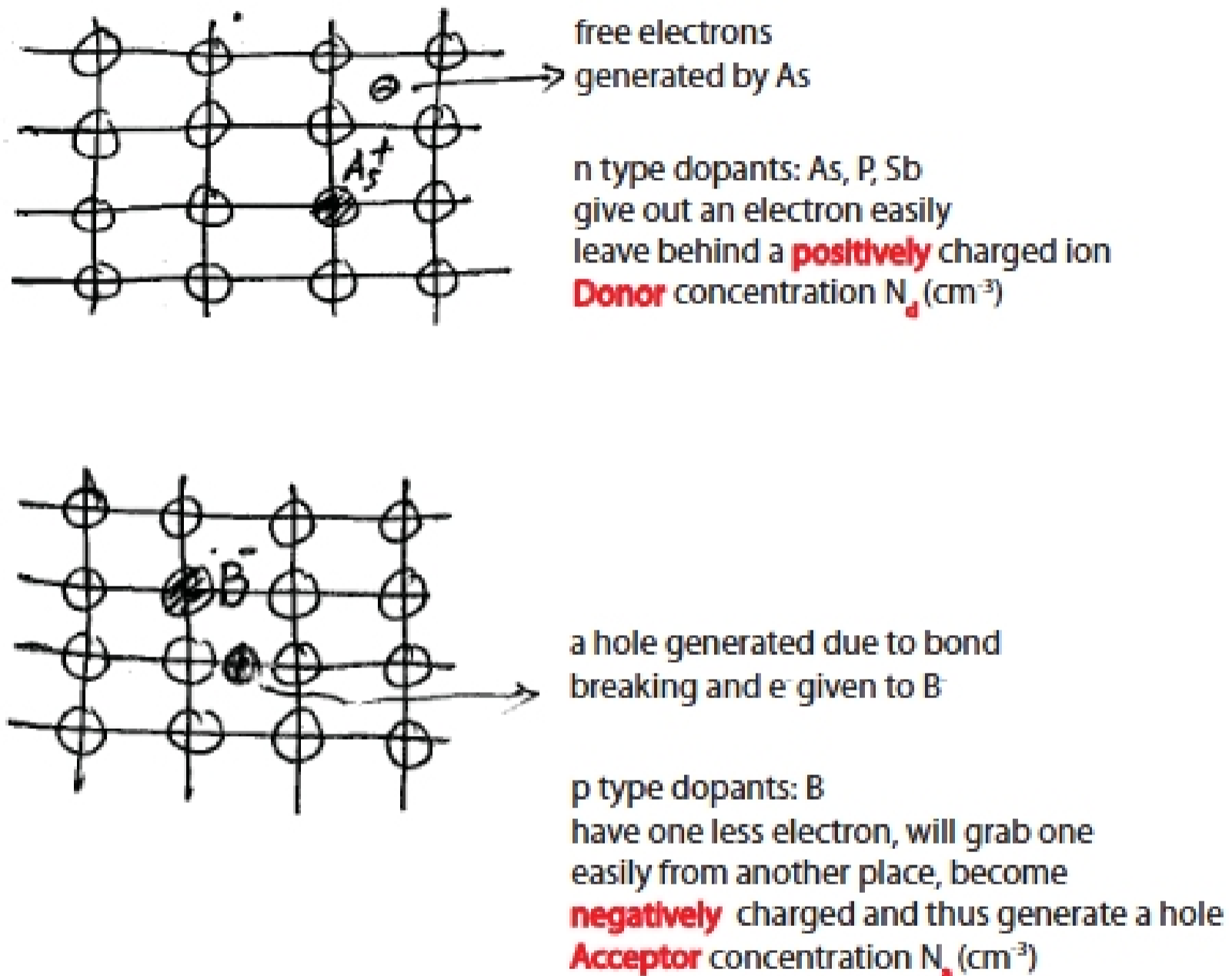


Figure 1: Types of Doping

Charge neutrality

Although foreign atoms are introduced in Si, the overall semiconductor is charge neutral. Therefore, concentration of positive charges = concentration of negative charges. The positive charges include holes (p) and donors (N_d). The negative charges include electrons (n) and acceptors (N_a).

$$p_0 + N_d - n_0 - N_a = 0$$