

# ECE 255

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## 1 Bandgap and Periodic Table

### 1.1 Bandgap, Insulators, Semiconductors, and Conductors

Most materials have a bandgap. It is the energy gap between the conduction and valence band of a material. When the gap is large, it is hard for electron to jump from the valence band to the conduction band. Hence, there is no conduction electrons around: electric current cannot flow. This is the mark of an *insulator*. But when the gap is small, the electron may jump from the valence band to the conduction band even at room temperature. This material can conduct electricity but not well. This is the mark of a *semiconductor*. However, when the bandgap is small, or nonexistent, then the conduction band is replete with electrons, which form the conduction electrons. These electrons can conduct electricity well. This is the mark of a *conductor*.

### 1.2 Periodic Table, Mole, and Atomic Weight

The periodic table was discovered and put together by Mendeleev (1834-1907). Before him, scientist knew that different elements have different atomic weights. But Mendeleev saw the rhyme and reason behind them, and organized them in columns and rows: that was the beginning of the periodic table.

One other concept you should know is Avagadro's number (1776-1856) which is  $\approx 6 \times 10^{23}$ . It is a humongous number and is the number of atoms in one mole of elements. For instance, one gram of hydrogen has about  $6 \times 10^{23}$  atoms. This concept can be used to define *mole* and *atomic weight* (also called atomic mass).

## 2 Intrinsic Semiconductors

When a semiconductor is undoped, there will be holes and electrons generated in the material due to thermal agitation of the environment. According to

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Boltzmann's law (1844-1906), the following formula can be derived: The number of valence bond per  $\text{cm}^3$  that is broken forms electron-hole pair. The electron concentration (with similar number for hole concentration) is

$$n_i = BT^{3/2}e^{-E_g/(2k_B T)} \quad (2.1)$$

where

$$B = 7.3 \times 10^{15} \text{K}^{-3/2} \text{cm}^{-3} \quad (2.2)$$

$T$  is the temperature in degree Kelvin K,  $E_g$  is the bandgap energy, and  $k_B$  is  $8.62 \times 10^{-5} \text{K}^{-1} \text{eV}$  is the Boltzmann constant. The hallmark of the above formula is that the higher the temperature  $T$ , the larger the number of broken bonds, and hence, more the electron-hole pair generated. The larger the bandgap energy  $E_g$ , the harder the bond is to be broken, and hence, the less electron-hole pair generated. A sketch for the derivation of the above formula is given in the Appendix.

The room temperature  $T_{\text{room temp}}$  is usually taken at  $300^\circ \text{K}$ . The bandgap of silicon  $E_{g\text{-si}}$  is 1.12 eV where eV stands for electron volt which is a unit of energy.

For intrinsic (or undoped) semiconductor,

$$p_i = n_i \quad (2.3)$$

But it can be shown that  $pn$  or the product of electron-hole density is approximately a constant. Therefore it is often assumed that even for doped semiconductors

$$pn = n_i^2 \quad (2.4)$$

For intrinsic silicon,  $n_i = 1.5 \times 10^{10} \text{carriers/cm}^3$ , whereas the number of silicon bonds is about  $\approx 5 \times 10^{22} / \text{cm}^3$ . Therefore,  $n_i$  is very small, or one electron per  $10^{13}$  Si bond.

Because  $np$  is approximately a constant, the ratio of electron-hole concentration can be changed by doping. A donor atom contributes to an electron while an acceptor atom contributes to a hole (or a vacancy in a valence bond). The donor concentration is usually denoted by  $N_D$  while the acceptor concentration is denoted by  $N_A$ .

For doped silicon with phosphorous, which has five valence electrons, extra unpaired electrons are around, and hence, each phosphorous atom donates an electron to the lattice: it is called a donor impurity. For doping with boron, which has three valence electrons, each boron atom contributes to an unfilled valence bond or a hole: it is called an acceptor impurity. We assume an acceptor concentration of  $N_A \approx 10^{16} / \text{cm}^3$ . Therefore, if a silicon wafer is  $p$ -doped (or hole-doped) or doped with boron, then the hole concentration is

$$p \approx N_A \approx 10^{16} / \text{cm}^3 \quad (2.5)$$

The electron concentration is

$$n = \frac{n_i^2}{p} \approx \frac{10^{20}}{10^{16}} \approx 10^4/\text{cm}^3 \quad (2.6)$$

Hence, the electron concentration is much much less than the hole concentration.

## Appendix A Boltzmann's Law and Electron-Hole Pair Generation

Boltzmann's law is the underpinning law for many observations in semiconductor physics. It will not be derived but just stated here. If a system has many possible energy states  $E_i$ ,  $i = 1, \dots, N$ , when the system is in thermodynamic equilibrium with another system such as a heat bath, then the probability of the system in a state with energy  $E_i$  is proportional to

$$P_i \sim C e^{-E_i/(k_B T)} \quad (A.1)$$

where  $k_B$  is Boltzmann constant with value  $8.62 \times 10^{-5} \text{ K}^{-1}\text{eV}$ , and  $T$  is the temperature in degree Kelvin. The above formula makes physical sense that the higher the energy of the state is, the less likely is the system going to be in that state.

The energy it takes to generate electron-hole pair (EHP) is  $E_g$ . After EHP, the system is in a higher energy state. Hence, the probability of electron-hole pair generation is proportional to

$$P_{EHP} \sim C e^{-E_g/(k_B T)} \quad (A.2)$$

Also the probability of electron-hole pair generation is also proportional to the EHP recombination at equilibrium. The EHP recombination rate is proportional to the product of the densities of the electrons and holes. Hence,

$$P_{EHP} \sim n_i p_i \quad (A.3)$$

where  $n_i$  and  $p_i$  are the intrinsic electron and hole concentration in the semiconductor. Since  $n_i = p_i$  in an undoped semiconductor, we deduce that

$$n_i \sim C' e^{-E_g/(2k_B T)} \quad (A.4)$$

Deriving the constant  $C'$  is a lot more advanced and is given in some advanced books. The above is the partial rationale for (2.1). To show that  $pn = n_i^2$  will need the understanding of Fermi level which is outside the scope of this course.