CALIFORNIA INSTITUTE OF TECHNOLOGY
PHYSICS MATHEMATICS AND ASTRONOMY DIVISION

Freshman Physics Laboratory (PH003)

Basics on Semiconductors Physics

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Chapter 10

Semiconductors Conduction

This note is written with the purpose of giving a basic understanding of the conduction mechanism in semiconductors, and in particular on the p-n junction device commonly known as diode.

The topics are discussed to give a qualitative knowledge of the complex physics of conduction in crystals. The bibliography suggests some texts, which give a more detailed and quantitative treatment of semiconductor conduction.

10.1 Conduction in a Solid

The study of an isolated atom structure using quantum theory shows that the states of an electron surrounding the nucleus are numerable[1]and have energy $E_{\underline{n}}$, where $\underline{n}$ is a set of integer numbers, which univocally define the state .

In a solid, we have to take into account all the atoms which constitute the lattice. In this case, the interaction among the atoms and their number[2] ($\sim 10^{22}$atoms/cm^3) make the electron states so dense, that we practically have a continuous band of allowed energy. These bands can be separated by gaps that electrons cannot occupy (*forbidden gap*s).

Because of their fermionic nature (no more than a fermion in a given quantum state), electrons will fill the states starting from the lowest energy

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[1] i.e. they are infinite, but we can associate an integer number to each one of them.

[2] A crude estimate of the energy density levels is essentially the number N of atoms in the lattice.

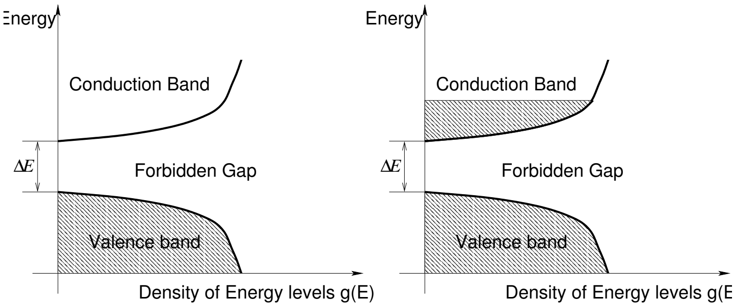

Figure 10.1: Possible qualitative configuration of the energy bands in a solid.

level available, filling up the energy bands to a maximum energy E_0 (see figure 10.1).

Qualitatively, there are two possible configurations, one wiht the last band partially filled, and the other with the last band completely filled. The partially filled or empty band is called the *conduction band,* while the band below it is referred to as the *valence band*. Because of the thermal energy available at the absolute temperature T, some higher energy levels are populated.

In the case of a partially filled band, the solid is a conductor, because when an electric field is applied the electrons can "freely" change states in the conduction band . In the case of completely filled bands, the gap width Φ between the valence band and the conduction band can make the solid an isolator ($\Phi \sim 10$eV)[3] or a semiconductor ($\Phi \sim 1$eV). In fact, the thermal energy available at $T \simeq 300$K, is sufficient to bring some electrons into the conduction band if the gap is on the order of 1eV.

To calculate the number of electrons with an energy above a given value E_0 , we must apply Boltzmann statistics[4], which gives the density of electrons having energy greater than E_0, i.e.

$$n(E > E_0) = e^{-\frac{E_0}{k_B T}}, \qquad k_B = 1.3807 \cdot 10^{-23}\text{J/K},$$

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[3] $1\text{eV} = 1q\text{J}$, $q = 1.60 \cdot 10^{-19}$C, where q is the magnitude of the electron charge in Coulomb. The "electronvolt" is a convenient unit for the energy values carried by an elementary particle.

[4] electrons follow the Fermi-Dirac statistic, which can be approximated by the Boltzmann statistic when $\exp(E/k_B T) \gg 1$.

where k_B is the Boltzmann constant.

10.1.1 Electron and Hole Current

Each time that an electron goes from the valence band to the conduction band, a *vacancy* or *hole* is created. This hole behaves as a positive charge with its own mobility, which contributes to the current in the crystal.

In general, the current in a semiconductor will be the sum of the electron current and the hole current.

10.1.2 Doped Semiconductors

By adding impurities to a semiconductor during the crystal growing process, we can control the number of holes and electrons available for conduction. Let's consider for example an often used semiconductor substrate, the germanium (Ge).

By doping the germanium (valence 4) with arsenic (As, valence 5), we will have 4 chemical bonds connected, leaving the electron of the fifth bond available to be ionized. Since the impurity is embedded in the lattice, its ionization energy will be enormously reduced, making the electron available for conduction.

If we dope Ge with Boron (B, valence 3), we will have 3 bonds connected and one Ge electron not bonded. The impurities in this case will create an energy level above the valence band making possible the ionization of an Ge electron which will create a hole.

A semiconductor having more electrons for conduction than vacancies is said to be an *n-type* semiconductor. If the semiconductor has more vacancies than electrons, is said to be *p-type*.

10.2 The Semiconductor Junction (Diode)

A Semiconductor junction or *p-n junction,* is a junction, of a p-type semiconductor with an n-type semiconductor. Let's focus on the study of the conduction mechanism of this peculiar device .

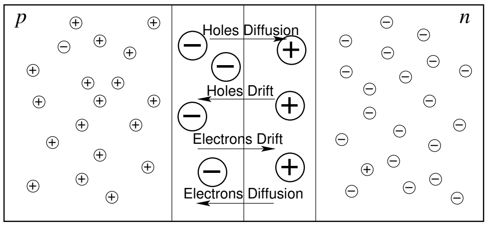

Figure 10.2: Junction at the Equilibrium.

10.2.1 Junction at the Equilibrium

Once the two types of semiconductors are connected with no interspace between, then a diffusion process of vacancies and electrons takes place to statistically balance the concentrations of vacancies and electrons on each side. Holes migrate from the p-side to the n-side, and electrons migrate from the n-side to the p-side (*diffusion current*), creating a sort of capacitor and a region depleted of holes and electrons.

The built-in electric field will create a *drift current* through the junction made of the few electrons on the p-side and the few holes on the n-side.

The diffusion and drift current will reach a statistical equilibrium with a null electron current flowing through the junction, a null hole current, and a depletion region around the junction.

The drift current of electrons from n to p must be proportional to electron density $n(E > \Phi)$[5], where Φ is the energy gap, i.e.

$$I_{n \rightarrow p} = Ce^{-\frac{\Phi}{k_B T}} = I_0$$

To maintain statistical equilibrium, the diffusion current must be the same, but with an opposite sign, i.e.

$$I_{p \rightarrow n} = -Ce^{-\frac{\Phi}{k_B T}} = -I_0$$

An equivalent argument can be used to analyze hole current.

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[5] For commodity we consider the zero energy level the gap base. The offset is indeed included in the C constant.

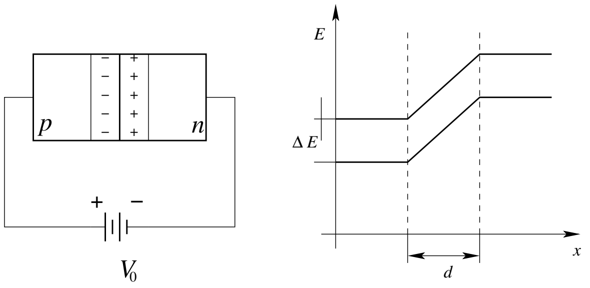

Figure 10.3: Forward biased junction

10.2.2 Forward Biased Junction

Applying a voltage V drop across the diode as shown in figure 10.3, the energy difference between the conduction band of the p-region and that of the n-region is

$$\Delta E = \Phi - qV,$$

where q is the magnitude of the electron charge.

In this case, the electron current favored by the applied electric field flows from the n-side to the p-side and will be

$$I_{n\to p} = Ce^{-\frac{\Phi - qV}{k_B T}}.$$

The opposite flow remains the same

$$I_{p\to n} = Ce^{-\frac{qV}{k_B T}},$$

and net current I is the sum of the two currents, i.e.

$$I = I_{n\to p} + I_{p\to n} = Ce^{-\frac{\Phi - qV}{k_B T}} - Ce^{-\frac{\Phi}{k_B T}} = I_0\left(e^{\frac{qV}{k_B T}} - 1\right).$$

The diode conducts a current that exponentially increases with the voltage V, and is said to be forward biased.

A similar argument can be used to obtain the hole current.

10.2.3 Reverse Biased Junction

Applying a voltage drop V across the diode as shown in figure 10.4, the difference of energy between the conduction band of the p-region and that

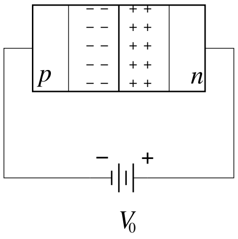

Figure 10.4: Reverse biased junction

one of the n-region is

$$\Delta E = \Phi + qV,$$

and the net current in this case I_d is

$$I_d = I_{n\rightarrow p} + I_{p\rightarrow n} = Ce^{-\frac{\Delta E}{k_B T}} - Ce^{-\frac{\Delta E + qV}{k_B T}} = I_0\left(1 - e^{-\frac{qV}{k_B T}}\right).$$

The diode conducts a very small current, and is said to be reverse biased.

For large negative voltage bias, we have the so called reverse breakdown current, which corresponds to an electric field across the junction strong enough to ionize some of the electrons of the depletion region. If the breakdown current is not limited, the device will be damaged.

A similar argument can be used to obtain the hole current.

10.2.4 Junction I-V Characteristic

The equation for the two previous cases can be resumed by the following formula

$$I_D(V) = I_0(e^{\frac{qV}{\eta k_B T}} - 1),$$

which is the c*urrent-voltage characteristic equation* of the diode (see figure 10.5), where now I is the conventional direction of the current, which is opposite to the electronic current, and V is the voltage drop across the junction.

I_0 is said to be the reverse saturation current.

The adimensional coefficient η that magically appears, comes out from more detailed quantum mechanical considerations.

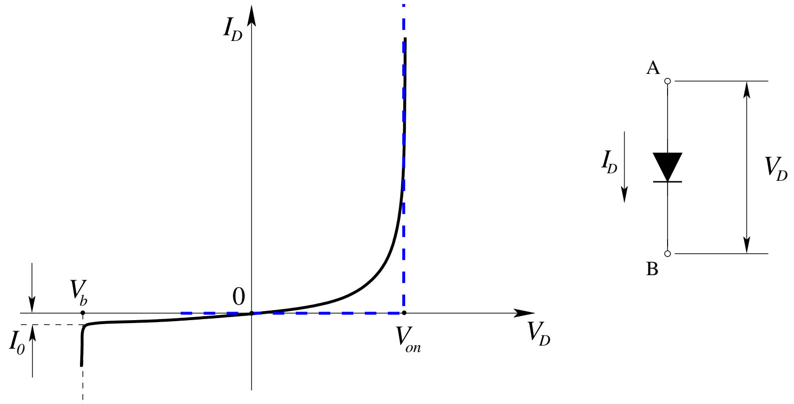

Figure 10.5: Diode characteristic (continuous curve), simplified diode characteristics(dashed curve), and diode standard symbol.

Figure 10.5 also shows the standard symbol for diodes. The arrow points to the current direction when the device is forward biased.

Silicon diodes have typically $\eta \simeq 2$ for currents below ~ 100mA, breakdown voltages $V_b \simeq -6$V, and typical reverse saturation current $I_0 \sim 1\mu$A.

10.2.5 The Diode Simplified Model

A simplified model of the p-n junction diode is that one of a perfect switch, i.e.

$$I_D(V) = \begin{cases} \infty & V \geq V_{on} \\ 0 & V < V_{on} \end{cases} ,$$

where V_{on} is the diode *turn-on* voltage, which depends on the junction type. For a silicon diode type $V_{on} \simeq 0.6$V , for a germanium diode type $V_{on} \simeq 0.3$V.

For voltages greater than V_{on}, as shown in figure 10.5, the diode is a short circuit (current is not limited by the diode) . For smaller values it is an open circuit (current across the diode is zero).

Bibliography

[1] J. Millman and I. Grabel, **Microelectronics,** Mac Graw Hill.

[2] N. W. Ashcroft, **Solid State Physics**, HRW International Editions.