كلية المستقبل الجامعة
قسم الفيزياء الطبية
المرحلة الثانية
أشباه موصلات

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The Second Stage
Semiconductors
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Lecture .3

Equilibrium Carrier Concentration

Semiconductors have majority carriers and minority carriers. The charge carriers more abundant are the majority carriers; while the minority carriers are the charge carriers less abundant. Doping can increase the equilibrium carrier concentration. Equilibrium carrier concentration is the total number of carriers in the conduction and valence bands. A constant is the product of the minority and majority charge carriers. Equilibrium carrier concentration is the number of carriers in the conduction and valence band with no externally applied bias. The equilibrium carrier concentration for majority carriers is equal to the intrinsic carrier concentration plus the free carriers number added by doping the semiconductor. In most cases, doping of the semiconductor is several orders of magnitude greater than the intrinsic carrier concentration, so that the majority carriers number is nearly equal to the doping.

Thermal Equilibrium

An important equation for determining the carrier concentrations in a material is defined by the Law of Mass Action, we must first understand the description of thermal equilibrium before further discussing. Thermal equilibrium is a relationship between the concentrations of charge carriers at a certain temperature. Described differently, at a given temperature, there is an equilibrium between both generation - formation of pairs of electron-hole as a result of thermal excitation or photon absorption - and recombination which is the natural destruction of pairs that happen when electrons from conduction band fall back again into valence band. In the intrinsic case, the bound electrons number is much higher than the free electrons number, thus the charge carriers generation is independent of the electron-hole pairs number which have been already formed. Though, as soon as generation occurs, recombination happens and it depends on the charge carriers concentration in the material. In fact recombination is directly proportional to the charge carriers number.

Law of Mass action Equations

The product of the majority and minority carrier concentration at equilibrium is a constant, which is mathematically expressed by the Law of Mass Action.

$$n_o p_o = ni^2$$

where **ni**: is the intrinsic carrier concentration

n_0: electron equilibrium carrier concentrations.

p_0: the hole equilibrium carrier concentrations.

By using the Law of Mass Action above, the majority and minority carrier concentrations can be expressed in the following equations:

$$\textbf{n-type: } n_o = N_D, \quad p_o = ni^2 / N_D$$

$$\text{p-type: } p_o = N_A, \quad n_o = n_i^2 / N_A$$

where N_D: donor atoms concentration , N_A : acceptor atoms concentration.

The equations above show that the minority carriers number decrease with the increase of the doping level. As an example, in the n-type material, some of the extra electrons which are added by doping the material will occupy the empty spots (the holes) which are in the valence band, thus lowering the number of holes.

Summery

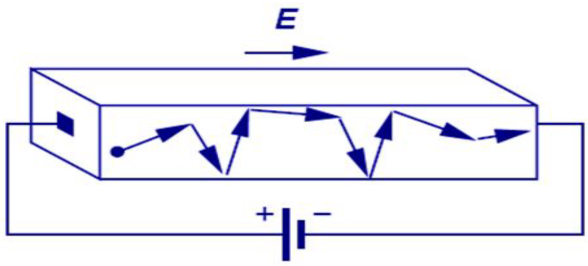
1. Semiconductors contain majority and minority carriers. The more abundant charge carriers are the majority carriers; the less abundant are the minority carriers.
2. The equilibrium carrier concentration can be increased through doping.
3. The total number of carriers in the conduction and valence band is called the equilibrium carrier concentration.
4. The product of minority and majority charge carriers is a constant.

What is carrier drift?

When an electric field is applied across the semiconductors, the carriers drift through the semiconductors. The carriers move with a constant drift velocity. The drift current in a semiconductor is caused due to the carrier drift.

Carrier Drift

- The process in which charged particles move because of an electric field is called ***drift***.
- Charged particles within a semiconductor move with an average velocity proportional to the electric field.
  - The proportionality constant is the carrier ***mobility***.



Hole velocity $\vec{v}_h = \mu_p \vec{E}$

Electron velocity $\vec{v}_e = -\mu_n \vec{E}$

Notation:
$\mu_p \equiv$ hole mobility ($cm^2/V \cdot s$)
$\mu_n \equiv$ electron mobility ($cm^2/V \cdot s$)

❖ Carrier Drift

- Electron and holes will move under the influence of an applied electric field since the field exert a force on charge carriers (electrons and holes).

$$F = qE$$

- These movements result a current of I_d;

$$I_d = nqV_d A$$

I_d : drift current

n : number of charge carriers per unit volume

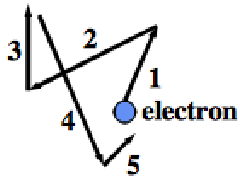
V_d : drift velocity of charge carrier

q : charge of the electron

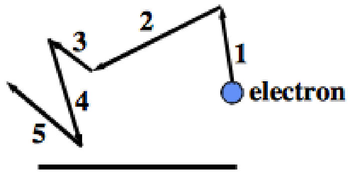
A : area of the semiconductor

Carrier Drift

- When an electric field is applied to a semiconductor, mobile carriers will be accelerated by the electrostatic force. This force superimposes on the random thermal motion of carriers:



***E* =0**



E

E.g. Electrons *drift* in the direction opposite to the *E*-field

→ Current flows

Average *drift velocity* = $| \mathbf{v} | = mE$

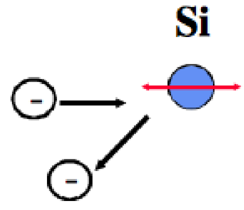
Carrier mobility

Carrier Mobility

- Mobile carriers are always in random thermal motion. If no electric field is applied, the average current in any direction is zero.

- **Mobility is reduced by**

1) collisions with the vibrating atoms "phonon scattering"

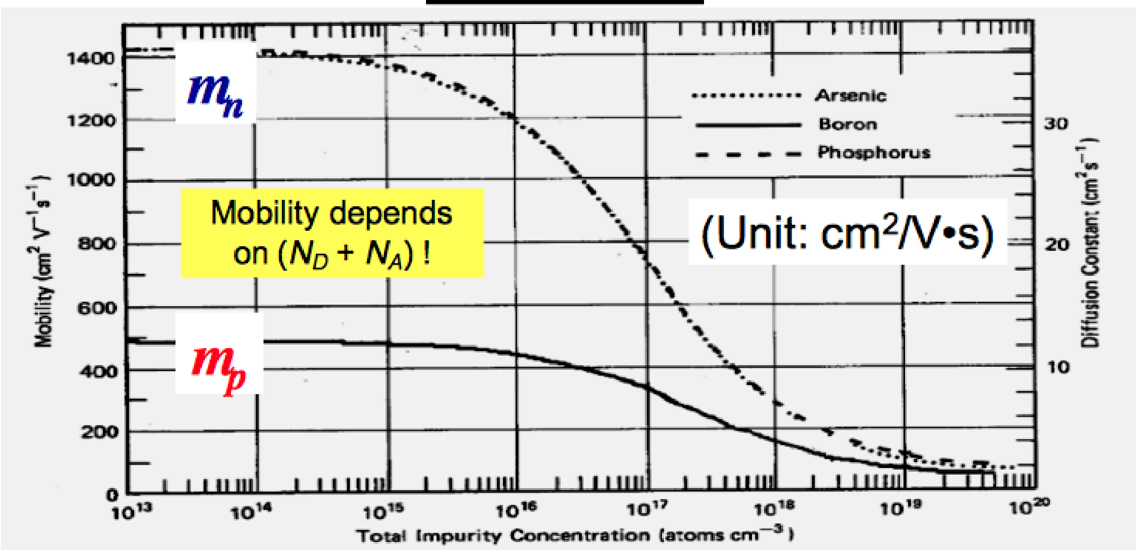


2) deflection by ionized impurity atoms "Coulombic scattering"

Carrier Mobility μ

Mobile charge-carrier drift velocity v is proportional to applied *E*-field:

$$| v | = mE$$



Electrical Conductivity σ

When an electric field is applied, current flows due to drift of mobile electrons and holes:

electron current density:

$$J_n = (-q)nv_n = qn\mu_n E$$

hole current density:

$$J_p = (+q)pv_p = qp\mu_p E$$

total current density:

$$J = J_n + J_p = (qn\mu_n + qp\mu_p)E$$

$$J = \sigma E$$

conductivity

$$\boxed{\sigma \equiv qn\mu_n + qp\mu_p}$$

Electrical Resistivity ρ

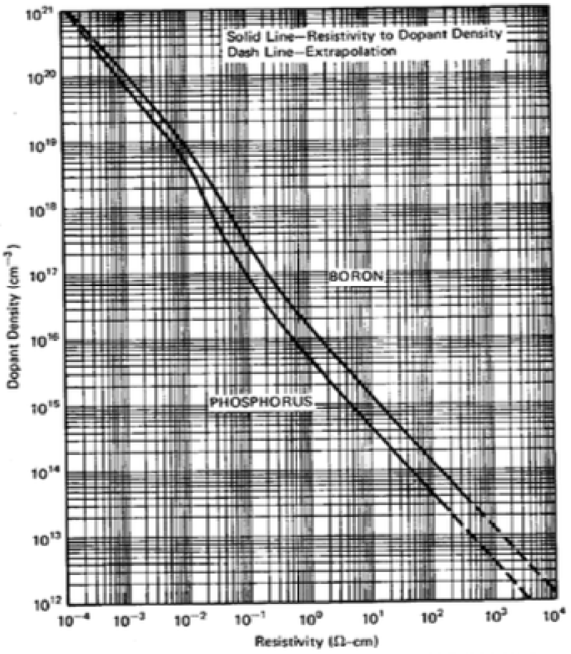


Figure 1.14 Dopant density versus resistivity at 23°C (296 K) for silicon doped with phosphorus and with boron. The curves can be used with little error to represent conditions at 300 K. [W. R.

$$\boxed{\rho \equiv \frac{1}{\sigma} = \frac{1}{qn\mu_n + qp\mu_p}}$$

$$\rho \cong \frac{1}{qn\mu_n} \quad \text{for n-type}$$

$$\rho \cong \frac{1}{qp\mu_p} \quad \text{for p-type}$$

(Unit: ohm-cm)

Note: This plot does not apply for compensated material!

Lecture .4

Diffusion

Movement of particles from regions of high concentration to regions of low concentration.

Diffusion current Density is a current in a semiconductor caused by the diffusion of charge carriers (holes and/or electrons). This is the current which is due to the transport of charges occurring because of non-uniform concentration of charged particles in a semiconductor. The drift current, by contrast, is due to the motion of charge carriers due to the force exerted on them by an electric field. Diffusion current can be in the same or opposite direction of a drift current. The diffusion current and drift current together are described by the drift–diffusion equation.

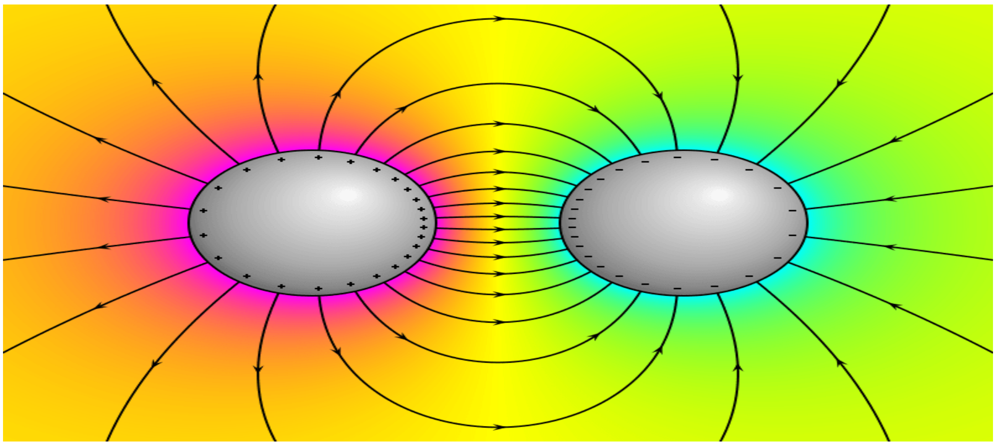
Diffusion current versus drift current

Diffusion current	Drift current
Diffusion current = the movement caused by variation in the carrier concentration.	Drift current = the movement caused by electric fields.
krainian tion of the diffusion current depends on the slope of the carrier concentration.	Direction of the drift current is always in the direction of the electric field.
Obeys Fick's law: $J = -qD\frac{d\rho}{dx}$	Obeys Ohm's law: $J = q\rho\mu E$

x

What is Electric Potential?

Electric potential is the amount of work done when a charged particle is moved from one place to another in an electric field. Here, the charged particle is either positively charged or negatively charged. Usually, the electric potential is measured for the movement of the charged particle from a reference point to a specific point. Moreover, this movement should not accelerate the charged particle. Typically, the reference point we take is Earth.

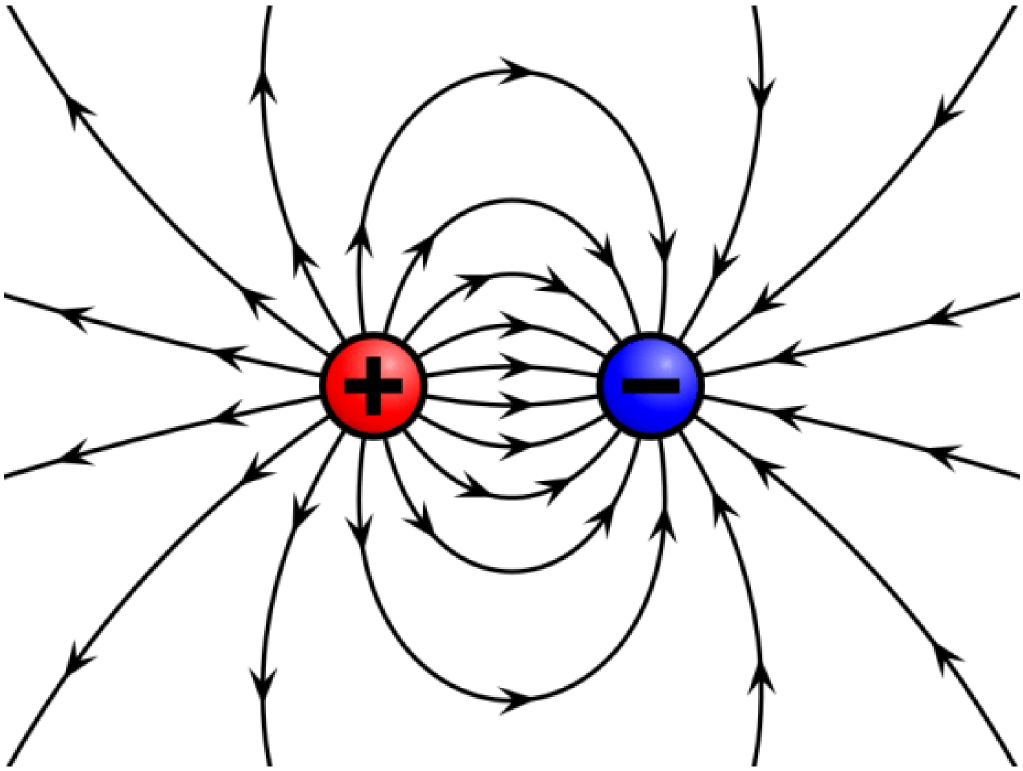


The SI unit for the measurement of electric potential is Volt (V). This is an extensive property of substances. When determining the value of electric potential, we can do it either in a static or a dynamic electric field. The electric potential at the reference point is considered as zero. Practically, electric potential is a continuous value which is a function of space.

What is Electric Field?

Electric field is the surrounding of an electric charge unit which can exert a force on other charged particles in the field. We can abbreviate this term as E-field as well. The charged particles in the electric field can be either attracted or repelled by the central charge unit, depending on the electrical charges and their magnitude.

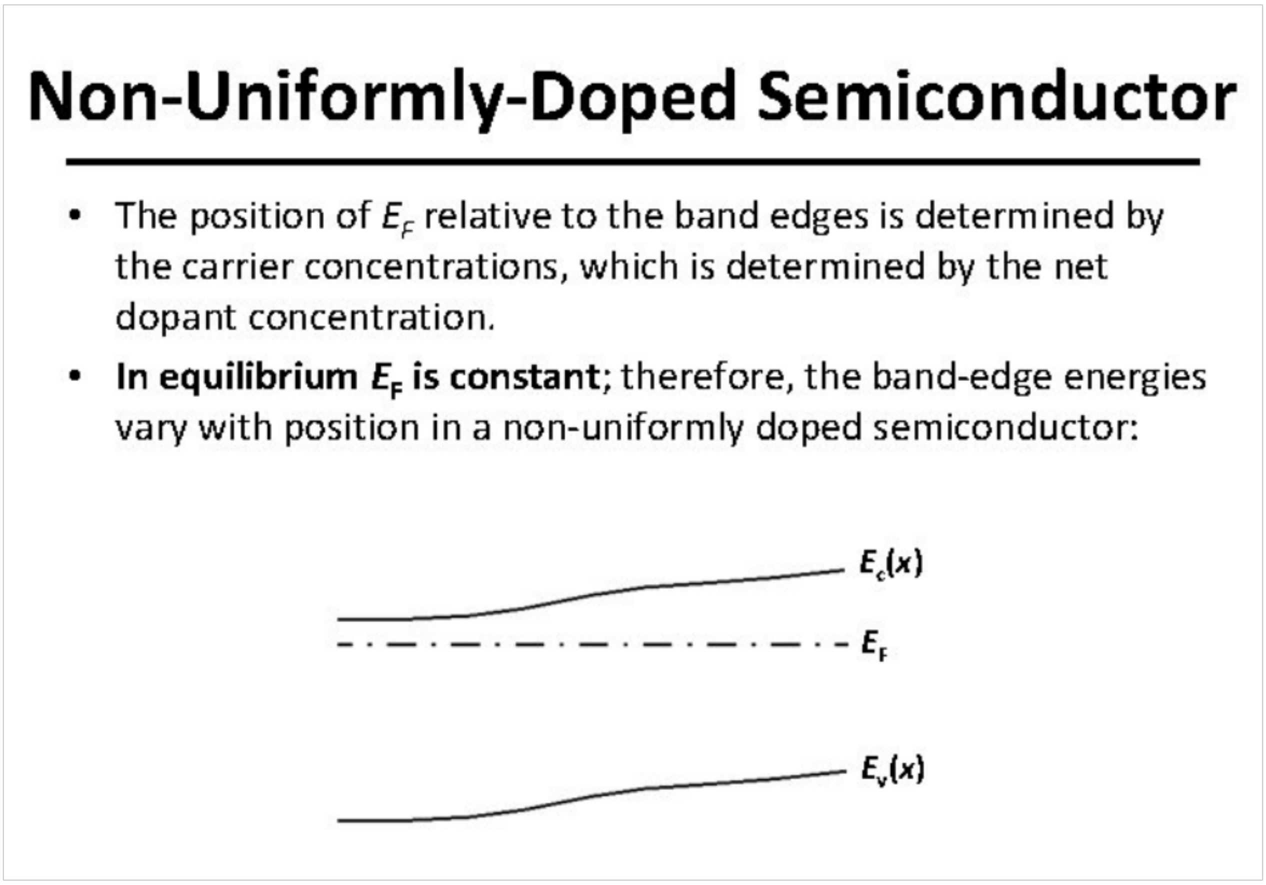
When considering the atomic scale, an electric field is responsible for the attractive force between the atomic nucleus and the electrons. This attractive force is the glue that holds the nucleus and electrons together to make up the structure of an atom. Also, these attraction forces are important in chemical bond formation. The unit of measurement for electric field is volt per meter (V/m). This unit is exactly equal to the unit Newton per coulomb (N/C) in the SI unit system.



What is the Difference Between Electric Potential and Electric Field?

The key difference between electric potential and electric field is that electric potential refers to the work need to be done in order to move a unit charge from one place to another, under the influence of an electric field, whereas electric field is the surrounding of an electrical charge which can exert a force on other charges in the field. In other words, electric potential measures the work done by an electric field, while electric field measures the force exerted on a charged particle in the field other than the central charged unit.

***The terms electric potential and electric field are useful in physical chemistry, under the subcategory of electrochemistry. The key difference between electric potential and electric field is that electric potential refers to the work need to be done in order to move a unit charge from one place to another, under the influence of an electric field whereas electric field is the surrounding of an electrical charge which can exert a force on other charges in the field.



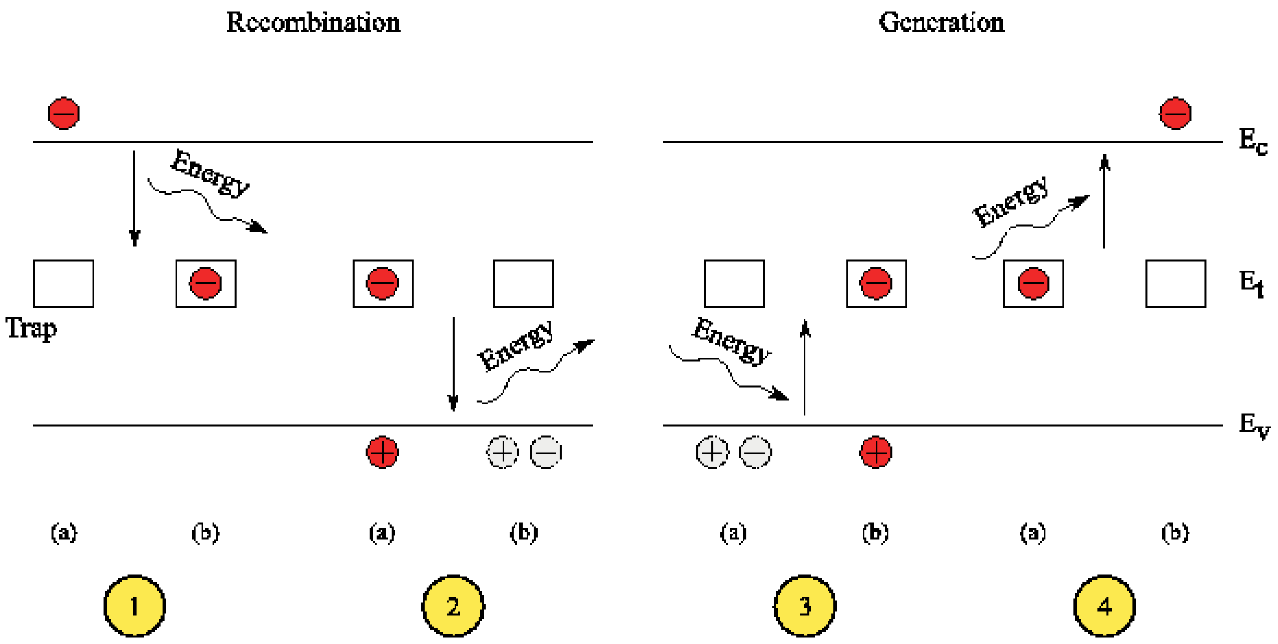
The "Non-Uniformly Doped Semiconductor " mean that is non uniformly doped, the electrons will tend to diffuse from higher concentration towards the lower concentration. leaving behind positively charged donor ions.

Carrier Generation and Recombination

Carrier generation is a process where electron-hole pairs are created by exciting an electron from the valence band of the semiconductor to the conduction band, thereby creating a hole in the valence band. Recombination is the reverse process where electrons and holes from the conduction respectively valence band recombine and are annihilated. In semiconductors several different processes exist which lead to generation or recombination, the most important ones are:

- photon transition or optical generation/recombination,
- phonon transition or Shockley-Read-Hall generation/recombination,
- Auger generation/recombination or three particle transitions, and
- impact ionization.

In thermal equilibrium the generation and recombination processes are in dynamic equilibrium. When the system is supplied with additional energy, for example through the absorption of photons or the influence of temperature, additional carriers are generated.


Recombination
Generation
Energy
Energy
Energy
Energy
Trap
Ec
Et
Ev
(a)
(b)
(a)
(b)
(a)
(b)
(a)
(b)
1
2
3
4