

Chapter 2

Semiconductors

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Electronics: Principles, Concepts and Practices

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Intro

Modeling Concept in Electronics

The text serves as a foundation for studying Electronics.

The lecture introduces students to the physics of semiconductors and the inner workings of semiconductor devices, providing them with insights that are valuable for understanding new semiconductor technologies.

In general, an engineer's task involves designing and implementing accurate models with minimal limitations and complexity.

Design criteria often require assumptions and trade-offs, posing a dilemma for engineers who want accuracy and simplicity.

This dilemma leads to the existence of various design models, such as small-signal and large-signal models.

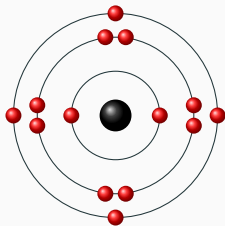
Models offer valuable insights into the performance of devices and circuits.



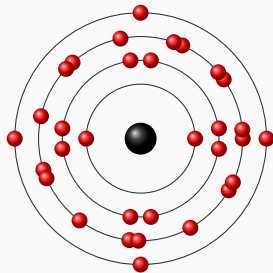
Covalent Bonding in Semiconductors

Covalent Bonding in Semiconductors

Semiconductors are group IV elements on the Periodic Table. They include silicon (Si), carbon (C), germanium (Ge), among others. The two often encountered semiconductors in electronics are silicon and germanium with atomic numbers 14 and 32, respectively. Figure 1 shows the two-dimensional atomic structure of Si and Ge; they both have four valence electrons.



(a) Silicon atom



(b) Germanium atom



Figure 1: Common semiconductor atoms

Covalent Bonding in Semiconductors

In semiconductors, atoms are bonded together in a crystal by covalent bonds in which nearby atoms are bonded together by sharing or pairing their valence electrons with four adjacent neighbours. Figure 2 illustrates the covalent bonding between silicon atoms.

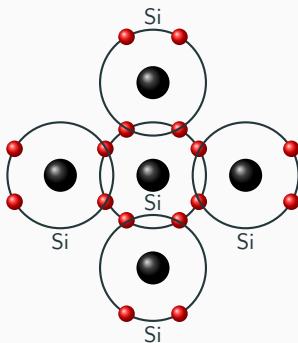


Figure 2: Covalent bonding in silicon



Compound Semiconductors

Compound Semiconductors

We often discuss the element semiconductors from group four, but interestingly some compound semiconductors are available and are the future of semiconductor technology. The operational speed, frequency and temperature are higher when compared to silicon and germanium. The compound semiconductors are mostly formed from a combination of group III and V elements or a combination of group II and VI elements. Some examples include:

1. Gallium arsenide
2. Silicon carbide
3. Gallium nitride



Uniform Semiconductor in Equilibrium

Thermal Equilibrium

Thermal Equilibrium

In the context of semiconductors, thermal equilibrium refers to a state of stability where the total number of electrons and holes remains constant within the semiconductor.

To begin our exploration of semiconductors, let us establish a baseline reference point known as the Equilibrium State. In this case, we refer to it as thermal equilibrium, although it does not strictly exist. However, it serves as a condition that we can assume before applying any external stimulation. Thermal equilibrium implies that there is no heat transfer occurring between bodies or their surroundings, resulting in a maintenance of their respective temperatures. In our framework, this means that, at thermal equilibrium, the object is neither illuminated nor influenced by electric or magnetic fields. It exchanges energy equally with its surroundings and exhibits no net change in condition over time or space.



Intrinsic Semiconductors

An intrinsic semiconductor refers to a perfect crystal without any impurities added. Silicon, with an atomic number of 14, is an example of an intrinsic semiconductor. This structure is electrically neutral and stable. However, when a bond is broken, an electron-hole pair is formed.

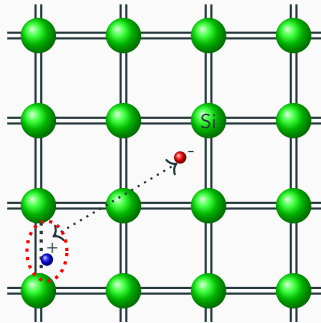


Figure 3: Covalent bonds in a silicon crystal



Intrinsic Semiconductor

- At thermal equilibrium, it is safe to assume no net flow of charges.
- A considerable amount of energy is needed to free an electron from the valence band to conduction band. This energy is in the order of KT where K is the Boltzmann constant $8.62 * 10^{-5}$ in ev/K and T is the temperature in Kelvin.
- Unlike conductors, the process of current flow in semiconductor is due to flow of positively charged carriers as well as negative charged carrier.
- The negative charges are referred to as the electron, whose concentration is designated as n while the positive charges are the holes whose concentration is designated as p .



Intrinsic Semiconductor

- When an electron is freed from the bond, it leaves behind an empty bond which is positively charged.
- Holes can equally move about the crystal, when bonds are broken, holes are left behind, an electron in a neighbouring atom moves into the newly created holes thereby also leaving a hole behind its original location.
- Let subscript 0 represent values in thermal equilibrium so that, n_0 and p_0 are the thermal equilibrium concentrations of electrons and holes, respectively measured in cm^{-3} .



Intrinsic Semiconductor

In a perfect crystal of pure silicon or intrinsic semiconductors, electrons and holes can only be created in pairs. Consequently, the intrinsic carrier concentration, designated as n_i is equal to n_0 and p_0 . n_i is largely temperature-sensitive and must be specified. Therefore, we write

$$n_i(T) = n_0 = p_0 \quad (1)$$

Typically for silicon at room temperature $n_i = 1.08 * 10^{10} \text{ cm}^{-3}$. This n_i ,

is a small concentration in the scheme of things and intrinsic silicon is closely an insulator. To improve its conductivity to suit our purpose, the concept of extrinsic silicon is introduced in the next section.



Extrinsic Silicon

Doping is the controlled process of adding impurities to an intrinsic semiconductor material to significantly increase the concentration of electrons or holes. This is commonly achieved through ion implantation or diffusion at high temperatures, resulting in an extrinsic semiconductor.

An extrinsic semiconductor is a semiconductor that has been doped with specific impurities, significantly modifying its electrical properties for electronic applications.

A carefully chosen impurities known as dopant, are added to pure silicon to form extrinsic silicon.

These dopant are of two categories, the donors and the acceptors; if the group 5 elements of the periodic table are used as dopant then we speak of a donor impurity to form the n-type extrinsic and if group 3 elements of the periodic table are used as the dopant then a p-type extrinsic semi-conductors is formed.



Donor: n-type

If one of the atoms of silicon in the diamond lattice of Figure 3 is replaced with an atom in group V of the periodic table such as phosphorous (P), Arsenic (As) or antimony (Sb). The resultant lattice would have an extra electron not involved in the covalent bond as shown in Figure 4.

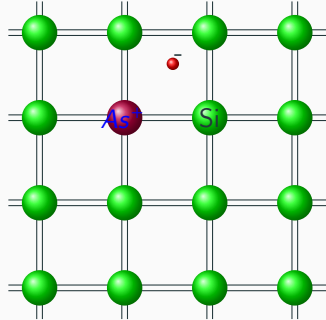


Figure 4: N-type: Introduction of group 5 dopant



Donor: n-type continued ...

- The dopant from group V is known as a donor and the extrinsic material is referred to as n-type.
- The extra electron introduced by the doping lies just some 50 meV below the conduction band as shown in Figure 6.
- If some external stimuli are applied to the now obtained extrinsic semi-conductor, the extra electron, on gaining 50 meV jumps to the conduction band (the jump to the conduction band is termed ionization)
- This extra electron along with the other conduction electrons are free to move in the conduction band.
- The energy required to excite the donor electron is known as the donor ionization energy E_d , and the donor whose electron has been excited into the conduction band is said to be ionized and denoted with N_d^+ .



Donor: n-type continued ...

Necessary to ask, what is the thermal equilibrium hole concentration and electron concentrations, in a silicon crystal doped with a known concentration of donors, N_d ?

Let this new concentration after doping be n'_0 . Thus far, this relationship for the concentration of interest can be written as

$$n'_0 = p_0 + N_d^+ \approx p_0 + N_d \quad (2)$$

Equation 2 simply indicates that electron concentration at thermal equilibrium is the sum of the thermal equilibrium concentration ($n_0 = p_0$) and the dopant impurity. In addition we say that all the impurity has been ionized to the conduction band, so that $N_d^+ \approx N_d$. Thus we can say this concentration n'_0 is the majority charge carrier.



Acceptor: p-type

If one of the atoms of silicon in the diamond lattice of Figure 2 is replaced with an atom in group III of the periodic table such as boron (B) the results is a missing electron in the covalent bond leaving us with a hole as shown in Figure 5.

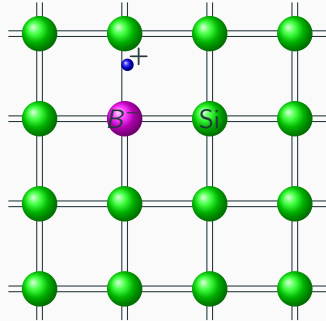


Figure 5: P-type: Introduction of group 5 dopant



Acceptor: p-type continued ...

Note the following

1. The dopant from group III are referred to as acceptors and the extrinsic material formed as p-type.
 2. The dopants introduce a new energy level E_a referred to as the acceptor (for p-type) or E_d donor ionization energy (for n-type).
- Figure 6 illustrate the location of the ionization energy on the energy band diagram of the semi-conductors.

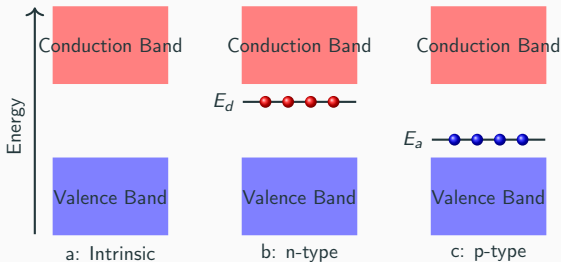


Figure 6: Energy Level illustration

Acceptor: p-type continued . . .

As was with the case with the donor atom, the concentration of interest can be written as

$$p'_0 = n_0 + N_a^- \approx n_0 + N_a \quad (3)$$

Equation 3 simply indicates that hole concentration at thermal equilibrium is the sum of the thermal equilibrium concentration and the dopant impurity. Thus we can say the net hole concentration is the majority charge carrier.

The students should carefully note the difference in the intrinsic and extrinsic silicon situation. In intrinsic both mobile holes and electrons are created. In contrast, in the extrinsic scenario, additionally a mobile electron or hole is created while the positive charge (e.g. As^+) associate with the column V ion or negative charge (e.g. B^-) associated with the column III ion is fixed and cannot move.



Extrinsic with both Donor and Acceptor dopants

It is possible to have silicon doped with both donor and acceptor atoms. In this case we may write a combining equation, such that,

$$n_0 + N_a^- = p_0 + N_d^+. \quad (4)$$

Let the ionization energy be shallow, it implies at room temperature all the donors and acceptors are completely ionized, so that

$$n_0 + N_a \approx p_0 + N_d. \quad (5)$$

$$\text{or } n_0 - p_0 \approx N_d - N_a. \quad (6)$$



Extrinsic with both Donor and Acceptor dopants

In this case of extrinsic material, we speak in terms of the difference in doping concentration or net concentration, $N_d - N_a$. For conveniences, we may define the net donor or acceptor concentration as N_D or N_A respectively. That is,

$$N_D = N_d - N_a \quad (7)$$

$$\text{or } N_A = N_a - N_d. \quad (8)$$

of interest here is obtaining the equilibrium electron and hole concentration n_0 and p_0 in the crystal, respectively, given N_d and N_a .



Extrinsic with both Donor and Acceptor dopants

From Equation (1), we can established that for intrinsic materials, Equation (9) holds true.

$$\therefore n_0 p_0 = n_i^2. \quad (9)$$

In the doped material, if $N_d \gg N_a$ then the material have electrons as the majority carrier and is an n -type, therefore

$$n_0 \approx N_D \quad (10)$$

And the minority hole concentration is obtained from equation 9 as

$$p_0 = \frac{n_i^2}{N_D} \quad (11)$$



Extrinsic with both Donor and Acceptor dopants

Similarly, for $N_a \gg N_d$ the material, has hole as the majority carrier and is a P-type.

$$p_0 \approx N_A \quad (12)$$

And the minority electron concentration is obtained from equation 9 as

$$n_0 = \frac{n_i^2}{N_A} \quad (13)$$



Effect of Changing temperature on Semi-Conductor

Effect of Changing temperature on Semi-Conductor

The intrinsic and extrinsic semi-conductors exhibit different behaviour as you decrease or increase the temperature.

In extrinsic semi-conductors, the primary assumption was that at room temperature, ALL the dopant atoms are ionized. If we decreased the temperature, the assumption that all of the dopant are ionized becomes invalid.

As the temperature increases, the intrinsic concentration becomes of concern as it increases exponentially until it exceeds the net dopant concentration and the sample no longer acts extrinsic but intrinsic.



Effect of Changing temperature on Semi-Conductor

The intrinsic concentration from a statistical mechanism view point is approximated as

$$n_i(T) = AT^{-\frac{3}{2}} \exp\left(\frac{-E_g}{2kT}\right) \quad (14)$$

where A is some constant that is material-dependent, k is the Boltzmann constant and E_g is the energy gap. It is sometimes convenient to write this in terms of n_i at $300K$, room temperature as

$$n_i(T) = n_i(300K) \left[\frac{T}{300} \right]^{\frac{3}{2}} \exp\left[-E_g \left(\frac{1}{2kT} - \frac{1}{600k} \right) \right] \quad (15)$$



Uniform Excitation of Semiconductors

Uniform Electric Field

- In the absence of an Electric Field, the particles are in constant motion, with large but random velocity due to the thermal energy. See fig. 7(a)
- Let us consider a case that an E_x is applied to a charged particle q ; see figure 7(b), the charged particle will experience some forces which shall result in some acceleration a_x , the particle has mass m .

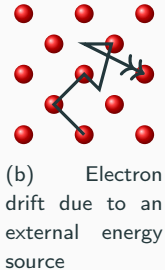
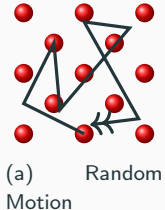


Figure 7: charged particle motion



Uniform Electric Field

Our E field is conveniently chosen as x-directed, E_x . Therefore the net velocity is written as

$$v_x = \pm \mu_1 E_x \quad (16)$$

Note that we are discussing semiconductors, where the particles of interest are mobile electrons and holes, designated as e and p , respectively.

$$v_{ex} = -\mu_e E_x \quad (17)$$

$$v_{px} = \mu_p E_x \quad (18)$$



Uniform Electric Field

Assuming thermal equilibrium, the net flux density of electrons crossing any plane normal to the applied E field is

$$D_{ex} = n_0 v_{ex} = -n_0 \mu_e E_x \quad (19)$$

$$D_{px} = p_0 v_{px} = p_0 \mu_p E_x \quad (20)$$

Current is charged flux (qD). Thus

$$J_{ex} = q n_0 \mu_e E_x \quad (21)$$

$$J_{px} = q p_0 \mu_p E_x \quad (22)$$

The electron and hole, carry a $-$ and $+$ charge, respectively. The total current density is

$$J_x = J_{ex} + J_{px} \quad (23)$$

$$J_x = q (n_0 \mu_e + p_0 \mu_p) E_x \quad (24)$$

$$J_x = \sigma E_x \quad (25)$$



Uniform Electric Field

- This current J_x is called the drift current density.
- The quantity $q(n_0\mu_e + p_0\mu_p)$ is called the conductivity and is given the symbol σ .
- The units of conductivity are Siemens per centimetre, S/cm .
- The inverse of the conductivity is called the resistivity $\rho = \frac{1}{\sigma}$ with unit as Ω/cm .

The equation 25 is the field description of ohms law. Given that,

$$E_x = \frac{V}{L} \quad (26)$$

$$J_x = \frac{I}{A} \quad (27)$$

So equation 25 relates to ohms law as

$$V = I \left(\frac{L}{\sigma A} \right) = IR \quad (28)$$



Uniform Optical Excitation

1. Optical excitation of semiconductor results in carrier generation and carrier recombination.
2. Carrier generation describes processes by which electrons gain energy and move from the valence band to the conduction band, producing two mobile carriers (holes and electrons).
3. Carrier recombination describes processes by which a conduction band electron loses energy and re-occupies the energy state of an electron-hole pair in the valence band.
4. Carrier generation and recombination processes are fundamental to the operation of many optoelectronic semiconductor devices and are critical to a full analysis of p-n junction devices



Uniform Optical Excitation continued . . .

The rate of change of the hole and electron populations in a uniform sample with uniform excitation will be the excess of generation rate G over recombination R :

$$\frac{dn}{dt} = \frac{dp}{dt} = G - R = G - npr \quad (29)$$

The rate of recombination R is some function that depends on the concentration of hole-electron pair, so the $R = npr$. Here r is the rate of recombination for the hole and electron. In direct band-to-band generation-recombination, at thermal equilibrium, the electrons and holes are created-annihilated in pairs, so that we may write equation 30 and 31

$$G_{n0} = G_{p0} = G_0 \quad (30)$$

$$R_{n0} = R_{p0} = R_0 \quad (31)$$



Uniform Optical Excitation continued . . .

At thermal equilibrium, the generation and recombination rates are equal, so equation 29 becomes,

$$G_0 = R_0 = n_0 p_0 r \quad (32)$$

Consider adding an external generation term in the form of light, $g_L(t)$. The total generation rate becomes

$$G = G_0 + g_L(t) \quad (33)$$

$$\frac{dn}{dt} = \frac{dp}{dt} = G_0 + g_L(t) - npr \quad (34)$$

Substituting Equation ?? in equation 33 yields

$$\frac{dn}{dt} = \frac{dp}{dt} = g_L(t) - (np - n_0 p_0)r \quad (35)$$

This is a second order differential equation and difficult to solve for hole-electron concentration, but we can get solutions in some important special cases.



Non-uniform Conditions

Non-uniform Conditions

Diffusion is the net motion of carriers in a density or concentration gradient. In semiconductors with gradient, the charged particles move from an area with a higher concentration to an area with a lower concentration.

Let the semiconductor in Figure 8 with cross sectional area A be divided into slabs normal to the x -direction, with width Δx .

Let slab centered about x , containing particles of species m , whose concentration is C_m . C_m varies along with position, thus the concentration at any point x is $C_m(x)$.

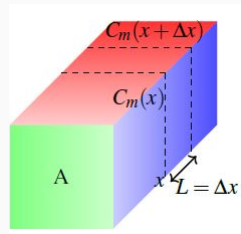


Figure 8: Modelling Diffusion Concept



Non-uniform Conditions continued ...

Safe to say the slab centred about x will contain ' $\Delta x C_m$ ' particles per unit area.

Per unit time, say a fraction ' a ' of those particles diffuses over to the slab at $x + \Delta x$ yielding a flow of particle to the right with concentration $a\Delta x C_m(x)$.

Similarly, the slab centered at $x + \Delta$ contains $a\Delta x C_m(x + \Delta x)$ particles per unit area, the same fraction ' a ' will move per unit time over to the left slab at x .

The fractions ' a ' are the same because we are assuming random, independent motion.

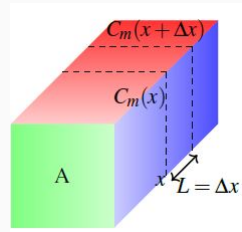


Figure 9: Modelling Diffusion Concept



Non-uniform Conditions continued . . .

Consequently, the net flux density is the difference in flow in both directions:

$$F_m = a\Delta x [C_m(x) - C_m(x + \Delta x)] \quad (36)$$

Applying Taylor's series expansion for equation 36. We have the second term in 36 as

$$C_m(x + \Delta x) \approx C_m(x) + \Delta x \frac{\partial C_m}{\partial x} \quad (37)$$

Substituting equation 37 into 36 yields 38

$$F_m = -a(\Delta x)^2 \frac{\partial C_m}{\partial x} \quad (38)$$

$$F_m = -D_m \frac{\partial C_m}{\partial x} \quad (39)$$

Equation 39 is the net flux density and the general diffusion relationship known as the **Fick's First law** measured in particles/cm².s. D_m is the diffusion coefficient with unit cm²/s.



Non-uniform Conditions continued . . .

If the diffusion particles are charged, the net flux will have a current density as

$$J_m = q_m F_m \quad (40)$$

This translates to equation 41 and 42 for electrons and holes, respectively.

$$J_e^{diff} = q D_e \frac{\partial n}{\partial x} \quad (41)$$

$$J_p^{diff} = -q D_p \frac{\partial p}{\partial x} \quad (42)$$

Diffusion is a widespread phenomenon that has essential applications in the fabrication of semiconductor devices as well as in their operation. It is one means of doping the semiconductor.



Modelling non-uniform Situation

Typically, non-uniformly doped semiconductors imply gradients in the charge carrier concentration; consequently diffusion current exists. Furthermore, the carrier will diffuse at different rates, thereby resulting in charge imbalance from which we expect an Electric Field to be established. In general, the non-uniformly doped and excited semiconductor will comprise of both the diffusion current as well as drift current.

$$J_e = J_e^{drift} + J_e^{diff} \quad (43)$$

$$J_p = J_p^{drift} + J_p^{diff} \quad (44)$$

$$J_e = qp\mu_e E_x + qD_e \frac{\partial n}{\partial x} \quad (45)$$

$$J_p = qp\mu_p E_x - qD_p \frac{\partial p}{\partial x} \quad (46)$$



Modelling non-uniform Situation continued . . .

Therefore the total current density is

$$J_{tot} = J_e + J_p \quad (47)$$

Note that a simple relationship exist between diffusion coefficient and mobility known as the Einstein Relationship written as

$$\frac{D_e}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{q} = V_T \quad (48)$$

where V_T is the thermal voltage and k is the Boltzmann constant.



Homework:
Check with the class rep for the numerical
task!



Recommendation:

See worked examples in reference material!

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