Chapter 1

UEEA3033
Microelectronics and Semiconductor Materials

Semiconductor Materials
Chapter 1 Semiconductor Materials ...........................................1
1.0 Introduction ........................................................................1
1.1 Type of Semiconductor .....................................................1
  1.1.1 Elemental Semiconductor ............................................1
  1.1.2 Compound Semiconductor ...........................................2
  1.1.3 Narrow Band-gap Semiconductor ..................................4
  1.1.4 Wide Band-gap Semiconductor .....................................4
  1.1.5 Oxide Semiconductor ..................................................4
  1.1.6 Magnetic Semiconductor .............................................4
1.2 Intrinsic Semiconductor ...................................................5
  1.2.1 Energy Band Diagram of Intrinsic Semiconductor ............5
1.3 Extrinsic Semiconductor ...................................................6
  1.3.1 Energy Band Diagram of Extrinsic Semiconductor ..........7
1.4 Fermi-Dirac Statistics .....................................................8
1.5 Density of State ............................................................11
1.6 Carrier Distributions and Carrier Concentration in Energy Bands 14
1.7 Charge Neutrality Relationship .......................................18
1.8 Carrier Concentration in Nondegenerate Semiconductor ..........18
1.9 Temperature Dependence of Carrier Concentration .............20
1.10 Degenerate and Nondegenerate Semiconductor .................23
1.11 Motion of Electron in a Crystalline Solid .........................25
1.12 Drift ..........................................................................25
  1.12.1 Mobility ..................................................................27
  1.12.2 Drift Current ..........................................................29
  1.12.3 Resistivity ..............................................................30
1.13 Diffusion ......................................................................31
  1.13.1 Diffusion Current ....................................................31
  1.13.2 Einstein Relationship ..............................................32
1.14 Recombination-Generation of Carrier .............................33
  1.14.1 Recombination-Generation Statistic ............................35
1.15 Continuity Equation .......................................................36
1.16 Diffusion Length ...........................................................37
1.17 Thermionic Emission .....................................................37
1.18 Tunneling Process ..........................................................38
1.19 High-Field Effect ...........................................................39
1.20 Metal Semiconductor Contact .......................................41
1.21 Ohmic Contact ..............................................................43
Exercises ............................................................................45
Bibliography ..........................................................................48
Figure 1.1: Intrinsic concentration and band-gap energy of GaAs, Si, and Ge semiconductors at temperature 300K.................................................................5
Figure 1.2: Energy band diagram of intrinsic semiconductor ................. 6
Figure 1.3: The valence electron shell illustrating intrinsic, p-type and n-type semiconductors ........................................................................................................7
Figure 1.4: Energy band diagrams of (a) n-type and (b) p-type of extrinsic semiconductor8
Figure 1.5: Fermi function plot for temperature approaches 0K ............. 10
Figure 1.6: Fermi function plot for temperature > 0K .......................... 10
Figure 1.7: Location of Fermi level of intrinsic and extrinsic semiconductors 11
Figure 1.8: Geometry used to calculate 3-D density of states ................... 12
Figure 1.9: Density of states in conduction and valence bands ................ 13
Figure 1.10: Carrier distribution of intrinsic, n-type and p-type semiconductors 15
Figure 1.11: The doping Fermi level of silicon at room temperature as the function of doping concentration................................................................. 19
Figure 1.12: Intrinsic carrier concentration and its variation with temperature 20
Figure 1.13: n/N_D plot of 10^{15} cm^{-3} phosphorous-doped silicon sample with temperature. Also shown in the plot is n/N_D .................................................. 21
Figure 1.14: Qualitative explanation of concentration versus temperature 21
Figure 1.15: The energy band diagram of degenerate semiconductor ........ 24
Figure 1.16: Random movement of electron in thermal equilibrium condition 25
Figure 1.17: Motion of electron due to electric field........................................ 26
Figure 1.18: Effect of electric field on the magnitude of drift velocity ........ 27
Figure 1.19: Effect of mobility with impurity concentration ......................... 28
Figure 1.20: Effect of mobility with impurity concentration and temperature 28
Figure 1.21: A_0 and n values of N_{ref}, \mu_{\text{min}}, \mu_0, and \alpha parameters 29
Figure 1.22: Visualized process of diffusion of holes and electrons ........... 31
Figure 1.23: Direct thermal recombination and generation ....................... 33
Figure 1.24: Indirect recombination and generation ..................................... 34
Figure 1.25: Auger recombination ................................................................. 35
Figure 1.26: (a) Energy band diagram of an n-type semiconductor showing its electron affinity and (b) the distribution of electron in conduction band 38
Figure 1.27: Potential barrier of two semiconductors and (b) the representation of wave function across the potential barrier....................... 39
Figure 1.28: Drift velocity versus electric field plot of some semiconductors 40
Figure 1.29: The various energy levels of metal - n-type semiconductor junction and its equilibrium state ............................................................. 41
Figure 1.30: The various energy levels of metal p-type semiconductor junction and its equilibrium state ............................................................. 42
Figure 1.31: Model of metal-semiconductor interface. Above Fermi level, the interface state is neutral if it is empty, whereas below the Fermi level it is neutral if it is filled ........................................................................................................ 43
Figure 1.32: Energy band diagram of (a) metal-n+/n contact and (b) metal-p+/p contact ... 44
Chapter 1
Semiconductor Materials

1.0 Introduction

In this Chapter, the discussion of semiconductor types and materials used for fabrication of integrated circuit will be presented. The characteristics and properties of the semiconductor material especially the silicon due to doping, its behavior at temperature, carrier movement etc. are to be discussed. The types of contacts are discussed at the end of this chapter.

1.1 Type of Semiconductor

Semiconductor materials can be classified into many types. They are elemental semiconductor, compound semiconductor, narrow energy band-gap semiconductor, wide band-gap semiconductor, oxide semiconductor, magnetic semiconductor, polysilicon semiconductor, amorphous semiconductor, organic semiconductor, low dimension semiconductor, and etc. We shall discuss the important type and a few other types.

1.1.1 Elemental Semiconductor

Silicon Si, germanium Ge, and diamond C are important group IV elemental semiconductors. These group IV elemental materials all of them have diamond crystal structure. Another group IV elemental semiconductor having such a structure is alpha tin $\alpha$-Sn, which is also referred as gray Sn. Other elemental structures differing from diamond structure include group III element boron (Rhombohedral), group V material phosphorus, and group VI materials such as sulphur S, selenium Se, and tellurium Te.

Currently silicon Si is the most important semiconductor material used in electronic devices. Some of the important advantages of silicon Si over other semiconductors are:

- A relative ease of passivating the surface by oxidizing in a controlled manner forming a layer of stable native oxide that substantially reduces the surface recombination velocity.
- Its hardness that large wafers to be handled safely without damaging it.
01 Semiconductor Materials

- It is thermally stable up to 1100°C that allows high-temperature processes like diffusion, oxidation, and annealing.
- It is relatively low cost due to established processes.

The basic limitations of silicon Si are the magnitude and type of its energy band-gap. Its energy band-gap is 1.12eV. It is a direct semiconductor that limits the application in optoelectronics, and it has relatively low carrier mobility as compared to other semiconductor such as gallium arsenide GaAs.

Emerging materials based on Si nanostructures e.g., Si nanocrystals, quantum wires and dots, and porous Si, and Si$_x$Ge$_{1-x}$ layers grown on Si substrate, appear to be promising materials in various applications. In nanostructures because of quantum confinement of carriers, it leads to increase of electron hole wave function overlap and hence, it increases photon emission efficiency. There is a high-energy shift toward the emission blue peak.

Porous Si can be obtained from the anodic etching of crystalline Si in aqueous hydrofluoric acid HF. It contains a network of pores and crystallites (microscopic crystal) with sizes in the order of several nanometers. This material exhibits relatively efficient luminescence, which is several orders of magnitude higher than that in crystalline Si, and it is believed to be related to the quantum confinement effects in nanocrystalline Si.

1.1.2 Compound Semiconductor

There are many compound semiconductor materials. They are usually formed from III-V group, II-VI, IV-VI, I-III-VI$_2$ elements. III-V group semiconductors are GaAs, GaP, GaN, AlAs, InSb, InAs, InP etc. In general, these crystallized materials have relatively high degree of stoichiometry (chemistry deal with the relative quantities of reactants and products in chemical reactions). Many of these compounds such as GaAs, InAs, InP, and indium antimonide InSb have direct energy band-gaps and high carrier mobilities. Thus, the common applications of these semiconductors are used to design a variety of optoelectronic devices for both the detection and generation of electromagnetic radiation, and also in high-speed electronic devices. The energy band-gaps of these compounds are useful for optoelectronic applications. The energy band-gap ranges from 0.17eV for InSb to 3.44eV for GaN covering the wavelength range from about 7.29 to 0.36µm, which is from infrared through visible and to ultraviolet spectral ranges. Materials such as GaAs and InP are also extensively used as substrates for a wide variety of electronic and optoelectronic devices such as light-emitting devices.
II-VI compound semiconductor such as Zn and Cd-chalcogenides such as compounds with oxygen O, S, Se, and tellurium Te cover a wide range of electronic and optical properties due to the wide variations in their energy band-gap. These compounds are also relatively easily miscible (can be mixed well in any proportion), which allows a continuous “engineering” of various properties. However, the preparation of high-quality materials and the processing technologies are not sufficiently developed in comparison with those related to silicon Si and some III-V compounds. The II-VI compounds are typically n-type as grown, except ZnTe, which is p-type. Among these compounds, the conductivity type of CdTe can be changed by doping, and thus n- and p-type materials can be obtained. Others II-VI compound such as ZnSe, ZnS and CdS can be doped to produce a small majority of holes. For device applications, it is possible to form heterojunctions in which the n- and p-sides of the junction are of different II-VI compound semiconductors, and to use metal-semiconductor and metal-insulator-semiconductor structures for carrier-injection device applications. All the II-VI compound semiconductors have direct energy band-gaps, thus, high efficient emission or absorption of electromagnetic radiation can be expected from these materials. Therefore, these semiconductors are important mainly for their optical properties. In addition to the binary II-VI compounds, materials such as ternary compound like Zn$_{1-x}$Cd$_x$S and ZnS$_x$Se$_{1-x}$, and quaternary compound such as Zn$_{1-x}$Cd$_x$S$_y$Se$_{1-y}$ alloys with “engineered” properties are also of interest.

IV-VI compound semiconductor like lead chalcogenides such as PbS, PbSe, and PbTe are characterized by narrow energy gaps, high carrier mobilities, and high dielectric constants. The unique feature of the direct energy gap in these compounds is that its energy band-gap increases with increasing temperature, which means the energy gap has a positive temperature coefficient, PTC. In contrast to the temperature behavior of the energy band-gap in other elemental and compound semiconductors, they have a negative temperature coefficient. Main applications of these compounds are in light-emitting devices and detectors in the infrared spectral region.

I-III-VI$_2$ chalcopyrite compound semiconductor such as CuAlS$_2$, CuGaS$_2$, and CuInSe$_2$ are direct semiconductors that have energy band-gaps between 1.0eV to 3.5eV. In additional CuAlS$_2$, CuGaS$_2$ can be made into p-type which is suitable for making heterojunction with wide energy band-gap n-type II-VI compound semiconductor. Some possible applications of this compound semiconductor are light emitting device and photovoltaic solar cells.
1.1.3 Narrow Band-gap Semiconductor

Narrow band-gap semiconductors such as InSb, InAs, PbSe have the energy band-gap below about 0.5 eV. Such semiconductors are extensively employed in such infrared optoelectronic device applications as detectors and diode lasers.

Photoconductive lead sulphide PbS and lead selenide PbSe detectors can be employed in the spectral range between about 1 and 6µm. Another important material used as a detector in the infrared range is Hg$_{1-x}$Cd$_x$Te.

1.1.4 Wide Band-gap Semiconductor

Wide band-gap semiconductor is also referred as refractory semiconductors since they are employed in high temperature application. The typical types of this semiconductor are SiC and II-V nitrides that have high thermal conductivity, high saturation electron drift velocity, high breakdown electric field, and superior chemical and physical stability. The semiconductor has high thermal conductivity indicates it can be used in high temperature at high power level operation. It has wide band-gap that enables detection and emission of light in short-wavelength region likes blue and ultraviolet. It has high saturation electron drift velocity that can be used in RF and microwave operations. High breakdown electric field enables the realization of high power electronic devices and also allows high device packing density for integrated circuit.

1.1.5 Oxide Semiconductor

Oxide semiconductors are also referred as semiconductor ceramics. These materials are polycrystalline and polyphase materials with grain sizes in the range between 1.0 to 10.0µm. The properties of grains and grain boundaries play a crucial role in both the understanding and application of the materials. Some examples of oxide semiconductors are Cu$_2$O (2.1eV), Bi$_2$O (2.8eV), ZnO (3.4eV) etc. They are used in electronic devices and sensors such as positive temperature coefficient PTC thermistor, varistor - resistor with non-linear but symmetric current-voltage characteristics, capacitor of high dielectric constant, gas sensor, and electro-optic modulators.

1.1.6 Magnetic Semiconductor

Semiconductor compound that contains magnetic ions such as Cr, Mn, Fe, Co, Ni, and europium Eu may exhibit magnetic properties. Some oxides such as
FeO and NiO exhibit antiferromagnetic properties and oxide such as europium oxide EuO and EuS are ferromagnetic properties. The semiconductor exhibits large magneto-optical effect that can be used to design optical modulators.

There are many other semiconductor types such as amorphous semiconductor and organic semiconductor that are discussed. Student may take your own initiative to study on your own.

1.2 Intrinsic Semiconductor

Intrinsic semiconductor is pure undoped semiconductor i.e. there is no foreign atom in its crystal lattice. Since it is an intrinsic semiconductor material, therefore, its carrier concentration is low at room temperature. For an example, the intrinsic carrier concentration $n_i$ of silicon Si is $1.5\times10^{10}\text{cm}^{-3}$ at temperature 300K. These carriers are generated due to thermal agitation. This number is far below the density of silicon Si atom of $5.0\times10^{22}\text{cm}^{-3}$. From the indices, these carriers are not sufficient enough to conduct good electricity. Figure 1.1 shows the intrinsic concentration $n_i$ at temperature 300K and their energy band-gap for three common types of semiconductor, which are GaAs, Si, and Ge.

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>Intrinsic Concentration $n_i$</th>
<th>Band-gap Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs</td>
<td>$2.0\times10^6\text{cm}^{-3}$</td>
<td>1.42eV</td>
</tr>
<tr>
<td>Si</td>
<td>$1.5\times10^{10}\text{cm}^{-3}$</td>
<td>1.12eV</td>
</tr>
<tr>
<td>Ge</td>
<td>$2.0\times10^{13}\text{cm}^{-3}$</td>
<td>0.66eV</td>
</tr>
</tbody>
</table>

Figure 1.1: Intrinsic concentration and band-gap energy of GaAs, Si, and Ge semiconductors at temperature 300K

Since it is an intrinsic material, the concentration of both hole $p$ and electron $n$ carriers are the same because each free electron created will leave a hole in valence band. Therefore,

$$p = n = n_i$$

Intrinsic carrier concentration is dependent on temperature and band-gap of the semiconductor.

1.2.1 Energy Band Diagram of Intrinsic Semiconductor

The energy band diagram of the intrinsic semiconductor is shown in Fig. 1.2.
Figure 1.2: Energy band diagram of intrinsic semiconductor

From the energy band diagram, it shows that equal number of electron and hole are present and the Fermi energy level $E_{Fi}$ is approximately at the middle of the band-gap $E_G$.

### 1.3 Extrinsic Semiconductor

The intrinsic semiconductor can be modified into an extrinsic semiconductor by adding impurity to improve its carrier concentration and this improved in electricity conductivity. Depending on the required carrier type, selected type of impurity atom called *dopant* can be added into intrinsic semiconductor. The amount of dopant and type will decide the resistivity $\rho$ and either hole or electron carrier concentration of the extrinsic semiconductor. By controlling the amount of dopants, the carrier concentration of either hole or electron can be increased from intrinsic concentration of $1.5 \times 10^{10} \text{cm}^{-3}$ to the range between $10^{14}$ to $10^{18} \text{cm}^{-3}$ or resistivity range between $10^{-2}$ to $10^{6} \text{ohm-cm}$.

Considering silicon is a group IV element that has four valence electrons. Each silicon atom forms covalent bonds with four neighboring atoms. In this state, it is an intrinsic semiconductor. Boron B, aluminum Al, indium In, and gallium Ga are from group III elements that have three electrons in their valence bands. When a small proportion of these atoms, less than 1 in $10^6$, is added into the silicon crystal lattice, the dopant atom has an insufficient number of valence electron to form covalent bond with four surrounding silicon atoms. One of the silicon atoms has a vacancy for an electron. Thus, it creates a hole that contributes to the conduction carrier at temperature. Dopant that creates hole in this manner is known as acceptor because it would accept electron to fill the hole. This type of extrinsic semiconductor is known as $p$-type semiconductor because it has net positive charge carriers. Elements that belong to group V of the periodic table such as arsenic As, P, Sb have five electrons in the valence
band. When they are added as dopant into intrinsic silicon, the dopant atom contributes an additional electron to the crystal lattice. Dopant that adds electrons to the crystal are known as donor because it can donor electron and this extrinsic semiconductor material is named as $n$-type semiconductor. Figure 1.3 shows the valence electron shell illustrating intrinsic $p$-type and $n$-type semiconductors.

![Image of electron shells](image)

Figure 1.3: The valence electron shell illustrating intrinsic, $p$-type and $n$-type semiconductors

Doping of compound semiconductors is slightly more complicated. The effect of the dopant atom depends on the site occupied by the atom. In III-V compound semiconductors such as GaAs, atom from group II acts as an acceptor when occupying the site of the Ga - group III atom, while atom from group VI act as donor when it takes the site of As - group V atom. Dopant atom from group IV has the property either acts as acceptors or donor depending on the site occupied by it. Such impurities are known as *amphoteric* donors.

At temperature, there are four carrier types present in extrinsic semiconductor. Beside the intrinsic carriers, which termed as minority carriers, they are donor and acceptor carriers whereby their doping concentrations are denoted by $N_A$ and $N_D$ respectively and they are termed as majority carriers.

### 1.3.1 Energy Band Diagram of Extrinsic Semiconductor

The energy band diagrams at temperature of the $n$-type and $p$-type extrinsic semiconductor are shown in Fig. 1.4.

Owing to the presence of donor and acceptor impurities, beside the valence energy level $E_V$, conduction energy level $E_C$, there are extra energy levels called donor level $E_D$ due to donor dopant and acceptor level $E_A$ due to acceptor dopant. These energy levels are much closed to either conduction level or valence level.
As it is illustrated in Fig. 1.4, at room temperature, the donor electrons at donor level are completely ionized and moved into conduction level, whilst the electrons from valence level are also completed ionized and moved into acceptor level. The ionization energy or at time called activation energy or binding energy is determined from Bohr’s theory of hydrogen atom taking the ground state energy level where $n = 1$ in which it follows equation (1.2)

$$E = -\frac{q^4 m_e^*}{8(\varepsilon, \varepsilon_0)^2 \hbar^2}.$$  \hspace{1cm} (1.2)

Substituting the known values for boron, indium, and phosphorus into equation (1.2), the activation energy is found to be $0.045\text{eV}$, $0.16\text{eV}$, or $0.045\text{eV}$ respectively.

In general the group III acceptor and V donor levels lay approximately 0.01 to $0.06\text{eV}$ above valence band and below conduction band.

### 1.4 Fermi-Dirac Statistics

Fermi-Dirac statistical function can be applied to any solid-state material. For nondegenerate semiconductor at thermal equilibrium, the energy distribution of electron is governed by the laws of Fermi-Dirac statistics. The results of these
statistics have given rise the Fermi-Dirac distribution function, which gives the probability that an electronic state with energy $E$ occupied by electron, is

$$\frac{N(E)}{g(E)} = f(E) = \frac{1}{1 + e^{(E-E_F)/kT}} \quad (1.3)$$

$N(E)$ is the number of particle per unit volume per unit energy and $g(E)$ is the number of energy state per unit volume per unit energy. $E_F$ is the Fermi energy level, which is defined as the probability of an energy state is occupied by an electron is exactly one-half.

Considering the case where temperature $T \to 0K$, $(E - E_F)/kT \to -\infty$ for all energies $E < E_F$ and $(E - E_F)/kT \to +\infty$ for all energies $E > E_F$. Hence $f(E < E_F) \to 1$ and $f(E > E_F) \to 0$. The result can be interpreted as when temperature approaches $0K$, all energy states below $E_F$ is filled and all energy states above $E_F$ is empty. The result is plotted in Fig. 1.5.

Considering the case where temperature $T > 0K$, if the energy $E = E_F$ then $f(E_F) = 1/2$. If $E \geq E_F + 3kT$, $\exp[(E - E_F)/kT] >> 1$ and $f(E) \approx \exp[-(E - E_F)/kT]$. Above energy $E_F + 3kT$, Fermi function or filled-state probability decay exponentially to zero with increase energy. Moreover, most states at energies $3kT$ or more above $E_F$ will be empty.

If $E \leq E_F - 3kT$, $\exp[(E - E_F)/kT] << 1$ and $f(E) \approx 1 - \exp[-(E - E_F)/kT]$. Below energy $E_F - 3kT$, Fermi function or filled-state will be filled.

At room temperature 300K, $kT$ is approximately equal to 0.026eV and $3kT$ is $\approx 0.078eV$, which is much less than the band-gap of silicon. Therefore, the probability of conduction state is filled is very low. Figure 1.6 shows the Fermi-function for temperature $T > 0K$. 

- 9 -
The Fermi-Dirac distribution function is symmetrical around Fermi level. If the number of the energy level in conduction band is same as the number of energy level in valence band and the number of hole in valence band is same as the number of electron conduction band, the Fermi level will be at the middle of band-gap. This is reason that the Fermi level is approximately located at the middle of the band-gap. In the $n$-type semiconductor, the electron in the conduction is more than the number of hole in valence band. Therefore, Fermi level of $n$-type semiconductor is closer to the band edge of conduction band. Likewise, for $p$-type semiconductor, the number of hole in valence is more than the number conduction band. Therefore, the Fermi level is located closer to band edge of valence band. Figure 1.7 illustrates the location of Fermi level for intrinsic semiconductor and $n$-type and $p$-type extrinsic semiconductor.
The total number of allowed states in each band is found to be four times the total number of atom in the crystal. How these states and their energy distribution in the band are what interest us at this time. The energy distribution of the state is at time called density of states. It is defined as the number of quantum state per unit volume per unit energy around energy $E$. Mathematically, it is denoted as $g(E)$.

From Schrödinger wave mechanic, the wave function is considered as zero at the boundaries of volume $a^3$. This shall mean that the one dimensional wave solution is of the form $\sin(k_a)$ or $\cos(k_a)$ and the wave function $k$-values are restricted to the positive value $k_a = \frac{\pi}{a}, \frac{2\pi}{a}, \frac{3\pi}{a}, \ldots$. If $a$ is large and the spacing between allowed $k$ values is very small, it is meaningful to consider the volume in $k$-space that each quantum state occupies. The volume occupies by each quantum state shall be $\left(\frac{2\pi}{a}\right)^3$.

In 3-D density of quantum state analysis, the energies $E$ and $E + dE$ are represented by surfaces of sphere which is shown in Fig. 1.8. The $k$-space volume shall be $4\pi k^2dk$. This shall mean the number of quantum state in region between $k$ and $k+dk$ shall be $\frac{4\pi k^2dk}{(2\pi/a)^3} = \frac{k^2a^3dk}{2\pi^2}$. The number of quantum states per unit volume between $E$ and $E + dE$ shall be
\[ g(E)dE = \frac{k^2dk}{2\pi^2} \quad (1.4) \]

From earlier analysis, for \( k = 0 \), the energy \( E \) follows \( E = \frac{\hbar^2}{2m_e} k^2 \).

Differentiation of \( dE/dk \) of this equation and substituting \( k^2 \) into equation (1.4). Equation (1.4) shall be

\[ g(E)dE = \frac{(m_e^*)^{3/2} E^{1/2}dE}{\sqrt{2\pi^2\hbar^3}} \quad (1.5) \]

An electron can have two possible spin states with a given energy. Accounting for spin, the density of state \( g(E) \) obtained from equation (1.5) is simply multiplied by 2, which is

\[ g(E) = \frac{\sqrt{2}(m_e^*)^{3/2} E^{1/2}}{\pi^2\hbar^3} \quad (1.6) \]

**Figure 1.8:** Geometry used to calculate 3-D density of states

At thermal equilibrium, the density of states for a given energy level \( E \) in conduction band \( g_c(E) \) from energy at conduction band edge \( E_C \) and density of states in valence band \( g_v(E) \) for a given energy level \( E \) from energy at valence band edge \( E_V \) are respectively.

\[ g_c(E) = \frac{m_e^*\sqrt{2m_e^*(E-E_C)}}{\pi^2\hbar^3}, \quad E \geq E_C \quad (1.7) \]
Considering a small change of energy $dE$ for a given density of states, it will give rise to number of energy state per unit volume whereby $g_C(E)dE$ represents the number of energy state per unit volume in conduction band lying between energy $E$ and $E+dE$ and $g_V(E)dE$ for number of energy state per unit volume in valence band lying between energy $E$ and $E+dE$.

Since energy states do not exist within the energy band gap, therefore, $g_C(E)$ and $g_V(E)$ are equal to zero for energy level $E$ between $E_V$ and $E_C$.

Figure 1.9 shows the distribution of density of states in conduction and valence bands.

![Figure 1.9: Density of states in conduction and valence bands](image)

Let consider for the 2-D case where it is use for quantum well, the density of states for the parabolic band including the spin is

$$ g(E) = \frac{m^*_e \sqrt{2m^*_e(E - E)}}{\pi^2 \hbar^2}, \quad E \leq E_V \quad (1.9) $$

For 1-D system or a “quantum wire” case, the density of states is given by equation (1.10).
01 Semiconductor Materials

\[ g(E) = \frac{\sqrt{2m^*_e}}{\pi h} \cdot E^{-1/2} \]  

(1.10)

For direct band-gap semiconductor, the electron density of states mass is \( m^*_\text{dos} = m^*_e \), whilst the density of states mass for indirect band-gap semiconductor such as silicon is equal to \( m^*_\text{dos} = (m_1m_2m_3)^{1/3} \), where \( m_1, m_2, \) and \( m_3 \) are effective mass of three principle directions. For silicon, they are \( m^*_1 = m_1 \) and \( m^*_2 = m_2 = m_3 \).

Silicon has six conduction band minima in [100] direction. Therefore, the calculation for density of states for one valley must multiply by six.

The hole density of states mass is equal to \( m^*_\text{dos}^{3/2} = (m_h^* + m\text{hh}^*)^{3/2} \), since the valence band contains the heavy hole band, light hole band, and split off hole band. Split off hole band is quite in depth, thus, it has no effect to overall hole density of states mass.

### 1.6 Carrier Distributions and Carrier Concentration in Energy Bands

The carrier distribution in the bands is defined as the density of state multiply the probability of the states are occupied. Thus, the carrier distribution is conduction band, which is electron is

\[ g_C f(E) \]  

(1.11)

where else for valence band is

\[ g_V [1-f(E)] \]  

(1.12)

The carrier distribution of three of semiconductor materials is shown in Fig. 1.10.
If we take the number of energy state per unit volume multiply the probability of the energy state occupied by an electron and integrating over the entire energy band, it will give rise to the density or concentration of carrier. Thus,

\[
n = \int_{E_C}^{E_{\text{top}}} g_c(E) f(E) \, dE \quad (1.13)
\]

\[
p = \int_{E_{\text{bottom}}}^{E_V} g_v(E) [1 - f(E)] \, dE \quad (1.14)
\]

where \( n \) is the concentration of electron in conduction band and \( p \) is the concentration of hole in valence band. Substituting equation (1.3) and (1.4) into equation (1.13).

\[
n = \int_{E_C}^{E_{\text{top}}} \frac{m^*_e \sqrt{2m^*_e (E - E_C)}}{\pi^2 \hbar^3} \cdot \frac{1}{1 + e^{(E-E_p)/kT}} \cdot dE \quad (1.15)
\]

Letting \( \eta = (E-E_C)/kT \) and substituting into equation (1.15), its gives rise to equation (1.16) and (1.17).

\[
n = \frac{m^*_e \sqrt{2m^*_e (kT)^{3/2}}}{\pi^2 \hbar^3} \int_{0}^{\infty} \frac{\sqrt{\eta}}{1 + e^{\eta(E_p-E_C)/kT}} \cdot d\eta \quad (1.16)
\]

\[
n = 2 \left[ \frac{2\pi m^*_e kT}{\hbar^2} \right]^{3/2} \cdot \frac{2}{\sqrt{\pi}} \int_{0}^{\infty} \frac{\sqrt{\eta}}{1 + e^{\eta(E_p-E_C)/kT}} \cdot d\eta \quad (1.17)
\]
Essentially the limits of integration shall be from zero to infinity instead of $E_C$ to $E_{top}$ simply because the integrand falls off rapidly with increasing energy and is essentially zero for energy only a few $kT$ above $E_C$ and also the reference is now shifted to $E_C$. Therefore extending the upper limit to infinity has negligible effect for the integration. For non-degeneration case, equation (1.17) becomes

$$2 \left[ \frac{2\pi m^*_e kT}{h^2} \right]^{3/2} \cdot e^{(E_F - E_C)/kT} \text{ since } \frac{1}{1 + e^{(E_F - E_C)/kT}} \rightarrow e^{-(E_F - E_C)/kT} \text{ and the integration of}$$

$$\frac{2}{\sqrt{\pi}} \int_0^{\infty} \frac{\sqrt{\eta}}{1 + e^{\eta/(kT/2)}} \cdot d\eta \text{ yields } e^{(E_F - E_C)/kT}.$$ By the similar approach, the hole concentration $p = 2 \left[ \frac{2\pi m^*_p kT}{h^2} \right]^{3/2} \cdot e^{(E_F - E_C)/kT}.$

$2 \left[ \frac{2\pi m^*_e kT}{h^2} \right]^{3/2}$ and $2 \left[ \frac{2\pi m^*_p kT}{h^2} \right]^{3/2}$ are defined as effective density of state in conduction band and in valence band respectively. They are denoted as $N_C$ and $N_V$. Thus,

$$N_C = 2 \left[ \frac{2\pi m^*_e kT}{h^2} \right]^{3/2} \quad (1.18)$$

$$N_V = 2 \left[ \frac{2\pi m^*_p kT}{h^2} \right]^{3/2} \quad (1.19)$$

From the equation (1.18) and (1.19), the effective density of state in both conduction and valence bands is depending on $3/2$ power of temperature. Once would expect the effective density of state increases by the power $3/2$ with increase of temperature.

At room temperature 300K the effective density of state values for conduction and valence bands of silicon are $2.8 \times 10^{19}$ cm$^{-3}$ and $1.04 \times 10^{19}$ cm$^{-3}$ respectively.

Re-writing the electron and hole concentration equations, they are

$$n = N_C \cdot e^{(E_F - E_C)/kT} \quad (1.20)$$

$$p = N_V \cdot e^{(E_F - E_C)/kT} \quad (1.21)$$
For intrinsic semiconductor $n = p = n_i$ and $E_F$ is equal to $E_i$, therefore equation (1.20) and (1.21) become

$$n_i = N_c \cdot e^{(E_i - E_C) / kT} \quad (1.22)$$

$$n_i = N_v \cdot e^{(E_v - E_i) / kT} \quad (1.23)$$

The product of equation (1.22) and (1.23) will give rise

$$n_i^2 = N_c N_v e^{-(E_C - E_v) / kT} = N_c N_v e^{-E_o / kT} \quad (1.24)$$

For silicon, the intrinsic concentration shall be $n_i = \sqrt{N_c N_v e^{-E_o / 2kT}} = 3.87 \times 10^{16} T^{3/2} \text{exp}(-7.02 \times 10^3 / T)$. One can see that the intrinsic concentration increases with temperature.

Substitute equation (1.22) and (1.23) into equation (1.20) and (1.21),

$$n = n_i \cdot e^{(E_p - E_i) / kT} \quad (1.25)$$

$$p = n_i \cdot e^{(E_i - E_p) / kT} \quad (1.26)$$

The product of equation (1.25) and (1.26) yields a very important equation called Law of Mass Action.

$$np = n_i^2 \quad (1.27)$$

From equation (1.22) and (1.23), it can be shown that the intrinsic energy level $E_i$ is

$$E_i = \frac{1}{2} (E_C + E_v) + \frac{1}{2} kT \ln \frac{N_v}{N_c} \quad (1.28)$$

The term $\frac{1}{2} kT \ln \frac{N_v}{N_c}$ is very small as compared with the term $\frac{1}{2} (E_C + E_v)$, therefore, $E_i \approx \frac{1}{2} (E_C + E_v)$, in which it can be shown that it is approximately at mid band-gap where the magnitude of $E_i \approx \frac{1}{2} E_G$. 

- 17 -
1.7 Charge Neutrality Relationship

Let’s consider a uniformly doped semiconductor at thermal equilibrium. There exists no net charge. Thus, its charge neutrality follows equation (1.29).

\[ q_p - q_n - qN_{A}^- + qN_{D}^+ = 0 \]  \hspace{1cm} (1.29)

where \( q \) is the electronic charge, \( N_{A}^- \) and \( N_{D}^+ \) is concentration of ionized acceptor and donor sites. However, owing to low binding energy, at room temperature, all donors and acceptors are ionized. Thus, \( N_{A}^- = N_A \) and \( N_{D}^+ = N_D \) and therefore equation (1.29) becomes

\[ p - n - N_A + N_D = 0 \]  \hspace{1cm} (1.30)

\( N_D \) is the doping concentration of donor atom and \( N_A \) is the doping concentration of acceptor atom respectively.

1.8 Carrier Concentration in Nondegenerate Semiconductor

The concentration of hole is \( p = n_i^2/n \) or electron is \( n = n_i^2/p \). Substituting \( p = n_i^2/n \) into equation (1.30) gives

\[ n^2 - n(N_D - N_A) - n_i^2 = 0 \]  \hspace{1cm} (1.31)

Solving the quadratic equation (1.31) for concentration of electron \( n \) and it is found to be

\[ n = \frac{n_i^2}{p} = \frac{N_D - N_A}{2} + \left( \frac{N_D - N_A}{2} \right)^2 + n_i^2 \]  \hspace{1cm} (1.32)

Using the similarly approach, the concentration of hole \( p \) is found to be

\[ p = \frac{n_i^2}{n} = \frac{N_A - N_D}{2} + \left( \frac{N_A - N_D}{2} \right)^2 + n_i^2 \]  \hspace{1cm} (1.33)

Equation (1.32) and (1.33) are the generally formulae used to calculate the carrier concentration of any doped or not doped semiconductor materials.
Let's consider the case of intrinsic semiconductor whereby \(N_A = 0\) and \(N_D = 0\). Equation (1.32) and (1.33) simply to \(n = n_i\) and \(p = n_i\).

For doped semiconductor where either \(|N_D - N_A| >> n_i\) or \(|N_A - N_D| >> n_i\), the simplification of equation (1.32) and (1.33) yield different results. For the case of \(n\)-type material where \(N_D >> N_A\), equation (1.32) and (1.33) simplified to \(n \approx N_D\) and \(p \approx n_i^2/N_D\) because \((N_D - N_A) \approx N_D >> n_i\). For the case of \(p\)-type material where \(N_A >> N_D\), equation (1.32) and (1.33) simplified to \(p \approx N_A\) and \(n \approx n_i^2/N_A\) because \((N_A - N_D) \approx N_A >> n_i\). For \(n\)-type semiconductor where \(n \approx N_D\) into equation (2.25) \(n = n_i \cdot e^{(E_F - E_i)/kT}\), it yields equation (1.34).

\[
N_D = n_i \cdot e^{(E_F - E_i)/kT} \quad (1.34)
\]

Similarly for \(p\)-type semiconductor \(p \approx N_A\), equation (1.26) yields

\[
N_A = n_i \cdot e^{(E_F - E_i)/kT} \quad (1.35)
\]

Equation (1.34) and (1.35) also indicate that at constant temperature the Fermi level is shifted toward conduction band edge and valence band edge as doping concentration increases. The illustration is shown in Fig. 1.11.

For doped semiconductor where \(n_i >> (N_D - N_A)\). This happens when there is systematically increasing ambient temperature such the intrinsic concentration exceeds the impurity doping concentration. For this case, equation (1.32) and (1.33) simplified to \(p \approx n \approx n_i\).

For compensated semiconductor where both impurity doping concentration \(N_A = N_D\), then equation (1.32) and (1.33) simplified to \(p \approx n \approx n_i\).

**Figure 1.11:** The doping Fermi level of silicon at room temperature as the function of doping concentration
1.9 Temperature Dependence of Carrier Concentration

The variation of intrinsic carrier concentration with temperature is indicated by equation $n_i^2 = N_c N_v e^{-E_g / kT}$. From the equation, the effective density of state is temperature dependent. The energy band-gap $E_G$ for silicon is also temperature dependent following equation $E_G(T) = E_G(0) - \alpha T^2/(T + \beta)$, whereby $E_G(0K) = 1.166eV$, $\beta = 636K$ and $\alpha = 4.73 \times 10^{-4} V/K$. The variation of carrier concentration with temperature becomes complicated which will be dealt later. However, the plot of logarithmic concentration $n_i$ with respect to $1/T$ indicating a fairly straight line indicating that it is heavily dependent on inverse temperature. Figure 1.12 shows the plot of intrinsic carrier concentration of three commonly used semiconductors with temperature.

For sufficiently high temperature all semiconductors irrespectively whether it is doped or not, become intrinsic semiconductor. This is because $n_i >> |N_D - N_A|$ at sufficiently high temperature, whereby equation (1.32) and (1.33) simplified to $p \approx n \approx n_i$. Figure 1.13 shows $n/N_D$ plot of phosphorous doped $N_D = 10^{15} \text{cm}^{-3}$ silicon sample with temperature range from 0K to 600K.

![Figure 1.12: Intrinsic carrier concentration and its variation with temperature](image-url)
Figure 1.13: $n/N_D$ plot of $10^{15}\text{cm}^{-3}$ phosphorous-doped silicon sample with temperature. Also shown in the plot is $n_i/N_D$.

At temperature 0K, all energy states in valence band are filled, all energy states in conduction band are unfilled, and all the doped sites are intact not ionized. At temperature range between 0K and 100K, not all doped sites are ionized. Thus, the ratio of $n/N_D$ is less than one. This region is called freeze out region. Ionization increases as temperature increases until to a point where all doped sites are ionized. This is indicated by the increase of $n/N_D$ ratio. When all doped sites are ionized, the ratio of $n/N_D$ is approximately equal to one. The ratio maintains up to temperature 500K. This region is called extrinsic region. Beyond temperature 500K, electron in valence obtained sufficiently energy and begins to ionize and move to conduction band. The ratio of $n/N_D$ is greater than one in this case. This region is called intrinsic region. Figure 1.14 illustrates the qualitative explanation of concentration change with temperature.

Figure 1.14: Qualitative explanation of concentration versus temperature.
One postulation used in the derivation of Fermi-Dirac probability function was Pauli exclusive principle. Each donor level has two quantum states. The insertion of an electron into one quantum state precludes putting an electron into the second quantum state. By adding one electron, the vacancy requirement of the atom is satisfied. Addition of a second electron in the donor level is not possible. Thus, the probability function for donor state has to be modified to

$$n_D = N_D - N_D^+ = \frac{N_D}{1 + \frac{1}{2} \exp \left( \frac{E_D - E_F}{kT} \right)}$$  \hspace{1cm} (1.36)$$

where \(n_D\) is the density of electrons occupying the donor level and \(E_D\) is the energy of the donor level. \(1/2\) is the degeneracy factor, which is the direct result of \(1/2\) spin factor of the electron and can be generally written as \(1/g\), where \(g\) is degeneracy factor.

The analysis for the density \(p_A\) of hole occupying the acceptor level \(E_A\) is

$$p_A = N_A - N_A^- = \frac{N_A}{1 + \frac{1}{4} \exp \left( \frac{E_F - E_A}{kT} \right)}$$  \hspace{1cm} (1.37)$$

where \(g\) is equal to 4 for silicon and gallium arsenide band structure.

If \((E_D - E_F) \gg kT\) then equation (1.36) shall be

$$n_D \approx \frac{N_D}{1 + \frac{1}{2} \exp \left( \frac{E_D - E_F}{kT} \right)} = 2N_D \exp \left[ -\frac{(E_D - E_F)}{kT} \right]$$  \hspace{1cm} (1.38)$$

The electron density in conduction band follows equation (1.20), which is \(n = N_c \cdot e^{(E_F-E_c)/kT}\). The fraction of not ionized electron from donor level into conduction band shall be \(\frac{n_D}{n + n_D}\). Using equation (1.20) and (1.38), \(\frac{n_D}{n + n_D}\) shall be

$$\frac{n_D}{n + n_D} = \frac{1}{1 + \frac{N_c}{2N_D} \exp \left[ -\frac{(E_c - E_D)}{kT} \right]}$$  \hspace{1cm} (1.39)$$
Similarly the fraction of not ionized acceptor hole from acceptor level into valence band shall be

\[
\frac{p_A}{p + p_A} = \frac{1}{1 + \frac{N_v}{4N_A} \exp \left[ -\frac{(E_A - E_V)}{kT} \right]}
\]

(1.40)

\((E_C - E_D)\) and \((E_A - E_V)\) are the activation energy of the donor electron and acceptor hole, which are dopant dependent.

Perhaps, this juncture it is worth to mention about energy band-gap dependent with the doping concentration. At constant temperature condition, the change of energy band-gap \(\Delta E_G\) with doping concentration follows equation (1.41).

\[
\Delta E_G = -\frac{3q^2}{16\pi\varepsilon_s} \sqrt{\frac{q^2N_{D,A}}{\varepsilon_s kT}}
\]

(1.41)

As doping concentration increases, the energy band-gap is reduced. This is because of the electrons bound to the impurity atoms start to overlap. For an example, at doping concentration of \(10^{18} \text{ cm}^{-3}\), the average distance between two impurities is only 10 nm. This overlap forces the energies to form an energy band rather than a discrete level.

### 1.10 Degenerate and Nondegenerate Semiconductor

So far what has been discussed is nondegenerate semiconductor where the doping concentration is small as compared with concentration of the host atom and the density of state where Pauli’s exclusive principle can be neglected and the electron statistic can be described by Boltzmann statistics. The donor and acceptor levels have a distance from the conduction level and valance level. Thus, the non-interacting discrete donor or acceptor states are maintained.

As the impurity concentration is increased the Fermi-level is moving toward either valence band or conduction as indicated by equation (1.20) and (1.21). When the impurity concentration is greater than density of state, which is in the order \(10^{19} \text{ cm}^{-3}\) for silicon semiconductor, the Fermi-level will either lie in conduction band or valence band. Such a semiconductor material is called degenerate semiconductor, where Pauli’s exclusive principle becomes
important and Fermi-Dirac statistics has to be used instead of Boltzmann statistic to describe the electron statistic.

Mathematically, it can be shown from equation (1.20) that for Fermi-level lying on conduction band edge, the doping concentration of $n$-type shall be equal to effective density of state for conduction, which is $2.8 \times 10^{19} \text{cm}^{-3}$. Likewise for Fermi-level lying at the valence band edge, from equation (1.21), the doping concentration of $p$-type should be equal to effective density of state for valence band, which is $1.04 \times 10^{19} \text{cm}^{-3}$.

Figure 1.15 illustrates the energy band diagram of degenerate semiconductor.

![Energy Band Diagram](image)

(a) $n$-type degenerate semiconductor  (b) $p$-type degenerate semiconductor

Figure 1.15: The energy band diagram of degenerate semiconductor

As illustrated in Fig. 1.14(a), the energy level between $E_F$ and $E_C$ are mostly filled with electron while the level between $E_V$ and $E_F$ shown in Fig. 1.14(b) are mostly filled with hole. Thus, the electron and hole concentrations are very high.

The concentration of hole $p$ or electron $n$ can be assumed to be $p = N_A$ and $n = N_D$. This is because there is a strong interaction between hole and electron such that not all dopants are ionized. The carrier concentration would eventually reach a saturation value typically at around $10^{20} \text{cm}^{-3}$. Based on the understanding, the law of mass action $np = n_i^2$ is not valid for degenerate semiconductors.

A good use of this semiconductor is for the design of devices such as Esaki diode or tunnel diode for the microwave application and semiconductor laser.
1.11 Motion of Electron in a Crystalline Solid

The electron in semiconductor crystal lattice would wonder around randomly due to its thermal energy. Since we know that the movement of electron constituent flow of current, due to randomness of motion, there is no net flow of charge. Thus, there is no net flow of current. The random movement of the electron is illustrated in Fig. 1.16.

![Random movement of electron in thermal equilibrium condition](image)

**Figure 1.16:** Random movement of electron in thermal equilibrium condition

As the temperature increases, the movement of electron will also be faster and more random. The thermal velocity \( v_{\text{thermal}} \) acquired by electron is equal to

\[
v_{\text{thermal}} = \left( \frac{3kT}{m_e^*} \right)^{1/2}
\]  

(1.42)

1.12 Drift

If electric field is applied across the homogeneous semiconductor crystal. The basic random pattern of motion is retained but the body of electrons moves towards the positive side of the electric field as shown in Fig. 1.17. This movement of electron is called *drift*. Thus, drift can also be defined as charged particle motion in response to an applied electric field.

Since there is movement of the electron due to electric field, the electron will acquire the drift velocity \( v_{\text{drift}} \). The drift velocity \( v_{\text{drift}} \) is less than thermal velocity because of collision is displaced with large atom in the crystal lattice. Owing to the collision, one has to define a quantity called *mean time between
**01 Semiconductor Materials**

*collision* $\tau$. Knowing the mean free time between collisions, the drift velocity $v_{\text{drift}}$ can be defined as

$$v_{\text{drift}} = \left( \frac{q\tau}{m_e} \right) E$$  \hspace{1cm} (1.43)

![Diagram of electron motion due to electric field](image)

**Figure 1.17:** Motion of electron due to electric field

Equation (1.43) can be re-written as $v_{\text{drift}} = \mu E$, where $\mu = \frac{q\tau}{m_e}$. $\mu$ is mobility which is defined as how easily electrons and holes can move through the lattice of the material. Higher mobility leads to higher conductivity, higher current level, and faster response time. This is one of the typical parameters that an engineer would like to see for semiconductor device design.

Equation (1.43) is valid only if the drift velocity is small as compared with the thermal velocity, which is as high as $10^7$ cm/sec for silicon and $\tau$ is independent of electric field. Experiment has shown that as the drift velocity is comparable with thermal velocity, the equation (1.43) is no valid as shown in the drift velocity $v_{\text{drift}}$ versus electric field plot of Fig. 1.18. At large enough electric field, a maximum drift velocity is reachable. After reaching the maximum drift velocity, any further increase of electric field will not has any effect on the drift velocity.
1.12.1 Mobility

Lattice scattering and impurity scattering dominate the effects on the mobility of the electron and hole. Lattice scattering is due to thermal vibration of the atom, which disrupts the periodicity of the atom thus affects the movement of electron or hole. Impurity scattering is the cause when electron or hole passes through the charged particle would deflect its path and movement. Other effects are carrier-carrier scattering, neutral impurity and defect scattering, and piezoelectric scattering. In general the mobility $\mu$ of electron or hole follows *Matthiessen rule* as shown in equation (1.44).

$$\frac{1}{\mu} = \frac{1}{\mu_L} + \frac{1}{\mu_i}$$

(1.44)

Theoretically, the mobility due to impurity scattering $\mu_i$ can be shown to be proportional to $T^{3/2}/N$, where $N$ is the impurity concentration. While theoretical analysis shows the mobility due to lattice scattering $\mu_L$ is proportional to $1/(T^{3/2}m_c^{5/2})$, where $m_c$ effective conductive mass. The impurity scattering is proportional to $T^{3/2}/(N_{D,A}m^*/1/2)$. Figure 1.19 shows the effect of mobility with impurity concentration while Fig. 1.20 shows the effective of mobility with impurity concentration and temperature.
For temperature below 150K, the increase of mobility is due to increase of ionization into conduction band and valence band. After full ionization, impurity and lattice scatterings become dominate.
Mobility dependence on temperature and doping concentration can be empirically fit to the relation shown in equation (1.45).

\[
\mu = \mu_{\min} + \frac{\mu_0}{1 + \left(\frac{N}{N_{\text{ref}}}\right)^\alpha}
\]  

(1.45)

Beside concentration \( N \), which can be either \( N_A \) or \( N_D \), all other parameters \( \mu_{\min} \), \( \mu_0 \), \( N_{\text{ref}} \), and \( \alpha \) exhibit a temperature dependence in the form of \( A = A_0(T/300)^n \). \( A_0 \) is the temperature-dependent constant specified at temperature 300K. \( T \) is the temperature and \( n \) is the exponent specific to a parameter. \( A_0 \) and \( n \) values can be obtained from Fig. 1.21.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Temperature Independent Factor ( A_0 )</th>
<th>Temperature Exponent ( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Electrons</td>
<td>Holes</td>
</tr>
<tr>
<td>( N_{\text{ref}} ) (cm(^{-3}))</td>
<td>1.30x10(^{17})</td>
<td>2.35x10(^{17})</td>
</tr>
<tr>
<td>( \mu_{\min} ) (cm(^2)/V-s)</td>
<td>92</td>
<td>54.3</td>
</tr>
<tr>
<td>( \mu_0 ) (cm(^2)/V-s)</td>
<td>1268</td>
<td>406.9</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>0.91</td>
<td>0.88</td>
</tr>
</tbody>
</table>

**Figure 1.21:** \( A_0 \) and \( n \) values of \( N_{\text{ref}}, \mu_{\min}, \mu_0, \) and \( \alpha \) parameters

### 1.12.2 Drift Current

In earlier part, we know that there is net flow of charge means there is current. There are two types of drift current. One is due to electron and one due to hole. The drift current due to electric field is defined as

\[
I_{n|\text{drift}} = qnV_{n|\text{drift}}A
\]  

(1.46)

\[
I_{p|\text{drift}} = qpV_{p|\text{drift}}A
\]  

(1.47)

\( p \) and \( n \) are concentration of minority hole and electron and \( A \) is the cross-sectional area where the electron or hole flow. In practical current density \( J \) is used instead of current \( I \), where current density is \( J = I/A \). Thus, from equation (1.46) and (1.47), the equations for current densities are

\[
J_{n|\text{drift}} = qnV_{n|\text{drift}}
\]  

(1.48)

\[
J_{p|\text{drift}} = qpV_{p|\text{drift}}
\]  

(1.49)

Current densities \( J_{n|\text{drift}} \) and \( J_{p|\text{drift}} \) are also equal to
01 Semiconductor Materials

\[ J_{n\text{drift}} = q n \mu_n E \] (1.50)

\[ J_{p\text{drift}} = q p \mu_p E \] (1.51)

The total drift current density \( J \) flows in homogeneous semiconductor due to electric field is equal to the sum of electron and hole drift current densities.

\[ J_{\text{drift}} = q(p \mu_p + n \mu_n) E \] (1.52)

1.12.3 Resistivity

Resistivity \( \rho \) is an important material parameter, which is closely related to carrier drift. Qualitative resistivity is the measure of a material's inherent resistance to current flow. It is defined as the proportionality constant between the electric field impressed across a homogeneous material and the total particle current per unit area flowing in the material that is

\[ E = \rho J \] (1.53)

Or

\[ J = \sigma E = \frac{1}{\rho} E \] (1.54)

where \( \sigma = \frac{1}{\rho} \) is the material conductivity. From equation (1.52), (1.53) and (1.54), the resistivity \( \rho \) can be defined as

\[ \rho = \frac{1}{q \mu_p n + \mu_n p} \] (1.55)

For \( n \)-type semiconductor and \( p \)-type semiconductor, their resistivities are respectively equal to

\[ \rho = \frac{1}{q \mu_n N_D} \] (1.56)

\[ \rho = \frac{1}{q \mu_p N_A} \] (1.57)
For \( n \)-type semiconductor \( n \approx N_D >> p \) thus \((\mu_n n + \mu_p p) \approx \mu_n N_D\) and for \( p \)-type semiconductor \( p \approx N_A >> n \) thus \((\mu_n n + \mu_p p) \approx \mu_p N_A\).

1.13 Diffusion

Diffusion is a process whereby particles tend to spread out or redistribute as a result of their random thermal motion, migrating on a macroscopic scale from regions of high particle concentration into regions of low particle concentration. Now we can say that for diffusion to occur there exists a concentration gradient i.e. \( \nabla p \neq 0 \) for hole and \( \nabla n \neq 0 \) for electron. The one-dimensional visualized process of diffusion of holes and electrons are shown in Fig. 1.22.

![Visualized process of diffusion of holes and electrons](image)

**Figure 1.22:** Visualized process of diffusion of holes and electrons

1.13.1 Diffusion Current

Diffusion in semiconductor gives rise to diffusion current in which it has two components - one due to electron and one due to hole. The diffusion current density due hole and electron are respectively equal to

\[
J_{pl\text{diff}} = -qD_p \nabla p \tag{1.58}
\]

and

\[
J_{nl\text{diff}} = qD_n \nabla n \tag{1.59}
\]

where \( D_n \) and \( D_p \) are the diffusion coefficients that have unit \( \text{cm}^2/\text{sec} \). Since diffusion occurs from high concentration to low concentration, thus, the concentration gradient is negative. However, the electron has negative charge and hole has positive charge. It gives rise to negative hole diffusion and positive electron diffusion current.
01 Semiconductor Materials

If both drift and diffusion are present in the semiconductor then the total hole current density and electron current density are

\[ J_p = q(\mu_p p E - D_p \nabla p) \]  (1.60)

and

\[ J_n = q(\mu_n n E + D_n \nabla n) \]  (1.61)

The total current density \( J \) shall be

\[ J = J_p + J_n = q(\mu_p p E - D_p \nabla p) + q(\mu_n n E + D_n \nabla n) \]  (1.62)

1.13.2 Einstein Relationship

A nonzero electric field is established inside non-uniformly doped semiconductor under equilibrium condition, the one dimension electron diffusion current and drift current should balance each other. Thus,

\[ J_n|_{\text{drift}} + J_n|_{\text{Diff}} = q\mu_n n E + qD_n \frac{dn}{dx} = 0 \]  (1.63)

However,

\[ E = \frac{1}{q} \frac{dE}{dx} \]  (1.64)

From equation \( n = n_i e^{(E_p - E_n)/kT} \). Differentiating it with respect to \( x \) yields

\[ \frac{dn}{dx} = -n_i e^{(E_p - E_n)/kT} \frac{dE_p}{dx} = -\frac{q}{kT} n E \]  (1.65)

Substitute equation (1.65) into equation (1.63), it establishes

\[ qn E \mu_n - qn E \frac{q}{kT} D_n = 0 \]  (1.66)

Since \( E \neq 0 \) because of non-uniformity of doping therefore,

\[ \frac{D_n}{\mu_n} = \frac{kT}{q} \]  (1.67)
By similar approach of analysis for hole, it yields equation (1.68).

\[
\frac{D_p}{\mu_p} = \frac{kT}{q}
\]  

(1.68)

Equation (1.67) and (1.68) are the Einstein equations for hole and electron in semiconductor. Although the equations are established based on the equilibrium condition, it can be shown that they are true for non-equilibrium condition too. But the restriction for non-degenerate type of semiconductor is still applied. At room temperature 300K, \(kT/q\) is approximately equal to 0.0258V. \(D_n = kT/q(\mu_n)\) is calculated to be equal to 35.36cm\(^2\)/sec taking \(\mu_n = 1,360\)cm\(^2\)/V-s.

### 1.14 Recombination-Generation of Carrier

Recombination-generation is perhaps the most interesting of the three primary types of carrier motion and at this time is the most challenging type of carrier movement to be studied. Recombination is a process whereby electrons and holes are annihilated or eliminated, whilst generation is a process whereby electrons and holes are created. Thus, generation is a reversal of recombination.

Recombination-generation R-G process can be classified into two main types namely direct and indirect types. Figure 1.23 shows the direct thermal R-G type, which is called band-to-band R-G process.

![Diagram of direct thermal recombination and generation](Image)

**Figure 1.23:** Direct thermal recombination and generation
In semiconductor, indirect R-G dominates creation and annihilation of electron. Direct R-G process involves direct transition of electron from valence band into conduction and recombination with hole when it loses energy falling from conduction band to valence band. Indirect R-G involves an intermediary or called R-G trap center takes place only at a special location such as lattice defect or special doped impurity atom like gold, iron and copper. Trap center is normally having energy level $E_T$ in between $E_V$ and $E_C$. Figure 1.24 illustrates various ways of indirect R-G.

![Figure 1.24: Indirect recombination and generation](image)

The surface of the semiconductor has abrupt discontinuity of lattice structure. It has a large number of localized energy states or generation-recombination centers due to presence of dangling bonds on the surface. The energy state is called surface state that would enhance recombination similar to those direct and indirect recombination mentioned earlier. This process of recombination is termed as surface recombination.

Auger recombination process occurs by transferring of energy and momentum released by the recombination of an electron-hole pair to a third particle that can be an electron or hole. An example of Auger recombination is illustrated in Fig. 1.25.

Electron $e_1$ recombines directly with hole $h_1$. The energy and momentum released are transferred to electron $e_2$. This causes the electron $e_2$ to elevate to a higher energy level in the conduction band. Upon returning to the lower energy level in the conduction band, electron $e_2$ releases it energy and momentum to the lattice.

Auger recombination is more noticeable when the doping concentration is very high or high injection. The rate of Auger recombination $R_{Aug}$ follows equation (1.69).
01 Semiconductor Materials

\[ R_{\text{Aug}} = B N_e^2 p \text{ or } B n N_A^2 \text{ for } n\text{-type or } p\text{-type} \quad (1.69) \]

where \( B \) is constant that is a strong dependence of temperature.

\[
\frac{\partial n}{\partial t} \bigg|_{\text{light}} = \frac{\partial p}{\partial t} \bigg|_{\text{light}} = G_L
\]

(1.70)

Equation (1.69) has the unit number/cm\(^3\)-sec and normally under equilibrium, \( G_L \) shall be a constant. The R-G statistic involving R-G center mechanism is far more complex which is not covered here. The reader shall take it from different course.

For low level injection which shall mean low thermal generation of electron-hole pair such that \( \Delta n = n - n_0 \ll n_0 \) and \( n \approx n_0 \), and \( \Delta p = p - p_0 \ll p_0 \) and \( p \approx p_0 \), where \( n_0 \) and \( p_0 \) are the concentration of electron and hole before perturbation from light source.
From the above discussion, one can show that for $n$-type semiconductor after the light perturbation, the electron concentration is approximately the same before and after perturbation but not the hole concentration. When the $n$-type semiconductor is in the midst to restore its equilibrium, via R-G center, the factor that would have the greater effect shall be $\frac{\partial p}{\partial t}$. To get rid of excess hole, the hole must transition from valence band to already fill with electron R-G center since $E_F > E_T$ for $n$-type semiconductor. Logically speaking the greater number of R-G center, which is $N_T$, the higher the probability of annihilation and also the availability of excess hole $\Delta p$. Thus, a relationship of $\frac{\partial p}{\partial t}$, $N_T$, and $\Delta n$ for $n$-type semiconductor can be established such that

$$\frac{\partial p}{\partial t}_{\text{thermal R-G}} = -c_p N_T \Delta p$$ (1.71)

By a similar approach, for $p$-type semiconductor,

$$\frac{\partial n}{\partial t}_{\text{thermal R-G}} = -c_n N_T \Delta n$$ (1.72)

where $c_n$ and $c_p$ are the electron and hole capture coefficient.

$c_n N_T$ and $c_p N_T$ have the unit 1/time. Therefore, we define $\tau_p = 1/c_p N_T$ and $\tau_n = 1/c_n N_T$, which is the average time the minority carrier either hole or electron stays in the majority carrier of either electron or hole before they are recombined. Equation (1.71) and (1.72) shall then be

$$\frac{\partial p}{\partial t}_{\text{thermal R-G}} = -\frac{\Delta p}{\tau_p} \quad \text{for holes in } n\text{-type material}$$ (1.73)

$$\frac{\partial n}{\partial t}_{\text{thermal R-G}} = -\frac{\Delta n}{\tau_n} \quad \text{for electrons in } p\text{-type material}$$ (1.74)

### 1.15 Continuity Equation

After considering the physics of three carrier type motions, we know that all these carrier motions occur at the same time in the semiconductor system and no carrier created or destroyed at a given time point without considering the conservation of carrier. Thus, a set of continuity equation can be established. The time rate change of hole and electron concentration can be expressed as
\[
\frac{\partial p}{\partial t} = \frac{\partial p}{\partial t}_{\text{drift}} + \frac{\partial p}{\partial t}_{\text{diff}} + \frac{\partial p}{\partial t}_{\text{thermal R - G}} + \frac{\partial p}{\partial t}_{\text{other processes}}
\]  
(1.75)

\[
\frac{\partial n}{\partial t} = \frac{\partial n}{\partial t}_{\text{drift}} + \frac{\partial n}{\partial t}_{\text{diff}} + \frac{\partial n}{\partial t}_{\text{thermal R - G}} + \frac{\partial n}{\partial t}_{\text{other processes}}
\]  
(1.76)

However, time rate of change of hole and electron concentration for drift and diffusion can be written as

\[
\frac{\partial p}{\partial t}_{\text{drift}} + \frac{\partial p}{\partial t}_{\text{diff}} = \frac{1}{q} \left( \frac{\partial J_p}{\partial x} + \frac{\partial J_p}{\partial y} + \frac{\partial J_p}{\partial z} \right) = \frac{1}{q} \nabla \cdot J_p
\]  
(1.77)

\[
\frac{\partial n}{\partial t}_{\text{drift}} + \frac{\partial n}{\partial t}_{\text{diff}} = -\frac{1}{q} \left( \frac{\partial J_n}{\partial x} + \frac{\partial J_n}{\partial y} + \frac{\partial J_n}{\partial z} \right) = -\frac{1}{q} \nabla \cdot J_n
\]  
(1.78)

### 1.16 Diffusion Length

$L_p$ or $L_n$ is the diffusion length of minority hole or electron carriers. It is the average distance minority carriers can diffuse into the majority carrier. The one-dimensional analysis of diffusion length of hole and electron is

\[
\int_0^x x \Delta p_n(x) dx \int_0^x \Delta p_n(x) dx = L_p
\]  
(1.79)

\[
\int_0^x x \Delta n_p(x) dx \int_0^x \Delta n_p(x) dx = L_n
\]  
(1.80)

or alternative diffusion length is also equal to

\[
L_p = \sqrt{D_p \tau_p}
\]  
(1.81)

\[
L_n = \sqrt{D_n \tau_n}
\]  
(1.82)

### 1.17 Thermionic Emission

Carrier in the conduction band that has sufficient energy may thermionically emitted in vacuum level. This process is called *thermionic emission*. 
Figure 1.26(a) shows the energy band diagram of an $n$-type semiconductor. Its electron affinity $q\chi_s$ is the energy required to release an electron from conduction band edge to vacuum level. Figure 1.26(b) shows the distribution of electron in conduction band. It shows the electron that has energy greater than the electron affinity $q\chi_s$ can be thermionically emitted to vacuum level.

![Energy Band Diagram](image)

**Figure 1.26:** (a) Energy band diagram of an $n$-type semiconductor showing its electron affinity and (b) the distribution of electron in conduction band.

The density of electron $n_{th}$ that has energy greater than electron affinity can be obtained by integrating equation (1.13) with different energy limits, which is from $q\chi_s$ to infinity. The result yields equation (1.83).

$$n_{th} = \int_{E_F}^{\infty} g_c(E) f(E)dE = N_C \exp\left[-\frac{q\chi_s + (E_c - E_F)/q}{kT}\right]$$  \hspace{1cm} (1.83)

### 1.18 Tunneling Process

Two semiconductor samples are separated with a distance $d$ between them as shown in Fig. 1.27(a). The barrier height energy $q\phi_b$ is equal to its electron affinity $\chi_s$. If the distance $d$ is sufficiently small, electron from left side of the semiconductor may transport across the barrier to the right side semiconductor even if its energy is less than $q\phi_b$. This process of transportation of electron is termed *quantum tunneling*. Figure 1.27(b) shows the representation of wave function across the potential barrier.
The solution of the tunneling process can be solved from Schrödinger’s wave equation for the condition $x \leq 0$ and $\geq d$ and within the potential barrier, which shall be

$$\psi(x) = A e^{ikx} + B e^{-ikx} \quad x \leq 0$$

(1.84)

$$\psi(x) = C e^{ikx} \quad x \geq d$$

(1.85)

where $A$ is the amplitude of incident particle wave, $B$ is the amplitude of the reflected particle wave and $C$ is the amplitude of the transmitted particle wave.

The solution inside the barrier is

$$\psi(x) = F e^{i\beta x} + G e^{-i\beta x}$$

(1.85)

where $\beta = \sqrt{2m_e(q\phi_dE)/h^2}$.

![Figure 1.27: Potential barrier of two semiconductors and (b) the representation of wave function across the potential barrier](image)

1.19 High-Field Effect

At low electric field, the drift velocity of the electron or hole carrier is proportional the electric field as shown in Fig. 1.18. This is true as long as the drift velocity $v_d$ is small as compared to thermal velocity $v_{thermal}$ and the time interval between collisions $\tau$ is independent of electric field. As the drift velocity $v_d$ approaches thermal velocity $v_{thermal}$, the linear relationship is deviating away. The mean time between collisions $\tau$ will be smaller which would results small mobility as shown by equation (1.42). As the electric field
01 Semiconductor Materials

increases, the drift velocity \( v_d \) of the carrier becomes smaller due to lattice scattering. At sufficient high electric field, the drift velocity \( v_d \) will approach the saturation velocity \( v_s \). Experiment result shows that the empirical formula for drift velocity \( v_d \) and electric field \( E \) is shown in equation (1.87).

\[
v_n, v_p = \frac{v_s}{\left[1 + (E_0 / E)^\gamma \right]^{1/\gamma}}
\]

(1.87)

For silicon \( v_s = 1 \times 10^7 \text{ cm/s} \), \( E_0 = 7 \times 10^3 \text{ V/cm} \) for electron and \( E_0 = 2 \times 10^4 \text{ V/cm} \) for hole, \( \gamma = 2 \) for electron, and \( \gamma = 1 \) for hole.

The carrier drift velocity versus electric field plot for some semiconductor is shown in Fig. 1.28.

![Drift velocity versus electric field plot of some semiconductors](image)

**Figure 1.28:** Drift velocity versus electric field plot of some semiconductors

From the graph, we can see that for semiconductor such as gallium arsenide, its drift velocity changes to a smaller value after attaining maximum velocity as electric field increases. However, this is not happened for silicon. This transfer electron phenomenon is seen in microwave device.
1.20 Metal Semiconductor Contact

Metal-semiconductor contact is a metal-semiconductor junction. Under proper control condition, it can be acted as nonlinear response device such as schottky diode. It has essentially the characteristic of $pn$ junction except it has many applications and has much faster response time. It has schottky barrier height, which would be discussed shortly. Figure 1.29 shows the metal - $n$-type semiconductor junction.

\[ q\phi_b = q\phi_m - q\chi_s = q\phi_m - q\phi_s + (E_C - E_F) \]  

Figure 1.29: The various energy levels of metal - $n$-type semiconductor junction and its equilibrium state

For $n$-type semiconductor, the work function of metal $\phi_m$ is greater than work function of semiconductor $\phi_s$ is assumed to be true. When the metal and semiconductor come in contact, to ensure the continuity of vacuum level and keep the Fermi level flat, the Fermi level of semiconductor at the interface has to move inward into the band-gap. As the result, excess electrons move out of the semiconductor into metal. Thus, it creates a fixed positive charge at the interface of semiconductor. At the same time a dipole is created at the interface of metal, which is negatively charged.

From Fig. 1.29(a), the energy of ideal Schottky barrier height $q\phi_b$ is

\[ q\phi_b = q\phi_m - q\chi_s = q\phi_m - q\phi_s + (E_C - E_F) \]  

But $qV_{bi} = q\phi_m - q\phi_s$, therefore the built-in potential energy $qV_{bi}$ is defined as
01 Semiconductor Materials

\[
qV_{bi} = q\phi_m - q\phi_s = q\phi_b - kT \ln \left( \frac{N_C}{N_D} \right) \tag{1.89}
\]

Also the energy from electron affinity \( e\chi_s \) of semiconductor is

\[
q\chi_s = q\phi_s - (E_{Cs} - E_{Vs}) \tag{1.90}
\]

For \( p \)-type semiconductor, the work function of metal \( \phi_m \) is less than work function of semiconductor \( \phi_s \), and then the energy of built-in potential \( eV_{bi} \) shall be

\[
qV_{bi} = E_G - q\phi_b - (E_{Fs} - E_{Vs}) = E_G - q\phi_b - kT \ln \left( \frac{N_V}{N_A} \right) \tag{1.91}
\]

The various energy levels of metal \( p \)-type semiconductor junction and its equilibrium state are shown in Fig. 1.30.

\[\textbf{Figure 1.30:} \text{ The various energy levels of metal } p \text{-type semiconductor junction and its equilibrium state}\]

In order to align the vacuum energy level and maintain flat Fermi energy level, the Fermi level of semiconductor has to move in the band-gap. It creates deficiency of electron in the conduction band. Electrons from metal move into conduction band and create net positive for metal at the interface and net negative charge at interface for semiconductor.

Experimentally, it is found that the Schottky barrier is quite independent of the metal employed. Examples are 0.7V and 0.8V respective for aluminum in
contact with \(n\)-type silicon and \(p\)-type silicon, 0.5V and 0.61V respectively for titanium contact with \(n\)-type silicon and \(p\)-type silicon.

Basing on the above discussion, a new model of metal-semiconductor is proposed. Its interface has a distribution of interface states, which may arise from the presence of chemical defects such as oxide film or broken bonds, contamination, and etc. The defect leads to distribution of energy levels in the band-gap at interface as shown in Fig. 1.31. The distribution may be characterized by neutral level \(\phi_0\) having properties that states below. It is neutral if they are filled and above the neutral level if they are unfilled. If the density of band-gap states near \(\phi_0\) is very large then addition or depletion of electrons to the semiconductor does not alter the Fermi level position at the surface. In this case the Fermi level is pinned. The Schottky barrier height shall be

\[
q\phi_b = E_G - \phi_0
\]  

(1.92)

**Figure 1.31:** Model of metal-semiconductor interface. Above Fermi level, the interface state is neutral if it is empty, whereas below the Fermi level it is neutral if it is filled.

Basing on equation (1.92), one can say that the Schottky barrier height is almost independent of metal used in contact. However, in real mechanism of formation of interface state and Fermi level pinning is quite complex.

In the real situation, there is a lowering of barrier height due to image force, which is contributed by the electron above the metal that induces the opposite charge at the same distance below the metal surface. This may cause the barrier height lowering by 10 to 20mV.

### 1.21 Ohmic Contact

Ohmic contact is the interface between metal and semiconductor that does not has rectification effect. It allows current to flow freely. There are two possible
ways to create ohmic contact. One way is to use metal that has work function less than the work function of semiconductor. However, it is not practical because Fermi layer is pinned due to high interface density in the band-gap. The other way is to reduce the depletion width of the Schottky diode. The depletion width of the semiconductor with no voltage bias follows equation (1.93).

\[ W_b = \left[ \frac{2K_5e_0V_{bi}}{qN_D} \right]^{1/2} \] (1.93)

One can see that to reduce depletion width \( W_b \) is to increase the doping concentration \( N_D \). Near the interface, if the doping concentration is very high in the order of \( 10^{19} \text{cm}^{-3} \) that the semiconductor is indeed a degenerate semiconductor, the depletion width can be made extremely narrow such that the electron can tunnel through even through there is potential barrier. Figure 1.32 shows the energy band-diagram of metal-\( n^+/n \) contact that electron can tunnel through the spiked barrier easily.

![Energy band diagram](image)

**Figure 1.32:** Energy band diagram of (a) metal-\( n^+/n \) contact and (b) metal-\( p^+/p \) contact

The ohmic contact is defined as the normalized resistance called contact resistance \( R_c \), which is defined as RA where R is the resistance of contact over the area A. Thus,

\[ R_c = RA \] (1.94)

From the transport theory by tunneling through triangular barrier, it was found to be proportional to
Exercises

1.1. Name two factors that make silicon the most attractive semiconductor material in electronic application.

1.2. Name three properties and applications of wide band-gap semiconductor materials.

1.3. Explain why the conductivity of the intrinsic semiconductor is low at room temperature.

1.4. Explain the meaning of intrinsic and extrinsic semiconductor. Use the energy band diagram to show the position of Fermi level for $n$-type and $p$-type semiconductor.

1.5. Using Fermi-Dirac distribution, explain why the Fermi level of $n$-type semiconductor is closed to conduction band.

1.6. Given the band-gap of silicon is equal to 1.12eV, and the values of effective density of state in conduction and valence band at 300K are $2.8 \times 10^{19} \text{ cm}^{-3}$ and $1.04 \times 10^{19} \text{ cm}^{-3}$, calculate the value of intrinsic Fermi energy level $E_i$. Draw the energy band diagram to show the position of $E_i$ and prove that $\left( \frac{m_p^*}{m_n^*} \right)$ is equal to 0.516.

1.7. Calculate the intrinsic concentration of silicon at 300K, 373K, and 473K. Comment the results obtained by you.

1.8. Determine the temperature at which there is a 1 percent probability that energy state 0.3eV below the Fermi level of 0.95eV is empty.

1.9. A silicon sample is doped with $10^{17} \text{ cm}^{-3}$ of P atoms. What is the hole concentration $p$ at temperature 300 K? Where is its Fermi level with respect to conduction band edge?

1.10. Determine the position of Fermi level with respect to valence band for a $p$-type silicon semiconductor doped with $1.0 \times 10^{16} \text{ cm}^{-3}$ of boron atom.
1.11. Given that $N_A = 10^{14}$ cm$^{-3}$ doped silicon sample. Calculate the $E_F$ as a function of temperature $T$ in the material at 50K intervals from temperature $T = 300K$ to 500K.

1.12. What is the difference between nondegenerate semiconductor and degenerate semiconductor? Draw the energy band diagrams for an $n$-type semiconductor to illustrate the difference between the two types.

1.13. Consider a $p$-type semiconductor doped with boron of concentration $N_A = 1.1 \times 10^{16}$ cm$^{-3}$. Determine the temperature at which 90% of acceptor atoms are ionized given that $N_V = 1.04 \times 10^{19} \left( \frac{T}{300} \right)^{3/2}$ cm$^{-3}$.

1.14. Consider an $n$-type semiconductor doped with phosphorous of concentration $N_D = 1.05 \times 10^{16}$ cm$^{-3}$. At temperature $T = 300K$, 0.41% of the donor atom is still in donor state. Determine the activation energy of phosphorous, given that density of state in conduction band $N_C = 2.8 \times 10^{19}$ cm$^{-3}$ at $T = 300K$.

1.15. Name the three primary motions of carrier in semiconductor? Briefly describe your understanding of each type.

1.16. What will be the thermal velocity of the electron in silicon at temperature 300K?

1.17. A silicon sample at temperature 300K is uniformly doped with $N_D = 2 \times 10^{16}$ cm$^{-3}$ donors. Calculate the resistivity of the sample.

1.18. Using the results shown in the graph, calculate the mobility at temperature 300 K of $p$-type and $n$-type silicon semiconductor for doping concentration of $10^{14}$, $10^{16}$, $10^{17}$, $10^{18}$ and $10^{19}$ cm$^{-3}$. Comment your results.
1.19. The mobility of electron and hole in silicon semiconductor is dependence on the relationship \( \mu = \mu_{\text{min}} + \frac{\mu_0}{1 + (N / N_{\text{ref}})\alpha} \) and the general temperature dependence formula \( A = A_0(T/300)^n \). Calculate the mobility of the electron and the hole at temperature 300K and 400K for doping concentration \( N_A \) and \( N_D \) equal to \( 10^{16} \) and \( 10^{18} \) cm\(^{-3} \).

1.20. A piece of uniformly doped semiconductor of cross-sectional area 4.0cm\(^2\) and length 4cm is doped with As of concentration \( 2 \times 10^{17} \) cm\(^{-3}\). A voltage of 3V is applied across it. Calculate its drift current and resistivity at temperature 300K. You may use \( \mu_n \) and \( \mu_p \) at 300 K to be 1,450cm\(^2\)/V-s and 450cm\(^2\)/V-s respectively.

1.21. Consider a silicon sample doped with \( N_D = 1.6 \times 10^{15} \) cm\(^{-3}\) at room temperature subject to a light source perturbation where \( \Delta p = \Delta n = 1.2 \times 10^9 \) cm\(^{-3}\). Find the concentration of hole and electron after perturbation and comment your results.

1.22. Calculate the density of thermionically emitted electron at temperature \( T = 373K \) for an \( n \)-type silicon that has electron affinity = 4.05eV and \( (E_C - E_F) = 0.1 \) eV.
Bibliography

### Index

<table>
<thead>
<tr>
<th>Letter</th>
<th>Term</th>
<th>Page</th>
</tr>
</thead>
</table>
| A      | Alpha tin
Amphoteric donor                                             | 7    |
|        | Armorphous semiconductor                                            | 1    |
|        | Auger recombination                                                | 34   |
| B      | Bismuth oxide                                                      | 4    |
|        | Bohr's theory                                                      | 8    |
| C      | Compound semiconductor                                             | 1    |
|        | Contact resistance                                                 | 44   |
|        | Continuity equation                                                | 36   |
|        | Cuprous oxide                                                      | 4    |
| D      | Degenerate semiconductor                                           | 23   |
|        | Density of states                                                  | 11   |
|        | Diffusion length                                                   | 37   |
|        | Dopant                                                             | 6    |
|        | Drift                                                              | 25   |
|        | Drift velocity                                                     | 25, 26, 40 |
| E      | Einstein equation                                                  | 33   |
|        | Electro-optic modulator                                            | 4    |
|        | Elemental semiconductor                                            | 1    |
|        | *Esaki* diode                                                      | 24   |
| F      | Fermi-Dirac statistical function                                    | 8    |
|        | Freeze out                                                         | 21   |
| G      | Gallium arsenide
GaAs See Semiconductor                                     | 22   |
|        | Gallium nitride
GaN See Semiconductor                                                    | 2    |
| I      | I-III-VI2 chalcopyrite compound semiconductor                      | 3    |
|        | III-V compound semiconductor                                       | 2    |
|        | II-VI compound semiconductor                                       | 3    |
|        | Intrinsic semiconductor
See Semiconductor                                                       | 3    |
| L      | Lattice scattering                                                 | 27   |
| M      | Magnetic semiconductor                                             | 1, 4 |
|        | Matthiessen rule                                                   | 27   |
|        | Mobility                                                           | 27   |
| N      | Narrow band-gap semiconductor                                      | 1, 4 |
|        | Nondegenerate semiconductor                                        | 23   |
| O      | Ohmic contact                                                      | 43   |
|        | Organic semiconductor                                              | 1    |
|        | Oxide semiconductor                                                | 1, 4 |
| P      | Pauli exclusive principle                                          | 23   |
|        | Piezoelectric scattering                                           | 27   |
|        | pn junction                                                        | 41   |
|        | Polysilicon semiconductor                                          | 1    |
| Q      | Quantum tunneling                                                  | 38   |
|        | Quantum wire                                                       | 13   |
| R      | Recombination-generation process                                   | 33   |
|        | Resistivity                                                        | 30   |
| S      | Schottky barrier                                                   | 41, 42 |
|        | Schottky diode                                                     | 44   |
|        | Semiconductor
Alpha tin
Extrinsic semiconductor
Gallium arsenide
Gallium nitride
Intrinsic semiconductor
Silicon
Si nanostructures
Surface state
Thermal velocity
Thermionic emission | 1, 6, 16, 26, 40 |
|        |                                                                       | 2    |
|        |                                                                       | 5    |
|        |                                                                       | 2    |
|        |                                                                       | 6    |
|        |                                                                       | 16   |
|        |                                                                       | 26   |
|        |                                                                       | 34   |
|        |                                                                       | 25, 26, 39 |
|        |                                                                       | 37   |
## Index

<table>
<thead>
<tr>
<th>W</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide band-gap semiconductor ..........1, 4</td>
<td>Zinc oxide ..................................................4</td>
</tr>
</tbody>
</table>