1. Carrier Concentration

a) Intrinsic Semiconductors
- Pure single-crystal material

For an intrinsic semiconductor, the concentration of electrons in the conduction band is equal to the concentration of holes in the valence band.

We may denote,
n_i : intrinsic electron concentration
p_i : intrinsic hole concentration

However,
$n_i = p_i$

Simply,
n_i :intrinsic carrier concentration, which refers to either the intrinsic electron or hole concentration

Commonly accepted values of n_i at $T = 300$°K

Silicon	1.5×10^{10} cm^{-3}
Gallium arsenide	1.8×10^{6} cm^{-3}
Germanium	2.4×10^{13} cm^{-3}

b) Extrinsic Semiconductors
- Doped material

The doping process can greatly alter the electrical characteristics of the semiconductor. This doped semiconductor is called an extrinsic material.

n-Type Semiconductors (negatively charged electron by adding donor)
p-Type Semiconductors (positively charged hole by adding acceptor)

c) Mass-Action Law

n_0 : thermal-equilibrium concentration of electrons
p_0 : thermal-equilibrium concentration of holes

$n_0 p_0 = n_i^2 = f(\text{T})$ (function of temperature)

The product of n_0 and p_o is always a constant for a given semiconductor material at a given temperature.

d) Equilibrium Electron and Hole Concentrations

Let,
n_0 : thermal-equilibrium concentration of electrons
p_0 : thermal-equilibrium concentration of holes
n_d : concentration of electrons in the donor energy state
p_a : concentration of holes in the acceptor energy state
N_d : concentration of donor atoms
N_a : concentration of acceptor atoms
N_d^+ : concentration of positively charged donors (ionized donors)
N_a^- : concentration of negatively charged acceptors (ionized acceptors)

By definition,
$N_d^+ = N_d - n_d$
$Na^- = N_a - p_a$

by the charge neutrality condition,
$n_0 + Na^- = p_0 + N_d^+$

or
$n_0 + (N_a - p_a) = p_0 + (N_d - n_d)$

assume complete ionization,
$p_a = n_d = 0$

then, eq # becomes,
$n_0 + N_a = p_0 + N_d$

by eq # and the Mass-Action law ($n_0 p_0 = n_i^2$)
$n_0 = ½\{(N_d - N_a) + ((N_d - N_a)^2 + 4n_i^2)^{1/2}\}$, where $N_d > N_a$ (n-type)
$p_0 = ½\{(N_a - N_d) + ((N_a - N_d)^2 + 4n_i^2)^{1/2}\}$, where $N_a > N_d$ (p-type)
$n_0 = p_0 = n_i$, where $N_a = N_d$ (intrinsic)

If $N_d - N_a >> n_i$,
then
$n_0 = N_d - N_a$, $p_0 = n_i^2 / (N_d - N_a)$

If $N_a - N_d >> n_i$,
then
$p_0 = N_a - N_d$, $n_0 = n_i^2 / (N_a - N_d)$

Example 1)
Determine the thermal equilibrium electron and hole concentrations for a given doping concentration.

Consider an n-type silicon semiconductor at $T = 300$°K in which $N_d = 10^{16}$ cm^{-3} and N_a = 0. The intrinsic carrier concentration is assumed to be $n_i = 1.5 \times 10^{10}$ cm^{-3}.

- Solution
The majority carrier electron concentration is
$n_o = ½\{(N_d - N_a) + ((N_d - N_a)^2 + 4n_i^2)^{1/2}\} \cong 10^{16}$ cm^{-3}
The minority carrier hole concentration is
$p_0 = n_i^2 / n_0 = (1.5 \times 10^{10})^2/10^{16} = 2.25 \times 10^4$ cm^{-3}

- Comment
$N_d >> n_i$, so that the thermal-equilibrium majority carrier electron concentration is essentially equal to the donor impurity concentration. The thermal-equilibrium majority and minority carrier concentrations can differ by many orders of magnitude.

Example 2)
Determine the thermal equilibrium electron and hole concentrations for a given doping concentration.
Consider an germanium sample at $T = 300$°K in which $N_d = 5 \times 10^{13}$ cm^{-3} and $N_a = 0$.
Assume that $n_i = 2.4 \times 10^{13}$ cm^{-3}.

- Solution
The majority carrier electron concentration is
$n_o = ½\{(5 \times 10^{13}) + ((5 \times 10^{13})^2 + 4(2.4 \times 10^{13})^2)^{1/2}\} = 5.97 \times 10^{12}$ cm^{-3}
The minority carrier hole concentration is
$p_0 = n_i^2 / n_0 = (2.4 \times 10^{13})^2/(5.97 \times 10^{12}) = 9.65 \times 10^{12}$ cm^{-3}

- Comment
If the donor impurity concentration is not too different in magnitude from the intrinsic carrier concentration, the thermal-equilibrium majority carrier electron concentration is influenced by the intrinsic concentration.

Example 3)
Determine the thermal equilibrium electron and hole concentrations in a compensated n-type semiconductor.
Consider a silicon semiconductor at $T = 300$°K in which $N_d = 10^{16}$ cm^{-3} and $N_a = 3 \times 10^{15}$ cm^{-3}. Assume that $n_i = 1.5 \times 10^{10}$ cm^{-3}.

- Solution
The majority carrier electron concentration is
$n_o = ½\{(10^{16} – 3 \times 10^{15}) + ((10^{16} – 3 \times 10^{15})^2 + 4(1.5 \times 10^{10})^2)^{1/2}\} \cong 7 \times 10^{15}$ cm^{-3}
The minority carrier hole concentration is
$p_0 = n_i^2 / n_0 = (1.5 \times 10^{10})^2/(7 \times 10^{15}) = 3.21 \times 10^4$ cm^{-3}

- Comment

If we assume complete ionization and if N_d - N_a >> n_i, the the majority carrier electron concentration is, to a very good approximation, just the difference between the donor and acceptor concentrations.

2. Carrier Transport

The net flow of the electrons and holes in a semiconductor will generate currents. The process by which these charged particles move is called transport. The two basic transport mechanisms in a semiconductor crystal:

- Drift: the movement of charge due to electric fields
- Diffusion: the flow of charge due to density gradients

a) Carrier Drift - Drift Current Density

Let,
J^{dr} : drift current density
ρ : positive volume charge density
v_d : average drift velocity

then,
$J^{dr} = \rho v_d$

$J_p^{dr} = (qp)v_{dp}$ (hole)
$J_n^{dr} = (-qn)v_{dn}$ (electron)
$J^{dr} = J_p^{dr} + J_n^{dr} = (qp)v_{dp} + (-qn)\ v_{dn}$

for low electric field,
$v_{dp} = \mu_p$E (μ_p : proportionality factor, hole mobility)
$v_{dn} = -\mu_n$E (μ_n : proportionality factor, electron mobility)

thus,
$J^{dr} = J_p^{dr} + J_n^{dr} = q(p\mu_p + n\mu_n)$E

Example 1)
Calculate the drift current density in a semiconductor for a given electric field.
Consider a germanium sample at $T = 300$°K with doping concentration of $N_d = 0$ and $N_a = 10^{16}$ cm^{-3}. Assume complete ionization and electron and hole mobilities are 3900 cm^2/V·sec and 1900 cm^2/V·sec. The applied electric field is E = 50 V/cm.

- Solution
Since $N_a > N_d$, the semiconductor is p-type and the majority carrier hole concentration,

$p = ½\{(N_a - N_d) + ((N_a - N_d)^2 + 4n_i^2)^{1/2}\} \cong 10^{16}$ cm^{-3}
The minority carrier electron concentration is
$n = n_i^2 / p = (2.4 \times 10^{13})^2/10^{16} = 5.76 \times 10^{10}$ cm^{-3}
For this extrinsic p-type semiconductor, the drift current $^{\text{density}}$ is
$J^{dr} = J_p^{dr} + J_n^{dr} = q(p\mu_p + n\mu_n)E \cong qN_a\mu_pE$
Then
$J^{dr} = (1.6 \times 10^{-19})(1900)(10^{16})(50) = 152$ A/cm^2

- Comment

Significant drift current densities can be obtained in a semiconductor applying relatively small electric fields. The drift current will be due primarily to the majority carrier in an extrinsic semiconductor.