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DEPARTMENT OF ELECTRONICS ENGINEERING
ELECTRONIC DEVICES AND CIRCUITS 1 SEM III
Summary

N.B. :

1) Important concepts and formulae list.

1. CARRIER CONCENTRATION

1. We define the charge carriers in a semiconductor material as follows:

   $n =$ number of electrons$/cm^3$

   $p =$ number of holes$/cm^3$

2. In an intrinsic semiconductor under equilibrium conditions, the number of electrons and holes are equal:

   $n = p = n_i$

   where n_i is the intrinsic carrier concentration. Approximate intrinsic carrier concentrations for some important semiconductors at room temperature are given below:

   n_i for Si $= 1.5 \times 10^{10}/cm^3$

   n_i for Ge $= 2.4 \times 10^{13}/cm^3$

   n_i for GaAs $= 1.8 \times 10^{6}/cm^3$

3. The Law of Mass Action tells us that at equilibrium, the product of the electron concentration and the hole concentration are equal to the square of the intrinsic carrier concentration:

   $np = n_i^2$

2. CARRIER DISTRIBUTION

To determine the distribution of carriers as a function of energy within a semiconductor, we need to know two things:

1. The number of states that are found at a given energy level E. This is given by the density of states function $g(E)$ or $N(E)$ as shown in figure 1.

2. The probability that these states are occupied. This is given by the Fermi function $f(E)$:

   $$f(E) = \frac{1}{1 + e^{[(E-E_F)/kT]}}$$

   where E_F is the Fermi energy, k is the Boltzmann constant, and T is temperature.

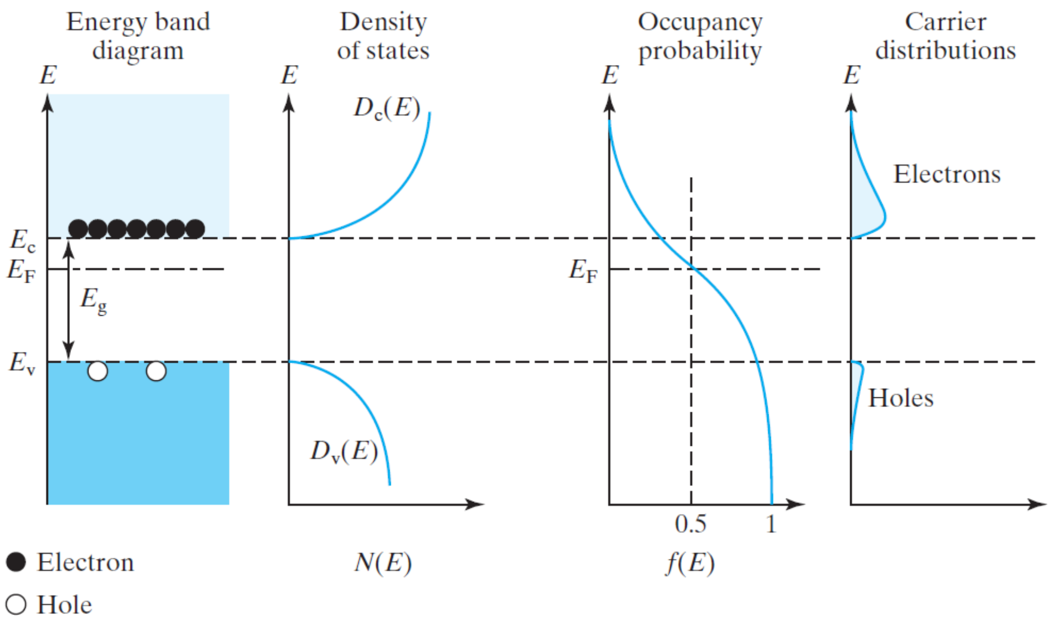

Figure 1: Schematic band diagram, density of states, FermiDirac distribution, and carrier distributions versus energy.

3. EQUILIBRIUM CARRIER CONCENTRATIONS

1. We determine the equilibrium concentration of electrons and holes by integrating $f(E)g(E)dE$ and making a few simplifying assumptions:

$$n = N_C \, e^{[(E_C - E_F)/kT]} \quad \text{OR} \quad n = n_i \, e^{[(E_F - E_i)/kT]}$$

$$p = N_V \, e^{[(E_F - E_V)/kT]} \quad \text{OR} \quad p = n_i \, e^{[(E_i - E_F)/kT]}$$

where N_C is the effective density of states in the conduction band, and N_V is the effective density of states in the valence band, E_F is the Fermi level, E_i is the Fermi level for the intrinsic semiconductor, k is the Boltzmann constant, and T is the temperature.

NOTE: In the above equations, we use the one's on the right-hand side in terms of intrinsic fermi level E_i and fermi level E_F.

2. The intrinsic carrier concentration n_i is given as:

$$n_i = \sqrt{N_C N_V} e^{-E_g/2kT}$$

where N_C is the effective density of states in the conduction band, and N_V is the effective density of states in the valence band. E_g is the band gap of the semiconductor.

4. **CARRIER ACTION**

There are three basic types of carrier action within semiconductors:

1. Drift
2. Diffusion
3. Recombination and Generation (R and G)

A. **DRIFT**

1. Drift is the movement of charged particles in response to an electric field. Drift is due to **potential gradient** in a semiconductor.

2. The drift velocity of a carrier is given as $v_d = \mu E$, where the variables are defined as follows:

   v_d is the drift velocity. Typical units are cm/s

   μ is the carrier mobility. Typical units are cm^2/Vs

   E is the electric field. Typical units are V/cm

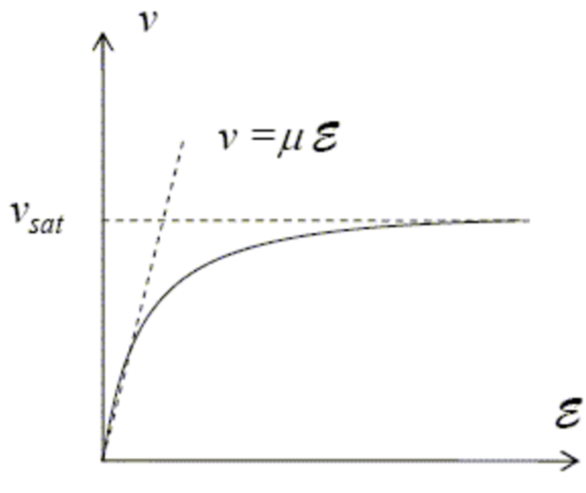

Figure 2: Velocity-field relation in Si

Please note that this linear relationship between electric field and drift velocity applies only at low and moderate electric field strength. In the presence of a high electric field, the drift velocity is limited by the saturation velocity v_{sat} of the carrier as shown in Figure 2.

3. **Current Density**

   The current density J associated with electron and hole drift is given as follows:

   $$J = q(n\mu_n + p\mu_p)E$$

   where q is the charge of an electron, n and p are the carrier densities, and μ_n and μ_p are the mobilities of the electrons and holes, respectively.J is typically expressed in A/cm^2.

4. **Conductivity**

   Since the conductivity σ is defined as J/E , we can now easily write an expression for conductivity as a function of carrier mobility:

   $$\sigma = q(n\mu_n + p\mu_p)$$

   where σ is typically expressed in the units of S/cm.

B. **DIFFUSION**

Diffusion Current

A diffusion current arises from the response of carriers to a concentration gradient. The total diffusion current J_{diff} is given as follows:

$$J_{diff} = qD_n\nabla_n + qD_p\nabla_p$$

where ∇_n and ∇_p are the concentration gradients of electrons and holes respectively (meaning concentration variation with distance x).

And D_n and D_p are the diffusion coefficients of electrons and holes. The units of D are typically in cm^2/s.

Einstein Relationship

The Einstein relationship allows us to relate the mobility of a carrier to its diffusion coefficient. This relationship is given as follows:

$$\frac{D}{\mu} = \frac{kT}{q}$$

where D and μ refer to the diffusion coefficient and mobility of either electrons or holes.

5. **INTERPRETING ENERGY BAND DIAGRAMS**

Here are some important ideas to remember when drawing and interpreting band diagrams:

1. A diffusion current arises in response to a concentration gradient.

   Carriers diffuse from areas of high concentration to areas of low concentration.

2. This diffusion current leads to the generation of an electric field within the material as a space charge develops.

3. This electric field can be either externally applied or internally generated, and leads to a drift current.

4. Tilted bands indicate the presence of an electric field.

   a) Electrons drift down the band. (**Think of them like marbles rolling down a hill**.)

   b) Holes drift up the band. (**Think of them like balloons floating to the sky**.)

5. **The Fermi Level E_F is flat at equilibrium**.

   If the Fermi Level isn't flat, the semiconductor isn't at equilibrium.

6. **RECOMBINATION AND GENERATION**

Recombination and generation occurs:

a) By direct R and G

b) Via Recombination centers (traps level)

1. The recombination rate R is proportional to the concentration of electrons and holes.

$$R = rnp$$

   where r is the rate constant.

2. At equilibrium, the rate of recombination R and the rate of generation G are equal:

$$R = G = rnp = rn_i^2$$

3. Shining light on a semiconductor causes additional generation of carriers. These excess carriers decay once the light is turned off.

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