Class notes

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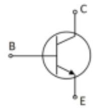
Introduction

ECE 214

- This topic examines a three-terminal device.
  - bipolar junction transistor

- Three-terminal devices are more useful than two-terminal ones, such as the diodes, because they can be used in a multitude of applications:
  1. signal amplification
  2. design of digital logic and memory circuits.



→ Bipolar because the device performance depend upon both hole's and Electrons

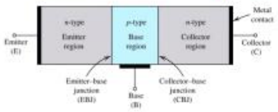
The basic principle is the use of the voltage between two terminals to control the current flowing in the third terminal.

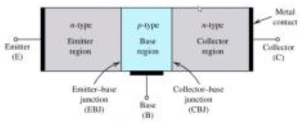
Device Structure and Physical Operation

ECE 214

- Simplified structure of BJT.
- Consists of three semiconductor regions:
  - emitter region (*n*-type)
  - base region (*p*-type)
  - collector region (*n*-type)

- This is referred to as *npn*.
  - However, *pnp* types do exist.





- Consists of two *pn*-junctions:
  - emitter-base junction (EBJ)
  - collector-base junction (CBJ)
- Operating mode depends on biasing.

Mode	EBJ	CBJ
Cutoff	Reverse	Reverse
Active	Forward	Reverse
Saturation	Forward	Forward

*) Intrinsic semiconductor

Intrinsic semiconductors are **made of semiconductors in their purest forms**. Their energy bandgap is in between those of conductors and insulators. The charge carriers consist of an equal number of holes and electrons. An ideal, perfectly pure semiconductor (with no impurities) is called an intrinsic semiconductor.

At T>0

- Electron-hole pairs (EHPs) are generated
- EHPs are the only charge carriers in *intrinsic material*
- **Since EH are created in pairs – the electron concentration in conduction band, *n* (electron/cm³) is equal to the concentration of holes in the valence band, *p* (holes/cm³).**
- **Each of these intrinsic carrier concentrations is denoted by n_i**
- Thus for intrinsic materials $n=p=n_i$

- Another way to **increase the number of charge carriers** is to add them in from an external source.
- Doping is the term given to a process whereby one element is injected with atoms of another element in order to change its properties.
- **Si** or **Ge** are **typically doped with elements** such as **Boron**, **Arsenic** and **Phosphorous** to change and enhance their electrical properties.
- **By doping,** a crystal can be altered so that it has a predominance of either electrons or holes.
- Thus there are two types of doped semiconductors, n-type (mostly electrons) and p-type (mostly holes).
- **When a crystal is doped** such that the equilibrium carrier concentrations n_o and p_o are different from the intrinsic carrier concentration n_i, **the material is said to be *extrinsic*.**

eg: Arsenic(Si) have 5e⁻ in outer most shell so it provide 1 extra e⁻, so it is called n-type semiconductor.

If the concentration of donor atoms is N_D, where N_D is usually much greater than n_i, the concentration of free electrons in the *n*-type silicon

Note will be: $n_n \approx N_D$ $n_e \simeq N_D$

- where the subscript *n* denotes *n*-type silicon. Thus n_n is determined by the doping concentration and not by temperature.

*Note This is not the case, however, for the hole concentration p_n. The p_n are those generated by thermal ionization. Their concentration can be found by using:

[if $N_D >> n_n$ so $N_D = n_n$] $p_n n_e = n_i^2$ $n_e n_n = n_i^2$ $p_n \approx \frac{n_i^2}{N_D}$ $n_n \simeq n_i^2 / N_D$

Finally, it should be noted that in the *n*-type silicon the concentration of free electrons will be much larger than that of holes. Hence electrons are said to be the **majority** charge carriers and holes the **minority** charge carriers in *n*-type silicon.

n_i: is intrinsic carrier concentration of free electrons will be much larger than that of holes. Hence electrons are said to be the **majority** charge carriers and holes the **minority** charge carriers in *n*-type silicon.

n_i: is intrinsic carrier concentration

N_D: concentration of donor atom, or

eg: Boron has 3 e^- so it create holes ~~current~~ current

Increasing conductivity by doping — ECE 214

- Each boron atom has three electrons in its outer shell, it **accepts** an electron from a neighboring atom, thus forming covalent bonds.
- The result is a hole in the neighboring atom and a bound negative charge at the **acceptor** (boron) atom.
- It follows that each acceptor atom provides a hole. If the acceptor doping concentration is N_A, where $N_A \gg n_i$, the hole concentration becomes:

$$p_p \approx N_A$$

Then: $p_p n_p = n_i^2$ $\quad n_p \approx \frac{n_i^2}{N_A}$ → acceptor atom holes

> It should be noted that a piece of *n*-type or *p*-type silicon is electrically neutral; the charge of the majority free carriers (electrons in the *n*-type and holes in the *p*-type silicon) are neutralized by the bound charges associated with the impurity atoms.

Q) eg) $N_D = 10^{17}\ cm^{-3}$ find n_e & n_p or n_h [hole = h]

Concentration of (n_e) electrons $= N_D = 10^{17}\ cm^{-3}$

$n_e \times n_h = n_i^2$

$N_D \times n_h = n_i^2$ [at $T = 300K$, $n_i = 1.5 \times 10^{10}/cm^3$]

$$\boxed{n_h = \frac{n_i^2}{N_D}}$$

$$\boxed{n_h = 2.25 \times 10^3 / cm^3}$$

Increasing conductivity by doping — ECE 214

Just reviewed how conductivity of a semiconductor is affected by:

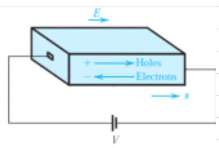
- Temperature – Increasing temperature causes conductivity to increase
- Dopants – Increasing the number of dopant atoms (implant dose) cause conductivity to increase.
- Holes are slower than electrons therefore n-type material is more conductive than p-type material.
- These parameters are in addition to those normally affecting conducting material:

Cross sectional area ↑	Resistance ↓
Length ↑	Resistance ↑

→ $R = \frac{\rho l}{A}$

Drift Current

When an electrical field E is established in a semiconductor crystal, holes are accelerated in the direction of E, and free electrons are accelerated in the direction opposite to that of E.



The holes acquire a velocity $v_{p\text{-drift}}$ given by: $v_{p\text{-drift}} = \mu_p E$

- For intrinsic silicon $\mu_p = 480\ cm^2/V.s.$

The free electrons acquire a drift velocity $v_{n\text{-drift}}$ given by: $v_{n\text{-drift}} = -\mu_n E$

- For intrinsic silicon $\mu_n = 1350\ cm^2/V.s.$

Apparently, the electrons move with much greater ease through the silicon crystal than do holes.

Drift velocity $V_{p\text{-drift}} = \mu_p \vec{E}$ → applied Electric field

current due to flow of holes

$$\boxed{\begin{array}{l} I_p = \text{Area} \times \text{charge magnitude} \times \text{concentration of holes} \times V_{p\,drift} \\ I_p = A \times q \times P \times V_{pd} \end{array}}$$

current due to flow of electrons

$\boxed{I_n = -A \times q \times n\, V_{nd}}$:- ve sign due to direction of hole's and $\bar{e}$ are opposite to each other

Total Drift Current

$$J = J_p + J_n = q(p\mu_p + n\mu_n)E \qquad J = \sigma E \qquad J = E/\rho$$

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

Current density P or J_p: it is current/area

$J_p = \frac{I_p}{A} = q P V_{p.D} = \underline{q P \mu_p E}$ ①

so $J_n = -q n \mu_n E$ ②

$V_p = \mu \vec{E}$, $J = \frac{I_p}{A}$ or $\frac{I_n}{A}$ = concentration (n)

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

$P = \frac{I_p}{A} = \ldots$

$V_p = \mu \vec{E}$, $J = \frac{I_p}{A}$ or $\frac{I_n}{A}$

concentration (n)

$J = \frac{\cancel{A} \times q \times P \times \cancel{V}_p}{A} = q P \mu E$

$J = \sigma E$

$J = \frac{E}{\rho}$

so $J_n = -q n \mu_n E$ (2)

so total drift density $J = J_p + J_n$

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

$[\sigma = q(P\mu_p + n\mu_n)]$

$J = \sigma E$ [where σ is Conductivity]

or

$J = \frac{E}{\rho}$ [where ρ is resistivity]

$\boxed{\rho = \frac{1}{\sigma}}$

in ohm. law form $\boxed{\rho = \frac{E}{J}}$ $\Omega \cdot cm = \frac{V/cm}{A/cm^2}$ ← unit

Find the resistivity of (a) intrinsic silicon and (b) p-type silicon with $N_A = 1.5 \times 10^{16}/cm^3$. Use $n_i = 1.5 \times 10^{10}/cm^3$, and assume that for intrinsic silicon $\mu_n = 1350 \frac{cm^2}{V.s}$ and $\mu_p = 480 \frac{cm^2}{V.s}$, and for the doped silicon $\mu_n = 1110 \frac{cm^2}{V.s}$ and $\mu_p = 400 \frac{cm^2}{V.s}$. (Note that doping results in reduced carrier mobilities).

[$J = \sigma E \Rightarrow$ $\rho = \frac{E}{J}$ [$J = n_e q \cancel{E}_{v.d} + n_p q \cancel{E}_{v.d}$]

$J = q E [n_e \mu_p + n_p \mu_e]$

$\rho = q(n_e \mu_p + n_p \mu_e)$

a) For intrinsic $n = P = n_i = 1.5 \times 10^{10}/cm^3$

$\rho = q(P\mu_p + n\mu_n) = 1.6 \times 10^{-19}(1.5 \times 10^{10} \times 1350 + 1.5 \times 1350 \times 10^{10})$

$\boxed{P = 2.28 \times 10^5 \; cm \cdot \Omega}$

(b) $P_p = N_A = 1.5 \times 10^{16}$

$n_p = \frac{n_i^2}{N_A} = \frac{(1.5 \times 10^{10})^2}{1.5 \times 10^{16}} = 2.25 \times 10^4/cm^3$

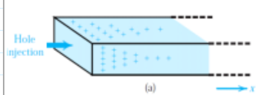
$\sigma = q(P\mu_p + n\mu_n)$

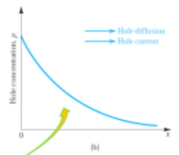
$= 1.6 \times 10^{-19}(1.5 \times 10^{16} \times 400 + 2.25 \times 10^4 \times 1110)$

$\boxed{\sigma = 1.56 \; \Omega \cdot cm}$

Diffusion Current

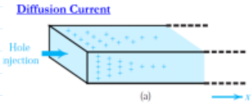
- Carrier diffusion occurs when the density of charge carriers in a piece of semiconductor is not uniform.
- For instance, if by some mechanism the concentration of, say, holes, is made higher in one part of a piece of silicon than in another, then holes will diffuse from the region of high concentration to the region of low concentration.
- The diffusion of charge carriers gives rise to a net flow of charge, or **diffusion current**.

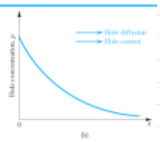




By some unspecified process, we have arranged to inject holes into its left side. This continuous hole injection gives rise to and maintains a hole **concentration profile**

Diffusion Current





- holes diffuse from left to right along the silicon bar → results in a hole current in the x direction.
- magnitude of current at any point is proportional to the slope of the concentration profile, or the **concentration gradient**, at that point.

$$J_p = -qD_p \frac{dp(x)}{dx}$$

J_p is the hole-current density (A/cm²)
q is the magnitude of electron charge,
D_p is a constant called the **diffusion constant** or **diffusivity** of holes
p(x) is the hole concentration at point x.
Note that the gradient (dp/dx) is negative, resulting in a positive current in the x direction, as should be expected.

Diffusion Current

- Similarly for electron diffusion $J_n = qD_n \frac{dn(x)}{dx}$

For holes and electrons diffusing in intrinsic silicon, typical values for the diffusion constants are $D_p = 12$ cm²/s and $D_n = 35$ cm²/s.

Relationship between D and μ

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = V_T$$

$V_T = kT/q$ Thermal Voltage

At room temp, T = 300K: $V_T = 25.9$ mV