Semiconductor, Diode, and Transistor Reference

Angelino Lefevers

July 8, 2017

Contents

Introduction

Just throwing together some concepts and examples for later reference

1 Semiconductor Physics, Materials, and Properties

1.1 Semiconductor Properties and Constants

1.1.1 Common Semiconductor Constants

Table 1: Semiconductor Constants

Material	Eg(eV)	B(cm^{-3}K$^{-3/2}$)
Silicon (Si)	1.1	5.23x10^{15}
Gallium Arsenide (GaAs)	1.4	2.10x10^{14}
Germanium (Ge)	0.66	1.66x10^{15}

1.1.2 Boltzmann's Constant

$$k = 86x10^{-6}\frac{eV}{k}$$

1.1.3 Einstein's Relation

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{e} \cong 0.026V$$

- e :=Charge of an Electron ($1.6x10^{-19}eV$)
- T := Temperature (K)
- k := Boltzmann's Constant ($86x10^{-6}$)($\frac{eV}{k}$)
- μ_n := Electron Mobility ($\frac{cm^2}{V-s}$)
- μ_n := Hole Mobility ($\frac{cm^2}{V-s}$)
- D_n := Electron Diffusion Coefficient ($\frac{cm^2}{s}$)
- D_p := Hole Diffusion Coefficient ($\frac{cm^2}{s}$)

1.1.4 Conductance

$$\sigma = en\mu_n + ep\mu_p$$

- e :=Charge of an Electron ($1.6x10^{-19}eV$)
- σ := Conductance ($(\Omega - cm)^{-1}$)
- μ_n := Electron Mobility ($\frac{cm^2}{V-s}$)
- μ_n := Hole Mobility ($\frac{cm^2}{V-s}$)

1.1.5 Resistivity

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

- σ := Conductance ($(\Omega - cm)^{-1}$)
- ρ := Resistivity ($\Omega - cm$)

1.1.6 Intrinsic Carrier Concentration

Returns the concentration of free electrons and holes in a material.

$$n_i = BT^{3/2}e^{-(E_g/2kT)}$$

- B := Semiconductor Material Coefficient ($cm^{-3}K^{-3/2}$)
- T := Temperature (K)
- k := Boltzmann's Constant ($86x10^{-6}$)($\frac{eV}{k}$)
- E_g := Bandgap Energy (eV)
- n_i := Intrinsic Carrier Concentration ($\frac{\#ofelectrons}{cm^3}$)

1.1.7 Fundamental Relationship Between Electron and Hole Concentration

$$n_o p_o = n_i^2$$

- n_i := Intrinsic Carrier Concentration ($\frac{\#ofelectrons}{cm^3}$)
- n_o := Concentration of Free Electrons at Thermal Equalibrium ($\frac{\#ofelectrons}{cm^3}$)
- p_o := Concentration of Free Holes at Thermal Equalibrium ($\frac{\#ofholes}{cm^3}$)

1.1.7.1 n-type

$$n_o \cong N_d$$

$$p_o = \frac{n_i^2}{N_d}$$

- N_d := Donor Concentration (cm^{-3})

1.1.7.2 p-type

$$p_o \cong N_a$$

$$n_o = \frac{n_i^2}{N_a}$$

- N_a := Acceptor Concentration (cm^{-3})

1.1.8 Excess Carriers

$$\boxed{n = n_o + n\delta}$$

$$\boxed{p = p_o + p\delta}$$

- n := Electron Concentration ($\frac{\#ofelectrons}{cm^3}$)
- p := Hole Concentration ($\frac{\#ofholes}{cm^3}$)
- n_o := Concentration of Free Electrons at Thermal Equalibrium ($\frac{\#ofelectrons}{cm^3}$)
- p_o := Concentration of Free Holes at Thermal Equalibrium ($\frac{\#ofholes}{cm^3}$)
- δ := Recombination Factor

1.2 Current in Semiconductors

1.2.1 Drift Velocity

$$\boxed{v_{dn} = -\mu_n E}$$

$$\boxed{v_{dp} = \mu_p E}$$

- E := Electric Field ($\frac{V}{cm}$)
- μ_n := Electron Mobility ($\frac{cm^2}{V-s}$)
- μ_n := Hole Mobility ($\frac{cm^2}{V-s}$)
- v_{dn} := Drift Velocity of Electrons ($\frac{cm}{s}$)
- v_{dp} := Drift Velocity of Holes ($\frac{cm}{s}$)

1.2.2 Drift Current Density

$$J_n = -env_{dn} = -en(-\mu_n E) = en\mu_n E$$

$$J_p = epv_{dp} = ep(\mu_p E) = ep\mu_p E$$

$$J = en\mu_n E + ep\mu_p E = E\sigma = \frac{1}{\rho}E$$

- e :=Charge of an Electron ($1.6x10^{-19}eV$)
- E := Electric Field ($\frac{V}{cm}$)
- σ := Conductance ($(\Omega - cm)^{-1}$)
- ρ := Resistivity ($\Omega - cm$)
- n := Electron Concentration ($\frac{\#ofelectrons}{cm^3}$)
- p := Hole Concentration ($\frac{\#ofholes}{cm^3}$)
  - n-type :=

$$n = N_d$$

$$p = \frac{n_i^2}{N_d}$$

  - p-type :=

$$p = N_a$$

$$n = \frac{n_i^2}{N_a}$$

- μ_n := Electron Mobility ($\frac{cm^2}{V-s}$)
- μ_n := Hole Mobility ($\frac{cm^2}{V-s}$)
- v_{dn} := Drift Velocity of Electrons ($\frac{cm}{s}$)
- v_{dp} := Drift Velocity of Holes ($\frac{cm}{s}$)
- J_n := Drift Current Density of Electrons ($\frac{A}{cm^2}$)
- J_p := Drift Current Density of Holes ($\frac{A}{cm^2}$)
- J := Total Drift Current Density in a Semiconductor ($\frac{A}{cm^2}$)

1.2.3 Diffusion Current Density

1.2.3.1 Diffusion Current Density due to the Flow of Electrons

$$\boxed{Jn = eD_n \frac{dn}{dx}}$$

1.2.3.2 Diffusion Current Density due to the Flow of Holes

$$\boxed{Jp = -eD_p \frac{dp}{dx}}$$

- e :=Charge of an Electron ($1.6x10^{-19}eV$)
- x := Distance (m)
- n := Electron Concentration ($\frac{\#ofelectrons}{cm^3}$)
- p := Hole Concentration ($\frac{\#ofholes}{cm^3}$)
- Jn := Diffusion Current Density of Electrons ($\frac{A}{cm^2}$)
- Jp := Diffusion Current Density of Holes ($\frac{A}{cm^2}$)
- D_n := Electron Diffusion Coefficient ($\frac{cm^2}{s}$)
- D_p := Hole Diffusion Coefficient ($\frac{cm^2}{s}$)

2 Diodes

2.1 Modes of Operation

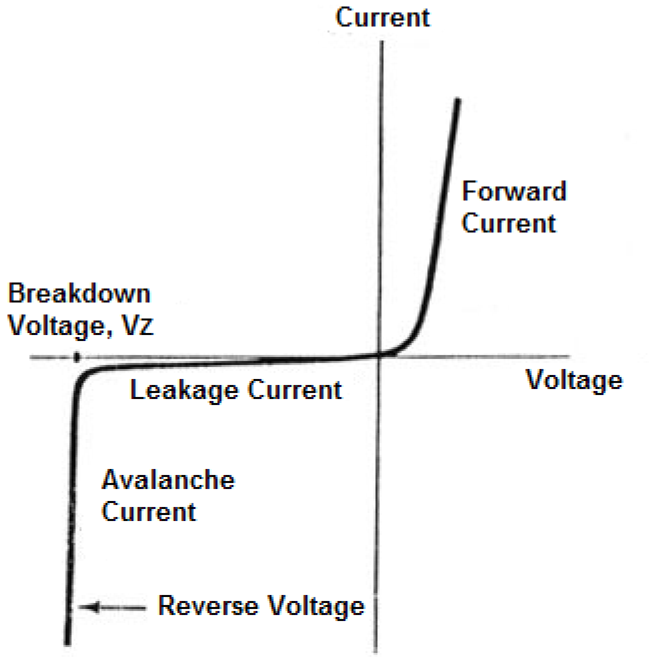

Figure 1: Diode Characteristic Curve

2.2 Equilibrium

2.2.1 Built-in Potential Barrier

$$V_{bi} = \frac{kT}{e} ln(\frac{N_a N_d}{n_i^2}) = V_T ln(\frac{N_a N_d}{n_i^2})$$

- e :=Charge of an Electron ($1.6x10^{-19}eV$)
- T := Temperature (K)
- k := Boltzmann's Constant ($86x10^{-6}\frac{eV}{k}$)
- n_i := Intrinsic Carrier Concentration ($\frac{\#ofelectrons}{cm^3}$)
- N_d := Donor Concentration (cm^{-3})
- N_a := Acceptor Concentration (cm^{-3})
- V_{bi} := Built-in Potential Barrier (V)
- V_T := Thermal Voltage at Room Temperature ($0.026V$)

2.2.2 Thermal Voltage at Room Temperature

$$V_T = 0.026, (T = 300k)$$

2.3 Forward-Biased

2.4 Reversed-Biased

2.4.1 Junction Capacitance

$$C_j = C_{jo}(1 + \frac{V_R}{V_{bi}})^{-1/2}$$

- V_{bi} := Built-in Potential Barrier (V)
- V_R := Reverse-Bias Voltage (V)
- C_j := Capacitance across a pn junction. (pF)
- C_{jo} := Capacitance across a pn junction when there is no voltage applied. (pF)

2.4.2 Reverse-Bias Saturation Current

$$i_D = I_S[e^{\frac{v_D}{V_T}} - 1]$$

- i_D := Diode Current (A)
- v_D := Diode Voltage (V)
- V_T := Thermal Voltage at Room Temperature $(0.026V)$
- I_S := Reverse-Bias Saturation Current (A)

3 Bipolar Junction Transistors (BJT)

3.1 Current Relationships

$$i_C = I_S e^{v_{BE}/V_T}$$

$$i_C = \beta i_B$$

$$i_C = \alpha i_E$$

$$i_E = i_C + i_B$$

$$i_E = (1+\beta) i_B$$

$$\alpha = \frac{\beta}{1+\beta}$$

$$\beta = \frac{\alpha}{1-\alpha}$$

- i_B := Base Current (AAC)
- i_C := Collector Current (AAC)
- i_E := Emitter Current (AAC)
- i_S := Saturation Current (ADC)
- α := Common-Base Current Gain
- β := Common-Emitter Current Gain

3.2 Common-Emitter Circuit

3.2.1 npn DC Analysis

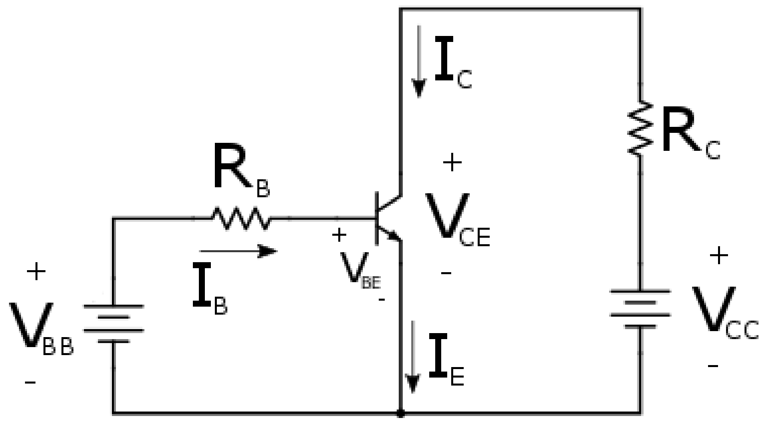

Figure 2: Common Emitter Circuit with npn BJT (DC Analysis)

$$I_B = \frac{V_{BB} - V_{BE}^{(on)}}{R_B}$$

$$V_{CC} = I_C R_C + V_{CE}$$

$$P_T = I_B V_{BE}^{(on)} + I_C V_{CE}$$

$$P_T \cong I_C V_{CE}$$

- R_B := Base Resistance (Ω)
- R_C := Collector Resistance (Ω)
- I_B := Base Current (ADC)
- I_C := Collector Current (ADC)
- I_E := Emitter Current (ADC)
- V_{BE} := Base-Emitter Voltage (V)
- V_{CE} := Collector-Emitter Voltage (V)
- V_{BB} := Base Voltage (V)
- V_{CC} := Collector Voltage (V)

3.2.2 pnp DC Analysis

3.2.3 npn AC Analysis

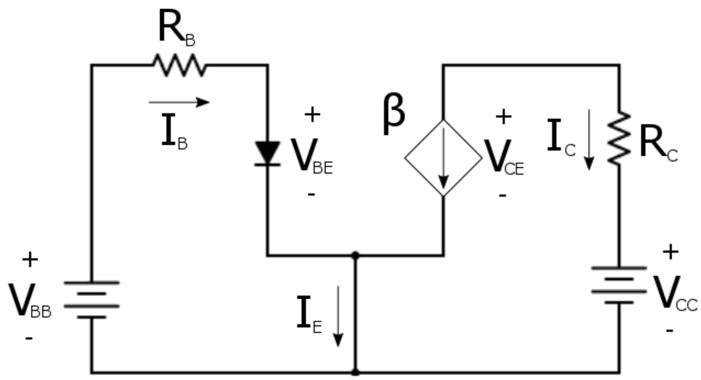

Figure 3: Common Emitter Circuit with npn BJT (AC Analysis)

$$I_B = \frac{V_{BB} - V_{BE}^{(on)}}{R_B}$$

$$V_{CC} = I_C R_C + V_{CE}$$

$$P_T = I_B V_{BE}^{(on)} + I_C V_{CE}$$

$$P_T \cong I_C V_{CE}$$

- R_B := Base Resistance (Ω)
- R_C := Collector Resistance (Ω)
- i_B := Base Current (AAC)
- i_C := Collector Current (AAC)
- i_E := Emitter Current (AAC)
- V_{BE} := Base-Emitter Voltage (V)
- V_{CE} := Collector-Emitter Voltage (V)
- V_{BB} := Base Voltage (V)
- V_{CC} := Collector Voltage (V)

4 Metal Oxide Semiconductor - Field Effect Transistors (MOS-FET)

Variables

B Semiconductor Material Constant.
C_j Juncton Capacitance.
C_{jo} Junction Capacitance at Zero Applied Voltage.
D_n Electron Diffusion Coefficient.
D_p Hole Diffusion Coefficient.
E Electric Field Applied.
E_g Bandgap Energy.
I_B Base Current (DC Conditions).
I_C Collector Current (DC Conditions).
I_E Emitter Current (DC Conditions).
I_S Reverse-Bias Saturation Current (DC Conditions).
J Total Drift Current Density.
J_n Drift Current Density of Electrons.
J_p Drift Current Density of Holes.
Jn Diffusion Current Density of Electrons.
Jp Diffusion Current Density of Holes.
N_a Acceptor Concentration.
N_d Donor Concentration.
T Temperature.
V_R Reverse-Biased Voltage.
V_T Thermal Voltage.
V_{bi} Built-in Potential Barrier.
α Collector Base Current Gain.
β Collector Emitter Current Gain.
δ Electron-Hole Recombination Factor.
μ_n Mobility of an Electron.
μ_p Mobility of a Hole.
ρ Resistivity.
σ Conductance.
e Charge of an Electron ($1.6x10^{19}$).
i_B Base Current (AC Conditions).
i_C Collector Current (AC Conditions).
i_D Current Through a pn Junction (Diode).
i_E Emitter Current (AC Conditions).
i_S Reverse-Bias Saturation Current (AC Conditions).
k Boltzmann's Constant ($86x10^{-6}\frac{eV}{k}$).
n Concentration of Electrons.
n_i Intrinsic Carrier Concentration.
n_o Free Electrons.
p Concentration of Holes.
p_o Free Holes.
v_D Forward-Bias Voltage.
v_{dn} Drift Velocity of Electrons.
v_{dp} Drift Velocity of Holes.
x Distance.

Glossary

Acceptror Concentration The concentration of holes (absense of electrons) free to accept electrons within a specific volume [5].

Bandgap Energy The minimal amount of energy if takes for an electron to break the covalent bond and become a valence electron [5].
Boltzmann's Constant Physical constant relating the average kinetic energy of particles in a gas [1].
Buit-in Potential Barrier The potential difference (voltage) across a pn junction [4].

Charge of an Electron Electronic charge of a single electron [5].
Common-Base Current Gain A constant which describes the relationship between the collector and emitter currents in a transistor as a ratio between the two respectively. The collector current is a factor or magnitude smaller than the emitter current, which is represented by this constant. This constant should never be lower or equal to 1 in a valid and operating transistor [3].
Common-Emitter Current Gain A constant which describes the relationship between the collector and base currents in a transistor as a ratio between the two respectively. The collector current is a factor or magnitude larger than the base current, which is represented by this constant. This constant should never be lower or equal to 1 in a valid and operating transistor [3].
Compound Semiconductor A semiconductor composed of elements from group III and V of the Periodic Table of Elements [5].
Conductance A measure of a material's ability to conduct an electric current [2].
Covalent Bond Bonds formed by the sharing of valence electrons between atoms [5].
Current Density of Electrons The current due to the flow of the electrons within a specified volume [5].
  Diffusion Current Density of Electrons The current due to the flow of electrons within a specified volume due to the process of diffusion [5].
  Drift Current Density of Electrons The current due to the flow electrons within a specified volume due to the pull of an electric field [5].
Current Density of Holes The current due to the flow of holes within a specified volume [5].
  Diffusion Current Density of Holes The current due to the flow of holes within a specified volume due to the process of diffusion [5].
  Drift Current Density of Holes The current due to the flow of holes within a specified volume due to the pull of an electric field [5].
Cutoff When the base-emitter voltage of a transistor has zero applied volts [3].

Donor Concentration The concentration of electrons free to donate in a material [5].
Donor Impurity A material, that when added to the composition of a semiconductor, allows for the controlled creation of free electrons without the creation of holes within the material [4].
Drift Velocity of Electrons The average speed of electrons [5].
Drift Velocity of Holes The average speed of holes [5].

Electric Field The electric field applied [5].
Electron Mobility How well an electron is able to move in a semiconductor [5].
Elemental Semiconductor A semiconductor composed of elements from group IV of the Periodic Table of Elements [5].

Forbidden Bandgap The phenomenon that an electron may not have any amount of energy less than that of the valance band, and more than that of the conductance band. The amount of energy required to move an electron from the conductance band to the valence band is the bandgap energy [5].

Free Electrons The concentration of electrons within a material which are not bound to an atom. Is measured in the number of electrons per volume cubed [5].
Free Holes The concentration of atoms within a material which has a hole in which an electron may enter. Is measured in the number of holes per volume cubed [5].

Hole An atom which has space availiable in the valence band for a free electron, denoted as a positive particle [5].
Hole Mobility How well a hole (area of the absence of electrons) is able to move in a semiconductor [5].

Insulator A material in which current cannot flow because the electrons are bound in their respective atoms with a certain amount of resistance [5].
Intrinsic Carrier Concentration The concentration of free electrons and holes within a specified volume [5].
Intrinsic Semiconductor A single-crystal semiconductor material composed of a single element from the Periodic Table of Elements [5].

Junction Capacitance Capacitance across a pn junction [4].

Metallurgical Junction Junction in which an n and p type material are connected. Located at x=0 [4].

Recombination The process of free electrons and holes attracting and combining together [5].
Resistivity A measure of how strongly a given material opposes sthe flow of electric current [2].
Reverse-Bias Saturation Current Current which flows from donor to acceptor in a pn junction when there is no voltage applied across the junction [4].

Semiconductor Material Coefficient Semiconductor material coefficient constant [5].

Temperature The temperature of an object or space [5].
Thermal Voltage The built-in voltage of a semiconductor at room temperature (T=300K) [4].
Total Drift Current Density The sum of the hole and electron current within a specified volume due to the pull of an electric field [5].

Valence Electrons Electrons in the outermost shell of an atom. May be passed on to another atom and form a covalent bond, and is therefore also deemed a *free electron* [5].

Index

References

[1] Wikipedia Contributors. Boltzmann constant, 2015.

[2] Wikipedia Contributors. Electrical resistivity and conductivity, 2016.

[3] Donald A. Neamen. *Basic Bipolar Junction Transistor*, chapter 5.1, pages 286–300. McGraw Hill, 4th ed. edition, 2010.

[4] Donald A. Neamen. *The pn Junction*, chapter 1.2, pages 23–33. McGraw Hill, 4th ed. edition, 2010.

[5] Donald A. Neamen. *Semiconductor Materials and Properties*, chapter 1.1, pages 9–22. McGraw Hill, 4th ed. edition, 2010.