ELEC 302 Summary

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Diodes

Ideal Diodes

Definition: The ideal diode has two regimes:

- Reverse Bias Regime ($v \leq 0$):
  - Zero current flow.
  - Diode behaves like an open circuit.
- Forward Biased Regime ($v > 0$):
  - Zero voltage drop across diode.
  - Diode behaves like a short circuit.

Analysis in DC Circuits:

1. Figure out whether the diode is being forward biased or reverse biased.
2. Replace the diode with either an open or short circuit and proceed as normal.

Peak Inverse Voltage: Max reverse bias voltage. You should always select a diode which can handle 1.5 times your PIV.

Conduction Angle: The conduction angle, 2θ is the total phase for which the diode is passing current. You can find this at:

$$2\theta = 2\cos^{-1}\frac{V_S^B}{V_S^A}$$

Where V_S^A is the amplitude of your alternating voltage source and V_S^B is the voltage of the source at which the diode becomes forward biased.

Real Diodes

Operation Modes: Real diodes have three operation modes:

- Forward Bias ($V > 0.7V$)
- Reverse Bias ($V_{ZK} \leq V \leq 0.7V$)
- Breakdown ($V < V_{ZK}$)

Hence, a real diode generally as a voltage drop of $0.7V$ across it. Real Diode Model: We can approximate the $i - v$ characteristics of a real diode by the following expression:

$$i = I_S\left(e^{\frac{v}{nV_T}} - 1\right)$$

Where:

- I_S is the *Reverse Saturation Current*. Typically very small (pA).
- n is the *Emperical Constant*, generally $1 \leq n \leq 2$ depending on the type of the diode and its physical structure. *In this course, assume* $n = 1$.

- V_T is the *Thermal Voltage*, defined as:

$$V_T = \frac{kT}{q}$$

  Where:

  - $k = 1.38 \cdot 10^{-23}$J/K (Boltzmann Constant)
  - T: Absolute temperature (K)
  - $q = 1.602 \cdot 10^{-19}$ (Electronic Charge)

  At 20°C, $V_T \approx 25$mV.

More notes on the diode model:

- When $v \ll 0$, reduces to $i \approx -I_S$.

Breakdown and Zener Diodes: Breakdown occurs when $V < -V_{ZK}$. Generally, $V_{ZK} \approx 30$V.

- *Zener Diodes* are diodes designed specifically to operate in breakdown regimes.
- This is useful for providing constant voltage in breakdown.

Tempearture Dependance: Just assume $T = 300$K in this course.

DC Circuit Analysis – Iterative Method: First, know your equations:

$$V_{DD} = f(I, V) \tag{1}$$
$$I = I_S(e^{V/V_T} - 1) \tag{2}$$

Assume for a "x-mA diode", assume:

$$I_S = x \cdot 10^{-3} e^{-0.7/V_T}$$

And thus (1) becomes:

$$I = x \cdot 10^{-3} e^{(V-0.7)/V_T}$$

For the first iteration, assume $V = 0.7V$.

Iterative Steps:

1. Using your guess for V, calculate I from (1).
2. Substitute I into (2) to get a new value for V.
3. Substitute V back into (1) to get a value for I.

Continue iterating until:

$$\frac{(I_n - I_{n-1})}{I_n} \leq 1\%$$

Simpler Models:

- Ideal
- Constant Voltage Drop
- Piecewise-Linear

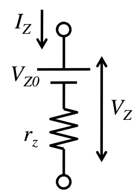
Power Supplies

Stages of a Power Supply: A power supply consists of three stages:

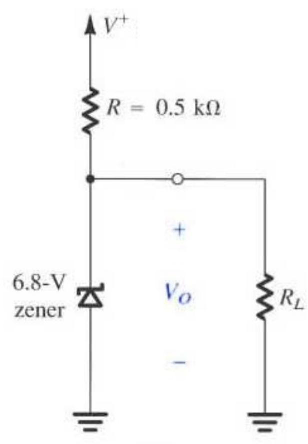
1. Rectifier
2. Filter
3. Regulator

Zener Diode Model: Since a Zener diode past breakdown is nearly linear, we can model it as:

$$V_Z = V_{Z0} + r_Z I_Z$$



Zener Voltage Regulator:



This has the following expressions:

$$V_0 = V_{Z0}\frac{\frac{R}{R_L}}{r_Z + \frac{R}{R_L}} + V^+\frac{\frac{r_Z}{R_L}}{R + \frac{r_Z}{R_L}}$$

Figures of Merit:

- Line Regulation:

$$\left.\frac{\Delta V_0}{\Delta V^+}\right|_{I_L=\text{constant}} = \frac{r_Z}{R + r_Z}$$

- Load Regulation:

$$\left.\frac{\Delta V_0}{\Delta I_L}\right|_{V^+=\text{constant}} = -\frac{r_Z}{R}$$

Rectifiers

Types:

- Half-Wave
- Full-Wave
  - Center-Tapped
    - Requires only 2 diodes
    - Less voltage loss
  - FULL BRIDGE
    - Requires fewer turns in the secondary winding of the transformer for the same output voltage.
    - Lower PIV.

Filters

Purpose is to smooth out the bumpy rectified signal. Also known as a peak detector.

Ripple Voltage:

$$V_r \approxeq \frac{V_p T}{2R_L C} = \frac{V_p}{2fR_L C}$$

Input Voltage:

$$\begin{aligned} V_p &\approxeq V_o = V_p - \frac{1}{2}V_r \approx V_p \\ &\approxeq V_p\left(\frac{4fR_LC - 1}{4fR_LC}\right) \end{aligned}$$

Load Current:

$$I_L \approxeq \frac{R_L}{V_L} = \frac{V_p - \frac{1}{2}V_r}{R_L} \approx \frac{V_p}{R_L}$$

Conduction Angle:

$$\omega\Delta t = \sqrt{\frac{2V_r}{V_p}}$$

Max Diode Current:

$$i_D^{\max} \approxeq I_L\left(1 + 2\pi\sqrt{\frac{2V_p}{V_r}}\right)$$

Average Diode Current:

$$i_D^{\text{ave}} \approxeq I_L\left(1 + \pi\sqrt{\frac{2V_p}{V_r}}\right)$$

Peak Inverse Voltage, 2-Diode Config:

$$PIV = 2V_p$$

Peak Inverse Voltage, 4-Diode Config:

$$PIV = V_p$$

Substitutions for Real Case, Constant Voltage Drop:

- Half-Wave

$$V_p \to V_p - V_D$$
$$PIV = 2V_p - V_D = (V_p - V_D) - (-V_p)$$

- Full-Wave

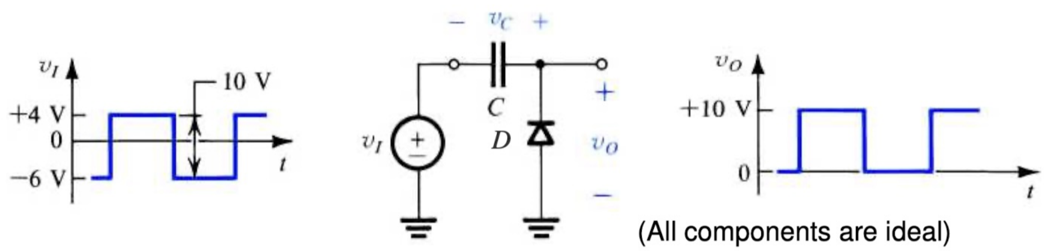
$$V_p \to V_p - V_D \qquad \text{(2-diode config)}$$
$$V_p \to V_p - 2V_D \qquad \text{(4-diode config)}$$

$$PIV \approxeq 2V_p - V_D \qquad \text{(2-diode config)}$$
$$PIV \approxeq V_p - V_D \qquad \text{(4-diode config)}$$

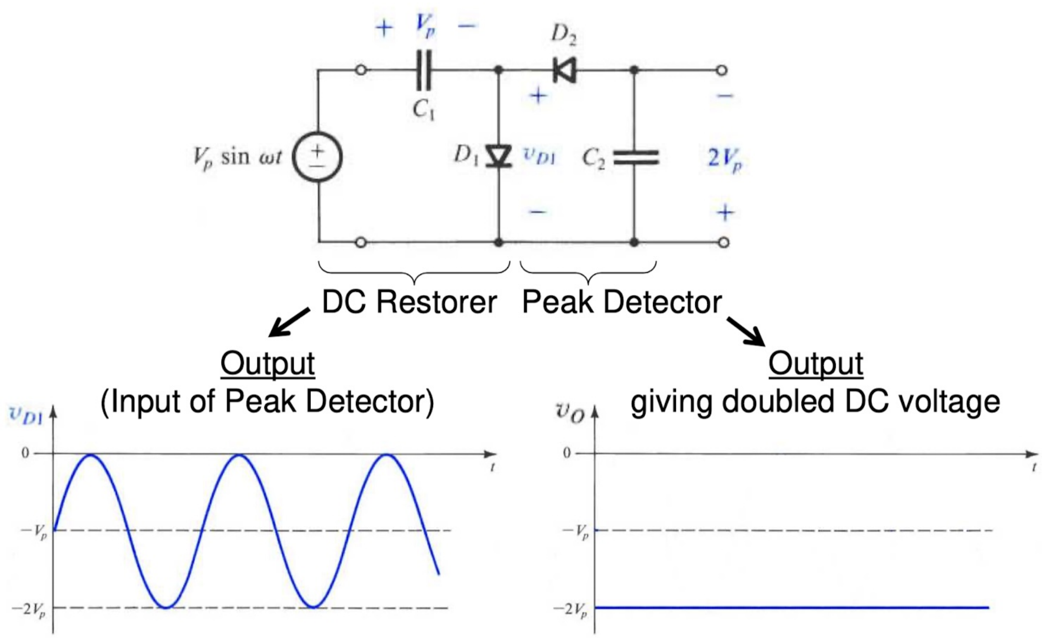
Other Similar Circuits

DC Restorer:

- Reversing the polarity of D makes the signal negative.



Voltage Doubler: Combination of DC restorer and peak detector:



Limiting/Clipping Circuits

Generally, a clipping circuit should have the following form:

$$v_o = \begin{cases} L_+ & v_i > \frac{L_+}{K} \\ Kv_i & \frac{L_-}{K} \leq v_i \leq \frac{L_+}{K} \\ L_- & v_i < \frac{L_-}{K} \end{cases}$$

Semiconductors

- Two types of charge carriers:
  - Electron (-ve)
  - Hole (+ve)
- Conductivity can be influenced by introducing impurities:
  - Adding electrons: n-type
  - Adding holes: p-type

This then leads to an equilibrium intrinsic carrier concentration:

Intrinsic Carrier Concentration for Pure Silicon

$$n_i^2 = BT^3 \exp\left(-\frac{E_g}{kT}\right)$$

where:
$E_g = 1.12$eV: band gap
T: temperature
$k = 8.62 \times 10^{-5}$eV/K: Boltzmann constant
$B = 5.4 \times 10^{31}$

Conductivity

Conducitivty relates the current density to the electric field:

Conductivity

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

Where:
p: Concentration of free holes
n: Concentration of free electrons
μ_p: Mobility of holes (RT: 480cm^2/V·s)
μ_n: Mobility of electrons (RT: 1350cm^2/iV·s)
$q = 1.6 \times 10^{-19}$C: Electron charge

Hence, conductivity depends on the concentration of free charge carriers and the mobility μ of the carriers in the material.

Dopants: It is possible to vary σ by "doping" the silicon with impurities, called *dopants.* Doped semiconductors are said to be "extrinsic".

Donors: Some atoms, depending on their structure, can "donate" one free electron per atom.

- These donors enhance σ by increasing $n \to n > p$.

- This Si is called “n-type”.

Acceptors: Some atoms, depending on their structure, can “accept” one free electron per atom.

- Enhance σ by increasing $p \to p > n$.
- This Si is called “p-type”.

Law of Mass Action: After doping, n and p are no longer, equal, but the following relationship must hold:

Law of Mass Action

$$n_i^2 = pn$$

Note: n_i for silicon is generally $1.45 \times 10^{10}\text{cm}^{-3}$.

as well as:

Charge Neutrality Relationship

$$N_D + p = N_a + n$$

N_D: Concentration of donor atoms
N_A: Concentration of acceptor atoms

It is also important to discuss majority and minority carriers, where some approximations can be made:

- P-type:

$$(N_D > N_A \wedge N_D \gg n_i) \implies n \approx N_D \implies p \approx \frac{n_i^2}{N_D}$$

- N-type:

$$(N_A > N_D \wedge N_A \gg n_i) \implies P \approx N_A \implies n \approx \frac{n_i^2}{N_A}$$

Drift Current

The current produced by an electric field is called a “drift current”. In semiconductors, it consists of one due to holes and one due to electrons.

Drift Current Density

$$J = \sigma E$$

Drift Current

$$J_{\text{drift}} = qp\mu_p E + qn\mu_n E$$

Diffusion Current

Like everything with concentration imbalances, diffusion will occur. Hence, we can quantify the current resulting from this diffusion current:

Diffusion Current for Holes

$$J_{p,\text{diffn}} = -qD_p \frac{dp}{dx}$$

Where $D_p = 34\text{cm}^2/\text{s}$ at 300K

Diffusion Current for Electrons

$$J_{n,\text{diffn}} = -qD_n \frac{dn}{dx}$$

Where $D_p = 12\text{cm}^2/\text{s}$ at 300K

And hence, it is also to be noted that both drift and diffusion current can exist in a semiconductor.

PN Junctions

Let's say we have a bar of silicon with a doped p-type side adjacent to a doped n-type side. Hence, holes and electrons will combine to ionize and reach an equilibrium state. This only happens in a specific area called the depletion region. Hence, this region holds charges, giving rise to a built-in voltage. This built-in voltage limits further diffusion. Hence, drift current and diffusion current balance, resulting in an equilibrium condition.

It is to be noted that the p side and n side should have equal charge. That is:

$$qN_A x_p A = qN_D x_n A.$$

Op-Amps

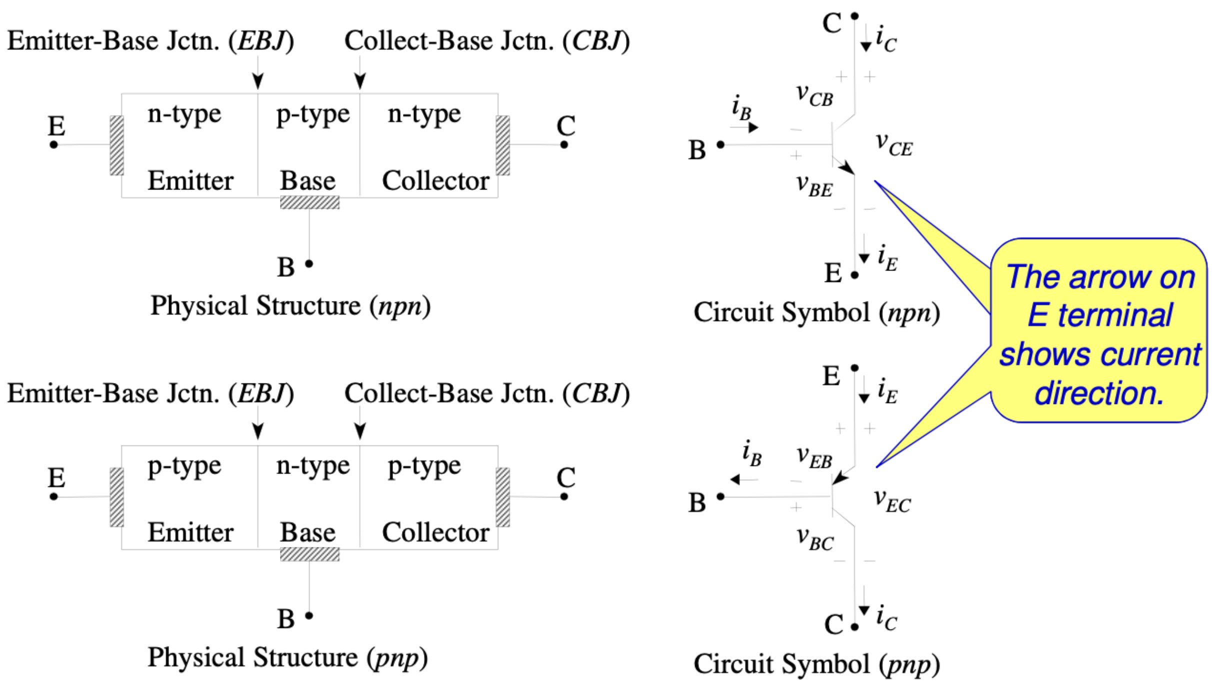
We will skip the basics.

Differential Amplifiers

- Amplifies the difference between signals and rejects the commonality.

BJTs

BJTs have two varieties, NPN and PNP. Their arrangements are as follows:



Operation Modes:

Mode	Emitter-Base Junction	Collector-Base Junction
Cut-Off (Switching)	Reverse	Reverse
Active (Amplification)	Forward	Reverse
Saturation (Switching)	Forward	Forward