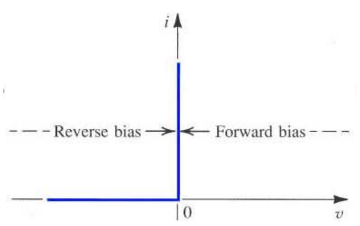
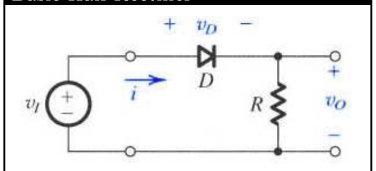
Ideal Diode Definition



DC Diode Analysis

Either know voltages and treat as open/short circuits, or guess and check.

Basic Half Rectifier



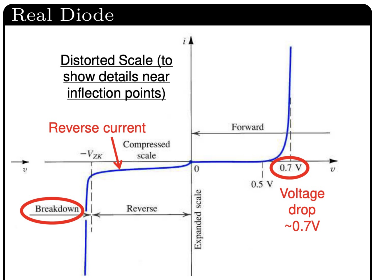
Ideal Diode Rectifier Conduction Angle

$$2\theta = 2\cos^{-1}\left(\frac{V_S^{\text{fwd}}}{V_S^{\text{amp}}}\right)$$

Seleting Peak Inverse Voltage

$$\text{PIV}_{\text{des}} = 1.5\text{PIV}$$

Real Diode



Real Diode Model

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

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

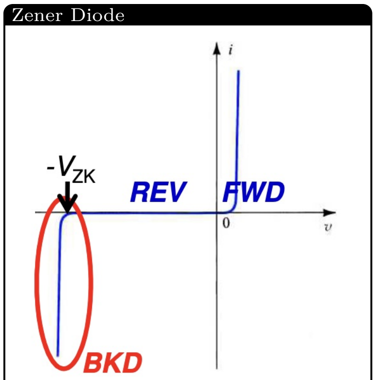
$n = 1$, $k = 1.38 \cdot 10^{-23}$J/K, $q = 1.602 \cdot 10^{-19}$C, $T = 300$K.

Simplified Diode Model

For $i \gg I_S$ or $v > 10nV_T$:

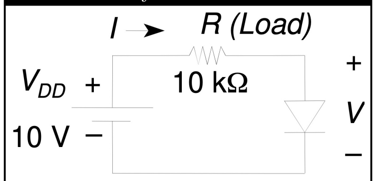
$$i \approx I_S e^{v/nV_T}$$

Zener Diode



Knee current is the min current at breakdown.

Iterative Analysis for Diodes



$$V_{\text{DD}} = IR + V \tag{1}$$

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

$$I_S \approx xe^{-0.7/V_T} \tag{3}$$

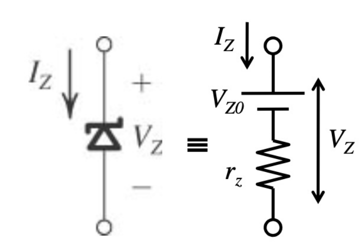
a. Using your guess for V, calculate I from (1).
b. Substitute I into (2) to get a new value for V.
c. Substitute V back into (1) to get a value for I.

Continue iterating until:

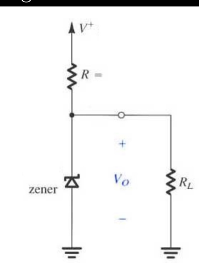
$$\frac{(I_n - I_{n-1})}{I_n} \leq 1\%$$

Zener Approximation in BKD

$V_Z = V_{Z0} + r_Z I_Z$



Zener Regulators



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

$$\Delta V_0 = \Delta V^+ \frac{\frac{R_L}{r_z}}{R + \frac{R_L}{r_z}}$$

$$V_0 = V_{Z0} + \frac{V^+ - V_0}{R} r_z$$

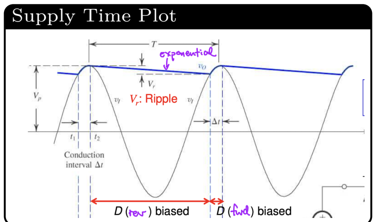
Line Regulation

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

Load Regulation

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

Supply Time Plot



Ripple Voltage – Full Rectifier

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

Ripple Voltage – Half Rectifier

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

Input Voltage

$$V_p \approx V_o = V_p - \frac{1}{2}V_r \approx V_p$$

$$\approx V_p\left(\frac{4fR_LC - 1}{4fR_LC}\right)$$

Load Current

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

Half Rectifier Average Output Voltage

$$V_o^{\text{avg}} = V_p - V_{\text{D}} - \frac{1}{2}V_r$$

Conduction Angle

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

Max Diode Current

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

Average Diode Current

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

Peak Inverse Voltage 2-Diode

$$PIV = 2V_p$$

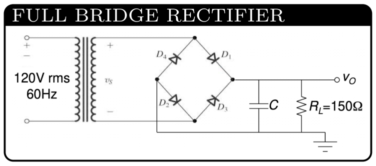
Peak Inverse Voltage 4-Diode

$$PIV = V_p$$

Average Voltage

You just have to integrate and divide by the total period (2π).

FULL BRIDGE RECTIFIER



Peak Voltage for Bridge Supply

$$V_{\max} = V_p - 2V_d$$

Conduction Time Fraction

$$\tau = \frac{\pi - 2\theta}{2\pi}$$

Substitutions for Real Case Constant Voltage Drop

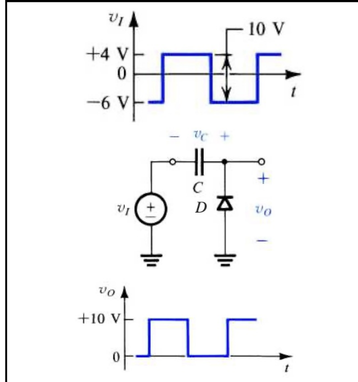
Half-Wave

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

Full-Wave

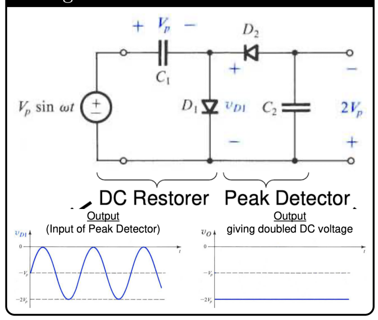
$$V_p \to V_p - V_D \quad \text{(2D)}$$
$$V_p \to V_p - 2V_D \quad \text{(4D)}$$
$$PIV \approx 2V_p - V_D \quad \text{(2D)}$$
$$PIV \approx V_p - V_D \quad \text{(4D)}$$

DC Restorer

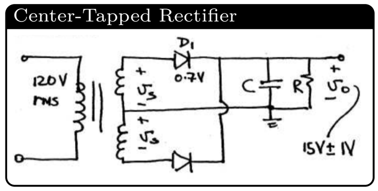


Reversing the polarity of D makes the signal negative.

Voltage Doubler



Center-Tapped Rectifier



Required Output Voltage for Supply

$$V_{\text{req}} = V_{o,\,\text{des}} + V_D + \Delta V_{o,\,\text{des}}$$

Required Secondary RMS

$$V_p = \frac{nV_{\text{req}}}{\sqrt{2}}$$

n is the number of equispaced "taps".

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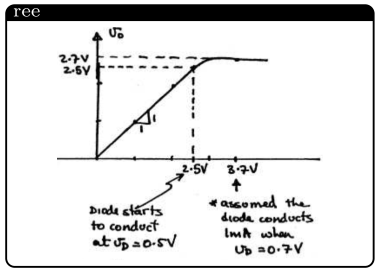
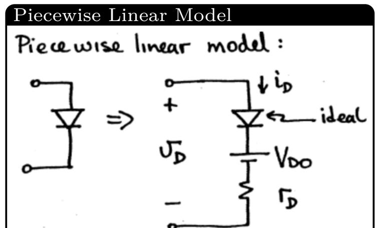


Piecewise Linear Model



Use the exponential model to find two points, and then $y = mx + b$.

Clipping Circuit

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

Intrinsic Carrier Concentration for Pure Silicon

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

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

Fraction of Ionized Atoms

$$\frac{n_i}{N}$$

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: $480\text{cm}^2/\text{V}\cdot\text{s}$)
μ_n: Mobility of electrons
(RT: $1350\text{cm}^2/\text{V}\cdot\text{s}$)
$q = 1.6 \times 10^{-19}\text{C}$: Electron charge

Charge Neutrality Relationship

$$N_D + p = N_a + n$$

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

Resistance

$$R = \frac{\rho L}{A}$$

where $\rho = \frac{1}{\sigma}$ (resistivity).

Law of Mass Action

$$n_i^2 = pn$$

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

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

Total Diffusion Current Density

$$J_{\text{diffn}} = J_{p,\text{diffn}} + J_{n,\text{diffn}}$$

Drift Current Density

$$J = \sigma E$$

Drift Current

$$I = \sigma E \cdot A$$

Mobility-Diffusivity Relationship (Einstein)

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

Where V_T is thermal voltage.

Drift Velocity

$v_{\text{drift},p/n} = \mu_{p/n}E$

Thermal Voltage

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

$k = 1.38 \times 10^{-23}$
$q = 1.6 \times 10^{-19}$

Built-In Voltage

$$V_0 = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

Depletion Region Width

$$W_{\text{dep}} = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_0 - V)}$$

$\varepsilon_s = 1.04 \times 10^{-12}\text{F/cm}$ (Dielectric constant of Si)

Charge in a Junction

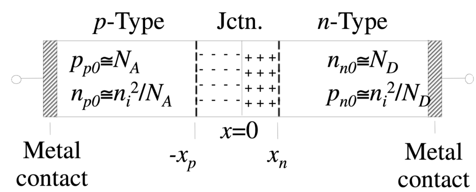
$$q_J = qNV$$

Drift Current pt2

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

Concentration Relationships: Open Circuit

$$p_{p0} = p_{n0}e^{\frac{V_0}{V_T}} \qquad n_{n0} = n_{p0}e^{\frac{V_0}{V_T}}$$



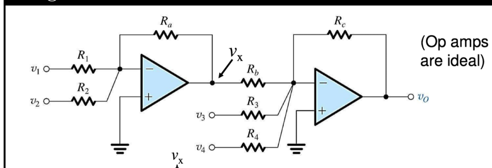
Common Mode Rejection Ratio

$$\text{CMRR} = 20\log\left(\frac{|A_d|}{|A_{cm}|}\right)$$

Op-Amp Golden Rules

1. Infinite Open Loop Gain ($A \to \infty$)
2. No current flow through the inputs
3. Potential difference between input pins is zero

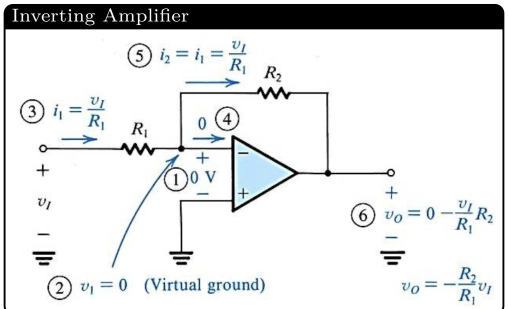
Weighted Summer



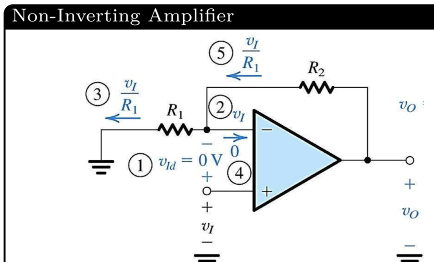
$$v_O = -\frac{R_c}{R_b}\Bigg[\overbrace{-\left(\frac{R_a}{R_1}v_1 + \frac{R_a}{R_2}v_2\right)}^{v_x}\Bigg] - \frac{R_c}{R_3}v_3 - \frac{R_c}{R_4}v_4$$

$$= \left(\frac{R_c}{R_b}\right)\left(\frac{R_a}{R_1}\right)v_1 + \left(\frac{R_c}{R_b}\right)\left(\frac{R_a}{R_2}\right)v_2 - \frac{R_c}{R_3}v_3 - \frac{R_c}{R_4}v_4$$

Inverting Amplifier



Non-Inverting Amplifier



$$G = 1 + \frac{R_2}{R_1}$$

Charge Density at Depletion Region

$$\rho_p = -qN_A \qquad \rho_n = qN_D$$

Charge Balancing

$$qN_A x_p A = qN_D x_n A \quad \text{or} \quad \frac{x_n}{x_p} = \frac{N_A}{N_D}$$

Depletion Zone Boundaries

$$x_p = W_{\text{dep}}\frac{N_D}{N_A + N_D} \qquad x_n = W_{\text{dep}} - x_p$$

Electric Field at Center of Depletion Zone

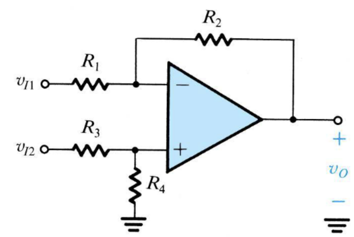
$$E(0) = -\frac{qN_A}{\varepsilon_S}x_p$$

Differential Amplifier – Common Mode Gain

$$A_{cm} = \frac{v_O}{v_{Icm}} = \left(\frac{R_4}{R_4 + R_3}\right)\left(1 - \frac{R_2R_3}{R_1R_4}\right)$$

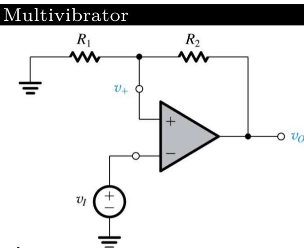
If ideal, can assume an error for $\frac{R_2R_3}{R_1R_4} = \gamma$ to calculate CMRR.

Ideal Differential Amplifier

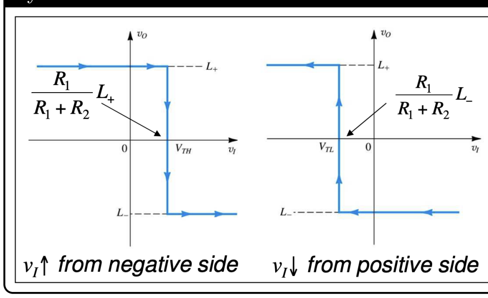


If $\frac{R_4}{R_3} = \frac{R_2}{R_1}$ or $R_3 = R_1 \wedge R_4 = R_2$ then $A_d = \frac{R_2}{R_1}$.

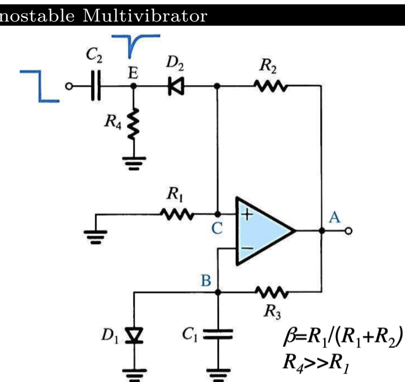
Bistable Multivibrator



Hysterisis in Multivibrator Circuit



Monostable Multivibrator



$$T = C_1R_3\ln\left(\frac{V_{D1} - L_-}{\beta L_- - L_-}\right) \approxeq C_1R_3\ln\left(\frac{1}{1-\beta}\right)$$

Monostable Multivibrator – Min Trigger Voltage

$$v_{t,\min} = \beta L_+ - V_{D2} + V_{D1}$$

Monostable Multivibrator – Recovery Time

$$v_B = L_- - (L_- - V_{D1})e^{-t/(C_1R_3)}$$

Setting $v_B = V_{\text{diode}}$, one can solve for the *recovery time*.

Non-Ideal Inverting Opamp Gain

$$G = \frac{-\frac{R_f}{R_{\text{in}}}}{1 + \frac{\left(1 + \frac{R_f}{R_{\text{in}}}\right)}{A}}$$