Lecture 14

VE 311 Analog Circuits

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2023 Summer

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Recap of Last Lecture

- MOSFET Circuits:
  - Diode Connected Load and its variations
  - Source degeneration

Topic to be covered

- Review for the midterm

Format of the Midterm

- 100 minutes, 4 sections in total.
- 1^{st} section consists of several quick-response questions, each shall take several minutes.
- The following four questions are
  - Diode Circuit
  - MOSFET
  - BJT

Suggestions on the Midterm

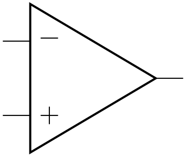
Suggestions on the exam:

- During preparation, you shall get very familiar with the basic concepts. Remember most of the stuff or know precisely where to find it in your cheating sheet.
- The suggested amount of time (which also implies the credit) is shown. If you find a question difficult, you can come back and solve it.
- If you find a question not reasonable, state your reason for receiving credit.
- To receive partial credit, you must write something.
- The exam will be curved, show your best effort.

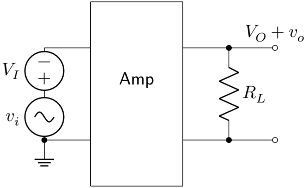
Review of the first-half of our course

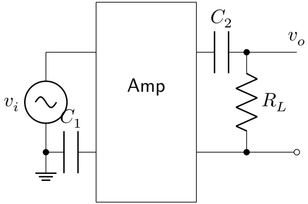
How to make an amplifier.

1. What is amplification?
   concepts: DC+AC / Diff+Comm Gain
2. The big picture of amplifiers
   input/output impedance, non-ideal op-amp
3. Component required:
   Linear and non-linear components
   Diode, BJT, MOSFET
   Till this stage, we' ve only investigated Common Emitter/source.
4. To be discussed: Inside an op-amp.
   (Bias, circuit components, Gain boosting, bandwidth and frequency.)



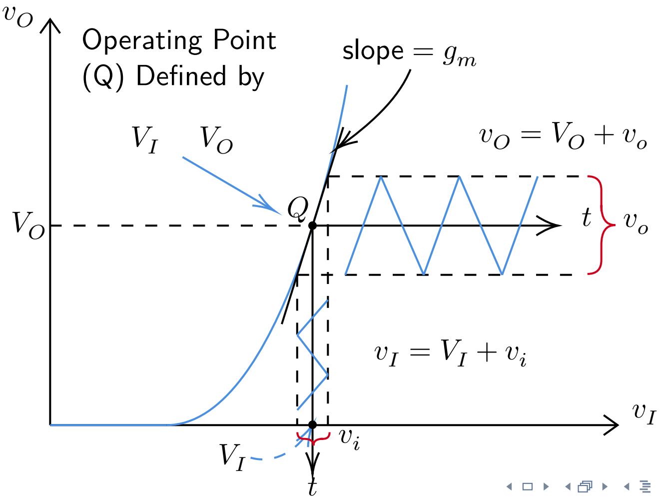
DC + AC Analysis



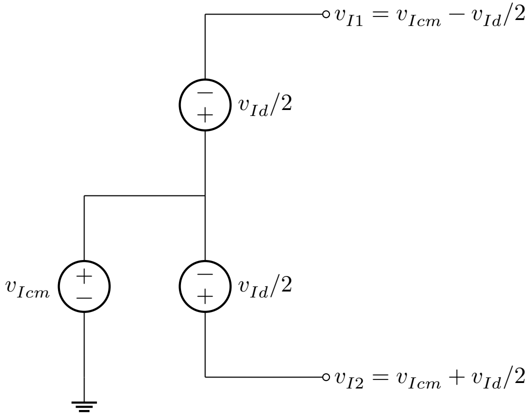


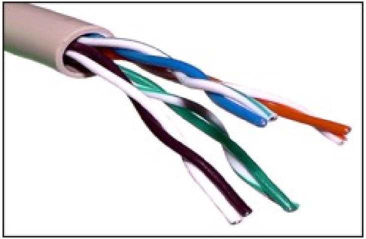
- DC sets the biasing condition.
- AC sets the gain at a specific frequency.

Small-Signal/Large-Signal

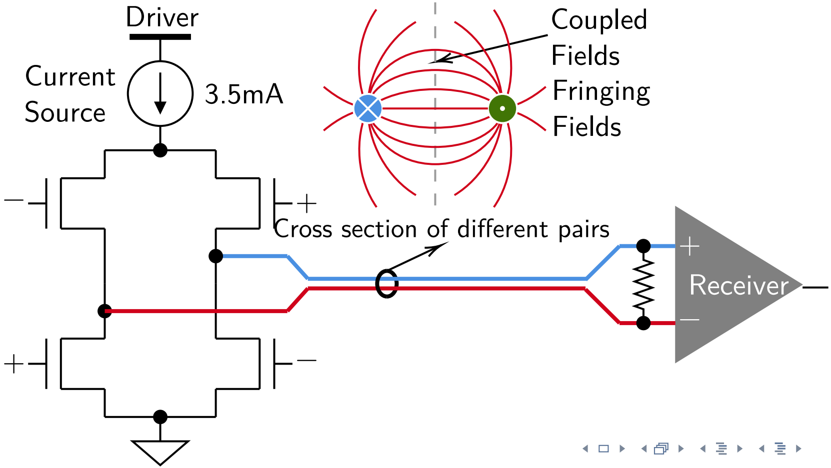


What is Amplification



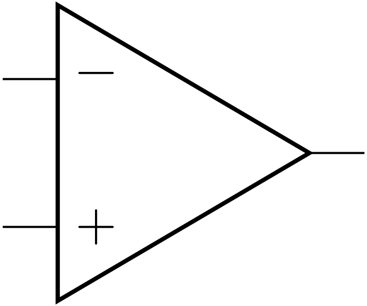


What is Amplification

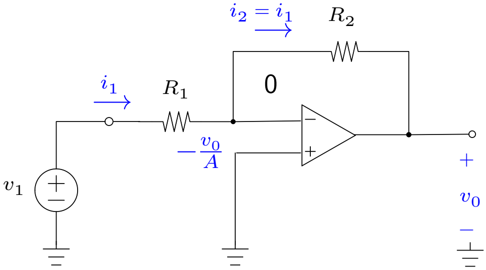


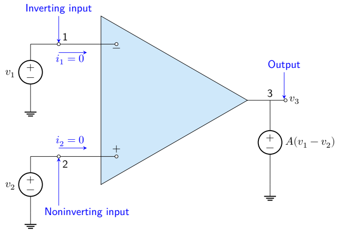
Non-Ideal Opamps

- Gain
- Rout
- Rin
- CMRR
- Offset voltage
- Clipping
- Bandwidth
- Slew rate



Non-Ideal Opamps



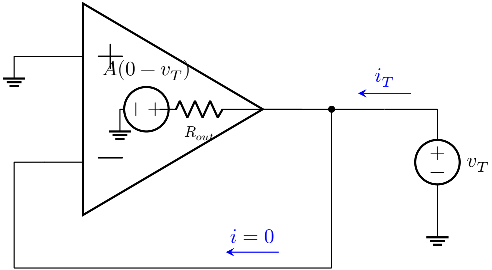


$$v_- - v_+ = -\frac{v_0}{A}$$

$$i_1 = \frac{v_i - (-v_o/A)}{R_1} = \frac{v_i + v_o/A}{R_1}$$

Output Impedance

Make sure you know how to find out output impedance.

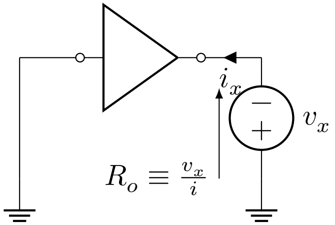


- How to find out the output impedance?
- Apply a test voltage and see what is V_T/i_T

In general, We want large input impedance and small output impedance.

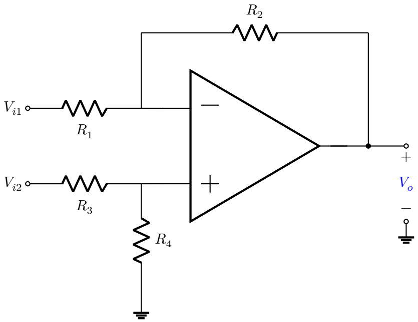
Determining R_o

To find the output resistance, we follow the same procedure as we did for finding the Thevenin equivalent resistance.



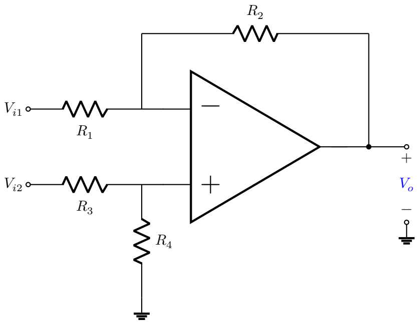
- Short the input terminal, since the input is an independent voltage source
- Apply a test source v_x
- Find i_x
- Find the ratio of $R_o = v_x/i_x$

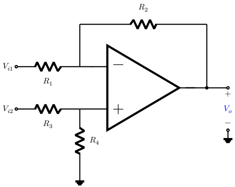
Difference Amplifier

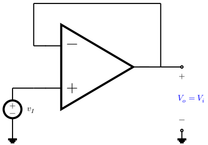


Cons: Input impedance is finite.
Gain is not high.

Difference Amplifier



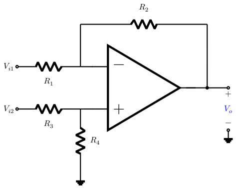


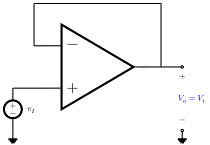


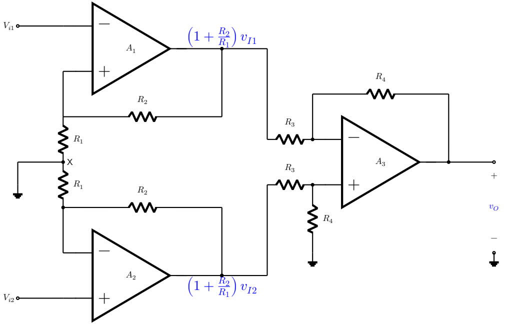
Use a unit gain buffer?

Impedance is fine. Gain is not.

Difference Amplifier





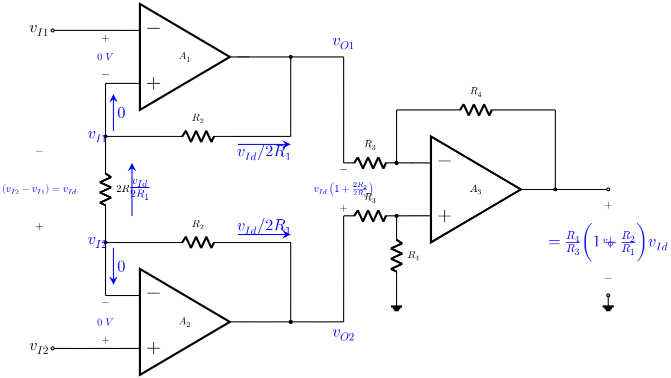


Cons: Possible op-amps saturation

Mismatch between branches

Instrumentation Amplifier

What defines a good amplifier? Common/ differential (CMRR ratio)



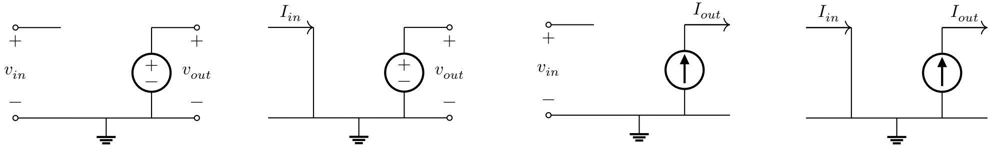
Instrumentation Amplifier

$$A_d \equiv \frac{v_O}{v_{Id}} = \frac{R_4}{R_3}\left(1 + \frac{R_2}{R_1}\right)$$

Common mode first stage gain $= 1$

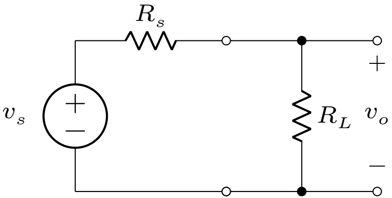
Thevenin and Norton Model of Amps

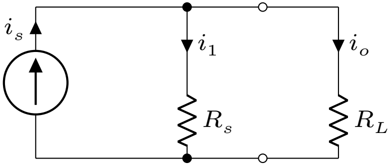
Voltage Amp. Transimpedance Transconductance Current Amp.



Do we want large or small input/output impedance?

Thevenin and Norton Model of Amps





Do we want larger or smaller Rs to get the largest output voltage?

From a current perspective, do we want large or small Rs?

Review of the first-half of our course

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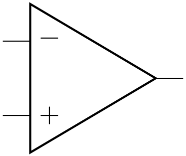
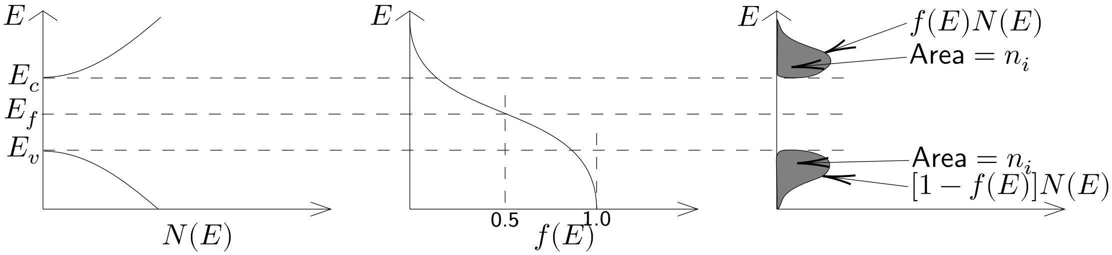
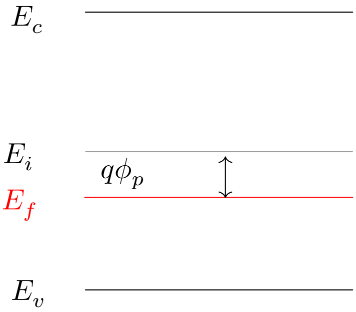


Electrons and Holes



I will not ask you for any calculations on devices this time.

P-Type



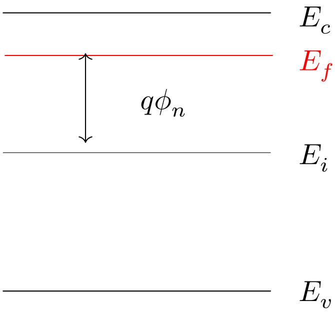
$$np = n_i^2 \tag{1}$$

$$p = N_a = n_i e^{\frac{E_i - E_f}{kT}} = n_i e^{\frac{q\phi_p}{kT}} \tag{2}$$

$$n = \frac{n_i^2}{N_a} = n_i e^{\frac{E_f - E_i}{kT}} = n_i e^{\frac{-q\phi_p}{kT}} \tag{3}$$

- Hu, Chenming. Modern semiconductor devices for integrated circuits.

N-Type

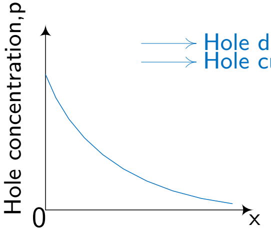


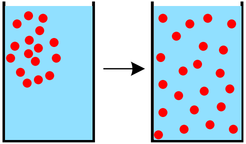
$$np = n_i^2 \tag{4}$$

$$n = N_d = n_i e^{\frac{E_f - E_i}{kT}} = n_i e^{\frac{q\phi_n}{kT}} \tag{5}$$

$$p = \frac{n_i^2}{N_d} = n_i e^{\frac{E_i - E_f}{kT}} = n_i e^{\frac{-q\phi_n}{kT}} \tag{6}$$

Diffusion

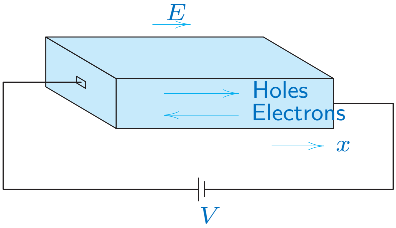




- Magnitude of the current at any point is proportional to the slope of the concentration profile, or the **concentration gradient** , at that point

$$J_{D,n} = qD_n \frac{dn(x)}{dx} \tag{7}$$

Drift Current

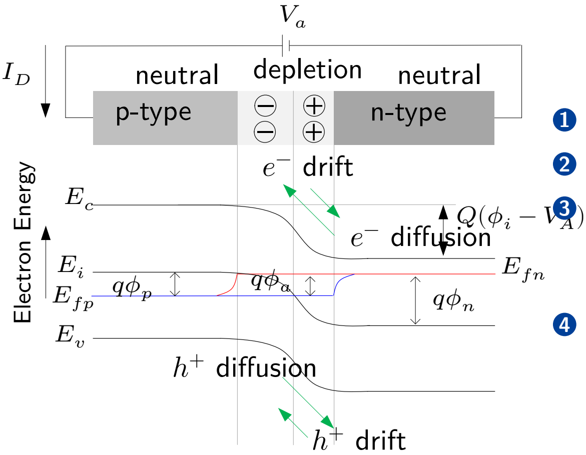


Drift current is independent of the value of the depletion-layer voltage V_0.

- The Junction Built-in Voltage

$$V_0 = V_T \ln(\frac{N_A N_D}{n_i^2}) \tag{8}$$

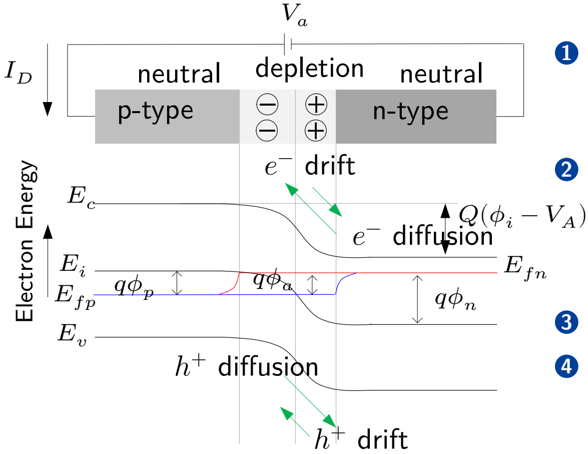
Forward Bias (When $V_a > 0$)



$$I_D = I_S \left(e^{\frac{qV_a}{kT}} - 1 \right) > 0 \tag{9}$$

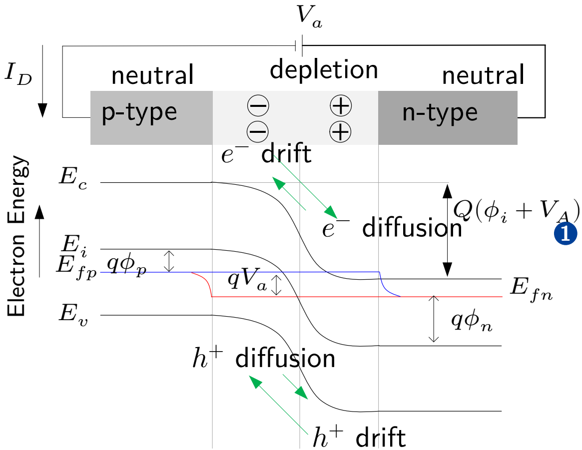
1. $e^{\frac{qV_a}{kT}}$ is the diffusion current.
2. -1 stands for the drift current.
3. The energy barrier formed by the built-in electric field becomes smaller, $q(\phi_i - V_a)$.
4. Neamen, Donald A. Semiconductor Physics and Devices Basic Principles, chapter 8

Forward Bias (When $V_a > 0$)



1. More electrons/holes diffuse to the opposite sides. $\rightarrow$ Diffusion current increases.
2. The drift current is limited by the number of minority carriers on either side of the p-n junction and is unchanged by the increased E-field.
3. There is $(+)$ net current flowing.
4. The depletion width becomes narrower.

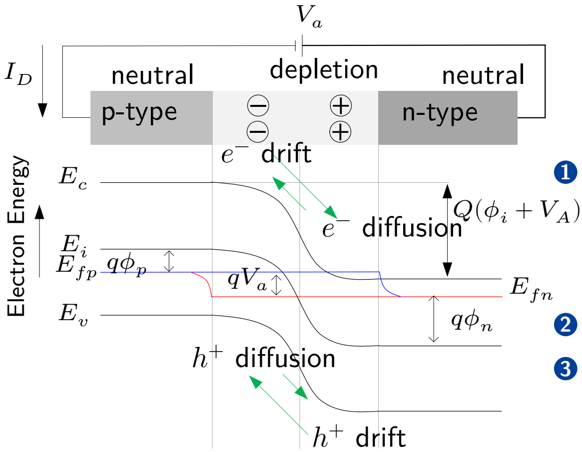
Reverse Bias ($V_a < 0$)



$$I_D = I_S\left(e^{\frac{qV_a}{kT}} - 1\right) < 0 \qquad (10)$$

1. The energy barrier formed by the built-in electric field becomes larger, $q(\phi_i + V_a)$.

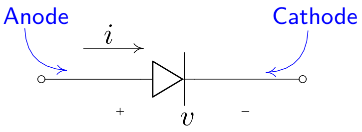
Reverse Bias ($V_a < 0$)

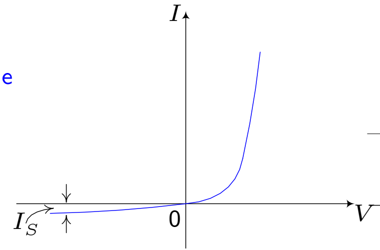


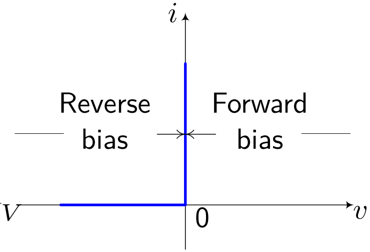
$$I_D = I_S\left(e^{\frac{qV_a}{kT}} - 1\right) < 0 \qquad (11)$$

1. Less electrons/holes diffuse to the opposite sides. $\rightarrow$ Diffusion current decreases, while drift current remains the same.
2. There is (-) net current flowing.
3. The depletion width becomes wider.

Diode model







Remember the following equation

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

Ideal model

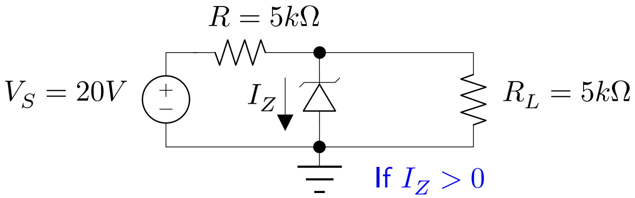
Constant voltage model

I will ask you to solve a diode related circuit!

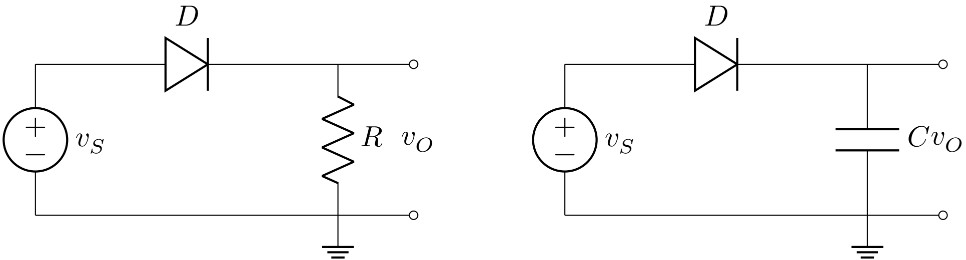
Application of Diodes

- Regulators
- Photodetectors
- Rectifiers

Regulator

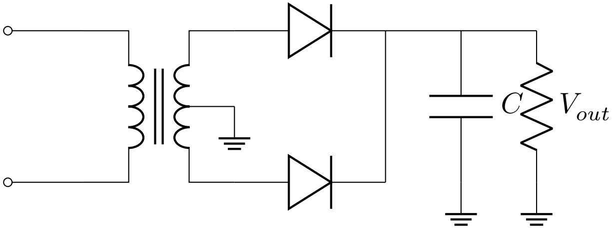


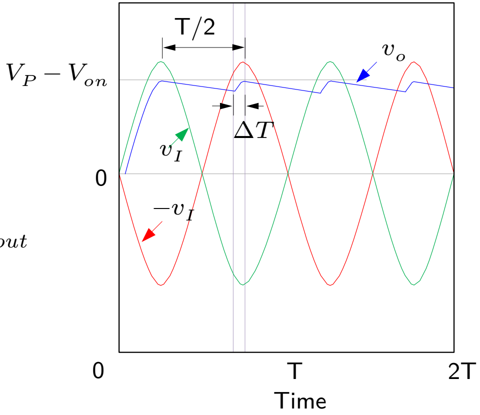
Rectifier



There is not going to be a difficult calculation on a full-wave rectifier. All caps are treated as ideal since we did not cover the frequency domain yet.

Full Wave Rectifier





Full Wave Rectifier

$$V_{dc} = V_s - V_{on} \tag{12}$$

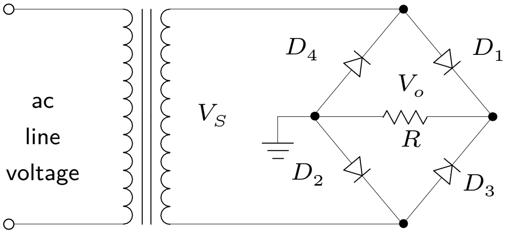
$$I_{dc} = \frac{V_{dc}}{R} \tag{13}$$

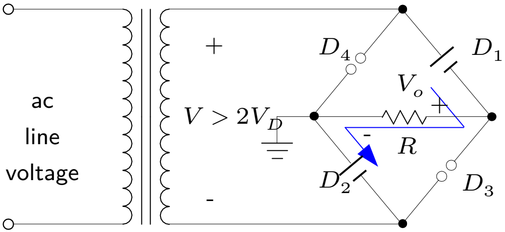
$$V_r = (V_s - V_{on})\left(1 - e^{-\frac{T/2 - \Delta T}{RC}}\right) \tag{14}$$

$$\cong (V_s - V_{on})\left(\frac{T/2 - \Delta T}{RC}\right) \text{ if } \left(\frac{T}{2} - \Delta T\right) \ll RC \tag{15}$$

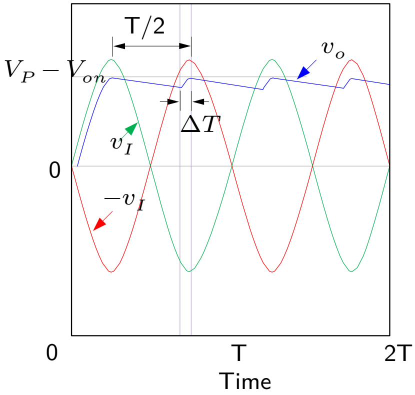
$$\cong (V_s - V_{on})\left(\frac{T}{2RC}\right) \text{ if } \Delta T \ll \frac{T}{2} \tag{16}$$

Diode-Based Full Wave Rectifier ($V > 2V_D$)





Ripple Voltage Derivation

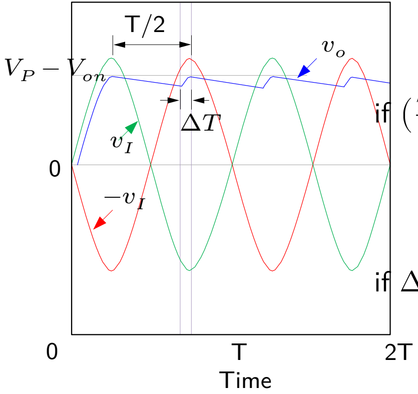


$$V_{dc} = V_s - V_{on} \tag{17}$$

$$I_{dc} = \frac{V_{dc}}{R} \tag{18}$$

$$V_r = (V_s - V_{on})\left(1 - e^{-\frac{T/2-\Delta T}{RC}}\right) \tag{19}$$

Ripple Voltage Derivation



$$V_r = (V_s - V_{on})\left(1 - e^{-\frac{T/2-\Delta T}{RC}}\right) \tag{20}$$

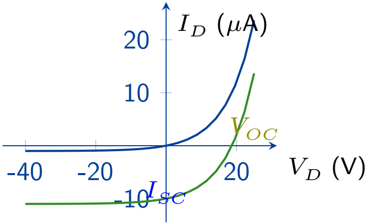
if $\left(\frac{T}{2} - \Delta T\right) \ll RC$

$$\cong (V_s - V_{on})\left(\frac{T/2 - \Delta T}{RC}\right) \tag{21}$$

if $\Delta T \ll \frac{T}{2}$

$$\cong (V_s - V_{on})\left(\frac{T}{2RC}\right) \tag{22}$$

I-V Curve of Solar Cells



IV of Diodes vs. that of solar Cells

Blue:

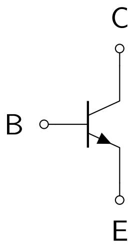
$$I = I_S\left(\mathbf{e}^{\frac{qV}{kT}} - 1\right)$$

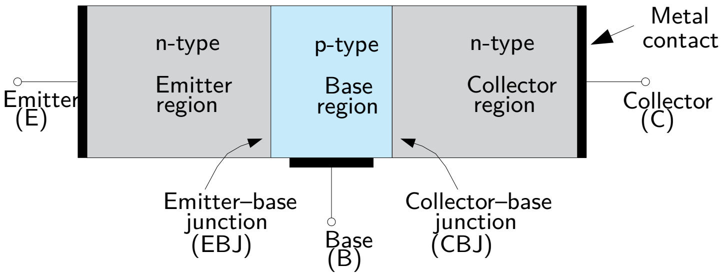
Green:

$$I = I_S\left(\mathbf{e}^{\frac{qV}{kT}} - 1\right) - I_{SC}$$

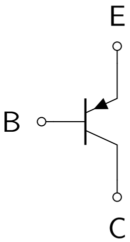
What are fill factor and power conversion efficiency?

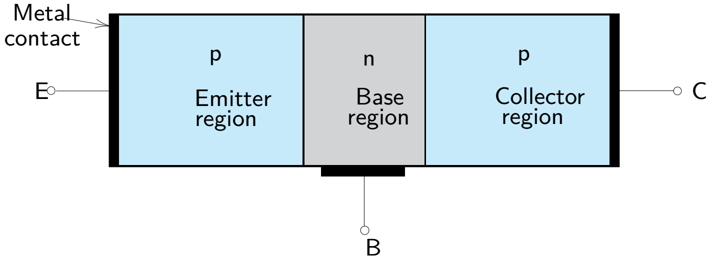
npn BJT Transistors



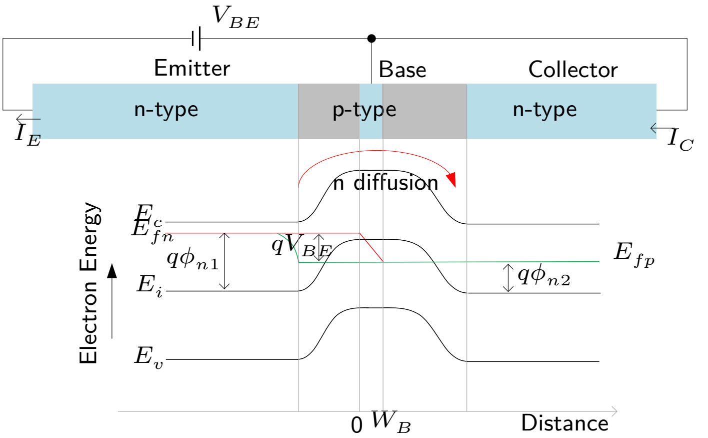


pnp BJT Transistors





$V_{BE} > 0$ and $V_{CB} = 0$ ($N_{d1} \gg N_a$, W_B very short)



$$I_B \cong 0 \tag{23}$$

$$I_C \cong I_E \tag{24}$$

$$I_E = I_C + I_B \tag{25}$$

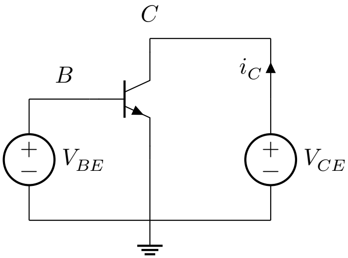
$$\frac{I_C}{I_E} = \alpha \tag{26}$$

$$\frac{I_C}{I_B} = \beta \tag{27}$$

$V_{BE} > 0$ and $V_{CB} = 0$ ($N_{d1} \gg N_a$, W_B very short)

- The n (electron) diffusion is much larger than the p (hole) diffusion at the Base-Emitter junction.
- Nearly all the n (electron) diffusion from the Base-Emitter junction pass through the Base, enter into the depletion region of the Base-Collector junction, and are swept to the Collector side by the built-in electric field.

NPN & PNP BJT Transistors



$$V_{CE} \geq V_{BE} \tag{28}$$

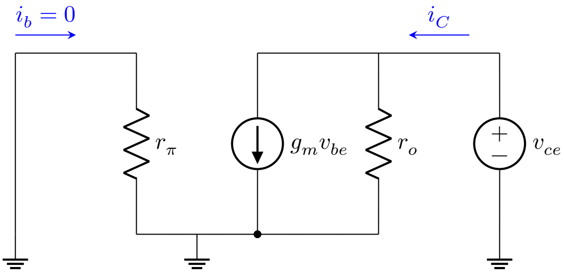
$$I_C = I_S \left(e^{\frac{qV}{BT}} - 1 \right) \tag{29}$$

$$\alpha = \frac{I_C}{I_E} \cong 1 \tag{30}$$

$$\beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha} \tag{31}$$

I_s is a constant in the spice model

Hybrid-π Model



$$I_C = I_S\left(e^{\frac{qV_{BE}}{kT}} - 1\right)\left(1 + \frac{V_{CE}}{V_A}\right) \tag{32}$$

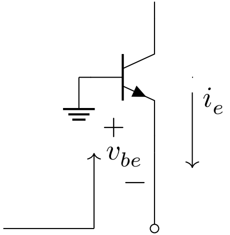
$$r_\pi = \frac{dV_{BE}}{dI_B} = \frac{1}{\frac{dI_C}{\beta dV_{BE}}} \tag{33}$$

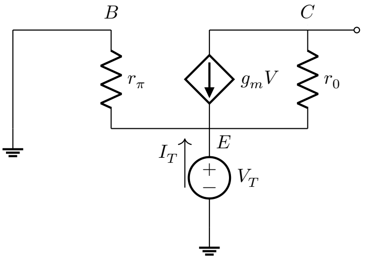
$$= \frac{1}{\frac{g_m}{\beta}} = \frac{\beta}{g_m} \tag{34}$$

$$g_m = \frac{dI_C}{dV_{BE}} \cong \frac{I_C}{kT/q} \tag{35}$$

$$r_o = \frac{1}{\frac{dI_C}{dV_{CE}}} \cong \frac{V_A}{I_C} \tag{36}$$

Impedance Looking into Emitter

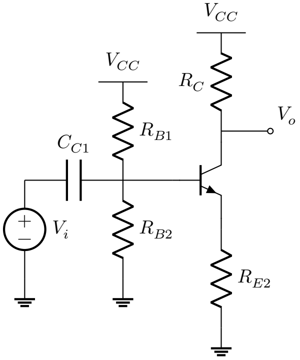




$$r_e = \frac{r_\pi}{(\beta+1)} \tag{37}$$

$$= \frac{1}{(\beta+1)}\frac{\beta}{g_m} = \frac{\alpha}{g_m} \cong \frac{1}{g_m} \tag{38}$$

Common Emitter With Degeneration



$$\frac{v_o}{v_i} \approx \frac{-g_m R_C}{1 + g_m R_E} \tag{39}$$

the gain has reduced by $1 + g_m R_E$

- If $g_m R_E \gg 1$ then the gain is:

$$\frac{v_o}{v_i} \approx \frac{-R_C}{R_E} \tag{40}$$

- This means the gain is independent of the BJT transistor