BJT

Collector current

$$I_C = \frac{A_E q D_n {n_i}^2}{N_E W_B}(exp(\frac{V_{BE}}{V_T}) - 1)$$

$$I_C = I_S exp(\frac{V_{BE}}{V_T})$$

Base emitter voltage

$$V_{BE} = V_T ln\frac{I_C}{I_S}$$

Thermal Voltage

$$V_T = 26mV$$

Transconductance

$$g_m = \frac{I_C}{V_T}$$

Output Impedance (Early Effect)

$$R_O = \frac{V_A}{I_S exp(\frac{V_{BE}}{V_T})} \approx \frac{V_A}{I_C}$$

Internal Small Signal Resistance

$$r_\pi = \frac{\beta}{g_m} = \beta\frac{V_T}{I_C}$$

Terminal Currents

$$I_E = I_C + I_B$$

$$I_C = \beta I_B$$

Input Impedances

Into Base, Emitter AC Grounded

$$r_\pi$$

Into Collector, Emitter AC Grounded

$$\infty$$

Into Collector, Emitter AC Grounded (Early)

$$r_O$$

Into Emitter, Base AC Grounded

$$\frac{1}{g_m}$$

Degenerated CE Stage

$$r_\pi + (\beta + 1)R_E$$

Self Biased Stage

$$r_\pi || \frac{1}{g_m}$$

Degenerated CE Stage (early)

$$R_{out} \approx r_o[1 + g_m(R_E || r_\pi)]$$

Common Base

Core

$$A_V = g_m R_C$$

With Source Resistance

$$A_V = \frac{R_C}{\frac{1}{g_m} + R_S}$$

Output Impedance (Early)

$$R_{out1} = [1 + g_m(R_E || r_\pi)]r_O + (R_E || r_\pi)$$

$$R_{out} = R_C || R_{out1}$$

Output Impedance of CB/CE are same if under same condition

Emitter Follower (Common Collector)

Output Resistance

$$R_{out} = (\frac{R_S}{\beta + 1} + \frac{1}{g_m}) || R_E || r_O$$

CMOS

Drain Current

Saturation No Channel Length Modulation

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})^2$$

Saturation With Channel Length Modulation

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})^2(1 + \lambda V_{DS})$$

Triode Region

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}[2(V_{GS} - V_{TH})V_{DS} + {V_{DS}}^2]$$

Transconductance

$$g_m = \mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})$$

$$g_m = \sqrt{2\mu_n C_{ox}\frac{W}{L} I_D}$$

$$g_m = \frac{2I_D}{V_{GS} - V_{TH}}$$

Gain

$$A_V = g_m R_D$$

Linear Resistance (Deep Triode Region)

$$R_{on} = \frac{1}{\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})}$$

Channel Length Modulation

$$R_o = \frac{1}{\lambda I_{DS}}$$

Regions of Operation

N-Channel Cut Off

$$V_{GS} \leq V_T$$

N-Channel Linear

$$V_{GS} > V_T, V_{DS} \leq V_{GS} - V_T$$

N-Channel Saturation

$$V_{GS} > V_T, V_{DS} > V_{GS} - V_T$$

P-Channel Cut Off

$$V_{SG} \leq |V_T|$$

P-Channel Linear (Triode)

$$V_{SG} > |V_T|, V_{SD} \leq V_{SG} - |V_T|$$

P-Channel Saturation

$$V_{SG} > |V_T|, V_{SD} > V_{SG} - |V_T|$$

Common Source

$$A_V = \frac{-R_D}{\frac{1}{g_m} + R_S}$$

Current Mirrors

Output Impedance Bipolar

$$R_{out} = [1 + g_m(R_E||r_\pi)]R_o + R_E||r_\pi$$

Output Impedance Bipolar Cascode

$$R_{out} = [1 + g_{m1}(r_{O2}||r_{\pi1})]r_{O1} + r_{O2}||r_{\pi1}$$
$$\approx g_{m1}r_{O1}(r_{O2}||r_{\pi1})$$

Maximum limited by beta and ro

$$R_{out,max} = \beta_1 r_{O1}$$

Improved Cascode using PNP current source

$$R_{out} \approx g_{m3}r_{O3}(r_{O4}||r_{\pi3})||g_{m2}r_{O2}(r_{O1}||r_{\pi2})$$

Output Impedance CMOS

$$R_{out} = R_S + (1 + g_m R_S)r_o$$

Output Impedance CMOS Cascode

$$R_{out} = (g_{m1}r_{O2})r_{O1} + r_{O2}$$
$$\approx g_{m1}r_{o1}r_{o2}$$

Improved Cascode using PMOS current source

$$R_{out} \approx g_{m3}r_{O3}r_{O4}||g_{m2}r_{O2}r_{O1}$$

Short Circuit Transconductance

$$G_m = \frac{i_{out}}{V_{in}}$$
$$A_v = -G_m R_{out}$$

Cascode Amplifier CMOS

$$G_m = g_{m1}$$

Current Mirror

$$I_{copy} = \frac{nI_{REF}}{1 + \frac{1}{\beta}(n+1)}$$

With an extra transistor to reduce error

$$I_{copy} = \frac{nI_{REF}}{1 + \frac{1}{\beta^2}(n+1)}$$

Differential Amplifiers

Bipolar Differential Amplifier

LSA Current

$$I_{C1} = \frac{I_{EE}exp\frac{V_{in1} - V_{in2}}{V_T}}{1 + exp\frac{V_{in} - V_{in2}}{V_T}}$$

$$I_{C2} = \frac{I_{EE}}{1 + exp\frac{V_{in} - V_{in}}{V_T}}$$

Linear Operation Mode

$$|V_{in} - V_{in}| < 4V_T \approx 104mV$$

Small Signal Mode

$$|V_{in} - V_{in}| < 10mV$$

MOS Differential Pair

Maximum Differential Input Voltage

$$|V_{in1} - V_{in}|_{max} = \sqrt{2}(V_{GS} - V_{TH})_{equil}$$

Small Signal Mode

$$|V_{in} - V_{in2}| << \frac{4I_{SS}}{\mu_n C_{ox}\frac{W}{L}}$$

Common mode to Differential Mode

$$A_{CM-DM} = \frac{\Delta R_D}{\frac{1}{g_m + 2R_{SS}}} \approx \frac{\Delta R_D}{2R_{SS}}$$

Frequency Response

Miller's Theorem

$$Z_1 = \frac{Z_F}{1 - A_V}$$
$$Z_2 = \frac{Z_F}{1 - \frac{1}{A_V}}$$
$$C_{in} = (1 - A_v)C_F$$
$$C_{out} = (1 - \frac{1}{A_v})C_F$$

Transit Frequency

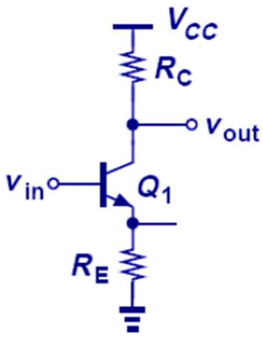
BJT

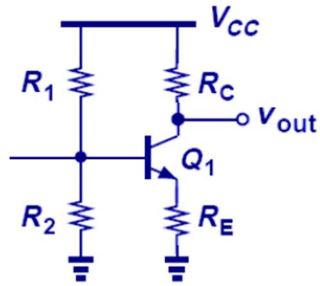
$$2\pi f_T = \frac{g_m}{C_{GS}}$$

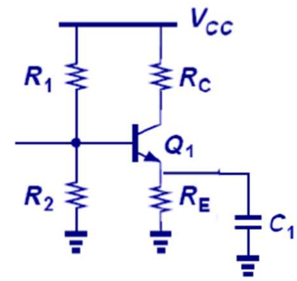
CMOS

$$2\pi f_T = \frac{g_m}{C_\pi}$$

RECAP: Degenerated CE Stage with Resistive divider







Without series resistance

$$A_v = -\frac{R_C}{\frac{1}{g_m} + R_E}.$$

$$R_{in} = r_\pi + (\beta + 1)R_E$$

$$R_{out} = R_C$$

With resistive divider

$$A_v = -\frac{R_C}{\frac{1}{g_m} + R_E}.$$

$$R_{in} = [r_\pi + (\beta + 1)R_E] \,||\, R_1 \,||\, R_2,$$

$$R_{out} = R_C$$

With resistive divider & C_1

$$A_v = -g_m R_C$$

$$R_{in} = r_\pi \,||\, R_1 \,||\, R_2$$

$$R_{out} = R_C.$$

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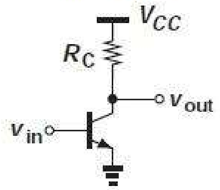
AMPLIFIER TYPE	COMMON BASE	COMMON EMITTER	COMMON EMITTER (Emitter Resistor)	COMMON COLLECTOR (Emitter Follower)
INPUT/OUTPUT PHASE RELATIONSHIP	0°	180°	180°	0°
VOLTAGE GAIN	HIGH $\frac{\alpha R_C}{R_s + r_e}$	MEDIUM $\frac{\beta (R_C \,\|\|\, r_o)}{R_s + r_\pi}$	MEDIUM $\frac{\beta R_C}{R_s + (\beta+1)(r_e + R_E)}$	LOW $\frac{(\beta+1)(R_L \,\|\|\, r_o)}{R_s + (\beta+1)[r_e + (R_L \,\|\|\, r_o)]}$
CURRENT GAIN	LOW α	MEDIUM $\beta \frac{r_o}{R_C + r_o}$	MEDIUM β	HIGH $(\beta+1)\frac{r_o}{r_o + R_L}$
POWER GAIN	LOW	HIGH	HIGH	MEDIUM
INPUT RESISTANCE	LOW r_e	MEDIUM $r_\pi = (\beta+1) r_e$	MEDIUM $(\beta+1)(r_e + R_E)$	HIGH $(\beta+1)[r_e + (r_o \,\|\|\, R_L)]$
OUTPUT RESISTANCE	HIGH R_C	MEDIUM $R_C \,\|\|\, r_o$	MEDIUM R_C	LOW $r_o \,\|\|\, \left[r_e + \frac{R_s}{(\beta+1)}\right]$

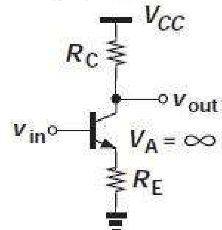
Voltage Gain Equations

Common Emitter



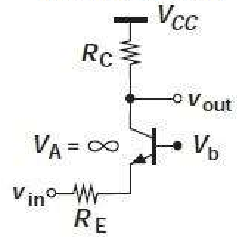
$$A_v = -g_m(R_C \| r_O)$$

Common Emitter (Degenerated)



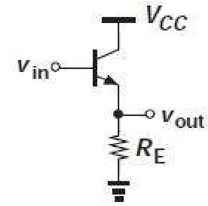
$$A_v = -\frac{R_C}{\frac{1}{g_m} + R_E}$$

Common Base (Source Resistance)



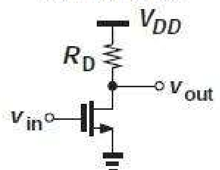
$$A_v = \frac{R_C}{\frac{1}{g_m} + R_E}$$

Emitter Follower



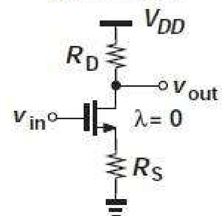
$$A_v = \frac{R_E \| r_O}{\frac{1}{g_m} + R_E \| r_O}$$

Common Source



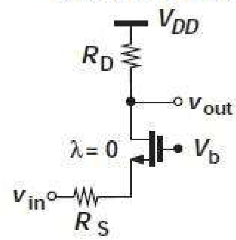
$$A_v = -g_m(R_D \| r_O)$$

Common Source (Degenerated)



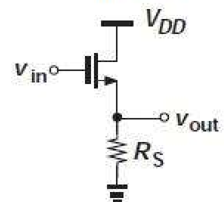
$$A_v = -\frac{R_D}{\frac{1}{g_m} + R_S}$$

Common Gate (Source Resistance)



$$A_v = \frac{R_D}{\frac{1}{g_m} + R_S}$$

Common Drain



$$A_v = \frac{R_S \| r_O}{\frac{1}{g_m} + R_S \| r_O}$$