Voltage Gain: $A_v = \dfrac{v_o}{v_i}$ Current Gain: $A_i = \dfrac{i_o}{i_i}$ Power Gain: $G = A_v A_i$

Decibel: $A_{v\text{dB}} = 20\log(|A_v|)$ $A_{i\text{dB}} = 20\log(|A_i|)$ $G_{\text{dB}} = 10\log(|G|)$

Energy Conservation: $P_i + P_s = P_o + P_d \longrightarrow \begin{cases} P_i & = \text{Power from Source} \\ P_s & = \text{Power from DC Supplies} \\ P_o & = \text{Output Power at Load} \\ P_d & = \text{Power Dissipated in the Op-Amp} \end{cases}$

Frequency Dependence:

Capacitor: $Z_c = \dfrac{1}{j\omega C}$ Inductor: $Z_L = j\omega L$

Summing Point Constraint:

- Only applies when the op-amp is in negative feedback
- Assuming ideal op-amp, $V_+ - V_- = 0$ (no current at terminals)
- For non-ideal op-amps: $V_o = A(s)(V_+ - V_-)$

$$f_{3\text{dB}} = \frac{\omega_{3\text{dB}}}{2\pi} \qquad \text{GBW} = |A_v||f_{3\text{dB}}$$

Diodes:

- In Forward Bias (FB): Permit current flow, have a positive voltage drop
- In Reverse Bias (RB): No current flow (open circuit)
  - Constant Voltage Drop (CVD): Diodes have same forward-bias drop ($\approx .7$[V])
- Assume bias mode for each diode in diagram, calculate values to verify assumptions
- CVD + resistance model: $r_d = \frac{nV_T}{I_{DQ}}$ (approximated around quiescent point, Q)

$I_D = I_s e^{\frac{V_D}{nV_T}} + 1$ Room Temp: $V_T \approx 26$[mV] $1 < n < 2$ $10^{-6} < I_s 10^{-18}$[A]

Temp Dependence: constant $I \rightarrow V$ drop decreases ≈ 2[mV] per 1[°C] temperature increase

Zener Diodes: $V_D = -V_{zo} - I_z r_z$ in breakdown, with $I_z = -I_D > 0$

Transformers: step voltages according to turns ratio $(N_p : N_s)$ or $(n : 1)$, with $V_s = V_p/n$

BJT Regions

EBJ	CBJ	Mode
FB	RB	Active
FB	FB	Saturation
RB	RB	Cutoff

Note: When designing an amplifier confirm that the BJT is in the active region

BJT Formulas

$$I_E = I_C + I_B$$

$$I_E = I_{ES}\left[e^{\frac{V_{BE}}{V_T}} - 1\right]$$

Active Region Only:

$$I_C = \alpha I_E$$
$$I_B = (1-\alpha) I_E$$
$$I_C = \beta I_B$$
$$I_S = \alpha I_{ES}$$

For BJTs: $\beta = \dfrac{\alpha}{1-\alpha}$ $\alpha = \dfrac{\beta}{1+\beta}$ Typically: $\alpha \approx 1$, and $I_C \approx I_E$ but $I_C < I_E$

BJT Models

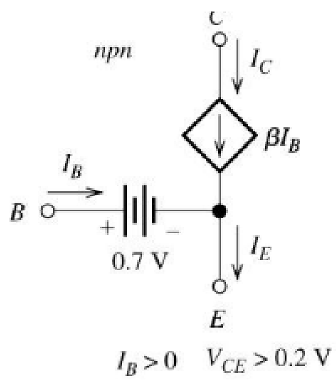

Figure 1: *npn* in Active Mode

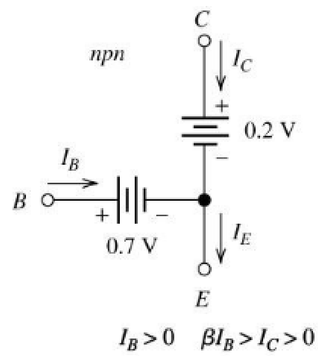

Figure 2: *npn* in Saturation

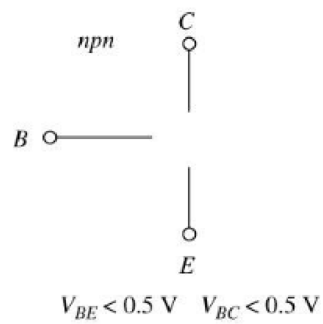

Figure 3: *npn* in Cutoff

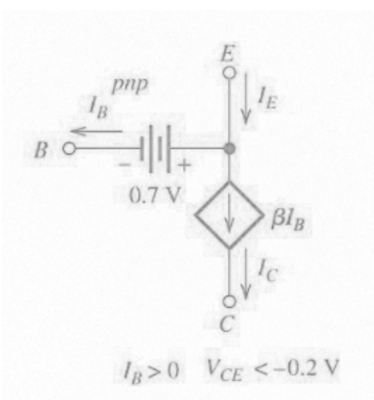

Figure 4: *pnp* in Active Mode

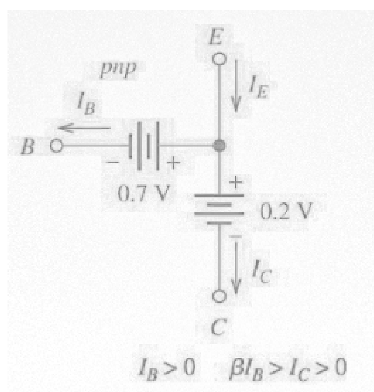

Figure 5: *pnp* in Saturation

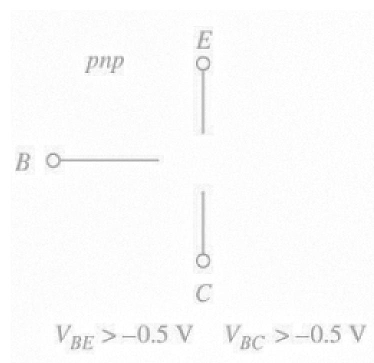

Figure 6: *pnp* in Cutoff

Small-Signal Equivalent ($|V_{BE}| < 10$[mV] $<< V_T$)

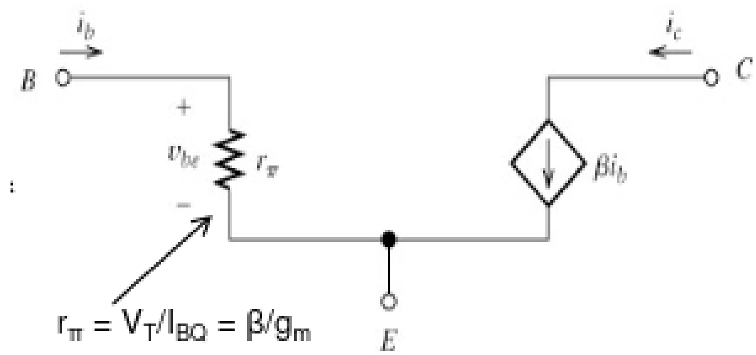

Figure 7: Small Signal Equivalent for *npn*/*pnp*'s

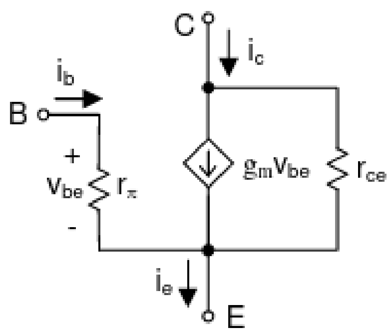

Figure 8: Hybrid π Model

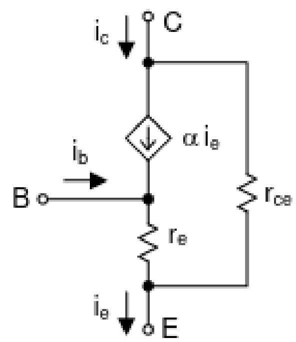

Figure 9: T-Model

Small-Signal Formulas

$$g_m = \frac{I_{CQ}}{V_T} = \frac{\alpha}{r_e}$$

$$r_\pi = \frac{V_T}{I_{BQ}} = \frac{\beta}{g_m}$$

- MOSFET Regions
  1. Cutoff ($V_{GS} < V_{to}$)
  2. Triode ($V_{GS} > V_{to}, V_{DS} < V_{GS} - V_{to}$)
  3. Saturation ($V_{GS} > V_{to}, V_{DS} > V_{GS} - V_{to}$)
- Drain Currents
  - Cutoff — $I_D = 0$

$$r_{ce} = \frac{V_{early}}{I_{CQ}}$$

$$r_e = \frac{V_T}{I_{EQ}} = \frac{V_T}{(1+\beta)I_{BQ}} = \frac{r_\pi}{1+\beta}$$

When r_{ce} not specified or $r_{ce} >> R_L$ and r_e, then it can be removed

  - Triode — $\left(\frac{W}{L}\right)\left(\frac{KP}{2}\right)[2(V_{GS} - V_{to})V_{DS} - V_{DS}^2](1+\lambda V_{DS})$
  - Saturation — $\left(\frac{W}{L}\right)\left(\frac{KP}{2}\right)(V_{GS} - V_{to})^2(1+\lambda V_{DS})$
  - TS Boundary — $\left(\frac{W}{L}\right)\left(\frac{KP}{2}\right)V_{DS}^2$

- For PMOS case, $V_{SG} = -V_{GS}$ and $V_{SD} = -V_{DS}$, $V_{to} < 0 \rightarrow |V_{to}|$ in formulas, and reversed reference direction

MOSFET Small Signal Model

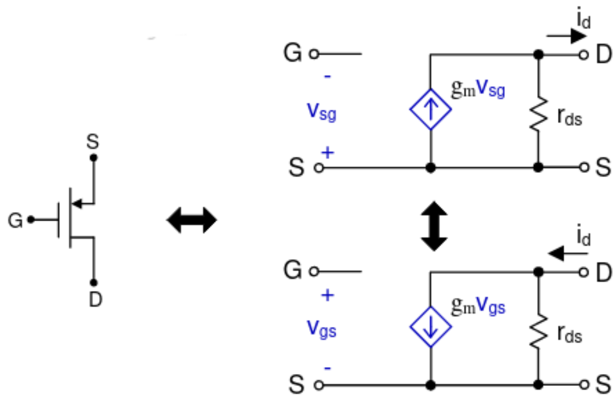

Figure 10: P (top) and N (bot) in Sat

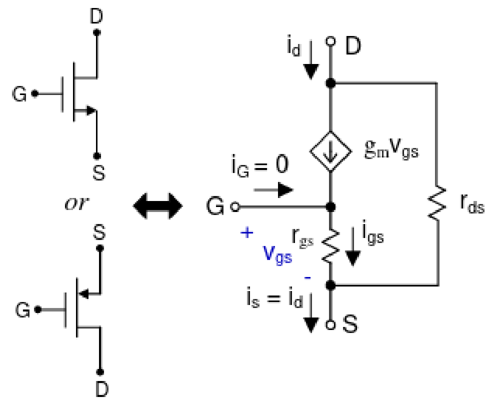

Figure 11: T-Model for MOSFETs

$\boxed{\text{MOSFET Saturation Formulas:}}$

$$r_{gs} = \frac{1}{g_m} \qquad\qquad r_{ds} = \frac{1}{\lambda I_D} = \frac{|V_A|}{I_D}$$

$$g_m = \frac{2I_D}{V_{GSQ} - V_{to}} = KP\frac{W}{L}(V_{GSQ} - V_{to}) = \sqrt{2KP\frac{W}{L}I_D}$$

$\boxed{\text{MOSFET Triode Formulas:}}$

Simply becomes a resistor with value r_{on}.

$$r_{on} = \left[KP\frac{W}{L}(V_{GSQ} - V_{to})\right]^{-1}$$