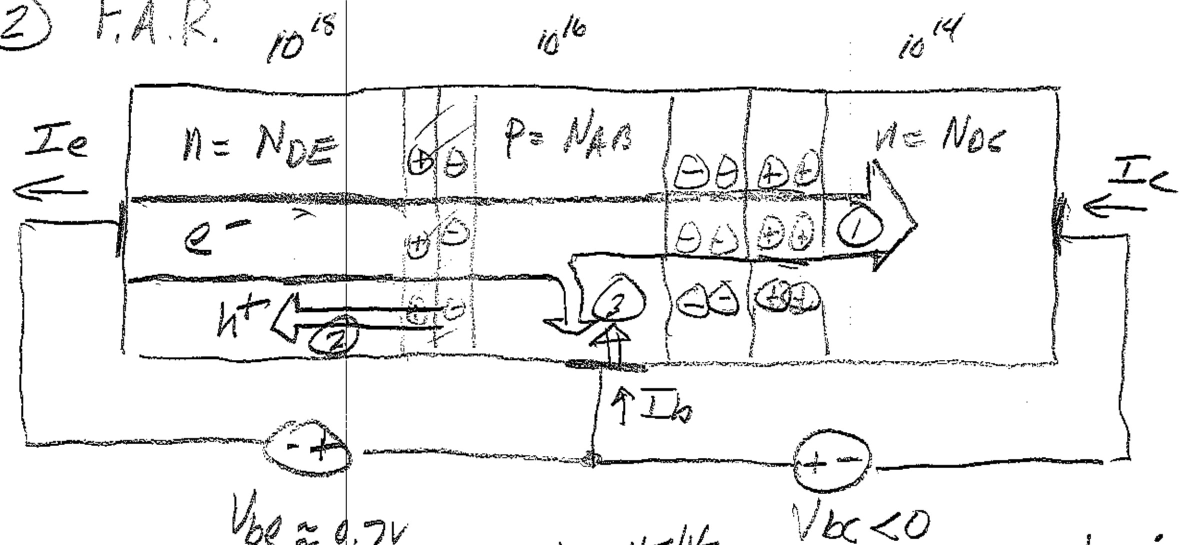
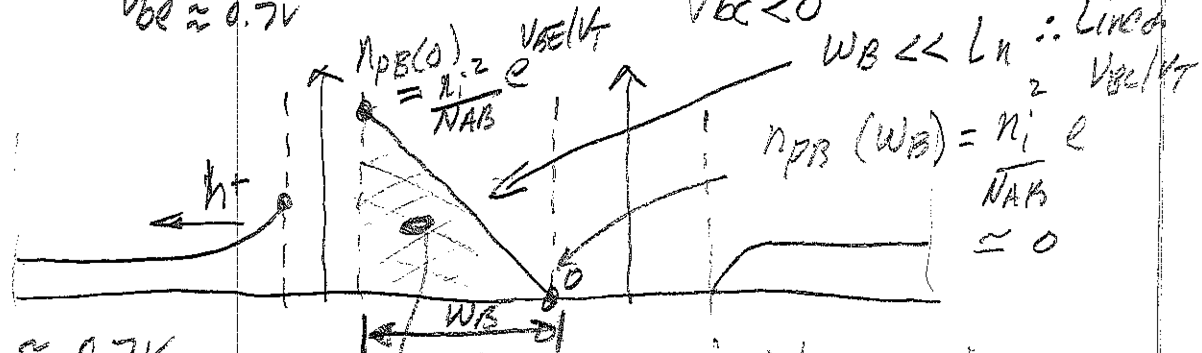
(2) F.A.R.





F.A.R.
$V_{BE} \simeq 0.7V$
V_{BC} negative

$Q_E \equiv$ minority carrier Base charge

(1) electrons injected from emitter - to base that reach collector

(2) holes injected from base to emitter

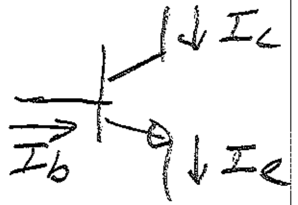
(3) Recombination of holes & electrons in base.

β_F = forward current gain in F.A.R.

$$\beta_F = \frac{(1)}{(2) + (3)}$$

$\simeq 100$ (typical value)

F.A.R Large-signal models



$$I_c = \beta_F I_b$$

$$I_e = I_c + I_b \quad \text{(KCL)}$$

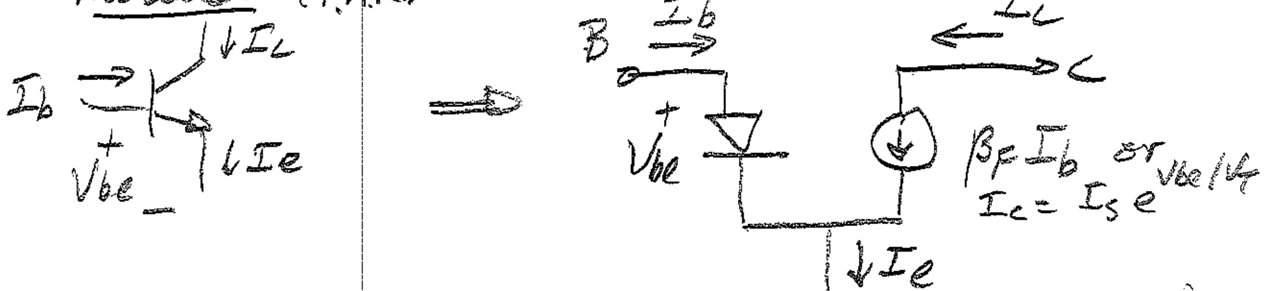
$$= (\beta_F + 1) I_b$$

$$= \left(I_c + \frac{I_c}{\beta_F}\right) = \left(\frac{\beta_F+1}{\beta_F}\right) I_c$$

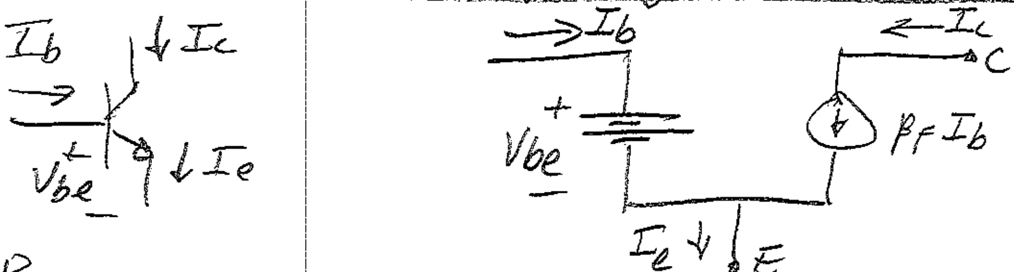
$$I_C = \frac{\beta_F}{\beta_F+1} I_E = \underbrace{\alpha_F}_{<1} I_E$$

- β_F typically 100

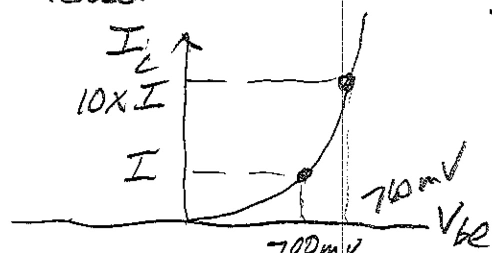
Models: (F.A.R.)



Often, we can simplify (e.g. for DC bias calcs):

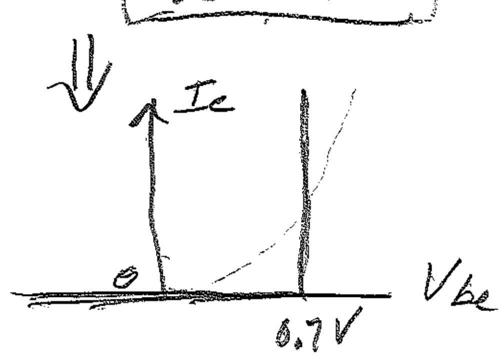


Reason:



Pick a value: $\boxed{V_{be} = 0.7V}$

$\Downarrow$



only 60 mV per decade of current

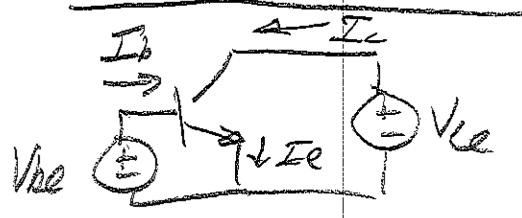
∴ 700 mV is good guess
SPICE for actual value

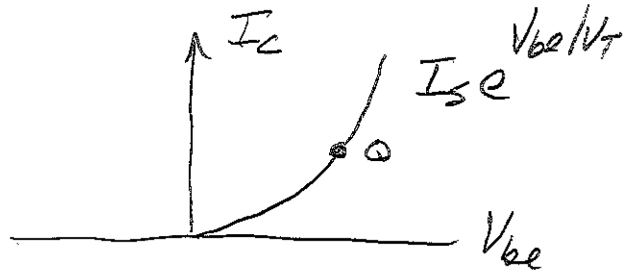
When determining dc operating point:

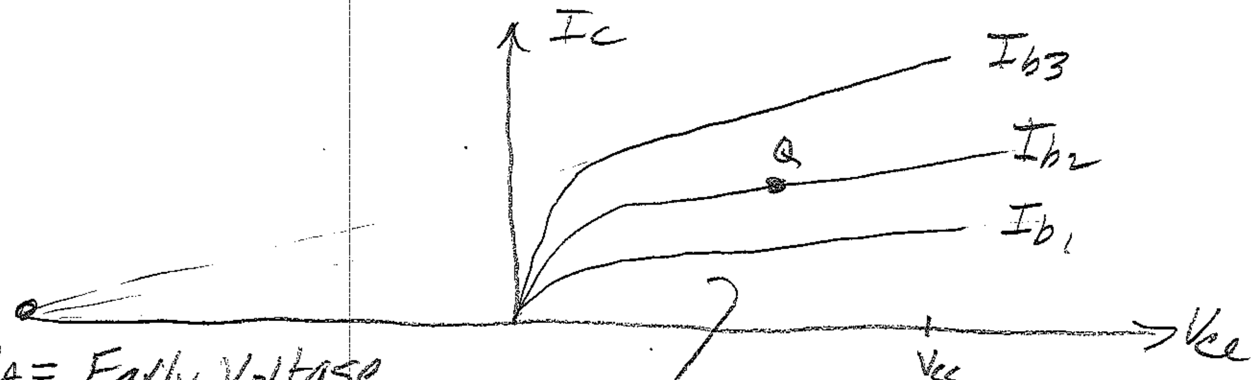
1. Assume F.A.R. (Check for cutoff – enough V_{be}?)
2. Determine V_{ce}
3. If $V_{ce} > 0.2V$ ($V_{ce}(sat)$) $\rightarrow$ OK it's F.A.R.

Otherwise, Assume Saturation and start over.

IV Characteristics



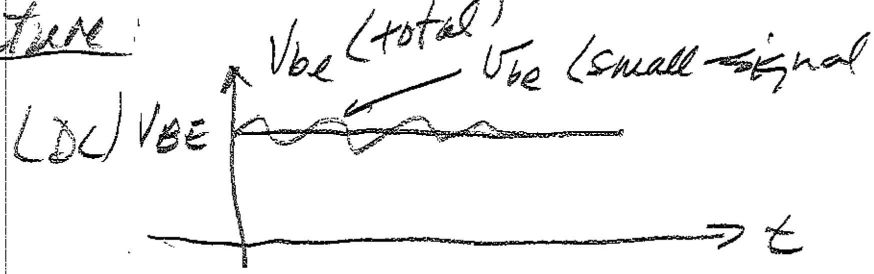




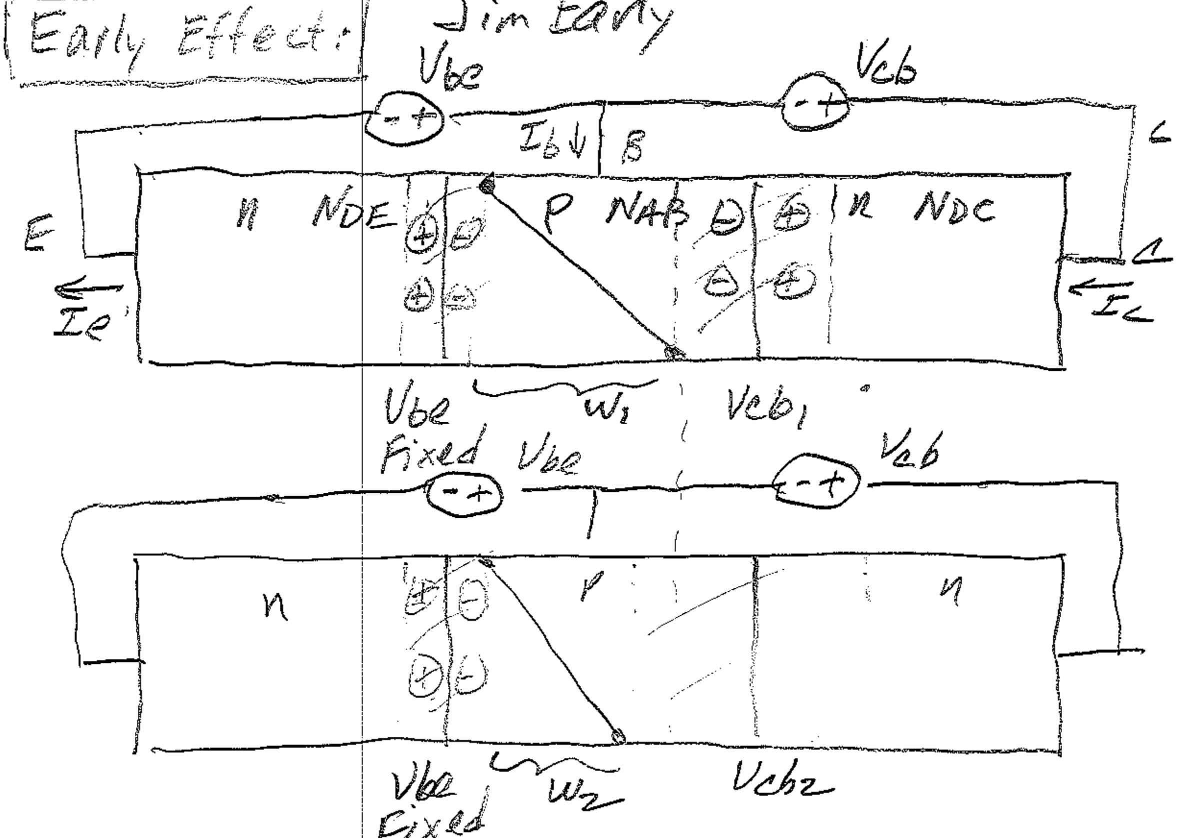
$V_A \equiv$ Early Voltage (e.g., 60 volts)

$$\boxed{I_c = I_s e^{V_{be}/V_T}\left(1 + \frac{V_{ce}}{V_A}\right)}$$

Nomenclature:



Early Effect: Jim Early

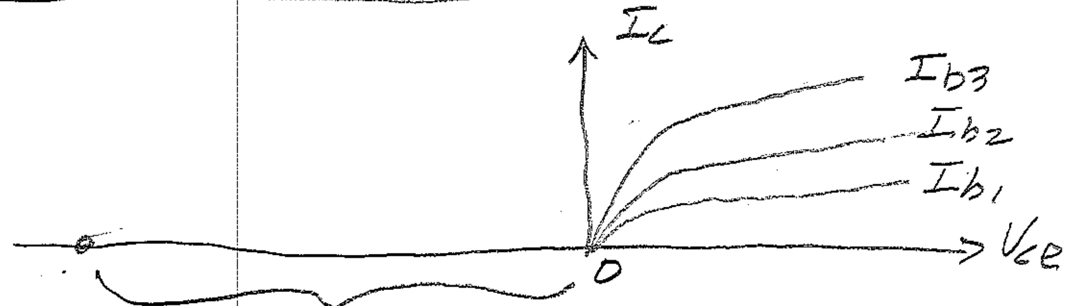


- I_c is due to diffusion current across base:

$$I_c = qAD_n \frac{\partial n_{pB}(x)}{\partial x} \propto \frac{\frac{n_i^2}{NAB} e^{V_{be}/V_T}}{W}$$

For $V_{cb2} > V_{cb1}$, $W_2 < W_1$ $\therefore$ $I_{c2} > I_{c1}$

Model of Early effect:



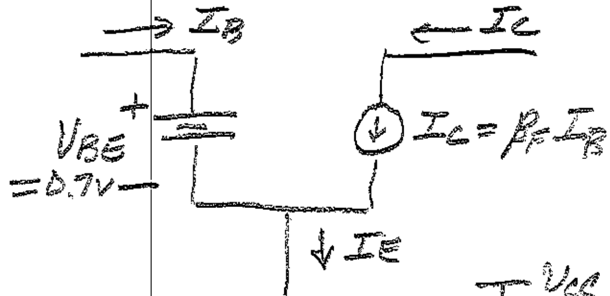
V_A = Early voltage (typically, 50-100V)

$$\boxed{\begin{aligned} I_c &= I_s\left(e^{V_{be}/V_T} - 1\right)\left(1 + \frac{V_{ce}}{V_A}\right) \\ &\simeq I_s e^{V_{be}/V_T}\left(1 + \frac{V_{ce}}{V_A}\right) \text{ in F.A.R.} \end{aligned}}$$

Example of DC Bias Calculations:

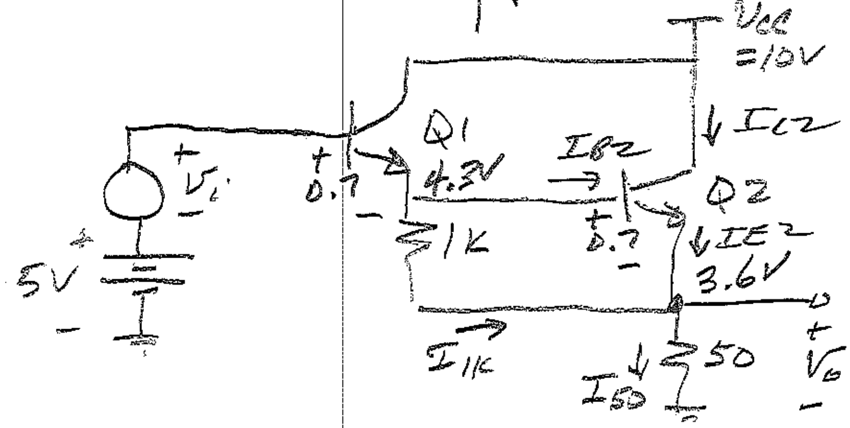
Back to page 10 first -

Models: (F.A.R.)



or $I_C = I_S e^{V_{BE}/V_T}$

(Don't use Early effect for DC calcs)



- Assume F.A.R.: $V_{BE} = 0.7V$; $\underbrace{V_{CE} > 0.2V}_{\text{Avoid saturation}}$
  $\beta_F = 100$
- Look for V_{BE}'s to find voltages
- Calculate currents: $I_{50} = \frac{3.6V}{50} = 720mA$

$I_{1K} = \frac{4.3-3.6}{1k} = 0.7mA$

KCL: $I_{E2} + I_{1K} = I_{50} \Rightarrow I_{E2} = (720 - 0.7)mA$
$= 719.3mA$

$I_{C2} = \frac{\beta_F}{\beta_F+1} I_{E2} = \frac{100}{101}(719.3mA) = 712.2mA$

$I_{B2} = \frac{I_{C2}}{\beta_F} = \frac{712.2mA}{100} = 7.12mA$

KCL: $I_{E1} = I_{1K} + I_{B2} = 0.7mA + 7.12mA = 7.82mA$

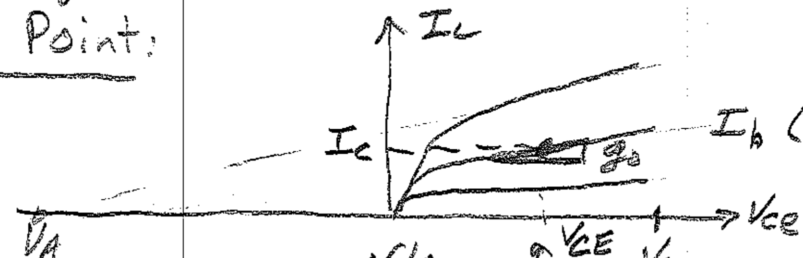
$I_{C1} = \frac{\beta_F}{\beta_F+1} I_{E1} = \frac{100}{101}(7.82mA) = 7.74mA$

$I_{B1} = I_{C1}/\beta_F = 7.74mA/100 = 77.4\mu A$

Check: $\underset{>0.2V}{V_{CE1} = V_{CC} - 4.3V = 5.7V}$; $\underset{>0.2V}{V_{CE2} = 10 - 3.6 = 6.4V}$
OK.

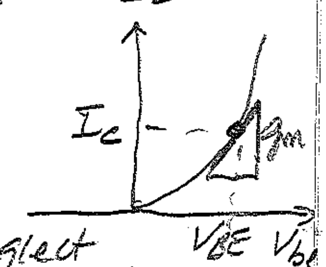
Low-Frequency small-signal model:

Bias Point:



often $\approx V_{cc}/2$ (Assumed)

Small-signal parameters:



$$g_m = \frac{\partial I_c}{\partial V_{be}}\bigg|_{\substack{Q\\ \text{point}}} = \frac{\partial}{\partial V_{be}}\left[I_S e^{V_{be}/V_T}\right]_Q \quad \text{(neglect Early effect)}$$

$$= \frac{I_S}{V_T} e^{V_{BE}/V_T} = \boxed{\frac{I_c}{V_T}} \longleftarrow g_m$$

$$g_\pi = \frac{\partial I_b}{\partial V_{be}}\bigg|_Q = \frac{1}{\beta_F}\frac{\partial I_c}{\partial V_{be}}\bigg|_Q = \boxed{\frac{g_m}{\beta_F}} \longleftarrow g_\pi$$

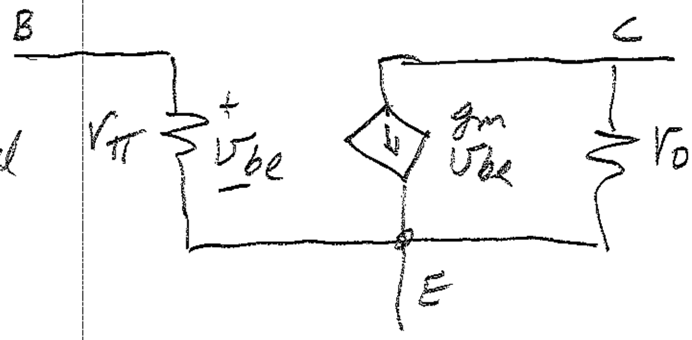
$$r_\pi = \frac{1}{g_\pi} = \boxed{\frac{\beta_F}{g_m}} \longleftarrow r_\pi$$

$$g_o = \frac{\partial I_c}{\partial V_{ce}}\bigg|_Q = \frac{\partial}{\partial V_{CE}}\left[I_S e^{V_{be}/V_T}\left(1 + \frac{V_{ce}}{V_A}\right)\right]_Q$$

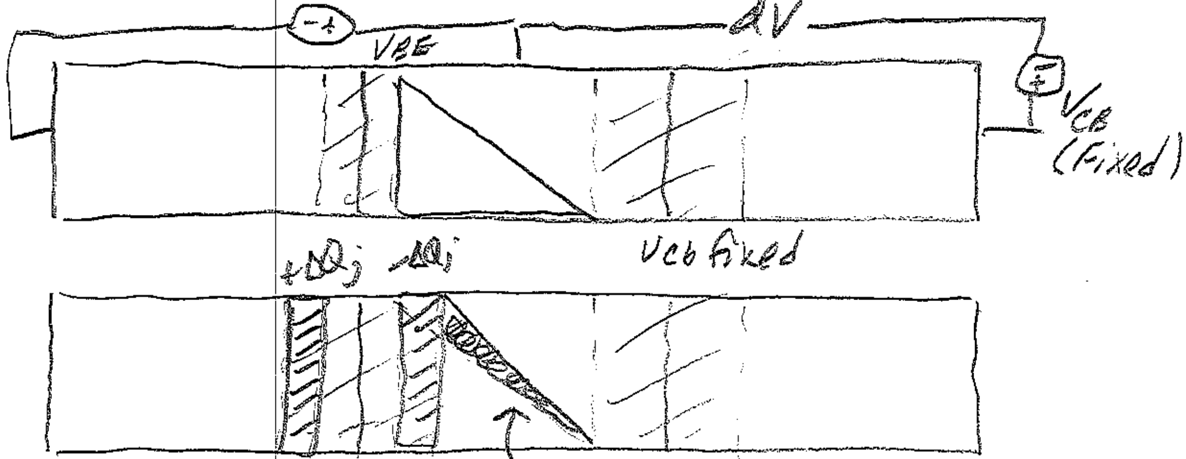
$$= \frac{I_S}{V_A} e^{V_{BE}/V_T} = \frac{I_c}{V_A + V_{CE}} \simeq \frac{I_c}{V_A} \longleftarrow g_o$$

$$r_o = \frac{1}{g_o} = \frac{V_A + V_{CE}}{I_c} \simeq \boxed{\frac{V_A}{I_c}} \longleftarrow r_o$$

Small-signal model



Capacitances: Recall: $C = \frac{dQ}{dV}$ (General)



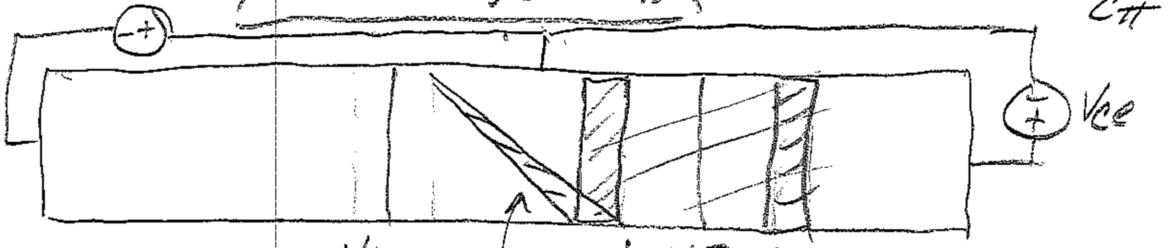
Changes in depletion region capacitance C_{je}

Change in stored minority carrier base charge

$C_B = \tau_F g_m$

τ_F = Base transit time (Average time for electron to traverse base)

$\boxed{C_\pi = C_{je} + C_B}$ ← C_π



V_{be} fixed

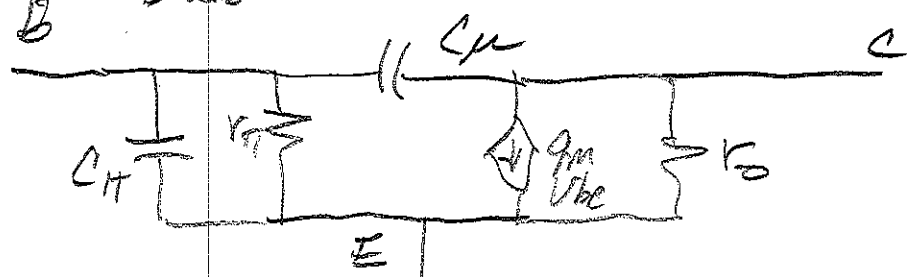
ΔQ

V_{cb_1}

V_{cb_2}

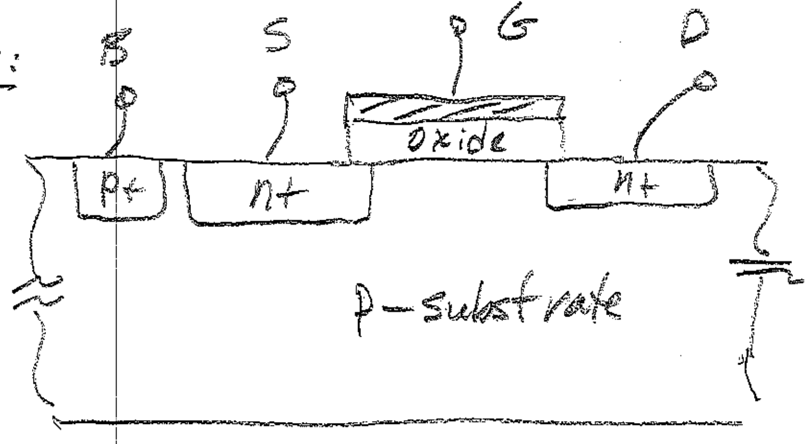
Change in depletion Capacitance is negligible because large negative V_{cb}

$$\frac{\partial Q_B}{\partial V_{cb}} = C_\mu$$

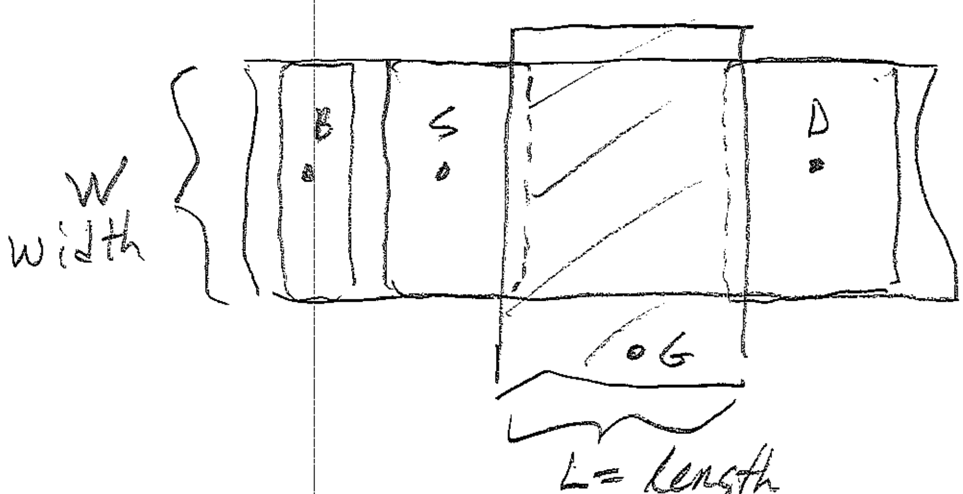


MOSFETs:

Structure:



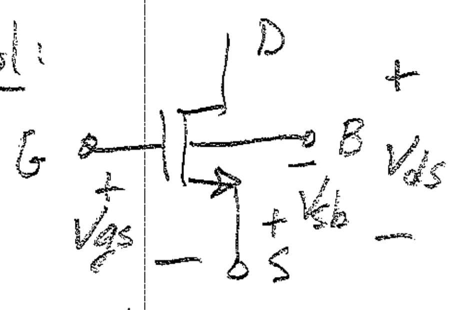
Side View



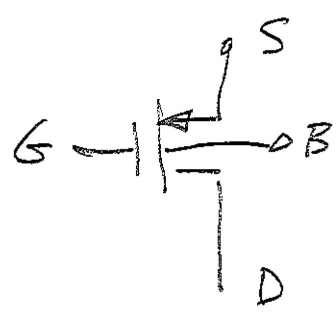
Top View

- Unlike BJT, Designer controls both W and L so long as they meet or exceed minimum dimensions

Symbol:



NMOS

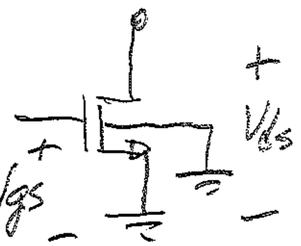


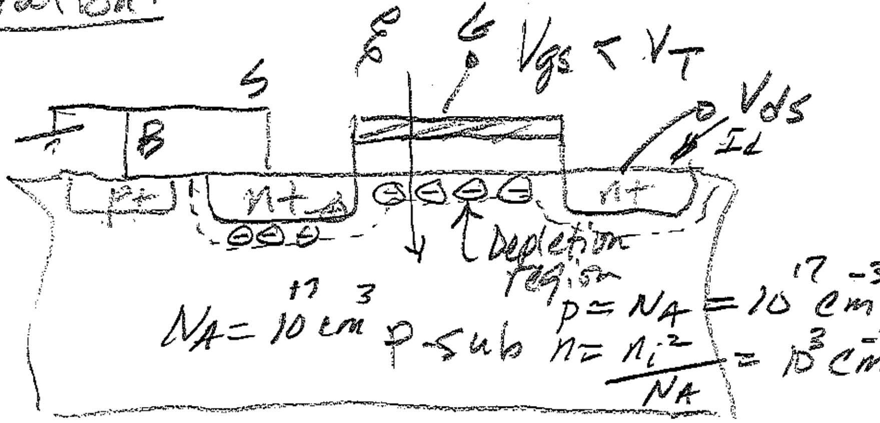
PMOS

- Arrow on source indicates direction of conventional current flow

Regions of Operation:

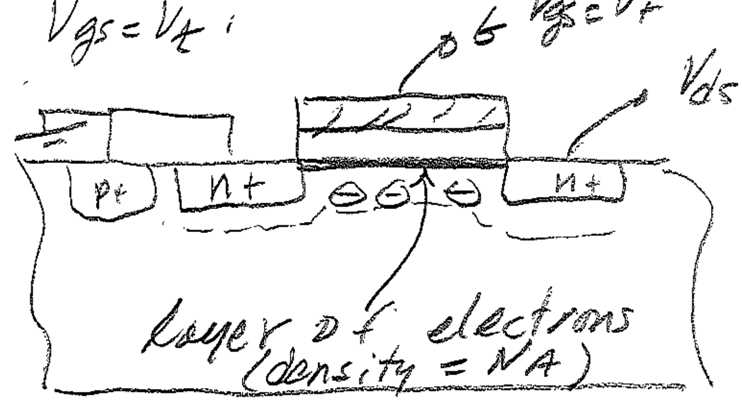
(A) cutoff





no layer of mobile electrons to connect drain to source. ∴ $I_d = 0$

(B) At threshold $V_{gs} = V_t$:

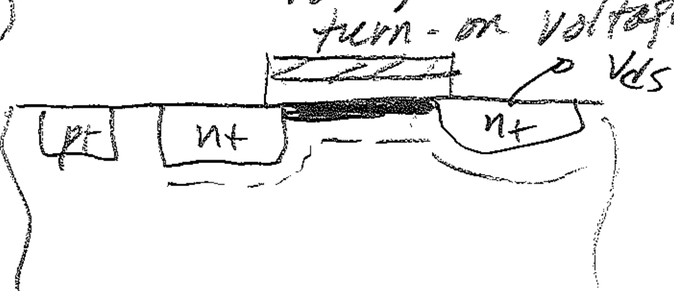


At edge of conduction (square-law model) but still $I_d = 0$

(C) ON with $V_{gs} > V_t$ but $\underbrace{(V_{gs} - V_t)}_{\substack{\text{Excess voltage or}\\ \text{turn-on voltage}}} > V_{ds}$ (small V_{ds})

For $V_{gs} > V_t$
and $V_{ds} < (V_{gs} - V_t)$

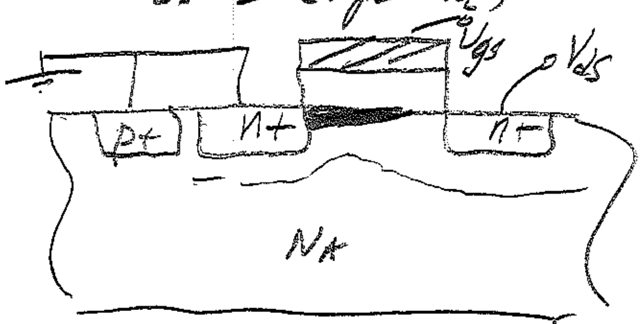
$$\boxed{I_d = \mu_n C_{ox}\left(\frac{W}{L}\right) \cdot \left[(V_{gs} - V_t)V_{ds} - \frac{1}{2}V_{ds}^2\right]}$$ ***

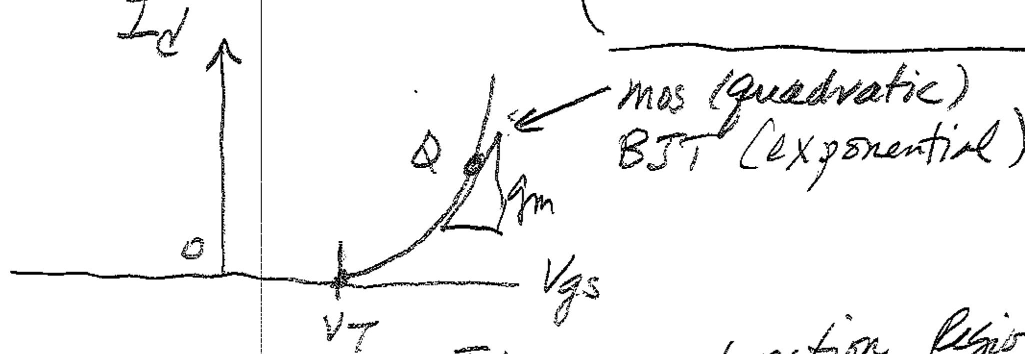


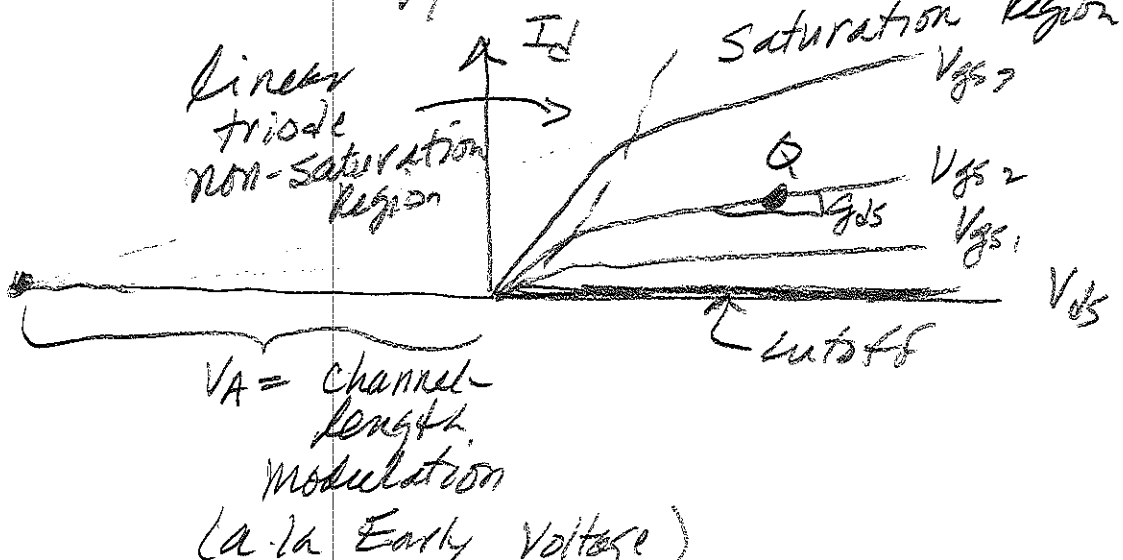
μ_n = electron mobility in channel
C_{ox} = gate oxide capacitance per unit area
$K_n' = \mu_n C_{ox}$

(D) on with $V_{gs} > V_t$ and $V_{ds} \geq (V_{gs} - V_t)$

$$I_d = \frac{k'}{2}\left(\frac{W}{L}\right)(V_{gs}-V_t)^2$$







non-sat. $I_d = k'\left(\frac{W}{L}\right)\left[(V_{gs}-V_t)V_{ds} - \frac{1}{2}V_{ds}^2\right] \left\{ \begin{array}{l} V_{gs} > V_t \\ V_{ds} < (V_{gs}-V_t) \end{array} \right.$

Sat $I_d = \frac{k'}{2}\left(\frac{W}{L}\right)\left[(V_{gs}-V_t)^2\right]\left[1 + \frac{V_{ds}}{V_A}\right]$

$$V_T = V_{T0} + \gamma\left(\sqrt{V_{sb}+2\phi_f} - \sqrt{2\phi_f}\right)$$

$\gamma \equiv$ Body-effect parameter

$\phi_f = \frac{kT}{q}\ln\frac{N_A}{n_i}$

Small-signal parameters (low frequency):

<u>In saturation:</u>

$$g_m = \frac{\partial I_d}{\partial V_{gs}}\bigg|_Q = \frac{\partial}{\partial V_{gs}}\Big[\underbrace{\tfrac{k'}{2}\left(\tfrac{W}{L}\right)(V_{gs}-V_t)^2}_{\text{neglect channel-length modulation}}\Big]$$

$$\boxed{g_m = k'\left(\frac{W}{L}\right)(V_{GS}-V_t)} \leftarrow g_m - \text{Form 1}$$

But, $I_d = \frac{k'}{2}\left(\frac{W}{L}\right)(V_{gs}-V_t)^2$

so $$g_m = \frac{2I_D}{(V_{GS}-V_t)^2}\cdot(V_{GS}-V_t) = \boxed{\frac{2I_D}{(V_{GS}-V_t)}} \leftarrow g_m \text{ Form 2 (Similar to BJT)}$$

or $$g_m = k'\left(\frac{W}{L}\right)\sqrt{\frac{2I_D}{k'\left(\frac{W}{L}\right)}} = \boxed{\sqrt{2k'\left(\frac{W}{L}\right)I_D}} \leftarrow g_m \text{ Form 3}$$

- All three forms are useful. Form 3 will be used most often

$$g_{ds} = \frac{\partial I_d}{\partial V_{ds}}\bigg|_Q = \frac{\partial}{\partial V_{ds}}\left[k'\left(\frac{W}{L}\right)(V_{gs}-V_t)^2(1+\lambda V_{ds})\right]$$

$$= \lambda k'\left(\frac{W}{L}\right)(V_{GS}-V_t)^2$$

$$= \frac{\lambda I_D}{1+\lambda V_{DS}} \simeq \boxed{\lambda I_D} \leftarrow g_{ds}$$

$$r_{ds} = \frac{1}{g_{ds}} \simeq \boxed{\frac{1}{\lambda I_D}} \leftarrow$$