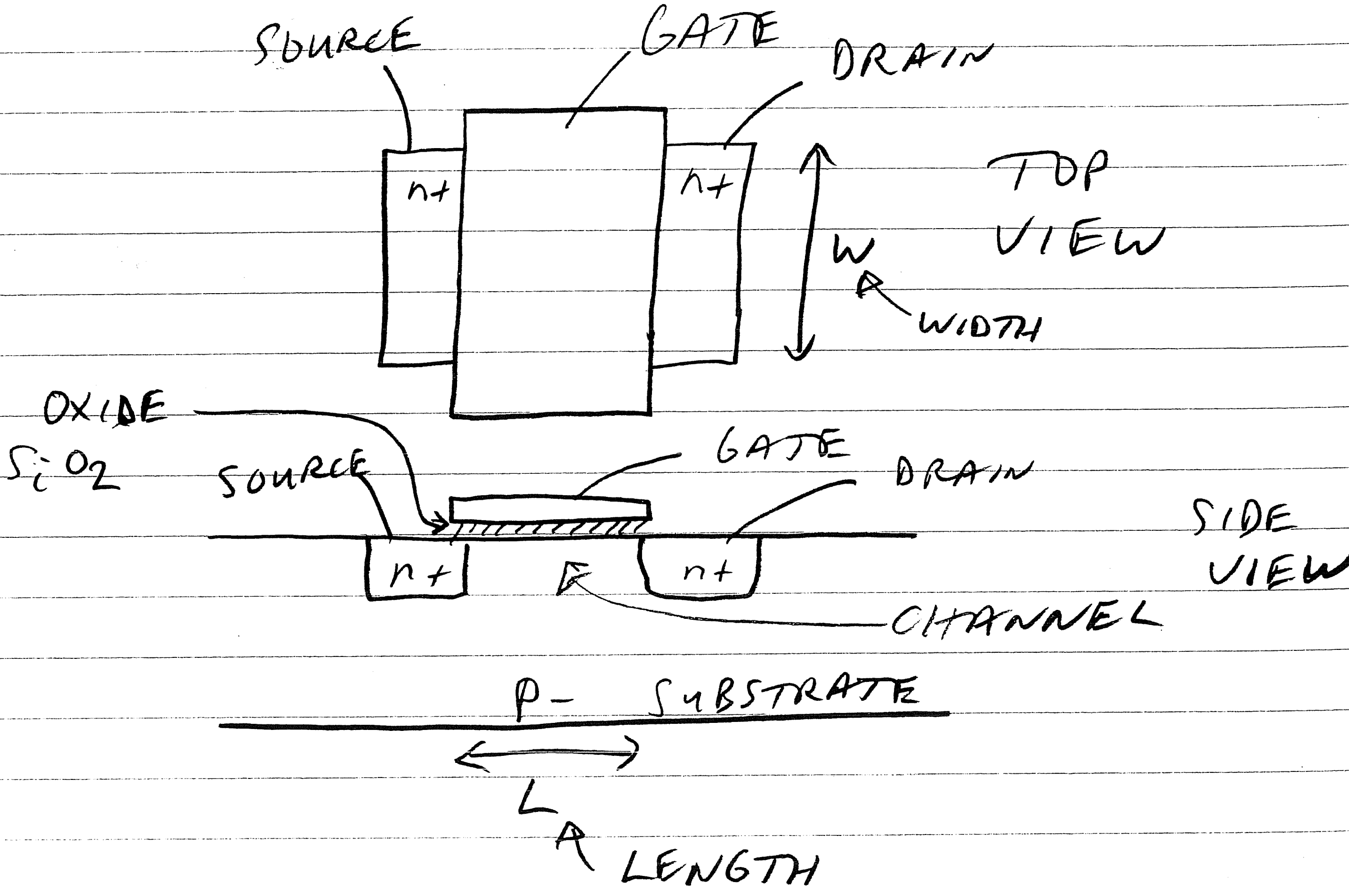
TR1

TRANSISTER REVIEW

MOSFET — N-CHANNEL ⇒ NMOS

METAL **O**XIDE **S**EMICONDUCTOR **F**IELD **E**FFECT **T**RANSISTOR



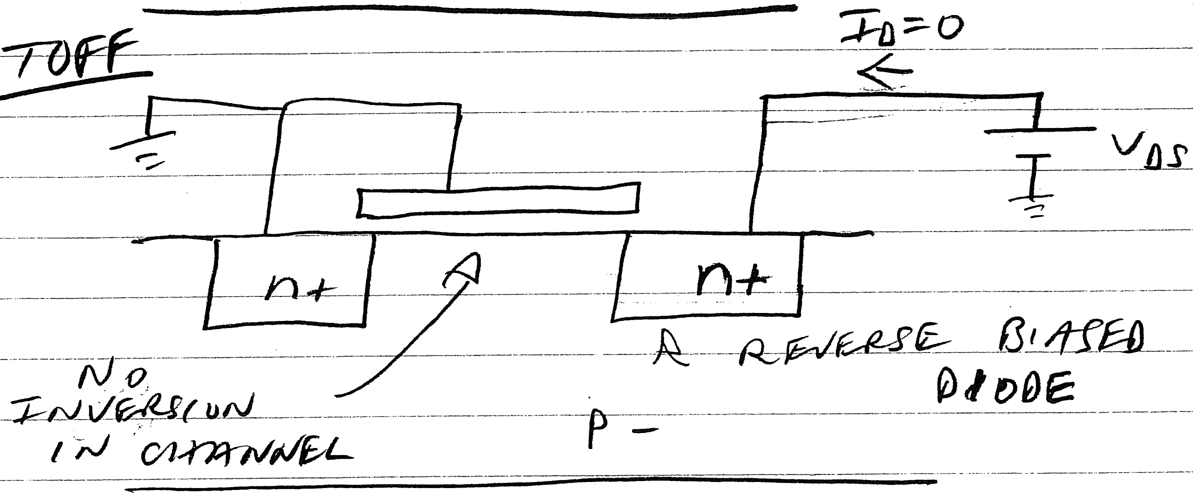
n+ SILICON WITH HIGHLY DOPED ARSENIC, As OR PHOSPHORUS, P

P- SILICON WITH LIGHTLY DOPED BORON, B

TR2

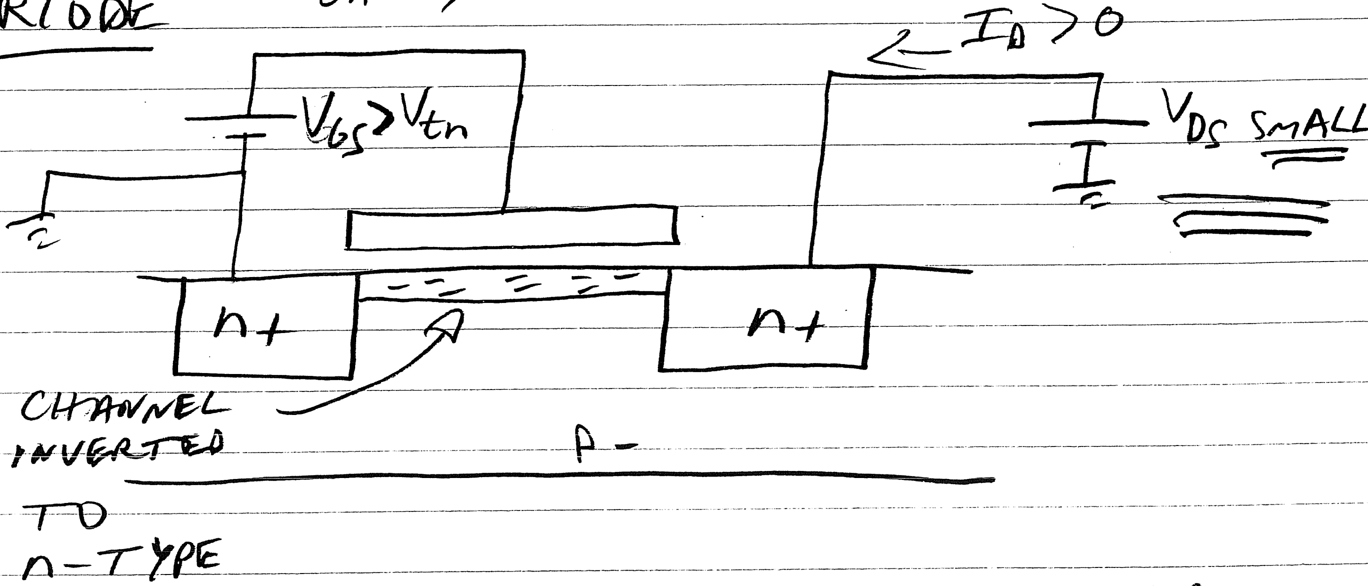
MOSFET OPERATION

CUTOFF



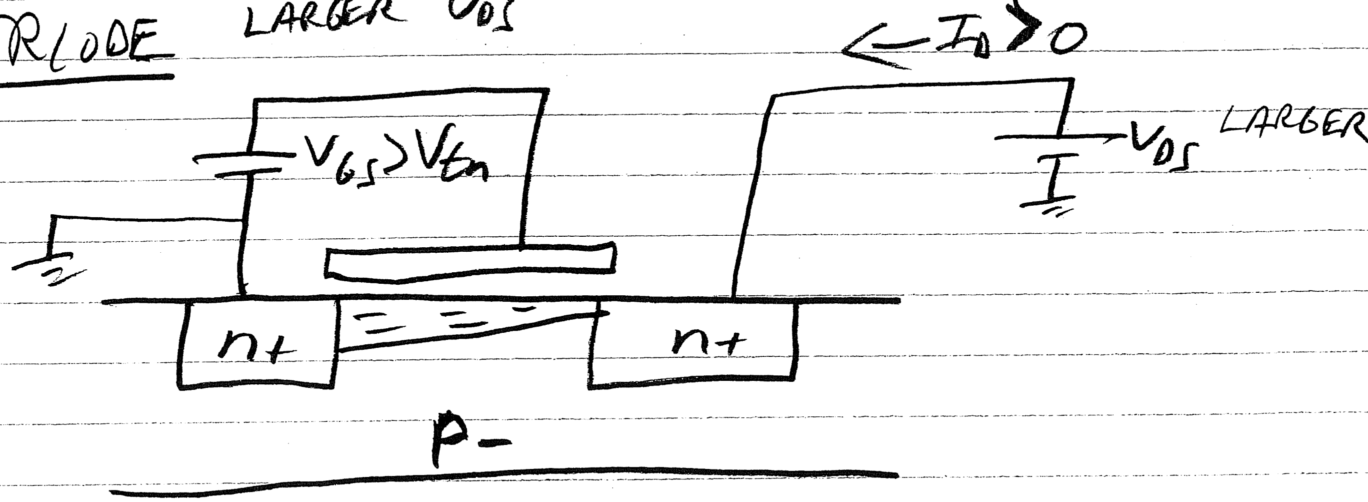
TRIODE

V_{tn} => THRESHOLD VOLTAGE



ELECTRONS ATTRACTED UNDER GATE TO INVERT CHANNEL

TRIODE LARGER V_{DS}



SMALLER CHANNEL NEAR DRAIN

SINCE $V_{GD} < V_{GS}$

AS V_{DS} INCREASES V_{GD} DECREASES

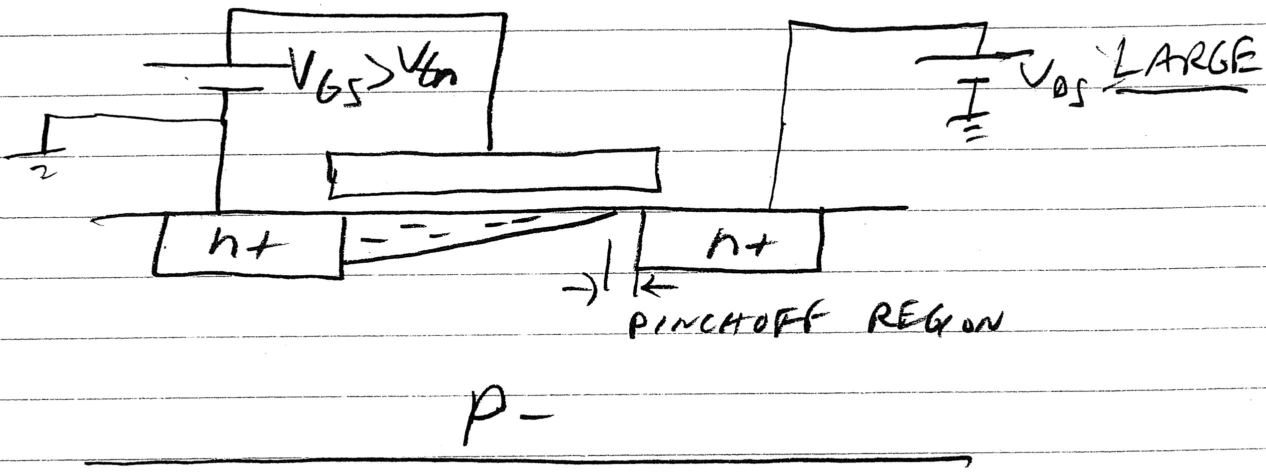
UNTIL => $V_{GD} < V_{tn}$ THEN

CHANNEL NOT INVERTED NEAR DRAIN

=> PINCH - OFF

TR4

ACTIVE (OR SATURATION)



PINCH OFF OCCURS WHEN

$$V_{GD} \leq V_{tn}$$

$$V_{GS} - V_{DS} \leq V_{tn}$$

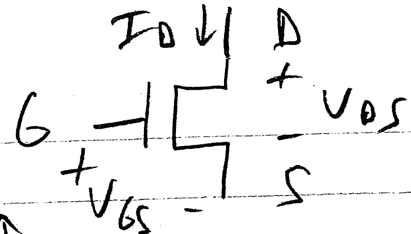
$$\boxed{V_{DS} \geq V_{GS} - V_{tn}}$$ PINCH-OFF OCCURS.

AS $V_{DS} \uparrow$ PINCH-OFF REGION INCREASES & I_D CONSTANT

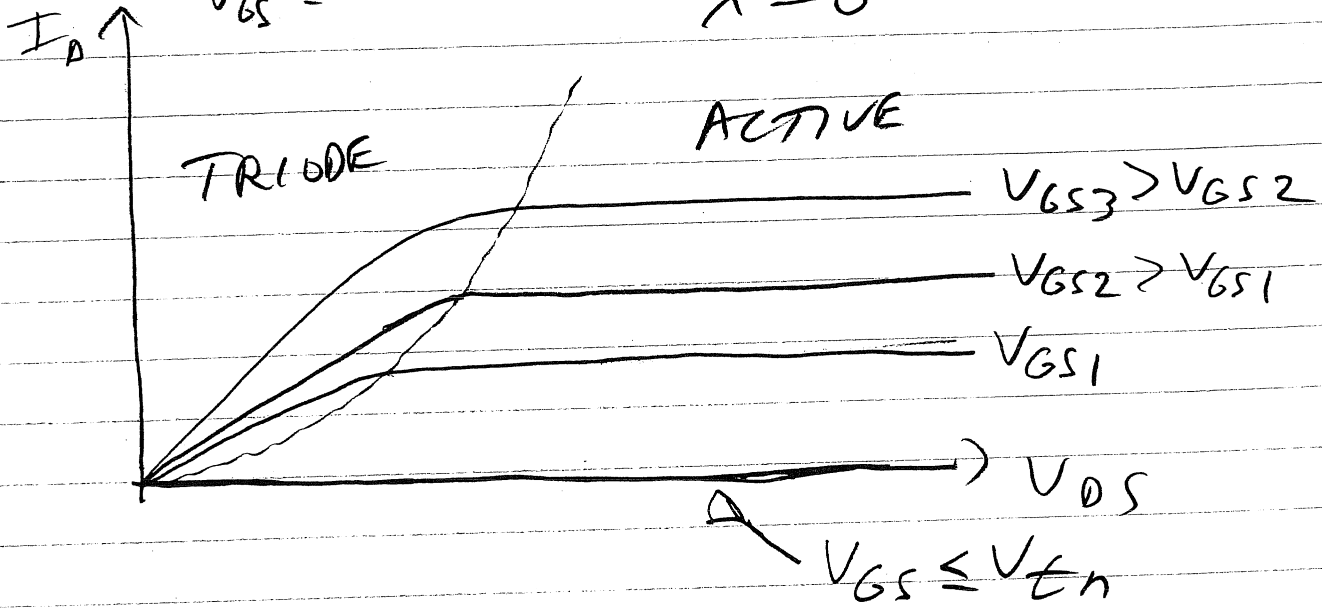
(ELECTRONS SWEPT ACROSS PINCH-OFF REGION)

ACTUALLY I_D SMALL CHANGE DUE TO SMALLER CHANNEL ⇒ MODEL WITH $\underline{\underline{\lambda}}$

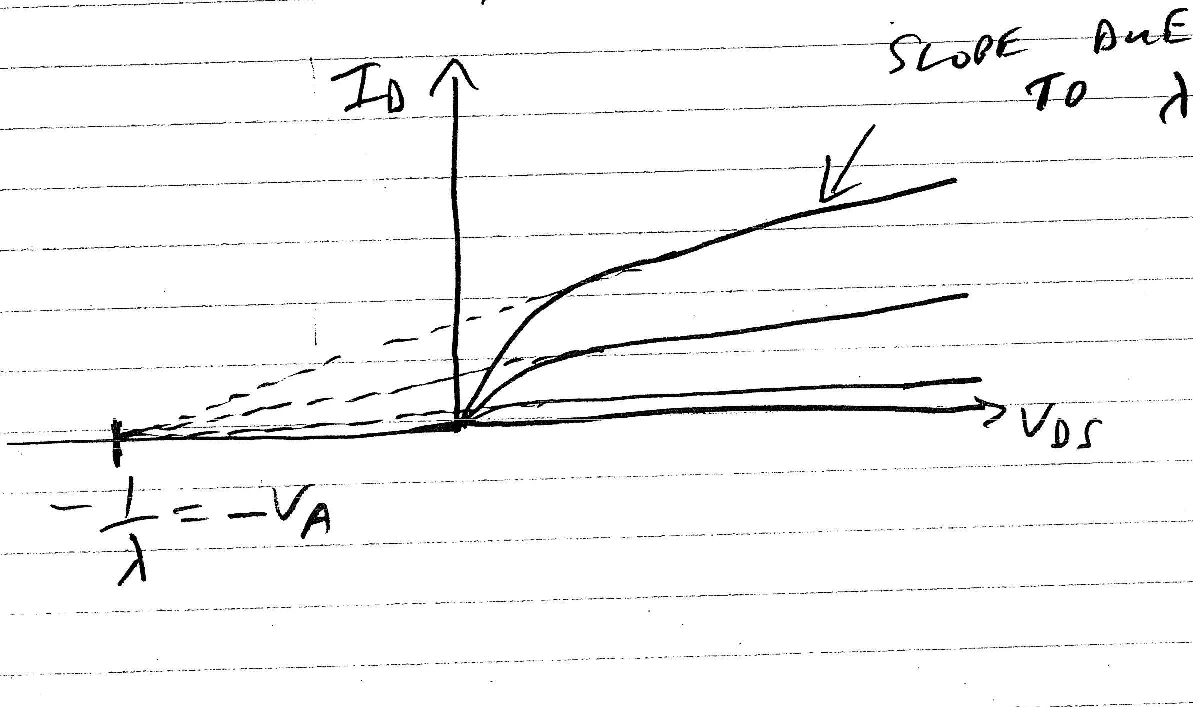
TR4A



IF $\lambda = 0$



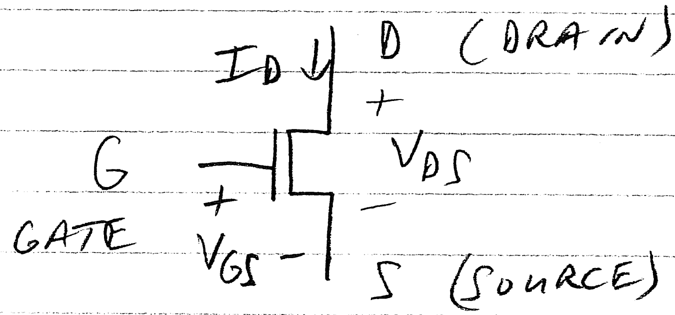
IF $\lambda \neq 0$



TRANSISTOR REVIEW

TR5

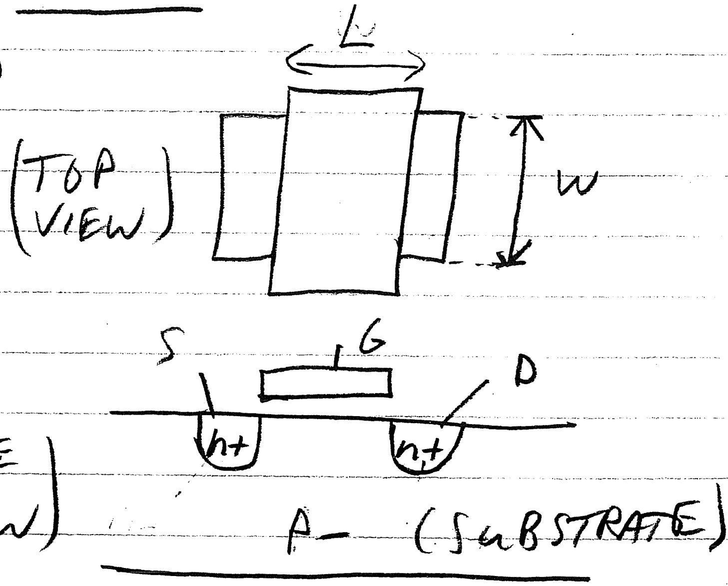
MOSFET



$V_{DS} \geq 0$

$I_D \geq 0$

NMOS



A MOSFET IS A SYMMETRICAL DEVICE

⇒ THE SOURCE IS THE n+ REGION WITH **LOWER** VOLTAGE

(IT COULD SWITCH DURING OPERATION)

DEFINE $V_{ov} \equiv V_{GS} - V_{tn}$

V_{ov} ⇒ OVERDRIVE VOLTAGE

V_{tn} ⇒ THRESHOLD VOLTAGE

$V_{tn} > 0$ (ENHANCEMENT NMOS)

TR6

$W \Rightarrow$ WIDTH OF TRANSISTOR [m]

$L \Rightarrow$ LENGTH OF TRANSISTOR [m]

$\mu_n \Rightarrow$ ELECTRON MOBILITY IN CHANNEL $[m^2/V \cdot s]$

$C_{ox} \Rightarrow$ GATE OXIDE CAPACITANCE/AREA $[F/m^2]$

$\lambda \Rightarrow$ CHANNEL LENGTH MODULATION PARAMETER $[V^{-1}]$

$\lambda = \frac{1}{V_A}$ V_A IS EARLY VOLTAGE

NMOS

3 REGIONS OF OPERATION

CUTOFF $V_{GS} \leq V_{tn}$

$$I_D = 0$$

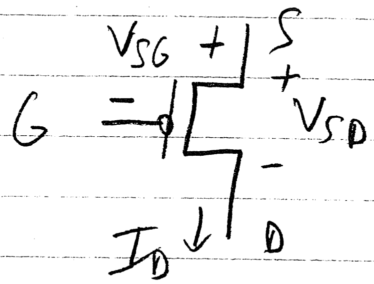
TRIODE $V_{GS} \geq V_{tn}$, $V_{DS} \leq V_{OV}$

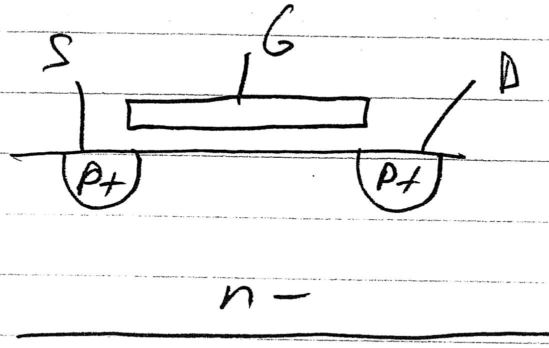
$$I_D = \mu_n C_{ox} \left(\frac{W}{L}\right)\left(V_{OV} - \frac{V_{DS}}{2}\right) V_{DS}$$

ACTIVE $V_{GS} \geq V_{tn}$, $V_{DS} \geq V_{OV}$

$$I_D = \left(\frac{\mu_n C_{ox}}{2}\right)\left(\frac{W}{L}\right) V_{OV}^2 \left[1 + \lambda V_{DS}\right]$$

PMOS





$V_{SD} \geq 0$

$I_D \geq 0$

SOURCE IS DRAIN / SOURCE JUNCTION AT <u>HIGHER</u> VOLTAGE

μ_p ⇒ MOBILITY OF HOLES IN CHANNEL

C_{ox} ⇒ SAME AS NMOS

V_{tp} ⇒ THRESHOLD VOLTAGE, $V_{tp} < 0$

DEFINE V_{OV}

$$V_{OV} \equiv V_{SG} - |V_{tp}|$$

TR8

PMOS 3 REGIONS OF OPERATION

CUTOFF

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

$$I_D = 0$$

TRIODE $V_{SG} \geq |V_{tp}|$, $V_{SD} \leq V_{OV}$

$$I_D = \mu_p C_{ox} \left(\frac{W}{L}\right)\left(V_{OV} - \frac{V_{SD}}{2}\right) V_{SD}$$

ACTIVE $V_{SG} \geq |V_{tp}|$, $V_{SD} \geq V_{OV}$

$$I_D = \left(\frac{\mu_p C_{ox}}{2}\right)\left(\frac{W}{L}\right) V_{OV}^2 \left[1 + |\lambda| V_{SD}\right]$$

$\lambda < 0$ FOR PMOS

TR9

SMALL-SIGNAL MODELS

SAME FOR PMOS + NMOS

$$r_o = \frac{1}{|\lambda| I_D'}$$ WHERE I_D' IS I_D WHEN $\lambda = 0$

$$g_m = \mu_n C_{ox} \left(\frac{W}{L}\right) V_{ov}$$ (μ_p FOR PMOS)

$$g_m = \sqrt{2 \mu_n C_{ox} \left(\frac{W}{L}\right) I_D}$$

$$g_m = \frac{2 I_D}{V_{ov}}$$

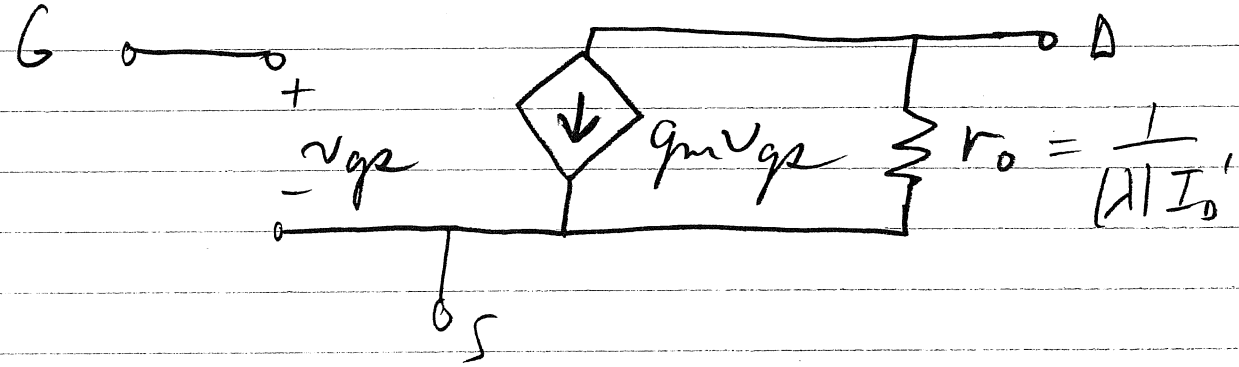
$$r_s \equiv \frac{1}{g_m}$$

NOTE λ IS CONSTANT FOR A GIVEN LENGTH, L
BUT AS L ↓ λ ↑

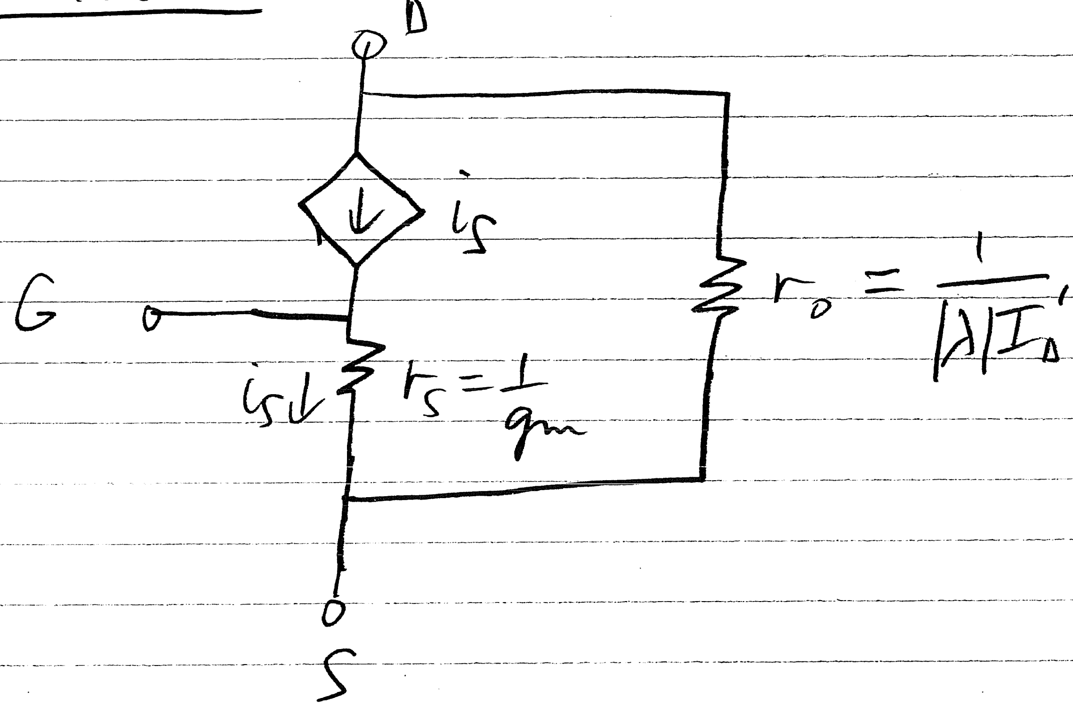
$$\lambda = \frac{\lambda'}{L}$$ WHERE λ' IS INDEPENDENT OF L

TR10

π-MODEL



T-MODEL



TR11

EXAMPLE 1

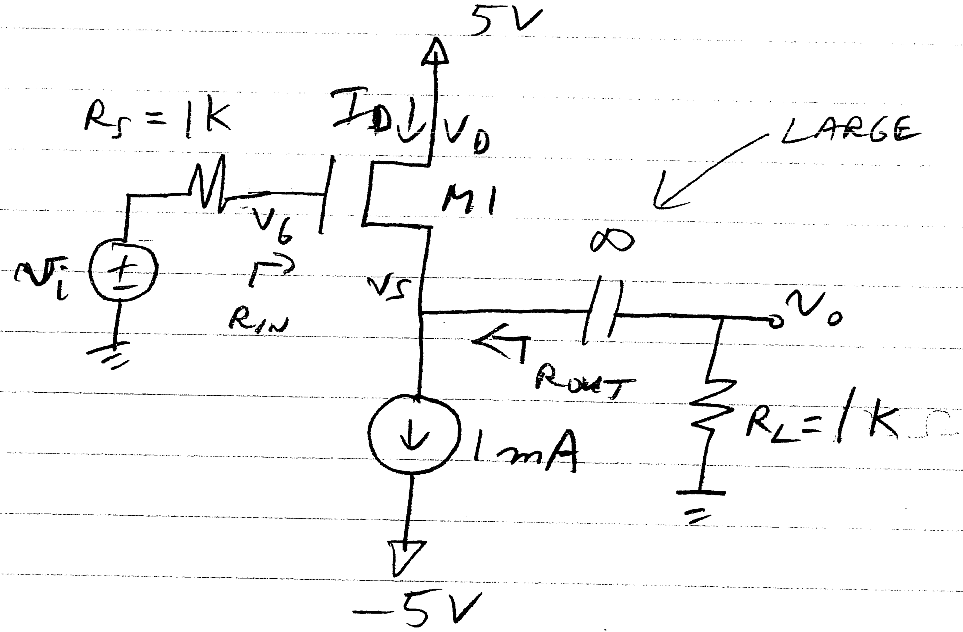
GIVEN $\mu_N C_{ox} = 120\ \mu A/V^2$

$V_{tn} = 0.5V$

$W/L = 10$

$\lambda = 0.05\ V^{-1}$

FIND DC OPERATING POINTS & v_o/v_i SMALL SIGNAL R_{IN} & R_{OUT}



DC

$I_G = 0 \Rightarrow \underline{\underline{V_G = 0}}$

ASSUME M1 ACTIVE

$I_D = 1\,mA \Rightarrow$

$$I_D = \frac{\mu_N C_{ox}}{2}\left(\frac{W}{L}\right)(V_{OV})^2$$

$$1\,mA = \left(\frac{120e\text{-}6}{2}\right)(10)(V_{OV})^2$$

$$V_{OV} = 1.291\ V$$

$V_{OV} = 1.291 \Rightarrow V_{GS} - V_{tn} = V_{OV}$

$V_{GS} = V_{OV} + V_{tn} = 1.291 + 0.5$

$V_{GS} = 1.791 \text{ V}$

SINCE $V_G = 0 \Rightarrow V_{GS} = V_G - V_S$

$V_S = V_G - V_{GS} = -1.791 \text{ V}$

$V_D = 5\text{V} \Rightarrow V_{DS} = 5 - (-1.791) = 6.791 \text{ V}$

$V_{DS} > V_{GS} - V_{tn}$ SO ACTIVE IS ✓ (CORRECT)

$g_m = \frac{2I_D}{V_{OV}} = \frac{2(1\text{mA})}{1.291} = 1.55 \text{ mA/V}$

$r_S = \frac{1}{g_m} = 646\ \Omega$

$r_o = \frac{1}{\lambda I_D} = 20\text{k}$

TR12A

IF ASSUME M1 CUTOFF

$I_G = 0 \Rightarrow V_G = 0$

$I_D = 0 \Rightarrow V_S = -5V$

SO $V_{GS} = +5V$ & $V_{GS} > V_{tn}$

SO **NOT** CUTOFF ✗

IF ASSUME M1 TRIODE SO $V_{GS} \geq V_{tn}$, $V_{DS} \leq V_{OV}$

$$I_D = \mu_n C_{ox}\left(\frac{W}{L}\right)\left(V_{OV} - \frac{V_{DS}}{2}\right)V_{DS}$$

$$1e{-3} = (120e{-6})(10)\left(V_{OV} - \frac{V_{DS}}{2}\right)V_{DS}$$

$$\left(V_{OV} - \frac{V_{DS}}{2}\right)V_{DS} = 0.8333 \quad (1)$$

& $V_{DS} = V_D - V_S \qquad V_D = 5V$

$V_S = V_G - V_{GS} = V_G - (V_{OV} + V_{tn})$

$V_S = 0 - (V_{OV} + 0.5) = -V_{OV} - 0.5$

$V_{DS} = 5 + V_{OV} + 0.5$

$V_{DS} = 5.5 + V_{OV} \quad (2)$

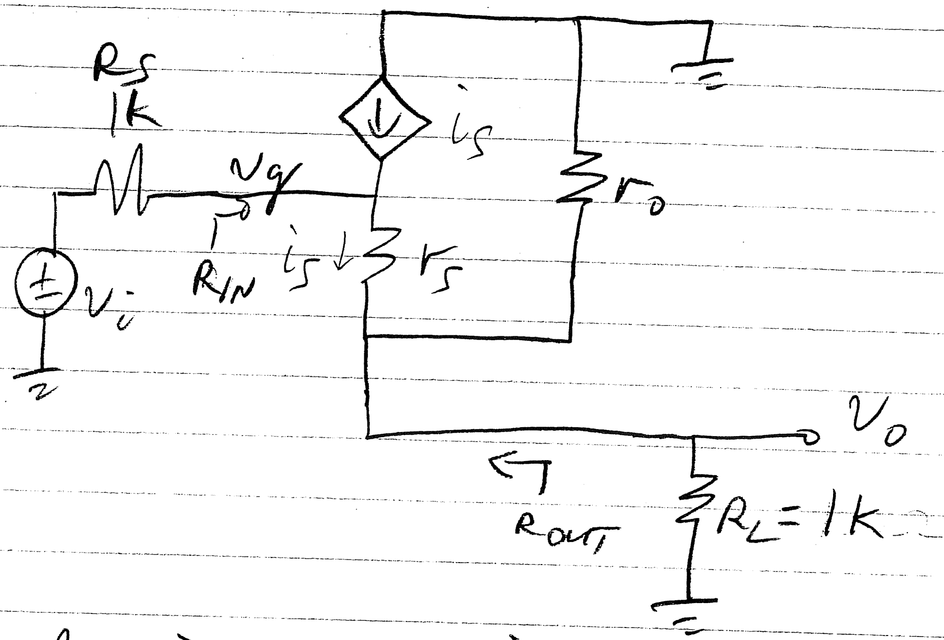
COMBINE (1) & (2) $\quad 0.5V_{DS} - 5.5V_{DS} - 0.8333 = 0$

$V_{DS} = 11.15$ OR -0.15

$V_{DS} > V_{OV}$ ✗ $\qquad V_{DS} < 0$ ✗

NOT TRIODE

SMALL-SIGNAL



$R_{IN} \to \infty$ SINCE $i_g = 0$

$$v_g = \frac{R_{IN}}{R_{IN}+R_S} v_i = v_i \quad \text{SINCE } R_{IN} \to \infty$$

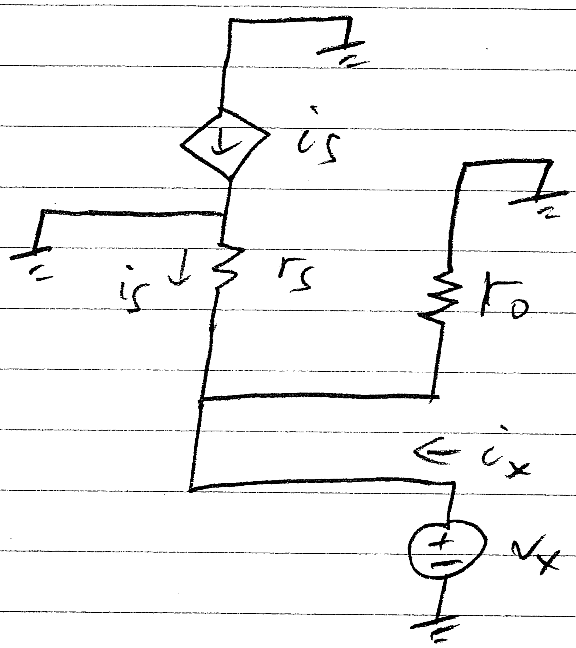
$$v_o = \frac{R_L \| r_o}{(R_L \| r_o) + r_S} v_g = \frac{(1k \| 20k)}{(1k)\|(20k) + 646} v_g$$

$$v_o = \frac{952}{952 + 646} v_g = 0.596\, v_g$$

So $v_o = 0.596\, v_i$ SINCE $v_g = v_i$

$$\frac{v_o}{v_i} = 0.596 \text{ V/V}$$

ROUT SET $v_i = 0 \Rightarrow v_g = 0$ SINCE $i_g = 0$



$R_{OUT} \equiv \frac{v_x}{i_x}$

$$i_x = \frac{v_x}{r_s} + \frac{v_x}{r_o} \Rightarrow \frac{i_x}{v_x} = \frac{1}{r_s} + \frac{1}{r_o}$$

$$R_{OUT} = \left(\frac{1}{r_s} + \frac{1}{r_o}\right)^{-1} = r_s \| r_o$$

$$= \underline{\underline{626\ \Omega}}$$

EXAMPLE 2

PMOS

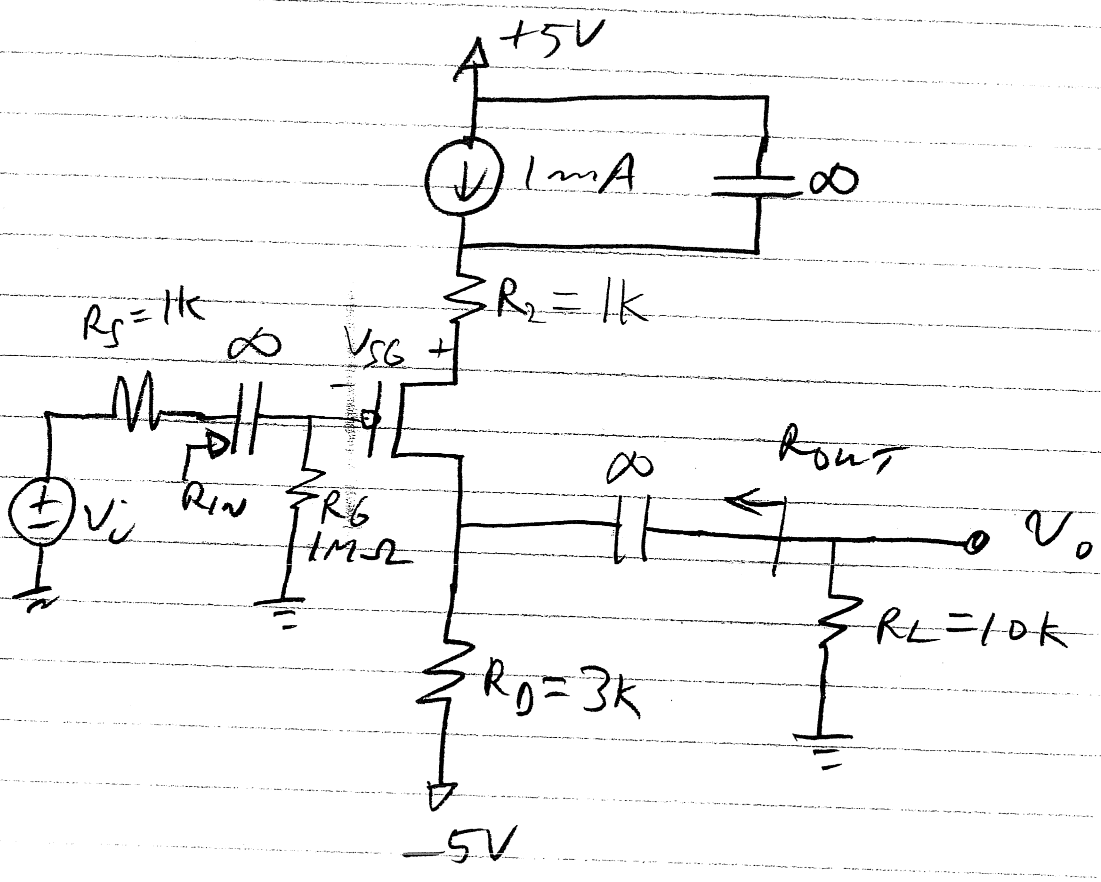
GIVEN $\mu_p C_{ox} = 30\,\mu A/V^2$

$V_{tp} = -0.6\,V$

$W/L = 10$

$\lambda = 0$

FIND OP POINT & $\frac{v_o}{v_i}$, R_{IN} & R_{OUT}



$V_G = 0$ AS BEFORE

(TR16)

$$I_D = \frac{\mu_p C_{ox}}{2}\left(\frac{W}{L}\right)(V_{SG} - |V_{tp}|)^2$$

$$1mA = \frac{30e-6}{2}(10)(V_{SG} - 0.6)^2$$

$V_{SG} = \underline{\underline{3.182\ V}}$ OR -1.982 « NOT POSSIBLE SINCE $V_{SG} \geq |V_{tp}|$

$V_S = 0 + V_{SG} = 3.182$ & $V_{ov} = V_{SG} - |V_{tp}| = 2.582$

$V_D = -5 + 3 = -2V$

$V_{SD} = 3.182 - (-2) = 5.182 \geq V_{ov} = 2.582$

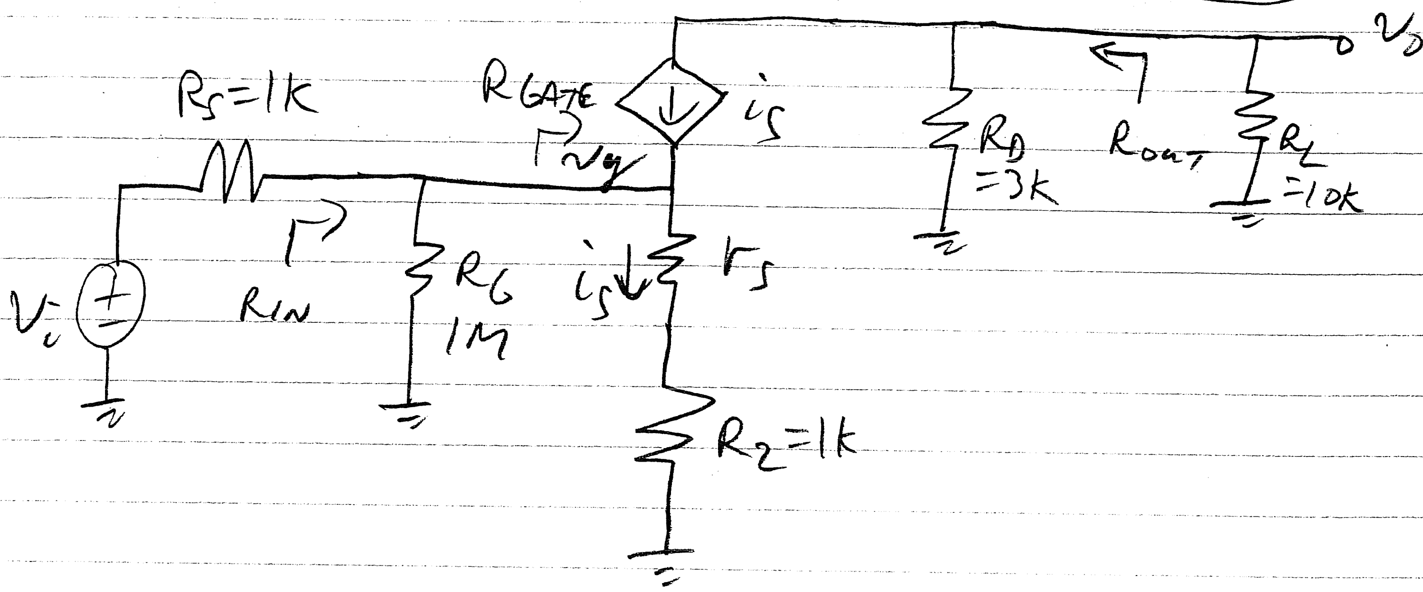
ACTIVE ✓

$$g_m = \frac{2I_D}{V_{ov}} = \frac{2(1e-3)}{2.582} = 0.775\ mA/V^2$$

$$r_s = \frac{1}{g_m} = 1.291\ k$$

$r_o \Rightarrow \infty$ SINCE $\lambda = 0$

TR17



$R_{IN} = R_G || R_{GATE}$ & $R_{GATE} \to \infty$

$= R_G = 1M\Omega$

$R_{OUT} = R_D = 3k$ SET $v_i = 0$ WHEN FINDING ROUT

$$v_g = \frac{R_G}{R_G + R_S} v_i = \frac{1M}{1M + 1k} v_i = 0.999 v_i \approx v_i$$

$$i_s = \frac{v_g}{r_s + R_2} \qquad v_o = -i_s (R_D || R_L)$$

$$v_o = \frac{-(R_D || R_L)}{r_s + R_2} v_g = \frac{-(3k || 10k)}{1.291k + 1k} v_g$$

$$v_o \approx -v_g, \Rightarrow \frac{v_o}{v_i} \approx -1 \ V/V$$

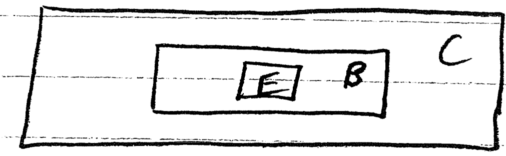
BIPOLAR TRANSISTORS

NPN & PNP TRANSISTORS

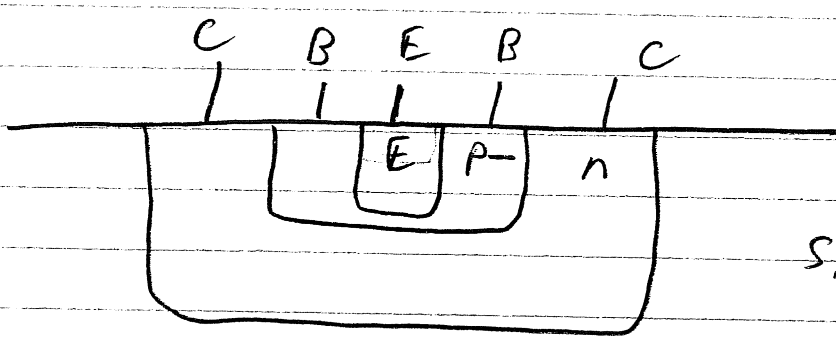
NPN

E – EMITTER
B – BASE
C – COLLECTOR

TOP VIEW



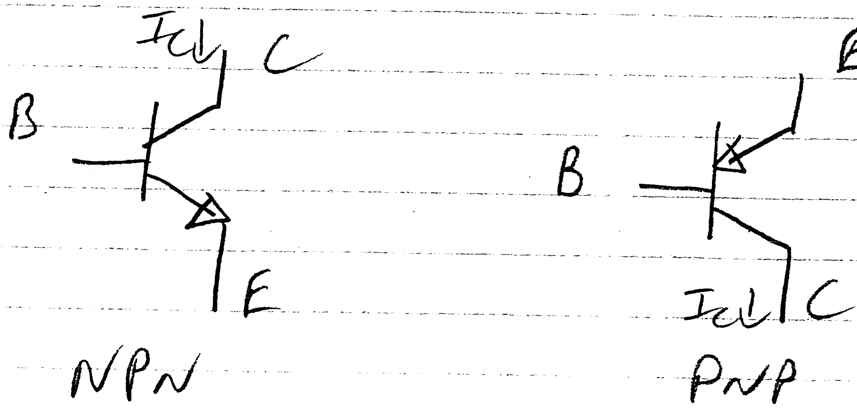
SIDE VIEW



NOT SYMMETRICAL

CB JUNCTION MUCH LARGER AREA THAN BE JUNCTION. MORE POWER DISSIPATED IN CB JUNCTION.

BASE IS LIGHTLY DOPED



$$i_E = i_B + i_C$$

3 MODES OF OPERATION

MODE	EBJ (EB JUNCTION)	CBJ (CB JUNCTION)	TYPICAL USE
CUTOFF	REVERSE	REVERSE	OFF SWITCH
ACTIVE	FORWARD	REVERSE	AMPLIFIER
SATURATION	FORWARD	FORWARD	ON SWITCH

FORWARD WHEN $V_J \gtrsim 0.5\,V$

REVERSE WHEN $V_J \lesssim 0.5\,V$

WHEN FORWARD BIASED ASSUME

$V_{BE} \approx 0.7\,V$

$V_{BC} \approx 0.5\,V$ SINCE MUCH LARGER

SO IF IN SATURATION $V_{CE} \approx 0.2\,V$

$$V_{CE} = V_{CB} - V_{EB} = -V_{BC} - (-V_{BE}) = -V_{BC} + V_{BE}$$

$$= 0.7 - 0.5 = \underline{0.2\,V}$$

SO $V_{CE} \approx 0.2\,V$ IN <u>SATURATION</u>

TR20

CUTOFF EBJ + CBJ REVERSE

$I_B \simeq 0 \quad I_C \simeq 0$

SATURATION EBJ + CBJ FORWARD

$V_{CE} \simeq 0.2V$ (ACTUALLY $V_{CE\,SAT}$ VOLTAGE)

ACTIVE EBJ FORWARD + CBJ REVERSE

$$i_C = I_S e^{v_{BE}/V_T}\left[1 + \frac{V_{CE}}{V_A}\right]$$

SUGGESTS $v_{BE} \simeq 0.7V$

I_S SCALE CURRENT + IS PROPORTIONAL TO BEJ AREA

V_T THERMAL VOLTAGE $V_T = \frac{kT}{q} \simeq 26\,mV$ AT ROOM TEMP

V_A EARLY VOLTAGE

TR21

$$i_C = \beta i_B$$

$\beta \approx 100$
DEPENDS ON DOPING LEVELS
BASE WIDTH, ETC.

$$i_E = (\beta+1) i_B$$

SINCE $i_E = i_B + i_C$

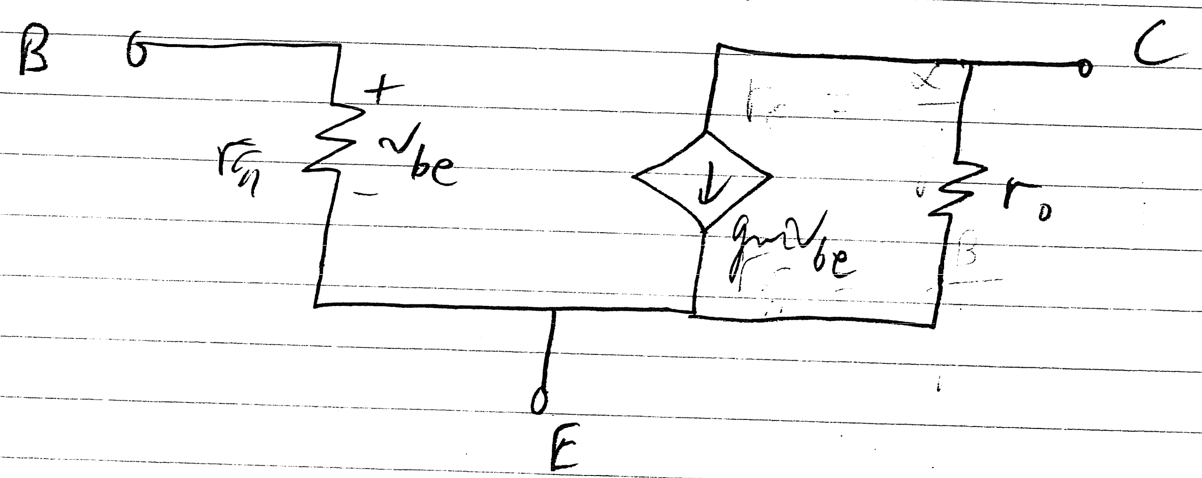
$$\alpha \equiv \frac{\beta}{\beta+1}$$

$$i_C = \alpha i_E$$

$\alpha \simeq 1$ (0.99 IF $\beta = 100$)

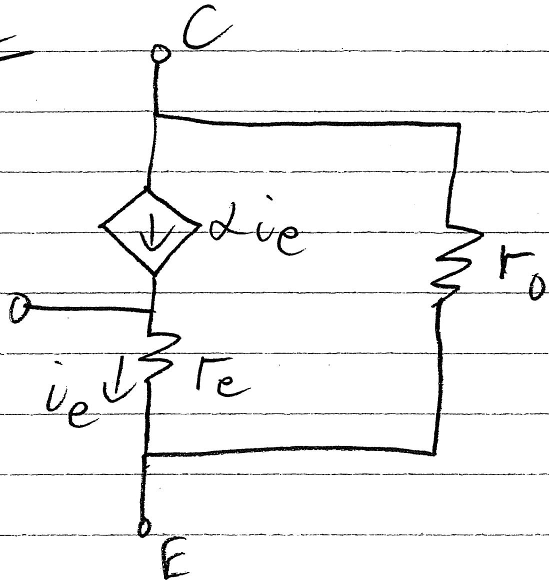
SMALL-SIGNAL

π-MODEL:



TR22

T-MODEL

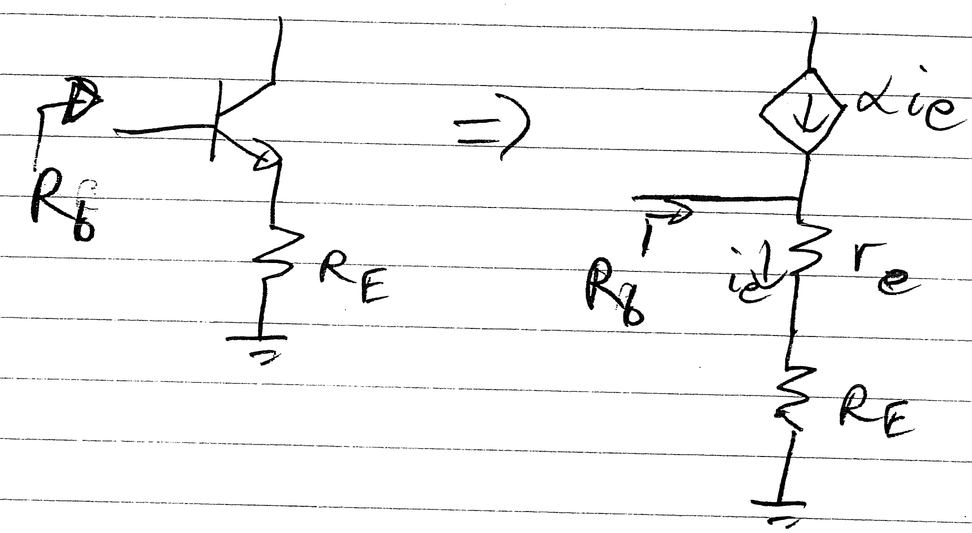


$$g_m = \frac{I_C}{V_T} \qquad V_T = \frac{kT}{q} \approx 26\ mV$$

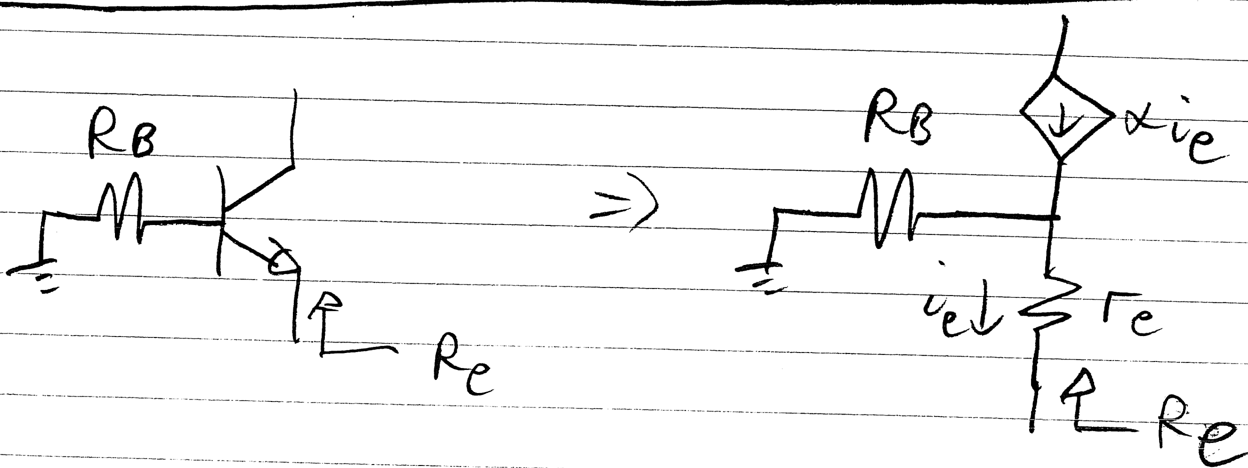
$$r_e = \frac{\alpha}{g_m} = \frac{V_T}{I_E} \qquad r_\pi = \frac{\beta}{g_m}$$

$$r_o = \frac{|V_A|}{I_C}$$

IMPEDANCE RULES FOR BJT



$$R_b = (\beta+1)(r_e + R_E) = r_\pi + (\beta+1)R_E$$



$$R_e = \frac{R_B}{\beta+1} + r_e = \frac{R_B + r_\pi}{\beta+1}$$