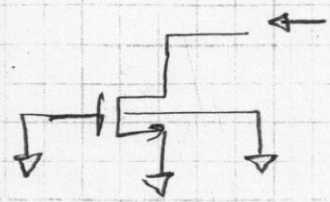
Small Signal MOS terminal impedances

①



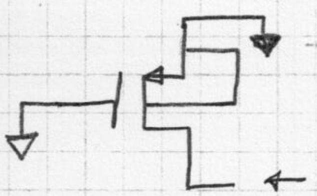
$g = g_{ds}$

$C = C_{gd} + C_{db}$

High impedance

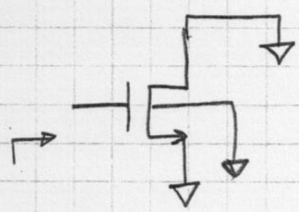
 ← ac ground

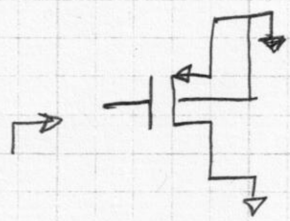
DC proper biasing to keep transistor in sat.



Looking into drain

②



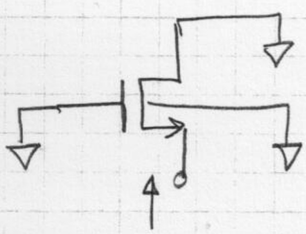


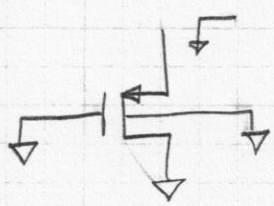
LOOKING into Gate

$g = 0$ $C = C_{gs} + C_{gd}.$

— High Impedance

③

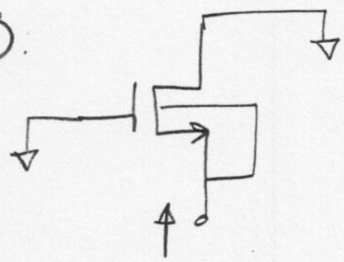


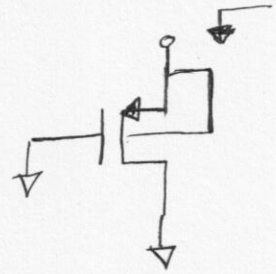


Looking into Source.

$g = \underbrace{g_m + g_{mbs} + g_{ds}}_{\text{Low impedance.}}$ $C = C_{gs} + C_{sb}$

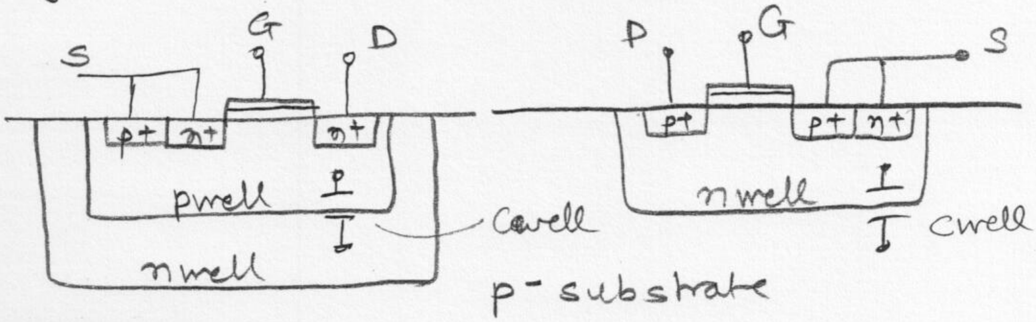
(4).



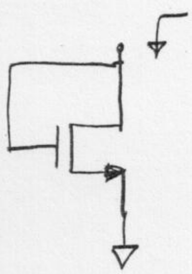


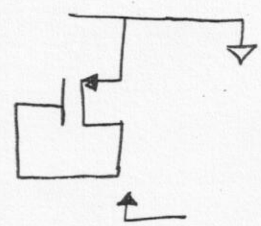
Looking into source (self biased well)

$g = g_m + g_{ds}$ $\qquad$ $C = C_{gs} + C_{gb} + C_{db} + \boxed{C_{well}}$



(5)



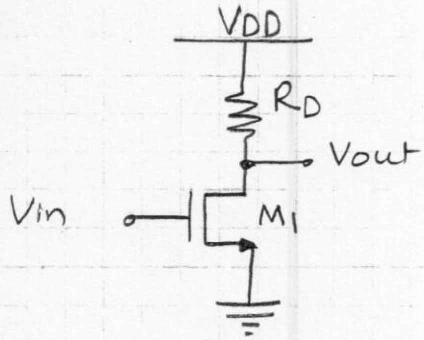


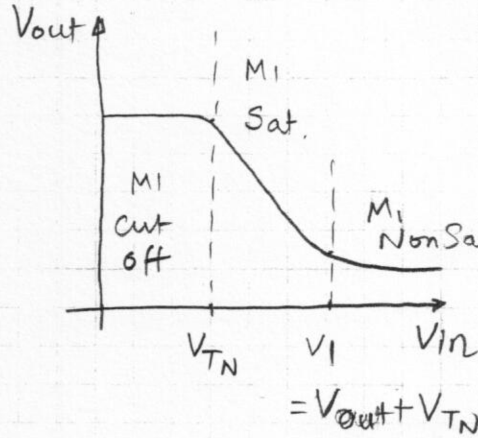
$g = g_m + g_{ds}$ $\qquad$ $C = C_{gs} + C_{db}$

Called <u>diode connected</u> device.

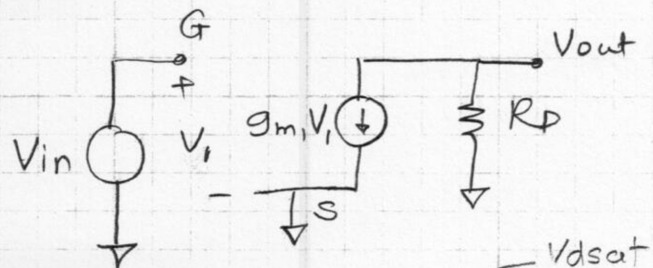
Amplifiers

1. Common-Source amplifier





Small Signal Model in sat. region (ignoring r_o)



$$V_{out} = \underbrace{-g_{m1} R_D}_{A_V \text{ voltage gain}} V_{in}$$

$$g_m = \mu_n C_{ox} \left(\frac{W}{L}\right) \underbrace{(V_{GS} - V_{TN})}_{V_{dsat}}$$

$$= \frac{2 I_D}{(V_{GS} - V_{TN})}$$

$$= \underbrace{\sqrt{2 \mu_n C_{ox} \left(\frac{W}{L}\right) I_D}}_{I_D,\, V_{GS} = \text{Bias values}}$$

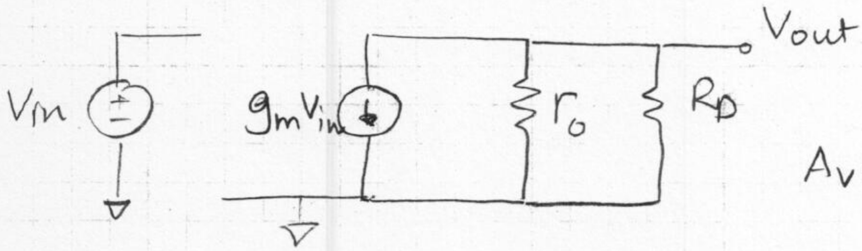
Small Signal Quantity

key observation
If i/p signal is large $(V_{GS} - V_{TN})$ & hence g_m & hence gain of the circuit changes a lot.

Gain varies with signal swing.

$\Rightarrow$ Distortion

Including channel length modulation (r_o) effect

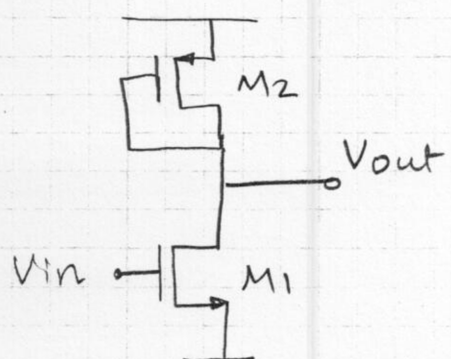


$$A_v = \frac{V_{out}}{V_{in}} = -g_{m_1} \frac{r_o R_D}{r_o + R_D}$$

$$A_v = -\underset{\substack{\uparrow \\ \text{Driver} \\ g_m}}{g_m} \cdot \underbrace{(r_o \parallel R_D)}_{\text{Effective output impedance}} = -\frac{g_m(\text{driver})}{g_{out\uparrow} + g_{out\downarrow}}$$

CS Amp with diode load

(1)



By inspection

$$A_v = -\frac{g_m(\text{driver})}{g_{out\uparrow} + g_{out\downarrow}}$$

$$A_v = -\frac{g_{m1}}{g_{m_2} + g_{ds_2} + g_{ds_1}}$$

$$\approx -\frac{g_{m1}}{g_{m2}} = -\frac{\sqrt{2\mu_n C_{ox}\left(\frac{W}{L}\right)_N I_D}}{\sqrt{2\mu_p C_{ox}\left(\frac{W}{L}\right)_p I_D}}$$

$$\approx -\sqrt{\frac{\mu_n \left(\frac{W}{L}\right)_N}{\mu_p \left(\frac{W}{L}\right)_p}}$$

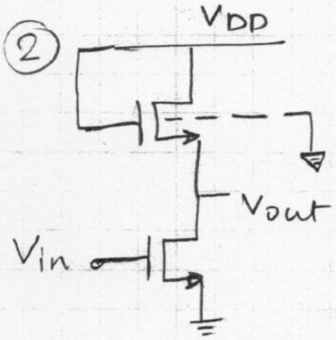
→ Low voltage gain ~ 2 - 6

→ Low o/p swing $\quad V_{o\,min} = V_{DSAT1} \quad (0.25V)$

$$V_{o\,Max} = V_{DD} - |V_{GSp}| = V_{DD} - |V_{Tp}| - |V_{DSAT_2}|$$

$$1.2V - 0.6 - 0.25V = (0.35V)$$

(2)



$$A_V = \frac{-g_m(\text{driver})}{g_{out\uparrow} + g_{out\downarrow}}$$

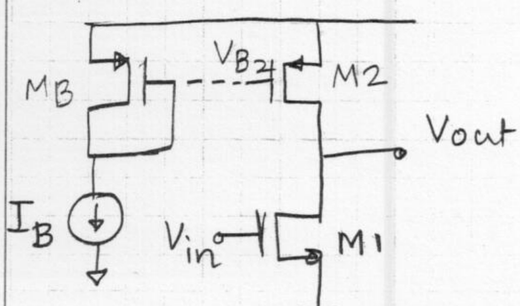
$$A_V = \frac{-g_{m1}}{g_{m2} + g_{mbs_2} + \underbrace{g_{ds_2} + g_{ds_1}}_{\text{ignore}}}$$

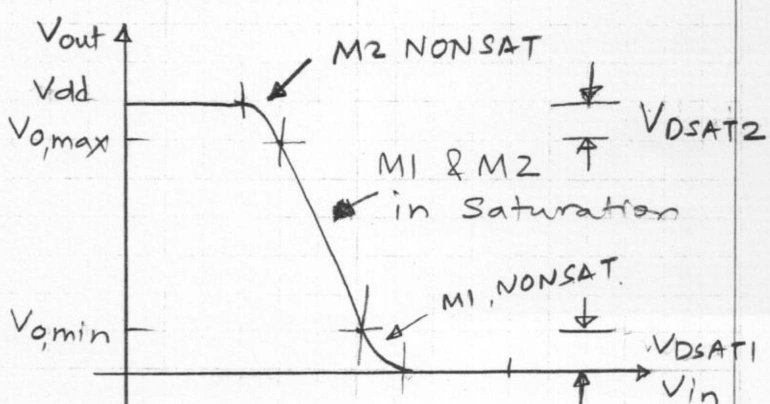
$$A_v = -\frac{g_{m1}}{g_{m2} + \underbrace{g_{mbs_2}}_{\text{body effect}}} = -\sqrt{\frac{(W/L)_1}{(W/L)_2}} \cdot \frac{1}{1+\eta}$$

$0.25 \cdot g_{m2}$

Low gain & Low swing.

C-S Amplifier with current source load.





$$(W/L)_B = (W/L)_2 \Rightarrow I_1 = I_2 = I_B$$

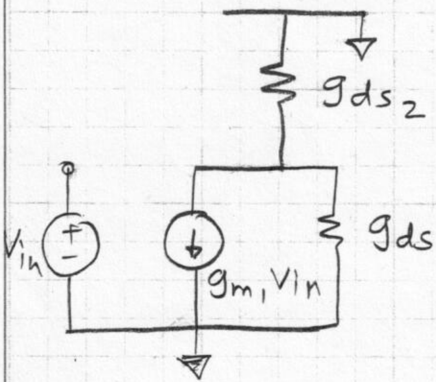
$$V_{B2} = V_{DD} - \left(|V_{Tp}| + V_{DSAT2}\right)$$

$$V_{B1} = V_{TN} + V_{DSAT1}$$

$$V_{DSAT1} = \sqrt{\frac{2 I_B}{\mu_n C_{ox} (W/L)_1}}$$

$$V_{DSAT2} = \sqrt{\frac{2 I_B}{\mu_p C_{ox} (W/L)_2}}$$

When Both M1 & M2 are in saturation
— small signal analysis



$$A_V = -\frac{g_{m_1}}{g_{ds_1} + g_{ds_2}}$$

$$= -\frac{2I_B/(V_{GS}-V_T)_N}{\lambda_N I_B + \lambda_p I_B}$$

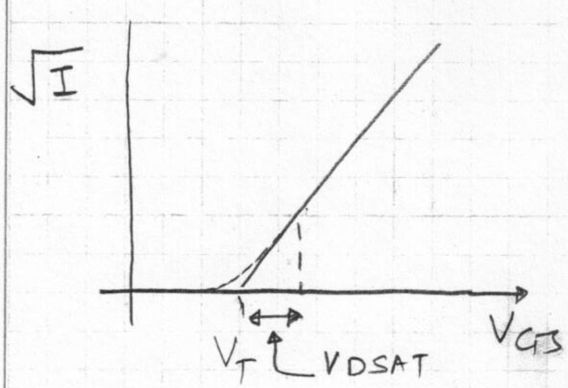
$$= -\frac{2}{V_{DSAT_1}(\lambda_N + \lambda_p)}$$

Insight: To increase gain, reduce V_{DSAT_1} & increase channel length to reduce λ_N, λ_p

★ Can you keep on reducing V_{DSAT} & ↑ gain?

$$V_{DSAT_1} = V_{GS} - V_T = \sqrt{\frac{2I}{\mu C_{ox}\left(\frac{W}{L}\right)}}$$

for given I as you ↑ W/L V_{DSAT} ↓

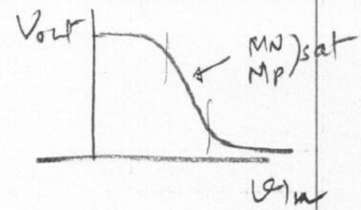


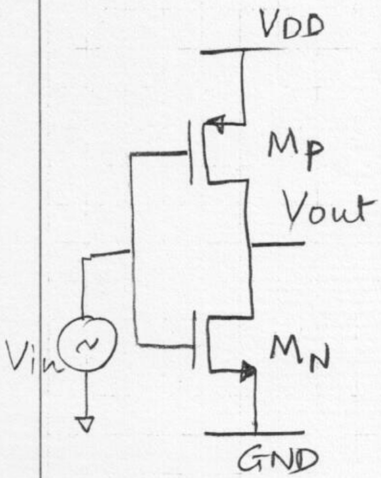
$$I = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_T)^2$$

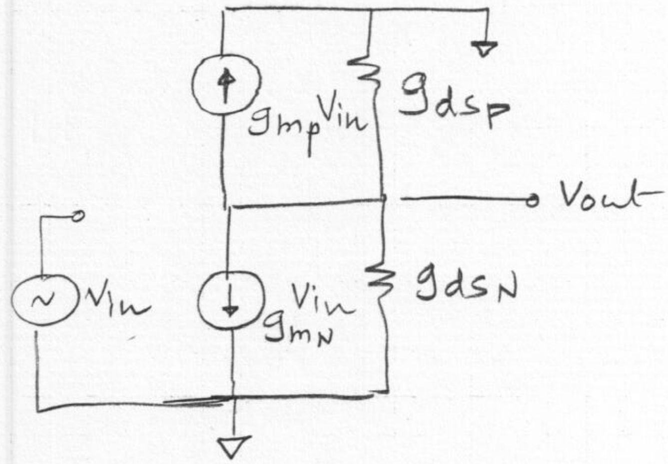
As you keep on reducing $V_{DSAT} = (V_{GS}-V_T)$, V_{GS} very close to V_T
→ sub-threshold operation

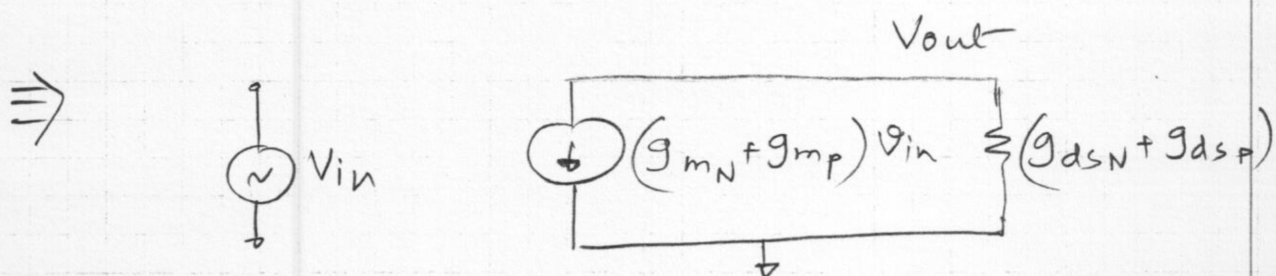
To allow for i/p signal swing & to keep out of subthrsh region $V_{DSAT} > 150\,mV$ (gen. design

CS Amp with Active Load









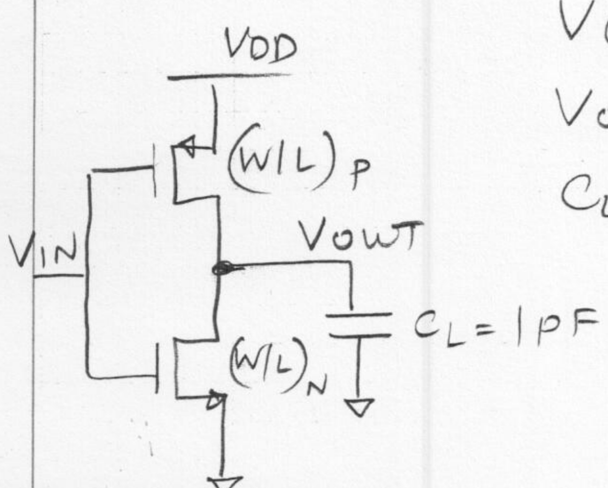
$$A_v = -\frac{(g_{mN} + g_{mp})}{(g_{dsN} + g_{dsp})}$$

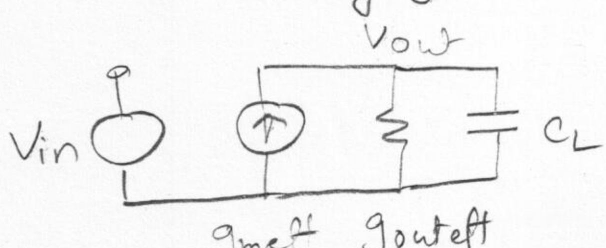
<u>Num. Example:</u> gain $A_v \geq 100$

$V_{out\,min} = 250\text{mV}$

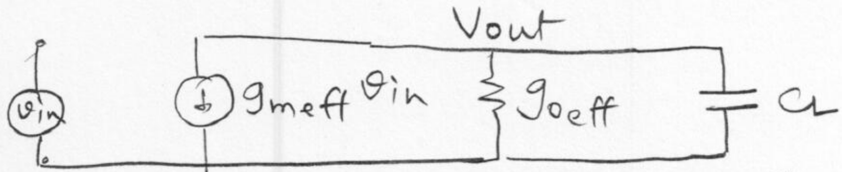
$V_{OUT\,max} = V_{dd} - 250\text{ mV}$

$C_L = 1\text{pF}$: $f_u = 100\text{ MHZ}$ unity gain frequency



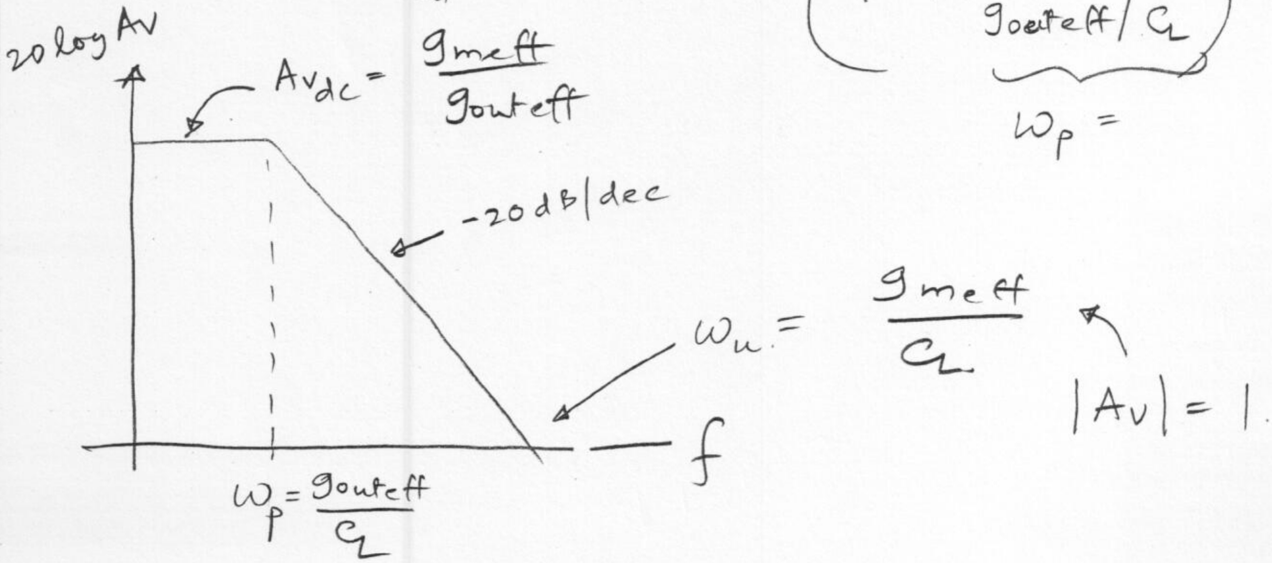


ignoring transistor internal caps. (<< 1pF)



$$v_{out} = \frac{-g_{meff}\, v_{in}}{(g_{oeff} + sC_L)} = \frac{-\dfrac{g_{meff}}{g_{outeff}}}{\left(1 + \underbrace{\dfrac{s}{g_{oeteff}/C_L}}_{\omega_p\, =}\right)}$$

DC gain



$$f_u = \frac{\omega_u}{2\pi} = \frac{1}{2\pi} \cdot \frac{g_{meff}}{C_L} = 100\,\text{MHz}$$

$$g_{meff} = 2\pi C_L * 100\,\text{MHz} = 2 \times \pi \times 1 \times 10^{-12} \times 10^{8}\ \text{S}$$

$$= 628\ \mu\text{S} \quad \text{—— (1)}$$

Symmetric o/p voltage swing $\quad V_{DSATN} = V_{DSATP} = 250\text{m}$

$$\sqrt{\frac{2I}{K_N\left(\frac{W}{L}\right)_N}} = \sqrt{\frac{2I}{K_P\left(\frac{W}{L}\right)_P}} \Rightarrow \left(\frac{W}{L}\right)_P = \frac{K_N}{K_P}(W/L)_N$$

$$K_N = \mu_N C_{ox} = 136.5\ \mu\text{A}/\text{V}^2$$

$$K_P = \mu_P C_{ox} = 39\ \mu\text{A}/\text{V}^2$$

$$\left(\frac{W}{L}\right)_P = \frac{136.5}{39}\left(\frac{W}{L}\right)_N = 3.5\left(\frac{W}{L}\right)_N . \quad \text{—— (2)}$$

$$g_{mn} = g_{mp} = \frac{2I}{V\ldots} =$$

$g_{m\,eff} = g_{mN} + g_{mp} \Rightarrow g_{mN} = g_{mp} = 314\,\mu S$

$\frac{2I}{V_{DSAT}} = 314\,\mu S \Rightarrow I = \frac{314\,\mu S \times 250\,mV}{2}$

$I = 39.25\,\mu A$ ——— 3

To maximize voltage gain

$A_v = \frac{g_{mN} + g_{mp}}{g_{dsN} + g_{dsp}} \Rightarrow g_{dsN} = g_{dsp}$

$g_{dsN} = \lambda_N I$ $\qquad$ $g_{dsp} = \lambda_p I$

$= \frac{0.05}{L_n} I$ (in μm) $\qquad$ $= \frac{0.1}{L_p} I$ (in μm)

$\Rightarrow L_p = 2 L_n$ (Channel Length)

$A_v = \frac{628\,\mu S}{2 \cdot g_{ds}} = 100 \Rightarrow g_{ds_{N,P}} = 3.14\,\mu S$

$\frac{0.05 \times I}{L_n} = 3.14\,\mu S \Rightarrow L_n = \frac{0.05 \times 39.25\,\mu A}{3.14\,\mu S}$

(in μ)

$L_N = 0.625\,\mu m$.

$L_p = 2 \cdot L_N = 1.25\,\mu m$

0.5 μm Technology → grid 0.25 μm

Round up L values to get on grid & make sure $A_v > 100$

$L_N = 0.75\,\mu m$ $\qquad$ $L_p = 1.5\,\mu m$

$$V_{DSAT_N} = \sqrt{\frac{2I}{K_N (W/L)_N}} < 0.25\,V$$

$$\left(\frac{W}{L}\right)_N > \frac{2I}{K_N \cdot (0.25)^2} = \frac{2 \times 39.25\,\mu A}{136.5\,\mu A/V^2 \times (0.25)^2 V^2}$$

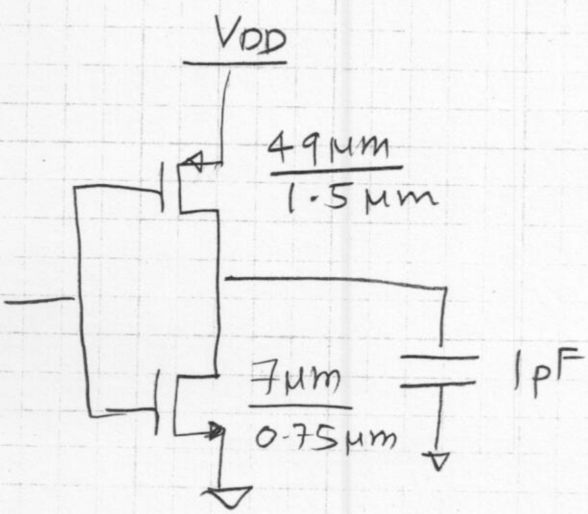
$$= 9.2$$

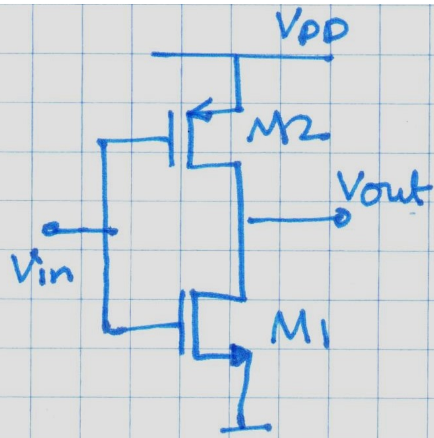
$$W_N > 9.2 \times 0.75\,\mu m = 6.9\,\mu m$$

$$W_N = 7\,\mu m$$

$$\left(\frac{W}{L}\right)_P = 3.5 \times \left(\frac{W}{L}\right)_N \Rightarrow W_P = 3.5 \times \frac{7}{0.75} \times 1.5$$

$$W_P = 49\,\mu m$$





Represents AC behavior of circuit.

DC circuit – different

$V_{Dsat_N} = V_{Dsat_P} = 0.25\,V$

$\therefore V_{GS_N} = V_{T_N} + V_{Dsat\,n} = 0.5 + 0.25$

$= 0.75\,V$

$V_{SG_P} = |V_{T_P}| + V_{Dsat\,p} = 0.6 + 0.25$

$= 0.85\,V$

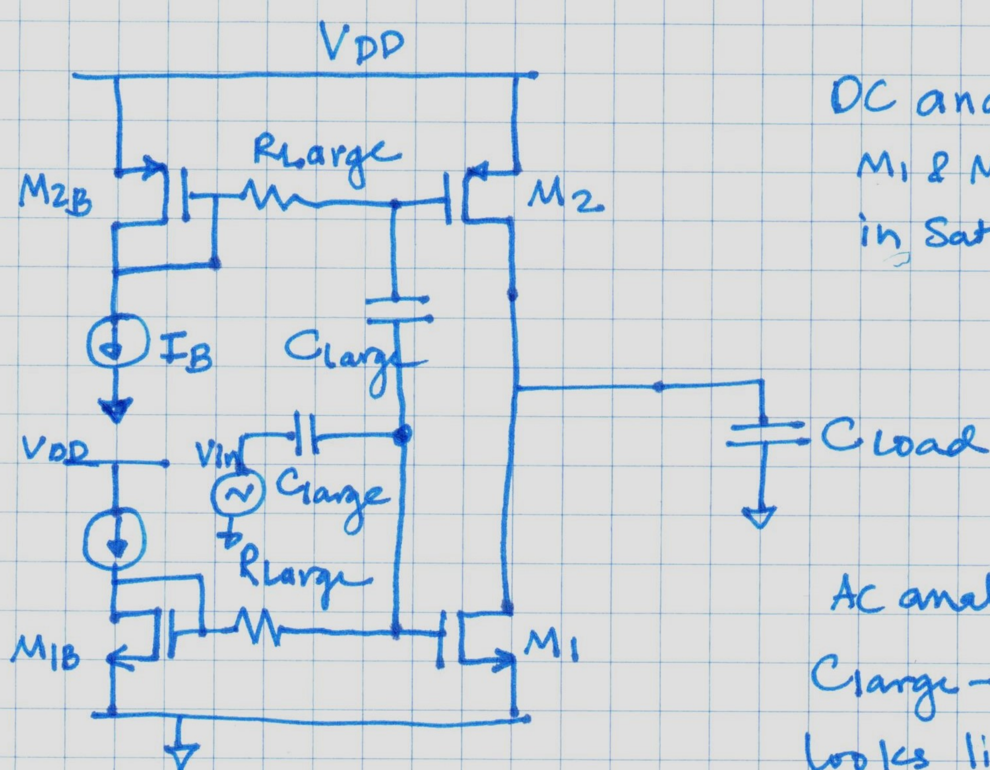
DC condition

$V_{DD} = V_{SG_P} + V_{GS_N}$

$= 0.85 + 0.75 = 1.6\,V$

Satisfied only for $V_{DD} = 1.6\,V$.

Actual circuit implementation DC & AC



DC analysis

M_1 & M_2 are biased in Sat with I_B

AC analysis

C_{large} – short

Looks like inverter amplifier.