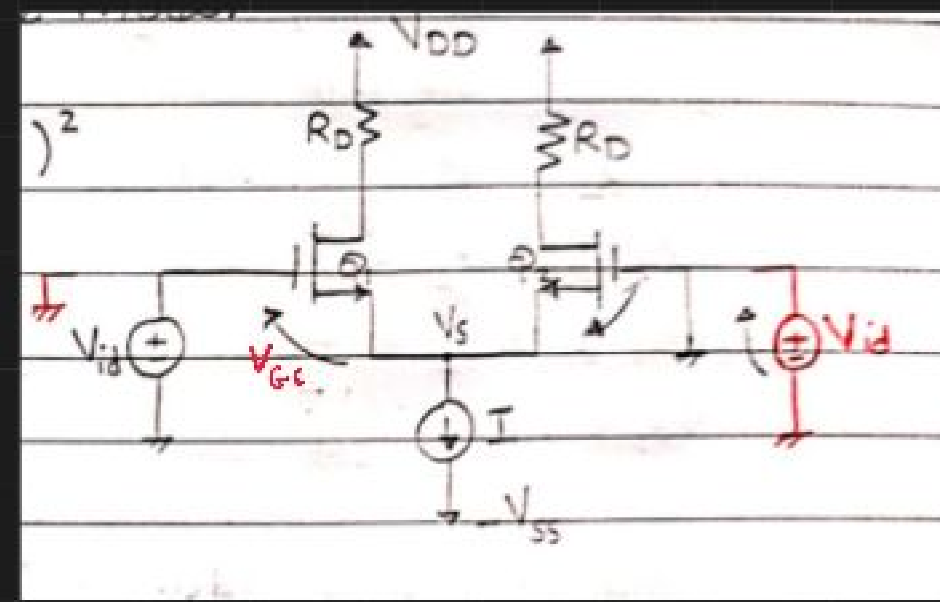
* Operation with a differential input voltage: (difference mode)



→ Current steers on branch only because $V_{G_1}=0$ or $V_{G_2}=0$

- if $V_{G_2}=0$, $V_{G_1}=V_i$ ⇝ $i_{D_1}=I_D$, $i_{D_2}=0$
- $I=\frac{1}{2}k_n'\left(\frac{W}{L}\right)(V_{GS_1}-V_t)^2$ ⇝ $\therefore V_{GS_1}=V_t+\sqrt{\frac{2I}{k_n'\left(\frac{W}{L}\right)}}$

→ from common mode: $\frac{I}{2}=\frac{1}{2}k_n'\left(\frac{W}{L}\right)(V_{ov})^2$

$$\therefore V_{ov}=\sqrt{\frac{I}{k_n'(W/L)}}$$

$\therefore V_{GS_1}=V_t+\sqrt{2}\,V_{ov}$

where V_{ov} is the overdrive voltage corresponding to a current of $\frac{I}{2}$

$\therefore V_{id_{max}}=V_{GS_1}+V_S$

$\therefore i_{D_2}=0$ ⇝ $\therefore$ Cutoff $\therefore V_{GS_2}=V_t$ ⇝ $\therefore \cancel{V_{G_2}}^{0}-V_{S_2}=V_t$ ⇝ $\therefore V_{S_1}=V_{S_2}$ ⇝ $\therefore V_{S_1}=V_{S_2}=-V_t$

$\therefore V_{id_{max}}=\cancel{V_t}+\sqrt{2}\,V_{ov}-\cancel{V_t}$

$\therefore \boxed{V_{id_{max}}=\sqrt{2}\,V_{ov}}$

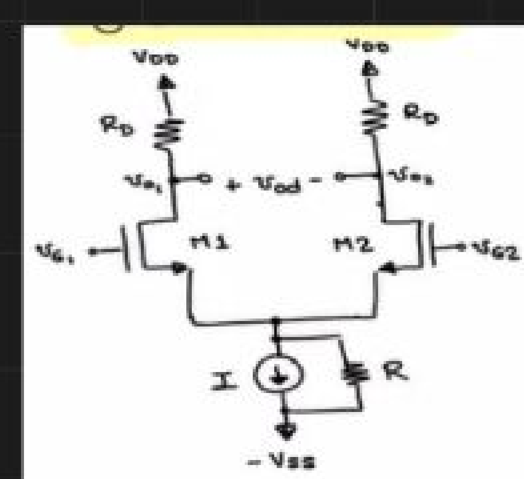
→ $V_{id}>V_{id_{max}}$ will cause all current to steer towards one branch.

So for small differential signal: $|V_{id}|<\sqrt{2}\,V_{ov}$

$$-\sqrt{2}\,V_{ov}\leq V_{id}\leq\sqrt{2}\,V_{ov}$$

- $V_{GS_2}>V_{GS_1}$
  ↳ $I_{D_2}=I$, $I_{D_1}=0$
- $V_{GS_1}>V_{GS_2}$
  ↳ $I_{D_1}=I$, $I_{D_2}=0$

* Large signal operation:



→ $|V_{id}|>\sqrt{2}\,V_{ov}$, taking into consideration that

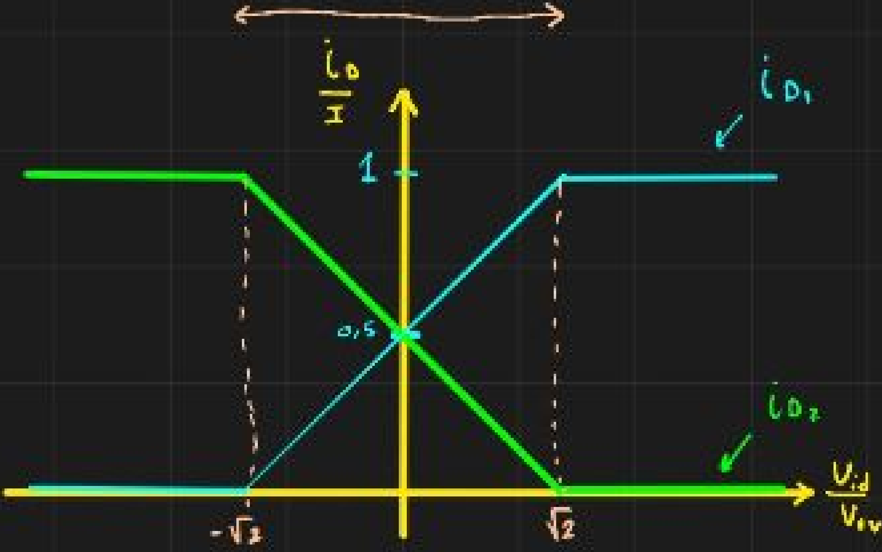
$V_{id}=V_{GS_1}-V_{GS_2}=V_{G_1}-V_{G_2}$, and $i_{D_1}+i_{D_2}=I_D$

→ we can get the following expression:

- $i_{D_1}=\frac{I}{2}+\left(\frac{I}{V_{ov}}\right)\left(\frac{V_{id}}{2}\right)\sqrt{1-\left(\frac{V_{id}}{2V_{ov}}\right)^2}$
- $i_{D_2}=\frac{I}{2}-\left(\frac{I}{V_{ov}}\right)\left(\frac{V_{id}}{2}\right)\sqrt{1-\left(\frac{V_{id}}{2V_{ov}}\right)^2}$

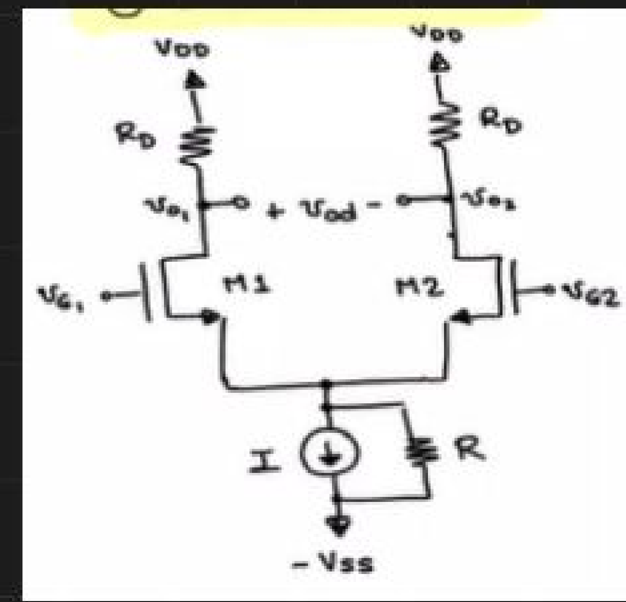
→ normalized plot of current (i_{D_1}, i_{D_2}) vs V_{id}:

region where linear amp is possible



Small signal amp.

★Small signal operations:



→ $V_{id} < \sqrt{2}\, V_{ov}$, $V_{id} << V_{ov}$ ∴ $\frac{V_{id}}{2V_{ov}} <<$

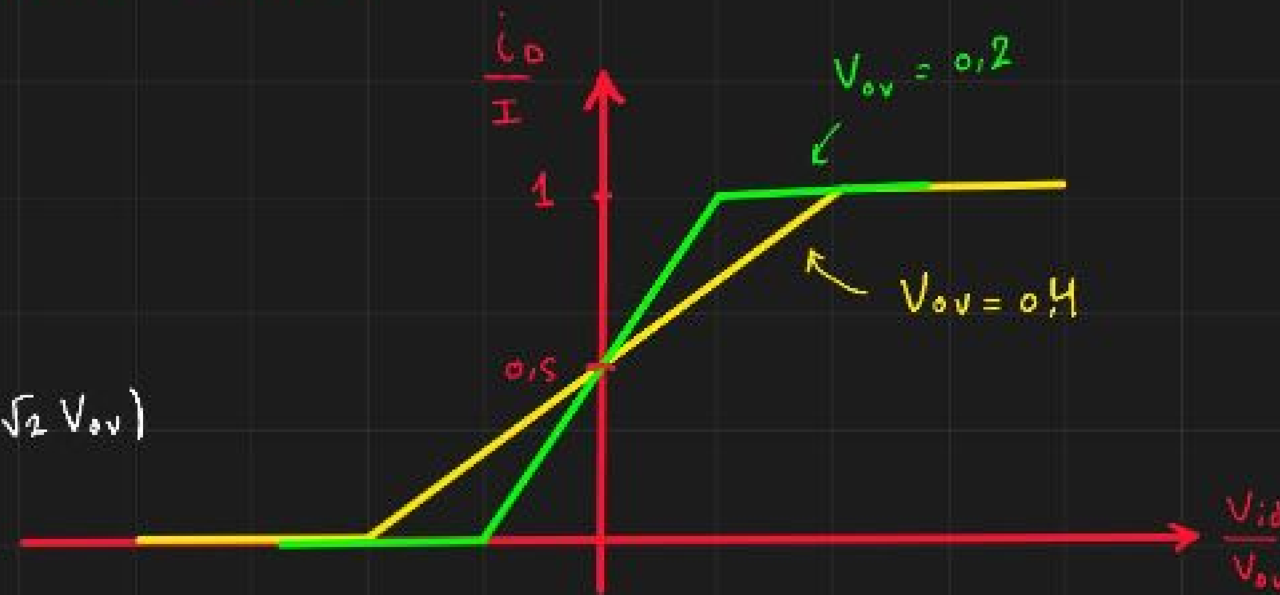
• $i_{D_1} = \frac{I}{2} + (\frac{I}{V_{ov}})(\frac{V_{id}}{2})\sqrt{1-(\frac{V_{id}}{2V_{ov}})^2}$ ⟶ ∴ $i_{D_1} = \frac{I}{2} + \overbrace{(\frac{I}{V_{ov}})(\frac{V_{id}}{2})}^{i_d}$

• $i_{D_2} = \frac{I}{2} - (\frac{I}{V_{ov}})(\frac{V_{id}}{2})\sqrt{1-(\frac{V_{id}}{2V_{ov}})^2}$ ⟶ ∴ $i_{D_2} = \underbrace{\frac{I}{2}}_{\text{Large signal}} - \underbrace{(\frac{I}{V_{ov}})(\frac{V_{id}}{2})}_{\text{Small signal}}$

Large signal DC Component — Small signal Component

• $i_d = (\frac{I}{V_{ov}})(\frac{V_{id}}{2})$, ∴ $g_m = \frac{2I_D}{V_{ov}} = \frac{I}{V_{ov}}$

∴ $i_d = g_m(\frac{V_{id}}{2})$



→ Notes:

1). increasing Vov extends the linear range ($-\sqrt{2}V_{ov} < V_{id} < \sqrt{2}V_{ov}$)

tradeoff: decrease in gain (g_m ↓↓ → $g_m = \frac{2I_D}{V_{ov}}$)

2) decrease Vov gain ↑↑ but linear region ↓↓

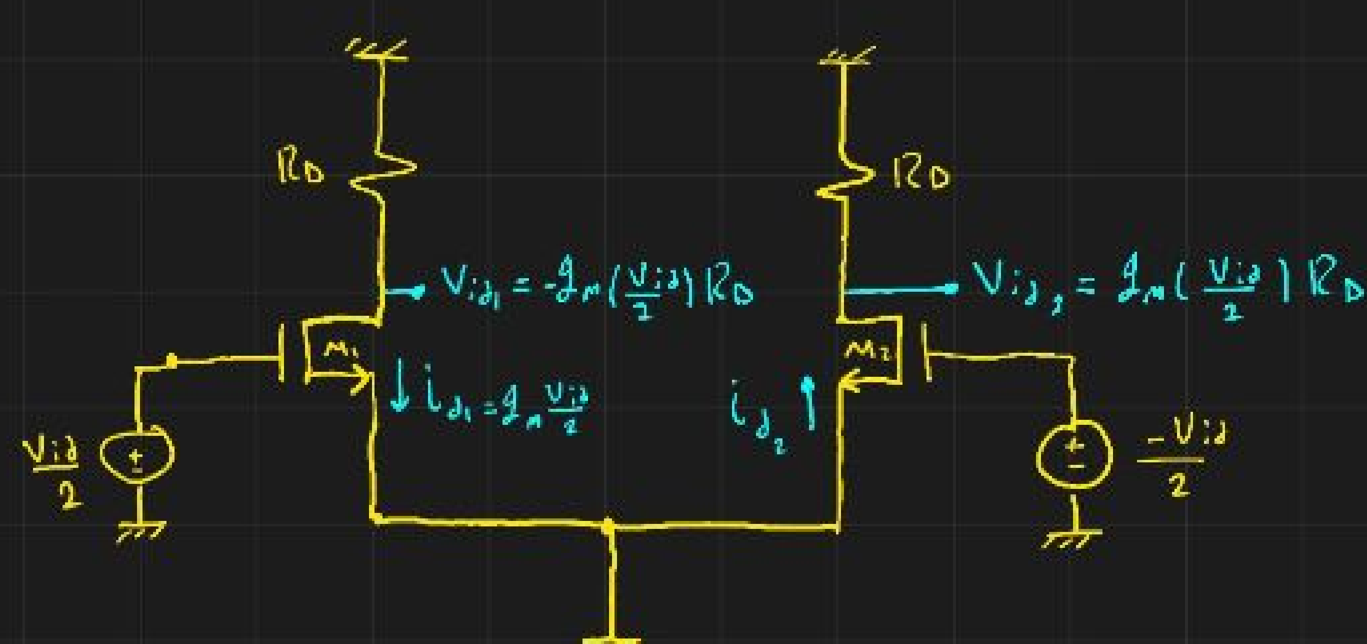
3) we can increas I (bias current) to increase gain

tradoff: higher power dissipation.

→ $V_{G_1} = V_{CM} + \frac{V_{id}}{2}$ → $V_{G_2} = V_{CM} - \frac{V_{id}}{2}$

→ $i_{D_1} = \frac{I}{2} + g_m(\frac{V_{id}}{2})$

→ $i_{D_2} = \frac{I}{2} - g_m(\frac{V_{id}}{2})$

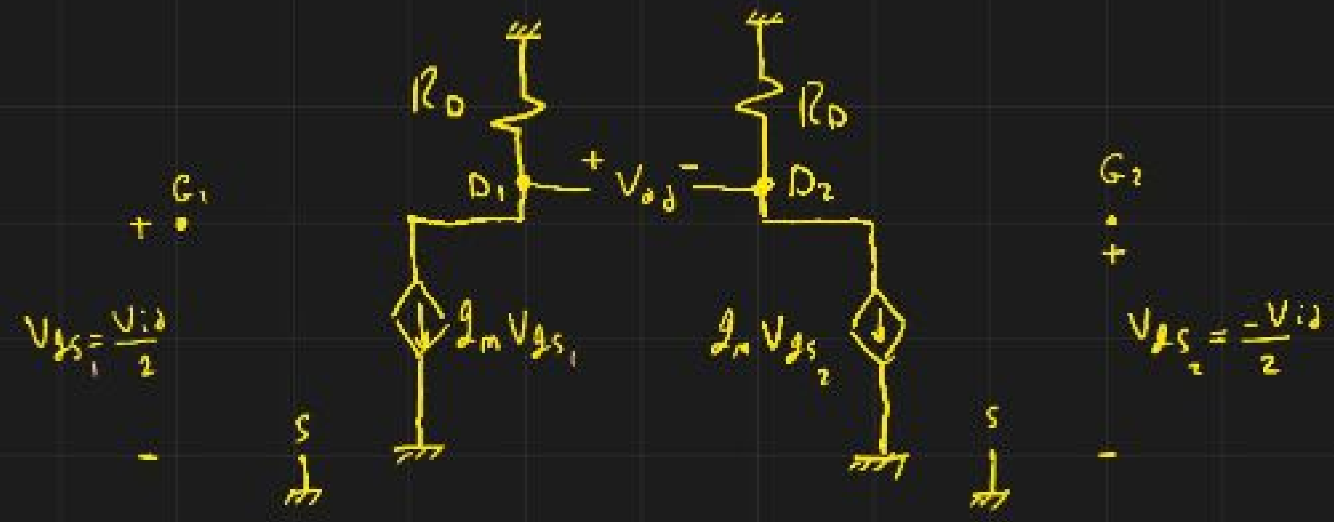


∴ $V_{D_1} = (V_{DD} - \frac{I}{2}R_D) - g_m(\frac{V_{id}}{2})R_D$

∴ $V_{D_2} = \underbrace{(V_{DD} - \frac{I}{2}R_D)}_{DC} + \underbrace{g_m(\frac{V_{id}}{2})R_D}_{AC}$

→ $A_d = \frac{V_{od}}{V_{id}} = \frac{V_{od_1} - V_{od_2}}{V_{id}} = \frac{-g_m \cancel{V_{id}} R_D}{\cancel{V_{id}}}$ ⟶ ∴ $A_d = -g_m R_D$

. AC equivalent circuit:



$V_{od} = V_{d_1} - V_{d_2}$

$\rightarrow V_{d_1} = -g_m V_{gs_1} R_D = -g_m \frac{V_{id}}{2} R_D$

$\rightarrow V_{d_2} = -g_m V_{gs_2} R_D = g_m \frac{V_{id}}{2} R_D$

$\therefore V_{od} = -g_m V_{id} R_D$

$\therefore A_{v_d} = \frac{V_{od}}{V_{id}} \rightsquigarrow \therefore A_{v_d} = -g_m R_D$

→ diff. amp. cancels noise because it's applied to both terminals.

→ gain of diff. amp = 2 gain of each trans.

→ note that the o/p at D_1 will be flibed ($V_{d_1} = -g_m V_{gs} R_D$)

$i_{D_1} = g_m \left(\frac{V_{id}}{2} \right)$

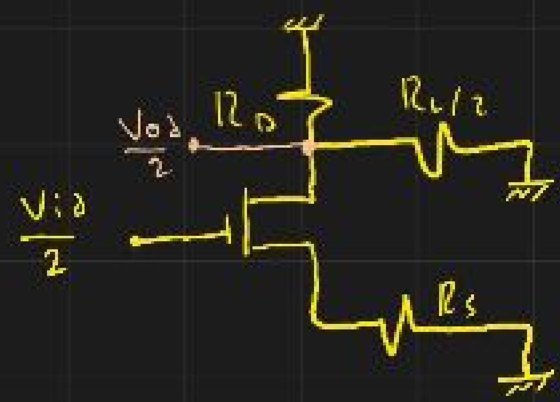
$i_{D_2} = -g_m \left(\frac{V_{id}}{2} \right)$

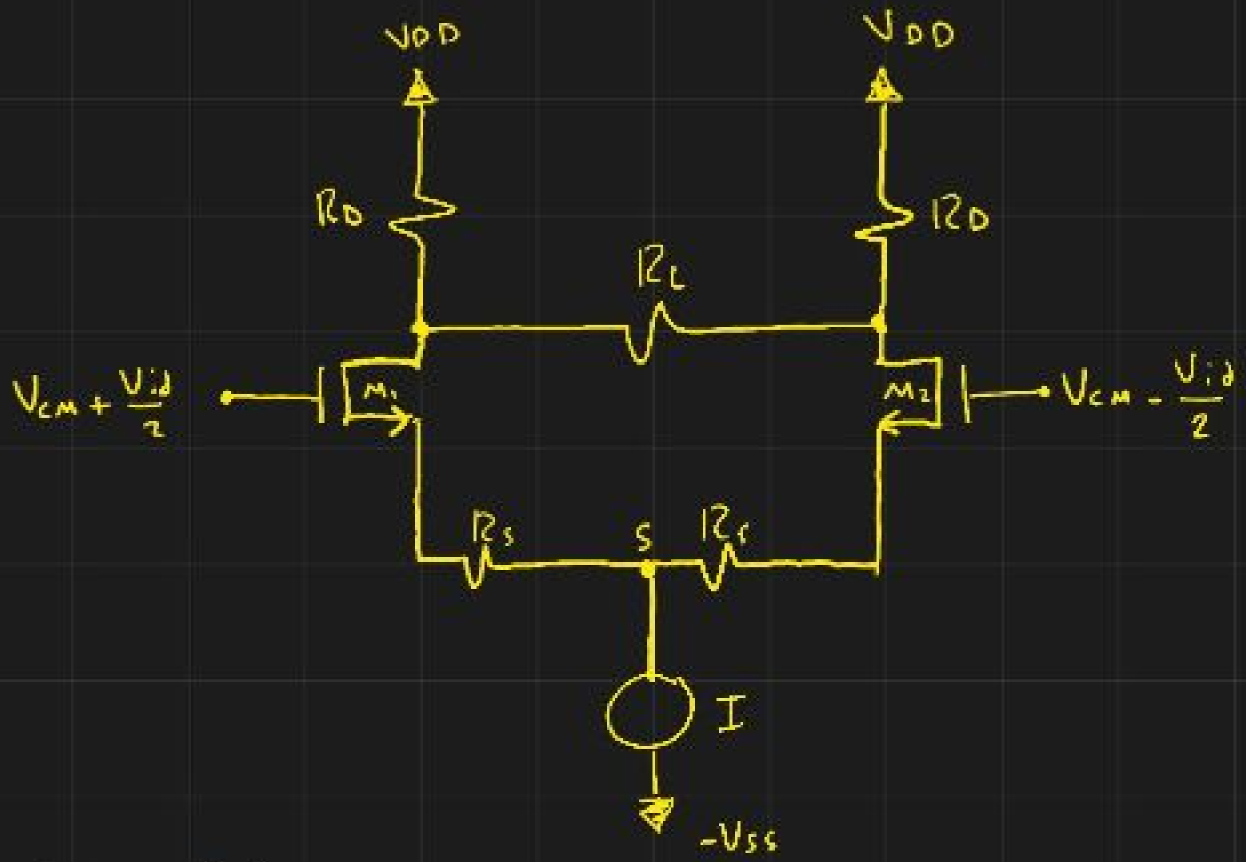
$i_{D_1} + i_{D_2} = I \; , \; g_m = \frac{I}{V_{ov}}$

. Ex (9.2) Page (621)

→ get diff voltage gain $A_d = ?$

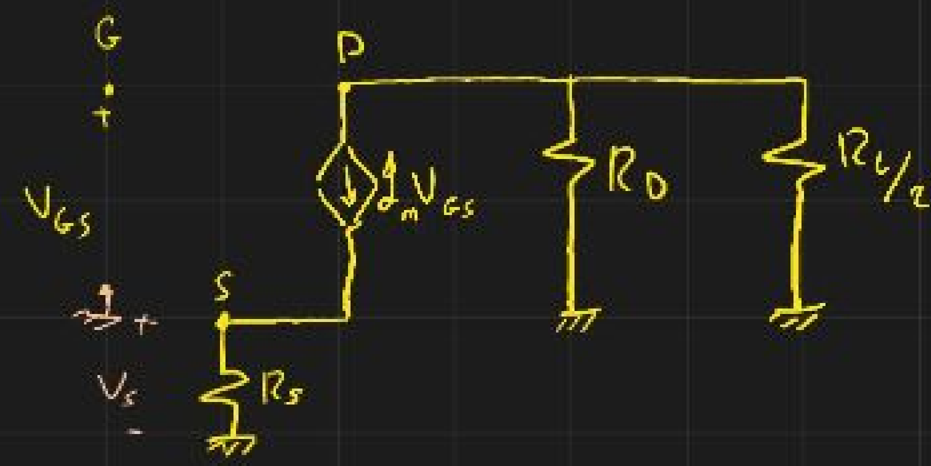
→ AC analsys (half circuit):





→ at first glance (Rs ussully very small) → $A_d = -g_m (R_D // \frac{R_L}{2})$

→ Small signal model:



$. A_{vd} = \frac{V_{od}}{V_{id}} = \frac{V_{od}/2}{V_{id}/2} = \frac{V_D}{V_G}$

$\rightarrow V_D = -g_m V_{GS} (R_D // \frac{R_L}{2}) \rightarrow ①$, $V_{GS} = V_G - V_S = \frac{V_{id}}{2} - V_S$

$\therefore V_D = -g_m (\frac{V_{id}}{2} - V_s)(R_D // \frac{R_L}{2})$

$\therefore V_s = g_m V_{GS} R_s = g_m (\frac{V_{id}}{2} - V_s) R_s$

$\therefore V_s = g_m \frac{V_{id}}{2} R_s - g_m V_s R_s \rightarrow \therefore V_s (1 + g_m R_s) = g_m \frac{V_{id}}{2} R_s \rightarrow \therefore V_s = \frac{g_m \frac{V_{id}}{2} R_s}{1 + g_m R_s}$

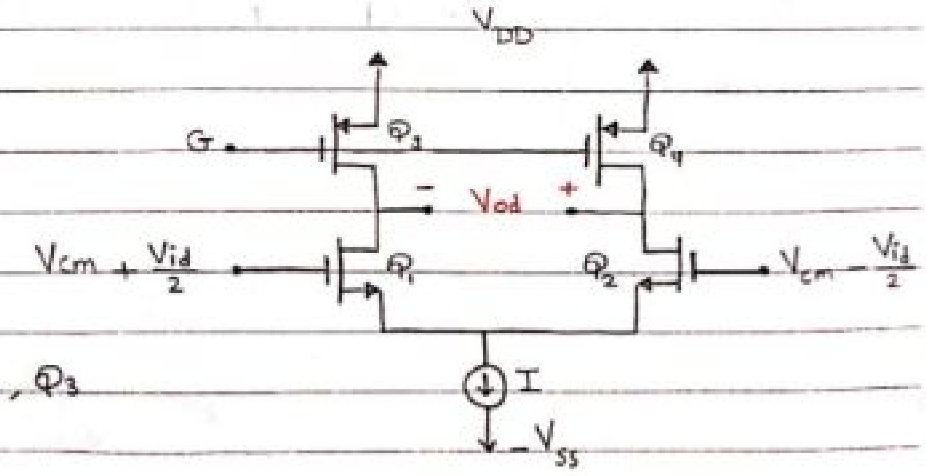
$\therefore V_{GS} = V_G - V_s = \frac{V_{id}}{2} - \frac{g_m (V_{id}/2) R_s}{1 + g_m R_s} = \frac{V_{id} + \cancel{V_{id} g_m R_s} - \cancel{V_{id} g_m R_s}}{2(1 + g_m R_s)} = \frac{V_{id}/2}{1 + g_m R_s}$

$\therefore ① \rightarrow V_D = -g_m (\frac{V_{id}/2}{1 + g_m R_s})(R_D // \frac{R_L}{2})$

$\therefore A_{vd} = \frac{V_D}{V_{id}/2} \longrightarrow \therefore \boxed{A_{vd} = -g_m (\frac{1}{1 + g_m R_s})(R_D // \frac{R_L}{2})}$

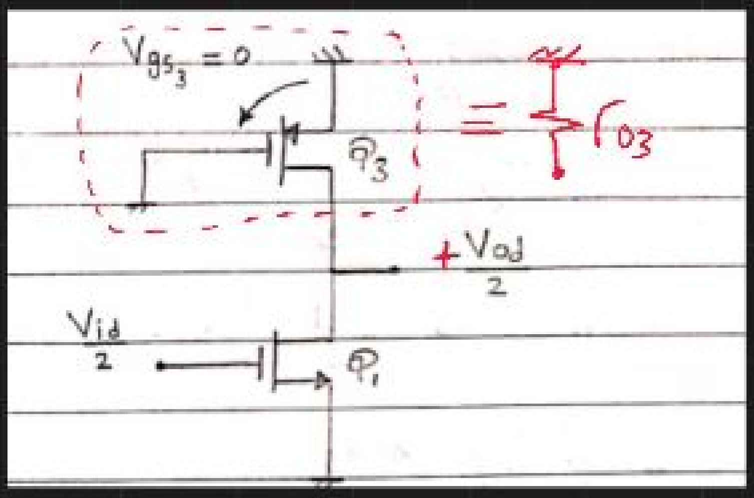
* The differential amplifier with Current source Loads
Page (622)

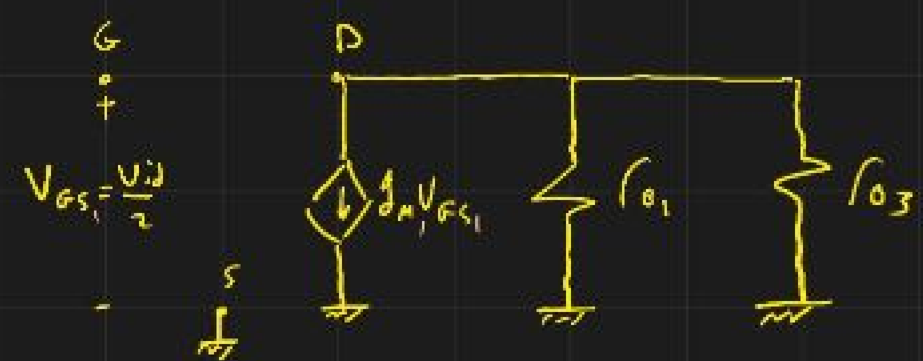
Get $A_d = \frac{V_{od}}{V_{id}}$



Q_4, Q_3 عندهم نفس ال V_G

→ AC analysis (half circuit) → Q_3 is considered a load and it's o/p resistance is r_{o3}
So in the small signal model Q_3, Q_4 will be replaced by r_{o3}, r_{o4}





→ $A_{vd} = \frac{V_{od}}{V_{id}} = \frac{V_{od}/2}{V_{id}/2} = \frac{V_D}{V_{GS}}$

→ $V_D = -g_{m_1} V_{GS_1} (r_{o1} \parallel r_{o3})$

→ $\therefore A_{vd} = -g_{m_1} (r_{o1} \parallel r_{o3})$