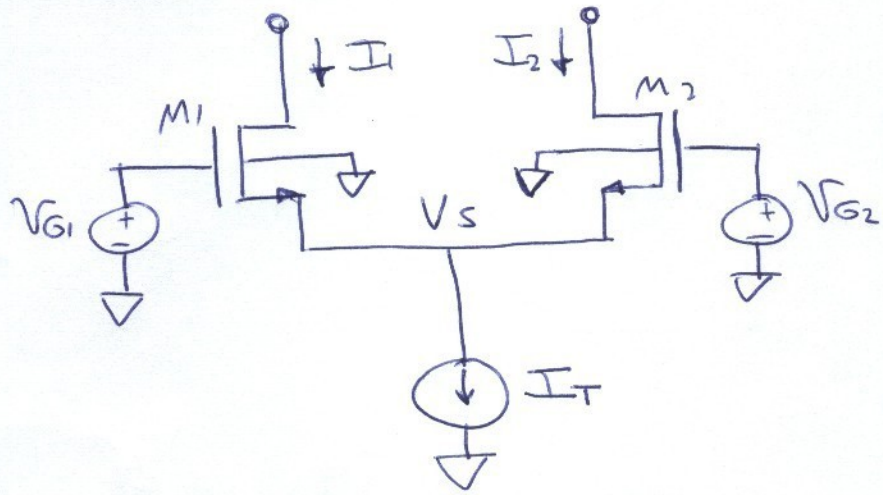
DIFFERENTIAL AMPLIFIER: SOURCE-COUPLED PAIR



$V_{ID} = V_{G1} - V_{G2}$

- ASSUME $M1 = M2$, AND BOTH IN ACTIVE REGION ($i_f \gg i_r$)

$$\left.\begin{aligned} I_{OD} &= I_1 - I_2 \\ I_T &= I_1 + I_2 \end{aligned}\right\} \Rightarrow \begin{cases} I_1 = \dfrac{I_{OD}+I_T}{2} \\ I_2 = \dfrac{I_T - I_{OD}}{2} \end{cases}$$

$$\begin{cases} \dfrac{V_{P1} - V_S}{V_T} = \mathcal{F}\left(\dfrac{I_1}{I_S}\right) & \text{(SAME FOR M2)} \\ V_{P1} \cong \dfrac{V_{G1} - V_{th}}{n} \end{cases}$$

$$\frac{V_{G1} - V_{th}}{n V_T} - \frac{V_S}{V_T} = \mathcal{F}\left(\frac{I_1}{I_S}\right)$$

$$\therefore \mathcal{F}\left(\frac{I_1}{I_S}\right) - \mathcal{F}\left(\frac{I_2}{I_S}\right) = \frac{V_{G1} - V_{G2}}{n V_T} = \frac{V_{ID}}{n V_T}$$

$$\boxed{\frac{V_{ID}}{n V_T} = \mathcal{F}\left(\frac{I_{OD}+I_T}{2}\right) - \mathcal{F}\left(\frac{I_T - I_{OD}}{2}\right)}$$

NOTE: INDEPENDENT OF V_S

- WEAK INVERSION:

$$\frac{I_{OD}}{I_T} = \tanh\left(\frac{V_{ID}}{2 n V_T}\right) \quad \text{(SAME AS WITH BJTs)}$$

(SATURATION FOR $|V_{ID}| \gtrsim 4 n V_T$)

- STRONG INVERSION

$$\frac{I_{OD}}{I_T} = \frac{V_{ID}}{n V_T \sqrt{\frac{I_T}{I_S}}} \sqrt{2 - \left(\frac{V_{ID}}{n V_T \sqrt{\frac{I_T}{I_S}}}\right)^2} \quad , \quad \frac{|V_{ID}|}{n V_T \sqrt{\frac{I_T}{I_S}}} \leq 1$$

(SATURATION FOR $|V_{ID}| > \underbrace{n V_T \sqrt{\frac{I_T}{I_S}}}$)

OVERDRIVE VOLTAGE TO CONDUCT I_T THROUGH M_1 OR M_2

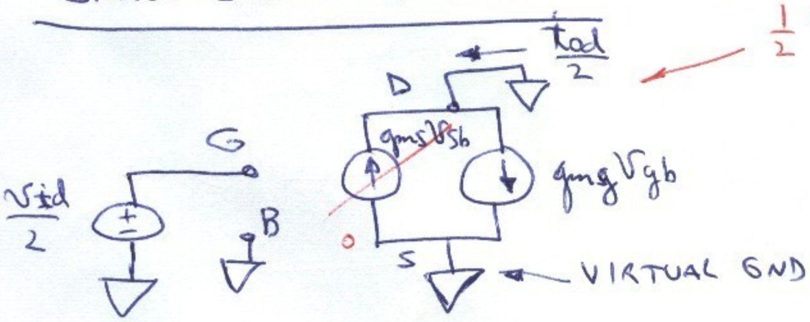
OBSERVATION: FOR VERY SMALL V_{ID}, $\frac{I_{OD}}{I_T}$ CAN BE APPROXIMATED LINEAR:

W.I.) $$\frac{I_{OD}}{I_T} \simeq \frac{V_{ID}}{2 n V_T}$$

S.I.) $$\frac{I_{OD}}{I_T} \simeq \frac{\sqrt{2}}{n V_T \sqrt{\frac{I_T}{I_S}}} \cdot V_{ID}$$

SMALL-SIGNAL ANALYSIS: (TO CONFIRM THIS)

$\frac{1}{2}$ DIFFERENTIAL CIRCUIT.



$$\underbrace{g_{mg}}_{= g_m} = \frac{2 I_S}{n V_T} \left(\sqrt{1+i_f} - 1\right)$$

$$i_f = \frac{I_T}{2 I_S}$$

$$\frac{i_{od}}{2} = g_m \frac{v_{id}}{2}$$

$$i_{od} = g_m v_{id}$$

WI: $i_{od} \simeq \frac{2 I_S}{n V_T} \frac{i_f}{2} v_{id} = \frac{I_T}{2 n V_T} v_{id}$ ✓

S.I: $i_{od} \simeq \frac{2 I_S}{n V_T} \sqrt{i_f}\, v_{id}$

$= \frac{2 I_S}{n V_T} \sqrt{\frac{I_T}{2 I_S}}\, v_{id}$ ✓

COMMON-MODE INPUT RANGE

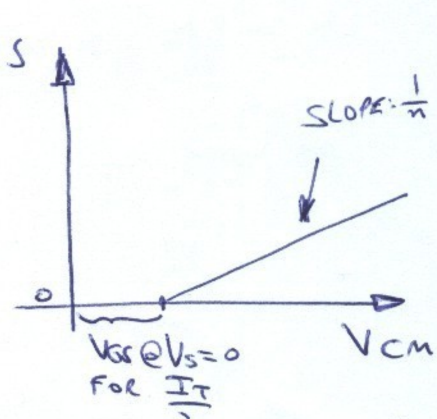
- COMMON-MODE VOLTAGE CONTROLS: $\underline{V_S}$
- ASSUME: $V_{G1} = V_{G2} = V_{CM}$

$$\overset{(1)}{V_P = \frac{V_{CM} - V_{th}}{n}}, \quad \overset{(2)}{\frac{V_P - V_S}{V_T} = \mathcal{F}(i_f)}, \quad \overset{(3)}{i_f = \frac{I_T}{2 I_S}}$$

$$V_S = -V_T\, \mathcal{F}\left(\frac{I_T}{2 I_S}\right) + \frac{V_{CM} - V_{th}}{n}$$

$$= \frac{V_{CM}}{n} - \underbrace{\text{CONSTANT}}_{C_1}$$

(ASSUMING n = CONSTANT)



- 2 LIMITS
  - CURRENT SOURCE NEEDS MINIMUM V_S TO WORK.
  - M_{1-2} NEED $V_{DS_{SAT}}$ TO BE ACTIVE

$$V_{S_{MIN}} \leq V_S \leq V_D - V_{DS_{SAT}}$$

$$V_{S_{MIN}} \leq \frac{V_{CM}}{n} - C_1 \leq V_D - V_{DS_{SAT}}$$

$$\boxed{n\left(V_{S_{MIN}} + C_1\right) \leq V_{CM} \leq n\left(V_D - V_{DS_{SAT}} + C_1\right)}$$

EXAMPLE (7.6 SCHNEIDER/GALUP)

$I_T = 140\ nA$

$V_{D1} = V_{D2} = 3.3\ V$

$V_{S_{MIN}} = 100\ mV$

$V_{th} = 0.5V$

$n = 1.2$

$I_{SQ} = 70\ nA$

a) $\frac{W}{L} = 100$

$$i_f = \frac{140\,nA}{2 \times \underbrace{70nA \times 100}_{I_s}} = 0.01 \quad (W.I.)$$

$$V_{DS_{SAT}} = V_T\left(\sqrt{1+i_f} + 3\right) = 104\,mV$$

$$C_1 = \frac{V_{th}}{n} + V_T\, \mathcal{G}(i_f) = 0.5V + 26mV\, \underbrace{\mathcal{G}(0.01)}_{=-6.3} = 0.253V$$

$$\boxed{0.423V \le V_{CM} \le 4.14V}$$

← CAN GO LOWER IN W.I.

b) $\left.\begin{array}{l}\frac{W}{L} = 0.01 \\ i_f = 100\end{array}\right\} \longrightarrow \boxed{0.93V \le V_{CM} \le 4.37V}$

INPUT OFFSET VOLTAGE

ASSUME: $V_{th_1} = V_{th_2} + \Delta V_{th}$, $I_{s_1} = I_{s_2} + \Delta I_s$

$$I_D \simeq I_s\, i_f(V_G - V_{th}, V_s)$$

~~$$I_D \simeq I_{D_0} + I_s\left[\frac{\partial i_f}{\partial V_G}\Delta V_G - \frac{\partial i_f}{\partial V_{th}}\Delta V_{th} + \partial I_s\right]$$~~

$$I_{D_2} = I_{D_1} + \underbrace{\frac{\partial I_D}{\partial I_s}}_{=i_f}\Delta I_s + \underbrace{\frac{\partial I_D}{\partial V_G}}_{=g_m}\Delta V_G + \frac{\partial I_D}{\partial V_{th}}\Delta V_{th}$$

$$I_{D_2} - I_{D_1} = \Delta I_s + g_m(\Delta V_G - \Delta V_{th})$$

$$\frac{\Delta I_D}{I_D} = \frac{\Delta I_s}{I_s} + \frac{g_m}{I_D}(\Delta V_G - \Delta V_{th})$$

$$\Delta V_G\Big|_{\frac{\Delta I_D}{I_D}=0} = -\frac{I_D}{g_m}\frac{\Delta I_s}{I_s} + \Delta V_{th}$$

$$g_m = \frac{2 I_D}{n V_T} \frac{1}{\sqrt{1+i_f}+1}$$

$$V_{os} = \Delta V_G = -\frac{n V_T}{2}\left(\sqrt{1+\frac{I_T}{2 I_S}}+1\right)\frac{\Delta I_S}{I_S} + \Delta V_{th}$$ OFFSET VOLTAGE

NOTES:

1. CAN NOT CANCEL ΔV_{Th} WITH ΔI_S BECAUSE SIGNS UNKNOWN
2. $\frac{\Delta I_S}{I_S}$ BECOMES LESS IMPORTANT IN MODERATE/WEAK INVERSION → BETTER THAN STRONG INVERSION.

EXAMPLE:

$I_T = [100\,nA, 2\,mA]$

$I_S = 1\,\mu A$

$\Delta V_{th} = 1\,mV$

$\Delta I_S = 10\,nA$

$n = 1.2$

$V_T = 25\,mV$

} WORST-CASE V_{os}?

$$V_{os} = [0.3\,mV + 1\,mV,\ 4.8\,mV + 1\,mV]$$

DIFF-MODE & COMMON-MODE SMALL-SIGNAL ANALYSIS (NEEDS RESISTIVE LOAD AT LEAST)

(TAKE FROM OLD NOTES)