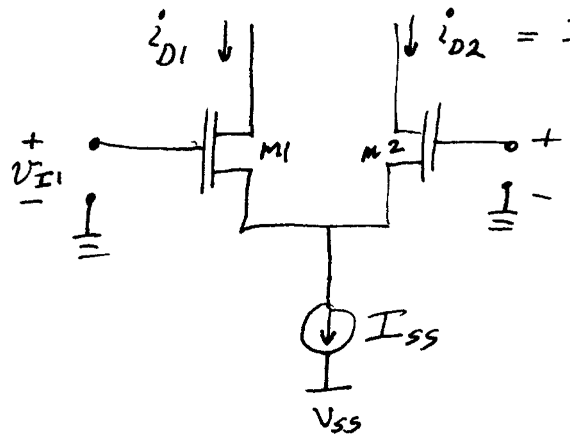
CH 24

Differential Amps   Diff-Amp

24.1 SOURCE Coupled Pair



$i_{D2} = I_{D2} + i_{d2}$ = total I.

$v_{I2} = V_{G2} + v_{g2}$ = total V.

$\beta_1 = \beta_2 = \beta$

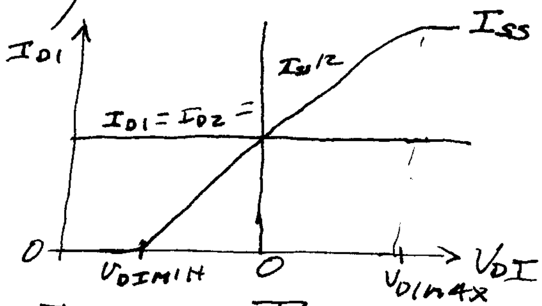
$V_{TH1} = V_{TH2}$

- Define $v_{DI} = v_{I1} - v_{I2} =$

$$= v_{G1} - v_{G2} = v_{G1} - \cancel{v_{S1}} - (v_{G2} - \cancel{v_{S2}})$$

$$= v_{GS1} - v_{GS2}$$

$$v_{DI} = \sqrt{\frac{2}{\beta}}\left(\sqrt{i_{D1}} - \sqrt{i_{D2}}\right)$$



- ~~GROUND $v_{I2} = 0$~~
- $\dfrac{v_{DIMAX}}{\cancel{v_{DI} = v_{I1}}}$
- FIX v_{I2} & $\uparrow v_{I1}$ until ~~$I_{SS} = I_{D1}$~~

$$\boxed{v_{DIMAX} = \sqrt{\frac{2 I_{SS}}{\beta}}}$$

$$\left\{\begin{array}{l} I_{D1} = I_{SS} \\ I_{D2} = 0 \end{array}\right.$$

M2 turning off

$\Rightarrow V_S = v_{I2} - V_{THN}$

- $v_{DI\,MIN}$

$\downarrow v_{I1}$ until M1 shuts off, $I_{D2} = I_{SS}$

$v_S = v_{I1} - V_{THN}$ $\boxed{v_{DIMIN} = -v_{DIMAX}}$

$v_{GS2} = v_{I2} - v_{I1} + V_{THN} = -v_{DIMIN} + V_{THN}$

Differential Transconductance

$$G_m \equiv \left.\frac{di_{D1}}{dv_{DI}}\right|_{v_{DI}=0} = ?$$

$$v_{DI} = \sqrt{\frac{2}{\beta}}\left[\sqrt{i_{D1}} - \sqrt{i_{D2}}\right]$$

$$dv_{DI} = \sqrt{\frac{2}{\beta}}\left[\frac{1}{2}\frac{1}{\sqrt{i_{D1}}}di_{D1} - \frac{1}{2}\frac{1}{\sqrt{i_{D2}}}\frac{\partial i_{D2}}{\partial i_{D1}}di_{D1}\right]$$

$$i_{D2} = I_{SS} - i_{D1}$$

$$\frac{\partial i_{D2}}{\partial i_{D1}} = -1$$

$$\left.\frac{di_{D1}}{dv_{DI}}\right|_{v_{DI}=0} = \sqrt{\frac{\beta}{2}}\,\frac{1}{\frac{1}{2}\frac{1}{\sqrt{\frac{I_{SS}}{2}}} + \frac{1}{2}\frac{1}{\sqrt{\frac{I_{SS}}{2}}}}$$

$$= \sqrt{\frac{\beta}{2}}\sqrt{\frac{I_{SS}}{2}} = \frac{\sqrt{\beta I_{SS}}}{2}$$

$$= \frac{1}{2}\sqrt{2\beta\underbrace{(I_{SS}/2)}_{I_{D1}}} = \frac{g_m}{2}$$

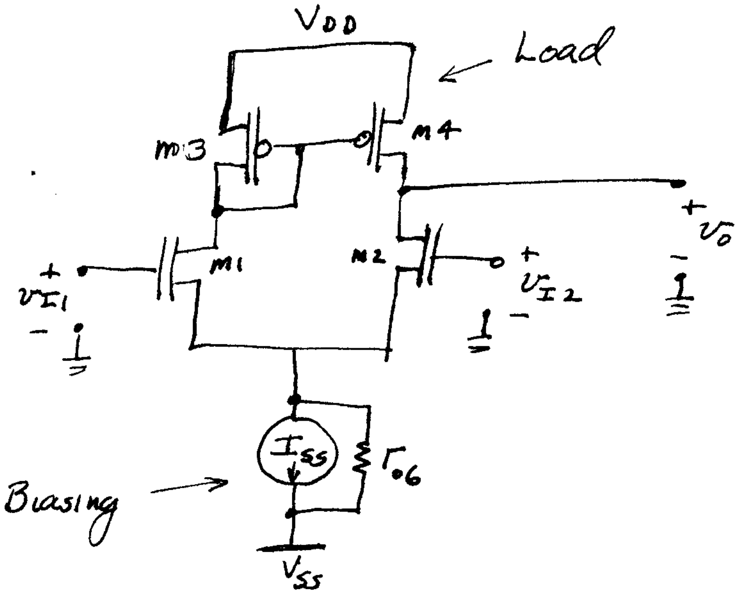
$$I_D = \frac{\beta}{2}(V_{GS} - V_t)^2$$

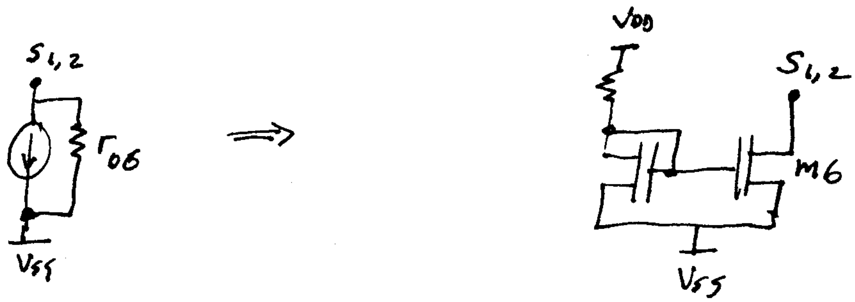
$$\frac{\partial I_D}{\partial V_{GS}} = \beta(V_{GS} - V_t)$$

$$= \sqrt{I_D\beta 2}$$

Compare (24.12)

CURRENT SOURCE LOAD (24.1.1)





Common Mode Range (CMR)

SET $v_{I1} = v_{I2} = v_I$

V_{Imin}

- As $v_I \rightarrow V_{SS}$, $V_{DS,6} < (V_{GS6} - V_{THN})$
  $M6 \rightarrow$ triode.

$$v_{IMIN} - V_{GS1} - v_{DS6} - V_{SS} = 0$$

$$\boxed{V_{IMIN} = \sqrt{\frac{I_{SS}}{\beta_1}} + V_{THN} + \sqrt{\frac{2I_{SS}}{\beta_6}} + V_{SS}}$$

W6

V_{Imax} ~~$v_{IMAX} =$~~

- As $V_I \rightarrow V_{DD}$, m1 & m2 $\rightarrow$ triode

$$v_{DS1} = v_{GS1} - V_{THN}$$

$$v_{D1} = v_{G1} - V_{THN}$$

$$v_{IMAX} = v_{G1} = V_{D1} + V_{THN}$$

$$v_{IMAX} = V_{DD} - v_{SG3} + V_{THN}$$

$$\cancel{V_{D1} + v_{SG1} + V}$$

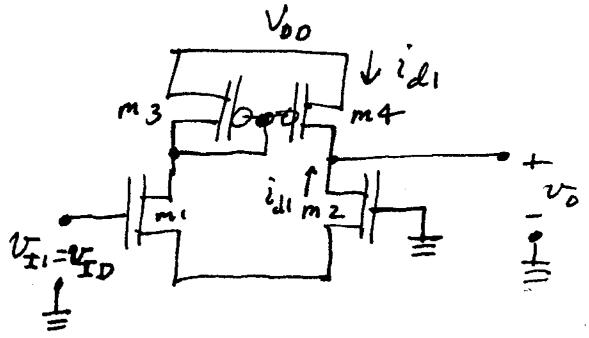
$$V_{D1} = V_{DD} - v_{SG3}$$

$$v_{IMAX} = V_{DD} - \underbrace{\left[\sqrt{\frac{I_{SS}}{\beta_3}} + V_{THP}\right]}_{V_{SG3}} + V_{THN}$$

$$\boxed{v_{IMAX} \approx V_{DD} - \sqrt{\frac{I_{SS}}{\beta_3}}}$$

SMALL SIGNAL GAIN

- Ground G2



$$v_{I1} = v_{ID} = v_{gs1} - v_{gs2} = \frac{i_{d1}}{g_{m1}} - \frac{i_{d2}}{g_{m2}}$$

$$i_{d1} = -i_{d2} = i_d$$

$$v_{i1} = i_d \frac{2}{g_m} \implies i_d \frac{g_m}{2} v_{i1}$$

Total I flowing into output node is
$2\ i_d$

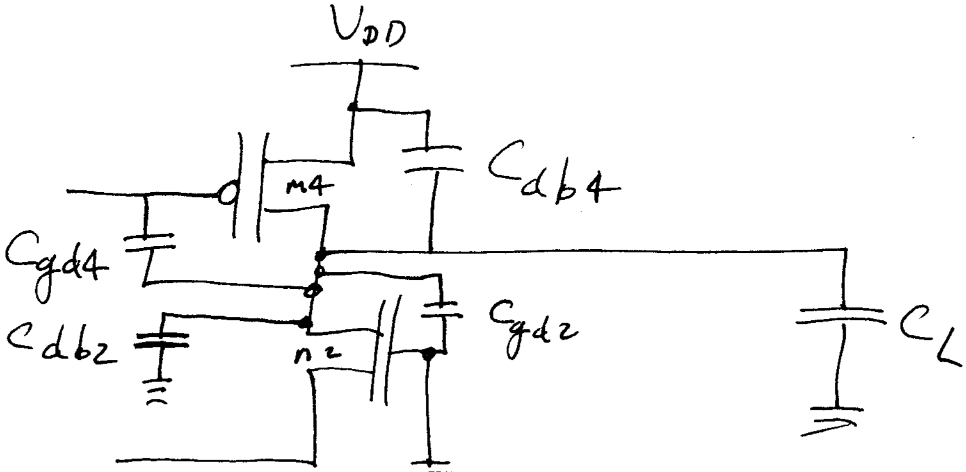
$$v_o = 2 i_d\ r_{o2} \| r_{o4} = g_m v_{i1}\ r_{o2} \| r_{o4}$$

$$A_{vd} = \frac{v_o}{v_{i1} - v_{i2}} = g_m\ r_{o2} \| r_{o4}$$

$$r_o = \frac{1}{\lambda I_{ss}/2} \qquad g_m = \sqrt{\beta I_{ss}}$$

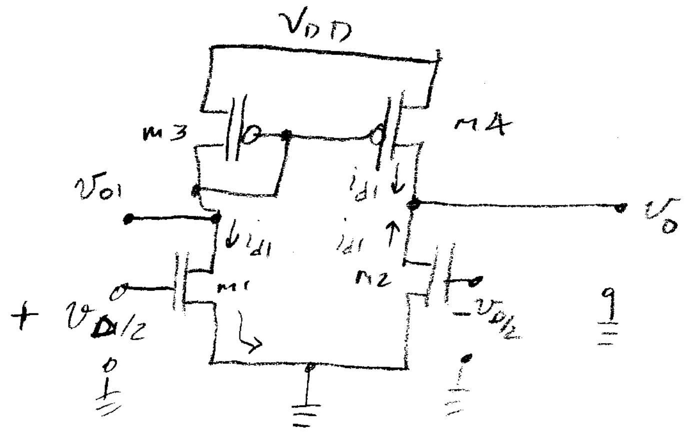
$$A_{vd} = \frac{\sqrt{\beta I_{ss}}}{(\lambda_2 + \lambda_4)\frac{I_{ss}}{2}} = \frac{2\sqrt{\beta}}{(\lambda_4 + \lambda_2)\sqrt{I_{ss}}}$$

SMALL SIGNAL FREQ. RESPONSE



$$R_o = r_{o2} \| r_{o4}$$

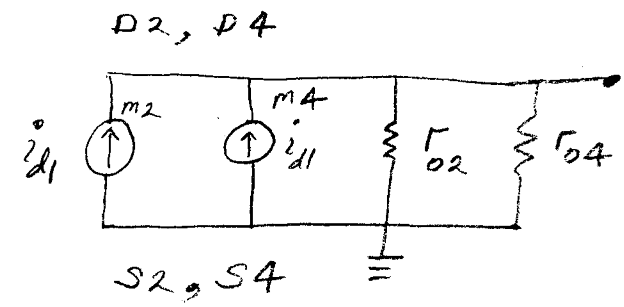
$$C_o = C_L + C_{db4} + C_{gd4} + C_{db2} + C_{gd2}$$



$i_{d2} = -i_{d1}$ DC BIAS : $v_o = 0 \Rightarrow I_{D1} = I_{D2} = I_{SS}/2$

$\cancel{g_m} v_{gs2} = -\cancel{g_m} v_{gs1}$

$\Rightarrow v_S$ is fixed at V_S. $\Rightarrow$ a.c. ground



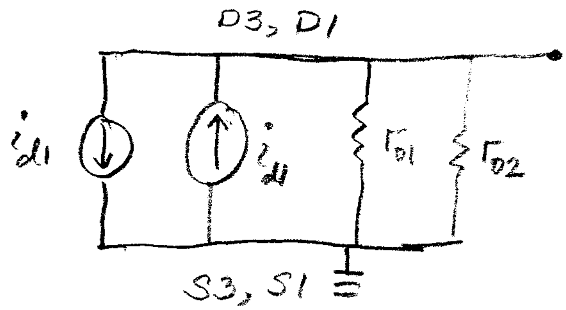
$v_o = g_{m1}\, r_{o2} \| r_{o4}$

$i_{d1} = g_{m1}\, v_D/2$

$v_o = g_{m1} \frac{v_D}{2} (2)(r_{o2} \| r_{o4})$

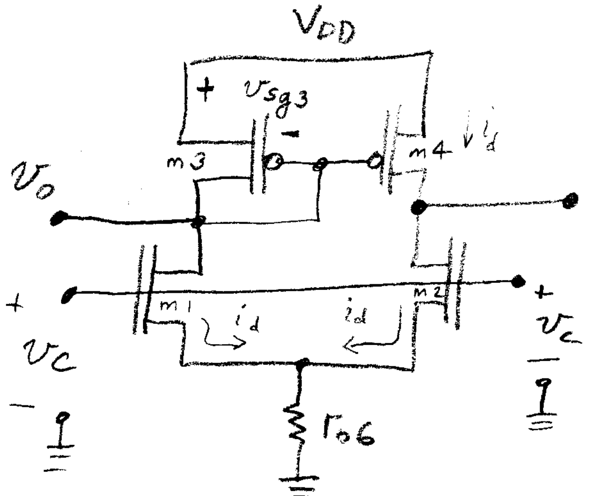
$A_{v_D} \equiv \frac{v_o}{v_D} = g_{m1}(r_{o2} \| r_{o4})$ (Differential Gain)

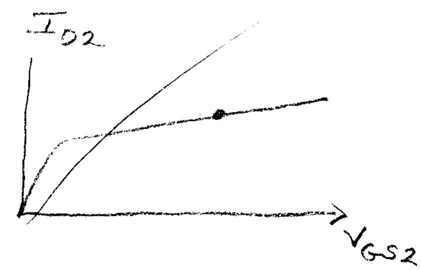
$\stackrel{?}{=} \frac{v_o - v_{d1}}{v_D}$

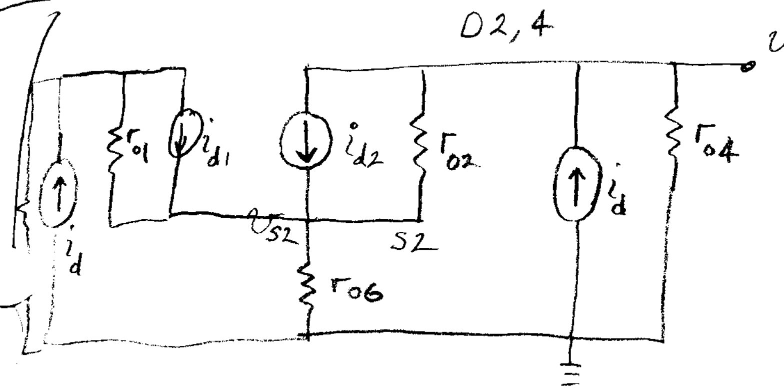


$v_{D1} = 0$

Common Mode Rejection Ratio (24.1.2) (CMRR)







$$\frac{v_o}{r_{o4}} + \frac{v_o - v_{S2}}{r_{o2}} = 0$$

$$-\frac{v_{S2}}{r_{o6}} + \frac{v_o - v_{S2}}{r_{o2}} + i_d = 0$$

$$v_{S2}\left(\frac{1}{r_{o6}} + \frac{1}{r_{o2}}\right) = \frac{v_o}{r_{o2}} + i_d$$

$$v_{S2} = \frac{v_o}{r_{o2}} \frac{r_{o6}\, r_{o2}}{r_{o6} + r_{o2}} + i_d\,(r_{o2} \| r_{o6})$$

$$v_o\left(\frac{1}{r_{o4}} + \frac{1}{r_{o2}}\right) = v_o \frac{r_{o2} \| r_{o6}}{r_{o2}^2} \qquad i_d \frac{r_{o2} \| r_{o6}}{r_{o2}}$$

$$v_o\left[\frac{1}{r_{o2} \| r_{o4}} - \frac{r_{o2} \| r_{o6}}{r_{o2}^2}\right] = i_d \frac{r_{o2} \| r_{o6}}{r_{o6}}$$

$$v_c = v_{gs1} + 2 i_d r_{o6}$$

$$v_c = v_{gs1} + 2 i_d r_{o6}$$

$$= i_d \left(\frac{1}{g_{m1}} + 2 r_{o6} \right)$$

$$v_o = -v_{sg3} = -\frac{i_d}{g_{m3}} = \frac{-i_d}{g_{m4}}$$

$$A_c \equiv \frac{v_o}{v_c} = \frac{-1/g_{m4}}{\frac{1}{g_{m1}} + 2 r_{o6}}$$

$$\boxed{A_c \simeq \frac{-1}{2 g_{m4} r_{o6}}}$$

$$A_{v_D} = g_{m1}\, r_{o2} \| r_{o4}$$

$$CMRR = 20 \log_{10} \left| \frac{A_v}{A_c} \right| = 20 \log_{10} \left(2 g_{m1} g_{m4} (r_{o2} \| r_{o4}) r_{o6} \right)$$

$$\approx 40 \log_{10} (g_m r_o)$$

$r_{o6} = R_o$ of biasing I source

$\boxed{\text{As } R_o \to \infty,\quad A_c \to 0,\quad CMRR \to \infty.}$

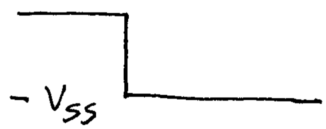
FOR IDEAL CURRENT SOURCE, $CMRR = \infty$.

$$\tau_{out} = C_o \, r_{o2} \| r_{o4}$$

$$f_{3dB} = \frac{1}{2\pi \tau_{out}} \approx \frac{1}{2\pi C_L \, r_{o2} \| r_{o4}}$$

SLEW RATE (Switching perspective)
Large signal

$v_{I1} =$



$\Longrightarrow$ turns off $M_{1,3,4}$

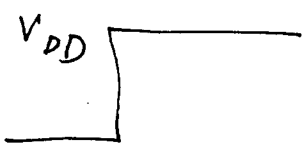
M2 triode

All of I_{SS} drawn from C_L

$$\frac{dV}{dt} = \frac{I_{SS}}{C_L}$$

Max rate of charge/discharge (SLEW RATE)

$v_{I1} =$

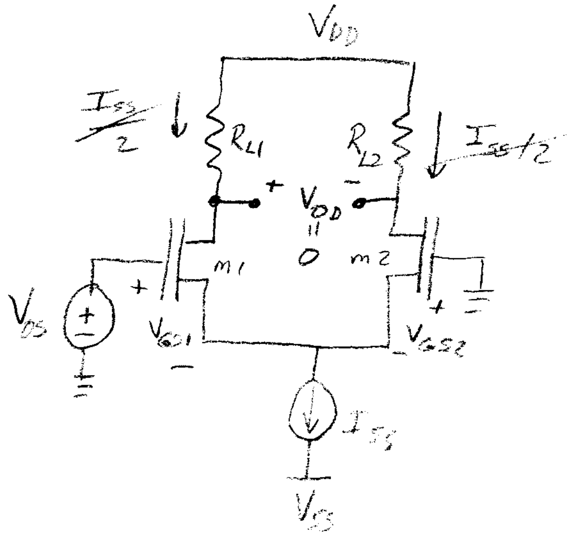


$\Longrightarrow$ M1, 3, 4 $\rightarrow I_{SS} = I_D$

All I_{SS} applied to C_L

$$\frac{dV}{dt} = \frac{I_{SS}}{C_L}$$

MATCHING



$$V_{OS} = V_{GS1} - V_{GS2} = V_{G1} - V_{G2} = V_{G1} = V_{OS}$$

$$V_{OS} = V_{t1} + \sqrt{\frac{2 I_{D1}}{\beta_1}} - V_{t2} - \sqrt{\frac{2 I_{D2}}{\beta_2}}$$

DEFINE:

$$\Delta I_D = I_{D1} - I_{D2}$$
$$I_D = (I_{D1} + I_{D2})/2$$
$$\Delta\left(\frac{W}{L}\right) = (W/L)_1 - (W/L)_2$$
$$\frac{W}{L} = [(W/L)_1 + (W/L)_2]/2$$
$$\Delta V_t = V_{t1} - V_{t2}$$
$$V_t = (V_{t1} + V_{t2})/2$$
$$\Delta R_L = R_{L1} - R_{L2}$$
$$R_L = (R_{L1} + R_{L2})/2$$

$$I_{D1} R_{L1} = I_{D2} R_{L2}$$

$$I_{D2} = I_{D1} \frac{R_{L1}}{R_{L2}}$$

$$I_{D1} = \frac{\Delta I_D + 2 I_D}{2}$$

$$V_{OS} = \Delta V_t + \frac{V_{GS} - V_t}{2}\left[\frac{-\Delta R_L}{R_L} - \frac{\Delta(W/L)}{W/L}\right]$$

~~V_{GS}~~

Effect of ΔR_L & $\Delta \frac{W}{L}$ reduced by $\downarrow (V_{GS} - V_t)$.
$\Delta V_t \sim 2\text{ mV} \sim \sigma$ over die (wafer).

Layout: Common Centroid Layout. Fig. 24.15.

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