Table 6.1

| | | Typical Parameter Value | | |
|---|---|---|---|---|
| Parameter Symbol | Parameter Description | n-Channel | p-Channel | Units |
| $V_{T0}$ | Threshold voltage($V_{BS}$=0) | 0.7 | -0.8 | V |
| K | Transconductance parameter(in saturation) | 134 | 50 | $\mu A/V^2$ |
| γ | Bulk threshold parameter | 0.45 | 0.4 | $V^{1/2}$ |
| λ | Channel length modulation parameter | 0.1 | 0.2 | $V^{-1}$ |
| $2\|\phi_F\|$ | Surface potential at strong inversion | 0.9 | 0.8 | V |

$K = \mu C_{OX}$

6.1 Calculate the differential transconductance $g_{md}$ and the differential voltage gain $A_v$ of an n-channel input differential amplifier shown in Figure 6.1 , with the parameters shown in table 6.1. Consider $I_{ss}$=100μA (the drain current of M5), and $W_1/L_1=W_2/L_2=W_3/L_3=W_4/L_4=1$. Assuming all the channel lengths are equal to 1μm, and $V_{DD}$=5V. If $W_1/L_1=W_2/L_2=10W_3/L_3=10W_4/L_4=10$, repeat the calculation

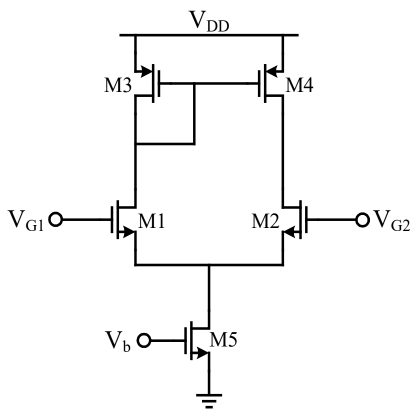



Figure 6.1

## Answer:

a) $\left(\frac{W}{L}\right)_1=\left(\frac{W}{L}\right)_2=\left(\frac{W}{L}\right)_3=\left(\frac{W}{L}\right)_4=1$

$$g_{md} = g_{m1} = g_{m2} = \sqrt{2 \times K_n \left(\frac{W}{L}\right)_1 \frac{I_{ss}}{2}} = 115.8\ \mu S$$

$$A_v = \frac{g_{m2}}{r_{ds2} + r_{ds4}} = \frac{2g_{m2}}{(\lambda_2 + \lambda_4)I_{ss}} = 7.72$$

b) $\left(\frac{W}{L}\right)_1=\left(\frac{W}{L}\right)_2=10\left(\frac{W}{L}\right)_3=10\left(\frac{W}{L}\right)_4=10$

$$g_{md}=g_{m1}=g_{m2}=\sqrt{2\times K_n\left(\frac{W}{L}\right)_1\frac{I_{ss}}{2}}=366.1\ \mu S$$

$$A_v=\frac{g_{m2}}{r_{ds2}+r_{ds4}}=\frac{2g_{m2}}{(\lambda_2+\lambda_4)I_{ss}}=24.4$$

6.2 Calculate the maximum($V_{IC}$(max)) and the minimum input common-mode voltages ($V_{IC}$(min)), and the input common mode voltage range (ICMR) of an n-channel input differential amplifier shown in Figure 6.1, with the parameters shown in table 6.1. Assume all MOSFETs are in saturation, all the $(W/L)_i$ are equal to 10μm/1μm, $I_{SS}$=10μA, and $V_{DD}$=5V.

## Answer:

The maximum input common-mode input is given by

$$V_{(IC)}(max)=V_{DD}+V_{T1}-V_{T3}-V_{GS3}=V_{DD}+V_{T1}-V_{T3}-\sqrt{\frac{I_{ss}}{K_P\left(\frac{W}{L}\right)_3}}=4.76V$$

The minimum input common-mode input is given by

$$V_{(IC)}(min)=V_{SS}+V_{T1}+V_{GS3}+V_{GS5}=V_{SS}+V_{T1}+\sqrt{\frac{I_{SS}}{K_n\left(\frac{W}{L}\right)_3}}+\sqrt{\frac{2\times I_{SS}}{K_n\left(\frac{W}{L}\right)_5}}=0.91V$$

So, the input common-mode range becomes

$$ICMR=V_{(IC)}(max)-V_{(IC)}(min)=3.85V$$

6.3 Find the value of the unloaded differential-transconductance, $g_{md}$, and the unloaded differential-voltage gain, $A_v$, for the p-channel input differential amplifier of Figure 6.2 when $I_{SS}$=10μA and $I_{SS}$=1μA. What is the slew rate of the differential amplifier if a 100 pF capacitor is attached to the output? Assuming $W_1/L_1=W_2/L_2=W_3/L_3=W_4/L_4=1$, and all the channel lengths are equal to 1μm. Use the transistor parameters of Table 6.1.

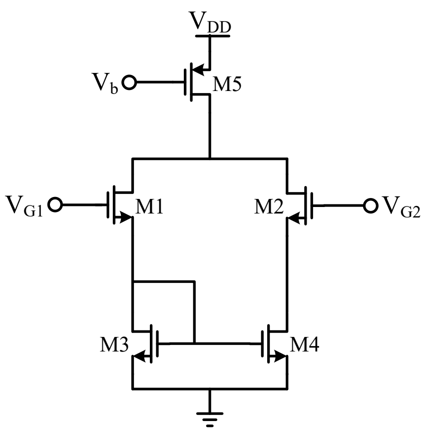



Figure 6.2

## Answer:

Given $I_{SS}$=10μA

$$g_{md} = g_{m1} = g_{m2} = \sqrt{2 \times K_p \left(\frac{W}{L}\right)_1 \frac{I_{ss}}{2}} = 22.36\ \mu\text{S}$$

$$A_v = \frac{g_{m1}}{g_{ds2} + g_{ds4}} = \frac{2g_{m1}}{(\lambda_1 + \lambda_2)I_{ss}} = 14.9$$

Given $I_{SS}$=1μA

$$g_{md} = g_{m1} = g_{m2} = 7.07\ \mu\text{S}$$

$$A_v = \frac{g_{m1}}{g_{ds2} + g_{ds4}} = \frac{2g_{m1}}{(\lambda_1 + \lambda_2)I_{ss}} = 47.13$$

Slew rate can be given as

$$SR = \frac{I_{ss}}{C_L}$$

For $I_{SS}$=10μA and $C_L$=100pF

$$SR = \frac{I_{ss}}{C_L} = 0.1V/\mu s$$

For $I_{SS}$=1μA and $C_L$=100pF

$$SR = \frac{I_{ss}}{C_L} = 0.01V/\mu s$$

6.4 In the circuit of Fig 6.3, assume that $I_{SS}$=1mA, $V_{DD}$=3V and W/L=50/0.5 for all the transistors. And $I_{D5}=I_{D6}=0.8(I_{SS}/2)$. Assuming **λ≠0**.

(a) Determine the voltage gain.

(b) Calculate $V_b$.

(c) If $I_{SS}$ requires a minimum voltage of 0.4V, what is the maximum differential output swing?

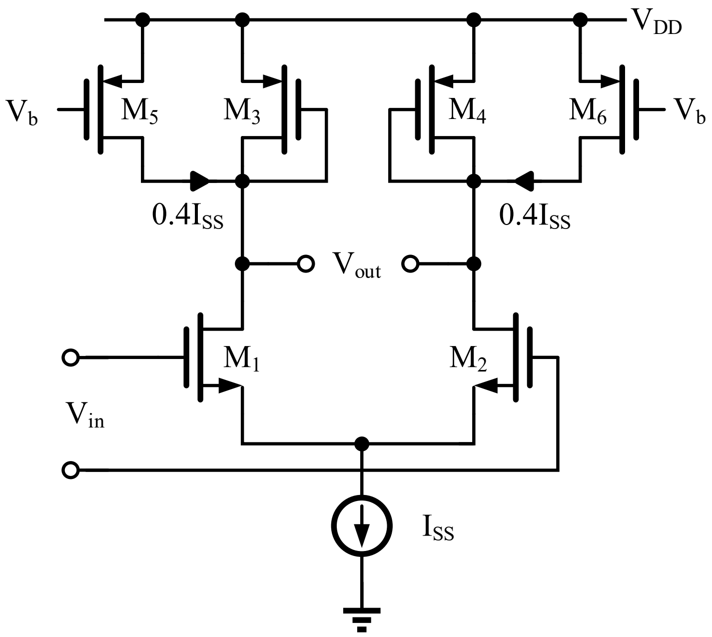



Figure 6.3

## Answer:

a) $A_V \approx -\frac{g_{m1}}{g_{m3}} = -\sqrt{\frac{K_n I_{D1}}{K_p I_{D3}}} = -\sqrt{\frac{134\times 0.5 I_{SS}}{50\times 0.2\frac{I_{SS}}{2}}} = -3.66$

b) $I_{D5} = I_{D6} = 0.8\frac{I_{SS}}{2} = 0.4mA, V_b = V_{DD} - V_{SG5} = V_{DD} - |V_{TH}| - \sqrt{\frac{2I_{D5}}{K_p\frac{W}{L}}} = 1.8\text{V}$

c) $(V_{OUT1,2})max = min(V_b + |V_{TH,p}|, V_{DD} - |V_{TH,p}|) = min(1.8 + 0.8, 3 - 0.8) = 2.2V$

$(V_{OUT1,2})min = max(V_{Imin} + V_{GS1}|_{I_D=0.6I_{SS}} - V_{TH,N}, V_{DD} - V_{SG3}|_{I_D=0.2I_{SS}})$

$$V_{GS1}|_{I_D=0.6I_{SS}} = V_{TH,N} + \sqrt{\frac{2\times 0.6I_{SS}}{K_n\frac{W}{L}}} = 0.7 + 0.299 = 0.999V$$

$$V_{SG3}|_{I_D=0.2I_{SS}} = |V_{TH,p}| + \sqrt{\frac{2\times 0.2I_{SS}}{K_p\frac{W}{L}}} = 0.8 + 0.28 = 1.08V$$

$(V_{OUT1,2})min = max(0.4 + 0.999 - 0.7, 3 - 1.08) = 1.92V$

$V_{out,swing} = 2\times(2.2 - 1.92) = 0.56V$

6.5 The circuit shown in Figure 6.4 called a folded-current mirror differential amplifier and is useful for low values of power supply. Assume that all W/L values of each transistor is 100. Using the parameters shown in table 6.1,

a) Find the maximum input common mode voltage, $V_{IC}$(max) and the minimum input common mode voltage, $V_{IC}$(min). Keep all transistors in saturation for this problem.

b) What is the input common mode voltage range, ICMR?

c) Find the small signal voltage gain, $v_{out}/v_{in}$, if $v_{in} = v_1 - v_2$.

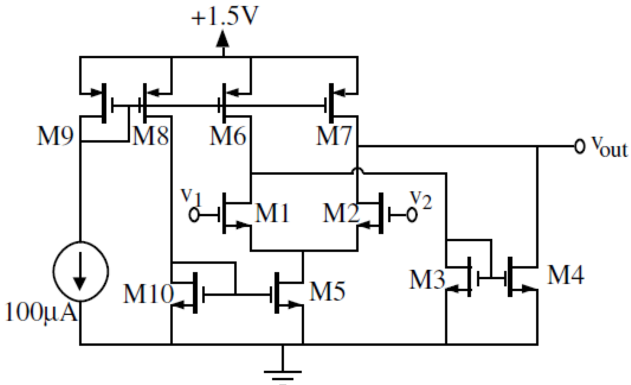



Figure 6.4

## Answer:

a) $v1(max) = V_{GS3} + 2\times V_{TN} = 0.7 + \sqrt{\frac{2\times 50}{134\times 100}} + 0.7 = 1.486\text{V}$

$$v1(min) = V_{SS} + V_{GS5} - V_{TN} + V_{GS1} = \sqrt{\frac{2\times 100}{134\times 100}} + \sqrt{\frac{2\times 50}{134\times 100}} + 0.7 = 0.908\text{V}$$

b) $V_{ICMR} = v1(max) - v1(min) = 1.486V - 0.908V = 0.578V$

c)

$$g_{md} = g_{m1} = g_{m2} = \sqrt{2 \times K_N \left(\frac{W}{L}\right)_1 \frac{I_{SS}}{2}} = 1157.58\,\mu S$$

$$r_{o4} = r_{o2} = \frac{2}{\lambda_n I_{SS}} = 0.2M\Omega$$

$$r_{o7} = \frac{1}{\lambda_p I_{SS}} = 0.05M\Omega$$

$$A_v = g_{m1} \times (r_{o2}//r_{o4}//r_{o7}) = 38.586$$

6.6 In the circuit of Fig 6.5, assume that $I_{SS}$ = 0.5mA, $V_{DD}$ = 3V, $(W/L)_{1,2}$ = 50/0.5 and $(W/L)_{3,4}$ = 10/0.5. $I_{SS}$ current is provided by NMOS, and its W/L = 50/0.5. Assuming **λ≠0**.

a) Calculate the range of input common mode voltage.

b) If $V_{in,CM}$ = 1.5V, draw a sketch of the small signal differential voltage gain of the circuit when $V_{DD}$ changes from 0 to 3V.

c) If the mismatch threshold voltage of $M_1$ and $M_2$ is 1mV, calculate CMRR.

d) If the $W_3$ = 10μm and $W_4$ = 11μm, calculate CMRR.

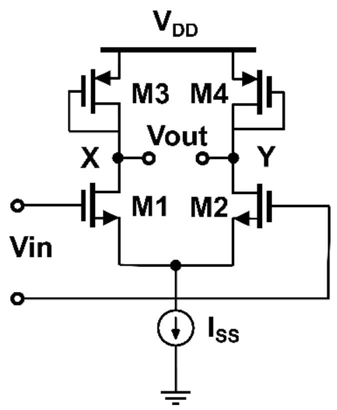



Figure 6.5

## Answer:

a) $(Vin,cm)min = V_{GS1} + V_{odSS} = V_{TH1} + \sqrt{\frac{2I_{D1}}{K_n\left(\frac{W}{L}\right)_1}} + \sqrt{\frac{2I_{SS}}{K_n\left(\frac{W}{L}\right)_{SS}}} = 0.7V + 0.193V + 0.273V =$

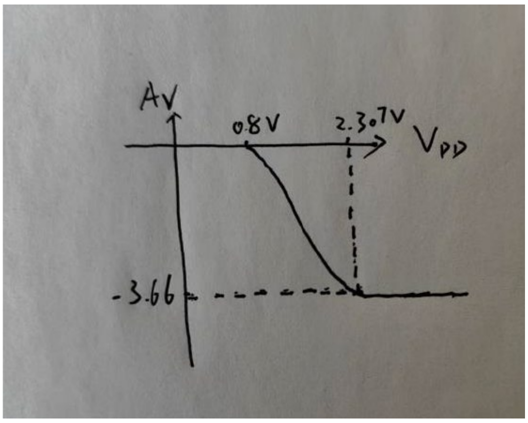
$1.166V$

$$(Vin,cm)max = V_{DD} - V_{od3} - V_{TH3} + V_{TH1} = V_{DD} - \sqrt{\frac{2I_{D3}}{K_p\left(\frac{W}{L}\right)_3}} - V_{TH3} + V_{TH1}$$

$$= 3V - 0.707V - 0.8V + 0.7V = 2.193V$$

$ICMR = 2.193V - 1.166V = 1.027V$

b) 三个标记点：开启电压为 0.8V，增益是-3.66，饱和点电压是 2.307V




c) 由于 M1 和 M2 的阈值电压失配，因此有：$g_{m1} \neq g_{m2}, g_{m3} \neq g_{m4}$，所以计算$A_{cm-dm}$有：

$$i_{D1} = g_{m1}(Vin,cm - Vp)$$

$$i_{D2} = g_{m2}(Vin,cm - Vp)$$

$$Vout1 = -\frac{i_{D1}}{g_{m3}} = -\frac{g_{m1}(Vin,cm - Vp)}{g_{m3}}$$

$$Vout2 = -\frac{i_{D2}}{g_{m4}} = -\frac{g_{m2}(Vin,cm - Vp)}{g_{m4}}$$

$$\frac{g_{m1}}{g_{m3}} = \sqrt{\frac{K_n\left(\frac{W}{L}\right)_{1,2}}{K_p\left(\frac{W}{L}\right)_{2,4}}} = \frac{g_{m2}}{g_{m4}}$$

$$\therefore Vout1 = Vout2$$

$$\therefore Acm - dm = 0, CMRR = \infty$$

d) $Adm - dm = -g_m R_D$

$$Acm - dm = \frac{g_m R_D}{1 + 2g_m R_{SS}} - \frac{g_m(R_D + \Delta R_D)}{1 + 2g_m R_{SS}} = -\frac{g_m \Delta R_D}{1 + 2g_m R_{SS}}$$

$$\therefore CMRR = \left|\frac{Adm - dm}{Acm - dm}\right| = \frac{1 + 2g_m R_{SS}}{\Delta R_D / R_D}$$

$$\because R_{D1} = \frac{1}{g_{m3}}, R_{D2} = \frac{1}{g_{m4}}$$

$$\therefore \frac{\Delta R_D}{R_D} = \frac{R_{D1} - R_{D2}}{R_{D1}} = 1 - \frac{R_{D2}}{R_{D1}} = 1 - \sqrt{\frac{2K_p\left(\frac{W}{L}\right)_3 I_D}{2K_p\left(\frac{W}{L}\right)_4 I_D}} = 1 - \sqrt{\frac{10}{11}} = 0.0465$$

$$g_m = \sqrt{2K_n\left(\frac{W}{L}\right)_1 i_{D1}} = 2.588m\Omega^{-1}, \lambda = 2 \times 0.1 = 0.2, R_{SS} = \frac{1}{\lambda I_{SS}} = 20k\Omega$$

$$\therefore CMRR = 2270$$