Table 4.1

| Parameter | Description | n-channel | p-channel | Units |
|---|---|---|---|---|
| $V_{TH0}$ | Threshold voltage ($V_{BS}$=0) | 0.7 | -0.7 | V |
| $K=\mu C_{OX}$ | Transconductance Parameter (in saturation) | 110 | 50 | $\mu A/V^2$ |
| $\gamma$ | Bulk threshold parameter | 0.4 | 0.57 | |
| $\lambda$ | Channel length modulation parameter | 0.04(L=1μm)<br>0.01(L=2μm) | 0.05(L=1μm)<br>0.01(L=2μm) | $V^{1/2}$ |
| $2\|\Phi_F\|$ | Surface potential at strong inversion | 0.7 | 0.8 | V |

4.1 Calculate the output resistance and the minimum output voltage, while maintaining all devices in saturation, for the circuits shown in Figure 4.1. Assume that $i_{OUT}$ is actually 10μA. Use Table 4.1 for device model information.

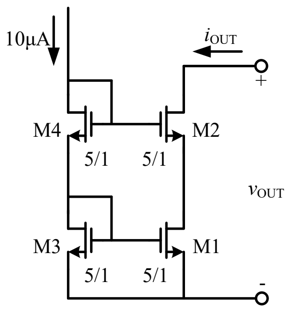


Fig 4.1

解：

$$V_{GS3}=V_{G3}=\sqrt{\frac{2i_D}{\beta}}+V_T=\sqrt{\frac{2\times 10\times 10^{-6}}{5\times 110\times 10^{-6}}}+0.7=\sqrt{\frac{20}{550}}+0.7=0.891$$

$V_{SB2} = V_{G3} = 0.891$

$V_{DS1} = V_{G3} + V_{GS4} - V_{GS2}$ because all devices are matched.

$$g_{m2} = g_{m4} \cong \sqrt{(2K'W/L)|I_D|} = \sqrt{2\times 110\times10^{-6} \times 5/1 \times 10\times10^{-6}} = 104.9 \times10^{-6}$$

$$g_{mbs2} = g_{mbs4} = g_{m2} \frac{\gamma}{2(2|\phi_F| + V_{SB})^{1/2}} = 104.9 \times10^{-6} \frac{0.4}{2(0.7 + 0.891)^{1/2}} = 16.63\times10^{-6}$$

$$r_{out} = \frac{v_{out}}{i_{out}} = r_{ds1} + r_{ds2} + [(g_{m2} + g_{mbs2})r_{ds2}]\, r_{ds1}$$

$$g_{ds1} = g_{ds2} \cong I_D \lambda = 10\times10^{-6} \times 0.04 = 400\times10^{-9}$$

$$r_{ds1} = r_{ds2} = \frac{1}{g_{ds}} = 2.5\times10^{6}$$

$$r_{out} = 2.5\times10^{6} + 2.5\times10^{6} + [(104.9 \times10^{-6} + 16.63\times10^{-6})\, 2.5\times10^{6}]\, 2.5\times10^{6}$$

$$r_{out} = 764\times10^{6}$$

$$v_{out(\min)} = V_{GS3} + V_{GS4} - V_{T2} = V_{GS3} + \sqrt{\frac{2i_D}{\beta}} + V_{T4} - V_{T2}$$

$$= V_{GS3} + \sqrt{\frac{2i_D}{\beta}} = 0.891 + \sqrt{\frac{2\times10\times10^{-6}}{5\times110\times10^{-6}}} = 1.082\text{V}$$

4.2 In Fig. 4.2, assume that $(W/L)_1 = 50/0.5$, $\lambda = 0$, $I_{out} = 0.5$ mA, $V_{DD}=3V$ and $M_1$ is saturated.

**(a)** Determine $R_2/R_1$.

**(b)** Calculate the sensitivity of $I_{out}$ to $V_{DD}$, defined as $\partial I_{out}/\partial V_{DD}$ and normalized to $I_{out}$.

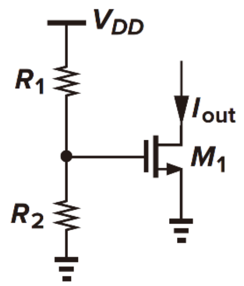


Fig 4.2

(a)

$$\text{V}_{\text{GS}} = \sqrt{\frac{2I_D}{K_n\, W/L}} + V_{TH} = 1\text{V} = \text{V}_{\text{DD}} \frac{R_2}{R_1 + R_2}$$

$$\frac{\text{R}_2}{R_1} = \frac{1}{2}$$

(b)

$$I_D = \frac{1}{2} K_n \frac{W}{L}\left(V_{DD}\frac{R_2}{R_1+R_2} - V_{TH}\right)^2$$

$$\frac{\partial I_D}{\partial V_{DD}} = K_n \frac{W}{L}\left(V_{DD}\frac{R_2}{R_1+R_2} - V_{TH}\right)\frac{R_2}{R_1+R_2} = 1.1\times 10^{-4}$$

$$\frac{\partial I_D}{\partial V_{DD}}/I_D = 2.2$$

4.3 Design M3 and M4 of Figure 4.3(a) so that the output characteristics are identical to the circuit shown in Figure 4.3(b). It is desired that $i_{OUT}$ is ideally 10uA.

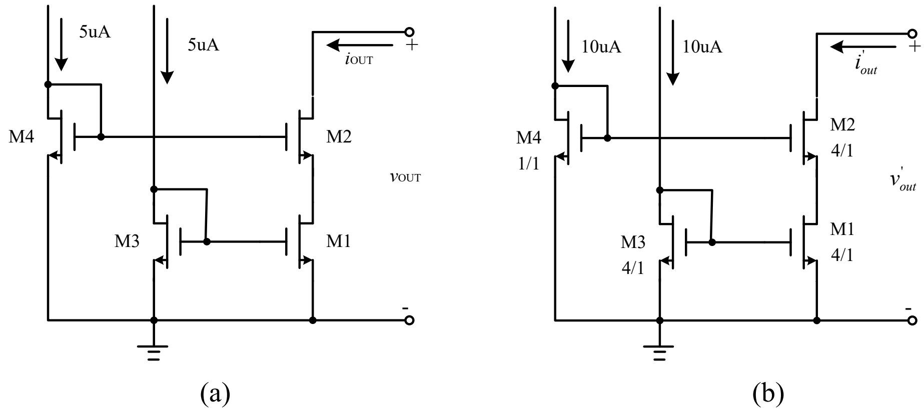


Figure 4.3

解:

For getting $i_{out}' = i_{out} = 10\mu A$

In Fig.4.2a), $\because \quad i_3 = i_4 = 5\mu A$

Thus to ensure $i_{out} = 10\mu A$

We must have $\left(\frac{W}{L}\right)_1 = 2\left(\frac{W}{L}\right)_3$

$$\left(\frac{W}{L}\right)_3 = \frac{1}{2}\left(\frac{W}{L}\right)_1 = \frac{1}{2}\cdot\frac{4}{1} = \frac{2}{1}$$

In Fig. 4.2b) $i_4 = i_3 = i_1$

$$\left(\frac{W}{L}\right)_4 \Delta V_4^2 = \left(\frac{W}{L}\right)_1 \Delta V_1^2 \Rightarrow \left(\frac{1}{1}\right)\Delta V_4^2 = \left(\frac{4}{1}\right)\Delta V_1^2$$

$$\therefore \frac{\Delta V_4^2}{\Delta V_1^2} = \frac{4}{1} \Rightarrow \Delta V_4 = 2\Delta V_1$$

$$V_{G4} = V_T + 2\Delta V_1$$
$$V_{G2} = V_{G4} = V_T + 2\Delta V_1$$
$$\therefore V_{MIN} = 2\Delta V_1$$

And we get $V_{MIN}$ in Fig.5.2(a): $V_{MIN} = 2\Delta V_1$

$\therefore V_{G2} = V_{G4} = V_T + 2\Delta V_1$ and $\Delta V_4 = 2\Delta V_1$

In Fig.5.2(a): $i_4 = i_3 = \frac{1}{2} i_1$

$$\left(\frac{W}{L}\right)_4 \Delta V_4{}^2 = \frac{1}{2}\left(\frac{W}{L}\right)_1 \Delta V_1{}^2$$

$$\left(\frac{W}{L}\right)_4 = \frac{1}{2}\left(\frac{W}{L}\right)_1 \left(\frac{\Delta V_1}{\Delta V_4}\right)^2$$

For $\left(\frac{\Delta V_4}{\Delta V_1}\right)^2 = 4 \Rightarrow \left(\frac{\Delta V_1}{\Delta V_4}\right)^2 = \frac{1}{4}$

$$\left(\frac{W}{L}\right)_4 = \frac{1}{8}\left(\frac{W}{L}\right)_1 = \frac{1}{8}\cdot\frac{4}{1} = \frac{1}{2}$$

4.4 Assume that W/L ratios of Figure 4.5 are $(W/L)_1$ = 2µm/1µm and $(W/L)_2 = (W/L)_3 = (W/L)_4$ =1µm/1µm. Find the dc value of $v_{IN}$ that will give a dc current in M1 of 110µA. Calculate the small signal voltage gain and output resistance using the parameters of Table 4.1. Assume $\lambda=\gamma=0$.

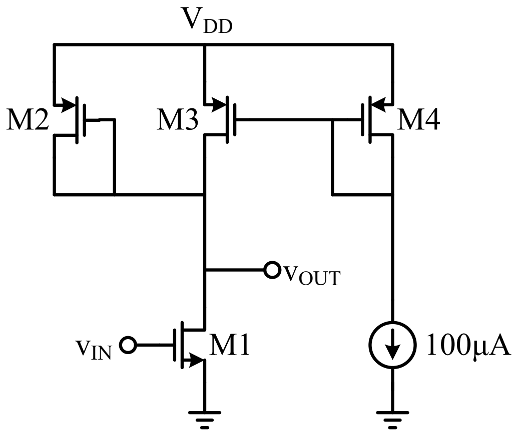


Figure 4.4

Solution:

$$I_{D1} = \frac{1}{2} K'_N \left(\frac{W}{L}\right)_1 (V_{in} - V_{TH1})^2$$

$$110\mu = \frac{1}{2} \times (110\mu) \times \frac{2}{1} \times (V_{in} - 0.7)^2$$

$$V_{in} = 1.7V$$

$$I_{D3} = I_{D4} = 100\mu A$$

$$I_{D2} = I_{D1} - I_{D3} = 10\mu A$$

$$A_v \cong -\frac{g_{m1}}{g_{m2}} = -\sqrt{\frac{K_N'}{K_P'}\frac{(W/L)_1}{(W/L)_2}\frac{I_{D1}}{I_{D2}}} = -\sqrt{\frac{110\mu}{50\mu}\times\frac{2}{1}\times\frac{110\mu}{10\mu}} = -6.96V/V$$

$$R_{out} \cong \frac{1}{g_{m2}} = \frac{1}{\sqrt{2K_P'(W/L)_2 I_{D2}}} = \frac{1}{\sqrt{2\times 50\times 10^{-6}\times 1\times 10\times 10^{-6}}} = 31.6K\Omega$$