Solutions to the written Exam in Analog IC Design

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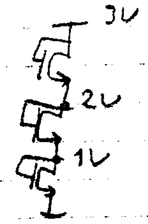
1) a) Neglecting the body effect, the transistors being identical, they will have the same voltage drop, that is



The current:

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left(V_{GS}-V_T\right)^2 = \frac{1}{2}\cdot 115\cdot 10^{-6}\cdot 10\cdot (1-0{,}46)^2 = 0{,}17\ mA$$

b) With body effect the threshold voltages of the upper transistors would increase, increasing the voltage drop over those transistors, and reducing the current.

$\Rightarrow$ reduced node voltages and drain current.

2a V_{G8}: $V_{ov8} = \sqrt{\frac{2 I_{BIAS}}{\mu_p C_{ox} W/L}} = \sqrt{\frac{100\mu}{40\mu \cdot 40}} = 0{,}25V$

$V_{G8} = V_{dd} + V_{tp0} - V_{ov8} = 3 - 0{,}60 - 0{,}25 = \underline{2{,}15\ V}$

Assume M_5, M_1 & M_2 in saturation $\Rightarrow$

$I_{D5} \approx I_{D8} = \underline{50\ \mu A}$, $I_{D1} = I_{D2} = \frac{1}{2} I_{D5} = \underline{25\ \mu A}$

$V_{ov5} = V_{ov8} = \sqrt{2} \cdot V_{ov1} = \sqrt{2} \cdot V_{ov2} \Rightarrow$

$V_{ov5} = 0{,}25$, $V_{ov1} = V_{ov2} = 0{,}18\ V$

$V_{S1,2} = V_I - V_{tp0} + V_{ov1} = 1{,}5 + 0{,}60 + 0{,}18 = \underline{2{,}28\ V} = V_{D5}$

$V_{GD5} = 2{,}15 - 2{,}28 = -0{,}13V > V_{tp0} = -0{,}60 \Rightarrow \underline{M_5 \text{ in saturation}}$

(if assumption M_1, M_2 in saturation is valid)

$V_{ov3,4} = \sqrt{\frac{2 I_{D3}}{\mu_n C_{ox} (W/L)_3}} = \sqrt{\frac{2 \cdot 25\mu}{115\mu \cdot 8}} = 0{,}23\ V$

$V_{D3} = V_{tn0} + V_{ov3} = 0{,}46 + 0{,}23 = \underline{0{,}69\ V} \Rightarrow M_1$ in saturation

$I_{D7} \approx I_{BIAS} \cdot \frac{(W/L)_7}{(W/L)_8} = 50\mu A \cdot 2{,}5 = \underline{125\ \mu A}$

$V_{ov6} = \sqrt{\frac{2 \cdot I_{D6}}{\mu_n C_{ox} (W/L)_6}} = \sqrt{\frac{2 \cdot I_{D7}}{\mu_n C_{ox} (W/L)_6}} = \sqrt{\frac{250\mu}{115\mu \cdot 40}} = 0{,}233$

$\Rightarrow V_{D4} = V_{tn0} + V_{ov6} = \underline{0{,}69\ V}\ (= V_{D3}) \Rightarrow \underline{M_2 \text{ in saturation}}$

The assumption that all transistors are in saturation is valid.

b $BW = \frac{g_{m1}}{C_c}$

$g_{m1} = \sqrt{2 \mu_p C_{ox} \left(\frac{W}{L}\right)_1 I_{D1}} = \sqrt{2 \cdot 40\mu \cdot 40 \cdot 25\mu} = 0{,}28\ mS$

$\Rightarrow BW = \frac{0{,}28m}{2p} = 2\pi \cdot 22M = 22\ MHz$

c. $g_{m6} = \sqrt{2 \mu_n C_{ox} \left(\frac{W}{L}\right)_6 I_{D6}} = \sqrt{2 \cdot 115\mu \cdot 40 \cdot 125\mu} = 1{,}1\ mS$

$p_2 \approx -\frac{g_{m6}}{C_1 + C_2} = -\frac{1{,}1m}{5{,}6p} = -2\pi \cdot 30{,}5M = -30\ MHz$

$z = \frac{1}{\left(\frac{1}{g_{m6}} - R_z\right) \cdot C_c}$ = close to ∞, ignore

$\varphi_m = 90° - \arctan\left(\frac{22M}{30M}\right) = 54°$

3.

$C = 2pF = 2000\ fF$

poly1 – poly2 : $0,86\ fF/(\mu m)^2$, $0,082\ fF/\mu m$

assume quadratic shape with side $a\ (\mu m) \Rightarrow$

$C = 0,86 \cdot a^2 + 4a \cdot 0,082\, a\ fF = 2000 \Rightarrow a = 48\ \mu m$

$C_{bottom} = 48^2 \cdot 0,119 + 48 \cdot 4 \cdot 0,052\ fF = 284\ fF$

$ratio = \frac{284}{2000} = 14\,\%$

m2-m3-m4 :

$C \sim \frac{1}{t_{ox}}$, $C_{polys} = 0,86\ fF/(\mu m)^2$, $t_{pox} = 41\ nm \Rightarrow$

$t_{mox2} = 1,00\ \mu m \Rightarrow C_{m2m3} = 0,86 \cdot \frac{41}{1000} = 0,035\ fF/(\mu m)^2$

$t_{mox3} = 1,00\ \mu m \Rightarrow C_{m3m4} = 0,035\ fF/(\mu m)^2$

$C = (0,035 + 0,035)\, a^2\ fF \Rightarrow a = \sqrt{\frac{2000}{0,070}} = 169\ \mu m$

$C_{bottom} = 169^2 \cdot 0,012 + 4 \cdot 169 \cdot 0,036 = 367\ fF$

$ratio = \frac{367}{2000} = 18\,\%$

p1-m1-m2-m3-m4 :

$t_{mox} = 1,00\ \mu m \Rightarrow C_{m1-m2} = 0,035\ fF/(\mu m)^2$

$t_{pox} = 0,645\ \mu m \Rightarrow C_{m1-p1} = 0,055\ fF/(\mu m)^2$

$a = \sqrt{\frac{2000}{0,070 + 0,035 + 0,055}} = 112\ \mu m$

$C_{bottom} = 112^2 \cdot 0,119 + 4 \cdot 119 \cdot 0,052 = 1,5\ pF$

$ratio = \frac{1,5}{2} = 76\,\%$

Conclusion: The area becomes much larger without the poly1-poly2 option. It is possible to achieve almost the same $C_{bottom}/C_{desired}$ without poly2, but at a severe area penalty.

4

a) $$I_d = \mu_n C_{ox} \frac{W}{L} \left((V_{GS} - V_t) V_{DS} - \frac{V_{DS}^2}{2} \right) \approx \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_t) V_{DS}$$

for small V_{DS}

$$\Rightarrow R = \frac{1}{\frac{\partial I_d}{\partial V_{DS}}} = \frac{1}{\mu_n C_{ox} \frac{W}{L} (V_{GS} - V_t)} = \frac{1}{115 \cdot 10^{-6} \cdot \frac{W}{L} \cdot 2} = 1 M\Omega \Rightarrow$$

$$\frac{L}{W} = 230$$

Gate-channel capacitance $< 1 pF$ $\Rightarrow C_{gc} = C_{ox} W L < 2pF$

$$\Rightarrow WL < \frac{2000}{4,6} (\mu m)^2 = 434 (\mu m)^2$$

$$\begin{cases} WL = 434 \\ \frac{L}{W} = 230 \end{cases} \Rightarrow \begin{cases} W \cdot 230 W = 434 \\ L/W = 230 \end{cases} \Rightarrow \begin{cases} W = 1,35 \ \mu m \\ L = 310,5 \ \mu m \end{cases}$$

b) $$I_d = \mu_n C_{ox} \frac{W}{L} \left[(V_{GS} - V_t) V_{DS} - \frac{V_{DS}^2}{2} \right] =$$

$$= \mu_n C_{ox} \frac{W}{L} \left[\left(V_{dd} - V_{CM} + \frac{V_d}{2} - V_t \right) V_d - \frac{V_d^2}{2} \right] =$$

$$= \mu_n C_{ox} \frac{W}{L} \left[V_{dd} - V_{CM} - V_t \right] \cdot V_d$$, linear function of V_d. (in triode region)

c) $$R_{nom} = \frac{1}{\mu_n C_{ox} \frac{W}{L} (V_{dd} - V_{CM_{nom}} - V_t)}$$

$$R = \frac{1}{\mu_n C_{ox} \frac{W}{L} (V_{dd} - V_{cm} - V_t)}$$

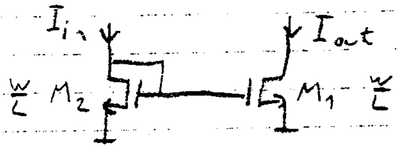
$$\frac{R}{R_{nom}} = \frac{V_{dd} - V_{cm_{nom}} - V_t}{V_{dd} - V_{cm} - V_t} = 1,2 \Rightarrow \frac{3 - 1 - 0,46}{3 - V_{cm} - 0,46} = \frac{1,54}{2,54 - V_{cm}} = 1,2$$

$$\Rightarrow 1,54 = 3,048 - 1,2 V_{cm} \Rightarrow V_{cm} = 1,26 \ V$$

$$\frac{R}{R_{nom}} = 0,8 \Rightarrow \frac{1,54}{2,54 - V_{cm}} = 0,8 \Rightarrow 1,54 = 2,032 - 0,8 V_{cm} \Rightarrow V_{cm} = 0,62 \ V$$

$\Rightarrow$ V_{cm} must be between 0,62 V and 1,26 V for the resistance to stay within 20% of the nominal. (of course process variations must be added to this...)

5. Since $V_{out,min}$ is just 200 mV, a simple current mirror should be used:



To minimize noise, use maximum overdrive $= V_{out,min} = 200\ mV$

$$I_{in} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_2 V_{ov2}^2 \Rightarrow \left(\frac{W}{L}\right)_2 = \frac{2 I_{in}}{\mu_n C_{ox} V_{ov}^2} = \frac{200\mu}{115\mu \cdot 0{,}2^2} = 44$$

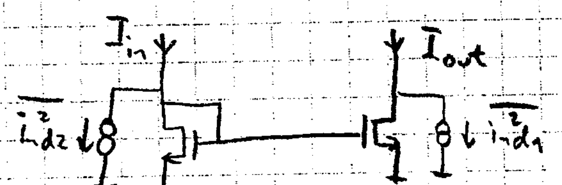
$$r_{out} = r_{dsn} \cdot \frac{L}{I_{out}} \Rightarrow L = \frac{r_{out}}{r_{dsn}} \cdot I_{out} = \frac{1M}{55} \cdot 100\mu = 1{,}8\ \mu m$$

choose $L = 2\mu m$ & $W = 88\ \mu m$, 4 fingers

$$C_{out} = C_{db1} + C_{dg1} < \frac{W}{2} \cdot 1{,}2\mu m \cdot 0{,}93\ fF/\mu m^2 + 2{,}4\mu m \cdot 0{,}28\ fF/\mu m + W \cdot C_{gdo} =$$

$$\underline{= 49{,}1 fF + 0{,}7 fF + 18{,}5\ fF = 68\ fF \ < 0{,}1\ pF}\ ,\ \underline{ok}$$

Calculate the output noise:



The noise $\overline{i_{nd2}^2}$ is mirrored to the output by the unity gain current mirror $\Rightarrow$

total output noise $\overline{i_{n\,out}^2} = \overline{i_{nd1}^2} + \overline{i_{nd2}^2} =$

$$= 4kT\gamma g_{m1} + 4kT\gamma g_{m2} = \left\{ g_{m1} = g_{m2}\ ,\ \gamma_1 = \gamma_2 = \frac{2}{3} \right\} = \frac{16}{3} kT g_m$$

$$g_m = \frac{2 I_d}{V_{ov}} = \frac{200\mu}{0{,}2} = 1mS$$

$$\Rightarrow \overline{i_{nd}^2} = \frac{16}{3} \cdot 1{,}38 \cdot 10^{-23} \cdot 300 \cdot 1m = 2{,}2 \cdot 10^{-23}\ A^2/Hz$$

in the range 10kHz to 100 kHz:

$$\overline{i_{nd}^2}\,(10k - 100k) = 2{,}2 \cdot 10^{-23}\ A^2/Hz \cdot 90kHz = 1{,}99 \cdot 10^{-18}\ A^2$$

$$\underline{i_{n,rms} = \sqrt{1{,}99 \cdot 10^{-18}} = 1{,}4\ nA \ < 2nA}\ ,\ ok$$