Solutions to Exam in Analog IC Design

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1) a) $R = R_{\square} \cdot \frac{L}{W}$ $I = \frac{3V}{R} = \frac{3V \cdot W}{L \cdot R_{\square}}$ $I_{max} = J \cdot W$

$I = I_{max} \Rightarrow \frac{3V \cdot W}{L \cdot R_{\square}} = J \cdot W \Rightarrow L = \frac{3V}{R_{\square} \cdot J}$

poly 1 : $L_{poly1} = \frac{3V}{R_{sp} \cdot J_p} = \frac{3V}{6\Omega \cdot 0{,}5\,mA/\mu m} = \frac{3}{6 \cdot 0{,}5 \cdot 10^{-3}}\,\mu m = \underline{1000\,\mu m}$

poly 2 : $L_{poly2} = \frac{3}{50 \cdot 0{,}3 \cdot 10^{-3}}\,\mu m = \underline{200\,\mu m}$

b) The length is chosen so that $I = I_{max} \Rightarrow I = J \cdot W$

poly 1 : $I = J_p \cdot W = 0{,}5\,mA/\mu m \cdot 1\,\mu m = \underline{0{,}5\,mA}$

poly 2 : $I = J_{p2} \cdot W = 0{,}3\,mA/\mu m \cdot 1\,\mu m = \underline{0{,}3\,mA}$

c) Poly 2 is best. Smallest size and least current.

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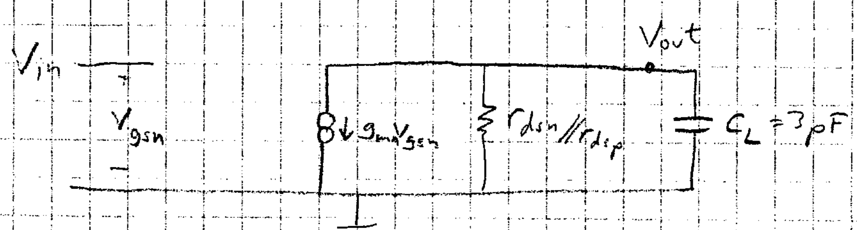
2) a) $I_{D_p} = \frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L}\right)_p (V_{GS_p} - V_{tp0})^2 = \frac{1}{2}\,40 \cdot 30 \cdot (-0{,}8 + 0{,}6)^2\,\mu A = 24\,\mu A$

$I_{D_n} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_n (V_{IN} - V_{tn0})^2 = \frac{1}{2} \cdot 115 \cdot 10 \cdot (V_G - V_{tn0})^2\,\mu A$

$I_{D_n} = I_{D_p} \Rightarrow V_{IN} - V_{tn0} = \sqrt{\frac{24}{\frac{1}{2} \cdot 115 \cdot 10}} = 0{,}204 \Rightarrow V_{IN} = 0{,}46 + 0{,}204\,V = \underline{\underline{0{,}66\,V}}$

b)



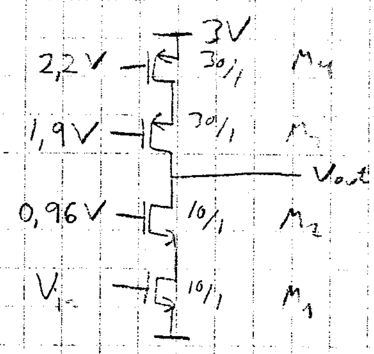
c) $g_{mn} = \frac{2 I_D}{V_{ovn}} = \frac{48\,\mu A}{0{,}204\,V} = 235\,\mu S$ $r_{dsn} = r_{dsp} = 55\,\Omega A/\mu m \cdot \frac{1\,\mu m}{24\,\mu A} = 2{,}3\,M\Omega$

$A_{v,dc} = -g_{mn} \cdot r_{dsn} // r_{dsp} = \underline{-270}$ $\omega_{-3dB} = \frac{1}{C_L \cdot r_{dsn} // r_{dsp}} = \underline{\underline{0{,}29\,Mrad/s}} = \underline{\underline{46\,kHz}}$

$\omega_{ta} = \frac{g_m}{C_L} = \underline{78\,Mrad/s} = 12\,MHz$

3)

a)



By choosing the same size of the transistors, and since they all have the same DC current, the V_{ov}'s will be the same = 0,2V.

At least 0,2V $V_{DS} = V_{ov}$ is needed to keep M_1 & M_4 in the active region.

Therefore the gate voltage of M_3 should be at least 0,2V below Gate of M_4. To give margin for body effect it is chosen 0,3V below, at 1,9V. Same with $V_{G2} > V_{G1} + 0,2V$

$V_{G2} = V_{G1} + 0,3V = 0,96V$ is chosen.

b) $R_o \approx g_{m2} r_{o1} r_{o2} \;//\; g_{m3} r_{o3} r_{o4}$

$g_{m2} = \frac{2I_D}{V_{ov2}} = 235\mu S \quad g_{m3} = \frac{2I_D}{V_{ov}} = \frac{48\mu A}{0,2V} = 240\mu S$

$r_{o1} = r_{o2} = r_{o3} = r_{o4} = 2,3\ M\Omega$ (from previous problem)

$R_o \approx 235 \cdot 2,3 \cdot 2,3\ M\Omega \;//\; 240 \cdot 2,3 \cdot 2,3\ M\Omega = 1,24G\Omega \;//\; 1,27G\Omega = 0,63\ G\Omega$

$A_{v,dc} = -g_{m1} \cdot R_o = -235\mu S \cdot 630M\Omega = -235 \cdot 157 = -1,5 \cdot 10^5$

c) The output range is limited by M_2 and M_3 having to stay in the active region:

$V_{G2} - V_{tn} < V_{out} < V_{G3} - V_{tp} \Rightarrow 0,96 - 0,46 < V_{out} < 1,9 + 0,6 \Rightarrow$

$0,5V < V_{out} < 2,5V$

(this is a slight underestimation, the body-effect will make the range slightly larger)

4)

a)

$$V_{ov} = V_{GS} - V_{tn0} = 1 - 0,46 = 0,54\,V$$

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}V_{ov}^2 = \frac{1}{2}\cdot 115\cdot 10^{-6}\cdot 10\cdot 0,54^2 = 168\,\mu A$$

$$g_m = \frac{2I_D}{V_{ov}} = \frac{2\cdot 168\,\mu A}{0,54\,V} = \underline{621\,\mu S}$$

$$g_{ds} = \frac{1}{r_{ds}} = \frac{1}{55\cdot\frac{1}{168\cdot 10^{-6}}} = \frac{168}{55}\,\mu S = \underline{3,05\,\mu S}$$

b)

$$V_t = V_{t0} + \gamma_n\left[\sqrt{2\phi_f + V_{SB}} - \sqrt{2\phi_f}\right] =$$

$$= 0,46V + 0,58\cdot\left[\sqrt{0,79+1} - \sqrt{0,79}\right] = 0,72\,V$$

$$V_{ov} = V_{GS} - V_t = 1 - 0,72\,V = 0,28\,V$$

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}V_{ov}^2 = \frac{1}{2}\cdot 115\cdot 10^{-6}\cdot 10\cdot 0,28^2 = 45\,\mu A$$

$$g_m = \frac{2I_D}{V_{ov}} = \frac{90\,\mu A}{0,28\,V} = \underline{321\,\mu S}$$

$$g_{ds} = \frac{1}{r_{ds}} = \frac{1}{55\cdot\frac{1}{45\cdot 10^{-6}}} = \frac{45}{55}\,\mu S = \underline{0,82\,\mu S}$$

c)

$$V_{DS} = 0 \Rightarrow I_D = 0 \Rightarrow g_m = \frac{\partial I_D}{\partial V_{GS}} = \underline{0} \quad (\text{deep triode})$$

$$g_{ds} = \{V_{DS} = 0\} = g_{ds0} = \mu_n C_{ox}\frac{W}{L}V_{ov} = 115\cdot 10^{-6}\cdot 10\cdot(2 - 0,46) =$$

$$= \underline{1,77\,mS}$$

5)

a) $I_1 = I_{DS} = \frac{1}{2}\mu_P C_{ox}\left(\frac{W}{L}\right)_5 (V_{GS5} - V_{tp0})^2 = 20\mu \cdot 40 \cdot 0{,}2^2 = 32\,\mu A$

$I_2 = I_{DS} \cdot \left(\frac{W}{L}\right)_7 / \left(\frac{W}{L}\right)_5 = 32\,\mu A \cdot 5 = 160\,\mu A$

$I_{TOT} = I_1 + I_2 = \underline{192\,\mu A}$

$g_{m1} = \frac{2 I_{D1}}{V_{ov1}} = \frac{I_1}{V_{ov6}} = \frac{32\,\mu A}{0{,}2V} = 160\,\mu S$

$\omega_{ta} = \frac{g_{m1}}{C_c} = \frac{160 \cdot 10^{-6}}{1 \cdot 10^{-12}} = \underline{160\ Mrad/s} \quad \left(f_{ta} = \frac{160M}{2\pi} = 25\,MHz\right)$

$r_{ds4} = 55\Omega \cdot \frac{1}{I_1/2} = \frac{55}{16} M\Omega = 3{,}4\ M\Omega = r_{ds2}$

$A_{v1,dc} = g_{m1} \cdot r_{ds2} /\!/ r_{ds4} = 275$

$g_{m6} = \sqrt{2 I_{DS}\,\mu_n C_{ox} \left(\frac{W}{L}\right)_6} = \sqrt{2 \cdot 160\mu \cdot 115\mu \cdot 50} = 1{,}36\ mS$

$r_{ds6} = r_{ds7} = \frac{55 \cdot 1}{160 \cdot 10^{-6}} = 344\ k\Omega$

$A_{v2,dc} = g_{m6} \cdot r_{ds6} /\!/ r_{ds7} = 234$

$A_{v,dc} = A_{v1,dc} \cdot A_{v2,dc} = 275 \cdot 234 = \underline{64 \cdot 10^3}$

$SR_1 = \pm \frac{I_1}{C_c} = \pm \frac{32\,\mu A}{1pF} = \underline{\pm 32\ V/\mu s}$ (input stage limited)

$SR_2 = \frac{I_2}{C_c + C_L} = \frac{160\,\mu A}{3\,pF} = 53\ V/\mu s$ (output stage not limiting)

b) $p_2 \approx -\frac{g_{m6}}{C_L} = -\frac{1{,}36m}{2p} = -680\ Mrad/s$

$z = \frac{1}{\left(\frac{1}{g_{m6}} - R_z\right) C_c} = \frac{1}{(735 - 2000)\, 1 \cdot 10^{-12}} = -790\ Mrad/s$

$\varphi_m = 90^\circ - \arctan\left(\frac{160}{680}\right) + \arctan\left(\frac{160}{790}\right) = 90^\circ - 13{,}2^\circ + 11^\circ = \underline{88^\circ}$

As C_L increases p_2 will drop, $\varphi_m = 60^\circ$ reached when

$\arctan\left(\frac{160m}{-p_2}\right) = (90^\circ - 60^\circ) + 11^\circ = 41^\circ \Rightarrow p_2 = -184\ Mrad/s$

$p_2 \approx -\frac{g_{m6}}{C_L} \Rightarrow C_L \approx -\frac{g_{m6}}{p_2} = -\frac{1{,}36m}{-184M} = \underline{7{,}4\ pF}$