UNIVERSITI TUN HUSSEIN ONN MALAYSIA

FINAL EXAMINATION
SEMESTER II
SESSION 2023/2024

COURSE NAME	:	ANALOG IC DESIGN
COURSE CODE	:	BEJ43903
PROGRAMME CODE	:	BEJ
EXAMINATION DATE	:	JULY 2024
DURATION	:	3 HOURS
INSTRUCTIONS	:	1. ANSWER ALL QUESTIONS 2. THIS FINAL EXAMINATION IS CONDUCTED VIA ☐ Open book ☒ Closed book 3. STUDENTS ARE **PROHIBITED** TO CONSULT THEIR OWN MATERIAL OR ANY EXTERNAL RESOURCES DURING THE EXAMINATION CONDUCTED VIA CLOSED BOOK

THIS QUESTION PAPER CONSISTS OF **TEN (10)** PAGES

Q1 (a) A MOS differential pair is shown in **Figure Q1.1.**

(i) Design the MOS differential pair for a voltage gain of 5 and a power dissipation of 1 mW if the equilibrium overdrive must at least 150 mV. Assume $\gamma = \lambda = 0$, $\mu_n C_{ox} = 100\ \mu A/V^2$, $V_{TH} = 0.6$ V and $V_{DD} = 1.8$ V.

(8 marks)

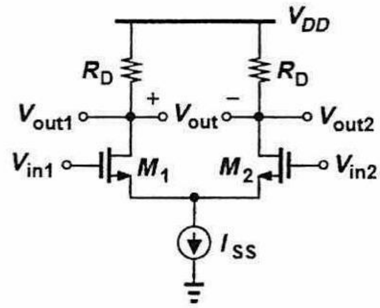

Figure Q1.1

(ii) Determine the maximum allowable input CM level if $V_{TH} = 0.4$ V is applied to the same circuit in **Figure Q1.1.**

(2 marks)

(b) **Figure Q1.2** shows the differential amplifier that uses a resistor rather than a current source to define a tail current of 1 mA. Assuming that the circuit is symmetrical and $\gamma = \lambda = 0$, $(W/L)_{1,2} = 20/0.5$, $\mu_n C_{ox} = 100\ \mu A/V^2$, $V_{TH} = 0.6$ V and $V_{DD} = 3$ V.

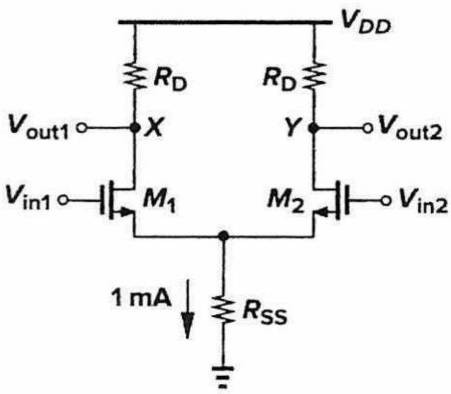

Figure Q1.2

(i) Determine the required input CM voltage for which R_{SS} sustains 0.5 V and calculate the R_{SS} value.

(8 marks)

(ii) Calculate R_D for a differential gain of 20.

(4 marks)

(iii) Draw the small-signal equivalent circuit for this amplifier.

(3 marks)

Q2 (a) A current mirror circuit senses the reference current and generates the copy of reference current with the same characteristics. **Figure Q2.1** shows a basic block diagram for current mirror circuit.

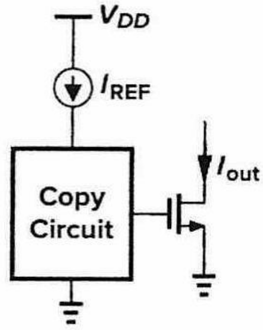

Figure Q2.1

(i) Complete the circuit by drawing the 'copy circuit'. Using the complete circuit, prove that $I_{out} = \frac{(W/L)_2}{(W/L)_1} I_{REF}$.

(4 marks)

(ii) Modify the circuit in **Figure Q2.1** such that the body effect can be ignored and constant output voltage.

(3 marks)

(b) The common-source stage depicted in **Figure Q2.2** must be designed for a voltage gain of 20 and a power budget of 2 mW. Assume the following: $\mu_n C_{ox} = 100\ \mu A/V^2, (W/L)_1 = 20/0.18\,, \lambda_n = 0.1\ V^{-1}, \lambda_p = 0.2\ V^{-1}, \gamma = 0$.

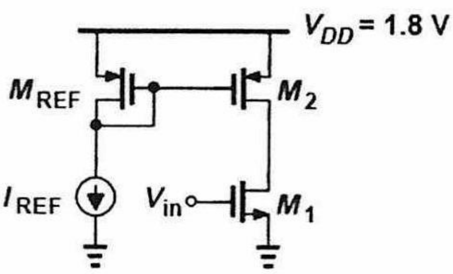

Figure Q2.2

(i) Determine the V_{GS1} and I_{D1}.

(5 marks)

(ii) Find I_{REF} and $\frac{(W/L)_2}{(W/L)_{REF}}$ if M_{REF} has $(W/L)_{REF}$.

(3 marks)

(c) A current source circuit is shown in **Figure Q2.3**. Given the following parameters, $(W/L)_1 = 2, (W/L)_2 = 10, V_{DD} = 2.5\ V,\ \mu_n C_{ox} = 100\mu A/V^2$, $V_{TH,n} = 0.5\ V,\ \lambda_n = 0.05\ V^{-1}, \gamma = 0.$

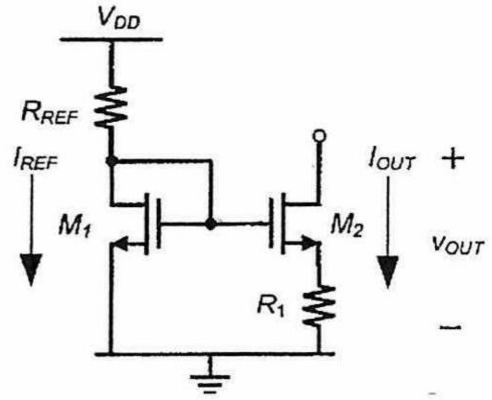

Figure Q2.3

(i) Find the value of R_{REF} such that $I_{REF} = 100\mu A$.

(3 marks)

(ii) Determine the value of R_1 that gives $I_{OUT} = 40\mu A$. Assume that M_2 is in saturation.

(4 marks)

(iii) Determine the lowest output voltage, V_{OUT} for which the circuit still acts as a current source.

(3 marks)

Q3 (a) Operation amplifiers (also known as op-amps) are key elements in analogue processing systems.

(i) Compare **TWO (2)** advantages of single stage amplifier and two stage amplifiers.

(4 marks)

(ii) Determine the input common-mode voltage range and the closed-loop output impedance of the unity-gain buffer depicted in **Figure Q3.1**. Assume the threshold voltage, $V_{TH} = 0.7$ V with supply voltage of 3V.

(4 marks)

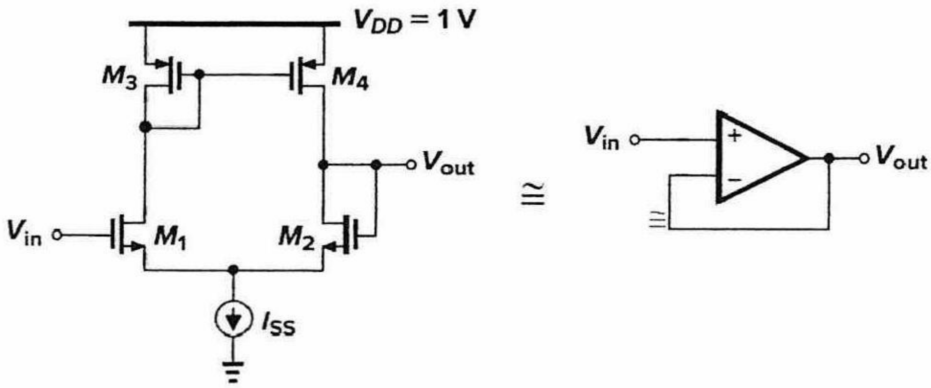

Figure Q3.1

(b) An amplifier circuit depicted in **Figure Q3.2** is designed based on the following specification. Assume M_1 operates at the edge of saturation if the input common-mode level is 1 V.

$$A_v = 10,\ P = 2\,mW, \mu_n C_{ox} = 2\mu_p C_{ox} = 100\,\mu A/V^2,$$

$$V_{DD} = 1.8\,V, V_{TH,n} = 0.6\,V, V_{TH,p} = -0.4\,V,\ \lambda_n = 0.1\,V^{-1}, \lambda_p = 0.2\,V^{-1}$$

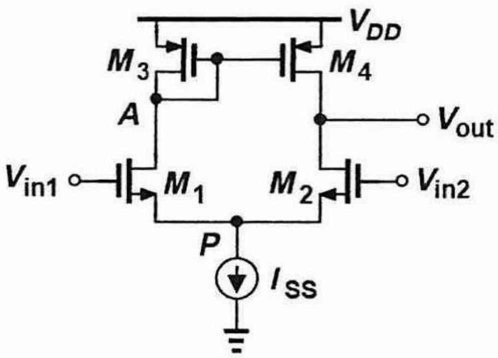

Figure Q3.2

(i) Find the I_{SS} and $g_{m(n)}$.

(5 marks)

(ii) Determine $\left(W/L\right)_{1-2}$ and $\left(W/L\right)_{3-4}$.

(4 marks)

(c) A simple implementation of a two-stage op amp in shown in **Figure Q3.3**. Assume the following parameters: $(W/L)_{1-8} = {}^{100}/_{0.5}, I_{SS} = 1\,mA$, $V_{DD} = 3\,V, V_{TH}{=}0.7\,V,\ \mu_n C_{ox} = 100\ \mu A/V^2,\ \mu_p C_{ox} = 50\ \mu A/V^2, \gamma = 0$.

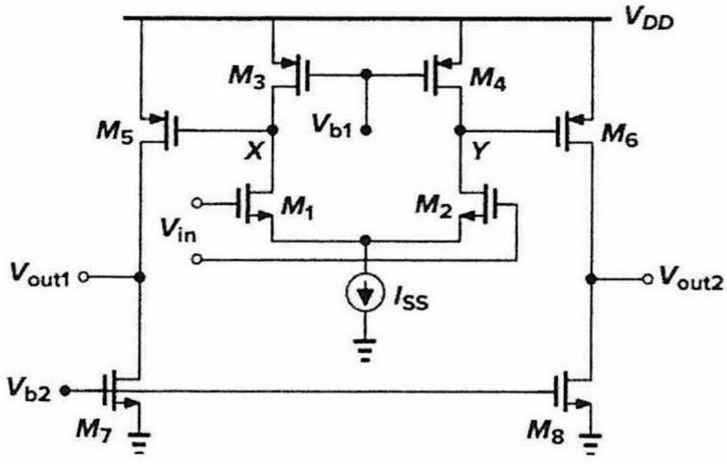

Figure Q3.3

(i) Analyse the CM level that must be established at the drains of M_3 and M_4 so that $I_{D5} = I_{D6} = 1$ mA.

(4 marks)

(ii) Based on part **Q3(c)(i)**, calculate the overall voltage gain and the maximum output swing.

(4 marks)

Q4 (a) A comparator detects if its input (voltage or current) is higher or lower than a reference level. Discuss **TWO (2)** key stage issues in comparator design and suggest the solution for each issue.

(4 marks)

(b) Find the propagation delay time of an open-loop comparator has a dominant pole at 10^3 rad/s, DC gain of 10^4, slew rate 1 V/μs, and a binary output voltage swing of 1 V for an applied input voltage 10 mV.

(8 marks)

(c) The two-stage comparator shown in **Figure Q4.1**. Assume that this comparator has no compensation capacitor, C_C, and the minimum value of $V_{G6} = 0$ V, $C_I = 0.2$ pF and $C_{II} = 5$ pF. Use the following specifications:

$$A_v = 8000 \quad V_{DD} = 2.5\,V \quad V_{SS} = -2.5\,V \quad GB = 5\,MHz \quad SR > 10\,V/\mu s$$

$$60°\,phase\ margin \quad V_{out}\ range = \pm 2\,V \quad ICMR = -1\,V\ to\ 2\,V$$

$$P_{diss} \leq 2\,mW \quad V_{Tp} = 0.7\,V \quad \beta_6 = 10 \times 10^6 \quad I_7 = 235\,\mu A$$

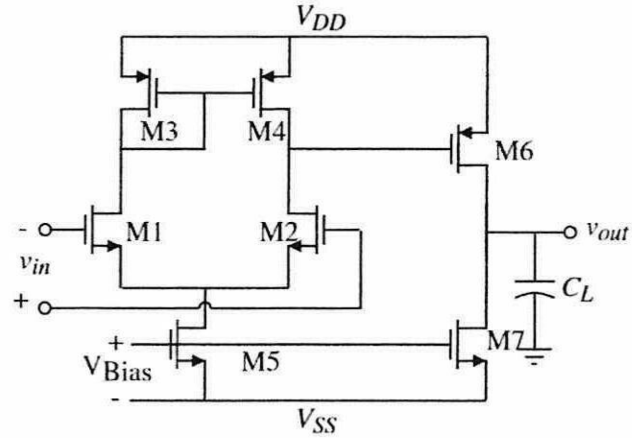

Figure Q4.1

(i) Determine the output range, V_{OH} and V_{OL}

(4 marks)

(ii) Find $V_{in}(min)$, p_1 and p_2

(6 marks)

(iii) Given $(W/L)_7 = (W/L)_6$, $V_{DD} = 2.5\,V$, $V_{SS} = -2.5\,V$, $V_{Bias} = 0\,V$, Determine the trip-point of inverter, V_{TRP} at the second stage.

(3 marks)

-END OF QUESTION-

APPENDIX A

Constants

kT = 0.026 eV, at room temperature
k = 8.62x10-5 eV/K, Boltzman's constant
V_T = 0.026 V, thermal voltage
q=1.6x10^{-19} C (coulombs)
$n_i = 1.45\times10^{10}$ cm^{-3}, Si at room temperature
$\varepsilon_0 = 8.85\times10^{-14}$ F/cm
$\varepsilon_{OX} = (3.9)\ 8.85\times10^{-14}$ F/cm
$\varepsilon_{si} = (11.8)\ 8.85\times10^{-14}$ F/cm

N-channel MOSFET:

Cut-off	$V_{GS} \le V_T$	$I_{DS} = 0$
Linear	$V_{GS} \le V_T, V_{DS} \le V_{SG} - V_T$	$I_{DS} = \mu_n C_{OX}\frac{W}{L}\left[(V_{SG} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right](1+\lambda V_{DS})$
Saturation	$V_{GS} > V_T, V_{DS} > V_{SG} - V_T$	$I_{DS} = \frac{1}{2}\mu_n C_{OX}\frac{W}{L}(V_{GS} - V_T)^2(1+\lambda V_{DS})$
		$g_m = \mu_n C_{OX}\frac{W}{L}(V_{GS} - V_T)(1+\lambda V_{DS})$
	$g_m = \mu_n C_{OX}\frac{W}{L}(V_{GS} - V_T) = \sqrt{2\mu_n C_{OX}\frac{W}{L}I_D} = \frac{2I_D}{V_{GS} - V_T}$ **(for $\lambda = 0$)**	

P-channel MOSFET:

Cut-off	$V_{SG} \le \lvert V_T\rvert$	$I_{SD} = 0$
Linear	$V_{SG} > \lvert V_T\rvert, V_{SD} \le V_{SG} - \lvert V_T\rvert$	$I_{SD} = \mu_p C_{OX}\frac{W}{L}\left[(V_{SG} - \lvert V_T\rvert)V_{SD} - \frac{V_{SD}^2}{2}\right](1+\lambda V_{SD})$
Saturation	$V_{SG} > \lvert V_T\rvert, V_{SD} > V_{SG} - \lvert V_T\rvert$	$I_{SD} = \frac{1}{2}\mu_p C_{OX}\frac{W}{L}(V_{SG} - \lvert V_T\rvert)^2(1+\lambda V_{SD})$

Diff.Amp :

$$|V_{in1} - V_{in2}| \ll \frac{4I_{SS}}{\mu_n C_{OX}\frac{W}{L}}$$

$$I_{D1} - I_{D2} \approx \frac{1}{2}\mu_n C_{OX}\frac{W}{L}(V_{in1} - V_{in2})\sqrt{\frac{4I_{SS}}{\mu_n C_{OX}\frac{W}{L}}} = \sqrt{\mu_n C_{OX}\frac{W}{L}I_{SS}(V_{in1} - V_{in2})}$$

$$I_D = \frac{K_n}{2}(V_{GS} - V_{TN})^2(1 + \lambda V_{DS}) \qquad K_n = \mu_n C_{OX}\frac{W}{L}$$

$$g_m = \sqrt{2\mu_n C_{OX}\left(\frac{W}{L_{eff}}\right)I_D} = \sqrt{2K_n I_D(1 + \lambda V_{DS})}$$

$$r_o = \frac{\lambda^{-1} + V_{DS}}{I_D} \approx \frac{1}{\lambda I_D} \qquad r_{ON} = \frac{1}{\lambda_n \frac{I_{SS}}{2}}(r_{ON}||r_{oP})$$

$$A_V = g_m(r_{oN}||r_{oP}) \qquad g_m = r_{oN}||r_{oP}$$

2 stage: $A_v = \frac{2I_D}{V_{GS5}-V_{TH}}.\left[\frac{1}{\lambda_n I_{D5}}||\frac{1}{\lambda_p I_{D6}}\right]$ where $r_{oi} = \frac{1}{\lambda_N I_{Di}}$

β = feedback factor $= \left.\frac{V_2}{V_1}\right|_{I_2=0} = -(g_{m7} + g_{m8})(R_{on7}||R_{on8})$

$$g_{m7} + g_{m8} = \mu_n C_{OX}\left(\frac{W}{L}\right)_{7,8} V_{DS7,8}.\frac{1}{2\mu_n C_{OX}(W/L)_{7,8}(V_{GS7,8} - V_{T7,8})}$$

$$=-2\mu_n C_{OX}(W/L)_{7,8} V_{DS7,8}.\frac{1}{2\mu_n C_{OX}(W/L)_{7,8}(V_{GS7,8}-V_{T7,8})}$$

$$=-\frac{V_{DS7,8}}{V_{GS7,8}-V_{T7,8}}$$

Power dissipated:

$P_D = V_{DS} \times I_D$

$P = I_{SS}.V_{DD}$

$$V_{CM,out}=V_{DD}-\frac{I_{SS}R_D}{2V_{DD}}=\frac{P_{RD}}{2V_{DD}}$$

$$R_D = \left[2V_{DD}\left(\frac{V_{DD} - V_{CM,out}}{P}\right)\right]$$

$$|A_v|=g_m R_D = \sqrt{\frac{W}{L}\mu_n C_{ox} I_{SS} R_D} = \sqrt{\frac{W}{L}\mu_n C_{ox} I_{SS}\frac{P}{V_{DD}}\left[2V_{DD}\left(\frac{V_{DD}-V_{CM,out}}{P}\right)\right]}$$

Unbuffered Op-Amp:

$$ICMR_{(max)}=\left(\frac{W}{L}\right)_3=\left(\frac{W}{L}\right)_4=\frac{I_5}{K'_3[V_{DD}-V_{in(max)}-|V_{T3}|+V_{T1}]^2}$$

$$g_m=GB.C_C \qquad \left(\frac{W}{L}\right)_3=\left(\frac{W}{L}\right)_2=\frac{(g_m 1)^2}{K'_1 I_5}$$

$$ICMR_{(min)} = \left(\frac{W}{L}\right)_5 = \frac{2I_5}{K'_5 V_{DS5}[sat]^2}, \qquad \left(\frac{W}{L}\right)_6 = \frac{g_{m6}}{g_{m4}}.\left(\frac{W}{L}\right)_4$$

$$I_i = \frac{{g_{m,i}}^2}{2K'_i\left(\frac{W}{L}\right)_i}$$

Two-stage Op-Amp:

$$SR = \frac{I_5}{C_C} \text{ where } I_7 \gg I_5 \text{ and } C_L > C_C$$

$$A_{v1} = \frac{g_{m1}}{g_{ds2}+g_{ds4}} = \frac{2g_{m1}}{I_5(I_2+I_4)} \qquad A_{v2} = \frac{g_{m6}}{g_{ds6}+g_{ds7}} = \frac{g_{m6}}{I_6(I_6+I_7)}$$

$$GB = \frac{g_{m1}}{C_C} \quad p_2 = -\frac{g_{m6}}{C_L} \quad z_1 = \frac{g_{m6}}{C_C}$$

$$g_{m6} = 2.2\, g_{m2}(C_L/C_C)$$

$$\text{Positive ICMR Vin(max)} = V_{DD} - \sqrt{\frac{I_5}{b_3}} - |V_{T03}|_{(max)} + V_{T1(min)})$$

$$\text{Negative ICMR Vin(max)} = V_{SS} + \sqrt{\frac{I_5}{b_1}} + V_{T1(max)} + V_{DS5(sat)})$$

Comparator

$$V_{OH} = V_{DD} - (V_{DD} - V_{G6(min)} - |V_{TP}|)\left[1 - \sqrt{1 - \frac{8I_7}{\beta_6 (V_{DD} - V_{G6(min)-|V_{TP}|})^2}}\right]$$

$$V_{OL} = V_{SS}$$

$$A_v(0) = \left(\frac{g_{m1}}{g_{ds2}+g_{ds4}}\right)\left(\frac{g_{m6}}{g_{ds6}+g_{ds7}}\right) \qquad A_v(s) = \frac{A_v(0)}{\left(\frac{s}{p_1}+1\right)\left(\frac{s}{p_2}+1\right)}$$

$$\text{Poles: } p_1 = -\frac{1}{C_I(g_{ds2}+g_{ds4})} \qquad p_2 = -\frac{1}{C_{II}(g_{ds6}+g_{ds7})}$$

$$v_{in} = V_{TRP} = V_{DD} - |V_{TP}| - \sqrt{\frac{K_N (W/L)_7}{K_P (W/L)_6}}(V_{Bias} - V_{SS} - V_{TN})$$

Slew rate:

$$SR = \frac{I_{tail}}{C_L} \qquad GBW = \frac{g_{m1} r_{o2}}{r_{o2} C_L} = \frac{g_{m1}}{C_L}$$

$$\tau = R_{out} \times C_{out} = R_{out} \times \left(C_{gd2+}C_{gd1}\left(1 - \frac{1}{A_V}\right)\right)$$

Propagation time delay:

$$\frac{V_{OH}-V_{OL}}{2} = A_v(0)[1-e^{-t_p/\tau_C}]V_{in}$$

$$t_p = \Delta T = \frac{\Delta V}{SR} = \frac{V_{OH}-V_{OL}}{2.SR} = \tau_C \ln \frac{1}{1 - \frac{V_{OH}-V_{OL}}{2A_v(0)V_{in}}}$$

$$V_{in(min)} = \frac{V_{OH}-V_{OL}}{A_v(0)} \quad where\ t_p = \tau_C \ln \frac{1}{1 - \frac{V_{in(min)}}{2V_{in}}} \qquad k = \frac{V_{in}}{V_{in(min)}}$$