$I_{DS_5} = I_{SS}$, which means

$$\boxed{I_{DS_1} = I_{DS_2} = \frac{I_{SS}}{2} = \frac{25}{2}\,\mu A = 12.5\,\mu A} \quad -[13]$$

Neglecting $(1+\lambda V_{DS})$ (λ = small) from Saturated Transistor current, we get

$$V_{GS} = V_T + \sqrt{\frac{2 I_{DS}}{\beta'(W/L)}} \qquad \text{i.e. } V_{ov} = \sqrt{\frac{2 I_{DS}}{\beta'(W/L)}}$$

(c) ICMR evaluation

Given $V_{in_{min}} = -1.15\,V$ $\qquad V_{in\,max} = 2\,V$

Now $V_{in\,min} = V_{SS} + V_{Dsat_5} + V_{GS1}$

$$= V_{SS} + V_{Dsat_5} + V_{T1} + \sqrt{\frac{2 I_{DS1}}{\beta'(W/L)_1}} = -1.15\,V$$

Also

$$V_{inmax} = V_{DD} - V_{Tp3} - \sqrt{\frac{2 I_{DS3}}{\beta_p'(W/L)_3}} - V_{DSsat} + V_{GS1} = 2V$$

$$2 = V_{DD} - V_{Tp3} - \sqrt{\frac{2 I_{DS3}}{\beta_p'(W/L)_3}} + V_{Tn1}$$

by using $V_{Dsat} = V_{GS} - V_T$ relation,

$$2 = V_{DD} - V_{Tp3} + V_{Tn1} - \sqrt{\frac{I_{DS5}}{\beta_p'(W/L)_3}}$$

$$2 = 2.5 - 0.7 + 0.7 - \sqrt{\frac{I_{DS5}}{\beta_p'(W/L)_3}}$$

or $\frac{I_{DS5}}{\beta_p'(W/L)_3} = (0.5)^2$ or $\beta_p'(W/L)_3 = 4 I_{DS5} = 100\,\mu A$

$$\therefore (W/L)_3 = \frac{2 \times 50\,\mu A}{50 \times 10^{-6}} = 2$$

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If we include Body Bias effect

$$V_{TP_{max}} = -0.85 \qquad V_{TP_{min}} = -0.55\,V$$

$$V_{Tn_{min}} = +0.55 \qquad V_{Tn_{max}} = +0.85\,V$$

Then $\quad 2 = 2.5 - 0.85 + 0.55 - \sqrt{\dfrac{I_{DSS}}{\beta_p'(W/L)_3}}$

$$\frac{I_{DSS}}{\beta_p'(W/L)_3} = 0.04$$

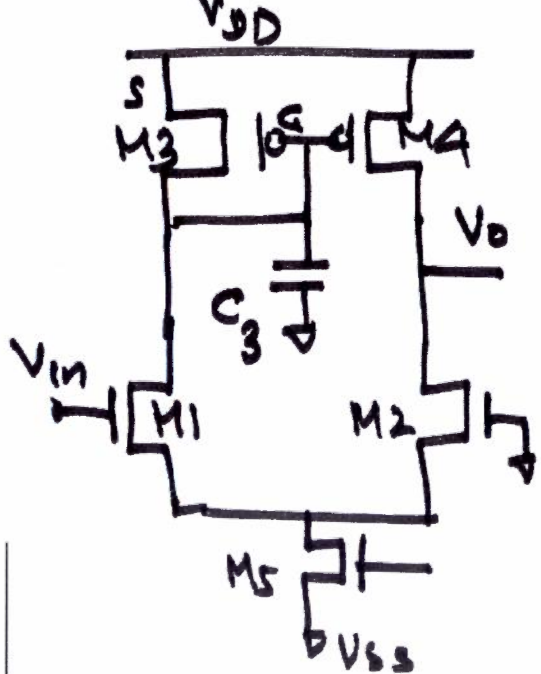
or $\quad (W/L)_3 = \dfrac{25\times10^{-6}}{50\times10^{-6}\times0.04}$

Then $\boxed{(W/L)_3 = 12.5 \simeq 12}$

Hence $\quad (W/L)_3 = (W/L)_4 =$ Either 2 or 12

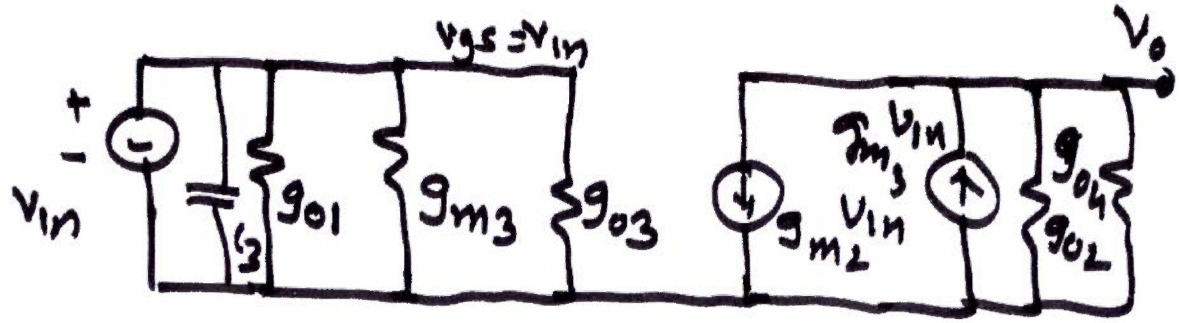
depends upon accuracy

Before we proceed further for evaluations of other $(W/L)_s$ of transistors, we wish to confirm that poles & zeros due to capacitor C_3 in the Diffamp ($M_1 - M_3$ arm) are far far away from GBW, so that they can be neglected in overall response evaluations.



Here
$C_3 = 2C_{gs_3}$

Eq. ckt is



$\therefore$ Gain Transfer F^n $A_1(s)$ is :

$$A_1(s) = \frac{V_o(s)}{V_{in}(s)} = -\frac{g_{m1}}{2(g_{o2}+g_{o4})}\left[\frac{g_{m3}+g_{o1}+g_{o3}}{g_{m3}+g_{o1}+g_{o3}+sC_3}+1\right]$$

$$\cong -\frac{g_{m1}}{2(g_{o2}+g_{o4})} \cdot \frac{2g_{m3}+sC_3}{g_{m3}+sC_3}$$

$$\therefore \quad p_3 = -\frac{g_{m3}}{C_3} = -\frac{g_{m3}}{2C_{gs_3}}$$

$$z_3 = -\frac{2g_{m3}}{2C_{gs_3}} = -\frac{g_{m3}}{C_{gs_3}}$$

Clearly $z_3 = 2p_3$

Given: $C_{ox} = 2.47 \times 10^{-15} / \mu^2$

$$\therefore \quad C_{gs} = \frac{2}{3} C_{ox} \cdot W_3 L_3$$

$$= \frac{2}{3} \times 2.47 \times 10^{-15} \times 12 \times 0.8$$

$$= 15.6 \text{ fF}$$

$$g_{m_3} = \sqrt{2 \times \beta_p' \left(\frac{W_3}{L_3}\right) I_{DS_3}}$$

$$= \sqrt{2 \times 50 \times 12 \times 12.5 \times 10^{-6} \times 10^{-6}}$$

$$= \cancel{38.7 \text{ mS}} \; 12.24 \times 10^{-5} \text{ S}$$

$$\therefore P_3 = \frac{g_{m_3}}{2 \times C_{gs}} = \frac{6.12 \times 10^{-5}}{15.6 \times 10^{-15}} = 3.9 \text{ GHz}$$

If we add parasitics to C_{gs} (overlap caps)
$$\begin{cases} P_3 \simeq 1.8 \text{ G}\cancel{\text{Hz}} \text{ radians/s} \\ f_3 = 3.9 \cancel{\text{GHz}}, \text{ radians} \end{cases}$$

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$$f_{p3} = \frac{3.9 \times 10^9}{6.28} \text{ Hz} = 625 \text{ MHz}$$

$$f_{z3} = 1.25 \text{ GHz}$$

Thus C_3 capacitor does not interfere with Stability of 2 stage Single ended OPAMP.

Evaluation of $(W/L)_1$ & $(W/L)_2$ (They are equal)

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Given $\underset{(Hz)}{GBW} = \frac{g_{m1}}{C_c} = \frac{g_{m2}}{C_c} = \cancel{6\ MHz}$ $= 2\pi \times 6 \times 10^6$ rad/s.

or $g_{m1} = g_{m2} = 2.5 \times 10^{-12} \times 6 \times 10^6 \times 6.28 = 94.2\ \mu S.$

or $6.28 \times 1.5 \times 10^{-5} = \sqrt{2 \beta_n' \left(\frac{W}{L}\right)_1 I_{DS1}}$

$= \sqrt{2 \times 110 \times 10^{-6} \times (W/L)_1 \times 12.5 \times 10^{-6}}$

$(6.28)^2\ 2.25 \times 10^{-10} = 220 \times 12.5 \times 10^{-12} (W/L)_1$

$(W/L)_1 = \frac{2.25 \times 10^{-10} \times 6.28 \times 6.28}{2.20 \times 12.5 \times 10^{-10}} = 3.23$

$\therefore (W/L)_1 = (W/L)_2 = 3.$

Evaluation of $(W/L)_5$:

ICMR given to us is -1.125 to 2 V

We know

$$V_{in_{min}} = -1.125 = V_{Dsat_5} + V_{SS} + V_{T1_{n max}} + \sqrt{\frac{2 I_{DS1}}{\beta_n' (W/L)_1}}$$

or $$V_{Dsat5} = -1.125 - (-2.5) - 0.85 - \sqrt{\frac{2 \times 12.5 \times 10^{-6}}{110 \times 10^{-6} \times 3}}$$

$$= 2.5 - 1.975 - \sqrt{\frac{25}{110 \times 3}}$$

$$= 2.5 - 1.975 - 0.275$$

$$= 0.246 \text{ V.}$$

Now $I_{DS_5} = \frac{\beta_n'}{2}\left(\frac{W}{L}\right)_5 \left[V_{Dsat_5}\right]^2$

$$\therefore \left(\frac{W}{L}\right)_5 = \frac{2\times 25\times 10^{-6}}{110\times 10^{-6}\times 0.060} = 7.58$$

$$\therefore \left(\frac{W}{L}\right)_5 \simeq 8$$

Evaluation of $(W/L)_6$:

From Phase Margin & zero placement chosen by us (ϕ_M & z_1), we have obtained

$$\frac{g_{m6}}{g_{m1}} \geq 10 \qquad \therefore g_{m6} = 10\, g_{m1}$$

$$\therefore g_{m6} = 94.2\times 10\times 10^{-6} = 942 \ \mu\text{Siemens.}$$

Now $I_{DS_6} = \frac{1}{2}\beta_p'\left(\frac{W}{L}\right)_6 (V_{Dsat_6})^2(1+\lambda V_{DS})$

$= \frac{1}{2}\beta_{p_6}(V_{GS_6}-V_{T_6})^2(1+\lambda V_{Dsat_6})$

$$\frac{\partial I_{DS_6}}{\partial V_{GS_6}} = g_{m_6} = \frac{1}{2}\beta_{p_6}\cdot 2\,(V_{GS_6}-V_{T_6})$$

$$g_{m_6} = \beta_{p_6} V_{Dsat_6}$$

$$\therefore \left(\frac{W}{L}\right)_6 = \frac{g_{m_6}}{\beta_{p_6}' V_{Dsat_6}}$$

Hence we must evaluate V_{Dsat_6} first.

We have $V_{out_{max}} = V_{DD} - V_{Dsat_6}$

$\therefore V_{Dsat_6} = V_{DD} - V_{out_{max}} = 2.5 - 2.0 = 0.5V$

Hence $\left(\frac{W}{L}\right)_6 = \frac{g_{m6}}{\beta_p' V_{Dsat_6}}$

$$= \frac{942 \times 10^{-6}}{50 \times 10^{-6} \times 0.5}$$

$(W/L)_6 = 37.7 \simeq 40$

$I_{DS_6} = 25 \times 10^{-6} \times 40 \times 0.25 = 235\,\mu A \rightarrow$ However this is V.V. High

However $(W/L)_6$ can also be found through g_{m6} and g_{m4} relationship

We see M4 & M6 are also in Mirror Configuration

$$\therefore \quad \frac{I_{DS_6}}{I_{DS_4}} = \frac{(W/L)_6}{(W/L)_4}$$

However that means

$$V_{SG_6} = V_{SG_4}$$

But

$$g_{m6} = \beta_p' \left(\frac{W}{L}\right)_6 (V_{SG_6} - V_{TP_6})$$

$$g_{m4} = \beta_p' (W/L)_4 (V_{SG_4} - V_{TP_4})$$

$$\therefore \quad \frac{g_{m6}}{g_{m4}} = \frac{(W/L)_6}{(W/L)_4}$$

However we know $g_{m4} = \sqrt{2\beta_p' \left(\frac{W}{L}\right)_4 I_{DS_4}}$

$$= \sqrt{2 \times 12.5 \times 10^{-6} \times 50 \times 10^{-6} \times 12}$$

$$= 12.24 \times 10^{-5}\ S$$

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We have $g_{m6} = 942 \times 10^{-6}$ S

$$\therefore \left(\frac{W}{L}\right)_6 = \frac{g_{m6}}{g_{m4}} \cdot \left(\frac{W}{L}\right)_4$$

$$= \frac{942 \times 10^{-6}}{122 \times 10^{-6}} \cdot 12$$

or $\left(\frac{W}{L}\right)_6 = 92.65 \cong 92$

We find out V_{Dsat6} by using expression

$$V_{Dsat6} = \frac{g_{m6}}{\left(\frac{W}{L}\right)_6 \cdot \beta_p'} = \frac{942 \times 10^{-6}}{92.65 \times 50 \times 10^{-6}}$$

$$= 0.2 \times \frac{942}{926.5} = 0.203 \text{ V}$$

Then $I_{DS6} = \frac{\beta_p'}{2}\left(\frac{W}{L}\right)_6 (V_{Dsat6})^2 = 95.8\ \mu A$ which is OK by magnitude

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Since M_5 & M_7 are in C. Mirror configuration

& using $I_6 = I_7$ we get

$$\frac{(W/L)_7}{(W/L)_5} = \frac{I_{DS_6}}{I_{DS_5}}$$

or $$\left(\frac{W}{L}\right)_7 = 8 \cdot \frac{I_{DS_6}}{I_{DS_5}} = 8 \cdot \frac{95.8 \times 10^{-6}}{25 \times 10^{-6}} = 30.65$$

$$\therefore \left(\frac{W}{L}\right)_7 = 30$$

From $I_{DS_7} = \frac{1}{2}\beta_n' \left(\frac{W}{L}\right)_7 (V_{Dsat_7})^2$

or $$V_{Dsat_7} = \sqrt{\frac{2 I_{DS_7}}{\beta_n' (W/L)_7}} = \sqrt{0.05663} = 0.23\ V$$

$\therefore V_{outmin} = V_{Dsat_7} = 0.23\ V - 2.5$ we have V_{outmin} required $\leq 2V$

$= -2.27\ V$

Power Dissipation Evaluation :

$$P_{Diss_{Max}} = 2.5\,mW$$

$$P_{Diss} = (I_{Bias\,ckt} + I_{Diff\,amp} + I_{Gain\,stage})(V_{DD} - V_{SS})$$

$$= [I_{Bias\,ckt} + (I_{DS_5} + I_{DS_6})](V_{DD} - V_{SS})$$

$$I_{Bias\,ckt} = I_{DS12} + I_{DS9}$$

Since M5 & M9 – M_{12} are in mirror conf.

We can assume $\left(\frac{W}{L}\right)_{12} = (W/L)_9$

or $I_{DS_9} = I_{DS_{12}}$ by Mirror

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However M5 is carrying $12.5 \times 2 = 25\,\mu A$ current

If we choose

$$\left(\frac{W}{L}\right)_9 = \left(\frac{W}{L}\right)_{12} = \frac{1}{2}\left(\frac{W}{L}\right)_5 = \frac{8}{2} = 4$$

Then $I_{DS_9} = I_{DS_{12}} = \frac{I_{DS_5}}{2} = 12.5\,\mu A$

$\therefore$ $I_{Bias\ Circuit_{Total}} = (12.5 + 12.5)\,\mu A$

$\therefore$ $P_{Diss_{Bias}} = 25 \times 10^{-6} \times 5 = 0.125\ mW$.

Now $V_{DSat_5} = 0.246\ V$ Hence $V_{GS12} = V_{GS9} = V_{GS_5}$

At edge of Sat case

$V_{GS} - V_T = V_{Dsat}$ $\therefore$ $V_{GS} = V_{Dsat} + V_{T_{min}}$.

$\therefore$ $V_{GS_{12}} = 0.246 + 0.7 = 0.946\ V$

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$$V_{GS_{12}} = V_{DS_{12}}$$

$$\therefore \quad R = \frac{(V_{DD} - V_{SS}) - V_{DS_{12}}}{I_{DS_{12}}}$$

$$= \frac{5 - 0.946}{12.5 \times 10^{-6}}$$

$$= \frac{4.054}{12.5}\ M\Omega = 325\ k\Omega$$

Given

Total $P_{Diss} \leq 2.5\ mW$

$$\therefore \quad P_{Diss_T} - P_{Diss_{Bias}} \leq 2.5\ mW - 0.125\ mW$$

$$\leq 2.375\ mW$$

or $\quad P_{Diss_{DiffAmp}} + P_{Diss_{CS}} \leq 2.375\ mW$

$5\ (25 + 95.8) \times 10^{-6} = 0.6\ mW$ which is certainly $< 2.375\ mW$

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Now DC Gain of Two Stage OPAMP is

$$A_V(0) = \frac{g_{m1}}{g_{o2}+g_{o4}} * \frac{g_{m6}}{g_{o5}+g_{o7}}$$

$$= \frac{2 g_{m1} g_{m6}}{(\lambda_2+\lambda_4) I_{DS_5} * (\lambda_6+\lambda_7) I_{DS_6}}$$

λ_2 & $\lambda_7 \Rightarrow \lambda_n = 0.04$

λ_4 & $\lambda_6 \Rightarrow \lambda_p = 0.05$

$$A_{V0} = \frac{2 \times 94.2 \times 942 \times 10^{-12}}{25 \times 10^{-6} (0.09)^2 * 95 \times 10^{-6}}$$

$\therefore$ $A_V(0) = 9225$ V/V which is much greater than $A(0)_{spec} = 4000$ V/V

Design Output

(1) choice of $C_c = 2.5\,pf$, $\phi_M = 60^0$, $z_1 = 10\,GBW$

(2) DC Gain $A_V(0) = 9225$ (4000) at $I_{SS} = 25\,\mu A$

(3) Bandwidth = 4 KHz (9 KHz desired)

(4) $V_{out_{max}} = 2.3\,V$ (+2V)

(5) $V_{out\,min} = 0.23V - 2.5\,V = -2.27V$ (−2V)

(6) $P_{diss} = 0.725\,mW$ (2.5 mW)

(7) Channel Length $L = 0.8\mu$

(8) Sizes: $(W/L)_1 = (\frac{W}{L})_2 = 3$; $(W/L)_3 = (W/L)_4 = 12$

$(W/L)_5 = 8$; $(W/L)_6 = 92$; $(W/L)_7 = 30$

$(W/L)_8 = ?$; $(W/L)_9 = 4 = (W/L)_{12}$ & Bias Resistor = 325 K

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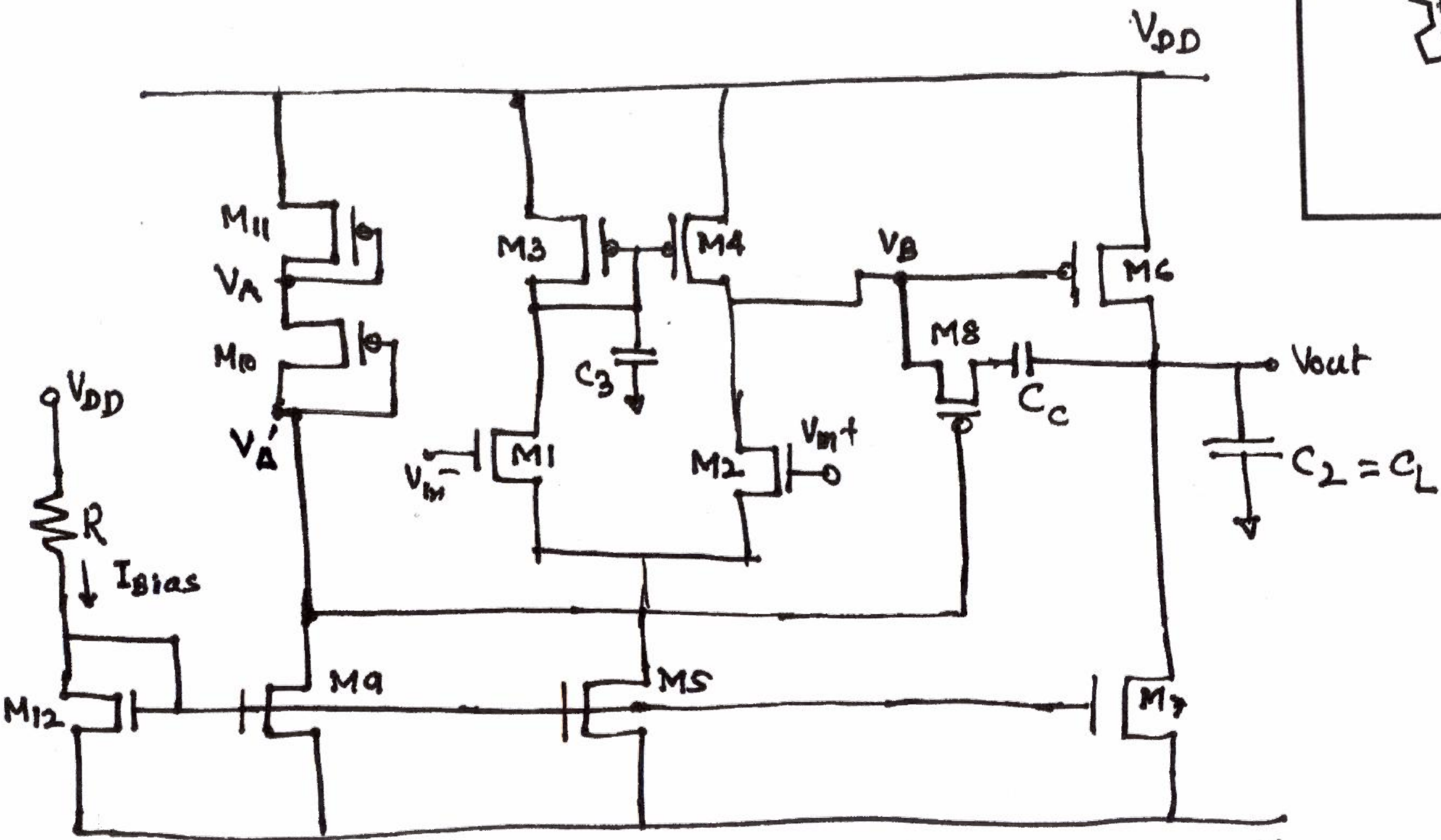
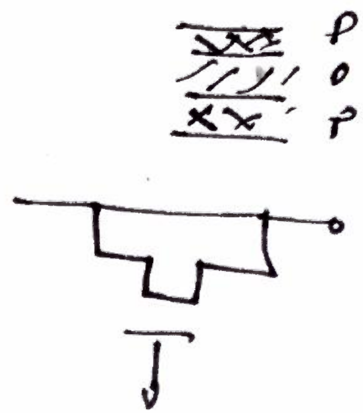
Full OPAMP schematic is shown below





We set $V_A = V_B$ or $V_A' = V_B$ such that $(W/L)_8$ can be evaluated