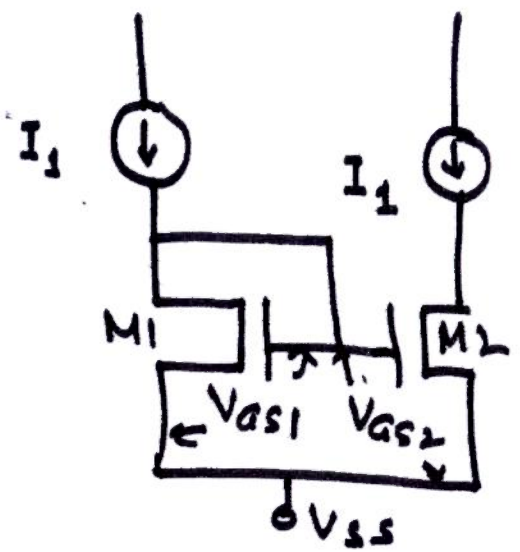
CDEEP
IIT Bombay

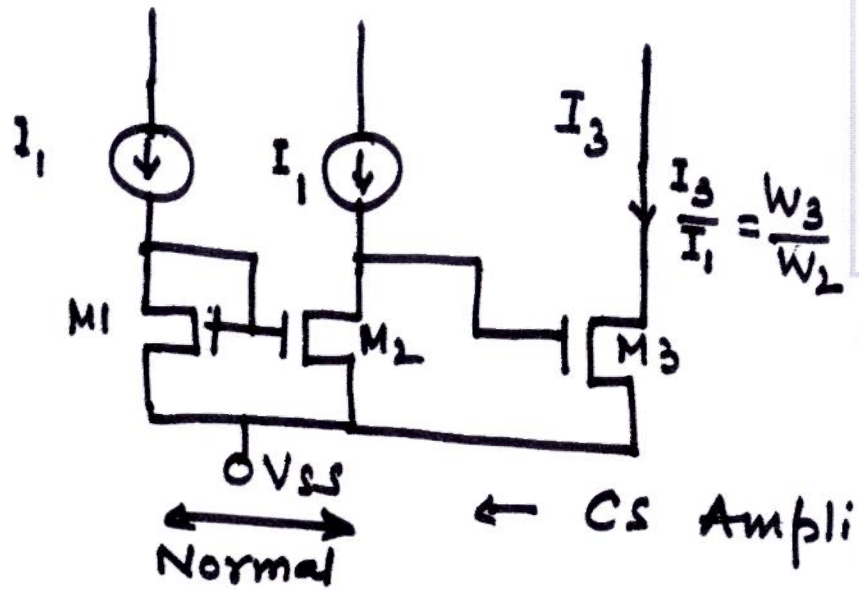
A Two Stage Single Ended OPAMP DESIGN

&

Other OPAMP Structures (Cascode type)

Proof for $V_{GS3} = V_{GS4} = V_{GS6}$ in OPAMP





Current Mirror: If $I_{DS_2} = I_{DS1}$ then $W_1 = W_2$ & V_T is same for both.

$$V_{GS1} = V_{GS2}$$

$$V_{GS1} = V_{DS1}$$

$$\therefore V_{GS2} = V_{DS1}$$

and $V_{DS1} = V_{DS2}$

Since $V_{GS1} = V_{GS2} = V_{DS2}$

Hence if D_2 (V_{DS_2}) is connected to G3, then

$$V_{GS_3} = V_{DS2} = V_{GS1} = V_{GS2}$$

$$\therefore I_3 = \beta_n' \left(\frac{W}{L}\right)_3 (V_{GS_3} - V_T)^2$$

$$I_2 = \beta_n' (W/L)_2 (V_{GS2} - V_T)^2$$

$$\therefore \frac{I_3}{I_2} = \frac{I_3}{I_1} = (W/L)_3 / (W/L)_1$$

Other OPAMPS

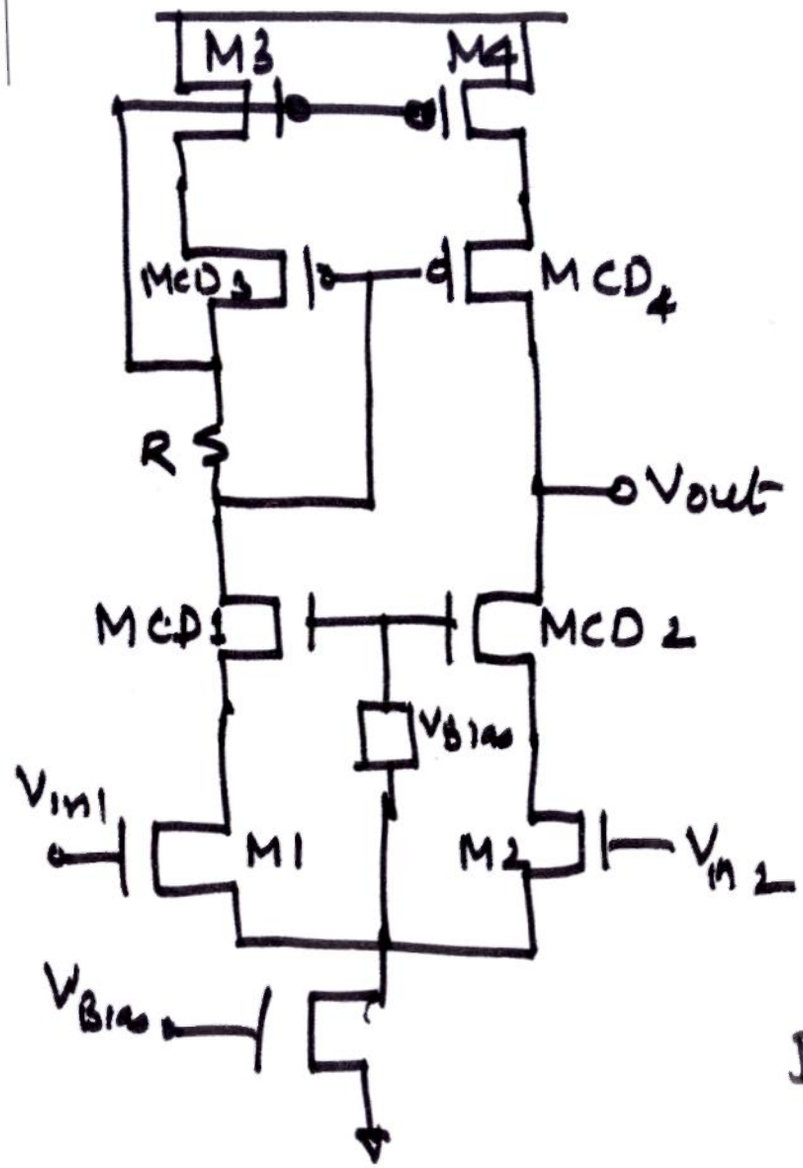
1. CASCODE OPAMP
2. High Performance OPAMP
3. High-Speed OPAMP
4. Differential Output OPAMP
5. Micropower OPAMP
6. Low Noise OPAMP
7. Chopper Stabilised OPAMP
8. Low-Voltage OPAMP

(A) Single Stage CASCODE OPAMP

To improve Stability Issues, one possibility that we have single stage OPAMP (DIFFAMP) with Larger Gain. Since there is no second Stage, 'second pole' will not exist. Thus increasing the Stability. To improve the Gain, we can have CASCODE DIFFAMP.

CASCODE STAGE improves Rout and hence we can get Higher Gain $g_{m_1} R_{out} = A_{vo}$. Then

$$\text{Bandwidth} = \frac{GBW}{A_{vo}} = \text{Dominant Pole} = \frac{1}{R_{out} C_{out}}$$



MCD_1 to MCD_4 gives cascode configuration

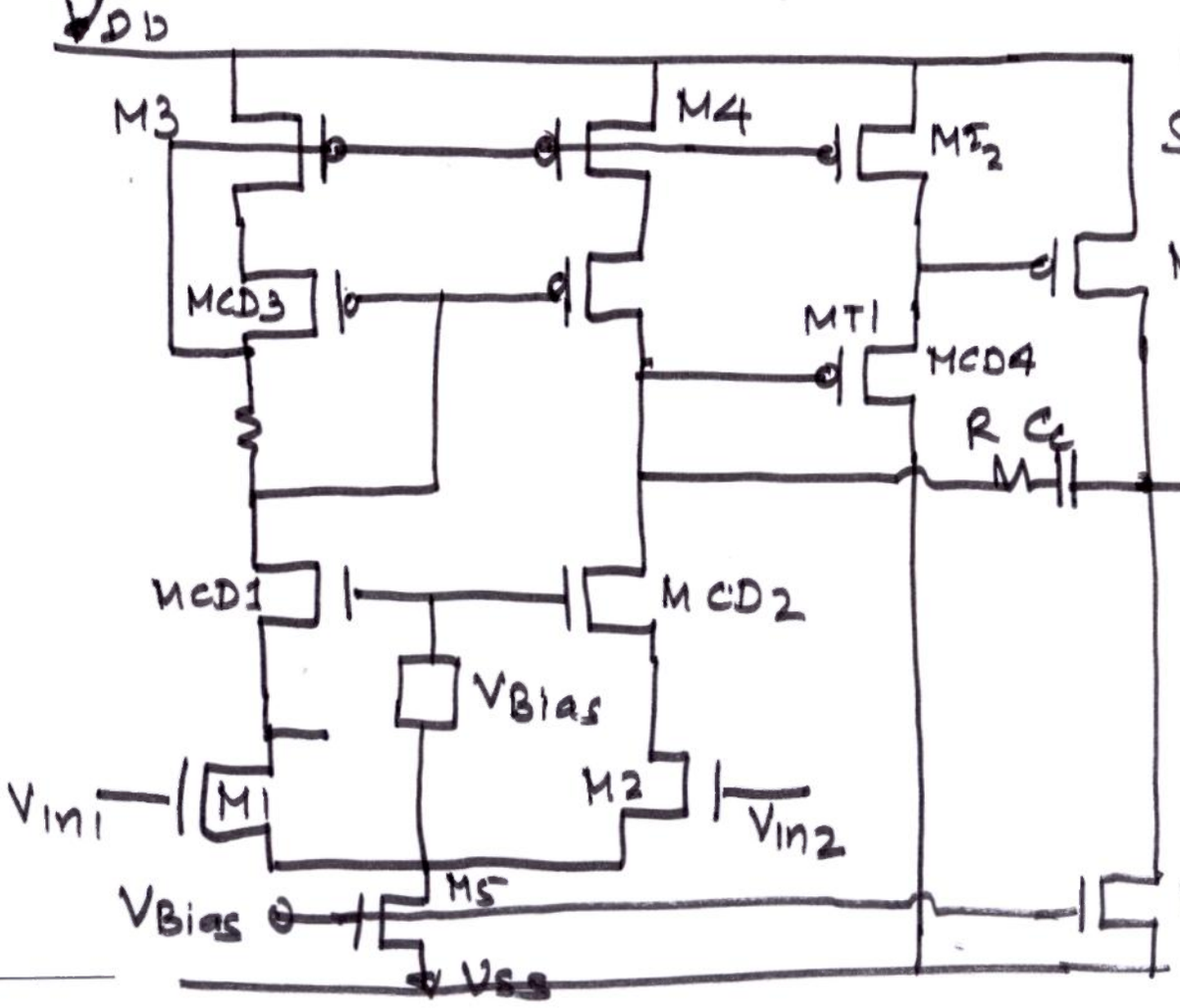
R provides V_{GS} for MCD_3 and allows mirror to MCD 4.

V_{Bias} provides bias for MCD1 and MCD2 and thus fixes V_{DS} for M1 & M2 close to

$V_{DSat_1} = V_{DSat_2}$

Drawback : Reduced ICMR & Voswing

Single Stage Cascode OPAMP with cascode in Diffamp stage can be improved by putting cascode at second stage (CS Amplifier) also.

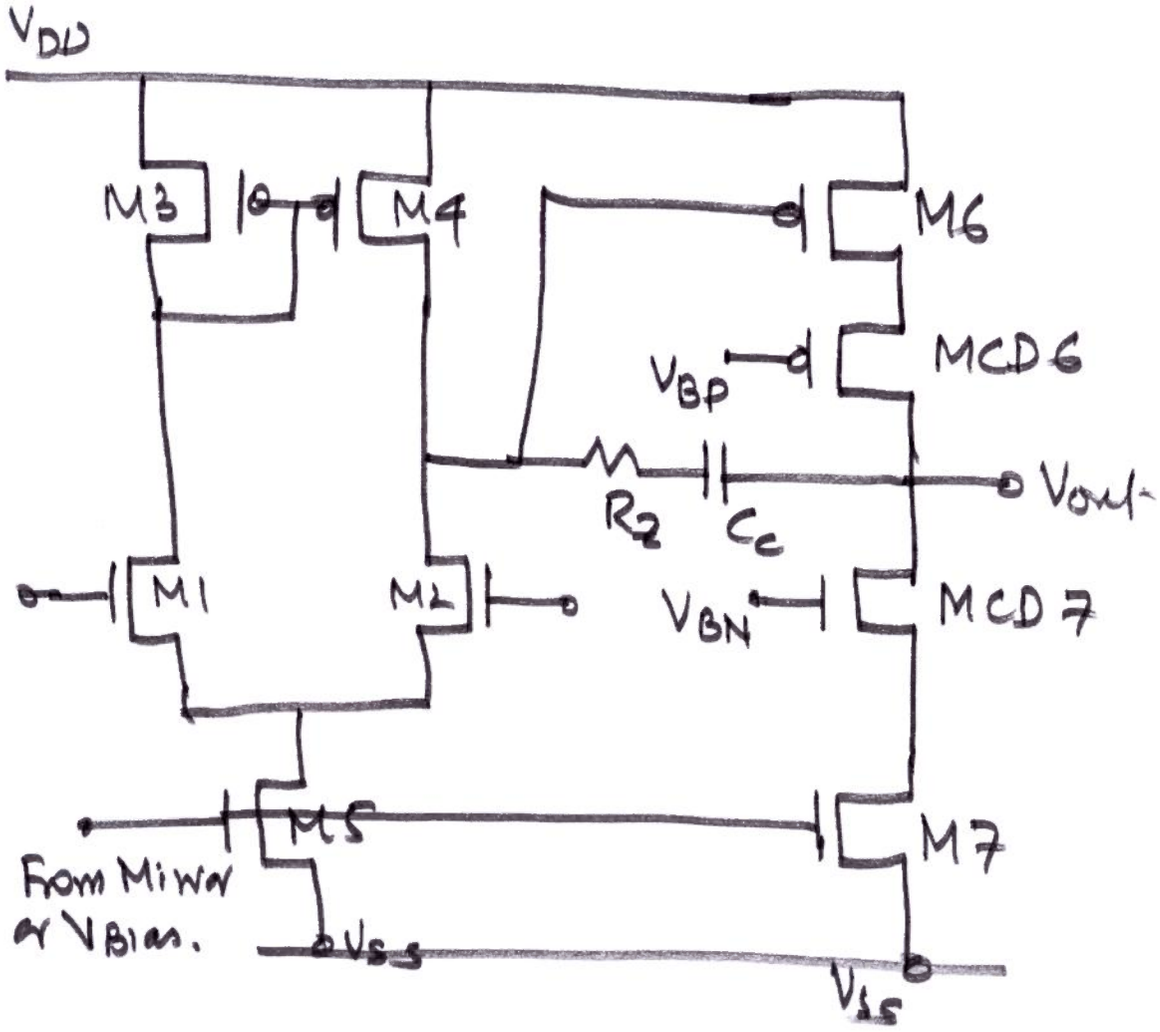


However the Single Cascode Stage output is to be given to Buffer Stage which we shall see later.

MT1 & MT2 are called level translater.

Drawback without MT1&MT2 :—

CASCODE only at Output Stage (CS stage) in an OPAMP



$$A_{V0} = A_{V01} \cdot A_{V02}$$

$$A_{V02} = -g_{m1}(r_{o2} \| r_{o4})$$

$$A_{V02} = -g_{m2}(R'_{o6} \| R'_{o9})$$

$$= -g_{m2} R_{out}$$

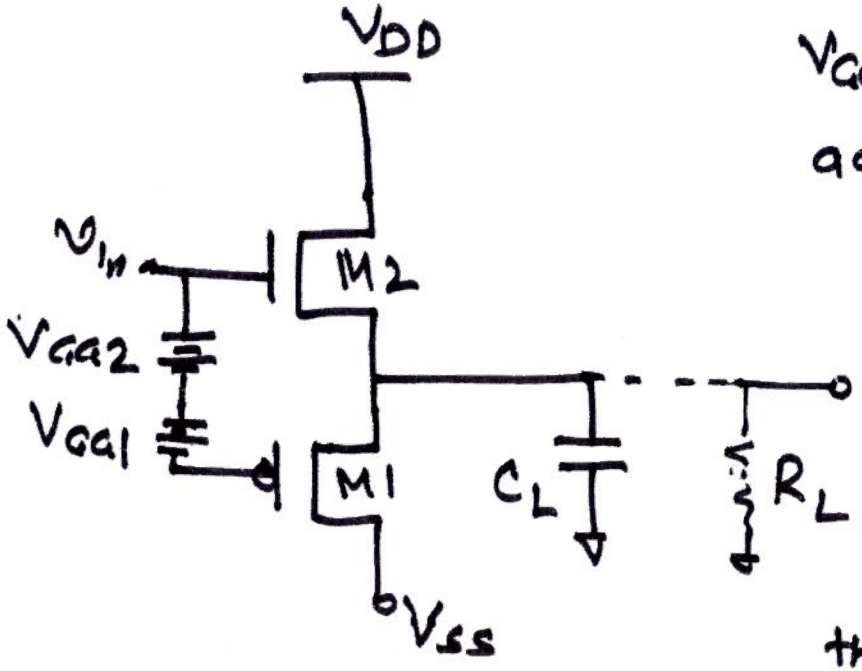
$$R_{out} = (g_{m_{CD6}} \cdot r_{o6} \cdot r_{oc}) \| (g_{m_{CD7}} \cdot r_{o7} \cdot r_{oc_7})$$

An OPAMP always has a Buffer Stage as Output Amplifier.

The Output Amplifier is necessary as output Capacitive load may be large an often not exactly known. Hence Slew Rate at the output load can only be improved if Driving current (Sinking Current) is large and not governed by Second Stage Amplifier requirements.

Typically an AB or B-type Amplifier can be used as an Output Amplifier.

A typical Class B or AB Amplifier basics could be understood by using circuit below



V_{ga1} & V_{ga2} are so adjusted that the Amplifier can be Class - A
Class - B
or Class - AB Type

If V_{in} (moderately large) increases then V_{gs_2} increases ⇒ Current in M2 Increases

And Also V_{sg_1} decreases ⇒ Current in M1 Decreases

When V_{in} is large enough (+tive), M1 can turn-off and then current in M2 charges C_L. Since current in M2 is not connected to currents in earlier CS stage, hence SR could be Larger.

By same argument, M1 can be fully on with M2 OFF, for V_{in} −ve and large. Thus C_L can discharge through M1.

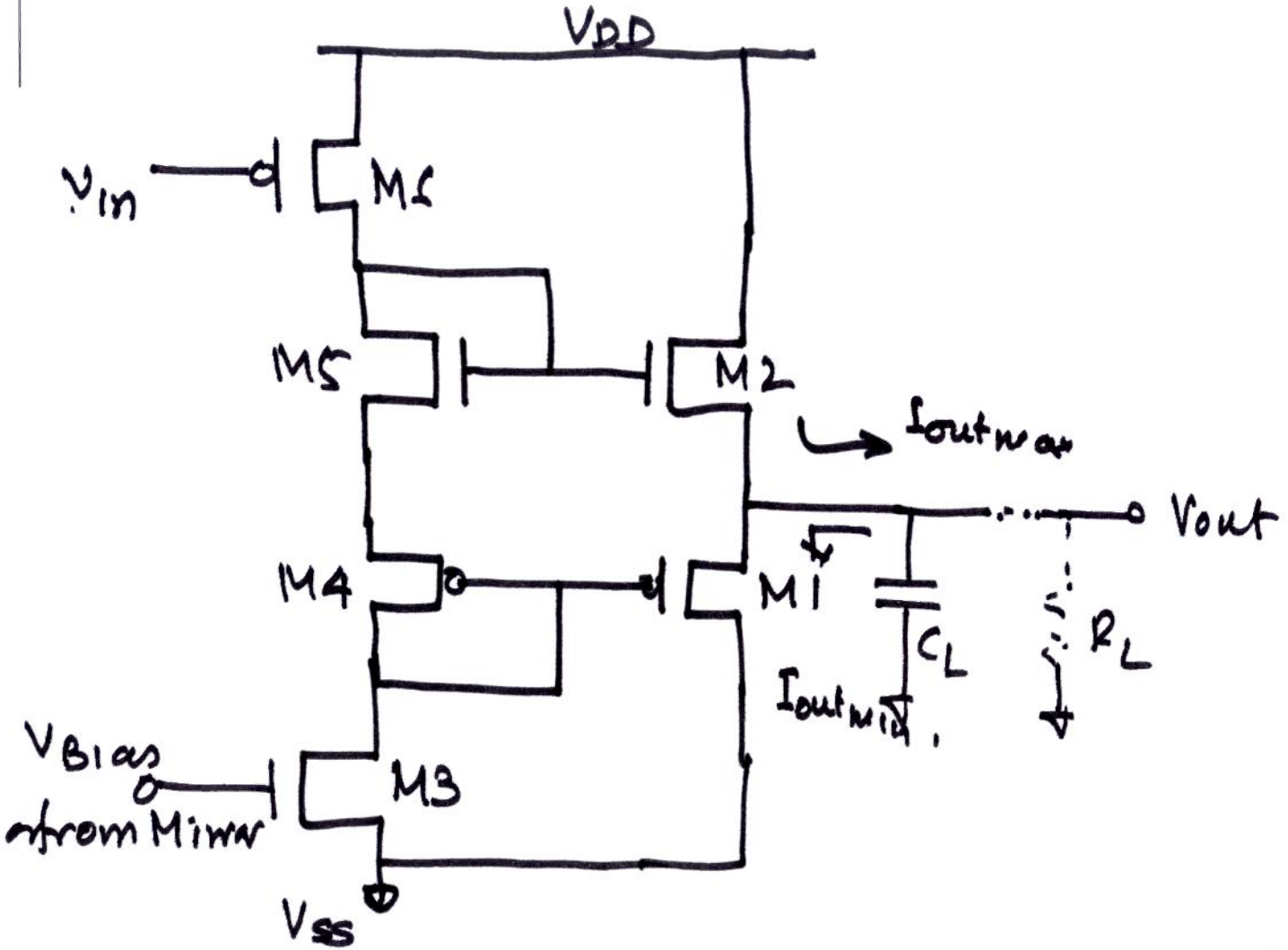
For some value-band of V_{in}, both M1 & M2 will be ON. This is what we say, the Amplifier working in class AB.

The output voltage swing will be then

$$V_{omax} = V_{DD} - V_{TN}$$

and $$V_{omin} = V_{SS} + V_{TP}$$

The implementation of V_{GA1} & V_{GA2} can be realised by a simple circuit embedded in this class AB (or B) Amplifier

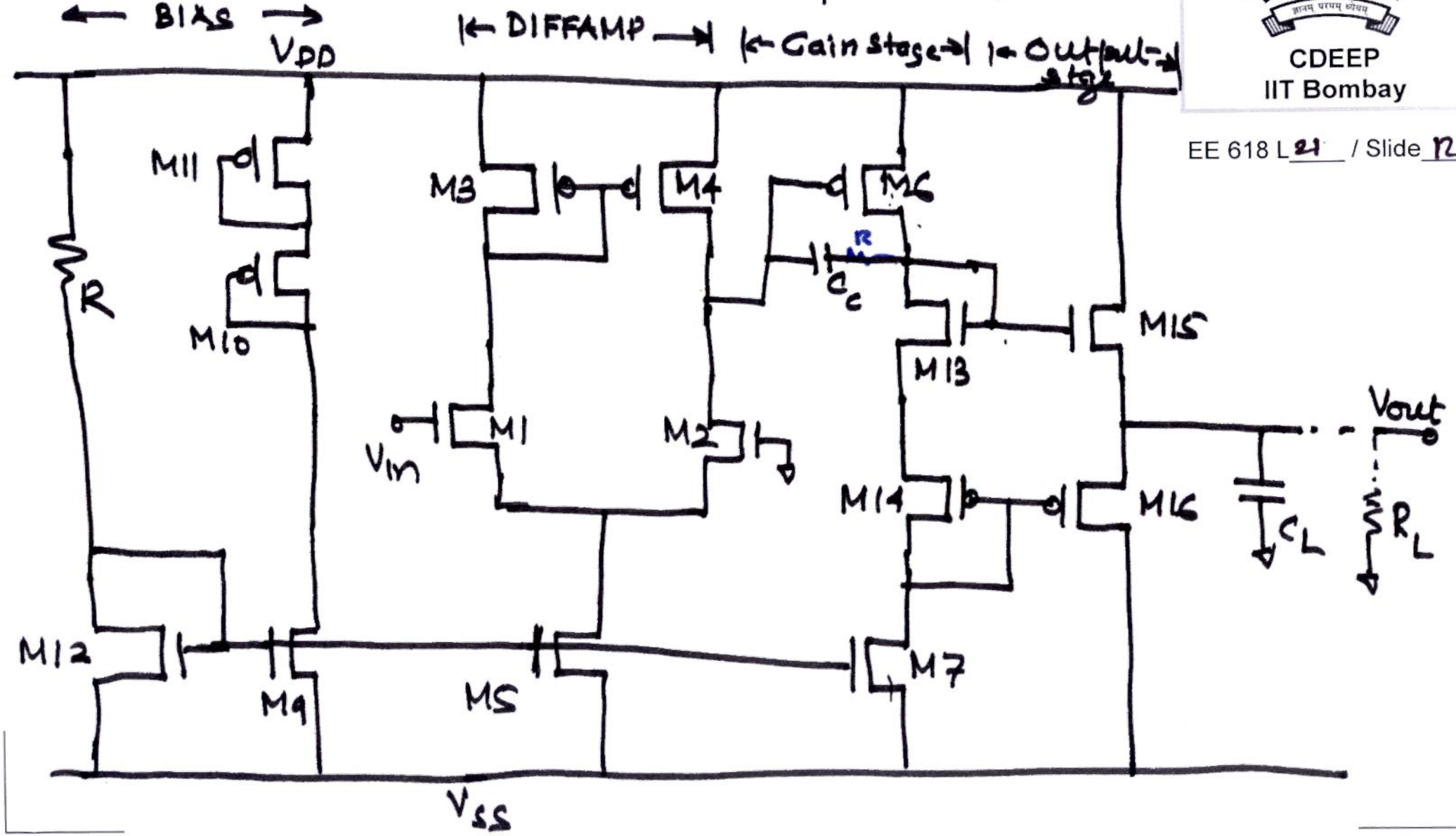


M1 & M2 Size decides I_{outmax} & I_{outmin}.

Class AB output Amplifier

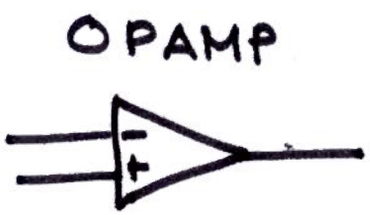
$$I_{outmax} = \frac{\beta_n}{2}(V_{ov_n})^2 \quad \& \quad I_{outmin} = \frac{\beta_p}{2}(V_{ov_p})^2$$

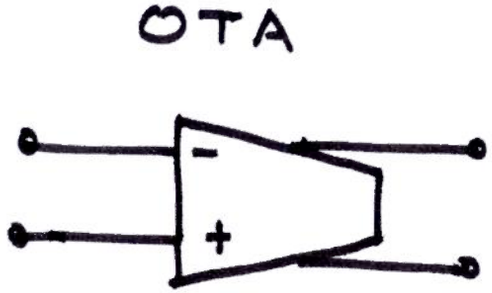
Basic CMOS OPAMP DESIGN can be extended to OPAMP with Output Amplifier

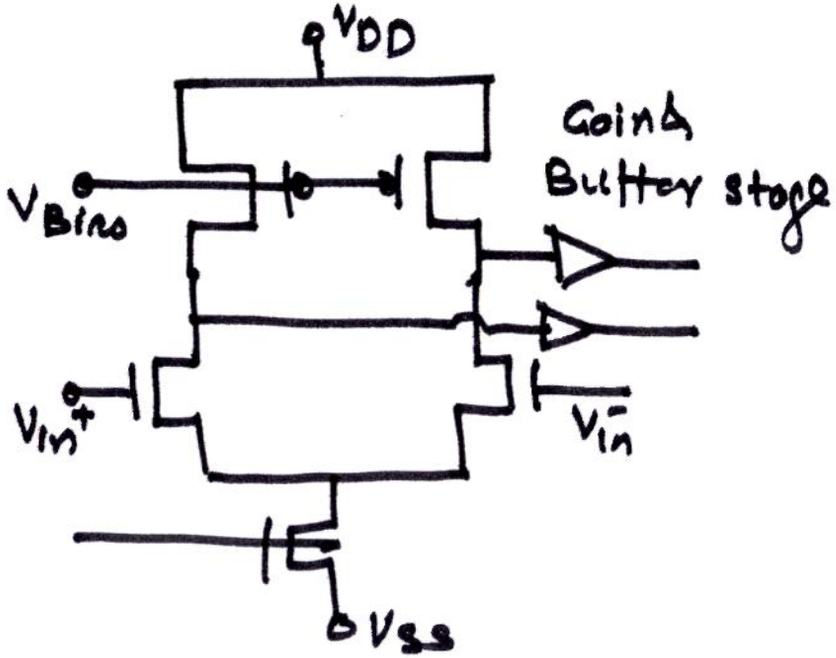


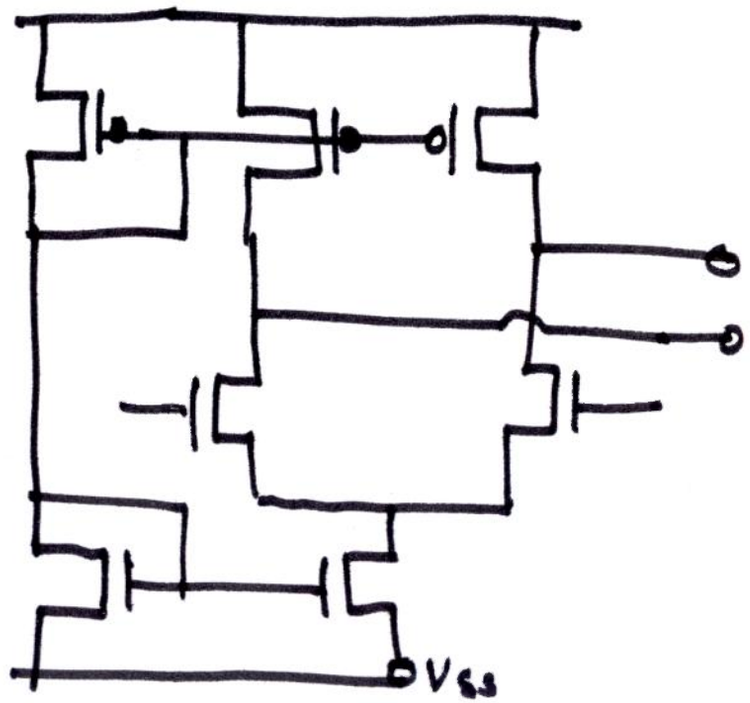
OPERATIONAL Transconductance Amplifiers

OTA



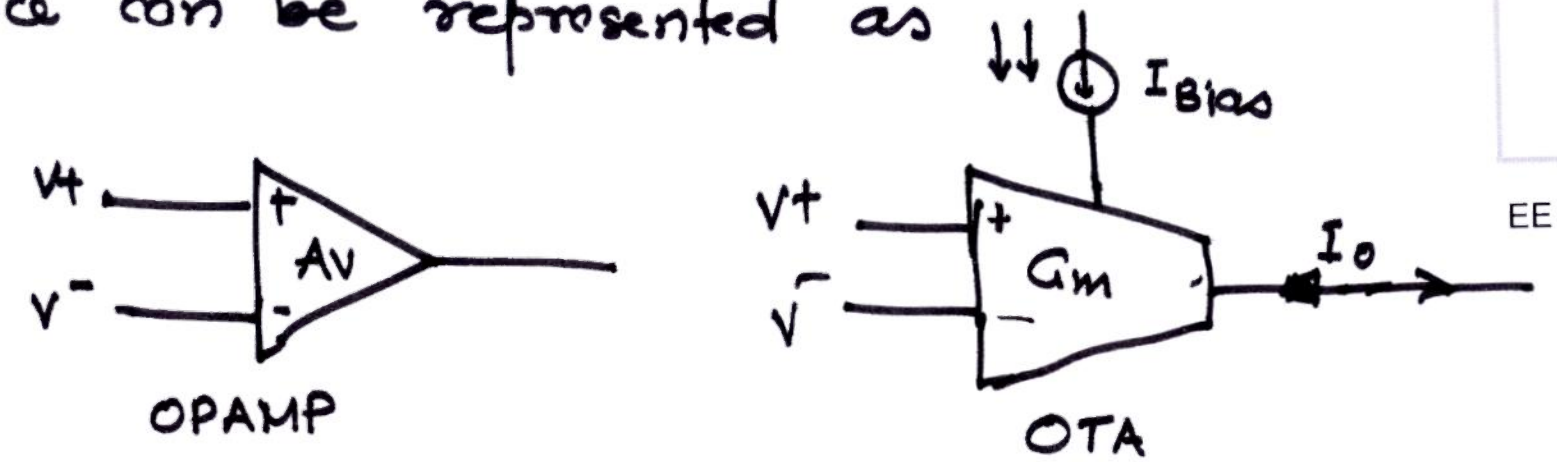


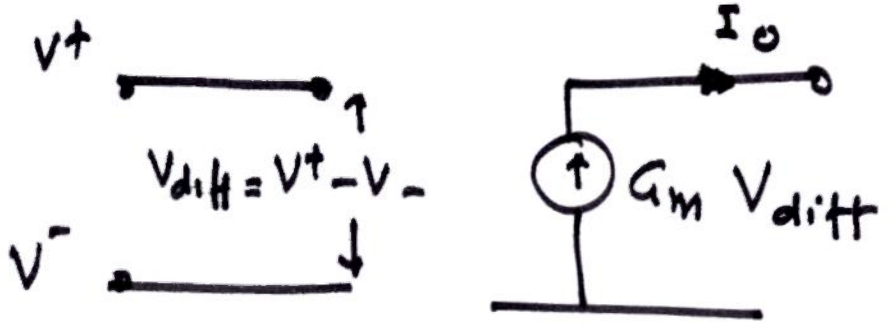




OPAMP	OTA
1. OTA + Buffer	OTA
2. VCVS (A_v)	VCCS (G_m)
3. Low Output Resistance	High Output Impedance
4. Drive possible for R & C loads	Drive Possible only Capacitive loads but not Resistive Loads
5. Larger Power Dissipation & Complex Circuit	On chip Amplifiers are normally OTAs
6. Useful in most General Purpose Applications	Useful in realisation of Active g_m-C filters.

As said earlier OTA is VCCS, and hence can be represented as

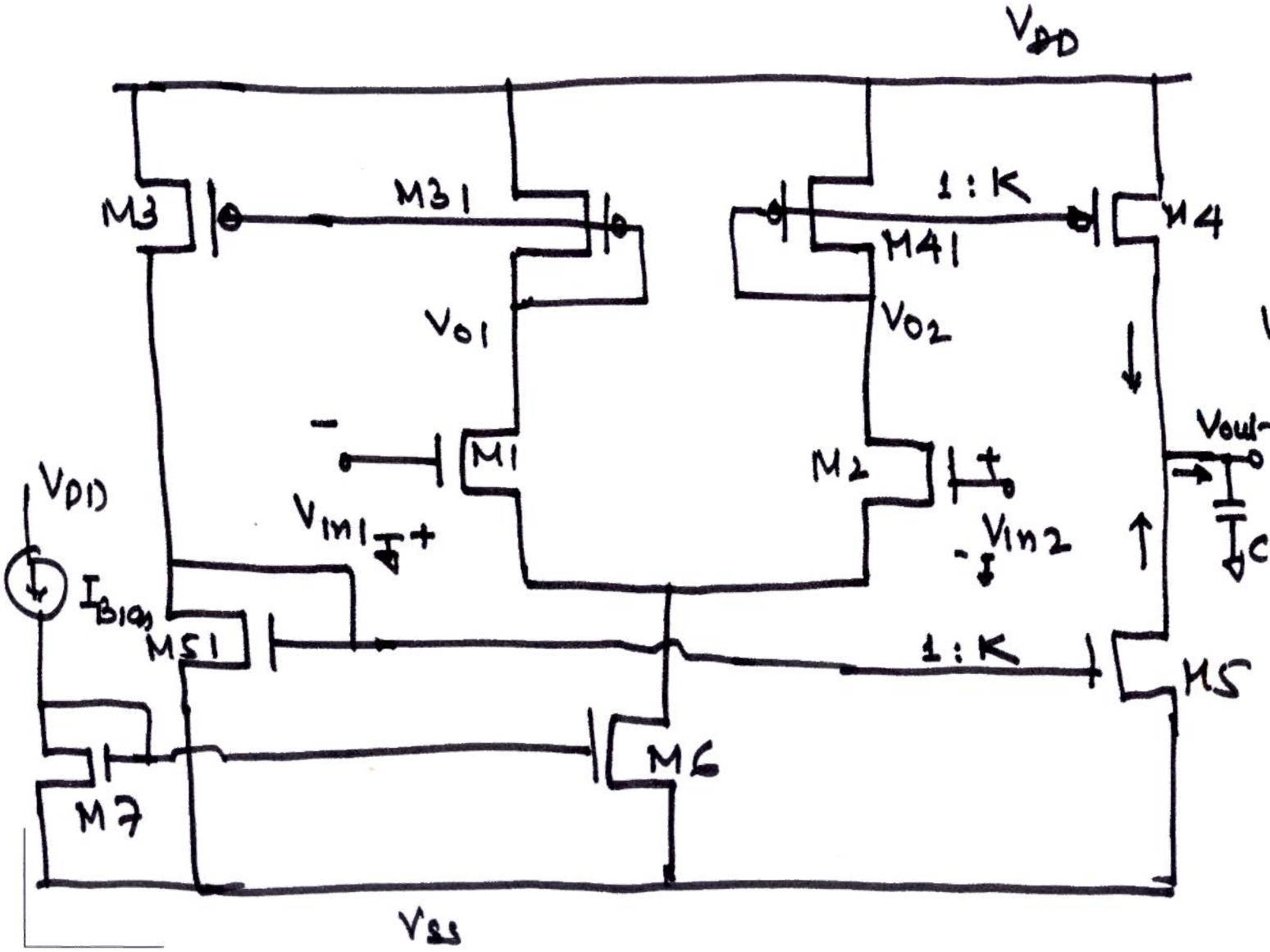




$$\therefore \quad I_o = g_m (V_+ - V_-) =$$

$$\therefore \quad \boxed{\frac{I_o}{V_{diff}} = G_M}$$ Transconductance Amplifier.

Typical Circuit of OTA



We have initially

$\beta_{n1} = \beta_{n2}$

$\beta_{p31} = \beta_{p41}$

By small signal Analysis, we observe that

$$i_{ds_{31}} = -\frac{g_{m1}}{2}(V_{in_2} - V_{in_1}) \qquad \text{— (i)}$$

But $i_{ds_{31}} = -i_{ds_{41}} = -\frac{g_{m1}}{2}(V_{in_2} - V_{in_1})$ — (ii)

We also have the following relations

$$\beta_4 = \beta'_{p_4}\left(\frac{W}{L}\right)_4 = K\,\beta_p'\left(\frac{W}{L}\right)_{41} \qquad \text{— (iii)}$$

or $$\beta_4 = K\beta_{41} = K\beta_{31} = K\beta_3 \qquad \text{(-iv)}$$

$$\beta_5 = K\beta_{51} \qquad \text{— (v)}$$

Clearly currents in M4 and M5 are out of phase

$\therefore i_{ds_4} = -i_{ds_5} = K i_{ds_{41}} = -K i_{ds_{31}}$

Output impedance at Vout,

$$R_{out} = (r_{o4} \,||\, r_{os}) \,||\, \left(\frac{1}{j\omega C_L}\right)$$

If $\frac{1}{j\omega C_L}$ is quite high then

$$R_{out} \cong (r_{o4} \,||\, r_{os})$$

We define $i_{ds} = -i_{ds_{31}} = i_{ds41} = \frac{g_{m1}}{2}(v_{in2} - v_{in1})$

Then $i_{out} = i_{ds_4} - i_{ds_5} = (K\, i_{ds_{41}}) - (+K\, i_{ds_{31}})$

$$i_{out} = 2K\, i_{ds} = 2K \cdot \frac{g_{m1}}{2}(v_{in2} - v_{in1})$$

or $$\frac{i_{out}}{v_{in2} - v_{in1}} = G_M = K \cdot g_{m1}$$ {Transconductance - Gain}

And then Voltage Gain A_{vo} is

$$A_{vo} = \frac{v_{out}}{v_{in2} - v_{in1}} = \frac{2K i_{ds} \cdot (r_{o4} \| r_{o5})}{v_{in2} - v_{in1}}$$

$$= \frac{2K \cdot \frac{g_{m1}}{2} (v_{in2} - v_{in1}) (r_{o4} \| r_{o5})}{(v_{in2} - v_{in1})}$$

$$A_{vo} = K g_{m1} (r_{o4} \| r_{o5})$$

If one chooses $K = 1$ (Equivalent of OPAMP case)

Then $G_M = g_{m1}$ & $A_{vo} = g_{m1} (r_{o4} \| r_{o5})$

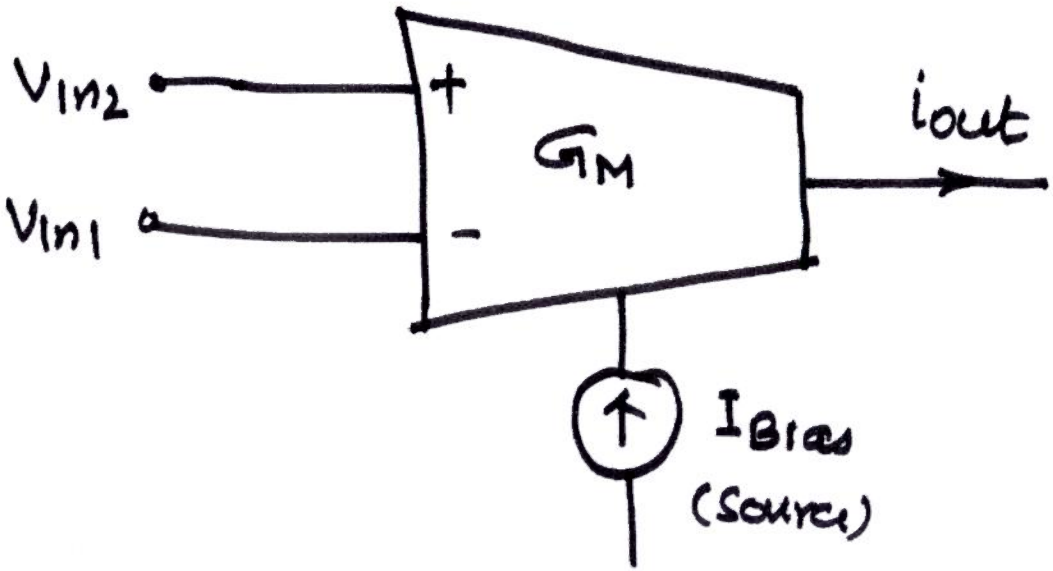
Since $g_{m1} = \sqrt{2 \beta_1 I_{SS}} = \sqrt{2 \beta_n' \left(\frac{W}{L}\right)_1 \cdot \frac{I_{DS_5}}{2}}$

We choose $I_{DS_5} = 2 I_{Bias}$

Then $g_{m1} = \sqrt{2\beta_1 \left(\frac{W}{L}\right)_1 I_{Bias}}$

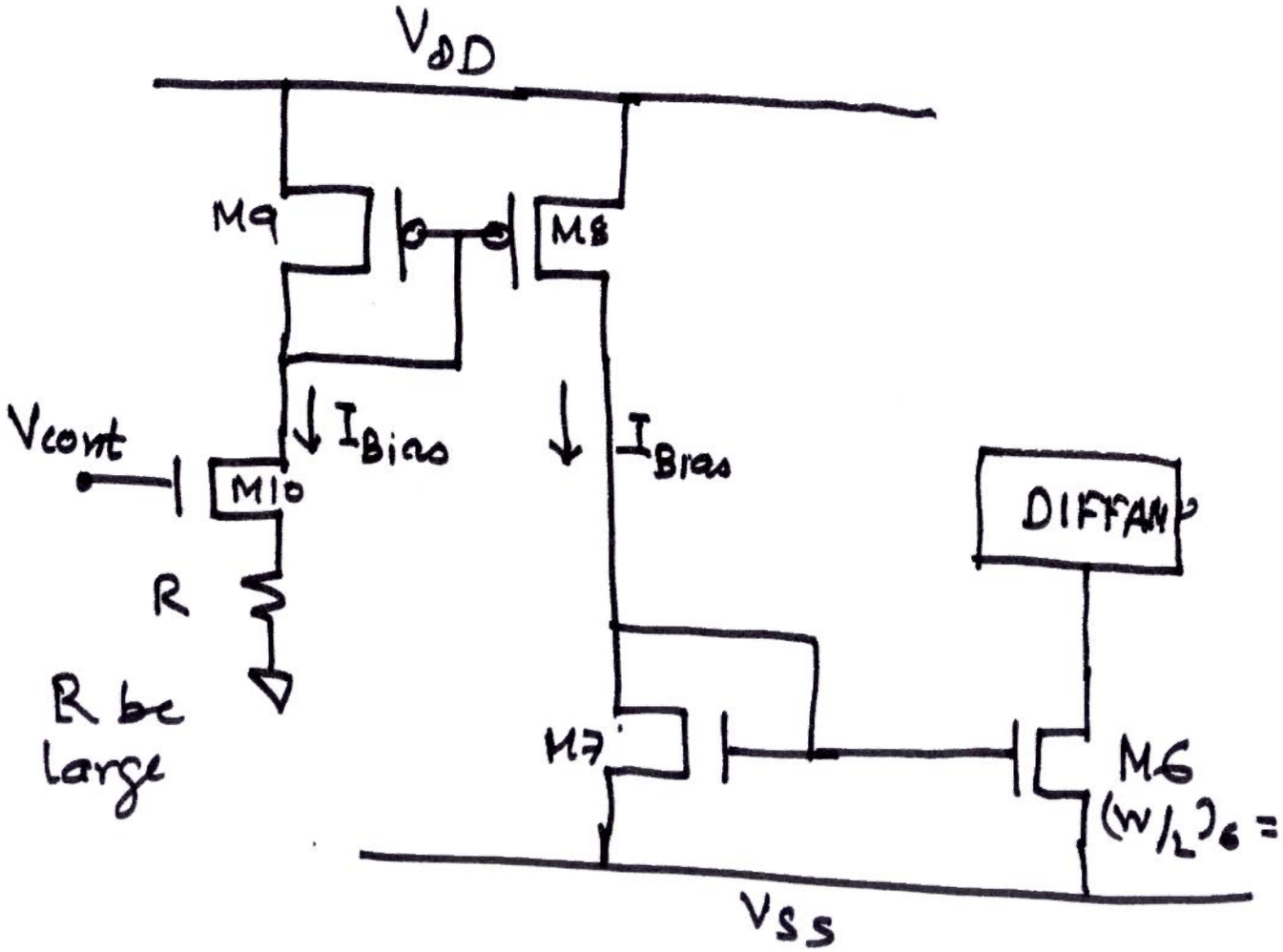
or $g_{m1} \propto \sqrt{I_{Bias}}$

or $G_M \propto \sqrt{I_{Bias}}$



OTA Symbol.

Typically I_{Bias} is created using some control voltage V_{cont}, which can have circuit as



$$I_{Bias} = \frac{V_{cont} - V_{GS_{10}}}{R}$$

$V_{GS_{10}} \cong V_T$

If $\left(\frac{W}{L}\right)_{10}$ is v. large (100–200)