*. MOS Differential Pair

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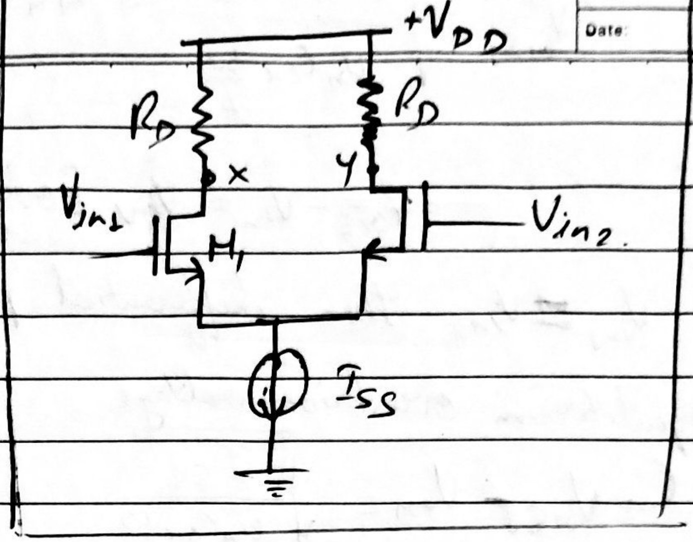

* General Properties

$\boxed{\text{Let } V_{DD} = 1V \quad \text{then } V_{CMin} \cong 0.8 \text{ or } 0.7V}$

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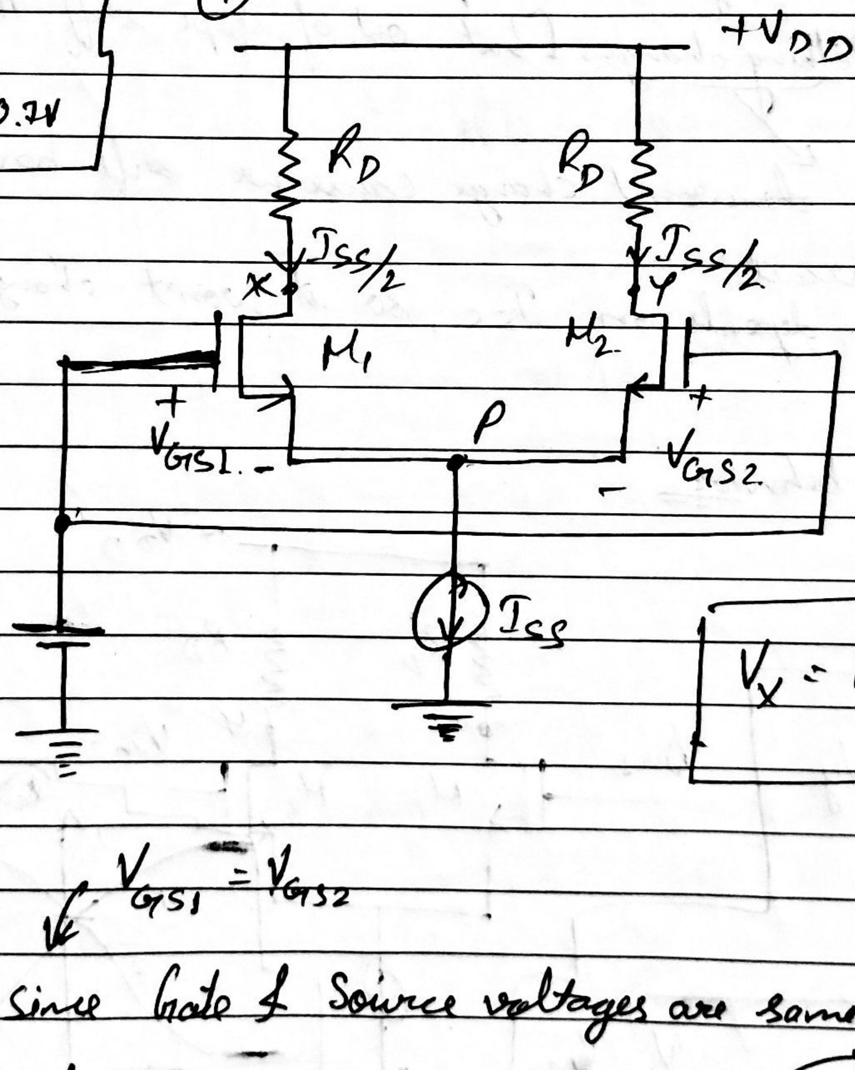


$$\boxed{V_X = V_Y = V_{DD} - R_D \frac{I_{SS}}{2}}$$

$V_{GS1} = V_{GS2}$

Since Gate & Source voltages are same.

$$I_D = \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L}\right) \left[V_{GS} - V_{th}\right]^2 \rightarrow \text{Sat. } [M_1]$$

Teacher's Signature:

$\boxed{I_{SS} = I_D}$

Now, $V_{GS1} = \sqrt{\dfrac{I_{SS}}{\mu_n C_{ox} \frac{W}{L}}} + V_{tn}.$

$V_{GS} - V_{tn} = V_{ov}$ [overdrive voltage]

→ If $V_{in1} = V_{in2}$ then differential pair is in equilibrium.

→ The equilibrium overdrive voltage.

↳ $V_{GS} - V_{tn} = \sqrt{\dfrac{I_{SS}}{\mu_n C_{ox} \frac{W}{L}}}$

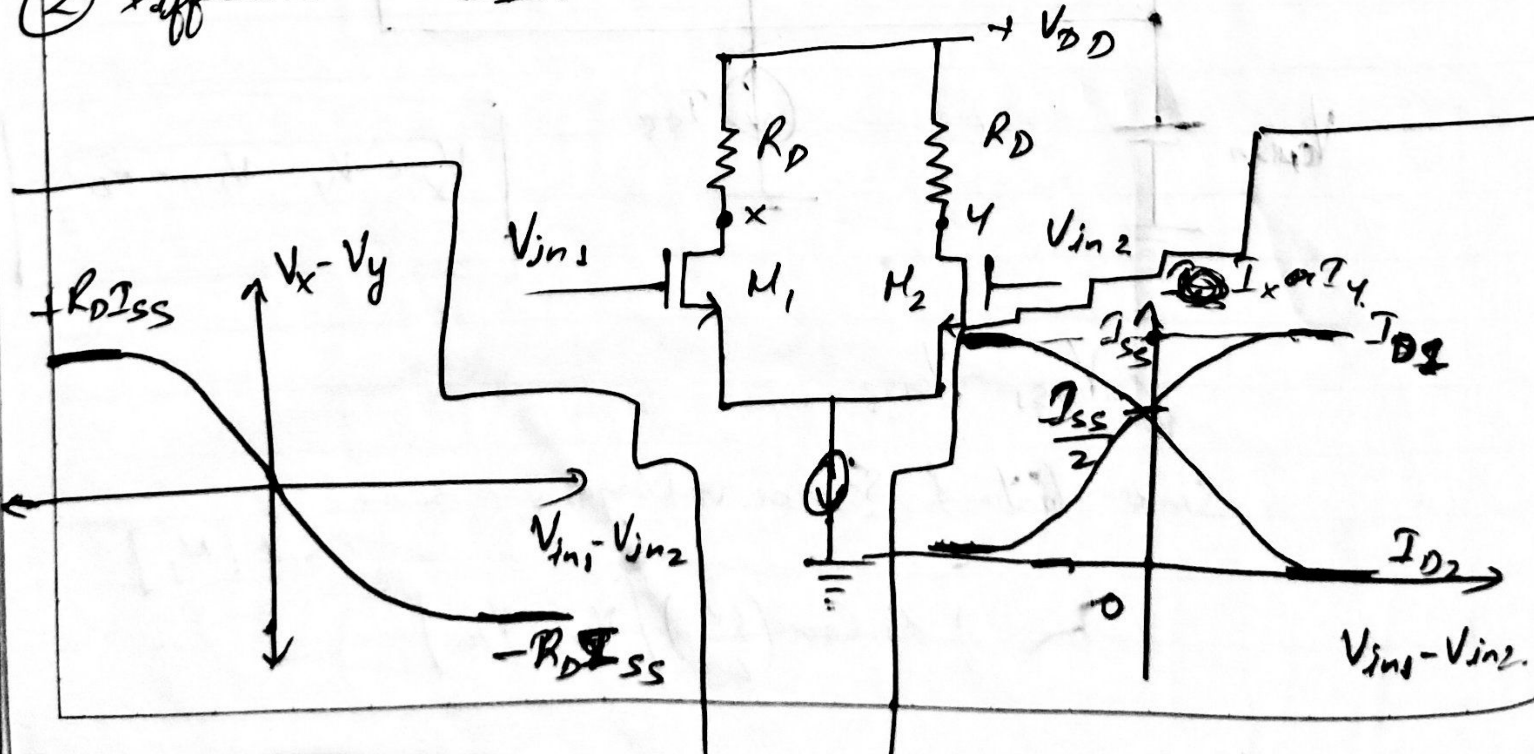
(Q) If V_{CM} in changes, what quantities in the circuit change

Ans ⇒ Nothing changes [but out of scope stuff that V_p changes]

→ I_{SS} ~~don~~ won't change cause we still have symmetry in the circuit

→ V_{GS1} depends on I_{SS}, so it won't change either.

(2) Differential behavior.



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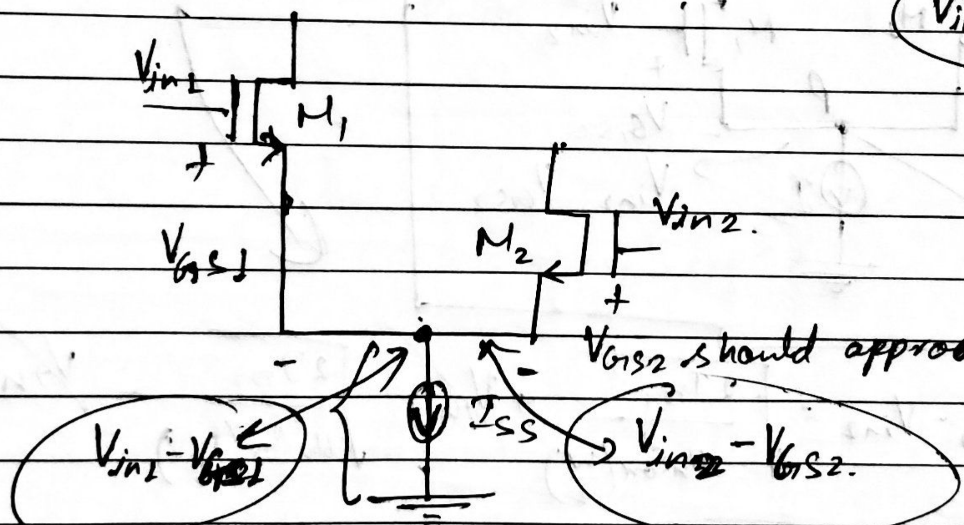
$$I_D = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)[V_{GS} - V_{th}]^2$$

Condition for satisfying saturation equation:-
① The device should be on [i.e $V_{GS} \geq V_{th}$]
② $V_{OV} > V_{DS}$

Example:-
What is the minimum value of $V_{in1} - V_{in2}$ at which one transistor turns off?

V_{in2} is decreasing



V_{GS2} should approach V_{th} } so, I_D is approaching zero.

$$V_{GS1} = \sqrt{\frac{2I_{SS}}{\mu_n C_{ox}\left(\frac{W}{L}\right)}} \cancel{+V_{th}} + V_{th}$$

$\frac{I_{SS}}{2} \rightarrow I_{SS}$

Since I_D for M_2 is $\frac{I_{SS}}{2} \rightarrow 0$.

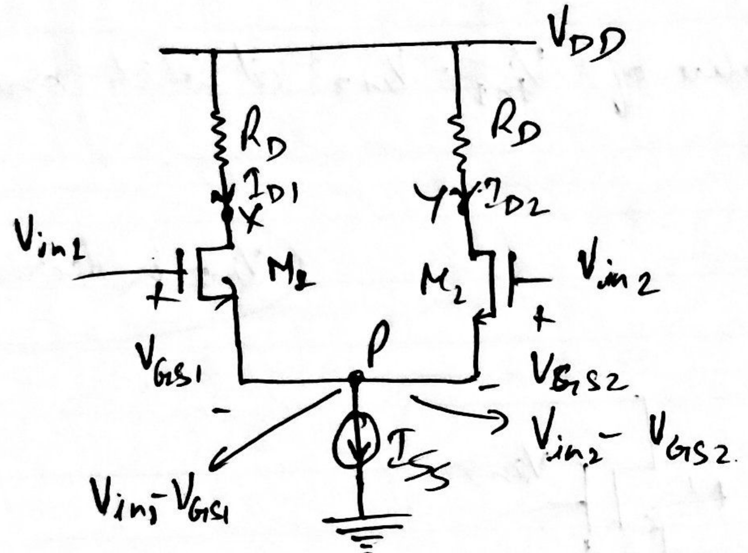
$$V_{in1} - V_{in2} = V_{GS1} - V_{GS2}.$$

$$\text{So, } V_{in1} - V_{in2} = \sqrt{\frac{2I_{SS}}{\mu_n C_{ox}\left(\frac{W}{L}\right)}} + \cancel{V_{th}} - \cancel{V_{th}}$$

Teacher's Signature:

So,
$$V_{in1} - V_{in2} = \sqrt{\frac{2 I_{SS}}{\mu_n C_{ox}\left(\frac{W}{L}\right)}}$$

* Large-Signal Analysis [Equation of $V_X - V_Y$ in terms of $V_{in1} - V_{in2}$] → Objective.



Always [KVL]:-
$$V_{in1} - V_{in2} = V_{GS1} - V_{GS2}$$

$$V_{in1} - V_{in2} = \sqrt{\frac{2 I_{D1}}{\mu_n C_{ox}\left(\frac{W}{L}\right)}} + \cancel{V_{TH}} - \sqrt{\frac{2 I_{D2}}{\mu_n C_{ox}\left(\frac{W}{L}\right)}} - \cancel{V_{TH}} \rightarrow (1)$$

I_{D1} & $I_{D2} \neq 0$ → M_1 & M_2 are not off.

We know that from ~~Bipolar analysis~~ KVL

$\cancel{V_X - V_Y = R_D I}$

$$V_X = V_{DD} - R_D I_{D1}$$

$$V_Y = V_{DD} - R_D I_{D2}$$

$$V_X - V_Y = -R_D [I_{D1} - I_{D2}] \rightarrow (2)$$

$\boxed{\text{Express } I_{D1} - I_{D2} \text{ in terms of } V_{in1} - V_{in2}}$ → Objective

Since we know, $I_{D_1} + I_{D_2} = I_{SS} \rightarrow (3)$

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So,

Squaring Eq^n (1)

$$\left[V_{in_1} - V_{in_2}\right]^2 = \frac{2I_{D1}}{\mu_n C_{ox}\left(\frac{W}{L}\right)} + \frac{2I_{D2}}{\mu_n C_{ox}\left(\frac{W}{L}\right)} - 2\sqrt{\frac{4I_{D1}I_{D2}}{\left[\mu_n C_{ox}\left(\frac{W}{L}\right)\right]^2}}$$

$$\left[V_{in_1} - V_{in_2}\right]^2 = \frac{2}{\mu_n C_{ox}\left(\frac{W}{L}\right)}\left[\frac{I_{D1} + I_{D2} - 2\sqrt{I_{D1}I_{D2}}}{1}\right]$$

Now,

using Eq^n (3)

So, $$\left[V_{in_1} - V_{in_2}\right]^2 = \frac{2}{\mu_n C_{ox}\left(\frac{W}{L}\right)}\left[I_{SS} - 2\sqrt{I_{D1}(I_{SS} - I_{D1})}\right]$$

~~Now, square again Eq^n (4) to find I_{D1} in terms of $V_{in_1} - V_{in_2}$~~

~~So,~~ $$\cancel{\left[V_{in_1} - V_{in_2}\right]^4 = \frac{4}{\left[\mu_n C_{ox}\left(\frac{W}{L}\right)\right]^2}\left[\frac{I_{SS}^2 + 4I_{D1}(I_{SS} - I_{D1}) -}{4I_{SS}}\right]}$$

$$\left[V_{in_1} - V_{in_2}\right]^2 - \frac{2 I_{SS}}{\mu_n C_{ox}\left(\frac{W}{L}\right)} = -\frac{4\sqrt{I_{D_1}(I_{SS} - I_{D_1})}}{\mu_n C_{ox}\left(\frac{W}{L}\right)} \rightarrow (4)$$

Now, again square both sides to get value of I_{D_1} in terms of $(V_{in_1} - V_{in_2})$.

$$\left[V_{in_1} - V_{in_2}\right]^4 + \frac{4 I_{SS}^2}{\left(\mu_n C_{ox} \frac{W}{L}\right)^2} - \frac{4 I_{SS} (V_{in_1} - V_{in_2})^2}{\mu_n C_{ox} \frac{W}{L}}$$

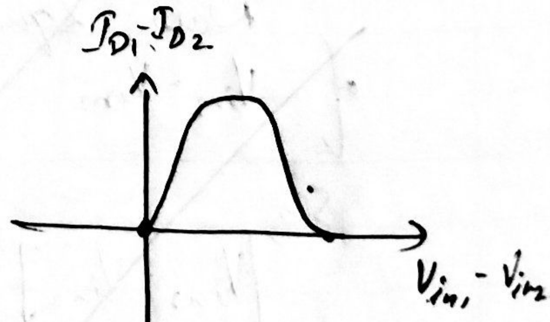
$$= \frac{16\left[I_{D_1}(I_{SS} - I_{D_1})\right]}{\left(\mu_n C_{ox} \frac{W}{L}\right)^2}$$

After the math we'll get

$$\boxed{I_{D_1} - I_{D_2} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)\left[V_{in_1} - V_{in_2}\right]\sqrt{\frac{4 I_{SS}}{\mu_n C_{ox} \frac{W}{L}} - (V_{in_1} - V_{in_2})^2}} \rightarrow (A)$$

Large Signal behaviour for Differential Pair.

Now, $\boxed{V_X - V_Y = -R_D (I_{D_1} - I_{D_2})}$



⇒ **Observations**

1. $I_{D_1} - I_{D_2} = 0$ if $V_{in_1} = V_{in_2}$
2. The equation is not applicable for large value of $V_{in_1} - V_{in_2}$. Since one of the transistor will turn off if $V_{in_1} - V_{in_2}$ becomes large.

Now continuing the point (2) that what should be the range of $V_{in1} - V_{in2}$.

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So, →

$$\boxed{V_{in1} - V_{in2} = V_{GS1} - V_{GS2} = \sqrt{\frac{2I_{SS}}{\mu_n C_{ox}\frac{W}{L}}}}$$

→ As previously shown.

(3) So, Equation (A) is valid only if M_1 & M_2 are ON or at the edge of turning OFF, up to

$$|V_{in1} - V_{in2}| = \sqrt{\frac{2I_{SS}}{\mu_n C_{ox}\frac{W}{L}}}.$$