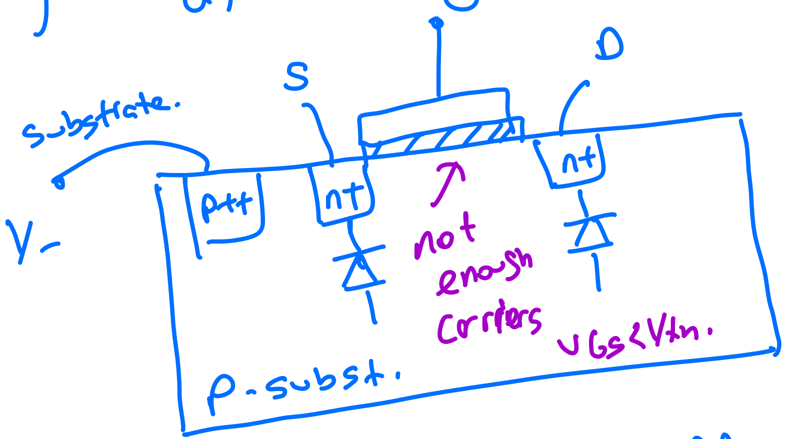
1)

a)



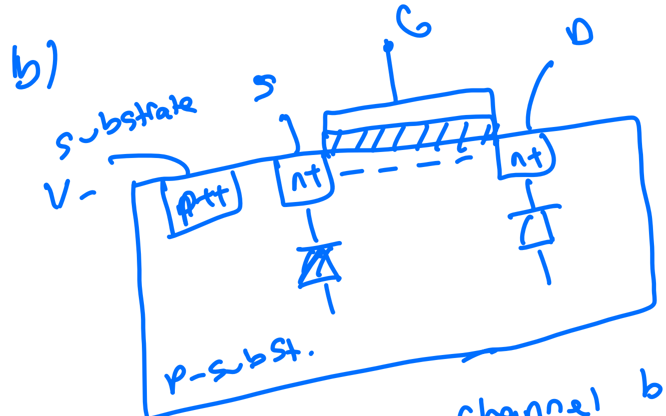
n-channel MOSFET is built on a p substrate where charge carriers are holes.

The substrate is connected to the most (−) voltage.

So Drain-substrate and source-substrate diodes are off. The current cannot flow through subst.

when $V_{GS} < V_{tn}$ there is not enough number of e^- for the current to flow between Drain to Source. Channel inversion is not formed. so $I_{DS} = 0$ for $V_{GS} < V_{th}$.

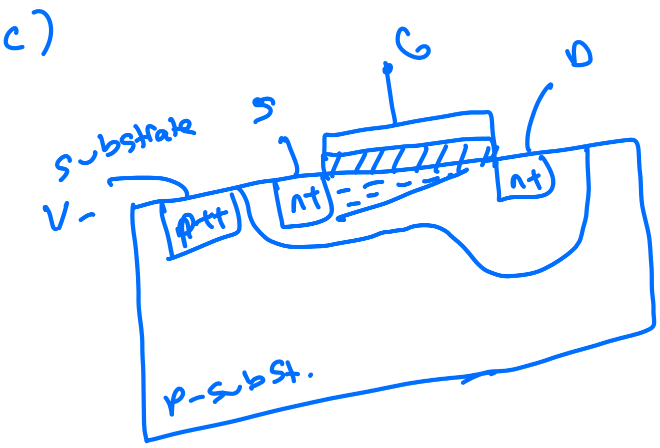
b)



when $V_{GS} > V_{tn}$ channel inversion occurs; i.e., at the surface the material becomes n-type although the main material is p-type.

* A conductive channel between Drain and Source is formed and this channel acts like a resistor for small V_{DS}.

c)



for large V_{DS}:

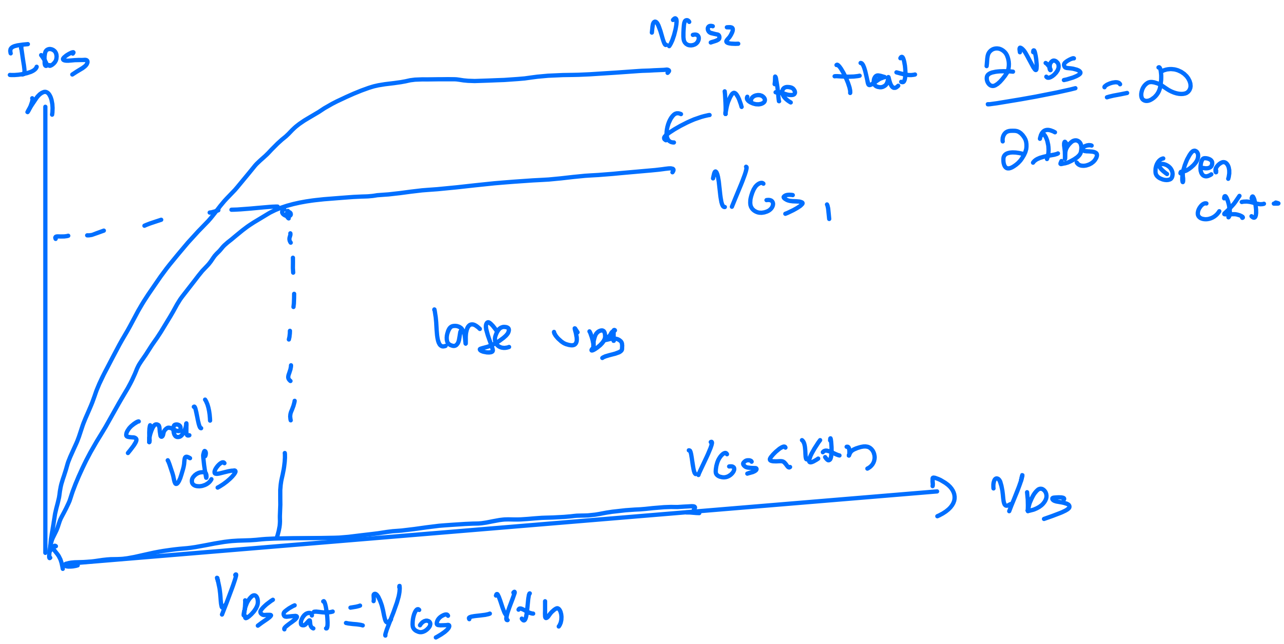
* Note that Drain to substrate and Source to substrate diodes are reverse biased and there is a depletion region around them.
* There are no charge carriers in the depletion region.

* As the drain voltage is increased the no charge carrier region around drain grows and at some point ($V_{DS_{sat}} = V_{GS} - V_{tn}$)

the channel charge carriers lose its connection with Drain.

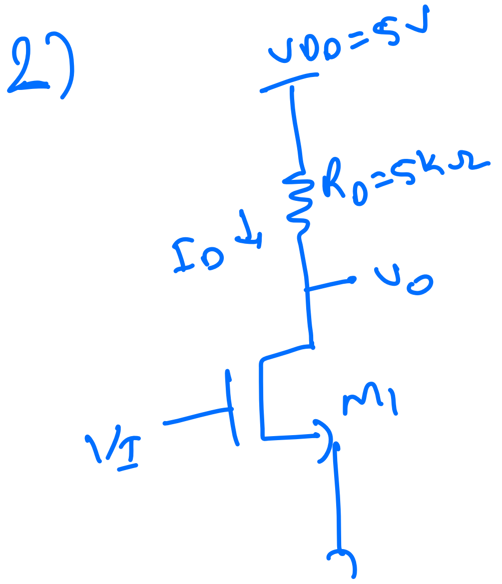
* At $V_{DS\,sat}$ point there is open ckt between Drain and Source. However there is an electric field due to V_{DS}. So the e^-s leave the source and then swept by the E field to the drain at he pinch off point. where e^- concentration in the channel $= 0$

* once $V_{DS\,sat}$ is exceeded we see open ckt. between Drain and source, but the current is constant.



as V_{GS} increases the current increases since we have more charge carriers in the channel.

2)



$V_{tn} = 1V$, $K_N = 0{,}2\,mA/V^2$

for $V_I < V_{tn}$ $I_D = 0$ $V_O = 5V$

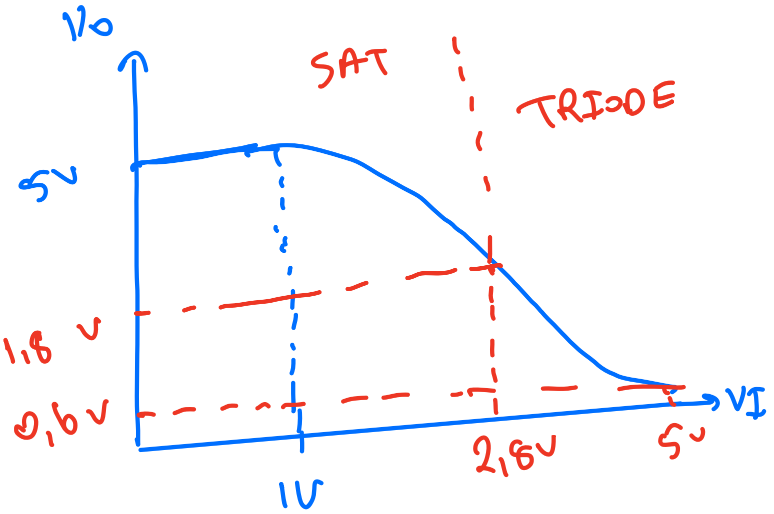
As V_I increases I_D will slowly increase.

for small V_I, V_O will be large

$V_I = V_{GS}$ $V_O = V_{DS}$ M1 will be in SAT

1st. Once V_I exceeds a certain value

M1 will be in TRIODE



when M1 moves from SAT to triode.

$V_{GS} - V_{tn} = V_{DS}$

$V_I - 1 = V_O$

$V_I - 1 = 5 - 5I_D$

$V_I - 1 = 5 - 5 \cdot 0{,}64$

$\boxed{V_I = 2{,}8V}$ SAT → TRIODE

$I_D = K_N (V_{GS} - V_{tn})^2$

$I_D = 0{,}2\,(5 - 5I_D)^2$

$I_D = 5\,(1 - I_D)^2$

$I_D = 5\,(1 - 2I_D + I_D^2)$

$I_D = 5 - 10 I_D + 5 I_D^2$

$I_D = 1{,}55\,mA$ ✗ $V_O < 0$

$\boxed{I_D = 0{,}64\,mA}$

for $V_I = 5V$, M1 in triode.

$I_D = 0{,}2\left[2 \cdot (5-1) \cdot V_O - V_O^2\right]$

$V_O = 5 - 5I_D \Rightarrow I_D = \frac{5 - V_O}{5}$

$\frac{5 - V_O}{5} = 0{,}2\left[8V_O - V_O^2\right]$

$5 - V_O = 8V_O - V_O^2$

$V_O^2 - 9V_O + 5 = 0$

$V_O = 8{,}4$ ✗

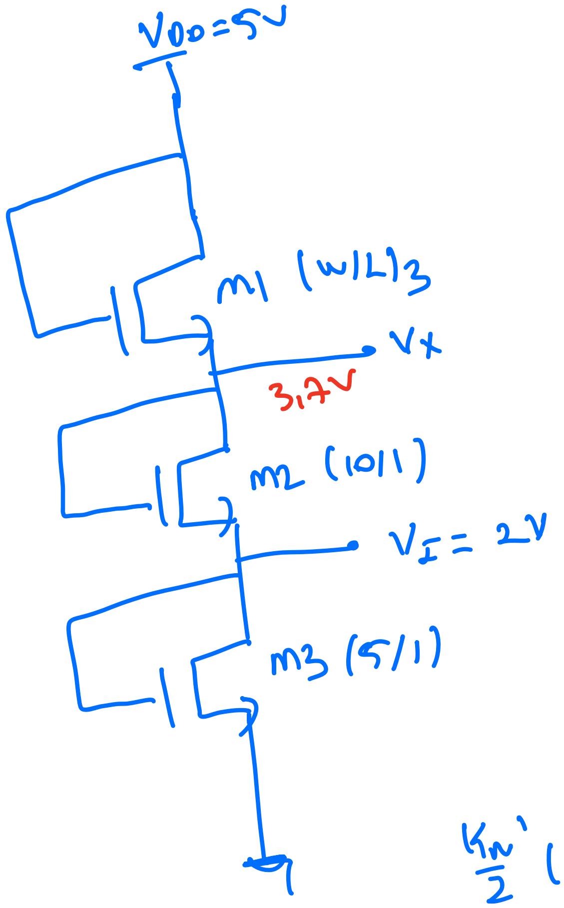
$\boxed{V_O = 0{,}6V}$

$\boxed{I_D = 0{,}88\,mA}$

$V_{GS} - V_{tn} > V_{DS}$

TRIODE ✓

3)



$\frac{k_n'}{2} = 100 \frac{\mu A}{V^2}$ $\quad V_{tn} = 1V$

since gate and drain are shorted for all transistors

$V_{GS} - V_{tn} < V_{DS}$

$V_{GS} = V_{DS}$, if $V_{GS} > V_{tn}$ the transistors are in SAT.

$I_{D_1} = I_{D_2} = I_{D_3}$

$I_{D_2} = I_{D_3}$

$$\frac{k_n'}{2}\left(\frac{W}{L}\right)_3 (V_I - 1)^2 = \frac{k_n'}{2}\left(\frac{W}{L}\right)_2 (V_{GS_2} - 1)^2$$

$$5\,(2-1)^2 = 10.\,(V_{GS_2} - 1)^2$$

$$\pm 0{,}7 = (V_{GS_2} - 1)$$

$V_x - V_I = 1{,}7$ $\quad\leftarrow\quad$ $\boxed{V_{GS_2} = 1{,}7V}$ $\quad$ $\cancel{V_{GS_2} = 0{,}3}$ $< V_{tn}$

$\boxed{V_x = 3{,}7V}$

$I_{D_1} = I_{D_3}$

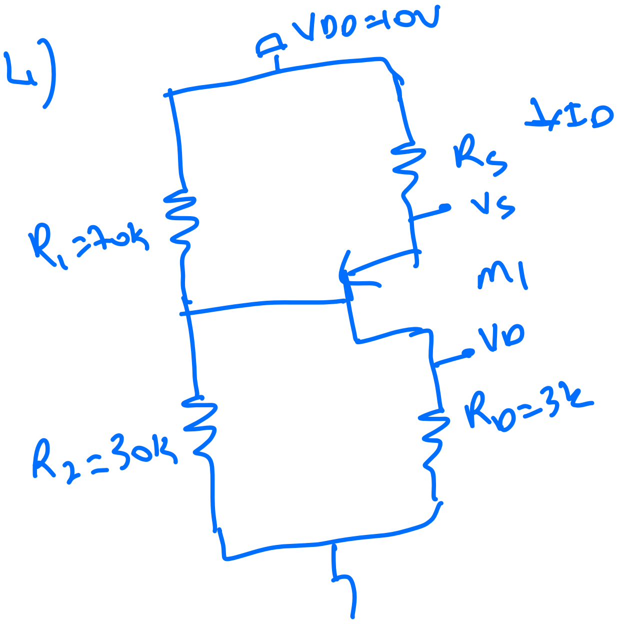
$$\frac{k_n'}{2}\left(\frac{W}{L}\right)_1 \cdot (5 - V_x - 1)^2 = \frac{k_n'}{2} \cdot \left(\frac{W}{L}\right)_3 (2-1)^2$$

$$\left(\frac{W}{L}\right)_1 (0{,}3)^2 = 5 \Rightarrow \boxed{\left(\frac{W}{L}\right)_1 = 55{,}55}$$

$V_{GS_3} = 2V$, $\quad V_{GS_2} = 1{,}7V$ $\quad V_{GS_1} = 1{,}3V$ all $> V_{tn}$

so all transistors are in SAT.

4)



$K_p = 0{,}25\ mA/V^2$ $\quad V_{tp} = -1V$

a) $R_s = 5\ k\Omega$

$V_G = \frac{R_2}{R_1+R_2} \cdot 10 = \frac{30}{30+70} \cdot 10 = 3V$

$V_S = 10 - I_D R_S = 10 - 5I_D$

$V_D = 3I_D$

$V_{SD} = 10 - (3+R_S)I_D = 10 - 8I_D$

$V_{SG} = 7 - 5I_D$

Let's assume SAT.

$I_D = K_p(V_{SG} - |V_{tp}|)^2$

$I_D = 0{,}25(7 - 5I_D - 1)^2$

$I_D = 0{,}25(6 - 5I_D)^2$

$4I_D = (6 - 5I_D)^2$

$4I_D = 36 - 60I_D + 25I_D^2$

$\boxed{I_D = 0{,}83\ mA}$

$I_D = 1{,}73\ mA$ $\quad V_{SG} < 0$ X

$V_{SG} = 2{,}85V$

$\boxed{V_{SD} = 3{,}36V}$

$V_{SD} > V_{SG} - |V_{tp}|$

SAT ✓

b) $R_s = 1\ k\Omega$

Let's assume triode.

$I_D = 0{,}25\left[2(10 - I_D \cdot 3 - 1)V_{SD} - V_{SD}^2\right]$

$V_{SD} = 10 - 4I_D \Rightarrow I_D = \frac{10 - V_{SD}}{4}$

$\frac{10 - V_{SD}}{4} = 0{,}25\left[2(6 - I_D)V_{SD} - V_{SD}^2\right]$

$10 - V_{SD} = 12V_{SD} - 2I_D V_{SD} - V_{SD}^2$

$10 - V_{SD} = 12V_{SD} - 2 \cdot \frac{10 - V_{SD}}{4} \cdot V_{SD} - V_{SD}^2$

$10 - V_{SD} = 12V_{SD} - 5V_{SD} + \frac{V_{SD}^2}{2} - V_{SD}^2$

$\frac{V_{SD}^2}{2} - 8V_{SD} + 10 = 0$

$V_{SD} = 14{,}6$ X $> 10V$

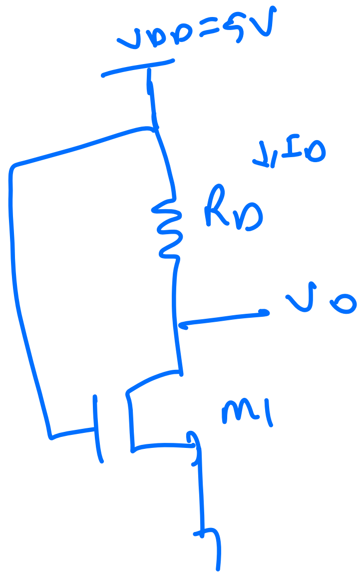
$\boxed{V_{SD} = 1{,}37V}$ $\quad \boxed{I_D = 2{,}16mA}$

$V_{SG} = 10 - 2{,}16 - 3 = 4{,}84V$

$V_{SG} - |V_{tp}| > V_{SD}$ $\quad$ TRIODE ✓

* In this case Rs sets the current, reducing Rs increases the ID and VD increases, VSD ↓, transistor is in triode for smaller Rs.

5)



$K_N = 0{,}2\,mA/V^2 \qquad V_{th} = 1{,}5V$

a) $V_G = V_{DD}$

$V_D = V_{DD} - I_D R_D$

$V_S = 0$

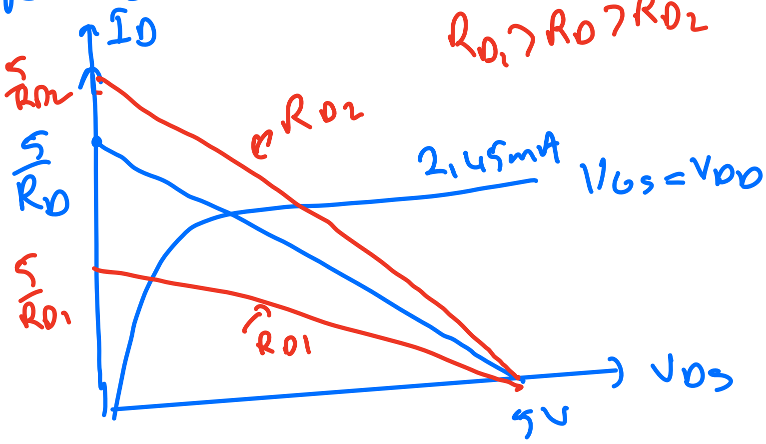
SAT condition : $V_{GS} - V_{th} < V_{DS}$

$V_{DD} - V_{th} < V_{DD} - I_D R_D$

$\boxed{I_D R_D < 1{,}5V}$

$I_D R_D < V_{th}$

The voltage drop on R_D should be smaller than the V_{th} for saturation.



$V_{DS} = 5 - I_D R_D$

$V_{DS} = 5V \quad I_D = 0$

$V_{DS} = 0 \quad I_D = \frac{5}{R_D}$

* As R_D increases M1 moves from SAT to triode.

$R_{D1} > R_{D2}$

* the voltage drop on R_D increases decreasing V_{DS}, pushing M1 towards triode.

b) If M1 is in SAT.

$I_D = 0{,}2(5 - 1{,}5)^2$

$I_D = 2{,}45\,mA$

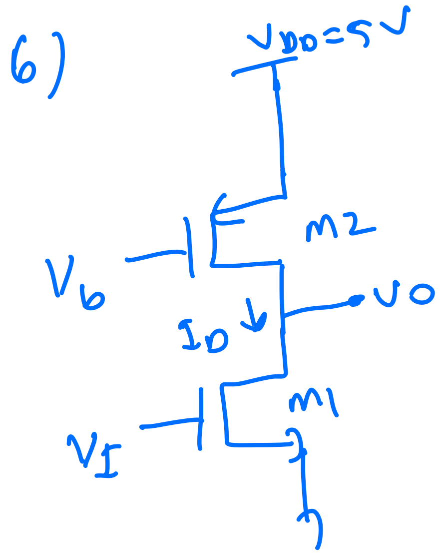
from part a

$I_D R_D < 1{,}5V$ for SAT.

$2{,}45 R_D < 1{,}5V$

$\boxed{R_D < 0{,}61\ k\Omega}$

6)



$K_N = K_P$, $V_{tn} = |V_{tp}| = 1V$

M1 SATURATION, M2 TRIODE

M1

$V_o > V_I - V_{tn}$

$V_o > V_I - 1$

M2

$5 - V_b - |V_{tp}| > 5 - V_o$

$4 - V_b > 5 - V_o$

$V_o - V_b > 1$

a) $V_I = 2V$

M1

$V_o > 1$

M2

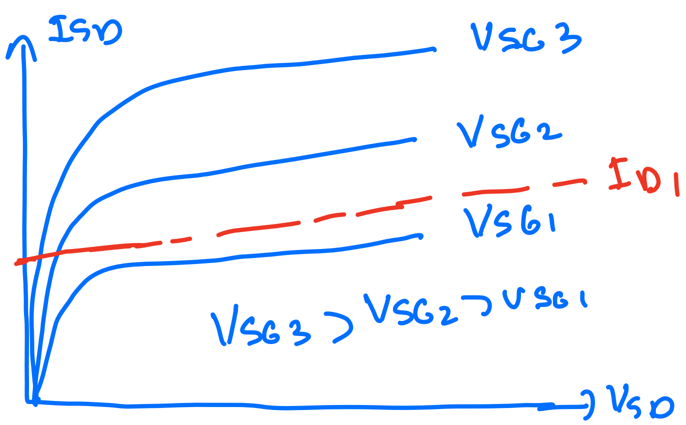
$V_o - V_b > 1$

$I_{D1} = I_{D2}$

$\cancel{K_N}(2-1)^2 = \cancel{K_P}\left[2(5-V_b-1).(5-V_o). - (5-V_o)^2\right]$

$1 = 2(4-V_b)\underbrace{(5-V_o)}_{V_{SD}} - \underbrace{(5-V_o)}_{V_{SD}}^2$

M1 generates a fixed current because M1 is in SAT and M2 has to adapt with Vb.



for large VSG M2 will be in triode, this means small Vb.

as Vb↑ VSG↓

M2 moves into SAT.

$V_b = 0V$

$1 = 2.4.V_{SD} - V_{SD}^2$

$V_{SD}^2 - 8V_{SD} + 1 = 0$

$V_{SD} = 7,88$ X

$\boxed{V_{SD} = 0,13V}$

$V_o = 5 - 0,13$

$V_o = 4,87V$

$V_{SG} - V_{th} > V_{SD}$

As Vb rises Vo ↓

for $V_o = 1$

$1 = 2(4-V_b).4 - 4^2$

$1 = 32 - 8V_b - 16$

$8V_b = 15$

$\underline{V_b = 1,875V}$

but $V_o - V_b > 1$ condition is not satisfied.

so M2 is in SAT.

we should find the point where.

$V_o = V_b + 1$

$1 = 2(4-V_b).(5-V_b-1) - (5-V_b-1)^2$

$1 = 2.(4-V_b)(4-V_b) - (4-V_b)^2$

$1 = (4-V_b)^2$ $V_b = 3$ $V_o = 4$

$V_b = 5$ $V_o = 6V$

$\boxed{0 < V_b < 3V}$

for larger Vb m2 moves into SAT. Since $\lambda = 0$ Vo cannot be found.

b) $V_I = 3V$

in this case.

$I_{D_1} = I_{D_2}$

$\cancel{K_N}(3-1)^2 = \cancel{K_p}\left[2(4-V_b)(5-V_o) - (5-V_o)^2\right]$

$4 = 2.(4-V_b)\underbrace{(5-V_o)}_{V_{SD}} - \underbrace{(5-V_o)^2}_{V_{SD}}$

$V_b = 0$

$4 = 8V_{SD} - V_{SD}^2$

$\boxed{V_{SD} = 0,53}$ $< V_{SG} - V_{th}$.

$V_{SD} = 7,46$ X

Similarly $V_o = 2V$ $(V_I - V_{tn})$

$4 = 2(4-V_b)3 - 9$

$4 = 24 - 6V_b - 9$

$6V_b = 11$

$V_b = 1,83$

$V_o - V_b > 1$ is not satisfied.

$V_o = V_b + 1$

$4 = 2.(4-V_b)(4-V_b) - (4-V_b)^2$

$4 = (4-V_b)^2$

$\boxed{V_b = 2V}$ $V_o = 3V$

$\boxed{0 < V_b < 2V}$

since the current of m1 increase m2 moves into SAT earlier.

* we check the SAT condition for m1 and triode condition for m2. It turns out that triode condition for m2 occurs first.