# Lecture 19 - MOSFETs!

Administrivia → Stuff on final → Check under Exams

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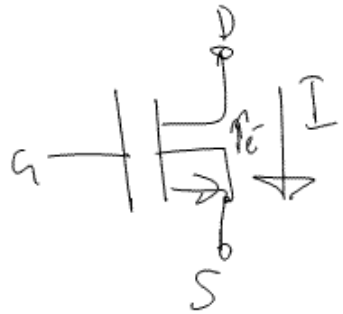
MOSFETs → up to 12.3 (Bias circuit, inclusive of 12.3)

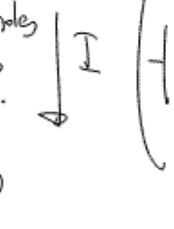
Recall:




NMOSFET

Book:


Book:



PMOSFET

Reference: (1) Microelectronics: An Integrated Approach, by Howe & Sodini

(2) The Art of Electronics, Horowitz & Hill, Latest Edition

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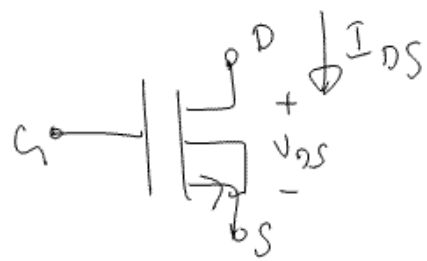
Nonlinear equation for an NMOS




Three regions of operation.

(1) Cutoff

(2) Triode

(3) Saturation.

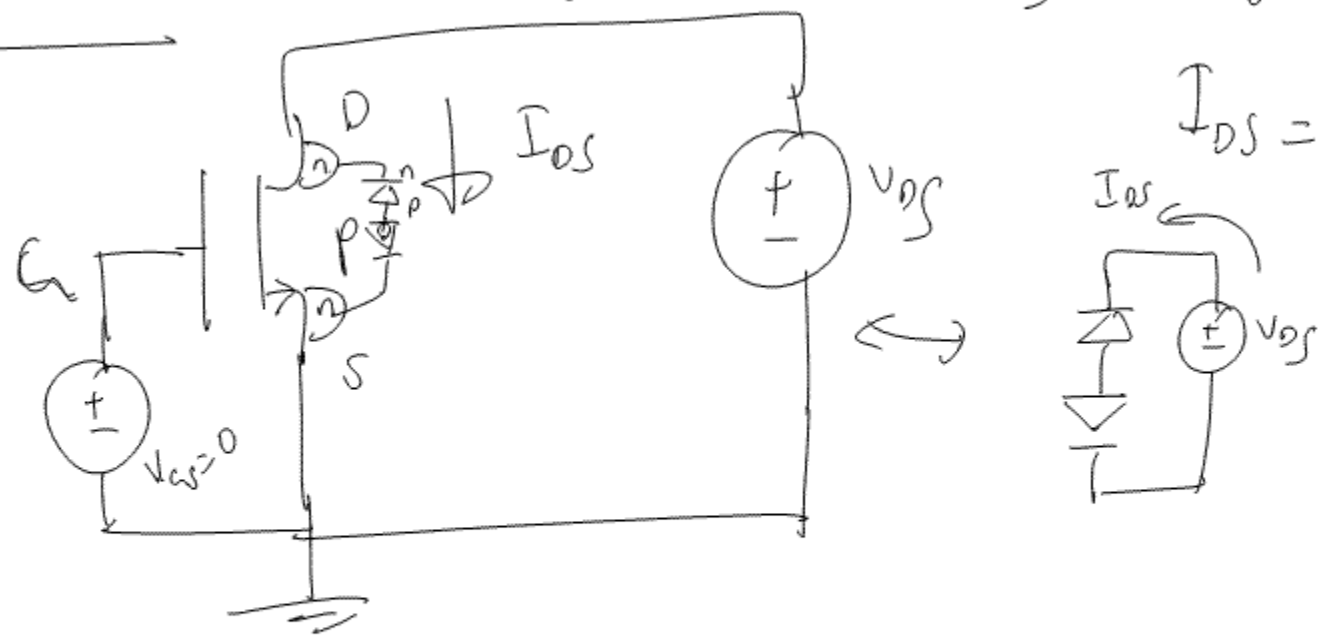
Goal: $I_{DS} = f(V_{DS}, V_{GS}, \text{constants})$

Sketch $I_{DS}$ vs. $V_{DS}$

Look at each individually

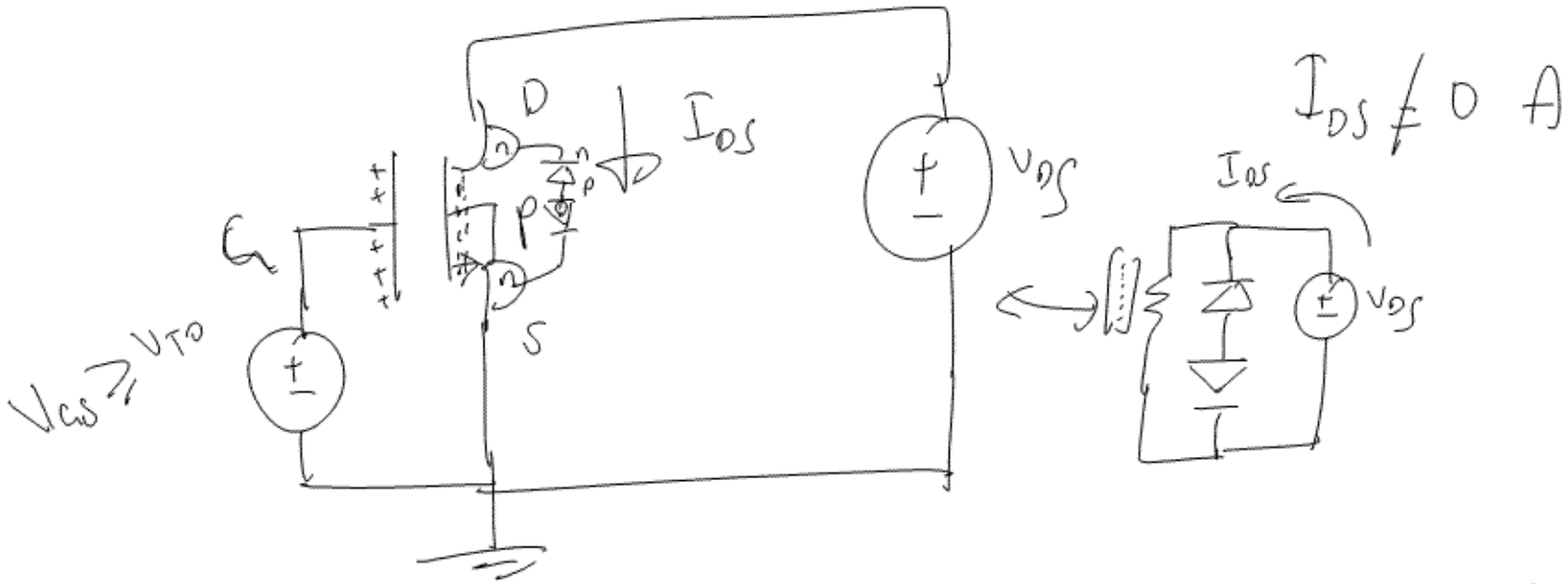
Region 1: Cutoff (Nmos is off): $V_{GS} = 0\ V$

$I_{DS} = 0\ A$



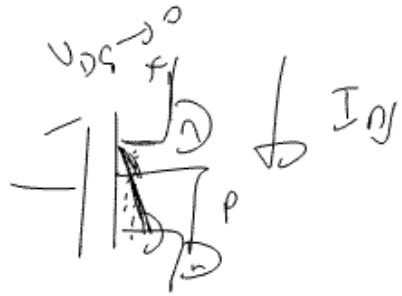

Region 2: Triode (Nmos is turning on).

$V_{GS} \geq V_{TO}$ (threshold voltage, usually around 1 V)




Transistor unfortunately cannot stay in the triode region forever. Fix $V_{GS}$ ($\geq V_{TO}$). As you increase $V_{DS}$, $V_{DG} \to 0$. The effect of

This is called "pinch-off":




Bottomline: Transistor $I_{DS}$ reaches a maximum value

[Region (3): Saturates]

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Equations: [Ref (1)]

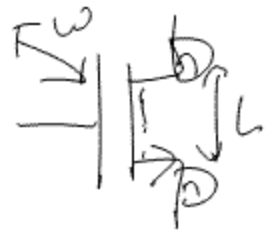
(1) $V_{GS} \leq V_{T0}$, $I_{DS} = 0$ A

(2) $V_{GS} \geq V_{T0}$, and $I_{DS} = \frac{1}{2}(KP)\left(\frac{W}{L}\right)\left(2(V_{GS}-V_{t0})V_{DS} - V_{DS}^2\right)$

constant $\left(50 \frac{\mu A}{V^2}\right)$

KEY: $V_{DS} \leq V_{GS} - V_{T0}$ : Triode

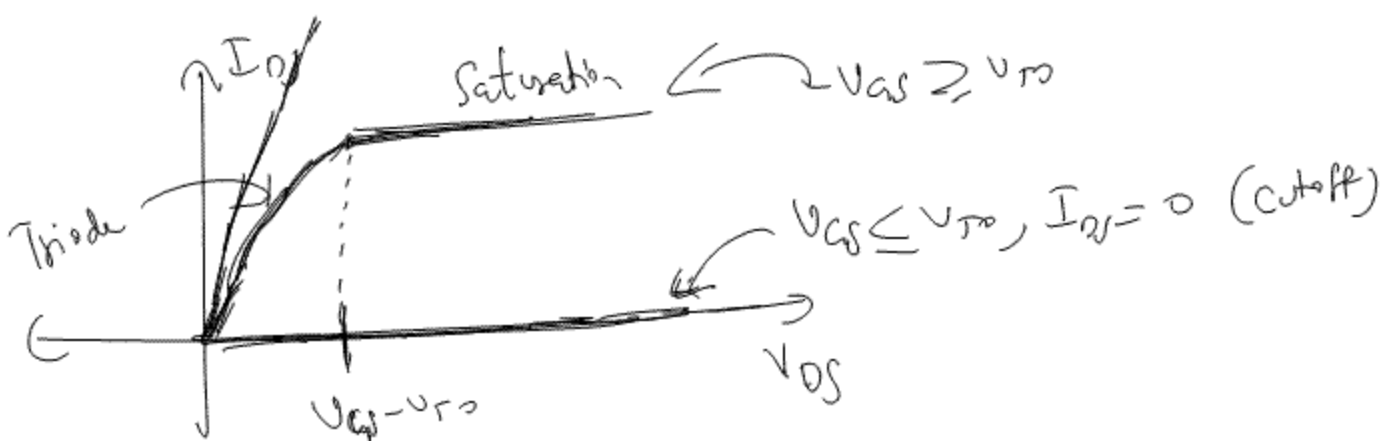
Transistor design: playing with $\left(\frac{W}{L}\right)$




(3) $V_{GS} \geq V_{T0}$ $\qquad I_{DS} = \left[\frac{1}{2} k_P \left(\frac{W}{L}\right)\right] (V_{GS} - V_{T0})^2$

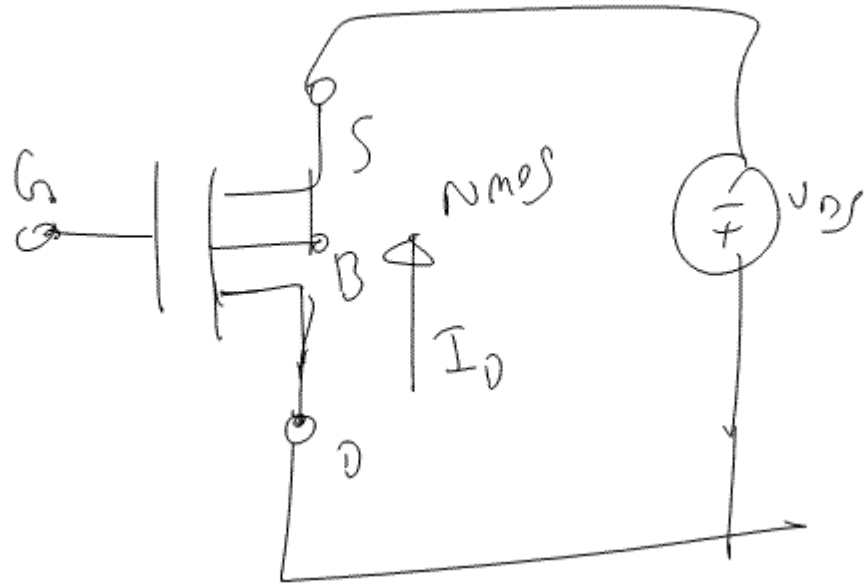
KEY: $V_{DS} \geq V_{GS} - V_{T0}$ : Saturation

Notice in saturation, $I_{DS}$ is independent of $V_{DS}$.



Comments:

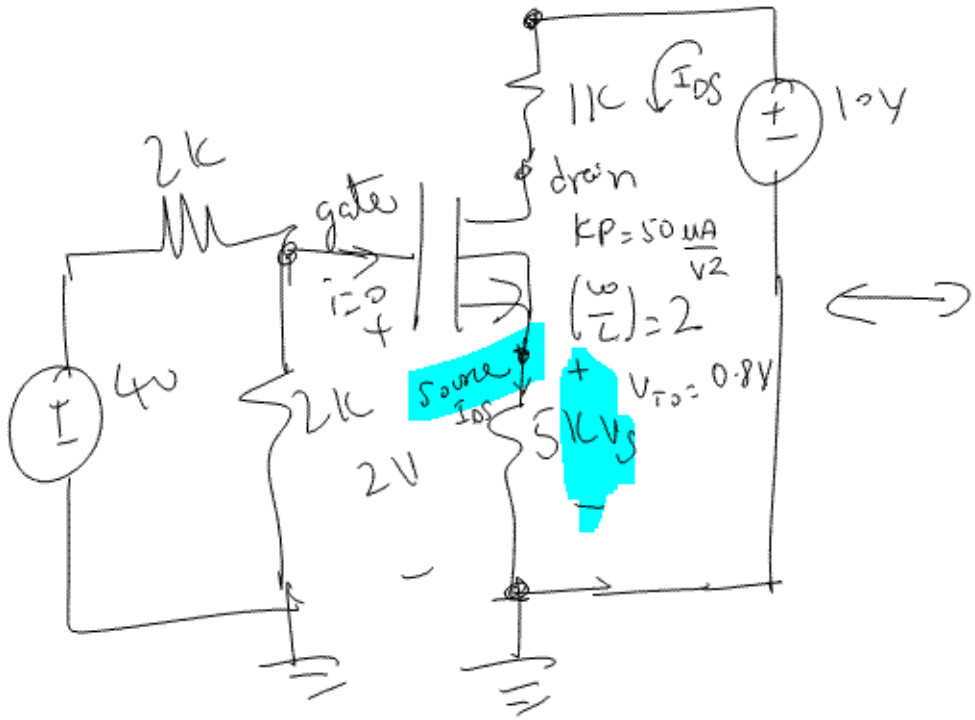
(1)

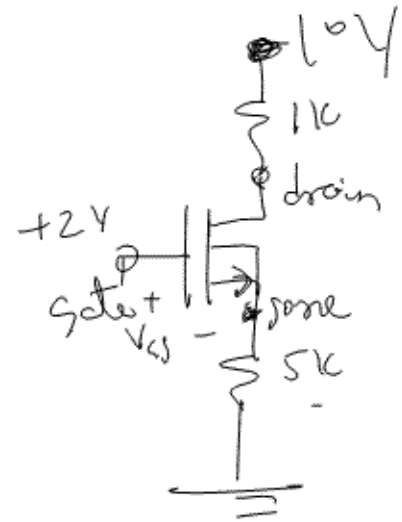




A transistor is actually symmetrical, if you can control the body terminal or bulk terminal.

(2) Example:




Shorthand

[GET USED TO IT]

(Q:) Find $I_{DS}$?

Step (1): Identify gate, drain & source

Step (2): Find $V_{GS}$,

for <u>Go</u>: $V_{GS} = V_G - V_S \Rightarrow \boxed{v_{GS} = 2 - V_S}$

Step (3): Uh... just do the problem.

Basically, you have two choices:

(1) Make an EDUCATED GUESS about transistor mode of operation (triode, saturation, <u>cutoff</u> HIGHLY UNLIKELY)

[Hint: If you have no clue, start with saturation]

(2) Verify your guess. Correct: Done!

Incorrect: Try another mode.

My guess: Saturation:

$$I_{DS} = \left(\frac{K_p}{2}\right)\left(\frac{W}{L}\right)\left[V_{GS} - V_{TO}\right]^2$$

$$\Rightarrow \frac{V_S}{5K} = \left(\frac{K_p}{2}\right)\left(\frac{W}{L}\right)\left[2 - V_S - 0.8\right]^2$$

$$\Rightarrow \frac{V_S}{5K} = \left(\frac{50\frac{\mu A}{V^2}}{2}\right)(2)(2 - V_S - 0.8)^2$$

$$\Rightarrow \boxed{V_S = 6.2\ V, \quad V_S = 0.23\ V}$$

Note: $V_S = 6.2\ V$ is NOT GOOD $\Rightarrow V_{GS} = 2 - V_S$

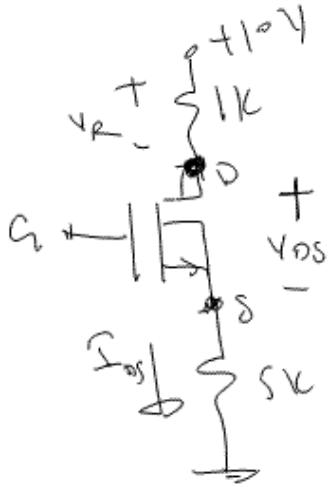
$\Leftarrow = 2 - 6.2 < 0$

OOPS nothing happens!

$\therefore \quad V_S = 0.23\ V$ ✓

Check: (1) $V_{GS} \geq V_{T0}$. $V_{GS} = 2 - V_S = 2 - 0.23 = 1.77\ V$ ✓
(if transistor is on?) $> 0.8\ V$

(2) Is transistor saturated: $V_{DS} \geq \underbrace{V_{GS} - V_{T0}}_{1.77 - 0.8 \Rightarrow 0.97\ V}$

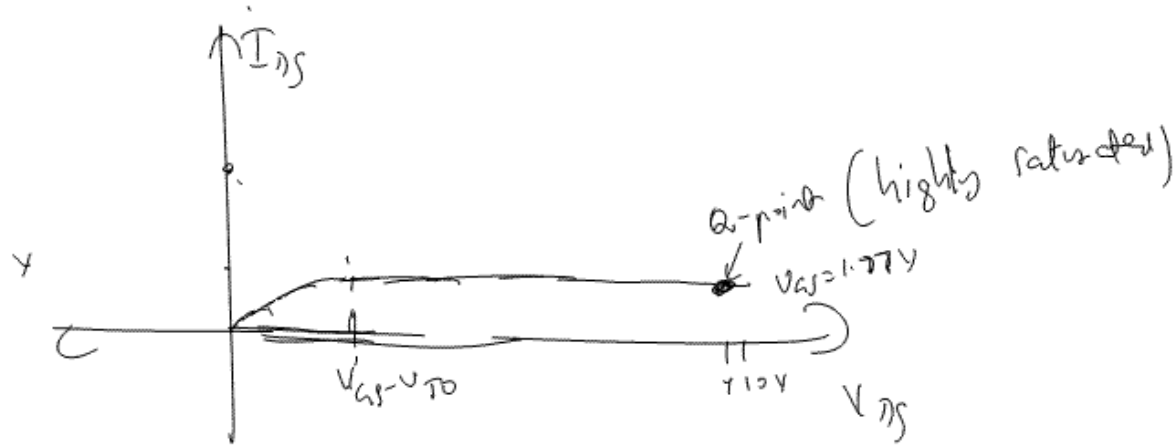



$$\boxed{I_{DS} = \frac{V_S}{5K} = \frac{0.23}{5K} = 46\ uA}$$

$\therefore V_R = (46\ uA)(1\ K) = 46\ mV$

$\therefore V_D = 10 - 46\ mV = 9.954\ V$

$\therefore \; V_{DS} = V_D - V_S = 9.954 - 0.23 \gg 0.97\,V$ ✓

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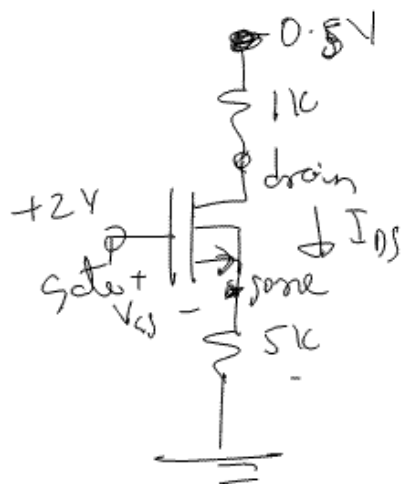
Eg:




(Q:) Find $I_{DS}$.

(A:) Step (1): Identify gate, drain & source

Step (2): Guess mode for transistor & solve

$$\therefore \; I_{DS} = \frac{1}{2} k_p \left(\frac{W}{L}\right) (V_{GS} - V_{TO})^2$$

$$\Rightarrow \frac{V_S}{5k} = \frac{1}{2}\left(50\,\frac{\mu A}{V^2}\right)(2)\,(2 - V_S - 0.8)^2$$

$$\Rightarrow \boxed{V_S = 6.23\ V,\ V_S = 0.23\ V}$$

Note: $V_S = 6.2\ V$ is NOT GOOD $\Rightarrow V_{GS} = 2 - V_S$

$\Leftarrow = 2 - 6.2 < 0$

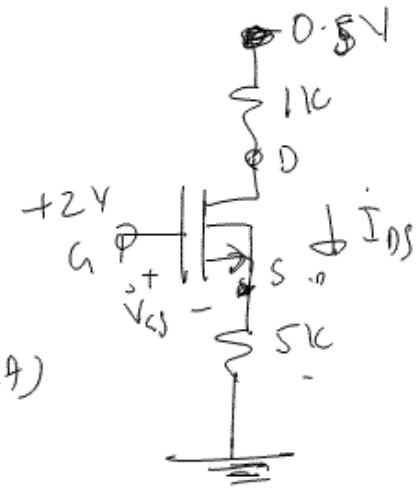
oops nothing happens!

$\therefore\ V_S = 0.23\ V \Rightarrow V_{GS} = 1.77\ V > 0.8\ V$

Now, verify if transistor is saturated:

$$V_{DS} \geq \underbrace{V_{GS} - V_{TO}}_{1.77V}$$

$$I_{DS} = \frac{V_S}{5k} = \underline{\underline{46\ uA}}$$




$$\therefore V_D = 0.5 - (1k)(46\ uA)$$

$$= 0.5 - 0.046V$$

$$= 0.454\ V$$

$$\therefore V_{DS} = 0.45 - 0.23 = 0.224\ V \ll \underset{(V_{GS} - V_{TO})}{1.77\ V}$$

Therefore, transistor is in triode region. Hence, we have to go back and use triode eqn.

$$I_{DS} = \frac{1}{2}\overset{50\,\frac{\mu A}{V^2}}{(KP)}\overset{2}{\left(\frac{W}{L}\right)}\left(2\,(V_{GS}-V_{to})\,V_{DS} - V_{DS}^2\right)$$

$$\frac{V_S}{5k} = \frac{1}{2}\left(50\,\frac{\mu A}{V^2}\right)(2)\left[2\,[2-V_S-0.8]\,V_{DS} - V_{DS}^2\right]$$

The problem with using the triode equation is that we need to rewrite $V_{DS}$ in terms of $V_S$ (our unknown) only:

$$V_{DS} = V_D - V_S$$

Ohm's law: $I_{DS} = \dfrac{0.5 - V_D}{1k}$

$$= \left[0.5 - (1k)I_{DS}\right] - V_S$$

$$= \left(0.5 - (1k)\frac{V_S}{5k}\right) - V_S \Rightarrow V_{DS} = 0.5 - 1.2V_S \quad \text{— (1)}$$

Therefore: $\frac{V_S}{5k} = \left(50 \frac{\mu A}{V^2}\right)\left[2(2-V_S-0.8)(0.5-1.2V_S) - (0.5-1.2V_S)^2\right]$

$\Rightarrow V_S = \underbrace{6.8\,V}_{\text{looks too big.}}$ or $0.14\,V$

Try: $V_S = 0.14\,V \Rightarrow V_{GS} = 2-0.14 = 1.86\,V > V_{T0}\,(0.8\,V)$

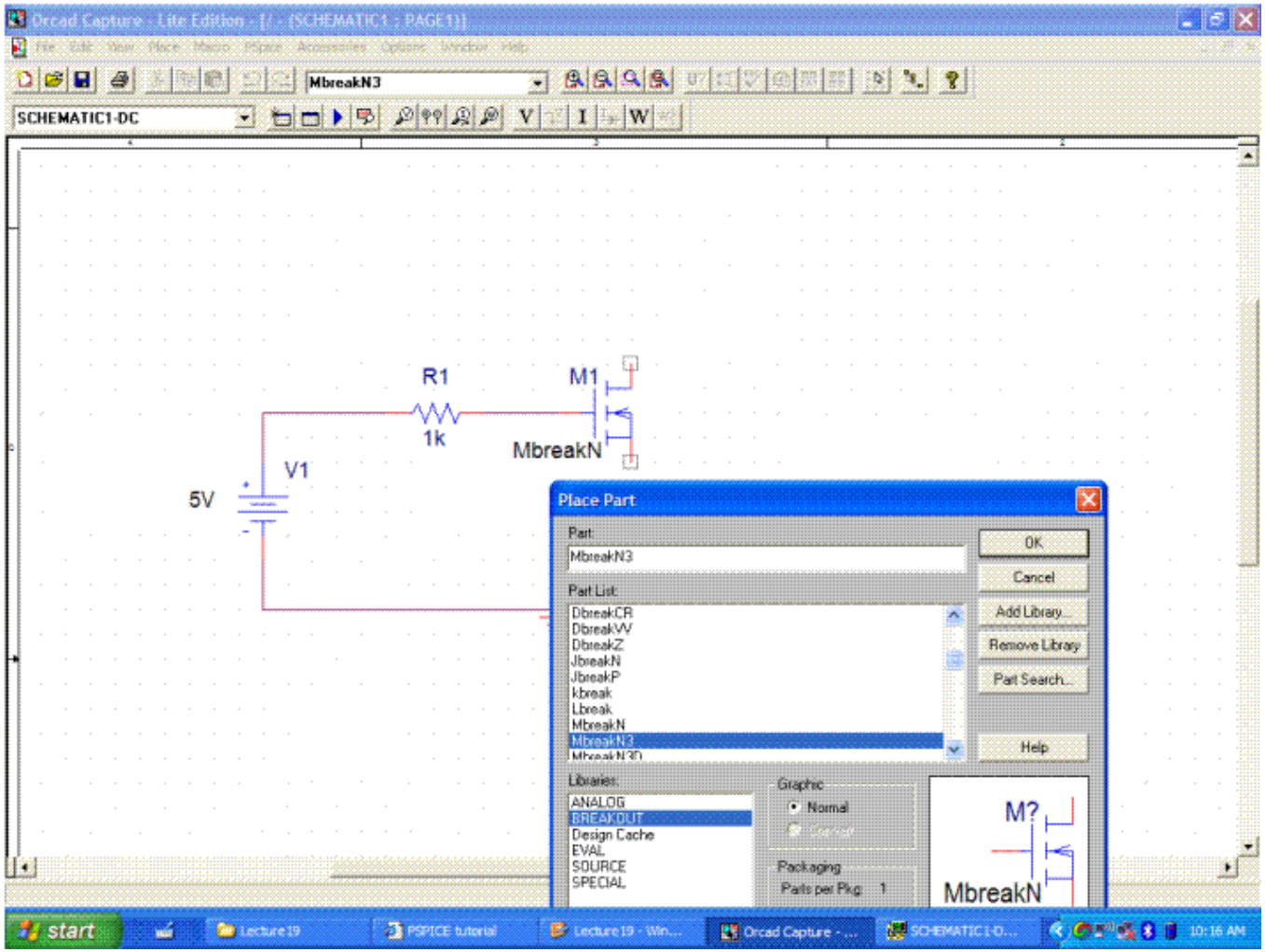
Is transistor in triode region? $V_{DS} = 0.5 - 1.2V_S$ [from ①]

$= 0.332 < V_{GS} - V_{T0}$ $(1.06\,V)$ ✓

Therefore, $\boxed{I_{DS} = \frac{V_S}{5k} = 28\,\mu A}$ ← This answer makes sense, much smaller than the $I_{DS}$ when transistor was saturated.

# Transistors in PSPICE:

(1) Choose MbreakN3 from BREAKOUT library as shown →



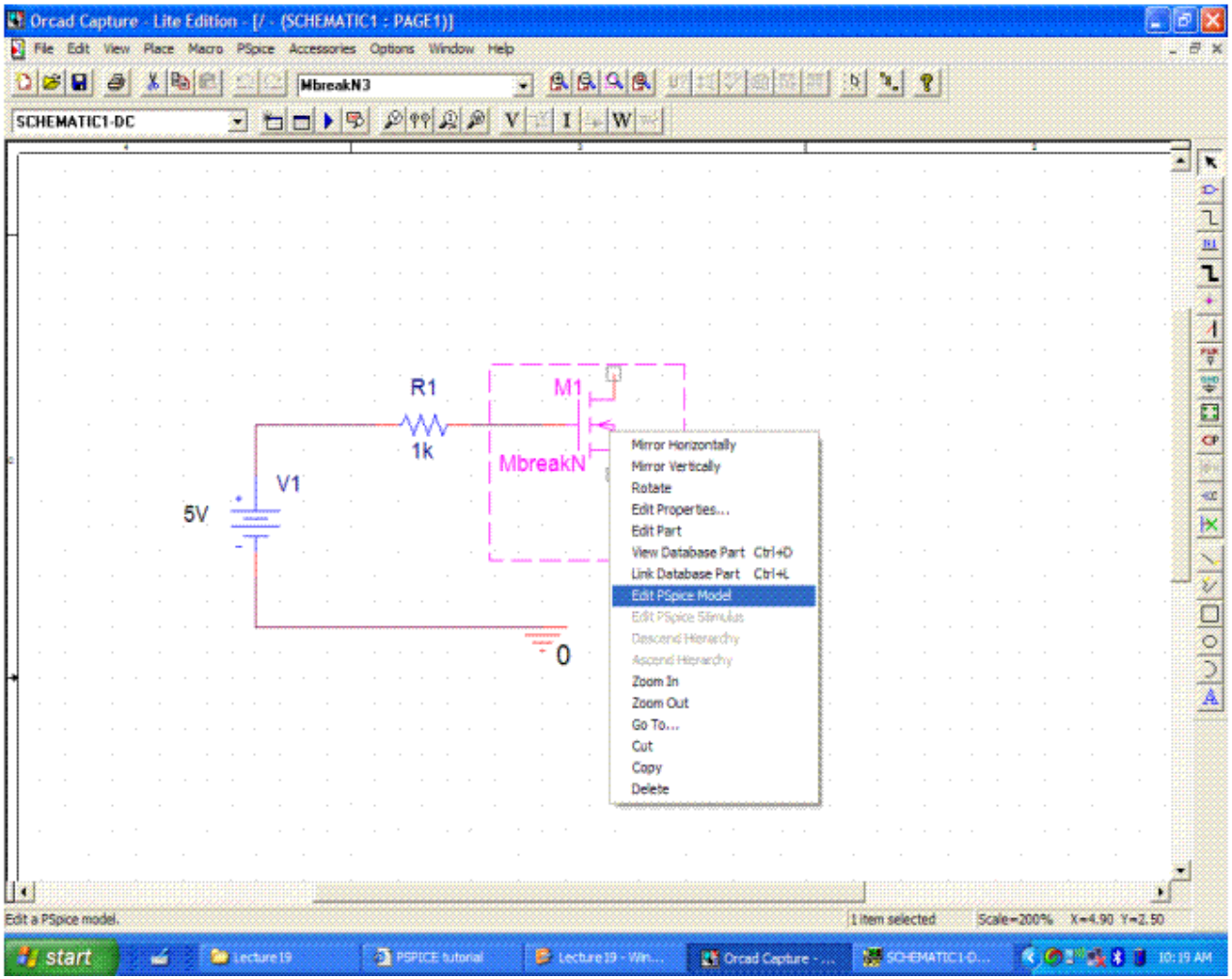
(2) The next step is to define transistor parameters:

(a) Double-click on the NMOS to open the Property-editor & enter W & L values as shown below:

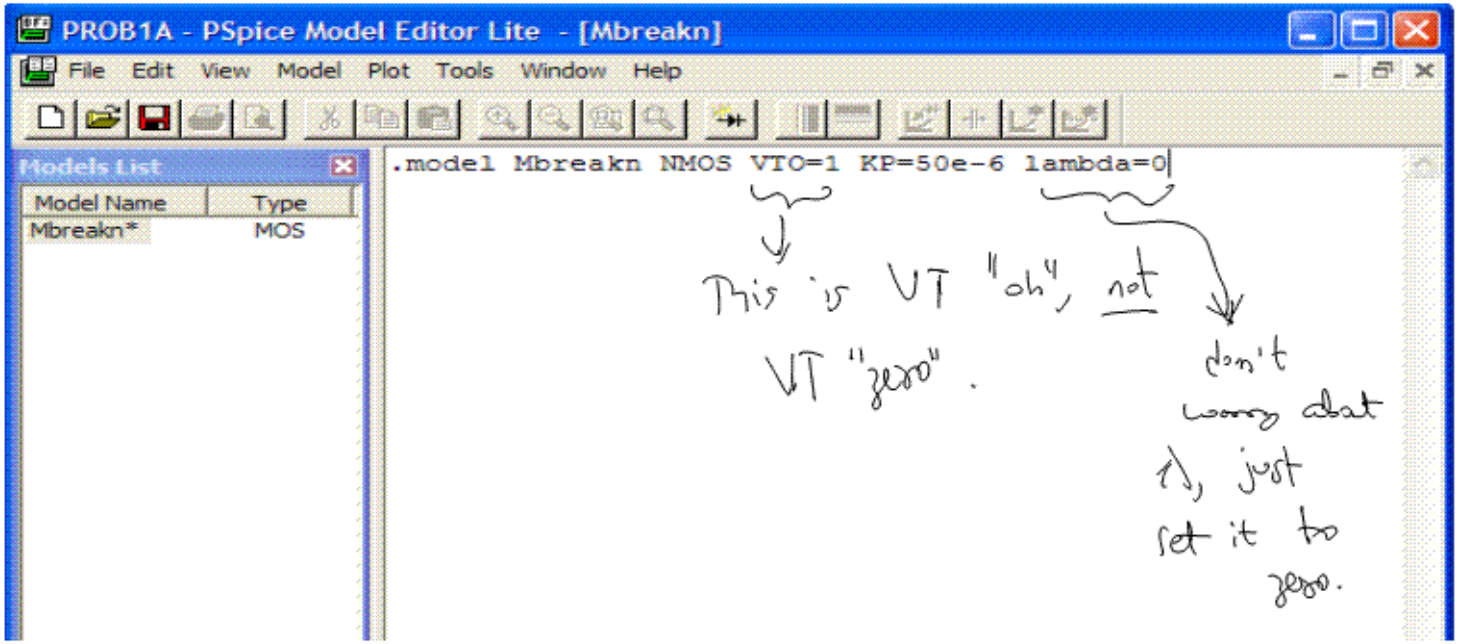
| | SCHEMATIC1 : PAGE1 |
|---|---|
| AD | |
| AS | |
| BiasValue Power | |
| Color | Default |
| Designator | |
| Graphic | MbreakN3.Normal |
| ID | |
| Implementation | Mbreakn |
| Implementation Path | |
| Implementation Type | PSpice Model |
| L | 1u |
| M | |
| Name | I06320 |
| NRB | |
| NRD | |
| NRG | |
| NRS | |
| Part Reference | M1 |
| PCB Footprint | |
| PD | |
| Power Pins Visible | ☐ |
| Primitive | DEFAULT |
| PS | |
| PSpiceOnly | TRUE |
| PSpiceTemplate | M^@REFDES %d %g %s % |
| Reference | M1 |
| Source Library | C:\PROGRAM FILES\O |
| Source Package | MbreakN3 |
| Source Part | MbreakN3.Normal |
| Value | MbreakN3 |
| W | 2u |

Note: DO NOT FORGET THE µs. PSPICE by default uses meters so if you enter W=2, L=1 that is a 2m X 1m NMOS. You CANNOT SIMULATE A TRANSISTOR THAT BIG!

(b) Close the Property Editor & right-click on the Nmos. Choose "Edit PSPICE Model" as shown below.

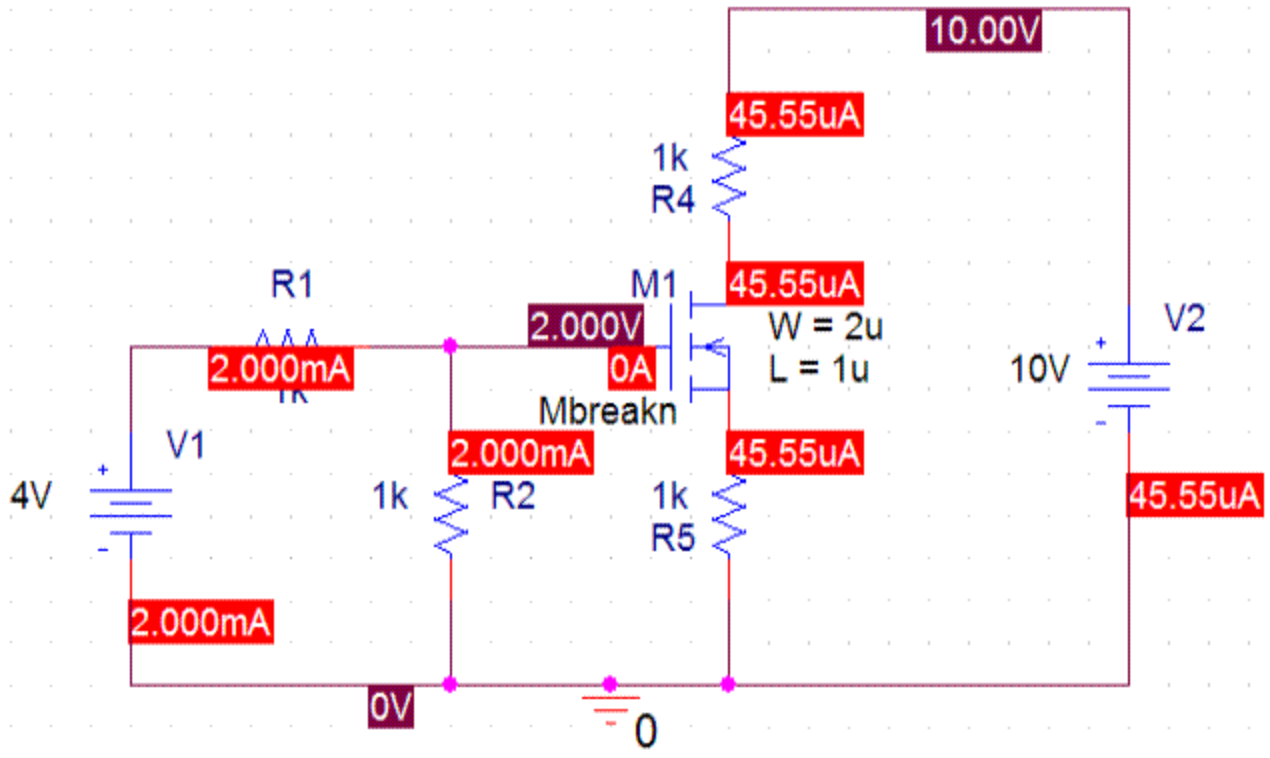


The PSPICE model Editor pops open. Complete the model line:




(Ref: http://www.icaen.uiowa.edu/~sparks/SPICEMODELS.htm)

(c) Save the model, complete the circuit & run DC simulation;


10.00V
45.55uA
1k
R4
R1
M1
45.55uA
2.000V
W = 2u
V2
2.000mA
0A
L = 1u
10V
Mbreakn
V1
2.000mA
45.55uA
4V
1k
R2
1k
R5
45.55uA
2.000mA
0V
0

## Pmos transistors:

These are almost the same as Nmos, however majority carriers are holes ("+ve" charge) instead of $e^-$s. Hence, everything is "backwards" → we should talk about $V_{SG}$ instead of $V_{GS}$. In otherwords, $V_{GS}$, $V_{DS}$, $V_{TO}$ & $I_{DS}$ are all negative. Of course, W, L, KP are positive. KP for Pmos is usually half that of an Nmos (since "+ve" charges move slower than electrons). So, Pmos transistors have usually twice the width of an Nmos for same current drive.

Of course, since I like to avoid negative signs, here are the equations I use for a pmos:

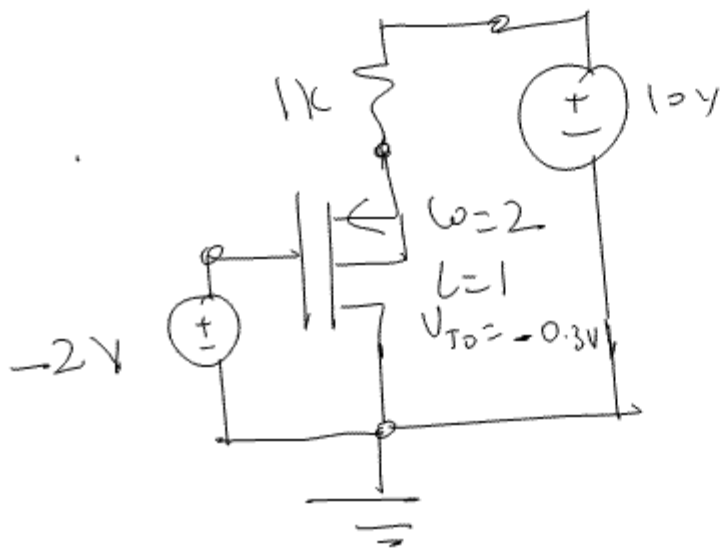
(1) <u>Cutoff:</u> $V_{SG} \leq |V_{T0}|$, $I_{SD} = 0$ [pmos off]

(2) <u>Triode:</u> $\left.\begin{array}{l} V_{SG} \geq |V_{T0}| \\ \& \ V_{SD} \leq V_{SG} - |V_{T0}| \end{array}\right\} \Rightarrow I_{SD} = K\left(2(V_{SG} - |V_{T0}|)V_{SD} - V_{SD}^2\right)$

$K = \frac{KP}{2}\left(\frac{W}{L}\right)$

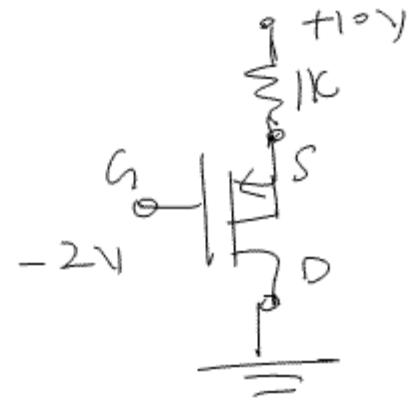
(3) <u>Saturation:</u> $\left.\begin{array}{l} V_{SG} \geq |V_{T0}| \\ \& \ V_{SD} \geq V_{SG} - |V_{T0}| \end{array}\right\} \Rightarrow I_{SD} = K\left(V_{SG} - |V_{T0}|\right)^2$

Ex:

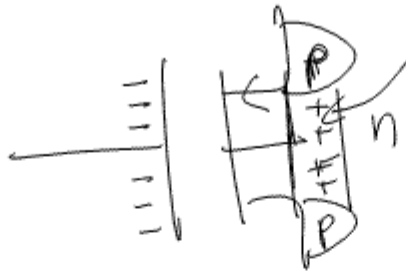



(Q.) Find $I_{SD}$

(A.) Step (1): Identify G, D & S for the PMOS:



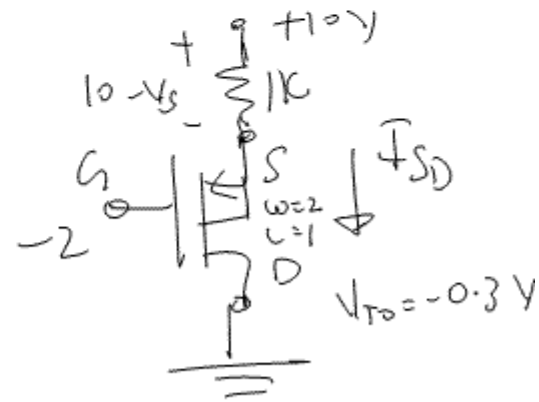

Notice how the gate voltage is negative. This makes sense if you look at the semiconductor properties of a PMOS:




channel, induced by -ve charge on gate.

(2) Guess a mode & solve for $I_{SD}$:

Guess saturation: $I_{SD} = k\left(V_{SG} - |V_{T0}|\right)^2$




$$\Rightarrow \frac{10 - V_S}{1k} = \frac{25\,\mu A/V^2}{2} \cdot \left(\frac{2}{1}\right)\left[V_S - (-2) - |-0.3|\right]^2$$

$\Rightarrow V_S = 7.76$ V or $V_S = \cancel{-11.2V}$

$\therefore V_S = 7.76\ V$

<u>Check</u>: Is pmos on & saturated?

$$V_{SG} = 7.76\ V - (-2\ V) = 9.76\ V \geq |\overset{V_{TO}}{-0.3}\ V|$$

$\Rightarrow$ pmos on

$$V_{SD} = V_S - V_D = 7.76 - 0 = 7.76\ V \leq \underbrace{9.76}_{V_{SG}} - \underbrace{|-0.3|}_{V_{TO}}$$

$\Rightarrow$ oops, pmos is actually in triode!

Redoing the problem using triode eqn:

$$I_{SD} = K\left[2(V_{SG} - |V_{TO}|)V_{SD} - V_{SD}^2\right]$$

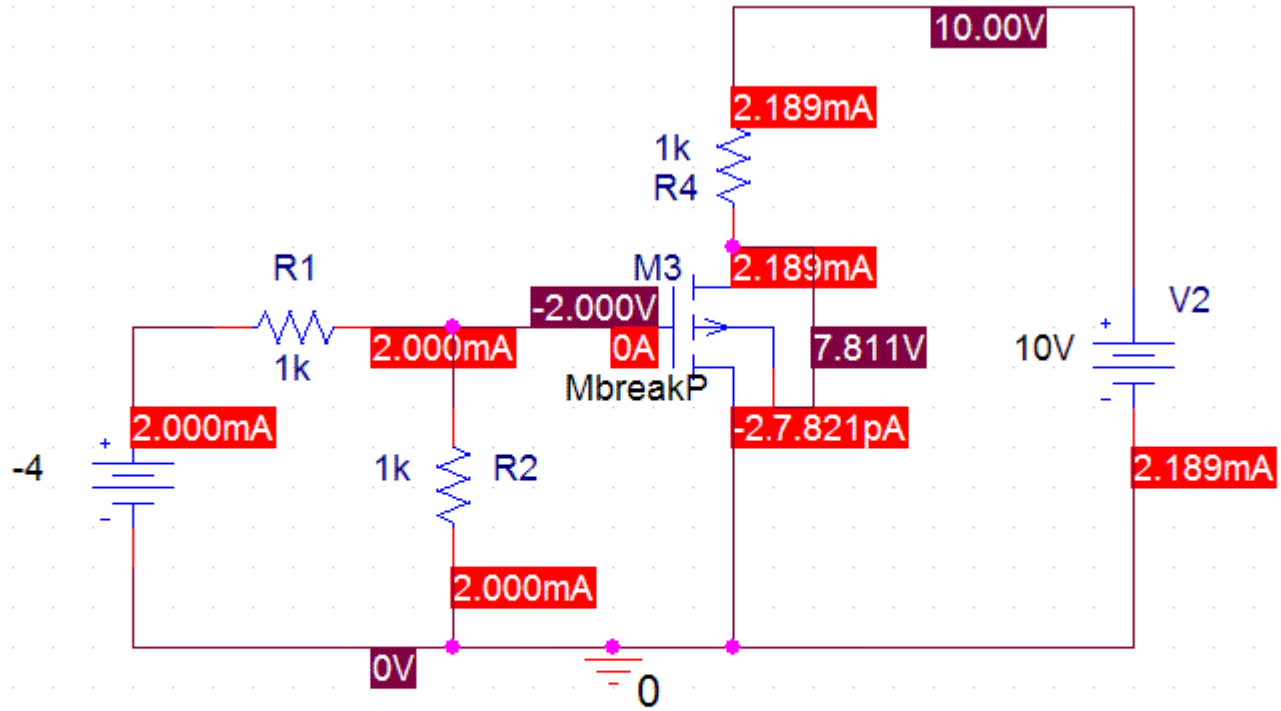
$$\Rightarrow \frac{10 - V_S}{11k} = \left(\frac{25\ \frac{\mu A}{V^2}}{2}\right)\left(\frac{2}{1}\right)\left[2\left(V_S - (-2) - |-0.3|\right)V_S - V_S^2\right]$$

$\Rightarrow V_S = 7.81\ V$ (or $\cancel{V_S = -5.2\ V}$)

works.

$\therefore \boxed{I_{SD} = \frac{10 - 7.81\ V}{1\ k} = 2.19\ mA}$

Notice how this problem shows the "reverse" behavior of a pmos compared to an Nmos. We would have expected the pmos to be in saturation since $10\ V > -2\ V$, but it is actually in triode!




Note: For simulating Pmos in PSPICE, select mbreakp from BREAKOUT and hook up Bulk to Source as shown above. Rest of the steps is the same.