Announcements

- Office hours today (Wednesday) 2-3pm and tomorrow (Thursday) 1-2pm.
- Please bring all graded homeworks to lab section and show to your TA.

Triode Region I-V Characteristics

$$i_D = K_n' \frac{W}{L}\left(v_{GS} - V_{TN} - \frac{v_{DS}}{2}\right) v_{DS}$$

- When v_{DS} is small, ignore 2nd order terms

$$i_D = K_n' \frac{W}{L}(v_{GS} - V_{TN}) v_{DS}$$

- i_D proportional to v_{DS} => the MOSFET is like a resistor (resistor value controlled by v_{GS})
- On-resistance:

$$R_{\text{on}} = \left(\frac{\partial i_D}{\partial v_{DS}}\right)^{-1} = \frac{1}{K_n' \frac{W}{L}(v_{GS} - V_{TN} - v_{DS})}$$

Triode Region I-V Characteristics

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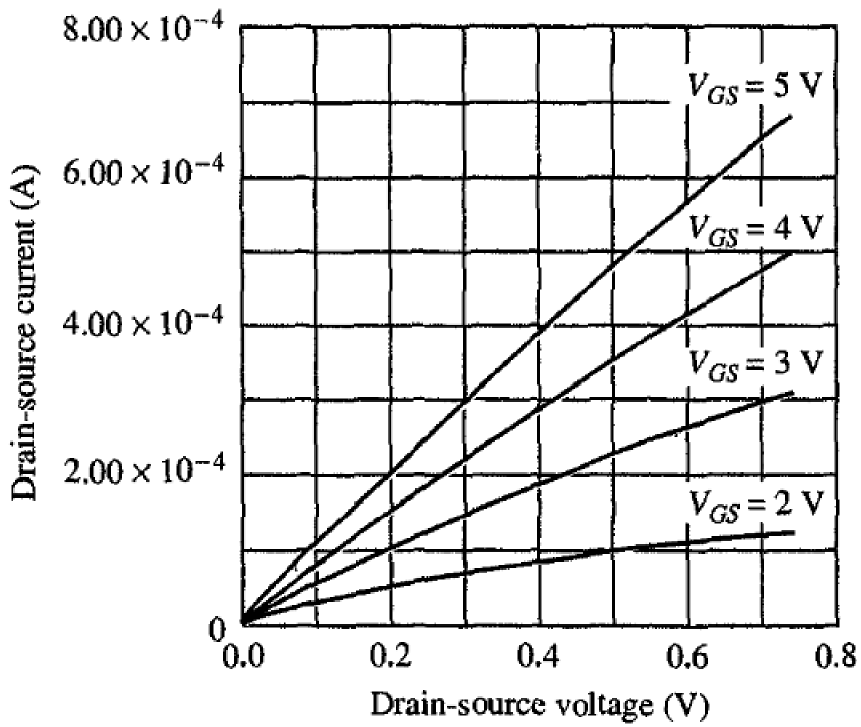
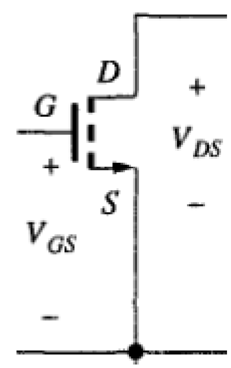
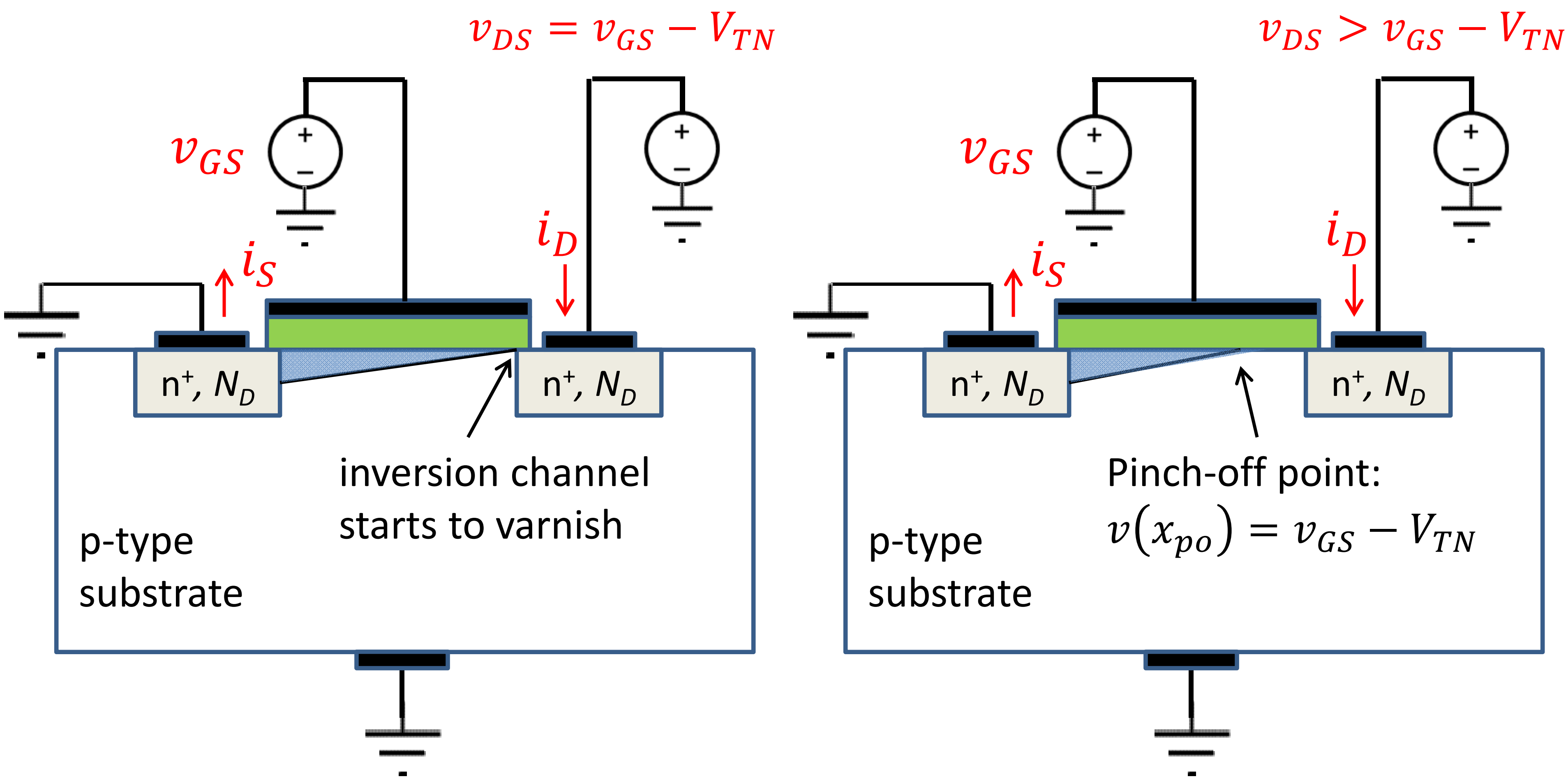


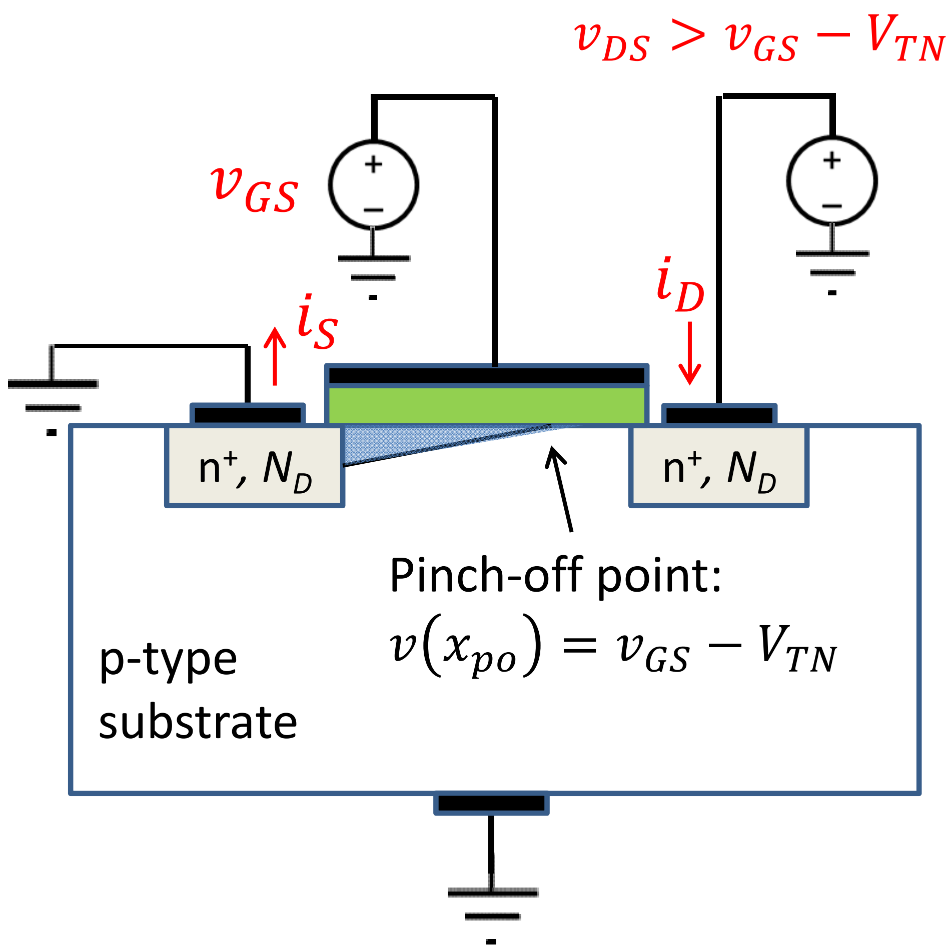


NMOS i-v characteristics in the triode region (V_{SB}=0)

Saturation (Pinch-off) region



Saturation (Pinch-off) region

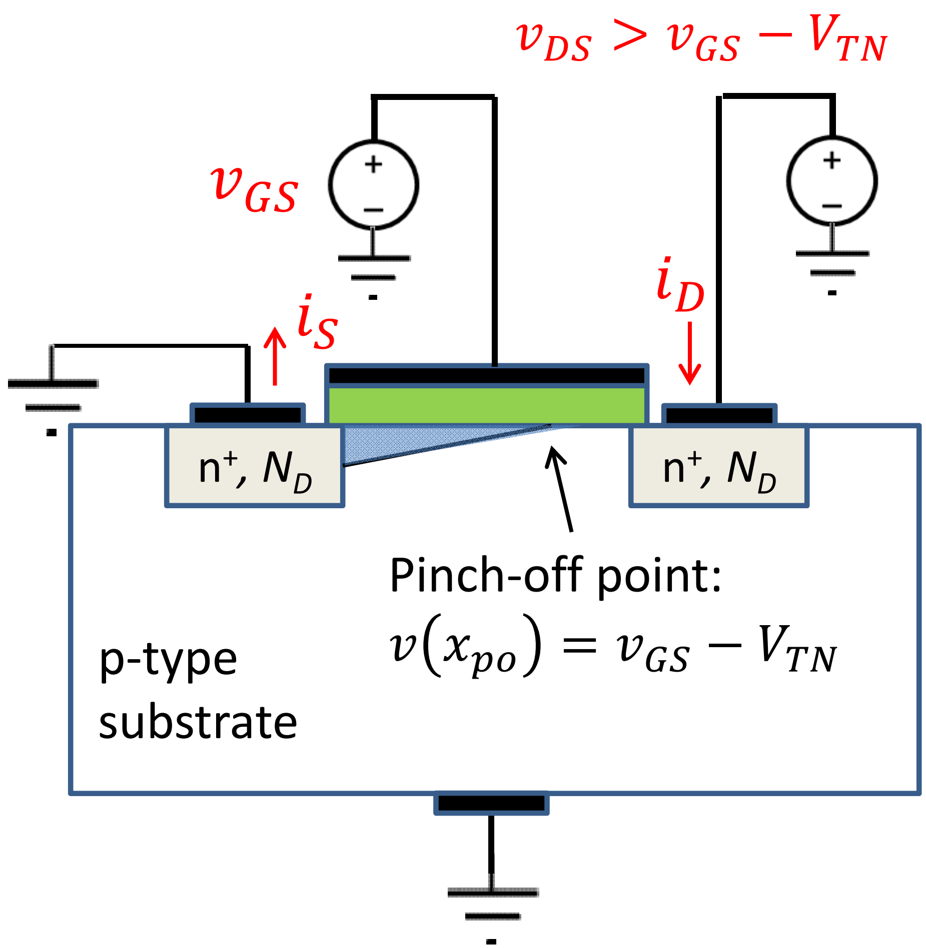


- Onset voltage of saturation is called saturation voltage:

$$v_{\mathrm{DSAT}} = v_{GS} - V_{TN}$$

- Under saturation, voltage across the inversion layer is fixed to be the voltage at the pinch-off point ($v_{GS} - V_{TN}$)
- High electric field in the depletion region sweeps the electrons beyond the pinch-off point to the drain.

Saturation (Pinch-off) region



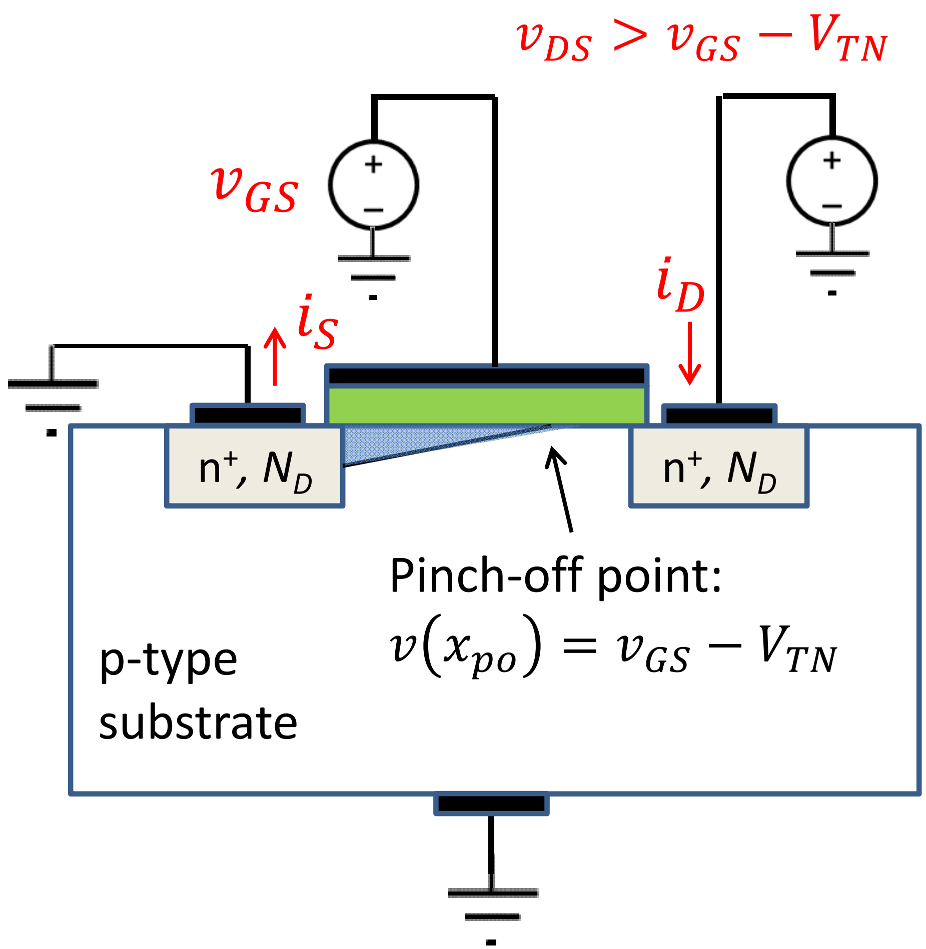
- When v_{DS} reaches v_{DSAT}, MOSFET enters the saturation region.
- Further increasing v_{DS}, voltage across the inversion layer remains constant ($v_{GS} - V_{TN}$)
- Thus the saturation region formula is obtained by substituting $v_{\mathrm{DSAT}} = v_{GS} - V_{TN}$ for v_{DS} in the triode region formula:

$$\boxed{i_D = \frac{K_n'}{2}\frac{W}{L}(v_{GS} - V_{TN})^2}$$

- Saturation condition:

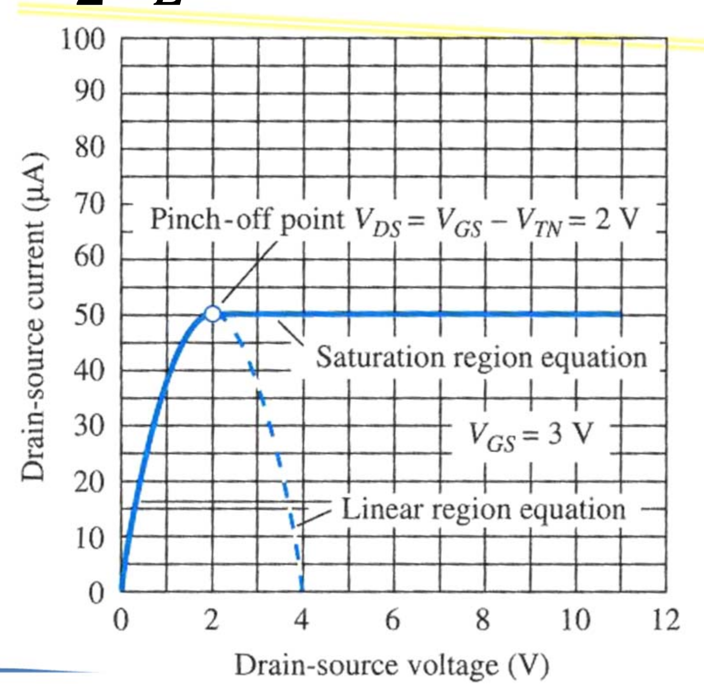
$$\boxed{v_{DS} \geq v_{GS} - V_{TN}}$$

Saturation (Pinch-off) region

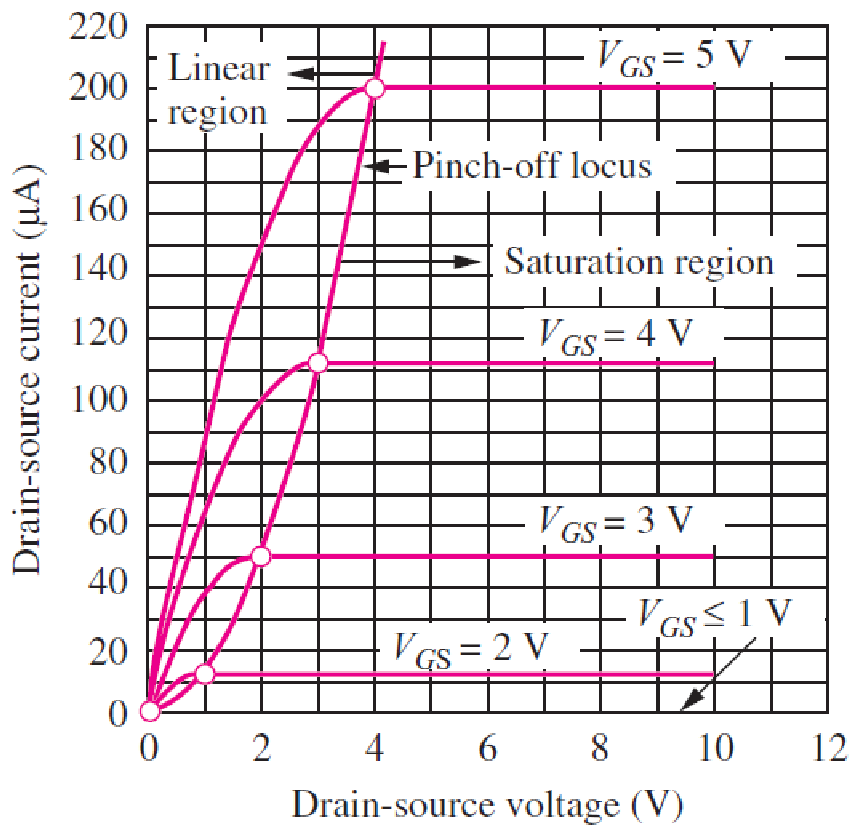


- $v_{\mathrm{DSAT}} = v_{GS} - V_{TN}$
- $v_{DS} \geq v_{\mathrm{DSAT}}$:

$$i_D = \frac{K_n'}{2}\frac{W}{L}(v_{GS} - V_{TN})^2$$

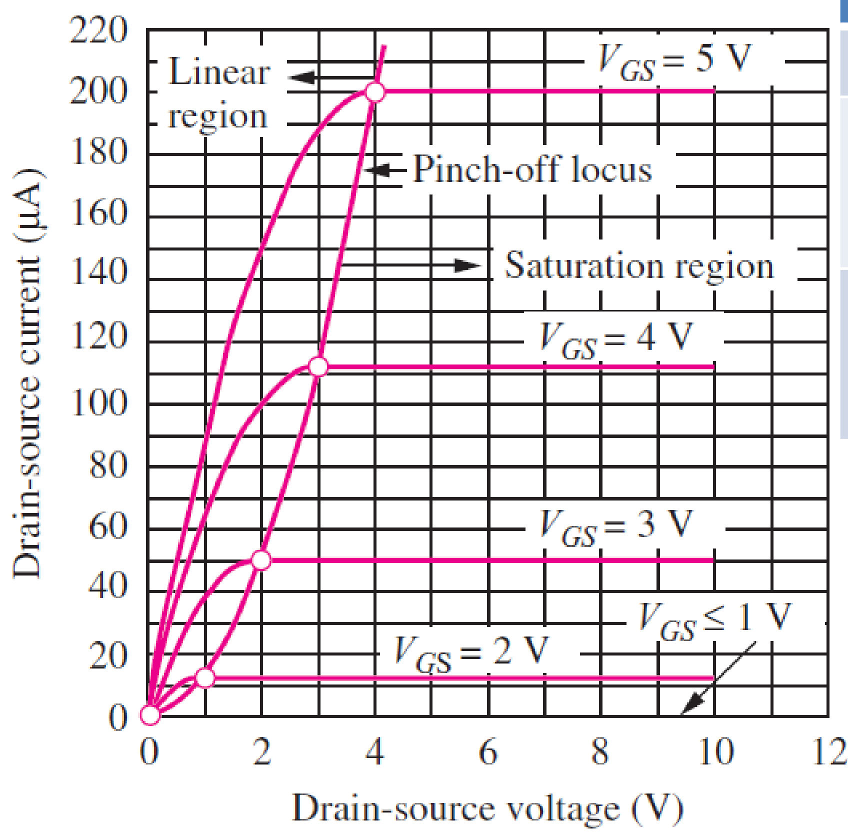


NMOS Output characteristics



Region	Current Equation	Condition
Cutoff	$i_D = 0$	$v_{GS} \leq V_{TN}$
Triode	$i_D = K_n \left(v_{GS} - V_{TN} - \frac{v_{DS}}{2}\right) v_{DS}$	$v_{GS} > V_{TN}$ $v_{GS} > V_{TN} + v_{DS}$ $[v_{GD} > V_{TN}]$
Satur-ation	$i_D = \frac{K_n}{2}(v_{GS} - V_{TN})^2$	$v_{GS} > V_{TN}$ $v_{DS} \geq v_{GS} - V_{TN}$

NMOS Regions and Currents



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Cutoff	$i_D = 0$	$v_{GS} \leq V_{TN}$
Triode	$i_D = K_n \left(v_{GS} - V_{TN} - \frac{v_{DS}}{2}\right) v_{DS}$	$v_{GS} > V_{TN}$ $v_{GS} > V_{TN} + v_{DS}$
Satur-ation	$i_D = \frac{K_n}{2}(v_{GS} - V_{TN})^2$	$v_{GS} > V_{TN}$ $v_{GS} \leq V_{TN} + v_{DS}$

Example, V_{TN}=1V:

- V_{GS}=1V, V_{DS}=1V: cutoff
- V_{GS}=3V, V_{DS}=1V: linear
- V_{GS}=5V, V_{DS}=5V: saturation

Transconductance (Saturation)

$$i_D = \frac{K_n'}{2}\frac{W}{L}(v_{GS} - V_{TN})^2$$

- Transconductance (change in i_D vs. change in v_{GS}):

$$g_m = \frac{di_D}{dv_{GS}} = K_n'\frac{W}{L}(v_{GS} - V_{TN})$$

Transfer characteristics

- Fix v_{DS}, see how i_D varies with v_{GS}
  - $v_{GS} < V_{TN}$, cut-off

$$i_D = 0$$

  - $V_{TN} \leq v_{GS} \leq V_{DS} + V_{TN}$, saturation

$$i_D = \frac{K_n'}{2}\frac{W}{L}(v_{GS} - V_{TN})^2$$

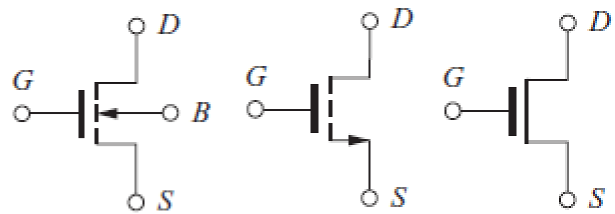
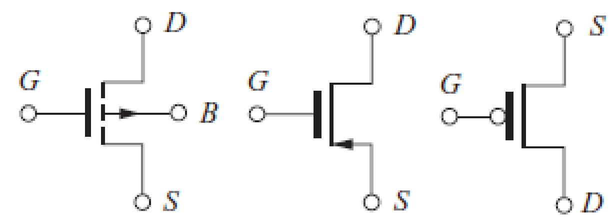
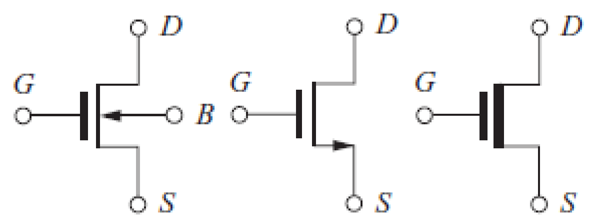
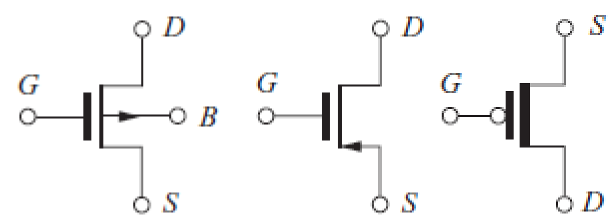
  - $V_{DS} + V_{TN} < v_{GS}$, triode

$$i_D = K_n'\frac{W}{L}\left(v_{GS} - V_{TN} - \frac{V_{DS}}{2}\right)V_{DS}$$

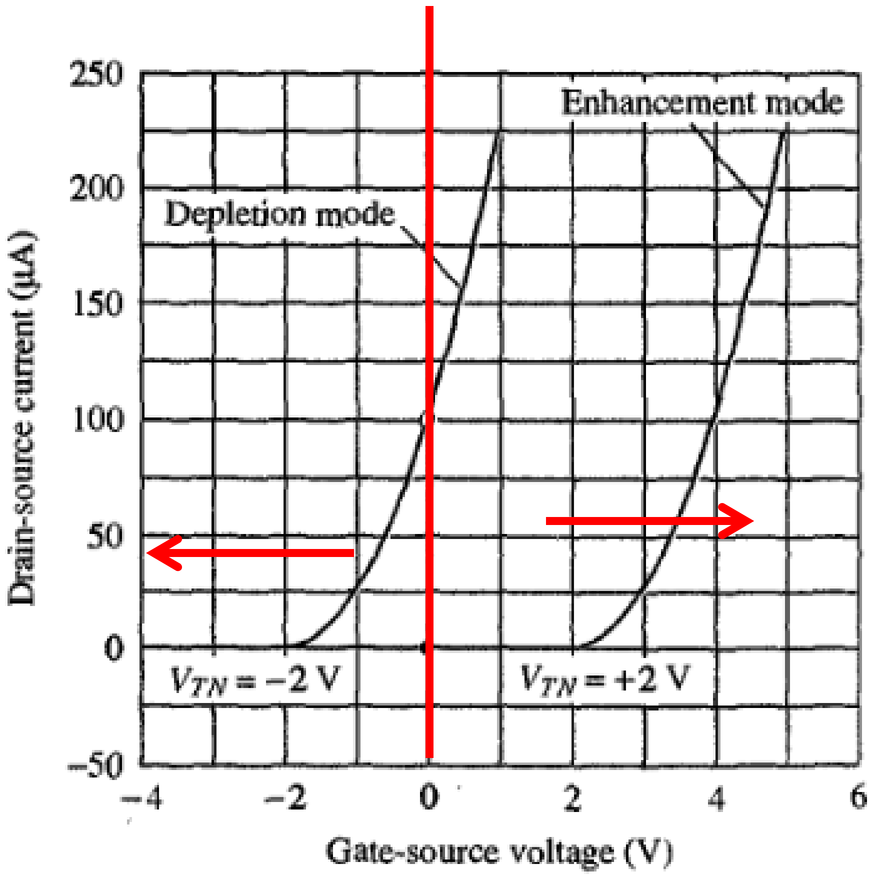
Transfer characteristics

- i_D increases monotonically with v_{GS} when MOSFET is on ($v_{GS} > V_{TN}$).
- V_{TN} can be either positive or negative.
  - ➢ V_{TN} positive, NMOS is OFF for $v_{GS} = 0$ => Enhancement-mode NMOS transistor (applying positive v_{GS} enhances channel conduction)
  - ➢ V_{TN} negative, NMOS is ON for $v_{GS} = 0$ => Depletion-mode NMOS transistor (applying negative v_{GS} depletes conduction layer)

MOSFET Circuit Symbols

	NMOS	PMOS
E-Mode		
D-Mode		

Transfer Characteristics



Transfer characteristics for enhancement-mode and depletion-mode NMOS transistors