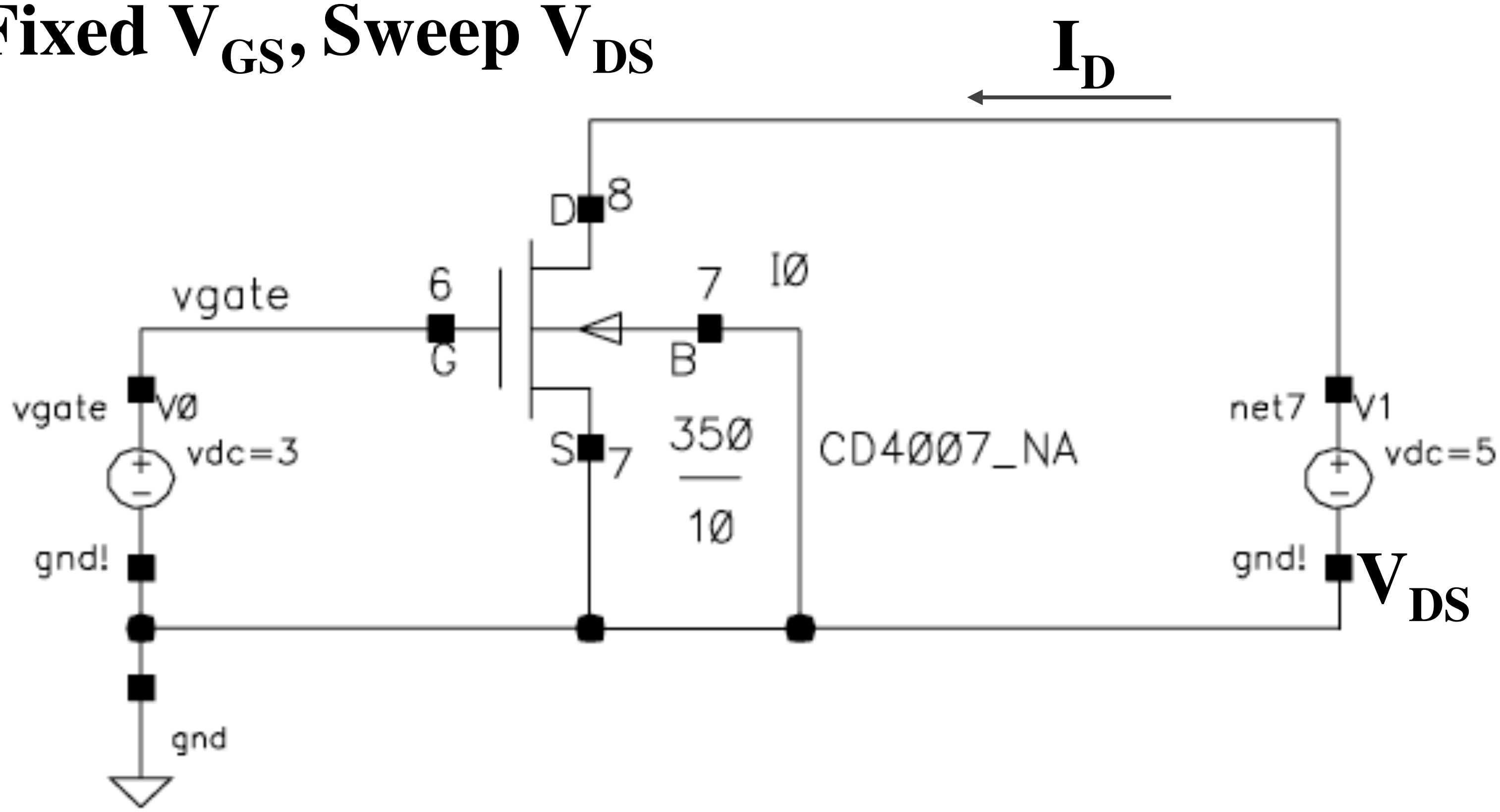
Studio 3 Review

- **MOSFET as current source**
- **Small V_{DS}:**
  Resistor (value controlled by V_{GS})
- **Large V_{DS}:**
  Current source (value controlled by V_{GS})

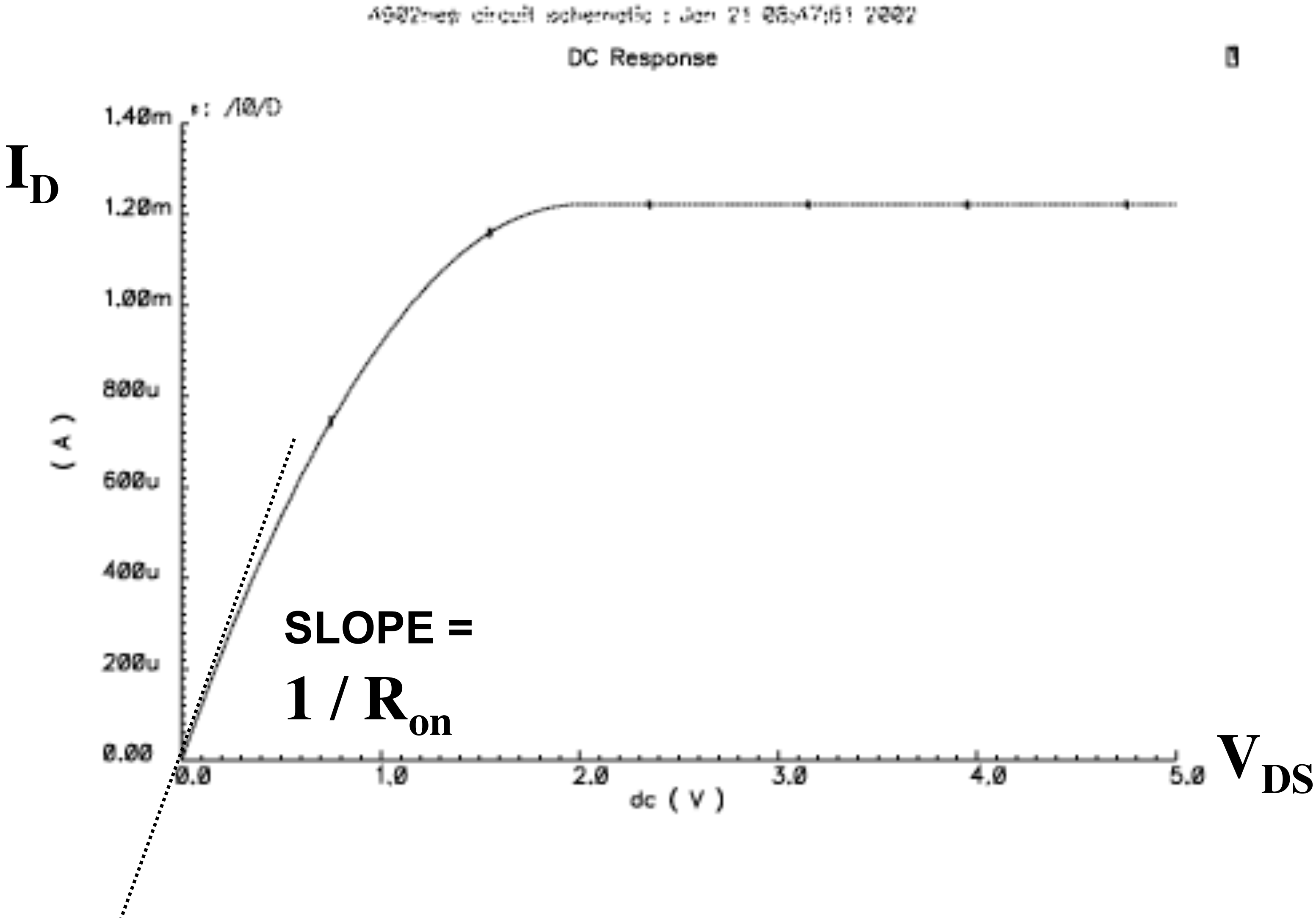
Simulation Review: Circuit

- **Fixed V_{GS}, Sweep V_{DS}**



Simulation Review: Result

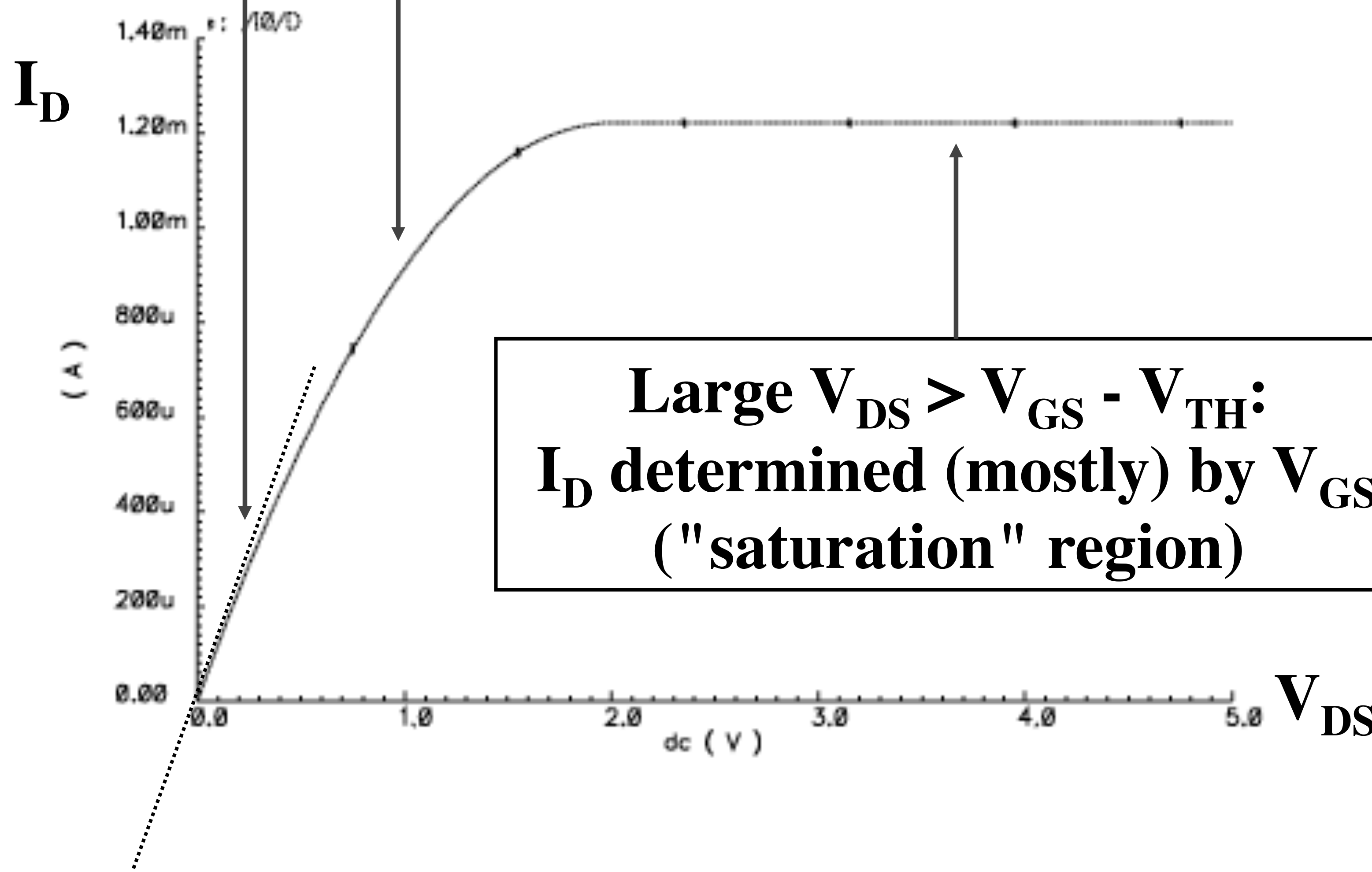
Follows linear R_{on} model only for "small" V_{DS}



Simulation Review: Result

Small V_{DS} linear R_{on}

Medium $V_{DS} < V_{GS} - V_{TH}$: nonlinear ("triode" region)



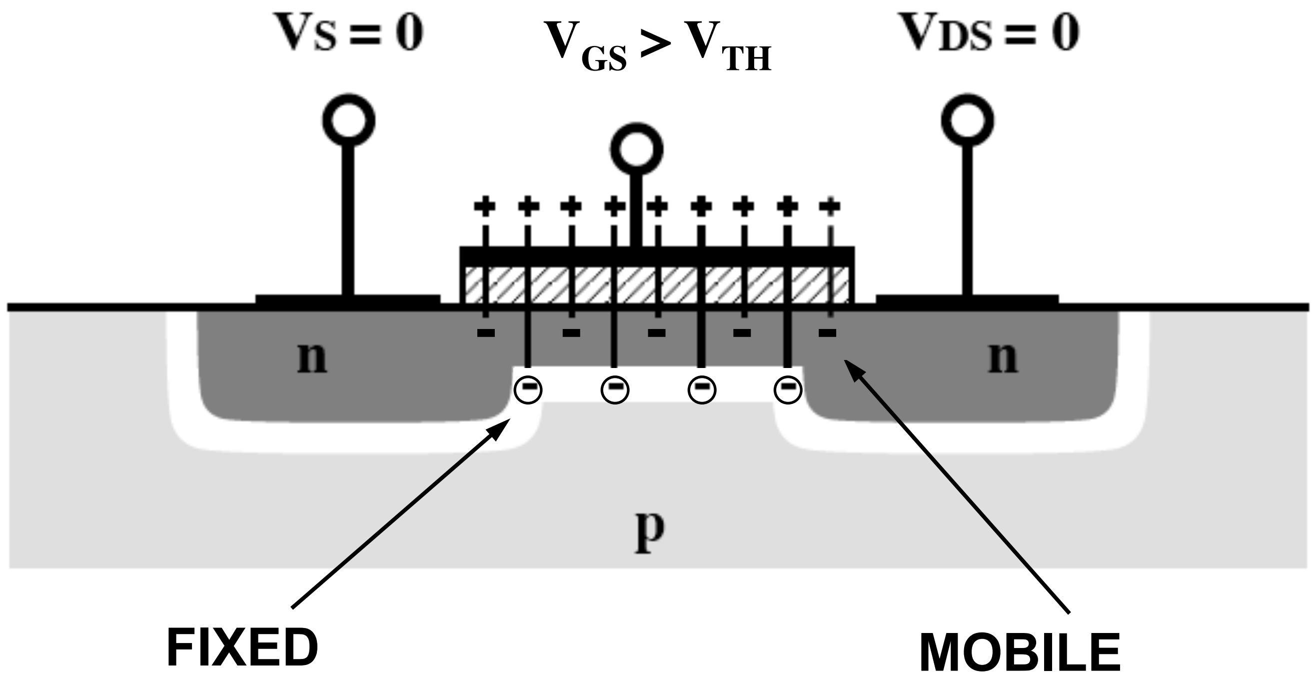
Large $V_{DS} > V_{GS} - V_{TH}$: I_D determined (mostly) by V_{GS} ("saturation" region)

MOSFET Behavior

- **MOSFET channel behaves differently as the channel drain-source voltage V_{DS} increases:**
- **Small V_{DS}:**
  linear V_{DS}-I_D relationship (model as R_{on})
- **Medium $V_{DS} < V_{GS} - V_{TH}$:**
  nonlinear ("triode") relationship
- **Large $V_{DS} > V_{GS} - V_{TH}$:**
  approximately constant current determined (mostly) by V_{GS}

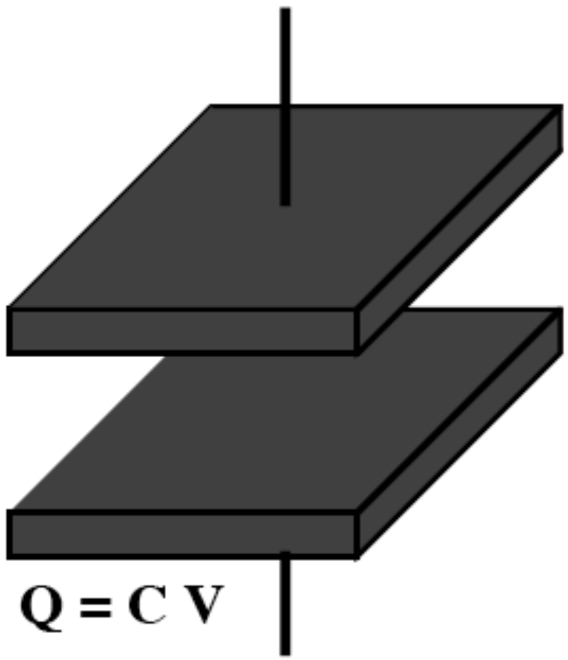
What Changed?

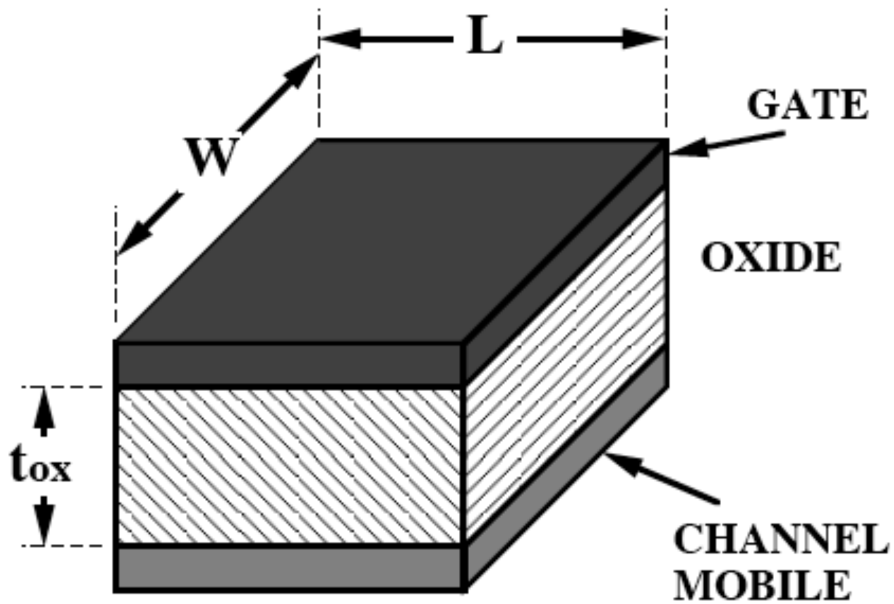
- Reexamine R_{on} derivation:
  - Apply V_{GS} : inversion layer of mobile charge



Reexamine R_{on} Derivation

- **Calculate mobile channel charge**
- ***Assumed same voltage along channel***

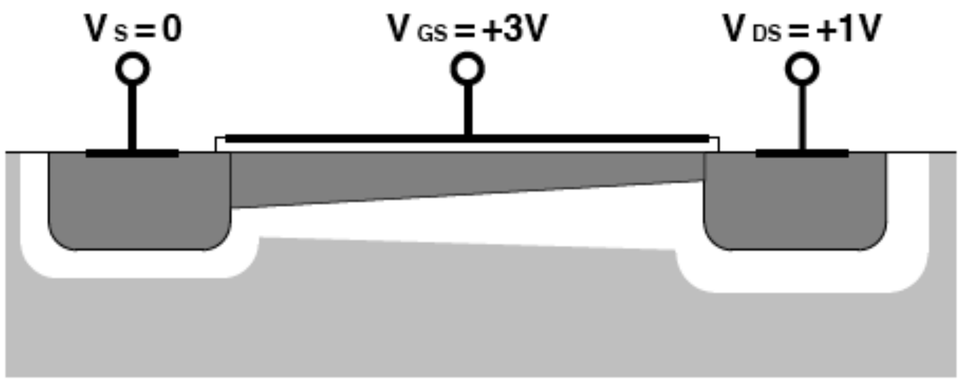


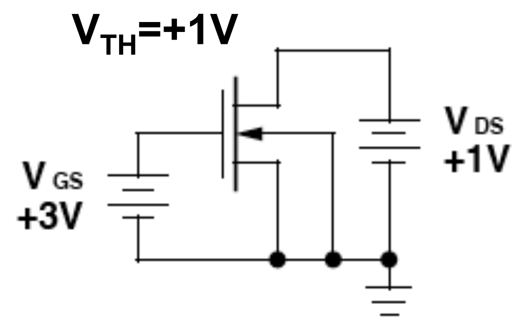


$Q = C_{gs}(V_{GS} - V_{TH})$

What Changed: Voltage in V_{DS} Channel

- **Problem: apply V_{DS} (to make current flow)**

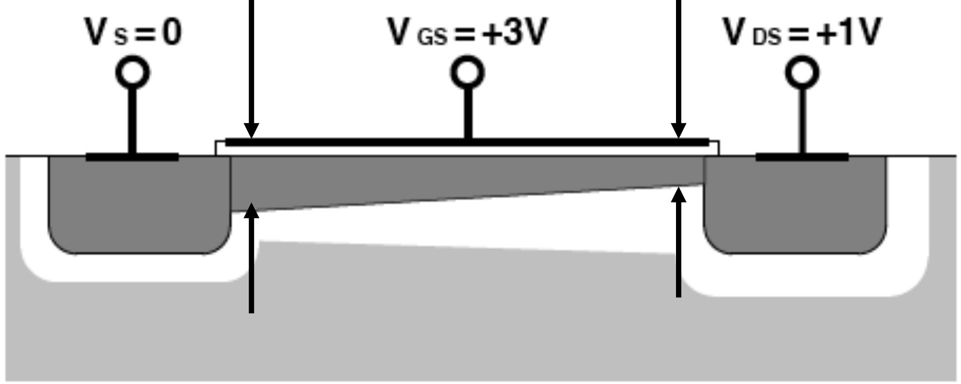


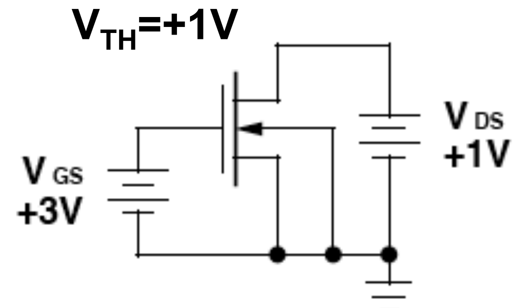


Example: Apply 1V V_{DS}

- **Voltage drop from gate to channel:**

3V at S end .... 2V at D end

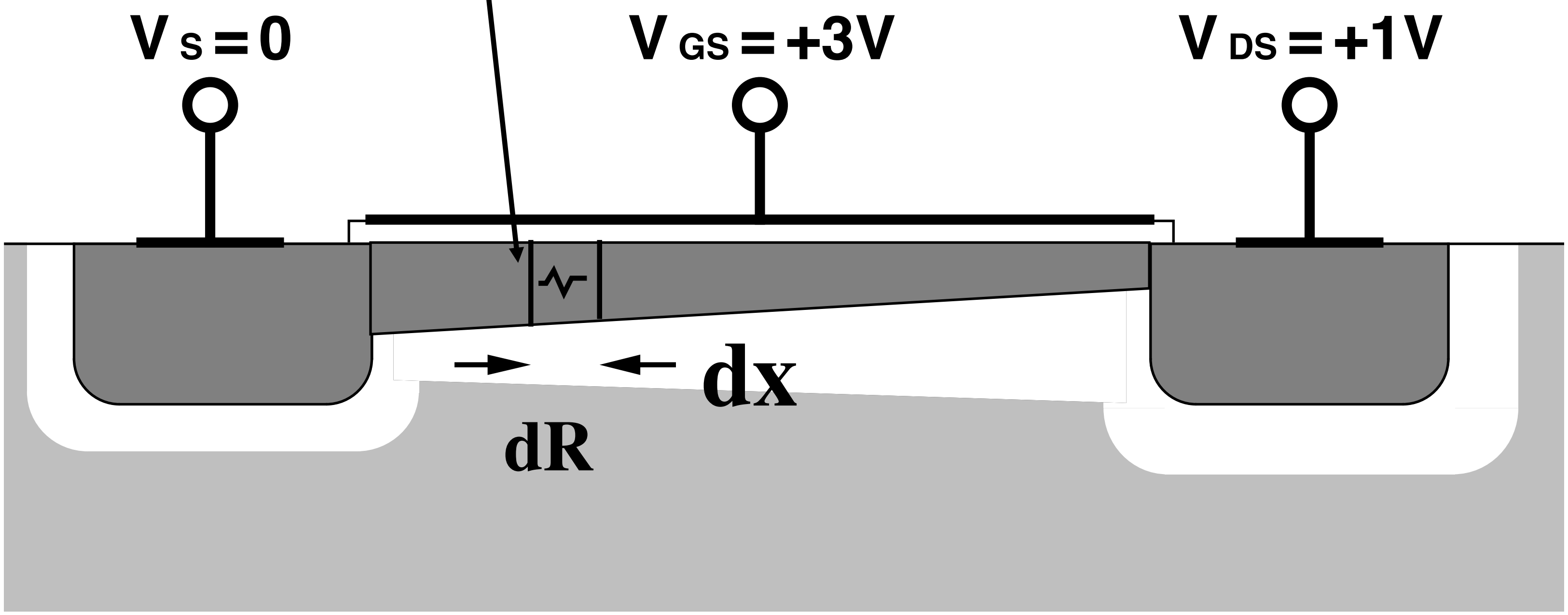




- **Less mobile charge at D end**
- **Can't assume same charge density across channel**

Approach:

- Divide channel along length x into segments dx
- Within segment, voltage change negligible
- Current I_D same all along channel (Kirchhoff)
- "KVL" from source to drain
- Define $\boxed{V_{ch}(x)}$ voltage in channel vs. position



Resistance of dx segment

- **Original equation:**

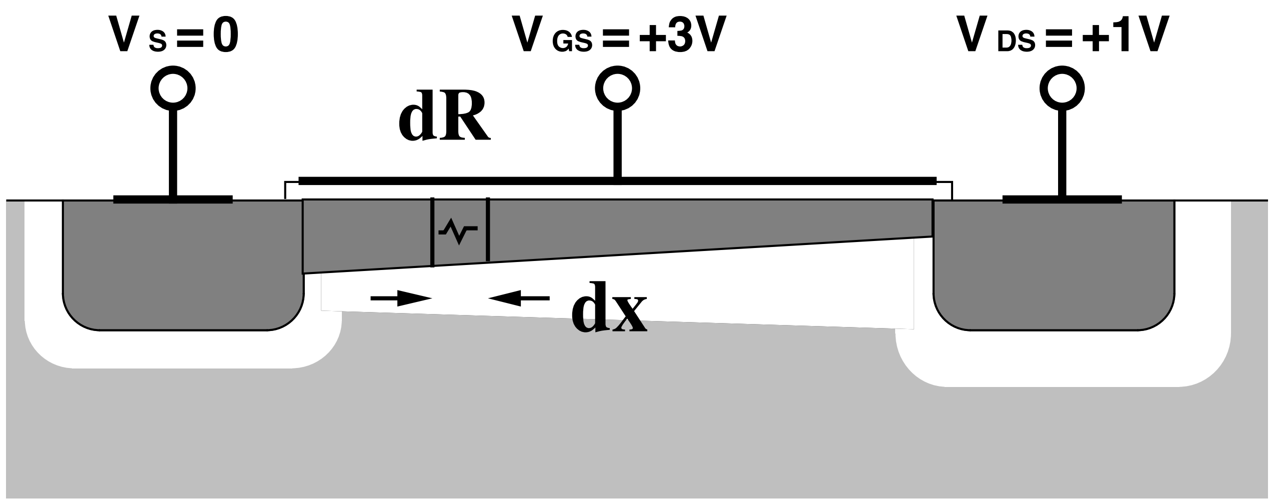
$$R_{on} = \frac{1}{\mu_n C_{ox} \frac{W}{L}\left(V_{GS} - V_{TH}\right)}$$

- **"Length" = dx; use $V_{ch}(x)$:**

$$dR(x) = \frac{1}{\mu_n C_{ox} \frac{W}{dx}\left(V_{GS} - V_{ch}(x) - V_{TH}\right)}$$

- **Massage**

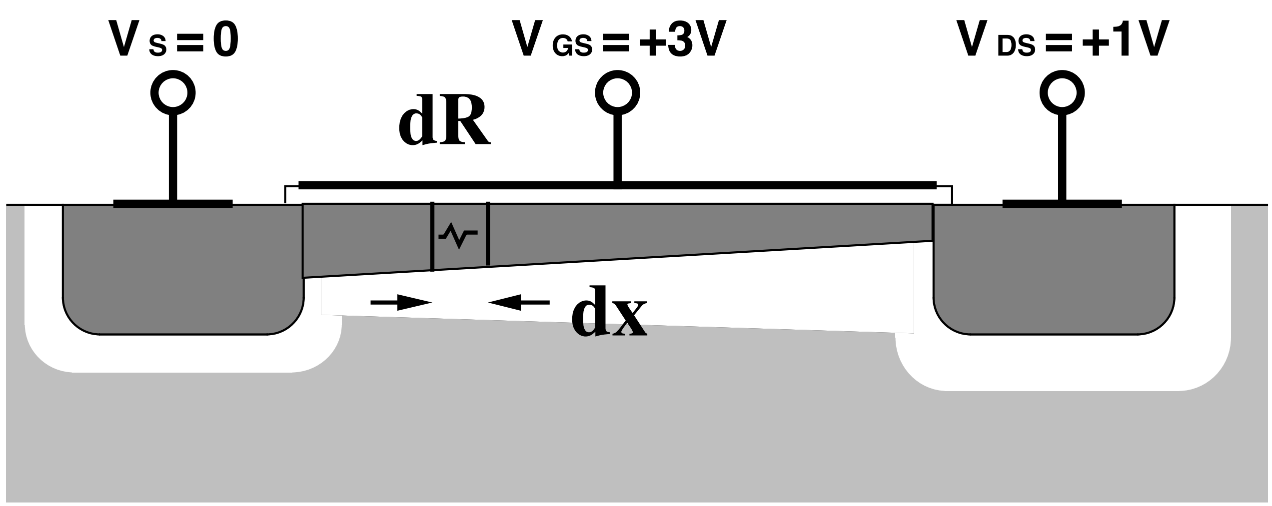
$$dR(x) = \frac{dx}{\mu_n C_{ox} W\left(V_{GS} - V_{ch}(x) - V_{TH}\right)}$$



Voltage drop dV across dx segment

- **Ohm's Law:** $$dV = I_D dR$$
- **Substitute for dR:** $$dV = \frac{I_D dx}{\mu_n C_{ox} W \left(V_{GS} - V_{ch}(x) - V_{TH}\right)}$$
- **Massage:**

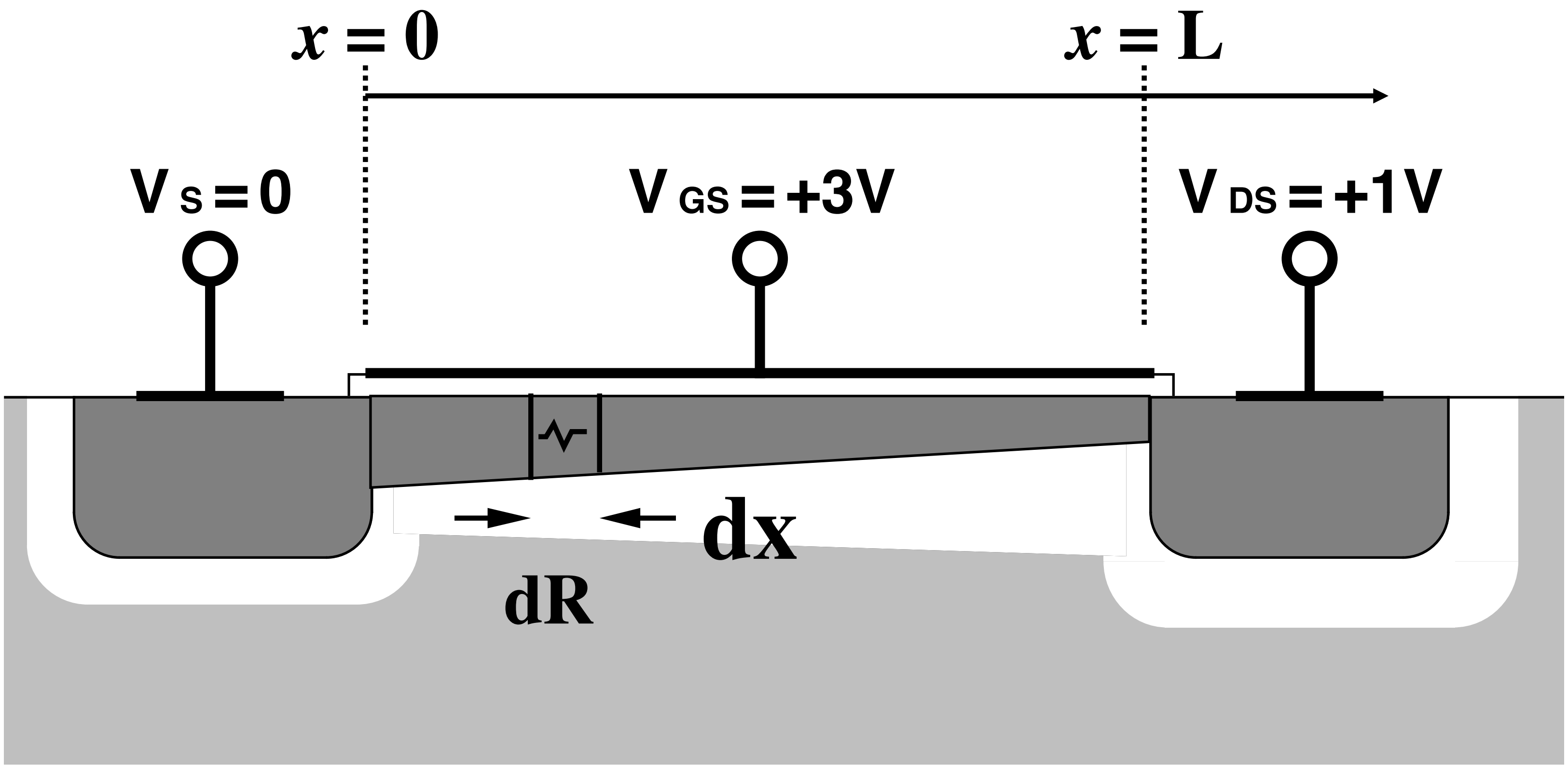
$$\mu_n C_{ox} W \left(V_{GS} - V_{ch}(x) - V_{TH}\right) dV = I_D dx$$



Integrate both sides

- **Limits on V: 0 to V_{DS} Limits on X: 0 to L**

$$\int_0^{V_{DS}} \mu_n C_{ox} W \left(V_{GS} - V_{ch}(x) - V_{TH}\right) dV = \int_0^L I_D dx$$



Integrate, evaluate both sides

- **Integral result**

$$\mu_n C_{ox} W \left[\left(V_{GS} - V_{TH}\right)V - \frac{V^2}{2} \right]\Bigg|_0^{V_{DS}} = I_D x \Big|_o^L$$

- **Evaluate**

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

- **TRIODE REGION EQUATION**

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

Triode region equation: Limit for $V_{DS} << V_{GS} - V_{TH}$

- V_{DS} small $\Rightarrow$ V_{DS}^2 very small

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

- Approaches resistive model

$$I_D \approx \mu_n C_{ox} \frac{W}{L}\left(V_{GS} - V_{TH}\right)V_{DS}$$

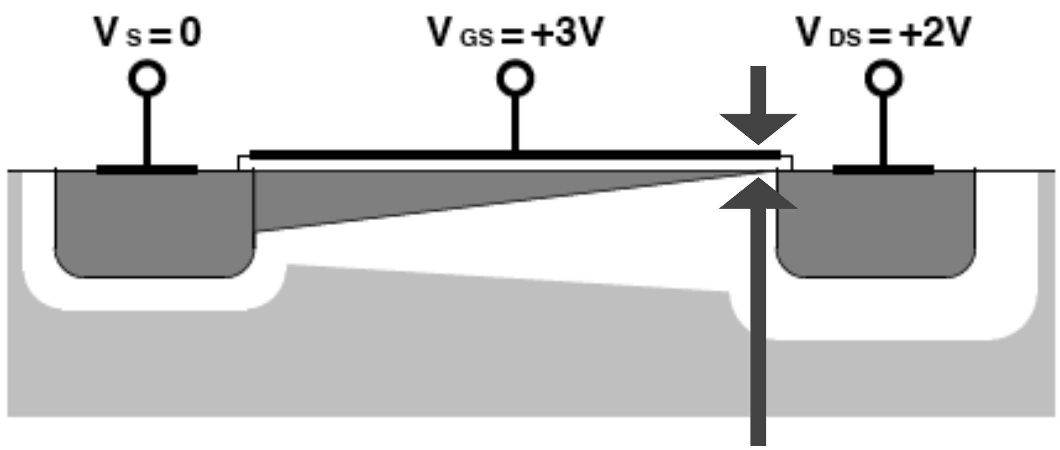
“Small” V_{DS}: How small is “small”?

$$I_D = \mu_n C_{ox} \frac{W}{L}\left[\underbrace{(V_{GS} - V_{TH})V_{DS}}_{\substack{LINEAR \\ IN\ V_{DS}}} - \underbrace{\frac{V_{DS}{}^2}{2}}_{\substack{QUADRATIC \\ IN\ V_{DS}}}\right]$$

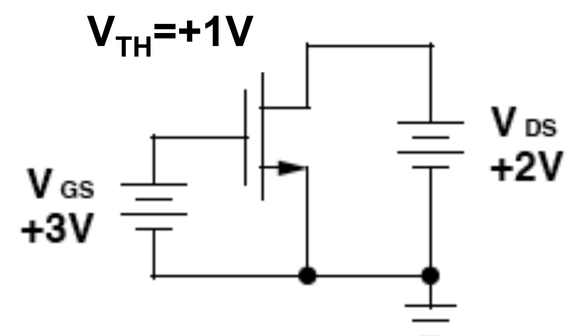
- **Compare magnitude of linear, quadratic terms**

Pinchoff

- Condition: $V_{GD}=V_{TH}$
  - Gate-to-channel difference must exceed V_{TH} for mobile charge in channel
- What is current at pinchoff?



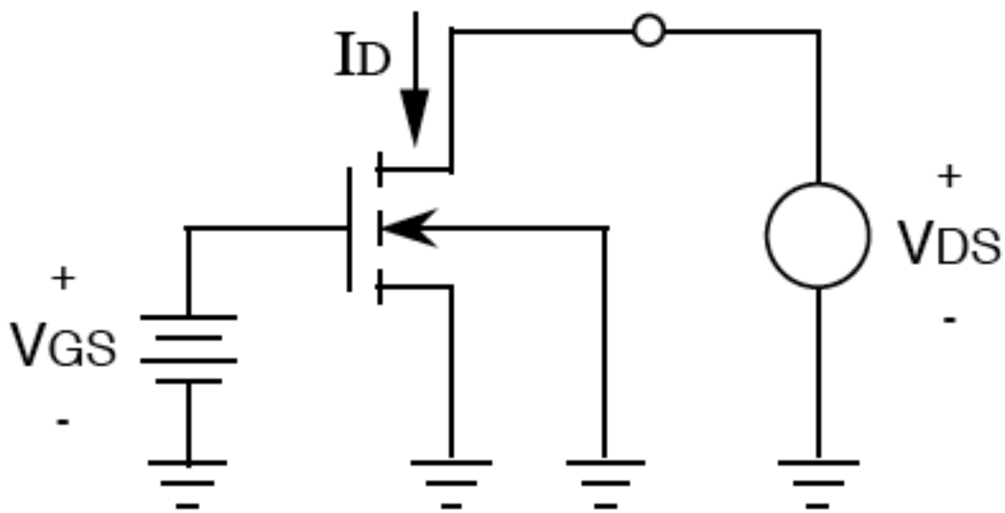
$V_{GD}=V_{TH}$

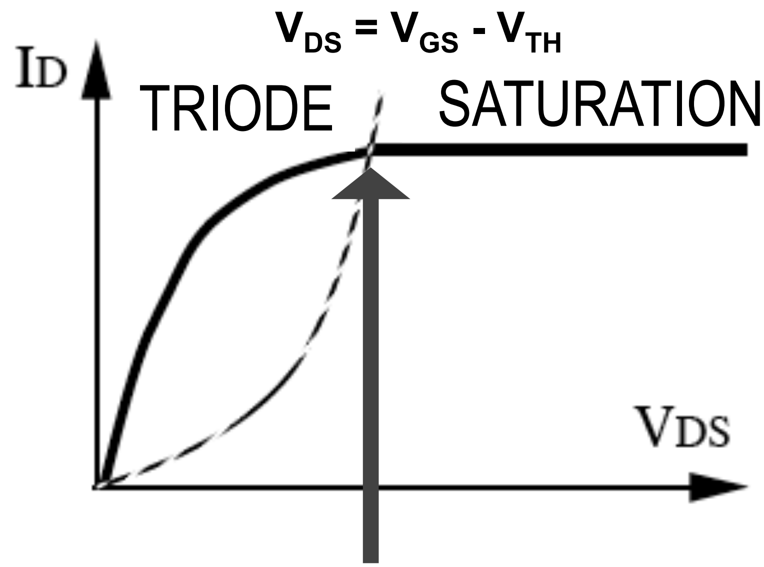


Current at Pinchoff

- $V_{GD}=V_{TH} \Rightarrow V_{GS} - V_{DS}=V_{TH} \Rightarrow V_{DS}=V_{GS} - V_{TH}$
- **Substitute condition into triode equation**

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

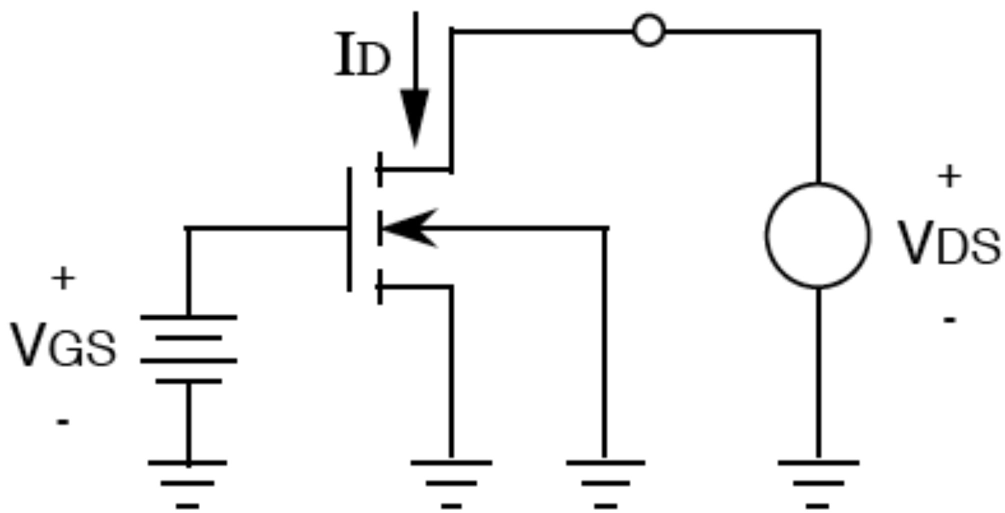


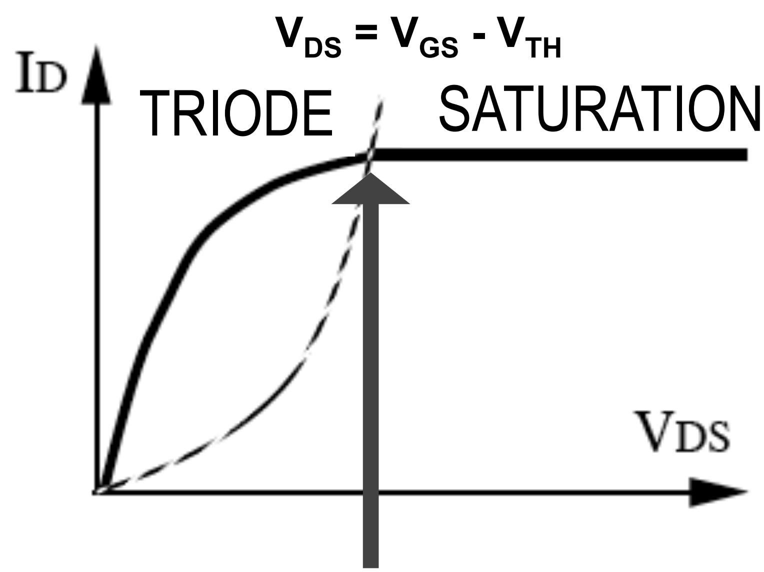


Current at Pinchoff

- **Current depends only on V_{GS} (ideally)**
- **SATURATION REGION EQUATION**

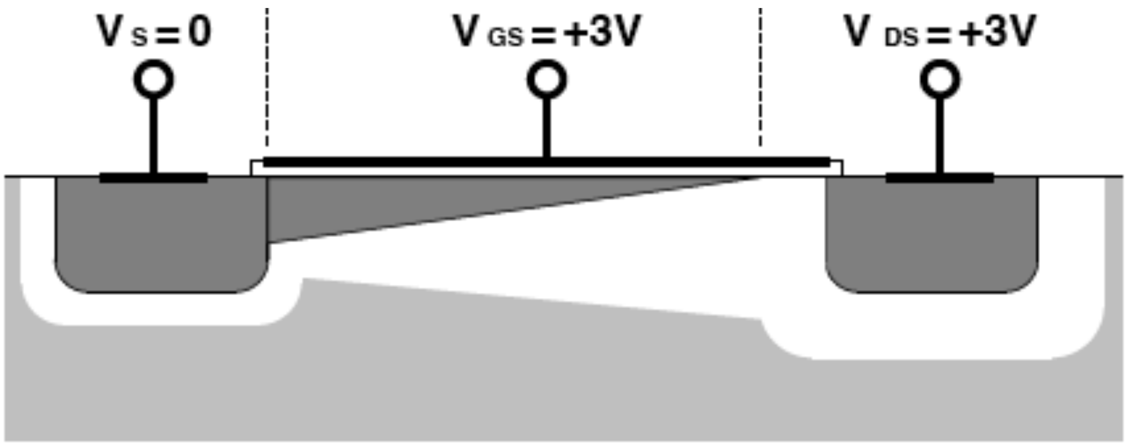
$$\boxed{I_D = \frac{\mu_n C_{ox}}{2}\frac{W}{L}\left(V_{GS} - V_{TH}\right)^2}$$

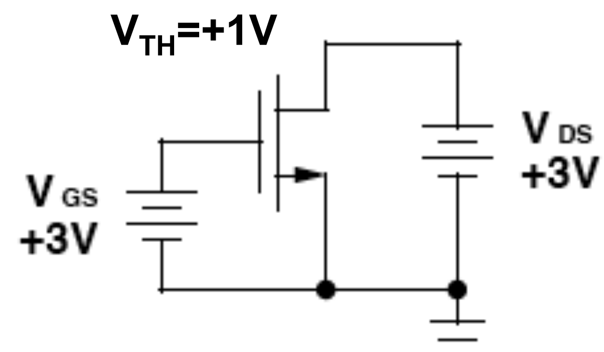




Beyond Pinchoff (Simplest Model)

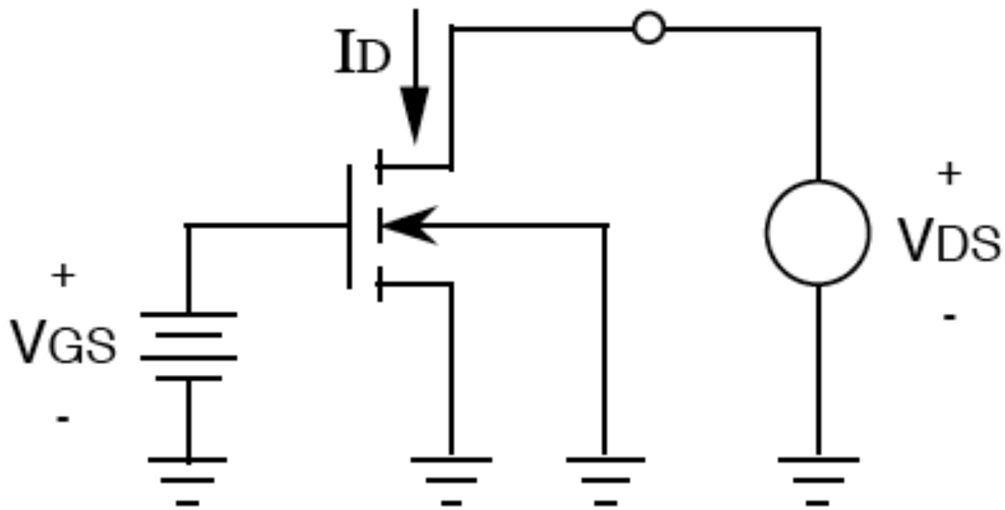
- Higher V_{DS} ⇒ No additional mobile charge in channel ⇒ No increase in current

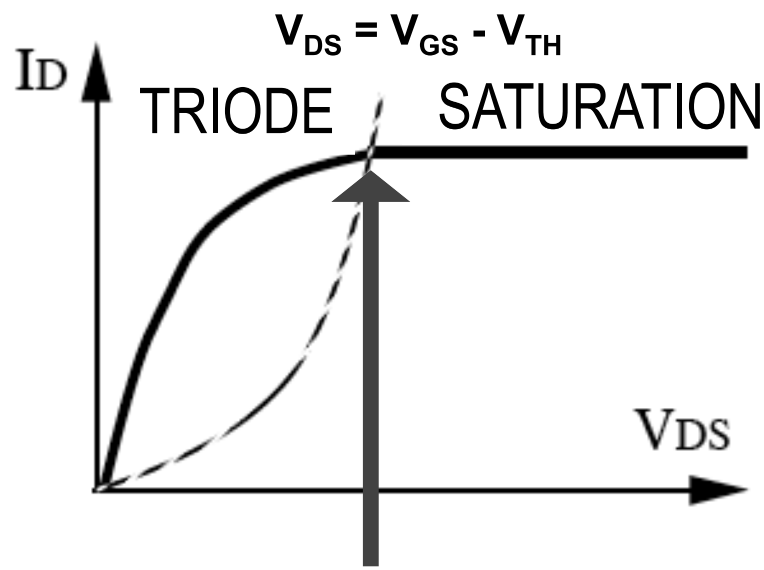




Behavior

- Current source, controlled by V_{GS}
- "Saturation region" (will be used as amplifier)





Summary: NMOS

GATE	DRAIN		APPROXIMATE BEHAVIOR
$V_{GS} > V_{TH}$	$V_{DS} > V_{GS} - V_{TH}$	**SATURATION**	I_D DEPENDS ONLY ON $V_{GS} - V_{TH}$ $$I_D = \frac{\mu_n C_{ox}}{2}\frac{W}{L}\left(V_{GS} - V_{TH}\right)^2$$
	$V_{DS} < V_{GS} - V_{TH}$	**TRIODE**	DRAIN-SOURCE CHANNEL "LOOKS" RESISTIVE FOR "SMALL" V_{DS} $$I_D = \mu_n C_{ox}\frac{W}{L}\left[\left(V_{GS} - V_{TH}\right)V_{DS} - \frac{V_{DS}^{\ 2}}{2}\right]$$
$V_{GS} < V_{TH}$		**CUTOFF**	$I_D = 0$

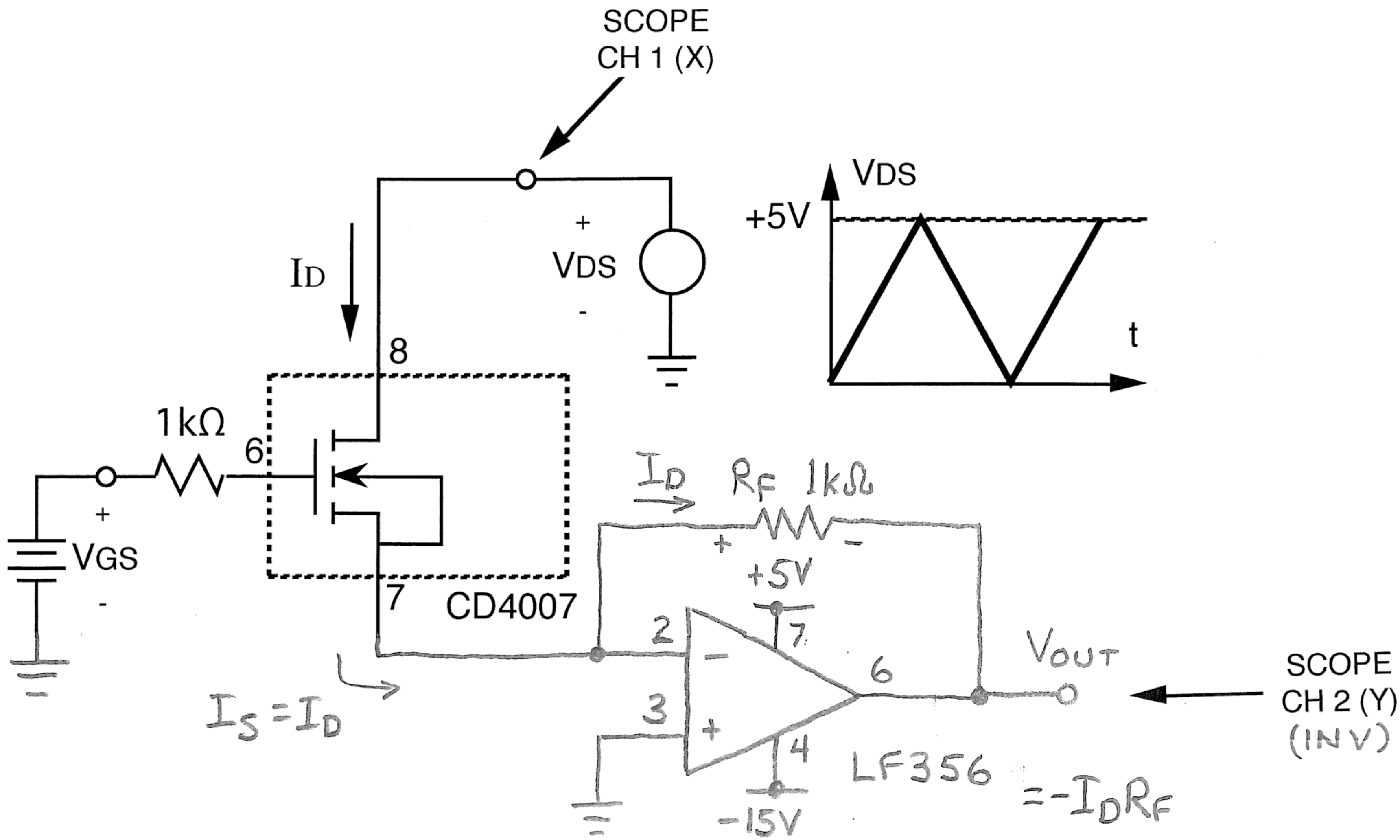
- **Analysis strategy: Assume / guess operating region, check for consistency**

Summary: PMOS

GATE	DRAIN		APPROXIMATE BEHAVIOR
$V_{GS} < V_{TH}$	$V_{DS} <$ $V_{GS} - V_{TH}$	**SATURATION**	I_D DEPENDS ONLY ON $V_{GS} - V_{TH}$ $$I_D = -\frac{\mu_n C_{ox}}{2}\frac{W}{L}\left(V_{GS} - V_{TH}\right)^2$$
	$V_{DS} >$ $V_{GS} - V_{TH}$	**TRIODE**	DRAIN-SOURCE CHANNEL "LOOKS" RESISTIVE FOR "SMALL" V_{DS} $$I_D = -\mu_n C_{ox}\frac{W}{L}\left[\left(V_{GS} - V_{TH}\right)V_{DS} - \frac{V_{DS}^{\ 2}}{2}\right]$$
$V_{GS} > V_{TH}$		**CUTOFF**	$I_D = 0$

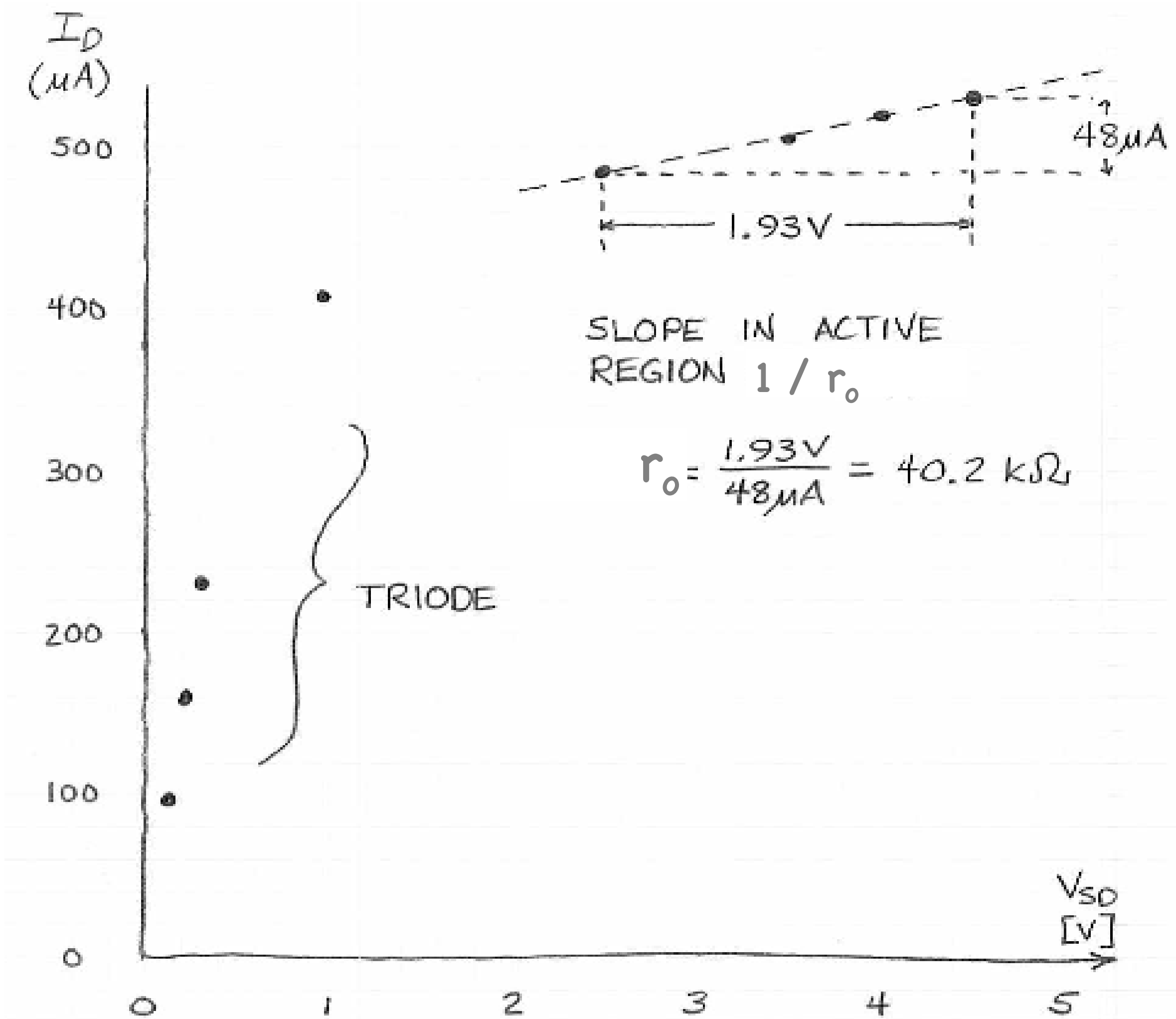
- **Positive current flows out of drain**
- **V_{GS}, V_{DS} negative**

Lab Exercise: Schematic



- **Display I_D - V_{DS} plot on scope**

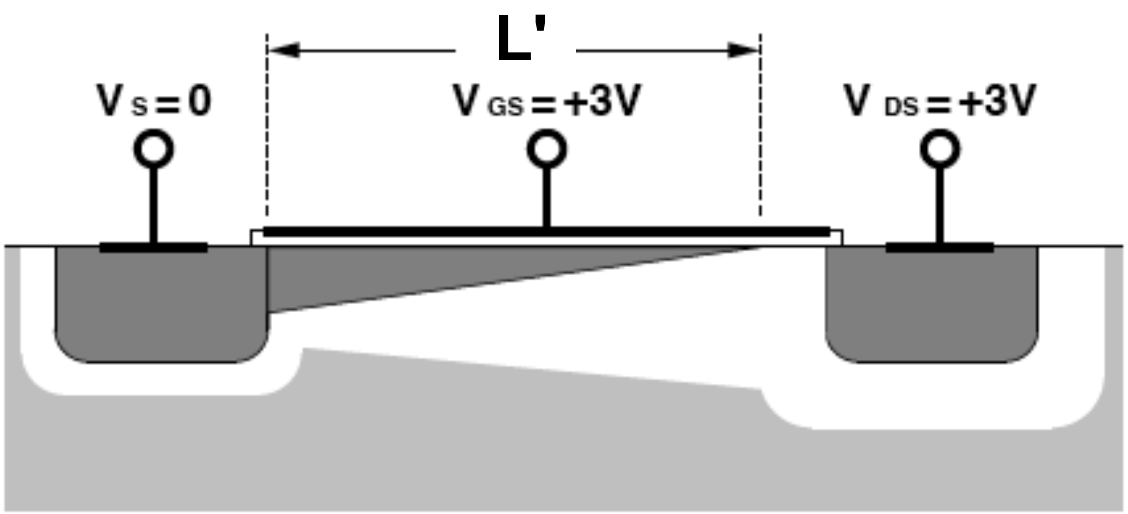
Lab Exercise: V-I plot

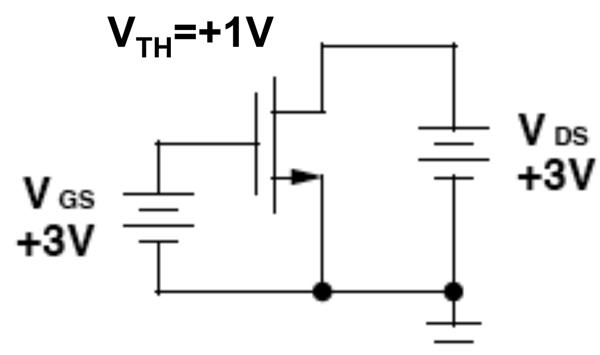


- **Note V_{DS} dependence in active region**
  - **Not accounted for in simple model**

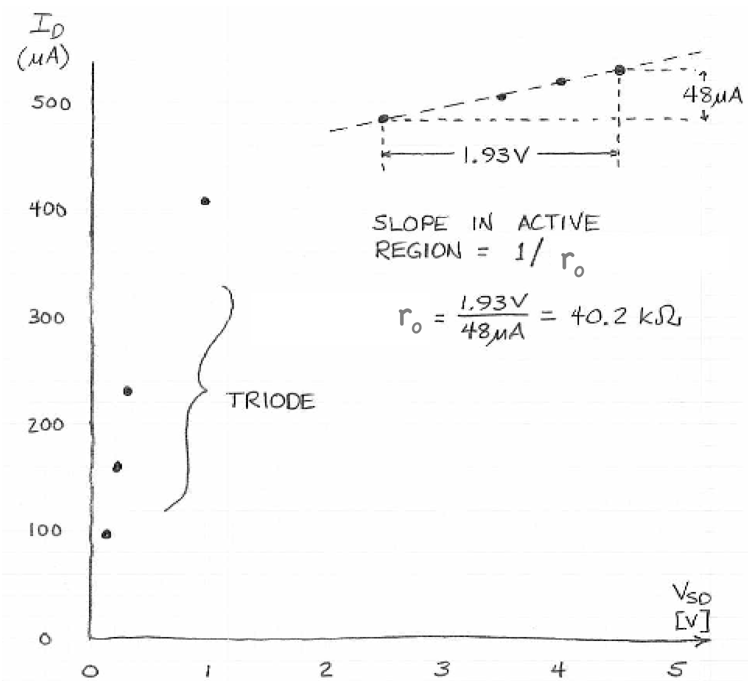
Beyond Pinchoff (Reality)

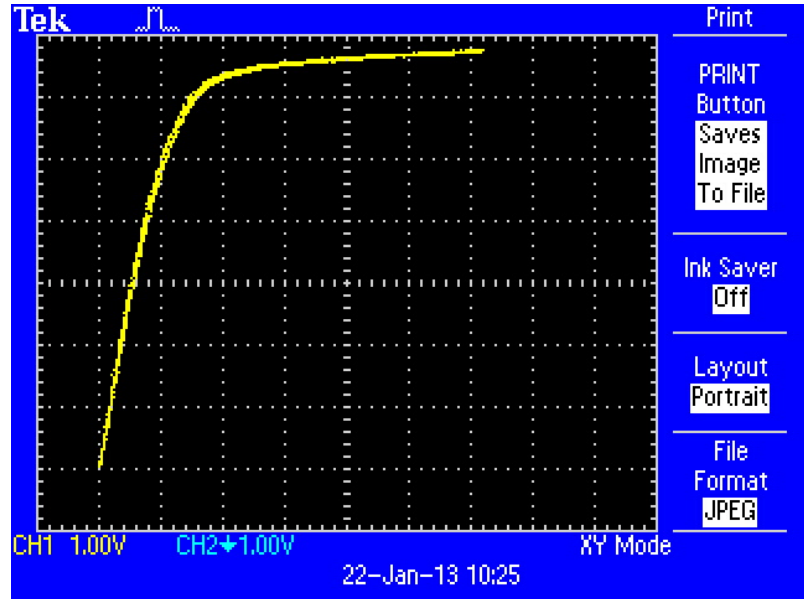
- **Higher V_{DS} ⇒ Pinchoff point moves toward S**
  ⇒ Effective channel length L' < L
  ⇒ "Channel Length Modulation"
  ⇒ I_D influenced by V_{DS}





Lab Exercise: Scope V-I plot

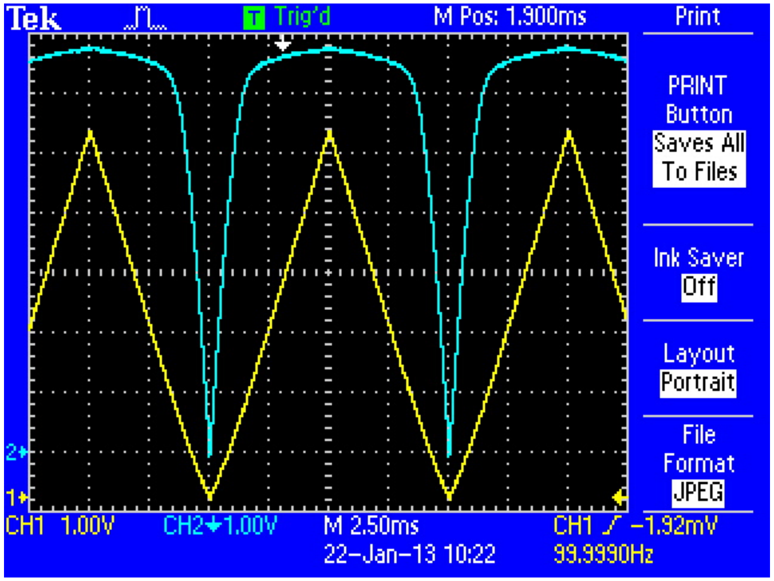


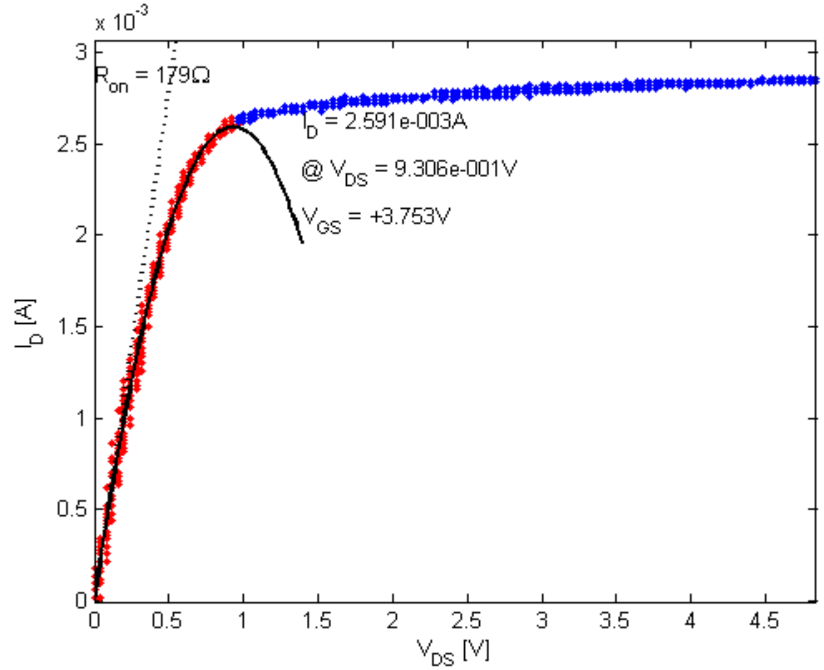


- **Try different values of V_{GS}**
  - **Note what changes, what doesn't in output characteristic**

Note: If you try to save the scope image to a USB stick and you get a message "Control is inactive in XY mode" use the Utility > Options > Printer Setup menu and be sure the PRIBT Button function is set to "Saves Image To File"

Data analysis "extra": MATLAB





- Use "Saves All To Files" option in YT mode to save V_{DS}, I_D data to .csv file
- MATLAB code online to fit parameters