Lecture 8

MOSFET(I)

MOSFET I-V CHARACTERISTICS

Outline

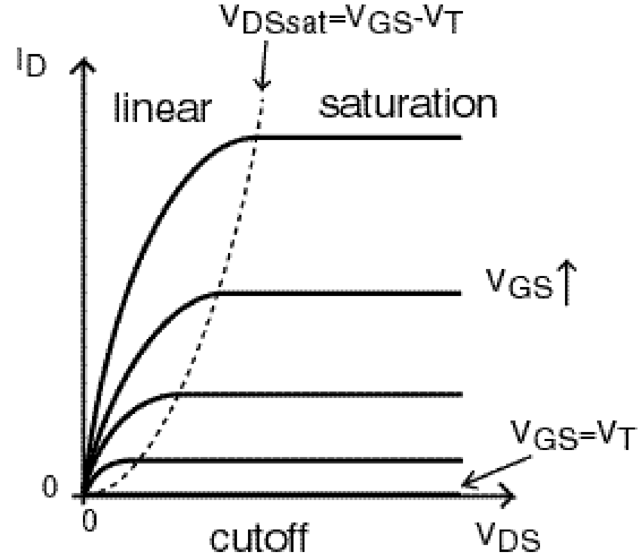
1. MOSFET: cross-section, layout, symbols
2. Qualitative operation
3. I-V characteristics

Reading Assignment:
Howe and Sodini, Chapter 4, Sections 4.1-4.3

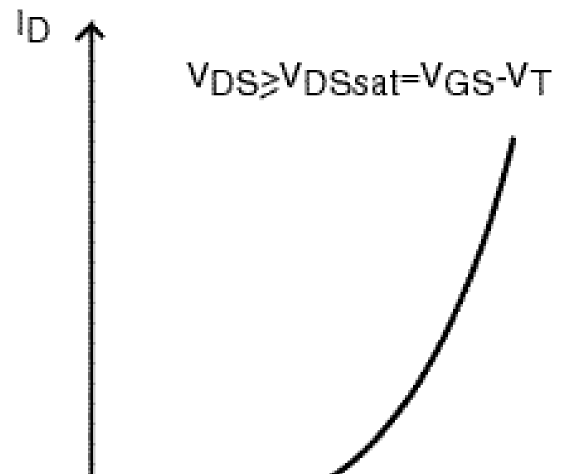
Announcement:
Quiz#1, October 11, 7:30-9:30PM, Walker Memorial; covers Lectures #1-9; open book; must have calculator

Summary of Key Concepts

- **MOSFET Output Characteristics**



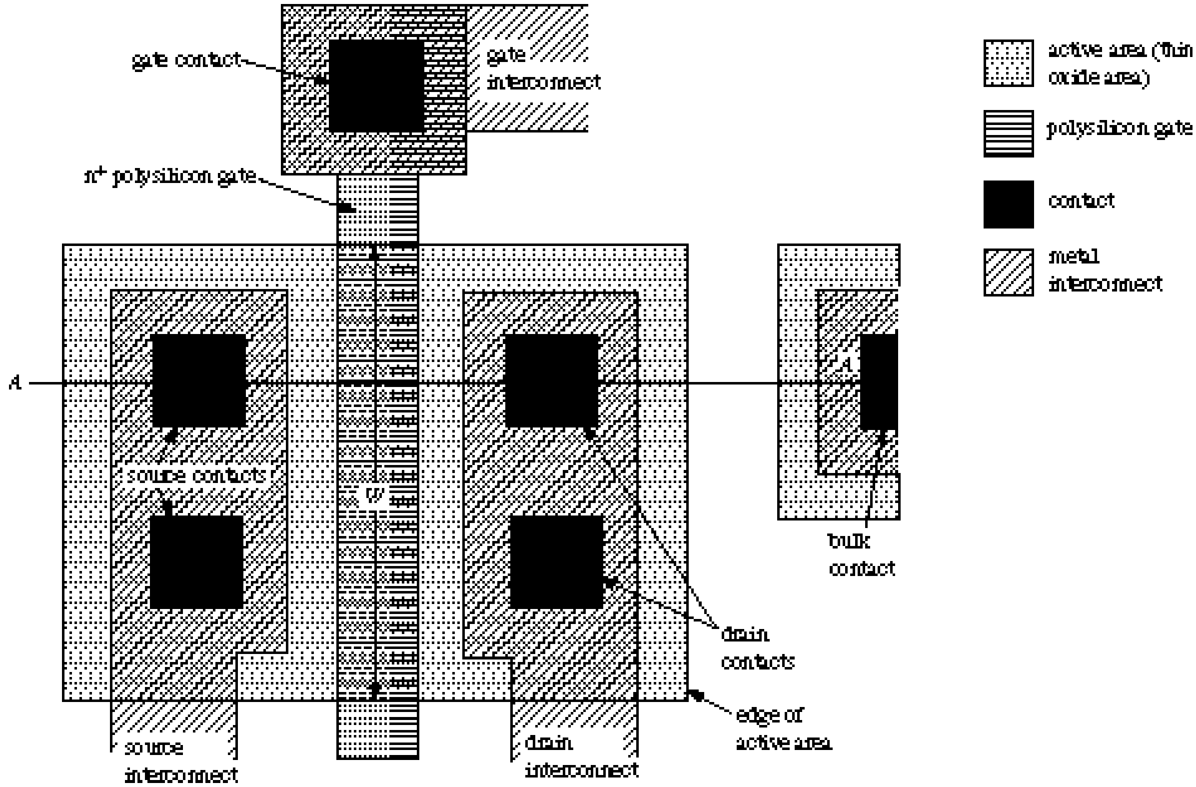
- **MOSFET Transfer Characteristics in Saturation**

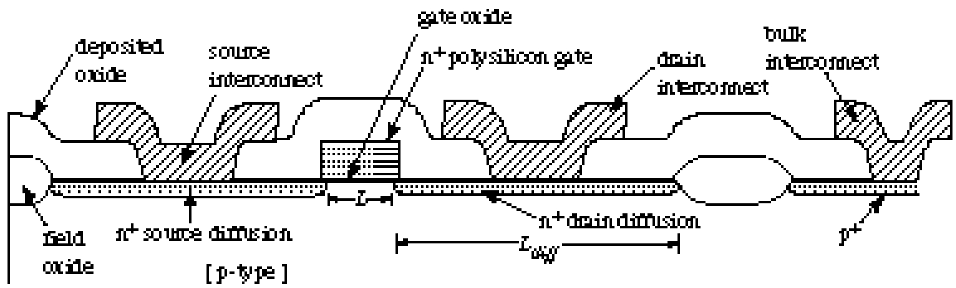


- **I-V Characteristics in Saturation Regime**

$$\mathbf{I_{Dsat}} = \frac{\mathbf{W}}{2\mathbf{L}}\mu_{\mathbf{n}}\mathbf{C_{ox}}\left(\mathbf{V_{GS}} - \mathbf{V_T}\right)^2$$

1. MOSFET: layout, cross-section, symbols





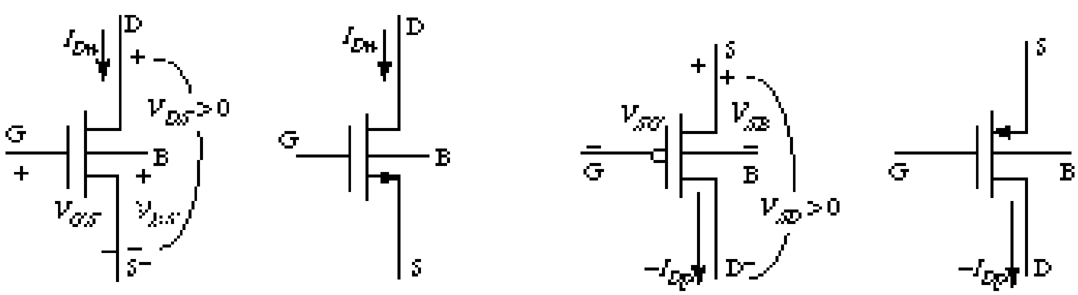
Key elements:

- Inversion layer under ***gate*** (depending on gate voltage)
- Heavily doped regions reach underneath gate ⇒
  - inversion layer to electrically connect ***source*** and ***drain***
- 4-terminal device:
  - ***body*** voltage important

Circuit symbols

Two complementary devices:

- n-channel device (n-MOSFET) on p-substrate
  - uses electron inversion layer
- p-channel device (p-MOSFET) on n-Si substrate
  - uses hole inversion layer



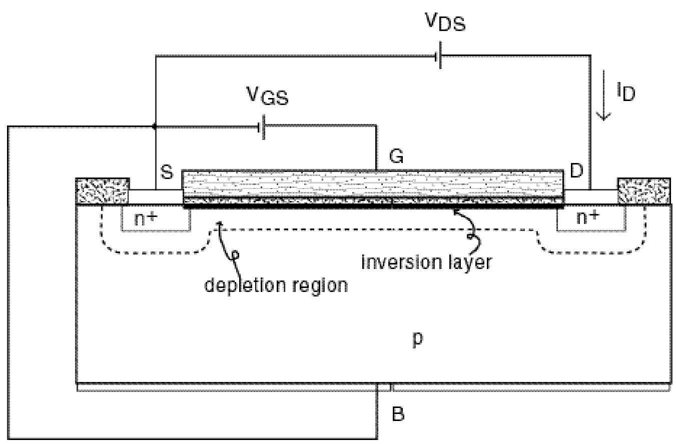
(a) n-channel MOSFET

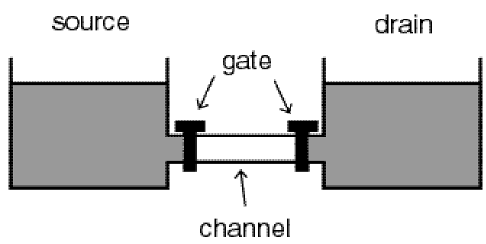
(b) p-channel MOSFET

2. Qualitative Operation

Water analogy of MOSFET

- ***Source***: water bath
- ***Drain***: water bath
- ***Gate***: faucets in source and drain baths
- ***Channel***: hose connecting source and drain baths



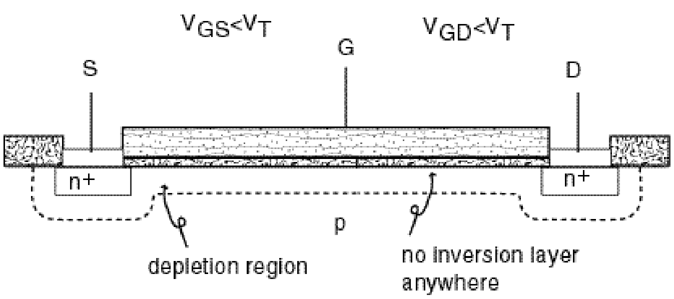


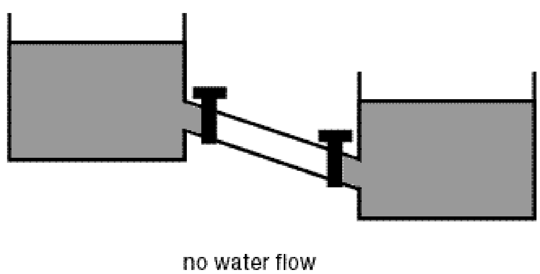
Want to understand operation of MOSFET as a function of ***gate-to-source voltage*** (**faucet status**) and ***drain-to-source voltage*** (**height difference between baths**).

Initially consider source tied up to body (substrate or back)

Three Regimes of Operation:
Cut-off Regime

- MOSFET:
  - $V_{GS} < V_T$, $V_{GD} < V_T$, with $V_{DS} > 0$
- Water analogy:
  - faucets closed;
  - no water can flow out of source regardless of relative height of source and drain.



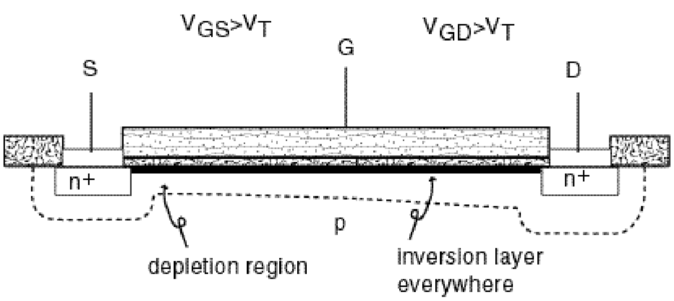


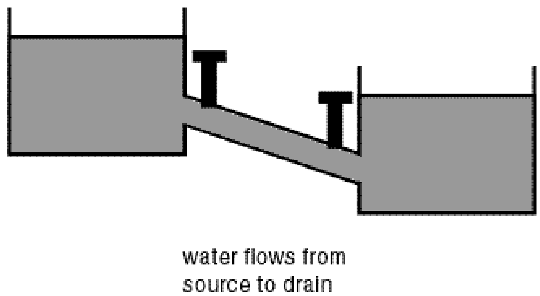
$I_D = 0$

Three Regimes of Operation:

Linear or Triode Regime

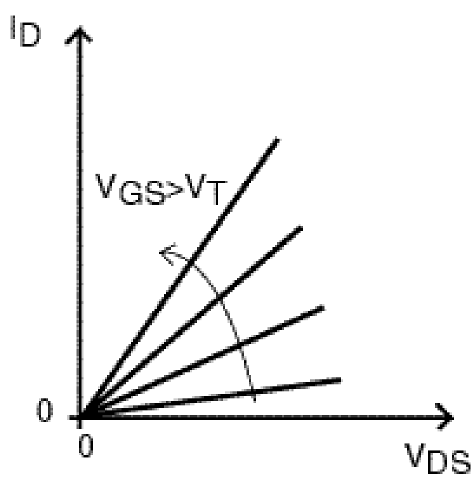
- MOSFET:
  - $V_{GS} > V_T$, $V_{GD} > V_T$, with $V_{DS} > 0$
- Water analogy:
  - faucets open;
  - water flows from source to drain.





Electrons drift from source to drain ⇒ **electrical current!**

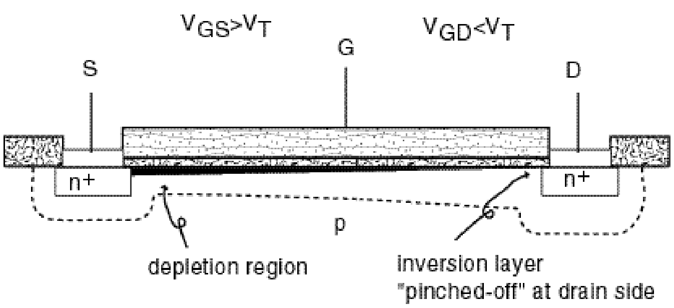
- $V_{GS} \uparrow \Rightarrow |Q_n,| \uparrow \Rightarrow I_D \uparrow$
- $V_{DS} \uparrow \Rightarrow E_y, \uparrow \Rightarrow I_D \uparrow$

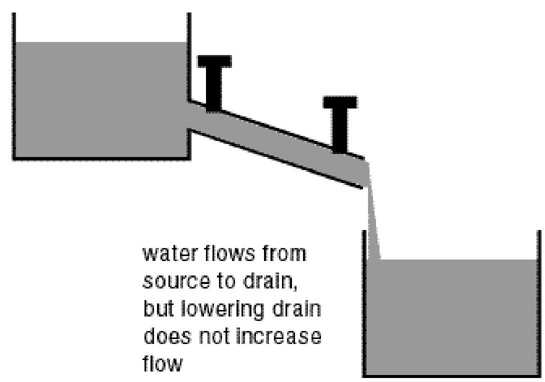


Three Regimes of Operation:

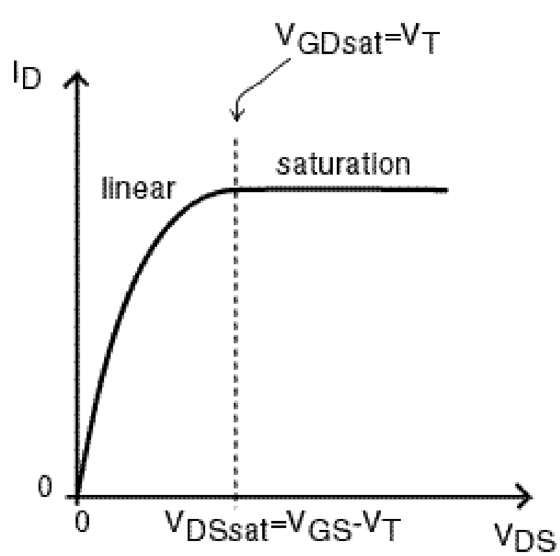
Saturation Regime

- MOSFET:
  - $V_{GS} > V_T$, $V_{GD} < V_T$ with $V_{DS} > 0$
- Water analogy:
  - faucets open;
  - water flows from source to drain but free-drop on drain side ⇒ total flow independent of relative bath height!



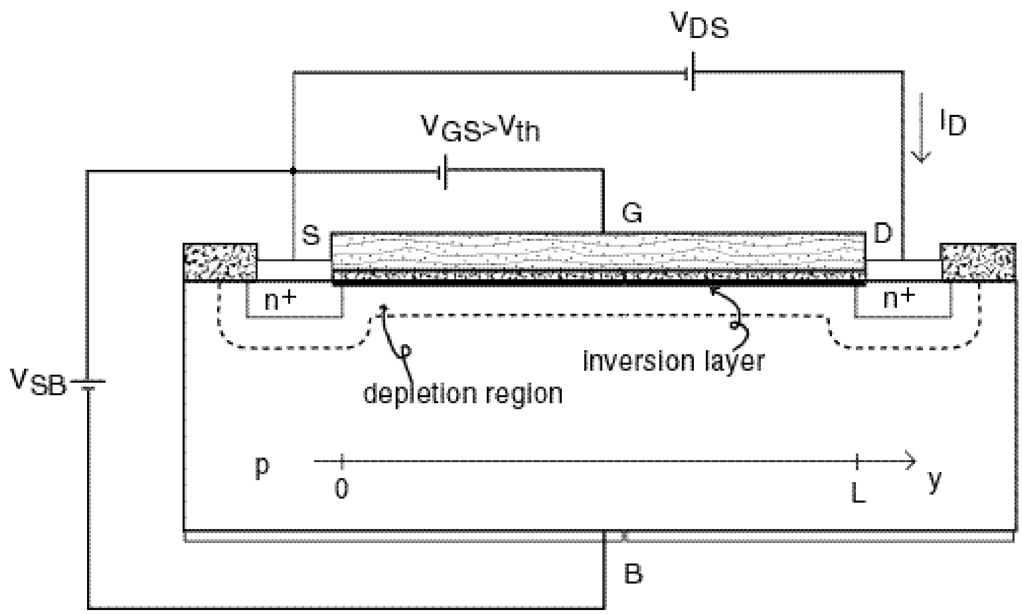


I_D is independent of V_{DS}: $I_D = I_{Dsat}$



3. I-V Characteristics (Assume V_{BS}=0)

Geometry of problem:



All voltages are referred to the ***Source***

General expression of channel current

Current can only flow in the y-direction:

$$\mathbf{J_y = Q_n(y) \bullet v_y(y)}$$

Total channel current:

$$\mathbf{I_y = W \bullet Q_n(y) \bullet v_y(y)}$$

Drain current is equal to minus channel current:

$$\mathbf{I_D = -W \bullet Q_n(y) \bullet v_y(y)}$$

I-V Characteristics (Contd.)

$$\mathbf{I_D = -W \bullet Q_n(y) \bullet v_y(y)}$$

Re-write equation in terms of voltage at location y, V(y):

- If electric field is not too high:

$$\mathbf{v_y(y) = -\mu_n \bullet E_y(y) = \mu_n \bullet \frac{dV}{dy}}$$

- For $Q_n(y)$, use charge-control relation at location y:

$$\mathbf{Q_n(y) = -C_{ox}\left[V_{GS} - V(y) - V_T\right]}$$

for $V_{GS} - V(y) \geq V_T$.

Note that we assumed that V_T is independent of y.
See discussion on body effect in Section 4.4 of text.

All together the drain current is given by:

$$\mathbf{I_D = W \bullet \mu_n C_{ox}\left[V_{GS} - V(y) - V_T\right] \bullet \frac{dV(y)}{dy}}$$

Simple linear first order differential equation with one un-known, the channel voltage V(y).

I-V Characteristics (Contd..)

Solve by separating variables:

$$\mathbf{I_D\,dy = W \bullet \mu_n C_{ox}\left[V_{GS} - V(y) - V_T\right] \bullet dV}$$

Integrate along the channel in the linear regime subject the boundary conditions :

- **Source**: y=0, V(0)=0
- **Drain**: y=L, V(L)=V_{DS} (linear regime)

Then:

$$\mathbf{I_D \int_0^L dy = W \bullet \mu_n C_{ox} \int_0^{V_{DS}} \left[V_{GS} - V(y) - V_T\right] \bullet dV}$$

Resulting in:

$$\mathbf{I_D\left[y\right]_0^L = I_D L = W \bullet \mu_n C_{ox}\left[\left(V_{GS} - \frac{V}{2} - V_T\right)V\right]_0^{V_{DS}}}$$

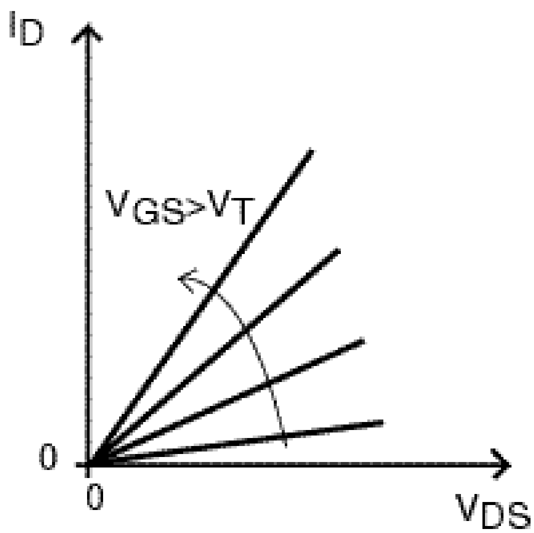
$$\mathbf{I_D = \frac{W}{L} \bullet \mu_n C_{ox}\left[V_{GS} - \frac{V_{DS}}{2} - V_T\right] \bullet V_{DS}}$$

I-V Characteristics (Contd…)

$$\mathbf{I_D = \frac{W}{L} \bullet \mu_n C_{ox} \left[V_{GS} - \frac{V_{DS}}{2} - V_T \right] \bullet V_{DS}}$$

Key dependencies:

- $V_{DS}\uparrow \rightarrow I_D\uparrow$ (higher lateral electric field)
- $V_{GS}\uparrow \rightarrow I_D\uparrow$ (higher electron concentration)

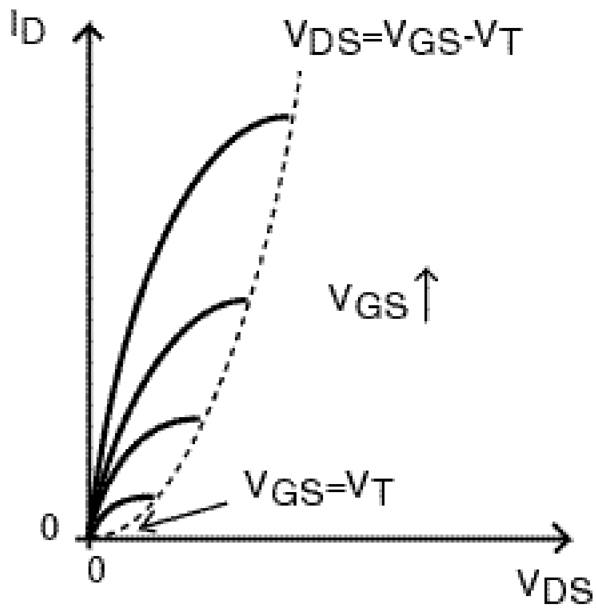


This is the ***linear*** or ***triode*** regime:

I-V Characteristics (Contd….)
Two important observations

1. Equation only valid if $V_{GS} - V(y) \geq V_T$ at ***every* y**. Worst point is y=L, where $V(y) = V_{DS}$, hence, equation is valid if

$$\mathbf{V_{DS} \leq V_{GS} - V_T}$$



I-V Characteristics (Contd…..)

Two important observations

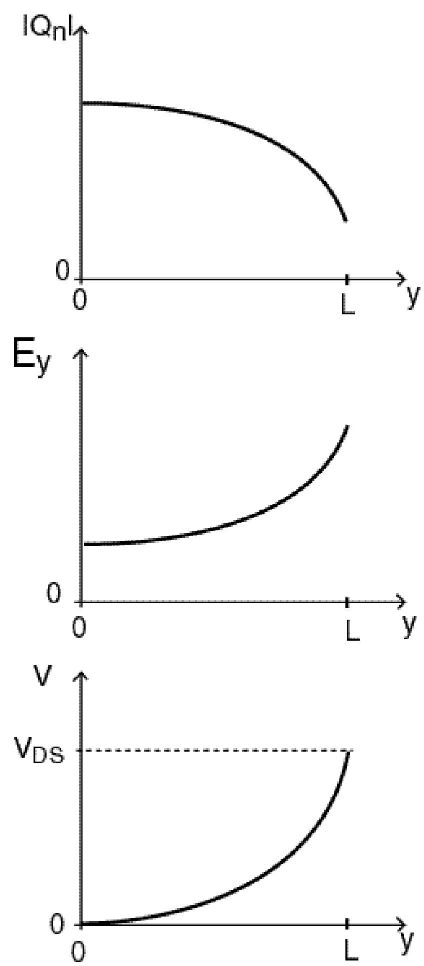
2. As V_{DS} approaches $V_{GS} - V_T$, the rate of increase of I_D decreases.

Reason:

As y increases down the channel, $V(y) \uparrow$, $|Q_n(y)| \downarrow$, and $E_y(y) \uparrow$ (***fewer carriers moving faster***)

$\Rightarrow$ inversion layer thins down from source to drain

$\Rightarrow I_D$ grows more slowly.



I-V Characteristics (Contd……)

Drain Current Saturation

As V_{DS} approaches

$$\mathbf{V_{DSsat} = V_{GS} - V_T}$$

increase in E_y compensated by decrease in $|Q_n|$
$\Rightarrow I_D$ saturates.

Value of drain saturation current:

$$\mathbf{I_{Dsat} = I_{Dlin}(V_{DS} = V_{DSsat} = V_{GS} - V_T)}$$

Then

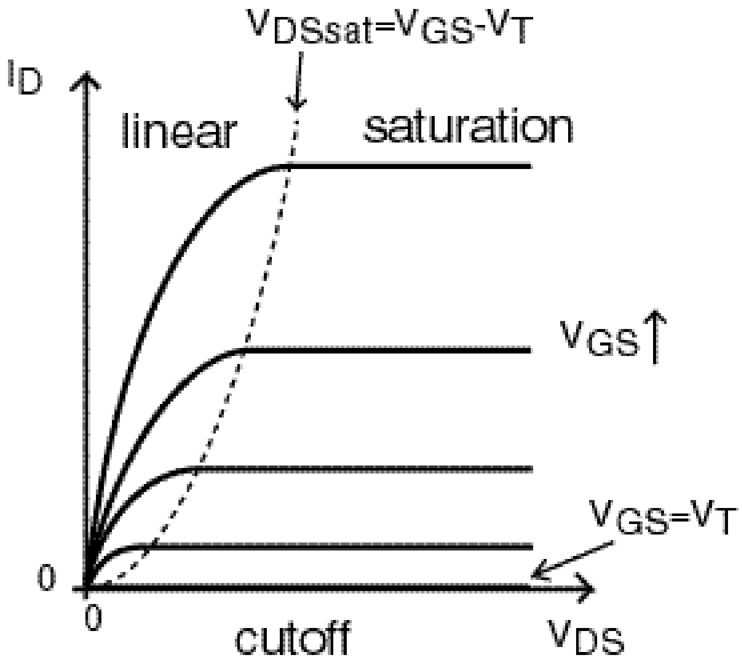
$$\mathbf{I_{Dsat} = \left[\frac{W}{L} \bullet \mu_n C_{ox}\left(V_{GS} - \frac{V_{DS}}{2} - V_T\right) \bullet V_{DS}\right]_{V_{DS} = V_{GS} - V_T}}$$

$$\mathbf{I_{Dsat} = \frac{1}{2}\frac{W}{L}\mu_n C_{ox}\left[V_{GS} - V_T\right]^2}$$

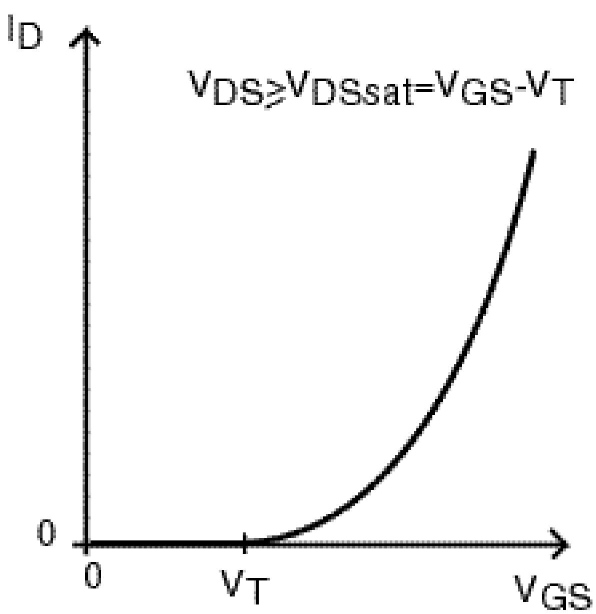
Will talk more about ***saturation regime*** next time.

I-V Characteristics (Contd…….)

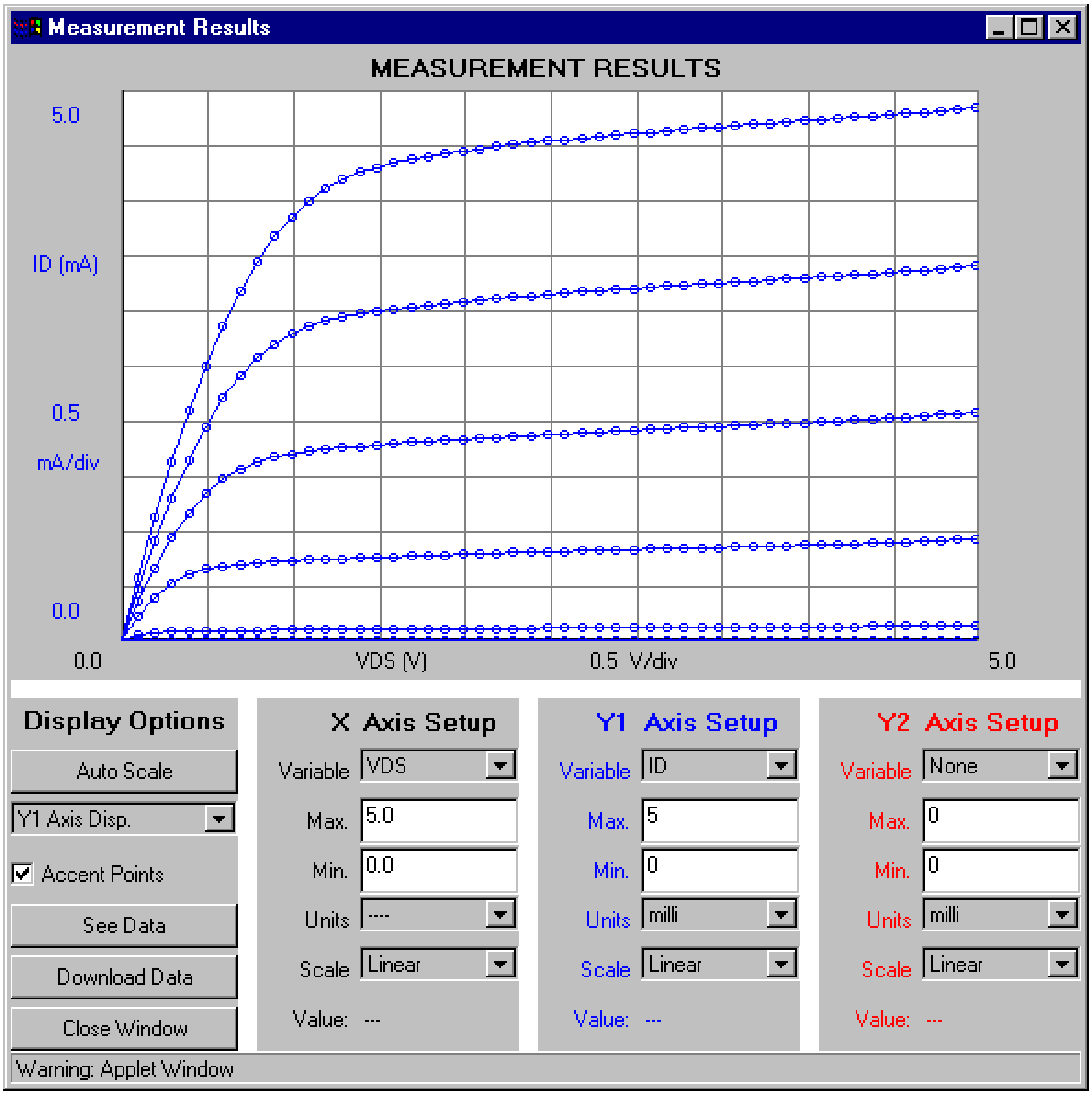
Output Characteristics



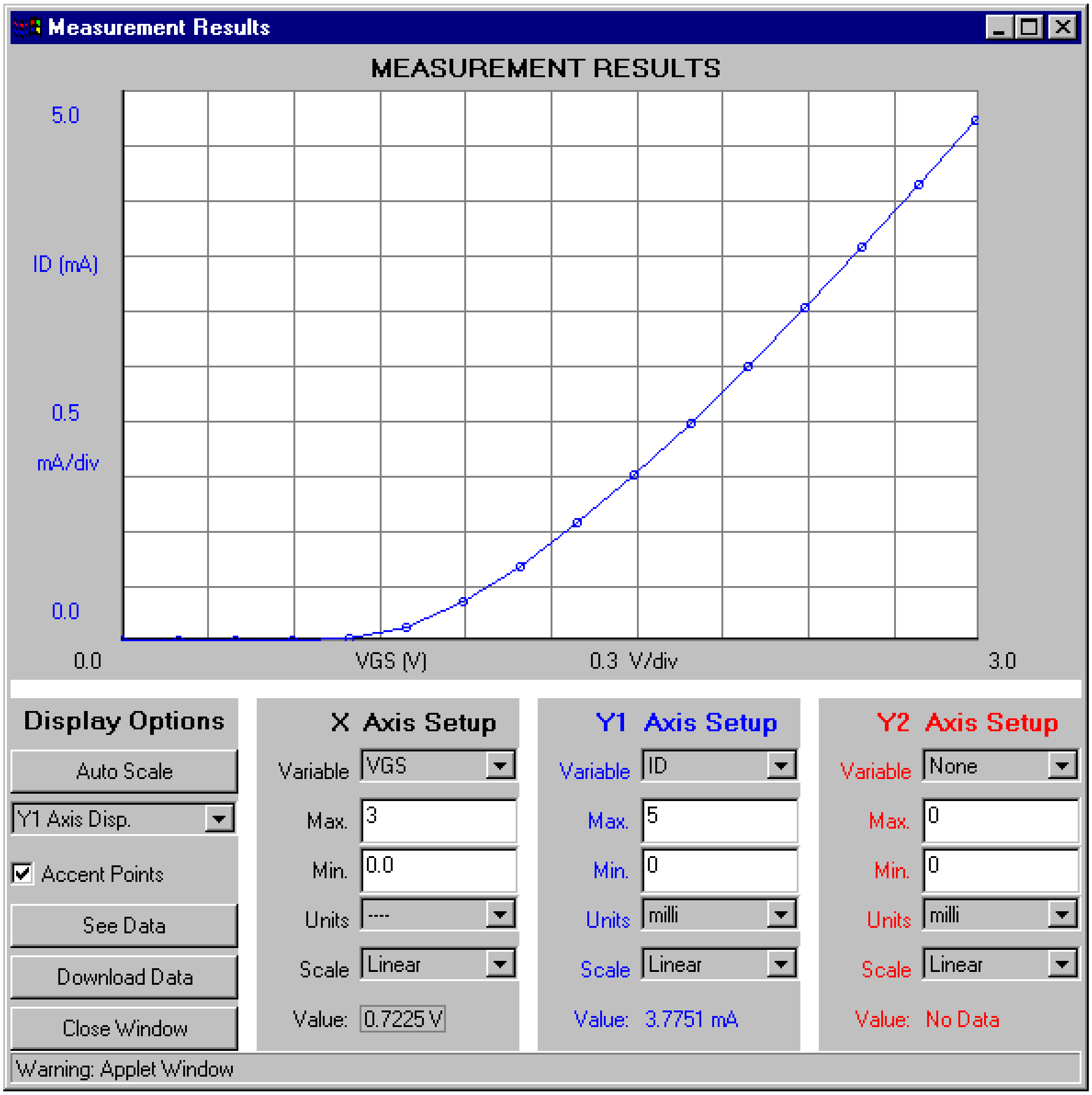
Transfer characteristics:



Output Characteristics



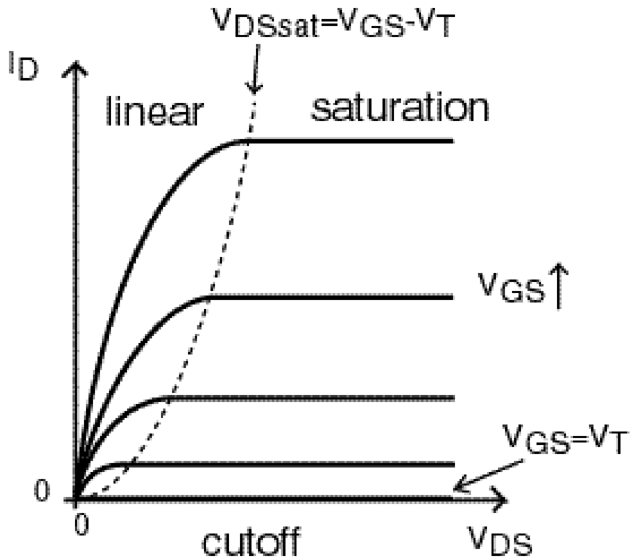
Transfer Characteristics



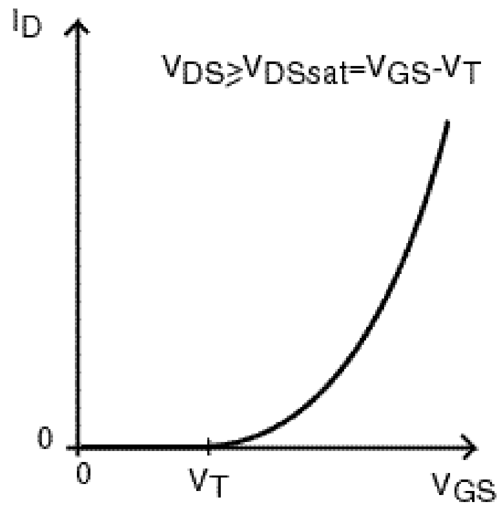
What did we learn today?

Summary of Key Concepts

- **MOSFET Output Characteristics**



- **MOSFET Transfer Characteristics in Saturation**



- **I-V Characteristics in Saturation Regime**

$$\mathbf{I_{Dsat}} = \frac{\mathbf{W}}{2\mathbf{L}}\mu_{\mathbf{n}}\mathbf{C_{ox}}\left(\mathbf{V_{GS}} - \mathbf{V_T}\right)^2$$