Lecture 8

MOSFET(I)

MOSFET I-V CHARACTERISTICS

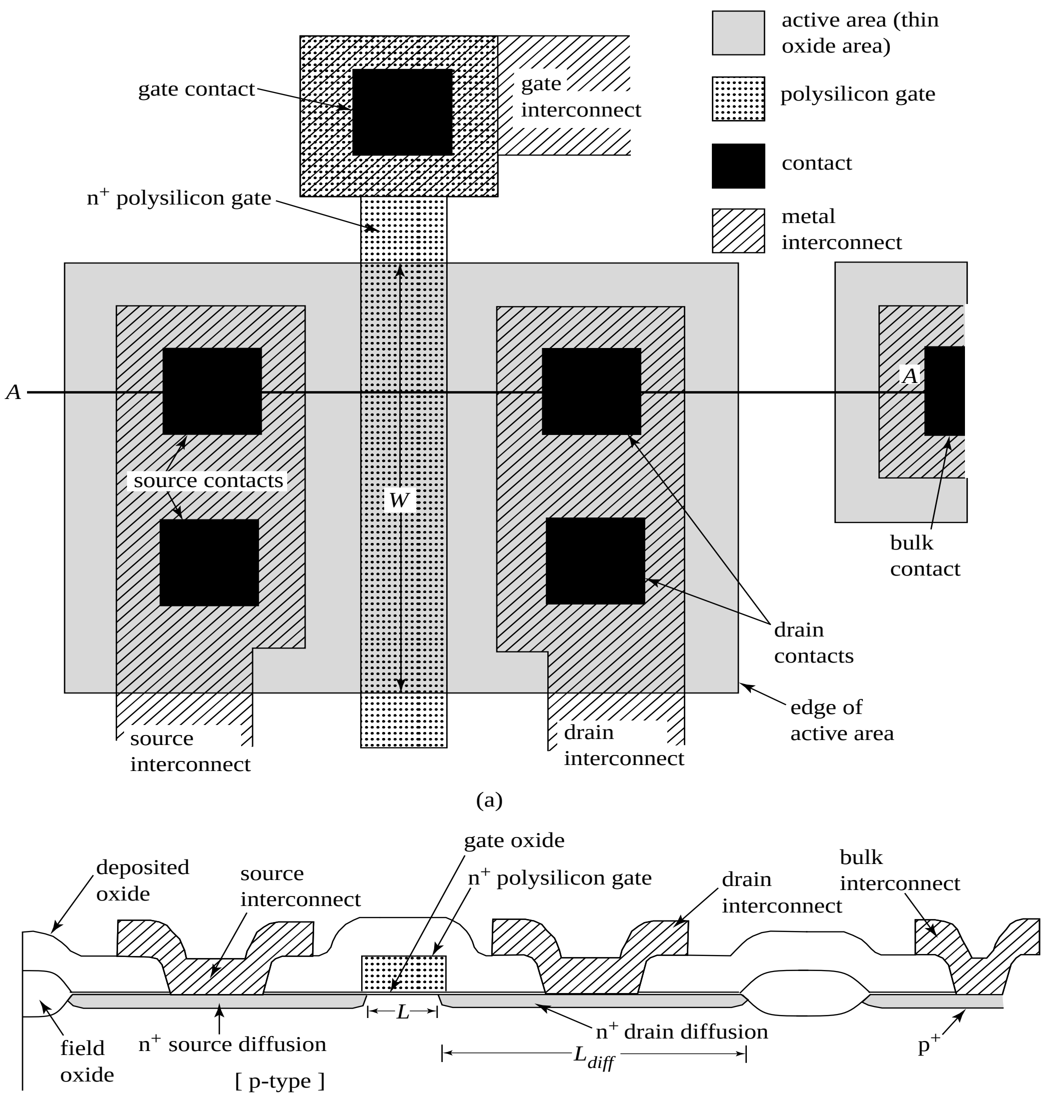
Outline

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, March 14, 7:30-9:30PM, Walker Memorial; covers Lectures #1-9; open book; must have calculator

1. MOSFET: layout, cross-section, symbols



(b)

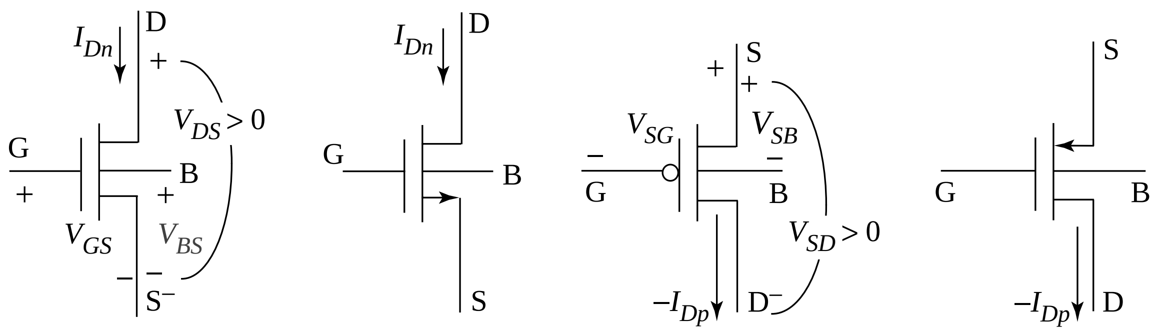
Key elements:

- 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

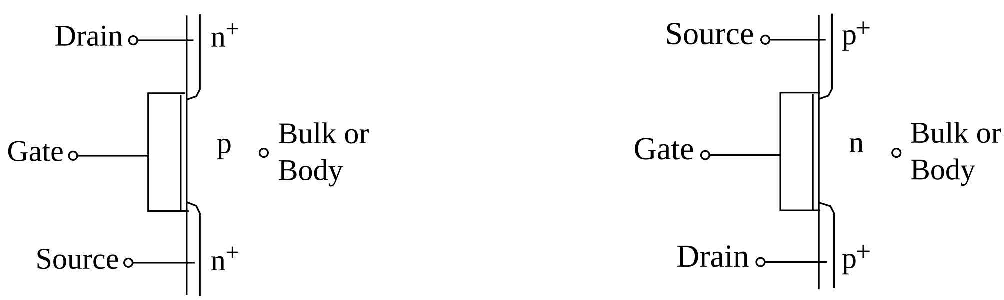
Two complementary devices:

- 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



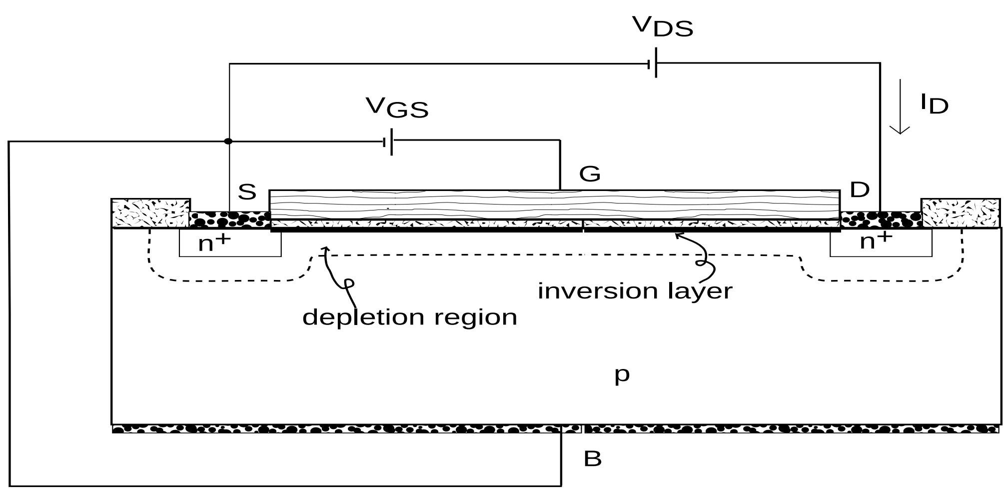
(a) n-channel MOSFET

(b) p-channel MOSFET



2. Qualitative Operation

- ***Drain Current (I_D)***: proportional to inversion charge and the velocity that the charge travels from source to drain
- ***Velocity***: proportional to electric field from drain to source
- ***Gate-Source Voltage (V_{GS})***: controls amount of inversion charge that carries the current
- ***Drain-Source Voltage (V_{DS})***: controls the electric field that drifts the inversion charge from the source to drain

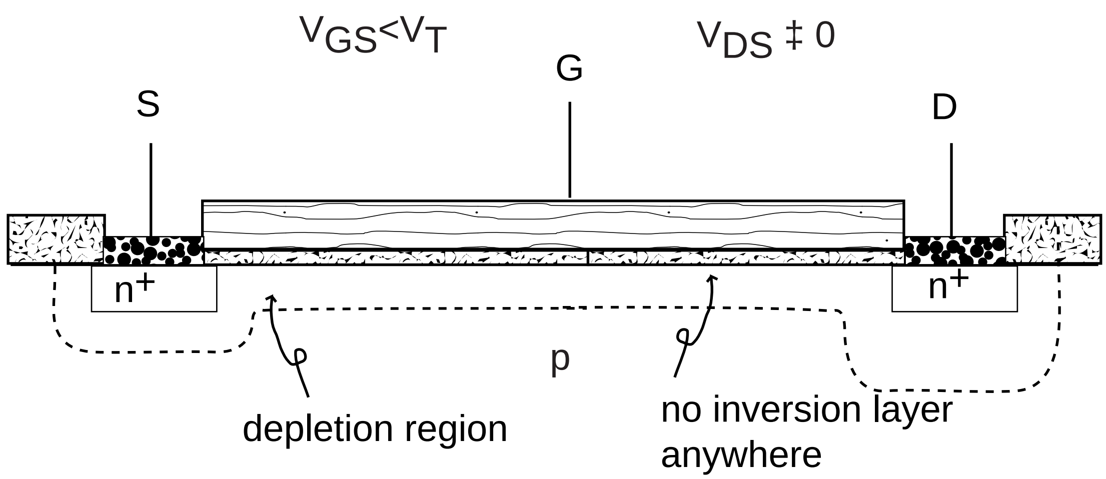


Want to understand the relationship between the ***drain current*** in the MOSFET as a function of ***gate-to-source voltage*** and ***drain-to-source voltage***.

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

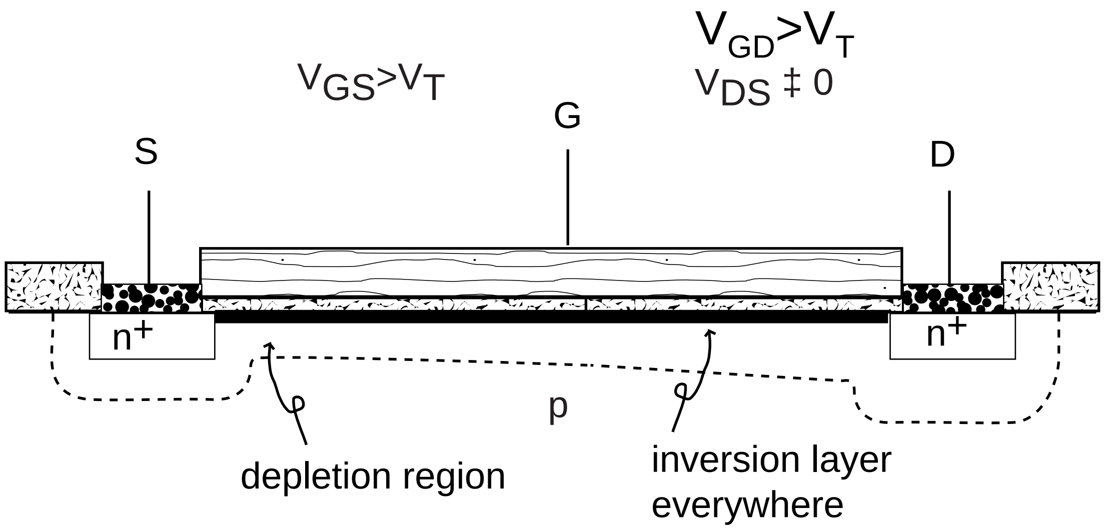
Three Regimes of Operation:
Cut-off Regime

- MOSFET:
  - $V_{GS} < V_T$, with $V_{DS} \geq 0$
- Inversion Charge = 0
- V_{DS} drops across drain depletion region
- $I_D = 0$



Three Regimes of Operation:

Linear or Triode Regime

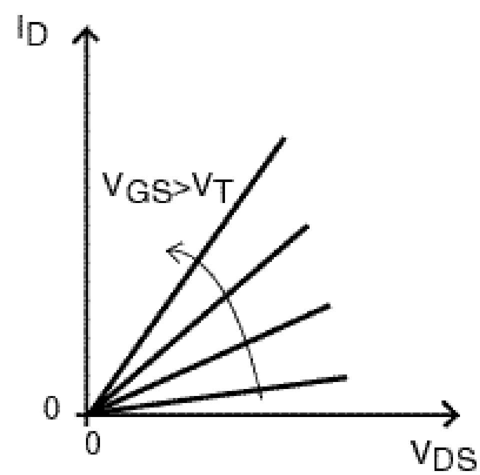


$$V_{GD} = V_{GS} - V_{DS}$$

Electrons drift from source to drain $\Rightarrow$ **electrical current!**

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

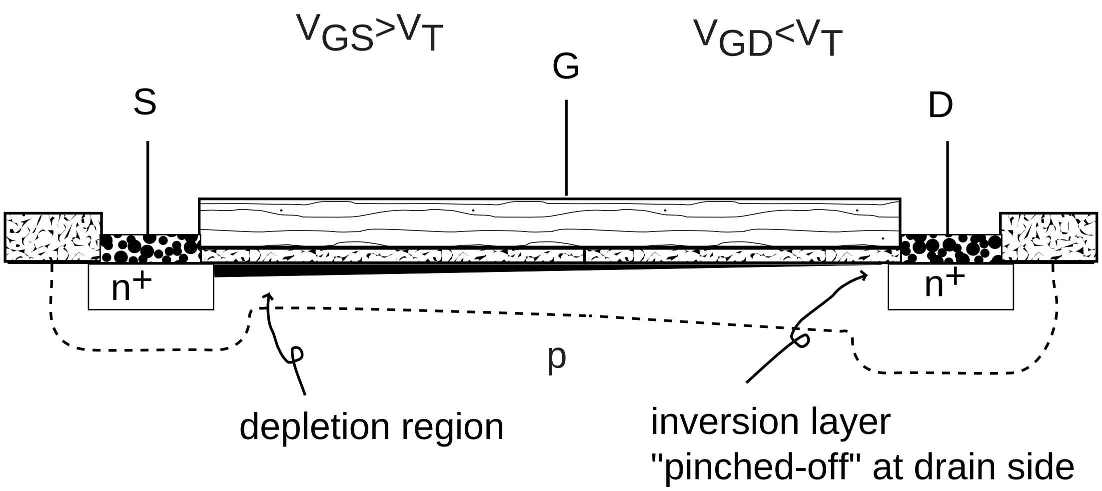
$V_{DS} << V_{GS} - V_T$



Three Regimes of Operation:

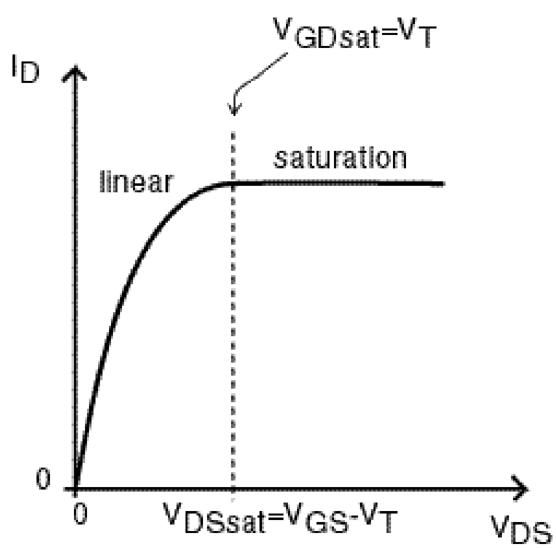
Saturation Regime $V_{DS} > V_{GS} - V_T$

- $V_{GS} > V_T$, $V_{GD} < V_T$ ---> $V_{DS} > V_{GS} - V_T$



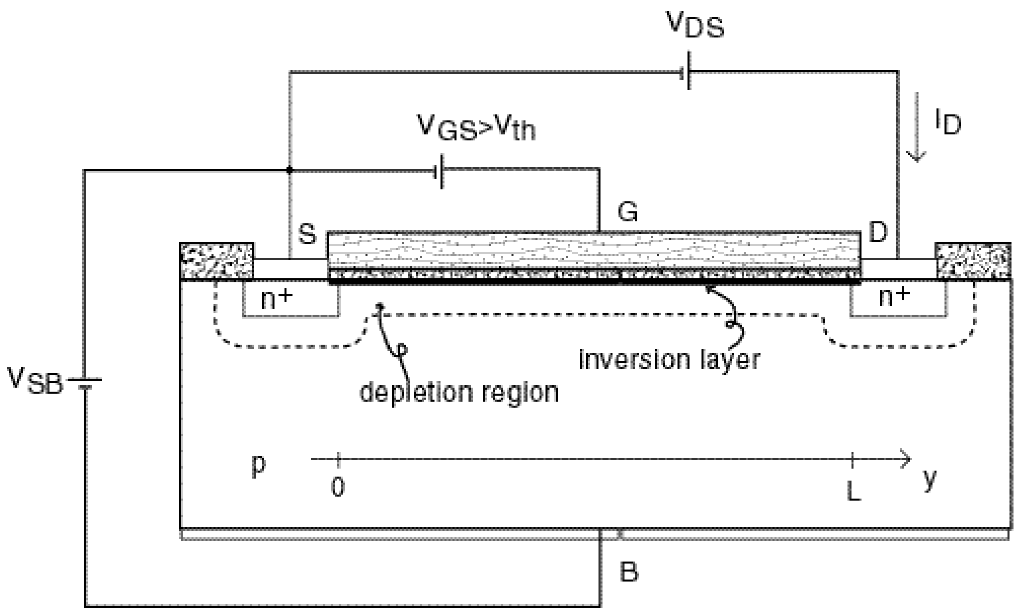
I_D is independent of V_{DS}: $I_D = I_{dsat}$

Electric field in channel cannot increase with V_{DS}



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

Geometry of problem:



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

General expression of channel current

Current can only flow in the y-direction:

Total channel current:

$$I_y = W \bullet Q_N(y) \bullet v_y(y)$$

Drain current is equal to minus channel current:

$$I_D = -W \bullet Q_N(y) \bullet v_y(y)$$

I-V Characteristics (Contd.)

$$I_D = -W \bullet Q_N(y) \bullet v_y(y)$$

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

- If electric field is not too high:

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

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

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

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

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

All together the drain current is given by:

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

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

I-V Characteristics (Contd..)

Solve by separating variables:

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

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:

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

Resulting in:

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

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

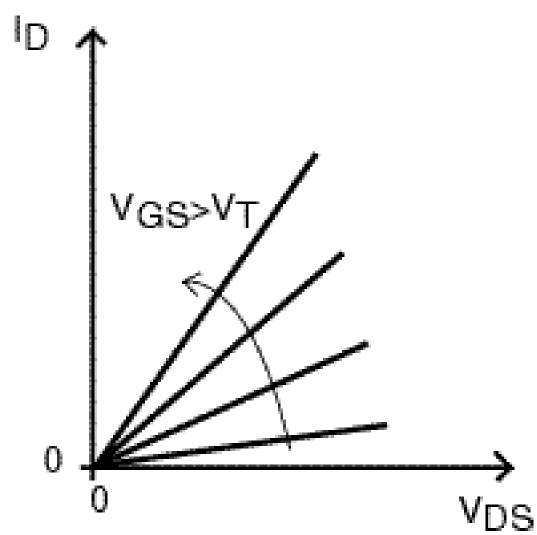
I-V Characteristics (Contd…)

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

$$\text{for} \quad V_{DS} < V_{GS} - V_T$$

Key dependencies:

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



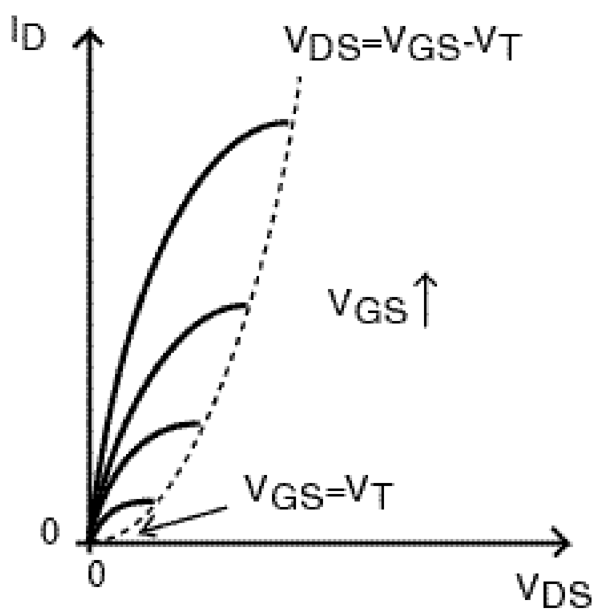
This is the ***linear*** or ***triode*** regime:
It is linear if $V_{DS} << V_{GS} - V_T$

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

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



I-V Characteristics (Contd…..)

Two important observations

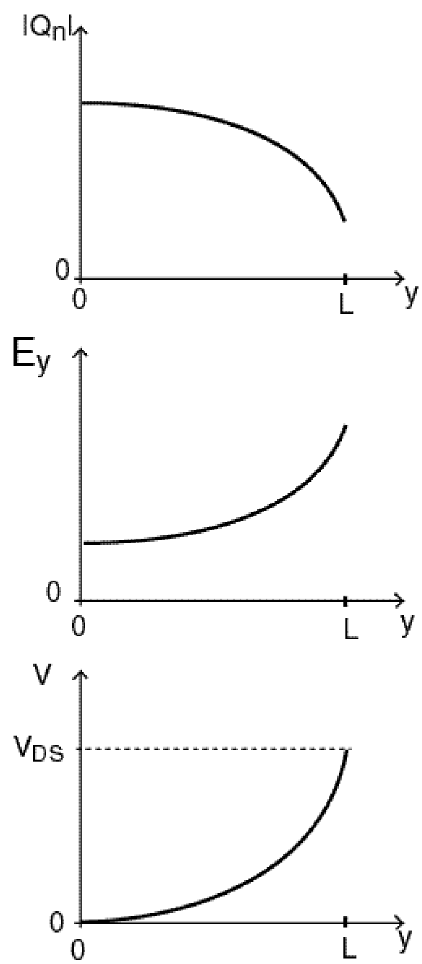
2. As V_{DS} approaches $V_{GS} - V_T$, the rate of increase of I_D decreases.

Reason:

As y increases down the channel, V(y) ↑, $|Q_N(y)|$ ↓, and $E_y(y)$ ↑ (***fewer carriers moving faster***)

⇒ inversion layer thins down from source to drain

⇒ I_D grows more slowly.



I-V Characteristics (Contd……)

Drain Current Saturation

As V_{DS} approaches

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

increase in E_y compensated by decrease in $|Q_N|$
$\Rightarrow$ I_D saturates when $|Q_N|$ equals 0 at drain end.

Value of drain saturation current:

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

Then

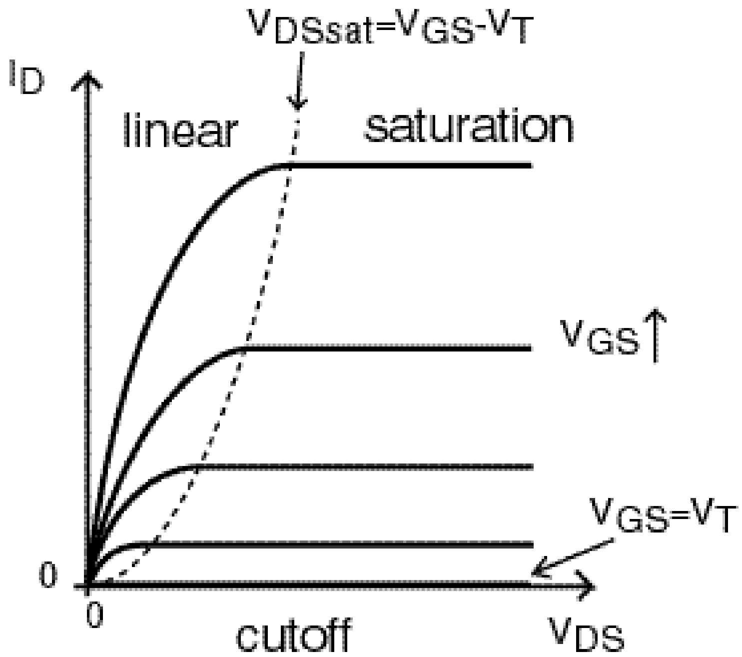
$$I_{Dsat} = \left[\frac{W}{L} \bullet \mu_n C_{ox} \left(V_{GS} - \frac{V_{DS}}{2} - V_T \right) \bullet V_{DS} \right]_{V_{DS}=V_{GS}-V_T}$$

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

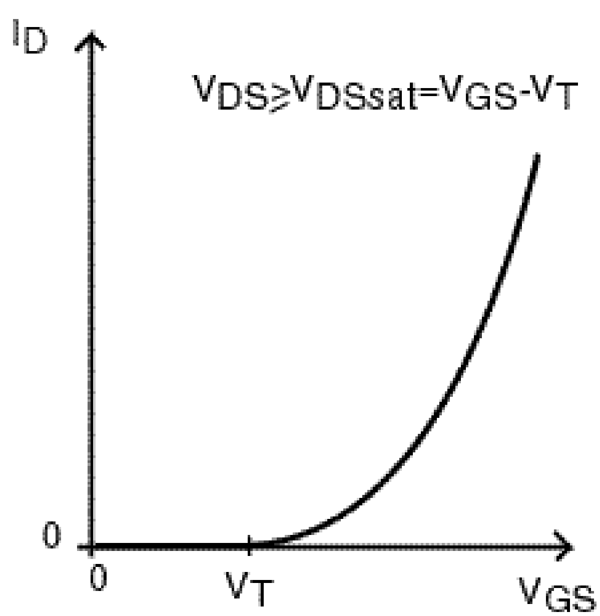
Will talk more about ***saturation regime*** next time.

I-V Characteristics (Contd…….)

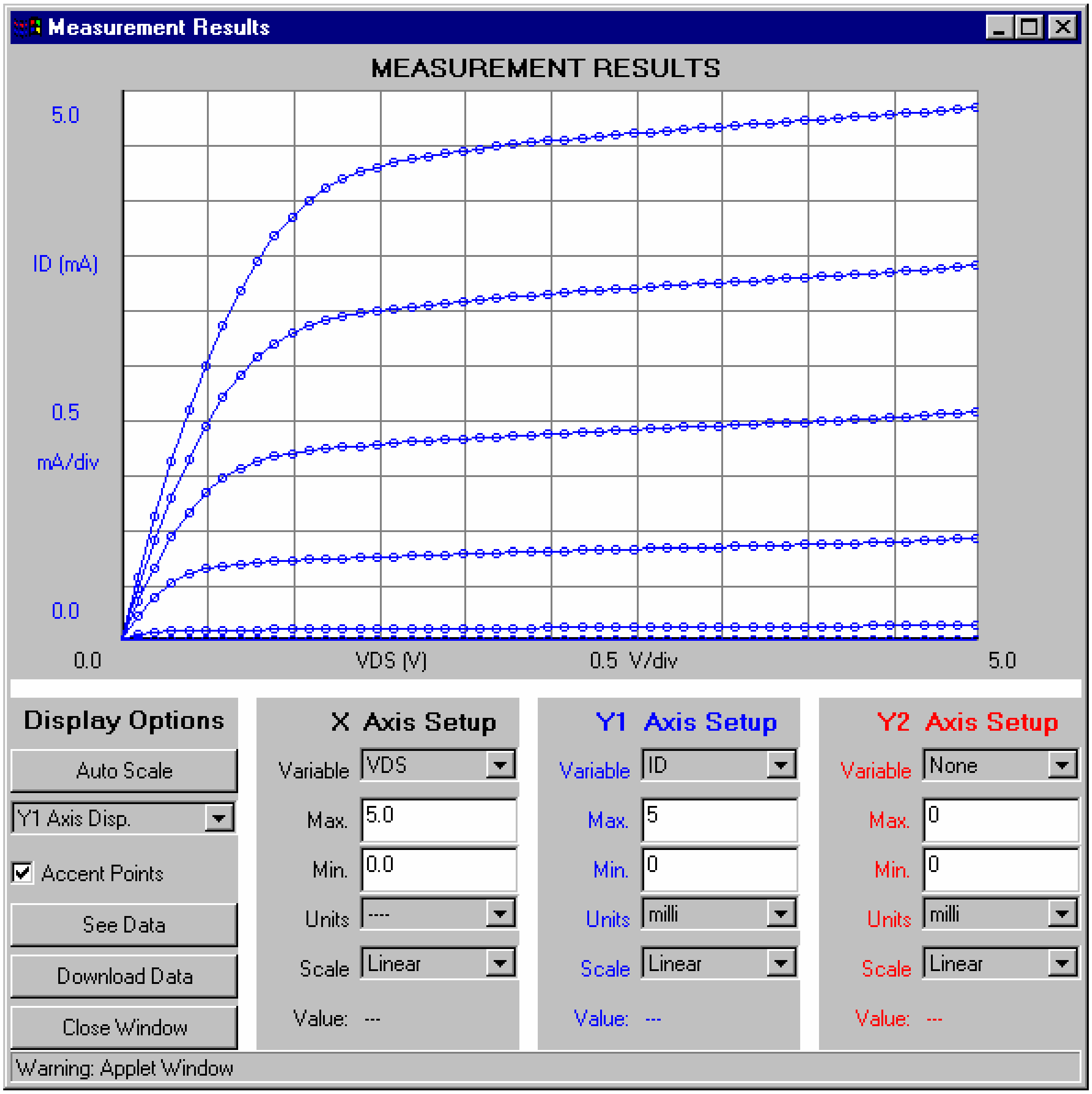
Output Characteristics



Transfer characteristics:

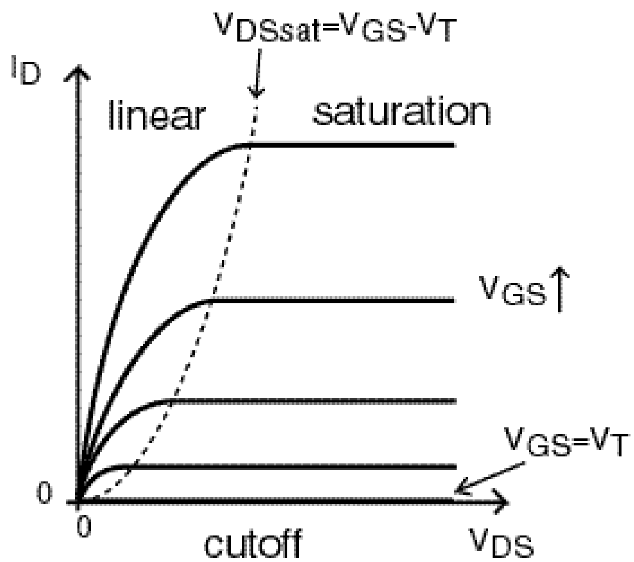


Output Characteristics



Summary of Key Concepts

- **MOSFET Output Characteristics**



I-V Characteristics in Cutoff Regime

$V_{GS} < V_T$ $\;I_D = 0$

I-V Characteristics in Linear Regime

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

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

I-V Characteristics in Saturation Regime

$V_{DS} \geq V_{GS} - V_T$

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