Lecture 9

MOSFET(II)

MOSFET I-V CHARACTERISTICS(contd.)

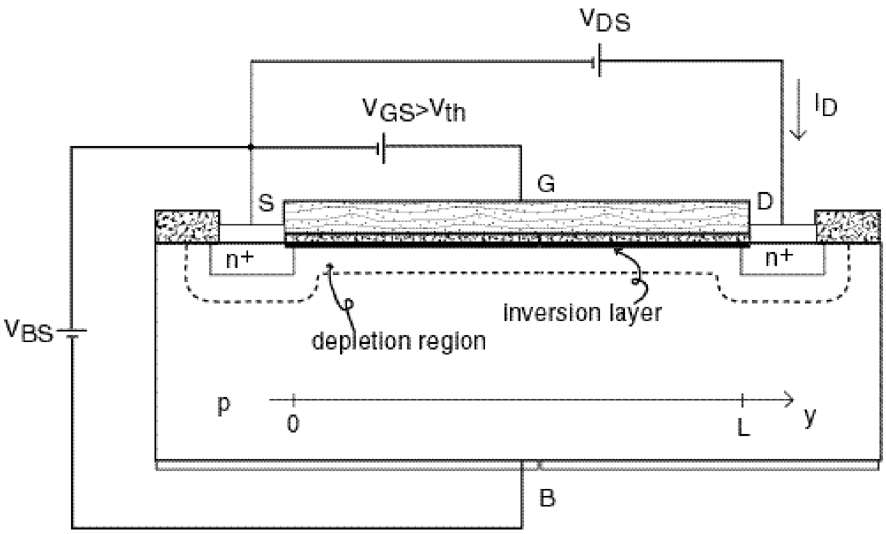
Outline

1. The saturation region
2. Backgate characteristics

Reading Assignment:
Howe and Sodini, Chapter 4, Section 4.4

1. The Saturation Region

Geometry of problem



Regions of operation:

- ***Cut-off:*** $V_{GS} < V_T$
  - No inversion layer anywhere underneath the gate

$$\mathbf{I_D} = 0$$

- ***Linear:*** $V_{GS} > V_T$ and $0 < V_{DS} < V_{GS} - V_T$:
  - Inversion layer everywhere under the gate

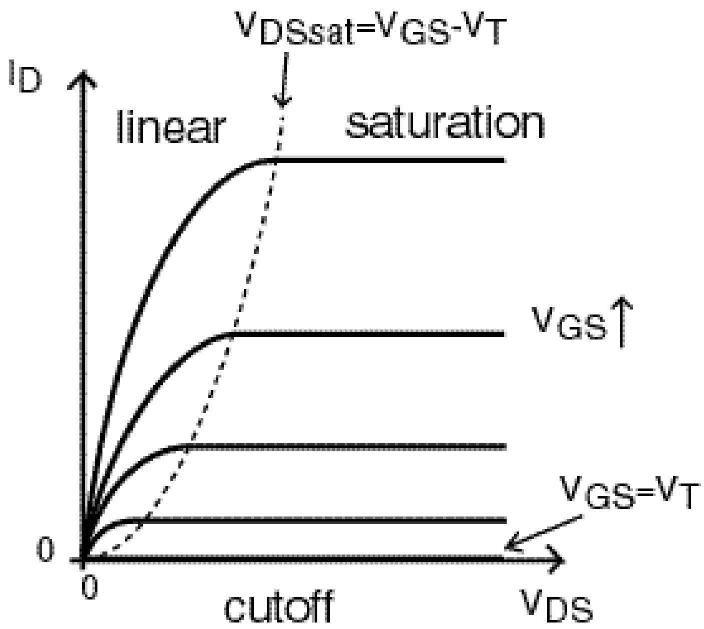
$$I_D = \frac{W}{L} \bullet \mu_n C_{ox} \left[V_{GS} - \frac{V_{DS}}{2} - V_T \right] \bullet V_{DS}$$

The Saturation Region (contd.)

- ***Saturation:*** $V_{GS} > V_T$, and $V_{DS} > V_{GS} - V_T$:
  - Inversion layer "pinched-off" at drain end of channel

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

Output characteristics:



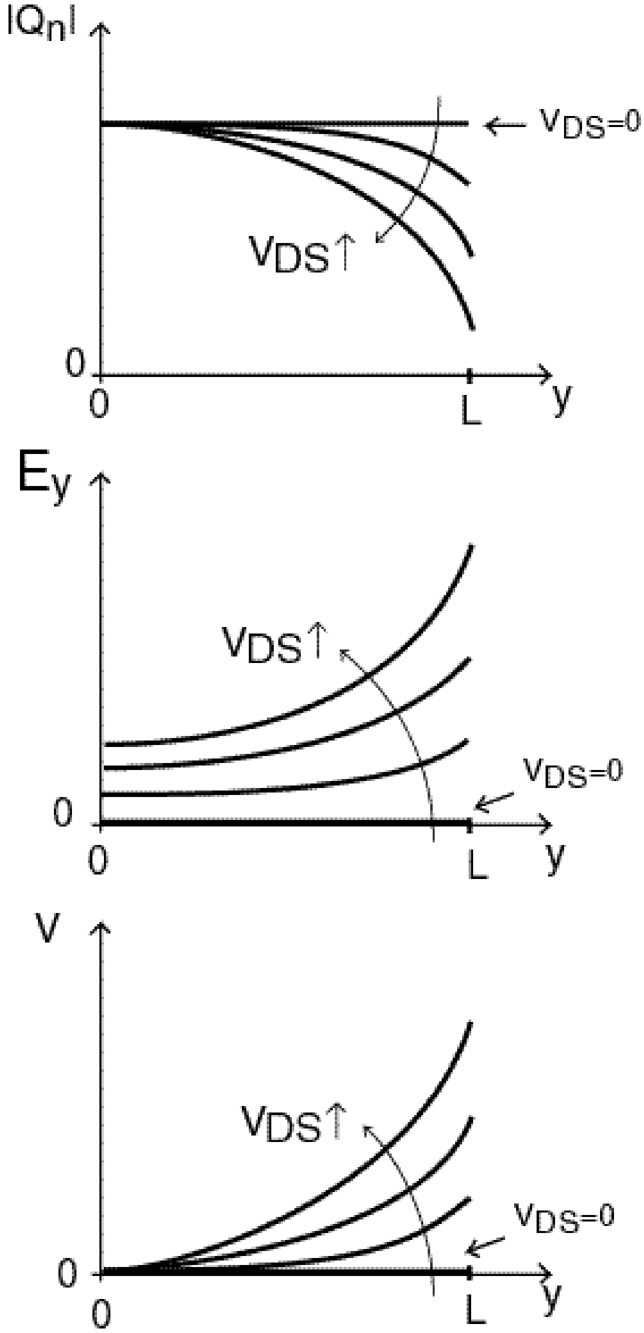
- **Last lecture**: To derive the above equations for I_D, we used for $Q_N(y)$, the charge-control relation at location y:

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

for $V_{GS} - V(y) \geq V_T$. **Note that we assumed that (a) $V_{BS} = 0 \Rightarrow V_{GS} = V_{GB}$, and (b) V_T is independent of y.** ***See discussion on body effect in Section 4.4 of text.***

The Saturation Region (contd..)

Review of Q_N, E_y, and V in linear regime as V_{DS} increases:



Ohmic drop along channel de-biases inversion layer
⇒ **current saturation**.

The Saturation Region (contd.)

What happens when $V_{DS} = V_{GS} - V_T$?

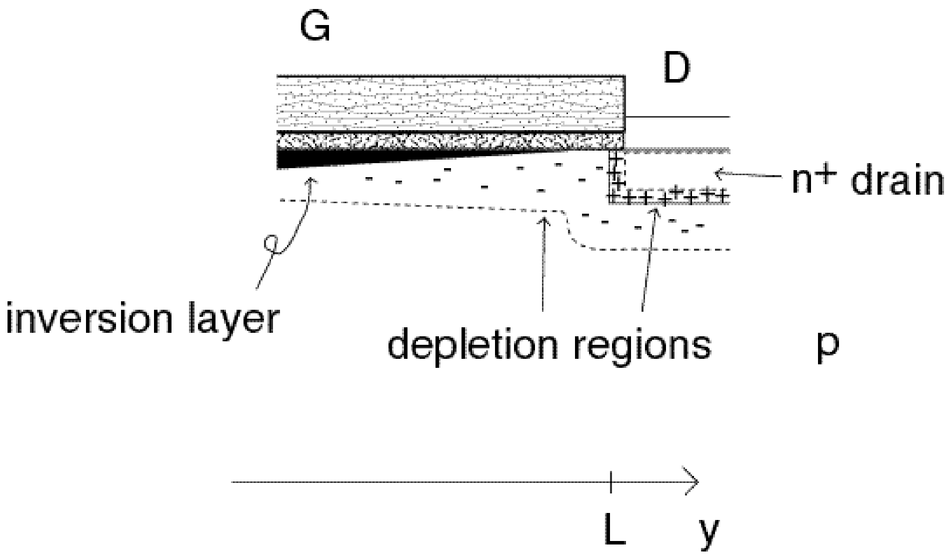
Charge control relation at drain:

$$Q_N(L) = -C_{ox}\left[V_{GS} - V_{DS} - V_T\right] = 0$$

No inversion layer at the drain end of channel ???!!!
⇒ ***Pinch-off.***

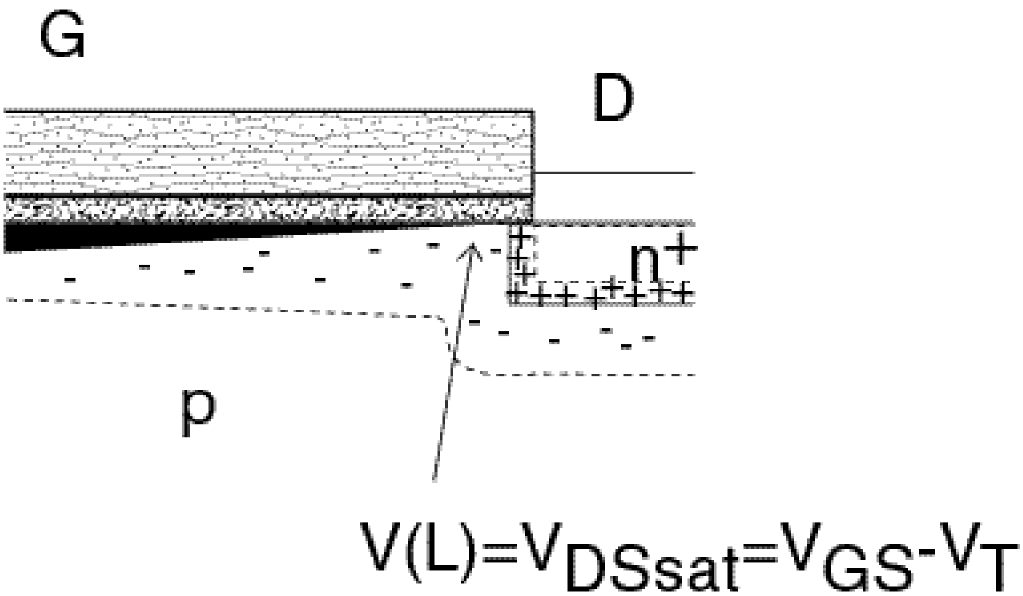
At pinch-off:

- Charge control equation inaccurate around V_T;
- Electron concentration small but not zero;
- Electrons move fast because electric field is very high;
- Dominant electrostatic feature
  - Acceptor charge
- There is no barrier to electron flow (**on the contrary!**).



The Saturation Region (contd…)

Voltage at pinch-off point (V=0 at source):



Drain current at pinch-off:

lateral electric field $\propto V_{DSsat} = V_{GS} - V_T$
electron concentration $\propto V_{GS} - V_T$

$$\Rightarrow \quad I_{Dsat} \propto \left[V_{GS} - V_T\right]^2$$

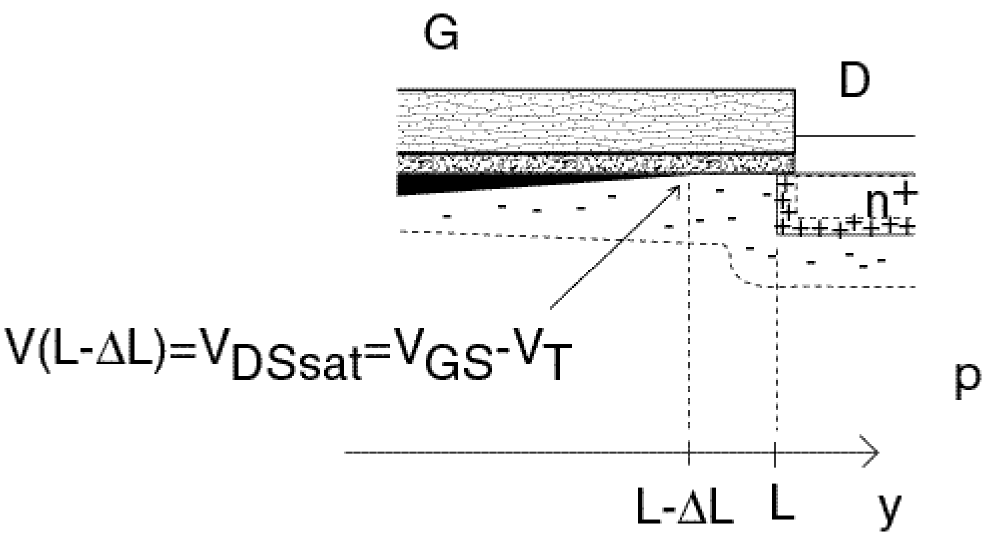
Also, L↓ $\Rightarrow$ E_y ↑:

$$I_{Dsat} \propto \frac{1}{L}$$

The Saturation Region (contd.)

What happens if $V_{DS} > V_{GS} - V_T$?

Depletion region separating pinch-off and drain widens



To first order, I_D does not increase past pinch-off:

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

To second order, electrical channel length affected:
$L\downarrow \Rightarrow I_D \uparrow$:

$$\boldsymbol{I_D \propto \frac{1}{L - \Delta L} \approx \frac{1}{L}\left[1 + \frac{\Delta L}{L}\right]}$$

The Saturation Region (contd.)

Experimental finding:

$$\frac{\Delta L}{L} = \lambda(V_{DS} - V_{DSsat})$$

with

$$\lambda \propto \frac{1}{L}$$

Typically,

$$\lambda = \frac{0.1\ \mu m \bullet V^{-1}}{L}$$

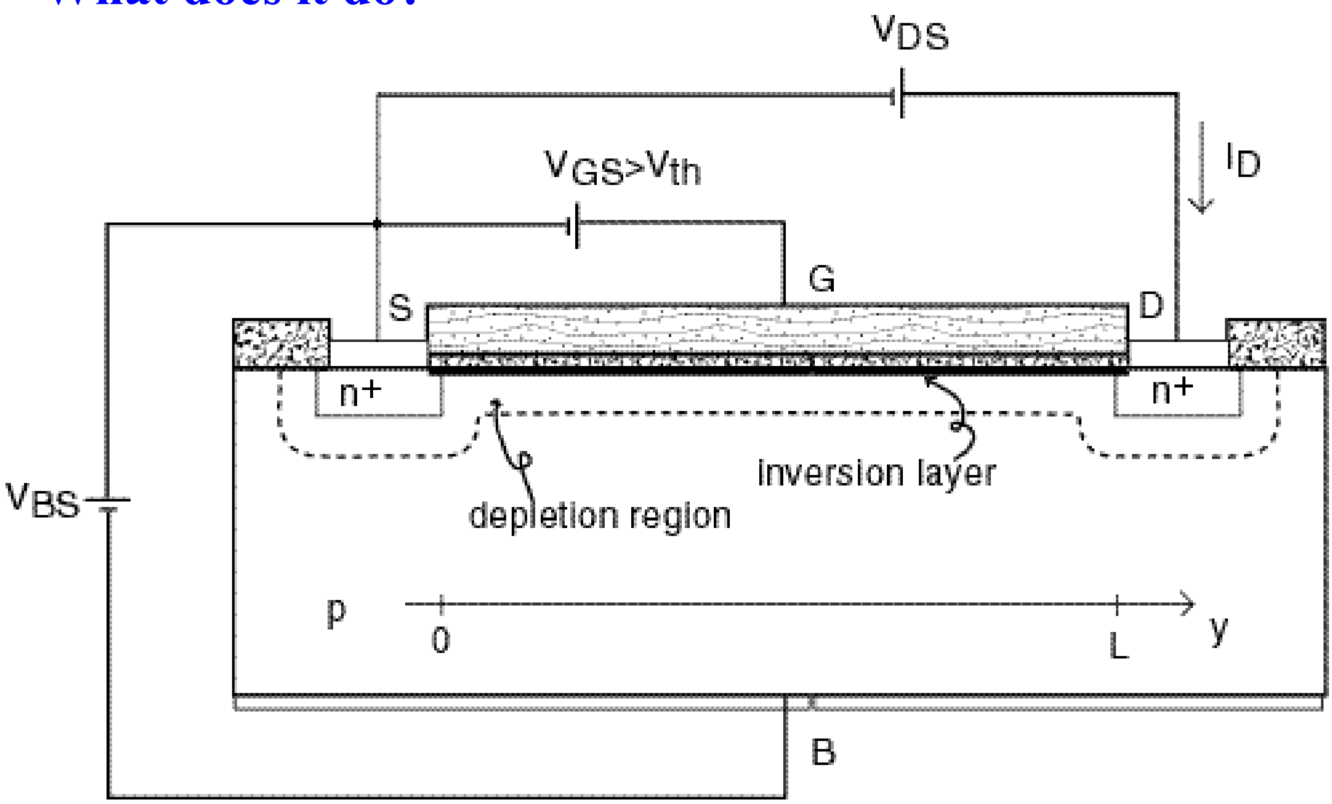
For L = 1µm, increase of V_{DS} of 1V past V_{DSsat} results in increase in I_D of 10%.

Improved but approximate model for the drain current in saturation:

$$I_D \approx \frac{W}{2L} \bullet \mu_n C_{ox} (V_{GS} - V_T)^2 [1 + \lambda V_{DS}]$$

2. Backgate Characteristics

There is a fourth terminal in a MOSFET: the *body*. What does it do?



Key Assumption (thus far): $V_{BS} = 0 \Rightarrow V_{GS} = V_{GB}$

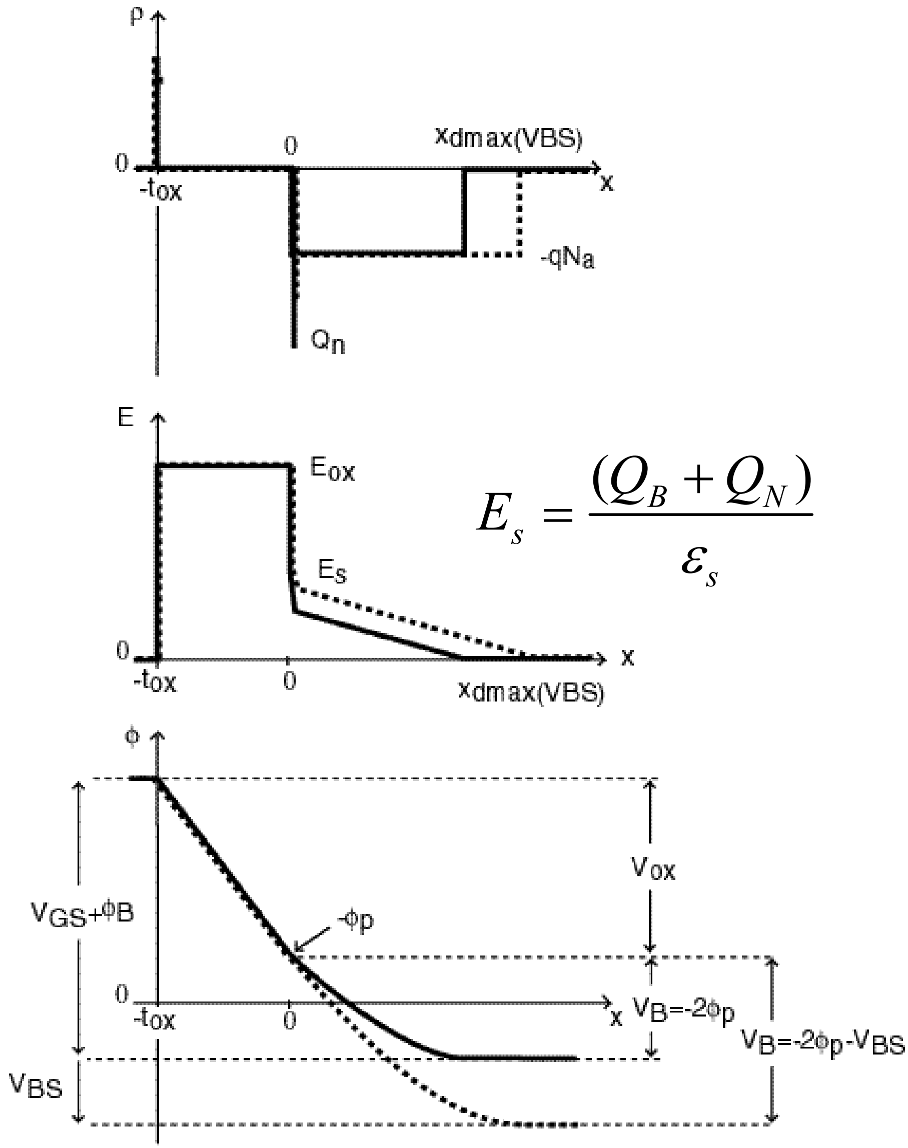
- Body contact allows application of bias to body with respect to inversion layer, V_{BS}.
- Only interested in $V_{BS} < 0$ (pn diode in reverse bias).
- Interested in effect on inversion layer
  $\Rightarrow$ examine for $V_{GS} > V_T$ (keep it constant).

Backgate Characteristics (Contd.)

Application of $V_{BS} < 0$ increases potential build-up across semiconductor:

$$-2\phi_p \Rightarrow -2\phi_p - V_{BS}$$

Depletion region at the *source* must widen to produce required extra field:



$$E_s = \frac{(Q_B + Q_N)}{\varepsilon_s}$$

Backgate Characteristics (Contd.)

Consequences of application of $V_{BS} < 0$:

- $-2\phi_p \Rightarrow -2\phi_p - V_{BS}$
- $|Q_B| \uparrow \Rightarrow x_{dmax} \uparrow$
- Since V_{GS} is constant, V_{ox} unchanged
  - $\Rightarrow E_{ox}$ unchanged
  - $\Rightarrow |Q_S| = |Q_G|$ unchanged
- $|Q_S| = |Q_N| + |Q_B|$ unchanged, but $|Q_B| \uparrow \Rightarrow |Q_N| \downarrow$
  - $\Rightarrow$ inversion layer charge is reduced!

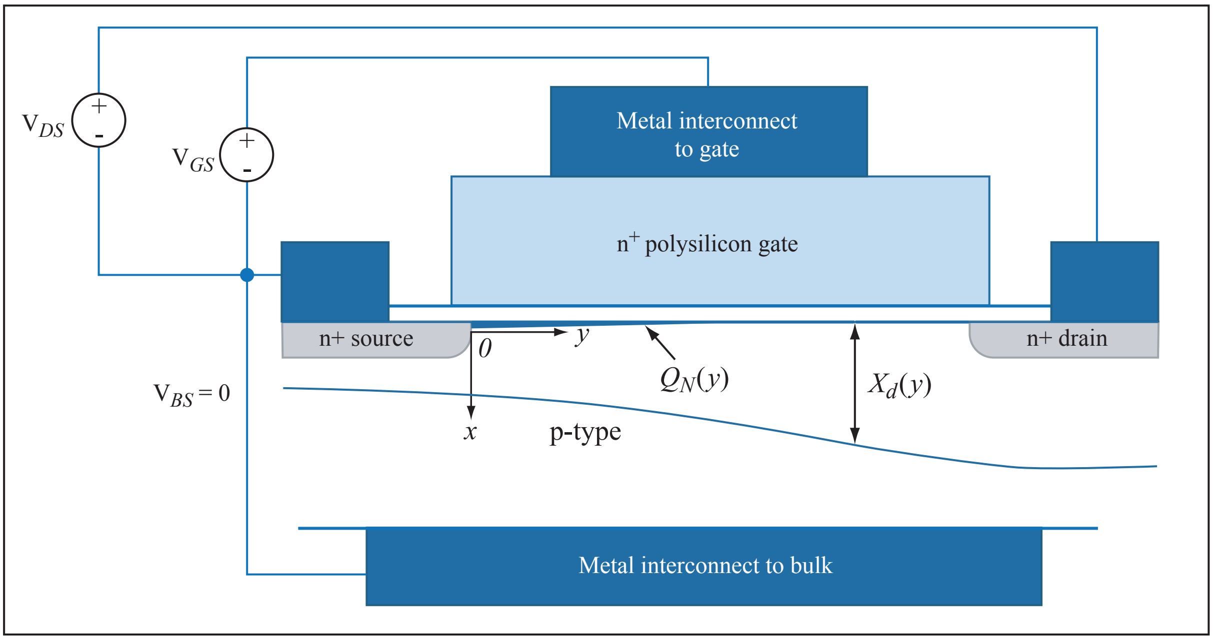


Figure by MIT OpenCourseWare.

For the same applied gate-to-source voltage V_{GS}, application of $V_{BS} < 0$ reduces the density of electrons in the inversion layer, in other words $V_T \uparrow$

Backgate Characteristics (Contd.)

How does V_T change with V_{BS} ?

In V_T formula change $-2\phi_p$ to $-2\phi_p - V_{BS}$:

$$V_T^{GB}(V_{BS}) = V_{FB} - 2\phi_p - V_{BS} + \frac{1}{C_{ox}}\sqrt{2\varepsilon_s q N_a\left(-2\phi_p - V_{BS}\right)}$$

In MOSFETs, interested in V_T between **gate** and **source**:

$$V_{GB} = V_{GS} - V_{BS} \Rightarrow V_T^{GB} = V_T^{GS} - V_{BS}$$

Then:

$$\mathbf{V_T^{GS} = V_T^{GB} + V_{BS}}$$

And:

$$V_T^{GS}(V_{BS}) = V_{FB} - 2\phi_p + \frac{1}{C_{ox}}\sqrt{2\varepsilon_s q N_a\left(-2\phi_p - V_{BS}\right)} \equiv V_T(V_{BS})$$

In the context of the MOSFET, V_T is always defined in terms of ***gate-to-source voltage***.

Backgate Characteristics (Contd.)

$$V_T(V_{BS}) = V_{FB} - 2\phi_p + \frac{1}{C_{ox}}\sqrt{2\varepsilon_s q N_a\left(-2\phi_p - V_{BS}\right)}$$

Define ***backgate effect parameter*** [units: $V^{1/2}$]:

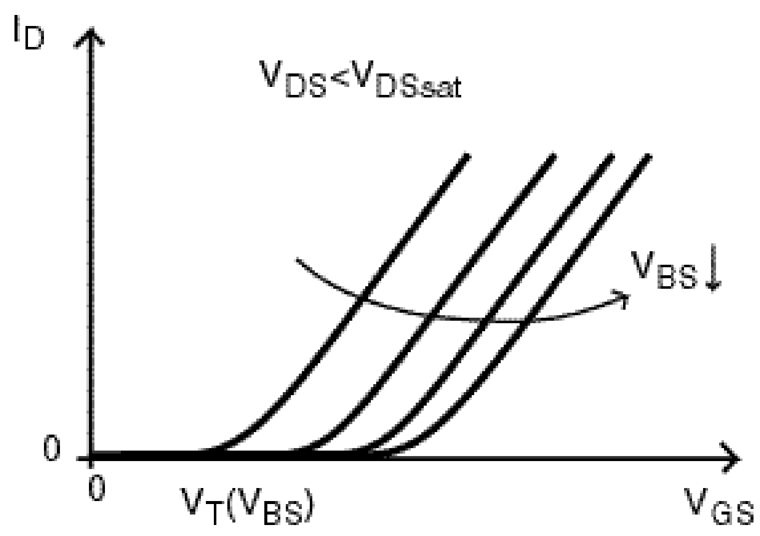
$$\gamma = \frac{1}{C_{ox}}\sqrt{2\varepsilon_s q N_a}$$

And:

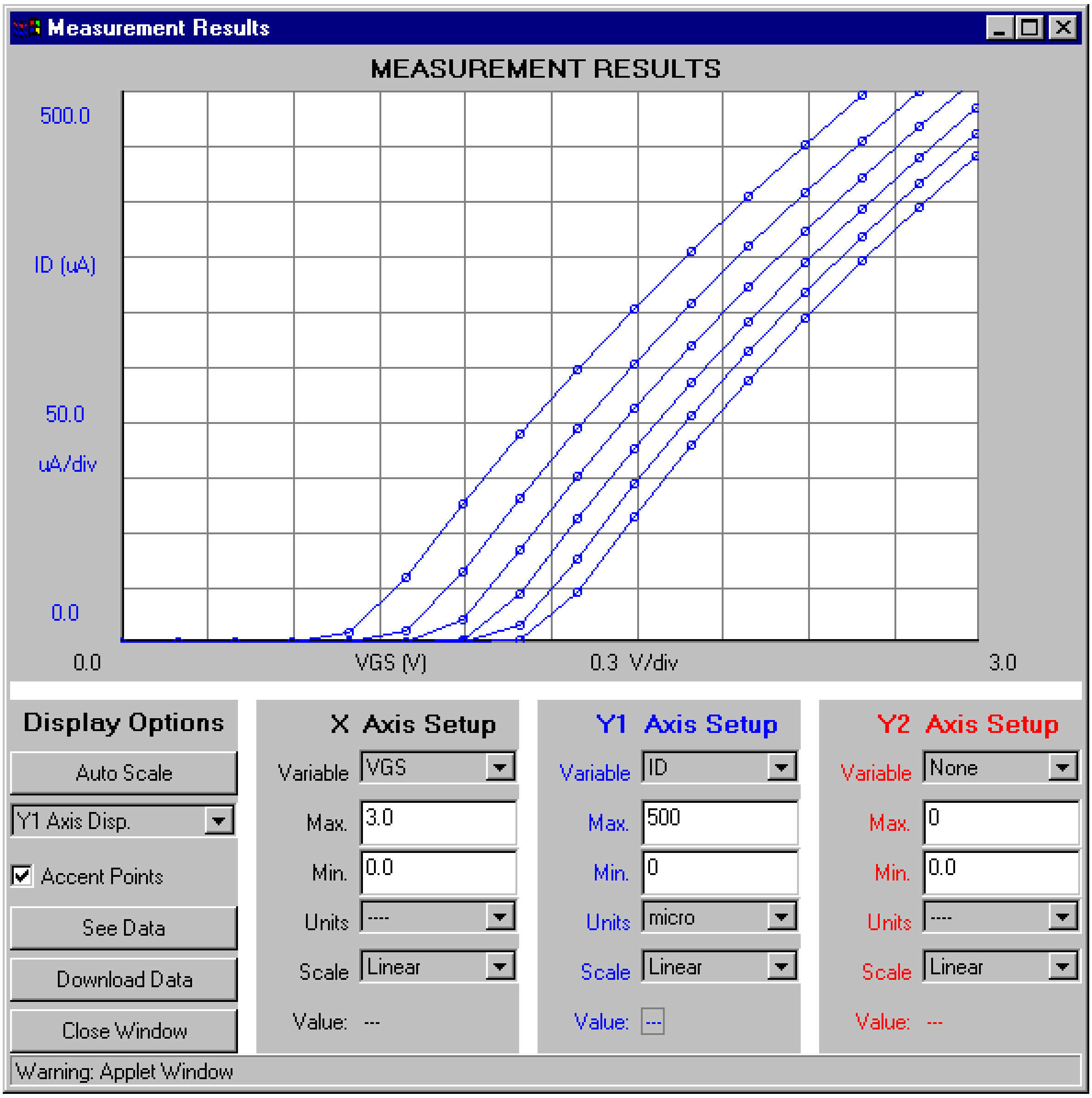
$$V_{To} = V_T(V_{BS} = 0)$$

Then:

$$V_T(V_{BS}) = V_{To} + \gamma\left[\sqrt{-2\phi_p - V_{BS}} - \sqrt{-2\phi_p}\right]$$



Backgate Characteristics (Contd.)



Triode Region $V_{DS} \sim 0.1V$

What did we learn today?

Summary of Key Concepts

- MOSFET in saturation ($V_{DS} \geq V_{DSsat}$): ***pinch-off*** point at drain-end of channel
  - Electron concentration small, but
  - Electrons move very fast;
  - Pinch-off point does not represent a barrier to electron flow
- I_{Dsat} increases slightly in saturation region due to ***channel length modulation***
- Backbias affects V_T of MOSFET