# Lecture 10 - MOSFET (II)

## MOSFET I-V Characteristics (*cont.*)

### October 13, 2005

**Contents**:

1. The saturation regime

2. Backgate characteristics

**Reading assignment:**

Howe and Sodini, Ch. 4, §4.4

**Announcements:** Quiz 1: 10/13, 7:30-9:30 PM, (lectures #1-9); open book; <u>must</u> have calculator.

# Key questions

- How does the MOSFET work in saturation?

- Does the pinch-off point represent a block to current flow?

- How come the MOSFET current still increases a bit with $V_{DS}$ in saturation?

- How does the application of a back bias affect the MOSFET I-V characteristics?

# 1. The saturation regime

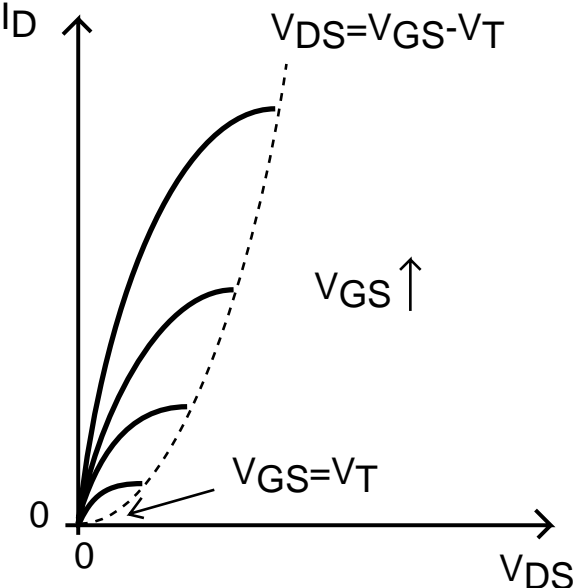Geometry of problem:
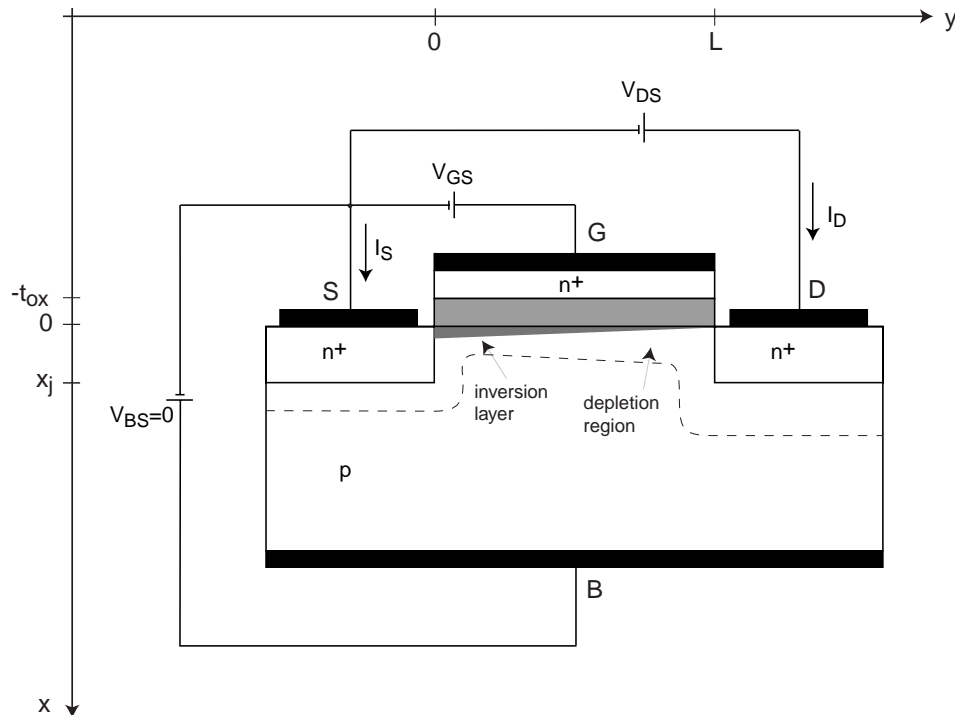


Regimes of operation so far ($V_{BS} = 0$):

- *Cut-off*: $V_{GS} < V_T$, $V_{GD} < V_T$:
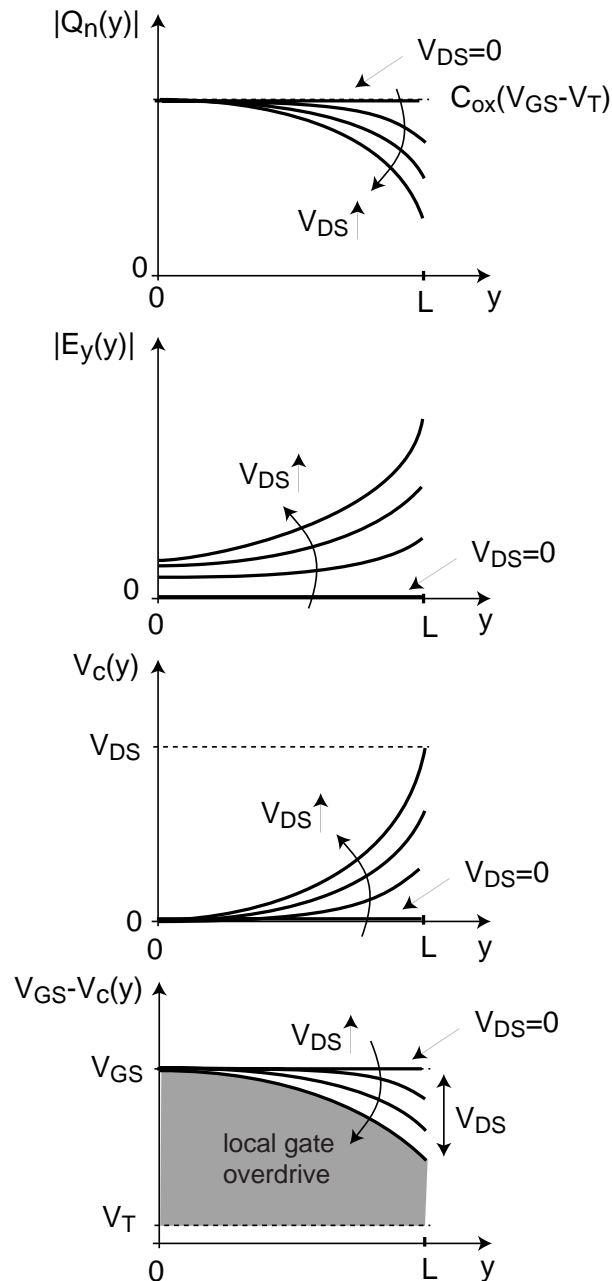  no inversion layer anywhere underneath gate

$$I_D = 0$$

- *Linear*: $V_{GS} > V_T$, $V_{GD} > V_T$ (with $V_{DS} > 0$):
  inversion layer everywhere underneath gate

$$I_D = \frac{W}{L}\mu_n C_{ox}(V_{GS} - \frac{V_{DS}}{2} - V_T)V_{DS}$$

# Output characteristics:

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

$$V_{GS}\uparrow$$

$$V_{GS}=V_T$$

$I_D$

$0$

$0$

$V_{DS}$

☐ Review of $Q_n$, $E_y$, $V_c$, and $V_{GS} - V_c(y)$ in linear regime as $V_{DS}$ increases:



Ohmic drop along channel debiases inversion layer
$$\Rightarrow I_D \text{ rises more slowly with } V_{DS}$$

$\square$ Drain current saturation
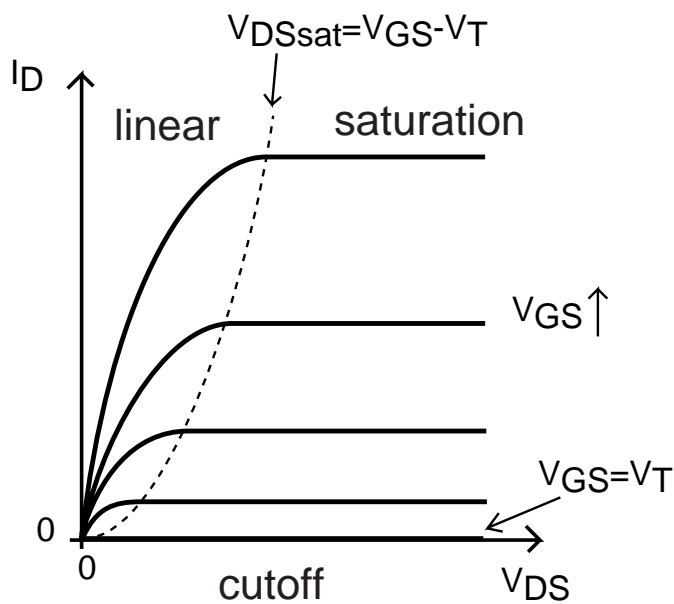
As $V_{DS}$ approaches:

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

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

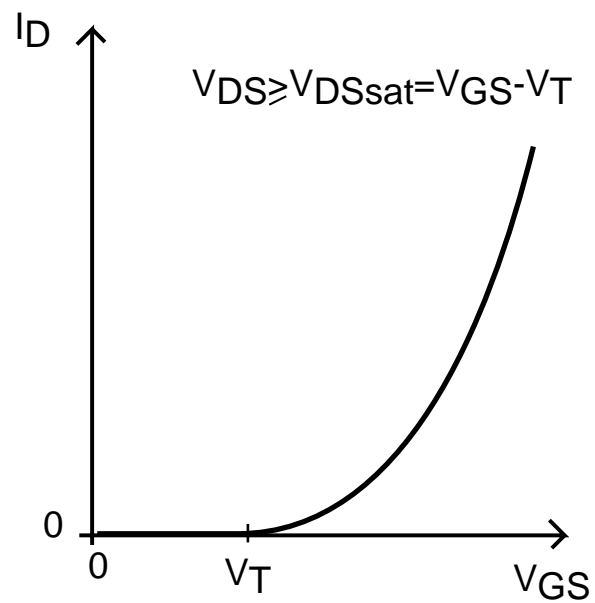$$I_{Dsat} = I_{Dlin}(V_{DS} = V_{DSsat} = V_{GS} - V_T)$$

Then:

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

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

Transfer characteristics in saturation:

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

Charge control relation at drain-end of channel:

$$Q_n(L) = -C_{ox}(V_{GS} - V_{DS} - V_T) = 0$$

No inversion layer at end of channel??!! $\Rightarrow$ *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

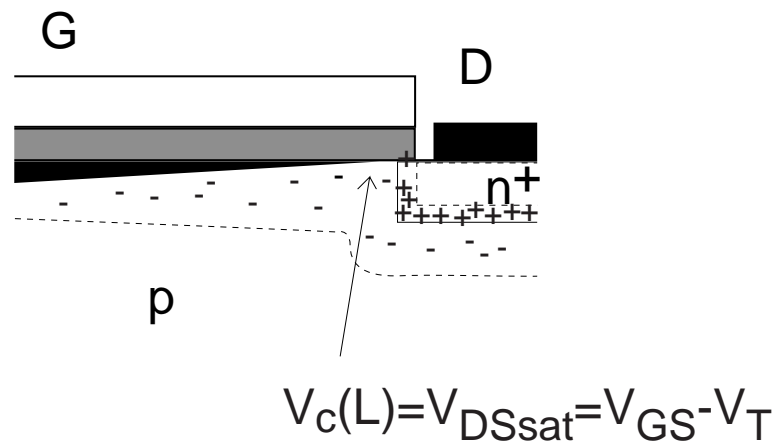- there is no barrier to electron flow (on the contrary!)
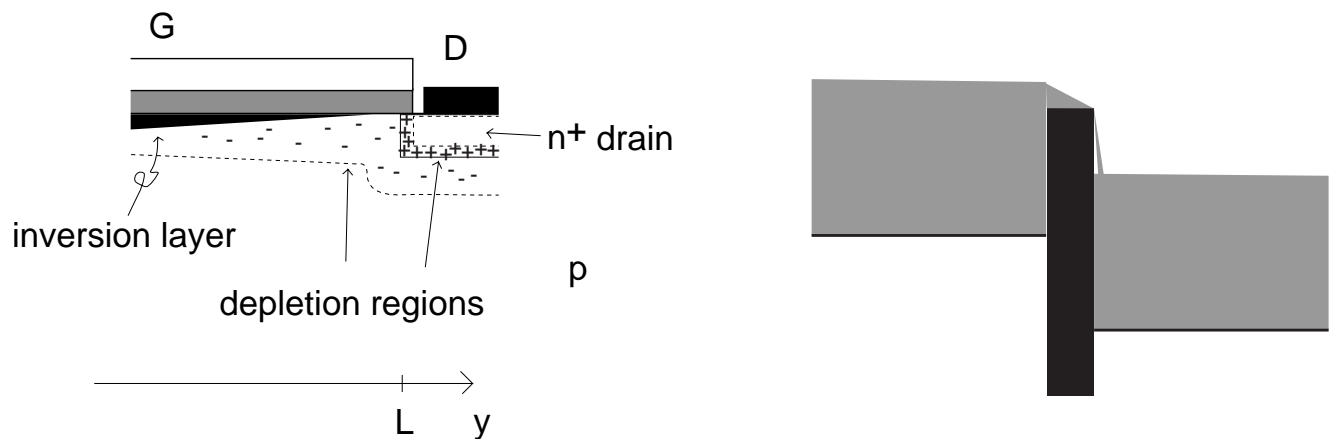
□ Key dependencies of $I_{Dsat}$

● $I_{Dsat} \propto (V_{GS} - V_T)^2$

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



$$V_c(L) = V_{DSsat} = V_{GS} - V_T$$

Drain current at pinch-off:

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

$\propto$ electron concentration $\propto V_{GS} - V_T$

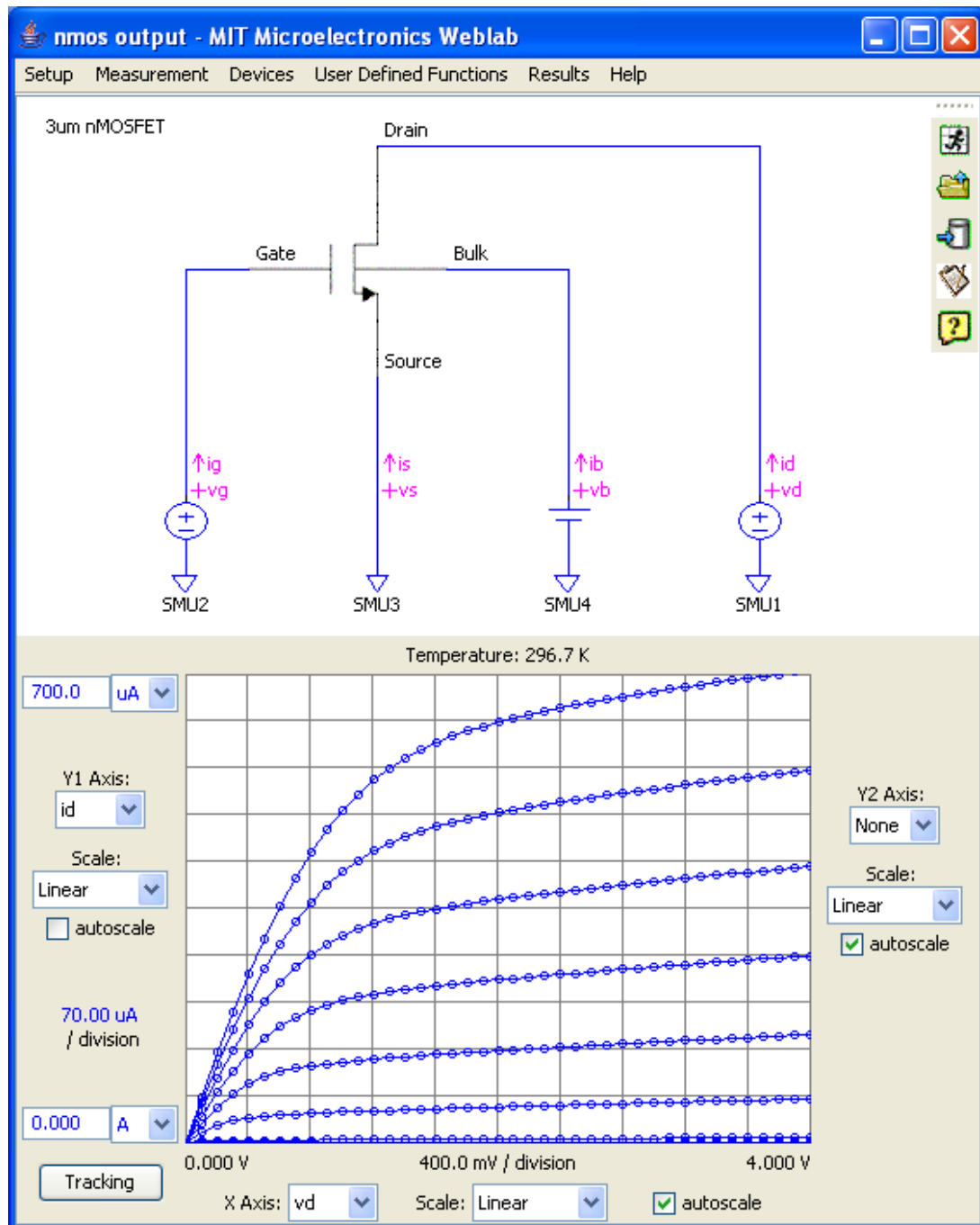$$\Rightarrow I_{Dsat} \propto (V_{GS} - V_T)^2$$

● $I_{Dsat} \propto \frac{1}{L}$

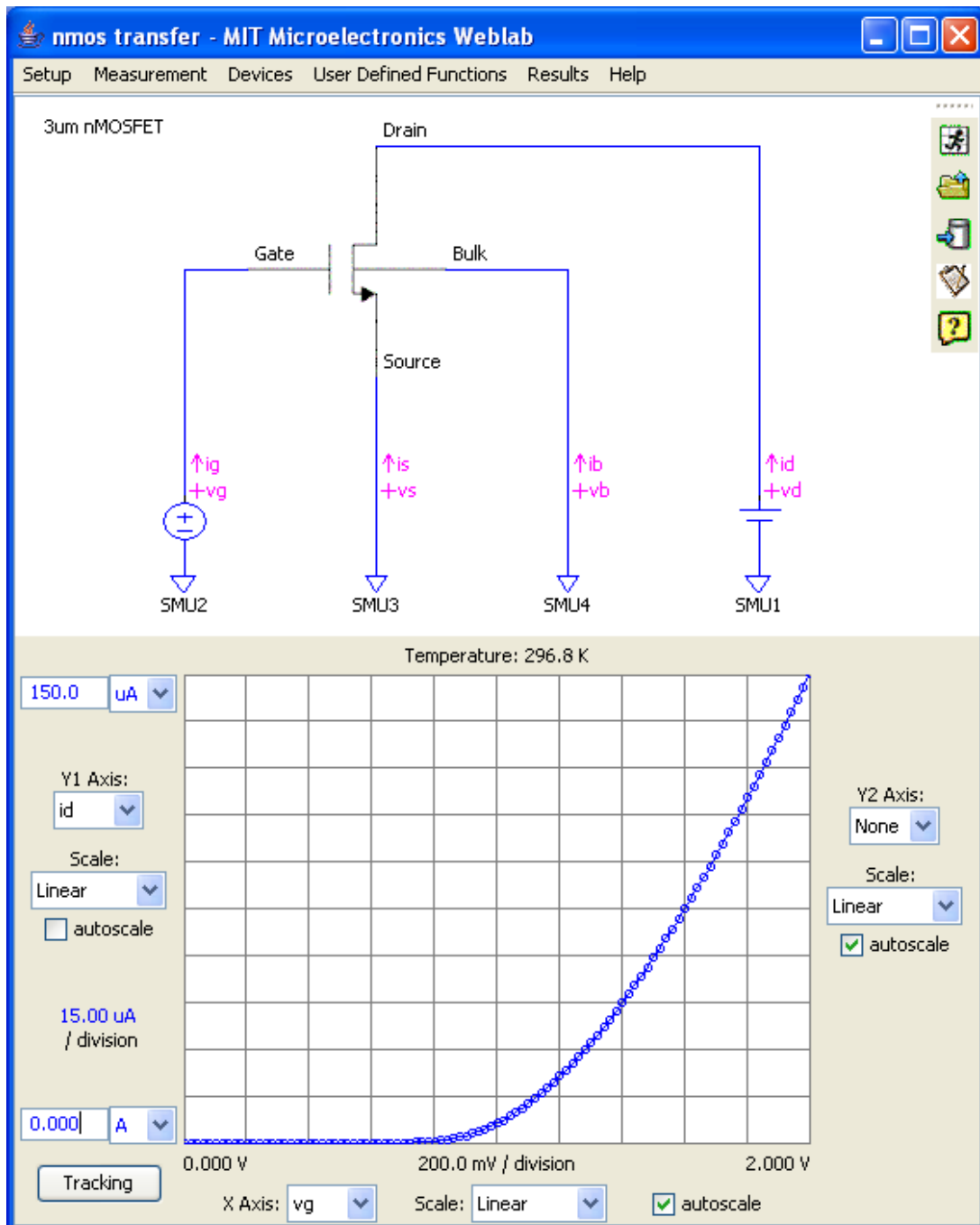$L \downarrow \rightarrow |E_y| \uparrow$

## $3\mu m$ n-channel MOSFET

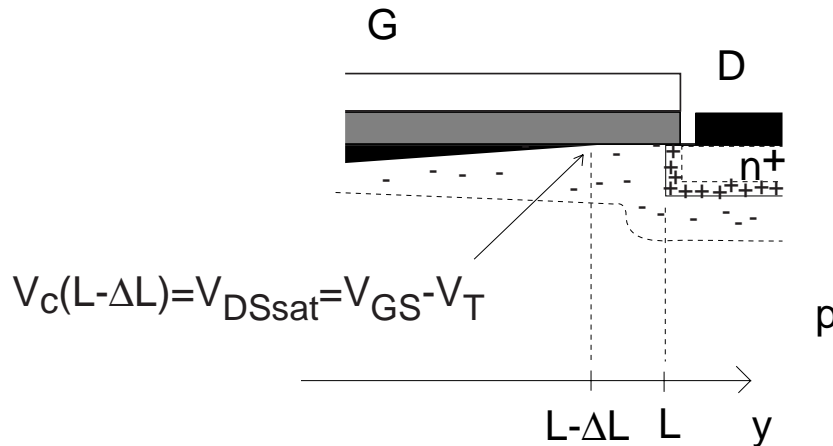## Output characteristics ($V_{GS} = 0 - 4\ V, \Delta V_{GS} = 0.5\ V$):

# Transfer characteristics in saturation ($V_{DS} = 3\ V$):

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

Depletion region separating pinch-off point and drain widens (just like in reverse-biased pn junction)



To first order, $I_D$ does not increase past pinchoff:

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

To second order, electrical channel length affected (*"channel-length modulation"*): $V_{DS} \uparrow \Rightarrow L_{channel} \downarrow \Rightarrow I_D \uparrow$

$$I_D \propto \frac{1}{L - \Delta L} \simeq \frac{1}{L}(1 + \frac{\Delta L}{L})$$
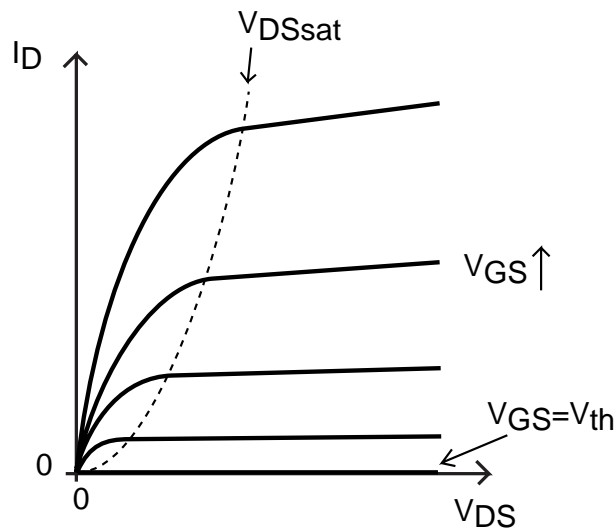
Experimental finding:

$$\Delta L \propto V_{DS} - V_{DSsat}$$

Hence:

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

Improved model in saturation:

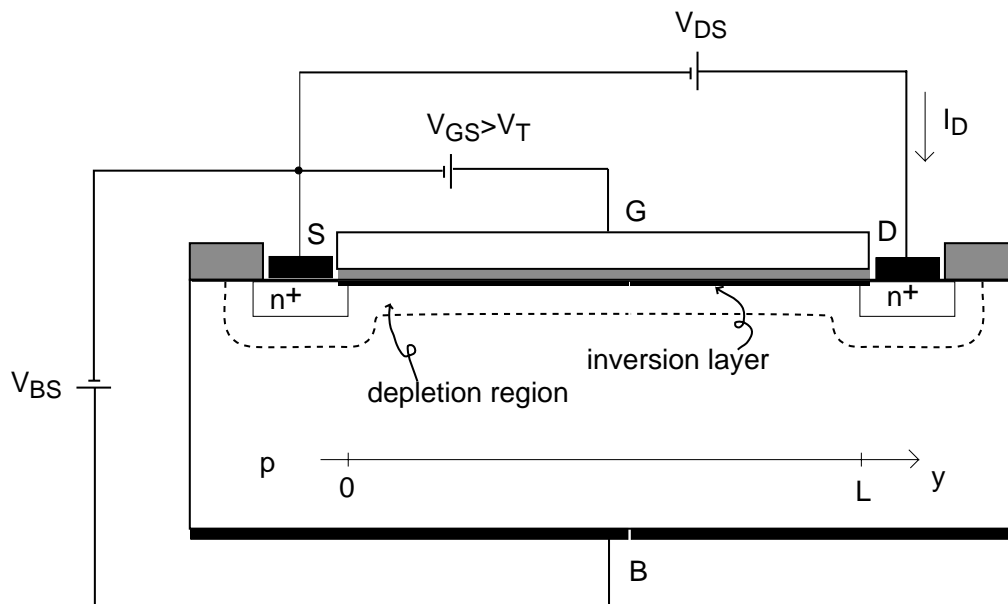$$I_{Dsat} = \frac{W}{2L}\mu_n C_{ox}(V_{GS} - V_T)^2[1 + \lambda(V_{DS} - V_{DSsat})]$$



Also, experimental finding:

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

# 2. Backgate characteristics

There is a fourth terminal in a MOSFET: the *body*.

What does the body do?



Body contact allows application of bias to body with respect to inversion layer, $V_{BS}$.

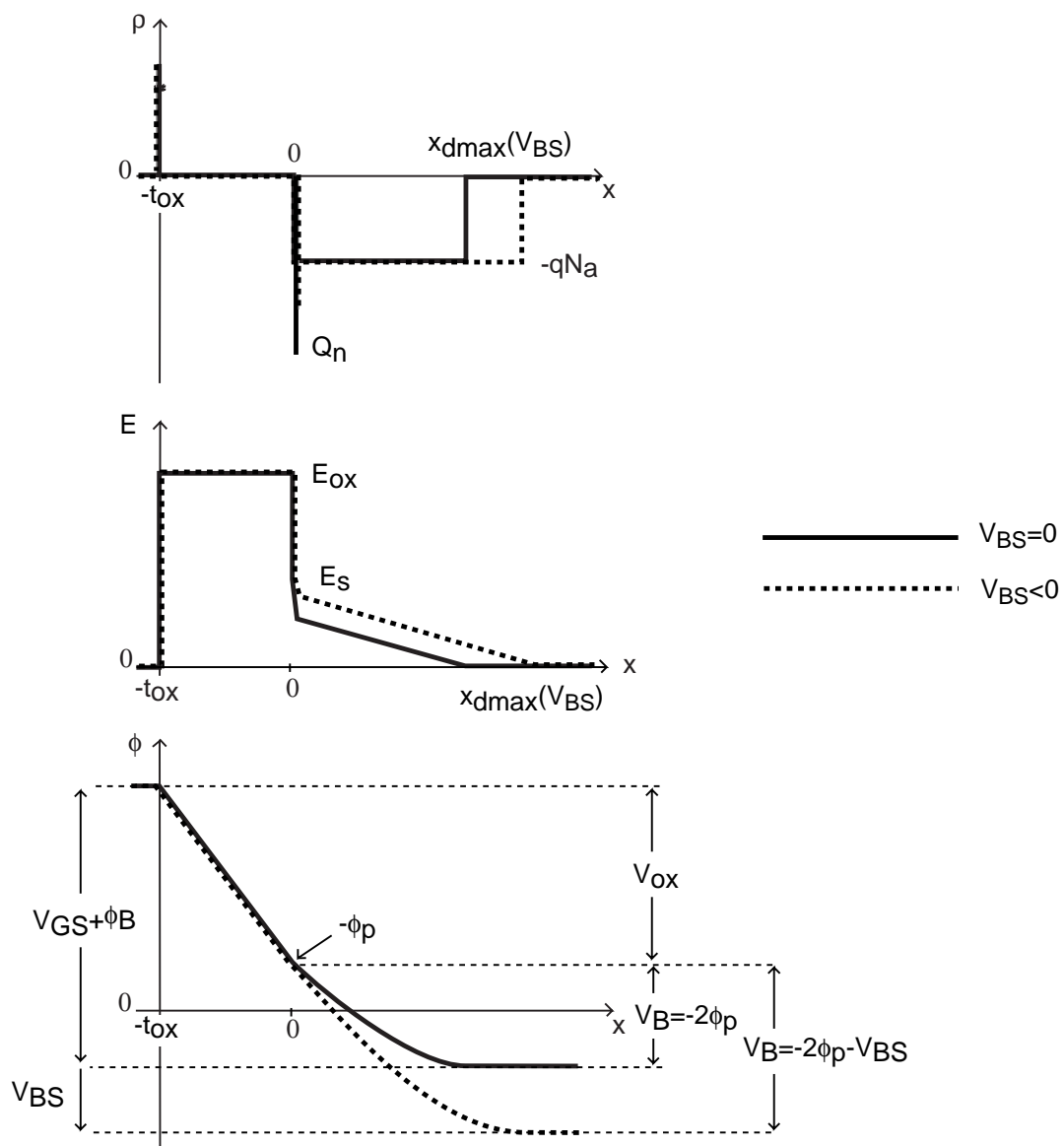Only interested in $V_{BS} < 0$ (pn diode in reverse bias).

Interested in effect on inversion layer
  $\Rightarrow$ examine for $V_{GS} > V_T$ (keep $V_{GS}$ constant).

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

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

# Depletion region must widen to produce required extra field:

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

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

- $|Q_B| \uparrow \Rightarrow x_{dmax} \uparrow$

- since $V_{GS}$ 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!

Application of $V_{BS} < 0$ with constant $V_{GS}$ reduces electron concentration in inversion layer $\Rightarrow V_T \uparrow$

How does $V_T$ change with $V_{BS}$?

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

$$V_T^{GB}(V_{BS}) = V_{FB} - 2\phi_p - V_{BS} + \gamma\sqrt{(-2\phi_p - V_{BS})}$$

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

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

Then:

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

And:

$$V_T^{GS}(V_{BS}) = V_{FB} - 2\phi_p + \gamma\sqrt{(-2\phi_p - V_{BS})} \equiv V_T(V_{BS})$$
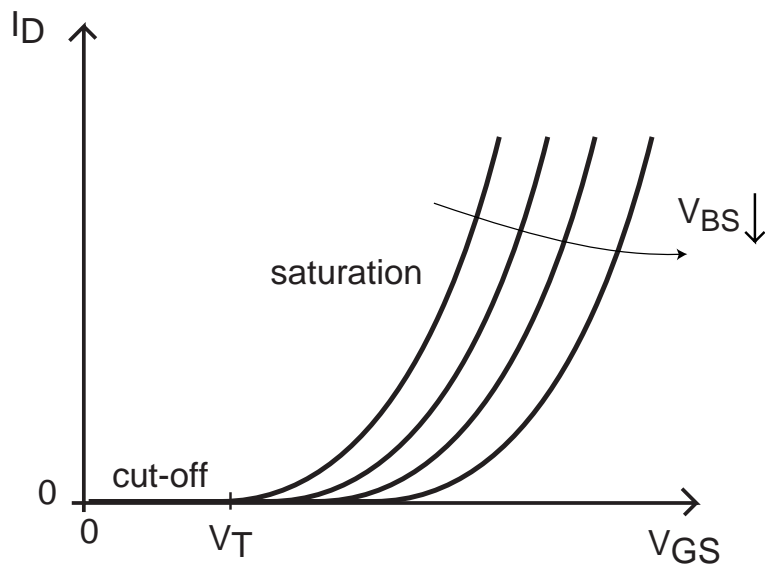
In the context of the MOSFET, $V_T$ is always defined in terms of *gate-to-source voltage.*
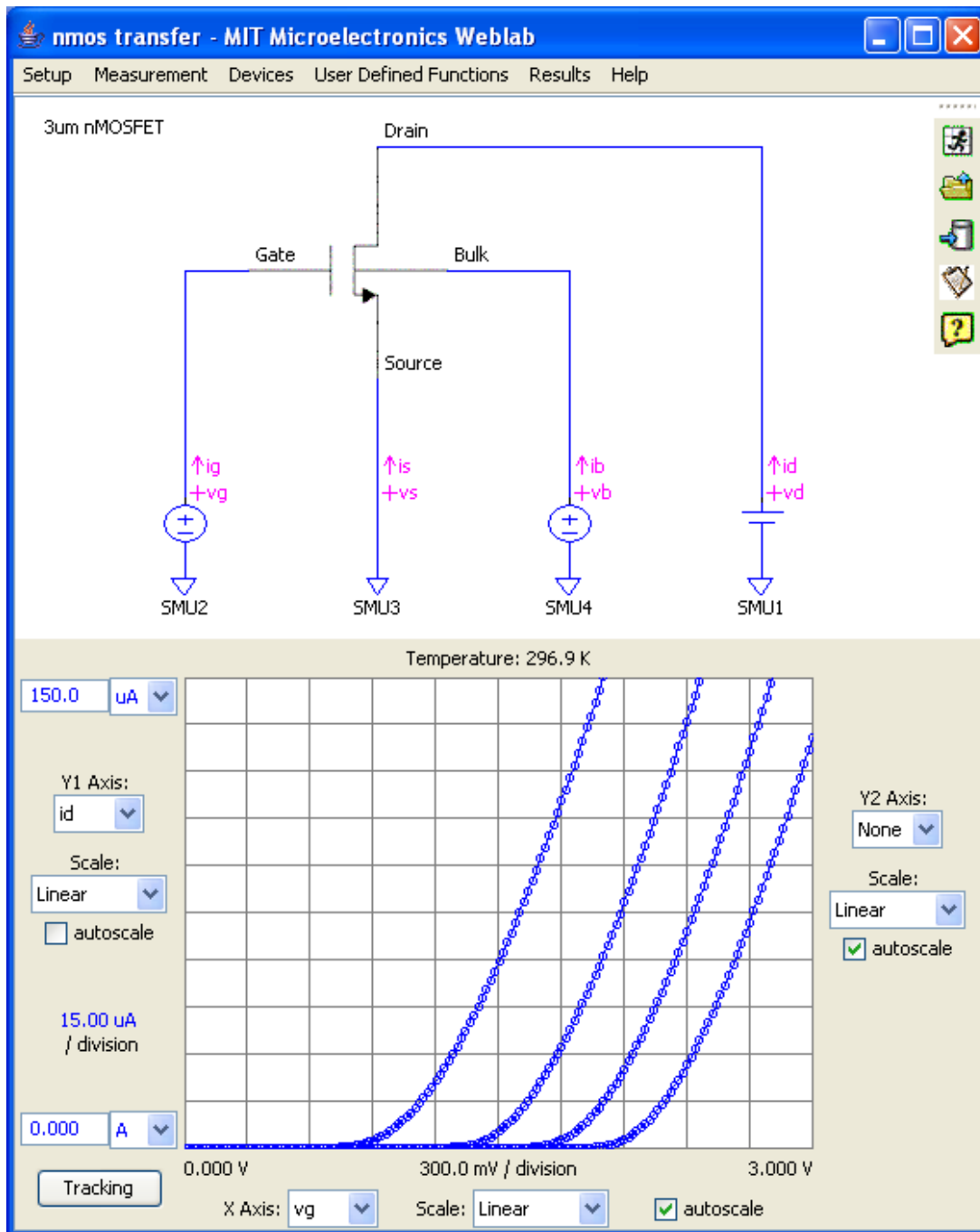
Define:

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

Then:

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

# Backate characteristics ($V_{BS} = 0, -1, -2, -3\ V, V_{DS} = 3\ V$):

# Key conclusions

- 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

- In saturation, $I_D$ saturates:

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

- But..., due to *channel-length modulation*, $I_{Dsat}$ increases slightly with $V_{DS}$

- Application of back bias shifts $V_T$ (*back-gate effect*)