Lecture 9 - MOSFET (I)

MOSFET I-V Characteristics

March 6, 2003

Contents:

1. MOSFET: cross-section, layout, symbols

2. Qualitative operation

3. I-V characteristics

Reading assignment:

Howe and Sodini, Ch. 4, §§4.1-4.3

Announcements: Quiz #1, March 12, 7:30-9:30 PM, Walker Memorial; covers Lectures #1-9; open book; <u>must</u> have calculator.

Key questions

- How can carrier inversion be exploited to make a transistor?

- How does a MOSFET work?

- How does one construct a simple first-order model for the current-voltage characteristics of a MOSFET?

1. MOSFET: layout, cross-section, symbols
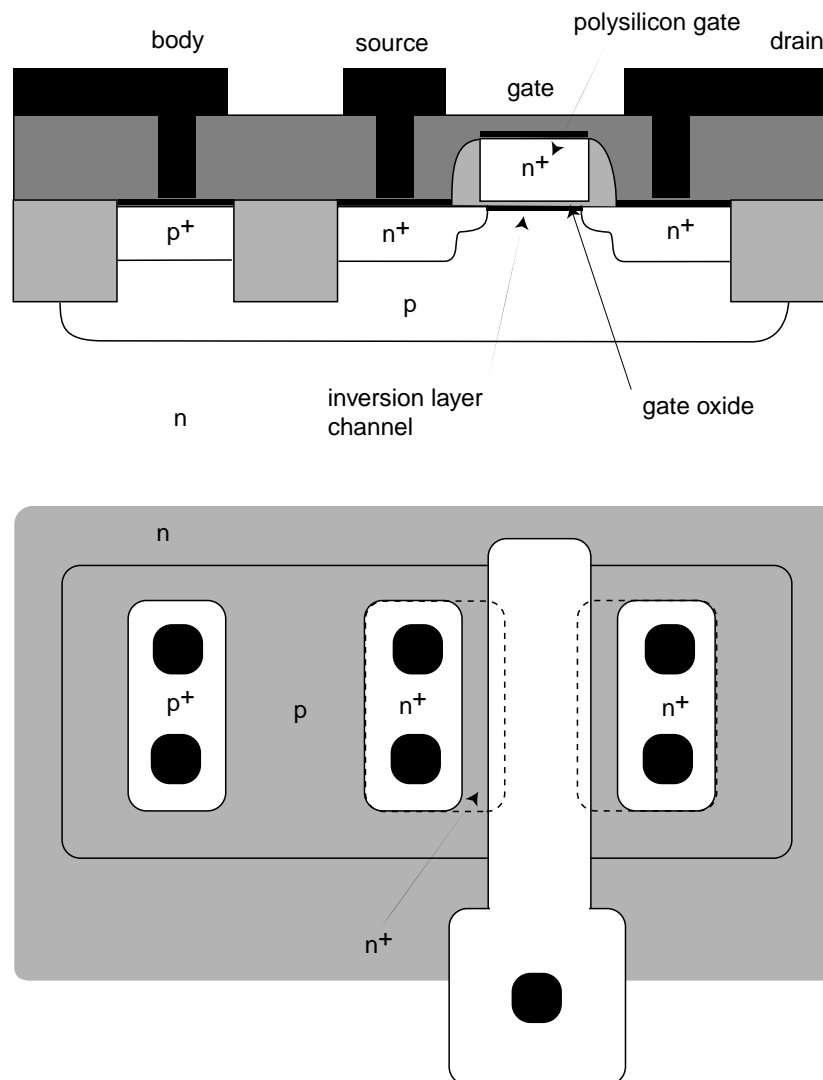
Key elements:

- inversion layer under *gate* (depending on gate voltage)

- heavily-doped regions reach underneath gate $\Rightarrow$ inversion layer electrically connects *source* and *drain*

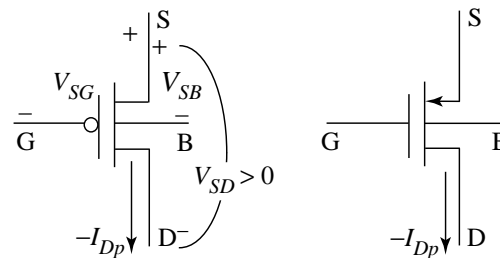- 4-terminal device: *body* voltage important
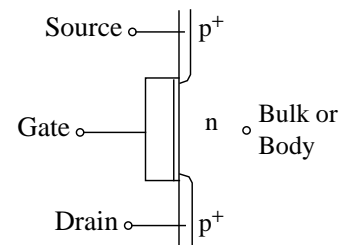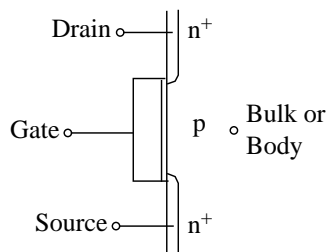
□ Circuit symbols

Two complementary devices:

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

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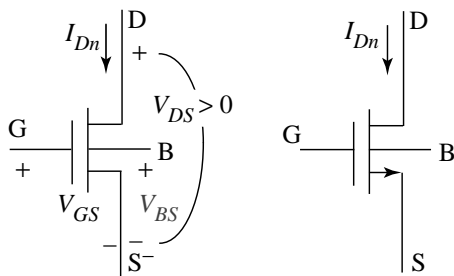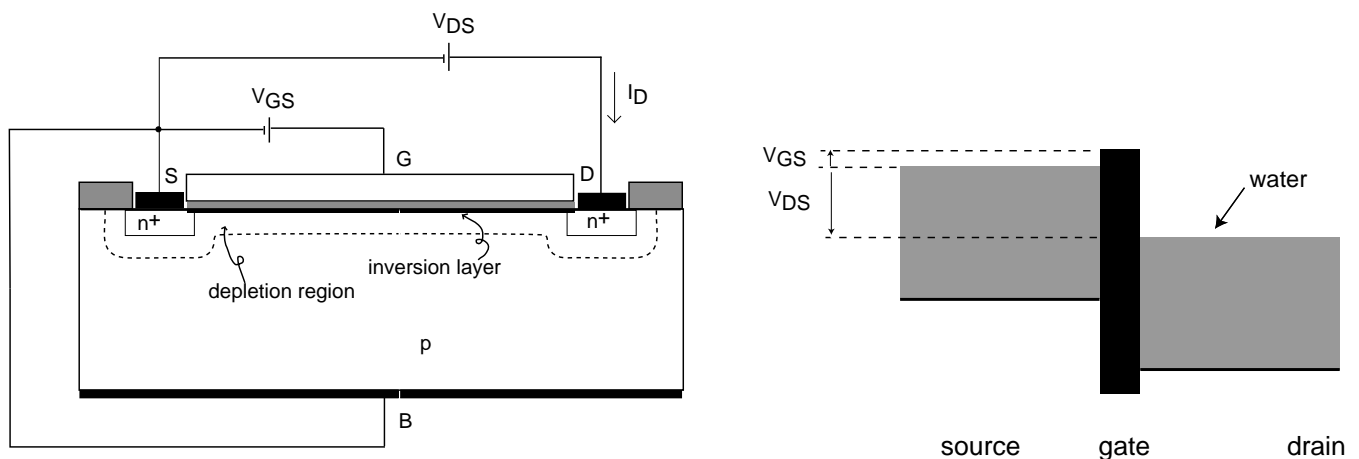

(a) n-channel MOSFET　　　　　　　　　　(b) p-channel MOSFET

2. Qualitative operation

Water analogy of MOSFET:

- *Source*: water reservoir

- *Drain*: water reservoir

- *Gate*: gate between source and drain reservoirs

Want to understand MOSFET operation as a function of:

- gate-to-source voltage (gate height over source water level)

- drain-to-source voltage (water level difference between reservoirs)

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: gate closed; no water can flow regardless of relative height of source and drain reservoirs.

$V_{GS} < V_T$ G $V_{GD} < V_T$

S   D

n⁺   n⁺

depletion region   p   no inversion layer anywhere
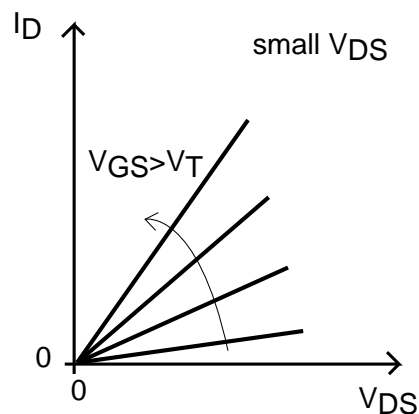
no water flow

$I_D = 0$

□ *Linear* or *Triode regime*:

• MOSFET: $V_{GS} > V_T$, $V_{GD} > V_T$, with $V_{DS} > 0$.

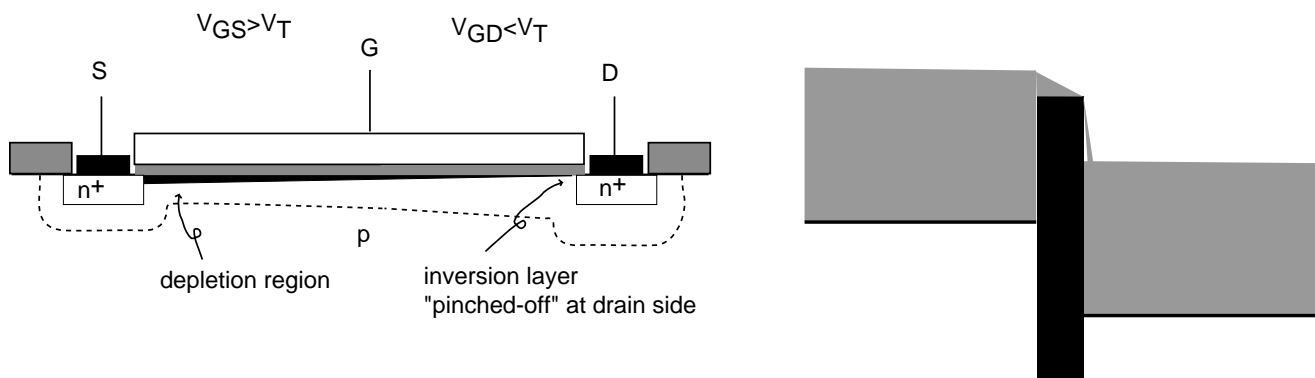• Water analogy: gate open but small difference in height between source and drain; water flows.
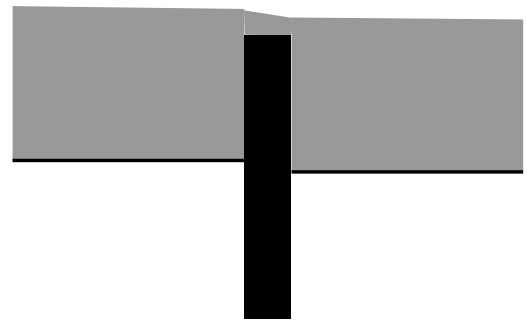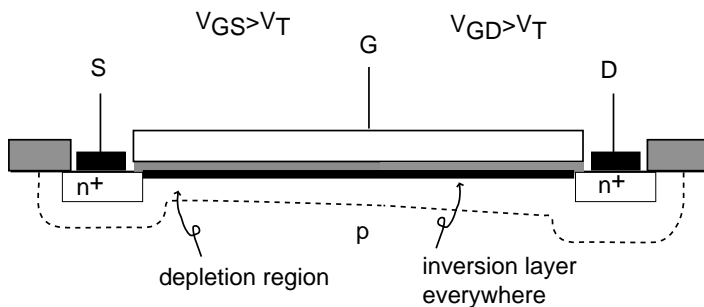
Electrons drift from source to drain $\Rightarrow$ electrical current!

• $V_{GS} \uparrow \rightarrow |Q_n| \uparrow \rightarrow I_D \uparrow$

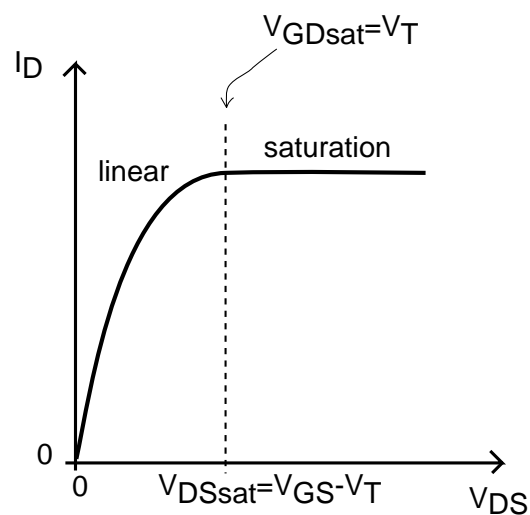• $V_{DS} \uparrow \rightarrow E_y \uparrow \rightarrow I_D \uparrow$
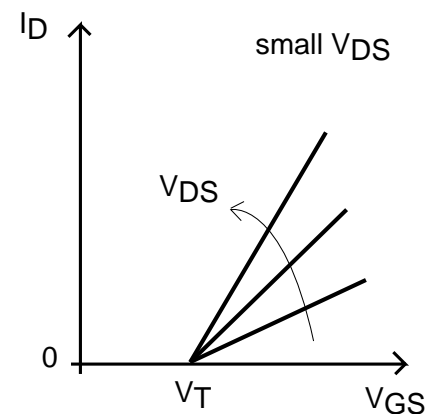
□ *Saturation regime*:

● MOSFET: $V_{GS} > V_T$, $V_{GD} < V_T$ ($V_{DS} > 0$).

● Water analogy: gate open; water flows from source to drain, but free-drop on drain side $\Rightarrow$ total flow indepen-dent of relative reservoir height!
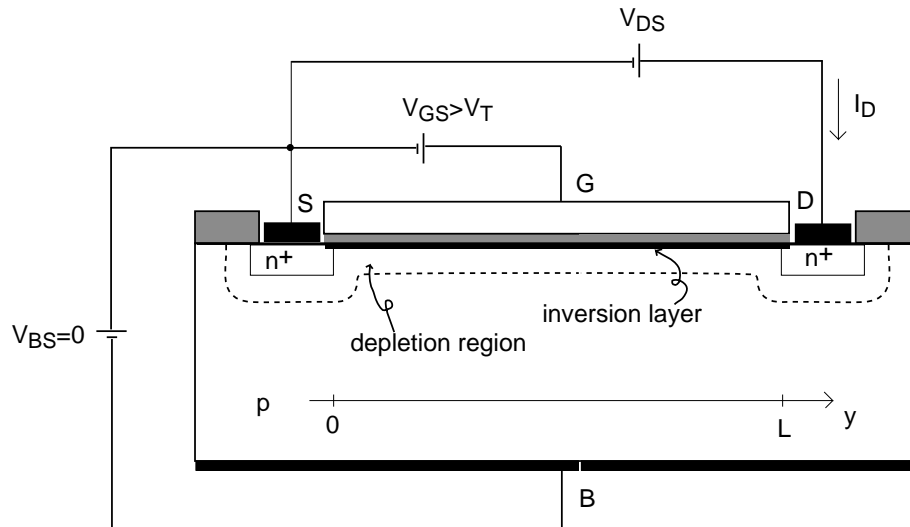

$V_{GS} > V_T$ G $V_{GD} < V_T$

S   D

n+   n+

p   p

depletion region   inversion layer "pinched-off" at drain side

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

$V_{GDsat} = V_T$

I_D

linear   saturation

0

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

3. I-V characteristics

Geometry of problem:

□ General expression of channel current

Current can only flow in y-direction:

$$J_y = Q_n(y)v_y(y)$$

Total channel current:

$$I_y = WQ_n(y)v_y(y)$$

Drain terminal current is equal to *minus* channel current:

$$I_D = -WQ_n(y)v_y(y)$$

$$I_D = -W Q_n(y) v_y(y)$$

Rewrite in terms of voltage at channel location y, $V_c(y)$:

● If electric field is not too big:

$$v_y(y) \simeq -\mu_n E_y(y) = \mu_n \frac{dV_c(y)}{dy}$$

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

$$Q_n(y) = -C_{ox}[V_{GS} - V_c(y) - V_T]$$

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

All together:

$$I_D = W \mu_n C_{ox}(V_{GS} - V_c(y) - V_T)\frac{dV_c(y)}{dy}$$

Simple linear first-order differential equation with one unknown, the channel voltage $V_c(y)$.

Solve by separating variables:

$$I_D dy = W \mu_n C_{ox} (V_{GS} - V_c - V_T) dV_c$$

Integrate along the channel in the linear regime:

-for $y = 0$, $V_c(0) = 0$

-for $y = L$, $V_c(L) = V_{DS}$ (linear regime)

Then:

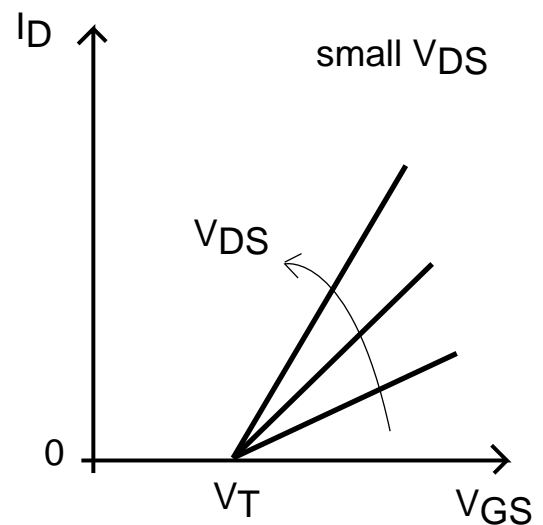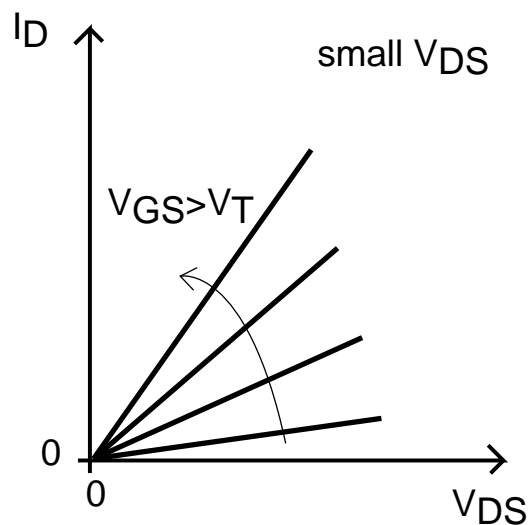$$I_D \int_0^L dy = W \mu_n C_{ox} \int_0^{V_{DS}} (V_{GS} - V_c - V_T) dV_c$$

or:

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

For small V_{DS}:

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

Key dependencies:

- $V_{DS} \uparrow \rightarrow I_D \uparrow$ (higher lateral electric field)
- $V_{GS} \uparrow \rightarrow I_D \uparrow$ (higher electron concentration)
- $L \uparrow \rightarrow I_D \downarrow$ (lower lateral electric field)
- $W \uparrow \rightarrow I_D \uparrow$ (wider conduction channel)
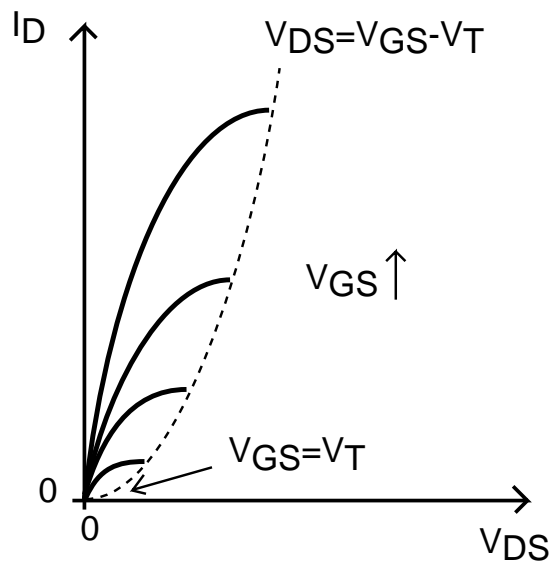

This is the *linear* or *triode* regime.

In general,

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

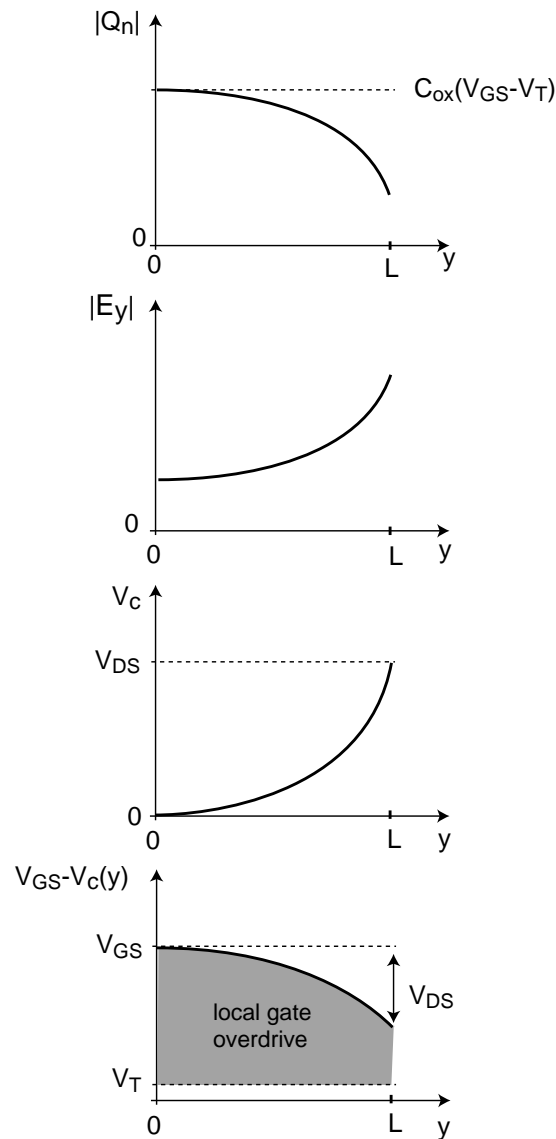Equation valid if $V_{GS} - V_c(y) \geq V_T$ *at every y.*

Worst point is $y = L$, where $V_c(y) = V_{DS}$, hence, equation valid if $V_{GS} - V_{DS} \geq V_T$, or:

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

term responsible for bend over of I_D: $-\frac{V_{DS}}{2}$

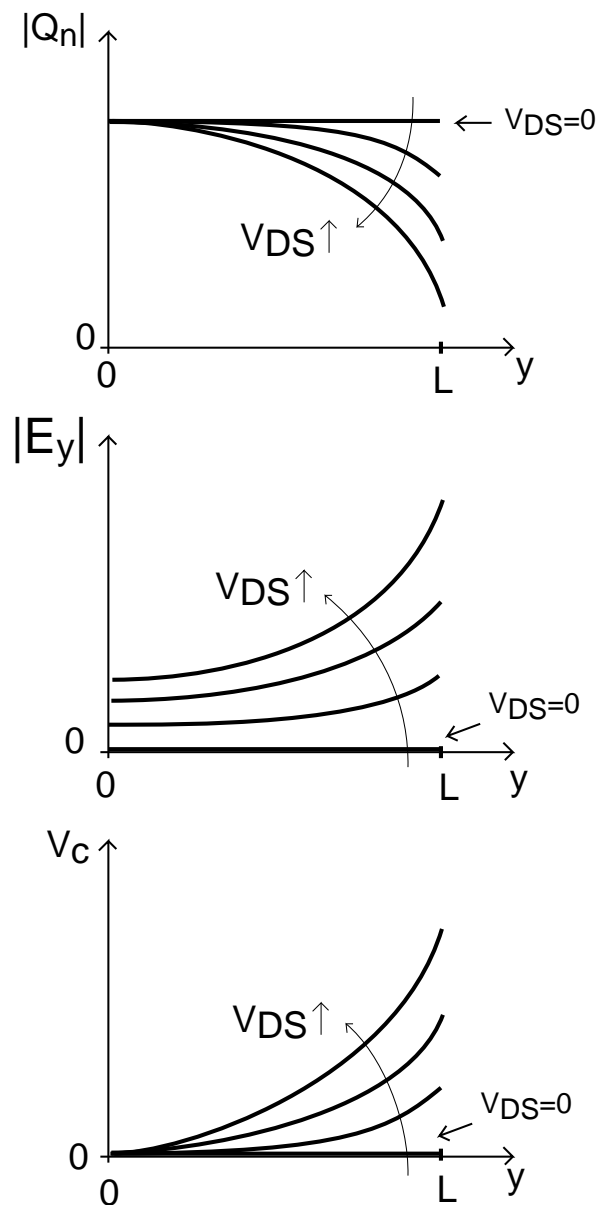To understand why I_D bends over, must understand first *channel debiasing*:

Along channel from source to drain:

$$y \uparrow \ \rightarrow \ V_c(y) \uparrow \ \rightarrow \ |Q_n(y)| \downarrow \ \rightarrow \ |E_y(y)| \uparrow$$
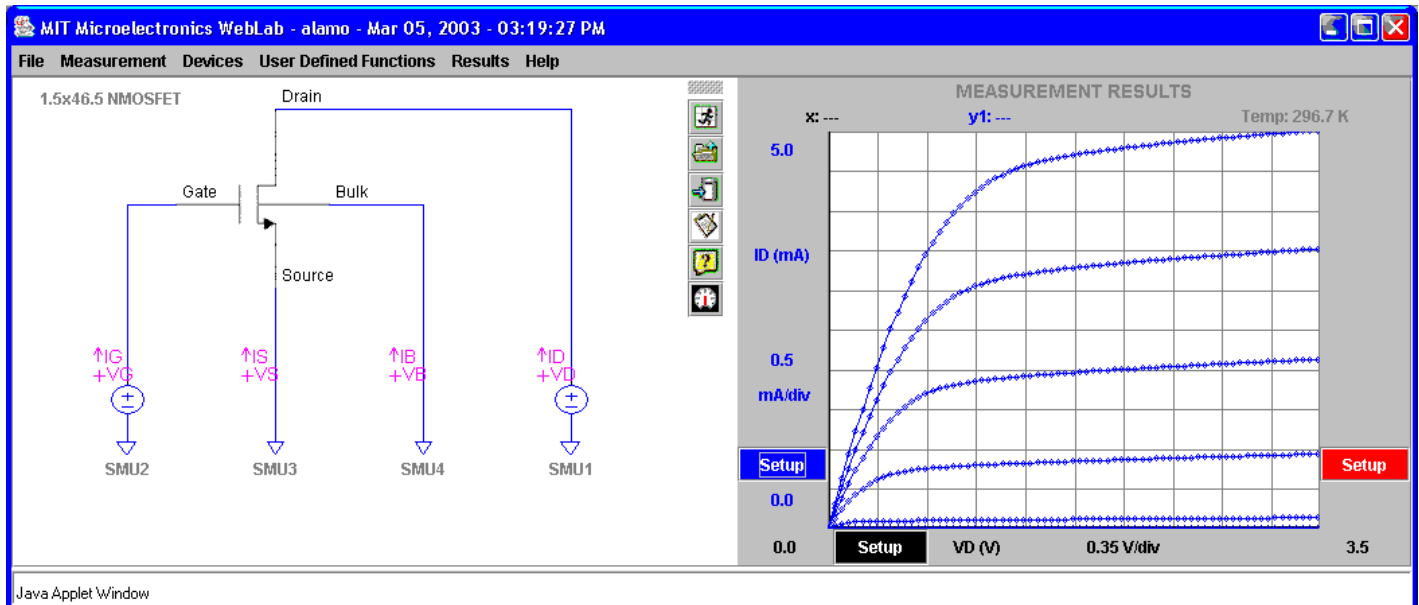
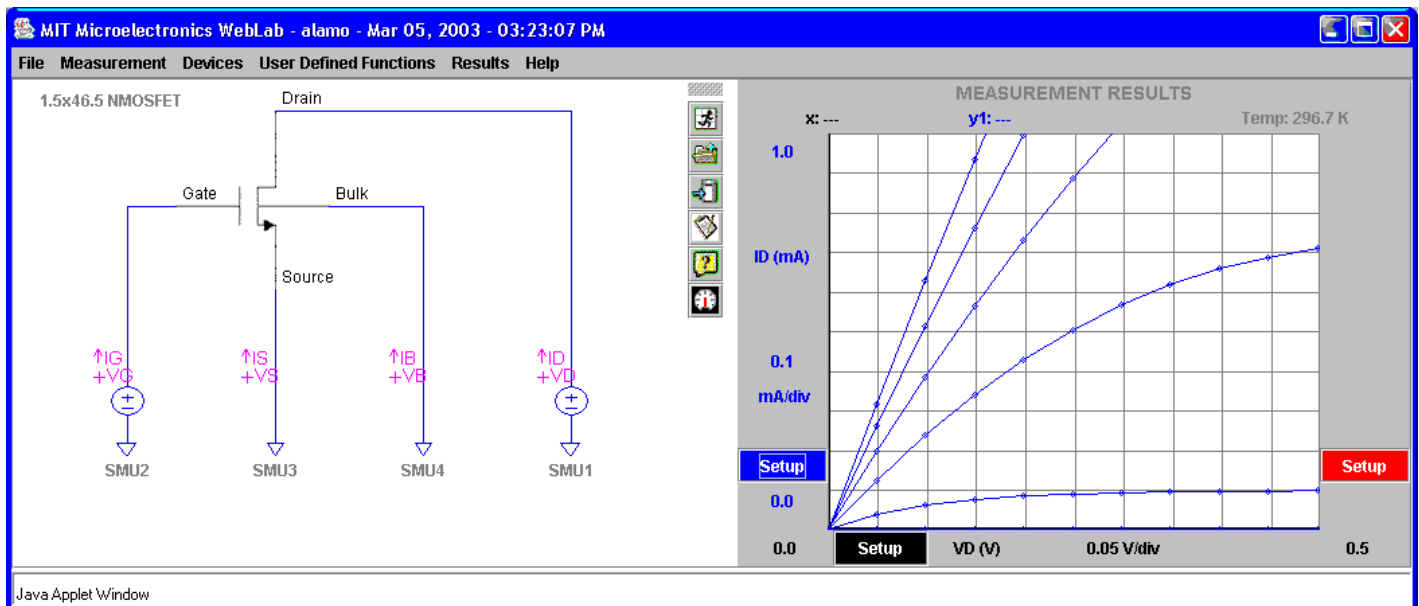Local "channel overdrive" reduced closer to drain.

Impact of V_{DS}:

As $V_{DS} \uparrow$, channel debiasing more prominent
$$\Rightarrow I_D \text{ rises more slowly with } V_{DS}$$
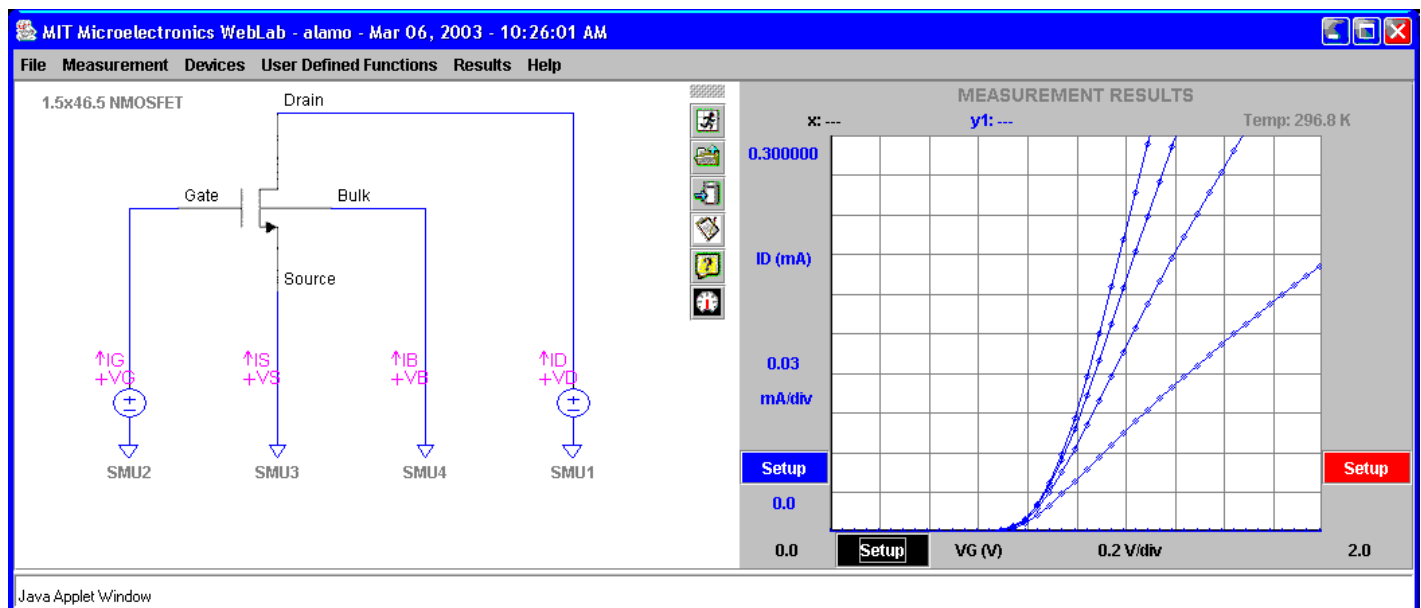
1.5×46.5 NMOSFET

Output characteristics ($V_{GS} = 0 - 3\ V, \Delta V_{GS} = 0.5\ V$):

Zoom close to origin:

Transfer characteristics ($V_{DS} = 0.1\ V$):

Key conclusions

- The MOSFET is a *field-effect transistor*:

  – the amount of charge in the inversion layer is controlled by the field-effect action of the gate
  – the charge in the inversion layer is mobile $\Rightarrow$ conduction possible between source and drain

- In the *linear regime*:

  – $V_{GS} \uparrow \Rightarrow I_D \uparrow$: more electrons in the channel
  – $V_{DS} \uparrow \Rightarrow I_D \uparrow$: stronger field pulling electrons out of the source

- *Channel debiasing*: inversion layer "thins down" from source to drain $\Rightarrow$ current saturation as V_{DS} approaches:

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