Lecture 10 - MOSFET (II)

MOSFET I-V Characteristics (*cont.*)

March 11, 2003

Contents:

1. The saturation regime
2. Backgate characteristics

Reading assignment:

Howe and Sodini, Ch. 4, §4.4

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

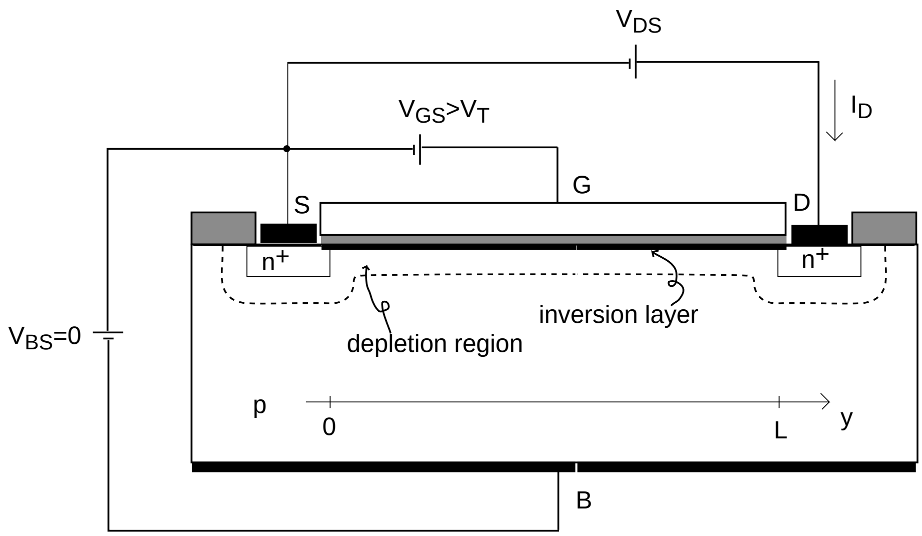
No recitations on March 12 (instructors available for consultation at their offices)

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 ($V_{BS} = 0$):

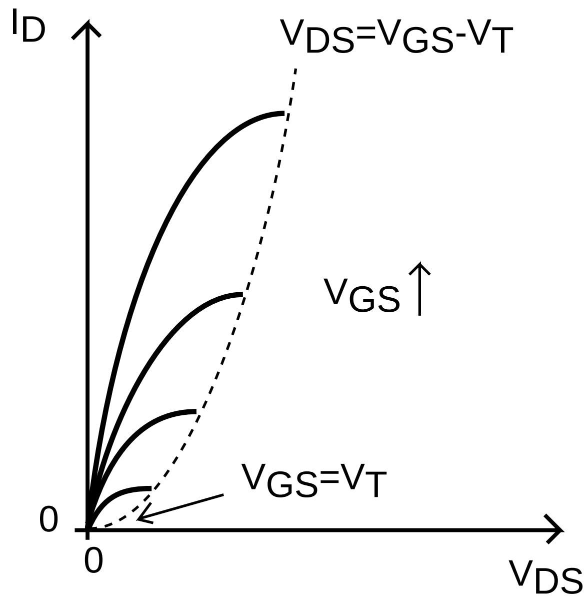
- *Cut-off*: $V_{GS} < V_T$, $V_{GD} < V_T$:
  no inversion layer anywhere underneath gate

$$I_D = 0$$

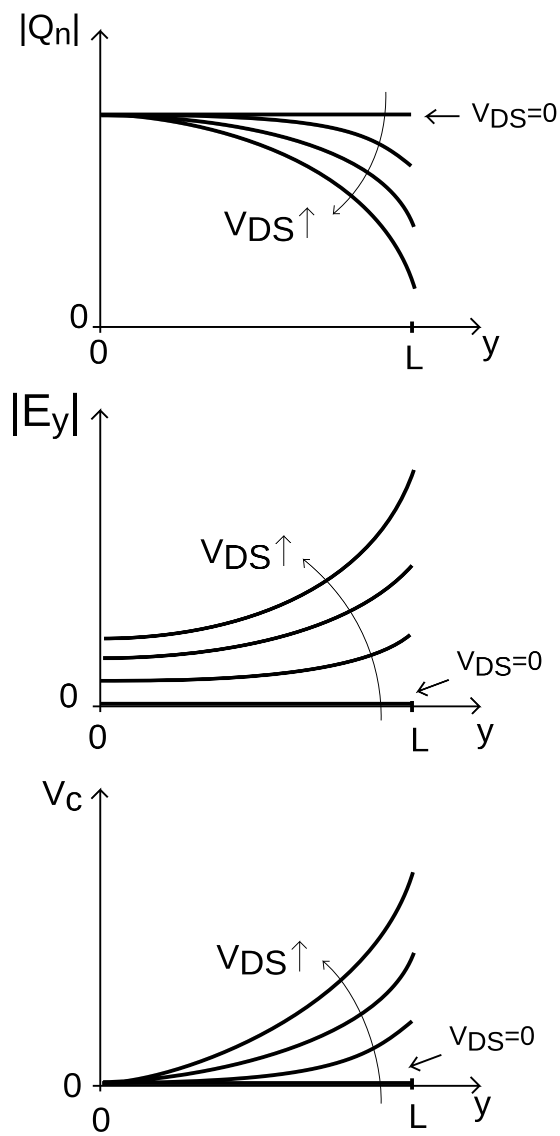
- *Linear*: $V_{GS} > V_T$, $V_{GD} > V_T$ (with $V_{DS} > 0$):
  inversion layer everywhere underneath gate

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

Output characteristics:



□ Review of Q_n, E_y, and V_c in linear regime as V_{DS} increases:



Ohmic drop along channel debiases inversion layer
$\Rightarrow$ current saturation

□ Drain current saturation

As V_{DS} approaches:

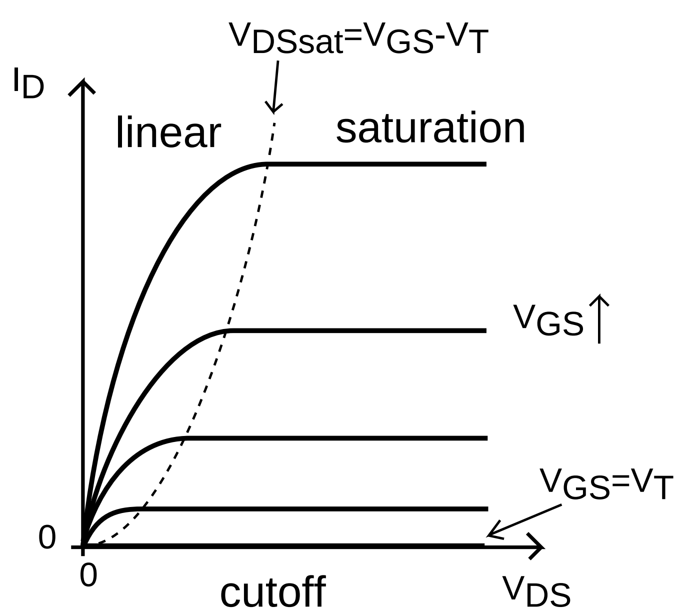
$$V_{DSsat} = V_{GS} - V_T$$

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

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

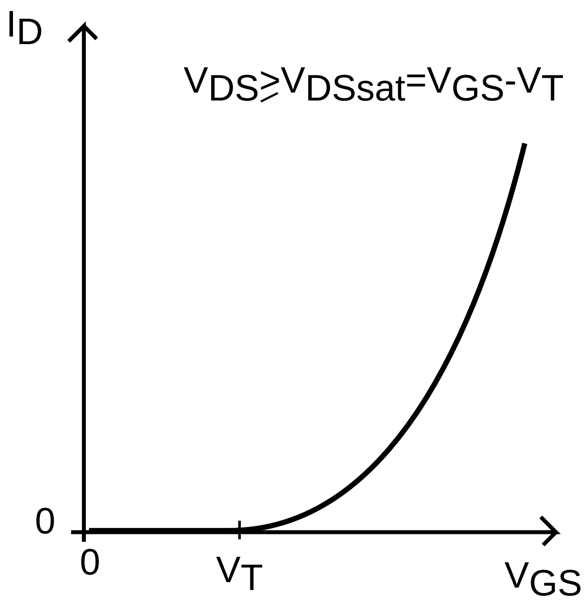
Then:

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



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

Transfer characteristics in saturation:



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

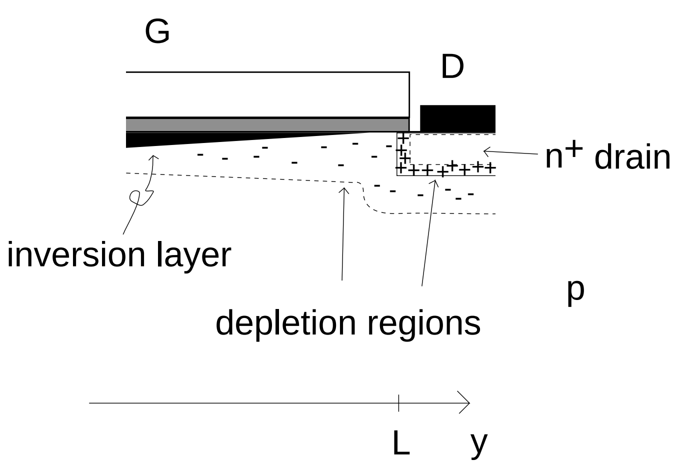
Charge control relation at drain-end of channel:

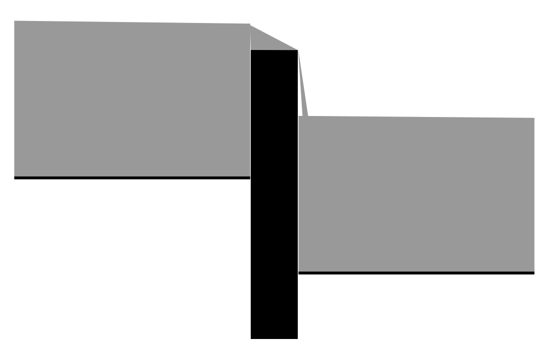
$$Q_n(L) = -C_{ox}(V_{GS} - V_{DS} - V_T) = 0$$

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!)

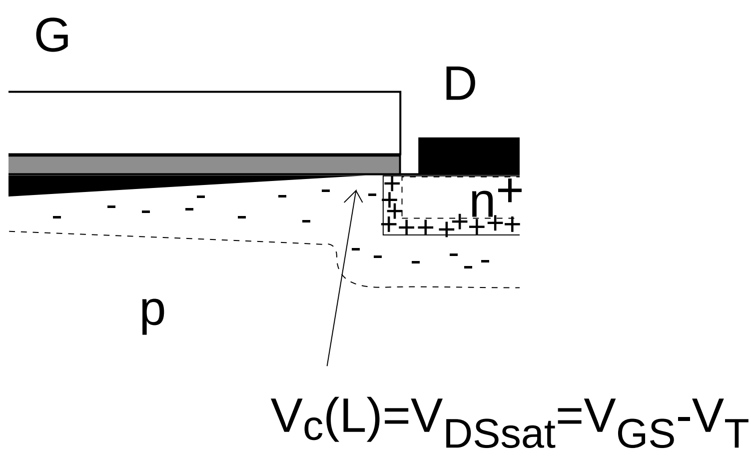




□ Key dependencies of I_{Dsat}

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

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



Drain current at pinch-off:

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

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

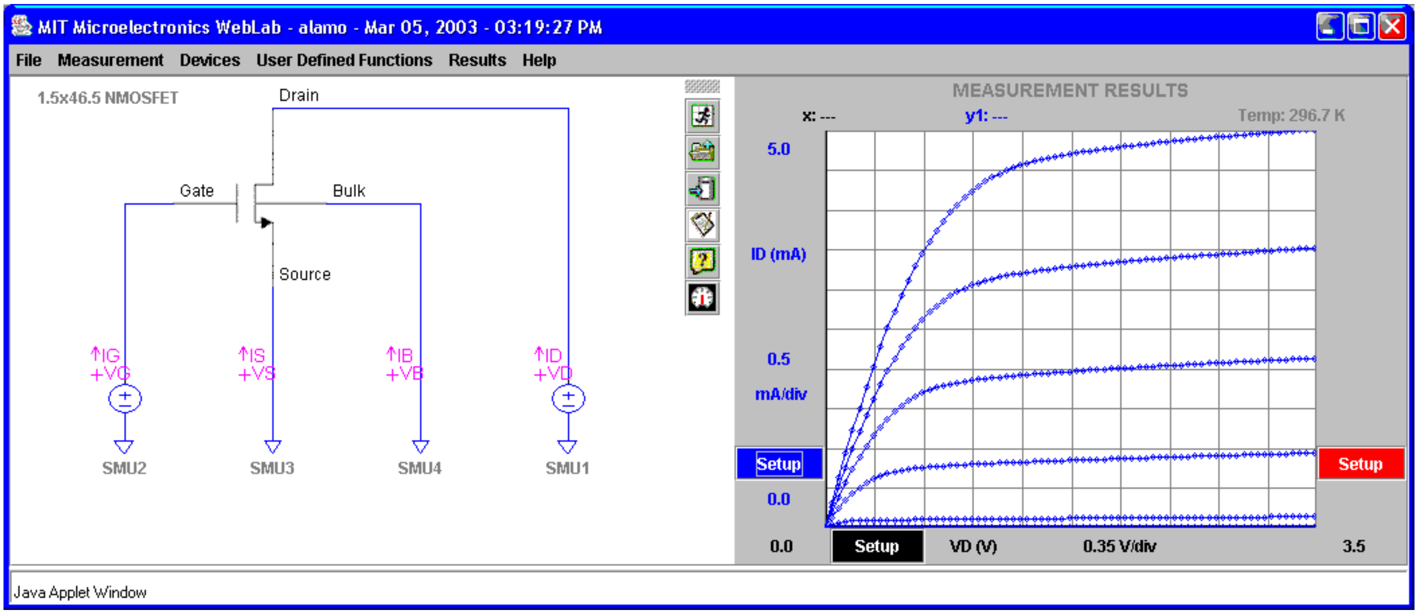
$$\Rightarrow I_{Dsat} \propto (V_{GS} - V_T)^2$$

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

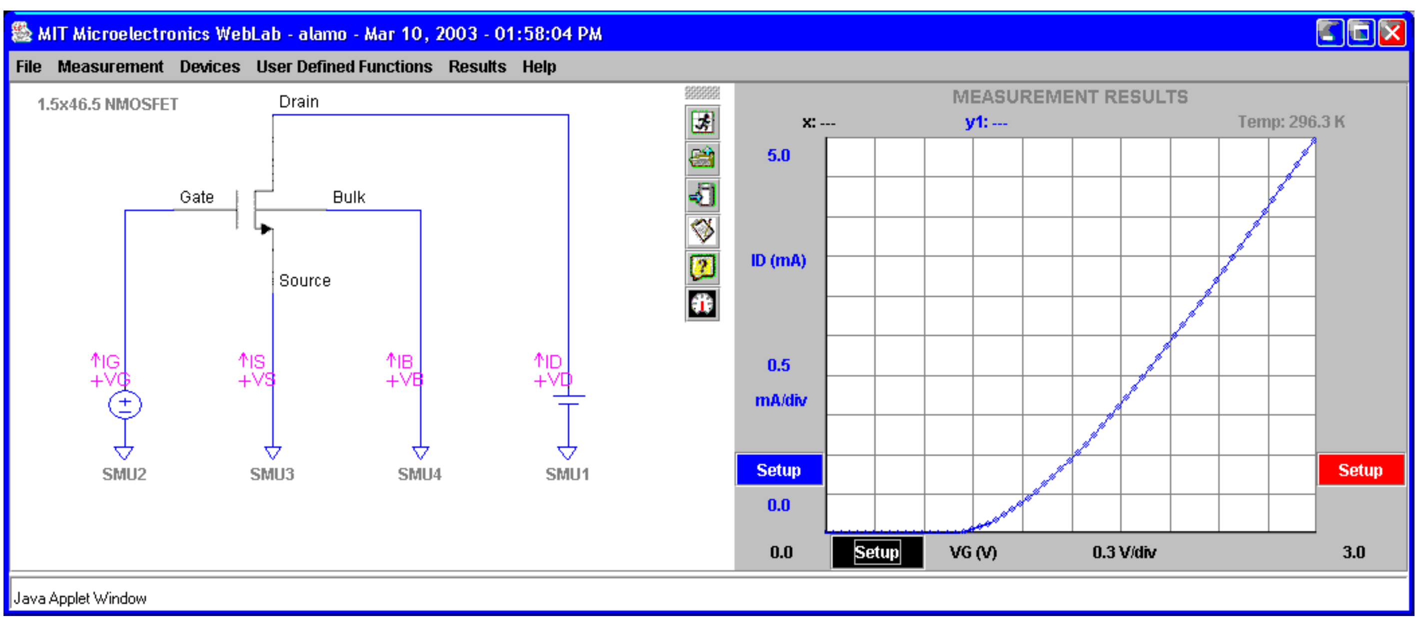
$L \downarrow \rightarrow \ |E_y| \uparrow$

1.5 × 46.5 NMOSFET

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

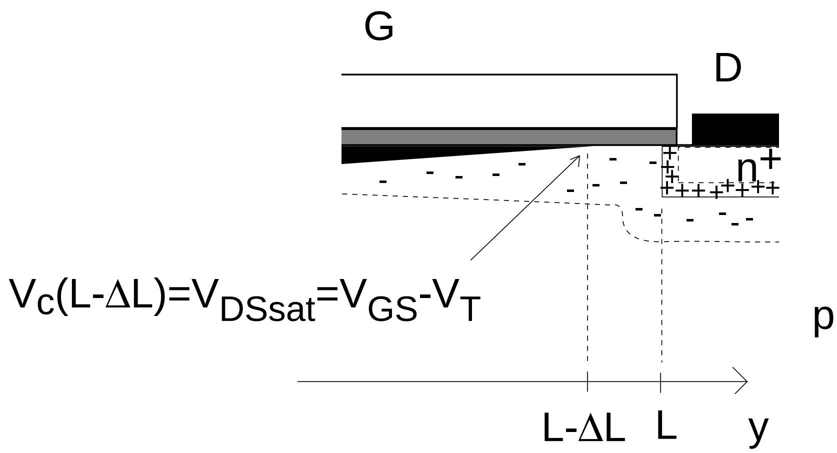


Transfer characteristics in saturation ($V_{DS} = 3\ V$):



□ 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:

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

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

$$I_D \propto \frac{1}{L - \Delta L} \simeq \frac{1}{L}\left(1 + \frac{\Delta L}{L}\right)$$

Experimental finding:

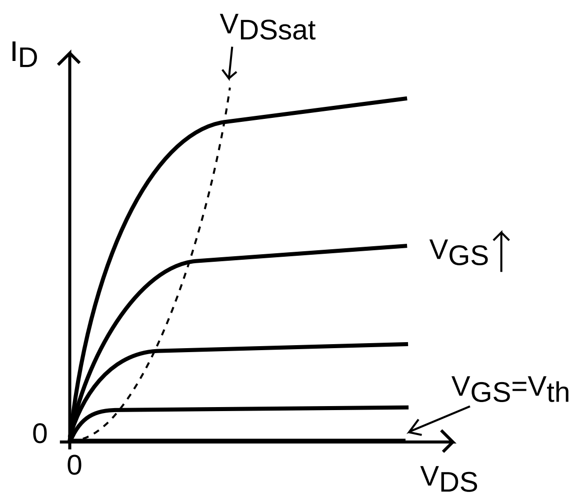
$$\Delta L \propto V_{DS} - V_{DSsat}$$

Hence:

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

Improved model in saturation:

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



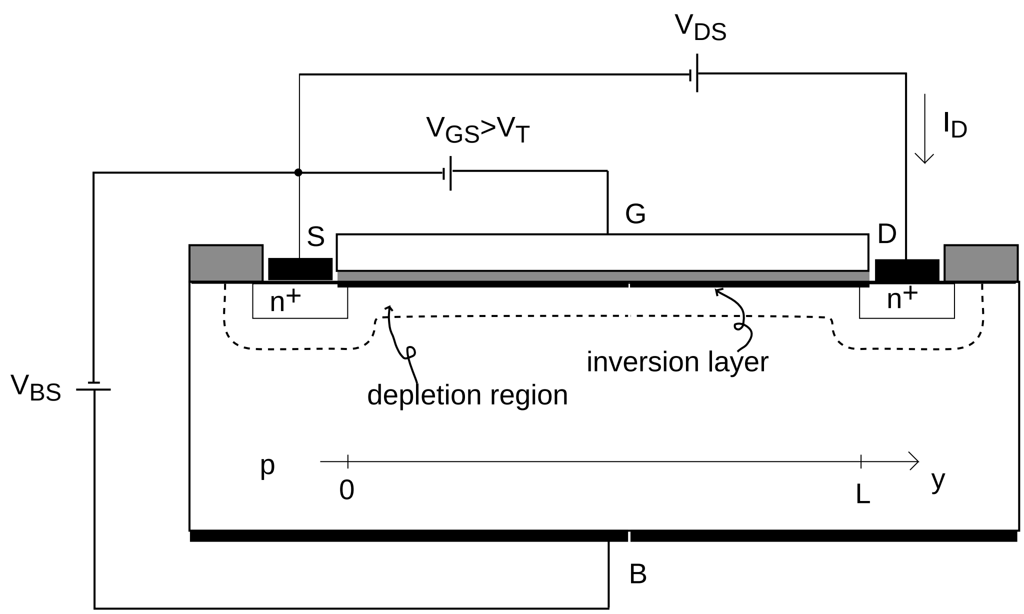
Also, experimental finding:

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

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}.

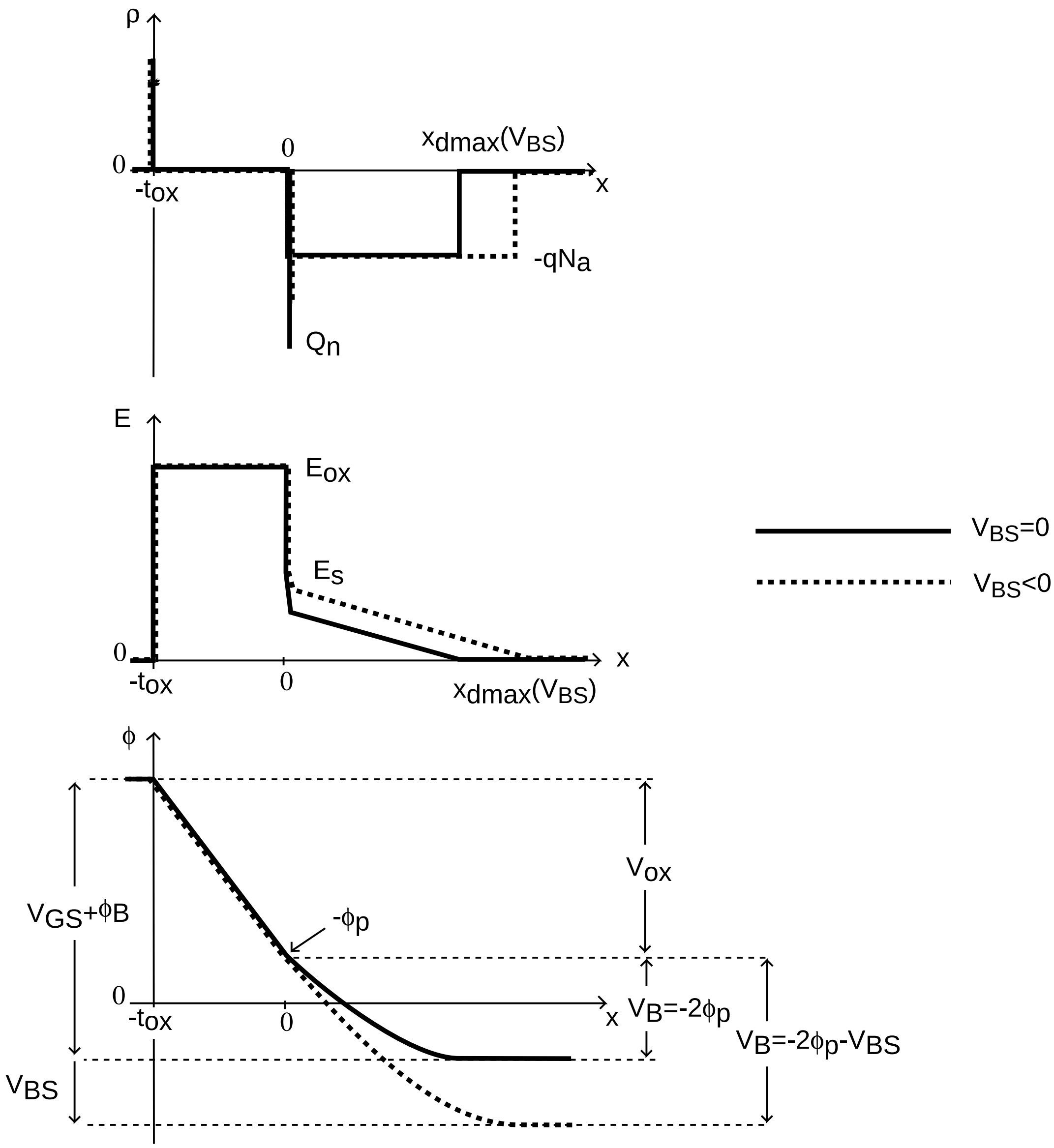
Only interested in $V_{BS} < 0$ (pn diode in reverse bias).

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

Application of V_{BSy}< 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 $V_{BSy}< 0$:

- $-2\phi_p \Rightarrow -2\phi_p - V_{BS}$
- $|Q_B| \uparrow \Rightarrow x_{dmax} \uparrow$
- 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 <u>source</u>:

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

Then:

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

And:

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

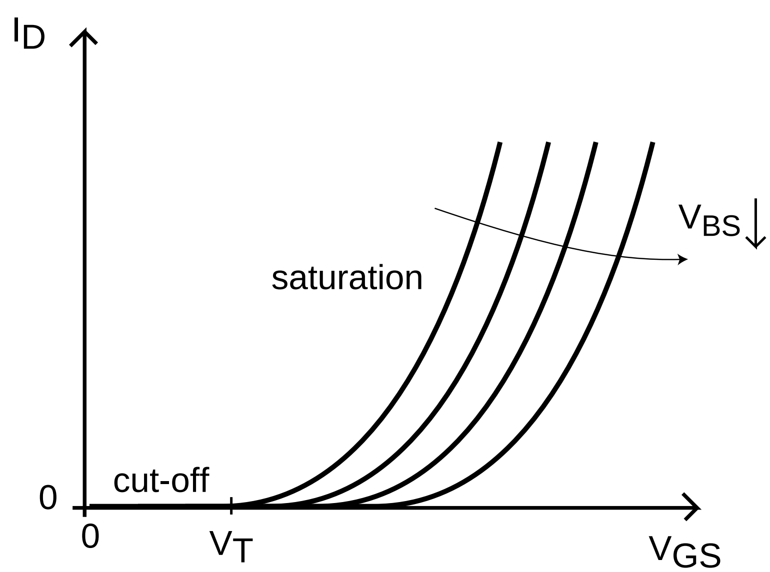
In the context of the MOSFET, V_T is always defined in terms of *gate-to-source voltage*.

Define:

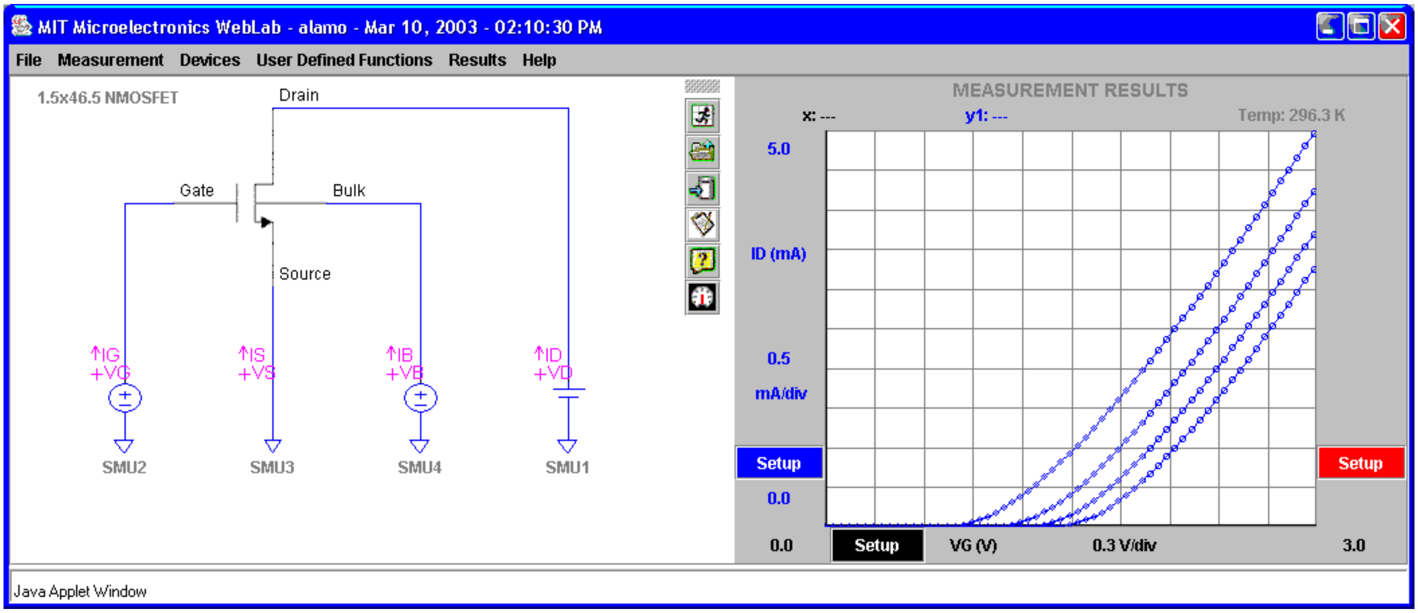
$$V_{To} = V_T(V_{BS} = 0)$$

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*)