# Lecture 26 - The "Long" Metal-Oxide-Semiconductor Field-Effect Transistor *(cont.)*

April 11, 2007

## Contents:

1. Current-voltage characteristics of ideal MOSFET *(cont.)*
2. Charge-voltage characteristics of ideal MOSFET

## Reading assignment:

del Alamo, Ch. 9, §§9.4 (9.4.3-9.4.5), 9.5

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# Key questions

- Why does the drain current in a MOSFET saturate at high $V_{DS}$?
- What charges should we keep track of as we construct a model for the charge-voltage characteristics of the MOSFET?

# 1. I-V characteristics of ideal MOSFET *(cont.)*

☐ Problems with MOSFET current model for linear regime as $V_{DS}$ approaches $V_{GS} - V_T$.

Problems centered around $y = L$:

- Local gate overdrive goes to zero $\Rightarrow |Q_i| \rightarrow 0$. How can current be supported?
- Gradual-channel approximation becomes invalid.
- Sheet-charge approximation becomes invalid.
- Lateral field so large that linearity between field and velocity invalid.

Model that can handle $V_{DS}$ values all the way up to $V_{GS} - V_T$ is rather complicated; but... actually, don't need new model!

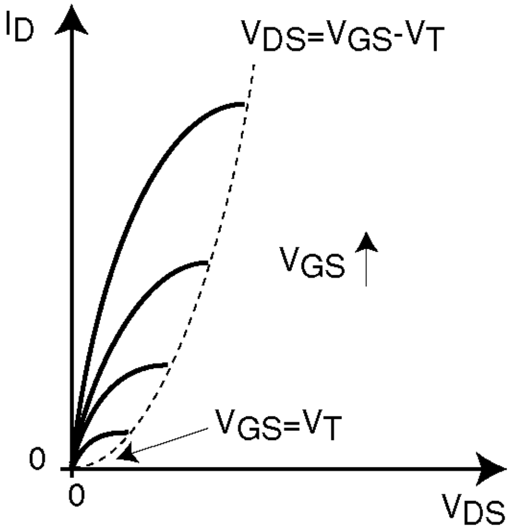
Reason: when $V_{DS}$ approaches $V_{GS} - V_T$, $I_D$ changes very little due to prominent debiasing on the drain side of the channel.

Ask a different question: how close can $V_{DS}$ get to $V_{GS} - V_T$ before simple model fails?

Answer:

- up to about 80% of $V_{GS} - V_T$
- which means up to about 96% of $I_{Dmax}$.

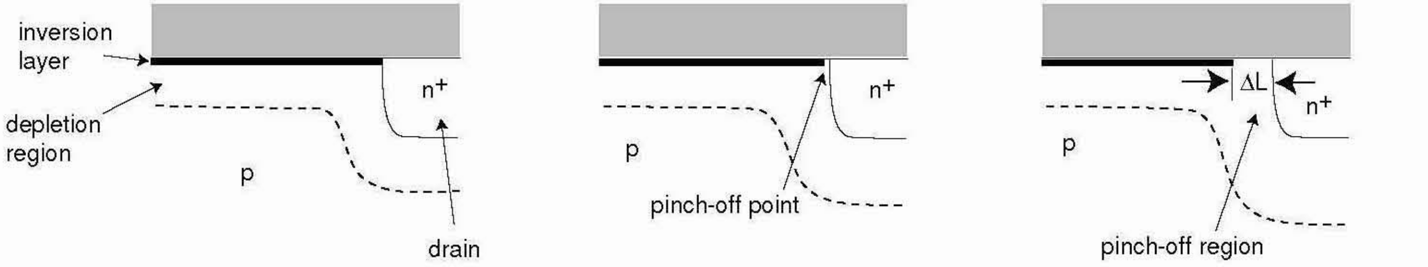
Hence, simple model is pretty good up to $V_{DS} = V_{GS} - V_T$.



□ What happens if $V_{DS}$ reaches or exceeds $V_{GS} - V_T$?

Electron concentration at $y = L$ drops to very small concentrations ⇒ depletion region appears at $y = L$: *pinch-off*.

Depletion region is no barrier to electron flow: field "pulls" electrons into drain.

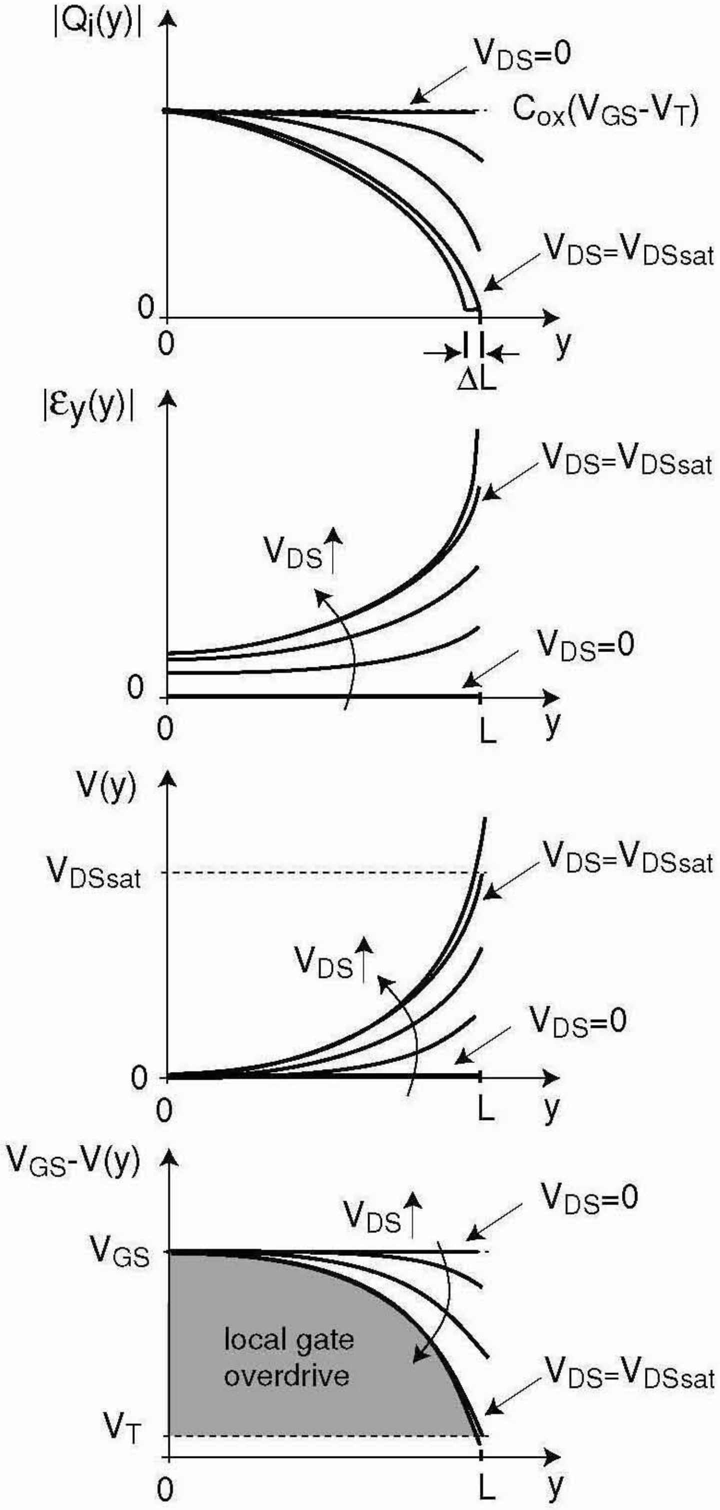


a) linear regime $V_{DS}<V_{DSsat}$ b) pinch-off $V_{DS}=V_{DSsat}$ c) saturation regime $V_{DS}>V_{DSsat}$

As $V_{DS}$ exceeds $V_{GS} - V_T$,

- depletion region widens into channel underneath gate;
- all extra voltage consumed in depletion region;
- electrostatics of channel, to first order, unperturbed;
- channel current unchanged ⇒ MOSFET in *saturation*.

# Lateral electrostatics in saturation:



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☐ Current model in saturation:

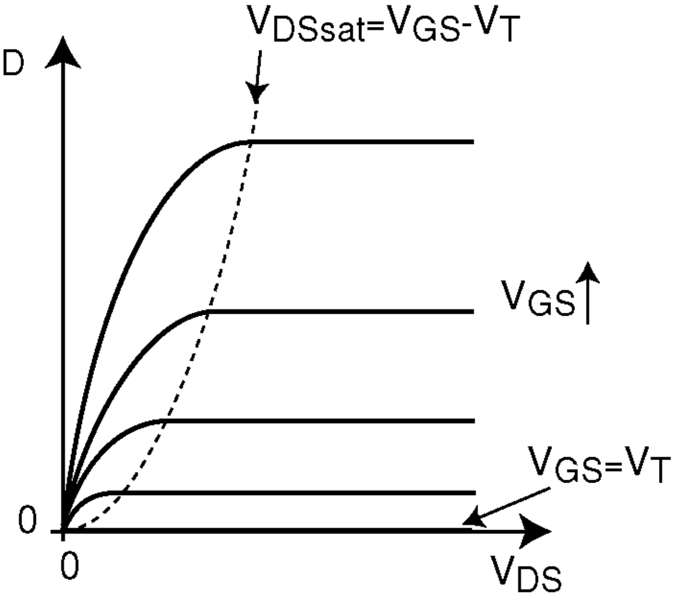
$I_D$ does not increase passed $V_{DS} = V_{GS} - V_T$. Hence, $I_{Dsat}$ is:

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

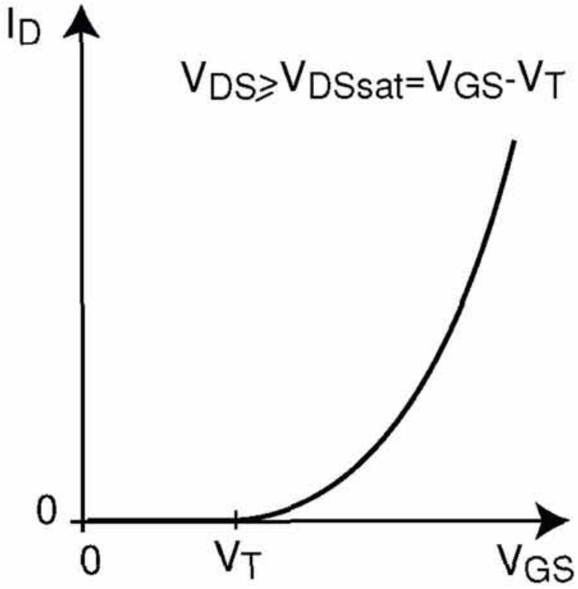
$V_{DS}$ at which transistor saturates is denoted as $V_{DSsat}$:

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

Current-voltage characteristics:



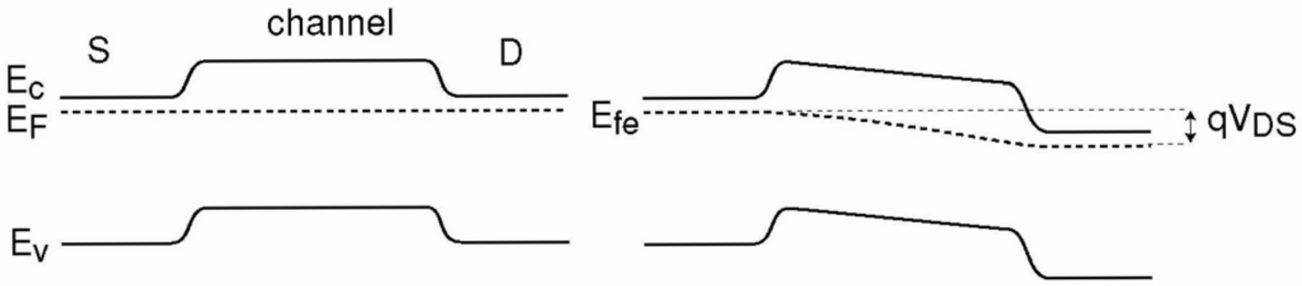
$$I_{Dsat} = \frac{W}{2L}\mu_e C_{ox}(V_{GS} - V_T)^2$$



Why square dependence?

- $V_{GS} \uparrow \Rightarrow |Q_i| \uparrow$
- $V_{GS} \uparrow \Rightarrow V_{DSsat} \uparrow \Rightarrow$ higher lateral field in channel at saturation.

□ Energy band diagrams ($V_{GS} > V_T$):

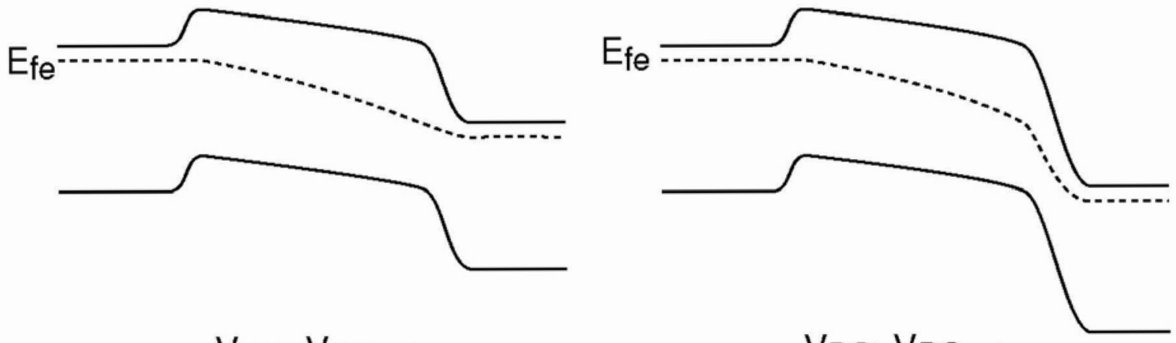


$V_{DS}=0$

a) linear

$0<V_{DS}<V_{DSsat}$

b) linear



$V_{DS}=V_{DSsat}$

c) pinch-off

$V_{DS}>V_{DSsat}$

d) saturation

Pinch-off point: region of "free fall" of electrons.

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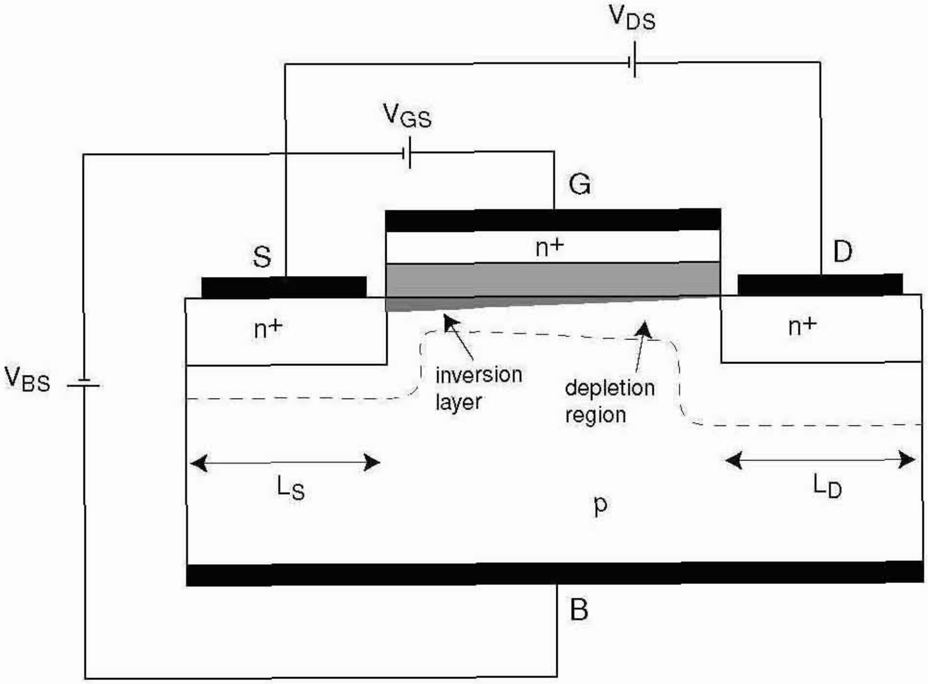
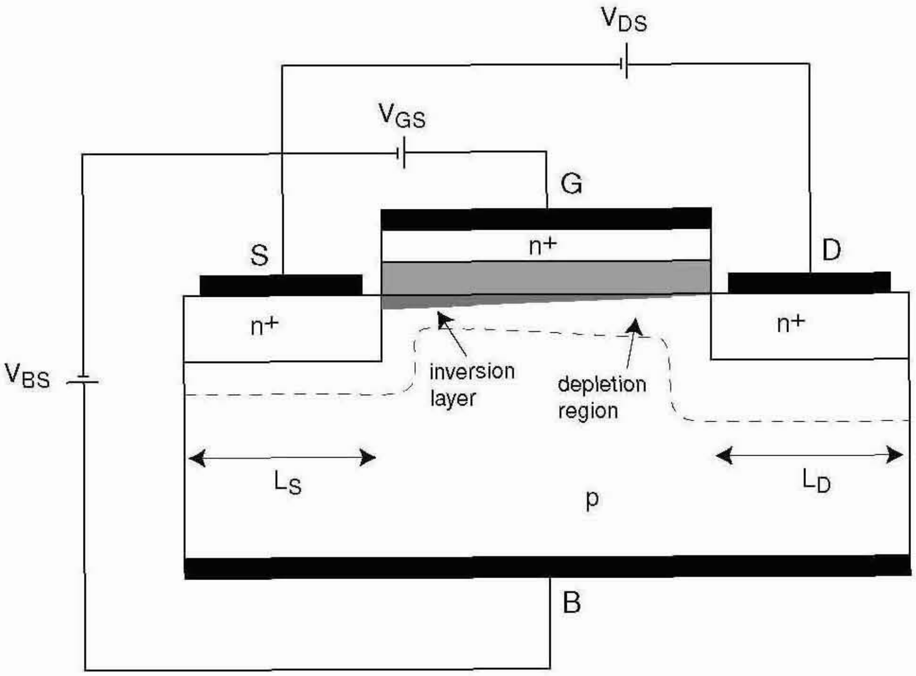
# 2. Charge-voltage characteristics of ideal MOSFET

Two types of stored charge in a MOSFET:

- depletion charge in:
  - source-body pn junction
  - drain-body pn junction
  - MOS structure
- inversion charge





□ Source-body junction depletion charge (assume strongly asymmetric junction):

$$Q_{jS} = L_S W \sqrt{2qN_B\epsilon(\phi_{bi} - V_{BS})}$$

Or

$$Q_{jS} = Q_{jSo}\sqrt{1 - \frac{V_{BS}}{\phi_{bi}}}$$

with

$$Q_{jSo} = L_S W \sqrt{2qN_B\epsilon\phi_{bi}}$$

□ Drain-body junction depletion charge (assume strongly asymmetric junction):

$$Q_{jD} = L_D W \sqrt{2qN_B\epsilon(\phi_{bi} - V_{BD})}$$

Or

$$Q_{jD} = Q_{jDo}\sqrt{1 - \frac{V_{BS} - V_{DS}}{\phi_{bi}}}$$

with

$$Q_{jDo} = L_D W \sqrt{2qN_B\epsilon\phi_{bi}}$$

☐ MOS depletion charge:

- In cut-off ($V_{GS} < V_T$):

There is no inversion layer. But there is a depletion layer:

$$Q_{jB} = L_G W \frac{1}{2}\gamma^2 C_{ox}[\sqrt{1 + 4\frac{V_{GB} - V_{FB}}{\gamma^2}} - 1]$$

Or

$$Q_{jB} = L_G W \frac{1}{2}\gamma^2 C_{ox}[\sqrt{1 + 4\frac{V_{GS} - V_{BS} - V_{FB}}{\gamma^2}} - 1]$$

Increases with $V_{GS}$.

- In linear and saturation regimes ($V_{GS} > V_T$):

$$Q_{jBmax} = L_G W \frac{1}{2}\gamma^2 C_{ox}[\sqrt{1 + 4\frac{V_T - V_{BS} - V_{FB}}{\gamma^2}} - 1]$$

Independent of $V_{GS}$.

Depletion charge gives rise to capacitive effects:

☐ Source-body junction capacitance:

$$C_{jS} = \frac{C_{jSo}}{\sqrt{1 - \frac{V_{BS}}{\phi_{bi}}}}$$

with

$$C_{jSo} = L_S W \sqrt{\frac{\epsilon q N_B}{2\phi_{bi}}}$$

☐ Drain-body junction capacitance:

$$C_{jD} = \frac{C_{jDo}}{\sqrt{1 - \frac{V_{BS}-V_{DS}}{\phi_{bi}}}}$$

with

$$C_{jDo} = L_D W \sqrt{\frac{\epsilon q N_B}{2\phi_{bi}}}$$

In general, $C_{jD} < C_{jS}$, because $L_S = L_D$ and $V_{DS} > 0$.

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☐ MOS depletion capacitance:

- In cut-off:

$$C_{jB} = \frac{L_G W C_{ox}}{\sqrt{1 + 4\frac{V_{GB}-V_{FB}}{\gamma^2}}}$$

- In linear and saturation regimes:

$$C_{jB} = 0$$

# Key conclusions

- MOSFET current in saturation regime:

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

- Value of $V_{DS}$ that saturates transistor:

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

- Three types of depletion charge in a MOSFET:
  - source-body pn junction
  - drain-body pn junction
  - MOS structure

- In saturation, capacitance associated with depletion layer under MOS structure:

$$C_{jB} = 0$$