Lecture 9 - MOSFET (I)

MOSFET I-V Characteristics

October 6, 2005

Contents:

1. MOSFET: cross-section, layout, symbols
2. Qualitative operation
3. I-V characteristics

Reading assignment:

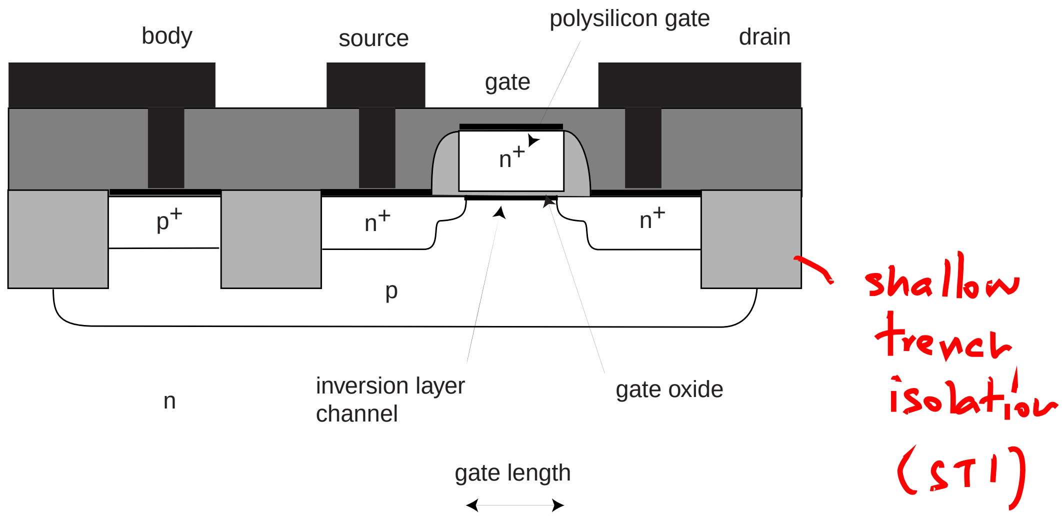
Howe and Sodini, Ch. 4, §§4.1-4.3

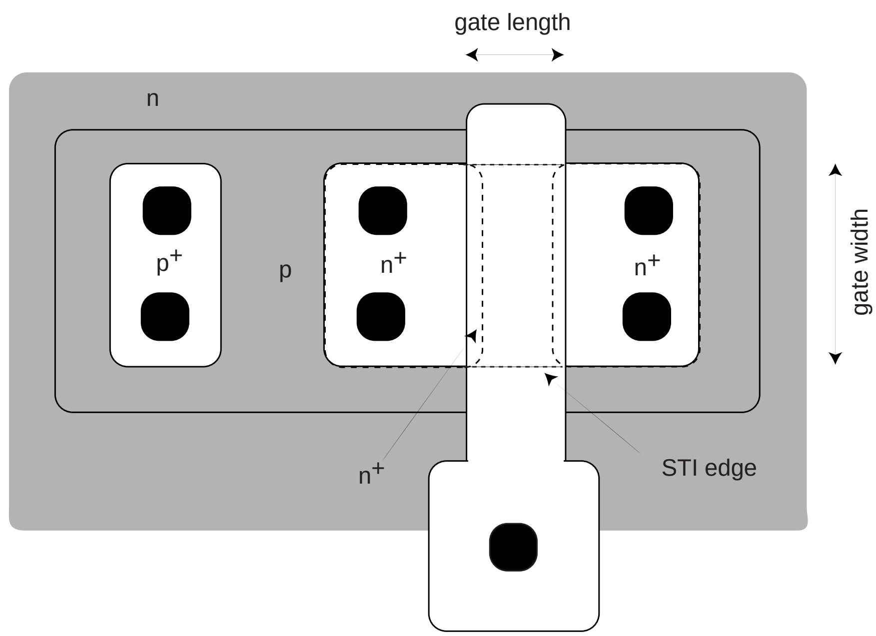
Announcements: Quiz 1: 10/13, 7:30-9:30 PM, (lectures #1-9); open book; must have calculator.

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





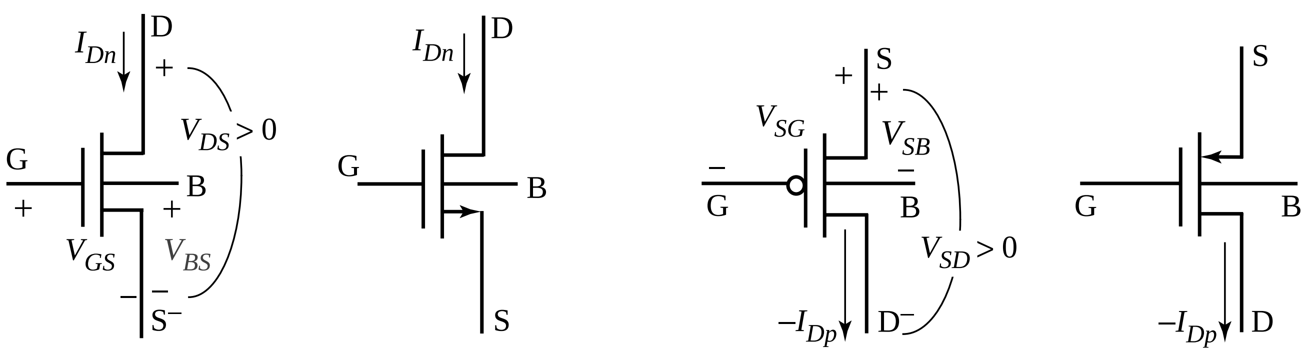
Key elements:

- inversion layer under *gate* (depending on gate voltage)
- heavily-doped regions reach underneath gate ⇒ inversion layer electrically connects *source* and *drain*
- 4-terminal device: *body* voltage important

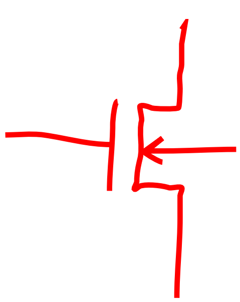
□ Circuit symbols

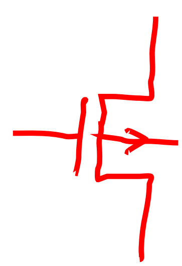
Two complementary devices:

- 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

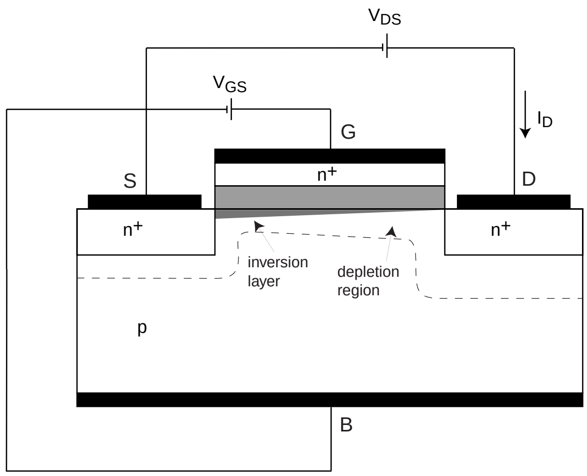


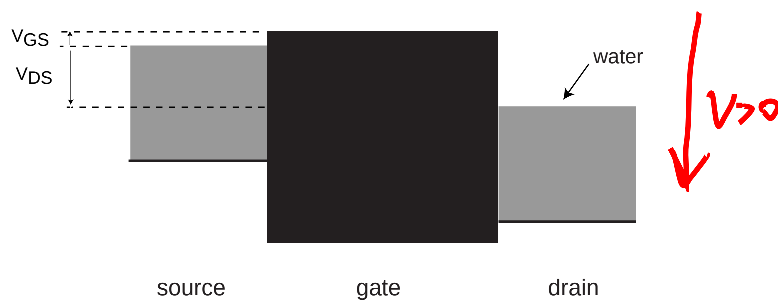


2. Qualitative operation

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)

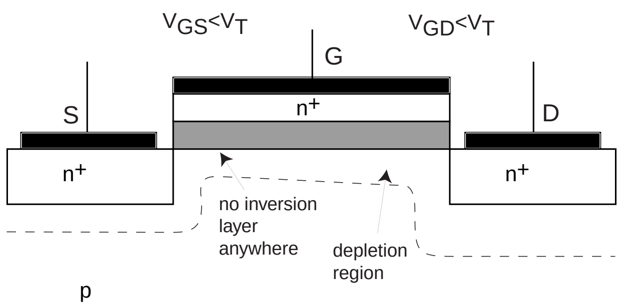
Initially consider source tied up to body (substrate or back).

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.



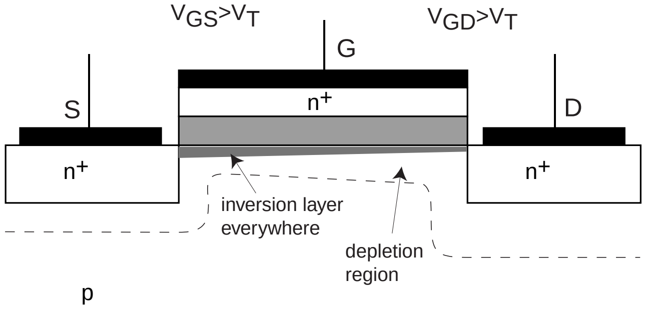
no water flow

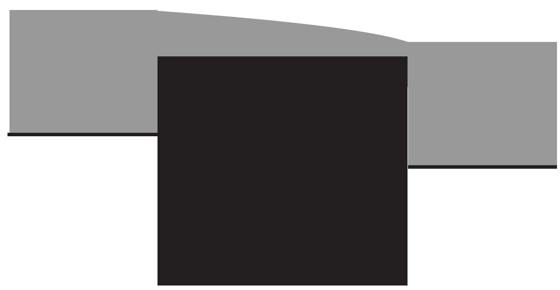
$I_D = 0$

□ ***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.

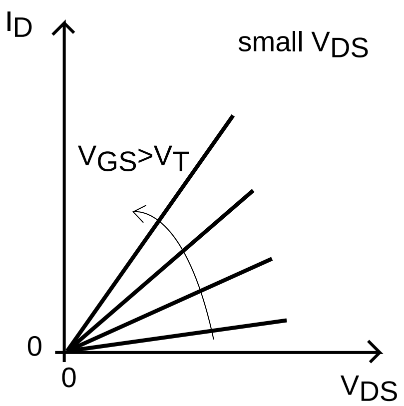


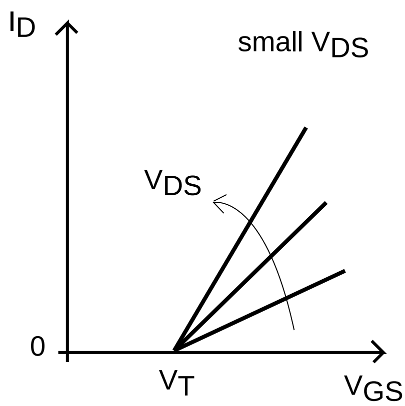


Electrons drift from source to drain ⇒ electrical current!

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

• $V_{DS} \uparrow \rightarrow \ |E_y| \uparrow \rightarrow I_D \uparrow$

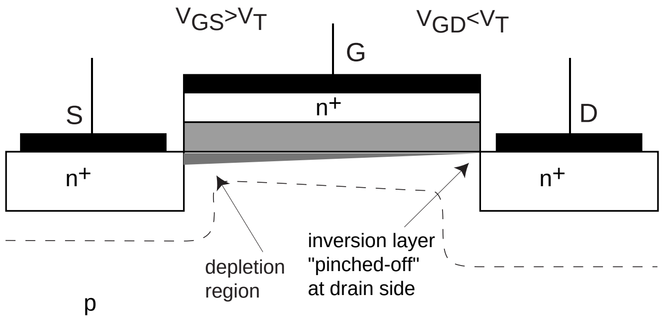




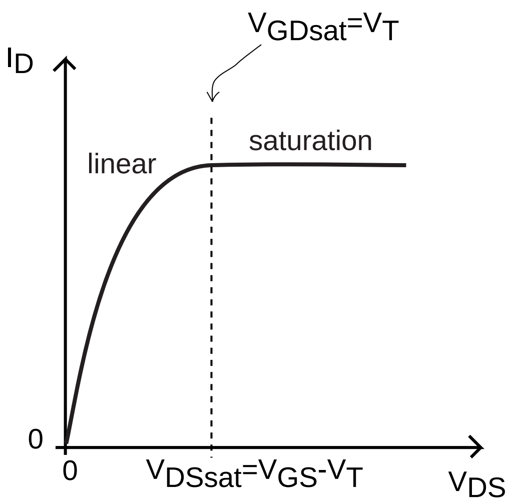
☐ *Saturation regime:*

- 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 ⇒ total flow independent of relative reservoir height!

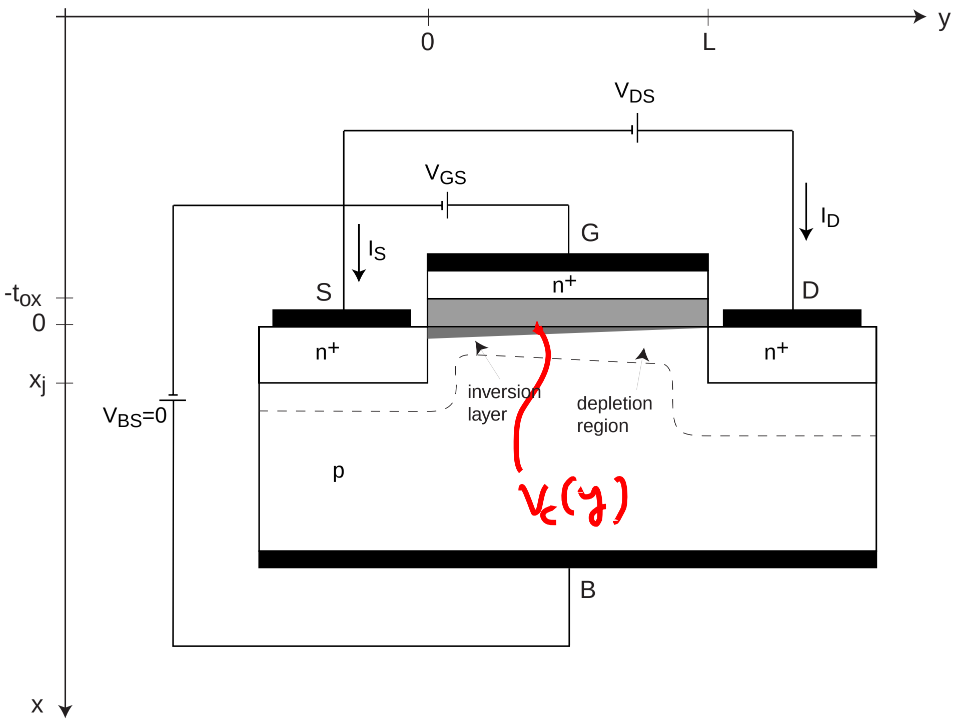


I_D independent of V_{DS}: $I_D = I_{Dsat}$



3. I-V characteristics

Geometry of problem:



☐ General expression of channel current

Current can only flow in y-direction:

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

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

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

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

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:

local channel voltage "overdrive"

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

gate-channel voltage

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:

source end → for $y = 0$, $V_c(0) = 0$

drain end → 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:

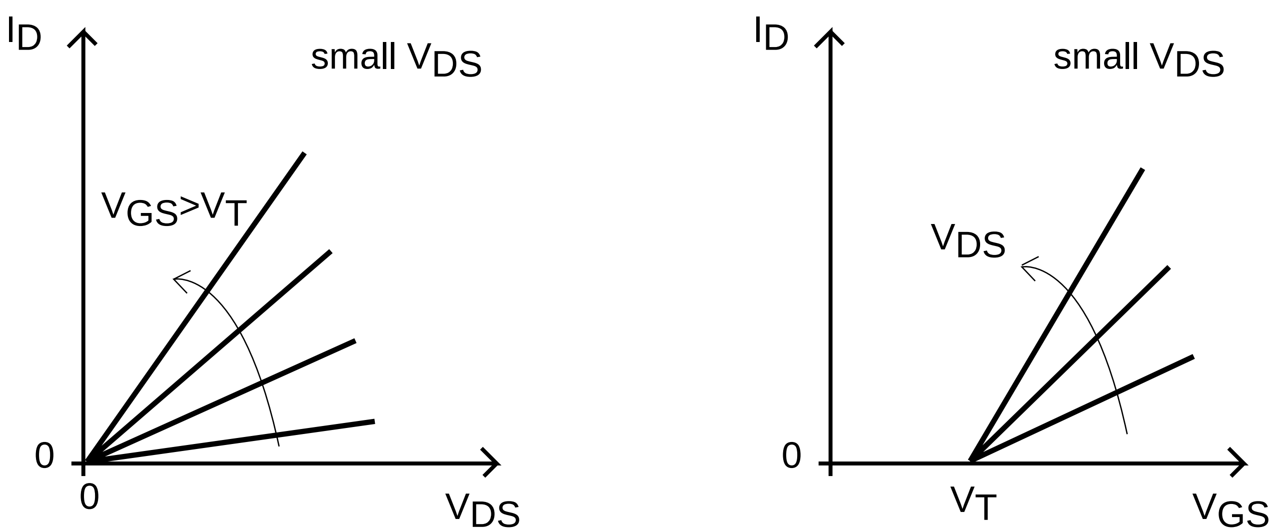
$$\boxed{I_D = \frac{W}{L}\mu_n C_{ox}(V_{GS} - \frac{V_{DS}}{2} - V_T)V_{DS}}$$ *

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,

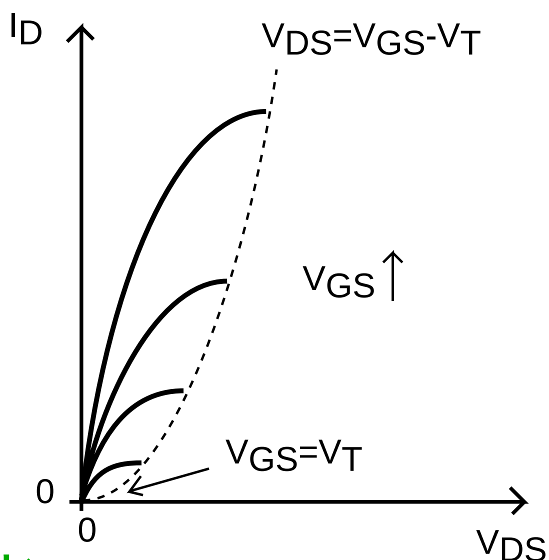
$$I_D = \frac{W}{L}\mu_n C_{ox}(V_{GS} - \frac{V_{DS}}{2} - V_T)V_{DS}$$

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:

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

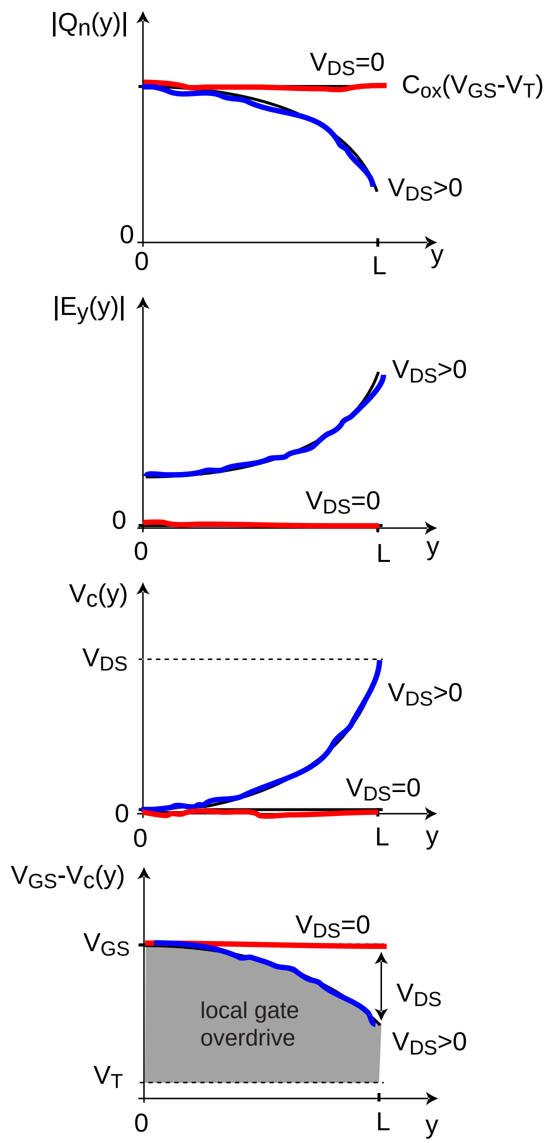
locus of linear regime with $V_{DS} > 0$



Note: $\frac{dI_D}{dV_{DS}} \to 0$ as $V_{DS} \to V_{GS} - V_T$

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.

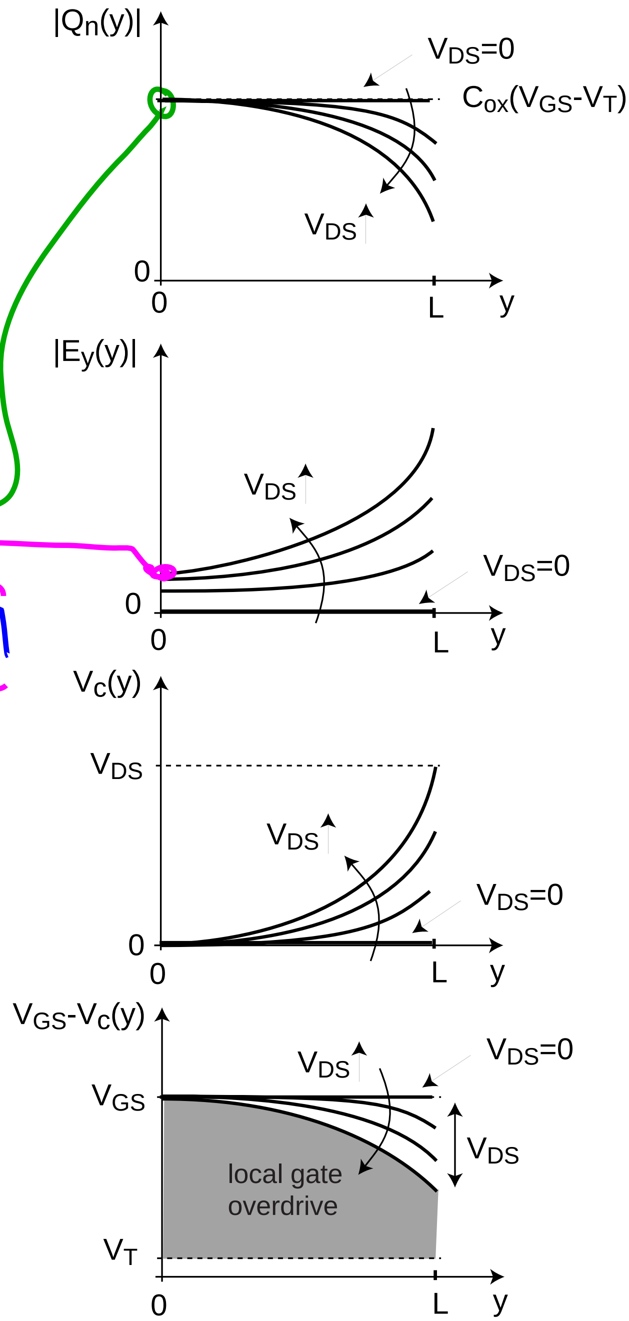
Impact of V_{DS}:

Think of current at source end of channel:

$I_D = W\mu_n |Q_n(0)| |E_y(0)|$

$|Q_n(0)| = C_{ox}(V_{GS}-V_T)$; $|E_y(0)|$ increases with V_{DS}

channel debiasing

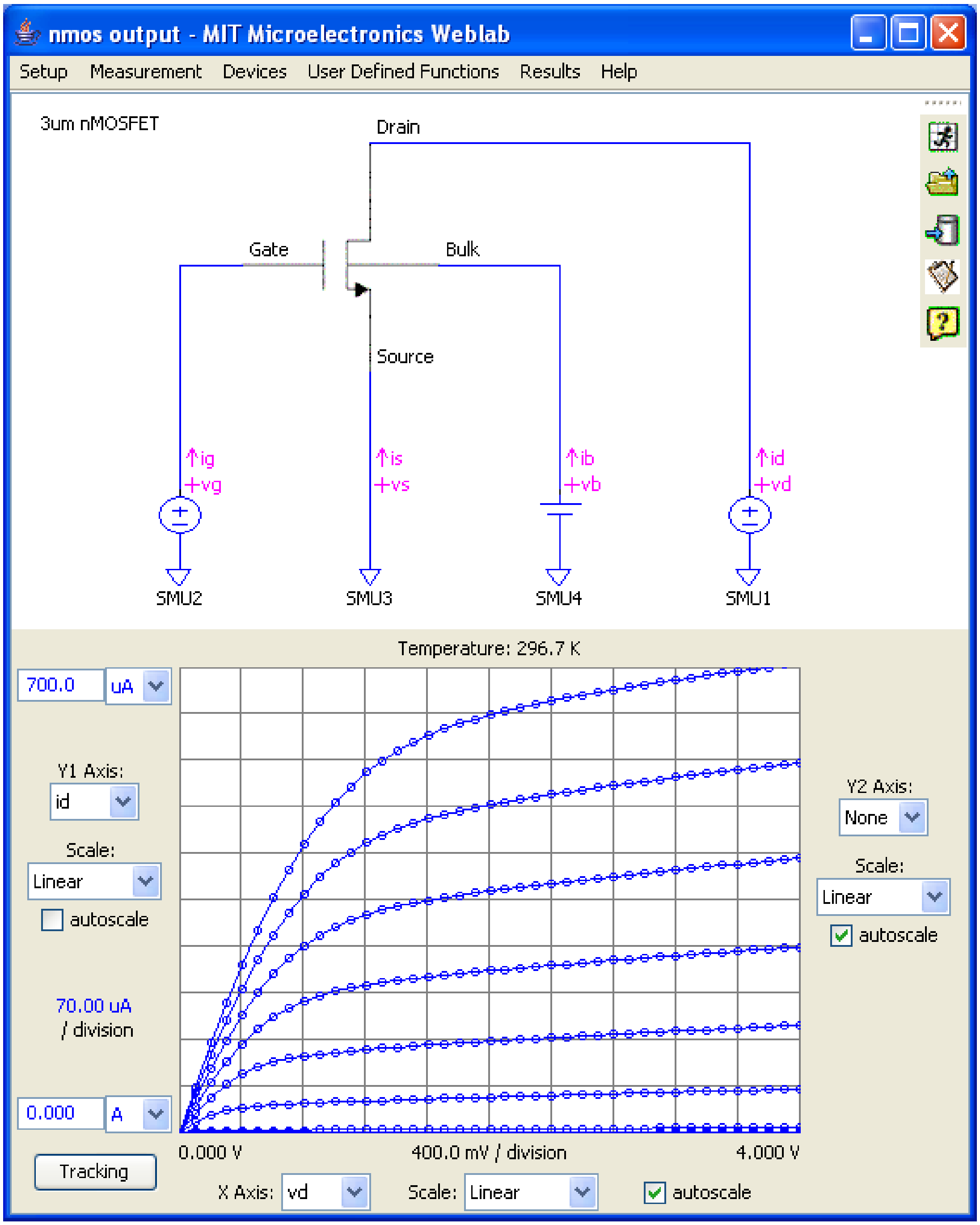


As $V_{DS}\uparrow$, channel debiasing more prominent

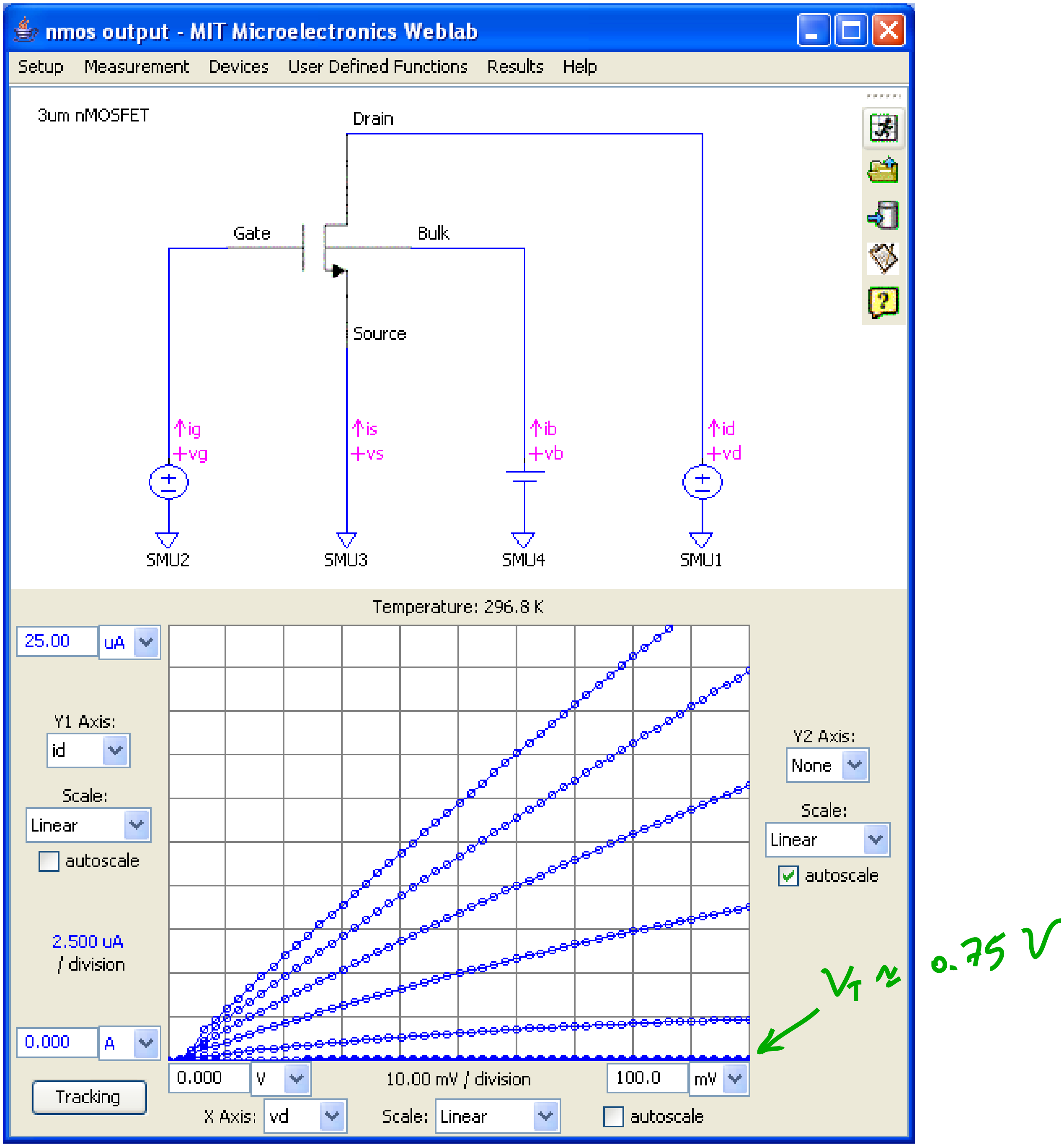
$\Rightarrow I_D$ rises more slowly with V_{DS}

$3\mu m$ n-channel MOSFET

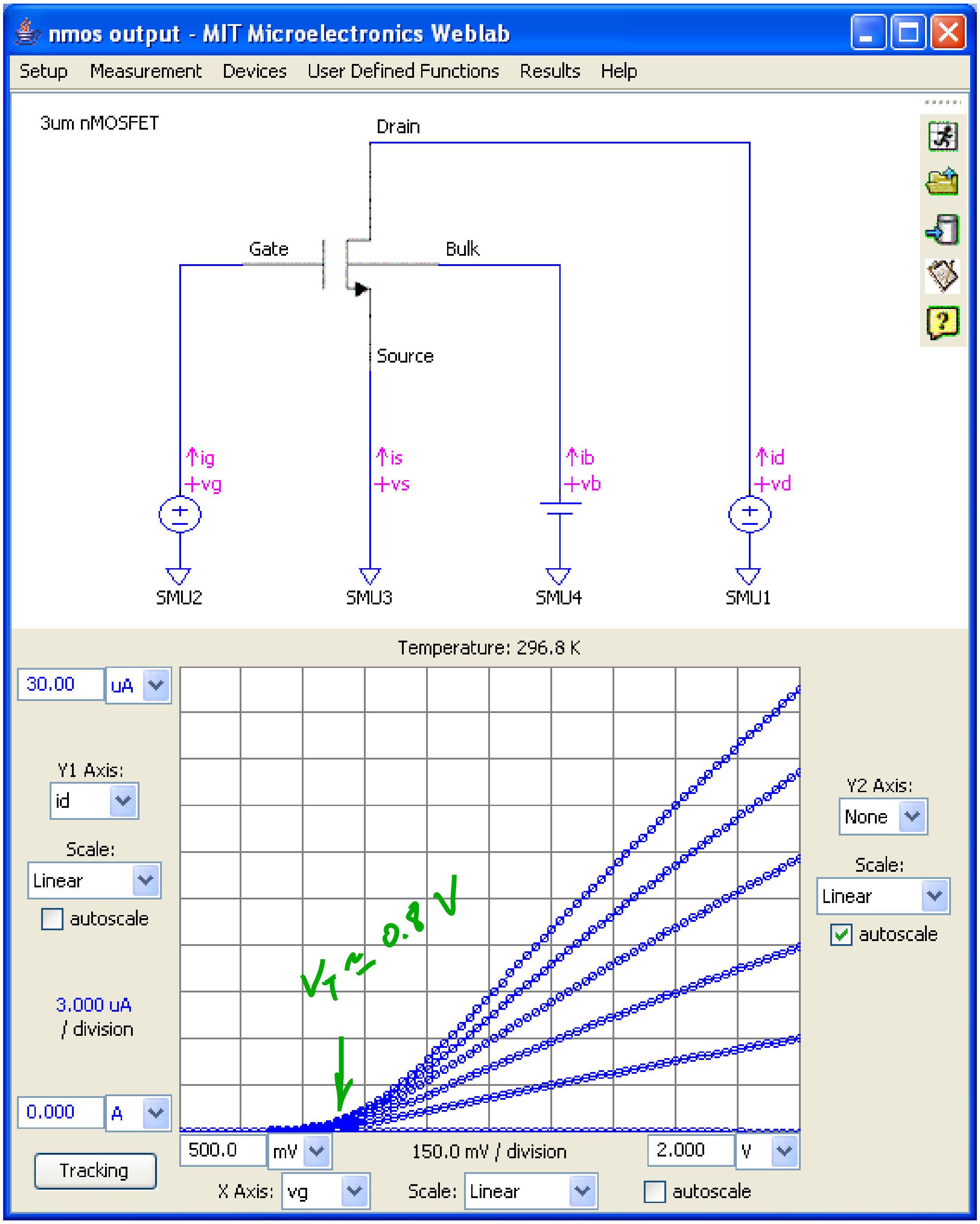
Output characteristics $(V_{GS} = 0 - 4\ V, \Delta V_{GS} = 0.5\ V)$:



Zoom close to origin ($V_{GS} = 0 - 2\ V, \Delta V_{GS} = 0.25\ V$):



Transfer characteristics ($V_{DS} = 0 - 100\ mV, \Delta V_{DS} = 20\ mV$):



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:

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