Lecture 10 - MOSFET (II)

MOSFET I-V Characteristics (cont.)

March 13, 2001

Contents:

1. The saturation regime
2. Backgate characteristics

Reading assignment:

Howe and Sodini, Ch. 4, §4.4

Announcements: Quiz #1, March 14, 7:30-9:30 PM, Walker Memorial; covers Lectures #1-9; open book; must 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 ($V_{BS} = 0$):

- **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

  $$I_D = \frac{W}{L} \mu_n C_{ox} (V_{GS} - \frac{V_{DS}}{2} - V_T) V_{DS}$$
- **Saturation**: $V_{GS} > V_T$, $V_{GD} < V_T$ ($V_{DS} > 0$):
  inversion layer "pinched-off" at drain end of channel

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

Output characteristics:

![Graph showing the output characteristics of a MOSFET with linear, saturation, and cutoff regions.]
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
What happens when $V_{DS} = V_{GS} - V_T$?

Charge control relation at drain:

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

No inversion layer at end of channel??!! ⇒ *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!)
Voltage at pinch-off point ($V = 0$ at source):

\[ V(L) = V_{DS_{sat}} = V_{GS} - V_T \]

Drain current at pinch-off:

\[ \propto \text{lateral electric field} \propto V_{DS_{sat}} = V_{GS} - V_T \]

\[ \propto \text{electron concentration} \propto V_{GS} - V_T \]

\[ \Rightarrow I_{D_{sat}} \propto (V_{GS} - V_T)^2 \]

Also, $L \downarrow \rightarrow |E_y| \uparrow$:

\[ I_{D_{sat}} \propto \frac{1}{L} \]
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:

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

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

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

$$\Delta L \propto V_{DS} - V_{DS_{sat}}$$

Hence:

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

Improved model in saturation:

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

Also, experimental finding:

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

Typical value:

$$\lambda = \frac{0.1 \, \mu m \cdot V^{-1}}{L}$$

for $L = 1 \, \mu m$, increase of $V_{DS}$ of 1 V past $V_{DS_{sat}}$ results in increase in $I_D$ of 10%.
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 $-2\phi_p - V_{BS}$:

$$V_{GB}^{TB}(V_{BS}) = V_{FB} - 2\phi_p - V_{BS} + \frac{1}{C_{ox}} \sqrt{2\epsilon_s q N_a (-2\phi_p - V_{BS})}$$

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

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

Then:

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

And:

$$V_{GS}^{TB}(V_{BS}) = V_{FB} - 2\phi_p + \frac{1}{C_{ox}} \sqrt{2\epsilon_s q N_a (-2\phi_p - V_{BS})} \equiv V_T(V_{BS})$$

In the context of the MOSFET, $V_T$ is always defined in terms of gate-to-source voltage.
\[ V_T(V_{BS}) = V_F - 2\phi_p + \frac{1}{C_{ox}} \sqrt{2\epsilon_s q N_a (-2\phi_p - V_{BS})} \]

Define *backgate effect parameter* [units: \( V^{-1/2} \)]:

\[ \gamma = \frac{1}{C_{ox}} \sqrt{2\epsilon_s q N_a} \]

And:

\[ V_{To} = V_T(V_{BS} = 0) \]

Then:

\[ V_T(V_{BS}) = V_{To} + \gamma (\sqrt{-2\phi_p - V_{BS}} - \sqrt{-2\phi_p}) \]
Key conclusions

- MOSFET in saturation ($V_{DS} \geq V_{DS_{sat}}$): *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

- $I_{D_{sat}}$ increases slightly in saturation regime due to *channel length modulation*

- Application of back bias shifts $V_T$