ECE 2C, notes set 2: Active Devices

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Goals of this note set:

Rough physical sense of FET operation

FET current - voltage characteristics.

Rough mathematical models of MOSFETs
  old - fashioned mobility - limited model.
  slightly less - old - fashioned velocity - limited model
N-Channel MOSFET

N-channel MOSFET:

Gate: $V_{gs} = 0$

Drain: $V_{ds}$

Source: $I_D = I_S$
Field-Effect Transistor Operation

Positive Gate Voltage
→ reduced energy barrier
→ increased drain current
Field-Effect Transistor Operation

Positive Gate Voltage
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N-Channel MOSFET

Plot common-source characteristics:

- Ohmic region
- Constant-current region

$V_{gs} = V_{th}$
Physical Sketch

Top view:

- Gate
- Source
- Drain
- Oxide, dielectric constant
- Thickness $T_{ox}$
- $N^+$
- $P^+$
- Electrons
- $W_g$
MOSFET Physical Structure

Cross-Section

- N+ source
- N+ drain
- P substrate
- Gate oxide
- N+ poly gate
- Gate metal (silicide)
- Dielectric sidewall
- Source contact (silicide)
- Drain contact (silicide)

Layout

- (6 FETs, each of gate width \(W_g\), connected in parallel)
If we have drain voltages above the knee voltage:

\[ \text{ID NOT HERE} \quad \text{HERE} \]

\[ V_{DS} \]
MOSFET I-V characteristics

Then we can plot $I_D$ vs $V_{gs}$:

There are 3 regions in the $I_D$ - $V_{gs}$ curve:
1) Subthreshold: $I_D \approx (V_{gs} - V_{th})^2 (1 + NW_{eq})$
2) Mobility-limited: $I_D \approx (V_{gs} - V_{th}) (1 + NW_{eq})$
3) Velocity-limited: $I_D \approx (V_{gs} - V_{th}) (1 + NW_{eq})$
MOSFETs: Three Regions of Gate Voltage

When $V_{gs}$ is less than threshold, transistor is (almost) off: "subthreshold"

When $V_{gs}$ is a little above threshold, current is mobility – limited

$$I_{D,\mu} \propto (V_{gs} - V_{th})^2$$

When $V_{gs}$ is far above threshold, current is velocity – limited

$$I_{D,v} \propto (V_{gs} - V_{th} - \Delta V)$$
MOSFET DC Characteristics: Mobility-Limited Case

 mobility – limited current :

\[
I_{D,\mu} = \left( \mu c_{ox} W_g / 2L_g \right) (V_{gs} - V_{th})^2 (1 + \lambda V_{DS})
\]

Applies for drain voltages larger than the knee voltage,
MOSFET DC Characteristics: Velocity-Limited Case

**velocity - limited current**

\[
I_{D,v} = c_{ox} W g v_{sat} (1 + \lambda V_{DS})(V_{gs} - V_{th} - \Delta V)
\]

\[
\Delta V = v_{sat} L_g / \mu
\]

Applies for drain voltages larger than the knee voltage,
DC Characteristics---Far Above Threshold

\[ I_d \approx c_{ox} W_g v_{sat} (V_{gs} - V_{th} - \Delta V) \quad \text{for} \quad \frac{(V_{gs} - V_{th})}{\Delta V} \gg 1 \]

where \( \Delta V = \frac{v_{sat} L_g}{\mu} \)

We will ignore the \( \Delta V \) term in ece2C, but please use it in your more advanced classes.
\[ \nu_{sat} = \text{saturation drift velocity} \sim 10^7 \text{ cm/s for N-MOSFETs} \]

\[ \mu = \text{carrier mobility at surface} \sim 300 - 400 \text{ cm}^2/(\text{V} \cdot \text{s}) \text{ for N-MOSFET} \]

For P-channel FETs, both \( \nu_{sat} \) and \( \mu \) are about half that of N-FETs

\[ \c_{ox} = \text{gate capacitance per unit area} = \epsilon_r \epsilon_0 / T_{ox} \quad (\epsilon_r = 3.8 \text{ for SiO}_2) \]

\[ T_{ox} = \text{equivalent oxide thickness} \sim \text{about 1 nm} = 10^{-9} \text{ m} \]

\[ V_{th} \text{ threshold voltage} \sim \text{usually 0.2 - 0.4 V for modern N-FETs} \]

\( \lambda \) gives slope of output characteristics: \( 1/\lambda \) typically 3 - 20 V
Knee Voltage: Mobility-Limited Case

The knee voltage defines the boundary between the Ohmic and constant-current regions.

In the mobility-limited regime, 

\[ V_{GD} = V_{th} \]

the knee in curve occurs when

\[ V_{dg} = V_{ds} - V_{gs} = -V_{th} \]

The Knee Voltage is further increased by voltage drops across the parasitic source & drain resistances.
Knee Voltage: Velocity-Limited Case

In the velocity-limited regime, the knee in curve occurs when $V_{ds} = \frac{v_{sat} L_g}{\mu}$

Again, the Knee Voltage is further increased by voltage drops across the parasitic source & drain resistances.
Which Model to use When?

If \( V_{gs} - V_{th} < \Delta V \) where \( \Delta V = \frac{\nu_{sat} L_g}{\mu} \), use the constant-mobility model.

If \( V_{gs} - V_{th} > \Delta V \), use the constant-velocity model.

\[ \Delta V = \frac{\nu_{sat} L_g}{\mu} \]
Linear vs. Square-Law Characteristics: 90 nm

Sorin Voinigescu, CSICS RF & High Speed CMOS, Nov. 12, 2006
Which Model to use When?

For 90nm CMOS, $AV$ is about 0.2-0.3V

For 45nm CMOS, $AV$ is about 0.15V

Short gate length devices obey the velocity model.

- but-

Short gate length devices have very low breakdown voltage.

- so-

Analog circuit design is very hard with short-gate-length devices.
N - channel
\[ g_m/W_g = c_{ox}v_{sat} = 1.4 \text{ mS/\mu m} = 1.4 \text{ S/mm} \]
\[ V_{th} = 0.6 \text{ V} \quad 1/\lambda \sim 3\text{V} \]

P - channel
\[ g_m/W_g = c_{ox}v_{sat} = 0.7 \text{ mS/\mu m} = 0.7 \text{ S/mm} \]
\[ |V_{th}| = 0.6 \text{ V} \quad 1/\lambda \sim 3\text{V} \]
180 nm MOSFET DC Characteristics

\[
g_m / W_g = c_{ox} v_{sat} = 35 \text{mA} / (2 \text{V} \cdot 80 \mu\text{m})
\]
\[
= 0.22 \text{mS} / \mu\text{m} = 0.22 \text{S} / \text{mm}
\]

This is lower than typical of a 180 nm device

\[V_{th} = 0.5 \text{ V}\]
P-Channel MOSFET

\[ V_{gs} \]  
\[ V_{gs} \]  
\[ V_{gs} \]  
\[ V_{gs} \]  
\[ V_{gs} \]

To turn the device on, the gate must be more negative than the source, by an amount exceeding the threshold voltage \( V_{th} \).
P-Channel MOSFET

\[
I_D = \min\left(\sqrt{\frac{W_g}{L}}, V_g - V_{th}\right) \left\{ -\left(V_{gs} - V_{th}\right)^2 \left(1 + AV_{gs}\right) \right\} \\
I_D = V_{sat}\sqrt{\frac{W_g}{L}} \left\{ -\left(V_{gs} - V_{th} - AV\right) \left(1 + AV_{gs}\right) \right\}
\]
The device is in the constant current region if \( V_{ds} \) above the knee voltage.

Example: Constant mobility model:

knee \( \Rightarrow V_{dg} < -V_{th} \)

Example: Suppose the threshold voltage is \(-1V\).

Then the P-MOSFET is in the constant current region if the drain is at most \(-1V\) more positive than the gate.