EE330
Integrated Electronics

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Devices in Semiconductor Processes

Resistors, Diodes, Capacitors, MOSFETs, BJTs
Basic Devices

- Resistor
- Diode
- Capacitor
- MOSFET
- BJT
The MOSFET is a 4-terminal device. We will start by considering the 4th terminal (the bulk) always connected to the source to develop a model, then the impact of the 4th terminal (the bulk) will be appended to the model later.

Let's start with the n-channel MOSFET.
N-Channel MOSFET
• Depletion region is always created whenever there is an interface between an n-type and a p-type material.
Apply a very small $V_{GS}$ (assume $V_{DS}$ very small and $V_{BS} = 0$) → depletion region continues to develop underneath the gate, but the device is off → no current flow from drain to source → This region of operation is called the “cutoff” region.

$I_D = 0$
$I_G = 0$
$I_B = 0$
As you increase $V_{GS}$ (assume $V_{DS}$ very small and $V_{BS} = 0$) → depletion region underneath the gate continues to grow but the device continues to be off → Still in the “cutoff” region.
As you further increase $V_{GS}$ (assume $V_{DS}$ very small and $V_{BS}=0$) → the area underneath the gate starts to be inverted → It becomes an n-type layer

The value of $V_{GS}$ at which inversion takes place is called the threshold voltage ($V_t$)

Current flows between the drain and the source and the device behaves like a thin film resistor → This region of operation is called the “triode” or “linear” or “ohmic” region

$V_{DS}$ very small and $V_{BS}=0$

$\begin{align*}
I_D &= V_{DS} \\
I_G &= 0 \\
I_B &= 0
\end{align*}$
N-Channel MOSFET: Triode Region

- With $V_{DS}$ very small $\rightarrow$ The device behaves like a resistor between the drain and the source.
- The resistance will strongly depend on $V_{GS}$ and the transistor size.
- Larger $V_{GS} \rightarrow$ deeper inversion layer $\rightarrow$ less channel resistance.
- Wider transistor $\rightarrow$ wider channel $\rightarrow$ less channel resistance.
- Longer transistor $\rightarrow$ longer channel $\rightarrow$ more channel resistance.

For $V_{DS}$ small

- $I_D = \mu C_{OX} \frac{W}{L} (V_{GS} - V_T) V_{DS}$
- $I_G = I_B = 0$

$$R_{CH} = \frac{L}{W} \mu C_{OX} \frac{1}{(V_{GS} - V_T)}$$
N-Channel MOSFET: Triode Region

- Since the channel resistance is controlled by $V_{GS}$, it is termed a Voltage Controlled Resistance (VCR)

For $V_{DS}$ small

$$R_{CH} = \frac{L}{W \mu C_{OX}} \left( \frac{1}{V_{GS} - V_T} \right)$$
N-Channel MOSFET: Triode Region

- What happens when we now start increasing $V_{DS}$?
- The channel starts to become thinner towards the drain side $\Rightarrow$ So channel resistance becomes different $\Rightarrow$ Nonlinear behavior $\Rightarrow$ The drain current starts to become nonlinear with respect to $V_{DS}$
- Yet, we continue to call this region of operation “triode” or “linear” or “ohmic”
We now must take into account the nonlinearity in the channel resistance and drain current.

For small $V_{DS}$:

$$I_D = \mu C_{OX} \frac{W}{L} \left( V_{GS} - V_T \right) V_{DS}$$

$$R_{CH} = \frac{L}{W} \frac{1}{\mu C_{OX} \left( V_{GS} - V_T \right)}$$

$I_G = I_B = 0$

For $V_{DS}$ larger:

$$I_D = \mu C_{OX} \frac{W}{L} \left( V_{GS} - V_T - \frac{V_{DS}}{2} \right) V_{DS}$$

$I_G = I_B = 0$
If we further increase $V_{GS}$ the inversion layer disappears at the drain side.

The critical values at which this happens $\rightarrow V_{DS} = V_{GS} - V_T$

Increasing $V_{DS}$ beyond that critical value no longer changes the channel $\rightarrow$ The drain current stops increasing with $V_{DS}$.

This region of operation is called the “saturation” region.

![Diagram of N-Channel MOSFET in saturation region](image)

Increase $V_{DS}$ even more

$V_{BS} = 0$

$I_D = ?$

$I_G = 0$

$I_B = 0$
**N-Channel MOSFET: Saturation Region**

- The drain current gets stuck at its value when \( V_{DS} = V_{GS} - V_T \) regardless of what the actual \( V_{DS} \) is (as long as it is larger than the critical value of \( V_{GS} - V_T \))

For \( V_{DS} > V_{GS} - V_T \)

\[ I_G = I_B = 0 \]

\[ V_{BS} = 0 \]

\[ I_D = \mu C_{OX} \frac{W}{L} \left( V_{GS} - V_T - \frac{V_{DS}}{2} \right) V_{DS} \] in triode region

Since the voltage across the channel gets stuck at \( V_{GS} - V_T \), then:

\[ I_D = \mu C_{OX} \frac{W}{L} \left( V_{GS} - V_T - \frac{V_{GS} - V_T}{2} \right) (V_{GS} - V_T) \]

or equivalently → \[ I_D = \frac{\mu C_{OX} W}{2L} (V_{GS} - V_T)^2 \]
**N-Channel MOSFET: Saturation Region**

- With $V_{DS} > (V_{GS} - V_T)$ → The device behaves like a current source between the drain and the source.
- The value of the current will strongly depend on $V_{GS}$ and the transistor size.
- Larger $V_{GS}$ → deeper inversion layer → larger current.
- Wider transistor → wider channel → larger current.
- Longer transistor → longer channel → less current.

\[ I_D = \mu C_{OX} \frac{W}{2L} (V_{GS} - V_T)^2 \]

\[ I_D = \mu C_{OX} \frac{W}{2L} (V_{GS} - V_T)^2 \]
Since the current is controlled by $V_{GS}$, it is termed a Voltage Controlled Current Source (VCCS).

For $V_{DS} > V_{GS} - V_T$

$$I_D = \mu C_{OX} \frac{W}{2L} (V_{GS} - V_T)^2$$
**N-Channel MOSFET: Model Summary**

- This is the third model we introduced for the MOSFET →
  It is termed the Ideal Square-Law model of the transistor

\[
I_D = \begin{cases} 
0 & \text{if } V_{GS} \leq V_T \\
\mu C_{OX} \frac{W}{L} \left( V_{GS} - V_T - \frac{V_{DS}}{2} \right) V_{DS} & \text{if } V_{GS} \geq V_T, \ V_{DS} < V_{GS} - V_T \\
\mu C_{OX} \frac{W}{2L} \left( V_{GS} - V_T \right)^2 & \text{if } V_{GS} \geq V_T, \ V_{DS} \geq V_{GS} - V_T 
\end{cases}
\]

- Deep triode is a special case of the triode operation when \( V_{DS} \ll V_{GS} - V_T \)
- In this case the transistor is modeled as a resistor

\[
I_D \approx \mu C_{OX} \frac{W}{L} \left( V_{GS} - V_T - \frac{V_{DS}}{2} \right) V_{DS} \rightarrow R_{CH} = \frac{L}{W \mu C_{OX} \left( V_{GS} - V_T \right)}
\]
N-Channel MOSFET: Model Summary

What does the above model of the transistor mean exactly?

- The transistor behaves like an open circuit between the drain and the source in the cutoff region.
- The transistor behaves like a nonlinear (depends on $V_{DS}$) VCR between the drain and the source in the triode region. In deep triode, the resistance can be assumed linear (independent of $V_{DS}$).
- The transistor behaves like an ideal VCCS between the drain and the source in the saturation region (independent of $V_{DS}$).
- The value of the resistance in the triode region, and the value of the current source in the saturation region are determined by $V_{GS}$ and transistor size.

\[
I_D = \begin{cases} 
0 & V_{GS} \leq V_T \\
\mu C_{OX} \frac{W}{L} \left( V_{GS} - V_T - \frac{V_{DS}}{2} \right) V_{DS} & V_{GS} \geq V_T, V_{DS} < V_{GS} - V_T \\
\mu C_{OX} \frac{W}{2L} (V_{GS} - V_T)^2 & V_{GS} \geq V_T, V_{DS} \geq V_{GS} - V_T \\
I_G = I_B = 0 &
\end{cases}
\]
N-Channel MOSFET: Model Summary

This is a nonlinear model characterized by the functions $f_1$, $f_2$, and $f_3$ where we have assumed that the port voltages $V_{GS}$ and $V_{DS}$ are the independent variables and the terminal currents are the dependent variables.

\[
\begin{align*}
I_D &= \begin{cases} 
0 & V_{GS} \leq V_T \\
\mu C_{OX} \frac{W}{L} \left( V_{GS} - V_T - \frac{V_{DS}}{2} \right) V_{DS} & V_{GS} \geq V_T, \ V_{DS} < V_{GS} - V_T \\
\mu C_{OX} \frac{W}{2L} (V_{GS} - V_T)^2 & V_{GS} \geq V_T, \ V_{DS} \geq V_{GS} - V_T
\end{cases} \\
I_G &= I_B = 0
\end{align*}
\]

where

\[
I_D = f_1 \left( V_{GS}, V_{DS} \right) \\
I_G = f_2 \left( V_{GS}, V_{DS} \right) \\
I_B = f_3 \left( V_{GS}, V_{DS} \right)
\]
The operation the n-channel MOSFET can be described graphically in all regions.

At the border between triode and saturation

\[ V_{DS} = V_{GS} - V_T \rightarrow I_D = \mu C_{ox} \frac{W}{2L} V_{DS}^2 \]

\[
I_D = \begin{cases} 
0 & \text{for } V_{GS} \leq V_T \\
\mu C_{ox} \frac{W}{L} \left( V_{GS} - V_T - \frac{V_{DS}}{2} \right) V_{DS} & \text{for } V_{GS} \geq V_T, V_{DS} < V_{GS} - V_T \\
\mu C_{ox} \frac{W}{2L} \left( V_{GS} - V_T \right)^2 & \text{for } V_{GS} \geq V_T, V_{DS} \geq V_{GS} - V_T \\
I_G = I_B = 0 & 
\end{cases}
\]