Devices in Semiconductor Processes

- Diodes
- Capacitors
- MOSFETs
Which model should be used?

The simplest model that will give acceptable results in the analysis of a circuit.
Example: Determine $I_{OUT}$ for the following circuit

Solution:

Strategy:
1. Assume PWL model with $V_D=0.6V$, $R_D=0$
2. Guess state of diode (ON)
3. Analyze circuit with model
4. Validate state of guess in step 2
5. Assume PWL with $V_D=0.7V$
6. Guess state of diode (ON)
7. Analyze circuit with model
8. Validate state of guess in step 6
9. Show difference between results using these two models is small
10. If difference is not small, must use a different model
Solution:

1. Assume PWL model with $V_D=0.6V$, $R_D=0$
2. Guess state of diode (ON)

3. Analyze circuit with model

\[ I_{OUT} = \frac{12V - 0.6V}{10K} = 1.14mA \]

4. Validate state of guess in step 2

To validate state, must show $I_D>0$

\[ I_D = I_{OUT} = 1.14mA > 0 \]
Solution:

5. Assume PWL model with $V_D=0.7V$, $R_D=0$
6. Guess state of diode (ON)

7. Analyze circuit with model
   
   $$I_{OUT} = \frac{12V - 0.7V}{10K} = 1.13mA$$

8. Validate state of guess in step 6
   
   To validate state, must show $I_D>0$
   
   $$I_D = I_{OUT} = 1.13mA > 0$$
Solution:

9. Show difference between results using these two models is small

\[ I_{\text{OUT}} = 1.14 \text{ mA} \text{ and } I_{\text{OUT}} = 1.13 \text{ mA} \]

are close

Thus, can conclude

\[ I_{\text{OUT}} \approx 1.14 \text{ mA} \]
Example: Determine $I_{OUT}$ for the following circuit

Solution:

Strategy:
1. Assume PWL model with $V_D=0.6V$, $R_D=0$
2. Guess state of diode (ON)
3. Analyze circuit with model
4. Validate state of guess in step 2
5. Assume PWL with $V_D=0.7V$
6. Guess state of diode (ON)
7. Analyze circuit with model
8. Validate state of guess in step 6
9. Show difference between results using these two models is small
10. If difference is not small, must use a different model
Solution:

1. Assume PWL model with $V_D=0.6\,\text{V}$, $R_D=0$
2. Guess state of diode (ON)

3. Analyze circuit with model

$$I_{\text{OUT}} = \frac{0.8 - 0.6\,\text{V}}{10\,\text{K}} = 20\,\mu\text{A}$$

4. Validate state of guess in step 2
   To validate state, must show $I_D>0$

$$I_D = I_{\text{OUT}} = 20\,\mu\text{A} > 0$$
Solution:

5. Assume PWL model with $V_D=0.7V$, $R_D=0$

6. Guess state of diode (ON)

7. Analyze circuit with model

$$I_{OUT} = \frac{0.8V - 0.7V}{10K} = 10\mu A$$

8. Validate state of guess in step 6

To validate state, must show $I_D>0$

$$I_D = I_{OUT} = 10\mu A > 0$$
Solution:

9. Show difference between results using these two models is small

\[ I_{\text{OUT}} = 10 \mu A \text{ and } I_{\text{OUT}} = 20 \mu A \]

are not close.

10. If difference is not small, must use a different model

Thus must use diode equation to model the device.

\[
I_{\text{OUT}} = \frac{0.8 - V_D}{10K} \quad \text{and} \quad I_{\text{OUT}} = I_S e^{\frac{V_D}{V_t}}
\]

Solve simultaneously, assume \( V_t = 25 \text{mV}, I_S = 1 \text{fA} \)

Solving these two equations by iteration, obtain \( V_D = 0.6148 \text{V} \) and \( I_{\text{OUT}} = 18.60 \mu A \).
Use of **Piecewise** Models for Nonlinear Devices when Analyzing Electronic Circuits

Process:

1. Guess state of the device
2. Analyze circuit
3. Verify State
4. Repeat steps 1 to 3 if verification fails
5. Verify model (if necessary)

Observations:

- Analysis generally simplified dramatically (particularly if piecewise model is linear)
- Approach applicable to wide variety of nonlinear devices
- Closed-form solutions give insight into performance of circuit
- Usually much faster than solving the nonlinear circuit directly
- Wrong guesses in the state of the device do not compromise solution (verification will fail)
- Helps to guess right the first time
- Model is often not necessary with most nonlinear devices
Types of Diodes

**pn junction diodes**
- Signal or Rectifier
- Pin or Photo
- Light Emitting LED
- Laser Diode
- Zener
- Varactor or Varicap

**Metal-semiconductor junction diodes**
- Schottky Barrier
Basic Devices and Device Models

- Resistor
- Diode
- Capacitor
- MOSFET
- BJT
Capacitors

• Types
  – Parallel Plate
  – Fringe
  – Junction
Parallel Plate Capacitors

A = area of intersection of $A_1$ & $A_2$

One (top) plate *intentionally* sized smaller to determine $C$

$$C = \frac{\varepsilon A}{d}$$
Parallel Plate Capacitors

If \( C_d = \frac{\text{Cap}}{\text{unit area}} \)

\[
C = \frac{\varepsilon A}{d}
\]

\[
C = C_d A
\]

where

\[
C_d = \frac{\varepsilon}{d}
\]
Fringe Capacitors

\[ C = \frac{\varepsilon A}{d} \]

A is the area where the two plates are parallel

Only a single layer is needed to make fringe capacitors
Fringe Capacitors

\[ C \]
Capacitance

Junction Capacitor

\[ C = \varepsilon \frac{A}{d} \]
\[ C = \frac{C_{j0} A}{\left(1 - \frac{V_D}{\varphi_B}\right)^n} \quad \text{for} \quad V_{FB} < \frac{\varphi_B}{2} \]

Note: \( d \) is voltage dependent
- capacitance is voltage dependent
- usually parasitic caps
- varicaps or varactor diodes exploit voltage dep. of \( C \)

\[ \varphi_B \approx 0.6V \quad n \approx 0.5 \]
Capacitance

Junction Capacitor

\[ C = \frac{C_{j0}A}{\left( 1 - \frac{V_D}{\phi_B} \right)^n} \quad \text{for} \quad V_{FB} < \frac{\phi_B}{2} \]

Voltage dependence is substantial

\[ \phi_B \approx 0.6V \quad n \approx 0.5 \]
Basic Devices and Device Models

• Resistor
• Diode
• Capacitor
• MOSFET
• BJT
n-Channel MOSFET

- Poly
- n-active
- Gate oxide
- p-sub
n-Channel MOSFET

Source
Gate
Drain

L
L_{\text{EFF}}
W

Bulk
n-Channel MOSFET
Apply small $V_{GS}$
($V_{DS}$ and $V_{BS}$ assumed to be small)

Depletion region electrically induced in channel
Termed “cutoff” region of operation

$I_D=0$
$I_G=0$
$I_B=0$
n-Channel MOSFET Operation and Model

Increase $V_{GS}$
($V_{DS}$ and $V_{BS}$ assumed to be small)

Depletion region in channel becomes larger

$I_D = 0$
$I_G = 0$
$I_B = 0$
n-Channel MOSFET Operation and Model

\[
\begin{align*}
V_{BS} & \quad I_B \\
V_{GS} & \quad I_G \\
V_{DS} & \quad I_D
\end{align*}
\]

Model in Cutoff Region

- \( I_D = 0 \)
- \( I_G = 0 \)
- \( I_B = 0 \)
n-Channel MOSFET Operation and Model

Critical value of $V_{GS}$ that creates inversion layer termed threshold voltage, $V_T$)

Increase $V_{GS}$ more

Inversion layer forms in channel
Inversion layer will support current flow from D to S
Channel behaves as thin-film resistor

$I_D R_{CH} = V_{DS}$
$I_G = 0$
$I_B = 0$
Triode Region of Operation

For $V_{DS}$ small

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

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

$$I_G = I_B = 0$$

Behaves as a resistor between drain and source

Model in Deep Triode Region
Triode Region of Operation

For $V_{DS}$ small

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

Resistor is controlled by the voltage $V_{GS}$

Termed a “Voltage Controlled Resistor” (VCR)
n-Channel MOSFET Operation and Model

Increase $V_{GS}$ more

Inversion layer in channel thickens

$R_{CH}$ will decrease

Termed “ohmic” or “triode” region of operation

$I_D R_{CH} = V_{DS}$

$I_G = 0$

$I_B = 0$
n-Channel MOSFET Operation and Model

Increase $V_{DS}$

Inversion layer thins near drain

$I_D$ no longer linearly dependent upon $V_{DS}$

Still termed “ohmic” or “triode” region of operation

$I_D = ?$

$I_G = 0$

$I_B = 0$
Triode Region of Operation

For $V_{DS}$ larger

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

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

$$I_G = I_B = 0$$

Model in Triode Region
n-Channel MOSFET Operation and Model

Increase $V_{DS}$ even more

Inversion layer disappears near drain
Termed “saturation” region of operation
Saturation first occurs when $V_{DS} = V_{GS} - V_T$

$I_D = ?$
$I_G = 0$
$I_B = 0$
Saturation Region of Operation

For $V_{DS}$ at onset of saturation

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

or equivalently

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

or equivalently

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

$I_G = I_B = 0$
n-Channel MOSFET Operation and Model

Increase $V_{DS}$ even more (beyond $V_{GS} - V_T$)

Nothing much changes !!

Termed “saturation” region of operation

$I_D=?$
$I_G=0$
$I_B=0$
Saturation Region of Operation

For $V_{DS}$ in Saturation

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

\[ I_G = I_B = 0 \]
Model Summary

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

\[I_G = I_B = 0\]

Note: This is the third model we have introduced for the MOSFET

(Deep triode special case of triode where \( V_{DS} \) is small)

\[R_{CH} = \frac{L}{W} \left( V_{GS} - V_T \right) \mu C_{OX}\]
End of Lecture 13