EE 330
Lecture 13

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 $I_{\text{OUT}}$ for the following circuit

Solution:

Strategy:
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
4. Validate state of guess in step 2
5. Assume PWL with $V_D=0.7\text{V}$
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)

\[ V_{OUT} = 12V - 0.6V = 11.4V \]

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 \( V_D = 0.7 \text{V}, \ R_D = 0 \)
6. Guess state of diode (ON)

7. Analyze circuit with model

\[
I_{\text{OUT}} = \frac{0.8 \text{V} - 0.7 \text{V}}{10 \text{K}} = 10 \mu \text{A}
\]

8. Validate state of guess in step 6

To validate state, must show \( I_D > 0 \)

\[
I_D = I_{\text{OUT}} = 10 \mu \text{A} > 0
\]
Solution:

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

\[ I_{OUT} = 10 \mu A \text{ and } I_{OUT} = 20 \mu A \] are not close

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

Thus must use diode equation to model the device

\[
\begin{align*}
I_{OUT} &= \frac{0.8 - V_D}{10K} \\
I_{OUT} &= I_S e^{\frac{V_D}{V_t}}
\end{align*}
\]

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 \( I_{OUT} = 18.60 \mu A \)
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 $C$

$$C = \frac{\epsilon A}{d}$$
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
Capacitance

Junction Capacitor

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

\[ C = \frac{C_{j_0} \cdot A}{d} \left( 1 - \frac{V_D}{\phi_B} \right)^n \]

\[ \text{for } V_{FB} < \frac{\phi_B}{2} \]

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

\[ \phi_B \approx 0.6V \quad n \approx 0.5 \]
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
n-Channel MOSFET

- Source
- Drain
- Gate
- Bulk
- $L_{EFF}$
- $W$
- $L$
n-Channel MOSFET

Poly
n-active
Gate oxide
p-sub
depletion region (electrically induced)
Apply small $V_{GS}$
($V_{DS}$ and $V_{BS}$ assumed to be small)

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

\[ I_D = 0 \]
\[ I_G = 0 \]
\[ I_B = 0 \]

Model in Cutoff Region
n-Channel MOSFET Operation and Model

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

Inversion layer forms in channel

Inversion layer will support current flow from D to S

Channel behaves as thin-film resistor

$V_{DS}$ and $V_{BS}$ small

Increase $V_{GS}$ more

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

$I_G = 0$

$I_B = 0$
Triode Region of Operation

For $V_{DS}$ small

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

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

$I_G = I_B = 0$

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

\[ I_D = V_{DS} \]
\[ I_G = 0 \]
\[ I_B = 0 \]

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

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

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

$$I_G = I_B = 0$$

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 in Saturation Region
Model Summary

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

\[ I_G = I_B = 0 \]

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

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

\[ R_{CH} = \frac{L}{W \left( \frac{1}{(V_{GS} - V_T)\mu C_{OX}} \right)} \]
End of Lecture 13