Devices in Semiconductor Processes

Diodes
Capacitors
MOS Transistors
Review from Last Time

Lets study the diode equation a little further

\[ I_d = I_S \left( e^{\frac{V_d}{V_t}} - 1 \right) \]

Diode Characteristics

Power Dissipation Becomes Destructive if \( V_d > 0.85V \) (actually less)
Review from Last Time

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\[ I_d = I_S \left( e^{\frac{V_d}{V_t}} - 1 \right) \]

For two decades of current change, \( V_d \) is close to 0.6V

This is the most useful current range for many applications
Let's study the diode equation a little further.

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I_d = I_S \left( e^{\frac{V_d}{V_t}} - 1 \right)
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Diode Characteristics

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\[ I_d = I_S \left( \frac{V_d}{V_t} - 1 \right) \]

Diode Characteristics

Widely Used Piecewise Linear Model
Let's study the diode equation a little further

\[ I_d = I_S \left( \frac{V_d}{V_t} - 1 \right) \]

**Diode Characteristics**

\[ I_d = \begin{cases} 
0 & V_d < 0.6V \\
> 0 & V_d = 0.6V 
\end{cases} \]
Lets study the diode equation a little further

\[ I_d = I_S \left( e^{\frac{V_d}{V_t}} - 1 \right) \]

**Piecewise Linear Model**

- \( I_d = 0 \quad V_d < 0.6V \)
- \( V_d = 0.6V \quad I_d > 0 \)

**Equivalent Circuit**

[Diagram showing diode in off state and on state]
Let's study the diode equation a little further:

\[
I_d = I_S \left( \frac{V_d}{V_t} e^{V_t} - 1 \right)
\]

![Diode Characteristics Graph]

Slightly More Accurate Piecewise Linear Model
Lets study the diode equation a little further

\[ I_d = I_S \left( \frac{V_d}{V_t} \right)^{e^{\frac{V_t}{V}} - 1} \]

Diode Characteristics

\[
\begin{align*}
I_d &= 0 & V_d &< 0.6V \\
V_d &= 0.6V + I_d R_d & I_d &> 0
\end{align*}
\]
Let's study the diode equation a little further

\[
I_d = I_S \left( e^{\frac{V_d}{V_t}} - 1 \right)
\]

Piecewise Linear Model with Diode Resistance

\[
\begin{align*}
I_d &= 0 & V_d < 0.6V \\
V_d &= 0.6V + I_d R_D & I_d > 0
\end{align*}
\]

\(R_D\) is rather small: often in the 20Ω to 100Ω range):

Equivalent Circuit

![Equivalent Circuit Diagram]
The Ideal Diode

$V_D \Rightarrow I_D = \begin{cases} 
0 & \text{if } V_D \leq 0 \\
I_D & \text{if } I_D > 0 
\end{cases}$
The Ideal Diode

\[ I_D = 0 \quad \text{if} \quad V_D \leq 0 \quad \text{“OFF”} \]
\[ V_D = 0 \quad \text{if} \quad I_D > 0 \quad \text{“ON”} \]

Valid for \( I_D > 0 \) \( V_D \leq 0 \)

\[ \text{“ON”} \quad \text{“OFF”} \]
Diode Models

Which model should be used?

The simplest model that will give acceptable results in the analysis of a circuit.
Diode Models

Diode Equation

\[ I_D = I_S \left( \frac{V_d}{V_t} - 1 \right) \]

\[ I_d = 0 \quad V_d < 0.6V \]
\[ V_d = 0.6V \quad I_d > 0 \]

Piecewise Linear Models

\[ I_d = 0 \quad V_d < 0.6V \]
\[ V_d = 0.6V + I_d R_d \quad I_d > 0 \]

\[ I_D = 0 \quad \text{if} \quad V_D \leq 0 \]
\[ V_D = 0 \quad \text{if} \quad I_D > 0 \]
Diode Models

Diode Equation

\[ I_D = I_S \left( e^{\frac{V_d}{V_t}} - 1 \right) \]

Piecewise Linear Models

When are the piecewise-linear models adequate?

When it doesn't make much difference whether \( V_d = 0.6V \) or \( V_d = 0.7V \) is used

When is the ideal PWL model adequate?

When it doesn't make much difference whether \( V_d = 0V \) or \( V_d = 0.7V \) is used
Example: Determine $I_{\text{OUT}}$ 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 $V_D = 0.7\, \text{V}$, $R_D = 0$
6. Guess state of diode (ON)

7. Analyze circuit with model

$$I_{OUT} = \frac{12\, \text{V} - 0.7\, \text{V}}{10\, \text{K}} = 1.13\, \text{mA}$$

8. Validate state of guess in step 6
   To validate state, must show $I_D > 0$

$$I_D = I_{OUT} = 1.13\, \text{mA} > 0$$
Solution:

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

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

are close

Thus, can conclude

\[ I_{OUT} \approx 1.14 \text{mA} \]
Example: Determine $I_{OUT}$ 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
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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 $I_D > 0$

$$I_D = I_{\text{OUT}} = 1.13\,\text{mA} > 0$$
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

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

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 \(I_{\text{OUT}} = 18.60\, \mu A\)
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
Capacitance

Junction Capacitor

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

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

\[ \phi_B \approx 0.6\text{V} \quad n \approx 0.5 \]

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

Junction Capacitor

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

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

Bulk

L

L_{EFF}

W
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

$I_D = 0$
$I_G = 0$
$I_B = 0$
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

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

$|D| R_{CH} = V_{DS}$
$I_G = 0$
$I_B = 0$
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

$IDR_{CH} = V_{DS}$

$I_G = 0$

$I_B = 0$
Triode Region of Operation

For $V_{DS}$ small

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

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

$$I_G = I_B = 0$$
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

$I_D = \text{?}$

$I_G = 0$

$I_B = 0$
Triode Region of Operation

For $V_{DS}$ larger

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

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

$$I_G = I_B = 0$$
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 saturation

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

or equivalently

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

or equivalently

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

$I_G = I_B = 0$
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

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

\[ I_G = I_B = 0 \]
Model Summary

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

Note: This is the third model we have introduced for the MOSFET
Graphical Interpretation of MOS Model

\[ I_D = \begin{cases} 
0 & \text{if } V_{GS} \leq V_T \\
\mu C_{ox} \frac{W}{L} \left( V_{GS} - V_T - \frac{V_{DS}}{2} \right) V_{DS} & \text{if } V_{GS} \geq V_T, \ V_{DS} < V_{GS} - V_T \\
\mu C_{ox} \frac{W}{2L} \left( V_{GS} - V_T \right)^2 & \text{if } V_{GS} \geq V_T, \ V_{DS} \geq V_{GS} - V_T 
\end{cases} \]
Example: Determine the output voltage for the following circuit using the square-law model of the MOSFET. Assume $V_T=1V$ and $\mu C_{OX}=100\mu AV^{-2}$

Solution:

Since $V_{GS}>V_T$, $M_1$ is operating in either saturation or triode region.

Strategy will be to guess region of operation, solve, and then verify region.
Example: Determine the output voltage for the following circuit using the square-law model of the MOSFET. Assume $V_T=1V$ and $\mu C_{OX}=100\mu AV^{-2}$

Solution:

Guess $M_1$ in saturation

$$5V=I_D10K+V_{OUT}$$

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

Required verification: $V_{DS}>V_{GS}-V_T$

Can eliminate $I_D$ between these 2 equations to obtain $V_{OUT}$
Example: Determine the output voltage for the following circuit using the square-law model of the MOSFET. Assume $V_T = 1V$ and $μC_{OX} = 100μAV^{-2}$

Guess $M_1$ in saturation

Required verification: $V_{DS} > V_{GS} - V_T$

\[
5V = I_D 10K + V_{OUT}
\]

\[
I_D = \frac{μC_{OX}W}{2L}(3-V_T)^2
\]

\[
V_{OUT} = 5V - 10K \left[ \frac{100μAV^{-2}10μ}{2 \cdot 2μ}(2V)^2 \right]
\]

\[
V_{OUT} = 5V - 10K \left[ \frac{100μAV^{-2}10μ}{2 \cdot 2μ}(2V)^2 \right]
\]

\[
V_{OUT} = -5V
\]

Verification: $V_{DS} = V_{OUT}$

-5 ? 2V - - 0 No! So verification fails and Guess of region is invalid
Example: Determine the output voltage for the following circuit using the square-law model of the MOSFET. Assume $V_T=1V$ and $\mu C_{OX}=100\mu A V^{-2}$

Guess $M_1$ in triode

Required verification: $V_{DS}<V_{GS}-V_T$

$$5V = I_D 10K + V_{OUT}$$

$$I_D = \frac{\mu C_{OX} W}{L} \left( 3 - V_T - \frac{V_{DS}}{2} \right) V_{DS}$$

$$V_{OUT} = 5V - 10K \left[ \frac{100\mu A V^{-2} 10\mu}{2\mu} \left( 2V - \frac{V_{OUT}}{2} \right) \right] V_{OUT}$$

$$V_{OUT} = 5V - \left[ 5 \left( 2V - \frac{V_{OUT}}{2} \right) \right] V_{OUT}$$

Solving for $V_{OUT}$, obtain

$$V_{OUT} = 0.515V$$

Verification: $V_{DS}=V_{OUT}$

$0.515 <? 2V$ - - 0 Yes! So verification succeeds and triode region is invalid

$V_{OUT} = 0.515V$