Devices in Semiconductor Processes

• Diodes
Diodes (pn junctions)

Depletion region created that is ionized but void of carriers
pn Junctions

- As forward bias increases, depletion region thins and current starts to flow
- Current grows very rapidly as forward bias increases

Simple Diode Model:

\[
\begin{align*}
V_D &= 0 \\
I_D &= 0 \\
I_D &> 0 \\
V_D &< 0
\end{align*}
\]

Simple model often referred to as the “Ideal” diode model
Rectifier Application:

\[ V_{IN} = V_M \sin(\omega t) \]

Simple Diode Model:
pn Junctions

Diode Equation:

\[ I = \begin{cases} 
J_S A e^{\frac{V}{nV_T}} & V > 0 \\
0 & V < 0 
\end{cases} \]

\( n \) is strongly temperature dependent

With \( n=1 \), for \( V>0 \),

\[
I(T) = \left( J_{SX} T^m e^{\frac{-V_{G0}}{V_t}} \right) A e^{\frac{V_D}{V_t}}
\]

Typical values for key parameters: \( J_{SX}=0.5A/\mu^2, V_{G0}=1.17V, m=2.3 \)
Analysis of Nonlinear Circuits
(Circuits with one or more nonlinear devices)

What analysis tools or methods can be used?

- KCL?
- KVL?
- Superposition?
- Voltage Divider?
- Current Divider?
- Thevenin and Norton Equivalent Circuits?

Review from Last Lecture

Nodal Analysis
Mesh Analysis
Two-Port Subcircuits
Review from Last Lecture

Let's study the diode equation a little further

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

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

This is the most useful current range when conducting for many applications
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 \( I_D > 0 \)

Valid for \( V_D \leq 0 \)

Review from Last Lecture
Which model should be used?

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

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

\[ C = \frac{C_{j_0}A}{\left(1 - \frac{V_D}{\varphi_B}\right)^n} \text{ for } V_{FB} < \frac{\varphi_B}{2} \]

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

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

Junction Capacitor

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

Voltage dependence is substantial

\[ \varphi_B \approx 0.6V \quad n \approx 0.5 \]
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
- \( L \)
- \( W \)
- \( L_{\text{EFF}} \)
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

$V_{BS}$

$V_{GS}$

$V_{DS}$

$I_D = 0$

$I_G = 0$

$I_B = 0$

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

Increase $V_{GS}$ more

$I_D R_{CH} = V_{DS}$
$I_G = 0$
$I_B = 0$
End of Lecture 13