Devices in Semiconductor Processes

• Diodes
Basic Devices

- **Standard CMOS Process**
  - MOS Transistors
    - n-channel
    - p-channel
  - Capacitors
  - Resistors
  - Diodes
  - BJT (in some processes)
    - npn
    - pnp
  - JFET (in some processes)
    - n-channel
    - p-channel

- **Niche Devices**
  - Photodetectors
  - MESFET
  - Schottky Diode (not Shockley)
  - MEM Devices
  - Triac/SCR
  - ....

**Primary Consideration in This Course**

**Some Consideration in This Course**

Review from Last Lecture
Basic Devices and Device Models

- Resistor
  - Diode
  - Capacitor
  - MOSFET
  - BJT
Resistivity of Materials used in Semiconductor Processing

- Cu: $1.7 \times 10^{-6} \ \Omega \text{cm}$
- Al: $2.7 \times 10^{-4} \ \Omega \text{cm}$
- Gold: $2.4 \times 10^{-6} \ \Omega \text{cm}$
- Platinum: $3.0 \times 10^{-6} \ \Omega \text{cm}$
- Polysilicon: $1 \times 10^{-2}$ to $1 \times 10^{4} \ \Omega \text{cm}$*
- n-Si: .25 to 5 $\ \Omega \text{cm}$*
- Intrinsic Si: $2.5 \times 10^{5} \ \Omega \text{cm}$
- SiO$_2$: $1 \times 10^{14} \ \Omega \text{cm}$

* But fixed in a given process
Temperature Coefficients

Used for indicating temperature sensitivity of resistors & capacitors

For a resistor:

\[
TCR = \left( \frac{1}{R} \frac{dR}{dT} \right)_{\text{op. temp}} \quad \cdot 10^6 \text{ ppm/°C}
\]

This diff eqn can easily be solved if TCR is a constant

\[
R(T_2) = R(T_1) e^{\frac{T_2 - T_1}{10^6} TCR}
\]

\[
R(T_2) \approx R(T_1) \left[ 1 + (T_2 - T_1) \frac{TCR}{10^6} \right]
\]

Identical Expressions for Capacitors
Review from Last Lecture

Periodic Table of the Elements

Review from Last Lecture

- **Boron (B):**
  - Atomic number: 5
  - Atomic weight: 10.811
  - Electron configuration: 1s² 2s² 2p¹

- **Silicon (Si):**
  - Atomic number: 14
  - Atomic weight: 28.0855
  - Electron configuration: [Ne]3s² 3p²

- **Phosphorus (P):**
  - Atomic number: 15
  - Atomic weight: 30.973762
  - Electron configuration: [Ne]3p³

- **Arsenic (As):**
  - Atomic number: 33
  - Atomic weight: 74.92160
  - Electron configuration: [Ar]3d¹⁰ 4s² 4p³

- **Antimony (Sb):**
  - Atomic number: 51
  - Atomic weight: 121.760
  - Electron configuration: [Kr]4d¹⁰ 5s² 5p³
Silicon Dopants in Semiconductor Processes

**B** (Boron) widely used as a dopant for creating p-type regions

**P** (Phosphorus) widely used as a dopant for creating n-type regions
(bulk doping, diffuses fast)

**As** (Arsenic) widely used as a dopant for creating n-type regions
(Active region doping, diffuses slower)
Diodes (pn junctions)

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

Anode

Cathode

I_D

V_D

Circuit Symbol

Review from Last Lecture
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:

- \( V_D = 0 \)  \( I_D = 0 \)
- \( V_D < 0 \)  \( I_D > 0 \)

Simple model often referred to as the “Ideal” diode model
pn junction serves as a rectifier passing current in one direction and blocking it in the other direction.
Rectifier Application:

$$V_{IN} = V_M \sin \omega t$$

Simple Diode Model:
I-V characteristics of pn junction
(signal or rectifier diode)

Improved Diode Model:

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

What is \( V_t \) at room temp?

\( V_t \) is about 26mV at room temp

Diode equation due to William Schockley, inventor of BJT

In 1919, William Henry Eccles coined the term *diode*

In 1940, Russell Ohl “stumbled upon” the p-n junction diode

\[ I_S \text{ in the } 10fA \text{ to } 100fA \text{ range} \]

\[ V_t = \frac{kT}{q} \]

\[ k = 1.3806504(24) \times 10^{-23} JK^{-1} \]

\[ q = -1.602176487(40) \times 10^{-19} C \]

\[ \frac{k}{q} = 8.62 \times 10^{-5} VK^{-1} \]
I-V characteristics of pn junction
(signal or rectifier diode)

Improved Diode Model:

\[
\begin{align*}
& \text{Diode Equation } I_D = I_S \left( e^{\frac{V_d}{V_t}} - 1 \right) \\
& \text{Simplification of Diode Equation:} \\
& \text{Under reverse bias } (V_d < 0), \quad I_D \approx -I_S \\
& \text{Under forward bias } (V_d > 0), \quad I_D = I_S e^{\frac{V_d}{V_t}} \\
& I_S \text{ in the } 10 \text{fA to } 100 \text{fA range} \\
& V_t = \frac{kT}{q} \\
& k = 1.3806504(24) \times 10^{-23} \text{JK}^{-1} \\
& q = -1.602176487(40) \times 10^{-19} \text{C} \\
& k/q = 8.62 \times 10^{-5} \text{VK}^{-1} \\
& V_t \text{ is about } 26 \text{mV at room temp} \\
& \text{Simplification essentially identical model except for } V_d \text{ very close to } 0 \\
& \text{Diode Equation or forward bias simplification is unwieldy to work with analytically}
\end{align*}
\]
I-V characteristics of pn junction
(signal or rectifier diode)

Improved Diode Model:

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

$I_S$ often in the 10fA to 100fA range
$I_S$ proportional to junction area

$V_t$ is about 26mV at room temp

**Diode Equation**

**Simplification of Diode Equation:**

Under reverse bias,  
$$I_D \approx -I_S \frac{V_d}{V_t}$$

Under forward bias,  
$$I_D = I_S e^{\frac{V_d}{V_t}}$$

How much error is introduced using the simplification for $V_d > 0.5V$?

$$\varepsilon = \frac{I_S \left( e^{\frac{V_d}{V_t}} - 1 \right) - I_S e^{\frac{V_d}{V_t}}}{I_S \left( e^{\frac{V_d}{V_t}} - 1 \right)}$$

$$\varepsilon < \frac{1}{e^{\frac{0.5}{0.026}}} = 4.4 \cdot 10^{-9}$$

How much error is introduced using the simplification for $V_d < -0.5V$?

$$\varepsilon < e^{\frac{-0.5}{0.026}} = 4.4 \cdot 10^{-9}$$

Simplification almost never introduces any significant error.
Will you impress your colleagues or your boss if you use the more exact diode equation when $V_d < -0.5V$ or $V_d > +0.5V$?

Will your colleagues or your boss be unimpressed if you use the more exact diode equation when $V_d < -0.5V$ or $V_d > +0.5V$?
Diode Equation: (good enough for most applications)

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

Note: $I_S = J_S A$

$J_S =$ Sat Current Density (in the 1aA/u² to 1fA/u² range)
$A =$ Junction Cross Section Area
$V_T = kT/q$ \( (k/q=1.381\times10^{-23}V\cdot°C/°K/1.6\times10^{-19}C=8.62\times10^{-5}V/°K) \)

$n$ is approximately 1
**pn Junctions**

*Diode Equation:* 

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

- \(J_S\) is strongly temperature dependent
- With \(n=1\), for \(V>0\),

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

**Typical values for key parameters:**
- \(J_{SX} = 0.5A/\mu^2\), \(V_{G0} = 1.17V\), \(m = 2.3\)
pn Junctions

Example:

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

What percent change in \( I_S \) will occur for a 1°C change in temperature at room temperature?

\[ \frac{\Delta I_S}{I_S} = \frac{\left( J_{SX} \left[ T^m e^{\frac{-V_{ao}}{V_{T_2}}} \right] Ae^{\frac{V_D}{V_{T_2}}} - \left( J_{SX} \left[ T^m e^{\frac{-V_{ao}}{V_{T_1}}} \right] Ae^{\frac{V_D}{V_{T_1}}} \right) \right)}{J_{SX} \left[ T^m e^{\frac{-V_{ao}}{V_{T_1}}} \right] Ae^{\frac{V_D}{V_{T_1}}}} \]

\[ \Delta I_S = \left( 1.240 \times 10^{-15} \right) - \left( 1.025 \times 10^{-15} \right) \]

\[ \frac{\Delta I_S}{I_S} = \frac{100\%}{100\%} = 21\% \]
Consider again the basic rectifier circuit

\[ V_{OUT} = ? \]
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?

Nodal Analysis
Mesh Analysis
Two-Port Subcircuits
Consider again the basic rectifier circuit

\[ V_{IN} = V_D + I_D R \]
\[ V_{OUT} = I_D R \]
\[ I_D = I_S \left( e^{\frac{V_d}{V_t}} - 1 \right) \]
\[ V_{OUT} = I_S R \left( \frac{V_{IN} - V_{OUT}}{V_t} - 1 \right) \]

Even the simplest diode circuit does not have a closed-form solution when diode equation is used to model the diode !!

Due to the nonlinear nature of the diode equation

Simplifications are essential if analytical results are to be obtained
Let's study the diode equation a little further.

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

Power Dissipation Becomes Destructive if \( V_d > 0.85V \) (actually less)
Let's study the diode equation a little further

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

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

This is the most useful current range for many applications.
For two decades of current change, Vd is close to 0.6V
This is the most useful current range for many applications
Let's study the diode equation a little further.

The diode equation is:

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

For \( V_d < 0.6 \) Volts:
\[ I_d = 0 \]

For \( V_d = 0.6 \) Volts:
\[ I_d > 0 \]

Diode Characteristics

Widely Used Piecewise Linear Model
Lets study the diode equation a little further

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

Better model in “ON” state though often not needed

Includes Diode “ON” resistance
Lets 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**

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

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

**Equivalent Circuit**
The Ideal Diode

\[ I \begin{cases} 0 & \text{if} \quad V \leq 0 \\ V & \text{if} \quad I > 0 \end{cases} \]

\[ V_D = 0 \quad \text{if} \quad V_D \leq 0 \]

\[ V_D = 0 \quad \text{if} \quad I_D > 0 \]
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 \( I_D > 0 \) \quad \text{and} \quad V_D \leq 0
Which model should be used?

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

Diode Equation

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

Diode Characteristics

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

Piecewise Linear Models

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

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

Diode Equation

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

Piecewise Linear Models

\[ I_d = 0 \quad \text{if} \quad V_d \leq 0 \]
\[ V_d = 0.6V + I_d R_d \quad \text{if} \quad I_d > 0 \]

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
End of Lecture 12