Devices in Semiconductor Processes
Quiz 11  Consider a p-n junction comprised of uniformly doped p-type and n-type materials where the doping density of the p-type material is 5 times that of the n-type material. If under zero bias the depletion region extends a distance $x$ into the p-type region, give the total thickness of the depletion region in terms of $x$ for the p-n junction.
And the number is ....
And the number is ....
Quiz 11  Consider a p-n junction comprised of uniformly doped p-type and n-type materials where the doping density of the p-type material is 5 times that of the n-type material. If under zero bias the depletion region extends a distance $x$ into the p-type region, give the total thickness of the depletion region in terms of $x$ for the p-n junction.

Solution: Since charge balance must be maintained, the depth of the n-side depletion region must be 5 times that of the p-side depletion region so its depth is 5$x$. Thus the total thickness of the depletion region is 6$x$. 

\[
\text{d} = 6x
\]
Review from Last Time

Basic Devices and Device Models

Resistor
- Diode
- Capacitor
- MOSFET
- BJT
Temperature Coefficients

Used for indicating temperature sensitivity of resistors & capacitors

For a resistor:

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

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

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

Identical Expressions for Capacitors
Voltage Coefficients

Used for indicating voltage sensitivity of resistors & capacitors

For a resistor:

$$VCR = \left( \frac{1}{R} \frac{dR}{dV} \right)_{\text{ref voltage}} \cdot 10^6 \text{ ppm/V}$$

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

$$R(V_2) = R(V_1) e^{\frac{V_2-V_1}{10^6} VCR}$$

$$R(V_2) \approx R(V_1) \left[ 1 + \frac{(V_2 - V_1) VCR}{10^6} \right]$$

Identical Expressions for Capacitors
Temperature and Voltage Coefficients

• Temperature and voltage coefficients often quite large for diffused resistors
• Temperature and voltage coefficients often quite small for poly and metal resistors
Review from Last Time

Basic Devices and Device Models

- Resistor
- Diode
- Capacitor
- MOSFET
- BJT
### Review from Last Time

<table>
<thead>
<tr>
<th>Period</th>
<th>Element</th>
<th>Symbol</th>
<th>Atomic Number</th>
<th>Mass Number</th>
<th>Mass (amu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IIA</td>
<td>Boron</td>
<td>B</td>
<td>5</td>
<td>2</td>
<td>10.811</td>
</tr>
<tr>
<td></td>
<td>Carbon</td>
<td>C</td>
<td>6</td>
<td>2</td>
<td>12.0107</td>
</tr>
<tr>
<td></td>
<td>Nitrogen</td>
<td>N</td>
<td>7</td>
<td>2</td>
<td>14.00674</td>
</tr>
<tr>
<td></td>
<td>Oxygen</td>
<td>O</td>
<td>8</td>
<td>2</td>
<td>15.9994</td>
</tr>
<tr>
<td></td>
<td>Fluorine</td>
<td>F</td>
<td>9</td>
<td>2</td>
<td>18.9984032</td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td>Al</td>
<td>13</td>
<td>3</td>
<td>26.981538</td>
</tr>
<tr>
<td></td>
<td>Silicon</td>
<td>Si</td>
<td>14</td>
<td>3</td>
<td>28.0855</td>
</tr>
<tr>
<td></td>
<td>Phosphorus</td>
<td>P</td>
<td>15</td>
<td>3</td>
<td>30.973761</td>
</tr>
<tr>
<td></td>
<td>Sulfur</td>
<td>S</td>
<td>16</td>
<td>3</td>
<td>32.066</td>
</tr>
<tr>
<td></td>
<td>Chlorine</td>
<td>Cl</td>
<td>17</td>
<td>3</td>
<td>35.453</td>
</tr>
<tr>
<td></td>
<td>Gallium</td>
<td>Ga</td>
<td>31</td>
<td>8</td>
<td>69.723</td>
</tr>
<tr>
<td></td>
<td>Germanium</td>
<td>Ge</td>
<td>32</td>
<td>8</td>
<td>72.64</td>
</tr>
<tr>
<td></td>
<td>Arsenic</td>
<td>As</td>
<td>33</td>
<td>8</td>
<td>74.92160</td>
</tr>
<tr>
<td></td>
<td>Selenium</td>
<td>Se</td>
<td>34</td>
<td>8</td>
<td>78.96</td>
</tr>
<tr>
<td></td>
<td>Bromine</td>
<td>Br</td>
<td>35</td>
<td>8</td>
<td>79.904</td>
</tr>
<tr>
<td></td>
<td>Indium</td>
<td>In</td>
<td>49</td>
<td>18</td>
<td>114.818</td>
</tr>
<tr>
<td></td>
<td>Tin</td>
<td>Sn</td>
<td>50</td>
<td>18</td>
<td>118.710</td>
</tr>
<tr>
<td></td>
<td>Antimony</td>
<td>Sb</td>
<td>51</td>
<td>18</td>
<td>121.760</td>
</tr>
<tr>
<td></td>
<td>Tellurium</td>
<td>Te</td>
<td>52</td>
<td>18</td>
<td>127.60</td>
</tr>
<tr>
<td></td>
<td>Iodine</td>
<td>I</td>
<td>53</td>
<td>18</td>
<td>126.90447</td>
</tr>
<tr>
<td></td>
<td>Thallium</td>
<td>Tl</td>
<td>81</td>
<td>18</td>
<td>204.3833</td>
</tr>
<tr>
<td></td>
<td>Lead</td>
<td>Pb</td>
<td>82</td>
<td>18</td>
<td>207.2</td>
</tr>
<tr>
<td></td>
<td>Bismuth</td>
<td>Bi</td>
<td>83</td>
<td>18</td>
<td>208.98038</td>
</tr>
<tr>
<td></td>
<td>Polonium</td>
<td>Po</td>
<td>84</td>
<td>18</td>
<td>209</td>
</tr>
<tr>
<td></td>
<td>Astatine</td>
<td>At</td>
<td>85</td>
<td>18</td>
<td>210</td>
</tr>
</tbody>
</table>
Review from Last Time

Silicon Dopants in Semiconductor Processes

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

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

**As** (Arsenic) widely used a dopant for creating n-type regions
(Active region doping, diffuses slower)
Review from Last Time

pn Junctions

Physical Boundary
Separating n-type and p-type regions
Positive voltages across the p to n junction are referred to forward bias.

Negative voltages across the p to n junction are referred to reverse bias.

As forward bias increases, depletion region thins and current starts to flow.

Current grows very rapidly as forward bias increases.

Current is very small under reverse bias.
Review from Last Time

pn Junctions

Circuit Symbol
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 Junctions

Simple 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:

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

Diode Equation

\[
\begin{align*}
\text{Under reverse bias,} & \quad I_D \approx -I_S \\
\text{Under forward bias,} & \quad I_D = I_S e^{\frac{V_d}{V_t}}
\end{align*}
\]

Simplification of Diode Equation:

- \( I_S \) in the 10fA to 100fA range
- \( V_t \) is about 26mV at room temp

Simplification essentially identical model except for \( V_d \) very close to 0

Diode Equation or forward bias simplification is unwieldy to work with analytically
I-V characteristics of pn junction
(signal or rectifier diode)

Improved Diode Model:

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

- \( I_S \) in the 10fA to 100fA range
- \( V_t \) is about 26mV at room temp

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 \( V_d > 0.5V \)?
\[ \varepsilon = -\frac{I_S \left( e^{\frac{V_d}{V_t}} - 1 \right) - I_S e^{\frac{V_d}{V_t}}}{I_S \left( e^{\frac{V_d}{V_t}} - 1 \right)} \]
\[ \varepsilon < \frac{1}{e^{0.026}} = 4.4 \cdot 10^{-9} \]

How much error is introduced using the simplification for \( V_d < -0.5V \)?
\[ \varepsilon < e^{-0.026} = 4.4 \cdot 10^{-9} \]

Simplification almost never introduces any significant error
pn Junctions

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

-\( J_S \) = Sat Current Density (in the 1aA/u² to 1fA/u² range)
-\( A \) = Junction Cross Section Area
-\( V_T = kT/q \)  \((k/q=1.381\times10^{-23}V\cdot°C/°K/1.6\times10^{-19}C=8.63\times10^{-5}V/°K)\)
n is approximately 1
pn Junctions

Diode Equation:

\[
I = \begin{cases} 
J_s Ae^{\frac{V}{nVT}} & \text{if } V > 0 \\
0 & \text{if } V < 0 
\end{cases}
\]

\(J_S\) is strongly temperature dependent

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

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

Typical values for key parameters: \(J_{SX}=0.45A/\mu^2\), \(V_{G0}=1.17V\), \(m=2.3\)
pn Junctions

Example:

\[
I(T) = \left( J_{\text{sx}} \left[ T_m e^{\frac{-V_{gs}}{V_t}} \right] \right) A e^{\frac{V_D}{V_t}}
\]

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

\[
\frac{\Delta I_S}{I_S} = \left( J_{\text{sx}} \left[ T_{T_2} e^{\frac{-V_{gs}}{V(T_2)}} \right] \right) A - \left( J_{\text{sx}} \left[ T_{T_1} e^{\frac{-V_{gs}}{V(T_1)}} \right] \right) A = \left( T_{T_2} e^{\frac{-V_{gs}}{V(T_2)}} \right) - \left( T_{T_1} e^{\frac{-V_{gs}}{V(T_1)}} \right)
\]

\[
\frac{\Delta I_S}{I_S} = \left( 5.77 \times 10^3 \right) - \left( 5.64 \times 10^3 \right) = \frac{100\%}{5.64 \times 10^3} = 2.3\%
\]
Consider again the basic rectifier circuit

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
Lets 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

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

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

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

Diode Characteristics

For two decades of current change, \( V_d \) is close to 0.6V
This is the most useful current range for many applications
Lets study the diode equation a little further

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

Diode Characteristics

Widely Used Piecewise Linear Model