EE 330
Lecture 12

Devices in Semiconductor Processes
Quiz 11  A wire obtained with a ball bond is shown sitting on a bonding pad. What is a typical value for the dimension $d_1$ shown?

$d_1 = ?$
And the number is ....
And the number is .... 3
Quiz 11  A wire obtained with a ball bond is shown sitting on a bonding pad. What is a typical value for the dimension d1 shown?

\[ d_1 = 25 \mu \]
Review from Last Time

Back-End Process Flow

1. Wafer Probe
2. Wafer Dicing
3. Die Attach
4. Wire Attach (bonding)
5. Package
6. Test
7. Ship
Review from Last Time

Basic Semiconductor Processes

Other Processes

• Thin and Thick Film Processes
  – Basic Device: Resistor
• BiMOS or BiCMOS
  – Combines both MOS & Bipolar Processes
  – Basic Devices: MOSFET & BJT
• SiGe
  – BJT with HBT implementation
• SiGe / MOS
  – Combines HBT & MOSFET technology
• SOI / SOS (Silicon on Insulator / Silicon on Sapphire)
• Twin-Well & Twin Tub CMOS
  – Very similar to basic CMOS but more optimal transistor char.
Devices in Semiconductor Processes

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

- **Standard Bipolar Process**
  - BJT
    - npn
    - pnp
  - JFET
    - n-channel
    - p-channel
  - Diodes
  - Resistors
  - Capacitors

- **Niche Devices**
  - Photodetectors (photodiodes, phototransistors, photoresistors)
  - MESFET
  - HBT
  - Schottky Diode (not Shockley)
  - MEM Devices
  - ....
Basic Devices and Device Models

- Resistor
- Diode
- Capacitor
- MOSFET
- BJT
Basic Devices and Device Models

Resistor

- Diode
- Capacitor
- MOSFET
- BJT
Resistors

- Generally thin-film devices
- Almost any thin-film layer can be used as a resistor
  - Diffused resistors
  - Poly Resistors
  - Metal Resistors
  - “Thin-film” adders (SiCr or NiCr)
- Subject to process variations, gradient effects and local random variations
- Often temperature and voltage dependent
  - Ambient temperature
  - Local Heating
- Nonlinearities often a cause of distortion when used in circuits
- Trimming possible resistors
  - Laser, links, switches
Resistor Model

Model:

$$R = \frac{V}{I}$$
Resistivity

- Volumetric measure of conduction capability of a material

\[ \rho = \frac{AR}{L} \]

for homogeneous material, \( \rho \perp A, R, L \)

Area is \( A \)

units: ohm cm
Sheet Resistance

\[ R_{\square} = \frac{RW}{L} \quad (\text{for } d \ll w, \; d \ll L) \quad \text{units: ohms/} \cdot \]

for homogeneous materials, \( R \) is independent of \( W, L, R \)
Relationship between $\rho$ and $R$. 

$$R = \frac{RW}{L}$$

$$\rho = \frac{AR}{L}$$

$$\rho = \frac{A}{W} R = \frac{W d}{W} R = d \times R$$

Number of squares, $N_S$, often used instead of $L / W$ in determining resistance of film resistors

$$R = R \times N_S$$
Example 1

\[ W \]

\[ L \]

\[ R = ? \]
Example 1

\[ \frac{L}{W} = N_s \]
Example 1

R = ?
Example 1

\[ R = ? \]

\[ N_S = 8.4 \]

\[ R = R. \ (8.4) \]
Corners in Film Resistors

Rule of Thumb: .55 squares for each corner
Example 2

Determine $R$ if $R_e = 100 \, \Omega$
Example 2

$N_S = 17.1$

$R = (17.1) R_0$

$R = 1710 \, \Omega$
Resistivity of Materials used in Semiconductor Processing

- Cu: $1.7E-6 \ \Omega cm$
- Al: $2.7E-4 \ \Omega cm$
- Gold: $2.4E-6 \ \Omega cm$
- Platinum: $3.0E-6 \ \Omega cm$
- n-Si: 0.25 to 5 \ \Omega cm
- intrinsic Si: $2.5E5 \ \Omega cm$
- SiO$_2$: $E14 \ \Omega cm$
Temperature Coefficients

Used for indicating temperature sensitivity of resistors & capacitors

For a resistor:

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

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

[For a resistor:]

\[ R_{2} 
\approx R_{1} e^{\frac{T_{2} - T_{1}}{10^{6} TCR}} \]

\[ R_{2} \approx R_{1} \left[ 1 + \left( T_{2} - T_{1} \right) \frac{TCR}{10^{6}} \right] \]

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

\[
\frac{V_2 - V_1}{10^6 VCR}
\]

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
Basic Devices and Device Models

- Resistor
- Diode
- Capacitor
- MOSFET
- BJT
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4 valence Electrons
Serves as an “acceptor” of electrons
Acts as a p-type impurity when used as a silicon dopant
The Atom of Boron (B)

B atom

level 1
level 2

Five Valence Electrons

Serves as an “donor” of electrons
Acts as an n-type impurity when used as a silicon dopant
The Atom of Phosphorus (P)
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)
Basic Devices and Device Models

- Resistor
- Diode
- Capacitor
- MOSFET
- BJT
Diodes (pn junctions)

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

If doping levels identical, depletion region extends equally into n-type and p-type regions.
pn Junctions

Extends farther into p-type region if p-doping lower than n-doping
pn Junctions

Extends farther into n-type region if n-doping lower than p-doping
• 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
pn Junctions

[Diagram of pn Junction with labels: Anode and Cathode]

Circuit Symbol

[Diagram of pn diode with labels: Anode, Cathode, V_D, I_D]
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:

\[ V_D = 0 \quad I_D = 0 \]
\[ I_D > 0 \quad V_D < 0 \]

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:

\[ V_{OUT} \]
**I-V characteristics of pn junction**

*(signal or rectifier diode)*

**Improved Diode Model:**

\[
\begin{align*}
\text{Diode Equation} & \quad I_D = I_S \left( e^{\frac{V_d}{V_t}} - 1 \right) \\
\text{Under reverse bias,} & \quad I_D \approx -I_S \\
\text{Under forward bias,} & \quad I_D = I_S e^{\frac{V_d}{V_t}} \\
\end{align*}
\]

Diode Equation or forward bias simplification is unwieldy to work with analytically.
End of Lecture 12
Diode Equation:  
$I = \begin{cases} J_S A e^{\frac{v}{nV_T}} & \text{V > 0} \\ 0 & \text{V < 0} \end{cases}$

$J_S =$ Sat Current Density (in the $1 \text{aA}/u^2$ to $1 \text{fA}/u^2$ range)
$A =$ Junction Cross Section Area
$V_T = kT/q$ \hspace{1cm} (k/q = 1.381x10^{-23} \text{V} \cdot \text{C}/ \text{K}/1.6x10^{-19} \text{C} = 8.63x10^{-5} \text{V}/ \text{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 \( V > 0 \),

\[
I(T) = \left( J_{S_X} \left[ T^m e^{\frac{-V_{G_0}}{V_t}} \right] \right) A e^{\frac{V_D}{V_t}}
\]

Typical values for key parameters:

\( J_{S_X} = 0.45 \text{A}/\mu^2, \quad V_{G_0} = 1.17 \text{V}, \quad m = 2.3 \)
pn Junctions

Example:

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

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

\[
\frac{\Delta I_S}{I_S} = \left( J_{SX} \left[ T^m_{T_e} e^{\frac{-V_{GO}}{V_{T_e}}} \right] \right) A - \left( J_{SX} \left[ T^m_{T_i} e^{\frac{-V_{GO}}{V_{T_i}}} \right] \right) A
\]

\[
= \left( \left[ T^m_{T_e} e^{\frac{-V_{GO}}{V_{T_e}}} \right] \right) - \left( \left[ T^m_{T_i} e^{\frac{-V_{GO}}{V_{T_i}}} \right] \right)
\]

\[
\frac{\Delta I_S}{I_S} = \frac{5.77 \times 10^3 - 5.64 \times 10^3}{5.64 \times 10^3} \times 100\% = 2.3\%
\]