Section 8: Metallization

Jaeger Chapter 7
Multilevel Metallization
Multilevel Metallization Components

- Si substrate
- Interconnects
- Contacts - Metal to poly and doped Si
- Vias - Metal to metal contacts
- Intermetal Dielectric (InteMetal Oxide e.g. BPSG. Low-K dielectric)
- Passivation (e.g. PECVD Si Nitride)
Interconnect RC Time Delay

**Interconnect Resistance**

\[ R_I = \frac{R}{L} = \frac{\rho}{(W_{Al} T_{Al})} \]

**Interconnect-Substrate Capacitance**

\[ C_V \equiv \frac{C}{L} = W_{Al} \varepsilon_{ox} / T_{ox} \]

**Interconnect-Interconnect Capacitance**

\[ C_L \equiv \frac{C}{L} = T_{Al} \varepsilon_{ox} / S_{Al} \]

* Values per unit length L
**Interconnect Requirements**

- low ohmic resistance
  - interconnects material has low resistivity

- low contact resistance to semiconductor device

- reliable long-term operation
# Resistivity of Metals

**TABLE 7.1** Bulk Resistivity of Metals ($\mu\Omega$-cm)

<table>
<thead>
<tr>
<th>Metal</th>
<th>Resistivity $\mu\Omega$-cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag: Silver</td>
<td>1.6</td>
</tr>
<tr>
<td>Al: Aluminum</td>
<td>2.65</td>
</tr>
<tr>
<td>Au: Gold</td>
<td>2.2</td>
</tr>
<tr>
<td>Co: Cobalt</td>
<td>6</td>
</tr>
<tr>
<td>Cu: Copper</td>
<td>1.7</td>
</tr>
<tr>
<td>Mo: Molybdenum</td>
<td>5</td>
</tr>
<tr>
<td>Ni: Nickel</td>
<td>7</td>
</tr>
<tr>
<td>Pd: Paladium</td>
<td>10</td>
</tr>
<tr>
<td>Pt: Platinum</td>
<td>10.6</td>
</tr>
<tr>
<td>Ti: Titanium</td>
<td>50</td>
</tr>
<tr>
<td>W: Tungsten</td>
<td>5</td>
</tr>
</tbody>
</table>

Commonly Used Metals:
- Aluminum
- Titanium
- Tungsten
- Copper

Less Frequently Utilized:
- Nickel
- Platinum
- Paladium

Ohmic Contact Formation

- Aluminum to p-type silicon forms an ohmic contact [Remember Al is p-type dopant]
- Aluminum to n-type silicon can form a rectifying contact (Schottky barrier diode)
- Aluminum to n+ silicon yields a tunneling contact
For a uniform current density flowing across the contact area,
\[ R_c = \frac{\rho_c}{\text{contact area}} \]

\( \rho_c \) of Metal-Si contacts \( \sim 1 \times 10^{-5} \text{ to } 1 \times 10^{-7} \ \Omega \text{-cm}^2 \)

\( \rho_c \) of Metal-Metal contacts \( < 1 \times 10^{-8} \ \Omega \text{-cm}^2 \)
Contact Resistivity

Specific contact resistivity

$$\rho_c = \exp \left[ \frac{2 \sqrt{m^* \varepsilon_s}}{h} \left( \frac{\phi_B}{\sqrt{N}} \right) \right]$$

$$\phi_B$$ is the Schottky barrier height

$$N$$ = surface doping concentration

$$\rho_c$$ = specific contact resistivity in ohm-cm$^2$

$$m$$ = electron mass

$$h$$ = Planck's constant

$$\varepsilon$$ = Si dielectric constant

Approaches to lowering of contact resistance:

1) Use highly doped Si as contact semiconductor
2) Choose metal with lower Schottky barrier height
Aluminum Spiking and Junction Penetration

- Silicon absorption into the aluminum results in aluminum spikes
- Spikes can short junctions or cause excess leakage
- Barrier metal deposited prior to metallization
- Sputter deposition of Al - 1% Si
Alloying of Contacts

Alloy to Obtain Very Low Contact Resistivity
Specific Contact Resistivity
\[ \rho_c = 1.2 \times 10^{-6} \Omega \cdot cm^2 \]

Contact Resistance \( R_C \)
\[ R_C = \frac{\rho_c}{A} \quad A = \text{contact area} \]
Electromigration

High current density causes voids to form in interconnections

“Electron wind” causes movement of metal atoms
Electromigration

- Copper added to aluminum to improve lifetime (Al, 4% Cu, 1% Si)

\[ MTF \propto \frac{1}{J^2} \exp \left( \frac{E_A}{kT} \right) \]

- Heavier metals (e.g., Cu) have lower activation energy

\( J \) = current density
\( E_A \) = activation energy
\( MTF \) = mean time to failure
**Metal Deposition Techniques**

- Sputtering has been the technique of choice
  - high deposition rate
  - capability to deposit complex alloy compositions
  - capability to deposit refractory metals
  - uniform deposition on large wafers
  - capability to clean contact before depositing metal

- CVD processes have recently been developed
  (e.g. for W, TiN, Cu)
  - better step coverage
  - selective deposition is possible
  - plasma enhanced deposition is possible for lower deposition temperature
Metal CVD Processes

TiN

– used as barrier-metal layer
– deposition processes:

\[
6\text{TiCl}_4 + 8\text{NH}_3 \rightarrow 6\text{TiN} + 24\text{HCl} + \text{N}_2
\]

\[
2\text{TiCl}_4 + 2\text{NH}_3 + \text{H}_2 \rightarrow 2\text{TiN} + 8\text{HCl}
\]

\[
2\text{TiCl}_4 + \text{N}_2 + 4\text{H}_2 \rightarrow 2\text{TiN} + 8\text{HCl}
\]
Electroplating
**Dual Damascene Process**

(a) Via resist
- Substrate
- Cu layer
- Insulator
- Etch stop (Si$_3$N$_4$)

(b) Metal resist
- Substrate
- Cu layer
- Insulator

(c) Insulator
- Cu layer
- Seed layer

(d) Barrier layer (TiN)
- Insulator
- Cu layer
Salicides

- Self-Aligned Silicide on silicon and polysilicon
- Often termed “Salicide”
Low-K Dielectrics

Potential low-k materials

Polymer

Inorganic

Organic-Inorganic Hybrid

Organic

Non-Fluorinated

Fluorinated

Porous material

See Table 3

See Table 2

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# Porous low-k dielectric examples

<table>
<thead>
<tr>
<th>Materials</th>
<th>Dielectric constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEOS* – based glass [9]</td>
<td>4.2</td>
</tr>
<tr>
<td>Fluorinated high-density plasma oxide (F-HDP) [10]</td>
<td>3.5 – 3.6</td>
</tr>
<tr>
<td>Fluorinated Amorphous carbon films [12-13]</td>
<td>2.3 – 2.4</td>
</tr>
<tr>
<td>Hydrophobic porous SOG (HPS) [14]</td>
<td>2.5</td>
</tr>
<tr>
<td>Xerogels &amp; aerogels [4,15-17]</td>
<td>1.3 – 3.0</td>
</tr>
<tr>
<td>Air [9]</td>
<td>1.0 – 2.0</td>
</tr>
</tbody>
</table>