SILVER METALLIZATION FOR ULSI APPLICATIONS

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Outline

♦ Introduction
♦ Results
  PHASE I:  Blanket Thin Ag Films
  PHASE II: Patterned Ag Structures
♦ Summary

National Science Foundation  (L. Hess)
Center for Low Power Electronics and member companies
Yuxiao Zeng, Lee Zou, Phucanh Nguyen, Yu Wang, Jason Hason
Technology Trend: 
**Continuous Device Scaling**

♦ **BENEFITS**
  - *Faster circuit speed*
  - *Higher functional density*

♦ **ISSUES**
  - *Propagation delay*
  - *Power dissipation*
  - *Cross talk noise*
Interconnect RC Delay: A Performance-Limiting Factor for Submicron Integrated Circuits

(S.-P. Jeng et al., Advanced Metallization for Devices and Circuits – Science, Technology, and Manufacturability, 1994.)
Conventional Al Metallization

- Relatively high resistivity
- Electromigration (EM) failure

— *Questionable for ULSI*
Approach to Reduce Interconnect RC Delay

♦ Low-\(\rho\) metals to replace Al(Cu)

\[
\begin{align*}
\text{Al(Cu)} & : 3.1 \, \mu\Omega \cdot \text{cm} \\
\text{Au} & : 2.4 \, \mu\Omega \cdot \text{cm} \\
\text{Cu} & : 1.7 \, \mu\Omega \cdot \text{cm} \\
\text{Ag} & : 1.58 \, \mu\Omega \cdot \text{cm}
\end{align*}
\]

♦ Low-\(k\) dielectrics to replace SiO\(_2\)

\[
\begin{align*}
\text{SiO}_2 & : k = 4.0-4.5 \\
\text{Low-}\!k\text{-dielectrics} & : k < 3
\end{align*}
\]
Ag Metallization

♦ Advantages
  - Lower resistivity than Al and Cu (~ 40% and 5%)
  - Higher EM resistance than Al

♦ Disadvantages
  - Poor adhesion to SiO$_2$
  - Rapid diffusion in Si
  - Corrosion in S or Cl ambient
  - Agglomeration
Challenges of Ag Metallization

- Address issues:
  - Diffusion
  - Corrosion
  - Agglomeration
  - Adhesion

- Improve EM resistance

- Produce Ag pattern
Project Objective:

*Demonstrate Ag as an interconnect material*

- Overcome Ag’s critical issues
- *Develop Ag reactive ion etch*
- *Optimize EM performance*
Strategy - Encapsulation Process

**PHASE I**: Blanket Thin Ag Films

**PHASE II**: Patterned Ag Structures
PHASE I: Blanket Thin Ag Films

Encapsulation process  Texture and microstructure optimization  Resistivity measurement

Metal (Ti,...)  \( NH_3 \) anneal (400-600 °C)
\[ \rho_{\text{alloy}} = \rho_0 + \kappa c_i \]

\[ \kappa = \frac{\Delta \rho}{\Delta c_i} \]

<table>
<thead>
<tr>
<th></th>
<th>Experimental</th>
<th>Theoretical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu (% Ti)</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>Ag (% Ti)</td>
<td>1.8</td>
<td>NA</td>
</tr>
<tr>
<td>Ag (% Al)</td>
<td>1.3</td>
<td>1.95</td>
</tr>
</tbody>
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Encapsulation Process

- Ti or Al diffuses through Ag
- Metal-N(O) forms on Ag surface
- Metal reduces the underlying SiO$_2$
- Negligible residual metal in Ag films

— Ti and Al are ideal for encapsulation
comparison of major texture parameters of Ag, Cu, and Al(Cu) thin films

<table>
<thead>
<tr>
<th></th>
<th>Condition</th>
<th>Volume fraction of grains</th>
<th>FWHM (°) of &lt;111&gt; texture component</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>&lt;111&gt; + &lt;511&gt; Random</td>
<td></td>
</tr>
<tr>
<td>Ag</td>
<td>As-deposited</td>
<td>0.74 + 0.17</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>400 °C 1 hr</td>
<td><strong>0.93 + 0.05</strong></td>
<td><strong>5.6</strong></td>
</tr>
<tr>
<td>Cu</td>
<td>As-deposited</td>
<td>0.63 + 0.13</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>400 °C 1 hr</td>
<td><strong>0.74 + 0.07</strong></td>
<td><strong>28.4</strong></td>
</tr>
<tr>
<td>AlCu</td>
<td>As-deposited</td>
<td>0.89</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>400 °C 1 hr</td>
<td>0.91</td>
<td>0.09</td>
</tr>
</tbody>
</table>

FWHM (°°°°) of <111> texture component

**Ag**
- As-deposited: 400 °°°° C 1 hr
  - Volume fraction of grains: 0.74 + 0.17
  - FWHM: 0.09
  - FWHM (°): 5.6

**Cu**
- As-deposited: 400 °°°° C 1 hr
  - Volume fraction of grains: 0.63 + 0.13
  - FWHM: 0.10
  - FWHM (°): 28.4

**AlCu**
- As-deposited: 400 °°°° C 1 hr
  - Volume fraction of grains: 0.89
  - FWHM: 0.11
  - FWHM (°): 10.2

- 400 °°°° C 1 hr
  - Volume fraction of grains: 0.91
  - FWHM: 0.09
  - FWHM (°): 6.6
a) as-deposited, and  
b) 600 °C 15 min annealed Ag/Ti bilayers,  
c) as-deposited, and  
d) 600 °C 15 min annealed Ag/Ta bilayers
Grain size distribution of Ag films in Ag/Ti and Ag/Ta bilayers

Ag/Ti: Monomodal       Ag/Ta: Bimodal
Surface and Strain Energy Controlled Grain Growth

$\text{Surface energy } (\Delta \gamma_s)$

$\text{Grain boundary energy } (\gamma_{GB})$

$\text{Strain energy } (\Delta F)$

$\text{Interfacial energy } (\Delta \gamma_i)$

- **Driving force**: energy minimization
- **Grain growth rate**: $v = m[\Delta \gamma/h + \Delta F + \gamma_{GB}(1/r_a - 1/r)]$
Ag Texture and Microstructure

♦ Underlayer Dependence
  - Ti: \textit{Strong Ag <111> texture, uniform microstructure}
  - Ta, Cr: \textit{Random orientation, abnormal grain growth}

♦ Mechanisms
  - \textit{Lattice match}
  - \textit{Surface-and-strain-energy-controlled grain growth}