Effects of Cap Layer and Grain Structure on Electromigration Reliability of Cu/Low-k Interconnects

Lijuan Zhang, Matthias Kraatz, Paul S. Ho
The University of Texas at Austin, Austin TX

Oliver Aubel, Christian Hennesthal
GLOBALFOUNDRIES, Dresden Germany

and Ehrenfried Zschech
Fraunhofer Institute for Non-Destructive Testing IZFP, Dresden Germany

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Objective

- Investigate the effect of cap layer and grain structure on EM reliability for the 45 nm technology node.

- Deduce the scaling effect on EM reliability for the 32 nm technology node and beyond considering both interfacial and grain boundary diffusions.
Motivation

EM results
- Type I structure: M1, different capping materials - SiCN/CoWP caps
- Type II structure: M2, different grain sizes with different capping materials - large/small grain, SiCN/CoWP caps

Implications of scaling effect on EM performance beyond the 32 nm technology node

Monte Carlo simulation of EM

Summary
EM Scaling Effect for Cu Interconnects

\[ v_d = \left( \frac{\delta_i}{h} D_i Z_i^* + \frac{\delta_{gb}}{d} D_{gb} Z_{gb}^* \right) e \rho j / kT \]

Interface engineering:
- Metal cap using CoWP
- CuSiN layer

In sub-micron Cu line with bamboo grain structures, SiNx interface diffusion dominates mass transport.

EM lifetime degrades by half for each new generation.
Effect of Grain Structure on EM Reliability

GB diffusion degrade Cu lifetime at 90 nm linewidth.

To investigate EM reliability at the 45nm node,

- Cap layer effect
- Grain structure effect
EM Test Structure Description

Type I (M1)

Type II (M2)

<table>
<thead>
<tr>
<th></th>
<th>Test line</th>
<th>Width (nm)</th>
<th>Height (nm)</th>
<th>Length (um)</th>
<th>Cap materials</th>
<th>Grain structure</th>
<th>purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>M1</td>
<td>~70</td>
<td>~110</td>
<td>200</td>
<td>SiCN/CoWP</td>
<td>Standard</td>
<td>Cap layer effect</td>
</tr>
<tr>
<td>Type II</td>
<td>M2</td>
<td>~70</td>
<td>~140</td>
<td>200</td>
<td>SiCN/CoWP</td>
<td>large/small</td>
<td>Both cap layer and grain size effect</td>
</tr>
</tbody>
</table>

Both test structures used for downstream testing

Wafer processed by GLOBALFOUNDRIES using 45 nm technology process
Type I structure: X-sectional TEM Images of M1 Cu Line

SiCN cap: ~30 nm; Ta/TaN barrier: ~10 nm
Type I: EDX Result of CoWP Cap

CoWP cap ~ 6 nm
Longitudinal TEM Images of M1 Lines

(a) CoWP cap

(b) SiCN cap

No significant difference in the grain structures of two different caps.
EM Results of Type I structures
SiCN vs. CoWP

- ~40x EM lifetime improvement by using CoWP cap.
- Small $\sigma$ indicates a well-controlled CoWP deposition process.
Failure Analysis: R-trace for SiCN Cap

1. Void incubation and growth to a critical value.
2. Void growth: step-like (surface grain thinning), or linear (vertical edge displacement).

Similar R-traces for CoWP capped samples.
Type II Test Structure: M2 line

Four types of Cu lines at the M2 level

A
Large grain with SiCN cap
SiCN cap

B
Small grain with SiCN cap

C
Large grain with CoWP/SiCN cap
CoWP cap

D
Small grain with CoWP/SiCN cap

12/20
Grain Size Characterization: Large Grain vs. Small Grain

Grain size along line A (nm)* _ top: Large grain 215, Small grain 123
Grain size along line B (nm)* _ bottom: Large grain 181, Small grain 126

(*) based on 5~10 um long Cu line, 40~60 grains; grain size was calculated by averaging along the dashed lines A and B.

TEM results confirmed the larger average grain size for large grain structure.
EM Results for Type II Structure

- CoWP cap greatly improves the EM lifetime for both grain structures.
- For each cap, EM lifetime is significantly degraded for the small grain structures due to the additional mass transport along the grain boundaries.
No abrupt R increase; progressive R increase for both modes.

- Mode I: voiding at the cathode via corner; small initial R increase; short EM lifetime.
- Mode II: voiding in the trench away from the via; large initial R increase; longer EM lifetime.
R-trace for SiCN samples with large grain structure

- Void under the via
- Small initial R jump
- Shorter EM lifetime

- Void away from the via
- Large initial R jump
- Longer EM lifetime

9 away from via
5 right at via

- Void away from via
- Void right next to via
R-trace for LG-CoWP cap

For large grain structure with CoWP cap, Mode II dominates with impact on EM statistics.
More mode II failures for LG structure. SG facilitates void formation at the via corner.

Longer EM lifetime, more mode II failures.

CoWP cap -- voids readily get trapped and grow slowly.

SiCN cap -- voids move readily along the interface and eventually accumulate at the via corner.
EM Mass Transport in Cu Interconnects

**EM drift velocity**

\[ v_d = \mu_{\text{eff}} F_e = (D_{\text{eff}} / kT) Z_{\text{eff}}^* e^\rho j \]

**\( Z_{\text{eff}}^* D_{\text{eff}} \) parameter:**

\[ Z_{\text{eff}}^* D_{\text{eff}} = \frac{Z_N^* D_N \delta_N}{h} + \frac{Z_{GB}^* D_{GB} f \delta_{GB}}{d} \]

**EM lifetime:**

\[ \tau = \frac{\Delta L_{\text{cr}}}{v_d} = \frac{\Delta L_{\text{cr}} h k T}{D_N \delta_N Z_N^* e^\rho j (1 + fgh / d)} \]

\[ (g = \frac{Z_{GB}^* D_{GB} \delta_{GB}}{Z_N^* D_N \delta_N}) \]

**f:** fractions of grain boundaries aligned with j direction;

**g:** ratio of GB vs. interface diffusion

**h:** line thickness; **d:** average grain size; **\( \Delta L_{\text{cr}} \):** critical void size
Scaling Effect on EM Reliability

- For standard SiCN cap
  - EM lifetime degrade by half for every new generation.
  - After 65 nm node, occurrence of small grains further degrades EM lifetime.

- For CoWP cap
  - EM reliability can be markedly improved.
  - With more small grains emerging with scaling, grain boundary together with the cap layer will control the scaling effect on EM lifetime.
Monte Carlo Simulation

Fig. 7. Simulated CDF plots of six cases for large and small grain Cu lines with different interfacial diffusivity.
Summary

- CoWP metal cap is an effective method to improve the EM performance by suppressing the interfacial diffusion.

- For both SiCN and CoWP caps, the small grains degrade the EM lifetime by additional mass transport. Bimodal failure for the SiCN cap and monomodal failure for the CoWP cap.

- With continued scaling and improved cap layer interface, grain structures will become important together with interfaces in controlling void formation and EM lifetime.

- Grain structure need be controlled with cap material to ensure EM performance for 22 nm technology node and beyond.

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