Enabling Erosion and Dishing Measurements with Electrical Test in Copper Damascene Process

SFR Workshop & Review
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2002 GOAL: to demonstrate the feasibility of an E-test based method to measure and study the pattern/process induced systematic variations in Cu CMP by 12/30/2002.
Motivation

- Measure non-destructively systematic metal loss in the over-polish step

- Build pattern/process induced CMP models to better understand erosion and dishing
  - To reduce process variability
  - To increase the robustness of process design
  - To evaluate the effect of process variation on circuit performance
Our Approach

- Start with scatterometry-based method for Inter-layer Dielectric (ILD) process metrology
  - Non-destructive
  - Fast and inexpensive
- Measured profiles were used for ILD CMP process modeling (in collaboration with LMA)
- Design special pattern density mask with E-test structures to measure and study erosion and dishing
- Evaluate the effect of systematic interconnect variations to circuit performance
  - Propose appropriate layout rule modification to account for the deterministic CMP variations
Why E-test?

- Basic idea is that the volume percentage loss of metal can be measured by four point probe

\[ \text{loss(\%) = } \frac{r \sqrt{\left(\frac{r}{2}\right)^2 + \left(\frac{x}{8r}\right)^2} - \frac{1}{2}x \sqrt{r^2 - \left(\frac{x}{2}\right)^2}}{Hx} \]

R: effective size of the pad asperity
H: metal height
X: the copper line width

When \( x \ll R \)
E-Test Structure Design

- Designed E-test structures to measure and study dishing, where copper line width ranges from 0.4 to 5 microns
- Total Line length for each four point structure is about 4mm
  - Expected resistance is around 100Ω depending on line width
  - Expected resistance change due to dishing is about 5% for 1 µm line
The difference in the resistance change percentage is a result of both erosion and dishing effects.

E-test cell
Mask Design (II)

- Mask has 7x7 array of the designed E-test cells
- The effective pattern density for each cell keeps constant
- Difference in the resistance change percentage only comes from dishing effect
Process Flow

- Six-inch wafers were used to take advantage of the ASML stepper
- Lithography and etching done at Berkeley microlab (minimum line-width 0.4micron)
- PVD and CMP done at RPI microlab
Metal Profile Modeling for E-Test

Assumptions:
- a. Rounding and post-CMP copper thickness are linewidth independent
- b. First order dishing is proportional to linewidth
- c. Ignore the barrier layer effect

Resistivity:
- Cu: 1.7E-6 Ohm.cm
- Ta: 13E-6 Ohm.cm

\[
R = \frac{\rho \cdot L}{W \cdot t} \quad Y = \frac{1}{R} = \frac{W \cdot t}{\rho \cdot L}
\]

Both \( \rho \) and \( L \) are const. Define \( y = Y \cdot \rho \cdot L \) we have

\[
y = y_0 - y_e - y_r - y_d
\]

hence

\[
y_1 = W_1 t - W_1 dt - 2(1 - \frac{\pi}{4})r^2 - (aW_1) \cdot W_1
\]

\[
y_2 = W_2 t - W_2 dt - 2(1 - \frac{\pi}{4})r^2 - (aW_2) \cdot W_2
\]

... ...

\[
y_N = W_N t - W_N dt - 2(1 - \frac{\pi}{4})r^2 - (aW_N) \cdot W_N
\]

\[
\begin{bmatrix}
y_1 \\
y_2 \\
y_N
\end{bmatrix} =
\begin{bmatrix}
W_1 - 2(1 - \frac{\pi}{4}) & -W_1^2 \\
W_2 - 2(1 - \frac{\pi}{4}) & -W_2^2 \\
W_N - 2(1 - \frac{\pi}{4}) & -W_N^2
\end{bmatrix}
\begin{bmatrix}
t - dt \\
r^2 \\
a
\end{bmatrix}
\]

\[
Y = Ax
\]

\[
x = (A^T A)^{-1} A^T Y
\]
Erosion and Dishing Extraction from E-test Results

Extracted parameters

\[
\begin{bmatrix}
    t - dt \\
    r^2 \\
    a
\end{bmatrix} = \begin{bmatrix} 0.3927 \\
    0.0751 \\
    0.0062 \end{bmatrix}
\]

Meaning

I. Erosion 0.5-0.39=0.11\(\mu\)m
II. Rounding was 0.27\(\mu\)m
III. Dishing factor 0.0062, i.e.
12nm (~3.1%) dishing for 2\(\mu\)m lines and 31nm (~7.7%) dishing for 5\(\mu\)m lines
Framework on Dishing Modeling

- Bending beam calculation showed that dishing was not a consequence of pad deformation

- Dishing is strongly correlated with
  - Pad asperity
  - Slurry size
  - Chemical aspects of slurry
  - Young’s modulus of the pad

From E-test results, the extracted dishing radius was 56.8 microns
2002 and 2003 Goals

- Finish mask design, design of experiments and copper damascene process data collection by 10/31/2002 (done).
- Develop comprehensive chemical and mechanical model (with Dornfeld, Doyle and Talbot); Evaluate the CMP variation impact on interconnect, by 5/31/2003.