Microstructure Evolution and Reliability Impact from Nano-interconnects to Through-Silicon Vias

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Acknowledgements
The Cu Interconnect Era

ITRS Roadmap, 2013
Challenges in Cu Scaling

• Cu does not scale so well…..

• Small grains emerge in Cu lines less than 90nm wide to degrade EM lifetime.

• GB scattering increases and Cu resistivity worsens substantially with interconnect scaling
Through-Silicon Via (TSV)-based 3D Integration

• Vertical stacking chips.

• Through-silicon via (TSV): vertical interconnection between stacked dies.

Source: IBM, Micron
Benefits of 3D Integration with TSVs

- Form factor
- Performance
- Power consumption
- Bandwidth
- Functionality

Source: Micron

Lu et al., 2007
Thermal Stress and TSV Reliability

• Large CTE mismatch between Cu and Si induces thermal stress
• Irreversible deformation (plasticity) contributes to via extrusion.
  • Extrusion increases with annealing temperature in the thermal cycle (beyond a critical T).
  • Mechanical properties of top grains play an important role.
• It has been proposed that TSV dimension scaling will reduce these risks.
The Statistical Nature of Via Extrusion

- Decreasing via dimensions and optimizing processing can alleviate average via extrusion, but annealing/CMP processes are not effective in improving the statistics of via extrusion.

- Weakest link: largest extrusion (0.1%) determines BEOL integrity and reliability

Smith et al., 2015
De Messemaker et al., 2013
Outline of Study

- Investigate stress and extrusion characteristics to search for mechanisms controlling the scaling effect on extrusion statistics.
  - TSVs of different diameters
    - 2x40 µm: post-plating anneal at 250°C for 1 hour
    - 5x50 µm: post-plating anneal at 350°C for 30 minutes
    - Anneal at 400°C for 3 hours
  - Stress behavior (wafer curvature)
  - Microstructure (EBSD)
  - Material properties (Nanoindentation)
  - Extrusion behaviors (optical profiler)
  - Plasticity (synchrotron x-ray microdiffraction)
Stress Behavior

• Wafer curvature measurement

• Curvature-temperature behavior of both TSV samples were measured for thermal cycling and isothermal annealing tests.
• Similar curvature behavior observed, indicating similar stress and relaxation behavior (global).
Microstructure Analysis

- Grain orientation statistically random in both as-received and annealed samples.

- In the top 5µm of the vias, the 2x40µm TSVs have larger grains and larger variability in the grain size.

- Many grains in the 2µm vias span from sidewall to sidewall, forming some bamboo structures.
Microstructure Analysis

- Grain size plotted for the top 5µm of the TSVs
- Grain size distributions are bimodal.
- Abnormal grain growth, small grains mixing with large grains.

- Near top of the via, 2µm vias have larger grain sizes than 5µm vias.
- Statistical spread in grain size with increasing spread after a 3-hour 400°C anneal.
Driving Force for Cu Grain Growth

- Energy minimization
  - GB energy
    \[ \kappa \gamma_{GB} \]
  - Surface/interface energy
    \[ \Delta \gamma_s \left( \frac{i}{h} \right) \]
  - Strain energy
    \[ \Delta M \varepsilon^2 \]

- Cu is elastic anisotropic.
- Surface/interface energies dominate microstructure scaling in Cu nanolines.
- For TSVs, grain structure evolution is driven by thermal strain energy, inducing abnormal grain growth with more (200) grains and twins.
Microstructure Analysis

- Cu is highly anisotropic: $E_{100}/E_{111} \sim 0.44$

- Nanoindentation results indicate a correlation between mechanical properties and extrusion height.

- Grain structure and mechanical properties (modulus and hardness) are important in controlling via extrusion.
Microstructure Effect on Elastic Modulus

◊ Plane strain Cu

\[
\sigma_r^A = \sigma_\theta^A = \frac{-E_f \varepsilon_T}{1 - 2v_f + \frac{1 + v_m}{1 + v_f} \frac{E_f}{E_m}},
\]

\[
\sigma_z^A = -E_f \varepsilon_T \left[ \frac{1 + \frac{v_m}{1 + v_f} \frac{E_f}{E_m}}{1 - 2v_f + \frac{1 + v_m}{1 + v_f} \frac{E_f}{E_m}} \right],
\]

◊ Plane strain Si solution: Ryu et. al, 2011.

\[
\sigma_r^A = -\sigma_\theta^A = \frac{-E_f \varepsilon_T}{1 - 2v_f + \frac{1 + v_m}{1 + v_f} \frac{E_f}{E_m}} \left[ \frac{D_f}{2r} \right]^2.
\]

• TSVs with smaller diameter depend on fewer grains to determine material properties at via top.
Via Extrusion

- Extrusion behavior shows statistical spread similar to grain size, with increasing spread after a 3-hour 400°C anneal.
- Annealing worsened magnitude and spread, especially for the 2µm TSVs.
Grain Size Correlated to Extrusion

- One study has demonstrated that the grain size at the top of the via is correlated to extrusion.
- Another study observed two types of extrusion behavior: “uniform extrusion” vs. protrusion of “individual grains”, and the protrusion of individual grains seem to correspond to tail of the distribution.
- The statistics for reliability are determined by the worst case vias – those with multiple grains at the top.
- Scaling reduces the average number of grains, less for the 2µm vias but statistical spread persists and is correlated to extrusion statistics.
Scaling and Via Extrusion

- Post-plating anneal stabilizes the extrusion, but subsequent annealing decreases number of grains in the via top and increases the extrusion height.
- Distribution of extrusion heights not normalized and maximum extrusions are not well-controlled.
Synchrotron White Beam Scanning X-ray Microdiffraction (µSXRD)

- Non-destructive and high resolution
- Peak shape → plastic deformation and dislocation distribution in the diffracted volume (qualitative).
- Plasticity → Extrusion

400°C (024) reflection
Microstructure and Plasticity

- Average peak width (APW) measures dislocation-induced plasticity and is higher at the top of all the vias and correlated to grain orientation.
- Grain statistics will thus affect plasticity and extrusion.

- APW vs. orientation for 2µm Vias after annealing at 400°C
- Orientation refers to the angle between the grain (001) and the sample normal.
Scaling Effect on Plasticity

- Statistical variation of local plasticity increases with decreasing diameter, both in magnitude and in distribution throughout the via.
- Variation within the via and from via to via is higher for the 2um vias than the larger vias.
Discussion

• The correlation of plasticity to the microstructure and extrusion has been proposed, but here it has been investigated.
• The results show that scaling TSV dimensions affects the copper microstructure and leads to more variation in local plasticity and via extrusion.
• 2x40µm vias have no clear advantages over the 5x50µm vias in terms of improving extrusion statistics.
• TSV structure is more complicated than Cu lines with complex stress state.
• Upon annealing, grain structure evolution is driven by thermal strain energy, inducing abnormal grain growth.
• The abnormal grain growth makes it difficult to control the microstructure distribution, and thus the extrusion statistics, especially with scaling of TSV dimensions.
Future Work

- Microstructure simulation (local strain, interface, and surface energy minimization, taking copper anisotropy into account).

- Results agree with EBSD measured grain size distribution.

- Alternative approaches to improve extrusion statistics, such as the application of cap layers.
Summary

• Cu microstructure plays important roles in the reliability of Cu interconnect and through-silicon vias.

• The effect of microstructure on via extrusion and its statistics has been observed but fully understood.

• In this work, the effect of scaling on microstructure and extrusion is investigated. Stress behaviors, extrusion behaviors, microstructure, material property, and plasticity of TSVs with 2 different diameters were measured.

• The results show that scaling TSV dimensions affects the copper microstructure and leads to more variation in local plasticity and via extrusion. 2x40µm vias have no clear advantages over the 5x50µm vias in terms of improving extrusion statistics.

• Additional work underway, including microstructure simulation.
Thank you!