INTERCONNECT STRUCTURE FOR ROOM TEMPERATURE 3D-IC STACKING EMPLOYING BINARY ALLOYING FOR HIGH TEMPERATURE STABILITY

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Outline

• Intro: Current Methods of 3D Assembly
• Proposed Solution: Room Temp Bonding
• Methodology and Characterization
• Evaluation of Experimental Results
• Conclusions and Next Steps
3D Promise / 3D Issues

Promise:
- High speed
- Low power
- High density

Issues:
- Bonding Registration Issues
- Serial Yield Issues
- Operability/Reliability Issues
Assessment of Conventional Reflow and Thermocompression Bonding for 3D-IC
# Conventional Reflow and Thermocompression Bonding

<table>
<thead>
<tr>
<th>REFLOW (e.g. SnAg/Cu)</th>
<th>THERMOCOMPRESSION (e.g. Cu/Cu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast</td>
<td>Slow</td>
</tr>
<tr>
<td>Solder Bridges</td>
<td>Confined, Stable</td>
</tr>
<tr>
<td>Low force</td>
<td>High Force</td>
</tr>
<tr>
<td>Lateral instability</td>
<td>Laterally Stable</td>
</tr>
<tr>
<td>Solder Compliance</td>
<td>Ultra Flatness Required</td>
</tr>
<tr>
<td>Unstable during stacking</td>
<td>Thermally Stable</td>
</tr>
<tr>
<td>CTE Mismatch</td>
<td>CTE Mismatch</td>
</tr>
<tr>
<td>Controlled Atmosphere</td>
<td>Controlled Atmosphere</td>
</tr>
</tbody>
</table>
Ideal 3D Metallurgy and Bond Process Would Have the Following Characteristics

• High speed bond cycle.
  – Room temperature bond at low force.
  – Air ambient.
• Fine pitch capability (<10µ) without bridging.
• Compliant metallurgy to give flatness margin.
• Unlimited wafer level chip stacking.
  – Mechanical stability during (1+n) bonds.
  – No concerns for oxidation buildup.
• Immune to “next-higher-assembly” reflow.
Proposal: A Novel Metallurgy and Bond Process for Room Temperature 3D Multi-Chip Stacking
Proposed Solution: InAg Binary
Advantages of InAg Binary

• Deoxidized Ag and In bond instantly at RT.
• Compliant Indium allows flatness tolerance.
• Indium has easily controlled squeeze-out.
• Low bonding force: < 0.1 gram per bump at atmospheric ambient.
• Mechanical stability during subsequent bonds.
• InAg alloy anneal is performed at 120-140°C (solid state), then stable to >600°C.
InAg Binary Bonding - Engineering Details
Detail: Surface Prep

• **De-oxidized** Indium and Silver will cold-weld instantly at room temp.

• Could wet etch oxide, but throughput is slow and oxide re-grows, making the process time-dependent.

• Atmospheric plasma quickly removes oxide and passivates die for bonding.

• Passivation enables long queue lifetime (hours).
Detail: In-Situ Probing

- Room temp bonding and no confinement enable in-situ probing during bonding.
Detail: In-Situ Probing

- Room temp bonding and no confinement enable in-situ probing during bonding.
- Operability of each bond can be checked during the stacking operation.
Detail: In/Ag Alloy Anneal

- Indium and Silver interdiffuse rapidly, even below the melting point of Indium. (~135°C)
- Since the bonded connections remain in the solid phase, no compression force is needed during anneal. Die flatness/bowing issues are avoided.
- Ideal volume ratio of Ag to In is 2:1 to form Ag₂In with a melting point of ~600°C.
- Diffusion kinetics depend on metal purity, time, volume, and temperature.
- Cross-section + EDS provide interdiffusion data.
Experimental
Test Chips

Substrate (Ag bump):

- Silicon substrate.
- 256 Copper daisy chain continuity channels.
- 1280 bumps each.
- Bumps are 4µ dia, 4µ tall
- 10µ centers.
- Copper pillars (plated).
- Nickel barrier (plated).
- Ag cap (plated).
- No CMP.

Chip (In bump):

- Silicon chip.
- 256 Copper daisy chain continuity channels.
- 1280 bumps each.
- Bumps are 4µ dia, 4µ tall
- 10 µ centers.
- Copper pillars (plated).
- Nickel barrier (plated).
- In cap (plated).
- No CMP.
Wet Etch Surface Preparation

• Pre-bond wet etch option:
  – Dilute HCL to remove oxidation from Ag and In.
  – Extreme care required to avoid over-etching.
  – Bond parts within 10 minutes to avoid re-oxidation.
Atmospheric Plasma Surface Prep

• Reducing chemistry converts bump oxide back to native metal.

• Passivating chemistry ties up metal dangling bonds.

• Process takes less than 1 minute. Atomic passivation inhibits re-oxidation for hours, is bond-able.

• Activates chip surfaces for enhanced underfill wicking.
Room Temperature Bonding

- 27° C substrate and chip.
- Compression bond at <0.1 gram per bump (32Kg total force on 640x512 bumps).
- Maintain 1 µ alignment accuracy thru bonding.
- Confining gas not required.
- Multiple-chip automatic placement available but not used for these experiments.
Post-Bond Alloy Anneal

- Alloy anneals performed in room air.
- Programmed ramp, temperature, and time.
- RT-140C alloy anneal temperature.
- 0-32 Kg compression force applied during anneal.
- 0-30 minutes alloy anneal time.
- Can be performed simultaneously with underfill cure.
Experimental Results
Atmospheric Plasma Cleanup, RT Bond, 200C 10 min Alloy Anneal (no force)

- Strong adhesion of In/Ag as evidenced by tensile rupture.
- Ag2In alloy is **ductile**, not fragile
- Capable of removing alloyed In/Ag bump from its Ni pad.
RT Bond, A.P., 200C 30 min Anneal
Cross-section and EDS

- No pure Indium remaining.
- Region B is ideal Ag$_2$In alloy ratio.
- Region C, D & E some Cu, so less Indium available for Ag alloying.
- Cu is probably a remnant of seed layer removal by sputtering. Wet etch next time!
- Nickel barrier (F) shows no diffusion of In, Ag, or Cu.
- Region A is still 96% Ag, indicating a depletion of In for alloying.
- Take-aways:
  - Indium prefers Cu to Ag for alloying.
  - Cu ties up Indium efficiently – must eliminate from bonding region.
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Makeshift Structure To Avoid Cu Contamination - Replace Ag-Bumped Sub With Ag Planar Coupon

- **Bond In-Bumped Chip To Ag coupon**
- **Planar Silver coupon**

- **Sputtered Cu “Jacket”**
- **Cu contam.**

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Indium Chip To Silver Coupon; AP Prep
RT Bond; Anneal (no force) 30 min/135

High force shear

InAg alloy separated in bulk
Electrical Continuity Testing

- 256 daisy chain strings per chip.
- 1260 bumps in each string.
- Samples potentially compromised by Cu contamination.

<table>
<thead>
<tr>
<th>Anneal Temp</th>
<th>Ramp up time</th>
<th>Hold Time</th>
<th>Avg. Ω/bump</th>
<th>Yield to opens</th>
<th>Yield to shorts</th>
</tr>
</thead>
<tbody>
<tr>
<td>135°C</td>
<td>20 sec</td>
<td>600 Sec</td>
<td>0.248</td>
<td>98%</td>
<td>98%</td>
</tr>
<tr>
<td>190°C</td>
<td>60 sec</td>
<td>90 sec</td>
<td>0.108</td>
<td>93%</td>
<td>96%</td>
</tr>
<tr>
<td>190°C</td>
<td>240 sec</td>
<td>90 sec</td>
<td>0.084</td>
<td>100%</td>
<td>98%</td>
</tr>
</tbody>
</table>

- Increased anneal time/temp appears to improve bump conductance.
- Anneal above Indium melt temp does not seem to affect opens or shorts.
- Limited data suggests capability for low resistance, high yield contact.

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Shear Testing

- Bonded pairs were shear-tested in accordance with MIL-STD-883 which specifies die shear strength for this size die as 5.0 kg.
- Although shear data is limited, shear strengths on all samples measured did easily exceed the MIL-STD requirement.
- Shear strength is expected to improve when Cu is kept out of bond zone.
- The current data suggest that this bond scheme is capable of robust mechanical performance.

<table>
<thead>
<tr>
<th>Anneal Temp</th>
<th>Ramp up time</th>
<th>Hold Time</th>
<th>Shear Strength (Kg)</th>
<th>Shear/MIL-STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>135C</td>
<td>20 sec</td>
<td>600 Sec</td>
<td>12.1</td>
<td>242%</td>
</tr>
<tr>
<td>190C</td>
<td>60 sec</td>
<td>90 sec</td>
<td>8.6</td>
<td>172%</td>
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Surface Activation for Capillary Underfill

Die surfaces are not naturally wetting.
Contact angle ~50-70

De-oxidizing Atmospheric Plasma also activates die surfaces for enhanced CUF.
Contact angle <10
Conclusions

• AgIn system is capable of high speed, low force, room temperature bonding.
• 3DIC stacking at room temperature has significant benefits.
• Metallurgy is capable of MIL-STD mechanical stability following solid-state alloy anneal.
• Copper participates aggressively in Indium metallurgy – keep isolated.
• Nickel appears to be a suitable barrier layer to isolate Cu from Ag and In.
• Atmospheric Plasma enables fluxless instant RT bonding of In-to-Ag bumps and enhanced wicking of capillary underfills.
• These preliminary results for InAg binary bonding are very encouraging, and warrant further investigation.
Future Plans

- Fabricate new test chips confining the Cu to the interconnect layer.
- Characterize the interdiffusion mechanisms of the Ag/In binary system for small bump volumes.
- Characterize series resistance, shear, and high-temperature stability of the Ag/In binary system.
- Demonstrate multi-chip 3D stacking and subsequent underfill and reflow with the Ag/In binary system.
- Cultivate industrial partnerships to develop and implement this technology.
Acknowledgements

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