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

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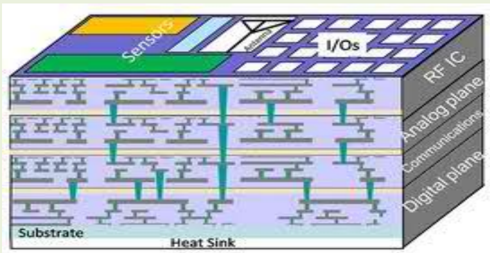
Outline

- 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



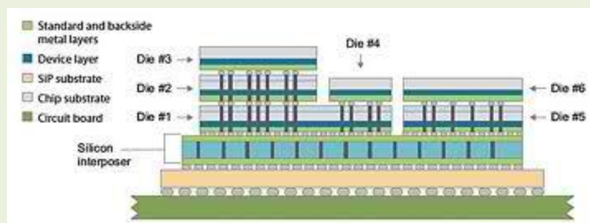
Promise:

- 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

REFLOW (e.g. SnAg/Cu)	***THERMOCOMPRESSION*** (e.g. Cu/Cu)
Fast	**Slow**
Solder Bridges	**Confined, Stable**
Low force	**High Force**
Lateral instability	**Laterally Stable**
Solder Compliance	**Ultra Flatness Required**
Unstable during stacking	**Thermally Stable**
CTE Mismatch	**CTE Mismatch**
Controlled Atmosphere	**Controlled Atmosphere**

Too Much Red Here!!

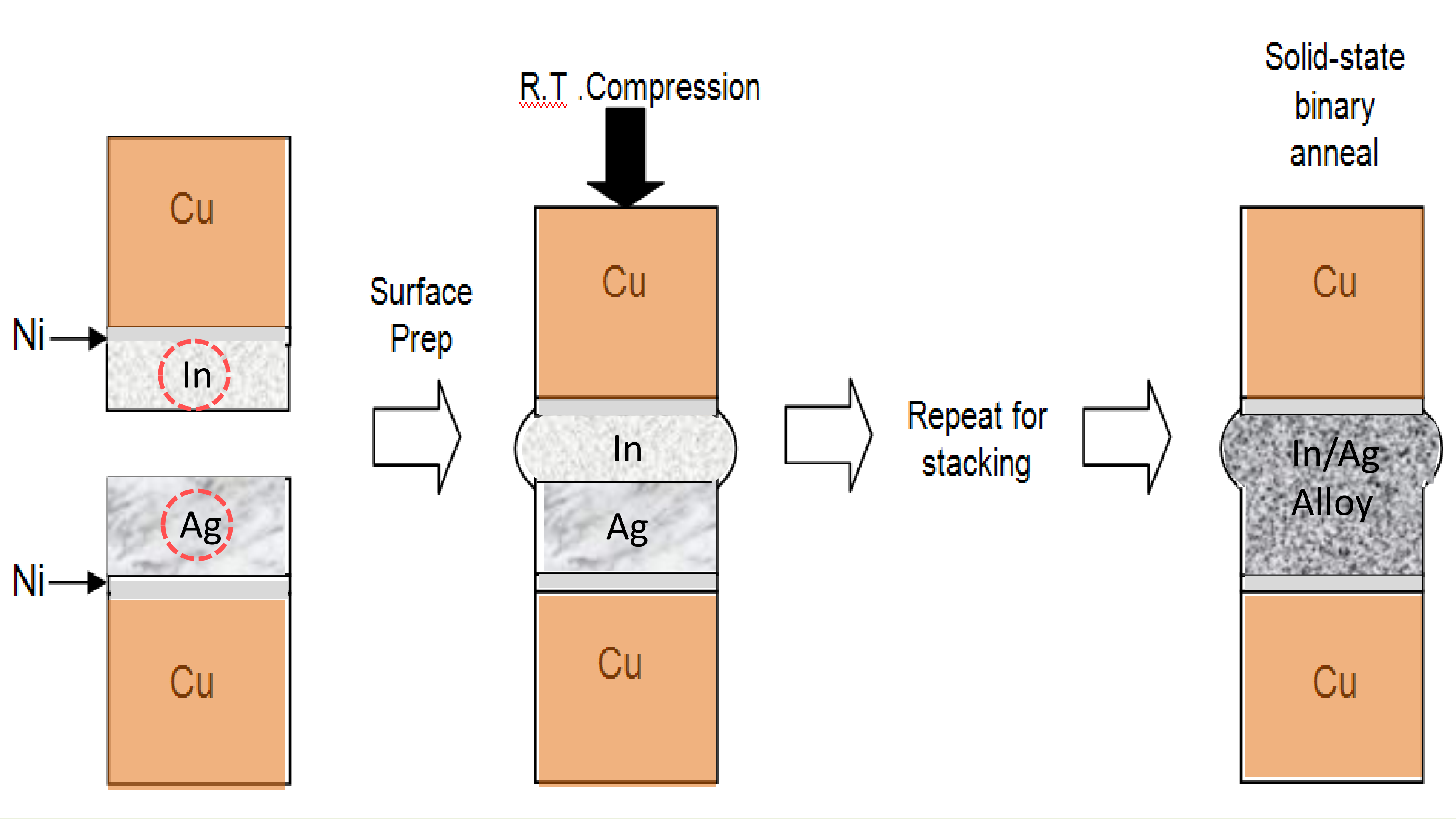
<u>Ideal</u> 3D Metallurgy and Bond Process Would Have the Following Characteristics

- **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 120-140C (solid state), then stable to >600C.**

InAg Binary Bonding-Engineering Details

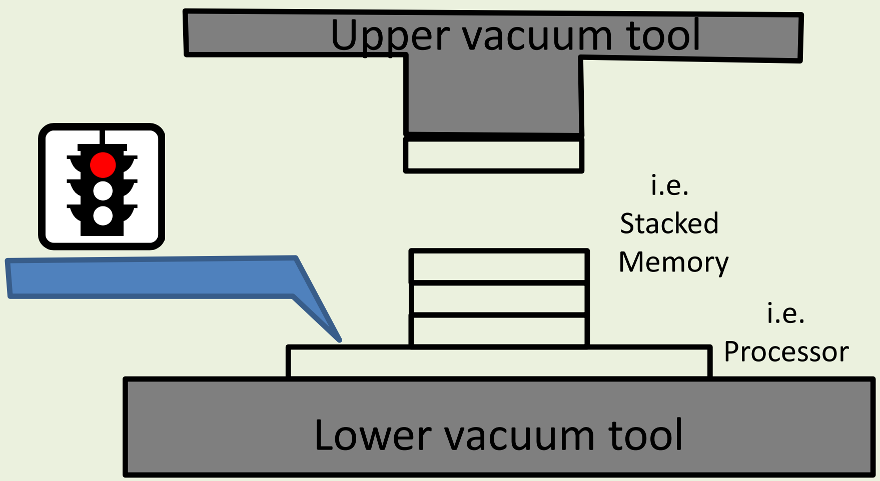
Detail: Surface Prep

- **<u>De-oxidized</u> Indium and Silver will cold-weld instantly at room temp.**
- **Could wet etch oxide, but thruput 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.**

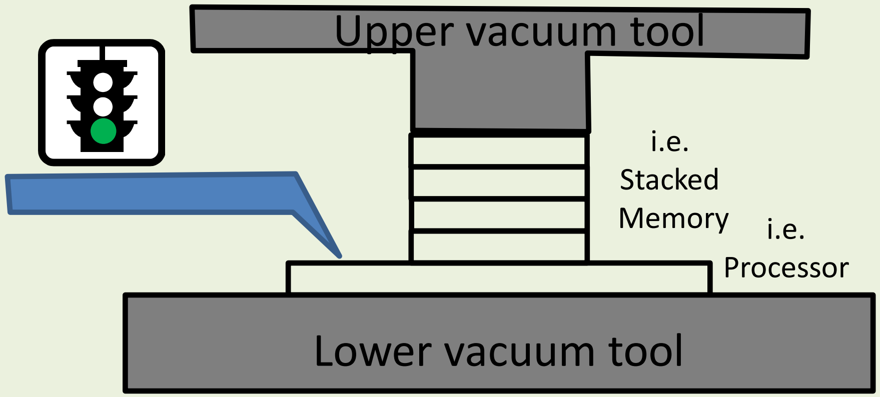
RT bond,
no confinement



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.**

RT bond,
no confinement

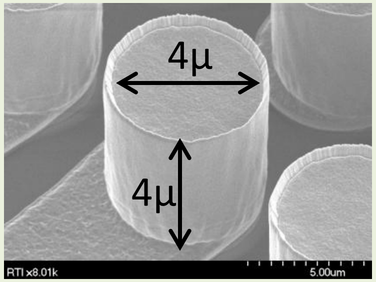


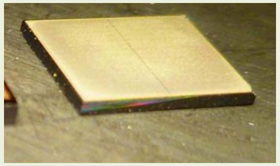
Detail: In/Ag Alloy Anneal

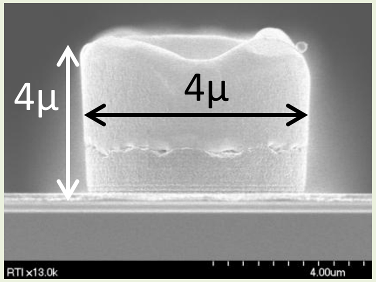
- **Indium and Silver interdiffuse rapidly, even below the melting point of Indium. (~135C)**
- **Since the bonded connections remain in the solid phase, no compression force is needed during anneal. Die flatness/bowing issues are avoided.**
- **Ideal volume ratio of Ag to In is 2:1 to form Ag_2In with a melting point of ~600C.**
- **Diffusion kinetics depend on metal purity, time, volume, and temperature.**
- **Cross-section + EDS provide interdiffusion data.**

Experimental

Test Chips







Substrate (<u>Ag bump</u>):

- 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 (<u>In bump</u>):

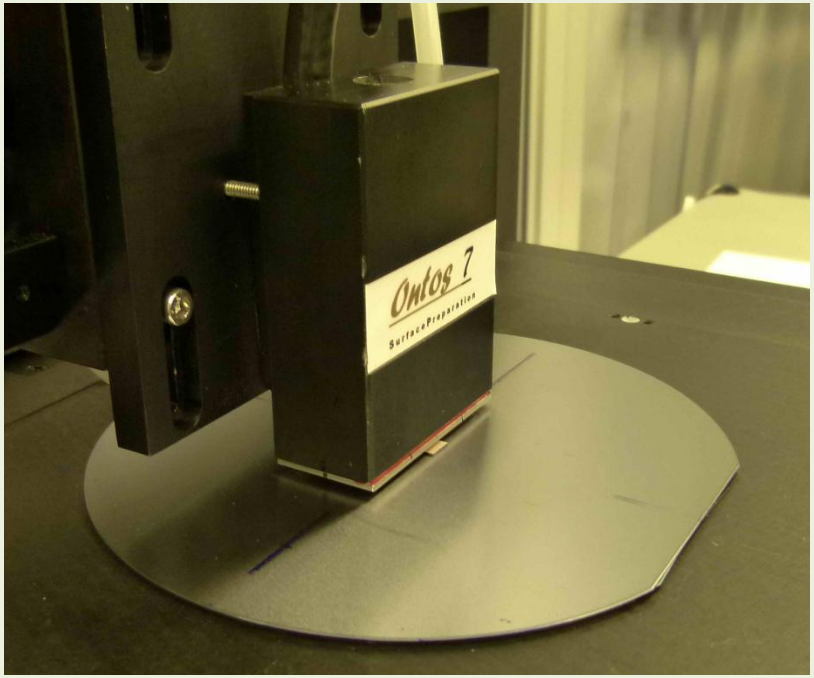
- Silicon chip.
- 256 Copper daisy chain continuity channels.
- 1280 bumps each.
- Bumps are 4µ dia, 4µ tall
- 10 µ centers.
- Copper pillars (plated).
- Nickel barrier (plated).
- In cap (plated).
- No CMP.

Wet Etch Surface Preparation

- Pre-bond wet etch <u>option</u>:
  - 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.**

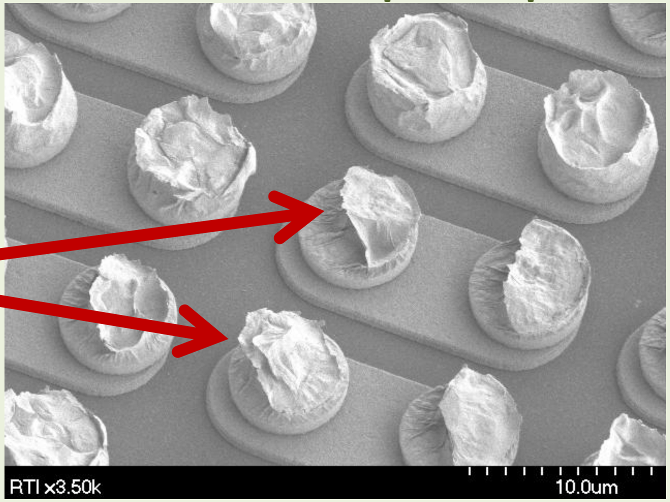
Experimental Results

Atmospheric Plasma Cleanup, RT Bond, 200C 10 min Alloy Anneal (no force)

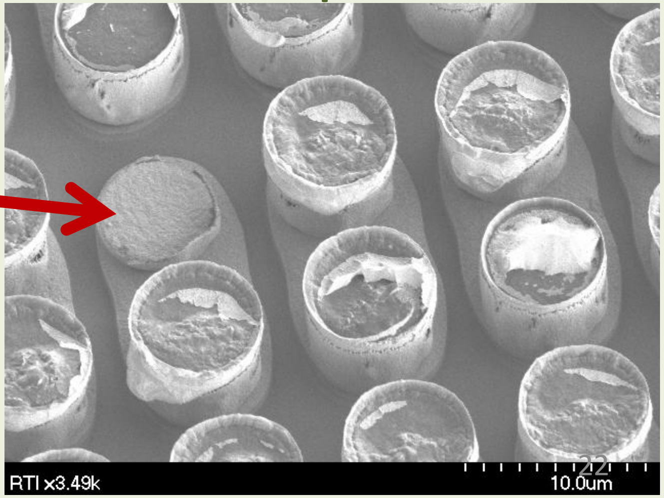
- **Strong adhesion of In/Ag as evidenced by tensile rupture.**
- **Ag2In alloy is ductile, not fragile**

- **Capable of removing alloyed In/Ag bump from its Ni pad.**

Indium-bumped chip

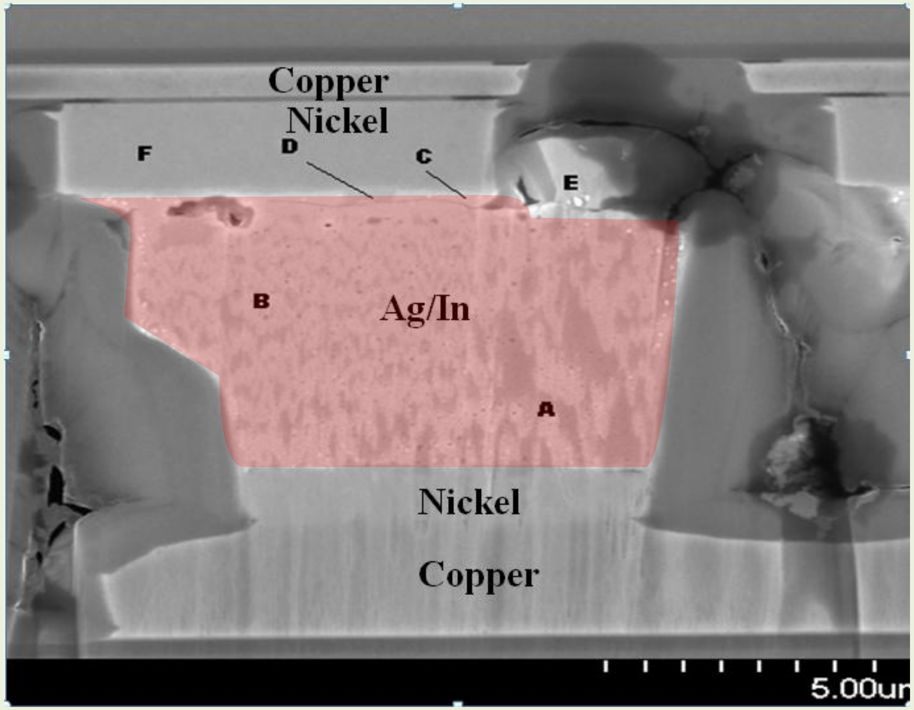


Silver-bumped substrate



RT Bond, A.P., 200C 30 min Anneal Cross-section and EDS

- No pure Indium remaining.
- Region B is ideal Ag_2In 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.
  - Cu/In intermetallic is reported as fragile – may explain signs of voiding/cracking at original bond interface.



	A	B	C	D	E	F
Ag	95.7%	67.6%	58.8%	25.1%	33.0%	0.0%
In	4.3%	32.4%	37.9%	65.1%	59.0%	0.0%
Ni	-	-	-	-	-	100.0%
Cu	0.0%	0.0%	3.3%	9.8%	7.2%	0.0%

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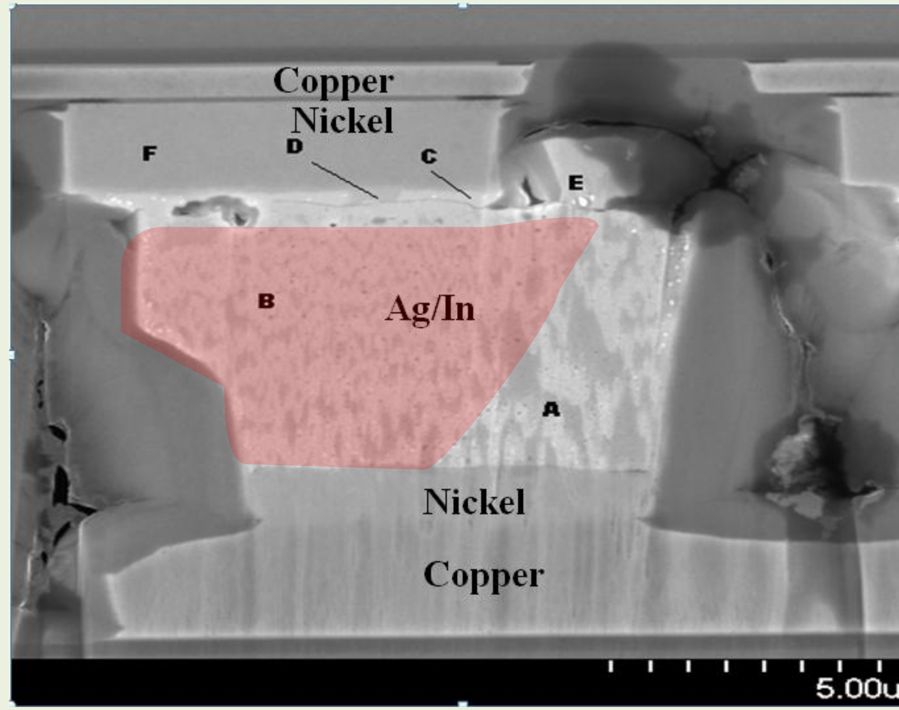

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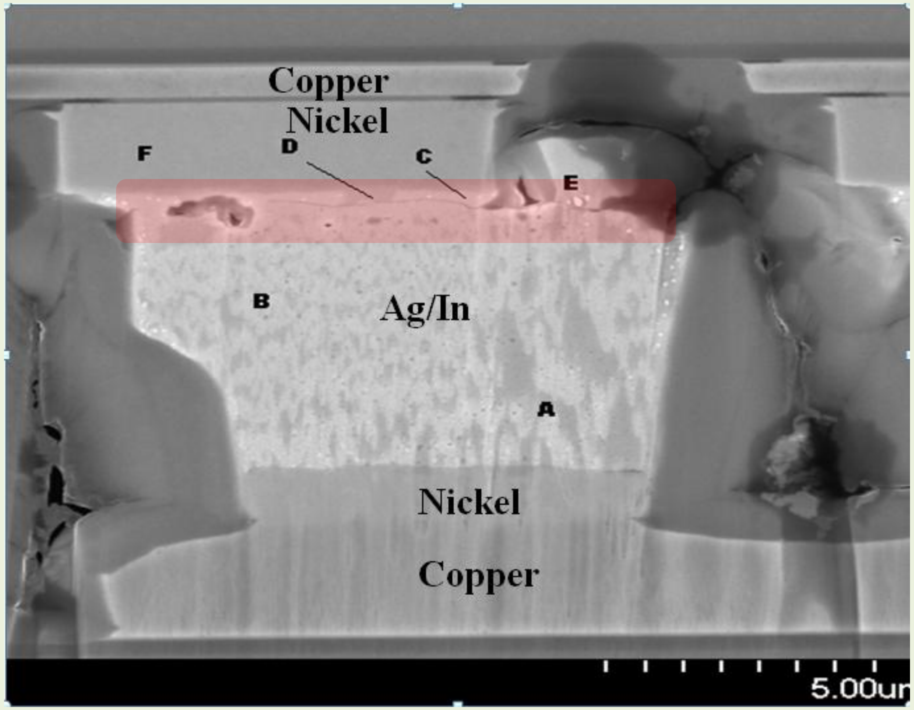

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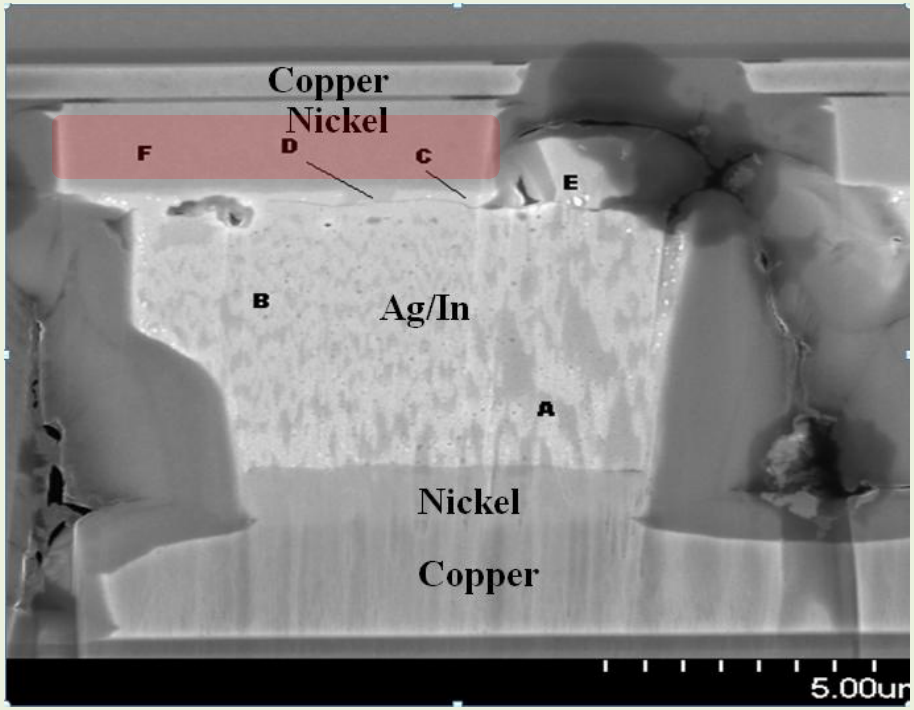

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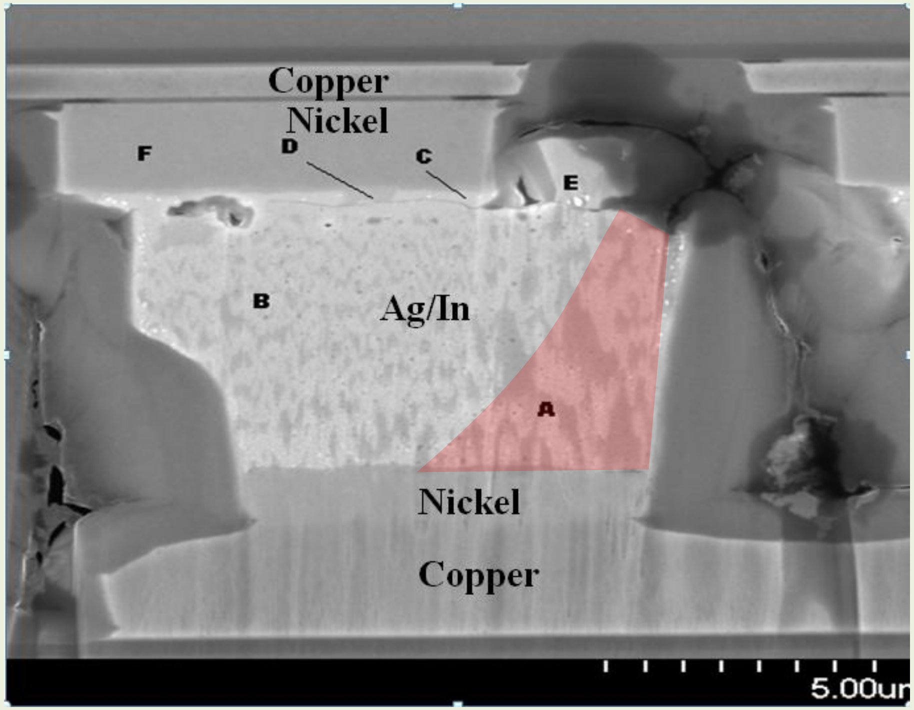

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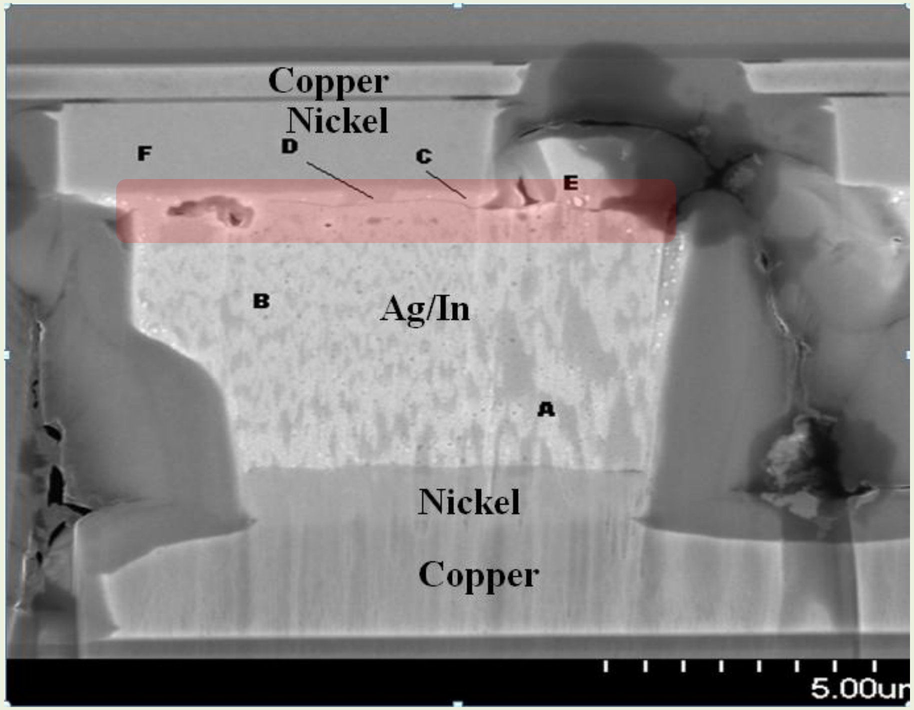

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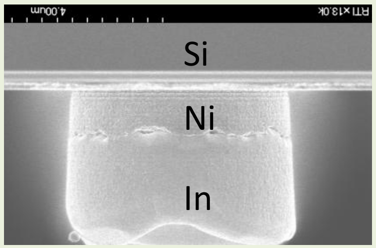
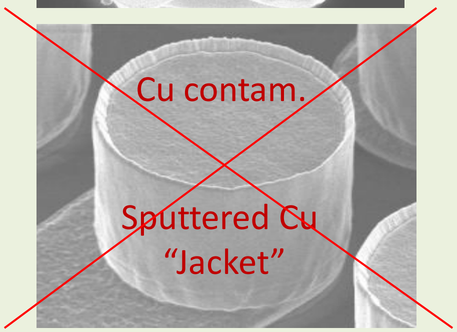
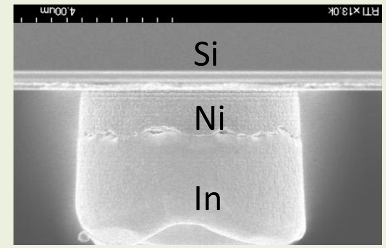
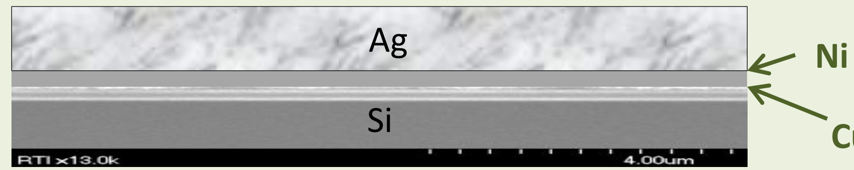
Makeshift Structure To Avoid Cu Contamination - Replace Ag-Bumped Sub With Ag Planar Coupon



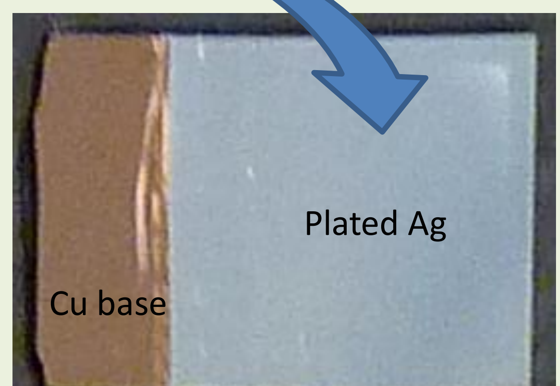






Planar Silver coupon

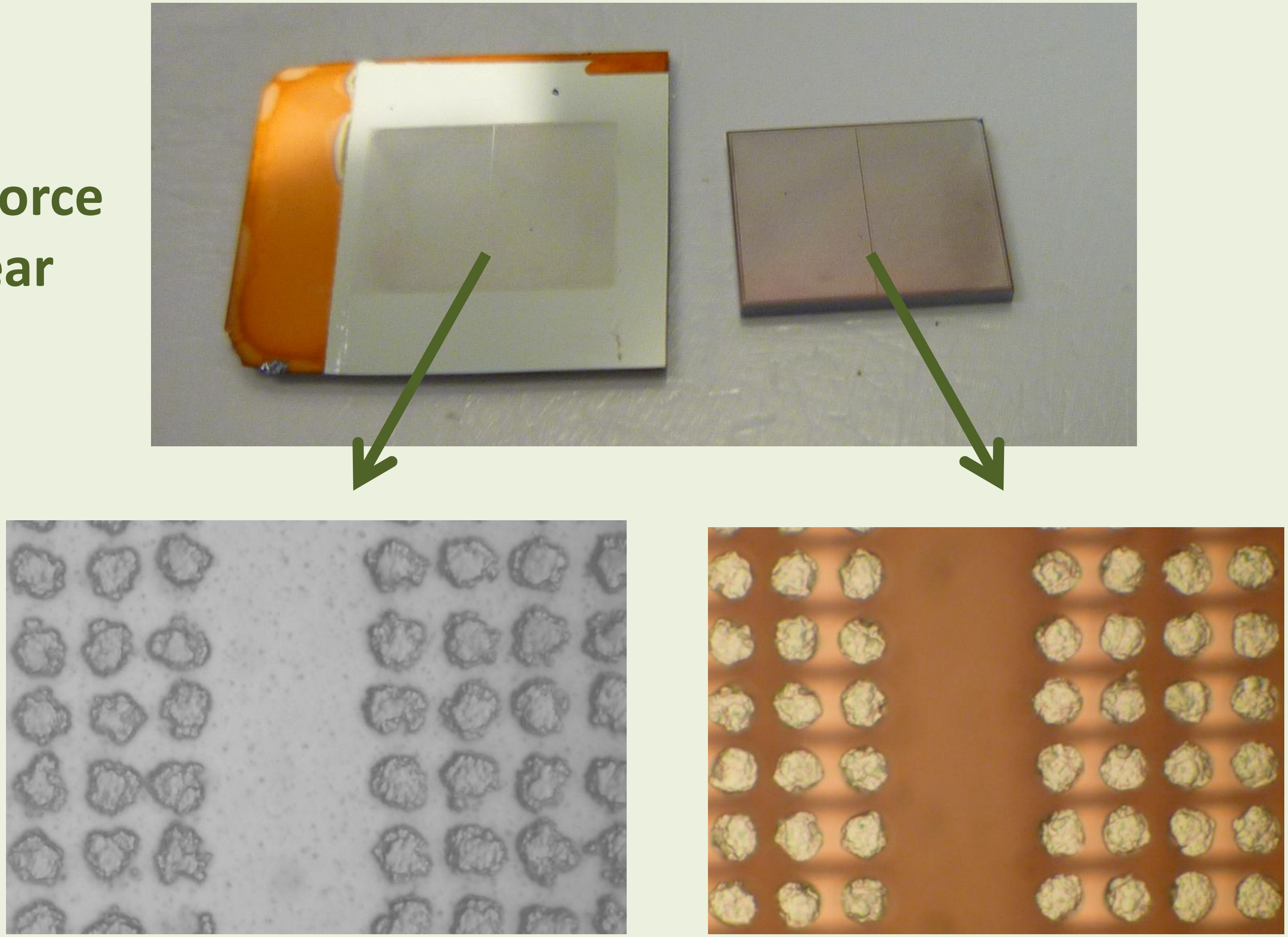
Bond In-Bumped Chip To Ag coupon



Ni Barrier

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.

Anneal Temp	Ramp up time	Hold Time	Avg. Ω/bump	Yield to opens	Yield to shorts
135C	20 sec	600 Sec	0.248	98%	98%
190C	60 sec	90 sec	0.108	93%	96%
190C	240 sec	90 sec	0.084	100%	98%

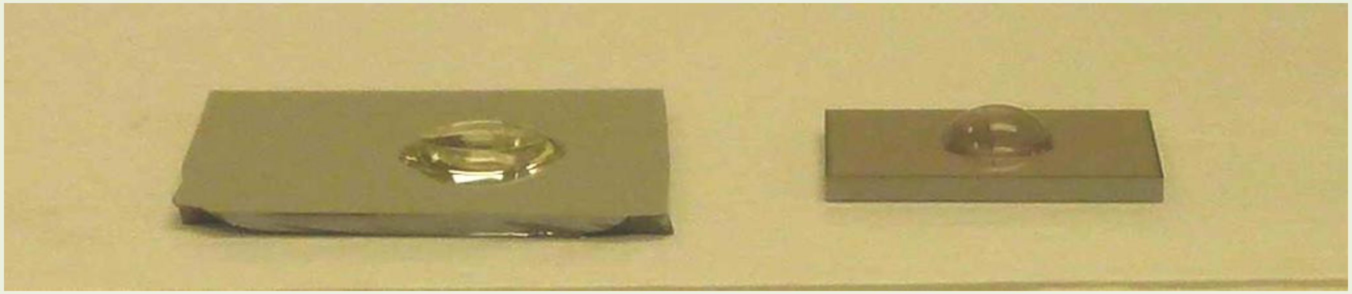
- **Increased anneal time/temp appears to improve bump conductance.**
- **Anneal above Indium melt temp does not seem to affect opens or shorts.**
- **Limited data suggests capability for low resistance, high yield contact.**

Shear Testing

Anneal Temp	Ramp up time	Hold Time	Shear Strength (Kg)	Shear/ MIL-STD
135C	20 sec	600 Sec	12.1	242%
190C	60 sec	90 sec	8.6	172%

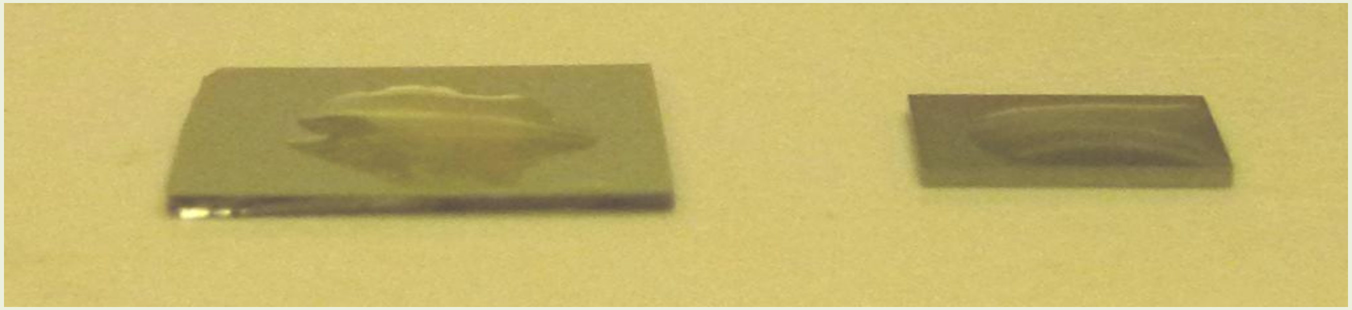
- **Bonded pairs were shear-tested in accordance with MIL-STD-883 which specifies die shear strength for this size die as 5.0 kg.**
- **Although shear data is limited, shear strengths on all samples measured did easily exceed the MIL-STD requirement.**
- **Shear strength is expected to improve when Cu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

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

- **The authors would like to thank Professor C.C. Lee and his students at U.C. Irvine. Their pioneering work in Ag/In metallurgy and processes provided inspiration for this development project.**

- **Fabrication, testing, and analytical work was performed and supported by RTI International CMET, internal funding.**

- **Surface preparation, bonding, and assembly process development was performed and supported by SETNA Corp.**