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Silver Flip-chip Interconnect Technology

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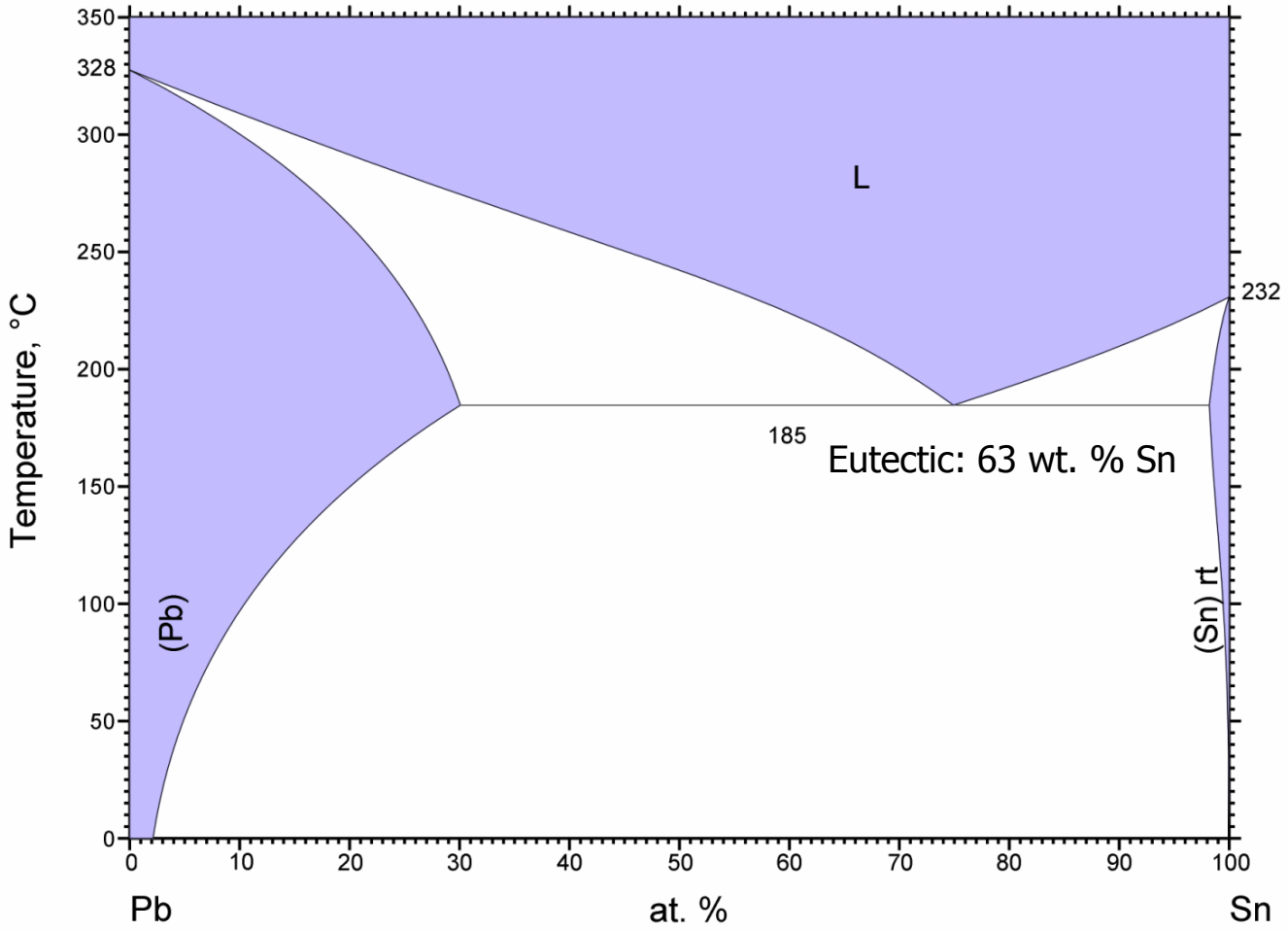
Outline

- Solders and Soldering
- Fluxless Soldering: 3 methods
- An example: Fluxless Ag-In Bonding
- Solid State Atomic Bonding
- Solder Flip-Chip Technology
- Silver Flip-Chip Technology
- Summary

Pb-Sn solders & phase diagram



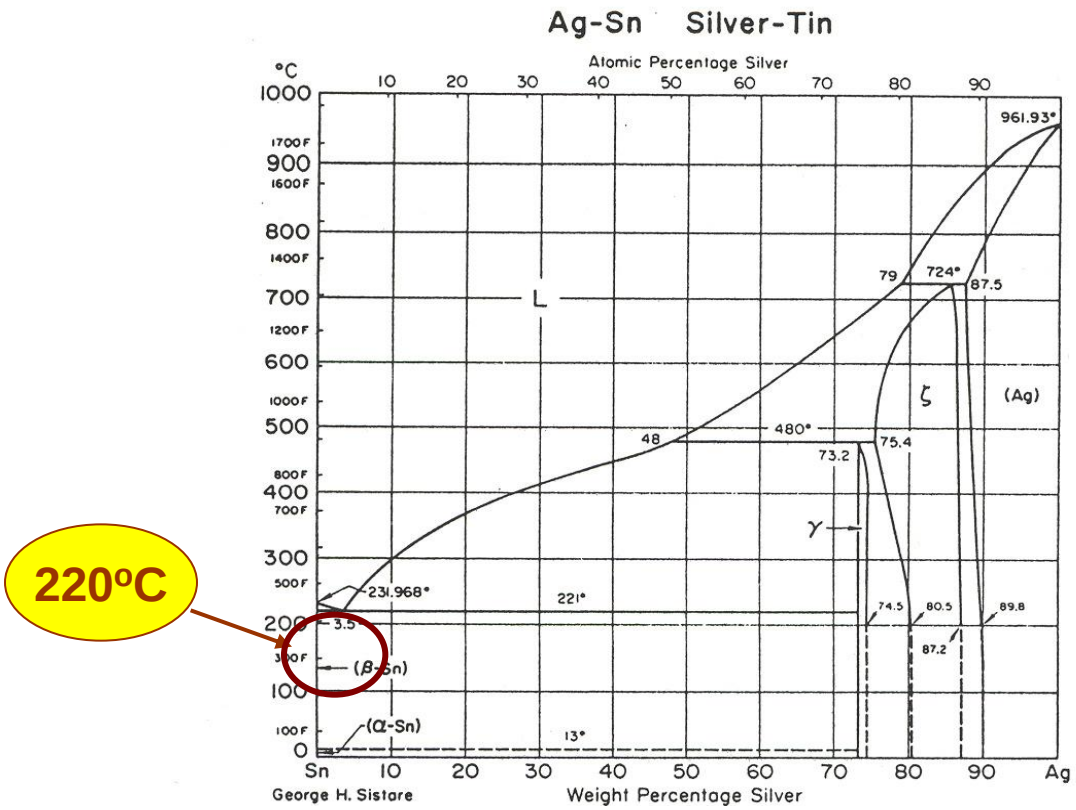
© ASM International 2009. Diagram No. 100247

Ohtani H., Okuda K., and Ishida K., Thermodynamic Study of Phase Equilibria in the Pb-Sn-Sb System, J. Phase Equilib., Vol. 16, 1995, p 416-429

Pb-free solders: SAC(Sn2.5Ag1.0Cu)

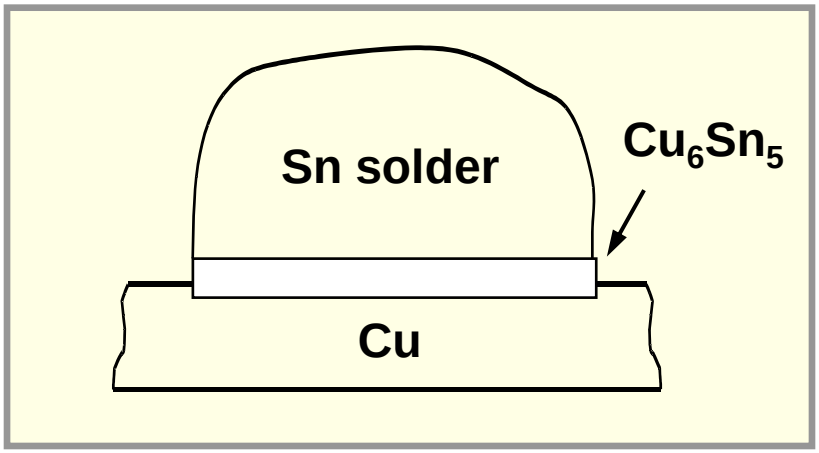
Most popular Pb-free solders: Sn with Ag and/or Cu

Sn3.5Ag eutectic: melting temperature 220ºC, plumber's solder



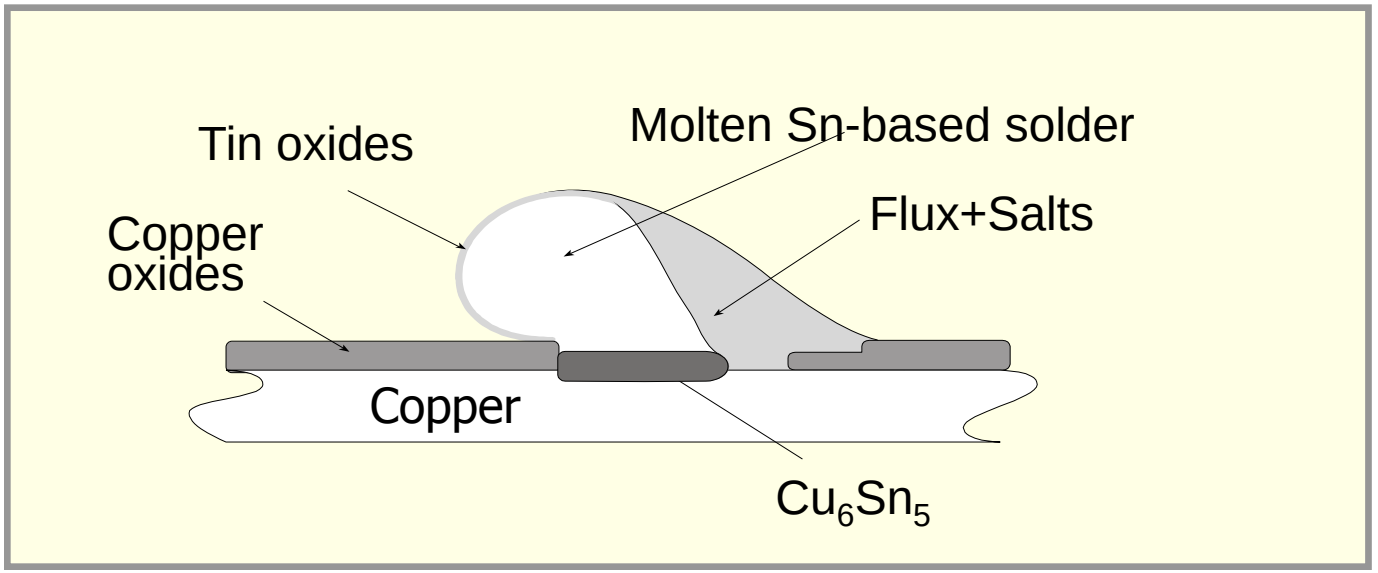
< Sn-Ag binary phase diagram >

Soldering process



Soldering is a chemical reaction, not a diffusion bonding
IMC formation is necessary for successful bonding
Exceptions: our fluxless bonding processes

Flux action in soldering



Flux (resin acid) + metal oxides → salts +H_2O

$2R\text{-}COOH + CuO \rightarrow (R\text{-}COO)_2Cu + H_2O$

$2R\text{-}COOH + SnO \rightarrow (R\text{-}COO)_2Sn + H_2O$ [R=carboxyl residue]

Fresh metal + fresh solder → IMC

It is not possible to produce void-free joint over large area

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Fluxless Processes Dealing with Tin Oxides

(I) Fluorine treatment: Plasma Assisted Dry Soldering (PADS) process,

$$SnO_x + yF \rightarrow SnO_xF_y$$

Potential problems:
(a) fluorine is known to etch SiO_2 and SiN,
(b) the RF power used may damage IC chips.

(II) Ar + 10% H_2 plasma (100-500 watts of RF power) dry cleaning agent to etch away the oxide layer on Sn3.5Ag and Sn63Pb solders.

Concern:

High RF power may damage IC chips or sensitive devices.

11. N. Koopman, S. Bobbio, S. Nangalia, J. Bousaba, B. Peikarski, "Fluxless soldering in air and nitrogen," *Proc. IEEE Electronic Components and Technology Conference*, pp. 595-605, Orlando, Florida, June 2-4, 1993.

14. Chang B. Park, Soon M. Hong, Jae P. Jung, Choon S. Kang and Y. E. Shin, "A study on the fluxless soldering of Si wafer/glass substrate using Sn3.5Ag and Sn37 Pb solder," *Materials Transactions*, 42, no. 5, pp.820-824, 2001.

16. Soon M. Hong, Choon S. Kang, and Jae P. Jung, "Plama reflow bumping of Sn3.5%Ag solder for flux-free flip chip package application," *IEEE Trans. Advanced Packaging*, 27, pp. 90-96, Feb. 2004.

- **How to achieve fluxless bonding?**
- **Our process**

To provide oxidation-free environment: 4 requirements

Process	Approach
Solder manufacture	Electroplating or vacuum deposition
Capping layer over solder	Au, Ag, or Cu
Dealing with capping layer	Dissolution
Bonding process	Vacuum or inert gas or H_2

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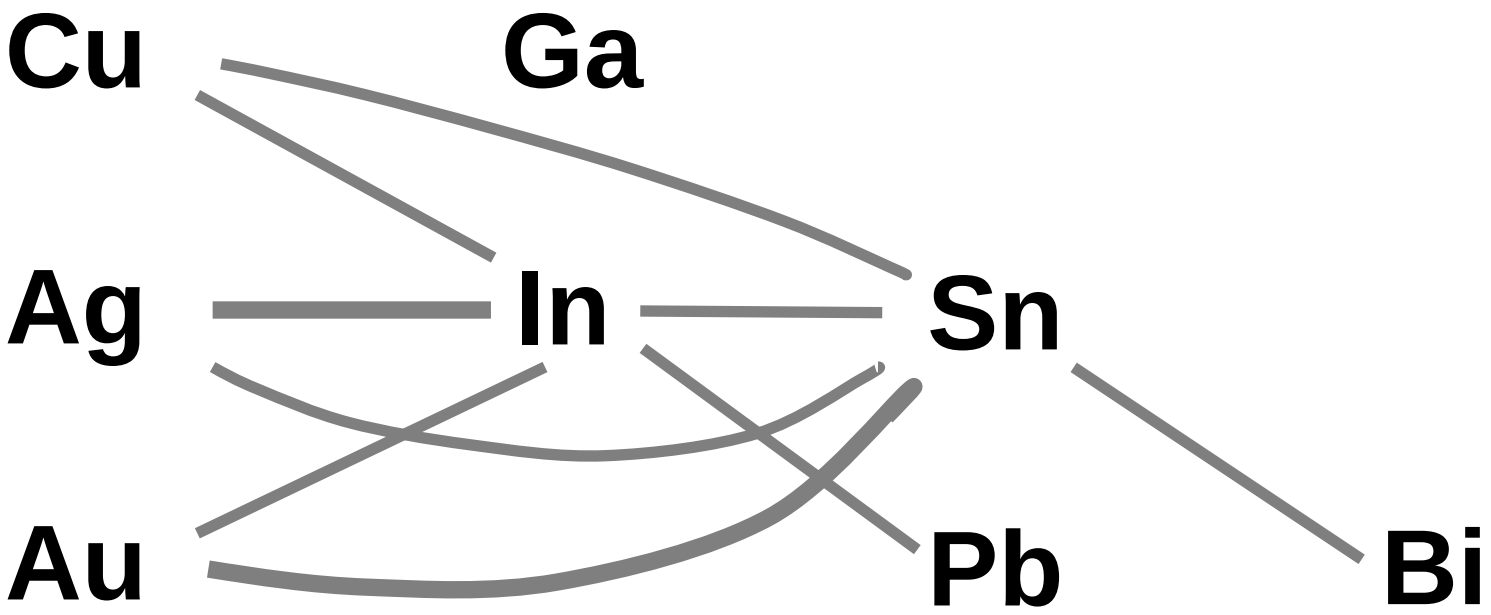
Fluxless Ag-In Bonding

Why Ag-In system?

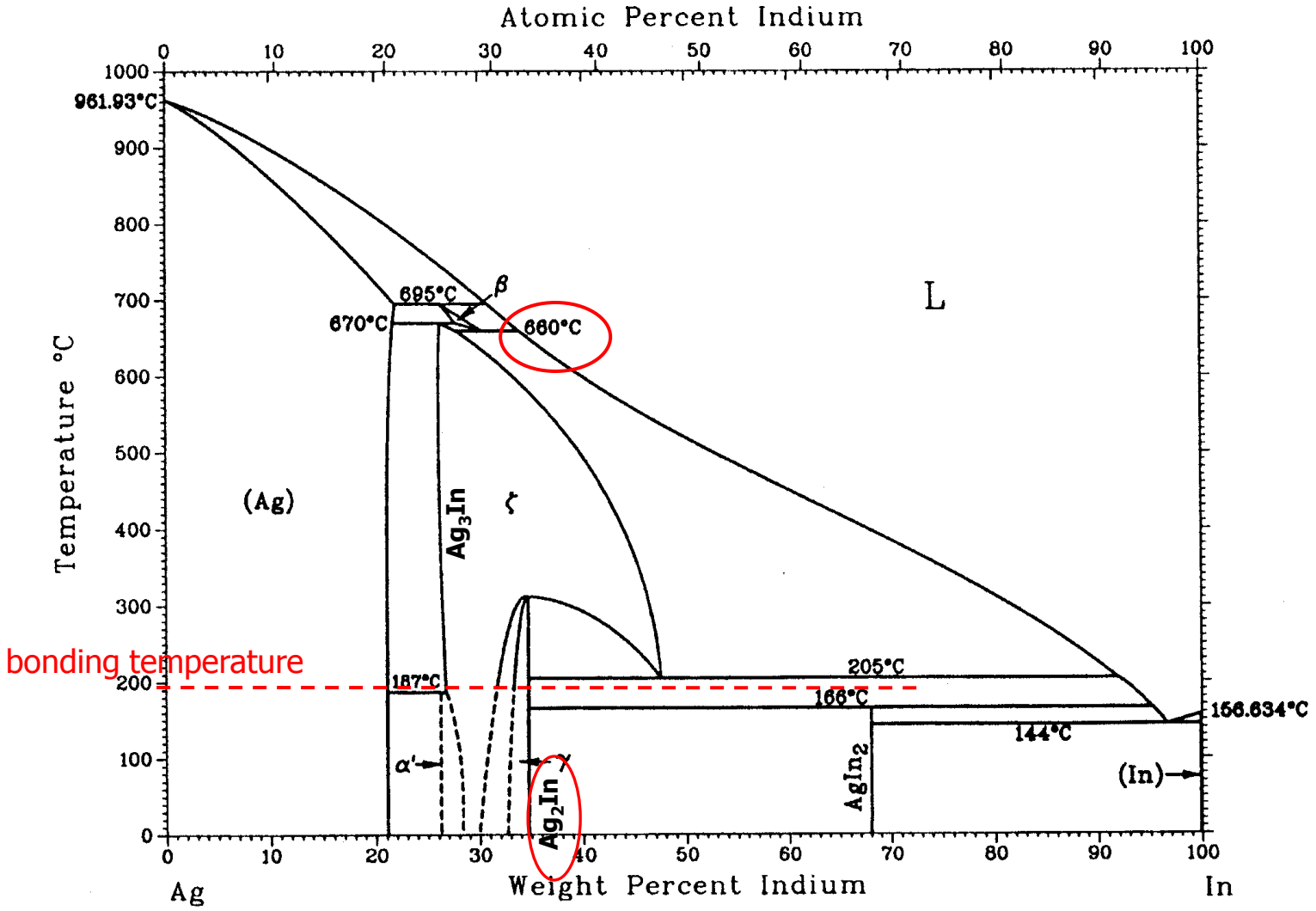
Requirements by sponsors:

Fluxless
Bonding temperature <200°C
Lifetime: 15 years at 150 deg. C
Pattern-able
Most recent: 200 deg. C continuous operation

The element matrix

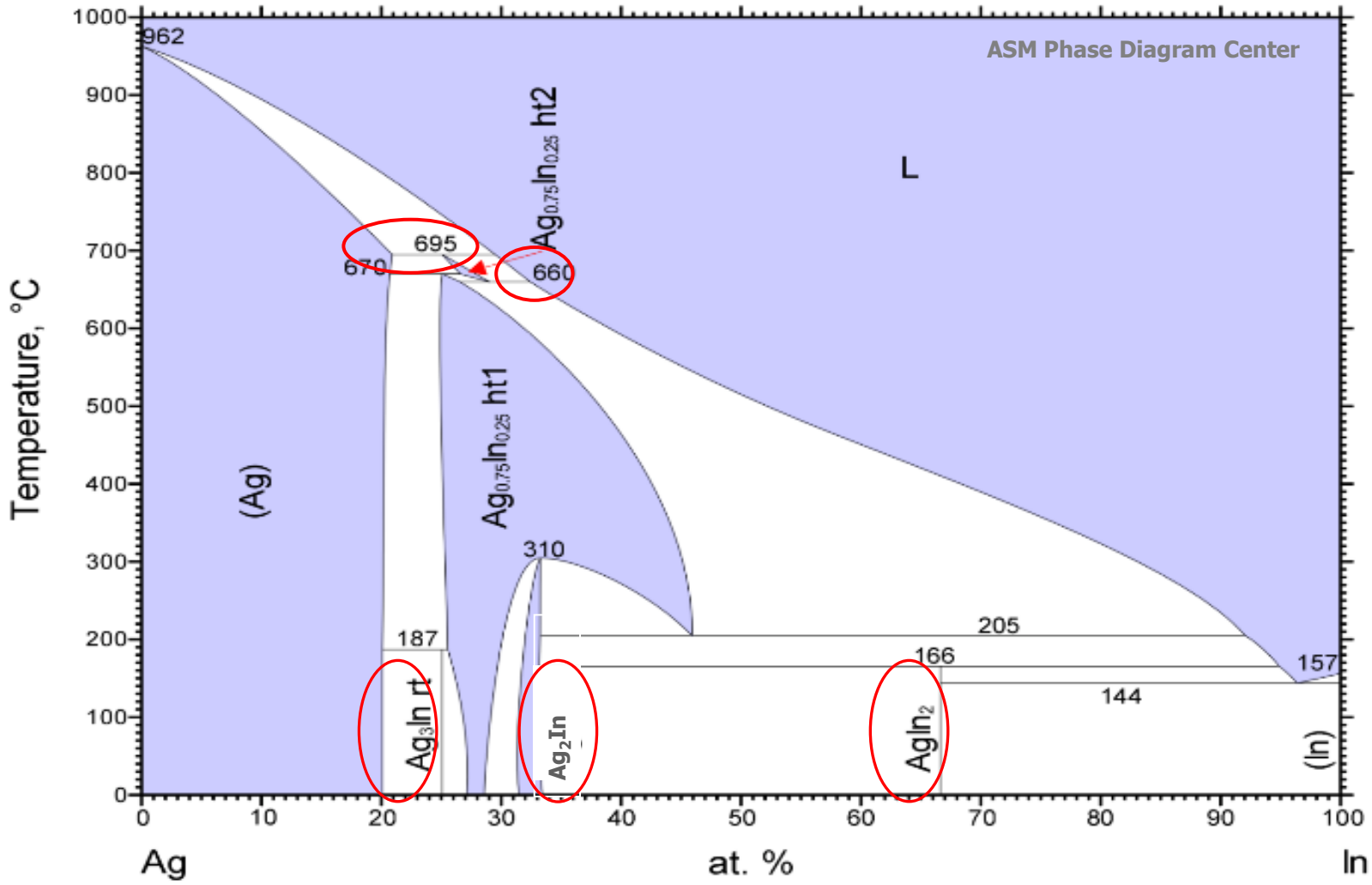


Ag-In Phase Diagram



(Ag): Ag solid solution

Ag-In phase diagram

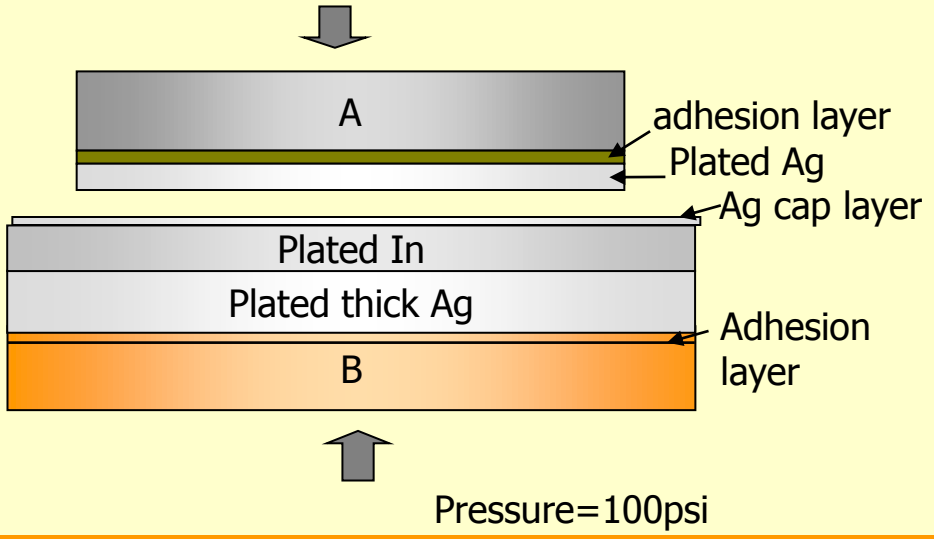


Indium melts at 157˚C

$2AgIn_2$ -> $3In(L)+Ag_2In$ 166˚C

$In(L \text{ or } S)+2Ag$ -> Ag_2In

Design of Ag-In bonding for high temperature operations



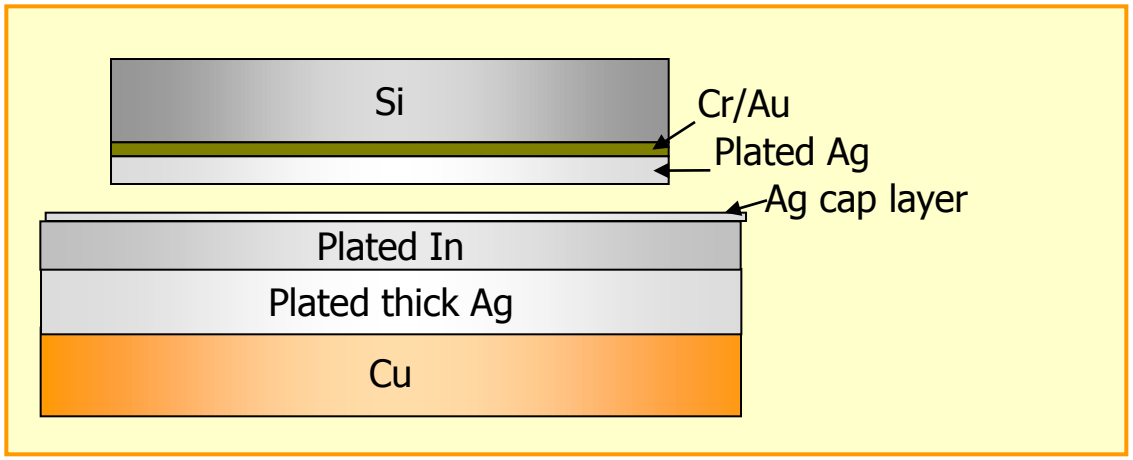
Final joint: thick Ag layer + AgIn alloy (Ag_2In)

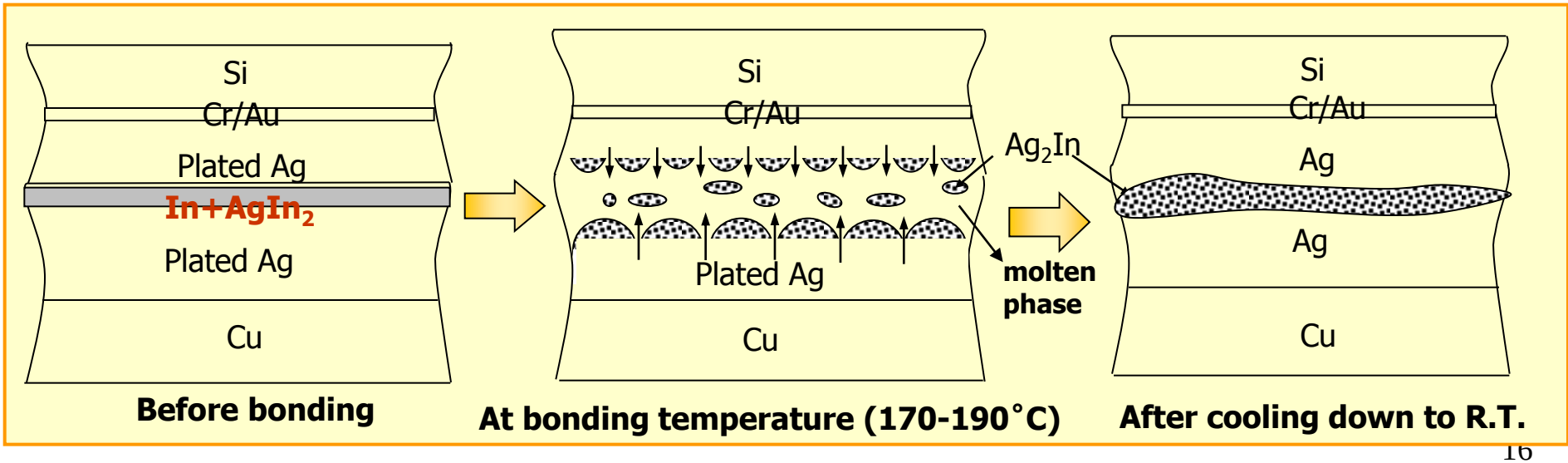
Advantages:

- Low bonding temperature: 170~190℃
- High re-melting temp. ≥ 660℃
- High electrical & thermal conductivities
- Joints become better at use: reverse the traditional trend
- Ductile Ag layer to manage CTE mismatch
- Pattern-able

The formation of Ag-In Joint

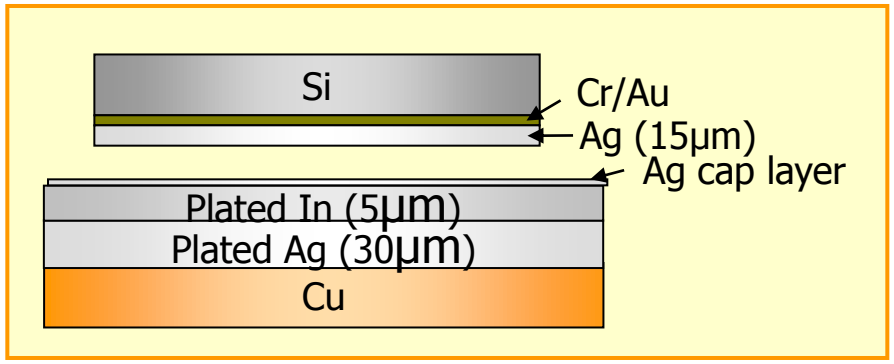
Bonding structure and Reactions

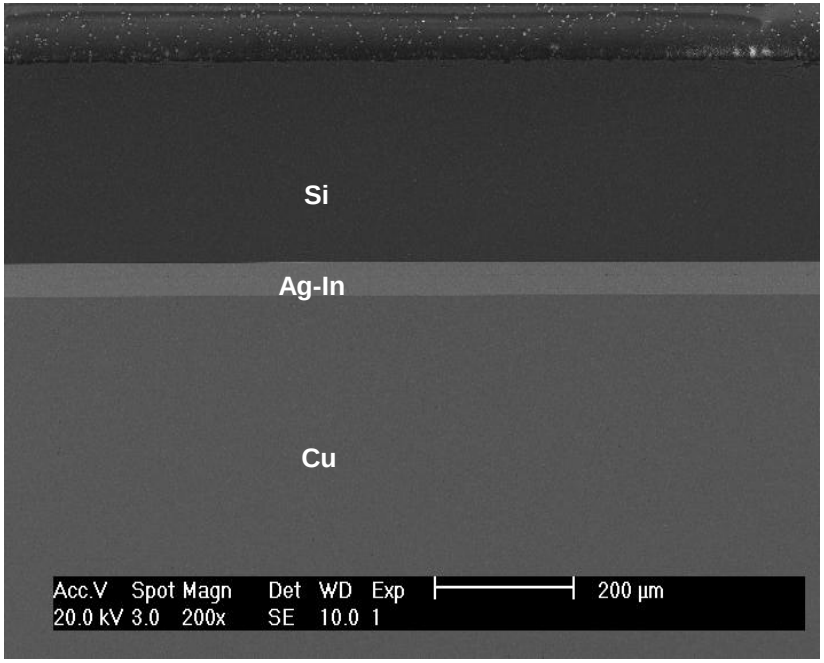




An example : Si bonded to Cu substrate

Bonding conditions: 180°C, 100psi, 0.1 torr vacuum





Maximum stress-free shear strain

$$\gamma = \frac{(\alpha_1 - \alpha_2)(T_2 - T_1)\frac{L}{2}}{h} = 0.15$$

α_1, α_2: CTE of Cu (17) and Si (3)

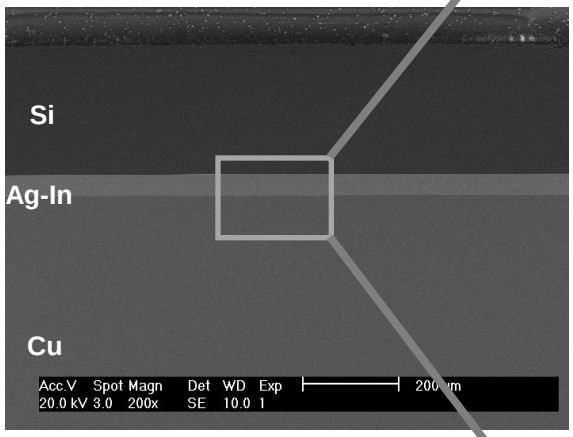
T_2: Solidifying temp., 166°C

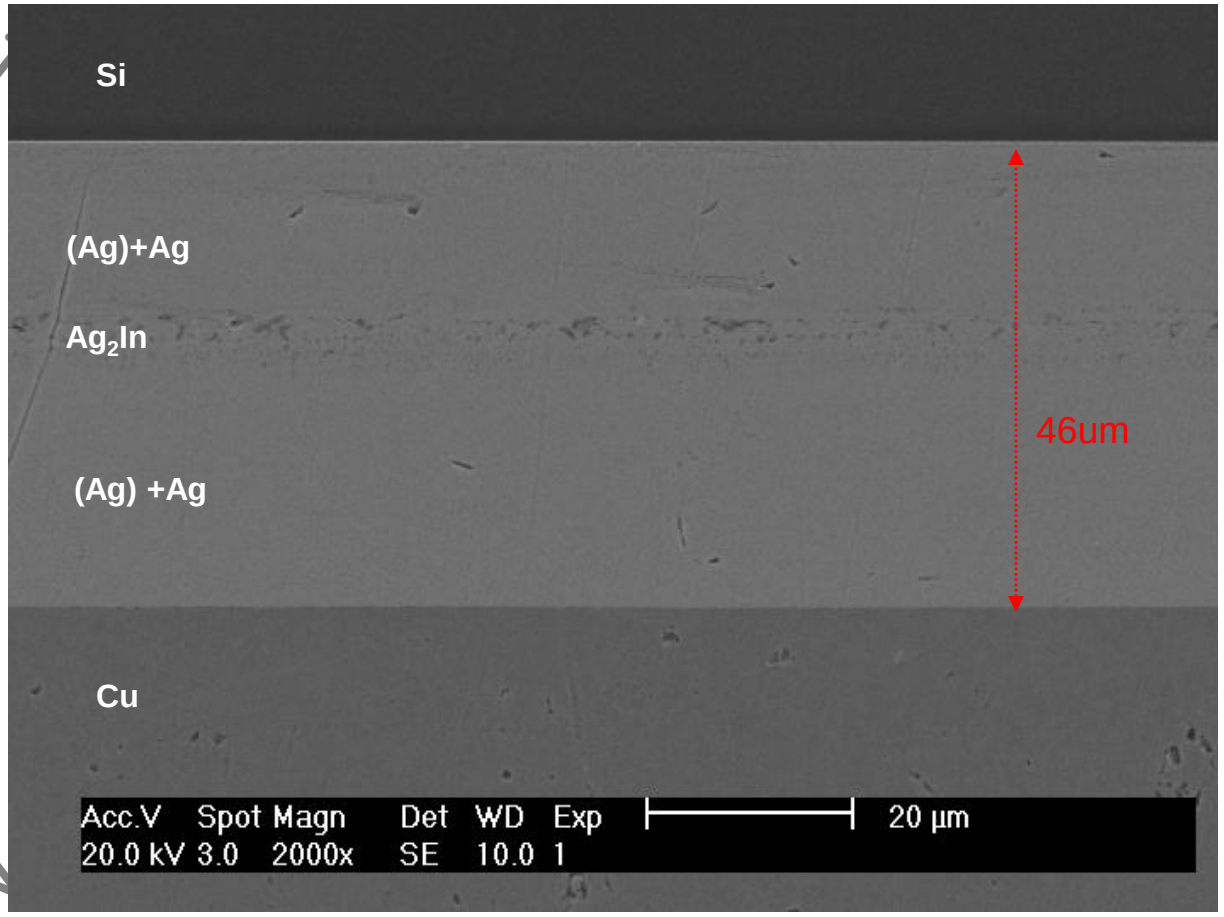
T_1: Room temperature, 25°C

L : Diagonal of Si chip (7mm)

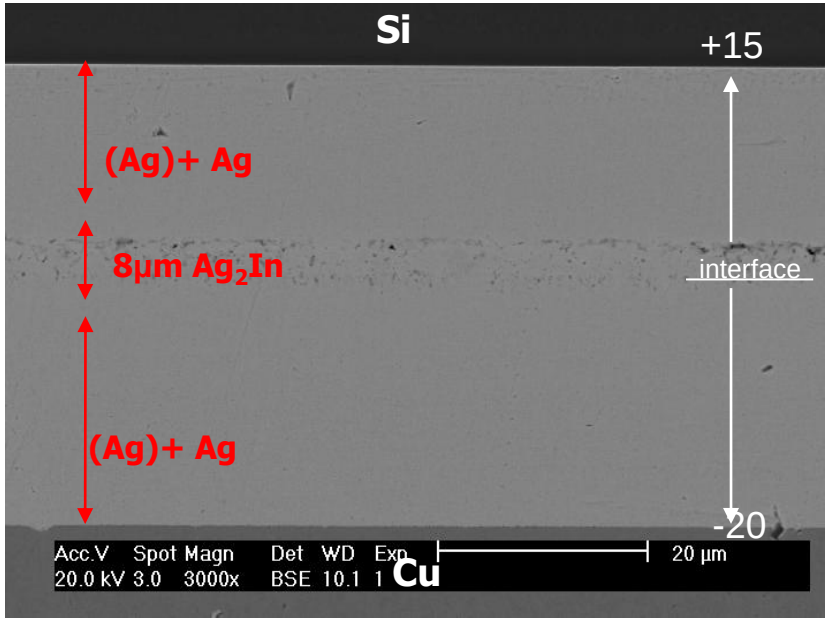
h : Thickness of bonding layer (45μm)

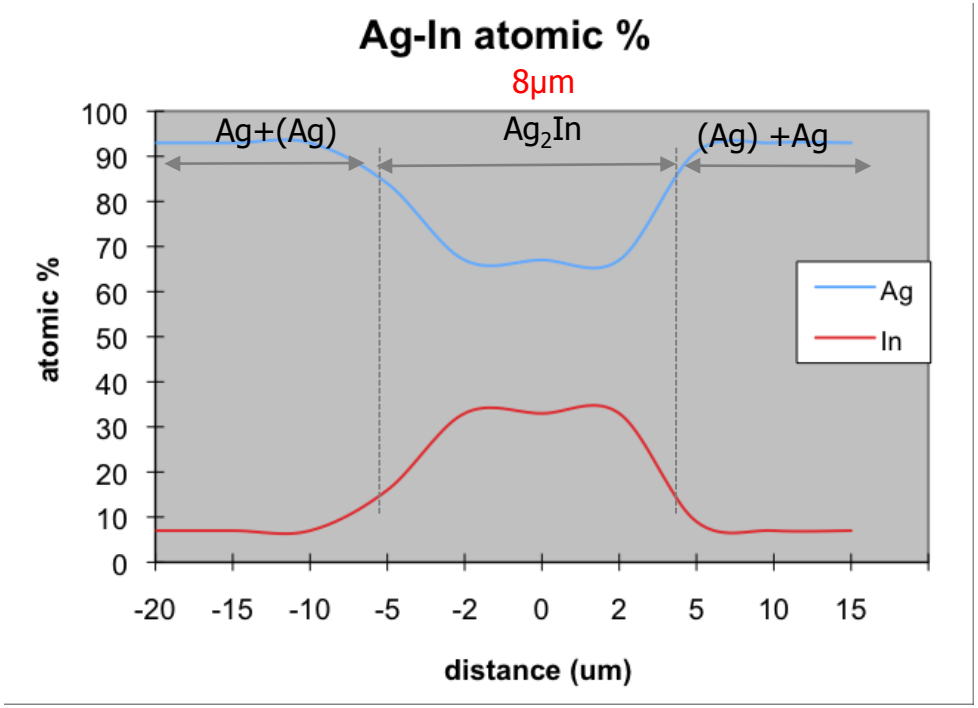
Si bonded to Cu: cross section SEM





Si bonded to Cu: EDX analysis of the joint





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Solid-state Silver Bonding

- The fundamental belief:
  - When A atoms and B atoms are brought within atomic distance so that they see each other, bonding will occur provided that they agree to share electrons.
- The challenge:
  - How to bring A atoms and B atoms within atomic range on the bonding interface?
- Approach:
  - Deformation of material A so that it conforms to and follow the surface of material B
  - What needed: pressure, temperature & clean surfaces

Conventional compression bonding methods

	Laminated metal	Procedure	Note
[1]	Ti to Al	Cold roll at R.T.	50% reduction in thickness
[2]	Ni to Pd-25wt.% Ag	Cold roll at R.T.	75% reduction in thickness
[3]	Cu to LCP	Surface activation → Cold roll at R.T.	Cold roll under pressure of 46,400 psi

In our process: 260°C at 1,000psi (6.9 MPa) for 4 minutes

We believe: they bond in seconds or less

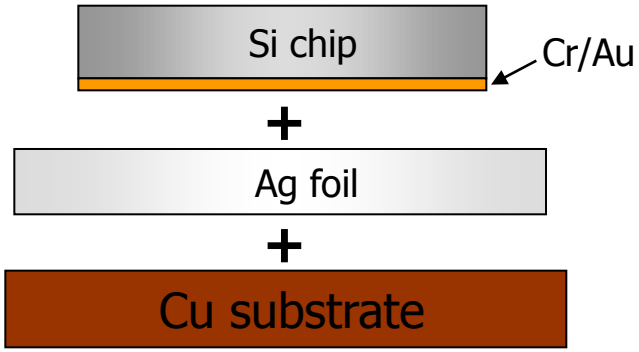
[1] J. G. Luo and Viola L. Acoff, "Using cold roll bonding and annealing to process Ti/Al multi-layered composites from elemental foils," *Materials Science and Engineering A*, 379, pp. 164-172, 2004

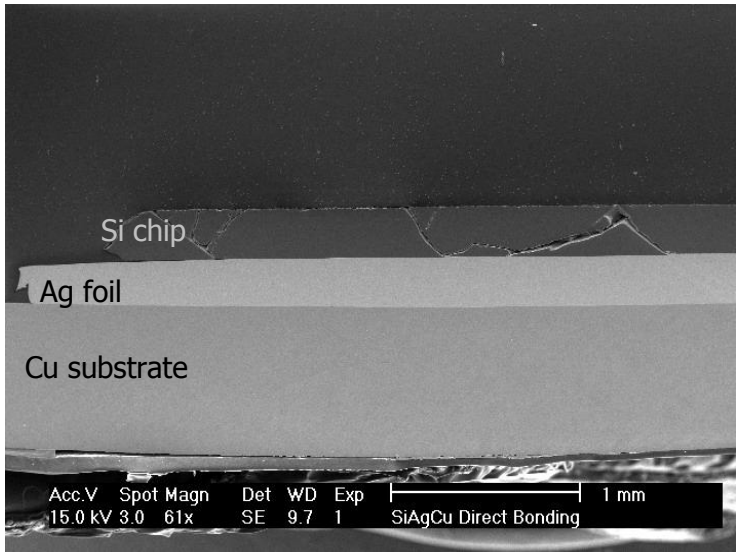
[2] S. Tosti, "Supported and laminated Pd-based metallic membranes," *International Journal of Hydrogen Energy*, 28, pp. 1445-2564, 2003

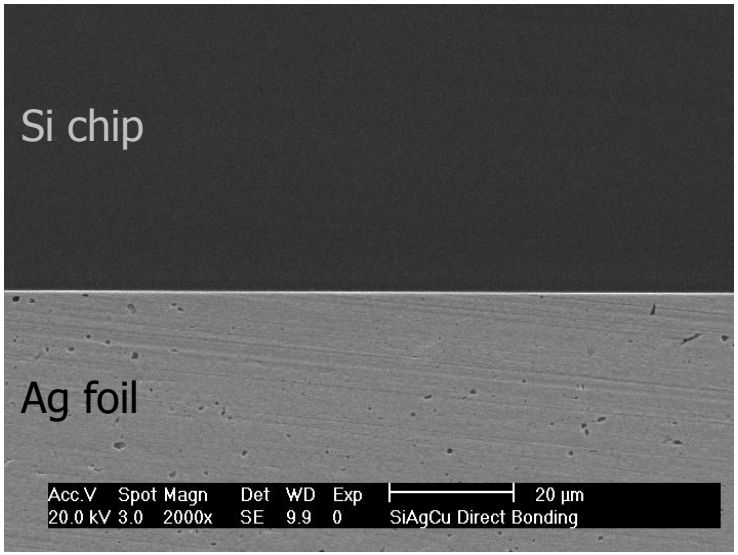
[3] Kouji Nanbu, Shinji Ozawa, Kazuo Yoshida et al., " Low temperature bonded Cu/LCP materials for FPCs and their characteristics," *IEEE Transactions on Components and Packaging Technologies*, 28, pp.760, 2005

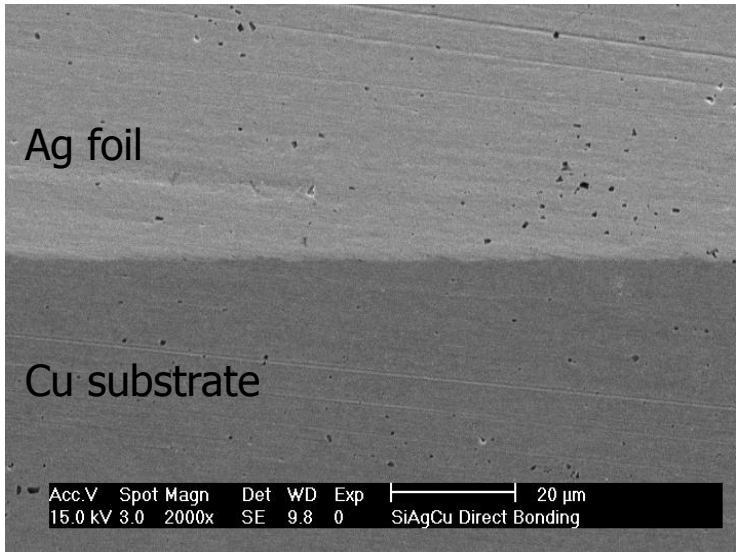
Bonding design I: Si-Ag foil-Cu

One step Bonding



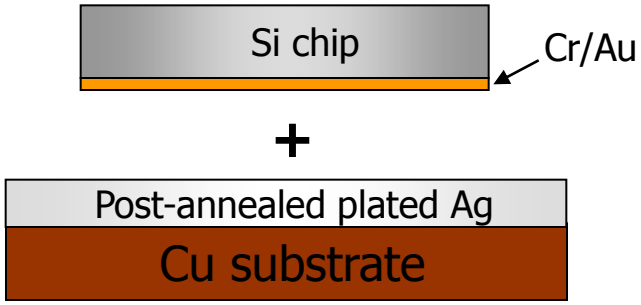


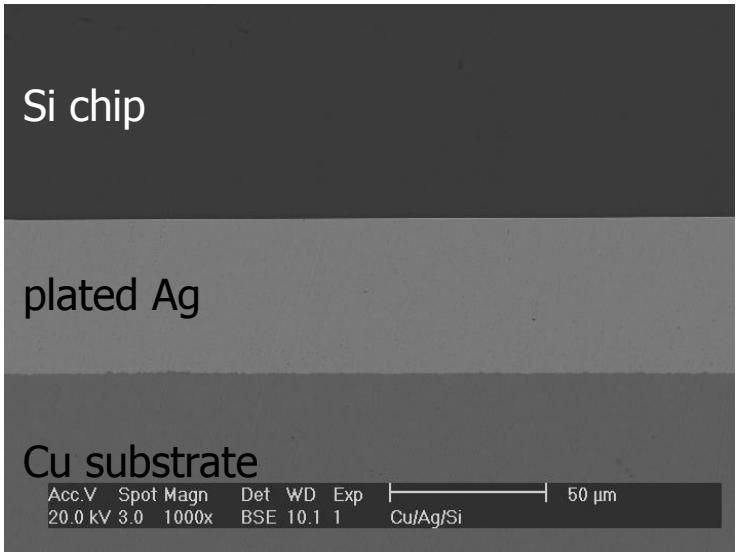


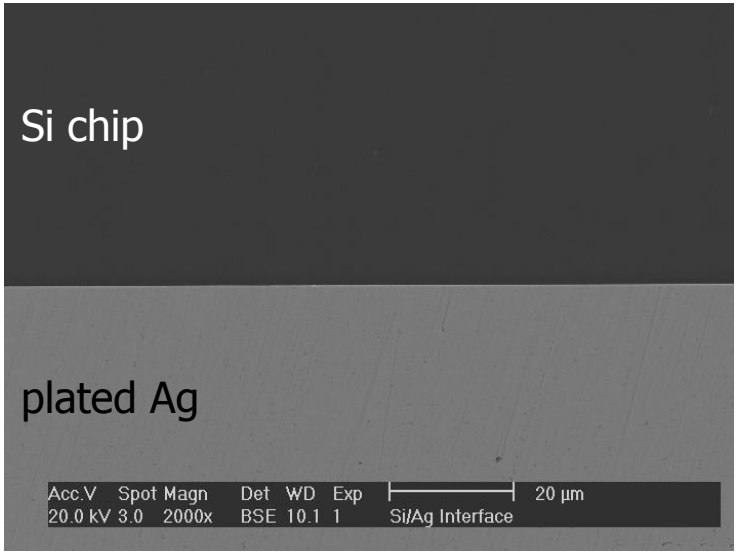


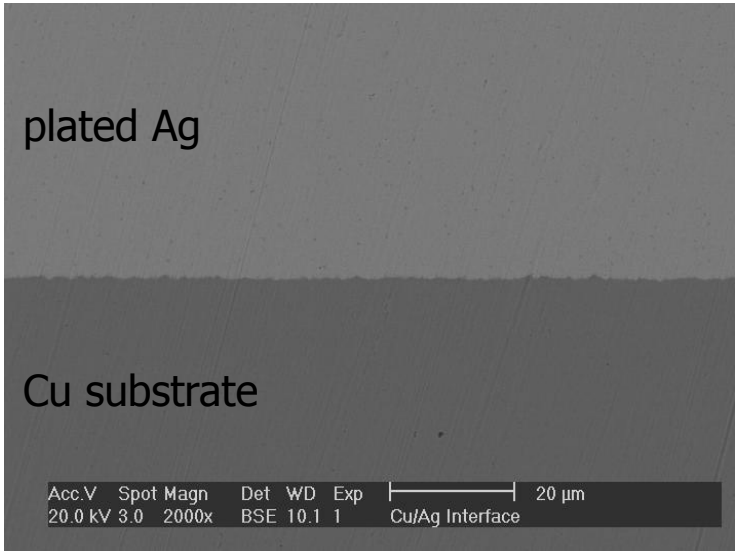
Bonding design II: Si – Ag(plated) on Cu

Bonding structure









Microstructure of plated Ag

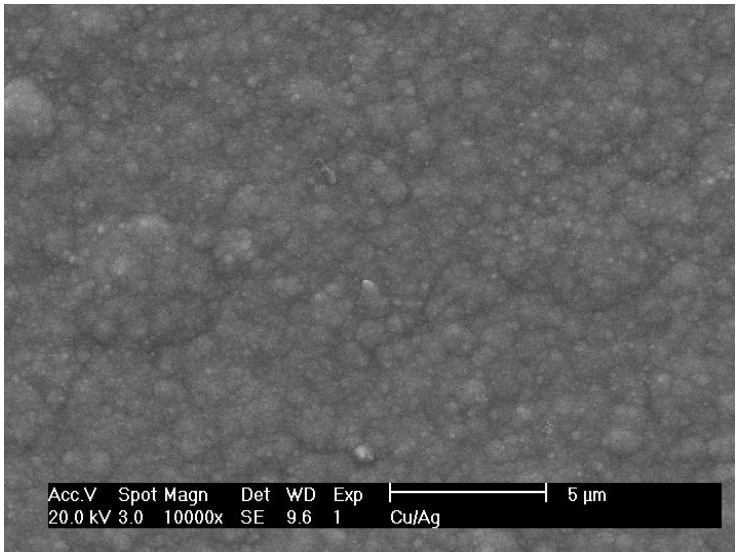
Hall-Petch Eq: $\sigma_y = \sigma_o + k_y * d^{-1/2}$

d: average grain diameter

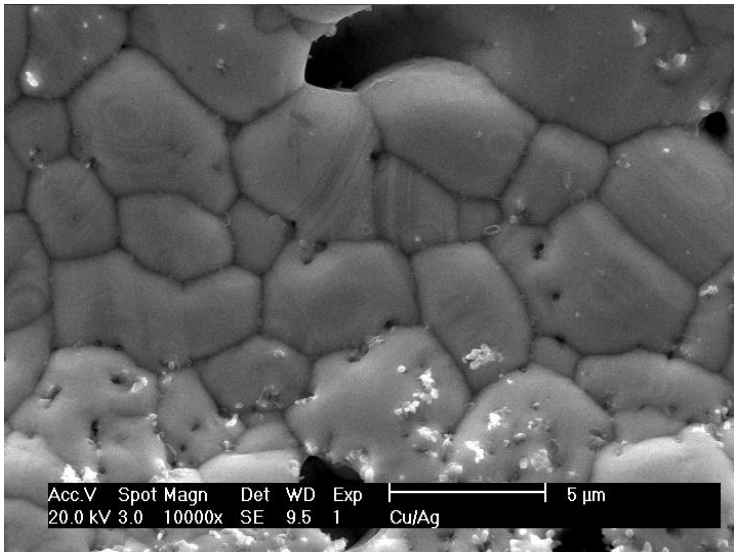
σ_y: yield strength

σ_o and k: material parameters

as-plated

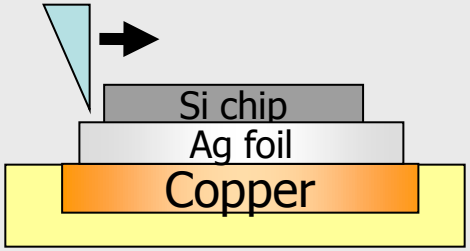


after annealing @450°C for 3hrs

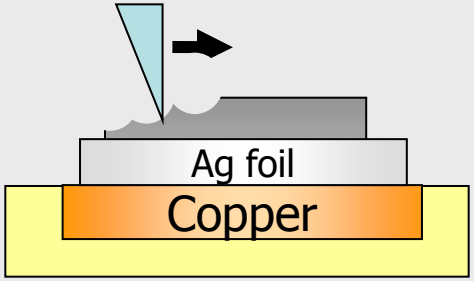


Shear strength: Si-Ag interface

Shear test

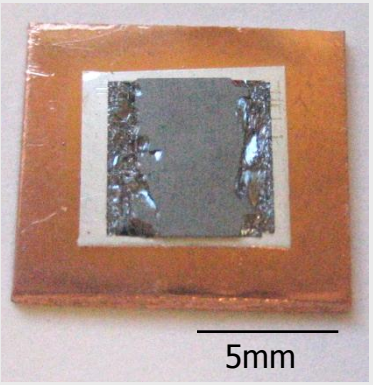


Test speed: 300μm/sec



- All Si chips broke except Sample D
- Fracture interface is inside Si

Sample E



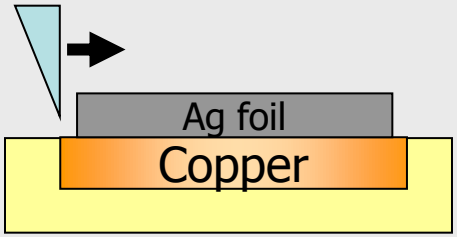
Failure force

Sample	Fracture force
A	51.5 Kg
B	29.3 Kg
C	32.4 Kg
D	10.8 Kg
E	22.4 Kg

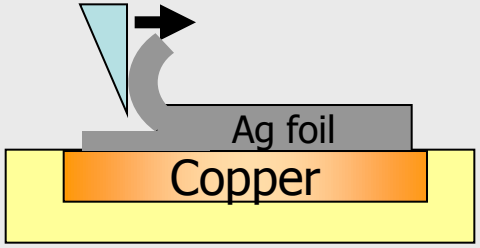
MIL-STD-883G: 5 Kg

Shear strength: Ag-Cu interface

Shear test

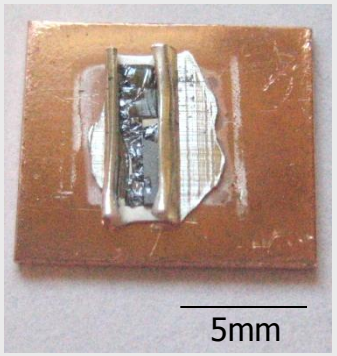


Test speed:300μm/sec



- Ag foil yields
- Fracture interface is inside bulk Ag

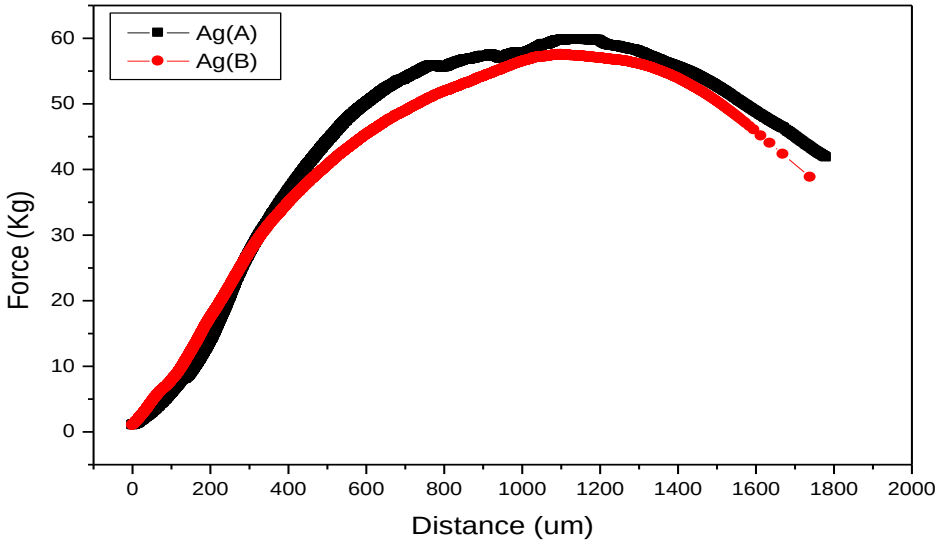
Sample A



Failure force

Sample	Failure force
A	59.8 Kg
B	57.5 Kg

Force vs. Distance



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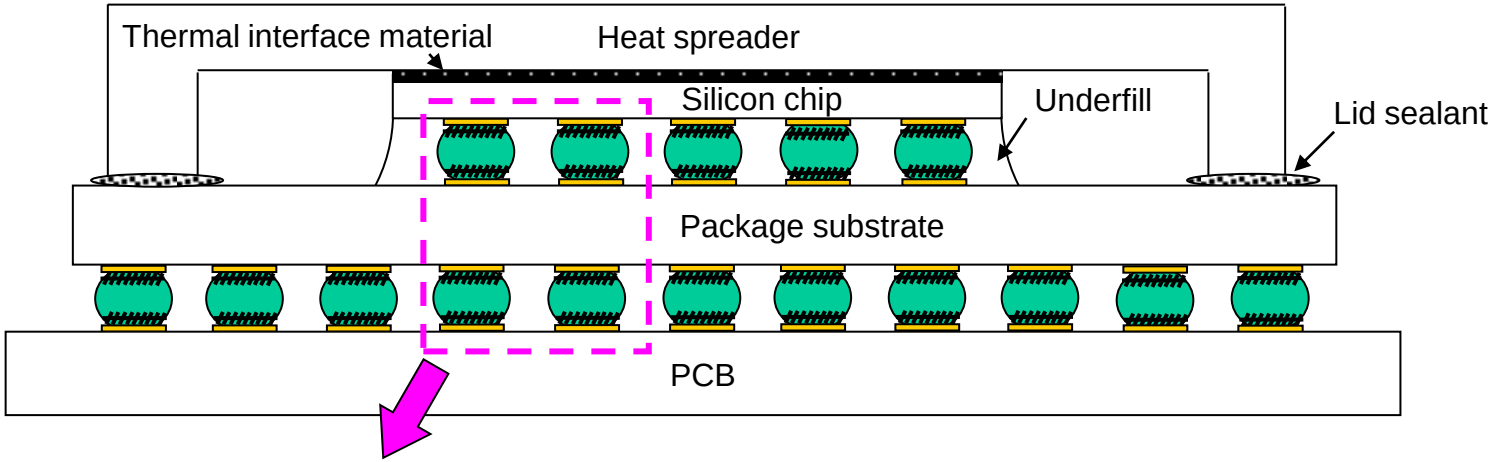
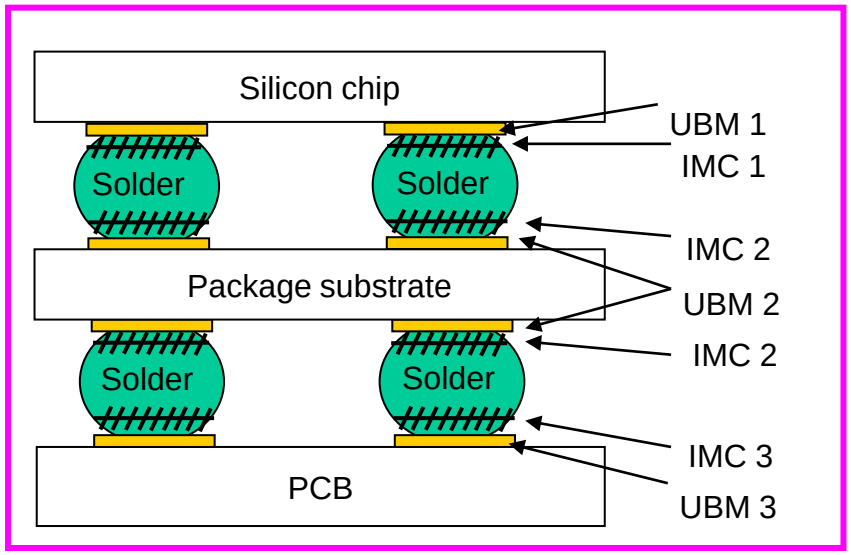
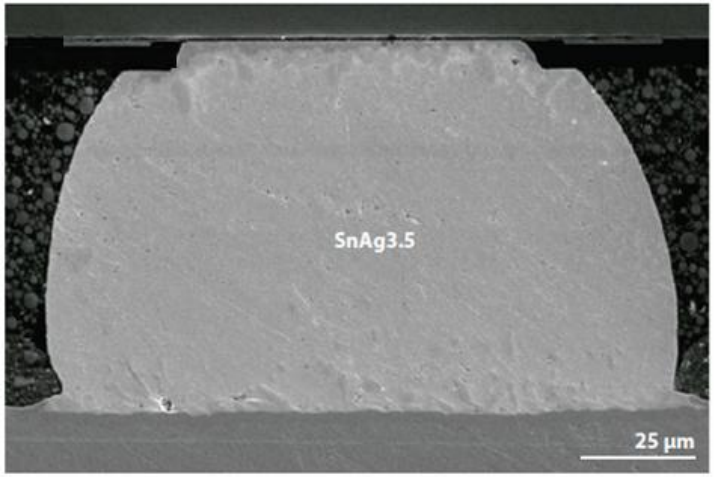
Solder flip chip interconnect



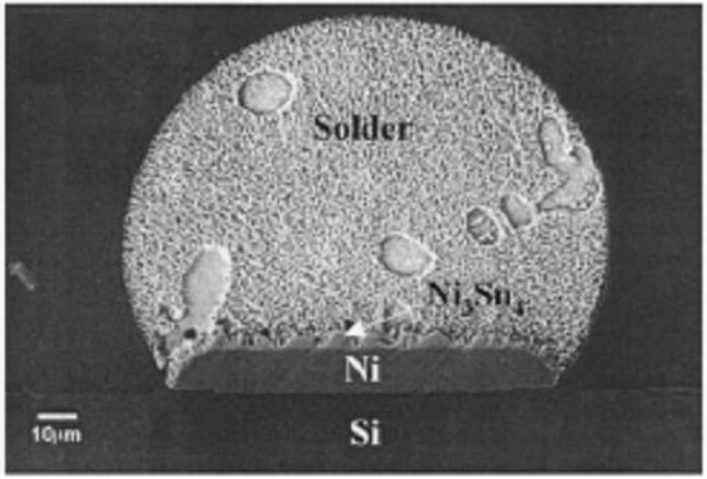


	Materials
Solder	Sn-Ag-Cu
UBM1	Ni/Au or Ni/Cu
IMC1	Ni_3Sn_4 or Cu_6Sn_5
UBM2	Ni/Au
IMC2	Cu_6Sn_5 or Ni_3Sn_4
UBM3	Cu
IMC3	Cu_6Sn_5

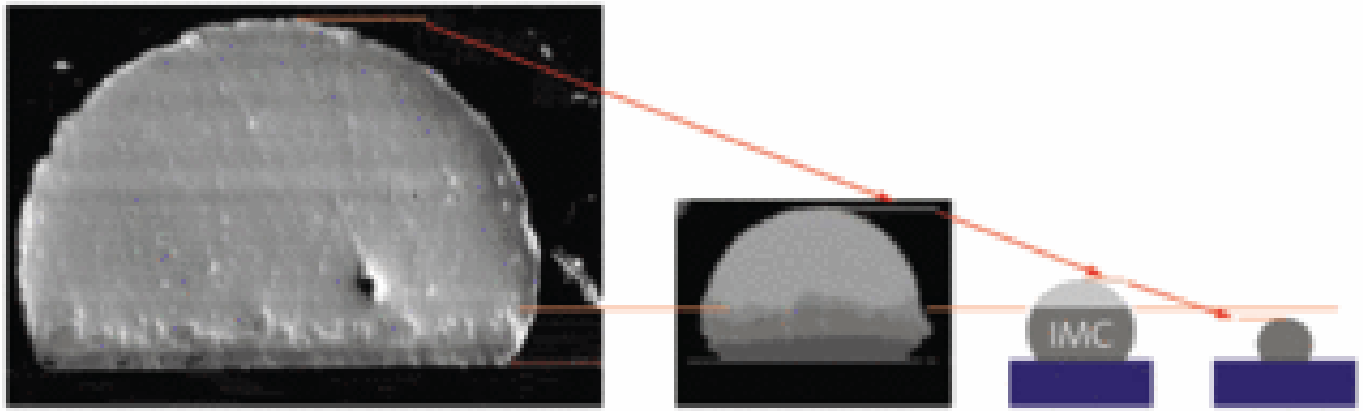
Flip chip solder joints



Ref: C. Chen, H. M. Tong, and K. N. Tu, "Electromigration and Thermomigration in Pb-free Flip Chip Solder Joints," *Annu. Rev. Mater. Res.*, vol. 40, pp. 531–555, 2010.



Ref: K. N. Tu and K. Zheng, "Tin-lead (SnPb) solder reaction in flip chip technology," *Mater. Sci. Eng. R.,* Vol. 34, pp. 1-58, 2001.



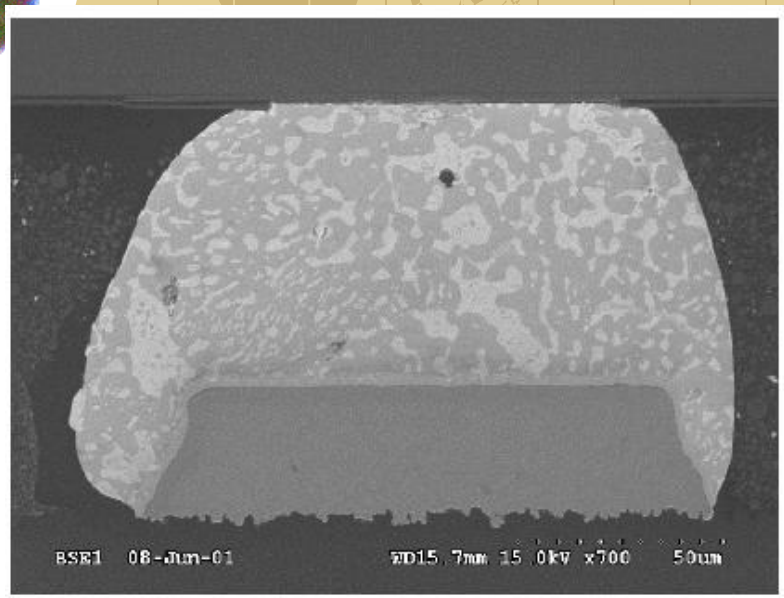
100µm pad
150-200 µm pitch

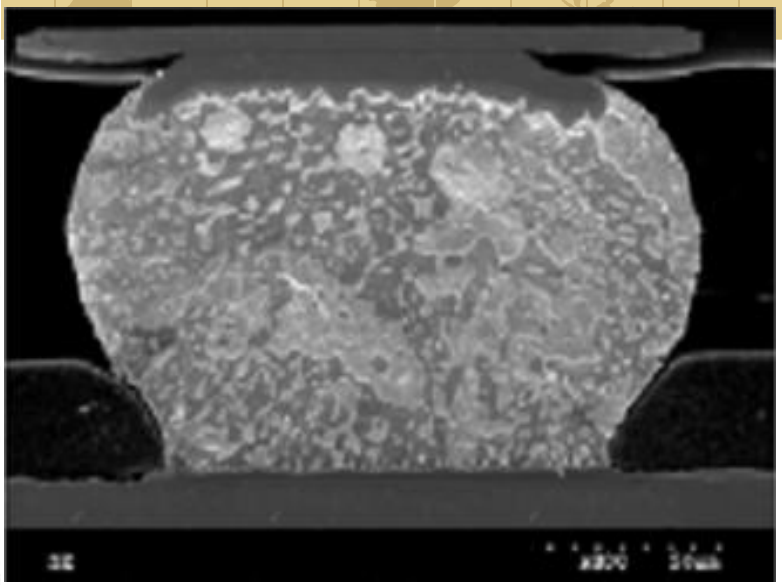
40µm pad
60µm pitch

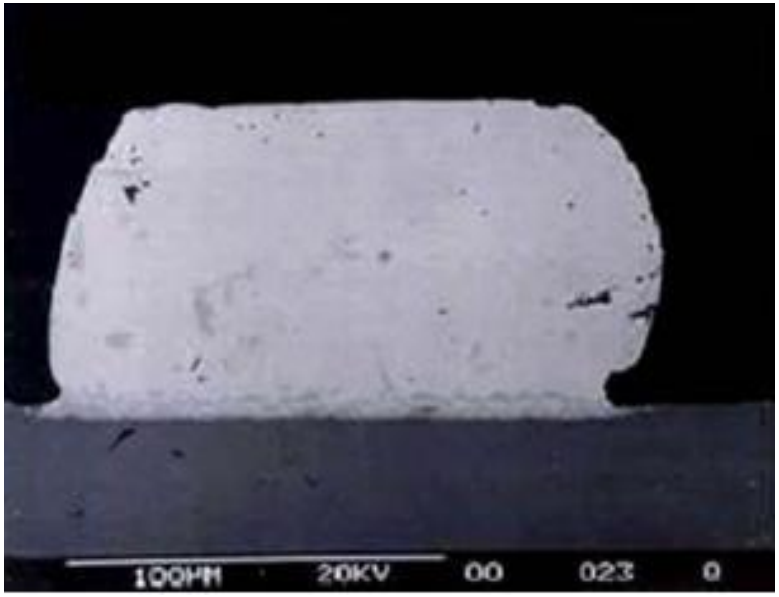
20µm pad
40µm pitch

10µm pad
20µm pitch

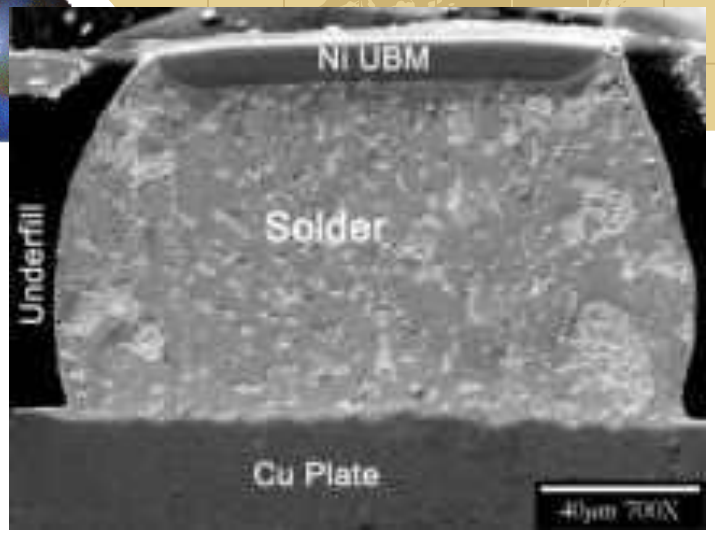
Ref: K. O'donnell, "UBM: Creating the Critical Interface," Available Online, http://www.electroiq.com/index/display/packaging-article-display/325754/articles/advanced-packaging/volume-17/issue-4/departments/editorial-board/ubm-creating-the-critical-interface.html



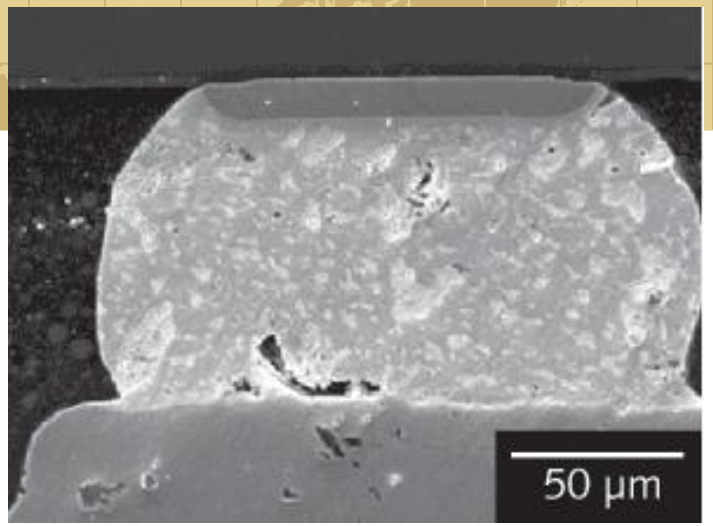




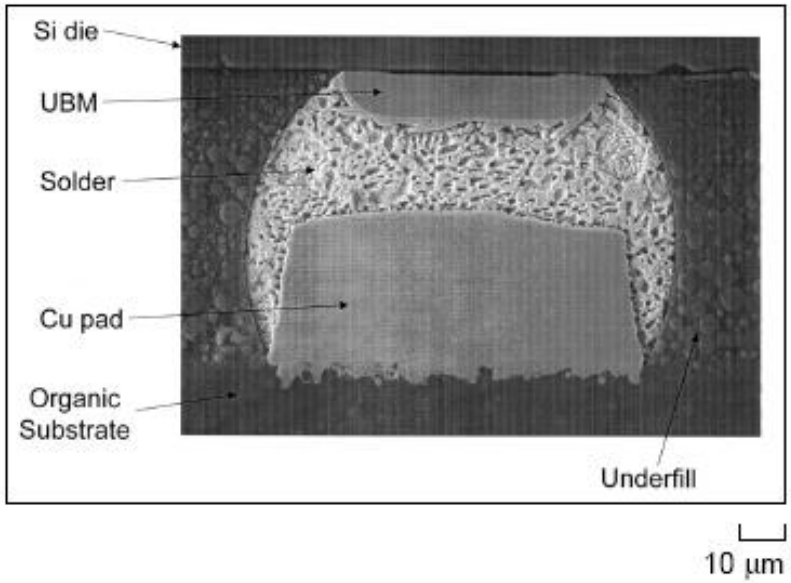
Ref: J. W. Nah and K. N. Tu, "Electromigration in flip chip solder joint," *Lead-free technology workshop, TMS Annual Meeting, San Francisco, CA, 2005.*



Ref: H. Ye, C. Basaran, and D. C. Hopkins, "Mechanical Implications of High Current Densities in Flip Chip Solder Joints," *IMECE,* pp. 477-483, ASME, 2002.

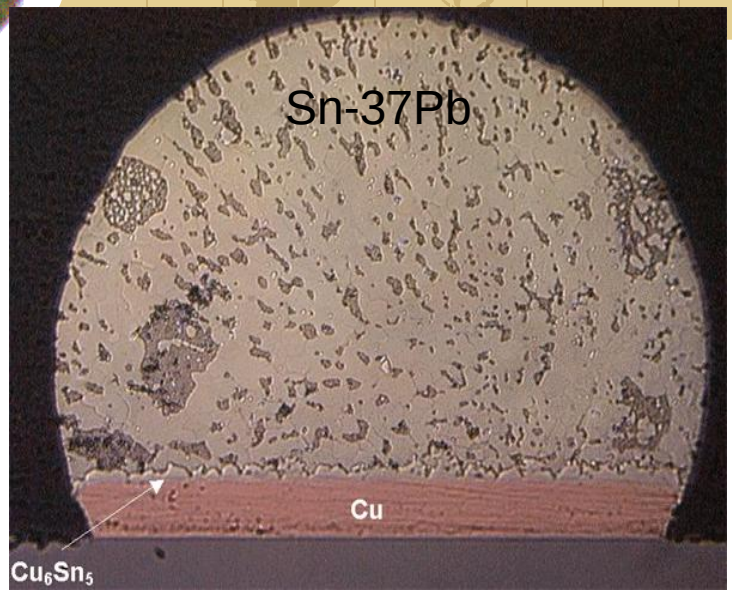


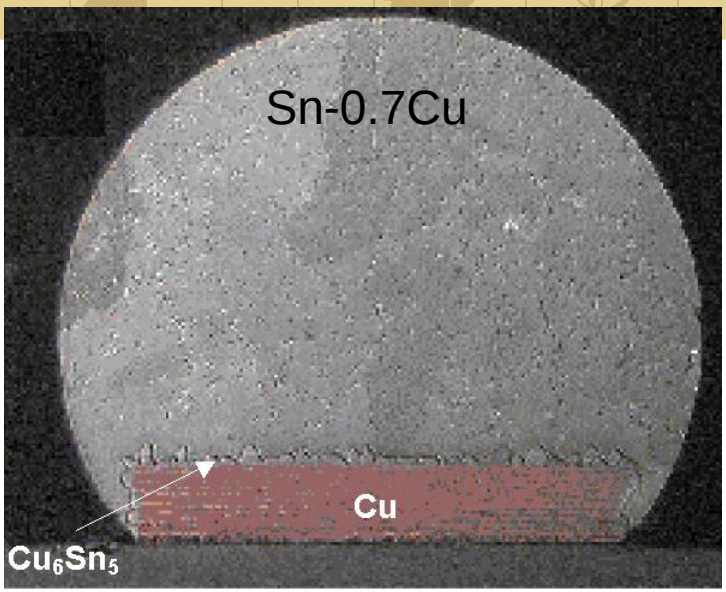
Ref: C. Basaran, H. Ye, D. C. Hopkins, D. Frear, and J.K. Lin, "Flip Chip Solder Joint Failure Modes," Available Online, http://www.electroiq.com/index/display/packaging-article-display/238913/articles/advanced-packaging/volume-14/issue-10/features/flip-chip-solder-joint-failure-modes.html

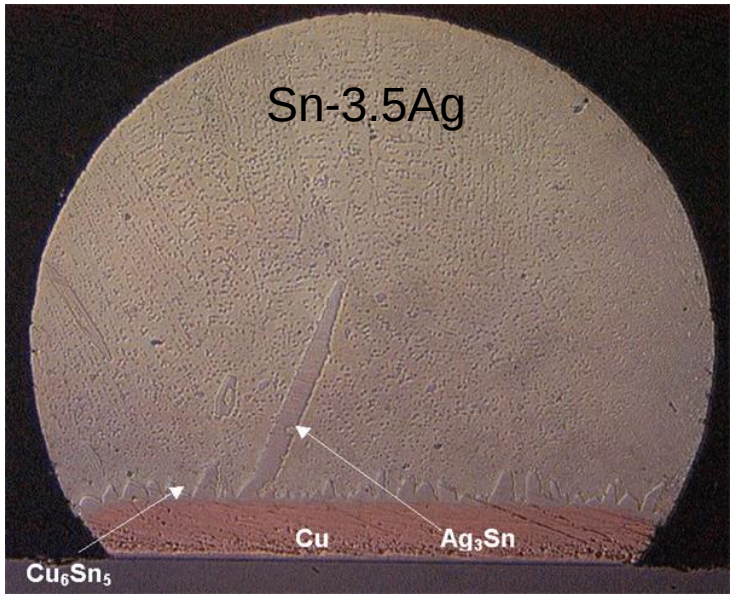


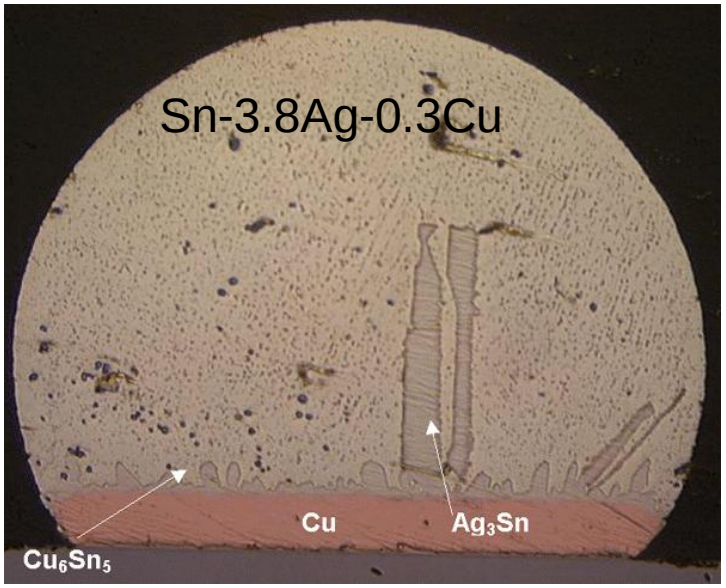
Ref: D. R. Frear, "Materials Issues in Area-Array Microelectronic Packaging," *JOM,* vol. 51, no. 3, pp. 22-27, 1999.

Optical Image: solder balls



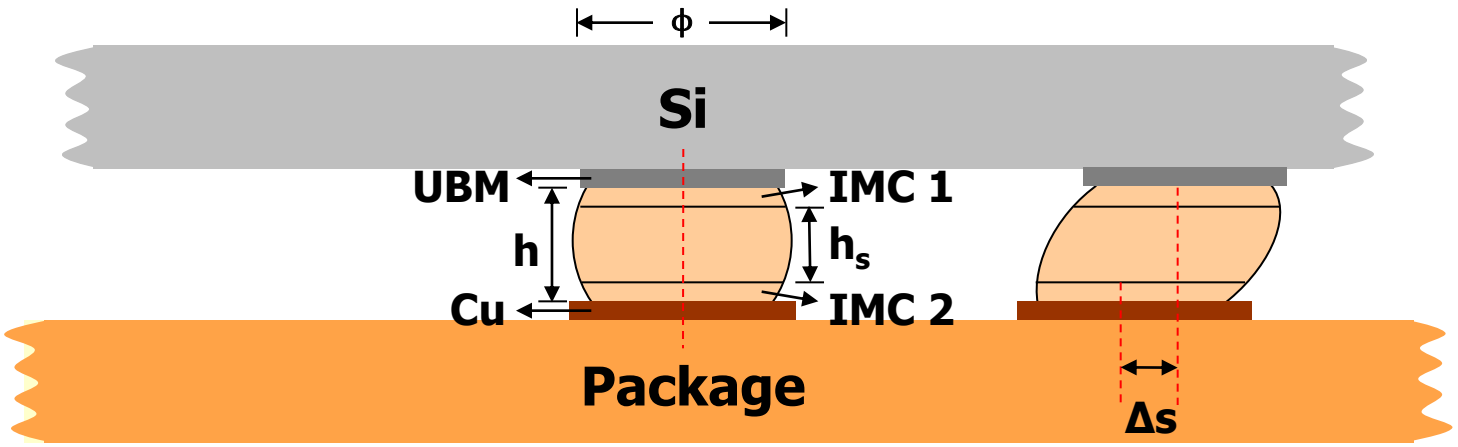






Ref: D. R. Frear, J. W. Jang, J. K. Lin, and C. Zhang, "Pb-Free Solders for Flip-Chip Interconnects," *JOM,* vol. 51, no. 6, pp. 28-32, 2001.

Solder flip chip joints: Analysis



- UBM: under bump metallurgy
- IMC: intermetalic compound layer
- h = joint height, h_s = solder height
- Shear strain: $\varepsilon_{sh} = \Delta s/h_s$
- Solder aspect ratio: $\gamma_s = h_s/\phi < 0.7$

  As $\phi \downarrow$ -> $h_s \downarrow$ & $\varepsilon_{sh} \uparrow$

  As time $\uparrow$ -> $h_s \downarrow$ & $\varepsilon_{sh} \uparrow$

  As $\phi \downarrow$ -> $R_{solder} = (\rho)(4h/\pi\phi^2) = (\rho)(4/\pi)(h/\phi)(1/\phi) \uparrow$

Outline

- Solders and Soldering
- Fluxless Soldering: 3 methods
- A UCI example: Fluxless Ag-In Bonding
- Solid State Atomic Bonding
- Solder Flip-Chip Technology
- Silver Flip-Chip Technology
- Summary

Silver flip-chip interconnect

Why silver?

It is simply the best choice.

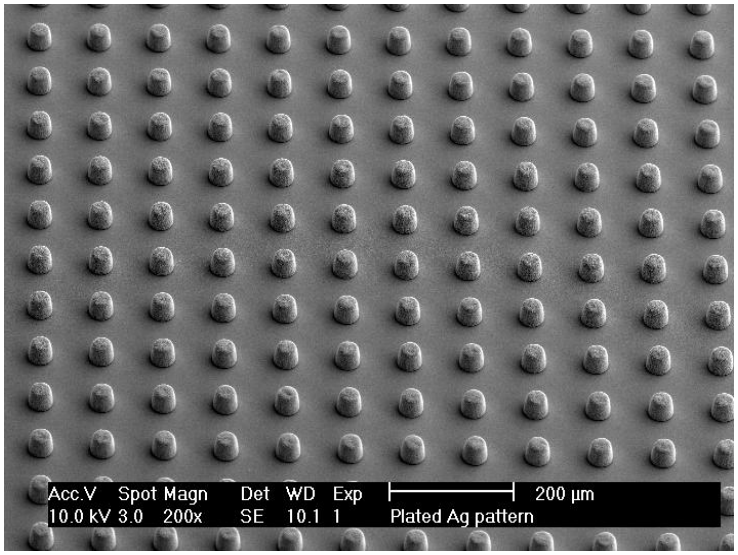
Challenge:
How to bond silver without it melting?

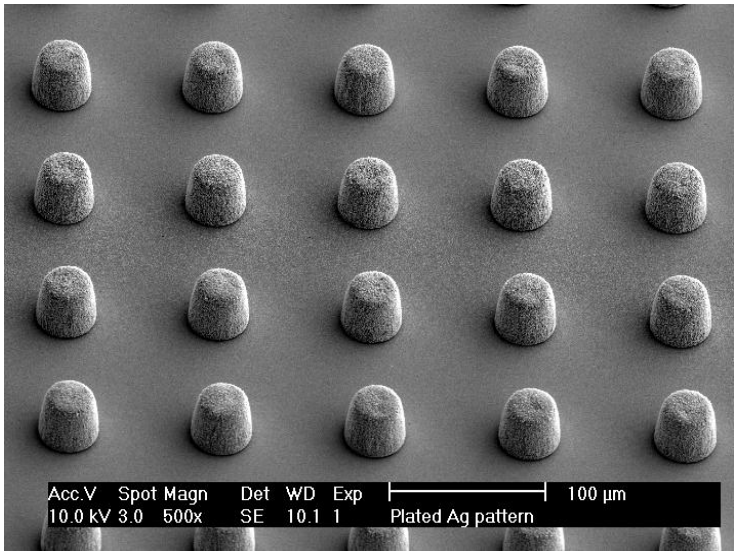
Answer:
Solid state atomic bonding.

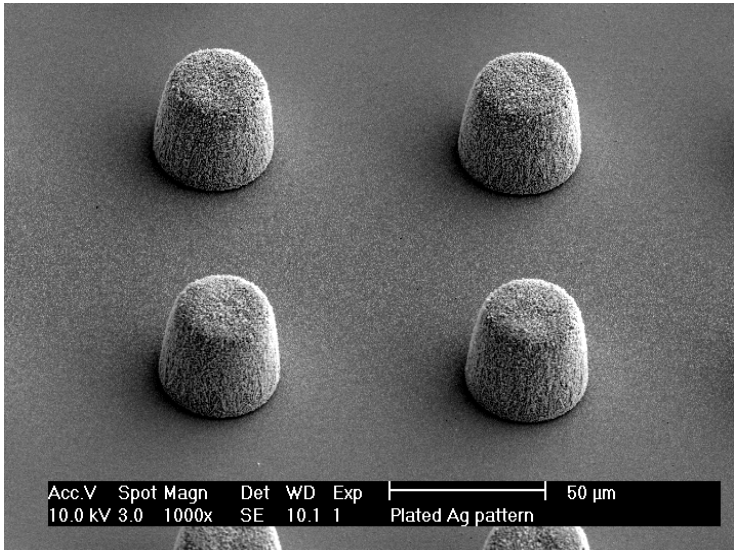
Properties of relevant materials

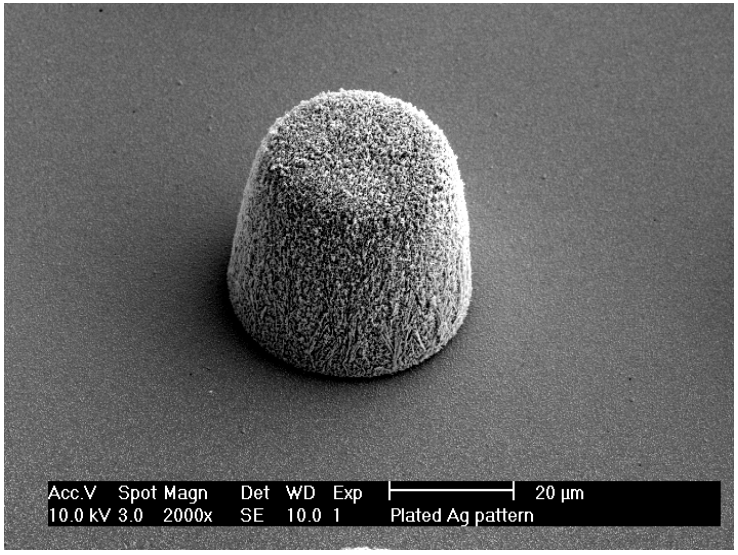
Properties	Copper	Silver	Gold	Tin	96.5Sn3.5Ag
Melting Point (^oC)	1,083	961	1,063	231	221
Density (g/cc)	8.94	10.5	19.3	7.29	7.4
Thermal conductivity (watt/cm-K)	3.862	4.075	3.151	0.665	0.78
Electrical Conductivity (/Ωcm)	$5.88x10^5$	$6.14x10^5$	$4.17x10^5$	$0.87x10^5$	$0.812x10^5$
Thermal Expansion Coeff. (/k)	$16.42x10^{-6}$	$18.6x10^{-6}$	$14.2x10^{-6}$	$22.2x10^{-6}$	$21.0x10^{-6}$
Yield Strength (psi)	10,000	1,000	250	1,300	3,600
Ultimate Tensile Strength (psi)	32,000	21,000	17,000	2,000	5,000~7,000
Young's modulus (psi)	$1.92x10^7$	$1.18x10^7$	$1.12x10^7$	$6.89x10^6$	$7.8x10^6$
Elongation at break (%)	51	50	50	50~80	37
Hardness (Brinell)	37	25	18.5	3.7	14.8

40µm Ag columns on Si/Cr/Au



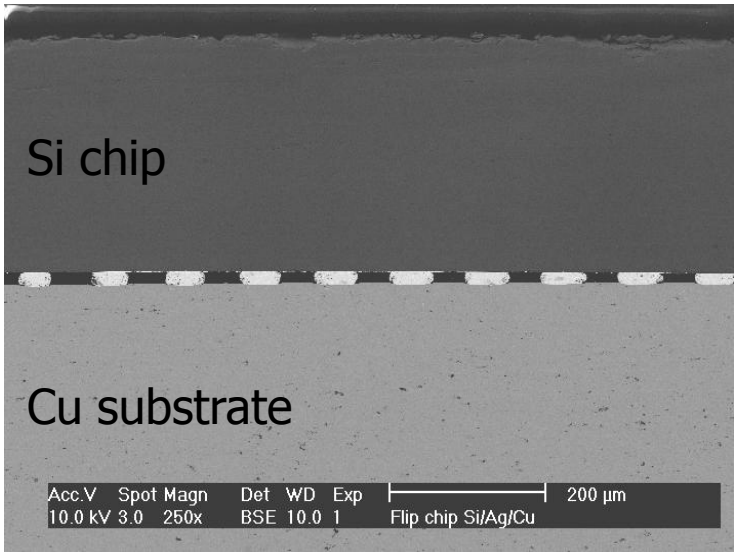


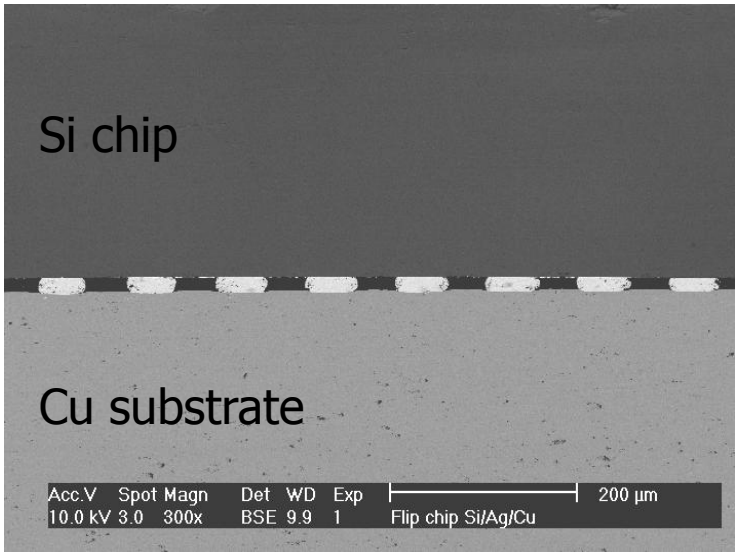


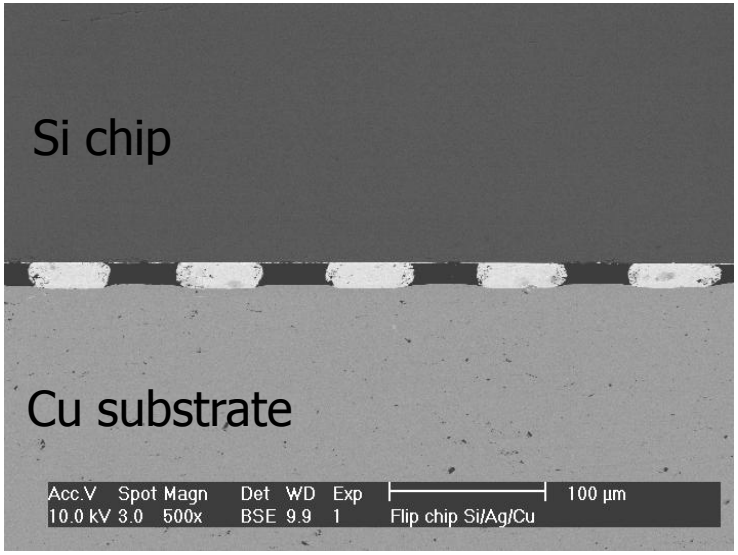


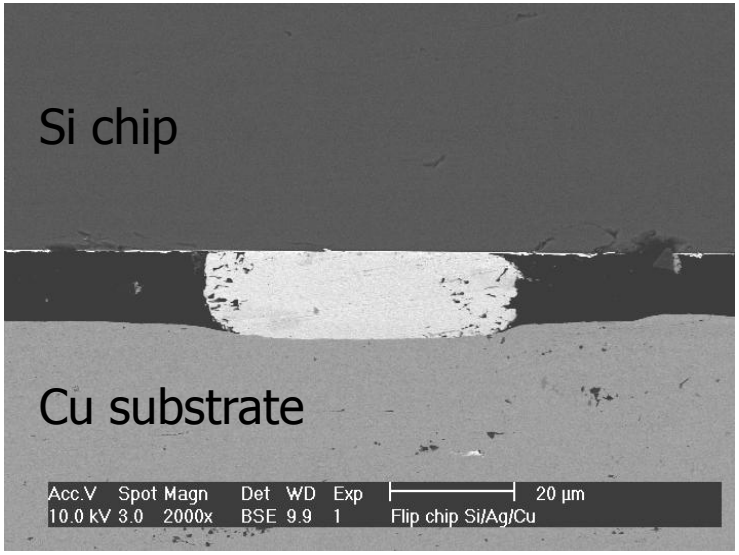
Si with Ag columns bonded to Cu: I

Peak temperature: **270°C**, Pressure applied: **960psi**



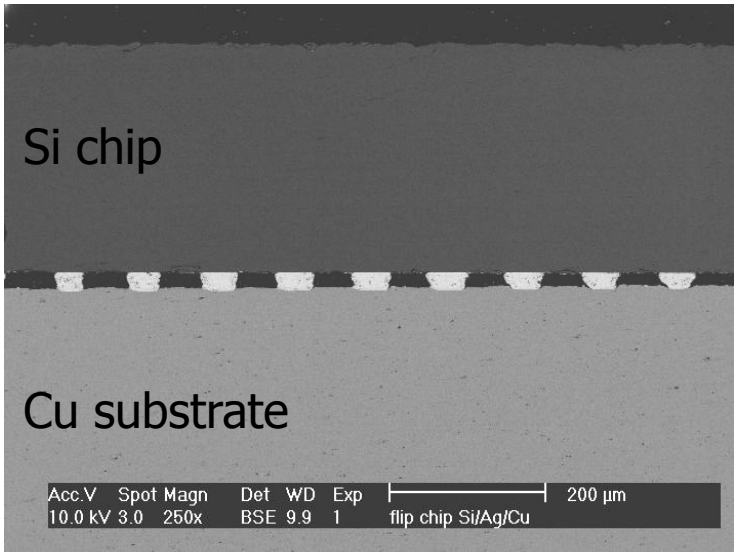


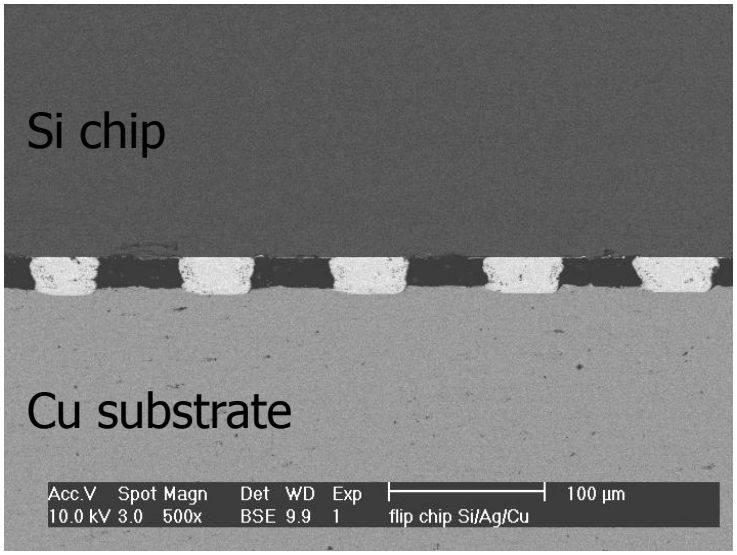


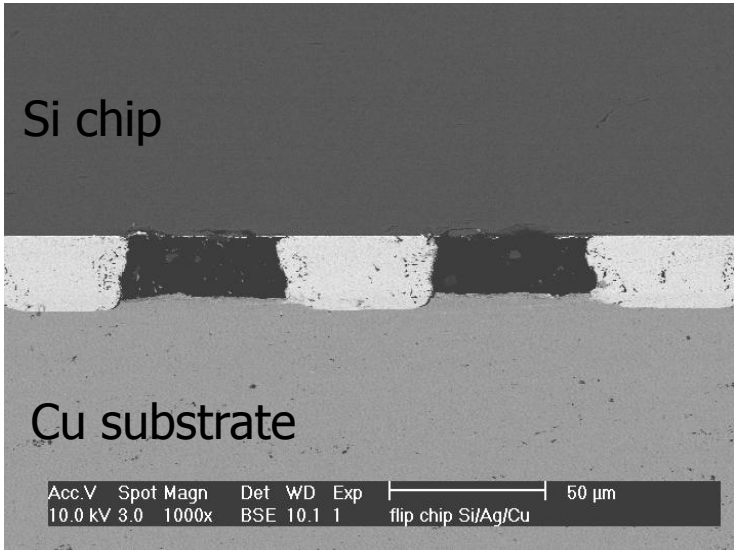


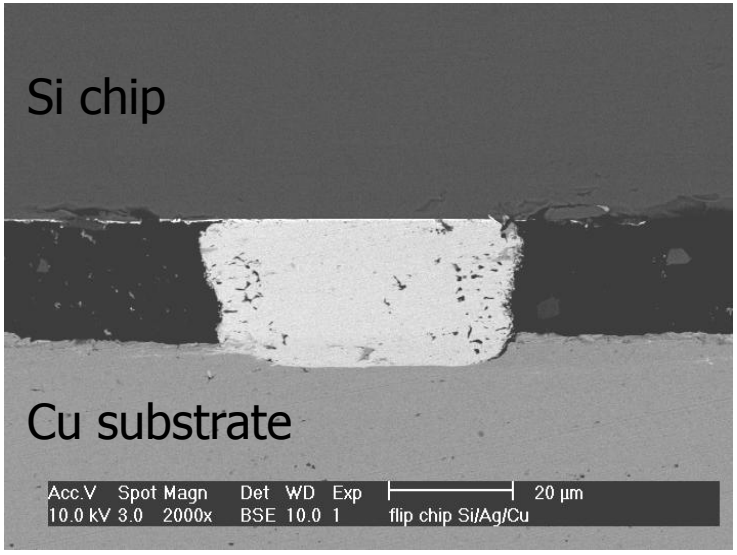
Si with Ag columns bonded to Cu: II

Peak temperature: **270°C**, Pressure applied: **760psi**



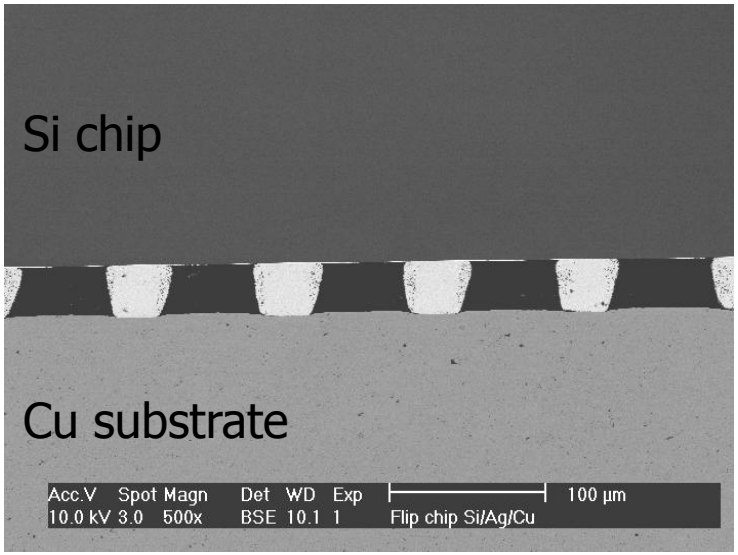


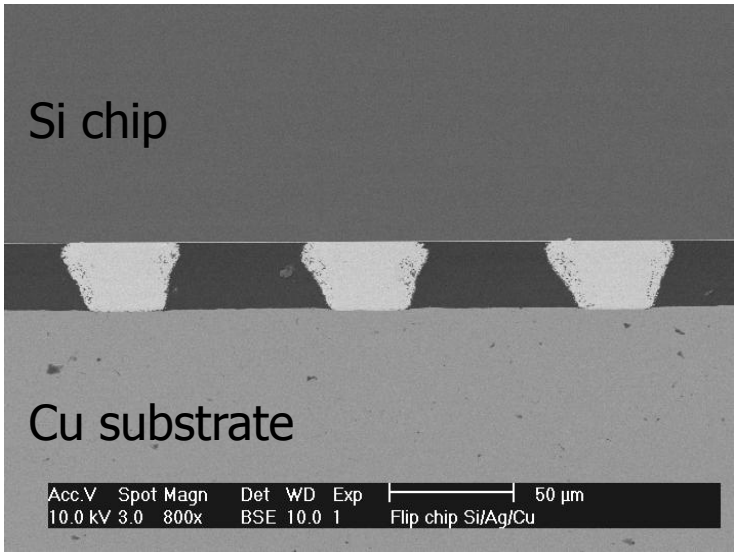


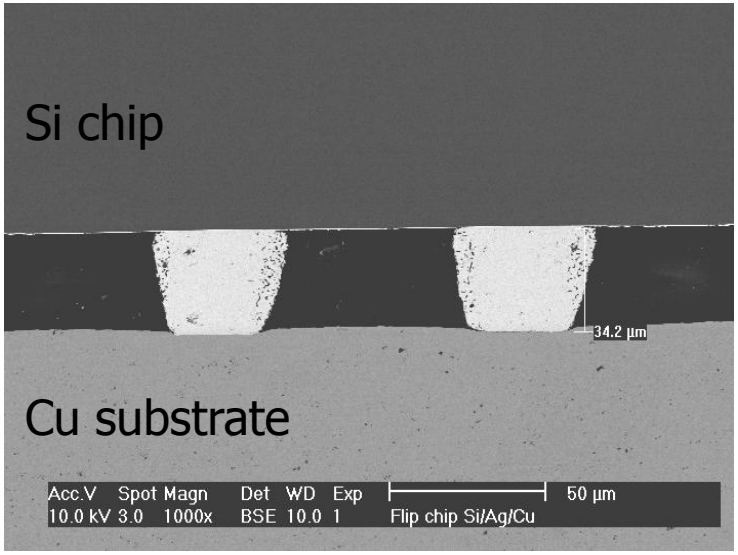


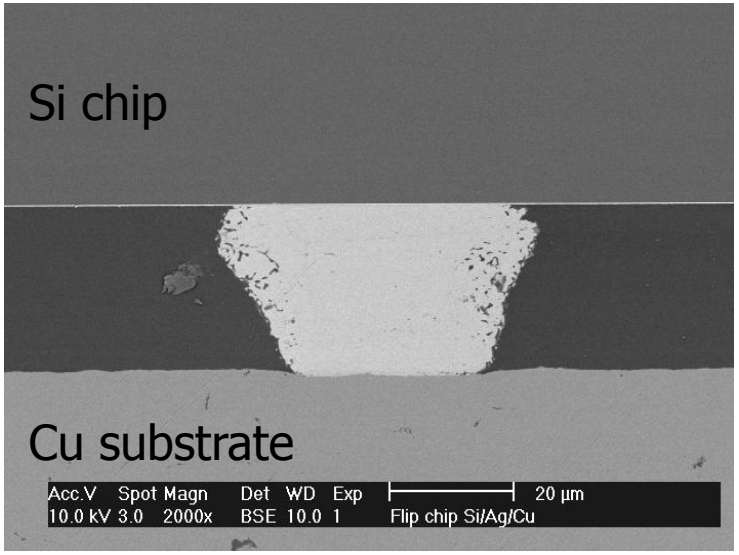
Si with Ag columns bonded to Cu: III

Peak temperature: **260°C**, Pressure applied: **680psi**





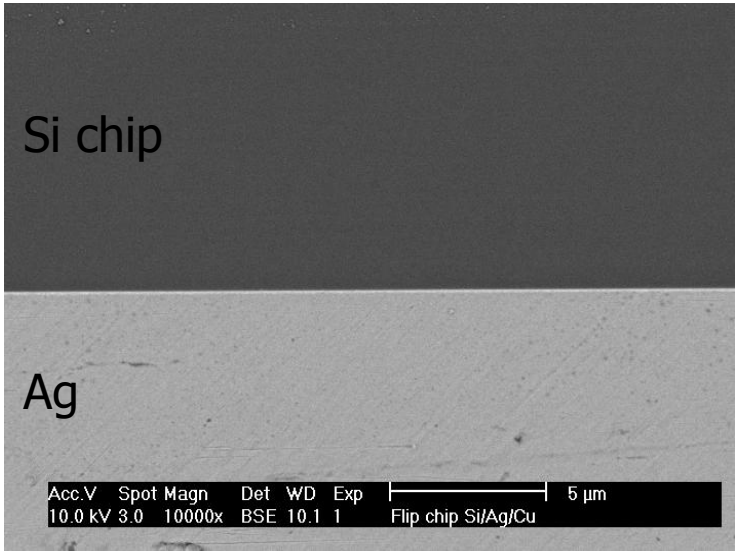




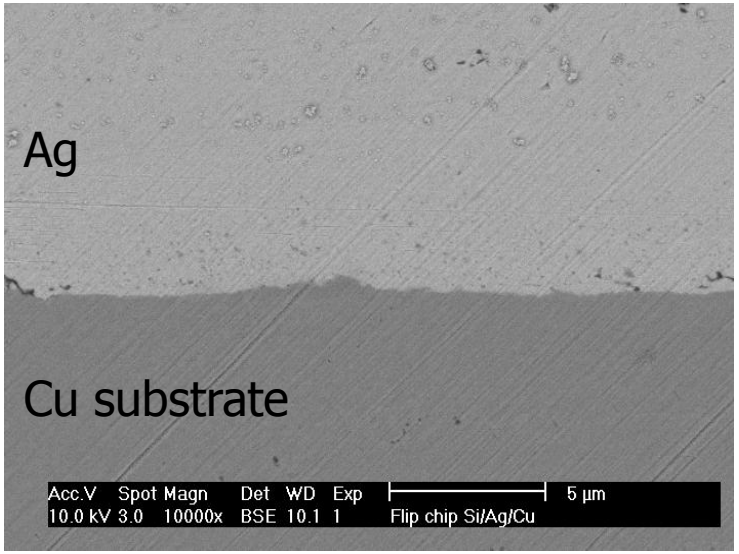
Bonding interfaces

High magnification SEM images on interfaces

Si/Cr/Au/Ag



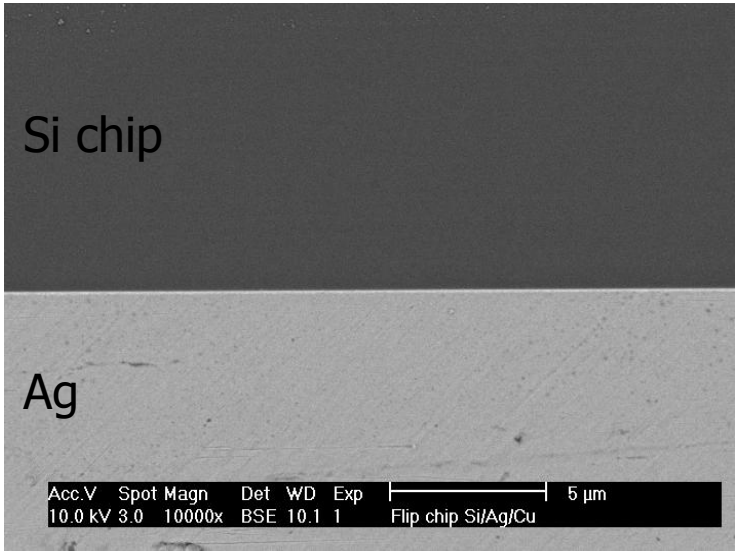
Ag/Cu



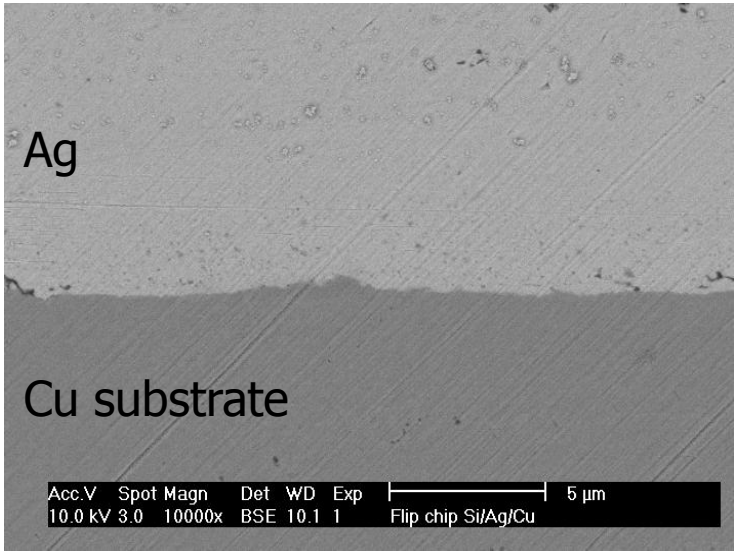
Bonding interfaces

Are they really bonded or just mechanical interlocking?

Si/Cr/Au/Ag



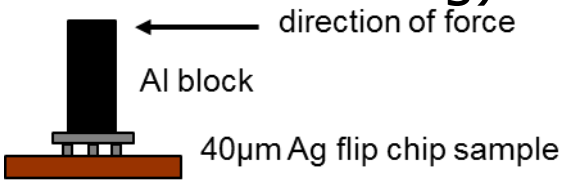
Ag/Cu



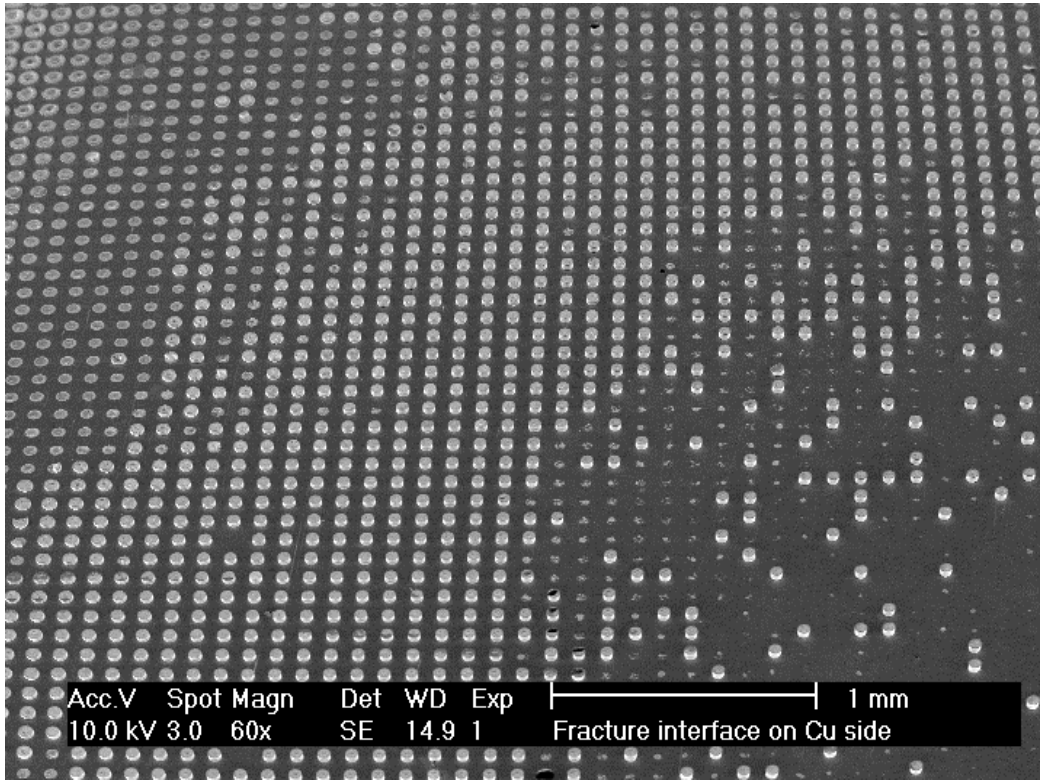
Fracture of 40μm Ag flip chip joints

Sample with 50x50 array withstands at least 6.3kg pull force (MIL-STD-883E failure force:1.93kg).

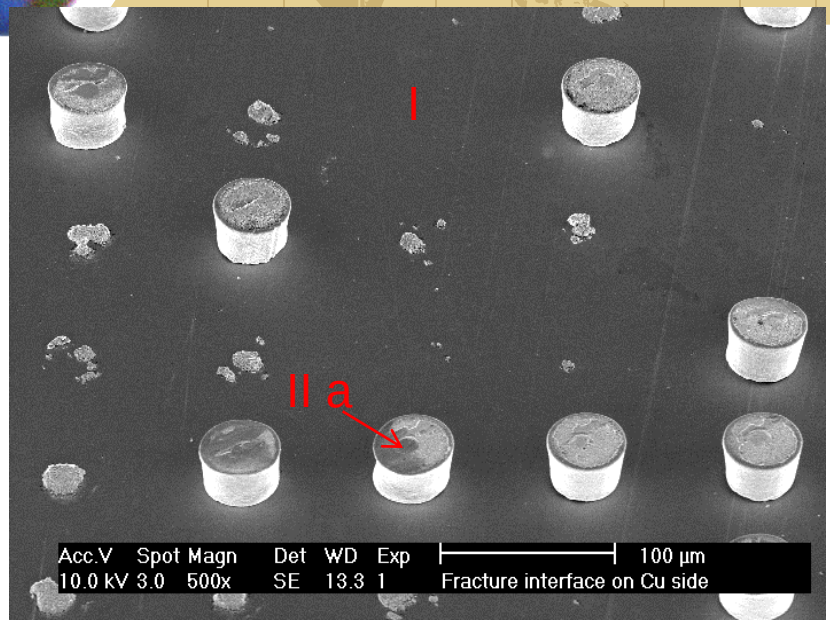
Broke by shear&pull

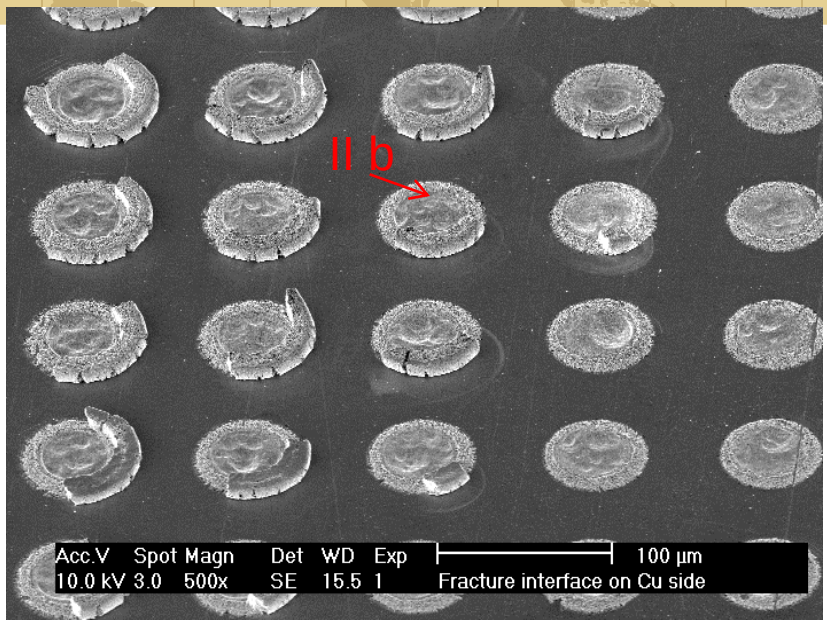


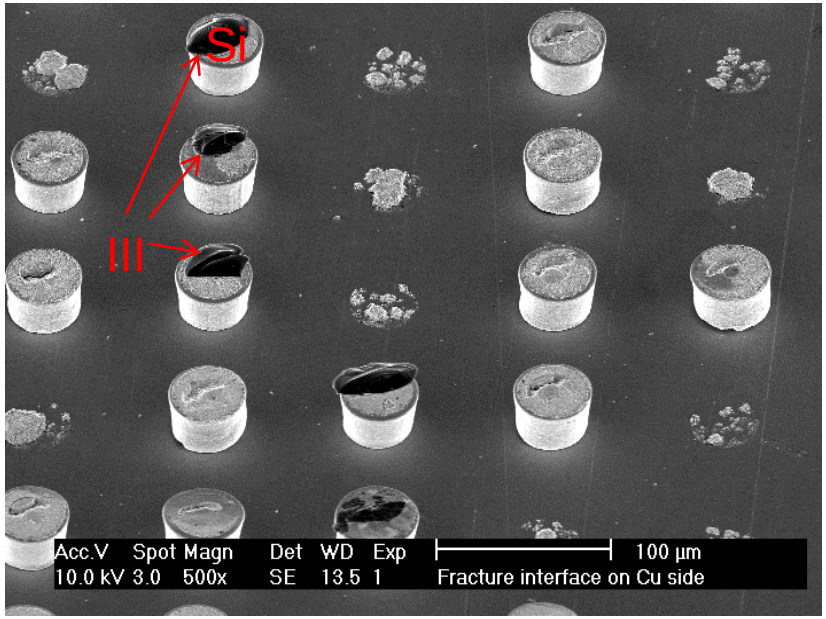
Fracture surface on Cu side



Fracture modes: Cu side







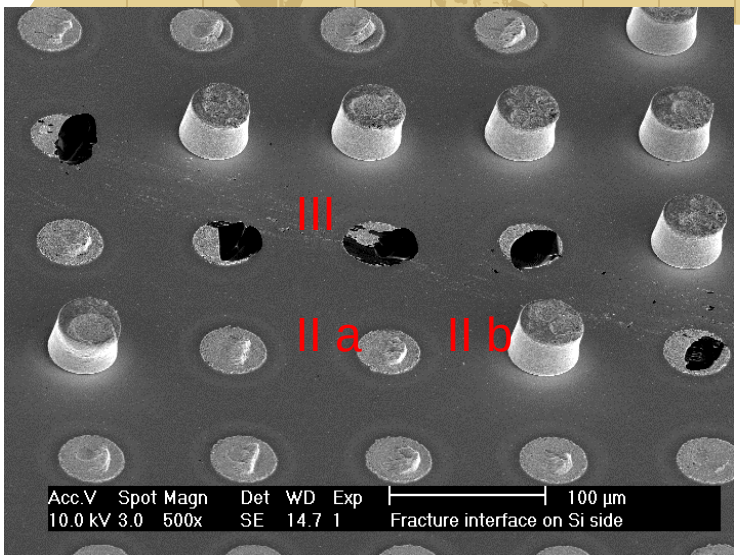
Fracture modes

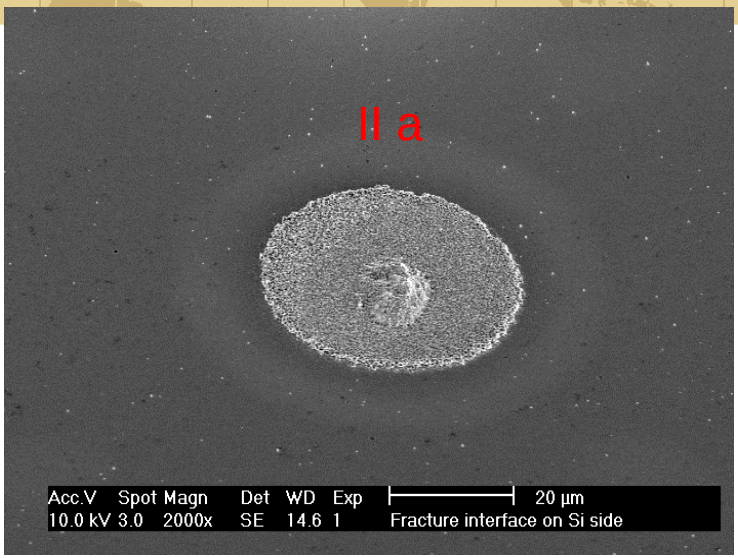
I. Ag-Cu interface: No Ag stays on Cu

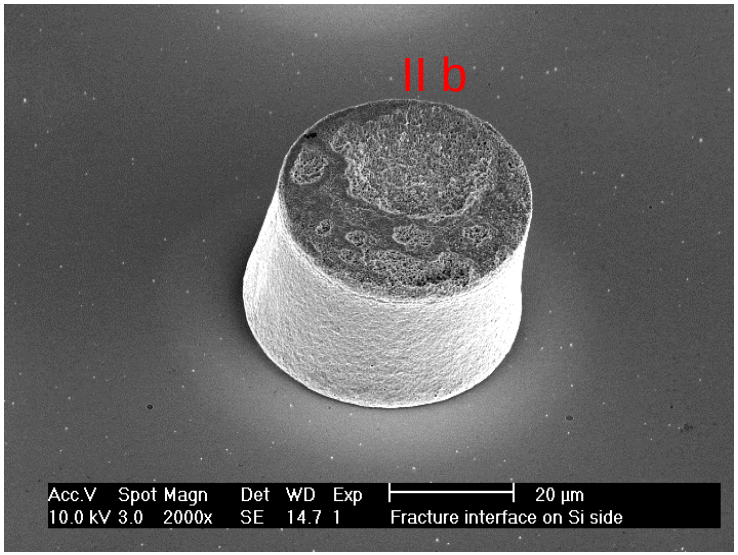
II. Within Ag column:
   a. Most Ag column stays on Cu
   b. Small portion of Ag stays on Cu

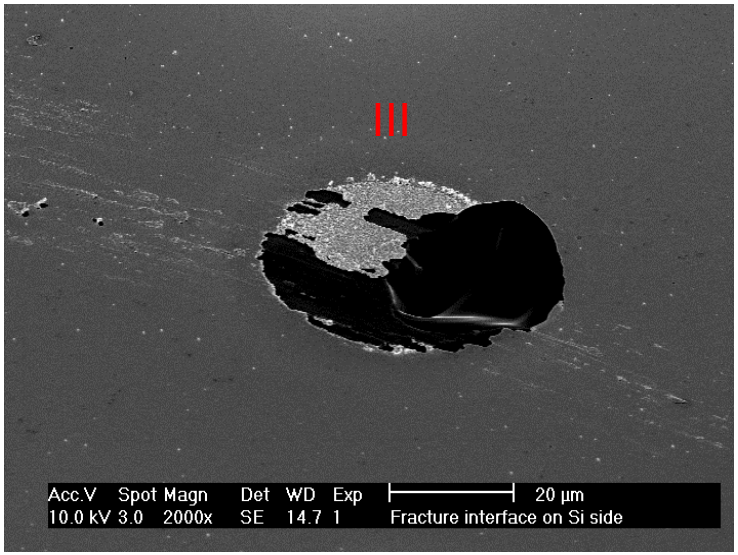
III. Within Si chip:
   Nearly all Ag column with Si piece stays on Cu

Fracture modes: Si side



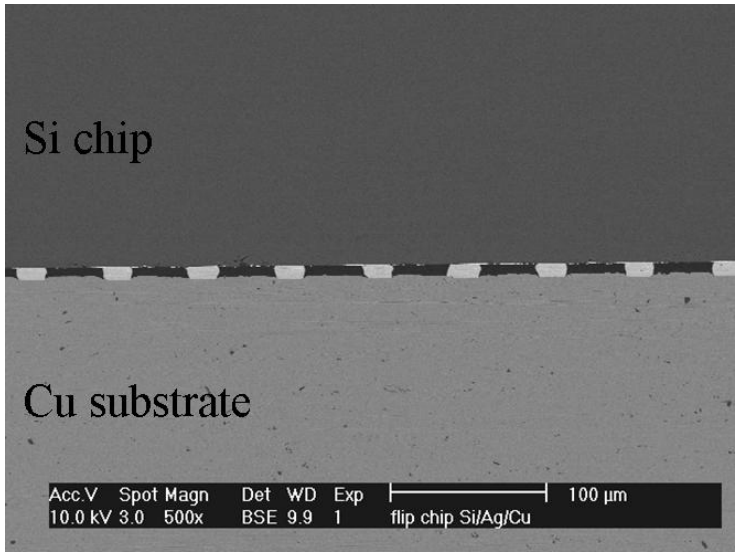


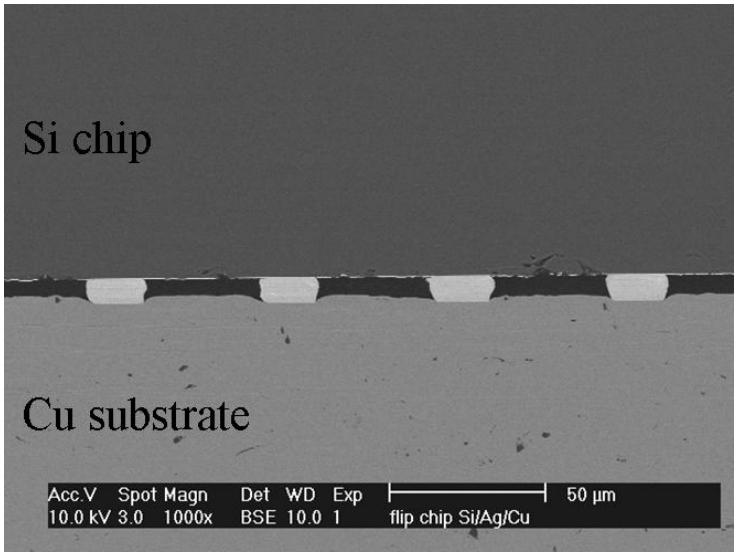


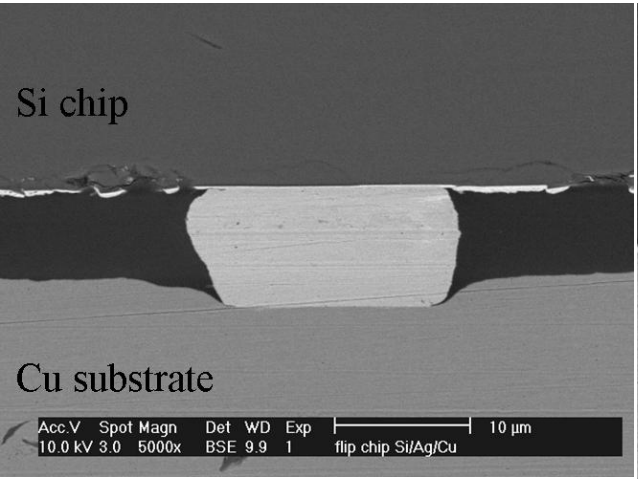


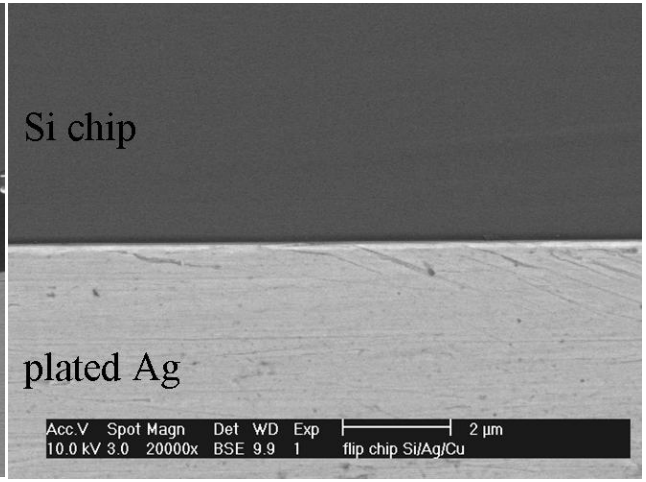
15μm Ag flip chip interconnect

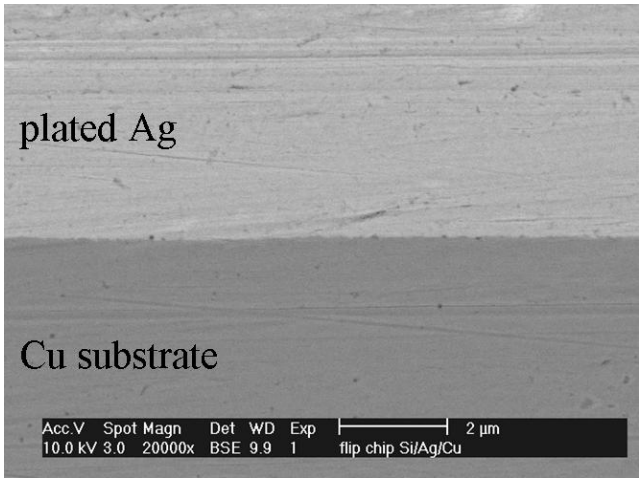
Total pressure = 800psi, 0.1gm per column, 125x125 array











Outline

- Solders and Soldering
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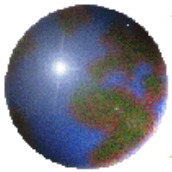
- A example: Fluxless Ag-In Bonding
- Solid State Atomic Bonding
- Solder Flip-Chip Technology
- Silver Flip-Chip Technology
- Summary

Potential Advantages of Ag flip-chip: In random order

- High electrical conductivity, 7.7 times of that of Pb-free solders.
- High thermal conductivity, 5.2 times of that of Pb-free solders.
- No flux; completely fluxless.
- No IMCs; issues associated with IMC & IMC growth do not exist.
- No solder mask needed.
- No molten phase involved; the bump can better keep its shape and geometry.
- No molten phase involved; bridging of adjacent bumps does not occur.
- Ductile Ag manages CTE mismatch between chips & packages.
- Ag joints have high melting temperature, 961ºC.
- Aspect ratio of bumps can be greater than 1.
- Alignment tolerance: up to ¼ pitch
- The size of columns is only limited by the lithographic process.
- Yet to be identified.



Thank you.

Questions?