Pb-free Solder for Flip Chip Interconnects

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Optimal Pb-free Solder Alloy for Flip Chip Applications

- Sn-0.7Cu is the lowest cost option
  - No expensive Ag in the composition
- Permits some reflow temperature hierarchy
- Highly processable
  - Both in solder paste and plated forms
- Uniform microstructure that evolves little with time and temperature
- Consumption of UBM (e.g., Cu) reasonable
  - Sn-0.7Cu slower than Sn-Pb in solid state
  - Slightly faster consumption during reflow
- Low, but sufficient strength
  - Limits damage to joined components
- Superior TMF behavior

Sn-0.7Cu is the optimal Pb-free solder alloy for flip chip applications

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Whisker Formation with Pb-free Solders

- Whisker formation is known to occur in pure Sn
- Some evidence exists that Sn-rich Pb-free solder whiskers may also form
- Accelerated testing for whisker formation is a "black art"
- No publicized acceleration test
- Testing needed...

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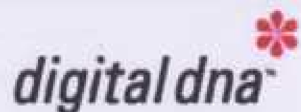


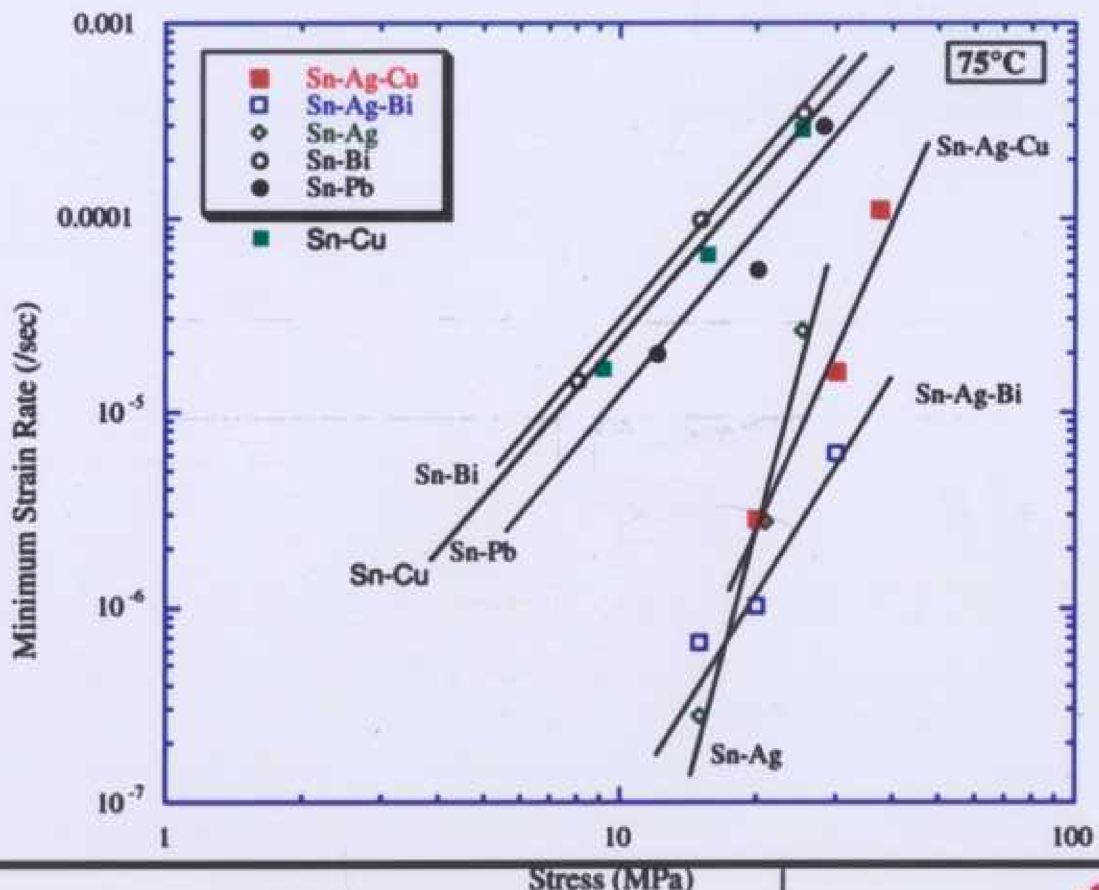
Solder Joint Creep Behavior

Accepted creep behavior and constitutive relations are needed

$$d\gamma/dt = A\sigma^n e^{-Q/RT}$$

$$d\gamma/dt = A\sinh(\alpha\sigma)^n e^{-Q/RT}$$

- Sn-Ag based solders have a much slower creep rate than Sn-Pb
- Sn-Cu creep rate similar to Sn-Pb



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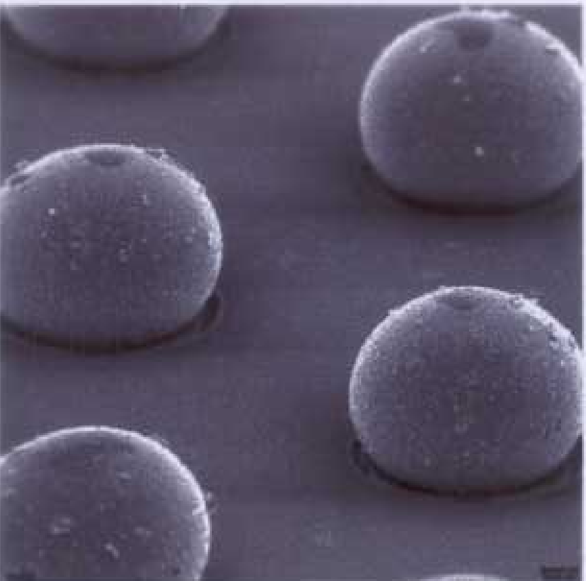
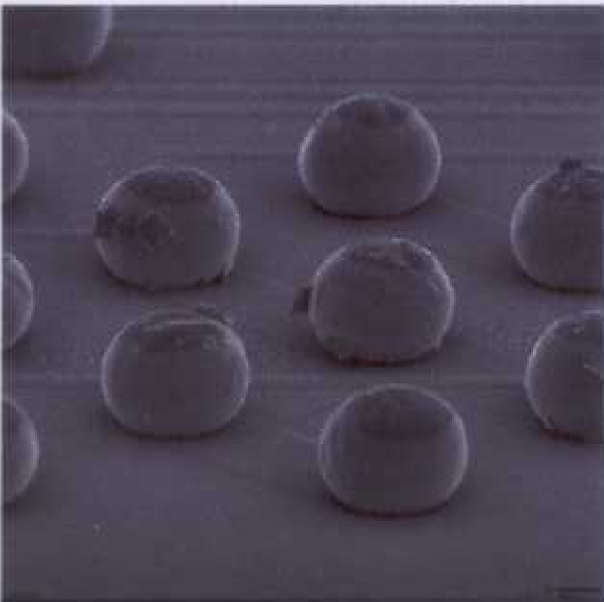
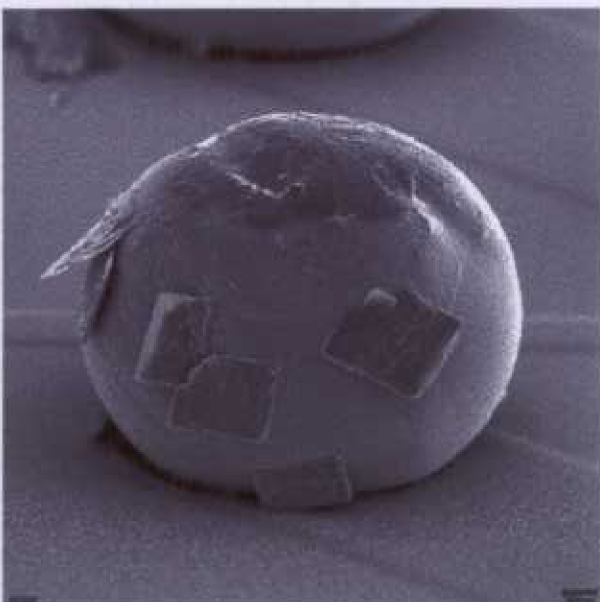
Whisker Formation



<u>Sn-40Pb</u>
Whiskers observed to form after 192 hrs. autoclave
2atm/100%RH/121°C





<u>Sn-0.7Cu</u>
No whiskers form after 192 hrs. autoclave
2atm/100%RH/121°C
Oxide "platelets" form

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Thermomechanical Fatigue Behavior

Eutectic Sn-37Pb
- Heterogeneous coarsening
- Failure near interface at chip side of joint
- No surface deformation of bumps

Sn-3.5Ag and Sn-3.5Ag-0.7Cu
- No microstructural evolution
- Cracks form at solder/IM interface
- No surface deformation of bumps

Eutectic Sn-0.7Cu
- No microstructural evolution
- Cracks for intergranularly in center of the joint
- Extensive bump deformation prior to failure

- Sn-0.7Cu has a superior lifetime
  - Exceeds eutectic Sn-37Pb and other Pb-free alloys

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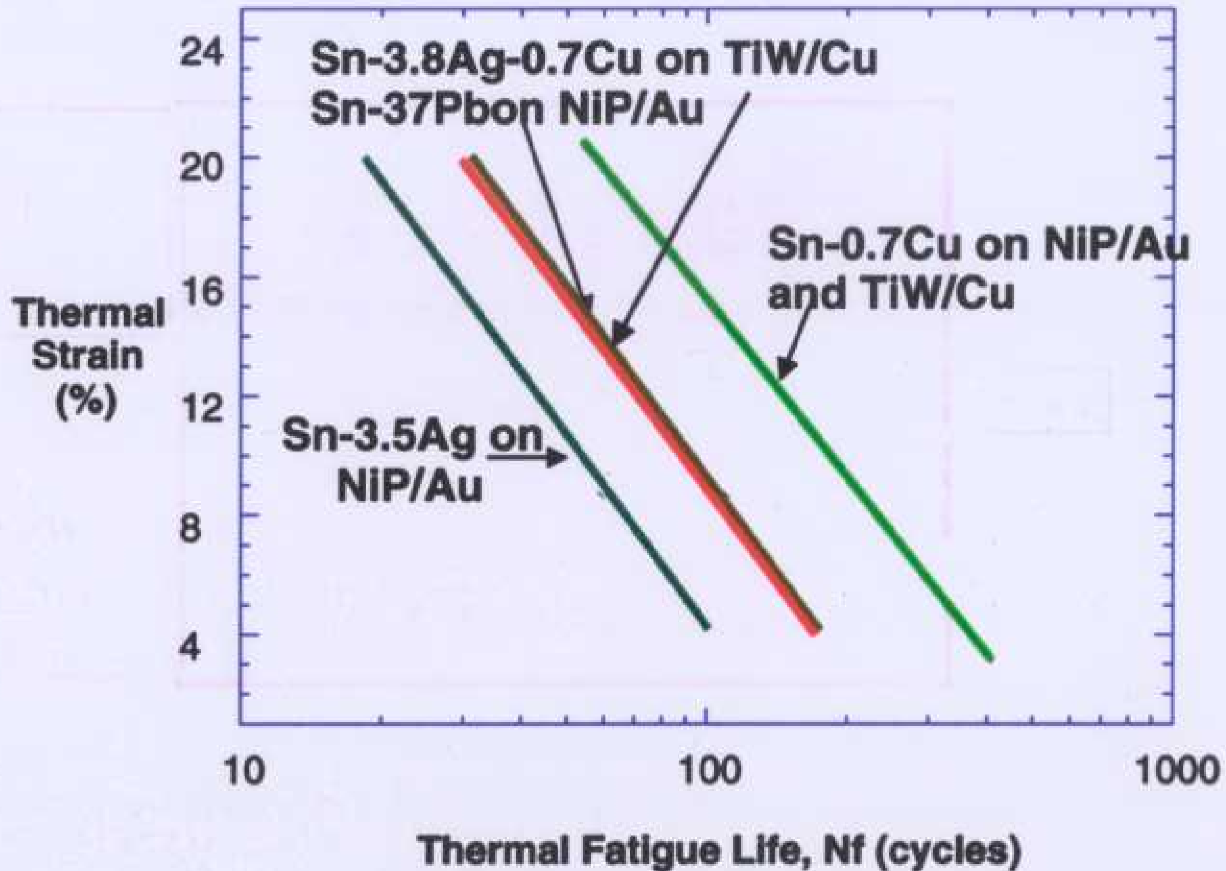
Thermomechanical Fatigue Behavior

- No underfill
- Tested to electrical failure
- Sn-Cu has the best TMF performance
    - UBM independent



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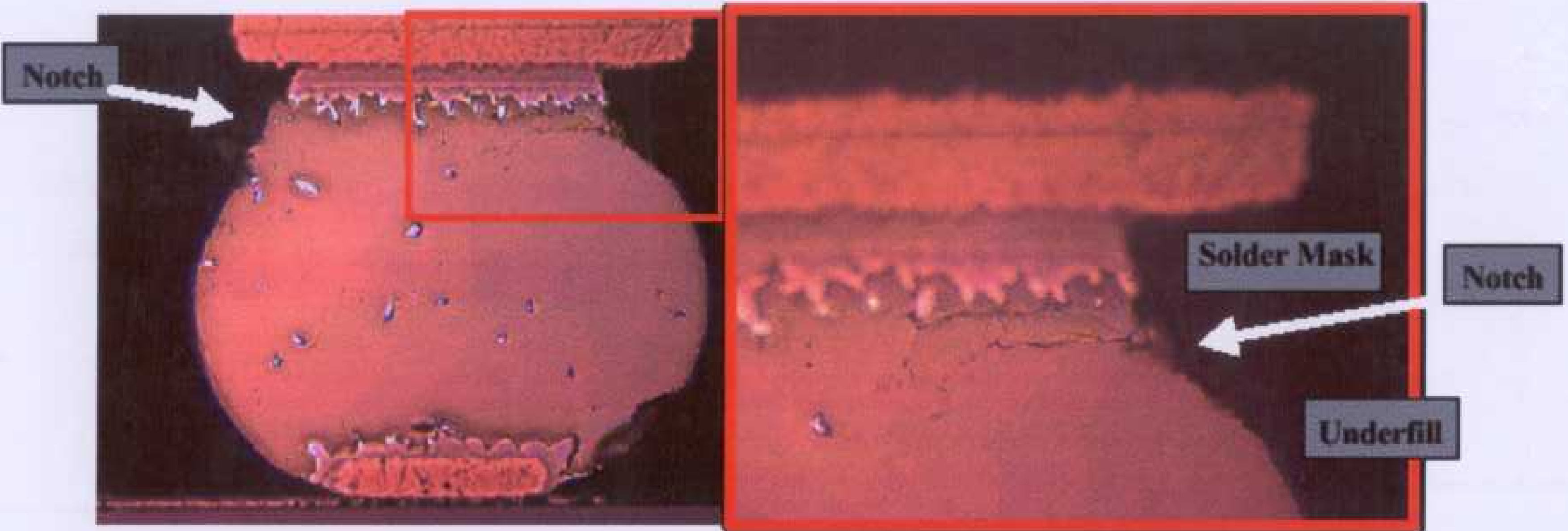
Thermomechanical Fatigue Behavior: Eutectic Sn-0.7Cu

FC-PBGA SnCu/Cu 2,200X L/L @ -55 to 125C



- Failures initiated at interface of solder mask/underfill.
- Cracks propagate through solder, did not involve IMC or UBM.

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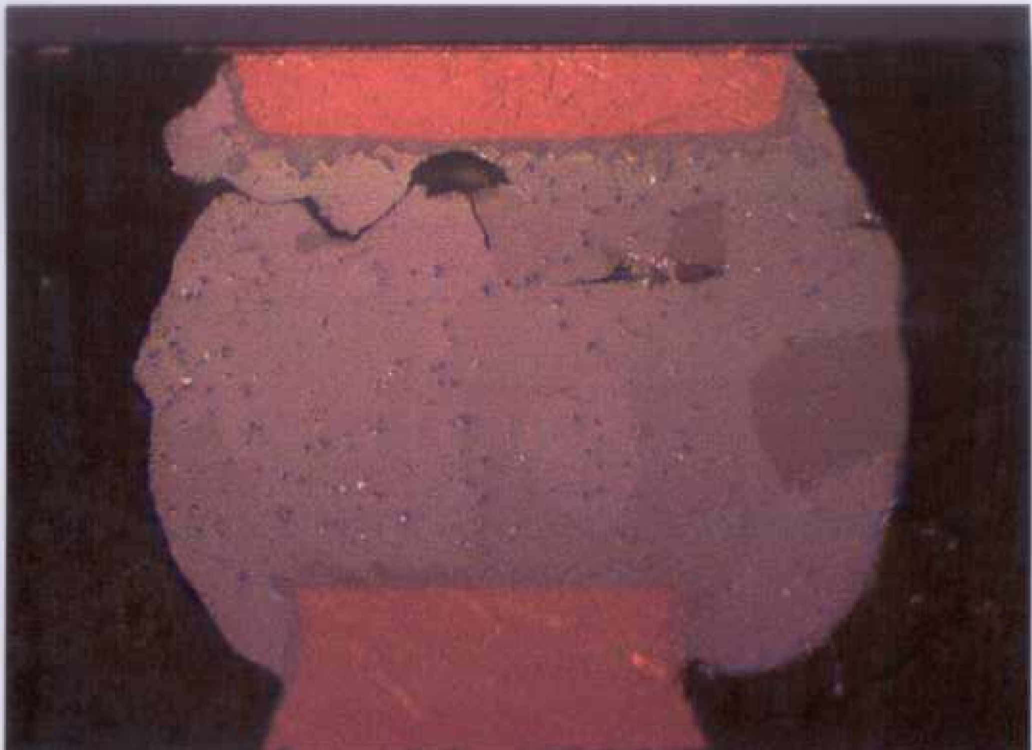
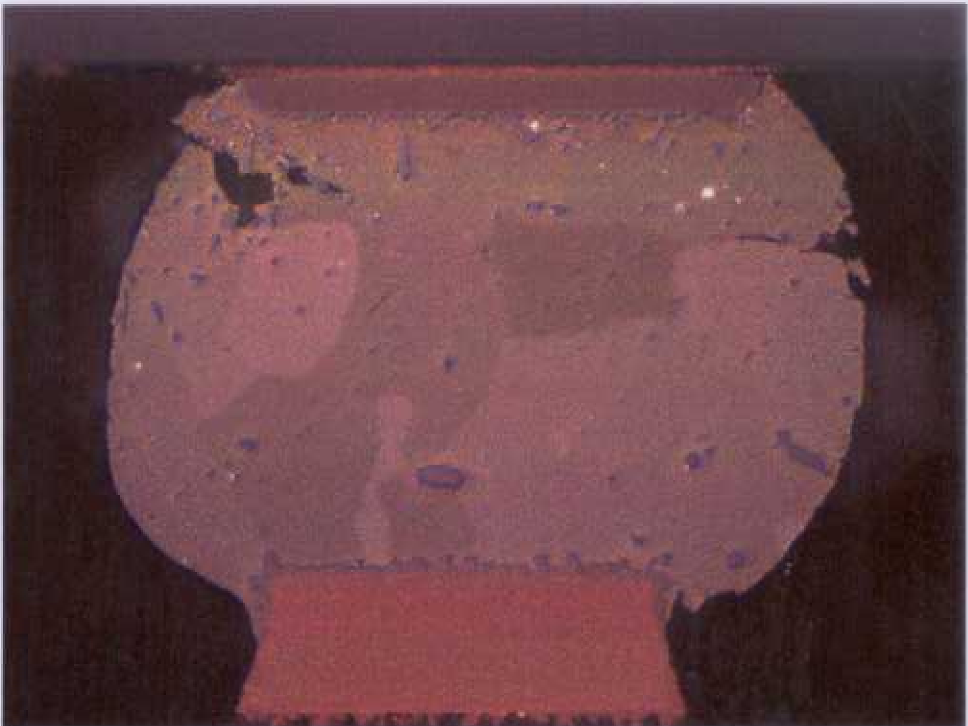
Thermomechanical Fatigue Behavior: Eutectic Sn-0.7Cu





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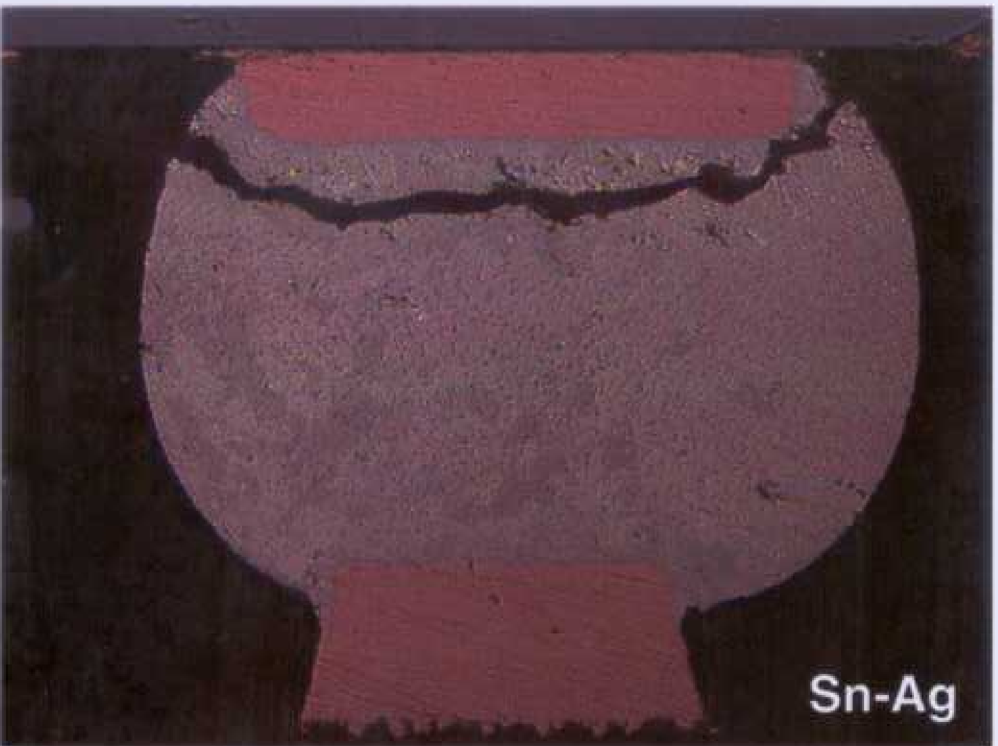
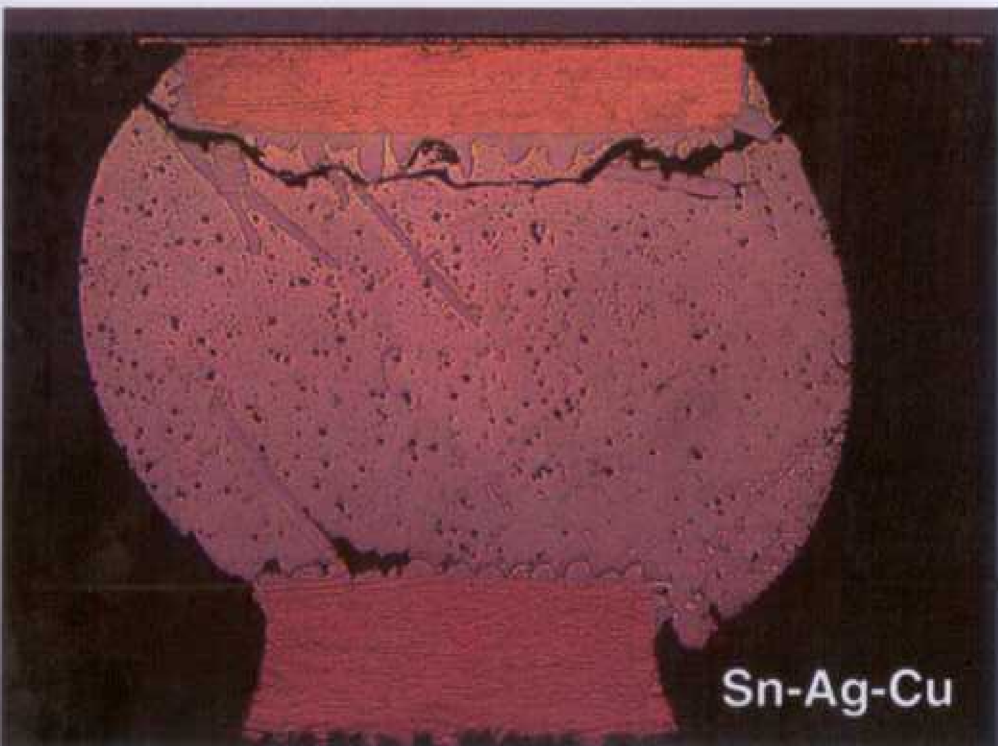
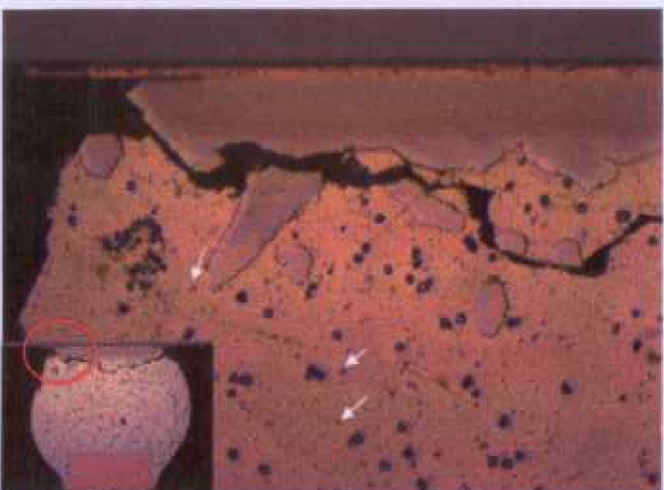
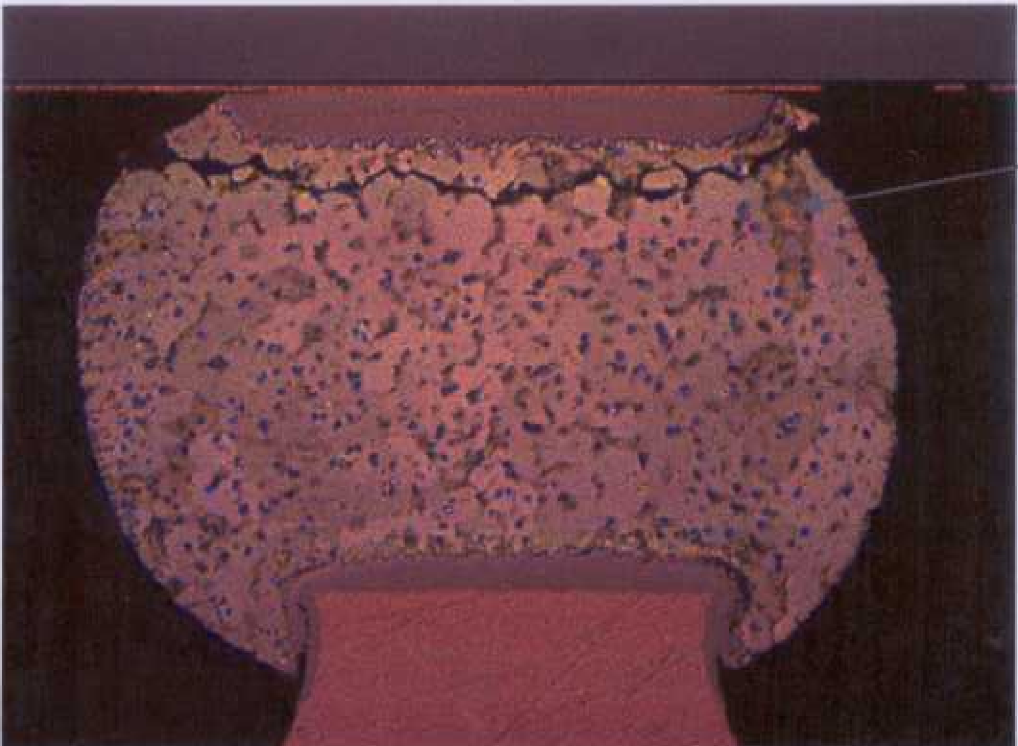
Thermomechanical Fatigue Behavior: Sn-3.5Ag and Sn-3.8Ag-0.7Cu







Thermomechanical Fatigue Behavior: Eutectic Sn-Pb



- Heterogeneous coarsened structure
- Failures at Sn-Sn grain boundaries

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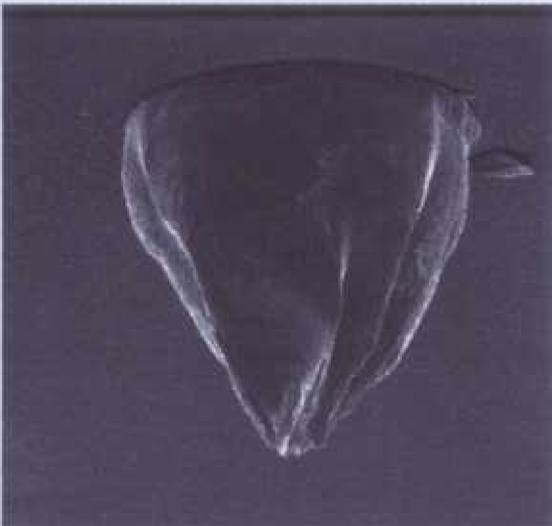
Solder Bump Strength: Tensile failure of Sn-Cu Solder

SnCu/Cu UBM

SnCu/Ni UBM



- Failure is in solder
- "Taffy pull" indicates good ductility

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Solder Bump Strength: Tensile failure of SnPb/SnAg Solder

Sn-Pb/Cu

Sn-Ag/Cu

- Failure is near/at interface
- Limited ductility observed

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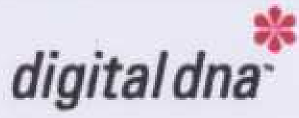
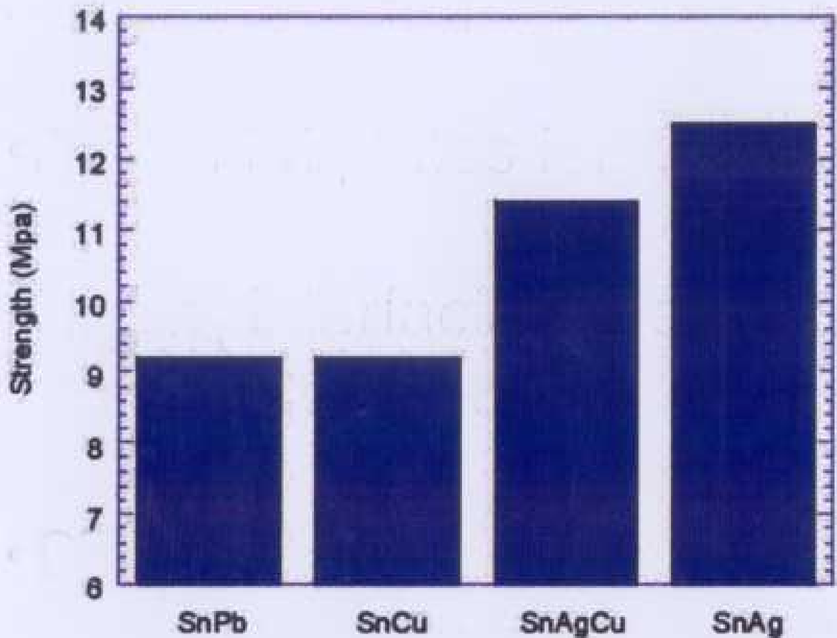


Solder Bump Shear Strength



- All failures in solder away from interface
- Cu-Sn and Sn-Pb have comparable shear strengths

Lower strength desired:

- Minimize potential impact to Si/package
- Damage limited to solder

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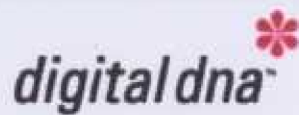

Observations of Intermetallic Growth

- Ag_3Sn IM plates form on IMC for Ni and Cu UBM
- Ni_3Sn_4 interfacial IM spall off into Sn-3.5Ag solder
  - Cu effect?
- Consumption of Ni (reflow and aging): Pb-free>Pb-Sn
  - Still consumption <2μm
- Consumption of Cu: Reflow Pb-free>Pb-Sn
  Solid-state aging Pb-Sn>Pb-free

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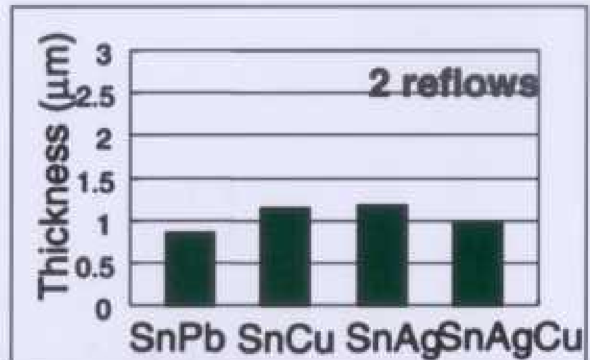
Interfacial Intermetallic Structure: Cu-based UBM

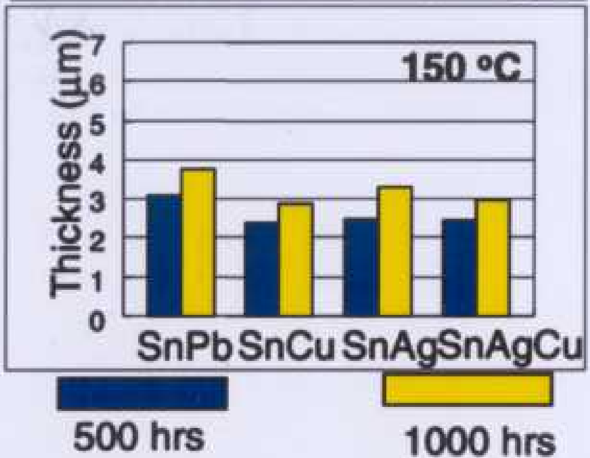
Eut-SnPb: Cu_6Sn_5, Cu, Ti/W

Eut-SnAg: Cu_6Sn_5, Ag_3Sn, Cu, Ti/W

Sn3.8Ag0.7Cu: Cu_6Sn_5, Cu, Ti/W

Sn0.7Cu: Cu_6Sn_5, Cu, Ti/W





- **Cu Consumption in liquid state: lead-free solder > SnPb solder**
  in solid state: lead-free solder < SnPb solder

The interfacial intermetallics change morphology and growth rate depending upon the solder alloy. Sn-Cu resulted in the most uniform structure.

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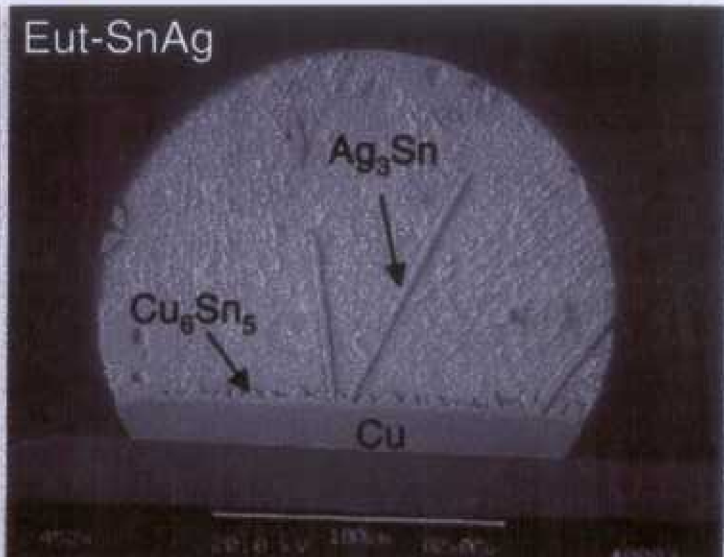
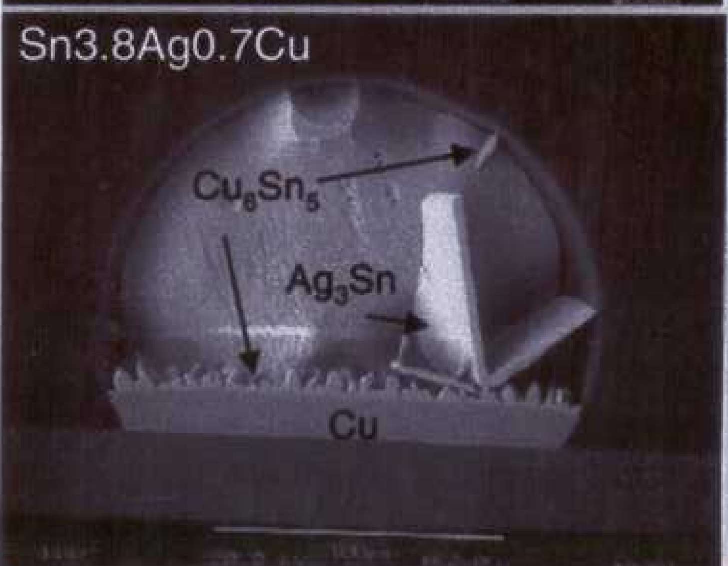
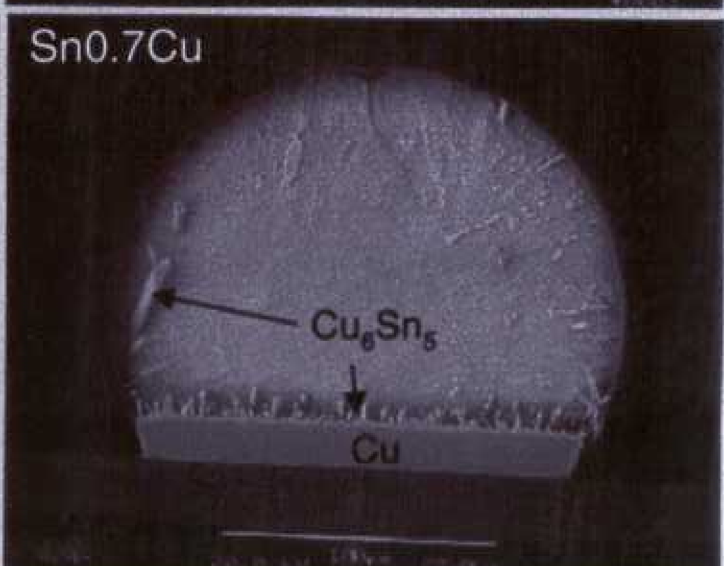
Interfacial Intermetallic Structure: Cu-based UBM

2 reflows







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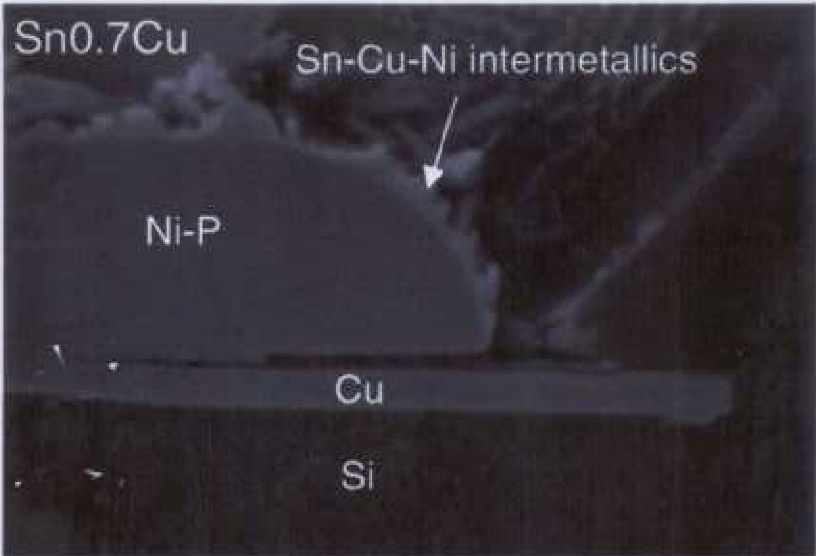
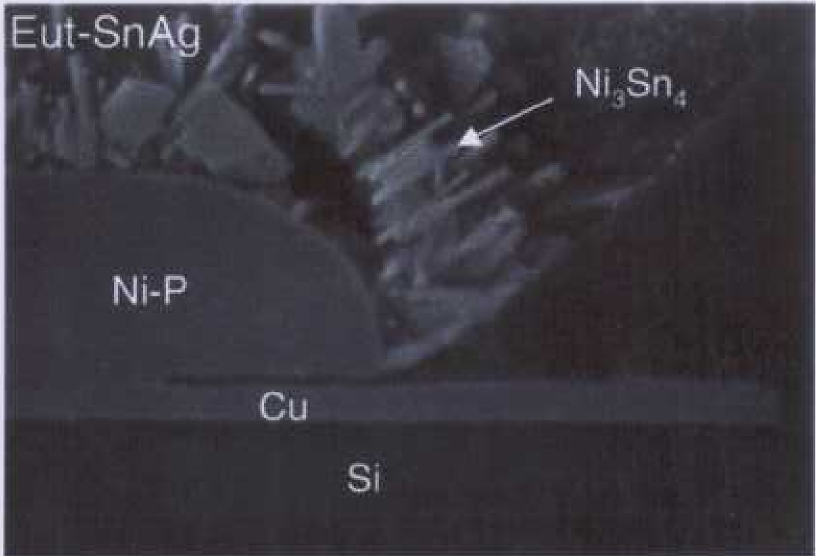
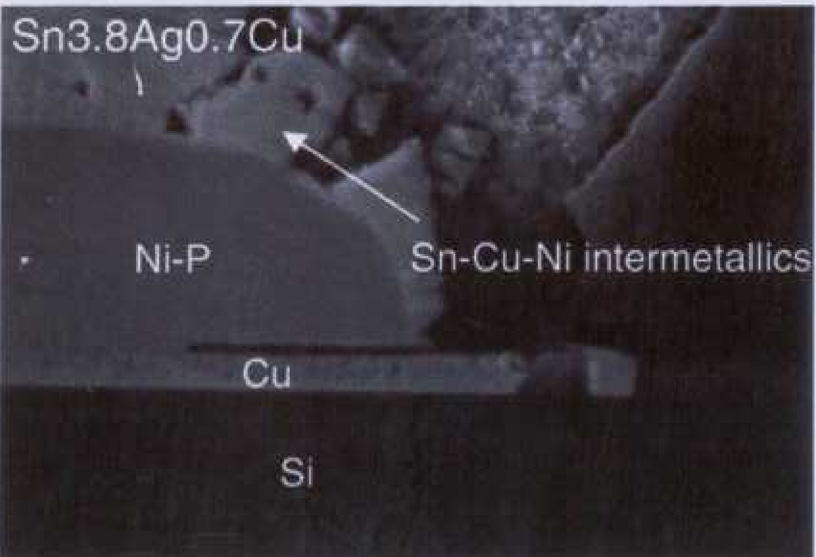
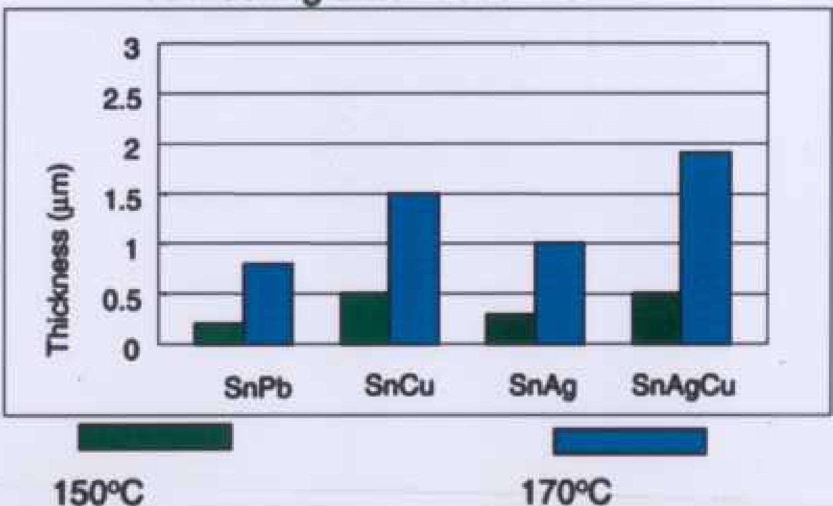
Interfacial Intermetallic Structure: Ni-based UBM







Initial condition: 2 reflows
Annealing time: 1000 hrs



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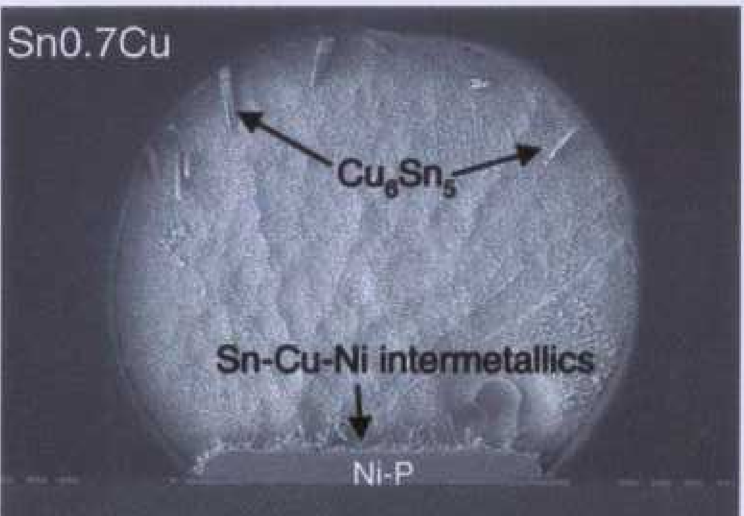
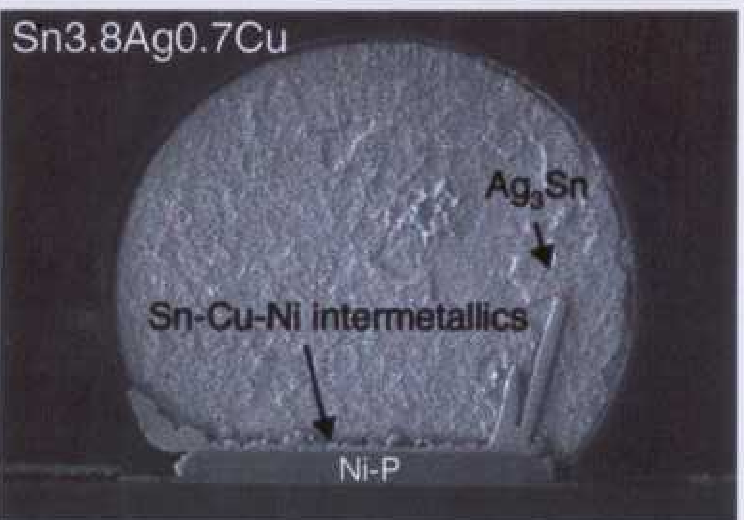
Interfacial Intermetallic Structure: Ni-based UBM

2 reflows





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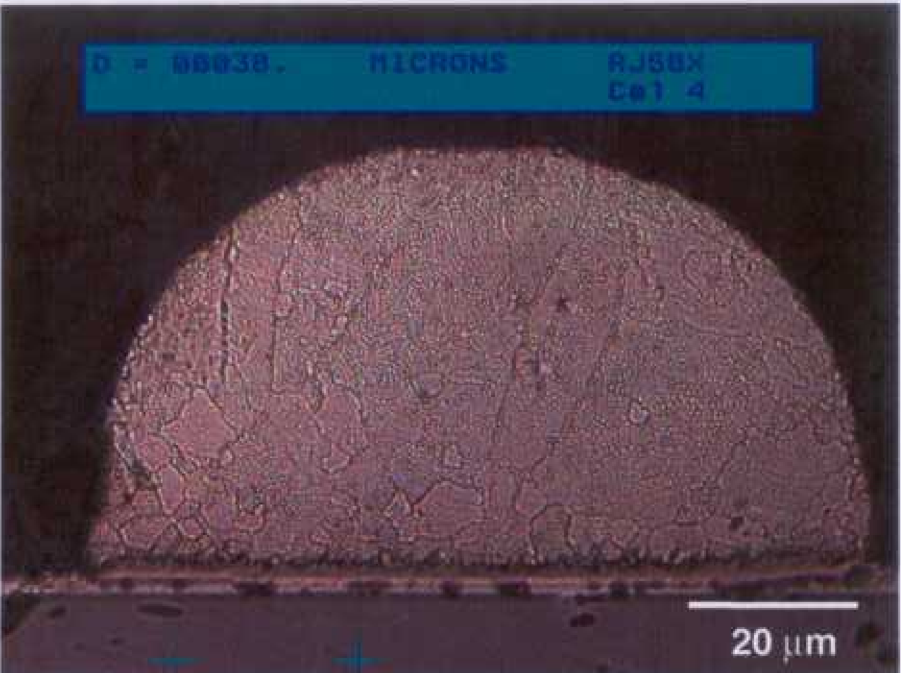
Solder Microstructure: Eutectic Sn-0.7Cu



- Large grains of Sn
- Fine dispersion of Cu_6Sn_5 throughout

10 µm

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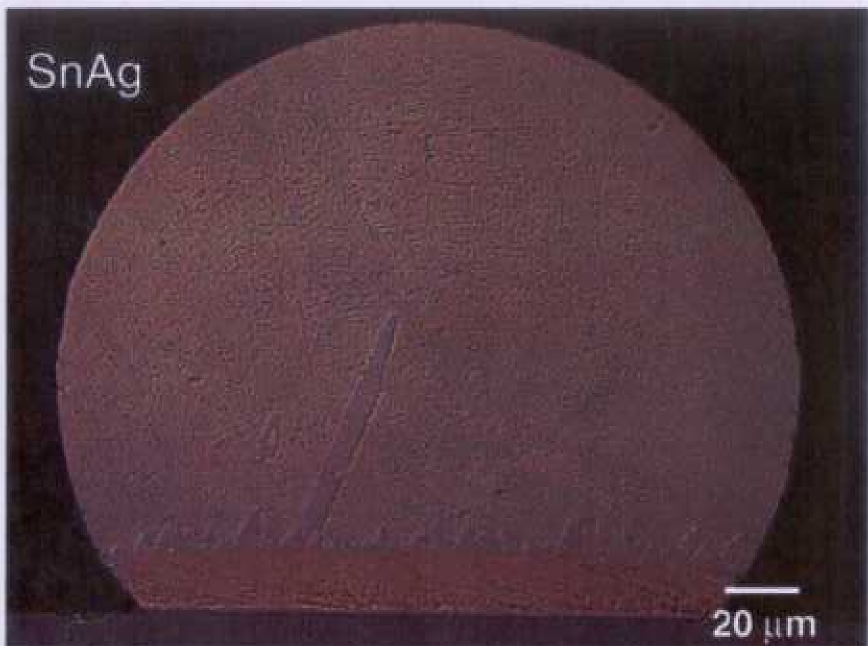
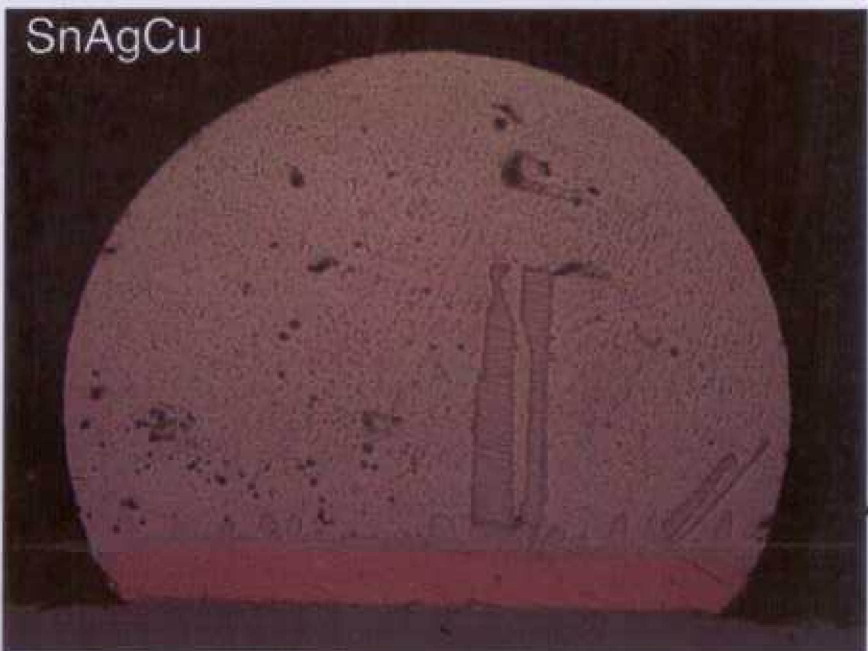
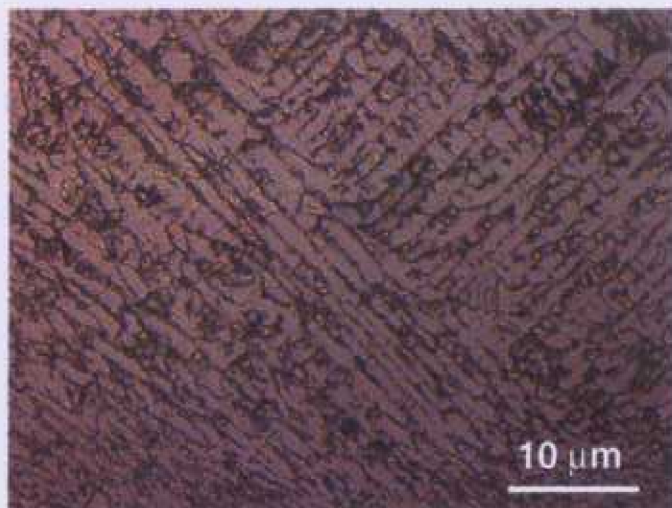
Solder Microstructure: Sn-3.5Ag and Sn-3.8Ag-0.7Cu

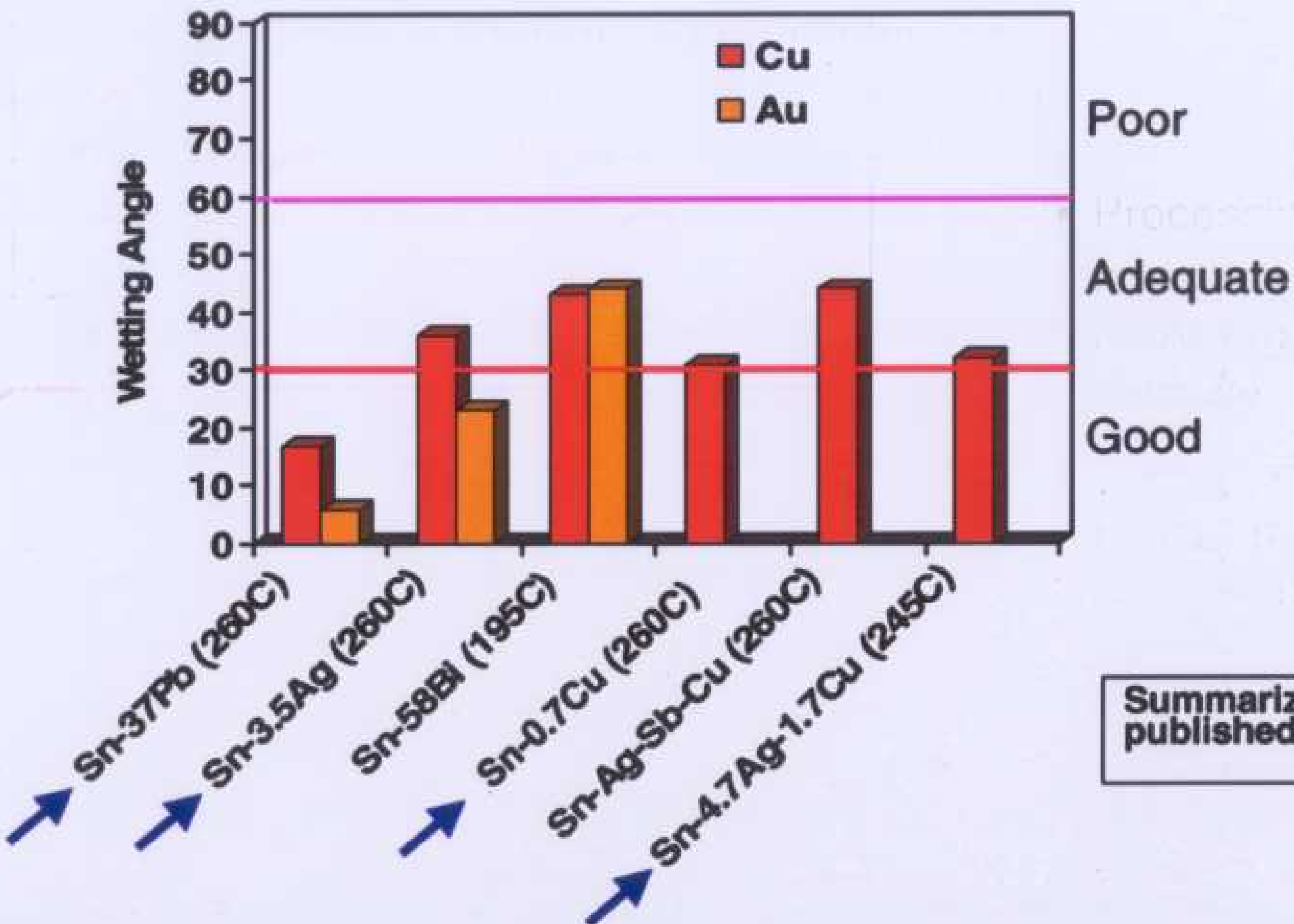






- Fine lamellar structure of Sn and Ag_3Sn
- Ag_3Sn precipitates as plates at solder/interfacial intermetallic interface
- Small precipitates of Cu_6Sn_5 in SnAgCu

Wetting Behavior



Summarized results from published papers

- Pb-free solders wetting is adequate but less than that of Sn-Pb

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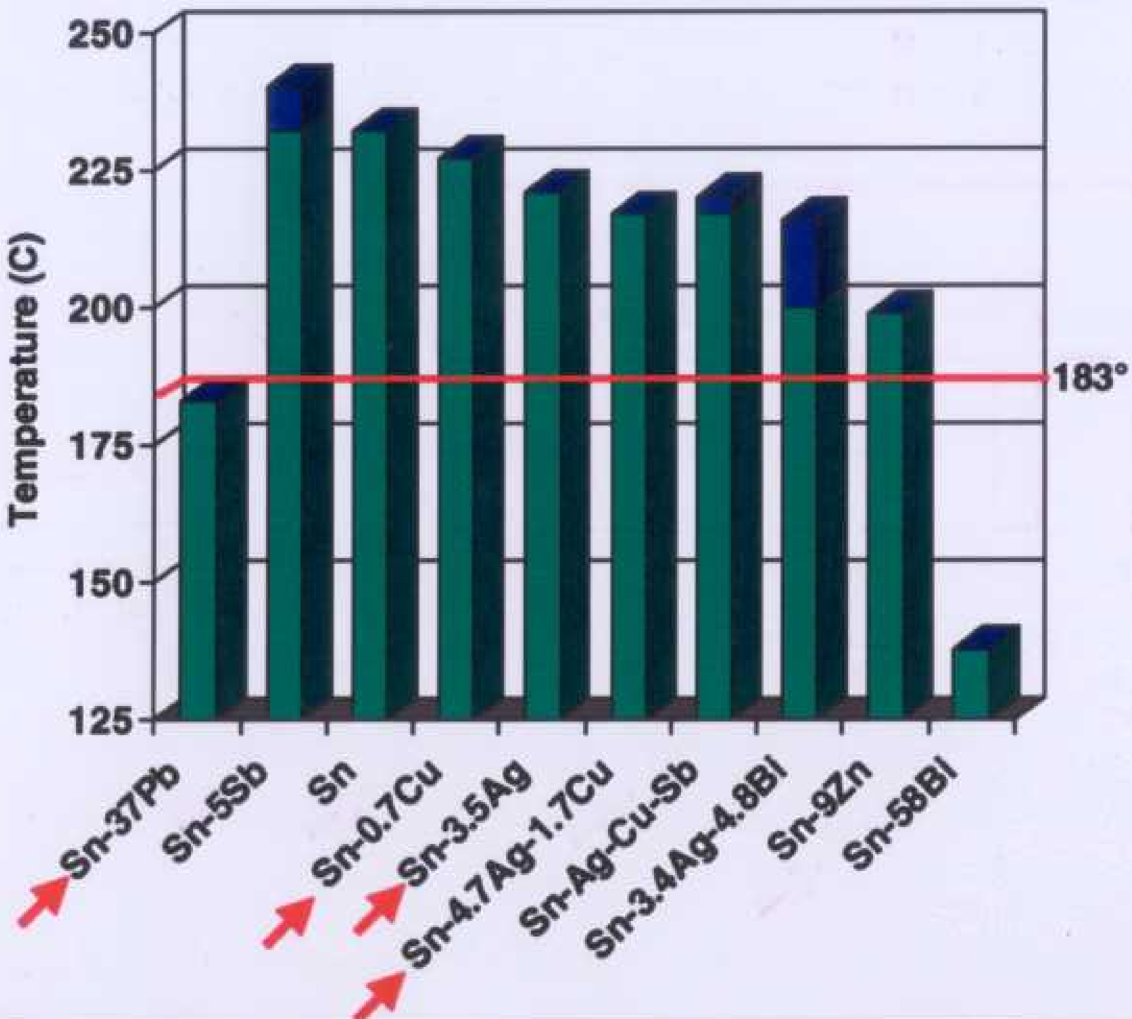
Physical Behavior - Melting Temperature



- Processing temperature must be below 260°C to avoid organic substrate damage
- Require small "two-phase" region to avoid disturbed joints

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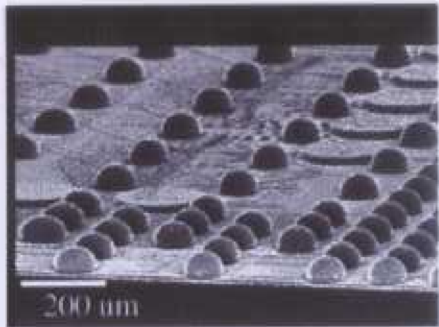
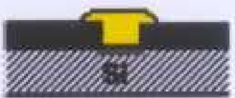
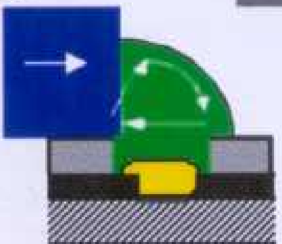
Flip Chip Process Flow

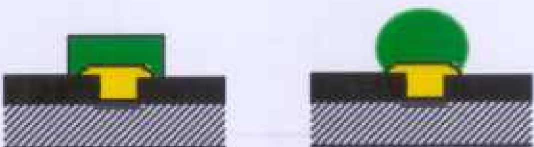




- Electroless NiP/Immersion Au

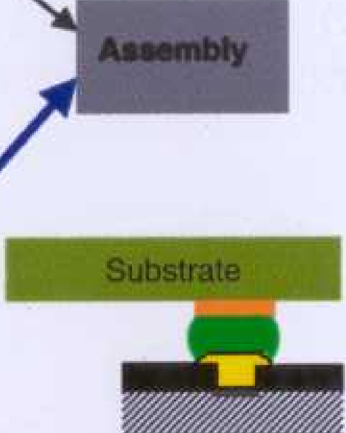
Under Bump Metallurgy → Print → Reflow → Assembly

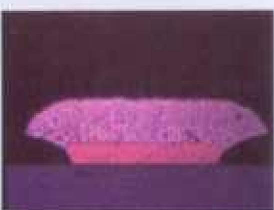


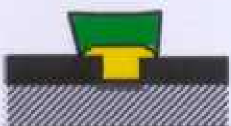


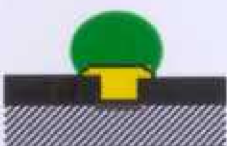
- Sputter TiW/Cu Cu plate
- Electrolytic Ni

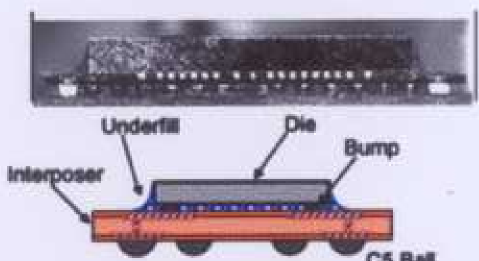
Under Bump Metallurgy → Plate → Reflow → Assembly











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Pb-free Solder Requirements

- Suitable melting temperature
    - < 260°C for board reflow
    - Melting temperature hierarchy
        - die to package / package to board
- Good wetting
- Suitable creep
    - Deform quickly, but not too quickly
- Suitable strength
    - Strong, but not too strong
- Good fatigue resistance
- Environmentally benign
- Cost = Pb/Sn

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Pb-free Solder for Flip Chip Applications

- Physical Behavior
- Microstructure
- Interfacial Reaction Products/Kinetics
- Mechanical Behavior (time dependant/independent)
- Fatigue Behavior
- Whiskers?
- Optimal Pb-free Solution for Flip Chip…

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