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
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...
Solder Joint Creep Behavior

Accepted creep behavior and constitutive relations are needed

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

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

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

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

Sn-0.7Cu
No whiskers form after 192 hrs. autoclave 2atm/100%RH/121°C Oxide “platelets” form
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
Thermomechanical Fatigue Behavior

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

![Graph showing different Sn-Cu alloys and their thermal strain and fatigue life]
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.
Thermomechanical Fatigue Behavior: Eutectic Sn-0.7Cu
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
Solder Bump Strength: Tensile failure of Sn-Cu Solder

- Failure is in solder
- “Taffy pull” indicates good ductility
Solder Bump Strength: Tensile failure of SnPb/SnAg Solder

- Failure is near/at interface
- Limited ductility observed
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

Strength (MPa)

14 13 12 11 10 9 8 7 6

SnAg
SnAgCu
SnCu
SnPb
Observations of Intermetallic Growth

- $\text{Ag}_3\text{Sn}$ IM plates form on IMC for Ni and Cu UBM
- $\text{Ni}_3\text{Sn}_4$ interfacial IM spall off into Sn-3.5Ag solder
- Cu effect?
- Consumption of Ni (reflow and aging): Pb-free $>\text{Pb-Sn}$
- Still consumption $< \mu\text{m}$
- Consumption of Cu: Reflow Pb-free $>\text{Pb-Sn}$
- Solid-state aging Pb-Sn $>\text{Pb-free}$
Interfacial Intermetallic Structure: Cu-based UBM

- 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.
Interfacial Intermetallic Structure: Cu-based UBM

2 refloows

Eut-SnAg

Eut-SnPb

Sn0.7Cu

Sn3.8Ag0.7Cu

Cu₆Sn₅

Ag₃Sn

Ag₃Sn
Interfacial Intermetallic Structure: Ni-based UBM

- Sn0.7Cu
- Sn-Cu-Ni intermetallics
- Ni-P
- Cu
- Si

- Eut-SnAg
- Ni-P
- Cu
- Si
- Ni₃Sn₄

- Sn3.8Ag0.7Cu
- Sn-Cu-Ni intermetallics
- Ni-P
- Cu
- Si

Initial condition: 2 refloows
Annealing time: 1000 hrs

Graph showing:
- Thickness (µm) vs. SnPb, SnCu, SnAg, SnAgCu at 150°C and 170°C.
Interfacial Intermetallic Structure: Ni-based UBM

2 refloows

Sn0.7Cu

Cu₃Sn₅

Sn-Cu-Ni intermetallics

Ni-P

Eut-SnAg

Ag₃Sn

Ni₃Sn₄

Ni-P

Sn3.8Ag0.7Cu

Ag₃Sn

Sn-Cu-Ni intermetallics

Ni-P
Solder Microstructure: Eutectic Sn-0.7Cu

- Large grains of Sn
- Fine dispersion of Cu₆Sn₅ throughout
Solder Microstructure: Sn-3.5Ag and Sn-3.8Ag-0.7Cu

- Fine lamellar structure of Sn and Ag₃Sn
- Ag₃Sn precipitates as plates at solder/interfacial intermetallic interface
- Small precipitates of Cu₆Sn₅ in SnAgCu

SnAg

SnAgCu

10 µm

20 µm
**Wetting Behavior**

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

![Bar chart showing wetting behavior of different solder compositions.](image-url)
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.
Flip Chip Process Flow (Flowchart)
Pb-free Solder Requirements

- Suitable melting temperature
  - $< 260^\circ C$ 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
Pb-free Solder for Flip Chip Applications

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