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Defining the Reliability of Pb-Free Interconnections

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*Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the US Dept. of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

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  - Materials
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  - Interface reactions
- **Outstanding issues**



Introduction: Legislation

- To date, high-reliability electronics:
  - Military products
  - Telecommunications systems
  - Space and satellite hardware

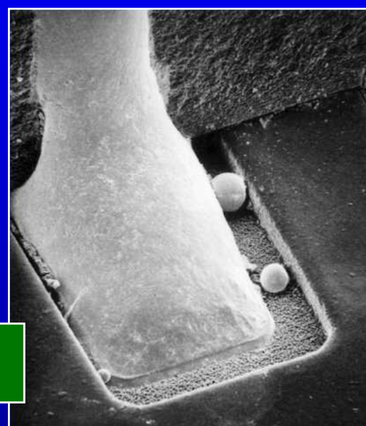
were exempt from the RoHS materials restrictions.

- The exemptions come under review in 2008.
- It is anticipated that the exemptions will be lifted from the directive, and that the effective date will be 2010.

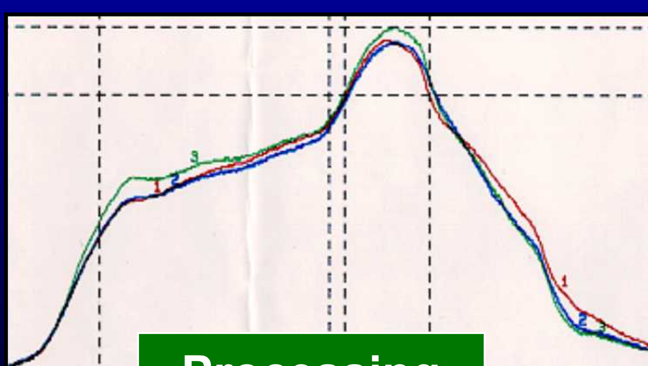
The storm approaches …

Introduction

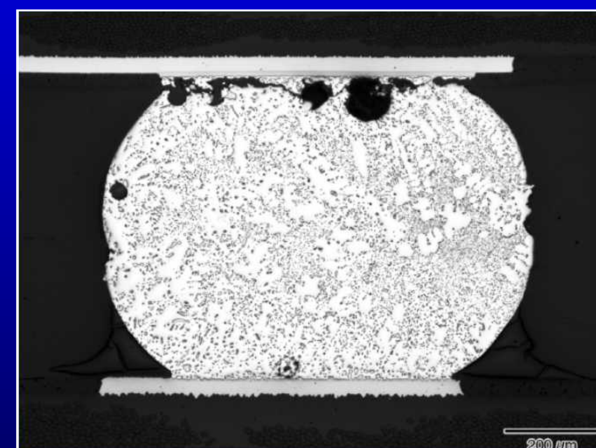
Solder joint reliability depends upon the materials properties and the quality of the interconnections.



Materials



Processing



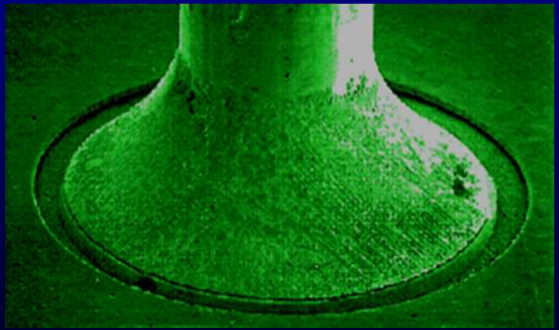
Reliability

Introduction: Materials

- Reflow (furnace) soldering ….. Sn-Ag-Cu "SAC" alloys

USA, Europe, and Japan	95.5Sn - 3.9Ag - 0.6Cu	SAC396 or "NEMI" alloy
	95.5Sn - 3.8Ag - 0.7Cu	SAC387
	96.5Sn - 3.0Ag - 0.5Cu	SAC305
	($T_s = T_l = 217°$ C)	

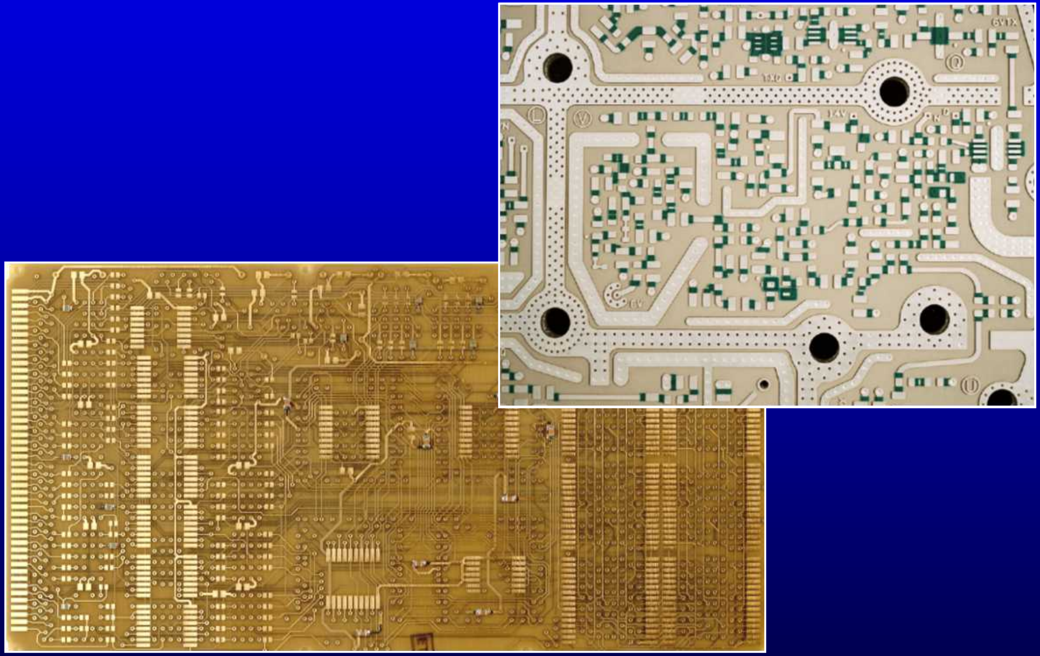
- Wave soldering …..
  - 99.3Sn-0.7Cu ($T_s = T_l = 227°$ C)
  - 99.3Sn-0.7Cu-(Ni) *"stabilized" alloy*
  - Sn-3.0Ag-0.5Cu (SAC305) !!!



Introduction: Materials

Surface finishes can alter the composition of the solder material within the interconnection

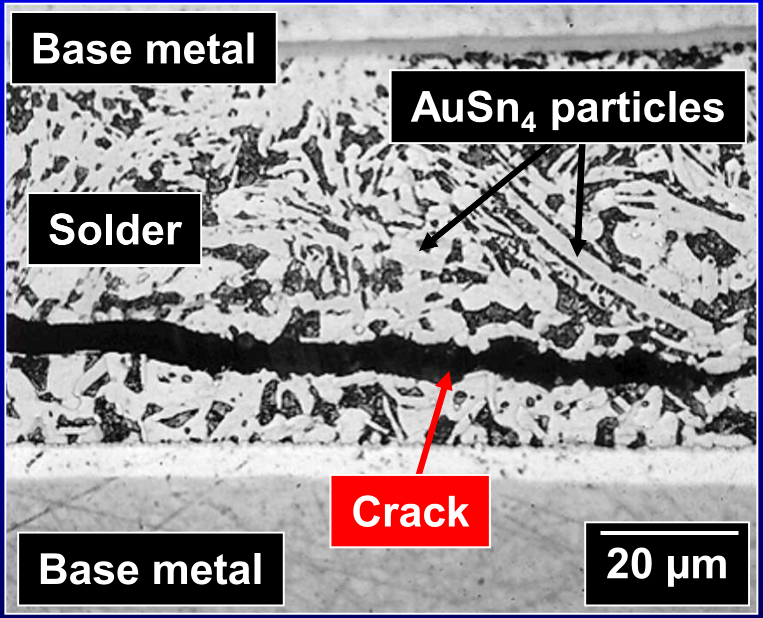
Components



Printed circuit boards

Introduction: Materials

Gold (over Ni) can impact solder joint reliability, not only through infant-mortality failures, but also by altering the mechanical properties of the alloy.



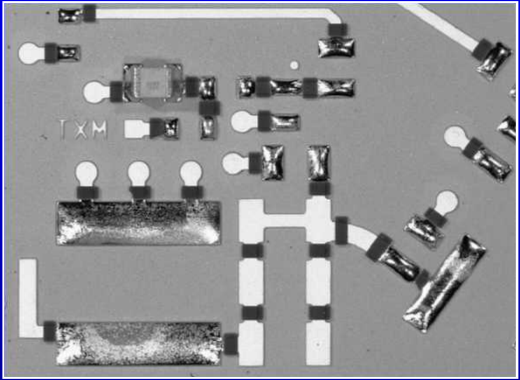
Further increasing the solder joint mechanical strength can be particularly troublesome for Pb-free solders due to their already higher, intrinsic strengths.

Introduction: Materials

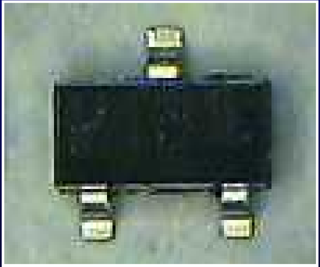
- **Immersion Ag** is sufficiently thin that it will not affect the mechanical properties and, thus, the reliability of *most* Pb-free solder joints.

Thicknesses:

- "Thin:" 0.07 - 0.12 µm
- "Thick:" 0.20 - 0.20 µm

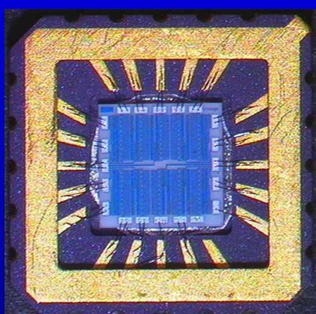


- **Sn finishes** will *generally* not impact the reliability of Pb-free solders:
  - Immersion Sn thicknesses ….. 0.3 - 1.5 µm
  - Electroless Sn thickness ….. ≤ 5 µm
  - Electroplated Sn thickness ….. 1.0 - 13 µm

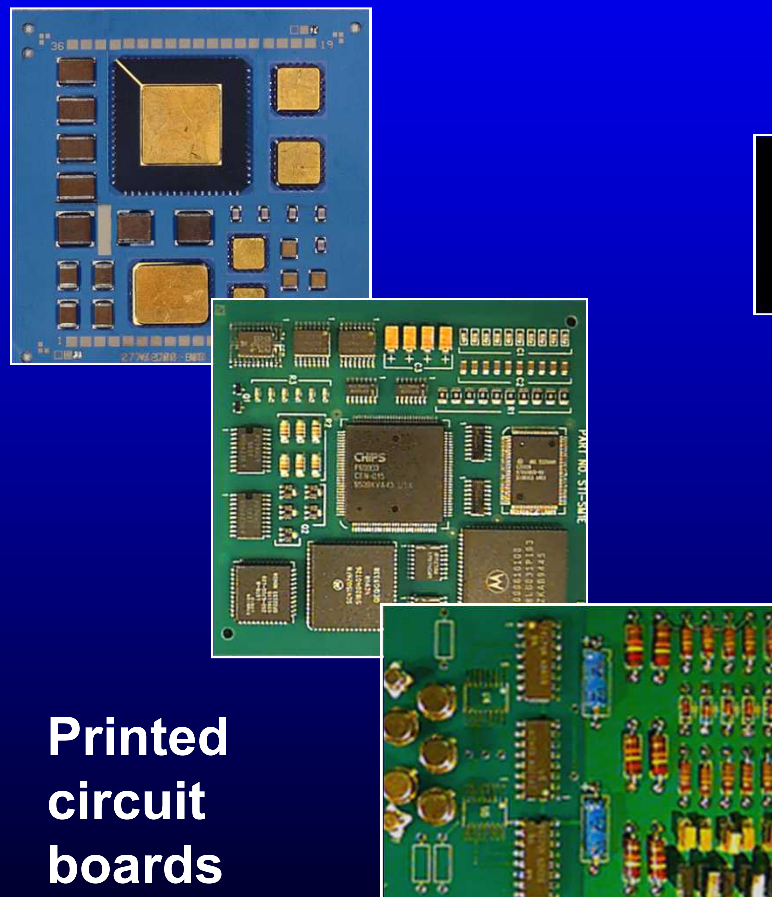


Introduction: Materials

There is a wide variety of component and substrate materials with unmeasured material properties.



Integrated circuits

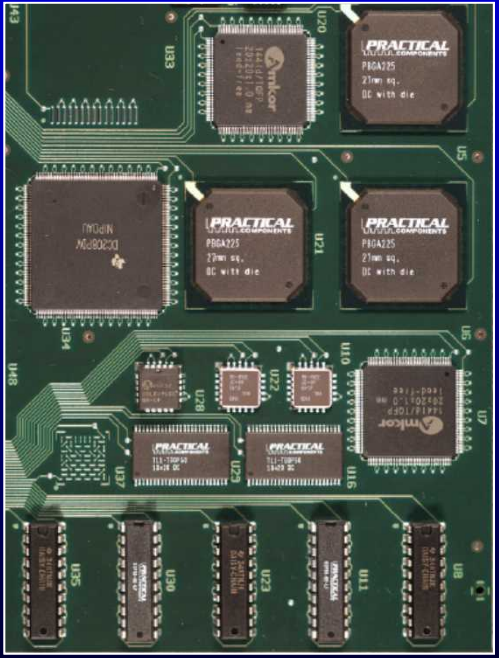


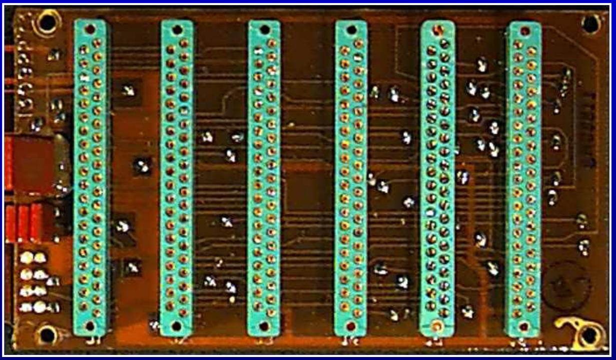
Printed circuit boards

Connectors

Introduction: Processes

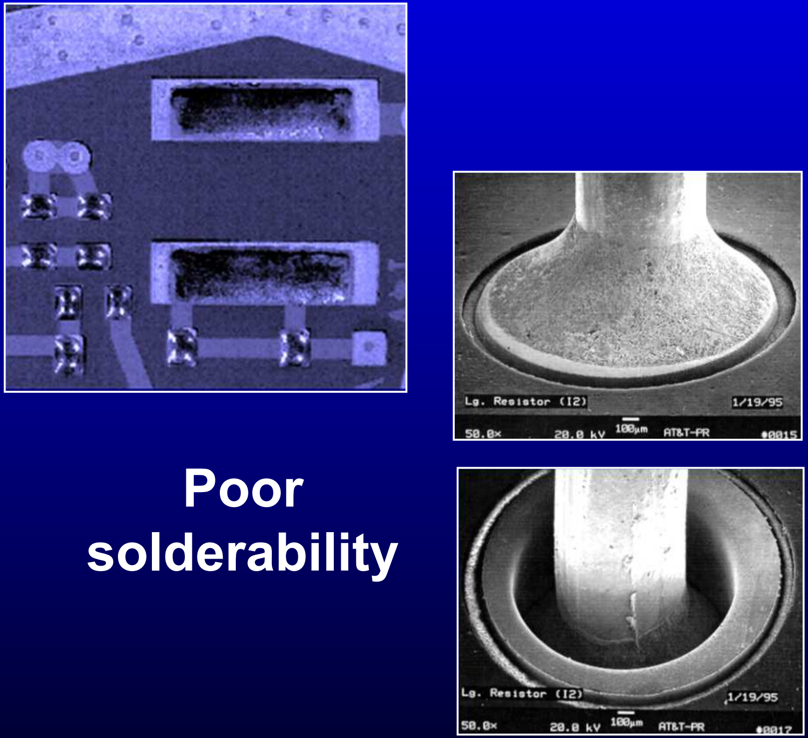
- An essential factor for reliability predictions is the consistent quality of the solder interconnections.
- 10^3 to 10^4 solder joints per circuit board or device !



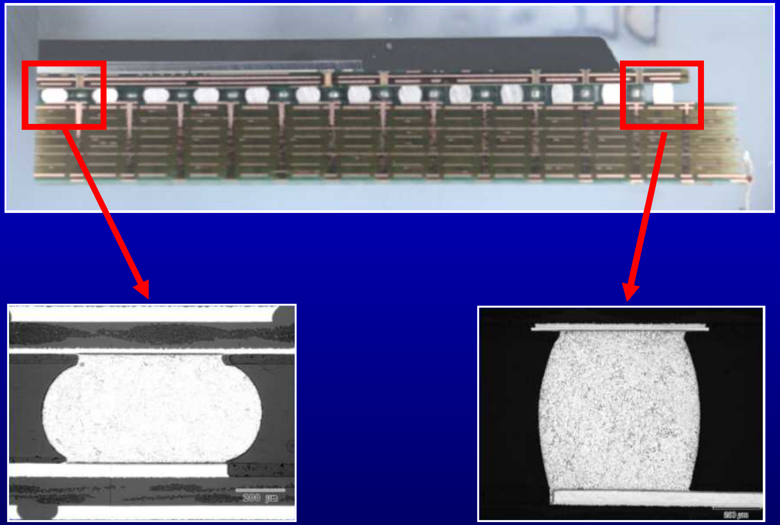


Introduction: Processes

Poorly formed solder joints resulting from inadequate solderability or geometry changes by the component will affect the reliability of the solder interconnections.



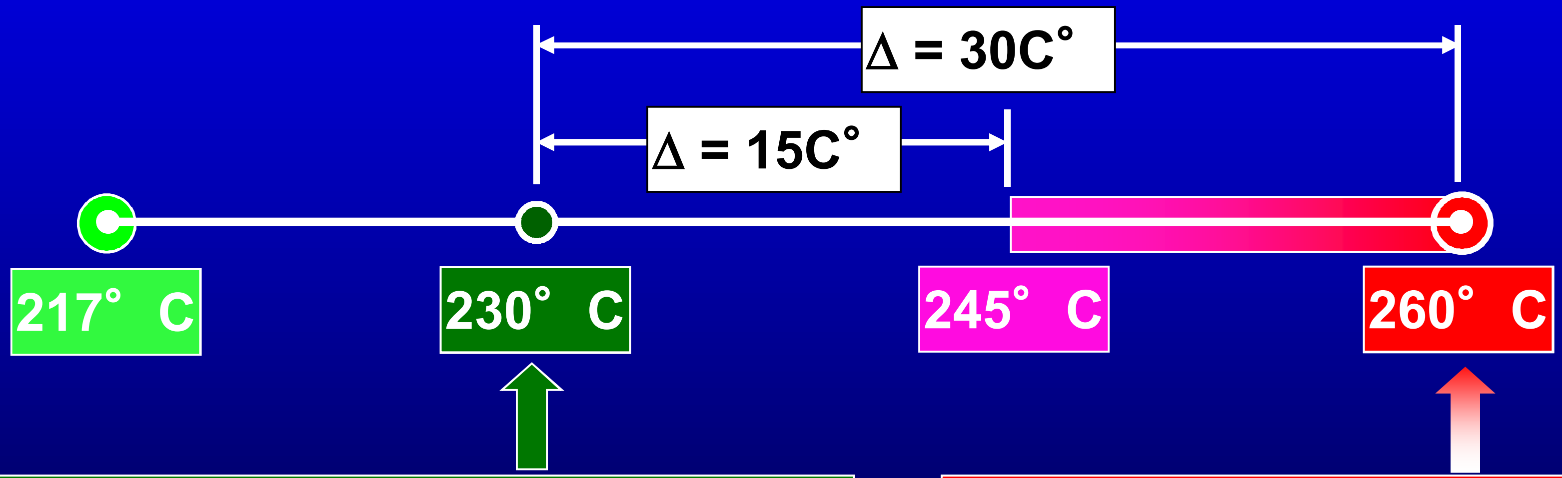
Poor solderability



BGA warpage

Introduction: Processes

The higher process temperatures of Pb-free alloys can alter the mechanical properties of temperature sensitive component and substrate materials.



Minimum process temperature to assure melting of the Sn-Ag-Cu alloy (T_{eut} = 217° C) and to compensate for dissolution effects, temperature error "budgets", etc.

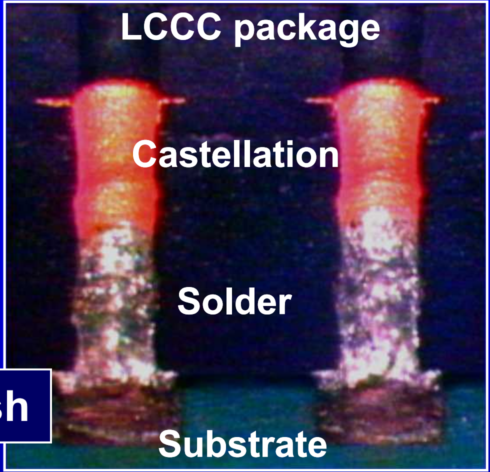
Maximum process temperature to prevent damage to organic laminates and passive chip devices (e.g, capacitors).

Introduction: Processes

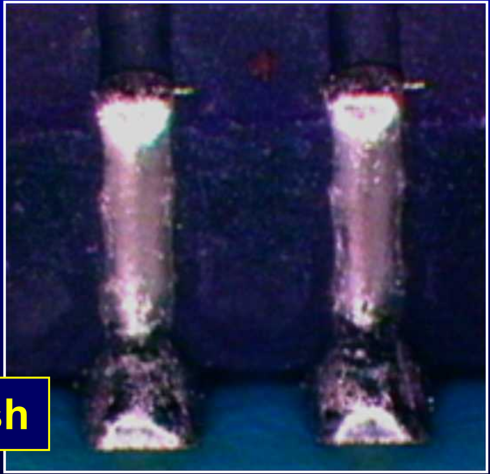
- Higher melting temperatures of the Pb-free solders reduce the available "temperature margin" within the assembly process.

- Au dissolution from the castellation resulted in constitutional solidification that inhibited solderability.

- It was necessary to remove the Au layer by hot-solder dipping in order to improve solderability.



100 Au Finish



Hot-Solder Finish

Reliability: Requirements

Reliability predictions begin by understanding the requirements of the particular hardware.

The electronics of these two systems have significantly different reliability requirements.

Reliability: Shock and Vibration

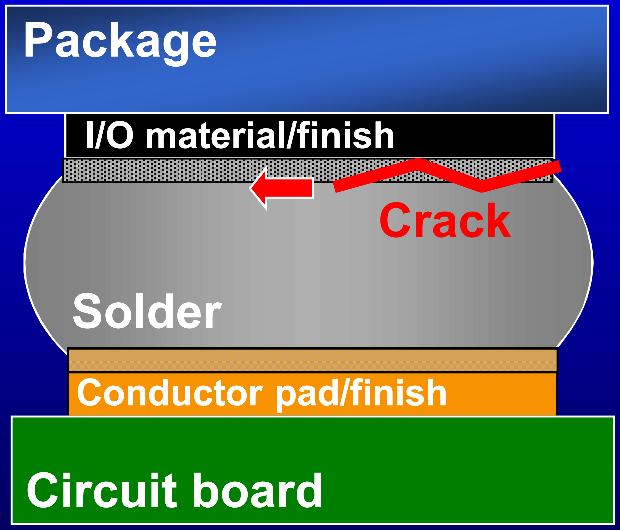
Clearly, long-term reliability is a primary concern associated with the adaptation of Pb-free solders to military and satellite electronics hardware.

Shock and vibration

- **Mechanical overload**
- **High cycle fatigue**

Reliability: Shock and Vibration

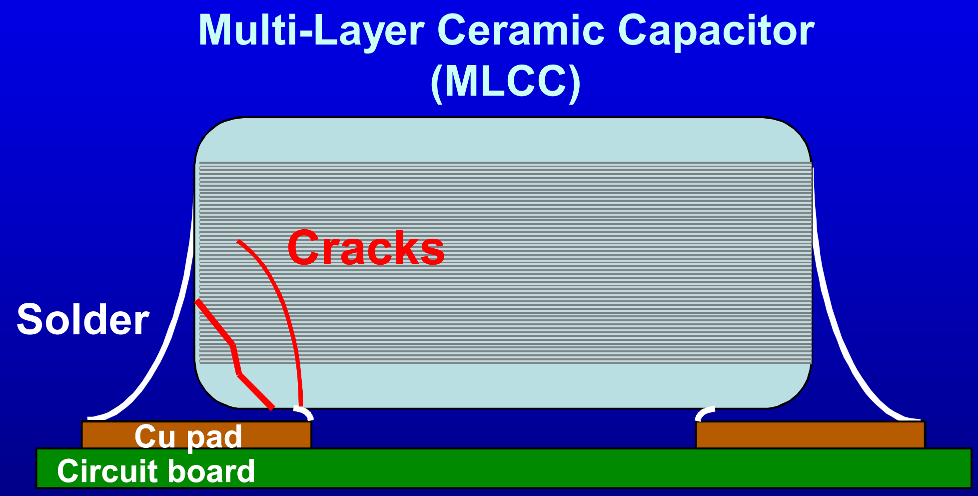
Cracks occur in the interface reaction layer or, in the solder very near to that layer.



Reliability: Shock and Vibration

There is an increased susceptibility of multilayer chip capacitors to cracking when attached with the Pb-free solders.

- **Sources:**
  - **Excessively fast cooling rates**
  - **Board flexure**



- **Root cause:**
  1. **Pb-free solders have higher elastic moduli and yield strengths.**
  2. **Residual stresses move away from the solder, into the capacitor.**

N. Blattau and C. Hillman, IPC/JEDEC 2004

Reliability: Thermal Mechanical Fatigue

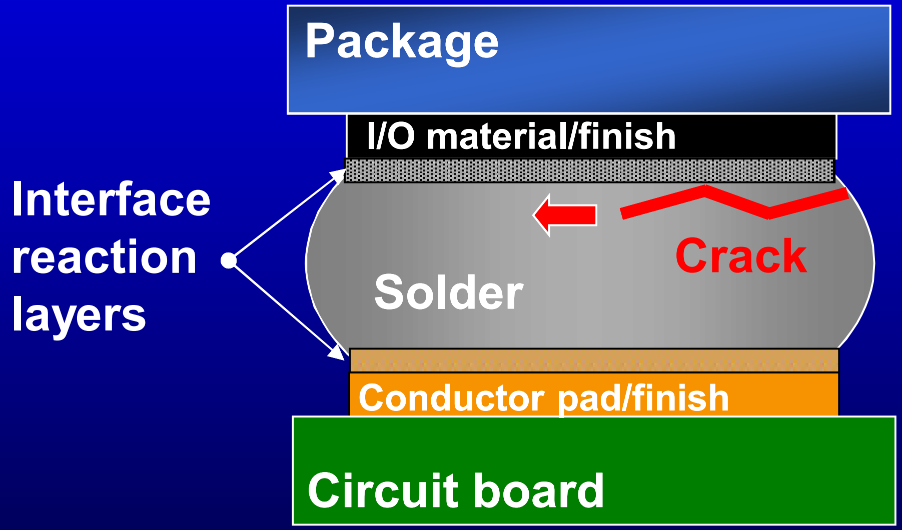
Thermal mechanical fatigue and interface reactions are the primary degradation modes of solder joints undergoing temperature extremes.

Temperature cycles

- **Thermal mechanical fatigue**
- **Interface reactions**

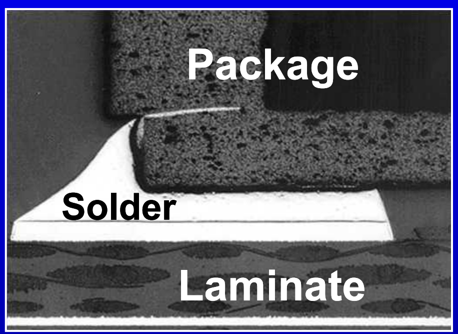
Reliability: Thermal Mechanical Fatigue

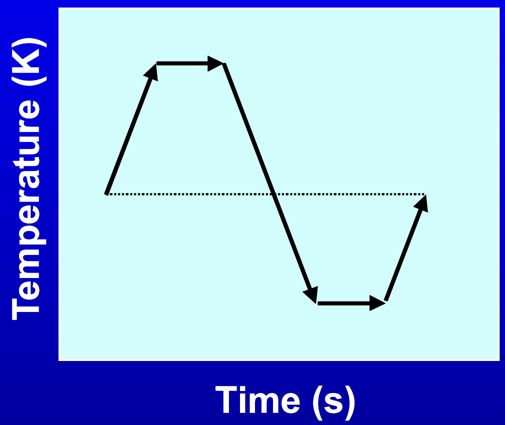
As a form of low-cycle fatigue, thermal mechanical fatigue cracks occur in the solder, near the interface of the *stiffer (less compliant)* material.

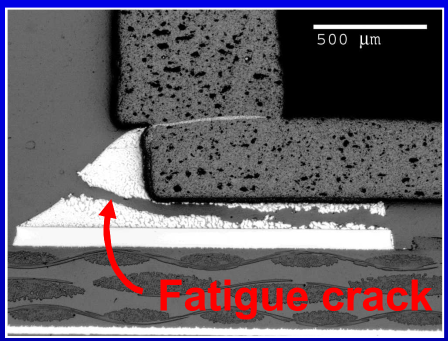


Reliability: Thermal Mechanical Fatigue

Thermal mechanical fatigue was becoming better understood for Sn-Pb solder joints.

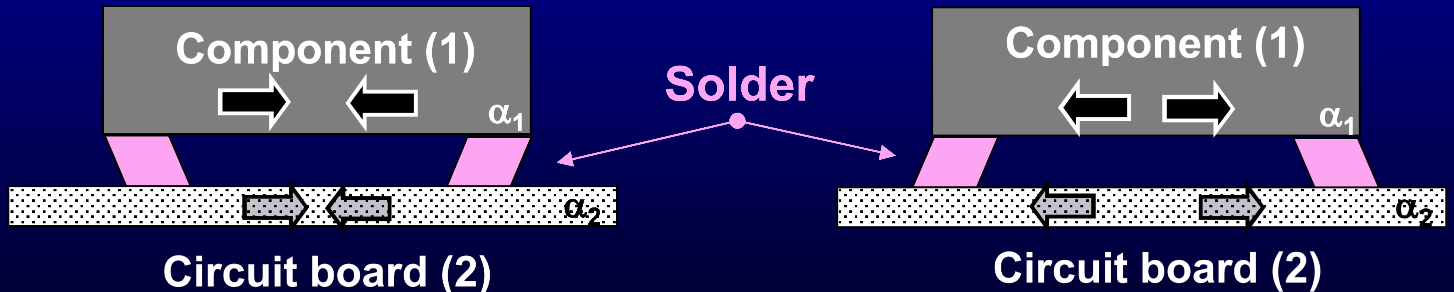






Cooling … *contraction*

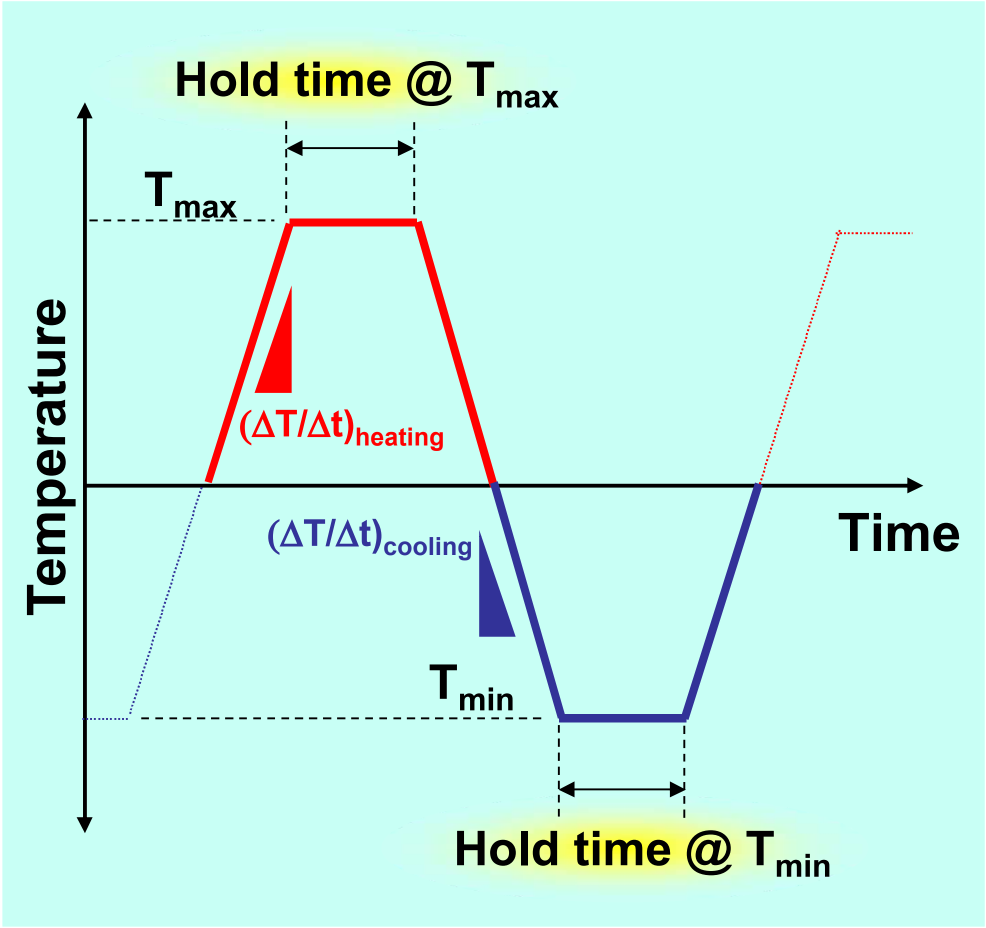
Heating … *expansion*



Reliability: Thermal Mechanical Fatigue

The objective of the hold time is to allow the solder to creep - actually, to stress-relax - as would be the case in actual service.

- Suitable hold times for Sn-Pb solders were typically 5 - 20 min.
- Currently, there have been discussions to lengthen the hold times for the Pb-free solders to 30 min in order to account for their higher creep resistance.
- The underlying factor is testing time, because the acceleration factor(s) will correlate the thermal cycle tests to the field conditions



Reliability: Thermal Mechanical Fatigue

The big question is always:

Are the new Pb-free solders more or less reliable than the traditional Sn-Pb alloys?

The answer is:

… It depends. But, in general …

Consumer electronics and telecommunications ***"0° C/100° C hardware"***	**Military electronics, avionics and underhood** ***"-55° C/125° C hardware"***
Sn-Ag-Cu solders perform *better* than the Sn-Pb alloys	**Sn-Ag-Cu solders perform *worse* than the Sn-Pb alloys**

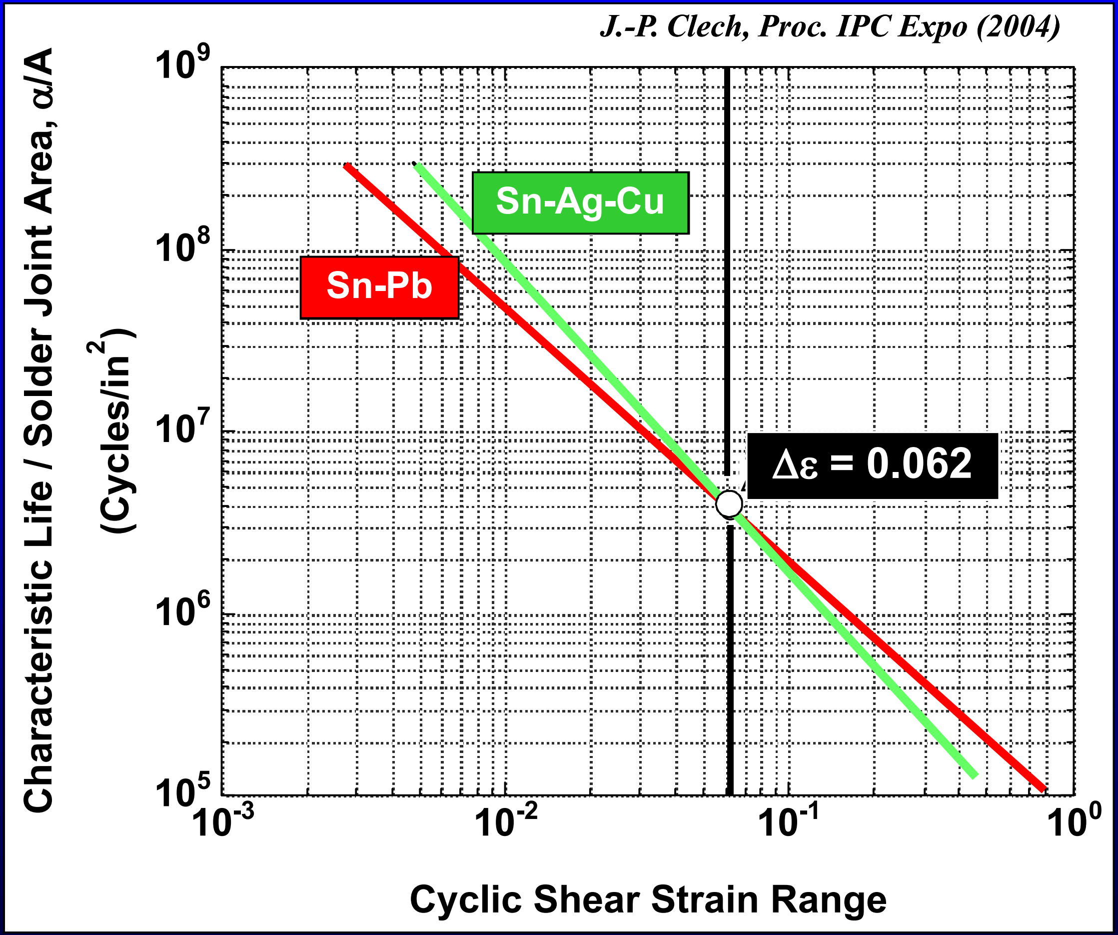
Reliability: Thermal Mechanical Fatigue

The "crossover" effect explained the discrepancy between the TMF lifetimes of Sn-Pb solder joints and Sn-Ag-Cu interconnections.

The "crossover" effect REVERSES between the Sn-Pb and Sn-Cu solders.

$\Delta\varepsilon = 0.028$

J.-P. Clech, Proc. IPC Expo (2004)



Reliability: Thermal Mechanical Fatigue

The "crossover" effect appears to be a consequence of the intrinsic strength/ductility of the solders and the strain resulting from the thermal cycles.

As solder strength increases, TMF performance degrades as the strain levels become greater.

Sn-Cu **Sn-Pb** **Sn-Ag-Cu**

Increased strength … lower ductility

0° C/100° C **-**

55° C/125° C

Increased strain/deformation

Net effect: **Poorer TMF performance**

Reliability: Thermal Mechanical Fatigue

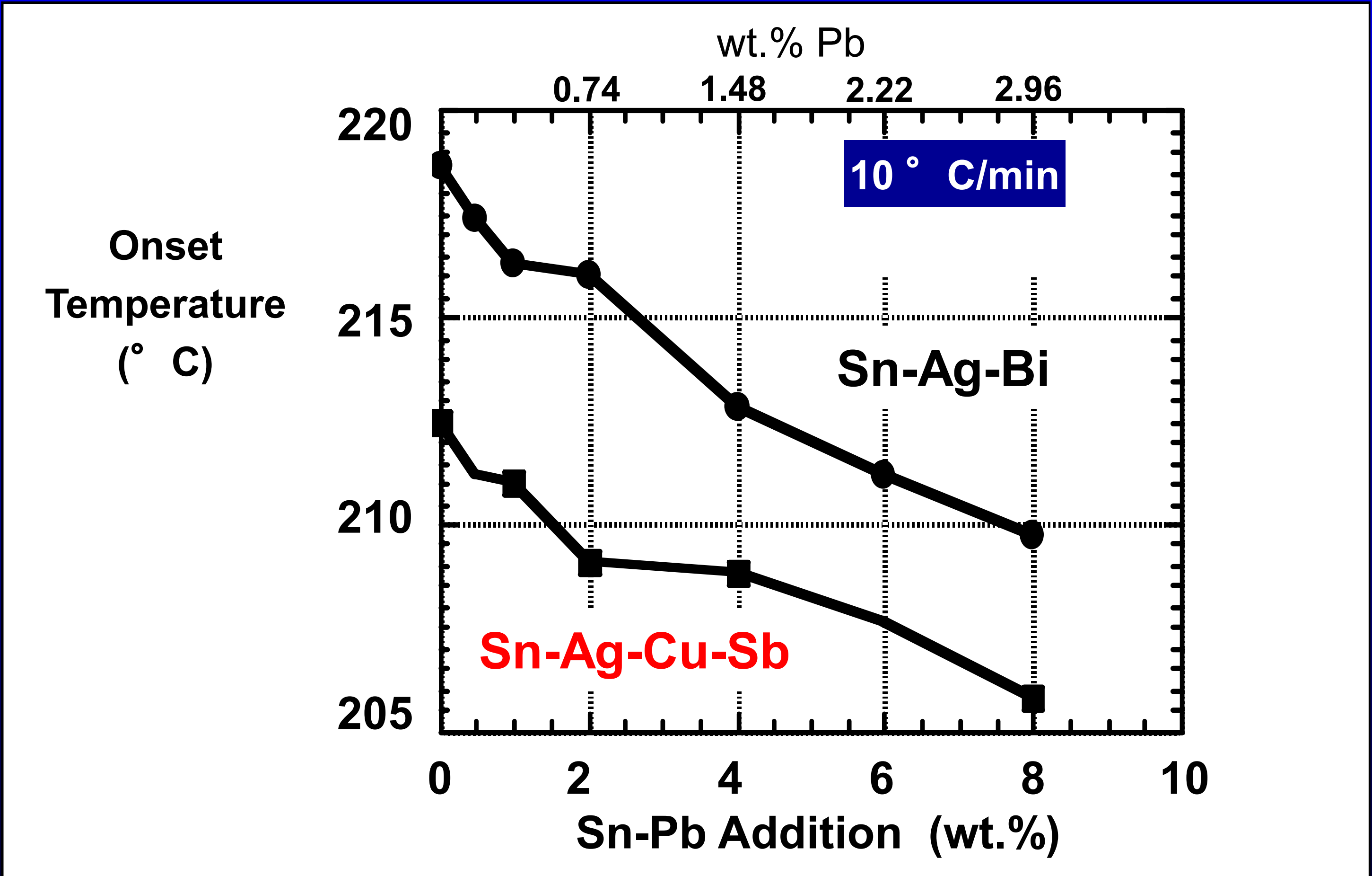
However, reliability is very sensitive to materials and geometries so that the cross-over effect is not always strictly reproduced.

Component	Solder	Temp. Cycle	Characteristic Life (2P Weibull)
2512 Resistor	63Sn-37Pb	-55° C/125° C	746
2512 Resistor	Sn-3.9Ag-0.6Cu	-55° C/125° C	681
2512 Resistor	63Sn-37Pb	0° C/100° C	2256
2512 Resistor	Sn-3.9Ag-0.6Cu	0° C/100° C	3063
TSOP 48	63Sn-37Pb	-55° C/125° C	1000
(Alloy 52 leads)	Sn-3.9Ag-0.6Cu	-55° C/125° C	614
TSOP 48	63Sn-37Pb	0° C/100° C	3500
(Alloy 52 leads)	Sn-3.9Ag-0.6Cu	0° C/100° C	2564

G. Swan, et al., Proc. IPC APEX (2001)

Reliability: Forwards/Backwards Compatibility

The addition of Pb reduces the (main peak) onset temperature as well as potentially causes a low-temperature (183° C) peak.



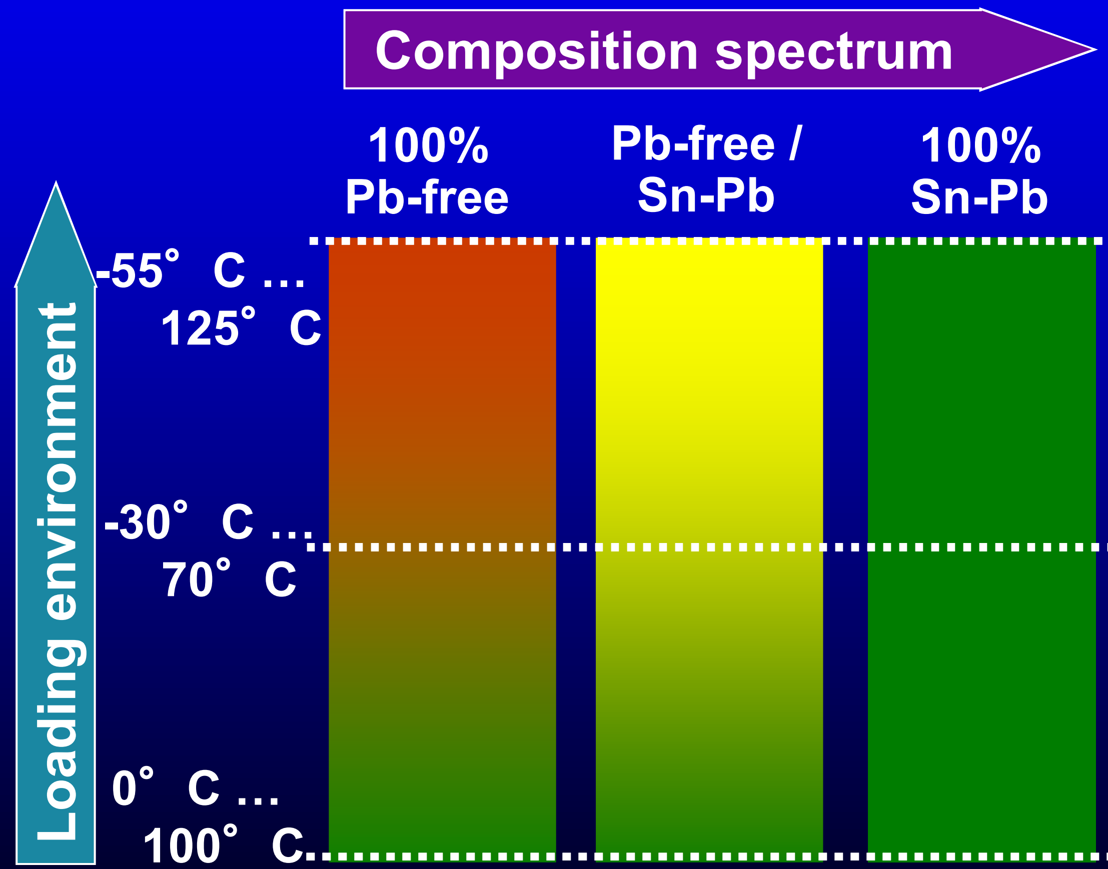
Reliability: Forwards/Backwards Compatibility

An important factor in Pb-free technology development is the effect of mixing the Pb-free alloys with Pb-bearing solders.

- **Forwards compatibility:**
  Sn-Pb finishes *(old)*
  Pb-free paste *(new)*

- **Backwards compatibility:**
  Pb-free finishes *(new)*
  Sn-Pb paste *(old)*

- **Several factors have synergistic roles in determining the solder mechanical properties.**



Reliability: Forwards/Backwards Compatibility

The following study examined the effects of 0 - 20 wt. % Pb contamination on the fatigue performance of 95.5Sn-3.8Ag-0.7Cu.

J. Oliver, et al., SMTAI (2002)

- **Mechanical fatigue (ring-and-plug test):**

  Cu pins and rings ……… 0.5 mm gap with Pb-contaminated solder
  ***homogeneous* contamination**
  Fatigue cycle …………… displacement control of 10 µm for a plastic strain range $\Delta\varepsilon_p$ = 0.01; 20% load drop
  Ramp: 0.32 µm/s; Temperature: 20° C

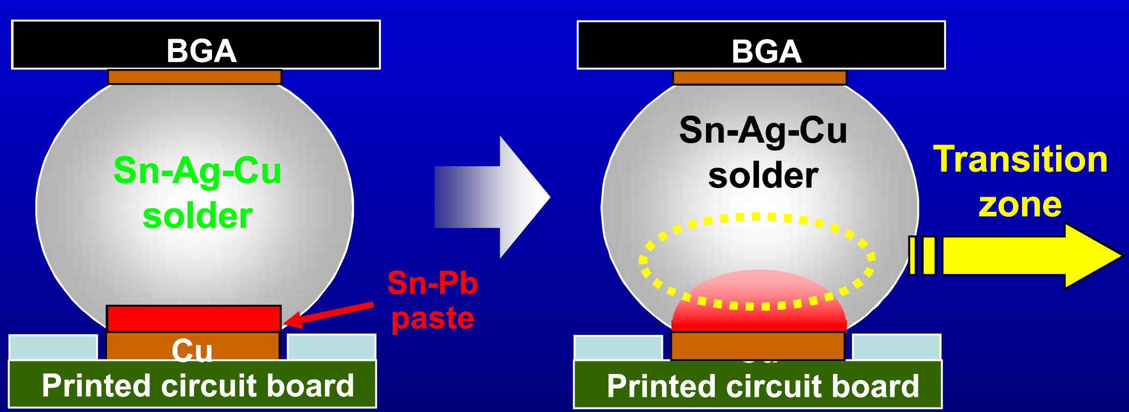
- **Findings:**

A *minimum* in the fatigue resistance of the 95.5Sn-3.8Ag-0.7Cu alloy was observed at Pb-contamination levels of 2% - 5%.

The fatigue performance of the Sn-Ag-Cu alloy at 2% - 5% Pb contamination was comparable to that of 63Sn-37Pb solder joints.

Reliability: Forwards/Backwards Compatibility

However … *inhomogeneous Pb contamination* of Pb-free solder joints (particularly BGA interconnections) can degrade reliability:



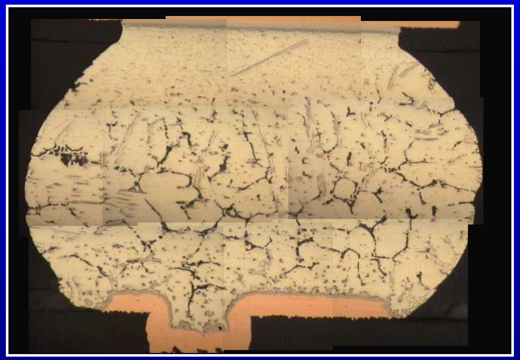


Photo courtesy of Intel Corp. and Radisys (R. Rowland)

Backwards compatibility: Pb-free finishes / Sn-Pb paste →	**"Exempt" hardware for the high-reliability applications**

Reliability: Forwards/Backwards Compatibility

T. Woodrow, 3rd Inter. Conf on Lead-Free Elect. Assem. and Component (2003)

- **Solders ……….** 95.5Sn-3.8Ag-0.7Cu | 96.5Sn-3.5Ag | 99.3Sn-0.7Cu | 91.84Sn-3.33Ag-4.83Bi | 93.2Sn-3.4Ag-3.3Bi-1.0Cu | 58Bi-42Sn | 63Sn-37Pb (control)
- **Package ………** LCCC (20 I/O)
  Hot-dipped finish per the assembly solder
- **Circuit board finish …….** Sn-Pb HASL (Pb content measured in each solder joint)
  Immersion Ag
- **Process ……….** Vapor phase reflow: T_{peak} = 260° C; t_{peak} 35 - 40 s
- **Thermal cycling conditions …….** -40° C to 125° C; 15 min dwells; 66 min cycle; 3441 cycles completed
  Failure: electrical open

Reliability: Forwards/Backwards Compatibility

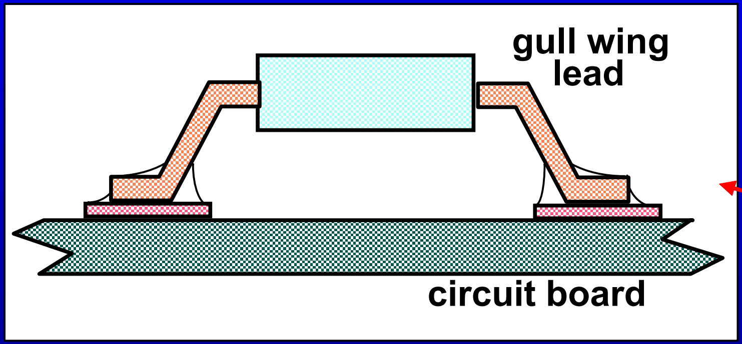
Solder Alloy (wt.%)	As-received First Failure	As-received 63% Failed	Pb-Contaminated Joints Pb (wt.%)	Pb-Contaminated Joints First Failure	Pb-Contaminated Joints 63% Failed
95.5Sn-3.8Ag-0.7Cu	350	800	+0.50	680	990
96.5Sn-3.5Ag	360	810	+0.67	550	1160
99.3Sn-0.7Cu	530	1140	+0.32	400	580
91.84Sn-3.33Ag-4.83Bi	710	2340	+0.78	370	770
93.2Sn-3.4Ag-3.3Bi-1.0Cu	1050	2940	+0.90	700	1850
58Bi-42Sn	>500	>3441	+0.23	550	770
63Sn-37Pb	*410*	*3350*	-------	-----	-----

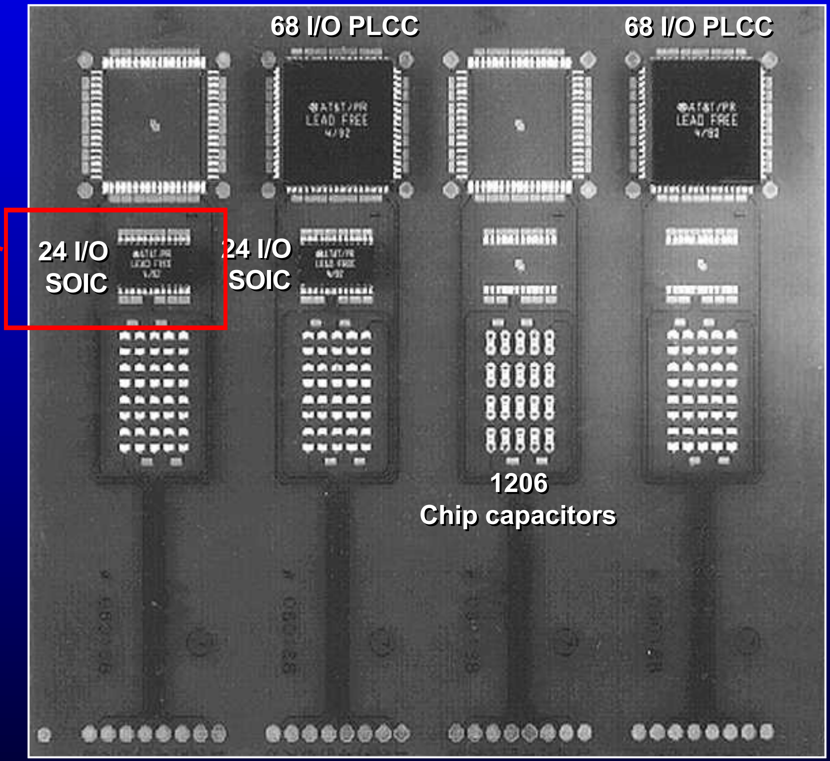
- Pb contamination improved the reliability of Sn-Ag and Sn-Ag-Cu joints.
- Pb degraded the reliability of the Bi-containing solders.
- Pb particularly degraded the reliability of Bi-Sn solder joints due to the formation of the Sn-Pb-Bi ternary composition (96° C melting temperature).

Reliability: Forwards/Backwards Compatibility

The effect of Pb contamination was examined for the pull strength of Sn-Ag-Cu-Sb and Sn-Ag-Bi 20 I/O SOIC (gull-wing) solder joints.

P. Vianco, et al., ECTC (1996)





Gull-wing lead finishes:

- 63Sn-37Pb
- 100Sn

Circuit board finishes:

- 63Sn-37Pb (HASL)
- Imidazole (OSP)

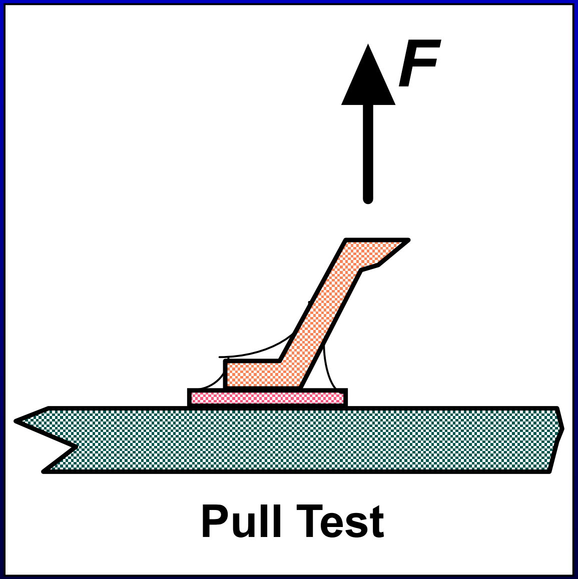
Reliability: Forwards/Backwards Compatibility

- The gull-wing solder joints were evaluated by metallographic cross section analysis and pull test strength measurements.
- The solder joints were evaluated in the as-fabricated condition as well as following thermal cycling:

Thermal cycling parameters:

0° C ….. 100° C
15 min holds
20° C/min ramps

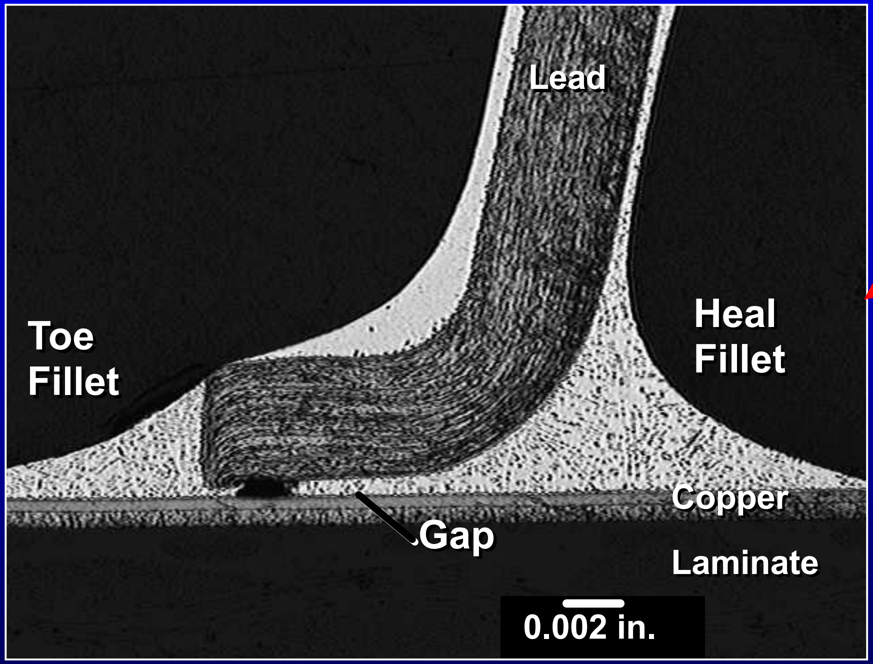
- 0 *(as-fabricated)*
- 2608 cycles
- 5068 cycles
- 10,106 cycles

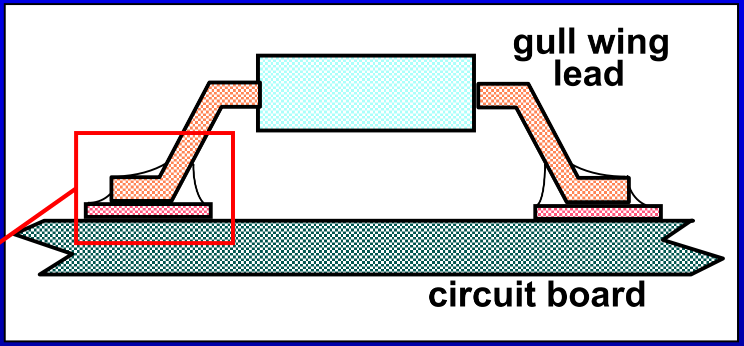


Cross-head speed ….. 9 mm/min

Reliability: Forwards/Backwards Compatibility

Visual inspection and metallographic cross sections of the solder joints indicated excellent quality for all of the solder alloys.





The as-fabricated condition was monitored to assure a consistent fillet quality that minimizes strength variations.

Reliability: Forwards/Backwards Compatibility

The effect of thermal cycling on the solder joint pull strength.

Thermal cycles	Sn-Ag-Cu-Sb			Sn - Ag - Bi		
	Sn-Pb/Sn-Pb (lb)	Sn-Pb/OSP (lb)	Sn/OSP (lb)	Sn-Pb/Sn-Pb (lb)	Sn-Pb/OSP (lb)	Sn/OSP (lb)
0	5.42$\pm$0.32	5.47$\pm$0.53	5.81$\pm$0.59	******	2.75$\pm$0.61	5.31$\pm$0.67
2602	4.79$\pm$0.79	5.57$\pm$0.52	4.22$\pm$0.55	******	******	******
5068	4.77$\pm$0.82	4.71$\pm$0.38	4.05$\pm$0.99	******	******	******
10,106	4.24$\pm$0.43	4.91$\pm$0.68	4.56$\pm$0.67	******	3.13$\pm$1.24	5.34$\pm$0.74

- The Sn-Ag-Cu-Sb solder joint strengths decreased due to primarily the *nominal* effects of the thermal cycling.
- The Sn-Ag-Bi solder joint pull strengths were degraded by the Pb contamination, albeit, the strength levels were acceptable.

Reliability: Modeling

Pb-free technology will require a new approach for predicting the reliability of solder joints.

- **Abandon the traditional empirical, resource-intensive procedures of accelerated aging to develop reliability databases for the new solder materials (Pb-free).**

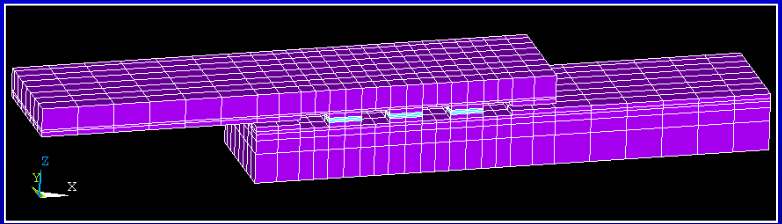
- **Improve the fidelity of predicting TMF and vibration-induced degradation of solder interconnections.**

- **Flexibility to accommodate the range of legacy, current, and new interconnection geometries.**

- **Flexibility to incorporate the properties of advanced package and substrate materials.**

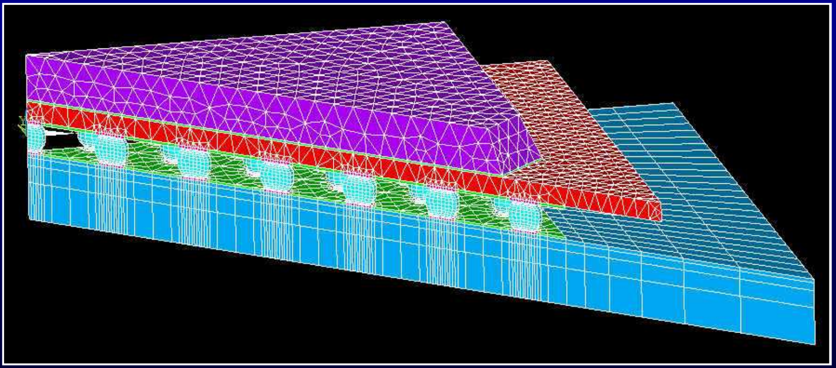
Reliability: Modeling

The new approach is to develop and validate computational models that numerically predict the reliability of Pb-free solder interconnections.



Lap-shear (structural) solder joints

Electronic packaging interconnections



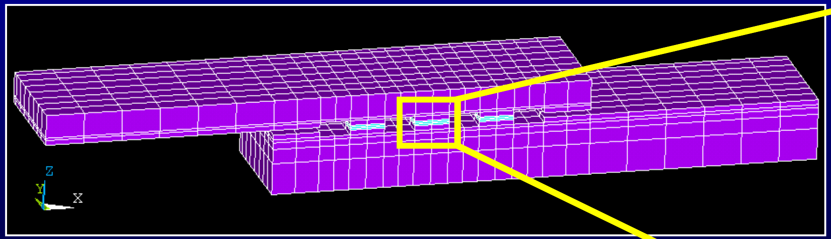
Reliability: Modeling

- The unified creep-plasticity (UCP) constitutive models:

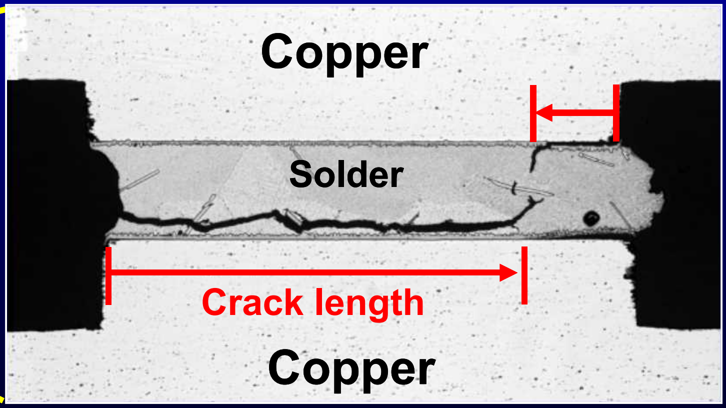
$$d\varepsilon/dt_{ij} = f_o \sinh^p[\sigma/(\alpha D_\omega)] \exp(\Delta H/RT)$$

- A damage parameter, D_ω, tracks crack length development:

$$D_\omega = (1 - \omega)D$$

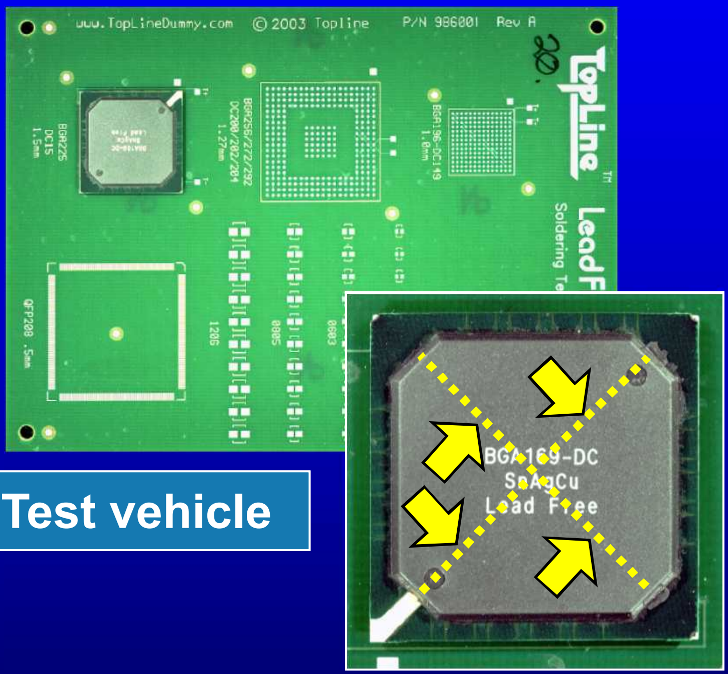


Lap-shear solder joint

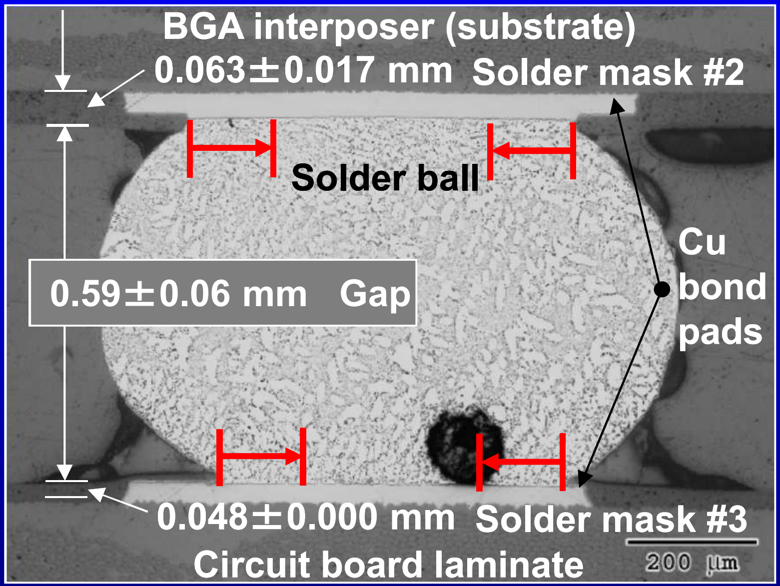


Reliability: Modeling

The key to computational model development is VALIDATION.



Test vehicle



Accelerated aging conditions … thermal cycling:

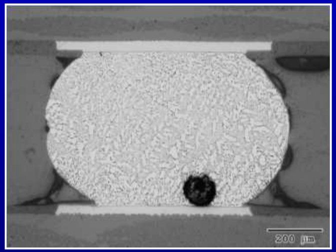
-55° C / 125° C … 10° C/min ramps … 15 min holds:

250, 500, 750, 1000, 1500, 2000, 2500, 3000, 3500, and 4000 cycles

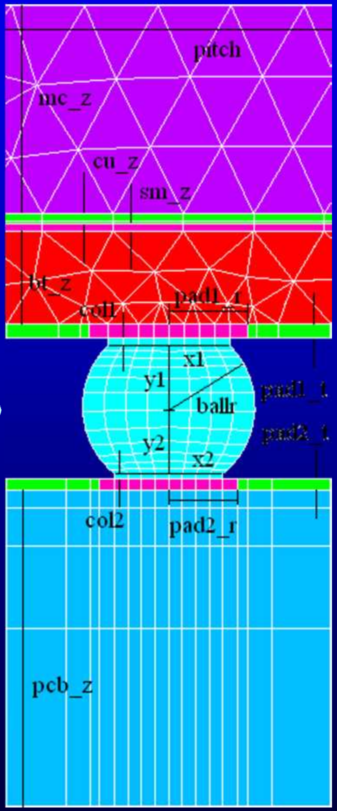
Crack lengths were documented throughout the solder joint.

Reliability: Modeling

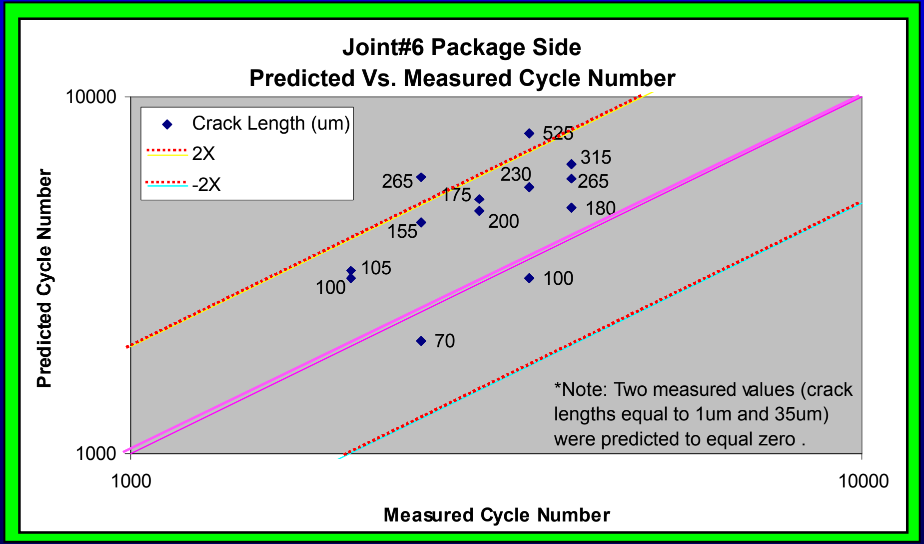
The key to computational model development is VALIDATION of the prediction, using a limited quantity of experimental data



Experimental data



Computational model



D. Pierce, M, Neilsen, A. Fossum, and P. Vianco, 2006

Model vs. data

Reliability: Interface reactions

- Porosity was observed in the IMC layer after solid-state aging between the 95.5Sn-3.9Ag-0.6Cu solder and wrought Cu.

The porosity was *not* observed in similar couples between other Sn-based solders and Cu.

- Measurable pores were noted under theses conditions:

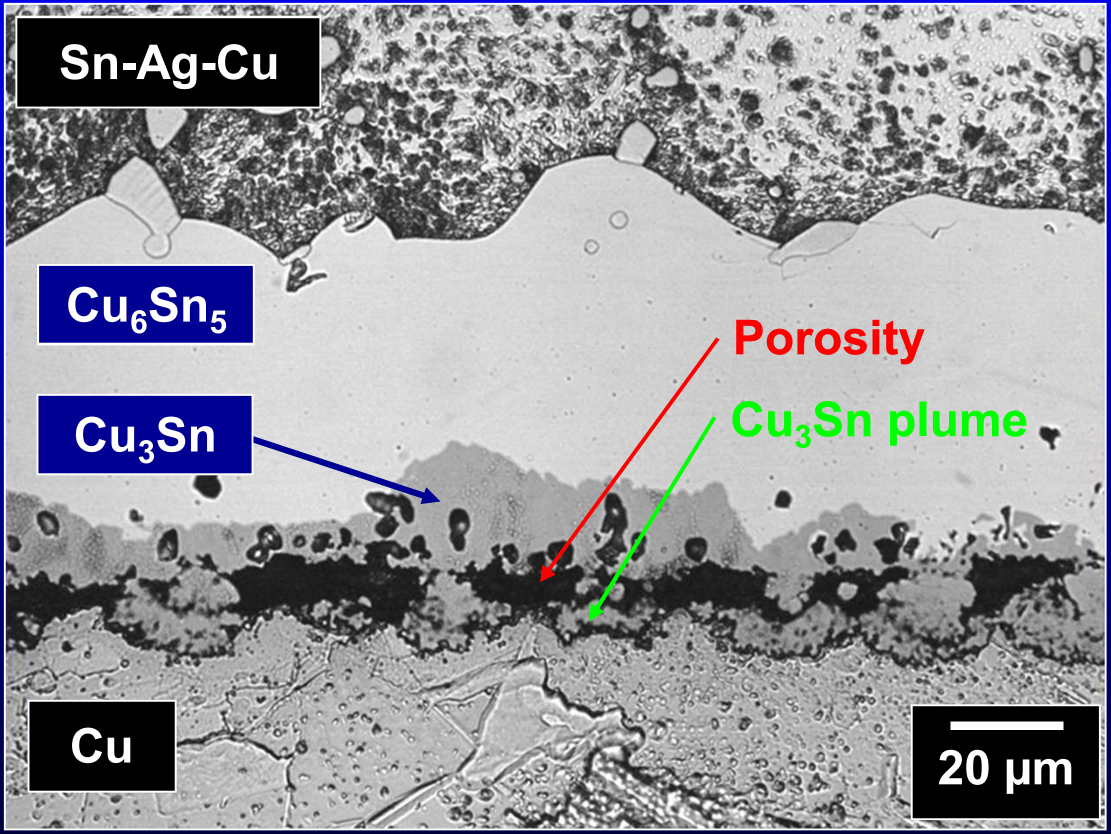
Temperatures … 170° C, 205° C
Times …………… t ≥ 150 days

Recent reports (August - September, 2004) of significant void formation at the IMC/Cu interface were reported for solid-state aging parameters of 100° C and as little as 10 days aging time.

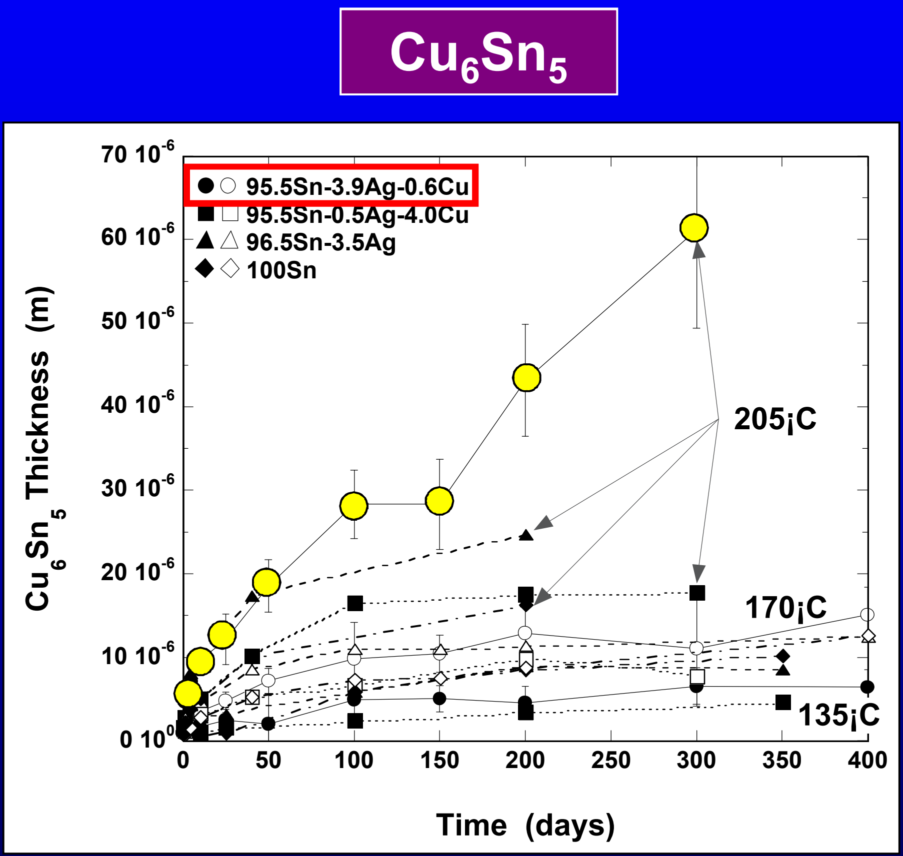
- Those latter findings were obtained from Sn-Ag-Cu alloy on circuit board pads that are typically electroplated Cu layers.

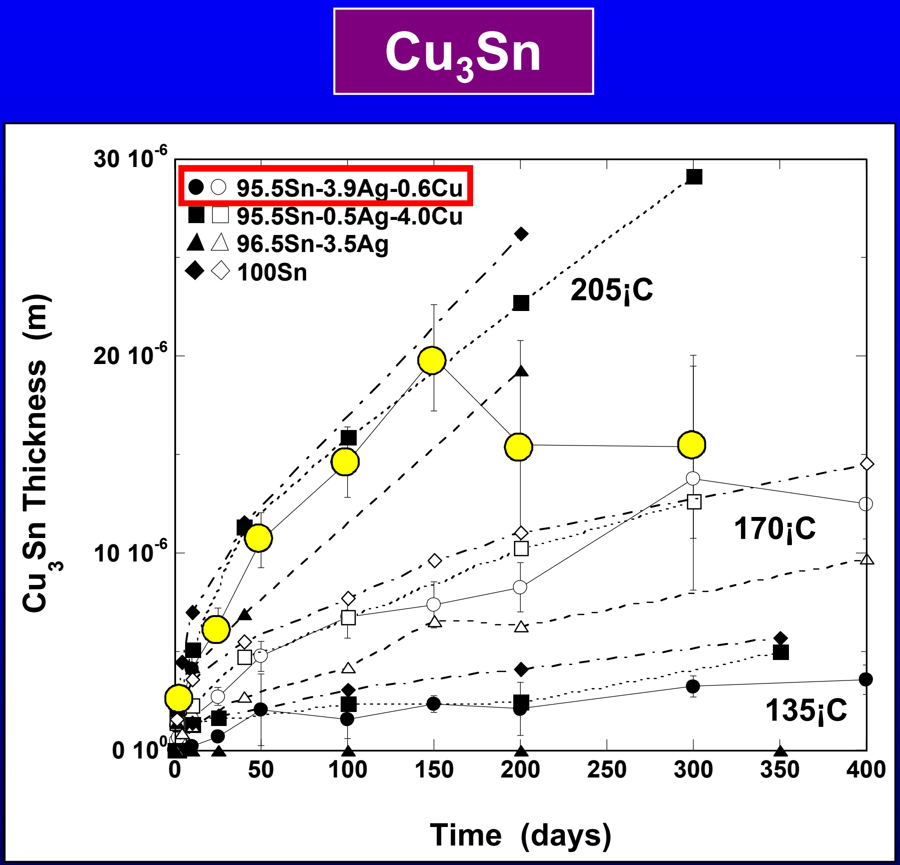
Reliability: Interface reactions

Extensive porosity developed at the Cu_3Sn/Cu interface for the solid-state aging conditions of: 205° C … 400 days.



Reliability: Interface reactions





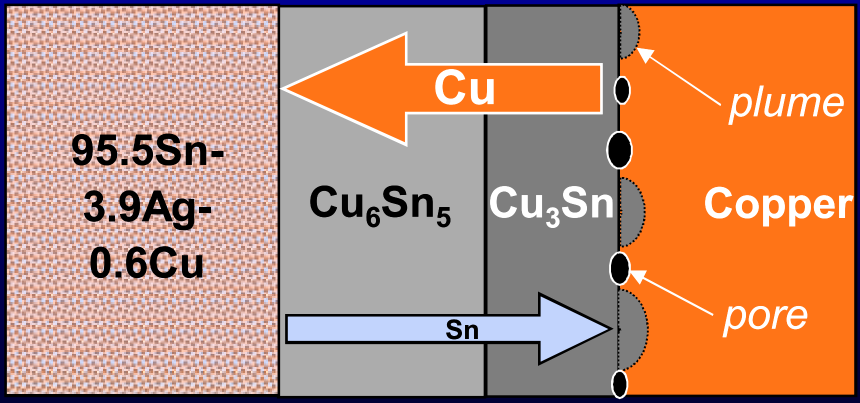
- Cu_6Sn_5 layer growth accelerates for T = 205° C … t ≥ 50 days.
- Cu_3Sn layer growth slows to a stop for T = 205° C … t ≥ 150 days.

… only the 95.5Sn-3.9Ag-0.6Cu solder

Reliability: Interface reactions

A scenario for the porosity and Cu_3Sn plumes is as follows:

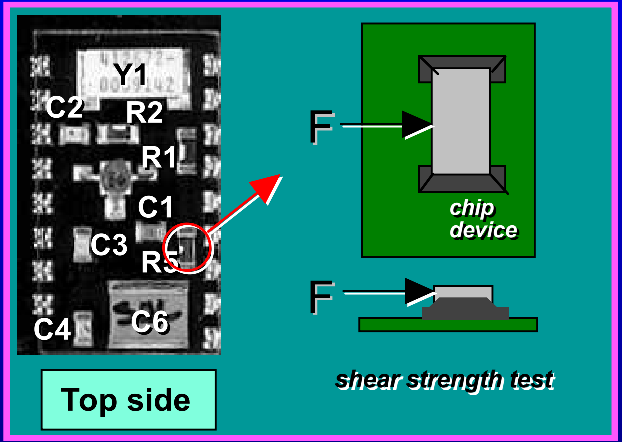
1. **Accelerated growth of Cu_6Sn_5 at *elevated temperatures*.**
2. **Sn diffusion to Cu cannot keep pace with diffusion of Cu to Cu_6Sn_5.**
3. **Kirkendall voids form at the Cu_3Sn/Cu interface; Cu_3Sn ceases to grow.**
4. **Where Sn reaches the Cu_3Sn/Cu interface, Cu_3Sn plumes develop.**
5. **Cu_6Sn_5 grows at the Cu_6Sn_5/solder interface due to a supply of Sn as well as Cu from the substrate *or Cu from a scavenged Cu_3Sn layer.***



Reliability: Interface reactions

- Solders: 91.84Sn-3.33Ag-4.83Bi … 96.5Sn-3.5Ag … 63Sn-37Pb
  - PCB Thickness: 0.079 in
  - PCB Laminate: polyimide-quartz
  - PCB Finish: 3.8 µm Ni and 0.51 µm Pd
  - Component finishes: 100Sn or HSD

- Mechanical (shear strength) testing:
  - (1) C1 - C5 = C', and C6
  - (2) All resistors and Y1 resonator
  - (3) Test speed: 10 mm/min

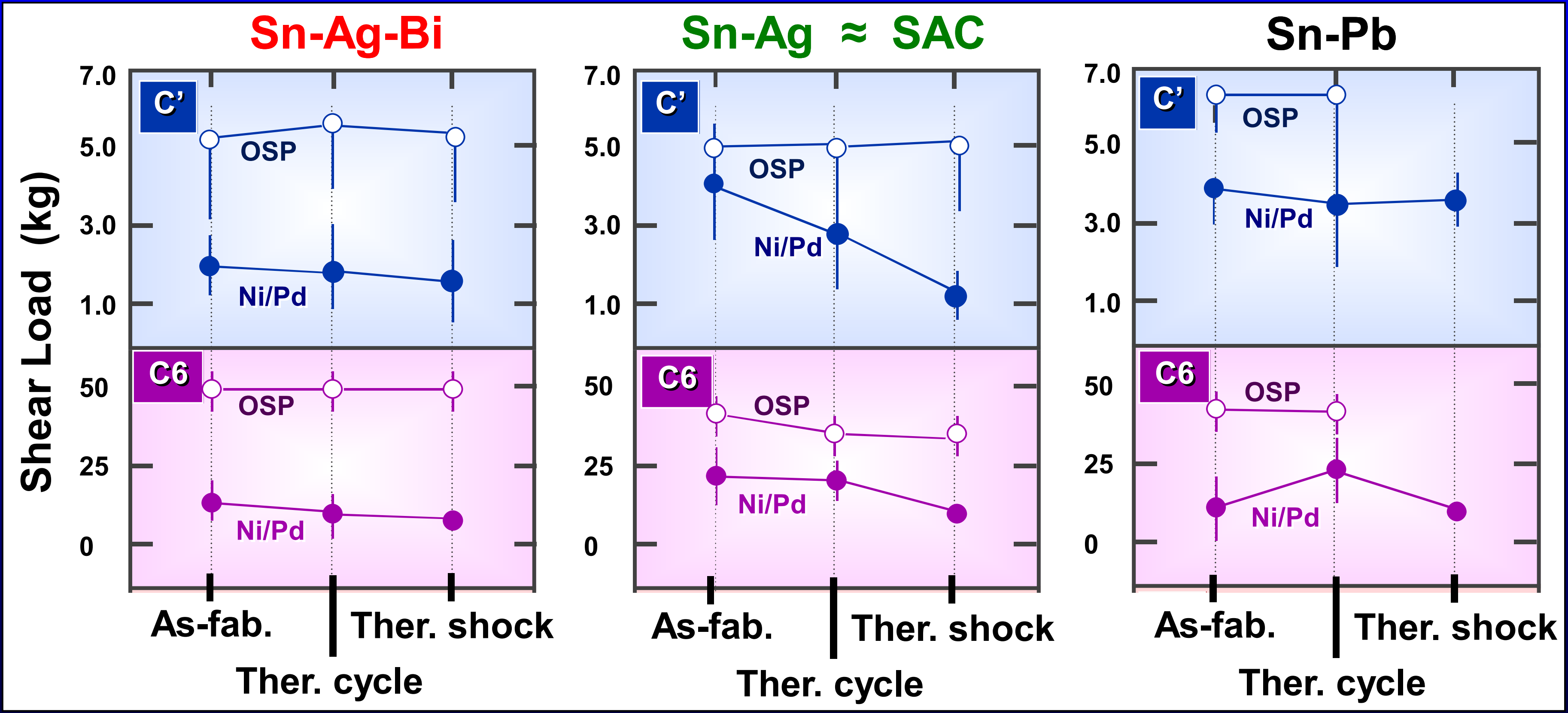


- Accelerated aging conditions:

Thermal cycling	Thermal shock
(1) Limits: -55° C, 125° C	(1) Limits: -55° C, 125° C
(2) Ramps: 4° C/min	(2) Ramps: Liq. to liq.
(3) Hold time: 30 min	(3) Hold time: 15 min
(4) 300 cycles	(4) 400 cycles

Reliability: Interface reactions

Shear strengths of joints made to pads with the Ni/Pd finish were compared to similar joints made to OSP coated Cu pads.



Reliability: Interface reactions

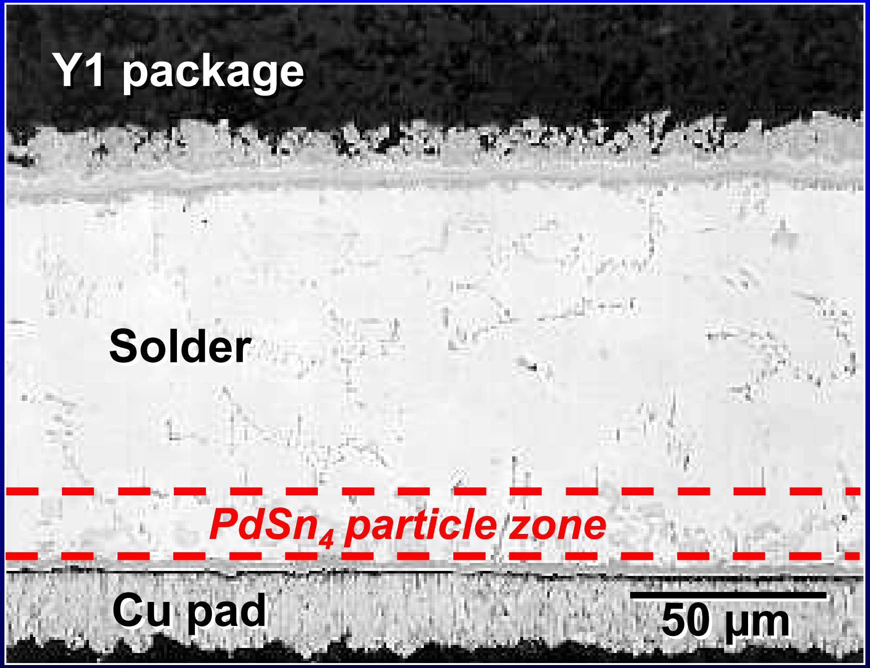
The solder/Cu pad interface was a potential source of failure under mechanical loading through the following scenario:

- **The presence of Pd and $PdSn_4$ particles embrittled the near-interface region of the solder**
- **Susceptibility to embrittlement correlated with solder strength:**

Sn-Ag-Bi (high) ⇨

⇨ Sn-Ag ⇨

⇨ Sn-Pb (low)

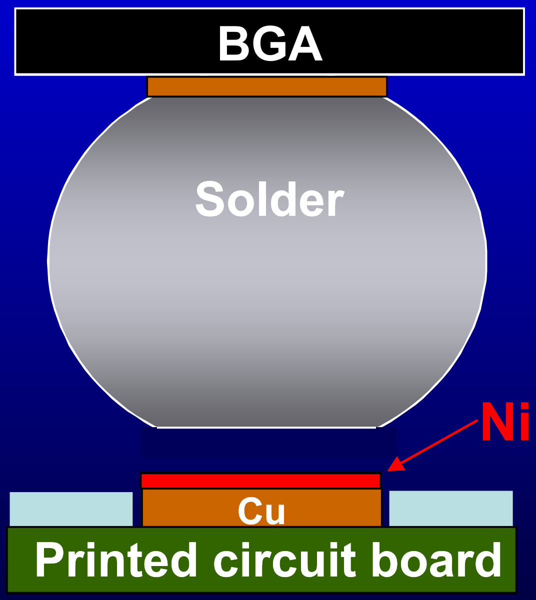


Reliability: Interface reactions

"Black Pad" Failure

BLACK PAD phenomenon is a low-frequency, yet catastrophic failure observed to occur between the solder and the Ni coating of a circuit board that has the *ENIG* (electroless Ni - immersion Au) finish.

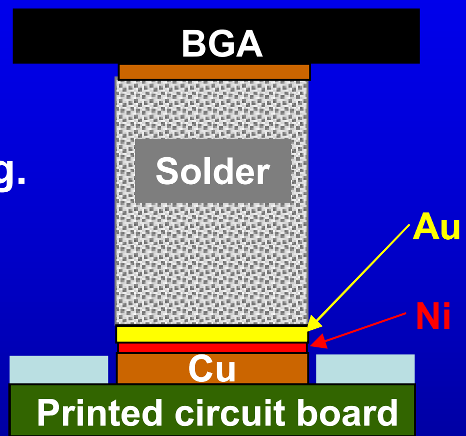
- The source of the black pad failure appears to be a corrosion reaction to the Ni coating by the immersion Au chemistry.
- Phosphorous (P) content of the electroless Ni layer thickness contributes to the brittle failure.
- The black pad failure has not been observed with immersion Sn, Ag, or Pd coatings.



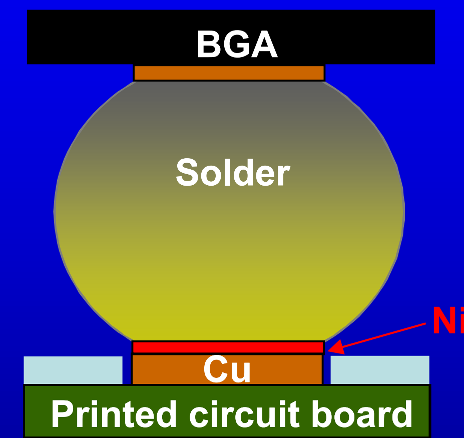
Reliability: Interface reactions

Electroless Ni - Immersion Au (ENIG) ….. "return of Au!"

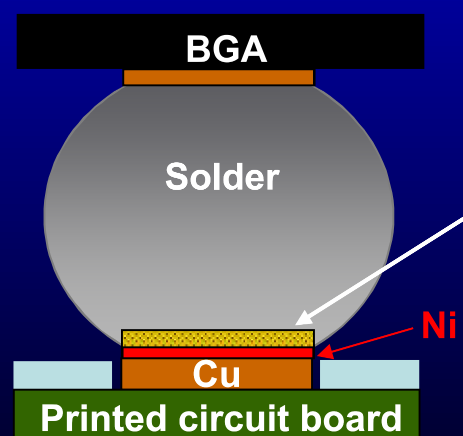
The materials "stack" at the time of printing.



Reflow: The Au layer is dissolved into the solder.



The Au in the solder diffuses back to the solder/Ni interface, forming a complex IMC layer there.

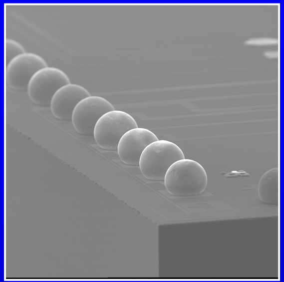


(Au, Ni, Cu)$_x$Sn$_y$ IMC layer

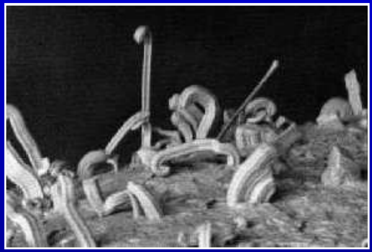
The complex IMC stoichiometry causes further embrittlement and the likelihood of premature failure, especially under mechanical loads or shocks.

Outstanding issues

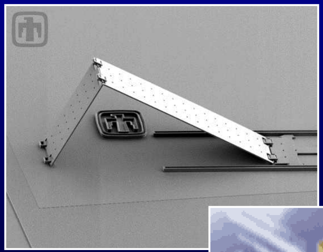
- **Die-attach methodologies**
  - **High temperature solders**



- **100Sn finishes … *Sn whiskers***

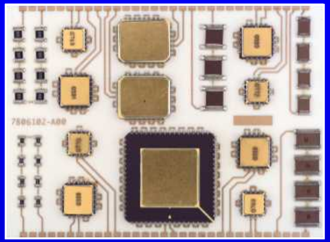


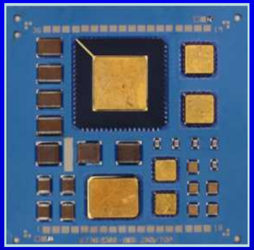
- **Low-temperature solders …**
  - **Low-cost electronics**
  - **MEMS & MOEMS**
  - **Optoelectronics**
  - **Step-soldering**



Outstanding issues

- Hybrid microcircuit technology:
  - Alumina, beryllia, and LTCC substrates
  - Au, Ag, Au-Pt, Ag-P thick film systems





- Compatibility of RF laminates with Pb-free processes.

- Level 3 technologies … e.g., connectors.