Solder Joint Fatigue Study Under Low Temperature Martian Conditions (#1310)

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Outline

- Acknowledgements
- Introduction
- Background
- Packaging Materials Selection
- Test vehicle design, assembly, testing
- Results and Discussion
- Conclusions
- Future Work
- References
- Bio

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- **This study was successful due to the help of several people who contributed a lot of time, effort, thought, and hardwork into the design, assembly, experimental work, and failure analysis. Special recognition goes out to Andrew Shapiro, Don Schatzel, Anarosa Arreola, Tosh Hatake, Chuck Derksen, Kirk Bonner, Atul Mehta, Reza Ghaffarian, Scott Cozy, Ken Evans, Ron Ruiz, Elizabeth Kolawa, Mohammad Mojaradi, Sharon Ling at APL, and Francisco Coronel at MEFAS.**

Introduction

- **Previously, electronics on Mars mission rovers have been centrally enclosed in a “warm electronics box” (WEB).**

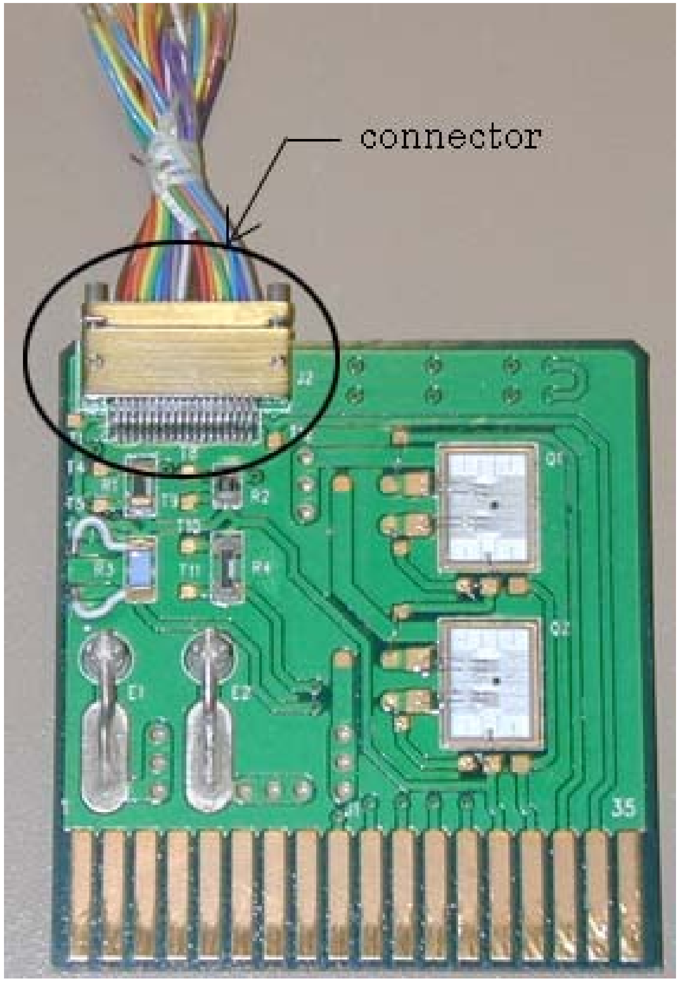
- **A distributed, non-heated architecture outside the WEB is being considered for MSL and will have to survive in 120ºC to 85ºC for 2010 cycles.**
  - **Typical Mil-Spec rating: -55 °C to 125°C for a few hundred cycles.**

- **Thermally induced fatigue due to CTE mismatches and materials property transitions, and the low temperature environment are high risk potential failure modes.**

Background

- **Extreme low temperature, fatigue conditions failure modes:**
  - **Martensitic phase transformation between the phases within the SnPb solder.**
    - **SnPb solder has the same unit cell structures as austenite (f.c.c.)- α/ Pb-phase and martensite (b.c.t)-β/ Sn-rich phase [1]**
  - **Under low temperature conditions below -110ºC, Sn phase becomes brittle [2].**
- **Intermetallic embrittlement of solder joints**
  - **Cracks can occur in the intermetallic or at the interfaces**
  - **Shear stresses due to CTE mismatch and delta T**
  - **Fatigue cracks were found underneath surface mount leads on Thin Small Outline Packages (TSOPs) under thermal shock conditions [3].**
  - **Intermetallic compounds in solders are typically more brittle than the bulk material [2,4,5].**

Packaging Materials selection



- **Connector:**
  - **37- pin Nanonics Dualobe® connector (nano-connector) with Sn60Pb40 finish**
  - **Selected as a part with standard finish.**
- **Solder:**
  - **In80Pb15Ag5 (Indalloy #2)**
  - **Selected for thermal fatigue resistance and better wetting to Au.**
- **Coating:**
  - **Dow Q1 4939 1:10 (silicone)**
  - **Selected for its high compliance and function as a good moisture barrier.**
- **Substrate:**
  - **Polyimide printed wiring board (PWB**
  - **Selected for its space heritage and advantageous material properties as an organic.**

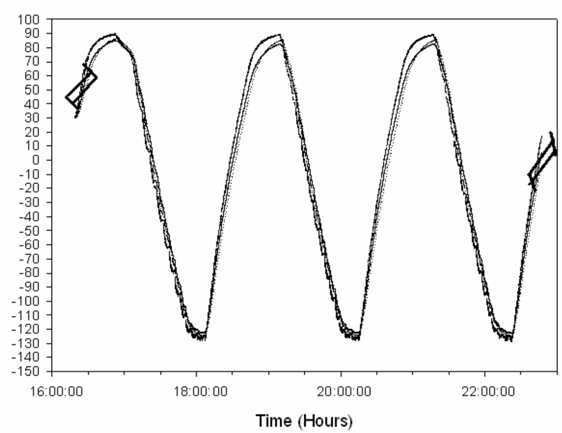
Test vehicle design, assembly, testing

- **Design:**
  - 8- layer polyimide PWB had a thickness of 1.60 mm +/- 0.127 mm.
  - Au plating (1.016-1.524 μm) at 99.97% purity with a Ni underplate (2.54 – 5.08 μm) per SAE-AMS-QQ-N-290 Class 2, over a top Cu layer (~107 μm).
- **Assembly:**
  - Leads and Au pads were pre-tinned with In80Pb15Ag5 solder and Indalloy Tacflux 012 RMA flux
  - PWBs were cleaned with ethyl alcohol and brushed carefully.
  - Dow Q1-4939 1:10 silicone coating was applied and cured at 80°C for 4 hours.
  - Continuity measurements were taken before and after conformal coating.
- **Testing:**
  - Environmental test chamber, Tenney Model T6C-LN2, was used
  - Each cycle, programmed between -130°C to 92°C, averaged a 5°C/minute ramp rate.
  - The test vehicles were thermal cycled between -120°C to 85°C and held at each temperature for at least 10 minutes.
  - Nano-connectors were continuously and periodically manually verified for functionality every 250-300 cycles.
  - High resistance values or infinity indicating electrical opens were defined as failures.

Flow of Test Vehicle Experiment

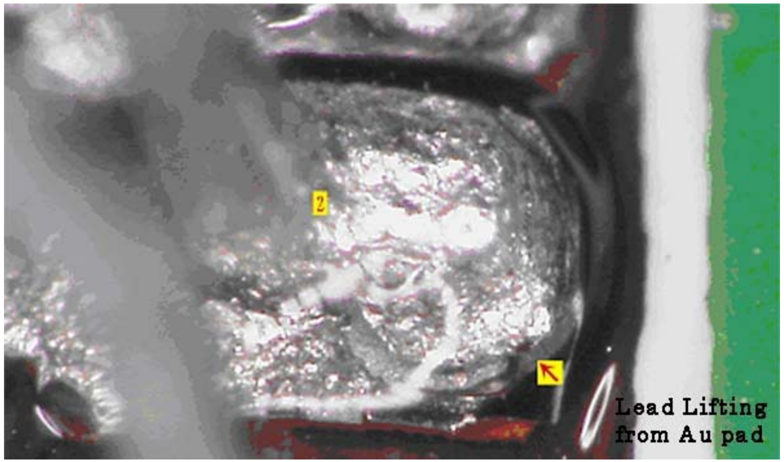
1. Materials Selection and DOE
2. Design of Test Vehicles (TVs)
3. Assembly of TVs
4. QA inspection and photograph TVs
5. Continuity at 0 cycles
6. Place into Thermal Chamber
7. Connect cables on Select test vehicles for continuous monitoring
8. Remove TVs At 500 cycles and Verify continuity manually
9. Remove TVs and manually verify continuity every ~250 cycles until 2100+ cycles and every 100 cycles thereafter

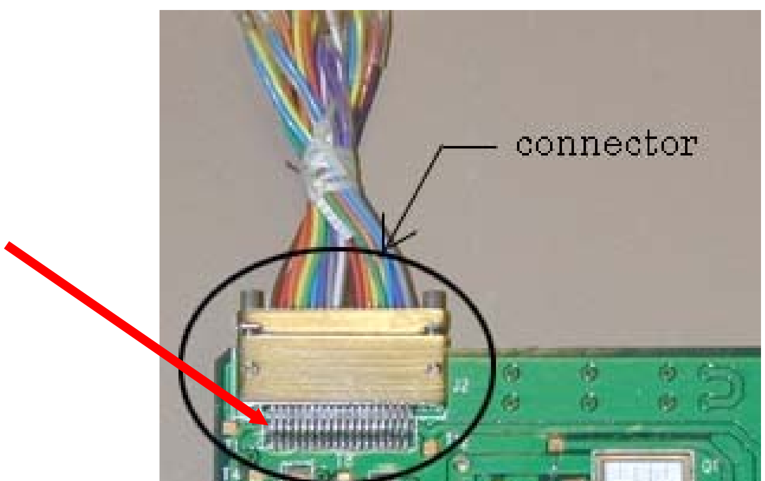
Tenney Model T6C-LN2
Environmental test chamber



Thermocouple Cycling Data

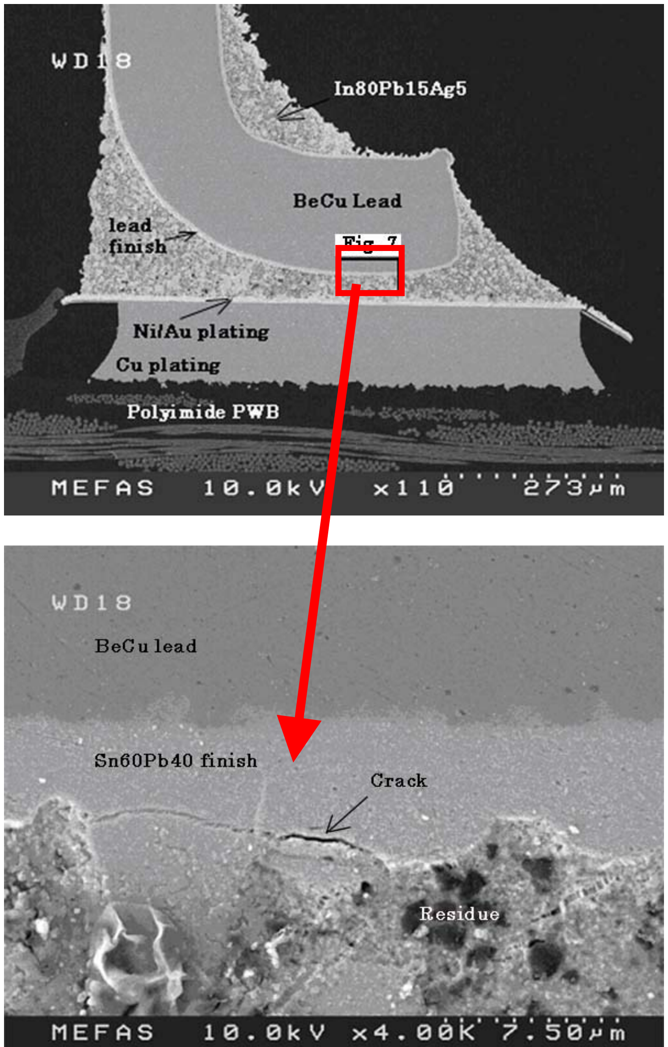
Results and Discussion-1





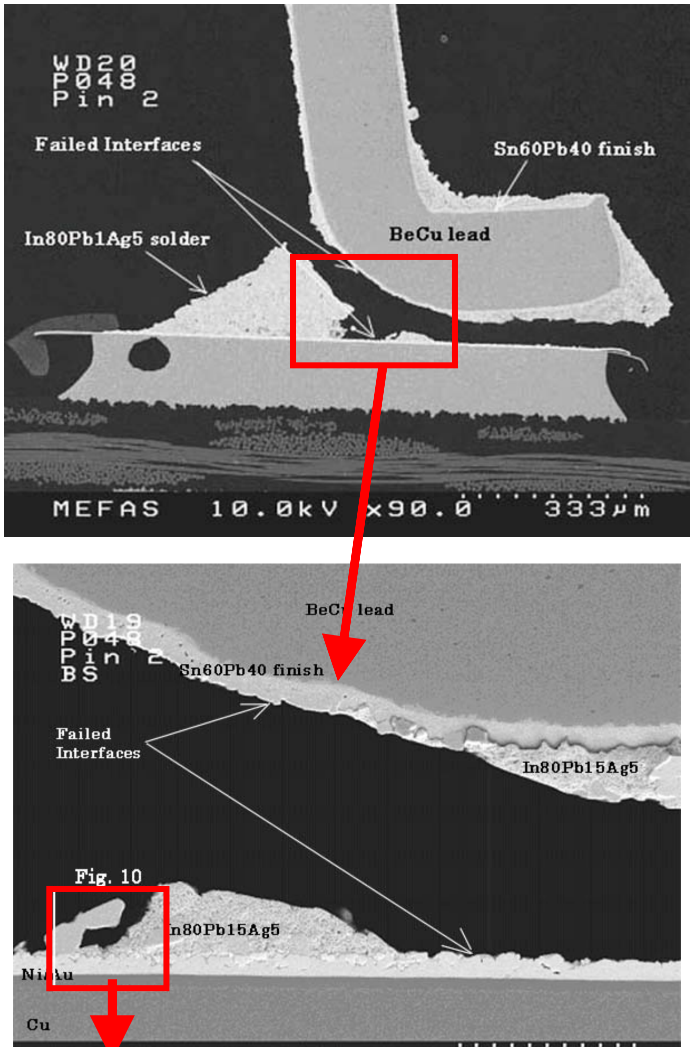
- **Between 638-1431 cycles 13 out of 1110 lead contacts on 4 out of 30 nano-connectors failed.**
- **First failures occurred between 638 – 863 cycles.**
- **Optical and SEM results have indicated that lead lifting was the cause of the open.**
- **Root cause of failure was due to micro-cracking.**
- **Failure Modes:**
  - **Martensitic phase transformation, brittle nature of Sn phase, and intermetallic embrittlement**

Results and Discussion-2



- Crack initiation site at the Sn60Pb40 lead finish and the In80Pb15Ag5 solder interface (at least one case)
- Two failure modes were crack propagation and separation at the interface.
- Martensitic phase transformation which resulted in a Sn-rich phase at low temperatures down to -120°C.
- Local stresses and volume changes within the microstructure due to phase transformation of the Sn in the SnPb phase (f.c.c) to a Sn-rich phase β (b.c.t)
- Loss of ductility of the Sn phase.

Results and Discussion-3



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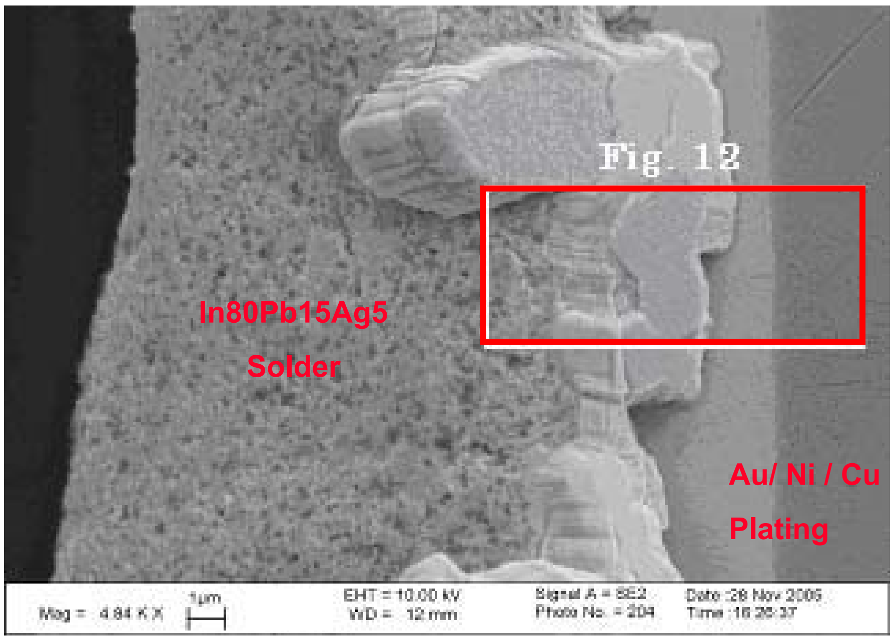
- **Secondary crack propagated at the In80Pb15Ag5 solder and PWB interface.**
- **Fatigue failure occurred due to fatigue stress and intermetallic embrittlement.**
- **Repetitive thermal cycling caused cyclic strains in the solder joint**
- **Δ T = 205 °C**
- **BeCu lead- 16.7 ppm/°C [6]**
- **Polyimide PWB- 16.50 ppm/°C (measured in the x, y- dir.) [7]**
- **In80Pb15Ag5 solder- 28 ppm/C [8]**

Results and Discussion-4



Note- rotated 90 °

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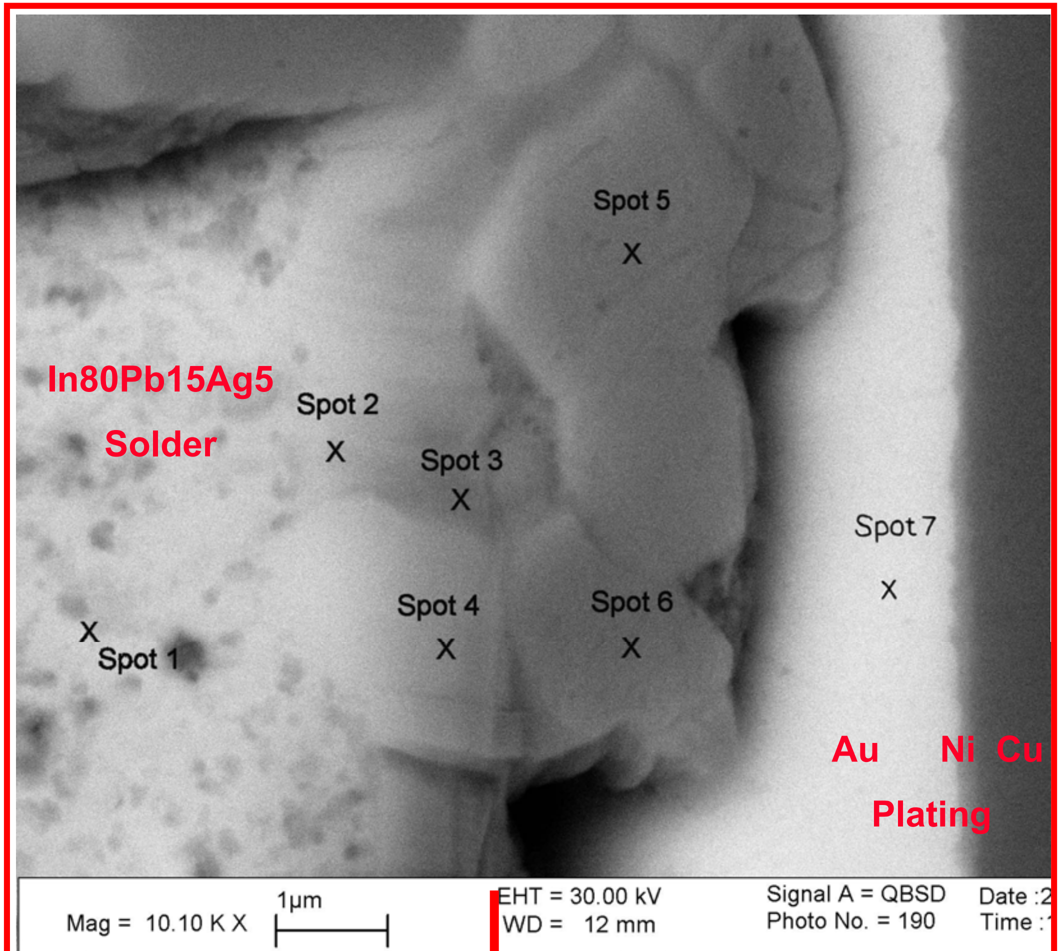
- **Spot Scans- 30keV, 10.10 kx, and a working distance of 12mm.**
  - **7 EDS Spectra (ZAF correction factor) 20 second spot scans since In and Sn are convoluted**
- **Dot map- 10 keV, 10 kx**
  - **8 micro-seconds time constant for 14 minutes.**
- **In, Ag, and Sn (L_{α})**
- **Au and Pb (M_{α})**
- **Ni, Cu (K_{α})**

Results and Discussion-4



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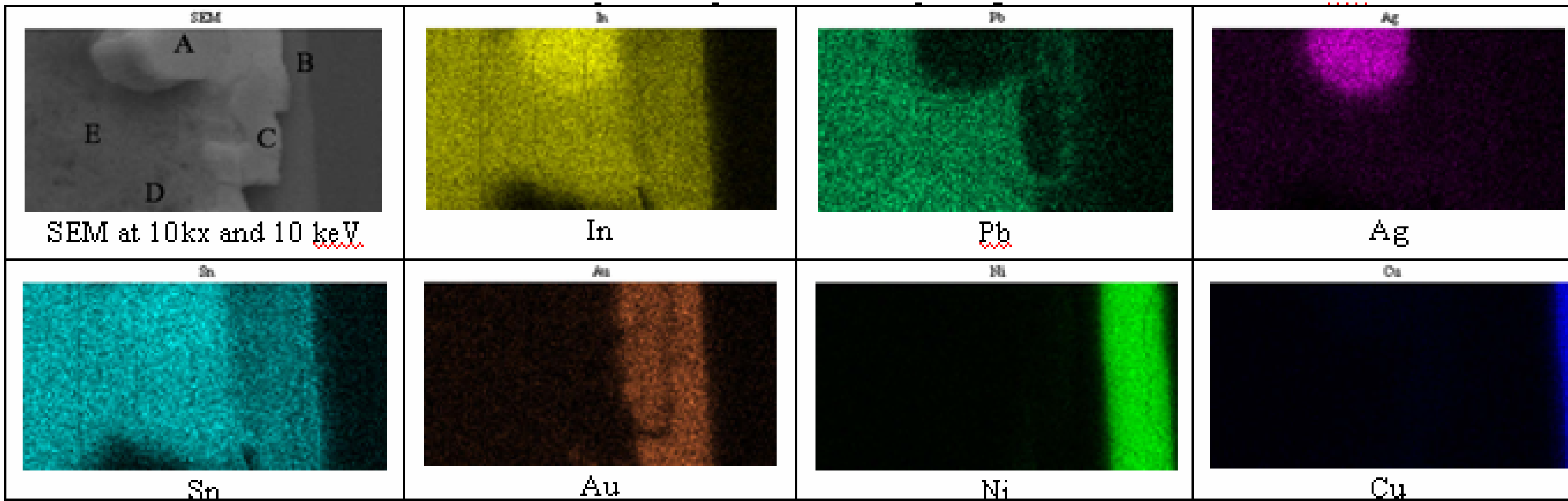
Spot	Intermetallic Compound
1	$In_xPb_ySn_z$
2	$In_xPb_ySn_z$
3	$In_xPb_ySn_z$
4	In_xPb_y
5	In_xPb_y
6	$In_wPb_xAu_ySn_z$
7	$In_xAu_ySn_z$

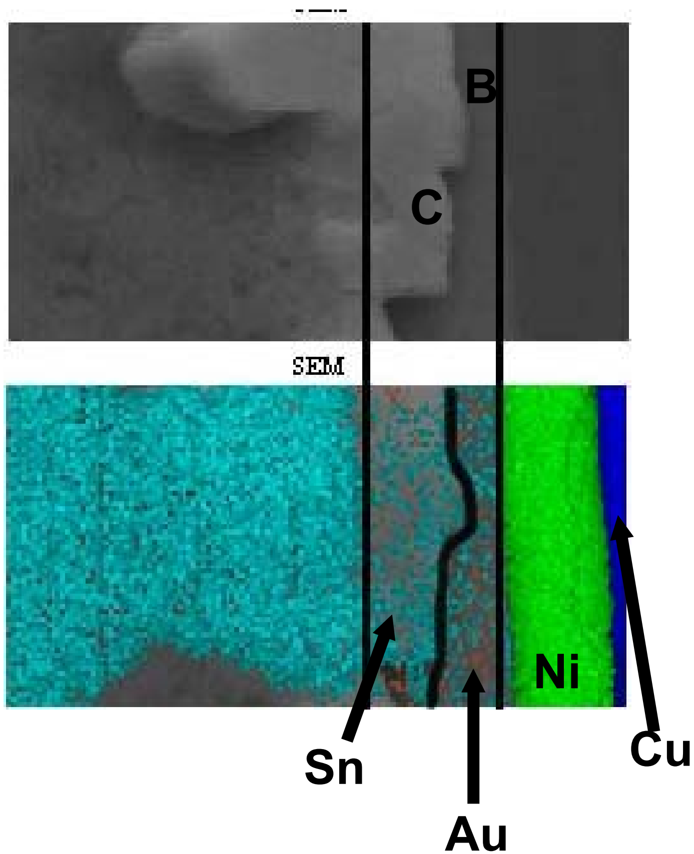
Results and Discussion-5



Location	Intermetallic Compound
Region A	$In_xAg_ySn_z$
Region B & Spot #7	$In_xAu_ySn_z$
Region C & Spot #6	$In_wPb_xAu_ySn_z$
Region D	Pb area
Region E & Spot #1	$In_xPb_ySn_z$

- **Intermetallics at spot location #2 and 3 are also shown in the same areas of the dot map.**
- **Sn may have formed with In_xPb_y found in the EDS spectra on spots #4 and #5, or it may be unlikely since In and Sn are convoluted on the dot map.**

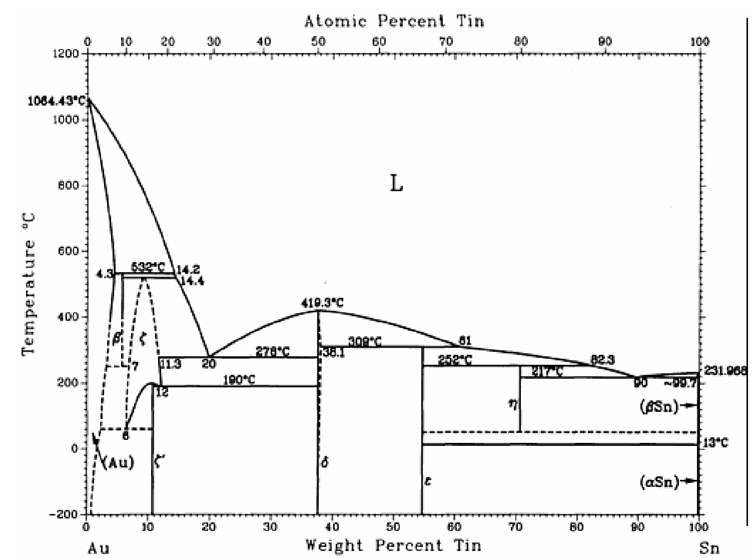
Results and Discussion-6



*Note- Left side has a higher concentration of Sn

Right side has a higher concentration of Au

Location	Estimated Intermetallic Compound
Region B	Au-Sn complex
Region C	Au-Sn complex



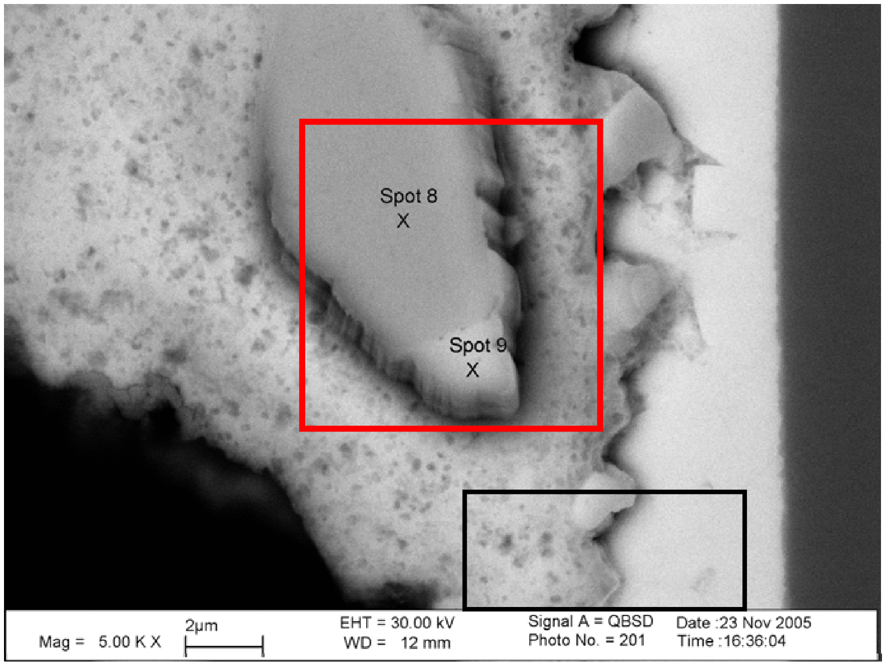
Au-Sn crystallographic data

Phase	Composition, wt% Sn	Pearson symbol	Space group
(Au)	0 to 4.3	cF4	$Fm\bar{3}m$
β or $Au_{10}Sn$	5.7	hP16	$P6_3/mmc$
ζ	7 to 12	hP2	$P6_3/mmc$
ζ' or Au_5Sn	10.8	(a)	$R\bar{3}$
δ or AuSn	38 to 38.08	hP4	$P6_3/mmc$
ε or $AuSn_2$	54.7	(b)	Pbca
η or $AuSn_4$	71	oC20	Aba2
(βSn)	99.7 to 100	tI4	$I4_1/amd$
(αSn)	99.990 to 100	cF8	$Fm\bar{3}m$

(a) Hexagonal.

(b) Orthorhombic

Results and Discussion-7



- **30 kev, Mag. of 5kx**

Spot	Intermetallic Compound
8	In_xAg_y
9	$In_xPb_ySn_z$

Conclusions

- **Nano-connector leads with Sn60Pb40 finish soldered to polyimide PWB with In80Pb15Ag5 failed due to lead lifting between 638 – 863 cycles.**
- **Primary crack propagation occurred at the lead finish near the heel which is the highest stress location, and secondary crack propagation at the solder/plating interface.**
- **Crack initiation occurred in the Sn-rich phase at the Sn60Pb40 lead finish, due to the martensitic phase transformation and brittle nature of Sn at low temperatures.**
- **The failure mode at the In80Pb15Ag5 bulk solder and PWB occurred due to cracking through the brittle intermetallic compounds.**
- **Sn is integral in intermetallic formation and likely the brittle nature of the Sn-phase caused brittle crack growth.**

Additional Current Work

- **A more detailed intermetallic analysis of the Sn60Pb40 lead finish is recommended for future work in order to study and confirm the Sn phase involved in the crack initiation site.**
- **Inspect for possible SnPb grain coarsening as a contributing failure mode.**
- **Thermal Cycle and study the survivability of nano-connectors with Ni/Au endcap finish and In80Pb15Ag5 solder**
- **Studying the survivability of other components on the test vehicle boards, e.g. resistors with Ni/Au endcap finish and In80Pb15Ag5 solder, and MOSFETS with heavy Al wire bonds**

References

[1] William D. Callister, Jr., Materials Science and Engineering Third Edition. Canada: John Wiley & Sons, Inc., 1994.

[2] Howard. H. Manko, Solders and Soldering Fourth Edition. USA: McGraw-Hill, 2001.

[3] Pradeep Lall, Michael G. Pecht, Edward B. Hakim, Influence of Temperature on Microelectronics. Boca Raton: CRC Press, Boca Raton, 1997.

[4] John H. Lau, ed., Solder Joint Reliability. New York: Van Nostrand Reinhold, 1991.

[5] Darrel Frear, Harold Morgan, Steven Burchett, John Lau, The Mechanics of Solder Alloy Interconnects. New York: Chapman and Hall, 1994.

[6] Beryllium Copper, UNS C17200, MatWeb website , http://www.matweb.com/search/SpecificMaterial.asp?bassnum=NBB486

[7] Internal JPL verbal communication- Results of TMA testing

[8] Master Solder Alloy Properties Table, from the Indium Corp. website http://www.indium.com/products/oldalloychart.php accessed November 2, 2004

[9] Au (Gold) Binary Alloy Phase Diagrams-Au-Sn Phase Diagram, from the ASM Handbook online website, http://products.asminternational.org/hbk/index.jsp accessed October 13, 2004

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