National Electronics Manufacturing Initiative, Inc.
2214 Rock Hill Road • Suite 110
Herndon, VA 20170-4214

Tel: 703-834-0330 Fax: 703-834-2735

NEMI, NIST and TMS Workshop on Tin Whiskers

March 2, 2003, San Diego, CA
Moderated by Dr. William Boettinger, NIST

Minutes of Meeting

The National Electronics Manufacturing Initiative (NEMI), the National Institute of Standards and Technology (NIST) and The Minerals, Metals & Materials Society (TMS) co-sponsored an all-day workshop, Tin Whiskers: *Cause and Effect*, on Sunday, March 2, at the San Diego Convention Center. The event was held in conjunction with the 2003 TMS Annual Conference and Exhibition, which began Monday, March 3, 2003.

This workshop brought together key researchers to compare work that has been done in the area of tin whiskers, and to see if a consensus could be developed on a basic model defining whisker formation, or define the work required to reach such a consensus. The end goal is to provide direction to the electronics industry that will assure that long-lifecycle applications will not be subject to tin whisker failures.

List of attendees is attached.

Handout to attendees: “Annotated Tin Whisker Bibliography”, a monograph by Dr. George Galyon, IBM, and Chair of the NEMI Tin Whisker Modeling Project. This monograph is available on the NEMI website (www.nemi.org).

The agenda consisted of four presentations during the morning and round table discussions in the afternoon as follows:

Introduction: Dr. William Boettinger, NIST

Chen Xu, **Stress in Electroplated Sn: Its Measurement and Implication in Spontaneous Whisker Growth**: Cookson Electronics PWB Materials and Chemistry

Dong Nyung Lee, **Spontaneous Growth Of Tin Whiskers From Tin Electrodeposits On Phosphor Bronze Sheet:** School of Materials Science and Engineering, Seoul National University

George T Galyon, **Tin-Whisker Microstructural Analysis using FIBs / Recrystallization Hypothesis**: IBM Server Group

King N. Tu, **Focused Ion Beam, Transmission Electron Microscopy, and Synchrotron Radiation Study of Sn Whiskers on Leadframe with Pb-free Surface Finish:** W. J. Choi, and T. Y. Lee, Dept. of Materials Science and Engineering, UCLA

Open Discussion

All papers are available on the NEMI website (www.nemi.org).

Introduction to the Workshop: *W.J. Boettinger,* C.A. Handwerker, Metallurgy Division, NIST, and R. W. Gedney, NEMI.
Tin Whiskers have been known for 50 years, and many mitigation strategies have been used to assure reliability in electronic assemblies. Most of these strategies involved the addition to lead to the tin coating. With the movement toward lead-free solders and coatings, the concern with pure tin coatings has once again come to the fore. Many theories have been advanced as to the cause of tin whiskers, primarily based on stress in the tin layer. In his introduction, Dr. Boettinger set the stage for examining whisker growth with a short description of the research history and data. He concluded with several questions that need to be addressed:

- What are the important conditions that sponsor whisker growth?
- What can we agree on concerning the causes and mechanisms of whisker formation?

Chen Xu, **Stress in Electroplated Sn: Its Measurement and Implication in Spontaneous Whisker Growth**: Cookson Electronics PWB Materials and Chemistry
Spontaneous whisker growth from electroplated Sn deposits has been widely studied. Among many factors affecting whisker growth rate, compressive stress has been identified as the thermodynamic driving force for whisker formation. Dr. Xu outlined his work on understanding the whisker growth rate and carrying out structural and chemical characterizations of whisker growths. He presented a "whisker index" – a proposal to characterize whiskers and presented data on this factor as a function of various types of tin plating. He discussed the use of X-Ray Diffraction (XRD) for measuring stress in tin plated films, showing the changes in stress as a function of time, probably due to the intermetallic growth of SnCu compounds. His data shows that compressive stress in the film leads to whisker growth, while tensile stress does not. He presented data to show that a nickel under layer will result in tensile stress in the tin layer, and he saw no whisker growth when a nickel layer was deposited between the copper and tin layers.

Dong Nyung Lee, **Spontaneous Growth Of Tin Whiskers From Tin Electrodeposits On Phosphor Bronze Sheet:** School of Materials Science and Engineering, Seoul National University
It is generally accepted that compressive macro stress in tin film is the cause of whisker growth. The spontaneous generation of compressive stress is caused by the diffusion of copper atoms from the phosphor bronze substrate into the tine film along its grain boundaries and their subsequent formation of the Cu_6Sn_5 phase. Dr. Lee showed results of microstructure characterization using SEM techniques, including angle of growth, and pole figures. He looked at texture as a function of current density and showed grain size as a function of plating conditions and annealing noting, the very ragged grain boundaries that result. Tin whiskers grow from grains whose orientation is different from the major orientation of the tin film. In this condition, the tin surface oxide film can be sheared along the boundaries of the grains. The shear force results from different strains generated in different grains in the direction normal to the substrate plane due to the biaxial compressive stress developed in the tin film. The different strains originate from the elastic anisotropy of tin. To release the compressive stress in the tin film, tin whiskers grow from the grain whose surface oxide is sheared. The whisker growth is controlled by the expansion of prismatic dislocation loop on the slip plane by climb, that is, by means of the operation of the Bardeen-Herring dislocation source. The dislocation loop expansion is restricted by the grain boundary. The loop now glides along is Burgers vector direction. As a result, tin whisker grows by one atomic step. The continuous operation of the Bardeen-Herring dislocation source gives rise to whisker growth until the stress is relieved.
If one anneals the tin layer for 150C for as little as one hour, substantial stress relaxation takes place and no whiskers form for up to 30 days. He noted that current density, grain size stress, and whisker growth are not simple relationships. He showed that current density of 1.0 A/dm^2 results in a larger grain size than 0.5 A/dm^2 or higher current densities; and whisker formation is lower for 1.0 A/dm^2 and 3.0 A/dm^2; higher for 0.5 A/dm^2, 2 A/dm^2, and 4 A/dm^2. This poses the question of why this happens.

George T Galyon, **Tin-Whisker Microstructural Analysis using FIBs / Recrystallization Hypothesis**: IBM Server Group

Dr. Galyon provided a critical analysis of the literature outlined in his bibliography (see above), noting that there appear to be necessary conditions for whisker formation (i.e. stress) that are not always sufficient to explain the overall phenomena. He provided a great deal of information on the use of the Focused Ion Beam tool in examining whiskers. Very little, and only recent, work has been reported using this new tool, and it seems to provide considerable additional insight into whisker structures. He postulated that eruptions are necessary first steps in the whisker formation process; that a whisker nucleates in eruption, and, from the FIB work believes whisker growth is associated with large IMCs near plating surface. The grain size seen in eruptions is larger than that in the plating. Grain structure in film under eruption is no longer columnar. He believes that whisker growth is the result of a recrystallization of the tin at the base of the whisker resulting in additional material pushing the whisker out of the film. Although he saw no grain subsidence in the bright tin coatings he examined, he pointed out that SEMs from P. Bush analyzing NEMI experiments on matte tin (large grains) did show grain subsidence separate from the grain underlying the whisker itself. Additionally, in PLAN view FIB micrographs there were voids found at the tin-copper substrate interface underneath the whisker grain which could be the source regions for the tin material found in the whisker itself.

King N. Tu, **Focused Ion Beam, Transmission Electron Microscopy, and Synchrotron Radiation Study of Sn Whiskers on Leadframe with Pb-free Surface Finish:** W. J. Choi, and T. Y. Lee, Dept. of Materials Science and Engineering, UCLA

Studies on tin whiskers have been performed with focused ion bean (FIB) imaging, cross-section transmission electron microscopy (XTEM) observation, and synchrotron radiation (SR) micro-diffraction analysis. Morphology of whiskers and orientation relationship between a whisker and grains in the tin plating has been studied by FIB and XTEM. A large amount of Cu_6Sn_5 precipitates in the grain boundaries were observed. The precipitation maintains the driving force for spontaneous whisker growth. Using the measured lattice parameters of Sn whiskers as reference of stress-free Sn, the stress distribution of the grains surrounding the root of a whisker was analyzed by SR, and the compressive stress level and gradient were found to be quite low.

Dr. Tu postulated the necessary conditions for whisker formation:

- Fast atomic diffusion at room temperature;
- low homologous temperature, also grain boundary diffusion;
- Stress needs to be maintained: phase transformations between Cu and Sn;
- Localized stresses must be able to be relaxed for nucleation

Dr. Tu feels that eruptions are not necessary for whiskers to grow. He used the Chang and Vook paper on hillock formation on oxidized aluminum under thermal stresses to explain eruption formation. He believes that although IMC forms at the interface, it is the IMC coarsening on the grain boundaries that leads to stress development. There is stress discontinuities at the interface when oxide cracks, allowing whisker to extrude. IMC coarsening is important. Also postulated that might be able to use electro migration to induce whisker growth in resistant material.

Afternoon Discussion

Discrepancies among the studies:

Evolving residual stresses are not consistent:

- Initial stresses; Lee and Xu see stresses originally tensile, then see it go compressive with time.
- NIST data on bright Sn shows an initial compressive, with the stress going towards zero with time.

General agreement: *whisker growth is function of:*

- Grain size
- Residual stress
- External stress
- Organic inclusion – carbon, sulfur, oxygen, …
- Inorganic inclusion
- Hydrogen, water incorporation
- Thermal stresses
- Substrate material
- Electric and magnetic fields
- Nucleation: Shear of surface oxide due to elastic anisotropy of the grain
- Electrolyte
- Plating conditions: current density, pulse plating
- Temperature
- Atmosphere
- Time

Important micro structural observations:

- Extrusion then whisker grows from center (Xu)
- Volume of the whisker greater than the volume of a single grain in the film; where are the extra atoms coming from? What is the mechanism for atomic transport?
- Extrusion versus diffusion? Relationship of local position of voids and whiskers; Galyon's FIB work shows them being very far away from the whiskers.
- What is source of crenulations on whiskers? Lee shows ragged grain boundaries probably pinned by IMC particles, which could be the source of the surface roughness/crenulations.
- IMC associated with the formation of eruptions and whiskers (Galyon and Tu). Is this required?
- Grain or group of grains as eruptions/nuclei for whiskers

Measurement issues

- Quantifying continuing nucleation events
- Parameter or group of parameters for characterizing growth
- Stress evolution: local and global
- Diffusion and interdiffusion (Kirkendall markers – Sn into intermetallic forms on the copper side (NIST work))

Measurement techniques – questions

Stresses

- XRD- spatial resolution, sensitivity, uncertainty; can you actually focus the beam at a buried layer?
- Wafer curvature
- Neutron measurements = large volumes required
- Synchrotron measurements – volume needed? Calibration

Texture

- Pole figures

Measurement techniques – questions *(continued)*

Imaging and crystallographic orientations of individual grams and whiskers

- EBSD – crystallographic orientation for grains larger than 0.25 micrometers and SEM imaging
- FIB cut and image – powerful tool for local cross sections
- TEM – greatest amount of structural and chemical information possible but samples must be cross-sectioned (FIB can be used to section whisker for TEM imaging)
- SEM – high resolution imaging useful for surface topography

Composition

- EDS/SEM and EDS/TEM – sensitivity limits are matrix and element dependent

What do we agree about?

Generally, everyone accepts that tin whiskers are caused by compressive stress in the tin plated film, and material somehow moves through the grain boundaries to form a whisker. The formation of copper-tin intermetallics contributes to the growth of a compressive stress. The whisker may take advantage of weakness in the oxide film to erupt. Whiskers seem to grow from material deposited at the base of the whisker. Other factors:

- Stresses must be high enough
- Relaxation cannot be too fast.
- Symmetry breaking event must occur for nucleation.
- Averages are not useful.
- Diffusion theory indicates sufficient material could be displaced to create whiskers.

Questions posed in discussion

- Recrystallization event is necessary?
- Cu in the deposit makes whiskers form and grow but we don't know why.

What don't we understand?

- Role of Pb in suppressing whisker formation
- Cracking of oxide in nucleation
- Oxide fragments at the top of the whisker (cause or effect)
- Whiskers in an essentially Cu-free system
- What controls nucleation rate?
- Texture
- Role of other impurities
- Need method to measure spatial distribution of buried IMCs to see their relationship to where whiskers begin to grow.
- Two camps in terms of Ni. Observations of whisker growth with and without Ni under layer.
- Ni plated Ni-contaminated Sn plate should show whisker growth.

Critical experiments:

- Patterned holes in the oxide
- Ni-doped film deposited on Ni

Submitted by: Maureen Williams, NIST & Co-Chair, NEMI Modeling Project
Ron Gedney, NEMI Consultant

ATTENDEES

The Aerospace Corporation

Analog Devices

Brocade Communications Systems, Inc.

Cookson Electronics

Hanyang University

Hewlett-Packard Company

IBM Corporation

Intel

KAIST

Kyocera Wireless Corp.

Los Alamos National Lab.

Michigan State University

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