A History of Tin Whisker Theory: 1946 to 2004

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ABSTRACT
Tin whiskers are filamentary growths that spontaneously grow from electroplated tin surfaces (Figure 1). Whisker growth starts after an incubation period that varies from seconds to years. Typical whisker diameters range between 1-5 microns and whisker lengths range upwards of 5000 microns. Tin whisker growth rates under ambient conditions range around 0.1 Å/second. Whiskers are highly conductive and readily short out electrical components by bridging gaps between closely spaced electrical conductors. Tin and tin alloys have been widely used in the electronic industry for over 50 years and whisker problems have always been a concern and a problem. There has been a long history of whisker related electronic failures due to pure tin without any lead content. In the past, lead (Pb) additions to tin (Sn) were widely used to mitigate whiskering. However, on July 1, 2006 the European Union will enforce the Reduction of Hazardous Substances (RoHS) directive, which requires lead (Pb) removal from electronic assemblies, thereby exposing a new generation of electronic equipment to massive field service failure rates because of unmitigated whisker growth. Concern over whisker-related reliability problems led to NEMI (National Electronics Manufacturing Initiative) forming a number of whisker-related projects to review the problem and recommend appropriate action. One of the projects is the NEMI Tin Whisker Modeling Project, currently chaired by this author. As part of the overall study of whisker fundamentals, a comprehensive tin whisker literature search was conducted by this author, the results of which have been published by NEMI [1] and made available at http://www.nemi.org/projects/ese/tin_whisker_activities.html. This paper will present a selected set of papers from this reference along with a summary of some key points from the author's "Integrated Theory of Whisker Formation and Growth" [2].

Key words: tin, whisker, lead, RoHS, NEMI, whisker mitigation, whisker fundamentals, integrated theory of whisker formation and growth.

THE 1940S
During WWII the electroplated material of choice for electrical components was electroplated cadmium (Cd). Repeated failures of electrical hardware led to a finding that many failures were due to shorting from cadmium whiskers. These findings were summarized in 1946 by H.L. Cobb [3]. Starting in 1948 similar failures were experienced by Bell Telephone on channel filters used for multi-channel transmission lines. Bell Labs immediately initiated a change-over to pure tin electroplating, but quickly found that pure tin had whisker problems very similar to those experienced with cadmium platings. These findings were reported in a 1951 paper by K.G. Compton, et al [4]. Bell Laboratories immediately initiated a long-term tin whisker study, as did other large research organizations such as ITRI (the International Tin Research Institute), ESA (the European Space Agency), Northern Electric, the L.M. Ericsson Telephone Company (Sweden), and others.

THE 1950s
The 1950s saw the establishment of whisker mitigation practices still in use today. Whisker fundamentals were addressed and most of the basic concepts currently used to describe whisker formation and growth were proposed in one form or another during the 1950s. As the decade progressed new experimental tools such as the SEM (scanning electron microscope) and TEM (transmission electron microscope) were used to gain new insights into the physics of whisker formation. Some highlights from that 1950s research will be briefly reviewed in the following sections.

The 1950s: Compton-Mendizza-Arnold
Bell Laboratories became very active in tin whisker research and their first external publication was in 1951 by K.G. Compton, A. Mendizza, and S.M. Arnold [4]. This article established that whisker formation occurred spontaneously on electroplated cadmium (Cd), zinc (Zn), and tin (Sn) and also reported that whisker growths were found on an aluminum (Al) casting alloy and on electroplated silver (Ag) exposed to an atmosphere of hydrogen sulfide (H_2S). The authors inferred, but did not conclude, that the whiskers were "not compounds but are metallic filaments in the form of single crystals."

The 1950s: Koonce-Arnold
In 1954 Koonce and Arnold of Bell Laboratories published a very short letter to the editor [5], which stated that whisker growth occurred by the continual addition of material to the base of a whisker rather than by addition of material to the tip of the whisker. Koonce and Arnold came to this conclusion by utilizing electron micrographs of a growing whisker over several weeks. They observed that the morphology of the whisker tip was maintained over time as the whisker grew in overall length, meaning that the whisker was being pushed up from material added to its base. This fundamental observation has never been contradicted and is accepted today without reservation.

The 1950s: dislocation theorists

Three dislocation-based theories were proposed during the 1950s to account for the Koonce-Arnold observation. The basic idea was to construct a dislocation mechanism that moved toward the film surface and deposited a layer of atoms at that surface. The continual operation of the dislocation mechanism would grow the whisker. The first such dislocation mechanism was published in 1953 by J.D. Eshelby [6], who proposed a mechanism whereby a Frank-Read source emitted dislocation loops that first expanded in their source plane to some boundary and then subsequently glided to the surface, depositing an extra half-plane of atoms at that surface. Figure 2 is a representation of the Eshelby mechanism. Also in 1953 F.C. Frank proposed a different mechanism [7] involving a rotating edge dislocation pinned to a screw dislocation located perpendicularly to the surface. Each revolution of the rotating edge dislocation deposited an additional half-plane of atoms on the surface. Figure 3 is a representation of Frank's mechanism. In 1957, S. Amelinckx, et al. [8], proposed a whisker dislocation theory that described a helical dislocation moving toward the surface by a climb mechanism and depositing a half-plane of atoms for each complete loop of the spiral reaching the surface. Figure 4 shows a schematic of the Amelinckx helical dislocation.

All subsequent dislocation proposals are essentially variants of the above 1950 dislocation theories. It is worth noting that there has not yet been any experimental evidence supporting the existence of any of the above described dislocation mechanisms and it is probably fair to say that the majority opinion of current theorists is that dislocation mechanisms are not involved in whisker growth. This disavowal of dislocations was first stated by G.S. Baker in 1957 [9] and subsequently by W.C. Ellis, et al., of Bell Labs in 1958 [10]. Baker's conclusions were based on the observation that whiskers did not grow with a root that was coherent with the base material, and that kinked whisker growth was incompatible with dislocation mechanisms for whisker growth. The Ellis monograph will be discussed in more detail in the following section.

The 1950s: W.C. Ellis

The Ellis, et al., 1958 monograph dealt at some length with the theoretical aspects of whisker growth and established concepts which form much of the basis for the present day debates on whisker fundamentals. Ellis compiled all the then available data on whisker growth orientations and showed that not all whisker growth directions were coincident with dislocation glide-planes. Ellis concluded that dislocations could not possibly explain non-glide growth directions and, therefore, quite possibly did not have any relevance to the growth of those whiskers which did grow in a glide growth direction. Ellis elaborated on these observations by showing that whiskers could grow by the movement of atoms out of a fixed and immobile grain boundary into a "whisker grain," thereby lifting the entire grain upwards by one atomic layer for each layer of atoms that moved out of the grain boundary into the grain. It was not necessary for the whisker atoms to move to the surface intersection with the whisker; it was only necessary for the whisker atoms to move into the whisker grain at the sub-surface grain boundaries.

Ellis and his co-authors did more than just cast doubt on the relevance of dislocation growth mechanisms for whiskers. They proposed, for the first time, that recrystallization played a key role in the formation and growth of whiskers. The exact quotation is:

"Whisker growth is but a special case of recrystallization and growth involving mass transport…should promote many experiments to examine its validity"….W.C. Ellis, et al., 1958.

Ellis and his co-authors also established that whiskers did not grow from an as-plated crystalline structure; that recrystallization was necessary to transform the as-plated structure into a structure amenable to the formation and growth of a whisker. Ellis' proposals were based on indirect evidence and were not stated as established fact. The concluding statements urged that future experimentalists consider the proposals and attempt to prove/disprove their validity.

The 1950s: Fisher-Darken-Carroll

Early speculations on driving forces for whisker growth culminated in a landmark 1954 paper from R.M. Fisher, L.S. Darken, and K.G. Carroll of U.S. Steel [11]. They applied clamping forces to tin films electrodeposited onto steel substrates and observed the resultant whisker growth rates. Figure 5 shows the clamp design. The results showed that applied compressive forces up to 7500 psi accelerated whisker growth rates from less than 1 Å/sec to as high as 10,000 Å/sec. The seminal importance of the Fisher, et al., paper is that it established the premise that whisker growth is driven by compressive stresses within the base material. It is worth noting that this effect has been twice corroborated in the published literature. The first corroboration was in 1962 by V.K. Glazunova [12] and the second was by C.H. Pitt and R.G. Henning in 1964 [13]. Glazunova studied tin-coated brass and steel, whereas Pitt and Henning evaluated tin with both steel and copper substrates.

This author would comment that we now can be fairly certain that the Fisher-Darken-Carroll experimentation also accelerated a recrystallization event of the kind that was subsequently proposed by W.C. Ellis in 1958. The clamping pressure apparently extruded some tin material from the clamp edges and this extruded material had a number of recrystallization events due to the high stored energy level. In summary, the clamp force experiments accelerated both the occurrence and subsequent growth rate of the whiskers.

The 1950s: S.M. Arnold

S.M. Arnold from Bell Laboratories was co-author of the aforementioned Koonce-Arnold observation published in 1954. In 1956 Arnold published [14] a review article compiling all the then available Bell Laboratory experimental data and discussing, for the first time, whisker mitigation strategies such as fusing and hot-dipping. Arnold further elaborated on mitigation strategies in a 1959 [15] paper where he reported on the beneficial effects from alloying tin (Sn) films with lead (Pb) in amounts ranging from 3-10% by weight. Based on this work, the predominant whisker mitigation strategy for electrodeposited tin films became lead (Pb) co-deposition. Interestingly, there were never any significant discussions as to why mitigation practices worked. There were occasional references to the possibility that such practices reduced the internal stresses within the tin film; but there were never any direct evidences of internal stress reduction.

The 1950s: A Summary

There were 16 major whisker publications during the 1950s, a select few of which have been reviewed in the preceding sections. It is striking to note that essentially all of the fundamental concepts still debated today were initially established during the 1950s. Many of these 1950s era proposals were perhaps little more than well-informed speculation at the time, but they were based on sound principles of materials science and they formed a basis for all current discussions relevant to whisker formation.

THE 1960S:

There were fewer whisker publications during the 1960s, but they nonetheless contributed a great deal of important data and insights to the overall understanding of whisker phenomena. Bell Laboratories continued to contribute and we see the first contributions from major Russian laboratories as well as the International Tin Research Institute.

The 1960s: the Russian Labs

In 1962 V.K. Glazunova published [12] an article on the influence of "certain factors on whisker growth". A key contribution of this 1962 publication was the corroboration of the aforementioned Fisher/Darken/Carroll clamp-pressure experiment. A year later, in 1963, V.K. Glazunova and N.T. Kudryavtsev published a very large set of experimental data [16] that established for the first time a number of important facts regarding whisker growth. They showed that the presence of zinc (Zn) in copper substrates greatly accelerated the formation of tin whiskers. This publication also reported the first mitigation data for annealing at temperatures between 150-200^{o}C. Of particular note was the following commentary:

"It may be assumed that the incipiency and subsequent growth of tin whiskers is a distinctive form of recrystallization"…
V.K. Glazunova, and N.T. Kudryavtsev, 1963.

The 1960s: the International Tin Research Institute

In 1964, S.C. Britton and M. Clarke from The International Tin Research Institute (ITRI) published a paper [17] that studied tin electrodeposited onto brass (Cu-Zn) substrates. They found that copper or nickel undercoats (i.e., underlays) were effective, long lasting barriers to zinc diffusion. The copper underlays were an effective whisker mitigator for bright tin but marginally effective for matte tin. Nickel underlays were found to be effective mitigators for bright tin on brass. There was no report on the effect of nickel underlays for matte tin. Britton and Clarke also reported that Zn and Cu intermetallics reached tin coating surfaces after a period of time dependent on storage conditions. For example, Cu atoms were detected at the surfaces of 10-micron tin films after 8 months of storage at 50^{o}C. The Cu and Zn atoms did not reach the surface as a uniform layer, but rather as "islands" of intermetallic embedded in a matrix of pure tin. Decreased solderability and increased corrosivity were associated with the presence of the Zn and Cu intermetallics at the tin coating surface.

Britton and Clarke's observations regarding the "islands" of intermetallic embedded in a matrix of pure tin were based on electrochemical potential measurements. It has taken 40 years for this observation to be corroborated by focused ion beam (FIB) microscopy. Figure 6 shows a FIB cross-sectional view for tin electroplated onto a copper substrate that was temperature cycled 1000 times between -40^{o}C and + 125^{o}C. It is evident that the intermetallic layer periodically extends all the way from the substrate interface to the film surface, thereby forming the "island" structure described by Britton and Clarke.

THE 1970S

Whisker interest continued during the 1970s. Mitigation practices were an area of focus, with several major publications dedicated to this topic, and there were some important theoretical publications.

The 1970s: the International Tin Research Institute

S.C. Britton reviewed 20 years of whisker research in a 1974 publication [18]. Britton recommended that tin coatings on brass substrates have either nickel or copper under-coatings and that all tin coatings not flow melted should be a minimum of 8 microns thick. Heat treatments (i.e. annealing) at 180-200^{o}C for 1 hour in a nitrogen atmosphere were also recommended. Britton also commented that organic coatings could not be relied upon to deter the emergence of whiskers, but they would mitigate the probability of shorting to an adjacent electrode.

The 1970s: the European Space Agency

B.D. Dunn from the European Space Agency published a set of papers in 1975-76 [19-20] showing some of the first (possibly the very first) high-quality SEM micrographs of whiskers. These publications are particularly noteworthy for Dunn's very strongly worded recommendation against the use of any tin, zinc, or cadmium coatings for spacecraft electronic hardware. Dunn recommended eutectic tin-lead finishes as an acceptable, minimum risk alternative.

The 1970s: the Swedish Telephone Co.—L.M. Ericsson

U. Lindborg, of L.M. Ericsson, published a 1975 paper [21] on the whisker growth characteristics for zinc electroplated onto steel substrates. This paper is rarely referenced in tin whisker literature, but the similarity between zinc and tin whiskers make it an important reference point.

Lindborg presented the first published X-ray determinations of stresses for electroplated (Zn) films and showed that a minimum stress level was required for the initiation of whisker growth. Furthermore, Lindborg was able to categorize his data by micro-stress levels by accurately measuring specific diffraction spectra broadening. Lindborg's results showed that whisker growth was independent of the micro-stress level within the electroplated (Zn) films. Micro-stress levels are related to internal defects such as dislocations, interstitials, and vacancies. Lindborg's analysis techniques have never been reproduced in any known technical publication. The relevance of this data today is that there is still debate on the relative significance of macro and micro-stresses within tin films. Lindborg's data counters these micro-stress arguments.

The 1970s: K.N. Tu

In 1973 K.N. Tu published [22] an article about tin films vacuum deposited onto quartz substrates with and without a vacuum deposited copper underlay. Whiskers were observed to grow only when there was a copper underlay. Tu attributed the whisker growth to internal stresses generated by Cu_6Sn_5 intermetallic formation at the boundary between the copper substrate and the tin films. This would be the first of several publications by K.N. Tu and co-authors over the next 30 years. No other author has contributed more whisker related publications over such a long span of time.

THE 1980S AND 1990S

There were relatively few whisker papers published during the 1980s and 1990s. A few of the key articles are presented below.

The 1980s: the European Space Agency

In 1987 B.D. Dunn of the European Space Agency (ESA) published a major treatise [23] on tin whisker experimental data accumulated by the ESA. Dunn's conclusions were that mechanical stressing did not accelerate whisker formation and growth for his samples. This statement was in direct contradiction to previous work. Dunn gave no explanation for his negative results from the mechanical stress testing. He did conclude that metallurgical processes such as diffusion and recrystallization occur during the whisker formation process. A singular observation was made that aluminum electromigration caused whisker growth at certain structural points in the films such as grain boundary junctions and hillocks.

This author will note that Dunn's mechanical stressing apparatus did not clamp directly onto the tin films as did the apparatus of Fisher, et al. Rather, the tin film was deposited on both sides of a Gring structure that was subsequently stressed by a bolt arrangement that caused a compressive stress on the inner surface of the C-ring and a tensile stress on the outer surface (Figure 7). This arrangement did not result in any extrusion of material as did the clamp fixture arrangement of Fisher, et al. Additionally, the stress levels in the Dunn fixture were far less than those in the Fisher, et al., device. The key difference between Dunn's results and Fisher / Darken / Carroll's results, in this author's opinion, was that Fisher accelerated both recrystallization and whisker growth, whereas Dunn's fixture did not accelerate recrystallization.

The 1990s: K.N. Tu

A new theoretical concept was offered by K.N. Tu in 1994 [24]. Tu proposed that a "weak oxide" layer enabled the localized relief of internal stresses by permitting whisker growth through a crack in the oxide layer.

The 1990s: B.Z. Lee and D.N. Lee

A major whisker paper was published by Lee and Lee in 1998 [25]. This paper showed the first published cantilever beam stress measurements for tin film on copper substrates with and without annealing treatment (Figure 8). The data showed that stress levels for annealed tin films remained at zero for at least 30 days after annealing. The un-annealed films showed an initial tensile stress of +11MPa that changed to a compressive stress of -8MPa after a few days. Lee and Lee's results were based on a version of Stoney's equation that required the tin film to be removed by etching. This procedure was based on the recognition that tin films deposited onto copper substrates result in a three-film composite of tin / copper-tin intermetallic / copper. Lee and Lee determined whisker growth orientations by electron beam diffraction of individual whisker segments. It was then possible for Lee and Lee to determine a spatial orientation for the parent whisker grain by using the angle made by the whisker with the parent grain and the specific orientation of the whisker. The results showed that the parent whisker grain orientation was always different from the major orientations of the as-deposited tin film. Lee and Lee also proposed a two-stage dislocation mechanism involving climb and glide that closely matched the mechanism proposed by Eshelby in 1953.

THE 21ST CENTURY

There have been more transactions and proceedings whisker publications in the first three years of the 21st century than in the previous 60 years. This whisker research upsurge is due to the impending European Union environmental regulations requiring lead (Pb) removal from electroplated tin films. New analytical techniques, such as focused ion beam (FIB) microscopy and micro-focus X-ray diffraction (XRD), were utilized to gain insight into tin film microstructures and internal stress levels. There have been numerous claims by plating shops about proprietary, whisker-free tin plating processes. A number of consortia were formed to investigate the impact of removing lead from electroplated tin and to recommend appropriate actions to minimize any reliability impact.

The 21st Century: Y. Zhang, Chen Xu, et al.

In 2001 Y. Zhang, C. Xu, et al., published a set of papers [26-27] utilizing X-ray diffraction (XRD) to measure internal stresses over time for a variety of tin films on copper substrates. FIB micrographs were used to characterize the microstructures. These were the first FIB micrographs ever published. From the XRD measurements it was determined that stresses became increasingly compressive over time for tin electrodeposited onto copper substrates. However, when there was a nickel underlay present, the tin stress levels were always tensile and remained so over time. FIB examination indicated that the whisker grains had roots in very close proximity to intermetallic particles projecting upward from the tin / substrate interface. In these papers the authors speculated that nickel underlays were an effective barrier to copper diffusion from the substrate into the tin films and that this was the reason for the tensile stresses found for tin / nickel / copper structures.

One year later (2002) Zhang, Xu, et al. published 3 papers [28, 29, 30] confirming their earlier findings and providing additional insight as to why nickel underlays were an effective whisker mitigator. They observed that annealing at 175^{o}C caused the boundary between tin and nickel to move into the nickel, which is in opposition to the situation for tin and copper where the interface moves into the tin. This observation meant that tin (Sn) readily diffuses into nickel (Ni), but the nickel does not diffuse into the tin. In support of this observation the authors pointed to a master's thesis from the National Central University, Chungli City, Taiwan [31] that showed data from Kirkendall marker experiments with a Sn-Ni couple. The results clearly showed that tin diffused into nickel at a much greater rate than for nickel into tin. From these results the authors concluded that nickel's whisker mitigation effect is primarily due to its inter-diffusional relationship with tin and not the diffusion blockage of copper atoms from the substrate into the overlying tin film.

The 21st Century: Micro-Focus X-Ray Diffraction

The first micro-focus X-ray data relevant to whisker growth results was published by W.J. Choi, T.Y. Lee, and K.N. Tu, in 2002 [32]. Choi, et al., used the synchrotron facility at Lawrence Livermore Laboratory to map 1.5 micron square regions immediately surrounding a whisker structure. The results showed stress variations from grain to grain such that the state of stress could only be considered to be biaxial when averaged over several grains. There was a very slight negative stress gradient from the whisker root area to the surroundings. In general, the regions immediately surrounding the whisker root were slightly more compressive than the whisker root area. Choi, et al. [33], repeated the analysis in 2003 for electrodeposited SnCu films and found the same kind of stress distributions previously reported. Additionally, they found that the whisker grain was of a different orientation (210) than the immediately surrounding grains (321). This report is the first report to demonstrate that the tin film grain orientations are predominantly one crystallographic direction, with the exception of the whisker grain. Most preferred orientation data from macro X-ray diffraction show a dominant orientation with one or more subsidiary orientations. However, macro X-ray diffraction cannot determine the relative number of grains with primary and subsidiary orientations.

The 21st Century: Industrial Reports

Egli, et al. from Rohm-Haas Corporation [34] published a 2002 paper that showed whisker formation to be dependent on crystallographic orientation factors. Whisker growth was enhanced by low-angle grain boundaries between adjacent grains. Egli hypothesized that low-angle boundaries inhibited stress relaxation by creep and favored stress relaxation by whisker formation. Egli, et al., have subsequently developed plating technologies to produce tin films with specific crystallographic orientation combinations. While it is generally considered impossible to control the specific primary orientation of a tin film, it appears to be possible to control the process so as to produce only certain specific combinations of primary and secondary orientation spectra.

K. Whitlaw and J. Crosby from Rohm-Haas Corporation published a 2002 paper [35] that studied 22 different tin finishes on substrates of brass, CDA194, and alloy 42 (Fe-47Ni). The results generally confirmed the benefits of nickel underlays, thicker tin deposits, and post-plate annealing as effective mitigation practices. A surprising result was the total absence of whiskers for some bright tin and bright tin-copper (Sn-Cu) films. The authors concluded that these unexpected results were due to "modern additives" that controlled the crystalline orientation structure so as to produce the primary and secondary orientation spectra described by Egli and co-workers (above). Whitlaw and Crosby also stated that Alloy 42 (Fe-47Ni) substrates had relatively few whiskers in comparison to copper alloy substrates.

In 2003 K. Whitlaw, A. Egli, and M. Toben from Rohm-Haas [36] published data on a new "proprietary" process that produced tin films with favorable combinations of crystal orientations. Key to the process was a specific substrate preparation process involving the removal of at least 2.5 microns of surface material by etching. A proprietary copper underlay process was also recommended.

M. Dittes, P. Oberndorff, and L. Petit from Infineon Technologies, ST Microelectronics, and Philips, published a 2003 report [37] showing results from pure tin films electrodeposited onto typical lead-frame materials. Their data showed that annealing at 150^{o}C for one hour was an effective mitigation practice for pure tin films. They also showed that both nickel and silver underlays were effective whisker mitigators for tin films on copper alloy substrates.

In 2003, D. Romm, et al., evaluated matte tin films plated onto a variety of commercially available lead-frame materials. Some of the test samples were subjected to a 5V electrical bias. Whiskers were consistently found on the electrically biased samples. These would be the first such results in the whisker literature. There was no current flow through the specimens. Based on this report, a 5V bias was incorporated into some acceptance testing procedures adopted by various commercial firms. No explanation for the bias effect was offered in this report.

R. Schetty, et al., from Technic, Inc. published a set of papers in 2002/2003 [38-39] that evaluated substrate effects on whisker formation. The authors concluded that substrate stress was an important factor influencing whisker formation and that substrate stresses could be affected by pre-treatment methods. Additionally, it was shown that substrate pre-treatment could affect preferred orientations, and that any given tin chemistry could be plated with either tensile or compressive stresses, depending on the pre-treatment process.

Sulfamate plating chemistries had very different preferred orientations, which were dependent upon the organic additives utilized. The authors indicated that a proprietary plating structure had been established based on this work.

The 21st Century: National Institute of Science & Technology (NIST)

A 2001 NIST publication [40] showed that no whiskering occurred for very pure electroplated bright tin deposited onto copper substrates. Analysis of the NIST high purity electrolyte showed copper (Cu) concentrations < 0.8ppm (mass). Controlled additions of copper to the electrolyte were easily co-deposited into the tin film and whiskers were observed for all samples with copper plating concentrations greater than 30ppm. All the NIST platings were done at ambient conditions and at highly efficient plating conditions. Flexure beam measurements showed that all (most) of the deposited tin films had compressive time zero (as measured within 800 seconds of plating) stress levels that decreased toward zero over time.

This NIST work raises the possibility that commercial tin plating solutions may get into occasional "trouble" due to bath contamination and inefficient bath process parameters. A FIB examination of a highly whiskered bright tin finish (Figure 9) shows numerous precipitates scattered throughout the matrix. These precipitates have been identified as a CuSn compound (almost certainly Cu_6Sn_5). Efforts to reproduce the CuSn precipitates by heat aging have not been successful to date. However, FIB examination of samples from NIST where Cu had been deliberately added to the plating solution does show similar precipitates.

The 21st Century: The Integrated Theory

In a very real sense all current theoretical approaches to whisker formation and growth integrate historical ideas with new observations. The differences between current theorists are ones of emphasis and omission. For example, theorists divide on the relevance of dislocation mechanisms. The driving force for whisker formation is widely considered to be compressive stresses with a minority view holding that grain boundary energies are the driving force for whisker growth. Mitigation practices are generally considered to be effective because they either reduce internal film stress levels to near zero or maintain a constant tensile film stress state.

This author has developed an Integrated Theory for Whisker Formation and Growth in conjunction with L. Palmer [2]. It is not the purpose of this review to detail elements of the theory. That has already been done and future elaborations are under development. Some of the salient points of the Integrated Theory are listed below:

1. Whiskers do not grow from as-plated microstructures… a "different" whisker grain must be formed.

2. Whisker grains are formed by recrystallization events. Recrystallization events are driven by macro - and/or micro-stresses within the film.

3. Tin atoms are transported to the whisker grain through a grain boundary network that connects the whisker grain with the film / substrate interface region.

4. The driving force for tin transport is a positive stress gradient…not a compressive stress state.

5. Intermetallic formation at the substrate interface generates very high compressive stresses in the intermetallic region. The intermetallic region is always a combination of intermetallic and unreacted/displaced tin atoms.

6. The unbalanced inter-diffusion of copper and tin results in a Kirkendall effect with a vacancy-rich zone within the copper substrate in the vicinity of the film/substrate interface.

7. The Kirkendall zone within the copper substrate results in a shrinkage effect that establishes a tensile stress state in the Kirkendall zone.

8. Dislocation mechanisms are probably not relevant to whisker growth. Tin atoms can move into the whisker grain from the whisker grain boundaries by diffusion and thereby lift the whisker grain surface so as to grow a filamentary whisker.

Figure 10 is a schematic representation for the film / substrate structure described in the Integrated Theory. As is evident, the structure is a four-zone structure. The intermetallic region (shaded) is a "horned" structure consisting of both intermetallic and tin, both of which are in compression. Previous descriptions of the intermetallic region have tended to assume that the intermetallic is in compression and the tin is in tension. The Integrated Theory predicts that both the tin and the intermetallic from the "intermetallic region" are mutually compressed. The compression results from a reaction between copper and tin atoms to form an intermetallic compound, which results in an expansive force on all the atoms in the intermetallic region.

The highly stressed intermetallic region will relax by diffusing tin atoms into the overlying tin film. As diffusion proceeds, there will be a build-up of an increasingly compressive stress within the tin film that will eventually stop the diffusion process. There will also be some surface area and volume increase for the film structure as diffusion proceeds. Whisker growth is a more efficient way to relax the internal stresses within the intermetallic region. The highly compressed tin atoms from the intermetallic region diffuse through the grain boundary network to the whisker grain. Whisker formation does not generate a back stress within the film structure. Diffusion of tin atoms to the whisker grain continues until all available strain energy has been utilized to produce the new surface area of the whisker structure or until such time as the necessary positive stress gradients have been neutralized.

The 21st Century: Consortia Activities

There are two major U.S. consortia involved in tin whisker issues. One is the Computer Aided Life Cycle Engineering (CALCE) group coordinated by the University of Maryland. The CALCE whisker committee consists primarily of defense contractors and some government laboratory liaisons. This group has coordinated research among its members and has been very active in evaluating conformal coatings as potential whisker mitigators. The second major consortium is the National Electronics Manufacturing Initiative (NEMI), which has three whisker projects; a modeling group, a user group, and a test methods group. NEMI membership consists mostly of representatives from major manufacturers in the commercial market and their suppliers. The NEMI modeling group is working to achieve a consensus amongst its members relative to the fundamentals of whisker formation and growth. The above referenced Integrated Theory is one of the proposals under discussion. The user and test groups have issued product acceptance position statements that are posted on the web at http:www.nemi.org/projects/ese/tin whisker activites.html. For example, the user group statement recommends that all electroplated tin finishes incorporate one of several acceptable mitigation practices. Pure tin is not acceptable.

Both consortia have held numerous workshops over the past 3 years and have been largely responsible for the increased activity and focus on tin whisker issues.

SUMMARY

The world has essentially lost the large industrial research facilities that once dominated the whisker literature during the 1950s and 60s. Experiments today are much more limited in scope. However, since Y2000 new analytical tools have permitted some important contributions to the understanding of tin film microstructure and stress states. Stress state measurements remain frustratingly limited with respect to stress gradients within the tin film and stress states within the underlying intermetallic and Kirkendall zones.

The technical industries should remain supportive of the consortia addressing whisker-related issues. The regular project meetings and periodic open workshops are the most viable approach for generating and sharing information and for achieving consensus. This author is convinced that consortia activities have been largely responsible for the recent willingness of commodity suppliers to adopt mitigation practices for electroplated tin films.

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Figures and Captions

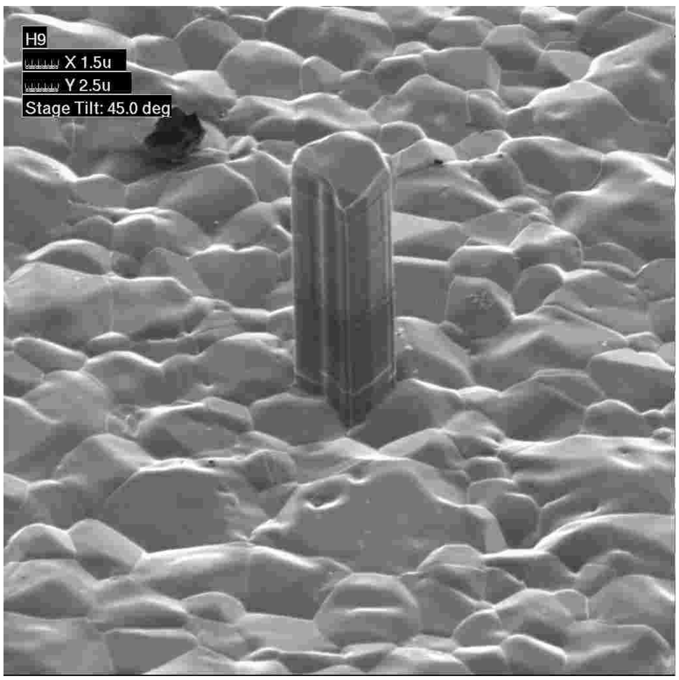

Figure 1. FIB Micrograph of a Matte Tin Whisker

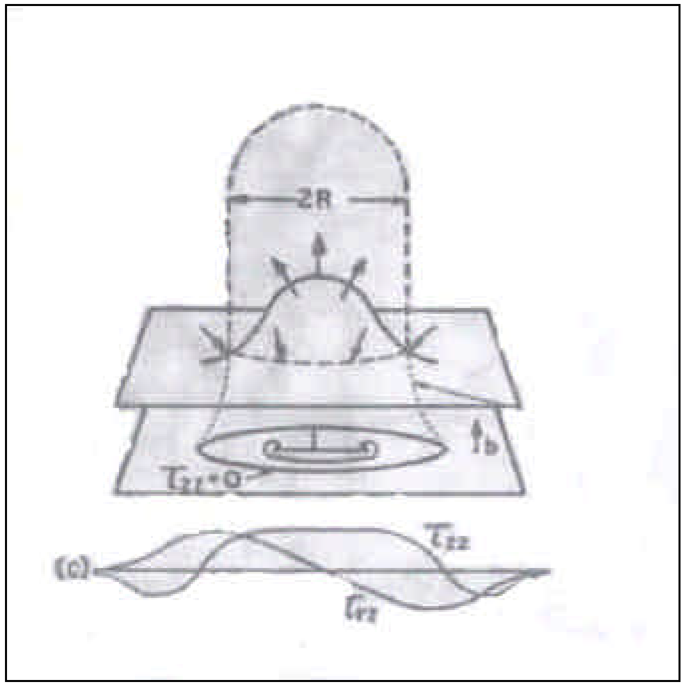

Figure 2. Schematic of Eshelby Whisker Dislocation Mechanism [6].

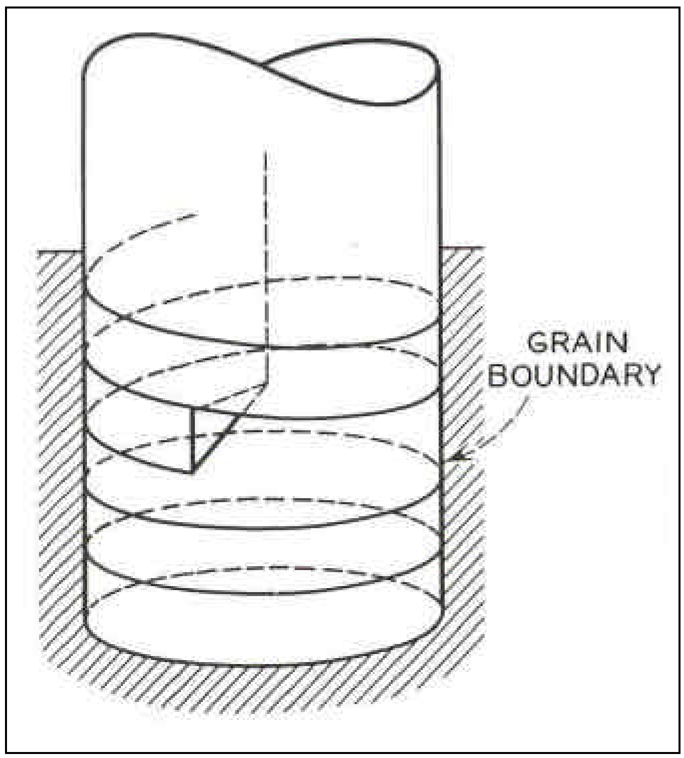

Figure 3. Schematic of F.C. Frank Whisker Dislocation Mechanism [7].

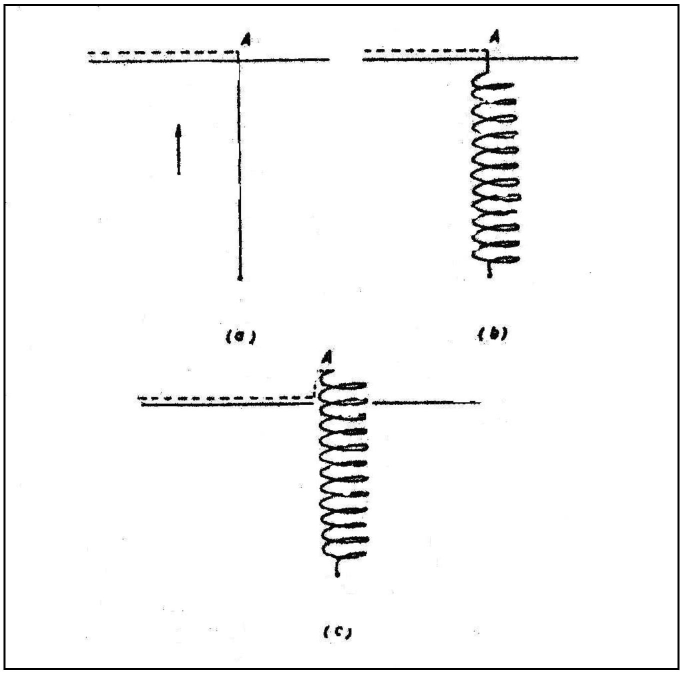

Figure 4. Schematic of Amelinckyx's Whisker Dislocation Mechanism [8].

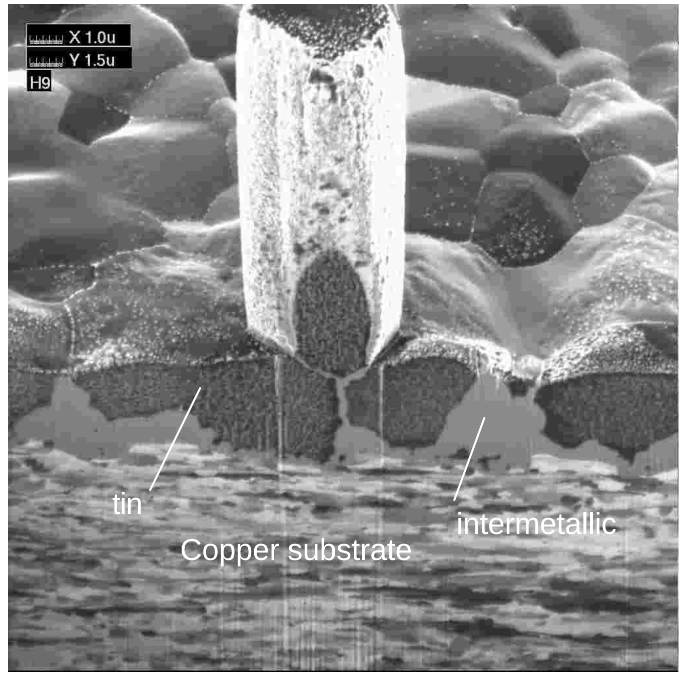

Figure 6. A FIB micrograph of a matte tin whisker structure from a temperature cycled specimen (printed courtesy of P. Bush-SUNY Buffalo)

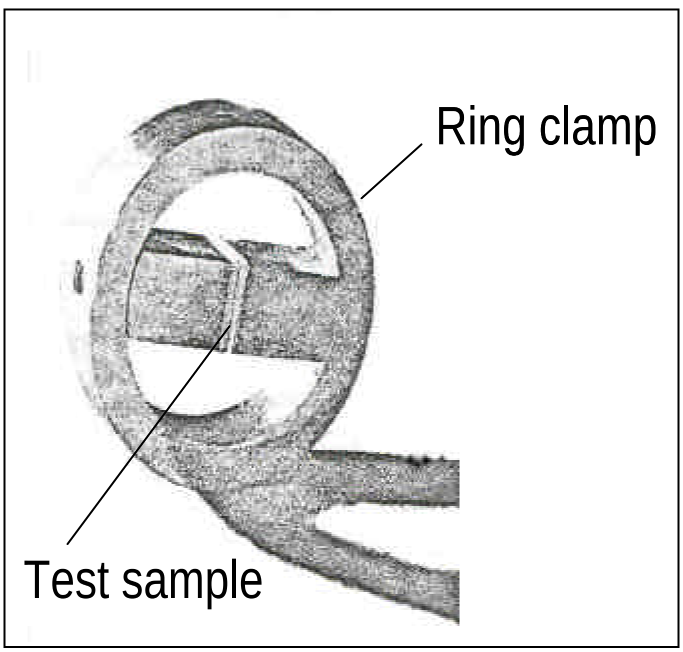

Figure 5. The Ring Clamp from Fisher/Darken/Carroll [11]

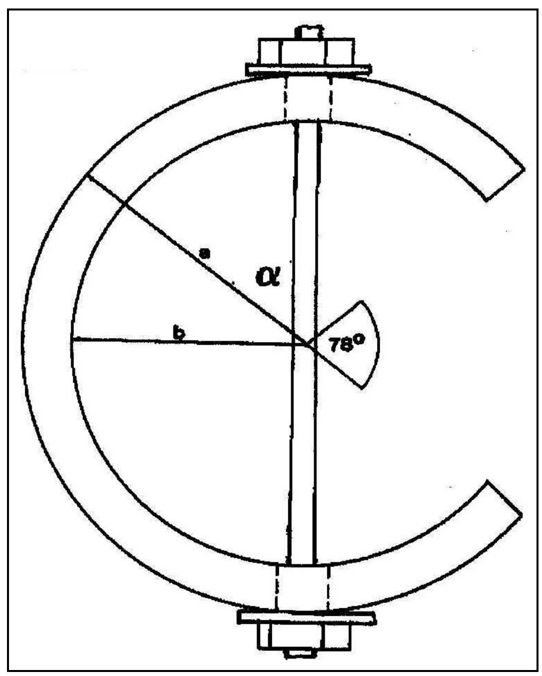

Figure 7. Ring Clamp from Dunn [23]

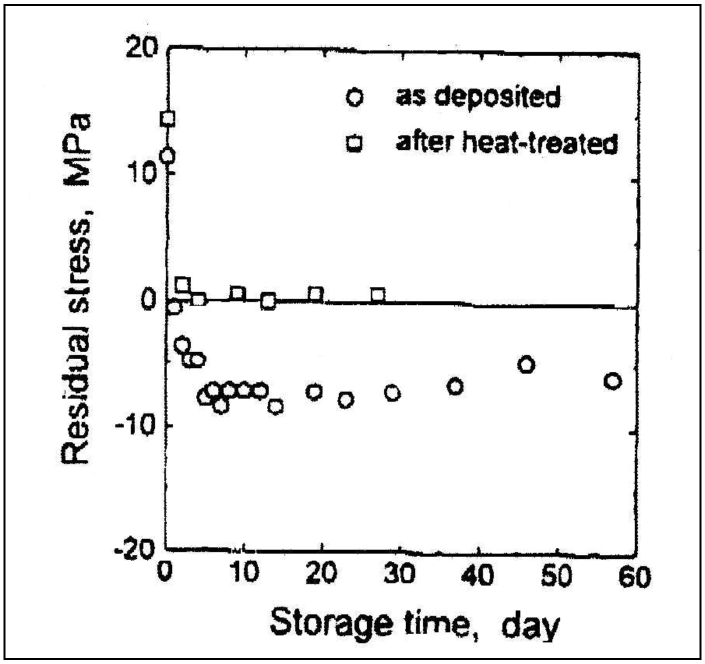

Figure 8. Flexure Beam Stress Measurements from Lee & Lee [25] based on complex Stoney's equation.

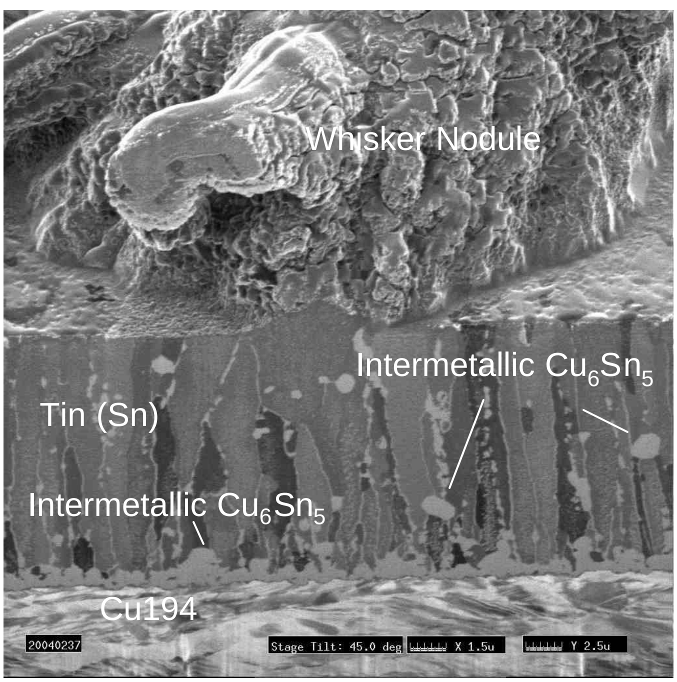

Figure 9. FIB Micrograph of Bright Tin with 1.0% Cu alloy

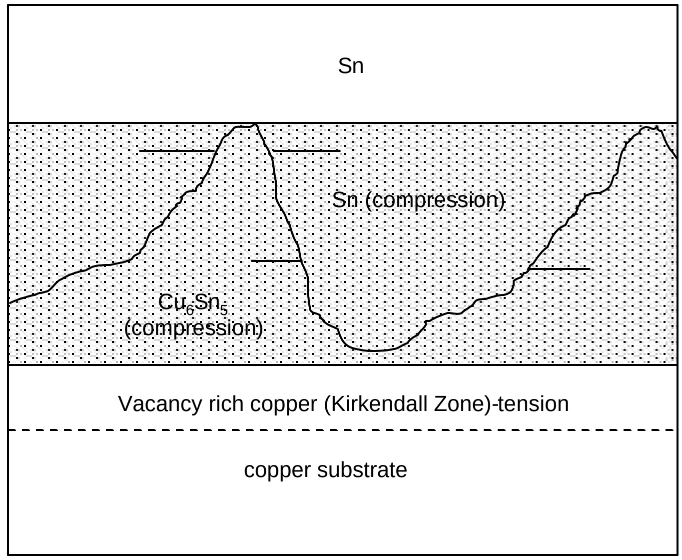

Figure 10. Schematic of the 4-Zone Tin Film Structure from the Integrated Theory