UNDERSTANDING WHISKER PHENOMENON - PART II
Competitive Mechanisms

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It is well understood that the root cause for whisker formation is the internal stress. Many factors contribute to internal stress. Three key factors are identified in our work "Understanding Whisker Phenomenon: Part I".

In this paper, we will describe our systematic, and in-depth investigation of these factors, and the dynamic nature of the whisker growth phenomenon. We will also offer our understanding of the competitive nature of various whisker growth mechanisms and what set of parameters determine a particular mechanism. This understanding provides the foundation for the recommendations that we offer to the electronic industry.

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Introduction

The electronic industry is under extreme pressure to remove tin-lead solders from electronic components[1-4]. Pure tin is one of the alternatives and may be the simplest system as a “drop-in” replacement. However, fear of “whiskers” has been a major concern inhibiting its implementation[5-11]. This is because that tin whiskers, with a length from a few micrometers to several millimeters, may grow from electroplated Sn and cause electric shorts in electronic devices, particularly, in fine-pitch high I/O (input/output) components.

Tin whisker formation appears to be favored by the presence of organic and hydrogen inclusion, small size grains, intermetallic formation, internal stress and the application of external mechanical stress [5-12]. The attempt by the deposit to decrease the internal energy through recrystallization and grain growth results in whisker growth, which is further accelerated by the stress in the Sn coating. It has been also recognized that long range mass transport of Sn is necessary for the formation of very large whiskers observed on electroplated Sn. The high mobility of Sn coupled with the desire to decrease the internal energy in the electroplated Sn leads to the whisker formation.

Several remedies have been proposed to overcome the problem of whiskering: alloying with a small percentage of other metals (e.g. Pb, Bi), hot dipped tin, as well as reflow tin after plating are some common practices. Compared with electroplated pure tin, these alternatives are less characterized and have much shorter reliability histories. Though each of them has significant merit in their own right, they have inherent limitations. For instance, solder joint embrittlement is a reliability issue when precious metals are involved. Tin alloys such as SnCu, SnBi and SnAg, on the other hand, have the following limitations: stability of plating process (excessive Sn oxidation and Sn immersion), alloy composition control, metal cost, and availability and compatibility with existing tin-lead solders (e.g. Bi and Ag).

Previously, we have reported our systematic kinetic studies on the whisker growth of various Sn finishes and identified various factors affecting the kinetics of whisker growth (see part 1 by Zhang et al. in this proceeding). In this paper, we will describe the results of our studies on the whisker growth mechanisms. Various techniques were used to examine the local structure and chemical composition of the whisker. The residual stresses were also determined using x-ray diffraction.

Experimental results and discussion

FIB results:

To review the local structure of whiskers, cross sections along the root of the whisker are made using focused ion beam (FIB). In a FIB experiment, an extremely small diameter beam of gallium ions is used to image the surface and locate the whisker. The same focused ion beam is then used to remove materials from the surface at high lateral resolution and cut through the whisker with an accuracy better than 10 nm.

Fig.1 shows FIB images of a whisker found on a matte Sn surface, which was plated directly on a Cu substrate. The sample was aged at room temperature for 13 months. The pictures in Fig.1 represent various stages of cutting through the whisker. Fig. 1a is the FIB image of the surface taken after a trench is cut into the coating next to the whisker. FIB is then used to gradually cut through the whisker and FIB images were taken at various stage of cutting. These results are shown in Figures 1b, 1c and 1d. The grain structure around the whisker is nicely revealed in these images.

Three different layers can be identified in these images: Cu substrate, Sn-Cu intermetallic layer and Sn layer. The intermetallic growth at the Sn and Cu interface shows strong anisotropy, with some areas growing much faster than others. There are also a very clear grain boundary between the whisker and adjacent grains. The whiskers seem to originate from the middle of the Sn coating, rather than from the Sn-Cu interface or the Sn surface. Apparently, a

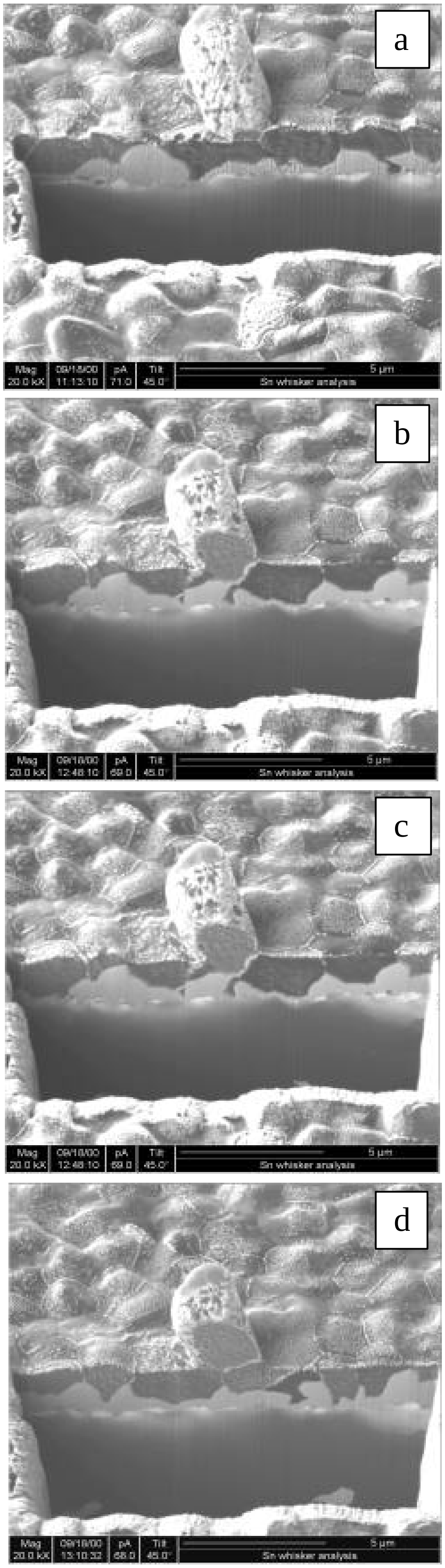

Fig.1 FIB images of whisker found on matte Sn

whisker nucleate is formed within the Sn coating and then grows out of the Sn coating.

Very similar results have been also obtained for satin bright Sn plated on Cu substrate. Fig.2 shows a FIB image for a whisker found on the satin bright Sn, which was aged at room temperature for 18 months. Here again, intermetallic compound formation is observed at Sn and Cu interface. Similar to the matte Sn, very clear grain boundary is observed between the whisker and adjacent grains and the whisker is originated within Sn film. It is also noteworthy that in both cases the whisker is sitting on top of the intermetallic phase.

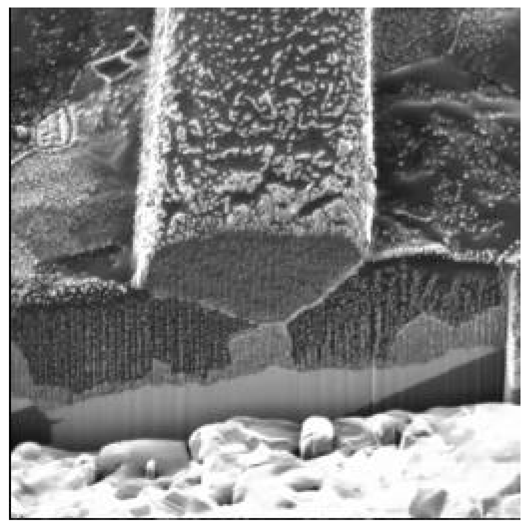

Fig.2 FIB image of whisker found on satin bright Sn

FIB experiments were also performed on bright Sn, which was plated over the Cu substrate. The sample was aged at room temperature for 18 months. Fig.3 shows FIB images with increasing magnification from a to c. The length of this particular whisker is about 250 μm (see Fig.3a). As Fig.3b and 3c show, the long filament-type whisker originates from the nodule on the surface. There is again a very clear grain boundary between the filament whisker and nodule whisker. The filament is not in direct contact with the Sn coating. The mass transport from Sn film to the filament whisker, necessary for the formation of this very long whisker, occurs through the nodule whisker. The nodule whisker apparently acts as a precursor state for the formation of the filament whisker. This is consistent with the observation that the nodule whisker is seen before the filament whisker during the aging at room temperature as well as 50^{o}C.

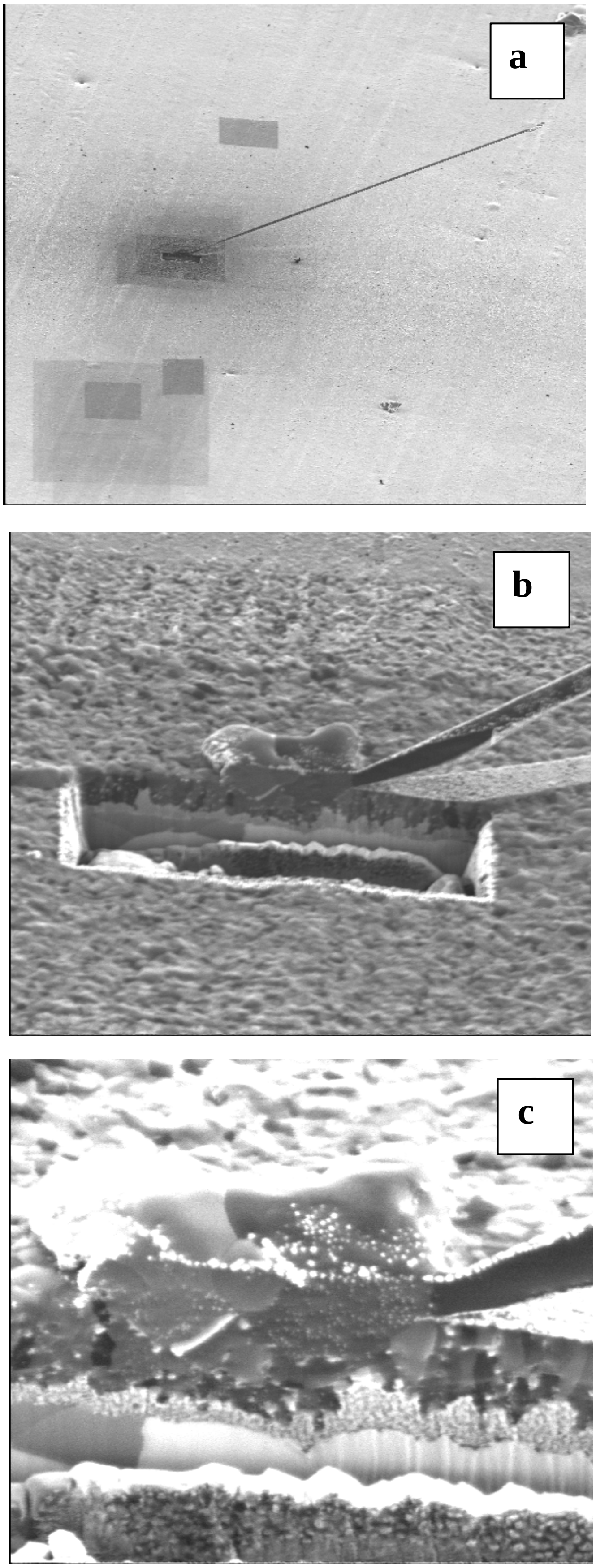

Fig.3 FIB images of whisker found on bright Sn

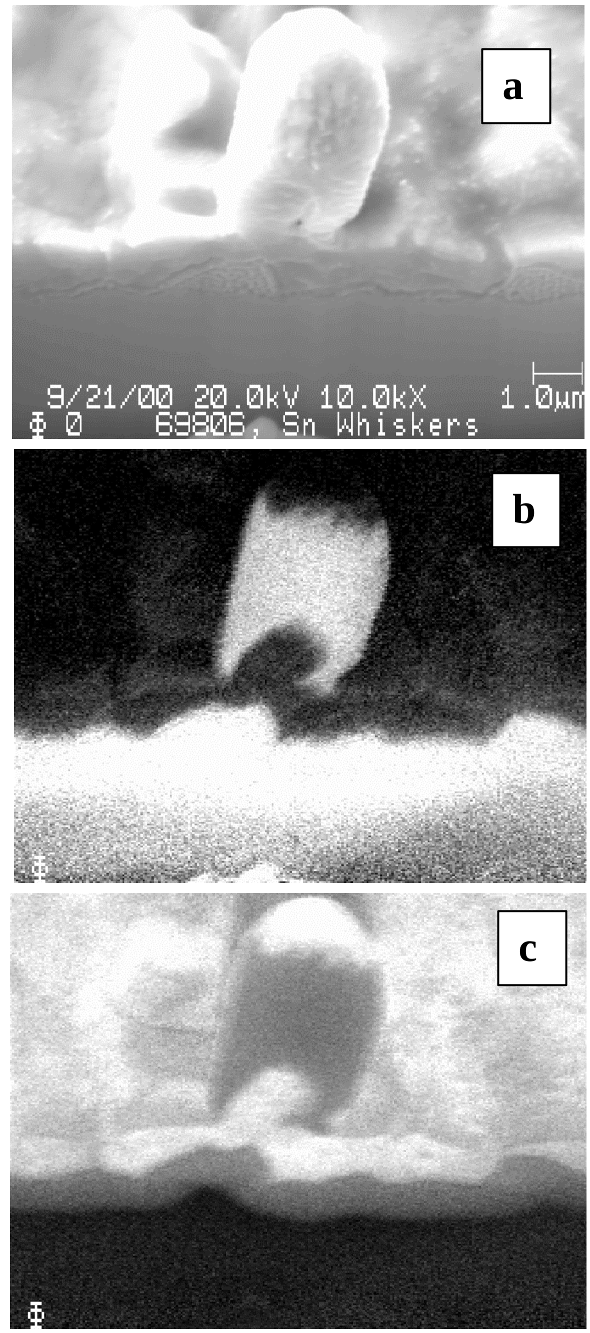

Fig.4 SAM mapping of whisker found on matte Sn

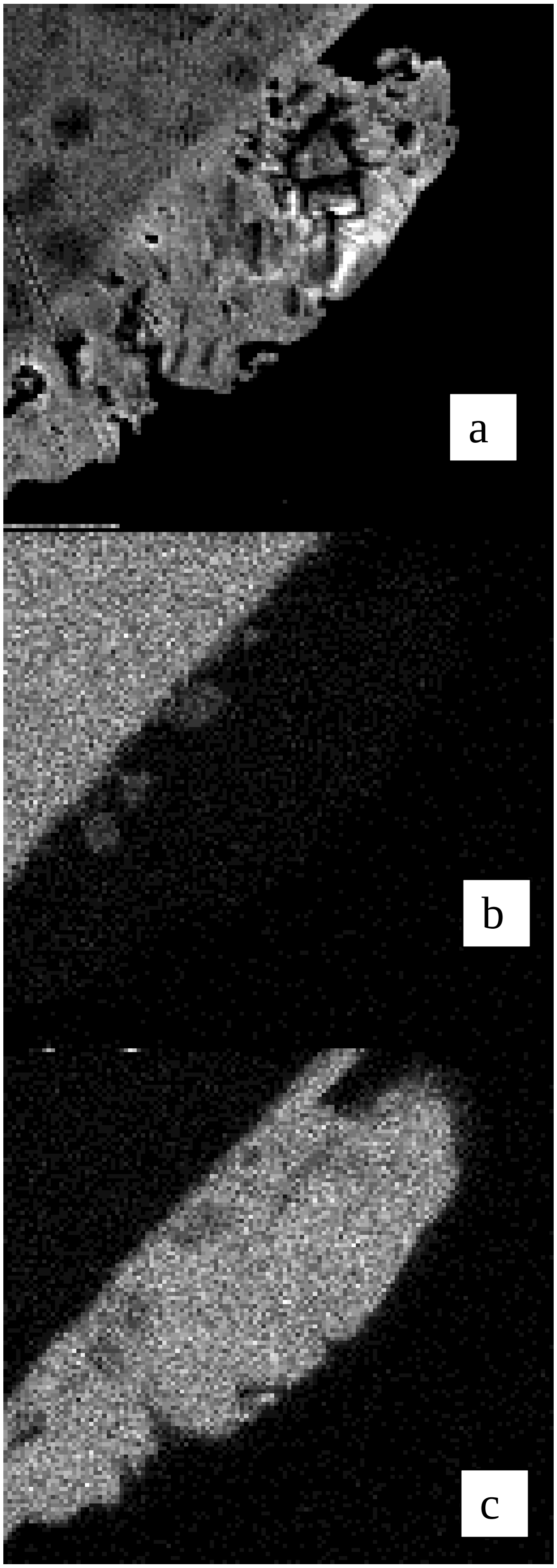

Fig.5 SEM/EDS mapping of whisker found on bright Sn

Auger and SEM/EDS Mapping:

Scanning Auger microscopy (SAM) and energy-dispersed spectroscopy (EDS) were used to determine the elemental composition around and within the whisker. For the SAM measurements, the cross section through the whisker was made using FIB. The sample is then transferred into the SAM chamber. Prior to the SAM mapping, the surface was cleaned by argon-ion sputter for 2 min. Fig.4 shows Auger mapping of a whisker found on the matte sample after 13 months aging at room temperature. The secondary electron image is provided in Fig.4a, while the Cu and Sn mapping are shown in Fig.4b and c, respectively.

Consistent with the FIB results, a Sn-Cu intermetallic layer is seen between Sn and Cu layer. Furthermore, large concentration of Cu is also seen within the whisker.

SEM/EDS was also performed on whiskers found on bright Sn. The bright Sn was plated directly on Cu and aged at room temperature for 18 months. The sample was cut using a diamond saw and fine-polished to reveal the whisker. Fig. 5a, 5b and 5c show secondary electron image, Cu mapping and Sn mapping around a nodule whisker. As the Sn and Cu mapping demonstrate, the whisker consists mostly of Sn. However, there is also some Sn-Cu intermetallic formation within Sn coating near Sn-Cu interface, even though not as much as in the case of matte and satin bright Sn. The intermetallic growth shows again strong anisotropy.

Stress Measurement:

Since it is generally believed that the internal stress promotes whisker growth, we also performed in-situ stress measurement during the electroplating of Sn as well as ex-situ measurement on plated parts. As discussed previously, the in-situ measurements shows a compressive stress for the bright Sn, a tensile stress for the matte Sn and an essentially zero stress for the satin bright tin. This is consistent with the observation that bright Sn shows the most whisker and satin bright Sn shows the least whisker.

Internal stress in the bright Sn coating was also measured using x-ray diffraction (XRD). In a XRD experiment, the change of the lattice constant due to the stress is measured. The macro-stress can than be calculated from this measurement. XRD provides means for non-destructive and local stress measurement. The real-time analysis of stress evaluation during the aging can also be performed.

The stress measurement results are summarized in Tab. 1. Measurements were performed both along the rolling direction as well as perpendicular to the rolling direction. As Tab.1 demonstrate, both directions show virtually identical stress, indicating an isotropic biaxial stress in the Sn coating. No shear stress was observed on any samples. The as-plated bright Sn coating on Cu shows compressive stress of about 5 MPa, consistent with the in-situ stress measurement on this sample. The same sample after aging for 15 months at room temperature shows a much higher compressive stress. The increase of the stress during the aging is most likely related to the intermetallic formation. The diffusion of Cu into the Sn coating occupies more space and generates compressive stress in the Sn-coating[12-13]. The built-up of compressive stress during the aging explains the incubation time observed for the whisker growth on bright Sn. The presence of a Ni-underlayer minimizes or even eliminates the diffusion of Cu into Sn and Sn-Cu intermetallic formation. As a result of that, no compressive stress is observed on Sn/Ni/Cu.

Tab. 1 Internal Stress measured by XRD

	Aging Time (M)	0^o	90^o
Sn/Cu	As plated	-4 ± 1 MPa	-5 ± 2 Mpa
Sn/Cu	15 months	-13 ± 2 MPa	-14 ± 1 MPa
Sn/Ni/Cu	3 months	14 ± 1 MPa	12 ± 1 Mpa

Conclusion:

Local structure and chemical composition of the whisker were studied using FIB, SAM and SEM/EDS. Residual macro-stress was also measured using XRD. Compressive stress (residual as well as generated by Sn-Cu intermetallic formation) has been identified to promote whisker formation.

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