Tin (Sn) whisker growth from electroplated Sn finished

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Abstract. Electroplated tin (Sn) finishes are widely used in the electronics industry due to their excellent solderability, electrical conductivity and corrosion resistance. However, since prohibiting the use of lead (Pb) in electronics, the issue of tin (Sn) whisker has become one of the most imperative issues that need to be resolved. Moreover, with the increasing demand for electronics miniaturization, Sn whisker growth is a severe threat to the reliability of microelectronic device. This paper investigates the effect of electroplating current density (10, 30 and 50 mA/cm²) on whisker growth at room temperature. A simple micro-indentation test was used to accelerate continuously the growth of Sn whisker at room temperature storage for 24 h. Morphology analysis of Sn whisker growth was done using scanning electron microscope (SEM) and image-J Software. Axial length of the Sn whisker was calculated by using JEDEC Standards (JESD22-A121A).

1 Introduction

Electroplated Sn finishes are widely used in the electronics industry due to their excellent solderability, electrical conductivity and corrosion resistance [1-4]. However, since the implementation of the Restriction of Hazardous Substances Directive (RoHS) in 2006 prohibiting the use of lead in electronics, the issue of tin (Sn) whisker has become one of the most imperative issues that need to be resolved. Moreover, with the increasing demand for electronics miniaturization, Sn whisker growth is a severe threat to the reliability of microelectronic device [1, 5, 6]. Sn whisker is a conductive tin structure that grows spontaneously from Sn finished surfaces, which can lead to well-documented system failures in electronics industries [7-11].

It has been believed that compressive stress in Sn solder coating is a necessary factor for tin whisker growth. Many factors may contribute to the compressive stress level in Sn solder finished, including residual stresses generated during plating process, grain size of coating, formation of intermetallic compound (IMC) due to interfacial reaction between Sn solder and copper substrate, mechanical loading, electroplating currents, and mismatch of coefficient of thermal expansion (CTE) between solder and substrate [5, 12-14].

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Limited study was discovered on the effect of electrical current on the growth of tin whiskers [15]. M.A. Ashworth et al. [1] studied the effect of electroplating parameters on tin whisker formation, they observed the electroplating current density strongly influenced the Sn grain structure of the electrodeposited coating and whisker morphology. As the deposition current density is increased, the deposit becomes increasingly columnar and the width of the columnar grains reduces, reflecting the reduction in grain size observed on the surface of the deposit. K.S. Kim et al. [16] have shown that the whisker has grain boundaries connected with the grain/whisker root to the intermetallic region and provides a path for highly-compressed intermetallic region tin atoms to diffuse toward the whisker grain boundaries.

This paper investigates the effect of electroplating current density on whisker growth at room temperature. A simple micro-indentation test was used to accelerate continuously the growth of Sn whisker at room temperature storage for 24 h. Morphology analysis of Sn whisker growth was done using scanning electron microscope (SEM) and image-J Software. Axial length of the Sn whisker was calculated by using Joint Electron Device Engineering Council (JEDEC) Whisker Standards (JESD22-A121A).

2 Methodology

In this experiment, pure Sn was electrodeposited onto Cu substrate (>99.9% Cu) using sulphate-based electroplating solution. Sheared Cu substrate 1.5 cm x 1.5 cm squares of 1.0 cm in thickness was immersed into acid liquid bath that contain of 5 g (35%) of hydrochloric acid with 95 g of deionized water (1.75%) for 5 s to remove surface oxides, rinsed with acetone followed by distilled water and dried. Electroplating was performed at different current density of 10, 30 and 50 mA/cm² calculated using Eq. 1. The time constant has been set up to 20 minutes.

\[
\text{Current density, mA/cm}^2 = \frac{\text{Current, mA}}{\text{cross-sectional area, cm}^2}
\]  

Eq. 1

Micro-indentation test, shown in Fig.1 is consisted of a 200 g weight was used to accelerate the growth of Sn whisker at room temperature storage. After the samples were indented for 24 hours, morphology analysis of Sn whisker growth was done using scanning electron microscope (SEM) and image-J Software. Length and density of the Sn whisker was calculated by using Joint Electron Device Engineering Council (JEDEC) Whisker Standards (JESD22-A121A). Based on JESD22-A121A, the axial length of whisker was measured from the electroplated surface to the whisker tip, shown in Fig.2.

![Fig. 1. Schematic of micro-indentation test apparatus for accelerated Sn whisker growth.](image-url)
3 Results and Discussion

Tin whiskers growth from Sn electroplated finished with different current density 10, 30, 50 mA/cm$^2$ has been observed after 24 hours of mechanical indentation test. Most of the observed whiskers had striations along the outer surface. Fig. 3 show the SEM images of Sn grain structure coating and type of Sn whiskers. It is evident that the grain structure of the electrodeposited tin coating is strongly influenced by deposition current density [1]. As the deposition current density is increased from 10 to 50 mA/cm$^2$ the grain size of the electrodeposited tin decreases. The increased grain size might be as a result of hydrogen evolution which was observed at the deposit surface during electroplating. Increasing levels of hydrogen evolution may hinder the adsorption of the plating additives onto the sample surface of the tin during deposition and result in an increased tin grain size. Hydrogen evolution may also increase mass transport and encourage grain growth rather than fresh nucleation. At a deposition current density of 100 mA/cm$^2$, the tin grains frequently have a cubic morphology. As the deposition current density increases the tin grain boundaries become progressively less faceted [1].

The length of whisker becomes slightly less as the deposition current density is increased. The longest filament needle shape whisker found is 29.6$\mu$m with the average diameter is 1.0$\mu$m for 10 mA/cm$^2$ as shown in Fig.3(b). In Fig.3 (d), the length of filament whiskers growth on substrate for 30 mA/cm$^2$ current density is 9.93$\mu$m and its diameter is 0.64$\mu$m. For 50 mA/cm$^2$ current density (Fig.3(f)), the ribbon shape whisker was initiate with average length 2.2$\mu$m-3.9$\mu$m and the diameter is 1.1$\mu$m-1.2$\mu$m. Studied by B. Jiang et al. [17], indicate that the ribbon like whiskers morphology often observed on finish plated with sulfate-based electrolyte and has a smooth surface with size is shorter and larger [17].

W.J. Boettinger et al. [18] believed the growth of hillocks is also a factor of compressive residual stress similar to the growth of whiskers. Growth of the hillock is often said to be localized diffusional creep or grain boundary sliding phenomenon which relieves the compressive stress. The differences between whiskers and hillock is surely about the shape. The whiskers shape emerges outward from the surfaces with very thin such as single filament or hair-like protrusion. The hillocks shape is growth of precursor to whiskers, but due to its size is not harmful, it is not considered to be whiskers [18].
Fig. 3. SEM images of Sn whisker growth from Sn electrodeposition coating with different current density (a) Sn deposition at 10 mA/cm² (b) Sn whisker at 10 mA/cm² (c) Sn deposition at 30 mA/cm² (d) Sn whisker at 30 mA/cm² (e) Sn deposition at 50 mA/cm² (f) Sn whisker at 50 mA/cm²

The driving force for whisker formation is generally accepted to be stress generated by the formation of Cu-Sn intermetallic (IMC) between the Sn and Cu. High compressive average residual stress was present in thinner films and the stress decreased with increase the film thickness. Fig. 4 shows the formation of Sn–Cu intermetallic compounds (IMC) at the interface between the electroplated Sn solder and the Cu substrate for 50 mA/cm² current density. The average thickness of Sn solder deposition is 19.4µm, and the average thickness of IMC is 0.42µm. The presence of IMC occurs when Cu seeps into the film Sn. The density changes between Cu₆Sn₆ and Cu causes the volume expansion on the IMC layer. Thus, the compressive stress is generated by the expansion of the volume in the vertical direction of the Cu and Sn interface. Therefore, compressive stresses can enhance to accelerate the growth of whiskers. Basically, IMC is able to promote whisker growth, but whisker growth is not directly proportional to IMC thickness [16, 19, 20].
Fig. 4. SEM images of the formation of Sn–Cu intermetallic compounds (IMC) at the interface between the Sn electrodeposit and the Cu substrate for 50 mA/cm² current density.

4 Conclusions

From the research, the following conclusions have been obtained;

i. After 24 h continuously indented by mechanical compressive stress with different current density 10, 30, 50 mA/cm², the tin whiskers growth from Sn electroplated finished. The grain structure of the electrodeposited tin coating is strongly influenced by deposition current density. As the deposition current density is increased from 10 to 50 mA/cm² the grain size of the electrodeposited tin decreases.

ii. The length of whisker becomes slightly lessen as the deposition current density is increased. The longest filament needle shape whisker found is 29.6µm with the average diameter is 1.0µm for 10 mA/cm². Meanwhile for 50 mA/cm² current density, the ribbon shape whisker was initiate with average length 2.2µm-3.9µm and the diameter is 1.1µm-1.2µm.

iii. Sn whiskers significantly is the most dangerous to circuit reliability as the conductive Sn whiskers can grow to several hundred microns, which are long enough to cause electrical shorts circuit by bridging neighbouring conductors or may break off and cause damage elsewhere in the device.

This work was financially supported by Unimap-Nihon Superior Research Colaboration (Grant No: 2016/10/0001) and Tin Solder Technology Researchs Group (TSTRG) Research Grant 2019.
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