Tin Whiskers on Lead-free Platings

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Abstract

Electroplated tin can be considered as a drop-in replacement for SnPb finishes on the terminations of semiconductor devices. However, Sn layers are known to form whiskers. These whiskers are spontaneous protrusions of few microns in diameter and up to hundreds of microns or even millimetres in length. These might cause short-circuits and the failure of electronic circuits. This paper shows that no accelerated test method is available for whisker growth and presents a mechanism for whisker growth, based on compressive stress that is introduced by irregular growth of intermetallics at the substrate/plating interfaces. This mechanism is illustrated with views of the intermetallics and diffusion theory. Furthermore, countermeasures to prevent whisker growth are presented. These countermeasures are explained with the help of the above-mentioned mechanism.

Introduction

With the introduction of lead-free soldering technology, also the SnPb finishes on the component leads also have to be replaced. For this purpose several options can be considered. Since post-plating is common practice, it is logical to look at replacement for the SnPb plating. In Table 1 SnPb as component finish is compared with the most common alternatives.

Aspect	Sn Bright	Sn Matte	SnBi Bi<4%	SnCu	SnAg	SnPb
(1) Solder Wettability	+	+	+	+/-	+	++
(2) Heat Resistance	See MSL					
(3) Adhesion to lead-frame	+	+	+	+	+	+
(4) Resistance to Leadbending	-	+	+/-			++
(5) Soldered joint Reliability	(+)?	+	+	+	+	+
(6) Corrosion Resistance	+	+	+		+	+
(7) Whisker resistance	-	+/-	+	-		++
(8) Migration resistance	+	+				+
(9) Cost	+	+	-	-	--	++
(10) Mass Productivity	++	++	+	+	-	++
(11) Compatibility	+	+	+	(+)	(+)	+
(12) Eco Impact	++	++	+/-	+/-	--	-

Table 1: Comparison of SnPb as post-plating with several Pb-free post-platings

As can be seen in Table 1 matte Sn could be used as a drop-in substitute for SnPb. The only problem remaining is the whiskering issue. Whiskers are spontaneous protrusions of a few microns in diameter and up to hundreds of microns or even millimetres in length (Fig. 1). They grow within weeks to years and a method of control has yet to be developed.

Since discovery of this phenomenon in the 1940s many publications have dealt with this issue. [1-7] However, a definitive explanation of the growth mechanism and a method to prevent whisker growth, have never been presented. In this paper we will discuss further details about whisker test conditions and present further evidence, based on work carried out in Infineon, STMicroelectronics and Philips. These companies have worked together, to show that compressive stress, caused by irregular intermetallic formation, is the root cause of whisker growth.

Fig. 1: Whiskers growing on a bright Sn plating

Experimental

Tin layers have been deposited on typical lead-frame materials, such as C19400 (CuFe2P), C1870 (CuCrSiTi), C70250 (CuNi3Si1Mg), C14415 (CuSn0.15), Alloy 42 (FeNi42), copper plated Alloy 42 and others. Various electrolytes from six different suppliers have been used, and in general, continuously operating electroplating production lines and laboratory scale set-ups employed. The thickness of the deposits was varied between 1.5 µm to 15 µm.

Plating surfaces have been studied with both optical microscopy and scanning electron microscopy (SEM).

In order to influence the whisker growth, several heat treatments and storage conditions have been used. The heat treatment was varied between 125 and 150 ^{o}C for times ranging from 15 minutes to 90 hours. The storage conditions have been selected based on the publications of various companies and institutes.

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The storage conditions after plating were:

- Ambient atmosphere (uncontrolled)
- 55 °C / ambient atmosphere
- 55 °C / 85 % relative humidity
- 5 °C / ambient atmosphere
- 85 °C / 85 % relative humidity
- Temperature cycling –35 °C / + 125 °C (500 cycles)
- Temperature cycling –55 °C / + 85 °C (500 cycles)

Cross-sections of the plating layers have been prepared and viewed with optical microscopy and SEM. To study the intermetallic compounds formed after plating and storage, a commercially available Sn stripper was used that selectively etches the Sn, while not attacking the intermetallic compound and lead-frame material.

Results and Discussion

For qualification purposes it is of major importance for industry to have an accelerated test for whisker growth and have an industrially accepted standard for whisker testing. The fact that until now no generally accepted acceleration test has been developed might be a reason why the whisker issue remains unresolved. As stated in the previous section, several storage conditions have been investigated in order to accelerate whisker growth. Figure 2 gives the temperature storage results.

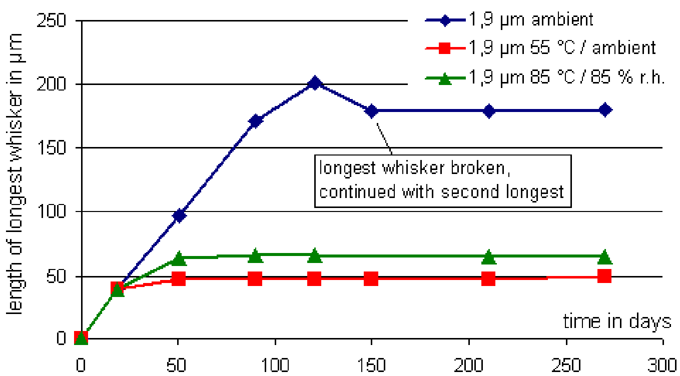

Fig. 2: Whisker growth under various storage conditions on a Cu-alloy lead-frame plated with 1.9 µm Sn

Referring to Fig. 2 it becomes clear that ambient temperature produces the longest whiskers for Cu alloy lead-frames. It should be noted that in the first few days (up to around 10 days) whisker growth at elevated temperatures is faster than at room temperature. Storage at lower temperature or storage with a higher relative humidity did not result in significantly longer whiskers.

When comparing different layer thicknesses at ambient storage (Fig. 3) several conclusions can be drawn.

The most obvious conclusion is that with increasing thickness the whisker length decreases. Secondly, incubation time for whisker growth appears to be longer for thicker layers. Thirdly, it can be concluded that whisker growth levels off after an initial growth period.

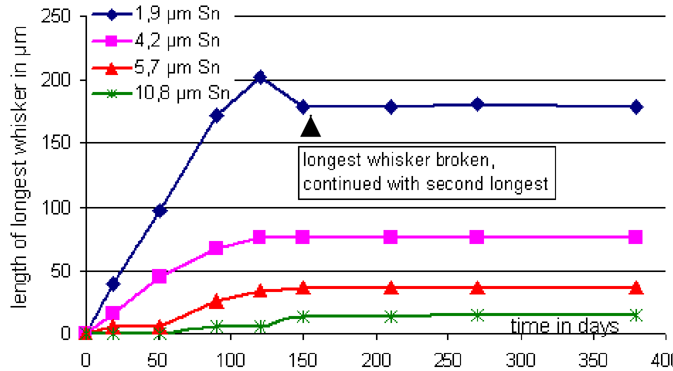

Fig. 3: Whisker growth for various thickness of tin, plated on copper alloy lead-frame.

Another method used to accelerate whisker growth often stated in literature is temperature cycling. After performing temperature cycling, under the conditions mentioned previously, it became clear that, if NiFe (A42) was used as lead-frame material, whisker growth was abundant (Fig. 4), in contrast with isothermal storage. Temperature cycling on Cu-based lead-frames did not result in excessive whisker growth. It has been concluded that this difference in whisker performance is due to the difference between coefficient of thermal expansion (CTE) of A42 and Sn (CTE(A42) = 5.5 ppm/K; CTE(Sn) = 23 ppm/K). This difference is much smaller between a Cu-alloy lead-frame (CTE(Cu) = 17 ppm/K) and Sn.

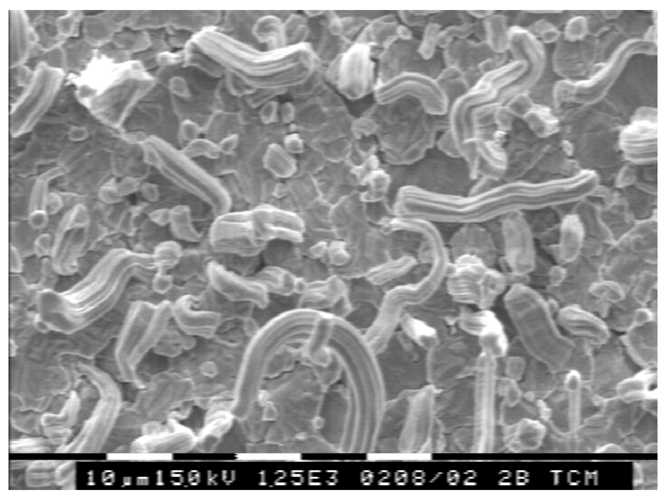

Fig. 4: Surface of a 5 µm Sn on A42 after 500 temperature cycles from –55 to 85 °C

Repeating the temperature cycling with A42 plated with SnPb also resulted in whisker growth. From these results it becomes clear that temperature cycling is not a test method reproducing the whisker growth mechanism during storage.

Several other whisker growth tests have been proposed, such as biased testing or applying external stress, but it is unclear whether these represent the proper whisker mechanism under storage and if these are discriminative enough. [4, 9]

These results leave us without an accelerated test and in order to judge other tests and solve the problem of whisker

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growth, a more fundamental understanding of the mechanism is necessary.

Nowadays, it is the general opinion that compressive stress plays an important role in the whisker formation, as stated by Lee and Lee. [7] This compressive stress can be caused by different factors. In bright Sn layers it is assumed that the stress is generated by organic inclusions in the plating. Lee and Lee state that this compressive stress is caused by irregular growth of Cu_6Sn_5 intermetallic at the Cu/Sn interface. Tu stated this previously. [8]

Simple calculation of the volume change occurring because of growth of Cu_6Sn_5 shows that the volume can increase with 45% maximum. This volume increase can result in compressive stress in the plating layer. Combining this with the results thus far mentioned, it becomes possible to give some explanations.

To study the growth of the Cu_6Sn_5 intermetallic growth Olin194 (CuFe2P) strips of equal size were weighed and plated with approximately 8 µm matte Sn. After plating the strips were stored at room temperature, 55 ^oC and 150 ^oC. At various times the strips were removed, the Sn selectively etched away and the strips weighed again. The weight difference can be attributed to the formation of intermetallic compounds (Cu_6Sn_5 in all storage conditions and Cu_3Sn at 150 ^oC). Figure. 5 shows the weight increase of the strips at room temperature compared to 55 ^oC. In this figure we can see that the intermetallic grows faster at 55 ^oC than at room temperature. But it also becomes clear that the intermetallic formation at 55 ^oC slows down earlier, due to the fact that diffusion follows Fick's law, meaning a parabolic growth rate.

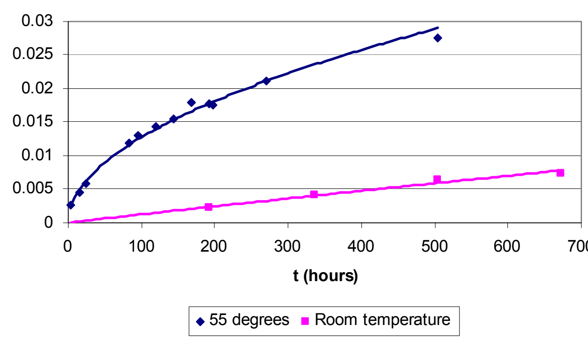
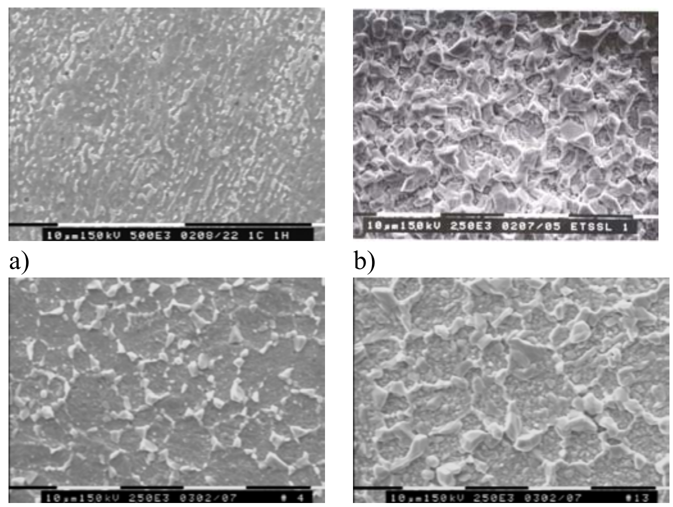


Fig. 5: Comparison of intermetallic growth at room temperature and 55 ^oC

Looking at the morphology of the intermetallic results in additional information supporting the theory (Fig. 6). In Fig. 6 the morphologies of the intermetallics formed during storage at room temperature and 55 ^oC are given. One hour after plating some Cu_6Sn_5 is already present (Fig. 6a). During storage at ambient temperature the Cu_6Sn_5 will continue to grow and cover the whole surface (Fig.6b). The former grain boundaries can still be discerned, because at room temperature grain boundary diffusion will be much more predominant than bulk diffusion. That is why large irregular intermetallics can be seen under what used to be the grain boundaries of Sn. While where the base of the Sn crystal used to be the lead-frame material is visible (Fig. 6c). While at elevated temperatures such as 55 ^oC, the ratio between grain boundary and bulk diffusion will slowly shift in favour of bulk diffusion. In Fig. 6d irregular Cu_6Sn_5 can be seen at what used to be the grain boundaries but the same intermetallic is present at what used to be the base of a Sn crystal. This results in less irregularity of the intermetallic and thus less stress.

Currently, we are combining the information gained from top views such as presented in Fig. 6 together with information gained from the irregularity in cross-sections in order to model the stress generated by Cu_6Sn_5 formation in the Sn plating layer.



a) b)

c) d)

Fig. 6: Top view of Cu_6Sn_5, after etching a 8-10 µm Sn layer, formed one hour after plating in ambient temperature (a), after 1 year (b) after 504 hours at ambient temperature (c) and 504 hours at 55 ^oC (d)

From these results and those from Fig. 2, several conclusions can be drawn concerning the storage condition most favourable for whisker growth.

At temperatures lower than room temperature intermetallic formation will be much slower due to the fact that the process is thermally driven and diffusion limited. This explains why lower temperatures will not result in accelerated whisker growth.

It should be noted that the type of lead-frame material is also of importance. It has been known that impurities, like the Fe in C19400, can influence short-circuit diffusion. [10]

This also explains why no whisker growth has been observed on a NiFe lead-frame at isothermal storage: the morphology of the intermetallics and the kinetics of formation is different.

With the above-mentioned explanation of the whisker growth mechanism it is now possible to define measures to prevent whisker growth. The first countermeasure discussed previously is the use of thicker layers. Thicker layers (> 7.5 µm) are able to absorb more stress and thus whisker growth will be retarded. However, thickness control cannot be

ISBN # 1-892568-76-4

considered as countermeasure that prevents the cause of whisker growth. So eventually whiskers can still grow.

The second countermeasure is to apply a post-bake after plating. A post-bake at 150 °C during one hour has been tested and subsequently no whiskers have been observed over a period of one year. During this post-bake the diffusion mechanism responsible for the intermetallic formation shifts from grain boundary diffusion at room temperature, which is responsible for irregular Cu_6Sn_5, to bulk diffusion which causes more regular intermetallics and thus less stress. Additionally, the stress already present will be annealed during the post-bake procedure. The smaller irregularity of the Cu_6Sn_5 can be seen in Fig. 7.

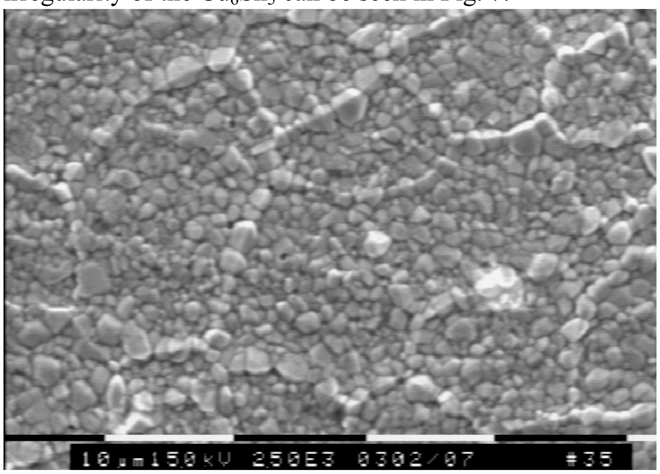


Fig. 7: Top view of Cu_6Sn_5 after 1 hour at 150 °C and subsequent etching the 8 μm Sn layer

After the post-bake a thick, more uniform Cu_6Sn_5 layer has formed, which will serve as a diffusion barrier for irregular formation of Cu_6Sn_5 through grain boundary diffusion at ambient temperature later on.

The last countermeasure to be mentioned here is the use of an under-layer, i.e. Ni or Ag. A commonly applied underlayer is Ni. Using a Ni underlayer on a Sn plating results in Ni_3Sn_4 intermetallic compound. Using the same calculation as was used previously for the Cu-Sn system, it appears that the volume change in the case of Ni_3Sn_4 formation would be maximally 16%. Other differences between Ni-Sn and Cu-Sn systems, influencing the stress build-up, are the morphology and the kinetics of intermetallic formation.

Regarding the morphology of intermetallics, Ni_3Sn_4 forms in a plate-like structure contrary to the irregular intermetallics of Cu-Sn described above.

It is known that intermetallic formation in the Ni-Sn system is slower than in the Cu-Sn system, resulting in less intermetallics in the same time period. [11] Similar arguments hold for Ag underlayers (see Fig. 8).

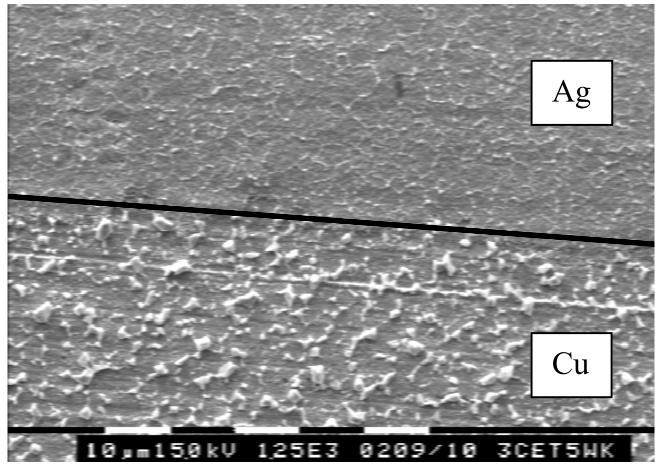


Fig. 8: Top view of intermetallics after 5 weeks at ambient atmosphere on a Cu-alloy lead-frame with a Ag spot, plated with 10 μm Sn (etched away).

Conclusions

Despite the whisker issue Sn post plating can be seen as a drop-in substitute for SnPb post plating.

Unfortunately, no accelerated test is available for whisker growth. For now room temperature storage results in the longest whiskers in the same time period for Cu alloy lead-frame material. Temperature cycling induces another mechanism for whisker formation on A42 than that during isothermal storage.

Whiskers form because of compressive stress, generated by irregular intermetallic formation. This Cu_6Sn_5 formation is more irregular at lower temperatures due to the predominance of grain boundary diffusion over bulk diffusion at low temperatures.

There are a number of countermeasures to combat whisker growth. One countermeasure is the use of Sn layer thickness of more than 7.5 μm. A second countermeasure is the application of a post-bake at e.g. 150 °C for one hour, resulting in more regular intermetallics, which serve as a diffusion barrier at ambient atmosphere later.

Another option discussed as a countermeasure is the use of an underlayer, which changes the intermetallics that are formed.

Acknowledgments

The authors would like to thank the electroplating departments of Philips, Infineon, and STMicroelectronics. Furthermore we thank the European Union which funds parts of the existing and ongoing work within the IST programme under the acronym PROTIN.

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ISBN # 1-892568-76-4