Lead-free Electroplated Layers as Solderable Finish for Semiconductor Devices

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1 Motivation

Lead-free production is one of the hot topics of the last years, whereas the questions of why and whether at all to convert to lead-free production has been replaced by the questions of how and when. Especially the time frame of conversion for board assemblers is often discussed with respect to availability of lead-free active and passive components. Furthermore different lead-free finishes are currently under discussion and available only on engineering sample level or not on the necessary product. The decision for the appropriate material is currently handled in a vicious circle, which is marked by the questions: What will be offered? What will be accepted? The lack of standardised test methods empowers the uncertainty both for semiconductor suppliers and board assemblers. The discussion is mainly driven by the necessary compatibility for lead-free and tin-lead soldering and the fear of whiskers. Hence the various options for leadframe components will be introduced and compared on a technical basis. The following pages shall highlight different aspects for the choice of the right material and will end with a recommendation for lead-free plating.

The current status of standardisation regarding lead-free and halogen-free products and processes has been described by [Dittes 2001] and has not improved since. Hence most of the results are based on the test methods and parameters recently published by the three largest European semiconductor manufacturers [IFX 2001] or currently valid standards.

2 Lead-free plating options

As today the solderable leadframe finishes can be divided in two groups. These are all kind of preplated finishes, which are applied before components assembly and postmold platings, which are deposited after molding of the plastic housing of the components. To the first group belong all variants of NiPd finishes, which are well known for more than one decade and will not be addressed in detail. However it should be noted that the increased temperatures for lead-free soldering processes generally are advantageous for NiPd-finishes in terms of wetting.

For postmold platings pure tin (Sn), tin-silver (SnAg), tin-bismuth (SnBi) and tin-copper (SnCu) alloys are under consideration. Meanwhile two major trends are to be observed. These are SnBi in Japan and pure tin in Europe and the United States.

Table 1 summarises the main factors that have to be considered for the choice of the appropriate alloy.

Table 1: Overview of the properties of various options for lead-free post mold platings

	Tin	SnBi	SnCu	SnAg
Wettability	+	+	+/-	+
Ductility	+	-	-	
Corrosion resistance	+	+		+
Whisker resistance	+/-	+	-	
Cost	+	-	-	--
Mass productivity	++	+	+	-
Compatibility	+	+/-	+	+
ECO-impact	++	+/-	+/-	-

++ very good, + good, +/- fair, - poor, blank field = no information

For SnAg mainly the poor availability, the relatively high costs, difficulty in alloy control and poor performance of the electrolytes in terms of processability have been the blocking points of introduction and will not be overcome in the next years.

The first electrolytes for SnCu have been designed for an eutectic deposition (SnCu0,7). This composition is very difficult to control and to measure especially on Cu-leadframes. Furthermore a very high propensity for whisker growth has been observed. Later developments now aim at a deposition of increased copper content (2 % - 3 %) and show better whisker performance. However the difficulties in process control are the main factor for limited acceptance at platers and will most likely hinder a broad introduction of SnCu plating.

SnBi has at first been introduced by Japanese manufacturers. For better understanding the history of this development shall be highlighted as follows. Bismuth is closest to lead (Pb) from metallurgical point of view and reduces the melting temperature of tin significantly [Hansen 1958]. In order to find an alloy with a melting range nearest to SnPb, SnBi with bismuth contents of approximately 10 % have been investigated in Japan. Due to brittleness and cracking in bending zones of leads the Bi-content has been reduced to approximately 3 %. This alloy performs well regarding solderability and reduces whisker growth almost to zero. When Japanese companies introduced first SnBi platings the knowledge in Europe and the US was very limited and no clear trend obvious. Hence Japanese companies agreed on SnBi.

Pure tin however has great advantages from the processability point of view. The composition of an alloy deposited by electroplating is dependent from the current density and varies due to the geometry of a leadframe [Dittes 2000]. Furthermore the composition within the electrolyte must be controlled very tightly because of the small range of appropriate composition of the deposit (e.g. ± 1,5 % for SnBi). For mono metals alloy control is no issue. Despite the well known propensity for whisker formation of electrodeposited tin layers [Fisher 1954], [Lee 1998] some concerns against SnBi made Europe and America favour pure tin. One concern is the fear of the appearance of the ternary Bi-Pb-Sn eutectic with a melting point of 96 °C [Osamura 88] when soldered with SnPb alloy, which might cause a decline of reliability. Another concern is a recycling issue. Most electronic waste is recycled via the copper converter route by copper smelters. Copper is very sensitive for Bi-contamination and suffers from hot shortages at Bi contents above some ppm. This is feared to have a negative cost effect for Bi-containing electronic waste.

However, according to the above statements only Sn and SnBi are viable options for the majority of applications and will be discussed in more detail.

3 Experimental

3.1 Plating process

All plating trials have been performed using a production belt line by MECO, whereas all descaling, activation and rinsing processes remained unchanged compared to standard SnPb processing. The only change made was a replacement of the SnPb elctrolyte by either SnBi or pure tin and a replacement of SnPb anodes by pure tin anodes in both cases. The electrolytes used are commercially available methane sulfonic acid (MSA) based and newly developed for the deposition of matte layers. After determination of the optimum parameter range (temperature, current density range, metals content, additive content) mainly the factors Bi content and current density (for SnBi) and layer thickness (for Sn) have been varied, whereas the belt speed has been adjusted in order to achieve either constant thickness for the variation of the current density or altered to influence the thickness of the deposit at constant current density.

In cases where additional Ni-underlayer has been applied before the deposition of tin, this Ni was deposited from a Ni-sulfamate electrolyte in the same process after descaling and prior to intense rinsing and tin plating.

3.2 Solderability

Solderability tests are performed using semiconductor devices for a dip & look test and test strips for measurements with a wetting balance (MUST II by Multicore). Components and strips have undergone various preconditions prior to testing. These are:

- as plated
- 155 °C / 16 h
- 85 °C / 85 % r.h. / 48 h or
- steam ageing 8 h

The solders used for dipping are SnPb40 (dip & look), SnPb36Ag2 (wetting balance) and SnAg3,8Cu0,7 (both tests) at temperatures of 215 °C for SnPb(Ag) solder and 245 °C for the lead-free in the dip & look test. The typical test temperature for wetting balance testing was 235 °C for SnPbAg and 245 °C for SnAgCu solder. The flux used for dip & look was a mixture of 25 % colophony and 75 % isopropanol. For the wetting balance test a low activated no-clean flux (CR 32 by Multicore) was used.

The leads of the components have been applied to SEM inspection in order to identify cracks in bending zones prior to solderability testing and to correlate to any wetting problems.

3.3 Whisker test

No appropriate accelerated test methods are known today. Hence a storage at ambient uncontrolled conditions is compared to storage in 55 °C / ambient humidity, and 85 °C / 85 % r.h. Whiskers have been investigated in optical microscope at at least 50 times magnification and their length measured at 200 times magnification with a digital measuring tool. Accuracy was at least ± 2 µm. The longest whiskers have been marked in order to identify for later inspection again and length documented for every 4 weeks. Leadframe material was K75 by Wieland (CuCrSiTi)

3.4 Board level reliability

Board level reliability tests have been performed with TQFP-100 and TO-263 daisy chain packages plated with pure tin and SnBi3 of approximately 8 µm thickness. The test board was a four metals layers conventional FR4 board, thickness 1.2 mm, metallisation Ni/Au. The components have been soldered to the boards by the use of SnPb36Ag2 (Litton Kester 229D) and SnAg3,8Cu0,7 (Multicore 96 SC) solder paste. The corresponding temperature profiles have been adapted in a convection system under nitrogen atmosphere. The lowest peak temperature at solder joint was well below 200 °C for the conventional paste and below 235 °C for lead-free soldering.

After initial optical inspection the boards have undergone temperature cycling between -40 °C and +125 °C, whereas two different ramp rates (10 K/s to 15 K/s and 5 K/min to 8 K/min) and dwell times (20 min and 30 min respectively) were used. The resistance of daisy chains was measured off-line every 250 cycles and cross sections prepared after 1000 and 2000 temperature cycles.

4 Results and discussion

4.1 Processability

For pure tin the general performance of the electrolyte, such as applicable current density, temperature, metal content and thickness deviation is of major interest. It was noted that the electrolyte performes in the typical range for SnPb electrolytes up to more than 20 A/dm² and needs no special control. The thickness deviation is even superior to the SnPb electrolytes currently used. From processability point of view the tin electrolyte is acceptable. However the more dull or satin bright appearance of the deposit reveals any inhomogeneities, which are hardly to be avoided. These are regarded to be only a cosmetic defect without impact on solderability.

For SnBi an influence of current density on the composition can be observed [Dittes 2000]. The bismuth content decreases with increasing current density (Figure 1 and Figure 2). Due to the use of pure tin anodes all the consumed bismuth has to be replaced directly to the electrolyte. The bismuth content in the electrolyte corresponds directly to the composition of the deposit (Figure 3) and requires a very tight control.
Moreover the bismuth tends to cement on metallic surfaces (e.g. the anodes) as soon as the current drops to zero. Especially when different products are processed

in the same line or when the line stops frequently the composition must be controlled with an automatic analysis and dosing system.

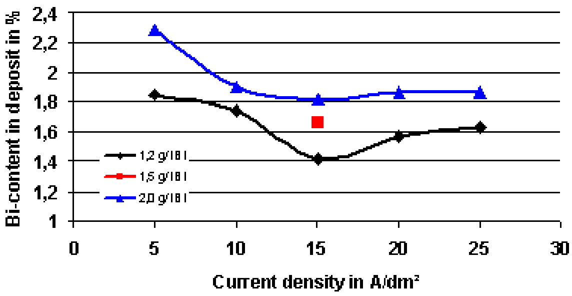

Figure 1: **The Bi content decreases by a maximum of 0,4 % in a range of 20 A/dm²**

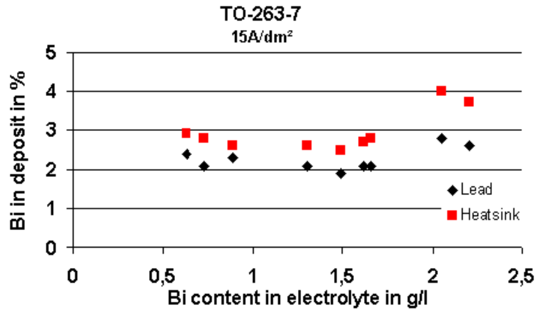

Figure 2: **Lower current density on heat sink causes increased Bi content in the deposit**

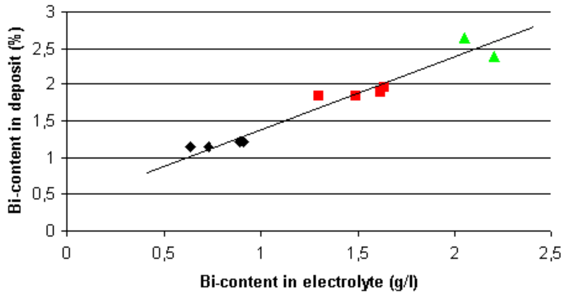

Figure 3: **An increase by 1 g/l Bi in the electrolyte corresponds with an increase of nearly 1 % Bi in the deposit**

Another serious concern with SnBi is that no rework is possible for copper leadframes, because the bismuth is not able to be stripped by chemical means only without affecting copper.

4.2 Solderability

According to [IEC 1999] the solderability of surface mount devices shall be tested in SnPb40 solder at 215 °C for 3 s. Applying this test to components with big thermal mass and high thermal conductivity such as components with large heatsinks, the different wetting properties of SnPb and lead-free platings becomes obvious. After a humid preconditioning such as steam ageing or 85 °C / 85 % r.h. storage components fail in this test. All other components even pass this test without any failure – even after preconditioning as described in section 3.2. Otherwise perfectly wetted terminations had been observed in all board level assembly trials with these components – even at very low reflow peak temperatures (see section 3.4). Hence 215 °C / 3 s are regarded as not being the appropriate test conditions. Increasing test temperature to 235 °C the components will pass again, which reflects the assembly process situation more properly. The use of lead-free solder at a temperature of

245 °C never revealed any failure, wherefrom it can be concluded that the current test conditions with SnPb solder mark the more severe test.

A more quantitative description is possible by the use of the wetting balance. Comparing Sn and SnBi plating to SnPb in the state as plated there is almost no significant difference to be observed when using SnPbAg solder at 235 °C (Figure 4). The use of lead-free solder at 245 °C shows a somewhat slower wetting for the lead-free alloys (Figure 5), but is still regarded as acceptable.

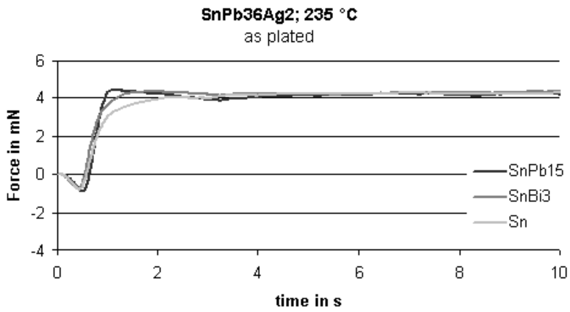

Figure 4: Wetting of SnPb15, SnBi3 and Sn as plated on copper with SnPbAg solder

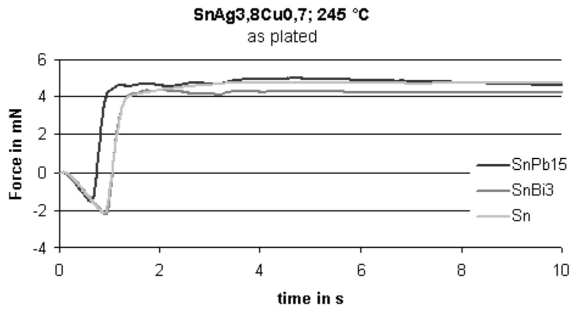

Figure 5: Wetting of SnPb15, SnBi3 and Sn as plated on copper with SnAgCu solder

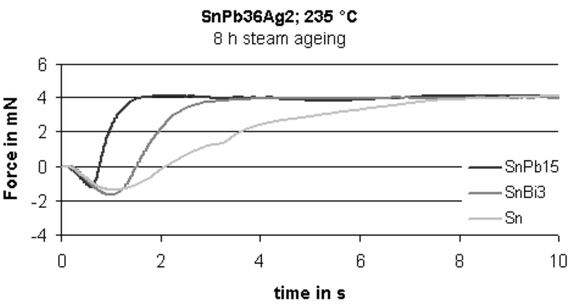

Figure 6: Wetting of SnPb15, SnBi3 and Sn plated on copper after 8 h steam ageing with SnPbAg solder

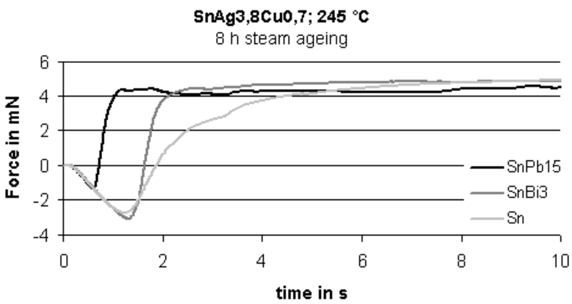

Figure 7: Wetting of SnPb15, SnBi3 and Sn plated on copper after 8 h steam ageing with SnAgCu solder

Steam ageing has a significant influence on the wettability of the platings, whereas the strongest effect can be observed for pure tin (Figure 6, Figure 7). However, the correlation of this test conditions to typical storage is unknown yet and must be investigated in more detail. In general it must be stated that lead-free platings will never meet the wettability of SnPb coatings. This statement is derived from wetting results at lower temperatures than the typical test temperatures as described above. On the other hand no defects have been observed in board assembly processes even at the low temperatures as described in section 3.4. This indicates that also tin and tin-bismuth platings will meet the requirements for electronics soldering.

Another aspect of solderability is the cracking of the coating in the bending area of the leads, which exposes the base material to atmosphere and causes non wettable heels due to corrosion. For pure tin platings no such cracks could have been found.

SnBi tends to cracking when exceeding a bismuth content of 3 % and plating thickness above 12 µm.

4.3 Whisker growth

There have been many reports on the phenomenon of whisker growth in the recent years [Zhang 2001], [Kadesh 2000] but with very inconsistent data. Especially there is no correlation available on the test method used and the growth rate under ambient storage conditions. The most popular test condition is a storage in elevated temperature (50 °C to 55 °C), which is right below the recristallisation temperature of tin. Another popular condition is the storage in high temperature and humidity (85 °C / 85 % r.h.). Both are regarded as having an acceleration effect on whisker growth. However, own investigations indicate that storage in uncontrolled ambient conditions cause longer whiskers than these so called accelerating conditions. One possible reason for contradictory results seem to be a shorter incubation time at elevated temperatures, but also an annealing effect which slows down the growth at later times. In summary it must be stated that no correlation for longer periods has been found yet and a correlation of the initiation of whisker growth to long time storage is not given.

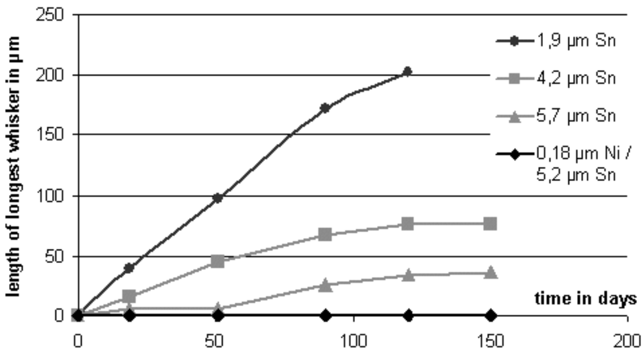

Figure 8: Whisker growth on tin layer at various thickness and with Ni-underlayer, storage in ambient conditions

Comparing the whisker growth rate and for various plating thickness in Figure 8 it can be derived that also the plating thickness has a significant influence on whisker formation, whereas thicker layers reduce the growth rate and maximum length of whiskers.

As can also be derived from Figure 8 a nickel underlayer of less than two micron thickness can prevent whisker growth for tin platings. Another effective method for the prevention of whisker growth is to apply an annealing process after plating. Typically 150 °C for one hour is sufficient to suppress whisker formation. The final goal for tin plating is to find a process that does not require any countermeasures as described. Therefore also effective test methods are needed. These are not yet available and need further research.

Whiskers have also been reported for SnBi and SnPb layers, but in our investigations no whiskers have been found on SnBi layers. SnBi is therefore regarded as whisker safe and requires no additional countermeasure like underlayers, annealing or an increase of the plating thickness.

4.4 Board level reliability

No failures could have been detected in the off-line measurement of the daisy chain resistance for none of the tested components. All combinations of plating (Sn, SnBi) and solder (SnPbAg , SnAgCu) passed 2000 temperature cycles, both the slow ramp (Figure 9, Figure 10) and the fast ramp cycling.

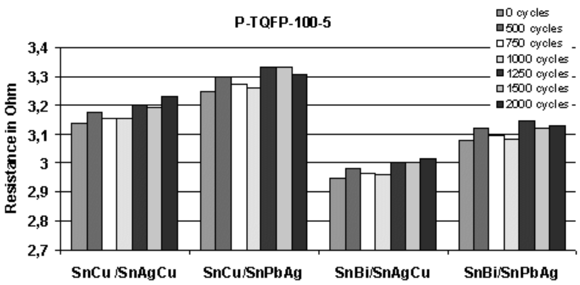

Figure 9: Resistance of daisy chains for TQFP-100 in various material combination up to 2000 temperature cycles (slow ramp rate)

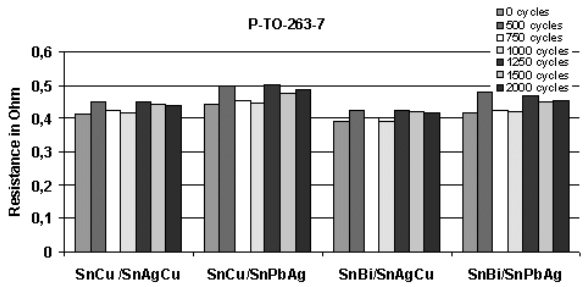

Figure 10: Resistance of daisy chains for TQFP-100 in various material combination up to 2000 temperature cycles (slow ramp rate)

The cross section confirm the electrical results. No critical degradation of the solder joint or any cracks have been observed, and no ternary eutectic Bi-Pb-Sn phase was found for the material combination of SnBi plating with SnPbAg solder. The test conditions exceed typical requirements by far. Hence both tin and tin-bismuth platings are compatible to standard and lead-free soldering.

5 Conclusion

Among the various options for lead-free post mold platings only pure tin and tin-bismuth are a reasonable choice and already widely used or under evaluation (SnBi in Japan, tin in Europe and the USA). From processability point of view SnBi is difficult to control and causes significant cost impact. Pure tin will be the closest drop-in replacement and requires no change of or complementary equipment and only little process adaptions. The wettability of both lead-free platings does not meet that of SnPb, but is acceptable for electronics soldering, whereas SnBi is slightly superior. Whiskers are no issue with SnBi, but require detailed investigation and more appropriate test methods, which are not available yet. However, countermeasures for whisker formation on tin platings are available and may act as an interim solution until whisker safe tin platings are found. Both the recycling issue with SnBi and the appearance of the ternary Bi-Pb-Sn eutectic are regarded as theoretical only and are of no technical relevance. In summary the poor processability and the fear of impact on cost or reliability affect the acceptance of both the component manufacturers and the board assemblers in a very serious way. Moreover, there are results indicating that a Bi-contamination in wave solder bath from SnBi-plated components can cause fillet lifting for through hole devices and will therefore not accepted. The whisker issue will be overcome within the next years. Hence pure tin will replace SnPb platings in the move towards lead-free components.

6 Acknowledgement

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