Tin Whisker Formation – Results, Test Methods and Countermeasures

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Abstract

Electroplated tin layers as used as lead-free solderable finish on the terminations of semiconductor devices are known to form whiskers. These whiskers are monocrystals of tin and grow within weeks to years with a diameter of some microns up to a length of several hundreds of microns or even millimetres. Thus they can cause shorts and the failure of a whole electronic circuit. This paper shows that these whiskers grow under the force of compressive stress in the layer, which is usually developed by the growth of an irregular intermetallic layer at the substrate / plating interface. We show that none of the actually known test methods can accelerate whisker growth or that growth rates can be correlated to ambient conditions. However, we show the effectivity of barrier layers to prevent whisker growth and propose a test method to judge on the whisker safety by extrapolation of the initial growth rate within the first weeks after electroplating.

Introduction

In the last decades the most popular solderable finish on semiconductor terminations was a tin-lead alloy in various compositions. Mainly caused by the recently adopted European directive on the “Restriction of certain Hazardous Substances (RoHS)” [1], which foresees among others the ban on lead (Pb), semiconductor industry is looking for and introducing alternative materials.

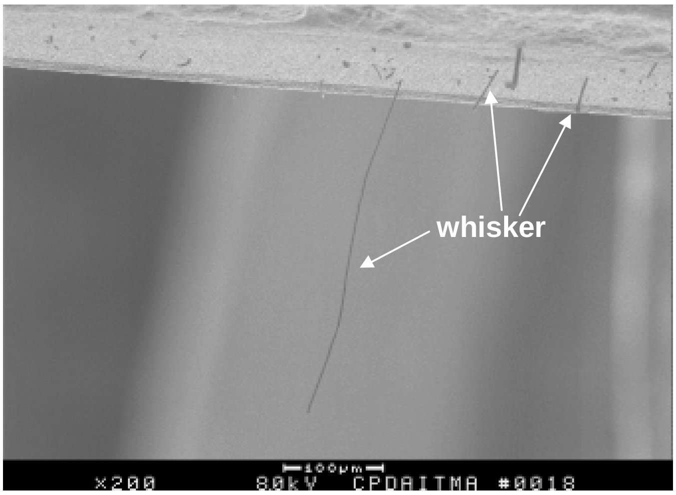

Fig. 1: Whiskers grown on SnCu1 plated copper after 1 year storage in ambient conditions.

From processability and compatibility point of view pure tin is the most viable option. But since the 50s [2] of the last century it is known that electroplated layers of tin and tin alloys show a certain propensity to whisker growth.

From literature, discussions in work groups and own investigations several conclusions have been drawn before having a closer look to existing results or designing new experiments. The most important conclusions are:

- The driving force for whisker formation is a compressive stress in the layer
- Whiskers grow from the bottom
- Whiskers are mono crystals of tin
- Whiskers can be straight, kinked, bended or of irregular shape
- Whisker propensity is influenced by alloying elements in the tin alloy
- Whisker propensity is different for various base materials, on which the tin layer is deposited

The most important questions that were subject of the subsequent investigations were:

- What is the origin of the compressive stress in the layer?
- How to suppress whisker growth?
- What is the appropriate test method to judge on the whisker safety of a tin layer?

Experimental

Tin layers have been deposited on typical leadframe materials, such as C19400 (CuFe2P), C18070 (CuCrSiTi), C14415 (CuSn0.15), C70250 (CuNi3Si1Mg), FeNi42, copper plated FeNi42 and others. Various electrolytes from six different suppliers have been used, whereas usually commercial continuously operating electroplating lines have been used, which are in use for actual production. The thickness of the deposits varied from 1.5 µm to 15 µm. Additional Ni- underlayer varying in the thickness from 0.2 µm to 1.5 µm has been applied in the same line in a continuous process before tin plating. Furthermore preplated leadframes with an Ag-underlayer of 2 µm to 6 µm thickness have been used.

Whisker growth has been observed both in optical microscope at magnifications 50x, 100x and 200x and SEM at various magnifications and both on leadframes without any additional process step and after singulation, trim & form.

Additional heat treatment has been applied either after plating or after trim & form. The parameters for this heat treatment varied from 30 min to 24 hours and 100 °C to 150 °C.

The storage conditions after plating were:

- Ambient atmosphere (uncontrolled)
- 55 °C / ambient humidity
- 5 °C / ambient humidity

- 85 °C / 85 % r.h.
- Temperature cycling –35 °C / + 125 °C (500 cycles)
- Temperature cycling –55 °C / + 85 °C (500 cycles)

In order to learn more about the microstructure of the layers, cross sections of the deposits have been prepared and ion polished. These were investigated in SEM and analysed with EDX. Additional FIB sections have been prepared. Selective etching with commercially available tin stripper was performed to get more information on the development of intermetallics. The substrate material and the intermetallics Cu_6Sn_5 are not attacked by the stripper, whereas tin is removed within some seconds at room temperature. Thus the distribution and the morphology of the intermetallics could be followed in an impressive way.

Results and Discussion

Investigation by Xu et al [6] and others have shown that bright tin layers are under compressive residual stress in the as plated state and that matt or semibright tin layers are stress free or under tensile stress. In the latter compressive stress is build up when stored at room temperature. Another observation made by the authors is that tin layers electroplated on FeNi42 leadframe material do not exhibit whisker growth under ambient conditions in contrast to tin on copper. Thus the conclusion was near to correlate this to the interdiffusion of metals and also to the formation of intermetallics. Fig. 2 shows the cross section of a tin layer on copper after an ambient storage of nine months.

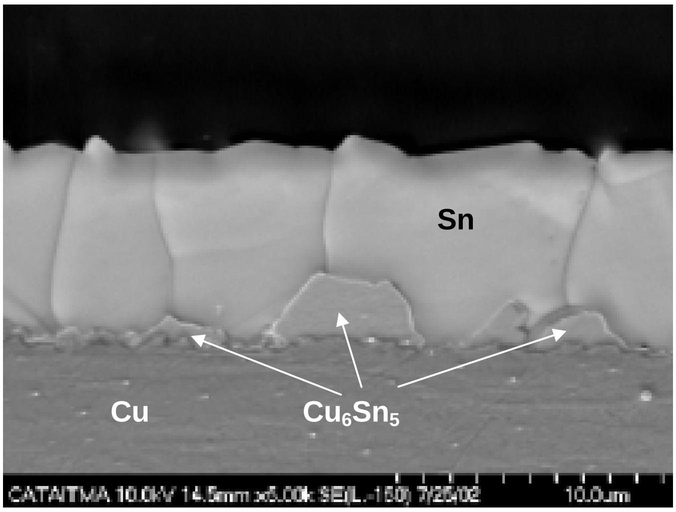

Fig. 2: Electroplated tin on copper after 9 months storage at ambient conditions with large Cu_6Sn_5 intermetallics

Very large intermetallics can be observed, which grow into the tin grain boundaries. These intermetallics have been identified as Cu_6Sn_5 by EDX. The diffusion of copper into tin and intermetallic formation causes a volume increase [9]. This can be calculated as an increase by 44.8 % when comparing the volume of Cu_6Sn_5 with the volume the respective amount of tin needed before. Thus it is evident that compressive stress is originated from the intermetallic formation. In Fig. 3 a tin layer electroplated on FeNi42 is shown after the same storage as the sample from Fig. 2.

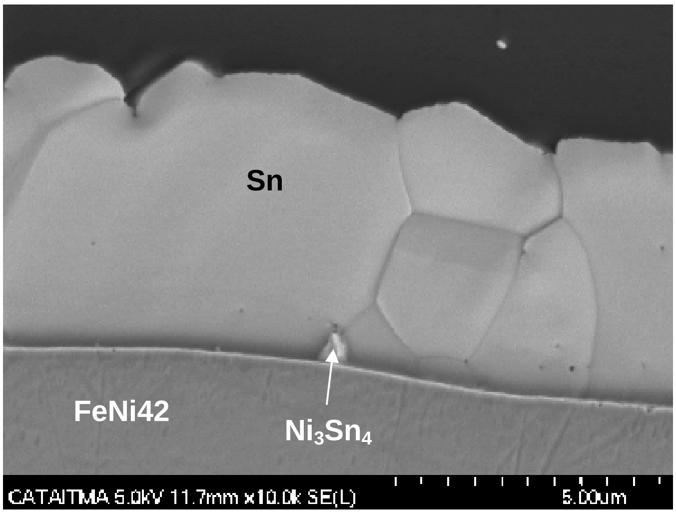

Fig. 3: Electroplated tin on FeNi42 after 9 months storage at ambient conditions with small Ni_3Sn_4 intermetallics

Only very small intermetallics Ni_3Sn_4 can be observed. No or only very little stress is build up by this intermetallic formation. Thus the difference in whisker formation for Cu-based and FeNi base materials can be explained. Based on this observation both Ni-barrier and Ag-barriers have been investigated. Ni-barriers, when non-porous show same intermetallic formation as FeNi42 base material. The intermetallic formation on Ag-layer can be derived from Fig. 4.

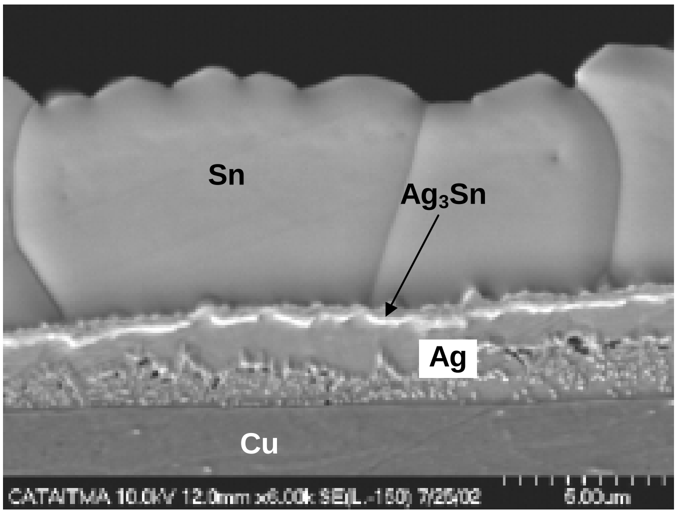

Fig. 4: Electroplated tin on silver after 9 months storage at ambient conditions with thin regular interlayer of Ag_3Sn.

It is evident that only a very thin and almost regular layer of Ag_3Sn is formed at the interface. Hence no stress is build-up that originates from interdiffusion and intermetallic formation.

Comparing whisker growth at room temperature for electroplated tin on Cu-based material, Ni-plated copper and Ag-plated copper, the above observation is verified. Fig. 5 shows the longest whiskers found on a given area of inspection (representing 10 components SOT 223). Whereas whiskers grow on copper, no whiskers can be found on Ni- or Ag-plated copper, even after 14 months storage.

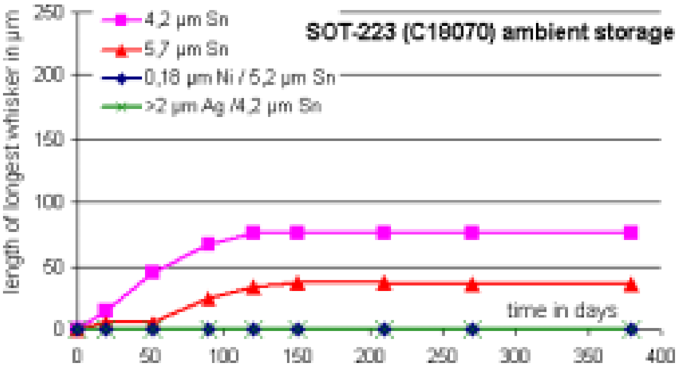

Fig. 5: Whisker growth for tin plated on copper, nickel or silver at comparable tin thickness

The speed of intermetallic formation and correlated stress build-up can be derived from Fig. 6 a to c. These pictures show a top view on the copper material after selective etching of the free tin within 1 hour, 6 days and 7 weeks after plating and storing at ambient conditions. The nucleation of intermetallics can be observed within the first few hours, whereas irregularities are obvious even after a few days and become larger in time.

Another observation was that no whiskers grow when the plated leadframes have undergone a heat treatment of, for example, 1 hour at 150 °C. This can again be explained by the formation of intermetallics.

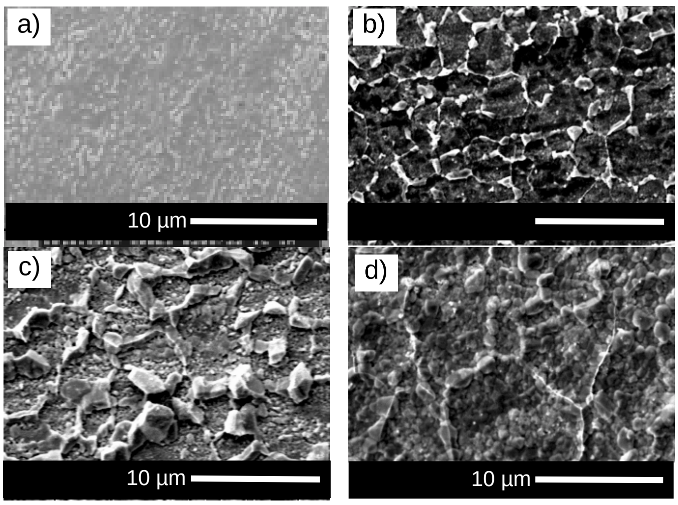

Fig. 6: Top view on copper leadframe with intermetallics after selective etching of the free tin 1 h after plating (a), 6 d after plating (b), 7 weeks after plating (c) and after 1 h bake at 150 °C immediately after plating (d)

Fig. 6 d shows the top view of a copper leadframe after selective etching of the free tin. The leadframe was heat treated for 1 hour at 150 °C and explicitly shows a dense layer of Cu_6Sn_5 intermetallics with only little irregularities (compared to the one after a seven week storage at room temperature). This close and thick layer of intermetallics reduces the diffusion speed of copper into tin to a minimum and eliminates further formation of irregularities completely. The former tin grain boundaries are marked by the topology of the intermetallics. Knowing that all pictures form Fig. 6 are taken at the same magnification it becomes obvious that the tin layer is coarsened and recristallised during heat treatment and thus all stress, that might have already been present before heat treatment, must be eliminated. The difference in intermetallic formation at room temperature and at 150 °C is a result of the change in diffusion mechanism from grain boundary diffusion at room temperature (=0,59 $T_{homologous}$) to bulk diffusion at 150 °C (=0.84 $T_{homologous}$). Thus it can be concluded that also an appropriate heat treatment can provide an effective diffusion barrier and thereby an effective whisker inhibition.

The effect of layer thickness on the whisker growth can be derived from Fig. 7.

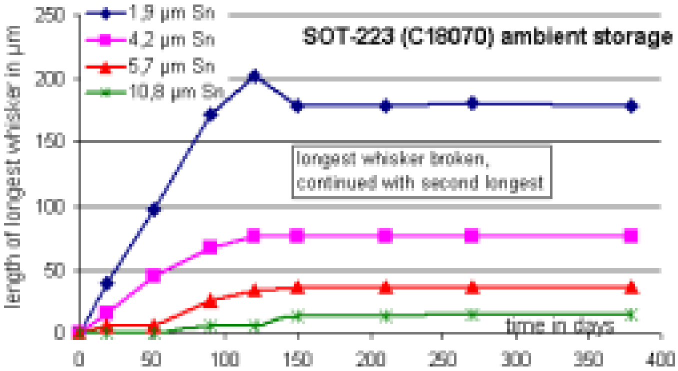

Fig. 7: Whisker growth for various thickness of tin plated on copper leadframe.

Several observations are evident:

- The maximum length reduces with increasing tin thickness.
- The maximum growth rate is decreasing with increasing layer thickness.
- Thicker layers show longer incubation times for first whiskers to appear.
- Whisker growth reduces to around zero after some weeks to months, independent from the thickness of the layer.

All these effects can be explained as follows: Due to the fact that the compressive stress is incorporated from the base metal/tin layer interface, this stress reduces with increasing distance from this interface. Hence the average stress (equals to the driving force for whisker growth per area unit) is the smaller the thicker the layer is. To start whisker growth a threshold for stress level must be exceeded. Both whisker formation and annealing effects reduce the stress, which is originated from the intermetallic formation. The intermetallic itself acts as diffusion barrier. Hence the speed of stress build-up reduces with the thickness of the existing intermetallic. The whisker growth stops when the stress build up by intermetallic formation and the stress release by annealing is in equilibrium and the stress has fallen below the threshold for whisker formation.

All the observations mentioned above are valid for storage under ambient conditions. Now the question is, whether it is possible to speed up whisker growth and correlate this accelerated growth to ambient conditions. Fig. 8 shows a comparison of ambient conditions to a storage in 55 °C and in 85 °C / 85 % r.h.

When having the first read out after three weeks storage it is obvious that ambient conditions cause whiskers of same length or longer ones at any time. However, the acceleration effect of 55 °C storage has been reported frequently [7,8].

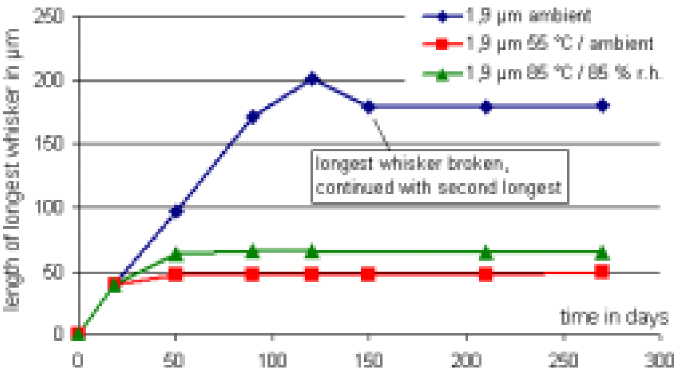

Fig. 8: Whisker growth under various storage conditions

Thus a more detailed look at the very beginning of the storage has been done (see Fig. 9). Here it can be observed that whisker growth starts earlier when stored at 55 °C than under ambient conditions. After a few days incubation and whisker growth, however, the whiskers observed at room temperature are longer than the ones on the 55 °C sample. This can be explained again by the effects as described above. Intermetallic growth is a diffusion controlled process and is thus faster at elevated temperatures. Thereby the stress build-up is faster at 55 °C and whisker growth starts earlier. But annealing is a diffusion effect as well and thus the opposing mechanism is enforced. In summary the annealing effects becomes predominant at earlier stage and makes whisker growth stop earlier at 55 °C than under ambient conditions. The same explanation is valid for the high temperature / high humidity storage conditions. Additional stress might in these cases be introduced by the preferred oxidation and hence volume increase in the tin grain boundaries. But this requires further investigations.

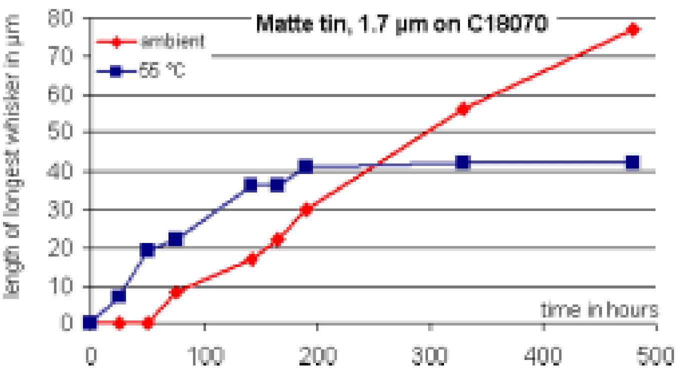

Fig. 9: Comparison of whisker growth at ambient conditions and at 55 °C in the initial stage after plating

Low temperature reduces the diffusion speed for all the processes involved in whisker formation. These being intermetallic growth, annealing and whisker growth itself. Thus whisker growth rate is significantly reduced, but will stop at later times due to the suppression of annealing. In summary it can be stated that there is a optimum condition for whisker growth in between 5 °C and 55 °C. Actually ambient conditions (18 °C to 30 °C) are identified as “best conditions” for whisker growth.

When submitting tin plated leadframes to temperature cycling excessive whisker growth can be observed on FeNi42 leadframes (see Fig. 10), but no or only little effect is observed for copper leadframes.

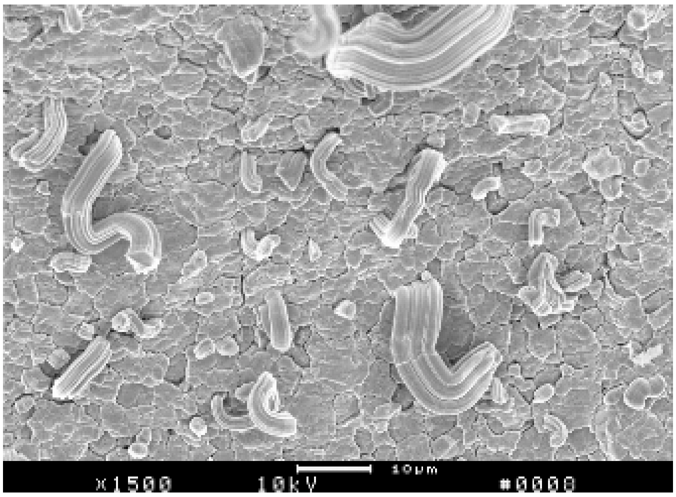

Fig. 10: Whiskers on 3.7 µm thick tin, electroplated on FeNi42 after 500 T-cycles – 40 °C / +125 °C (1 h/cycle, 15 min dwell time)

This can be explained by the difference in the coefficients of thermal expansion (cte). Tin has a cte of $23*10^{-6}$/K, copper has a cte of $17*10^{-6}$/K, which is rather close to the cte of tin, and FeNi42 has a cte of $4.3*10^{-6}$/K. The large difference in the cte of tin and FeNi42 causes excessive compressive stress in the tin layer when temperature rises. This effect is also clearly shown by the grain rupture in Fig. 10. Thus the whisker formation on tin plated FeNi42 is caused by a completely different mechanism than the ones described above. Hence, whiskers grown after temperature cycling cannot be correlated to whiskers grown in normal storage.

Attempts to correlate growth rates and whiskers lengths from storage conditions other than ambient are still ongoing, but to our knowledge no accelerated test method is available, which can predict whiskers in a reliable way.

However, the following approach is regarded to be a reliable way to judge on whisker safety under ambient conditions in a reduced time frame. The method is based on an acceptance criterion of a maximum whisker length of 50 µm after two years storage in ambient atmosphere. Based on above results thin layers are regarded to be more prone to whisker formation than thick layers. Hence the test layers must have an average thickness at the lower end of the specified thickness range. A leadframe of appropriate size (e.g. representing at least 5 components) is submitted to whisker read-out in optical microscope with a magnification of at least 100 for every 2 weeks after plating. The longest whiskers are recorded and plotted in a whisker length over time graph (Fig. 11). The respective length is the total of the subsections with various growth direction and must be measured with appropriate accuracy (e.g. ±2 µm). This must be done for at least 8 weeks, resulting in four read-out points. The first acceptance criterion is a maximum length of 20 µm after eight weeks ambient storage. The second criterion is that the extrapolation of the growth rate to two years must not result in a whisker length of more than 50 µm. If the first criterion is not fulfilled the plating is judged fail in terms of whisker safety. If the first criterion is passed and the second criterion is failed the whisker read-out must go on until the extrapolation of the graph to two years results in a whisker length of less than 50 µm. When this second criterion is not yet fulfilled after 26 weeks of ambient storage the plating is finally judged fail. The extrapolation is done by linear regression of the last three read-out points at any time according to the least square method.

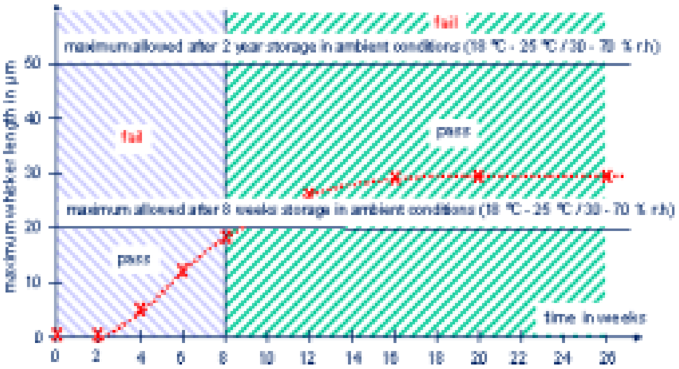

Fig. 11: Whisker monitoring for qualification purposes with tin plating thickness at its lower limit of specification

The mathematical description of the extrapolated straight line is given by equation 1 to 7.

$$y = a \cdot x + b \qquad \text{Equation 1}$$

with

$$a = \frac{N \cdot [xy] - [y] \cdot [x]}{N \cdot [x^2] - ([x])^2} \qquad \text{Equation 2}$$

and

$$b = \frac{[y] \cdot [x^2] - [xy] \cdot [x]}{N \cdot [x^2] - ([x])^2} \qquad \text{Equation 3}$$

whereas

$$[x] = x_1 + x_2 + x_3 \qquad \text{Equation 4}$$

$$[y] = y_1 + y_2 + y_3 \qquad \text{Equation 5}$$

$$[x^2] = x_1 \cdot x_1 + x_2 \cdot x_2 + x_3 \cdot x_3 \qquad \text{Equation 6}$$

$$[xy] = x_1 \cdot y_1 + x_2 \cdot y_2 + x_3 \cdot y_3 \qquad \text{Equation 7}$$

and

x_1 = time at last but two read out
x_2 = time at last but one read out
x_3 = time at last read out
y_1 = whisker length at last but two read out
y_2 = whisker length at last but one read out
y_3 = whisker length at last read out
N = Number of xy-pairs = 3

In other words: when x is 730 days (equals two years), y must not exceed 50 µm.

Conclusions

Whiskers on electroplated tin layers grow under compressive stress only. This stress can either be originated from the codeposition of organics (e.g. in bright tin layers), from the irregular growth of intermetallics or from temperature variation in combination with large mismatch in cte between the base metal and the tin layer. The main cause for whisker formation on today's matt tin layers is the irregular growth of intermetallics. Effective countermeasures to avoid or minimise whisker growth are known and can be categorised as follows:

- Symptomatic effects: The origin of stress remains untouched, but the stress distribution is influenced and the stress level is minimised, e.g. by the deposition of thick tin layers (e.g. 7.5 µm minimum)
- Causative effects: The formation of irregular intermetallics is suppressed by diffusion barriers, e.g. Ni, Ag or Cu_6Sn_5 (artificially grown by heat treatment).

No accelerated test method is known today, but whisker safety can be judged in reduced time by appropriate extrapolation of the growth rate.

Acknowledgments

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