Study of tin whisker inhibiting systems
Controlling the copper substrate roughness
and controlling the tin deposit crystal structure

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- Background
- The factors of tin whisker formation
- Mechanism of tin whisker formation at ambient
- Checking the effect of copper surface roughness in tin whisker formation
- Checking the effect of tin deposit crystal structure in tin whisker formation
- Summary
Pure tin and tin based alloys plating for alternative of tin-lead finish is being used on the majority of electronic components.

Tin whisker of tin and tin based alloy deposits are commonly known to cause the short circuits in electronic components.

In the case of tin finish on copper and copper based alloys, the major cause of tin whisker formation is compressive stress which is increased by irregular growth of copper-tin intermetallic compound (IMC) at ambient conditions.

It is known that tin whiskers are formed easily on the plated tin deposit, and are prevented on the tin-lead deposit. The tin deposit and tin-lead deposit are different in the crystal structure. So, we had a hypothesis of the crystal structure impacting tin whiskers. Then we checked tin whisker on tin deposit controlling the equiaxed crystal structure similar to tin-lead deposits.
Factors of tin whisker formation

Tin oxide film; SnO, SnO₂

Tin deposit or Tin alloy deposit;
  Surface morphology (grain size, crystal structure),
  Thickness,
  Alloy element, Carbon content, Crystal orientation,
  Internal stress

Intermetallic compound; Cu₆Sn₅, Cu₃Sn, Ni₃Sn₄

Underlayer; Nickel, Copper, etc.

Substrate;
  Material; Copper, Alloy42, Brass, etc.
  Stress; Etching, Stamping, Baking

After treatment; Baking, Reflow
Environment; Temperature, Humidity, Thermal cycle, Mechanical stress
Factors of tin whisker formation and whisker evaluation methods

**Factors**
- Growth of irregular IMC
- Oxidation/Corrosion
- Thermal expansion mismatch
- External applied force

**Test conditions**
- Room temperature: 30°C, 60%RH, 4,000 hrs.
- High temperature/High humidity: 55°C, 85%RH, 4,000 hrs.
- Thermal cycling: -55°C to 85°C, 1,500 cycles
- Indentation test: (ex.) Load: 2N, Dwell time: 120 hrs.

**Environment**
- Room temperature
- High temperature/High humidity
- Thermal cycling
- Indentation test

**Tin deposit**
- Internal stress (compressive stress)

**This condition is most serious condition**

- JESD201 (JEDEC), RC-5241 (JEITA)
The mechanism of tin whisker formation at ambient that is the most serious condition

Sn oxide film

Stress

Sn deposit

IMC (Cu₆Sn₅)

Cu alloy substrate
Approach to reduce tin whisker formation

- Controlled the crystal structure for dispersing internal stress
- Controlled the surface roughness for decreasing internal stress

Sn deposit
Cu alloy substrate
Study of Copper surface morphology vs. Tin whisker formation
Experiment

Test vehicle
- CDA19400 (Cu-2.3Fe-0.03P-0.12Zn) leadframe
  (Original leadframe)

Tin plating
- Plating bath : MSA matte tin plating bath
- Cathode current density : 10A/dm²
- Thickness ; 3μm (for evaluating whisker in the short term)
  10μm (typical thickness for leadframe)
The copper surface control method

Etching
- Etchant: Various etchants were used for forming surface roughness on copper substrate.
- Measurement
  Surface roughness was analyzed by laser microscope
  Parameter: $Ra(\mu m)$ arithmetic average of absolute values

$Ra = \frac{1}{\ell} \int_0^{\ell} |f(x)| \, dx$

$\ell = \text{Evaluation length}$

$Ra$; From the direction of the average line of the roughness curve of a sampled standard length, plot the direction of the average line of the sampled section on the $X$ axis and the direction of the vertical magnification on the $Y$ axis, and express the roughness curve using the equation $y=f(x)$. The roughness value is then expressed in micrometers ($\mu m$) as the value determined from the left expression.
Whisker test
- Storage condition: 30°C / 60%RH
- Storage time: 1,000 hours (for 3μm thickness tin deposit)
  4,000 hours (for 10μm thickness tin deposit)
- Parameter: Maximum whisker length
  Whisker density
- Definition of whisker
  Aspect ratio (length/diameter); more than 2
  Whisker length; more than 10μm
- Measurement method of whisker length; JEITA ET-7410
  The straight line distance from the point of emergence of
  the whisker to the most distant point on the whisker.
Outline of the evaluation

Plating process (Common process of tin plating)

1. Cleaning
2. Acid dipping
3. Etching
4. Pre-dipping
5. Tin plating
6. Neutralization
7. Drying

Various copper surface shape

Whisker evaluation process

1. Whisker test (30°C/60%RH)
2. Observation of whisker
Shape vs. Ra
the copper substrate surface

<table>
<thead>
<tr>
<th>Ra (μm)</th>
<th>0.087 (substrate)</th>
<th>0.120</th>
<th>0.187</th>
<th>0.249</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td></td>
<td>0.288</td>
<td>0.358</td>
<td>0.402</td>
<td>0.487</td>
</tr>
<tr>
<td></td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
</tbody>
</table>
Surface shape on copper substrate after etching

Substrate: CDA19400 leadframe / Etching depth: 2μm (average)

Cu substrate
Surface 1
Surface 2

Ra 0.08μm
Ra 0.15μm
Ra 0.45μm

The above 3D roughness map is analyzed by laser microscope.
Ra: arithmetical mean roughness
Observation of tin whisker after test

Samples: Tin thickness 3μm
Storage condition: 30°C / 60%RH / 1,000 hours

Whiskers were observed.

Ra 0.13μm  Surface roughness on Cu substrate  Ra 0.45μm

No whiskers
Maximum whisker length on 3μm thickness tin deposit

Samples: Tin thickness 3μm
Storage condition: 30°C / 60%RH / 1,000 hours
Whisker density on 3μm thickness tin deposit

Samples: Tin thickness 3μm
Storage condition: 30°C / 60%RH / 1,000 hours
The relation of Maximum whisker length vs. surface roughness

Samples: Tin thickness 10μm
Storage condition: 30°C / 60%RH / 5,000 hours
Comparision of the IMC with surface roughness after stripping tin deposit by cross section

Samples: Tin thickness 10μm
Storage condition: 30°C / 60%RH / 7,000 hours

- Large IMC grain
- Localized
- Small IMC grain
- Comparatively dispersed and uniform

Ra 0.13μm   Surface roughness on copper substrate   Ra 0.47μm
Comparison of the IMC with surface roughness after stripping tin deposit by surface SEM

Samples: Tin thickness 10μm
Storage condition: 30°C / 60%RH / 7,000 hours

45° tilt in SEM

Ra 0.13μm  Surface roughness on copper substrate  Ra 0.47μm

- Large IMC grain
- Localized
- Small IMC grain
- Comparatively uniform
Comparison of the tin surface morphology with copper surface roughness

Tin thickness: 10μm

- Ra 0.13μm on copper substrate
- Ra 0.47μm

✓ Tin deposits on two different copper surfaces had same surface morphology.
Solderability of tin deposits

Tin thickness: 10µm

Instrument: SWET-2100 (Tarutin Kester)
Method: Wetting Balance Method
Solder: Sn-3Ag-0.5Cu (Senju Metal Industry / M705)
Flux : CF-110VH-2A (Tamura Kaken)
Temperature: 255°C
Immersion Depth:2mm, Immersion Speed:2mm/sec.

Bending test (ductility)

Solderability and ductility of tin deposits on two different copper roughness were excellent. Surface roughness on copper substrate didn’t affect properties of tin deposits.
Consideration of tin whisker mitigation by copper substrate roughness

Small Ra surface

- Large IMC
- Localization

Localized compressive stress is generated in tin deposit.

Tin whisker is formed.

Large Ra surface

- Small IMC
- Comparatively dispersed and uniform IMC layer

Localized compressive stress in tin deposit is relieved.

Tin whisker is reduced.

General understanding
Study of
The crystal structure of tin deposit
vs.
Tin whisker formation
Checked the different crystal structure of the tin deposit and tin-lead alloy deposit

<table>
<thead>
<tr>
<th>Whisker formation</th>
<th>Whisker prevention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical tin deposit</td>
<td>Tin-lead alloy deposit</td>
</tr>
</tbody>
</table>

Cross section

<table>
<thead>
<tr>
<th>Crystal structure</th>
<th>Column structure</th>
<th>Equiaxed structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn</td>
<td>IMC (Cu₆Sn₅)</td>
<td>Sn-Pb</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dispersion of compressive stress

Irregular growth of IMC

Uniform IMC layer
Experiment

Test vehicle
- CDA19400 (Cu-2.3Fe-0.03P-0.12Zn) leadframe
  (Original leadframe)

Tin plating
- Plating bath : MSA matte tin plating bath
  : Three tin plating baths with different additives
- Cathode current density : 10A/dm²
- Thickness ; 10um (typical thickness for leadframe)
Whisker test
- Storage condition: 30°C / 60%RH
- Storage time: more than 4,000 hours
- Parameter: Maximum whisker length
  Whisker density
- Definition of whisker
  Aspect ratio (long/diameter); more than 2
  Whisker length; more than 10um
- Measurement method of whisker length: JEITA ET-7410
  The straight line distance from the point of emergence of the whisker to the most distant point on the whisker.
## Three kinds of tin deposit

<table>
<thead>
<tr>
<th>Kind of tin deposit</th>
<th>Type A</th>
<th>Type B</th>
<th>Type C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain size</td>
<td>Large</td>
<td>&gt;</td>
<td>&gt;</td>
</tr>
<tr>
<td>Crystal structure</td>
<td>Column</td>
<td>Column</td>
<td>Column + Equiaxed</td>
</tr>
<tr>
<td>Appearance of deposit</td>
<td>matte</td>
<td>matte</td>
<td>matte</td>
</tr>
<tr>
<td>Carbon content in deposit (wt%)</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
</tbody>
</table>
Surface morphology - Grain size -

Type A  Type B  Type C

Large  >  >  Small
Crystal structure - Cross section -

Type A  Type B  Type C

Column structure  Column structure  Column + Equiaxed structure
**Observation of tin whisker after test**

Samples: Tin thickness 10µm  
Storage condition: 30°C / 60%RH / 4,000 hours

<table>
<thead>
<tr>
<th>Type A</th>
<th>Type B</th>
<th>Type C</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Image of Type A] 100µm</td>
<td>![Image of Type B] 100µm</td>
<td>![Image of Type C] 100µm</td>
</tr>
</tbody>
</table>

Whiskers were found. Whiskers were found.  
Whiskers were shorter than Type A.  
No whiskers
Maximum whisker length

Samples: Tin thickness 10μm
Storage condition: 30°C / 60%RH / 4,000 hours

Graph showing the maximum whisker length over storage time for types A, B, and C.
Whisker density

Samples: Tin thickness 10μm
Storage condition: 30°C / 60%RH / 4,000 hours

Whisker density (per mm²)

<table>
<thead>
<tr>
<th>Kind of tin deposit</th>
<th>Whisker density (per mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A</td>
<td>40</td>
</tr>
<tr>
<td>Type B</td>
<td>5</td>
</tr>
<tr>
<td>Type C</td>
<td>0</td>
</tr>
</tbody>
</table>
Cross-section after 22,000 hours at 30°C / 60%RH

Samples: Tin thickness 10μm
Storage condition: 30°C / 60%RH / 22,000 hours

Type A
- Large IMC grain
- Localized

Whiskers were found.

Type C
- Uniform IMC layer

No whiskers
Observation of surface of IMC layer after stripping tin deposit

Sample: Tin thickness 10μm
Storage condition: 30°C / 60%RH / 22,000 hours

Type A
- Large IMC grain
- Localized

Type C
- Small IMC grain
- Comparatively uniform

45° tilt in SEM
Consideration of the tin whisker mitigation - Type B -

Type A
- Tin grain size is large.
- Large IMC grow into grain boundaries at local places.
- Localized compressive stress is generated in tin deposit.

Type B
- Tin grain size is small.
- >> many grain boundaries
- Dispersion of copper diffusion
- Small and uniform IMC layer
- Low compressive stress in tin deposit

Countermeasure

General understanding

Tin whisker growth

Tin whiskers are reduced.
Considering of the tin whisker mitigation - Type C -

Tin grain size is smaller. >> many grain boundaries +
Equiaxed and column structure
Dispersion of copper diffusion
Small and uniform IMC layer
Grain boundary diffusion of tin disperses and slows.
Compressive stress in tin deposit is relieved more.

Tin whiskers are restrained.

Type A
Countermeasure

Type B

Type C

Effect of copper substrate roughness
- Tin deposit on copper substrate that was formed large Ra by etching reduced tin whiskers at ambient conditions. It was thought that the uniform IMC layer prevented accumulating internal stress into tin deposit.

Effect of crystal structure in tin deposit
- Compared with large grain size tin deposit, tin deposit that had small grain size reduced tin whisker formation at ambient conditions.
- Tin deposit which had crystal structure similar to tin-lead deposit restrained tin whisker formation effectively.
- Crystal structure in tin deposit is one of the most important factors to restrain tin whiskers.