Advances in the high-density wiring of electronic parts have been accompanied by insulation degradation stemming from ion migration, creating serious problems. While a great deal of research has been carried out investigating the formation of dendrites, which are one form of ion migration, there has been a noticeable lack of clarification of the role of CAF (conductive anodic filament) formation. As a result, we decided to evaluate the CAF resistance of multi-layered PWBs (printed wiring boards). We investigated the relationship between the shape of the CAF that formed and the behavior of insulation resistance levels during CAF formation. We found that during CAF formation the insulation resistance levels repeatedly dropped temporarily and then recovered. In addition, we observed a substance presumed to be CAF at the sites of probable insulation degradation, and we were able to confirm that this substance occurred along the glass fibers.

1 Introduction

The electronic components of equipment such as cell phones include a great number of electronic parts embedded onto PWBs. These PWBs normally contain features such as copper patterns stamped onto the boards and through-holes that penetrate the boards. These lines and through-holes must have continuous insulation protection from adjacent lines and through-holes. (Fig.1)

Ion migration, which causes insulation degradation, is a phenomenon in which metallic ions from the electrodes migrate either on or through the insulation, causing short-circuits. Representative types of this phenomenon are dendrites and CAF. (Fig.2)
Until recently, measures such as refinements in PWB materials had managed to suppress the problem of ion migration, but with recent advances producing higher density wiring, ion migration has once again become a serious problem. In addition, the use of multi-layered circuit boards and built-in circuit boards has caused the formation of CAF to become an increasingly serious problem.

CAF is a failure mode in PWBs that occurs under conditions of high humidity and high voltage gradient. The filament, a copper salt, grows from the anode toward the cathode along the epoxy/glass interface.

There is a growing trend toward standardization in evaluating CAF resistance, and in 2003, the IPC Association Connecting Electronics Industries issued standards for the CAF Resistance Test.

Testing is being performed in Japan as well, with such examples as Company X and Company Y cited in Table 1, and calls are being made for proposals leading to international standardization. The information cited above indicates the growing importance placed on resistance to CAF.

Current research indicates that CAF is a conductive copper-containing salt created electrochemically that grows from the anode toward the cathode subsurface along the epoxy/glass interface. However, because CAF grows inside the PWB, the mechanism of its occurrence and growth has not been fully resolved. This need for further clarification led us to carry out temperature and humidity testing and HAST (highly-accelerated stress testing), and to investigate the relationship between the shape of CAF formation and the insulation resistance between through-hole walls.
For this research, we manufactured PWBs in which it was thought that the sites of insulation degradation would be easily identifiable. To carry out the reliability testing, we modified temperature and humidity, PWB materials, distance between through-hole walls, and through-hole diameter. Using this approach, we investigated the relationship between CAF formation and insulation degradation. We continuously monitored insulation resistance during the tests, and investigated its behavior. Following the tests, we used a grinder on the sites of presumed insulation degradation to visually observe each type with a microscope.

Photo 1 shows the test equipment. Test equipment included a Bench-top Type Temperature and Humidity Chamber in parallel with a Highly Accelerated Stress Test System (HAST Chamber) and an Ion Migration Evaluation (Electrochemical Migration Evaluation) System. We used four sets of temperature and humidity conditions: 60°C at 85%rh, 85°C at 85%rh, 110°C at 85%rh, and 120°C at 85%rh. The applied test voltage and the measured test voltage were both 50V DC.

During the tests, we continuously monitored leak current. We used a leak detection cycle that stopped the application of voltage upon detecting leak current above a pre-set resistance, and also a leak behavior mode (which triggers a behavior check cycle after confirming leak behavior) that stopped the application of voltage after being entered above a pre-set number of times. The standard leak current setting is 1μA (resistance: 5 x 107Ω), and failure time was determined as either leak current reset, or entering the behavior check cycle in five successive checks done at one-minute intervals, whichever

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**Table 1. Examples of testing CAF-resistance evaluation (including evaluating the reliability of the insulation between through-holes)**

<table>
<thead>
<tr>
<th>Test name</th>
<th>Temperature (°C)</th>
<th>Humidity (%RH)</th>
<th>Bias voltage (V)</th>
<th>Test voltage (V)</th>
<th>Test time (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPC-TM-650 2.6.25</td>
<td>65 ±2 or 85±2</td>
<td>87 ±3/2</td>
<td>100</td>
<td>100</td>
<td>500, 1000</td>
</tr>
<tr>
<td>Company x</td>
<td>85</td>
<td>85</td>
<td>100</td>
<td>*</td>
<td>500, 1000</td>
</tr>
<tr>
<td>Company y</td>
<td>85</td>
<td>85</td>
<td>50</td>
<td>*</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>110</td>
<td>85</td>
<td>50</td>
<td>*</td>
<td>1000</td>
</tr>
</tbody>
</table>

* Not given
came first.

Fig.3 shows a photo and a diagram of the surface pattern of the PWB used in the tests. The PWB type was an eight-layered FR-4, and we used types A, B (halogen-free), C, and D model PWBs. Ten through-hole pairs were used on each PWB, with the following relationship of distance between through-hole walls to size of through-hole diameter (refer to Fig.4): 0.3/0.2, 0.4/0.2, 0.5/0.2, 0.3/0.6, and 0.3/1.0 (units: mm, same below). The through-hole pairs were linked using a copper pattern, and during the tests each of the ten pairs received voltage application simultaneously. The specimens were constructed so that after the tests the copper patterns could be cut apart to permit each through-hole pair to have its resistance measured individually. Using this method, the resistance of each through-hole pair was measured, and the sites of insulation degradation were specified.
Test conditions and specimens:

**Conditions**  | Temp./ Humid. | 60 °C, 85%RH; 85 °C, 85%RH; 110 °C, 85%RH; 1200 °C, 85%RH;

Applied voltage | Bias voltage: 50 V. Test voltage: 50 V

**Specimens**  | Material type | FR-4 (8-layer)

Models | PWB A. PWB B (Halogen-free), PWB C, PWB D

PTH wall-to-wall spaces/Drilled hole sizes | 0.3/0.2, 0.4/0.2, 0.5/0.2, 0.3/0.6, 0.3/1.0

**Table 2 Test conditions and specimens**
45 hours. Fig.5 indicates that insulation resistance temporarily drops at the time of CAF formation, with resistance then recovering and the pattern being repeated.

Fig.5
Behavior of insulation resistance
(50V DC at 110°C and 85%rh, PWB C, 0.3/0.2)

4.2 Test results for temperature acceleration

Fig.6 shows a Weibull plot for temperature acceleration of specimens at 60°C and 85%rh, 85°C and 85%rh, 110°C and 85%rh, and 120°C and 85%rh tested at 50V DC for 2400 hours. The PWB was model C with a relationship of 0.3/0.2 for distance between through-hole walls to size of through-hole diameter. The Weibull plot trends show a difference only for the conditions of 120°C and 85%rh. The failure mode in the test at 120°C and 85%rh differed from the failure modes at the other temperature and humidity conditions. The conditions of 120°C and 85%rh in this test may have been too harsh for the specimens used.

Fig.6
Weibull plot of temperature acceleration
(50V DC for 3000 hours, PWB C, 0.3/0.2)
4.3 Test results for different PWBs

Fig. 7 shows a Weibull plot for each type of PWB tested for 500 hours at 110°C and 85%rh. The relationship used for the distance between through-hole walls to through-hole diameter was 0.3/0.2.

The test results indicated that PWB C had a shorter time to failure than PWBs A and B. Only three of the nine specimens of PWB B (halogen-free) failed within the 500 hours of test time, yielding the longest time leading to failure of any specimen.

Fig. 8 shows the humidity absorption characteristics of these PWBs at 110°C and 85%rh. No correlation was seen between humidity absorption rate and failure time, indicating that it may be difficult to determine CAF resistance solely on the basis of humidity absorption characteristics. Factors considered to affect CAF resistance include the flux residue in the inner layers, the damage to through-hole walls from drilling, and the interface bond between the epoxy and glass fibers.

4.3 Test results for different distances between through-hole walls and diameter sizes

Fig. 9 and 10 show Weibull plots for each specimen based on the different distances between through-hole walls. The specimens were tested for 3000 hours at 85°C and 85%rh. PWB C was used.
With the range of distances between through-hole walls of 0.3 to 0.5 mm, the smaller the distance between the through-hole walls, the shorter the time leading to failure. No clear difference was seen among the different through-hole diameters, from 0.2 to 1.0 mm. The data was not consistent, and so we plan to experiment further.

5 Results of observation

5.1 Results of observation (1)

Fig. 11 shows the changes in insulation resistance during the test at 110°C and 85%rh for PWB C, Sample 1. The relationship of distance between through-hole walls to size of through-hole diameter was 0.4/0.2. Approximately 90 hours after test start-up, insulation resistance fell below 5 x 105Ω (marked with a red x in the diagram), and the test was completed. Following the test, we observed cross sections of the sites of insulation degradation on the PWB.
Photos 2 and 3 are microscope photographs of pre- and post-test specimens. The unevenness of the through-holes in the pre-test photo is thought to be caused by damage from drilling where traces of Cu plating have become embedded. In microscopic observation following the test, substances thought to be CAF were observed along the glass fibers in the epoxy. To obtain a more detailed analysis, we performed a Cu mapping analysis using a metallurgical microscope and EPMA (Electron Probe Micro-Analyzer).

Photos 4 and 5 are images obtained from the metallurgical microscope and Cu mapping. From the metallurgical microscope image, this substance is believed to be metallic. From the Cu mapping image, the main component of the substance is found to be Cu.
Next, we shall consider changes in insulation resistance during the test, and post-test observation of insulation degradation sites for Samples 2, 3, and 4 of PWB C at the same test conditions of 110°C and 85%rh.

Fig.12, 13, and 14 show changes in insulation resistance for Samples 2, 3, and 4. The green X in the diagrams indicates the formation of leak touch, with a resistance below 5 x 10^7Ω. A red X indicates a resistance of 5×10^5Ω or below. (However, since the leak current standard setting for Fig.14 was 50μA, resistance indicated is below 1 x 10^6Ω.)

The repeated fall and recovery of resistance seen in Fig.13 is conjectured to be repeated breaking and connecting of a fine section of CAF.

**Fig.12 Changes in insulation resistance**
(Sample 2) (50V DC at 110°C and 85%rh, PWB C, 0.5/0.2) Leak current setting, 1μA (resistance, 5 x 10^7Ω)

**Fig.13 Changes in insulation resistance**
(Sample 3) (50V DC at 110°C and 85%rh, PWB C, 0.4/0.2) Leak current setting, 1μA (resistance, 5 x 10^7Ω)
Fig. 14 Changes in insulation resistance
(Sample 4) (50V DC at 110°C and 85%rh, PWB C, 0.3/0.2) Leak current setting, 50μA
(resistance, 1 x 10⁶Ω)

Photos 6 through 9 are post-test microscope images of insulation degradation’s sites. For Samples 1 and 2, the test was concluded when resistance fell below 5 x 10⁵Ω. For Sample 3, the test was concluded when resistance fell to 7.21 x 10⁸Ω. For Sample 4, the test was concluded when resistance fell to 5.11 x 10⁹Ω.

Photos 6 through 9 indicate that in the specimens with insulation degradation set at below 5 x 10⁵Ω the CAF diameter is thicker than that in the 7.21 x 10⁸Ω and 5.11 x 10⁹Ω. This experiment indicates that the density may have increased after the CAF connected the anode and cathode, leading to insulation degradation.

Photo 6. Site of insulation degradation
(below 5 x 10⁵Ω) (Sample 1) Photo 7. Site of insulation degradation
(below 5 x 10⁵Ω) (Sample 2)
5.3 Results of observation (3)

Fig.15 shows changes in insulation resistance during the test at 110°C and 85%rh for PWB D, Sample 5. The relationship of distance between through-hole walls to size of through-hole diameter was 0.3/0.2. Following the test, we observed cross-sections of sites of probable insulation degradation on this PWB. Photos 10 and 11 are microscope images of the pre- and post-test specimen. Observation indicated that the insulation degradation on this specimen was not caused by CAF along glass fibers, but rather by ion migration forming between the core material* and the prepreg sheets**.

*Core material: inner layer laminate of multi-layer PWB
**Prepreg sheets: Adhesive sheet used to bond core material layers
5.4 Results of observation (4)

Next, we shall consider PWB C Samples 6 and 7 in tests at 110°C and 85%rh with regard to examples of CAF observed even in specimens analyzed as non-defective when the test was concluded prior to insulation degradation. For Sample 6, Fig.16 shows changes in insulation resistance, Photo 12 is a post-test microscope image, and Photo 13 is a post-test metallurgical microscope image. For Sample 7, Fig.17 shows changes in insulation resistance, Photo 14 is a post-test microscope image, and Photo 15 is a post-test metallurgical microscope image.

From Fig.16 and 17 and Photos 12 through 15 we can see that neither Sample 6 nor Sample 7 have any major changes in insulation resistance. However, post-test observation revealed CAF along the glass fibers. Observation of Sample 7 revealed CAF growing from both the anode and the cathode, but since three-dimensional observation and observation during the test are problematic, this did not lead to clarification of the process of CAF growth.

Fig.16. Changes in insulation resistance (Sample 6)
(50V DC at 110°C and 85%rh, PWB C, 0.3/0.2)
Ion migration

Photo 12. Post-test microscope image (sample 6)

Photo 13. Post-test metallurgical microscope image (Sample 6)

Fig.17 Changes in insulation resistance (Sample 7)
(50V DC at 110°C and 85%rh, PWB C, 0.3/0.2)

Photo 14. Post-test microscope image (Sample 7)

Photo 15. Post-test metallurgical microscope image (Sample 7)
5.5 Results of observation (5)

Up to this point, we have considered observation of PWBs with the through-holes cross-sectioned vertically. Next we shall consider observation of PWBs with the through-holes cross-sectioned horizontally. Fig.18 shows changes in insulation resistance during the test at 120°C and 85%rh for PWB D, Sample 8. The relationship of distance between through-hole walls to size of through-hole diameter was 0.3/0.2. Photo 16 is a pre-test microscope image, while post-test images of sites of insulation degradation are presented in Photo 17, a microscope image, and Photo 18, a metallurgical microscope image.

The metallurgical microscope image shows CAF growing from the anode toward the cathode, and it was confirmed to be extending obliquely toward the back. This is presumed to be caused by the existence of CAF along the glass fibers.
We carried out High Temperature and Humidity Tests and Highly-Accelerated Stress Tests (HAST) to evaluate the CAF resistance of multi-layered PWBs. These experiments produced the following results:

- At the time of CAF occurrence, insulation resistance exhibits a cyclical behavior of repeatedly falling temporarily and then recovering.
- PWB C exhibited a shorter time leading to failure than either PWB A or B, but since PWB C did not exhibit a noticeably high level of humidity absorption in the Humidity Absorption test, determining CAF resistance characteristics solely on the basis of humidity absorption characteristics seems to be problematic.
- The tests at 120°C and 85%rh may have been too harsh for the PWB C specimen used in these tests, so that the failure mode may have been different from the failure mode at the other conditions of temperature and humidity.
- CAF along the glass fibers and a substance believed to be ion migration occurring between the core material and the prepreg sheets were observed at presumed sites of insulation degradation. In addition, CAF occurrence was observed in specimens that did not exhibit insulation degradation.

In this research, we observed CAF growing from the anode as well as from the cathode, and we plan to carry out further research regarding the growth process and mechanism. In addition, investigation is required on what effect the manufacturing conditions and pre-conditioning of multi-layered PWBs have on the formation and growth of CAF.

It must be stressed that the evaluations produced by this research are relative, and their correlation to actual failure in the field are a challenge for further research. We plan to carry out further reliability testing with other temperature and humidity conditions to investigate accelerated temperature and humidity characteristics.

**Bibliography**