Presented at IPC Printed Circuits Expo®
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Conductive Anodic Filament Growth Failure

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Abstract
With increasing focus on reliability and miniaturized designs, Conductive Anodic Filament (CAF) as failure mechanism is gaining a lot of attention. Smaller geometries make the printed circuit board (PCB) susceptible to conductive anodic filament growth. Isola has carried out work to characterize the CAF susceptibility of various resin systems under different process and design conditions. Tests were carried out to determine the effect of various factors such as resin systems, glass finishes, voltage bias and hole and line spacings on the CAF resistance.

This work was intended to provide information to the user on the suitability of various grades for specific end use applications. The focus of the work at Isola is to find the right combination of process and design conditions for improved CAF resistant products.

Conductive Failure Background

The concerns with board reliability and the possibility of conductive anodic growth in printed circuit board assemblies has increased in the last few years. Original equipment manufacturers have increased the design density, and are concerned with field failures due to conductive growth. The factors driving concern today are increased operating temperatures, and designs that have increased the density of holes and features on a printed wiring board. These boards are often intended for use in units that are operated in uncontrolled environments.

Conductive anodic filament failure is the growth or electro-migration of copper in a printed circuit board. This growth typically bridges two oppositely biased copper conductors. This failure can be manifested in four main ways: through hole to through hole, line-to-line, through hole to line, and layer-to-layer. The most common failure mode is hole to hole.[1,2]

It is known that a combination of bias voltage (voltage applied during the test) and high relative humidity can cause a CAF failure during testing. The electrical failure is caused when a filament grows from a copper anode to a copper cathode.

It is postulated that the CAF failure proceeds in two stages – the first stage involves the degradation of the resin glass interface followed by an electrochemical migration process, which allows the filament growth. The first step is believed to be reversible and the material's insulation resistance returns after baking and drying. The second step of actual CAF growth is believed to be irreversible. The mean time to failure is a function of voltage bias, relative humidity, hole-to-hole and line-to-line spacings, temperature and the resin system. The temperature relationship can be looked at as an Arhennius relationship while power laws approximate the relationship with other variables.

Once the degradation of the resin glass interface takes place the PCB behaves like a cell, the following reactions may occur:

At the anode:

$$Cu \rightarrow Cu^{n+} + ne^-$$
$$H_20 \rightarrow ½\ O_2 + 2\ H^+ + 2e^-$$

At the Cathode

$$H_20 + e^- \rightarrow ½\ H_2 + 2\ OH^-$$

The study of the effect of various factors such as pH, concentration and voltage on the rate of reaction can lead us to the mechanism of the CAF reaction. The Nernst equation defines the standard cell potential of the cell as

$$E = E^0 + RT/nF * Ln(Q) \qquad (1)$$

Where $\mathbf{E^0}$ is the equilibrium potential R is the gas constant and F is the faraday's constant and n is the number of electrons

RT/F at room temperature equals 25.7 mV

The thermodynamics of corrosion reactions can be represented by PourBaix diagram. The lines are drawn between the equilibrium potential and the pH.

A simplified pourbaix diagram for copper (see Figure 1) shows that at a pH of around and beyond 7 a passivation layer protects the corrosion. The cell potential as seen from equation (1) is a direct function of temperature and the concentration; and directly affects the kinetics.

Certain conditions must be present in order to cause conductive anodic failure. Several studies were completed by AT&T Laboratories and the Georgia Institute of Technology to determine the lower threshold of conditions required for a CAF failure.[2, 3] A certain level of humidity is required to initiate the CAF failure.

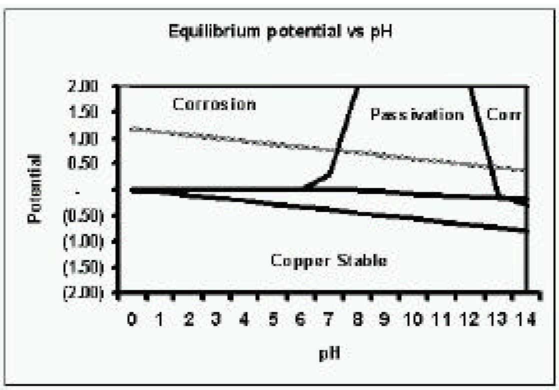

Figure 1 – Pourbaix Diagram

Test Vehicle Design

The test vehicle was designed after acquiring input from various OEM's. The vehicle is a four-layer board consisting of several rows of coupons with hole spacing from .006" to .035". These are positioned in both the X and Y direction on the panel. The failure mode is apparent and very easy to see with this design. The dielectric spacing can be changed with the use of different materials to understand its impact on CAF formation. (See Figure 2.)

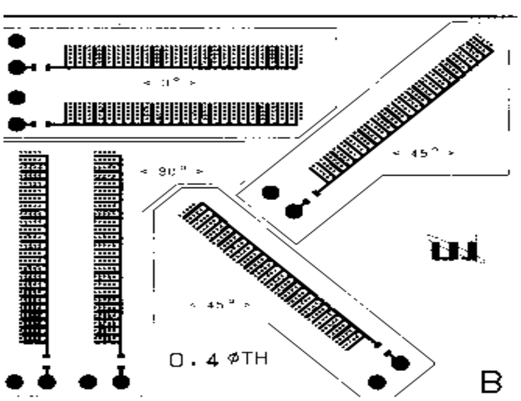

Figure 2 – CAF Test Vehicle

Test Conditions

Two test conditions were selected.

85 °C/ 85% RH Testing

Sample printed circuit boards are sanded with 120 grit paper to remove any crazing, fibers, etc. Samples are soldered with resistor (1 K ohm) and wires (24, stranded, tinned, PTFE coated). The samples are washed with IPA and DI water and dried for four hours @ 105 °C are placed in Temperature/Humidity Chamber @ 23 °C/50% RH for 24 hours.

An initial resistance measurement is taken. The chamber settings are raised to 85 °C/85% RH and the samples are subjected to the required bias voltage. After 96 hours the bias voltage is removed and the resistance measurement is taken again. The bias voltage is reapplied and the sequence is repeated every 96 hours.

23 °C/ 50 % RH Testing

The samples are removed from the chamber and baked in an air-circulating oven for 24 hours @ 105 °C. The samples are conditioned for 24 hours @ 23 °C/ 50% RH and the resistance is checked.

Studies

Two classes of products were chosen – products below 150 °C Tg used in automotive applications and products with Tg > 170 °C used in the networking applications.

The experiments were designed to provide information concerning the effect of various processing conditions on the CAF resistance of the material.

Standard Tg Products (<150 °C Tg)

The first set of experiments focused on determining the current performance level of standard Tg < 150 °C, materials for automotive CAF requirements.

The variables explored were:

1. Two resin systems
2. Three different glass finishes
3. Additives

Results

Results from the first Design of Experiment (DOE) showed that lower Tg standard formulation was improved with the addition of some additives but could not meet the 1000-Hour requirement. No actual CAF failures were identified. Baking always raised the insulation resistance back to normal.

Some trends were detected with grain direction. This needs further investigation. Further work is underway to look at additional resin systems and finishes.

High Tg products > 170 °C Tg

Low Bias Test

The second set of experiments focused on high Tg materials > 170 °C.

The Test conditions were

1. 24 mil hole to hole spacing
2. 13.5 volt bias, .0135" holes
3. 100 volt testing

Variables were:

1. Treating conditions and resin systems
2. Various glass finishes
3. The effect of mask

Test Conditions

Two Test conditions were explored.

The tests were carried out at 23 °C and 50% RH and at 85 °C and 85% RH.

Results

Resin system type showed a significant effect on the drop in Insulation resistance. One particular resin system out performed all other resin systems.

Glass finish had only a marginal effect and no special finish or treatment was needed to pass the test. Figures 3, 4, 5 and 6 show the performance of Isola's best performing products with and without mask.

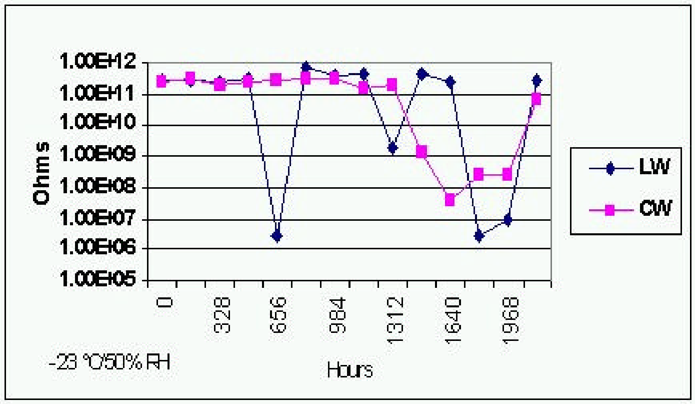

Figure 3 – Insulation Resistance Lengthwise and Crosswise with Solder Mask

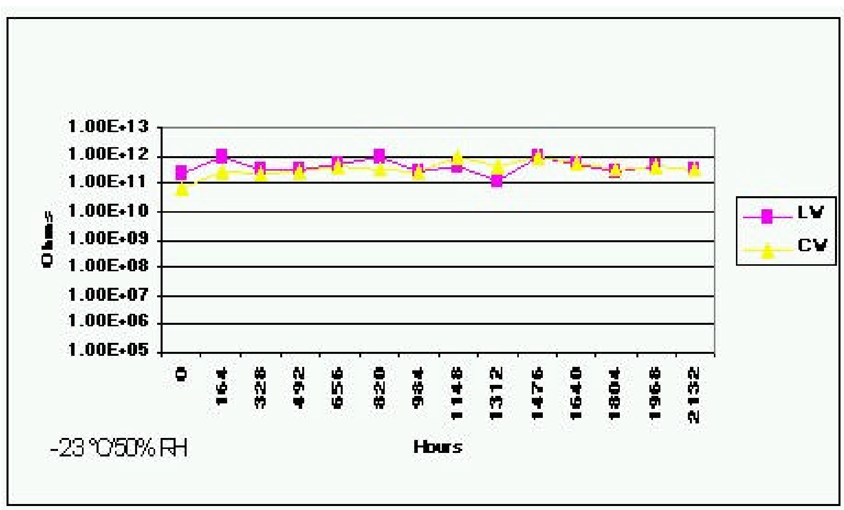

Figure 4 - Insulation Resistance Lengthwise and Crosswise/No Solder Mask

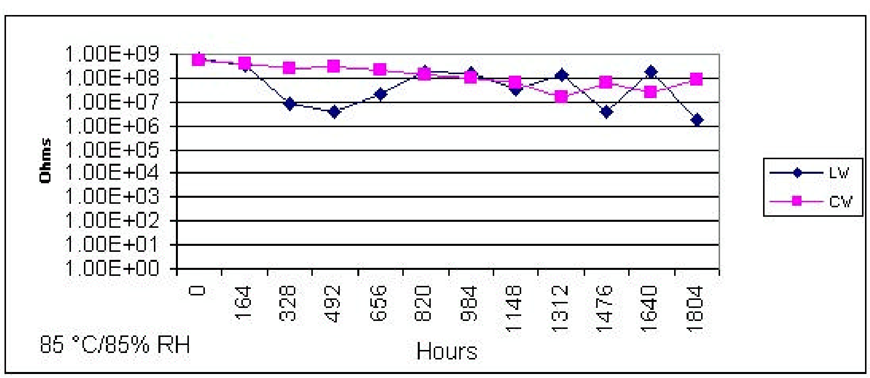

Figure 5 – Insulation Resistance Lengthwise and Crosswise (with Mask)

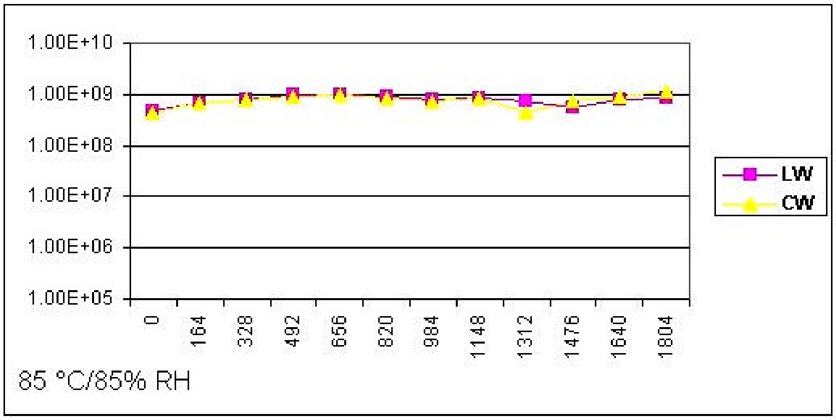

Figure 6 – Insulation Resistance Lengthwise and Crosswise (with Mask)

No CAF failure was seen, only a drop in insulation resistance and this was reversible.

The mask seems to play a major role. In the absence of the mask, the system stayed robust, but with the addition of the mask the drop was significant and the results were not very consistent.

The experiment raised some interesting points. While a great deal of emphasis is being placed on the finish as a possible solution to CAF failures, the robustness of the resin system is a very significant factor.

High Bias, Low Spacing Test

This testing was designed to simulate stringent conditions such as the effect of higher bias and reduced hole-to-hole spacings.

The test conditions were:

1. 12 Mil Hole to Hole Spacing
2. 100 Volt Bias, .0135 Inch Holes
3. 100 Volt Testing
4. Variables Were:
   - Three Resin Systems
   - Three Different Glass Finishes

Results

Figure 7 depicts that the glass finish has a significant impact on the magnitude of the insulation resistance. Isola's best performing grade, as far as insulation resistance is concerned, was also impacted by different finishes.

Figure 8 shows different resin systems with the best performing finish and one can see a significant difference in the magnitude of the insulation resistance of various resin systems.

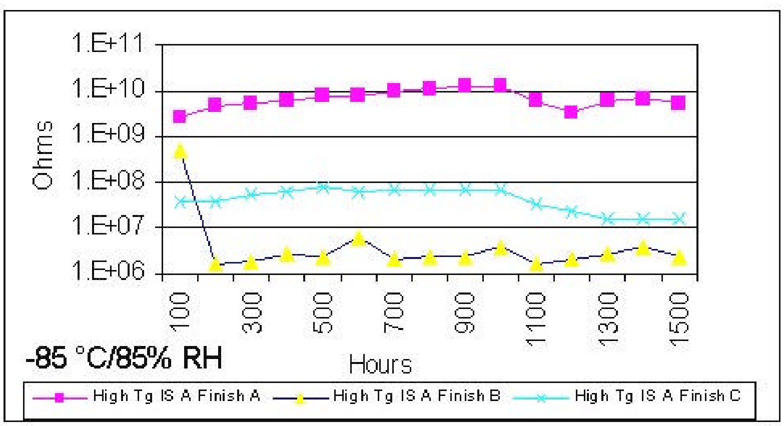

Figure 7 – Effect of Glass Finish on Resistance Drop

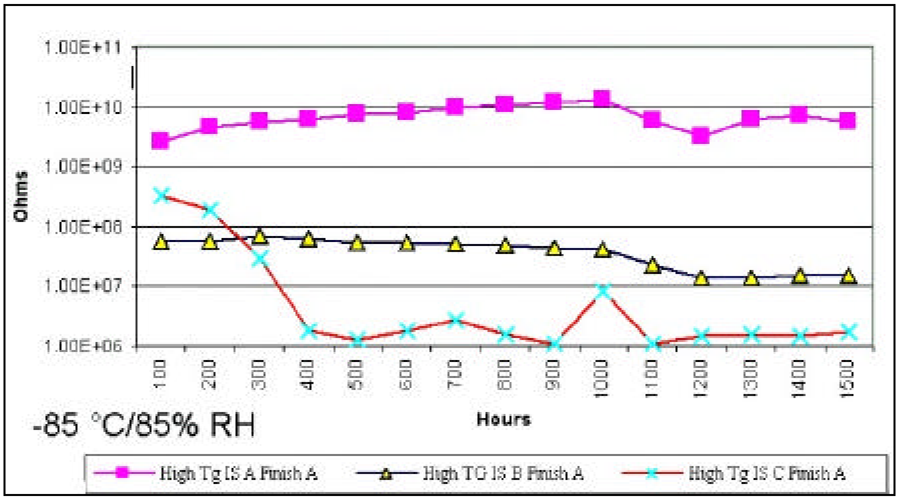

Figure 8 – Effect of Resin System on Resistance Drop

Conclusions

There seem to be quite a few mechanisms, which have been advanced as possible means to improve CAF resistance, mainly glass finish and resin systems.

While Isola's testing has so far been able to confirm an impact from the glass finish on the magnitude of insulation resistance, the tests have also shown an even greater effect of resin systems on the insulation resistance.

The inability to produce actual CAF failure probably indicates that the CAF failures are perhaps more a product of PCB fabrication process.

The higher voltages and lower hole-to-hole spacings did not cause any reduction in time to failure or insulation resistance. This confirms the commonly held belief that the voltage bias and Line spacings are factors influencing only the second step of the process. The breakdown in the resin glass interface is caused primarily by the increased humidity and or temperature. The voltage and spacings promote the second irreversible step, which promotes dendritic growth along the filaments. Unfortunately, we were not able to simulate the actual CAF growth with even increased voltage up to 100 V. The CAF failure is defined by some as a decade drop in insulation resistance. While the insulation resistance drop is a measure of CAF resistance, the magnitude of insulation resistance may be playing a part. The absence of actual CAF growth suggests that the threshold necessary for the growth to take place could not be achieved during the testing. The possible causes could be:

1. Absence of PCB fabrication related causes
2. There probably exists an Insulation resistance threshold for CAF failure
3. We may need to increase the voltage further and reduce the spacings to cause CAF failure.

Robust resin systems and glass finish combinations appear to be the best possible candidates for improving the insulation resistance of the laminate.

Isola's inability to produce an actual CAF failure, even at high voltages and close spacings, raises some interesting questions. Is thermal shock/ cycling a major contributing factor which weakens the resin to glass interface? Drilling conditions, mechanical stress, in fact the entire PCB fabrication process may hold the key to other contributing factors, which cause actual CAF failures.

Next Steps

Isola will work towards characterizing the insulation resistance/CAF performance at higher voltages and closer spacings. Additional resin systems are currently in testing. The effects of drilling parameters and thermal shock, along with other factors are included in the studies.

References

1. Welsher, T.L., Mitchell, J.P., Lando, D.J., "Conductive Anodic Filaments (CAF): An Electrochemical Failure Mechanism of Reinforced Polymeric Dielectrics".
2. Augis, J.A., DeNure, D.G., Luvalle, M.J., Mitchell, J.P., Pinnel, M.R., Welsher, T.L., "A humidity threshold for conductive anodic filaments in epoxy glass printed wiring boards" Proceedings from 3rd International SAMPE Electronics Conference.
3. Ready, W.J., Stock, S.R., Freeman, G.B, Dollar, L.L., Turbini, L.J., "Microstructure of Conductive Anodic Filaments Formed during Accelerated Testing of Printed Wiring Boards".
4. Laura Turbini and W. Jud Ready, "Conductive Anodic Filament Failure: A Materials Perspective".

5. Balu S. Rudra and Michael Pecht, "Conductive Filament Formation: A Focus on MCM-L Substrates".
6. Ikuo Sugawara and Hikari Murai, "New High Performance Materials for Packages".
7. Anand A. Shukla, Terrance J. Dishongh, Michael Pecht and David Jennings, "Hollow Fibers in Woven Laminates".
8. Physical Chemistry P.W. Atkins
9. Clarissa Navarro, "Standardizing a Test Method for Conductive Anodic Filament Growth Failure", IPC EXPO 2001.