Conductive Anodic Filament: Mechanisms and Affecting Factors

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Abstract: Conductive anodic filament (CAF) formation, a failure mode in printed wiring boards (PWBs) that are exposed to high humidity and voltage gradients, has caused catastrophic field failures. CAF is an electrochemical migration failure mechanism in PWBs. In this article, we discuss CAF, the factors that enhance it, and the necessary conditions for its occurrence. Published studies are discussed, and the results of historical mean time to failure models are summarized. Potential reasons for CAF enhancement solutions are discussed, and possible directions in which to develop anti-CAF materials are proposed.

1. Introduction

Conductive anodic filaments (CAF) on printed circuit boards have been of increasing concern in the past few years. The major reasons for that concern are the current trend toward smaller and thinner size, lighter weight, and higher performance, and the fact that the density of printed wiring boards (PWB) is designed for closely spaced conductors, small pitches, and single-ply dielectrics, such as those in mobile phones, laptop computers, and digital camcorders. Some electrical applications, however, may be exposed to extreme environments, accompanied by high temperatures, voltages, or humidity. To avoid electrical shorts, the insulation resistance of the material becomes very important.

The most common PWB substrate material used in modern electronics is FR-4 epoxy glass, which consists of an epoxy matrix that is reinforced with several plies of glass fibers which are woven in a 0°/90° manner. CAFs are copper-containing corrosion by-products that emanate from the positively charged anode and progress on the subsurface toward the cathode, frequently along the epoxy/glass fiber interface. They cause catastrophic failure if allowed to bridge between the anode and the cathode. CAFs can occur between any two oppositely adjacent conductors that are in contact with the glass fibers. Fig. 1 (a-d) shows those pathways. The coarse line that extends from the anode (+) illustrates the pathway that is followed by the filaments and their eventual progress toward the negative cathode. There are four conductor configurations: hole to hole (H-H), hole to track (H-T), track to hole (T-H), and track to track (T-T). This shows that susceptibility to CAFs is H-H > H-T, T-H > T-T and is due to the direct contact of the PTH barrel with the glass fiber for H-H configurations [1, 2].
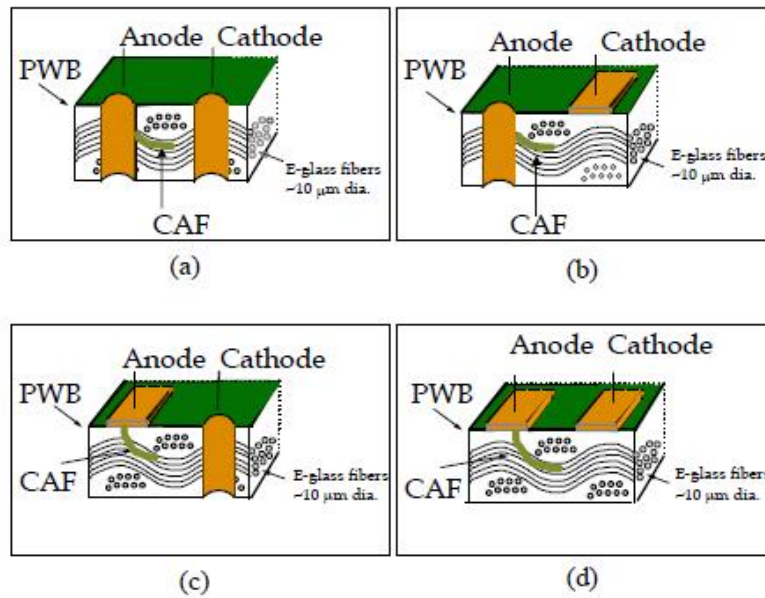
Fig. 1. Schematic Representation of CAF Pathways (dimensions exaggerated for clarity). (a) Hole to Hole, (b) Hole to Track, (c) Track to Hole, (d) Track to Track. [1]

2. Mechanism of CAF Formation
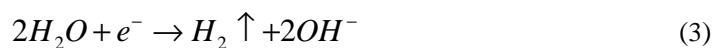
2.1 Electrochemical mechanism

Bell Labs researchers [3-7] detailed a two major step model for the mechanism of CAF formation and growth. The first step is the physical degradation of the epoxy/glass fiber interface. When moisture absorption occurs, it creates an aqueous medium along the separated epoxy/glass fibers interface, which provides an electrolytic pathway and facilitates the transport of corrosion products. The second step consists of electrochemical corrosion reactions that result in a loss of insulation resistance. After degradation and path formation with a continuous moisture medium between the conductors, an applied voltage produces an electrochemical process in which copper ions dissolve from the anode and migrate to the cathode through the resin/glass fiber interface. The insulation resistance then drops and, finally, the CAF phenomenon occurs.

This mechanism involves oxidation and the dissolution of copper at the anode; if copper ions reach the cathode, then they are reduced back to copper metal. The detailed chemical reaction scheme is illustrated as follows.

At the copper anode:

$$Cu \rightarrow Cu^{n+} + ne^- \tag{1}$$

$$H_2O \rightarrow \frac{1}{2}O_2 \uparrow + 2H^{2+} + 2e^- \tag{2}$$
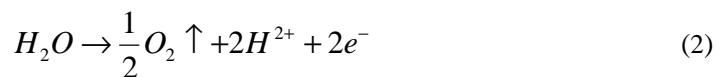
And at the copper cathode:

$$2H_2O + e^- \rightarrow H_2 \uparrow + 2OH^- \tag{3}$$

$$Cu^{n+} + ne^- \rightarrow Cu. \tag{4}$$

This process however, is solubility dependent in practice. The formation of Cu at the cathode does not readily happen because the copper may deposit as an insoluble salt due to its high pH.
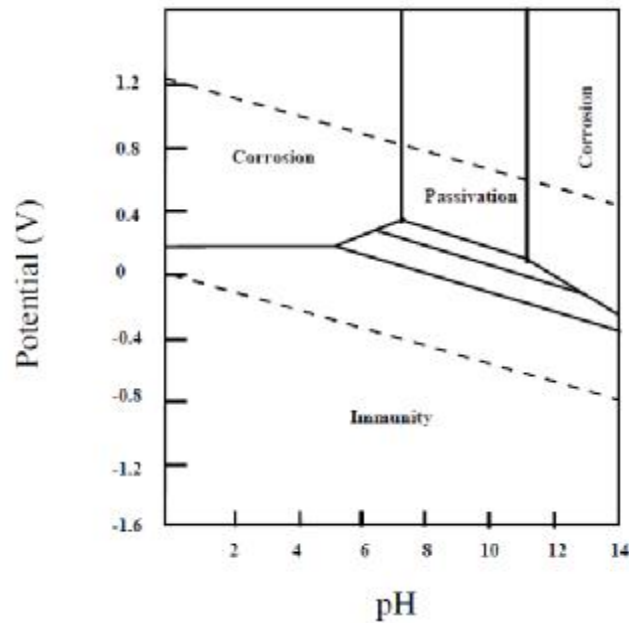
Fig. 2. Simplified Pourbaix Diagram for Copper. [9]

The generation of hydronium ions (H^+) at the anode and hydroxide (OH^-) ions at the cathode creates a pH gradient between these electrodes. A Pourbaix diagram for copper (Fig. 2) is a tool for viewing the relationship between pH and corrosion. In the region of pH = 7~11, copper is passivated and corrosion will not occur; but for pH < 7, corrosion will occur at potentials greater than 0.2V. In the case of CAF formation, electrochemical reactions generate hydronium ions at the anode, thus causing the local pH to drop and the corroded substances to become soluble. These mobile copper ions will travel along the separated epoxy / fibre interface towards the cathode as a result of the pH gradient. Eventually, they will reach a neutral region where they become insoluble and will deposit on the interface. The copper bearing filament known as CAF is formed [8]. The filament may initially grow in a random manner, but as time progress, the filament will grow preferentially toward the cathode along the separated epoxy/fibre interface.

2.2   Mean time to failure models
The formation of conductive filaments has been studied since the mid-1970s. Several models have been reported for assessing mean time to failure (MTTF) due to filament formation.

The notations for equations (4-7) are as follows.

H	Humidity (%RH)
E_a	Activation energy (J)
T	Temperature (ºC)
L	Spacing between the conductors (m)
V	Voltage (V)
$a, b,$ and d	Material parameters
$\alpha, \beta,$	Material-dependent constants
γ	Humidity-dependent constant
k	Boltzman's constant
f	Multilayer correction factor
$k,$	Shape factor
M	Fraction moisture content
M_t	Threshold fraction moisture content
m	Voltage accelerating factor

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Welsher et al. [5] conducted extensive tests on a filament formation-resistant material, triazine/glass, and proposed a two-step model that is consistent with the two-step filament formation process. The voltage-dependent and temperature-dependent models for MTTF are:

$$MTTF = a\left(H\right)^b \exp\left(\frac{E_a}{RT}\right) + d\frac{L^2}{V}. \tag{4}$$

They noted that additional work was needed to determine the exact dependence of CAF on conductor spacing and humidity, and also reported that glass-reinforced triazine is CAF resistant. In 1981, Welsher et al. expanded their view of MTTF and reported it as:

$$MTTF = a\left(1 + b\frac{L^n}{V}\right)H^g \exp\left(\frac{E_a}{kT}\right), \tag{5}$$

where n is related to the orientation of the conductors. This equation is valid for temperatures between 50°C and l00°C, and RH between 60% and 95%.

The CALCE group [2, 9] studied the physics of failure and used the term, "conductive filament formation" (CFF), which they defined as "an electrochemical process that involves the transport (usually ionic) of a metal through or across a non-metallic medium under the influence of an applied electric field." This definition is not specific to CAFs, but can include surface dendrites, CAFs, and copper plating in hollow glass fibers (which occurs during the board plating process). They defined the time to failure (t_f) as:

$$t_f = \left(\frac{af\left[1000kL\right]^n}{V^m\left[M - M_t\right]}\right), \tag{6}$$

Where a is a filament formation acceleration factor and n is a geometry accelerating factor.

Ready and Turbini [10] studied the effects of voltage and spacing on CAF failures for a H-H test pattern. Based on experimental data, they modified Welsher's equation as:

$$MTTF = c\,\exp\left(\frac{E_a}{kT}\right) + d\frac{L^4}{V^2}\quad. \tag{7}$$

The parameters for the above equations can be determined from testing that was conducted in studies which explored the CAF failure mechanism. Some of the studies only tested a limited number of these parameters; therefore, further work is needed to establish more physically meaningful models.

3. Factors influencing CAF formation
A number of factors can affect the susceptibility of a specific PWB to CAF formation and growth. These factors can be grouped into internal variables and external influences. Internal variables include the choice of substrate material, the components, and the circuit layout pattern. External influences are factors that can be easily changed or controlled when the assembly is in production or use and include operating conditions, laminate quality, and manufacturing process.

3.1 Substrate material choice
Different resin types also have different CAF performances. Researchers [1, 2, 10] have performed an extensive experimental comparison among FR-4 with several substrates: G-10 (a non-fire retardant epoxy/woven glass material), polyimide/woven glass (PI), triazine/woven glass, epoxy/woven Kevlar, bismaleimide triazine (BT), cyanate esters (CE), CEM-3 (a substrate similar to G-10, but with chopped glass), and MC-2 (a blended polyester and epoxy matrix with woven glass face sheets and a chopped glass core). Of these materials, BT proved to be the most resistant to CAF formation due to its low moisture

absorption characteristics. Conversely, the MC-2 substrate proved to have the least resistance to CAF formation. The susceptibility of the materials follows the trend:

MC-2 >> Epoxy/Kevlar > FR-4 » PI > G-10 > CEM-3 > CE > BT.

To ensure immunity to CAF formation, the ideal laminate is BT. However, it may be more expensive than other laminates.

3.2   Circuit Layout Pattern
The circuit layout pattern has the four configurations that are shown in Fig 1. Experiments show that a test pattern with smaller spaces between the adjacent conductors more readily causes CAF formation. Hole-to-hole failure is the most common CAF failure. This is because the through hole has a higher area of glass fiber contact with the copper.

3.3   Operating Conditions
The operating conditions include temperature, humidity, and voltage. Electrochemical corrosion will be accelerated by a critical operating condition. The reaction process of CAF occurs due to moisture absorption. Most laminate materials absorb moisture through surface absorption and diffusion in the interior, especially when exposed to high temperature and humidity environments, which accelerates the absorption and can result in quicker degradation and path formation. The different moisture absorption rates of resin and glass fiber can also lead to interface stress. Resin swells due to the absorption of moisture, which can lead to de-bonding at the resin/glass fiber interface. Voltage bias is a driving force for CAF formation. Higher voltage can lead to quicker failure.

3.4   Laminate Quality
Several features of laminate qualities prevent CAF formation, including the use of glass cloth, resin, impregnation, and lamination. Glass cloth must be properly treated. Silane is a bridge between the glass fibers and the resin, so the silane type and treatment is significant. The chemical hydrolysis of silane can lead to de-bonding, due to the absorption of moisture. In addition to the finish, there is a special process that will allow the glass fibers to splay more uniformly and become puffy to help the resin complete the wetting of each glass fiber. This ensures that the bonding of the resin/glass fibers is absolute. The resin should be pure, which leads to low levels of ion impurities. Such impurities cause corrosion when the matrix absorbs moisture, thus accelerating the copper dissolution process. The path formation of CAFs may result from incomplete bonding between the resin and glass fiber interface. Enhancing the wetting ability in the impregnation process increases the bond strength at the resin/glass fiber interface. Foreign materials are conductive media that can decrease insulation resistance, so a clean environment is also important in the impregnation and lay-up processes. The voids must be removed completely during lamination, as they promote the accumulation of moisture in the laminate.

3.5   Manufacturing Process
The PCB process includes line manufacture, lamination, drilling, and surface coating, all of which can result in CAF failure. In lamination processes that include temperature, the pressure must correspond to the performance of the prepreg to ensure the adhesive strength of the resin/core and that there are no lamination voids in the PCB. These defects can result in delamination under environmental stresses, thus providing a CAF path. The roughness of the hole must be minimized, which means it must be made straight and smooth. If drilling qualities are poor, delaminations, voids, and cracks may occur on the walls of the hole. Chemicals can be trapped inside the voids and cracks during the PTH process. Moisture may also be transferred by capillary action along cracks in the resin/glass fiber interface in high temperature and humidity environments.

4. Conclusions and Recommendations

Today's smaller feature sizes increase the potential of catastrophic failures due to inner/outer laminate conductive filaments being formed in the presence of humidity, ion impurities, and bias. CAF-resistant substrates are urgently required in design guidelines.

The development of anti-CAF substrates should be considered in terms of aspects of the raw materials, manufacturing processes, and qualities of the laminate to, for instance, prevent the pathway formation of CAFs, reduce the disruption of the epoxy resin, minimize water absorption, and enhance the bonding strength between the interface of the epoxy resin and the glass fibers. To summarize, the CAF-enhancement solution lies in the prevention of the primary step of the degradation of insulation resistance or debonding through the following.

- § Robust resin systems resistant to chemical attack.
- § Robust glass resin interface/robust finish.
- § Avoiding other fabrication-related causes, such as thermal shock and thermal stress.
- § Avoiding a high-humidity and high-voltage gradient between the anode and cathode during storage or use.

Robust resin systems and proper glass finish combinations are the best approaches to improving the insulation resistance of the laminate, which, in turn, is of benefit to the current trend toward the miniaturization of technology. Fabricators will be required to reduce surface ion impurities and develop better via formation techniques to create minimum stress at the via wall glass-to-resin interface.

However, reliability prediction models are also needed. Although many attempts have been made to derive a model to predict mean time to failure, these models are not robust. Empirical co-relations do exist, but these must be more specific, as they are affected by such factors as resin systems. To arrive at a meaningful model, we must understand the failure distribution, so that the testing duration is tied to mission reliability.

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