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Conductive Filament Formation: A Potential Reliability Issue in Laminated Printed Circuit Cards with Hollow Fibers

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Abstract:

E-glass fibers are used as a reinforcement material in the manufacture of laminates used in printed circuit cards and multichip module laminated substrates (MCM-Ls). The principal advantages of using E-glass fibers include high strength, high chemical resistance, and excellent insulating properties at reasonable cost. Although most fibers are solid, hollow fibers can be produced if there is insufficient process control during the manufacture of E-glass fibers. This creates a potential reliability problem in laminates since hollow fibers provide a path for conductive filament formation (CFF) between two differently biased points, which can result in short circuit failure modes. The probability of CFF is a function of temperature, moisture content, the voltage bias and other environmental conditions and physical factors.

This paper presents relevant information on E-glass laminate manufacture and the causes of hollow fibers, details of experiments performed to observe hollow fibers, the reliability issues in terms of the CFF mechanism, and analysis as to the opportunity for failure and recommendations for improvement.

Introduction

1. Background

Glass fibers were first used as reinforcement for polymers during the 1940s. Electrical (E) glass, a low-alkali composition which exhibits an excellent balance of electrical insulation properties and good resistance to water, is the most widely used reinforcement material for cost-effective electronic applications. Other glass types, such as the low dielectric D-glass, is available for high performance electronic applications, but at additional cost. The interested reader is referred to Coombs [1979] for more information about the different types of glass fiber and their properties.

E-glass, used for most printed circuit card and substrate applications, is a continuous filament glass yarn with a chemical composition displayed in Table 1. Table 2 displays some of the typical material properties of E-glass.

Table 1: Specifications for fabric woven from "E" glass

for printed boards [ANSI/IPC-EG-140 1997]

Material	**Composition (by weight)**
B2O3	5 to 10%
CaO	16 to 25%
Al2O3	12 to 16%
SiO2	52 to 56%
MgO	0 to 5%
Na2O and K2O	0 to 2%
TiO2	0 to 0.8%
Fe2O3	0.05 to 0.4%
F2	0 to 1%

Table 2: Properties of E-glass fibers [Katz and Milewski 1987]

Property	E-Glass
Physical properties:	
· Specific gravity (bare fiber)	2.52 to 2.61
· Pristine tensile strength (psi)	500,000
· Tensile elastic modulus (psi)	10,500,000
· Elongation at 72°F	3 to 4
· Poisson's ratio	0.22
Thermal properties	
· Softening point (°F)	1,540 to 1,555
· Coefficient of thermal expansion (in./in./°F x10-7)	28 to 33
· Specific heat at 72°F (BTU/lb/°F)	0.197

Optical properties	
· Index of refraction@550nm	1.55 to 1.56
Electrical properties:	
· Dielectric constant, 72°F, 106 Hz	6.1 to 6.7
· Loss tangent, 72°F, 106 Hz	0.001

2. Glass fiber manufacturing

The manufacture of glass fiber begins with the dry mixing of silicas, limestone, clay, and boric acid in appropriate proportions. In the direct-melt process, the mixture is melted in a refractory furnace at temperatures between 2600 and 2800 °F and fed directly into bushings, which are platinum alloy plates with nozzles. Alternatively, the melt can be formed into marbles, cooled to room temperature and stored for future use. Additional information about this process is supplied by Loewenstein [1983].

A homogeneous melt composition with negligible impurities is necessary for the successful manufacture of glass fibers. Solid inclusions of even submicron dimensions will act as stress concentrators that reduce the fiber strength. Furthermore, the decomposition of raw materials during glass melting can lead to trapped gases. In the raw materials, water, carbonates (CO_3), and organic materials will decompose with heat to form gases. Depending on the viscosity of the glass mixture and various manufacturing processes, these gases can get trapped as bubbles, called seeds. Seeds are a naturally occurring part of the process and thus methods to remove them are necessary. One approach is *fining*. Fining removes gases by adding gases (i.e., SO_2) which create nucleation sites for bubbles to coalesce and escape the melt. Fining can also be defined as increasing the temperature and modifying the heat flow pattern so bubbles are moved in positions to readily reach the surface to escape. The interested reader is referred to Shand [1958] for more information about the formation and removal of seeds.

After the molten glass is poured into the bushing, glass fibers are produced by drawing a solidified filament of glass from the molten drop. The thickness of the fiber depends on the rate of glass flow through the nozzles and the rate of attenuation. During drawing, any seeds present will become attenuated and elongated, forming capillaries several meters long in the glass filaments and effectively creating hollow fibers [Morley 1987]. These hollow fibers can provide a path for conductive filament formation.

3. Production of fiber weaves

Individual fibers being drawn from the nozzles in the bushing pass through a light water spray and then over an applicator that transfers a protective and lubricating size onto the filaments. Glass fibers are then gathered together to form a strand and then wound on a rotating cylinder called a "collet". The term *strand* refers to a unidirectional bundle of fibers drawn from a single bushing. The strands are then twisted into yarns. In the electronic substrate industry, the yarns are typically woven into a plain weave fabric which is impregnated with an epoxy to form a laminate. Examples of various fabrics used in the electronics industry are displayed in Table 3.

Fabric Style	Count/in. warp x fill	Warp yarn	Fill yarn	Weight (oz./sq. yd.)	Thickness (in.)
106	56 × 56	D 900 1/0	D 900 1/0	0.72	0.0013
1080	60 × 47	D 450 1/0	D 450 1/0	1.38	0.0021
1675	40 × 32	DE 150 1/0	DE 150 1/0	2.84	0.0040
2113	60 × 56	E 225 1/0	D 450 1/0	2.30	0.0031
2116	60 × 58	E 225 1/0	E 225 1/0	3.06	0.0037
2313	60 × 64	E 225 1/0	D 450 1/0	2.40	0.0033
7628	44 × 31	G 75 1/0	G 75 1/0	6.00	0.0068

Table 3: Fabric styles and construction [ANSI/IPC-EG-140 1997]. The prefix letters of the yarn designation identify the filament diameter, typically 5 to 9 micrometers. The first series of numbers in the numerical designation represents one-hundredth of the basic strand yield. The second series (resembling a fraction) specifies the number of single strands twisted together ("numerator") and the number of the twisted yarns plied together ("denominator"). The total number of basic strands in a plied yarn is determined by multiplying these two digits (0 being multiplied as 1). The yield is obtained by dividing the basic strand yield by the total number of strands in the yarn.

Measurement of Hollow Fibers in Common Laminates

A series of experiments were conducted to determine the number of hollow fibers within typical woven glass fabrics of various laminates used in the avionics industry. The resin types were polyimide (PI), bismaleimide triazine (BT), cyanate ester (CE), flame retardant (FR-4), a high-temperature FR-4, and Driclad, an IBM high T_g laminate advertised as having low moisture uptake. The manufacturers of the glass fabrics were unidentified.

1. Measurement technique

The laminates were cut into 2 x 2 inch test coupons to allow for ease of handling, sample preparation, and observation through an optical microscope. The resins in each laminate were burned-off in an oven. The initial burn-off temperature of 600 ^{o}C, as suggested by industry, was found to result in the fracture of glass fibers. The burn-off temperature was then reduced to 540 ^{o}C, which optimized the burn-off time while still maintaining the integrity of the glass fabric. Burn-off lasted 30 to 60 minutes, depending on the type of resin used. The four sides of the coupons were subsequently sealed with wax to prevent wicking, the capillary action of a fluid into a hollow fiber.

A technique used by the Fermi National Accelerator Laboratory to investigate leaks in fiberglass-reinforced pressure vessels [McAdams 1988] was used at CALCE to observe hollow glass fibers. Each coupon was submerged in oil with an optical refractive index that closely matched that of the fibers. Light directed onto the coupon travels freely until it hits a hollow fiber (air), where the change in refractive index at the fiber-air boundary partially reflects it. The unreflected light continues to propagate until it hits the outgoing air-fiber boundary, where again it is partially reflected.

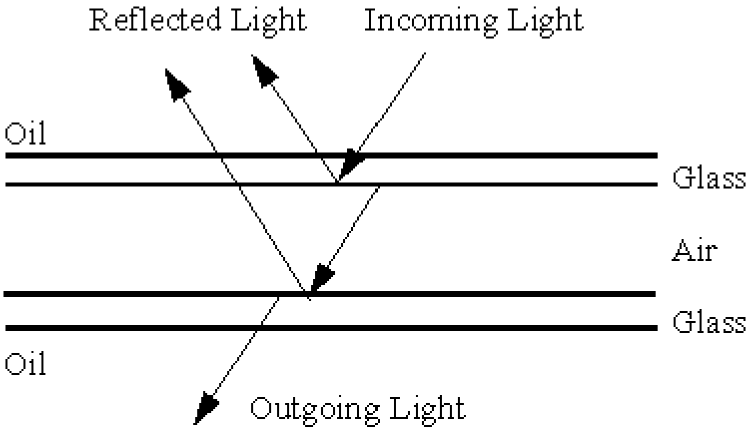

Figure 1: Reflective properties of a hollow filament

2. Experimental observations

Figure 2 shows a photograph of three hollow fibers (denoted by bright white lines) as seen through an optical microscope. Two of the hollow fibers are vertical and one runs horizontal.

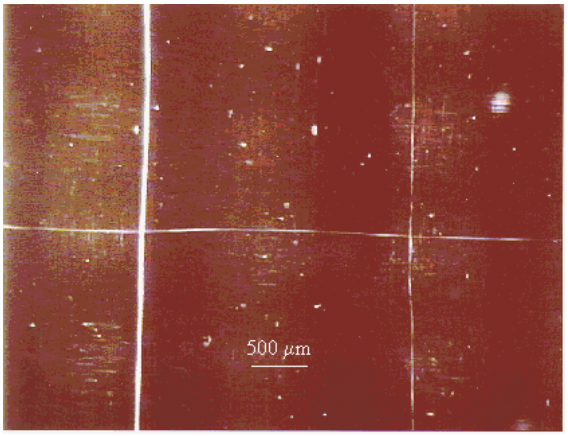

Figure 2: Photograph of three hollow fibers

The number of hollow fibers in each 2 x 2 inch coupon tested ranged from 0 to 158. Six to eight samples were tested for each laminate type. Since a common standard for fabric size is 1,000 in^2 and hollow fibers typically run all the way through a fabric, the count in each 2 x 2 inch coupon was multiplied by a conversion factor of 16. Thus the range of hollow fibers per 1,000 in^2 of fabric ranged from 0 to 2,528. The IBM Driclad laminate, promoted as "hollow-free fabric" to prevent conductive filament formation (CFF), had an average of 16 hollow fibers per 1,000 in^2. The number of hollow fibers found in fabrics depends on filament type, weave density, and number of plies. The potential for an increase in conductive formation failures as a function of the number of hollow fibers will be illustrated in a later section.

Discussion of the Hollow Glass Fiber Problem

Multi-layer organic laminates used in printed wiring boards and laminated multichip modules (MCM-L) can develop a loss of insulation resistance between two biased conductors due to the growth of conductive filaments. The phenomenon, called conductive filament formation (CFF) or electromigration, is an electrochemical process which involves the transport, usually ionically, of a metal through or across a nonmetallic medium under the influence of an applied electric field. The growth of metallic filaments is a function of temperature, humidity, voltage, laminate materials, manufacturing processes, and the geometry and spacing of the conductors.

CFF requires an applied electric field and both a source and sink of migration, such as a clad stripe, plating, metal-loaded ink, or base metal-substrate. These characteristics differentiate CFF from other modes of short circuit failure in laminates, such as tarnish creepage and tin whiskering [Krumbein 1988]. Although a dendritic structure also appears in tarnish creepage, the corrosion compound does not exhibit full metallic conduction and does not require an applied electrical field. While tin whiskering produces failure by shorting across closely spaced conductors, whiskering is caused by mechanical stresses in the plating rather than migrated metal in an electrical field. More extensive details of the conductive filament formation failure mechanism can be found in papers by Rudra and Pecht [1994], Augis et al. [1989], Boddy et al. [1989], Jennings et al. [1976], Krumbein et al. [1988], Lahti et al. [1979], Lucas et al. [1993], and Welsher et al. [1980].

CFF is most prone to occur between biased conductor such as vias and plated-through holes (PTHs), but can also occur between two traces (usually copper) or between a trace and a via or PTH [Rudra and Pecht 1994]. The formation of a continuous metallic path through or on the outside of the fiber will result in an electrical short. CFF is nearly impossible to detect in the field because once it occurs, sufficient heat is generated to "vaporize" the conductive filament and "clear" the failure. Furthermore, observation of a partial filament formation requires destructive analysis. It is nearly impossible to screen a circuit card in order to precipitate CFF, in part because of the ability of the problem to heal itself.

Failure Opportunities

1. Modeling

Rudra and Pecht [1994] have shown that PTH-to-PTH CFF failures represent the most significant population of failure opportunities, especially compared with line-to-line or line-to-PTH metallization failures. Thus, PTH-to-PTH adjacency is used as a convenient measure to study CFF. CFF failure opportunity is dependent upon the probability of any hollow fiber connecting two adjacent plated-through-holes (PTHs). This probability was found to be a function of the density of PTHs in the circuit card, the percentage of cross-sectional area a PTH occupies, and the percentage of cross-sectional area that the hollow fibers occupy (hollow fiber density). The geometric model used to calculate CFF failure opportunity is exhibited in Figure 3 and a micrograph of two PTHs in a woven laminate is displayed in Figure 4 to give the reader a feel for typical dimensions. The PTH-to-PTH spacing and grid dimensions depend on the circuit card layout design rules and the allowable exceptions.

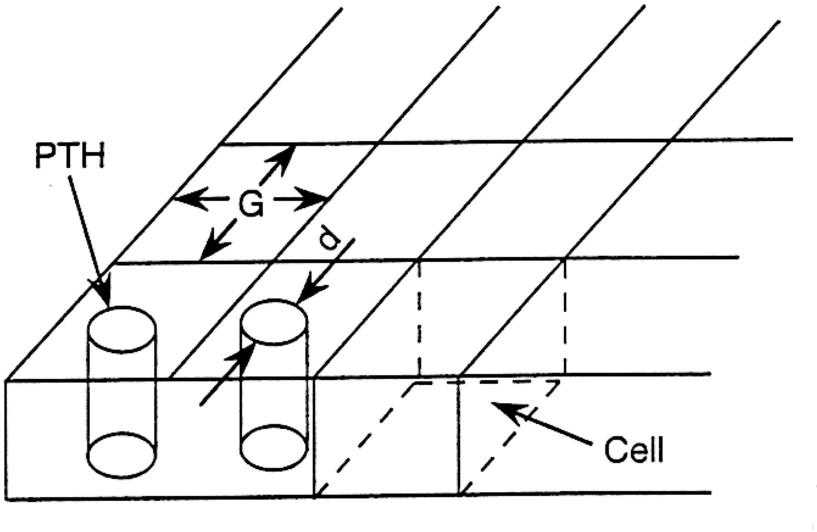

Figure 3: Geometry used to calculate CFF opportunity

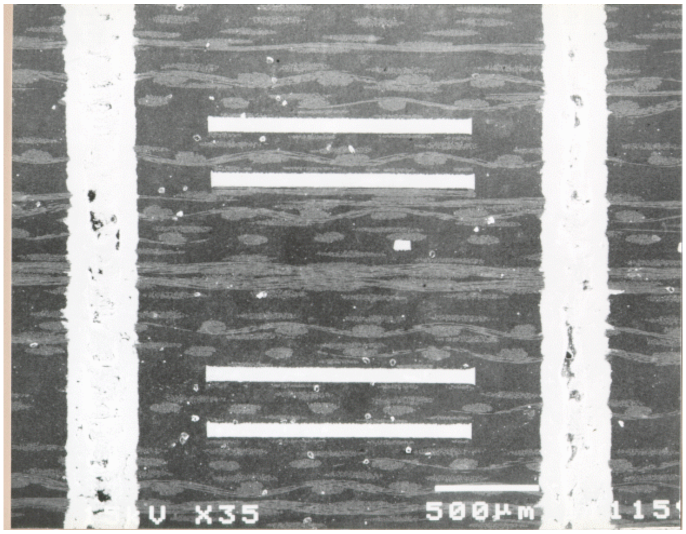

Figure 4: Laminate cross-section with two PTHs and four conductor traces

The results of the calculations using the CFF failure opportunity model are shown in Figures 5 and 6.

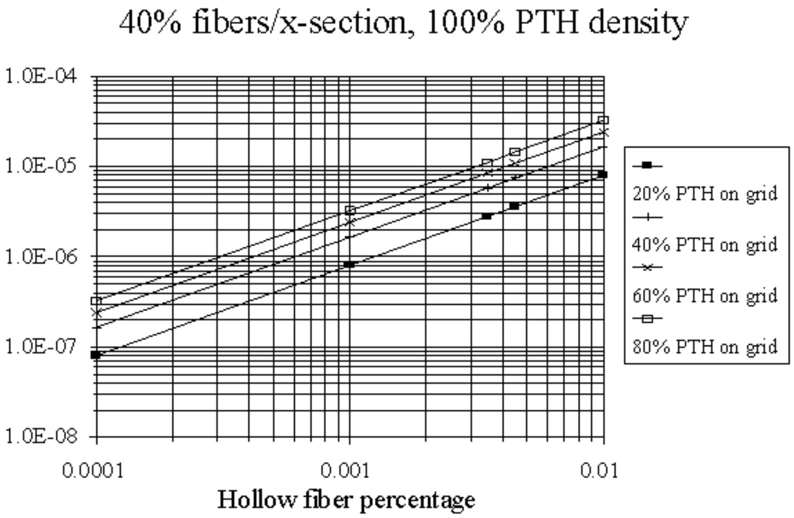

Figure 5: CFF Opportunity

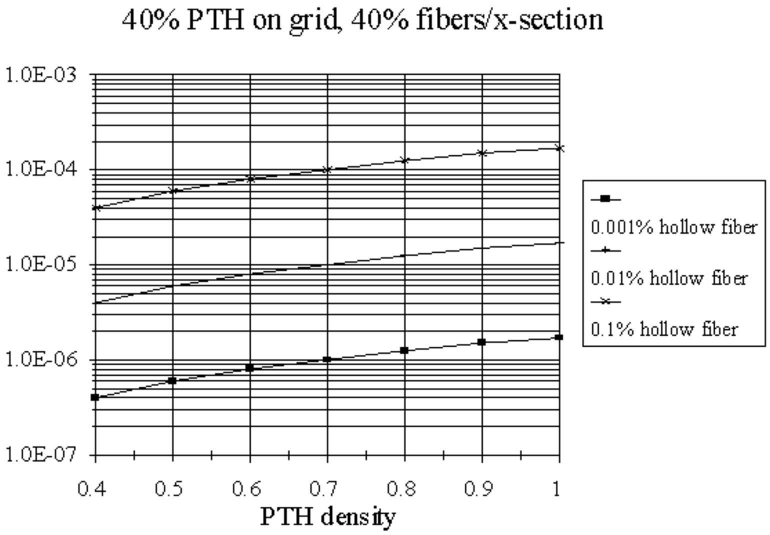

Figure 6: CFF Opportunity

However it must be noted that an opportunity for failure does not mean that failure will occur since it is dependent on spacing, voltage bias, temperature, humidity, and manufacturing conditions. For example, the Rudra and Pecht model [1994] assesses time-to-failure due to CFF failures as:

$$t_f = \frac{af(1000L_{eff})^n}{V^m(M - M_t)}, \qquad M > M_t$$

(1)

$$t_f = \infty, \qquad M \le M_t$$

where a is the filament formation acceleration factor, f is a multilayer correction factor, n is a geometry acceleration factor, V is the applied voltage bias (volts DC), m is a voltage acceleration factor, M is the percentage moisture content, M_t is the percentage threshold moisture content, and L_{eff} is the effective length between conductors ($L_{\text{eff}} = kL$). For further details of time-to-failure, the interested reader is referred to the study conducted by Rudra and Pecht [1994] which discusses how circuit card metallization dimensions and assembly processes affect the CFF process as a function of temperature, humidity, and bias.

2. Example calculation

As an example of the use of Figure 5, consider the E-glass laminate, constructed using fabric style 1080. The weave has 200 filaments per bundle with 60 x 47 (warp x fill) bundles per square inch. Assume there exists 8 hollow fibers per a 24 x 18 square inch of fabric. The total maximum number of hollow fibers per total number of fibers is thus,

$$\text{Hollow fiber percentage} = \frac{8x100\%}{(24\,x\,60 + 18\,x\,47)(200)} = 1.75x10^{-3}\% \qquad (2)$$

Next assume the layout design guidelines limit the PTH cross-sectional area to 60% on a grid and that the percentage of fiber per cross-sectional grid area is 40%. Using Figure 5, the CFF failure probability, Q_f is 4.2 x 10^{-6}. If there are 10,000 PTHs on a circuit card, then the total CFF failure opportunity (probability), Q_c, for the card is approximately

$$Q_c = 1 - \left(1 - Q_f\right)^{10{,}000} = 0.041 = 4.1\% \qquad (3)$$

Comments and Recommendations

The presence of hollow fibers can increase the opportunity for the formation of conductive filaments leading to the loss of insulation resistance between conductors on laminated substrates. Manufacture of high quality hollow-free glass fibers may be the primary solution to maintain the reliability of laminates used in the electronics industry, especially in the newer fine-line printed wiring boards and MCM-L. The formation of voids and capillaries in glass fibers can be reduced by ensuring seeds are not present when the molten glass is drawn into fibers.

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Appendix: Calculation of the Probability of Adjacent PTHs

Consider a rectangular PWB of size B_x x B_y which has a square grid of length G, such that B_x/G and

B_y/G are whole numbers. Consider the line segment consisting of $N = B_x/G$ non-overlapping intervals (cells) of equal length G. A given number, n, of plated-through-holes (PTHs) are placed on the board and centered in a grid. The n PTHs are placed such that the first PTH is placed with equal probability (1/N) in any unit interval. When a PTH has been placed in an interval, the interval is considered occupied and the next PTH is placed with probability 1/(N-1), and so on. Boundary effects are not taken into consideration.

The probability P that an arbitrarily chosen (taken at random) PTH (occupied cell) has at least one adjacent cell which is also occupied can be calculated by considering the arbitrary adjacent intervals (cells) a, b, and c. For clarity, denote the event "the interval a is empty" as A, and the event "the interval a is occupied" as A^+. The same notation will be used for the analogous events with intervals b and c.

The probability of interest, P, that an arbitrary chosen PTH (occupied cell) will be adjacent to another one from the left and/or from the right, is given by:

$$P = \frac{n}{N}\left[2\frac{(n-1)}{(N-1)}\left(1-\frac{(n-2)}{(N-2)}\right)+\frac{(n-1)}{(N-1)}\frac{(n-2)}{(N-2)}\right] \quad \text{(A.1)}$$

As an example, let N = 20 and n = 10. From Equation (A.1) the probability is P = 0.237.