An Improved Laminate for Embedded Capacitance Applications

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Abstract
The industry trend to smaller feature sizes and device miniaturization is making the use of embedded passive devices more attractive. This paper describes a recent advance in the fabrication and use of an epoxy-glass fabric laminate for embedded capacitance applications. The key performance enhancements in the buried capacitance laminate are precise thickness tolerance, improved dimensional consistency, and reduced levels of electrical breakdown during hipot testing. The use of a square-weave glass fabric with tight resin content control yields a laminate with a very precise thickness and improved dimensional consistency. A laminate with reduced levels of dielectric breakdown during a 500V DC test (hipot test) can be fabricated using a carefully controlled manufacturing process. The enhanced square-weave glass fabric also exhibits excellent resistance to Conductive Anodic Filament (CAF) growth during 1000 hour temperature/humidity aging under 100V DC bias.

Introduction
HADCO Corporation's Buried Capacitance™ (BC) technology provides an effective approach for decoupling high performance printed circuit board components and reducing electro-magnetic interference (EMI)[1-4]. Utilizing the BC internal power/ground plane construction can eliminate the need for, or enhance the performance of Integrated Circuit (IC) decoupling capacitors. To support an expanding market for buried capacitance products, Hadco has licensed over 20 printed circuit board (PCB) fabricators and several laminators to produce ZBC-2000™ PCBs.

Telecommunications is the largest market segment served by the BC technology as noted in Figure 1. Telecommunication products typically have very high speed switching devices, and a large number of surface decoupling capacitors that can be replaced through the incorporation of BC. The trend to smaller, lighter, and more portable electronics also drives the incorporation of embedded decoupling capacitors.

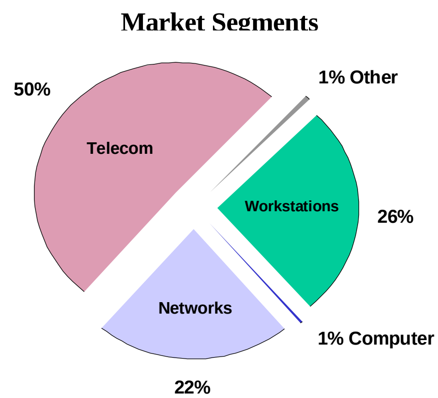

Figure 1. Market Segments for BC Laminates

Description
The ZBC 2000 laminate is constructed using a single ply of either 106 or 6060 style prepreg yielding a dielectric thickness after lamination of 0.002 +/- 0.0005 inches when measured by cross-sectioning. The double treat copper foil is utilized with the drum side in contact with the prepreg and matte surface on the outer face as shown in Figure 2. High tensile elongation (HTE) double treat copper foil with a minimum elongation of 6% is used. The laminate contains a fluorescent additive to enhance AOI inspection and also provides UV blocking. The minimum peel strength requirement is 4 lbs/inch when tested according to IPC TM-650, Method 2.4.8.

This paper explains the investigation of the use of a 6060 woven glass fabric from Clark Schwebel in AlliedSignals' laminates and compares it to the standard ZBC constructions that use 106 glass fabric.

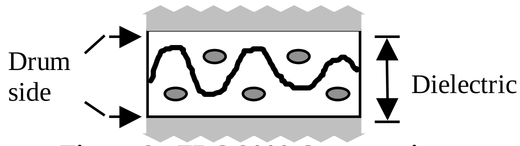

Figure 2. ZBC 2000 Construction

The goals of this investigation were to determine if the 6060 ZBC laminate could:

1) achieve better thickness tolerance
2) improve dimensional consistency
3) lower 500V DC high potential (hipot) failure rate
4) increase the resistance to Conductive Anodic Filament (CAF) growth

The 6060 glass style fabric is a balanced weave construction. The woven glass characteristics are summarized in Table 1.

Table 1 – Glass Fabric Comparisons

Style	**Ends/in**	**Yarns**	**Nominal Thickness**
106	56 x 56	D900 1/0	0.0013 in.
6060	60 x 60	DE 600 1/0	0.0018 in.

Physical Properties

Completion of a rigorous three phase qualification plan is required for a laminate supplier to become a licensed ZBC 2000 supplier. In phase one, the laminator's ability to supply usable BC laminates is evaluated. The dielectric thickness and copper orientation is verified using microsection evaluations. Inner layer samples are first produced in the normal PWB "print and etch" fashion. The laminate surface quality is checked either by visual inspection or AOI. The circuit images are then tested for power-ground shorts by high-potential test method (hipot) at 500V DC for 15 seconds. Power plane capacitance is also measured using a known surface area. The 6060 laminate successfully passed the phase one qualification.

Phase Two consists of submitting five lots of 6060 ZBC laminates. There were 100 panels in each press lot for a total of 500 ZBC laminates in our testing. Five panels forming each lot are randomly selected for testing. Cross-section evaluations of the 6060 showed good glass-centering characteristics within the dielectric layer. The dielectric thickness was measured across the diagonal of the 18x24 inch panels. The cross-section thickness data for 6060 glass is summarized in Table 2. The 6060 ZBC laminates exhibit a Cpk > 2.0 for Class III thickness tolerance (2.0 mils +/- 0.5 mils).

Table 2 – Thickness Data

	Thickness	Std. Deviation
Phase One	0.00199 in.	0.00007 in.
Phase Two	0.00205 in.	0.00005 in.

Twenty panels from four lots were hipot tested (total of 80 panels) as part of the Phase 2 qualification. The hipot data from all three parts of the qualification are summarized in Table 3.

Table 3 – Hipot Failure Data

	Hipot Fails	Hipot Yield
Phase One	4 out of 41	90.2%
Phase Two	2 out of 80	97.5%
Phase Three*	40 out of 2489	98.4%

* Available data at time of manuscript preparation.

The copper peel strengths were measured at room temperature and were in the range of 7.5-8.4 lbs/inch depending on double treat copper foil type.

Capacitance Testing

Capacitance measurements were performed using a conventional LCR meter. A plate pattern of a known area was imaged onto the BC-2000 cores. After electrical verification by high-potential 500V testing, all cores were capacitance tested.

ZBC-2000 laminates based on the 106 glass style and a standard 69% resin content (by weight) have an expected capacitance of 506pF/in^2. Due to typical process and material variations in manufacturing, ZBC-2000 laminates result in a capacitance variation of +/-50pF/in^2.

The 6060 glass fabric has a 0.0018 inch nominal thickness and requires a lower resin content (58%) to achieve a 0.002 inch dielectric thickness. This construction yields a slightly higher nominal capacitance value of 550pF/in^2, but still within the normal 106 capacitance range. The geometry of the parallel plate capacitor is shown in Figure 3. The area of the metal planes is denoted by A, and L is the dielectric thickness between the power and ground planes.

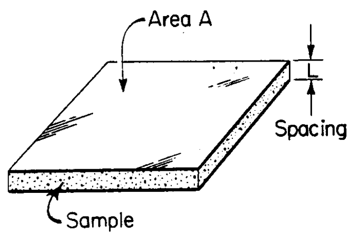

Figure 3 – Capacitor Geometry

The relationship governing the capacitance per square inch for a power-ground plane is represented by the following relationship:

$$C = K D_k / L$$

Where K is a constant (225 picofarad mil/in^2), D_k is the dielectric constant, L is the dielectric thickness in mils, and C is in the units of picofarads/in^2.

The actual measured values were comparable with our calculated values. In Table 4 the average measured capacitance and range is presented for the ZBC-2000 laminates using 6060 glass fabric during the first two qualification rounds.

Table 4 – Capacitance Measurements

	Capacitance	Deviation
Phase One	551 pf/in^2	+/- 15 pf/in^2
Phase Two	549 pf/in^2	+/-15 pf/in^2

The use of 6060 glass along the tight resin content control and an optimized lamination cycle leads to uniform dielectric thickness. The tight dielectric thickness is directly manifested in a smaller capacitance tolerance (+/- 15 pf/in^2 for 6060 compared with +/- 50 pf/in^2 for 106). The objective of the ZBC 2000 approach was not to replicate a specific capacitor value within the print circuit board, but to function as a distributed or shared capacitance. Thus, a tight tolerance on the capacitance value is an additional benefit when compared to the enhanced dimensional consistency and improved CAF resistance (to be discussed in the following sections).

Conductive Anodic Filament Testing

Conductive Anodic Filament (CAF) growth was first reported by AT&T Bell Laboratories[5-6]. Reliability life studies at high voltages and high humidities with glass reinforced epoxy-glass fabric printed circuit boards produced permanent shorts between closely spaced plated-through-holes (PTH). Subsequent analysis indicated that copper had migrated along the glass bundles causing either a decrease in resistance or a short circuit. The growth appeared to build from the positive electrode (anode) rather than on the negative electrode (cathode), hence the term "anodic" in the CAF. The purpose of the ZBC 2000 CAF testing was to determine the reliability of the 6060 glass fabric during accelerated temperature and humidity aging under electrical bias. ZBC 2000 laminates made using the standard 106 style glass were tested simultaneously as a control.

The CAF test vehicle was a four-layer construction with a ZBC-2000 core, plated-through-holes (PTH), and surface conductors on both sides. The core planes were segmented and clearances were provided for the through-holes. The design of the board offered potential migration paths across clearances between PTH and ground planes, and between PTH-to-PTH.

Nominal spacing:
PTH/PTH spacing was 25 and 35 mils
PTH/Power spacing was 8 and 13 mils

The spacings for each test vehicle were verified by cross-section analysis.

Test vehicles were fabricated by HADCO Santa Clara using ZBC-2000 laminates with both 106 and 6060 glass. The CAF testing protocol was conducted by an independent contract testing laboratory. The test vehicles were subjected to the following measurement conditions:

- 85^{o}C/85% RH for 1000 hours
- 85^{o}C/67% RH for 1000 hours
- Continuous 100V bias
- Resistance measurements were made daily without removing the test coupons from the T/H chamber
- Monitored the resistance as a function of time between PTH/PTH and between PTH and power planes
- Four test vehicles with 106 ZBC and four test vehicles with 6060 ZBC were tested

CAF failures are classified into two modes. A short circuit indicates that a copper filament has formed causing a direct path between the two features under bias. In addition, a major failure is classified as a decade decrease in resistance

(R_1/R_2 > 10) where R_1 is the initial resistance, and R_2 is the final resistance.

CAF testing summary:
106 ZBC – Total of 6 ZBC related short circuits
6060 ZBC – Total of 2 ZBC related failures (no short circuits)

A detailed summary of the failures for both the 106 and 6060 ZBC CAF testing is summarized in Tables 5 and 6. The 6060 ZBC related failures are shaded in the tables.

Table 5 - 106 ZBC CAF Failure Summary

Failure	Number	Location	Spacing
Short	5	PTH-Power	8 mils
Short	1	PTH-Power	13 mils
Major	4	PTH-PTH	24 mils
Major	4	PTH-PTH	35 mils

Table 6 - ZBC 6060 CAF Failure Summary

Failure	Number	Location	Spacing
Short	2	PTH-PTH	24 mils
Short	1	PTH-PTH	35 mils
Major	2	PTH-PTH	24 mils
Major	2	PTH-PTH	35 mils
Major	2	PTH-Power	8 mils

The ZBC 2000 laminates with the 6060 glass exhibited superior CAF performance compared with the 106 ZBC test vehicles. The 6060 had no PTH-Power short circuits during the 1000 hours of testing and only 2 cases where the resistance decreased by a decade during the testing.

Dimensional Consistency Evaluations

The development of microelectronic devices with higher circuit density requires materials with better performance in terms of dimensional consistency. In particular, epoxy-glass fabric laminates with uniform properties in both the X and Y directions are required. Consistent resin content and a uniform glass fabric are key contributors. The objective of the dimensional consistency measurements was to perform an evaluation of the movement and standard deviation of the movement after etching. Previous experience with ZBC 106 laminates showed baking improved dimensional consistency. The following experiment looked at ZBC laminates made with both 106 and 6060 glass fabric.

A limited comparison (20 laminate samples) using 106 versus 6060 epoxy-glass fabric laminate was conducted at the HADCO PWB operations in Santa Clara. The variables in this test were:

1) Laminate construction; BC laminates with 106 glass fabric and 6060 glass fabric
2) Pre-baking versus as received; the pre-bake was done in forced air convection ovens for a minimum of 4 hours at 325-330^{o}F.

The laminates were imaged and etched using the standard innerlayer process and less than 1% were scrapped, which is considered to be normal production fallout. Growth and shrinkage measurements were taken by measuring post etch punch targets using an Optek V-2800 series optical measuring system.

The average X and Y post etch punch (PEP) target deviation data is shown in Table 7. The standard deviations for the X and Y target movements are shown in Table 8. The panel size was 18” x 24” with the X-axis in the 24” dimension, and Y-axis in the 18" dimension.

Table 7 - X and Y Target Deviation Data

	Avg. X PEP target deviation	Avg. Y PEP target deviation
106 baked	-0.206	-0.069
106 unbaked	-0.197	-0.058
6060 baked	0.668	0.444
6060 unbaked	0.882	0.804

Table 8 - X and Y Standard Deviation Data

	X Standard deviation	Y Standard deviation
106 baked	0. 195	0.137
106 unbaked	0.559	0.253
6060 baked	0.328	0.154
6060 unbaked	0.175	0.178

The standard deviations in both the X and Y directions are plotted in Figure 4 for all of the samples both unbaked (as received) and baked. For the unbaked laminates, the 106 ZBC laminate exhibited a very large difference in the X and Y standard deviations. This difference was reduced after baking. The 6060 ZBC laminates have overall lower standard deviations in the “as received” condition. The AlliedSignal 6060 ZBC laminates have essentially the same standard deviations in both the X and Y directions. Comparing all the ZBC laminates tested, the AlliedSignal Laminate Systems' 6060 laminate in the unbaked version has the best dimensional consistency in both coordinates. An interesting and unexplained result is the apparent increase in the difference between the X and Y standard deviations after baking for the AlliedSignal Laminate Systems' 6060 ZBC laminates. In the case of 6060 ZBC laminates, baking is not necessary prior to processing. The elimination of the prebake is advantageous from both a cost savings perspective and elimination of possible handling damage during the baking operation.

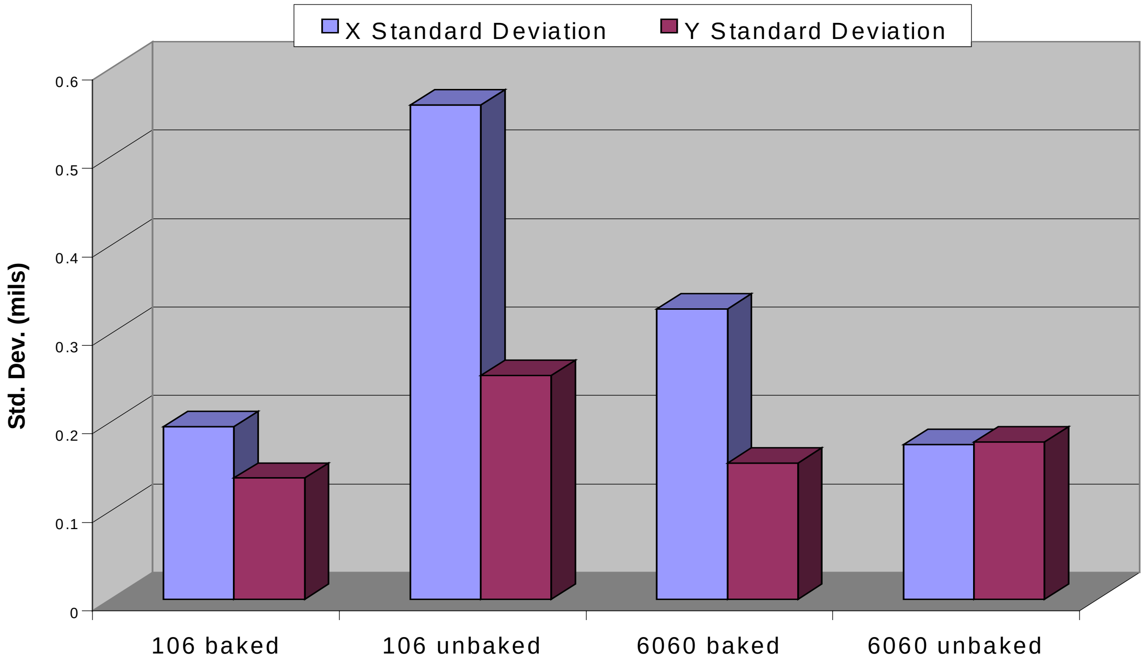

Figure 4. Dimensional Consistency Data

Conclusions

The use of a square-weave glass fabric with tight resin content control yields a BC laminate with a very precise thickness and improved dimensional consistency. A laminate with reduced levels of dielectric breakdown during a 500V DC test (hipot test) can be fabricated using a carefully controlled manufacturing process. The enhanced square-weave glass fabric also exhibits excellent resistance to Conductive Anodic Filament (CAF) growth during 1000 hour temperature/humidity aging under 100V DC bias.

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