Buried Capacitance and the Evolution of Thin Laminates

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Abstract
Buried Capacitance[1] (BC) laminates products have been in use in many high-speed applications for more than ten years. BC products are a significant contributor to complex multi-layer printed circuit board construction and also a major element in power distribution circuit design. The principle features of thin laminate BC technology are high frequency by-pass decoupling capacitance, very low loop inductance and EMI shielding. The newly developed, less than 2 mil thick, BC laminates shall allowed circuit designers to make significant advances in electronic systems speed, performance and reduce overall product cost. Manufacturability and reliability of the advanced

Introduction
BC buried distributive capacitance products have been in use in many high-speed applications for more than 10 years. They are a significant contributor to complex multi-layer printed circuit board construction and also a major element in power distribution circuit design. The principle features of thin laminate BC technology are high-frequency by-pass decoupling capacitance, very low by-pass loop inductance, and EMI shielding. These three features of BC laminates have allowed circuit designers to make significant advances in electronic systems' speed and performance.

Thin laminate BC started out as a single product type (ZBC-2000®)[1] consisting of a 2 mil dielectric, glass reinforced FR4 dielectric core (see Figure 1). The original 2 ml BC laminate was required to use double treat copper foil, with the tooth (standard adhesion treatment) side out. This was done to achieve as smooth a finish as possible against the 2 mil (50 μm) dielectric. If the laminate as developed was fabricated with the standard adhesion treatment against the dielectric, there would be an increased risk of electromigration failure over the life of manufactured product. As with all standard laminates, 2 mil BC laminate is required to meet the applicable IPC standards and holds a UL 94-V0 flammability rating.

At the time 2 mil BC laminate was introduced (1992) to the electronics industry, double treat copper was the only way to achieve a smooth, contiguous surface against the thin dielectric material. With improvements in copper foil manufacturing processes since its introduction, licensed laminators have been qualified and approved for Reverse Side Treated Foil (RSTF) versions of this material. Double treat copper foil is inherently more expensive to manufacture than is RSTF, and requires special processing, due to the tooth structure of the foil during PCB manufacture. In addition, many PCB manufacturers are not accustomed to processing double treat foil, which results in a learning curve, some process development, and higher cost. The RSTF version of 2 mil BC laminate thus has the advantages of being less expensive and more compatible with standard PCB manufacturing processes, while maintaining the same quality and reliability as the original double treat foil version of the material.

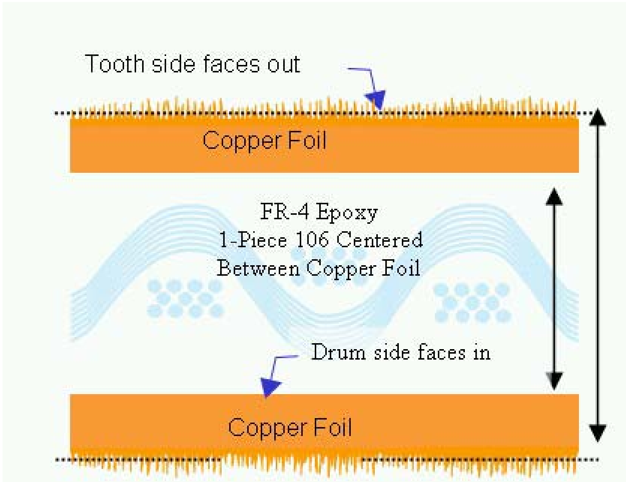

Figure 1a - Graphic Representation of a Reinforced BC Laminate

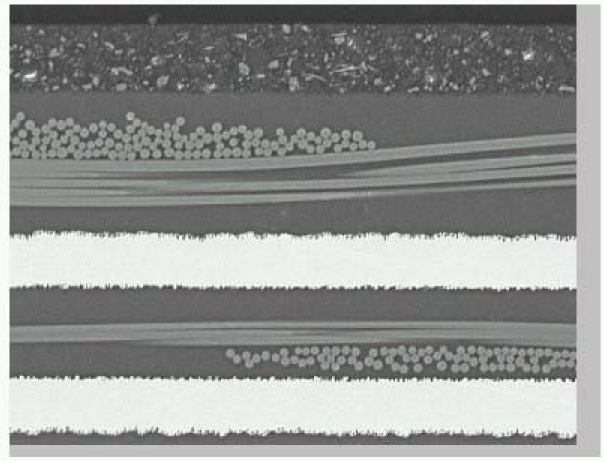

Figure 1b - Actual Cross-section of a 2mil Dielectric ZBC-2000® Laminate

As with all good technologies, BC thin core laminates have matured and improved. BC core laminate products are now available with dielectric core thicknesses less than 2 mil. Figure 2 shows a cross-section sample of the new ZBC-1000™ laminate with a 1 mil FR4 dielectric and reverse side treated copper foil. There are several dielectric types and foil thicknesses to choose from for new circuit design. The new BC products have been developed as a result of an increased understanding of BC laminate properties in conjunction with power distribution system (PDS) design. The newer BC thin laminates will give circuit designers more flexibility in advancing electronic system performance, speed, and functionality.

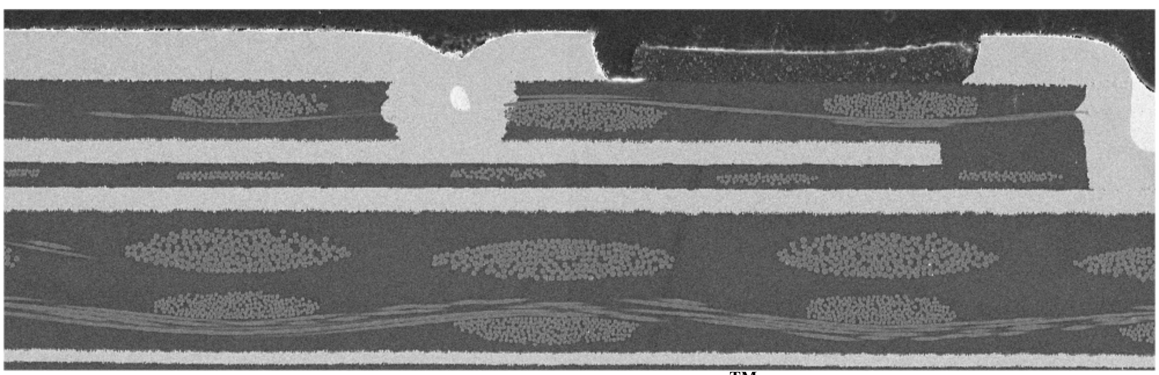

Figure 2 - Cross-section View of a 1 mil FR4 Dielectric ZBC-1000™ Laminate with Blind Via to Ground Layer 2 and Blind Via to Power Layer 3

Power-distribution networks often have to deliver hundreds of watts at low voltages with very fast reaction times to changes in voltage fluctuations. The required impedance of the power-distribution network necessary must be a few milliohms and low impedance must be maintained from DC to the GHz band. The simplified circuit diagram in Figures 3a and 3b shows how the BC core laminates (represented as C_{ZBC}) form an integral part of a power distribution system. Not only does the BC core laminate provide load capacitive bypassing, it also distributes current power to the various loads on the PCB. As shown in the figure, total current from and to the voltage regulator module (VRM) must go through circuit nodes (a) and (b) before being distributed to the loads. Figure 3b shows a typical cross-section view of the circuit of Figure 3a, noting that all current must first pass through the BC laminate planes before being distributed to the loads. Therefore, for good system design, it is important to consider the mechanical as well as the electrical properties of BC thin core laminates.

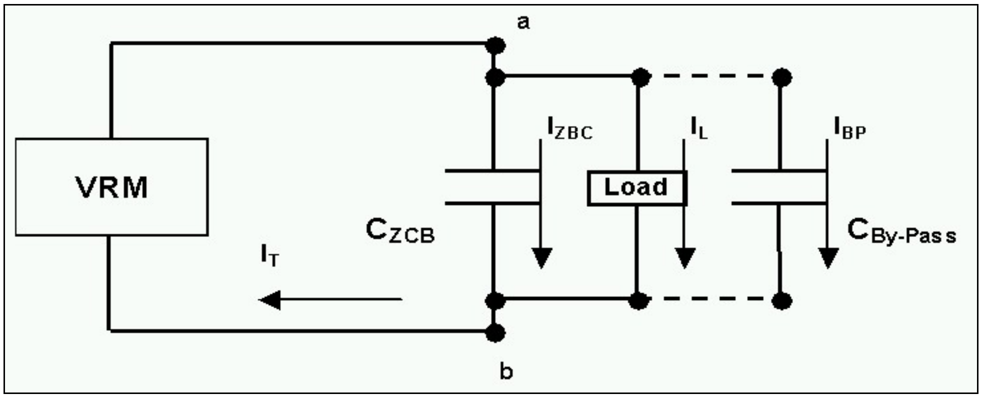

Figure 3a - Simplified Circuit Diagram of a Power Distribution Network

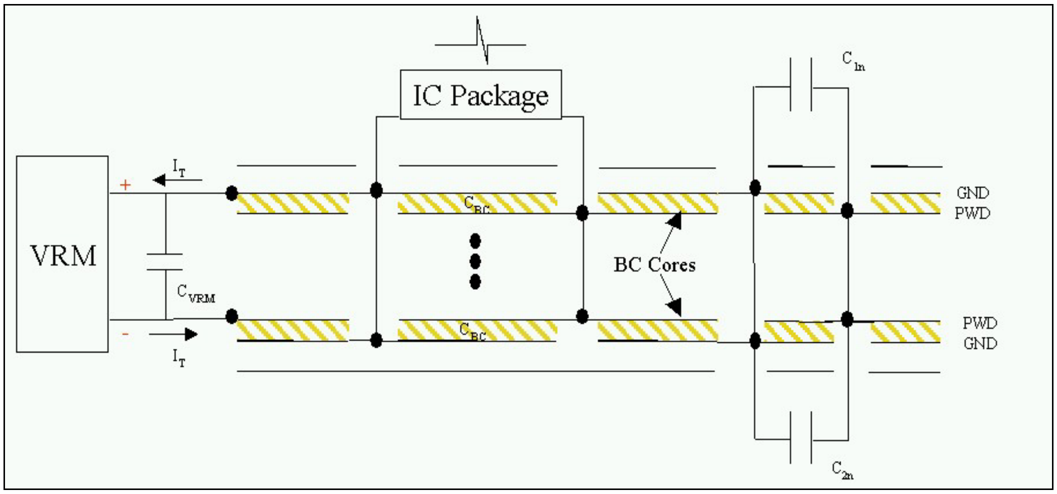

Figure 3b - Printed Circuit Board Cross-section with a Typical Placement of BC Laminates

BC Laminate Electrical Characteristics

As mentioned, the ideal electrical characteristics for a power distribution printed circuit board laminate would have capacitive by-pass coupling over a wide frequency range to reject induced IC switching current noise. The laminate should also have a very low and flat impedance response from several hundred megahertz up to several giga-hertz to minimize power supply voltage noise. The impedance profile for a 2 mil (50 μm) glass reinforced core laminate in Figure(s) 4a & 4b shows the electrical impedance characteristics vs. frequency and will be explained in more detail.

Referring to Figure 4a, the frequency region (a) from 1 to 100 MHz shows the frequency response of the BC core to be capacitive. Direct bypassing of switching current noise will be rejected from power to ground in this frequency range. At the minimal point (b) the impedance response of the BC core changes from being capacitive to inductive. At this frequency point the capacitive reactance for the BC core is equal and opposite of its inductive reactance and the impedance is therefore minimal. Going into frequency region (c) the inductive reactance of the BC core is now greater than its capacitive reactance and the core impedance now behaves in an inductive manner. All capacitors, be they distributive or discrete will have a typical V shape curve for the regions a, b, and c shown here. The dashed red line in the figure shows an ideal inductive behavior for the c region that is typical of discrete bypass capacitors with low equivalent series resistance (ESR). The capacitive to inductive transition point (b) is highly dependent on PCB board size or surface area of BC core. As shall be shown in the next section, the impedance magnitudes of the regions (a) and (c) can be changed to increase capacitance and reduce inductance.

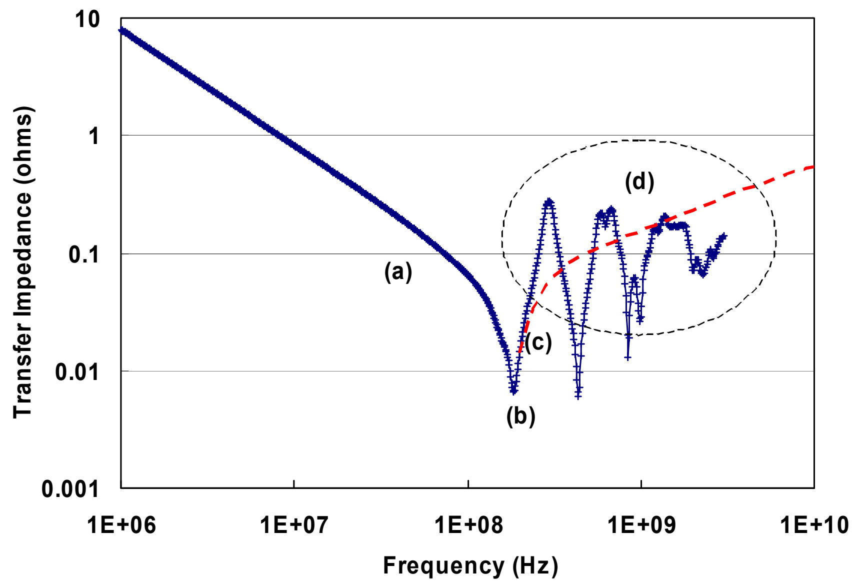

Figure 4a - A Broadband Transfer Impedance Magnitude Response for a 5" x 10" BC Printed Circuit Test Board. The Dashed Red Line shows the Inductive Impedance Response of an Ideal Capacitor

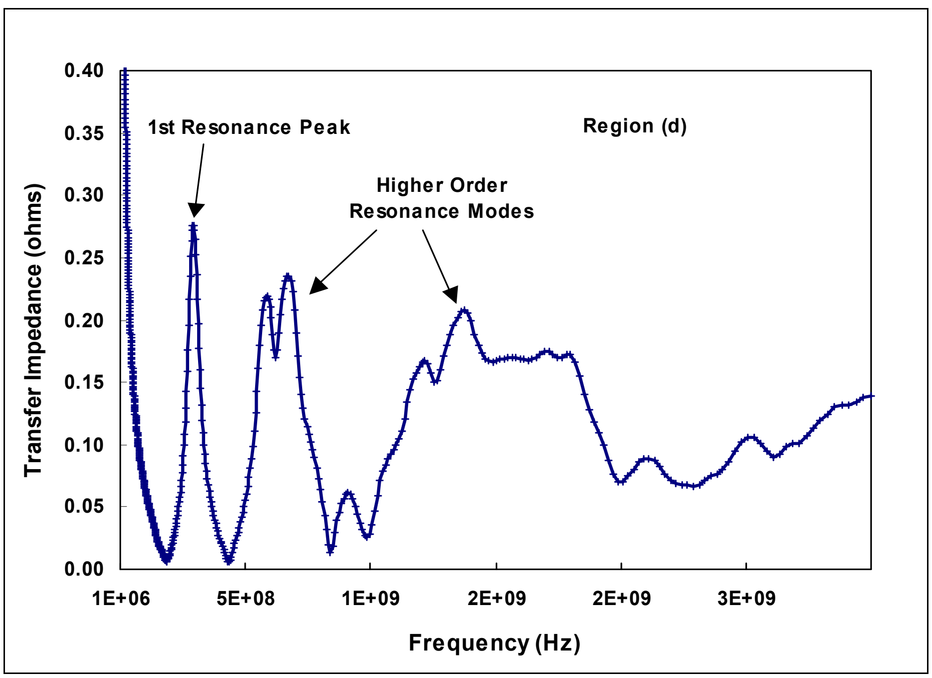

Figure 4b - Region (d) the High Frequency Transfer Impedance Response Showing Plane Resonance Modes

The frequency region (d) starting at about 300 MHz and going up to several gigahertz is shown in more detail in figure 4b. As shown, the impedance response goes through a series of minima and maxima points with increasing frequency. The minima/maxima points are caused by plane resonances and are characteristic to distributive capacitance parallel plane capacitors. The frequency points where plane resonances occur are determined by the length and width of the planes and the dielectric constant of the material between the planes.[2] The multiple maxima shown in the figure are higher order resonance modes due to multiple ½ wavelengths determined by the x and y dimensions of the plane. The thickness of the dielectric will have a very small effect on the determination of the resonance points. While the impedance response of region (d) is primarily inductive, the impedance magnitude of these resonance mode maxima may cause serious design issues for switching current noise injected into the power distribution system with frequency components of the noise at or near one of these resonance modes.

The injected switching current and the power distribution systems impedance determine power distribution system voltage noise. This is simply expressed by the relationship V = IZ. If the injected current is high (due to high switching rates and fast rise times) and the impedance is high, as in the case of resonance maxima, then the voltage noise may momentarily exceed the design limit noise margins of the operating device. This may cause IC devices to switch in a sporadic manner leading to system failure. The higher switching rates and faster rise times of newer IC's are quickly approaching the limits of 2 mil BC laminate in terms of system impedance requirements. Fortunately, developments in new BC products are keeping pace with the demands of high-speed circuit applications and designs.

New BC Products and Performance

The demand for higher performance, increased functionality, size reduction and cost has provided momentum for a whole range of BC product developments. Sanmina-SCI now offers a complete family of BC laminate products designed to meet or exceed the requirements of the most demanding power distribution networks. Sanmina-SCI's traditional 2 mil glass reinforced FR4 BC laminate is now joined with a 1 mil dielectric version. The 1 mil BC core laminate has twice the by-pass capacitance of its 2 mil sibling with an overall broadband reduction in its impedance profile. For even higher current switching load demand applications Sanmina-SCI has joined forces with Oak-Mitsui Technologies to provide non-reinforced BC laminate products under the brand name FaradFlex.[2] These new laminates have dielectric thicknesses of 0.94 mil (BC24-24 um), 0.63 mil (BC16-16 um), and 0.47 mil (BC12-12 um).

Figure 5a shows the broadband transfer impedance responses for the 2 mil BC core laminate as in the previous figure but includes, for comparison, Sanmina-SCI's new lineup of distributive capacitance laminate products. For impedance response comparison, the area and dimensions of the test PCB's are all the same for all laminates and the curves of figure 5a show the differences in electric properties for the BC product family. Data for the transfer impedance response curves were collected using an Agilent 8753ES vector network analyzer.[3] In the capacitive bypassing region, the overall impedance decreases for each new laminate which indicates successively more storage capacitance from 0.5 nF/in^2 for 2 mil BC laminate up to 2.0 nF/in^2 for the BC12 laminate. This represents an increase of more than 4 times the storage capacitance of the original 2 mil dielectric thin BC laminate. The transition points from capacitive impedance to inductive impedance are nearly identical for all laminates since the dielectric constants for the laminates are approximately the same and the test board dimensions are the same.

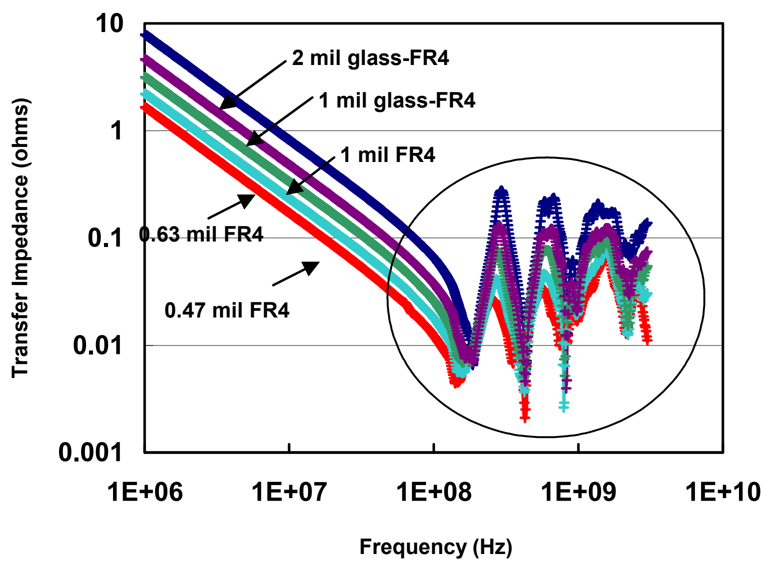

Figure 5a - Broadband Transfer Impedance Response for the BC Product Family

Figure 5b shows the inductive impedance response region for the BC laminate products. As in Figure 4b, several examples of plane resonance modes are shown. As the spacing between the copper planes decreases (thinner dielectrics) the self and mutual inductance to currents on the planes decreases and an overall reduction of the high frequency impedance is achieved. The overall impedance reduction can be directly converted into a decrease in power distribution voltage noise and reduced EMI in the higher frequency bands from several hundred megahertz up to several gigahertz. Table 1 gives an example of the level of impedance reduction at the first order plane resonance mode peak frequency for the BC products. For this test board configuration the 2-milglass-FR4 has an impedance magnitude of 272 milliohms at a peak frequency of 297 MHz. In comparison, 0.47 mil FR4 has an impedance of 29 milliohms at 245 MHz representing almost an order of magnitude reduction in inductive impedance at this frequency point.

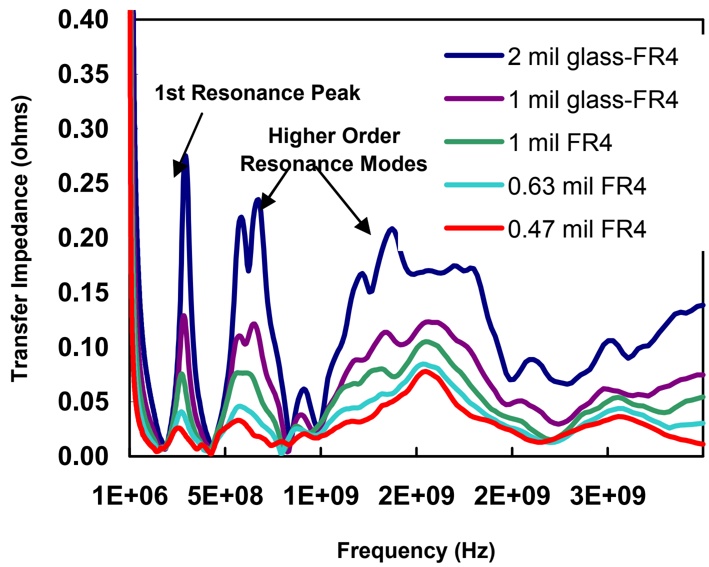

Figure 5b - High Frequency Response for the BC Product Family

Table 1 - BC Laminate Electrical Characteristics

			Glass-FR4		Modified Epoxy Resin		
	Condition	**Units**	**A**	**B**	**A**	**B**	**C**
Dielectric Thickness	**Nominal**	**Mils (µm)**	2.0 (50)	1.0 (25)	0.94 (24)	0.63 (16)	0.47 (12)
Capacitance Density	**@ 10 MHz**	**nF/in^2**	0.5	0.9	1.0	1.5	2.0
Dielectric Constant	**1 MHz**	**----**	4.2	4.2	4.6	4.6	4.6
Dissipation Factor	**1 MHz**	**----**	0.015	0.015	0.012	0.012	0.012
Inductive Impedance	**~ 300 MHz**	**Ohms**	0.272	0.124	0.074	0.040	0.029
Normalized Inductive Impedance		**----**	**1**	**0.45**	**0.27**	**0.15**	**0.11**

BC Laminate Material Characteristics and Quality Assurance

To meet the need for improved power distribution performance, Oak-Mitsui has developed a novel thin dielectric laminate using a modified epoxy resin. Figure 6 shows a cross-section view of a non-reinforced 0.47 mil BC core laminate. The modified epoxy resin electrical properties as shown in Table 1 provide higher capacitance values and ultra thin dielectric layers, allowing for significantly lower power/ground plane impedance. Optimization of proprietary dielectric resins and copper foil has resulted in laminates that are rugged enough to process through typical PCB inner layer processing. The BC laminate qualification process as described below insures high yields during PCB processing at any qualified fabricator.

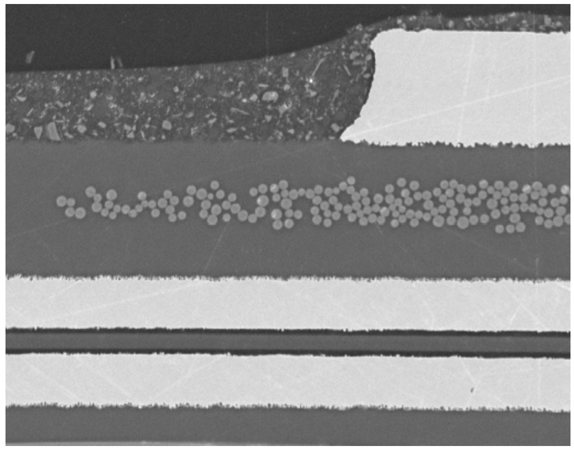

Figure 6 - A Cross-section of a 0.47 Mil (12 μm) Dielectric Thickness with Reverse Treat Foil

BC laminate qualification begins at the laminator. Laminators are licensed and qualified by Sanmina-SCI to produce and supply BC products to licensed PCB Fabricators. In order to maintain the quality and consistency of the BC family of products, licensed laminators must satisfactorily demonstrate that they can produce the products to a defined specification for each product. This is accomplished by undergoing a detailed qualification procedure, before the laminator can provide material under the license to licensed fabricators.

This qualification procedure involves initial sampling and multiple cross sections to examine compliance of the structural details of the laminate to the specification for that material. Underwriters Laboratories (UL) approval and multiple lots of peel strength data are also required from the laminator, for the type of copper foil, resin system, and fiberglass style being qualified. Standard test boards are then produced in a PCB manufacturing environment, and yields through the inner layer and outer layer manufacturing processes are documented. Hi-Pot test results, which determine the integral electrical strength integrity of the dielectric, are also documented. During the inner layer processes, layers are also tested for AOI processability and capacitive value.

Completed test boards are again Hi-Pot and electrically tested. The finished test boards then under-go a variety of testing which includes 6X solder float and 400 cycle liquid to liquid thermal cycling. Samples of the finished test boards are also submitted for electrical analysis. Electrical analysis includes dielectric constant (Dk) and dissipation factor (Df) measurements, and also self and transfer impedance response spectrum.

In order for a laminator to achieve full qualification, volume manufacturing of PCB's with that laminator's material must be completed. This is performed in one of Sanmina-SCI's volume manufacturing facilities. Yields throughout the process are monitored, as are Hi-Pot test results. Table 2 lists the qualification test results and material properties of BC laminate products.

PCB fabricators are also licensed to produce BC products for OEM's. A network of licensed fabricators exists around the world. As part of the licensing procedure, Sanmina-SCI engineering provides training and supports the licensed fabricator, in learning how to best process these materials.

The BC family of products provides circuit designers alternative levels of increasing electrical performance for their embedded distributive capacitance needs in printed circuit board design and functionality. These BC products are further supported with an established worldwide network of capable material suppliers and PCB fabricators, to meet industry needs.

Table 2 - BC Laminate Reliability and Materials Characteristics

			Glass-FR4		Modified Epoxy Resin		
Property	**Condition**	**Unit**	**2 mil**	**1 mil**	**1 mil**	**0.63 mil**	**0.47 mil**
Dielectric Resin	----	----	FR-4	FR-4	Modified FR-4	Modified FR-4	Modified FR-4
Dielectric Reinforcement	----	----	e-glass	e-glass	None	None	None
Hi-Pot Test	DC Volts	Volts	500	250	500	500	500
Electro-migration	85°C/85% RH (DC Volts)	Hours @ (Volts)	2000 (50)	2000 (50)	>1000 (50)	>1000 (35)	>1000 (35)
Thermal Shock	-35°C / 125°C 400 cycles	N/A	Pass	Pass	Pass	Pass	Pass
Peel Strength	As received	Ib/in^2	>6.0	>6.0	>6.0	>6.0	>6.0
Dielectric Breakdown	1 kV/sec	Volts (DC)	500	250	500	500	500
UL Rating	----	----	94-V0	94-V0	94-V0	94-V0	94-V0
Bellcore/Telcordia Exception	TR-NWT-000078	N/A	Granted	In progress	In progress	In progress	In progress

References

1. US patent numbers 5,010,641, 5,0779,069, 5,155,655, 5,161,086, and numerous foreign patents.
2. Lewis, R. L., Relative permittivity measurement of square copper-laminated substrates using the full-sheet resonance technique. Natl. Inst. Stand. Technol. NISTIR 5053; 1997.
3. Novak, I., Measuring Milliohms and PicoHenrys in Power Distribution Networks. Proceedings of DesignCon2000, February 1-4, 2000, Santa Clara, CA.