New Non-Reinforced Substrates for use as Embedded Capacitors

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Abstract
As CPUs increase in performance, the number of passive components on the surface of the boards are increasing dramatically. To reduce the number of components, as well as improve the electrical performance (i.e. reduce inductance), designers are increasingly embedding capacitive layers in the PCB. The majority of the products in use today utilize reinforced epoxy laminates. These products are relatively easy to handle, but the thickness and Dk limit the effectiveness of the layer to perform as a capacitor. Other materials are being developed that are thinner (and thus increase capacitance), but either have problems with dielectric breakdown strength, handling or only marginal improvement over the existing material. This paper will describe new non-reinforced substrates for use as embedded capacitance layers that address these issues. The material selection process, substrate processing and electrical performance will be reviewed.

Introduction
The development of Embedded Capacitor technology has been driven by the needs to save board size, increase functionality, lower costs and improve electrical performance of the boards. Current standard capacitive material used in the industry is mainly the 2mil dielectric thick material, mostly utilized for telecom and networking applications[1]). For this particular high-end application as PWBs, embedded capacitor technology has been utilized to realize the electrical performance they need to distribute capacitance, enhance signal integrity, reduce impedance at high frequency and dampen noises.

A number of papers have been published regarding development of materials for embedded capacitors and advantages of incorporating embedded capacitor in PWB. From the electrical performance standpoint, demand is increasing for thinner capacitor material, as low as 10 micron, as the signal frequency increases.[2])

In this paper, considerations of copper foil and dielectric resin properties (which make up the capacitor material) are discussed. Also, fabrication of the thin film capacitor material incorporating into PWBs and performance of electrical performance using the materials are described.

Investigations
Embedded capacitance materials are constructed from two metal layers (usually copper foils) and dielectric polymer film layer in between. In order to design the construction of the capacitance material, properties of the copper foil and dielectric layer will be the "keys" to determining the performance of the capacitance materials.

Investigation of the influences of copper foil, dielectric type and dielectric thickness has been conducted to design the construction of the thin capacitance material.

Copper Foil
Five different types of copper foils were prepared to investigate the influence of the copper foil to the performance of the capacitance material. What we expect from the copper foil is good performance in terms of peel strength, capacitance value and insulation resistance. Properties of copper foil used for the investigation are listed in Table 1.

Table 1 - Copper Foil Profile Properties

	Foil type				
Properties	A*1	B*2	C*3	D*4	E*5
Copper weight	1oz	1oz	1oz	1oz	1oz
Profile Rz µm	6.0	3.5	2.5	2.0	1.5

*1) Standard HTE electrodeposited (ED) copper foil
*2) RTF(Reverse treated foil)
*3) Super low profile ED foil
*4) Ultra low profile ED foil
*5) Wrought foil

Peel Strength
Figure 1 shows the result of the peel strength with various copper foils on standard epoxy resin system. It was found that the higher the profile of the copper foils, the higher the peel strength. The absolute value of the peel strength should be different depending upon resin properties (e.g. toughness) of the dielectric, but the tendency should be the same.

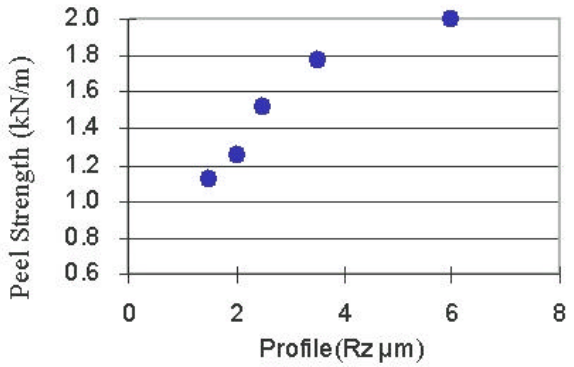

Figure 1 – Relation between Copper Profile and Peel Strength on Standard Epoxy Resin System

The appropriate profile of copper foil needs to be selected, since a too high profile will result in a drop in production yield due to shorts (especially when dielectric thickness gets thinner).

Capacitance

Capacitance using various types of copper foils was measured. Measured capacitance specimens were prepared by controlling the distance of the peak-to-peak distance of two sheets of copper foil to 20µm.

Capacitance measurement results are shown in Figure 2. Capacitance values are indicated in index, defining capacitance of foil "E" as 100. It was found that capacitance value increases with the increase in profile of copper foil. This can be explained by increase in surface area with the copper foil with higher profile.

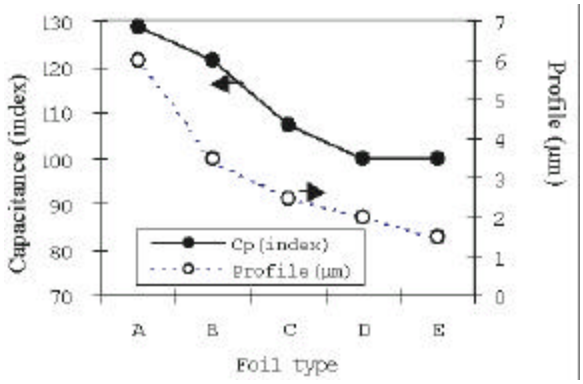

Figure 2 - Copper Foil Type and Capacitance

Dielectric Resin Property

One of the challenges for thin capacitive material is the physical property of the dielectric. The thin dielectric must be tough and flexible in order to withstand processing through PWB manufacturing process. Another challenge for thin dielectric is the insulation reliability, such as hi-pot test and electro-migration.

Two types of dielectric were selected for the evaluation. One type (A) is a conventional and industry standard epoxy resin system. Another type (B) is a proprietary, modified resin system, designed for capacitive material. With these 2 types of dielectric systems, substrates were prepared to evaluate physical properties and insulation reliability.

Tensile Strength

Resin toughness is an important property to determine the capability to be processed through PWB manufacturing steps. If the resin's toughness were too weak, since the resin thickness is so thin, the resin would break apart during the etching process. As shown in Table 2, resin type B exhibited about 4.5 times higher tensile strength than A, which signifies the advantage of resin type B for endurance during PWB manufacturing process.

Table 2 - Resin Type

	A	B
Tensile Strength* (N/mm2)	99	448

* Measured on 10µm thick resin

Electro-Migration

As the dielectric layer thinner, there is a concern regarding insulation reliability between the layers. Electro-migration tests were conducted at the condition of 85C/85%/35V, for two different resin systems. The dielectric thickness was prepared at 10µm. The result is shown in Table 3.

Although resin type A lasted only 682 hours before electrically shorted, resin type B lasted for over 1000 hours. The differences in ion contamination, moisture absorption and polymer structure seems to be influencing the electro-migration endurance period.

Table 3 - Electro Migration Test

	Lasted hours		
Resin type	N=1	N=2	Avg.
A	658	706	682
B	>1000	>1000	>1000

Description of the Thin Capacitance Material

Based on the investigations of copper foil and dielectric resin properties, suitable copper foil and resin type was selected to construct/manufacture 10 and 25 µm dielectric thickness capacitive material. Characteristics of the developed capacitive material are listed in Table 4.

Table 4 - Dielectric Material Characteristics

Properties	25µm Material	10µm Material
Copper foil type	B	C
Dielectric type	B	B
Copper weight (oz)	1	1
Peel strength (kN/m)	1.0	1.0
Dielectric thickness µm	25	10
Capacitance at 1MHz	0.16	0.35
Dk at 1MHz	4.0	4.0
Df at 1MHz	0.02	0.02
Dielectric breakdown V	>500	>500
Tg(DMA) Celsius	>220	>220
Electrical migration*(hrs)	>1000	>1000
Solder float (288Cx5times)	Passed	Passed

*RH85%/85C/35V

Processing of the Capacitance Material

Fabrication test was conducted on thin film capacitance materials, 10 and 25 µm dielectric thickness, to see the capability of processing the material with existing conventional PWB manufacturing equipment.

Pattern Formation

Figure 3 shows the patterned capacitance material.
The material was processed through the following processes:

1. Chemical etching
2. Dry Film lamination
3. Image transfer
4. Pattern etching (Dual sides)
5. Black oxidizing

Due to the tough and flexible nature of the resin, the material was processed without being damaged.

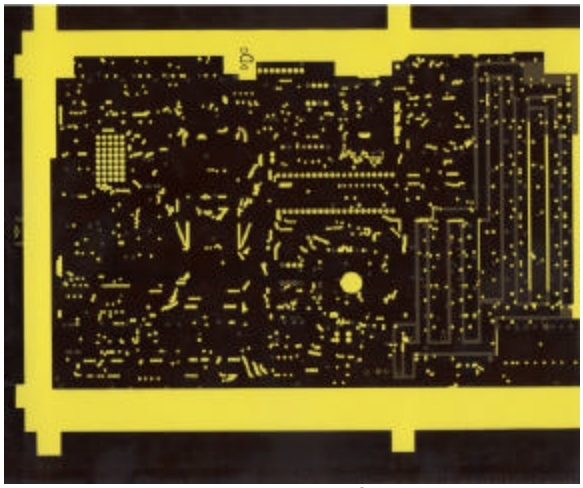

Figure 3 – Processed Pattern after B/O Treatment

Although, processing thin capacitance material can be challenging and may need modifications /adjustment to the process, the material was capable of processing through the conventional PWB manufacturing steps. This was proven at two PWB shops.

Hi-Pot (High Potential) Test

The patterned laminate was tested to Hi-Pot test. The entire panels passed 500V test, including the 10 microns dielectric thickness material.

Lamination

Scaling is a very important parameter for multilayer lamination. Figure 4 shows the measured result of the movements of the distance between the holes during the process. As it can be seen, thin capacitance material's movement was equivalent to that of 50µm (2mil) core material. Hence, the scaling factor for the thin capacitance material can be the same as the 50µm core material.

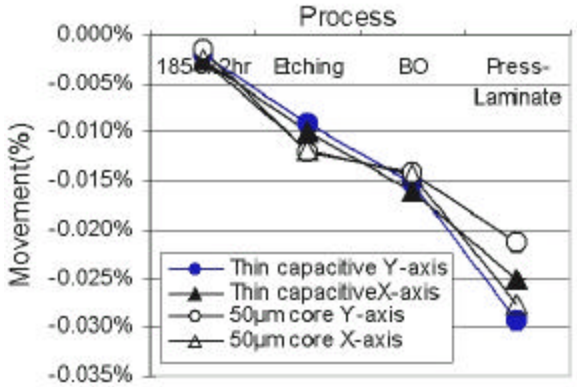

Figure 4 – Dimensional Stability During the Process

Through Hole and Plating Reliability

Figure 5-7 shows the cross-sections of the boards using thin capacitive material. Figure 5 is the cross-section of a board using 50µm dielectric thickness capacitive material as a reference, followed by 25µm in Figure 6 and 10µm in Figure 7. Good connection of the plated copper to the thin dielectric layers is observed. Also, they showed good compatibility with the surrounding FR-4 laminates.

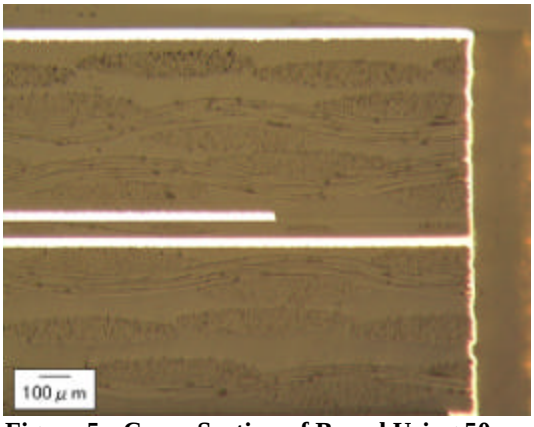

Figure 5 - Cross-Section of Board Using 50µm Capacitive Core as a Reference

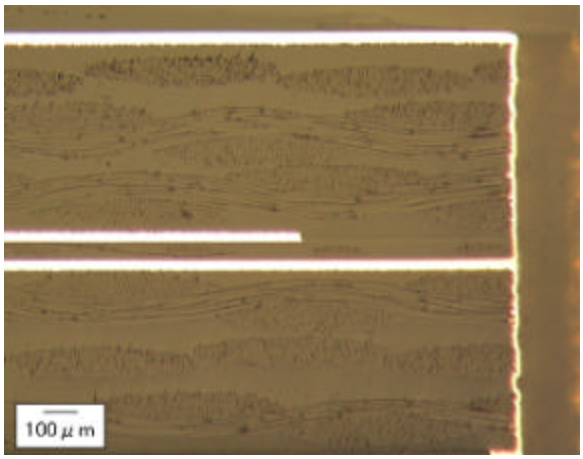

Figure 6 - Cross-Section of Board Using 25μm Capacitive Layer

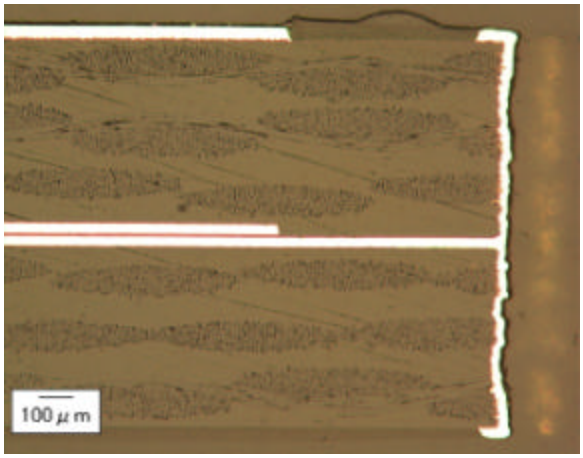

Figure 7 - Cross-Section of Board Using 10 μm Capacitance Layer

Electrical Performance of the Board Using Thin Capacitive Material

Many advantages on electrical performance, such as power distribution and Electro Magnetic Interference (EMI), can be expected by using thin capacitive material in PWB.

Conducted emissions on the supply line for a microprocessor (MPU) running at 40MHz were measured by VDE method. No discrete decoupling capacitors were mounted on the four-layer board (See Figure 8). Comparison of conducted emissions between conventional standard 400μm laminate core and 10μm thin film capacitive core are shown in Figure 9. Significant reduction of emissions in the frequency range of 150 to 550MHz, which is known as the difficult range to reduce by discrete capacitors were observed by the thin film capacitive core. Lower effective inductance and larger capacitance of the thin film core structure improves performance of supply decoupling for MCUs.

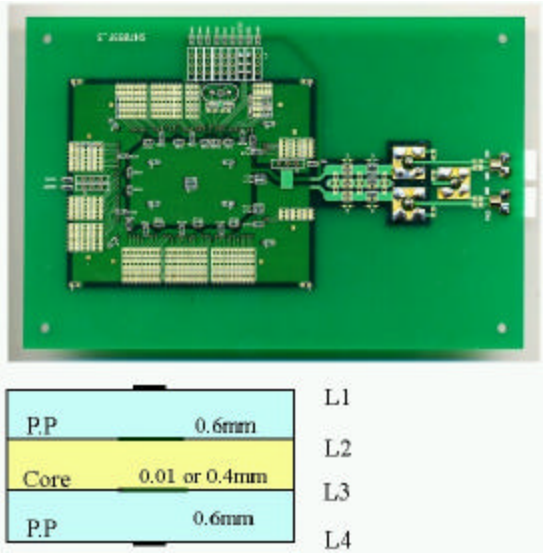

Figure 8 - Board Used for the Noise Current Measurement[3])

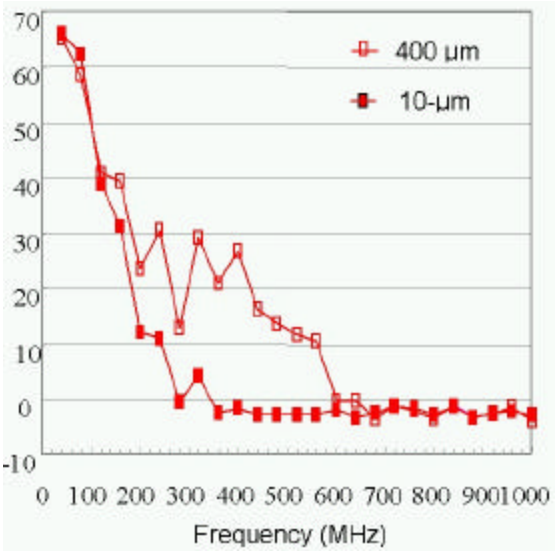

Figure 9 – Comparison of Noise Current with Standard Laminate Core and 10 μm Core[4]

The change in capacitance (due to change in dielectric constant) with change in frequency was also measured. Figure 10 shows that the material is relatively stable at these frequencies.

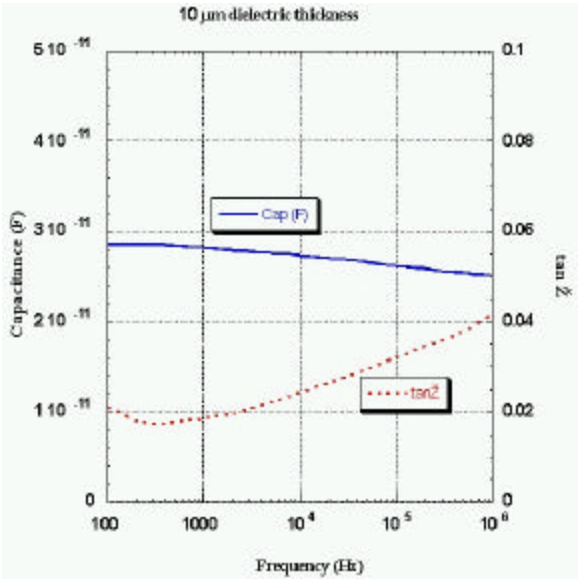

Figure 10 – Capacitance of 10 µm Core vs. Frequency

Conclusion

Contributions and influences of copper foil and dielectric resin properties to construct a thin dielectric capacitive material have been investigated.

Suitable copper foil type and dielectric resin was selected to construct thin film capacitive material.

The thin film capacitive materials, 10 and 25micron dielectric thickness, were capable of processing through the conventional PWB manufacturing steps. This was shown at multiple PWB shop locations.

The electrical performance and capacitance values are improved over the traditional FR4 laminate substrates. The ability to withstand 500 volt Hi-Pot testing (even at 10µm) is significant, and has not been demonstrated by any other thin polymer capacitive substrate. Further testing of capacitance versus frequency and temperature changes is planned.

As the demand for a power distribution system with low impedance and control of EMI increases for hi-end computing boards with high signal frequency, the usage of thin film capacitive material in PWBs is expected to grow.

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Reference

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