

Use of High Dk, Low Loss Composite Material as used for Embedded Capacitors in High Frequency Applications

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Abstract

In order to meet the never ending desire for smaller and cheaper electronics, many companies are pursuing the use of embedded passive technologies. There are several examples of embedded capacitors, especially for digital functions such as decoupling. Up to this point however, it has been more difficult to use embedded capacitors as part of RF circuitry such as filters. This is due to the fact that most materials used for forming embedded discrete capacitors have relatively high loss at GHz frequencies. Also, the capacitance density can change as a function of frequency and temperature and affect the performance.

New materials have been developed to address the loss and capacitance variation of the typical embedded capacitor materials. The paper will show a comparison of the new versus existing materials used for embedded capacitors and demonstrate a lower loss at frequencies up to 10 GHz and stable capacitance density to 10 GHz as well as a lower temperature coefficient of capacitance (TCC).

In addition, several manufacturing techniques will be shown to incorporate this material into an organic chip package, as well as ways to minimize the variation of the electrode areas to improve total tolerance.

In summary this paper will show a path for those who are designing RF modules on LTCC (due to stable performance) a way to reduce cost by going to organic packages and incorporating embedded capacitor materials.

Introduction

The development of embedded capacitor technology has been driven by the need to save board area and/or reduce board size, increase functionality, lower costs and improve electrical performance. Many examples exist for the use of this technology (current capacitive material is used in the high-end computing industry, mostly for telecom and networking applications) [1]. For these particular high-end printed wire board (PWB) applications, embedded capacitor technology has been utilized to enhance signal integrity, reduce impedance at high frequency and dampen noise. A goal in its use has not necessarily been to remove discrete decoupling capacitors in designs.

Only a few publications regarding the development of materials for embedded capacitors and the advantages of incorporating embedded capacitors in PWBs are

acknowledged here [2,3,4]. These publications show the benefits of having capacitance embedded in the PWB, but they refer to high speed digital boards with switching frequencies less than 2 GHz. For these types of applications, the inductance of the power distribution network (PDN) is the overriding factor. This is governed more by the thickness of the power/ground plane pair and not the permittivity (also called dielectric constant- Dk). Because of this, a change in Dk with frequency has little or no effect on the performance of the PDN. The same can not be said for designing embedded capacitors into RF/Microwave modules.

Most RF/Microwave modules are manufactured using Low Temperature Co-fired Ceramics (LTCC). The base inorganic material is very stable both thermally and electrically, but the material and manufacturing

processes are expensive. LTCC technology is also limited by its incompatibility with large-area processing and has low component density integration capability. The result is that designers are seeking alternatives to LTCC and organic packages are the leading choice.

LTCC manufacturing does allow the integration of the analog components of the modules into the substrate while having the digital components mounted on the surface. Based on the different properties of the base materials when using organic packaging, it now appears beneficial to embed the digital components while bringing some of the analog functions to the surface in discrete form. In order to accomplish this, we must have materials for these embedded components that can operate satisfactorily over the frequency ranges utilized.

Liquid crystal polymer (LCP) based RF circuits are one alternative. However, the low dielectric constant of this material makes the RF components larger in size. This limits the component integration density, increases coupling between the components and limits the total system performance. Combining different ceramic particles with appropriate polymers can result in thermally stable composites that can have higher dielectric constant without compromising the quality factor. A new material has been developed based on these criteria.

Material Properties Review

Most of the materials for embedded capacitors in PWBs are polymers that are similar to those used to make the rest of the PWB. These polymers typically have Dks between 2.7 to 3.5. This low of a Dk does not provide enough capacitance density to replace the pF size capacitors we are interested in within the allowable area. In order to boost the capacitor density, high Dk ceramic particles (such as Barium Titanate) are added to the polymers. Unfortunately, due to mixing phenomena, the highest Dk that can be achieved is about 40. And at this level of filler, the material becomes brittle and loses copper adhesion. Commercially available materials have Dks between 10 and 30. One such material has been discussed previously [5].

When a Barium Titanate loaded polymer is tested at 1 GHz or higher, you see a significant drop off (from the tests at 1 MHz) in Dk from 30 to 22 as well as a dramatic increase in the loss tangent (Df) from 0.02 to 0.034. This is due to the ferroelectric nature of Barium Titanate. At 10 GHz the numbers get worse (although there appears to be a leveling off). This change with

frequency is not acceptable for most RF/microwave designs. Also the loss tangent is too high regardless of the change with frequency. A reformulation was required to address these issues.

In order to reduce Dk variation with frequency, different fillers were evaluated. We evaluated a number of materials, but in order to flatten the response we had to sacrifice the initial Dk. The best material is still a Titanate that results in a composite Dk of 18.6 at low frequency and only drops to 17.3 at 10 GHz. Although there is a Dk difference of 11.4 at 1 MHz with the Barium Titanate product the difference drops to only 3.7 (21 versus 17.3) at 10 GHz.

To lower the loss coefficient it was also necessary to adjust the polymer formulation. Again, several combinations were tried and an optimal combination was formulated. The loss at low frequency was reduced from 0.02 to 0.004 and at 10 GHz from 0.038 to 0.009. These numbers are now in the range in which practical circuits can be built. Table 1 lists the key properties of this new material.

<i>Properties</i>	<i>Method</i>	<i>Unit</i>	<i>25ST</i>
Dielectric Thickness	Nominal Thickness	μm	25
Capacitance @1MHz	IPC TM-650 2.5.5.3	pF/mm ²	7
Permittivity @1MHz	IPC TM-650 2.5.5.3	-	18.6
Loss Tangent @1MHz	IPC TM-650 2.5.5.3	-	0.004
Dielectric Strength	IPC TM-650 2.5.6.3	kV/mm	>20
Peel Strength	IPC TM-650 2.4.9	kN/m	0.7
Glass Transition Point	IPC-TM-650 2.4.41.3	°C	170
CTE α1/α2	IPC-TM-650 2.4.41.3	PPM/°C	32/97
Thermal Stress	20sec Float @288°C	times	>6
Tmax (TGA, 5% wt loss)	IPC TM-650 2.4.24.6	°C	380
TCC @ 1MHz	-	%	+4/-4
Temp./Humidity Bias Test	85°C/85%/10V	hrs	>1000
RoHS compliance	-	-	Pass

Table 1. Properties of Capacitor Material

The data above is based on a dielectric thickness of 25 μm (or about 1 mil) and the following illustration (Figure 1) shows the approximate area needed to make various size pF capacitors.

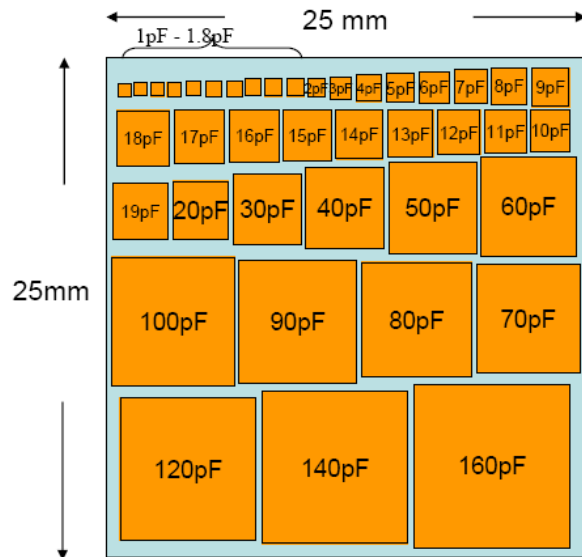


Figure 1. Area required for Embedded Capacitors

Formation of Embedded Capacitors

There are several methods to form discrete embedded capacitors inside the modules. One technique is to start with a laminate composed of two sheets of copper with the dielectric in between. With traditional materials the laminate would be etched on both sides simultaneously, but since this material does not contain any reinforcement and has a high particle loading, it would not survive this method. Instead one side of the copper is etched to form the capacitor electrode on one side and then an oxide or oxide alternative is applied. The oxidized side is laminated with prepreg and copper to form a subassembly. This subassembly (Figure 2) can now be processed with both sides of the copper etched since the prepreg will provide the necessary reinforcement. One or more of these subassemblies can be incorporated into the final product.

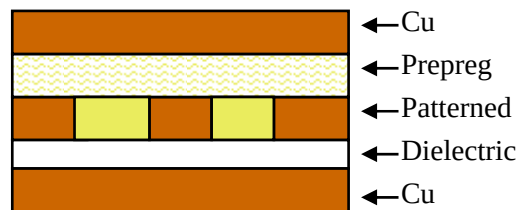


Figure 2. Subassembly

Other methods involve the use of resin coated foil (RCF). The copper foil is coated with the high Dk resin and is heated to drive off solvents and slightly advance the cross-linking of the resin. This process is

controlled to allow bonding to other materials, but not allow the resin to flow too much and squeeze out of the module during lamination.

In one method a standard fiberglass reinforced or film based laminate clad with copper on both sides has an oxide applied to the copper on one or both sides. A sheet of RCF is applied (laminated in a press) to one or both sides of the laminate. The resulting composite is now processed through standard inner-layer processing to form the top capacitor electrodes. The next step is to remove the background capacitor material using either a sandblasting process or plasma ablation. After the material removal is performed, the bottom electrode is formed using standard print and etch processing. An oxide is applied to the copper and the composite is laminated with either a standard resin coated copper or prepreg and copper. Connection to the capacitor electrodes can be performed using either thru hole or laser vias. Figure 3 shows the process.

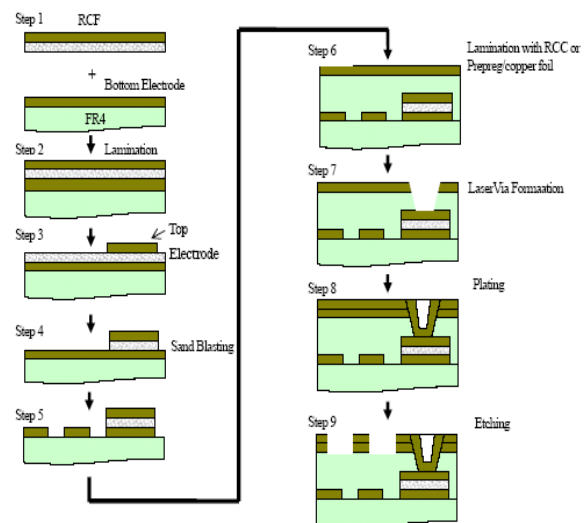


Figure 3. Capacitor using RCF- Method 1

Another technique involving RCF starts with etching the standard reinforced or film based laminate first. A planarization resin (such as a non-conductive hole file) is coated on the laminate to fill in the areas of the etched copper. The laminate is then “planarized” (resin covering the copper is removed) using an abrasive (similar to the deburr operating after drilling). After the copper is oxidized the high Dk RCF is applied to the laminate (see Figure 4) and then the top electrode is etched. Finishing of the module can then be done using standard processing.

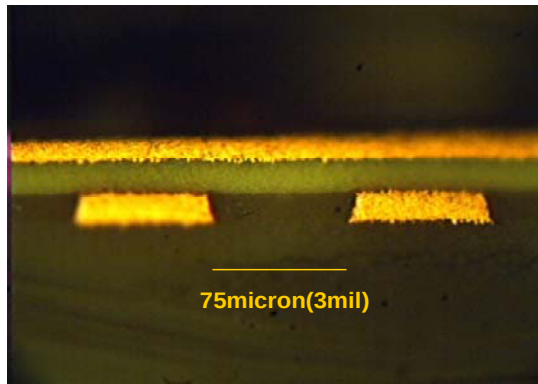


Figure 4. Capacitor Formation after Planarization and application of High Dk RCF- Method 2

Material Characteristics and Performance

Discrete surface mount capacitors can be purchased with fairly tight tolerance. Plus or minus 1% of nominal value is readily available and usually not at a big price premium over lower tolerance capacitors. Because of this, designers usually specify the tighter tolerances whether or not the circuits require them. When forming discrete capacitors inside the module, the materials and processes don't currently allow for these types of tolerances. With proper process optimization and control, we can still achieve values that will result in highly functional circuits.

The use of proper dispersion techniques for the ceramic in the polymer and the right coating method for putting the polymer on the copper can result in fairly tight material tolerances. Repeated testing of laminates (3 panels per lot over several lots) indicates that it is possible to hold better than $\pm 5\%$ with $\pm 3\%$ being achievable. The formation of the electrodes by etching will also add to the tolerance. For larger capacitors (<100 pF) an additional $\pm 1\%$ can be expected and for the smallest (<5 pF) there can be additional ± 5 to 10% to the tolerance. Use of thinner copper foils and laser direct imaging can help minimize the variation. Additionally, laser trimming is possible, but this adds costs and is usually not required.

Initial tolerance is important, but we need to understand the materials properties under various environmental and electrical conditions. One characteristic of discrete capacitors that is specified is the temperature coefficient of capacitance (TCC). The capacitance is measured at room temperature and the deviation from nominal is measured from -55°C and 125°C . Most of the existing materials for embedded capacitors meet X7R requirements of $\pm 15\%$. Many designs however specify NPO type capacitors which have a $\pm 30\text{ppm}/^\circ\text{C}$ (effectively $\pm 0.3\%$ over the temperature range) requirement.

As with the initial tolerance, it is currently not possible to meet the tightest requirements of discrete capacitors, but the new material has demonstrated a significant improvement over the existing materials. The TCC has been reduced to only $\pm 4\%$ (Figure 5) over the temperature range, and should also allow for functional circuits.

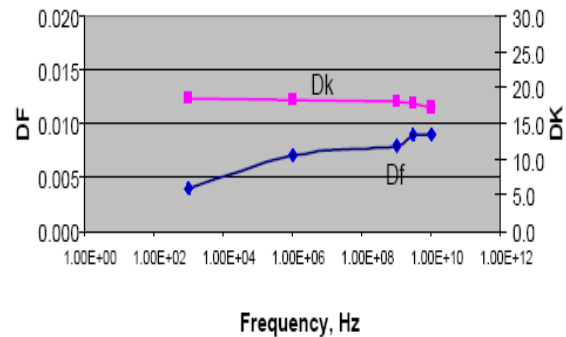


Figure 5. TCC of New Material

Another important characteristic is the impact that moisture may have on the material. Most polymers can pick up some degree of moisture which could affect the electrical and mechanical properties. Although these embedded capacitors will be inside the module, they still can be subject to moisture that may penetrate the surrounding material. To test the susceptibility of the material, capacitors were formed on a laminate and it was exposed to 85% RH at 85°C for 1000 hours. The materials were pulled periodically during this time and tested. It was determined that this exposure did not significantly affect the Dk and thus the capacitance of the material. (Figure 6.)

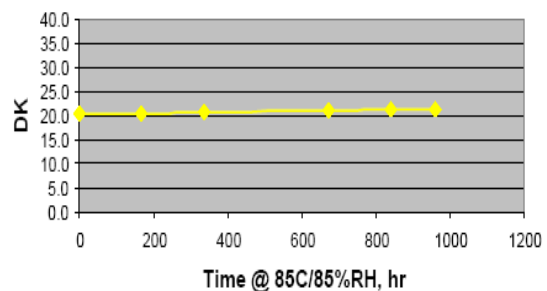


Figure 6. Moisture affect on Capacitor Material

With the temperature and humidity impacts on the material studied, we next investigated the stability of the material versus frequency. At lower frequencies (less than about 500 MHz) there are several good

methods for checking Dk and Df. IPC TM-650 2.5.5.3 was used for these frequencies. At higher frequencies everything becomes critical to the test (such as the cable and probe characteristics). Also because these materials are extremely thin, most methods can't handle these samples.

We evaluated several techniques and found the one described by Agilent (6) as being ideal for our application. It is similar to IPC TM-650 2.5.5.13, but a new standard is being developed around this technique. The benefit of this technique is that it is simply to set up and is highly repeatable. It can also accept thin samples (as long as the dielectric can stay intact without any support). The main drawback of this technique is that each resonator cell is designed for specifically one frequency. Due to this we purchased cells for specifically 1, 3 and 10 GHz.

The following chart (Figure 7) shows the results of the tests. The first two points used the lower frequency method and the remaining 3 used the split post resonator cells.

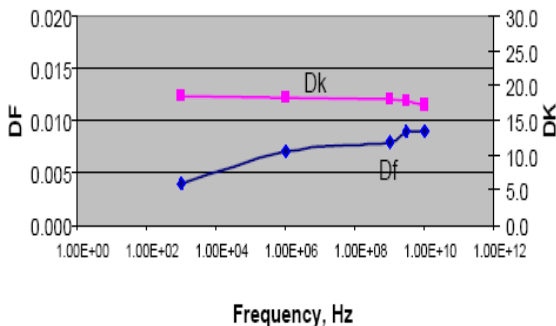


Figure 7. Dk and Df versus Frequency

Although it is not completely accurate to put both methods on the same chart it does show that the values between the MHz range and the 1 GHz range do agree closely and only a slight change in values above 1 GHz.

In addition to the above performance factors, we must make sure that the material will pass the standard reliability tests. All the standard tests including, solder shock, solder float, Time to Delamination (at both 260 °C and 288 °C) and High Potential testing were performed. All these tests passed and so we felt comfortable in subjecting the material to a Temperature/Humidity Bias test (THB).

To perform the THB test we prepared discrete capacitors as we did for the moisture test previously

described. Electrodes were soldered to the top and bottom electrodes and a 10 volt bias was applied to the capacitors (this was picked based on being at least two times the normal operating voltage). The laminate was placed in the temperature and humidity controlled oven and run until a 10% change in resistance occurred or 1000 hours (which ever came first). After the initial acclimation of the samples, the material held steady for the 1000 hours (Figure 8). Thus the material should be acceptable for an extended period of time for applications under 10 volts.

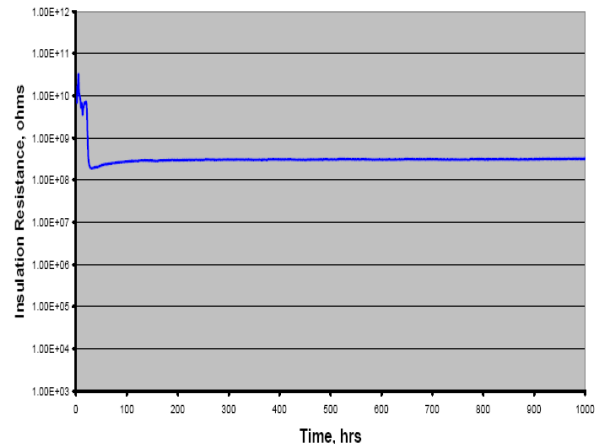


Figure 8. Temperature/Humidity Bias Test @ 10V

Ongoing Activities

Now that we have characterized the material, several module designers are investigating this material for use in their designs. Several of the CAD programs support placement of embedded components, thus making it easier to implement this technology. To date most of these designs involve with wireless communications, but other applications are being examined. In the future, we hope our customers will report on their results.

In addition to evaluations at customers, we continue to work on improving the material. To increase the capacitance density, we are reducing the thickness of the dielectric. We can successfully make product down to 16 microns and are pushing to go thinner. Unlike materials based on reinforced composites (like PTFE filled with ceramic particles) we do not have limitations due to the reinforcements (they can not go below 25 µm, and even this is difficult). We must balance yields and properties against the increase in capacitor density. Also, other formulations are being investigated to further reduce the loss at higher frequencies and further improve TCC.

Conclusions

A new material for embedded capacitors has been formulated that has show excellent properties at high frequency and is stable with temperature and humidity. It can be incorporated into organic modules using standard printed circuit board manufacturing and is at least reliable as the surrounding material.

Use of this material should allow module designers working with high frequencies to successfully design embedded capacitors into their designs and thus improve form factor, improve electrical performance and possibly reduce overall costs.

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