As originally published in the IPC APEX EXPO Conference Proceedings.

RF Capacitor Material for Use in Printed Circuit Board

Jin-Hyun Hwang, John Andresakis, Ethan Feinberg, Bob Carter, Yuji Kageyama, Fujio Kuwako
Oak-Mitsui Technologies
8 First Street, Hoosick Falls, NY, 12090 USA
Ph: 518-686-8023; Fax: 518-686-8095
Email: jin.hwang@oakmitsui.com

Abstract
A novel ceramic-functional-particle-filled polymer composite material has been developed for the use either in discrete elements on the printed circuit board or in being embedded within the packaging substrate for high frequency circuit applications. This material provides the desired properties such as low loss at high frequencies, about 0.002 or less up to 10GHz, and high dielectric strength, among other improved properties. The electrical properties were influenced significantly by the ceramic-functional-particle, i.e. type and particle size/distribution in the polymer matrix. Their contributions to the electric strength and temperature stability of capacitance which is an important material issue for practical device application will be discussed. In addition, capacitance tolerance for manufacturing embedded RF capacitor will be presented in terms of etching uniformity to minimize the variation of the capacitor electrode areas.

Key words
RF capacitor, dielectric loss, dielectric strength, TCC, capacitance tolerance, embedded capacitors

I. Introduction

Organic-based dielectric materials have been explored for the use either in discrete passive components on the PCB (printed circuit board) or in being embedded within the packaging substrate as part of RF/microwave circuits [1]-[4]. Using ceramic-functional-particles (fillers) filled polymer composite material is merely a convenient and inexpensive way (to compete with ceramic chip capacitors) achieving low ESR (equivalent series resistance), high SRF (self-resonant frequency) for RF capacitor application that can support frequencies well above 1GHz. Embedding fillers into the polymer enhances properties of dielectric materials (by optimizing filler chemistry and its distribution in the polymer matrix) such as temperature stability of capacitance for high precision RF circuit and dielectric strength (the maximum dc electric field strength applied across the dielectrics in RF capacitor) for a high voltage rating which is essential especially for servers, pico cell and femto cell in base station market space. Generally, fillers are widely accepted in various applications because of their advantage in addressing several limitations of polymers, making its way onto benefits such as better dimensional stability for polymer composite membrane, lower CTE (coefficient of thermal expansion) for build-up layer, increasing thermal conductivity for TIM (thermal interface materials), improved stiffness for underfill materials. As for the fillers in RF capacitor application, it is presently based on almost entirely on the simple perovskite $BaTiO_3$ (barium titanate), but there is strong demand on the class of materials known as paraelectrics mainly due to the fact that their dielectric properties are much more stable with regard to most of operating conditions such as frequency, temperature and DC bias [5].

Well-dispersed fillers in polymer composite matrix play a crucial role in achieving RF capacitor requirements as described above and thus factors that determine fillers distribution should be controlled and optimized. Any existence in the particle agglomerates is accompanied by the formation of possible defects such as trapped porosity that make the dielectrics vulnerable under practical operating conditions. Fig. 1 shows typical example of severe filler agglomerates which are clearly visible concentrating on the coating surface as discrete protuberances and appear to be more in numbers. Filler agglomeration is easy to observe by improper usage of dispersion agents and their mis-matching to a solvent composition in formulation. The agglomerated filler could degrade electrical properties, in particular dielectric strength and temperature stability of capacitance (both will be described in next section). Various types of coupling agents can be added to the polymer compositing to take advantage of the absorption of a functional polymer to the particle surface to modify the filler/polymer interface chemistry, giving rise to complete de-agglomeration of the fillers and subsequent elimination of the air void [6]. It is also necessary to adjust the solvent composition combined with the coupling agents, which is associated with coupling, adhesion and dispersion. In this study, a titanium-based coupling agent and a typical solvent mixture were selected and formulated with a paraelectic filler and a phenylene-based polymer. The optimum amount of the coupling agent was determined by the viscosity response for various levels of the application of the coupling agent. The de-agglomeration effect was pronounced when significant reduction in suspension viscosity was observed. Optimal combination was formulated to make RF capacitor laminate that used thin dielectrics having thickness range of 12- 25 ㎛.

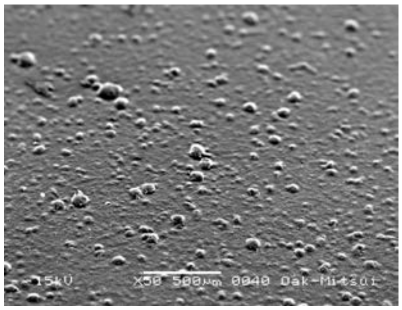

Fig. 1. SEM image (at tilt angle) of the typical filler agglomerates of ceramic filled polymer composites (on the coating surface)

II. Results and Discussion

A. Effect of Ceramic Functional Particles (Fillers)

For practical device application, the contribution of the filler to the dielectric strength and the temperature stability of the capacitance are of greatest interest. The dielectric strength was examined by measuring dielectrics breakdown voltage (BDV) of the samples having fillers with different size (Fig. 2). A circular pattern with 0.5 inch diameter was placed on a bottom electrode grounded to the DC tester. A probe was placed on the center of a circle and subjected to the voltage. The electrode material was made on one side of the copper of a RF capacitor laminate. The dielectric thickness was set to 25μm for all samples. As shown in Fig. 2, the effect of the filler size on the BDV was clearly detectable, and the BDV of the dielectrics composed of the larger size filler revealed a considerable improvement in BDV compared to the case of formulating with the smaller size filler. Lower BDV may result from non-uniform dispersion of the filler and it may induce the charging of the weak interface chemistry, probably representing the filler agglomerates. We continue to work on improving the material to achieve relatively high BDV even with small size filler by controlling the suspension chemistry.

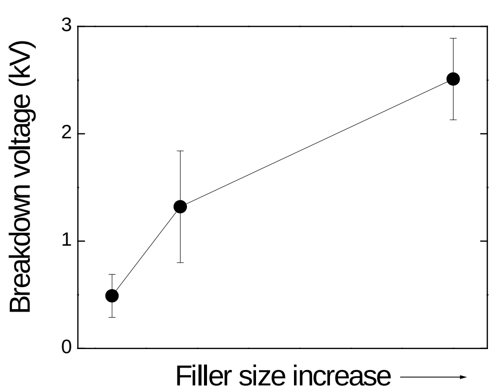

Fig. 2. BDV variation of polymer compositing with the filler size

Indirect evidence for the improvement of the filler distribution was sought by measuring capacitance change with temperature for samples fabricated with different suspension preparation routes. TCC (temperature coefficient of capacitance) is an important material parameter to meet the tighter RF/microwave design tolerances. (Details on TCC was described previously [7]) Fig. 3 shows that the TCC was rotating counterclockwise (direction to the positive TCC) toward the end of each curve at high temperature region. We mixed fillers with the polymer in an arbitrary way. Thus, in this physical construction of the polymer compositing, the dielectric is comprised of filler and polymer with the filler occupying the majority of the dielectric. The filler selected ended up slight positive TCC and the plain polymer (without filler) showed negative TCC. The filler contribution to the net composite TCC is dependent on its volume fraction and distribution. Therefore, it is assumed that the filler can control complete TCC by compensating for negative TCC of the polymer and positive TCC at higher temperature could be regarded as being responsible for the uniform filler distribution in the polymer matrix. SEM photos in Fig. 4 supports this with different level of dispersion of the filler in polymer between two samples.

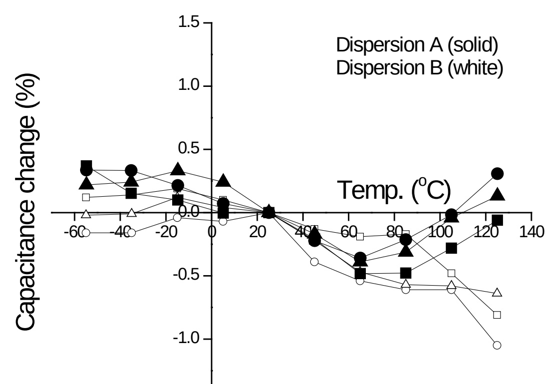

Fig. 3. Temperature stability of capacitance of two samples prepared by different suspension preparation routes

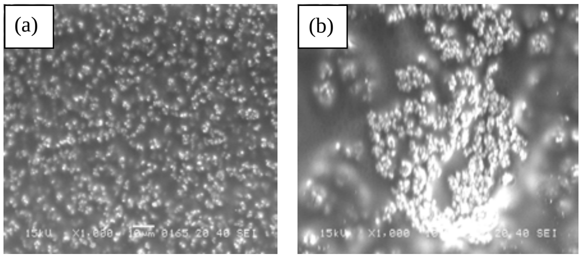

Fig. 4. SEM images (on the coating surface) of samples with (a) dispersion condition A and (b) dispersion condition B

B. Characteristics of RF Capacitor Laminate

Fig. 5 shows frequency stability of Dk (dielectric constant) and DF (dielectric loss) of our developed RF capacitor laminate product using the ceramic-particle-filled polymer composite. As for the method for checking Dk and DF, the first point in Fig. 5 used the lower frequency method (LCR meter) and the remaining 3 used the split post resonator cells which is useful to measure Dk for isotropic mixtures (when fillers are randomly oriented) [8][9]. The product is the copper clad laminate (CCL) with a standard panel, 18 by 24 inches. It was composed of two sheets of copper foils on both ends with organic based composite dielectrics having fillers dispersed into polymer in between. Copper foils are available in various thicknesses, ½ ounce and 1 ounce being the dominant thickness, but thinner copper foil would help to minimize the variation in capacitance during etching process in PCB manufacturing. The typical Dk and DF of the RF capacitor laminate at 1GHz were measured, 7.8 and 0.002, respectively. We are expanding the product's capacitance density range up to 670 pF/㎠ by thinning dielectrics and process optimization. The standard reliability tests including solder shock, solder float, time to delamination and THB (temperature, humidity and bias) testing were performed and all these tests passed.

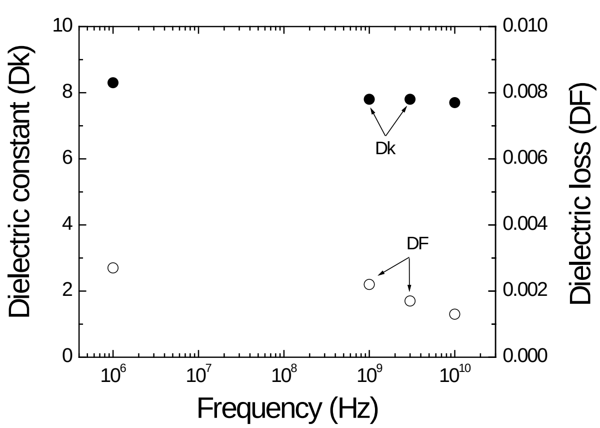

Fig. 5. Frequency dependence of Dk and DF of the developed RF capacitor laminate

C. Uniformity of Capacitance

Capacitance tolerance for the organic-based RF capacitor laminate is critical for the application of forming discrete type embedded capacitors inside the organic packaging substrate. In this case, capacitance tolerance can be expressed as 3 sigma in the form of (mean of capacitance) ± (3 sigma) for the foot print size of the capacitor. Smaller tolerance in capacitance is desirable to achieve better yield performance of the RF device in manufacturing [2]. However, when forming discrete embedded capacitors inside the organic substrate for RF module, the materials and processes don't currently allow for the tight tolerances due to the material and the process variation. The dispersion techniques for the ceramic fillers in polymer and the right coating method for putting the ceramic-filled polymer composite material on the copper can minimize the material variation. In addition to the material variation, the process variation (mainly the etching pattern variation) in formation of the electrodes by the etching process in PCB manufacturing will add to the tolerance. In order to understand the capacitance tolerance of high Dk capacitor laminate with dielectric thickness of 16 μm, uniformity of capacitance was investigated as a function of various capacitor electrode areas (0.25mm. square ~ 3mm. square) which were prepared by the standard etching on the test board. Fig. 6 shows a typical result, showing the measured capacitance tolerance and calculated tolerance (expected) of capacitance. Actual measured uniformity of capacitance in the small foot print capacitors showed a good correlation with an assumption that the etching variation is around ±7μm. Small foot print capacitors with tight tolerance is still being challenged, but the result in Fig. 6 indicates that we can achieve fairly uniform capacitance values with proper process optimization and control that will result in functional RF circuits.

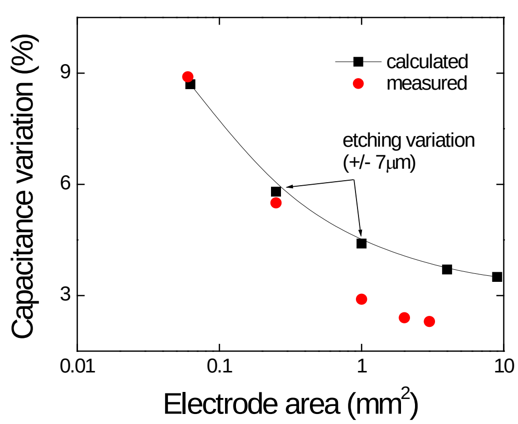

Fig. 6. Capacitance variation with electrode area: calculation *vs*. measurement result

III. Conclusion

The ceramic filled organic-based composite material has been used to make RF capacitor laminates to compete with ceramic chip capacitors. Using this material, we successfully achieved low DF of ~0.002 at GHz frequencies up to 10GHz, higher dielectric strength and better TCC by optimizing size of the filler and controlling its distribution in the polymer matrix. This material can be applicable for the use either in discrete RF components or in being embedded within the packaging substrate as an embedded RF capacitor material.

References

[1] *New 500 & 250V Multilayer Organic Capacitors (MLOCs)*, AVX Co., 2012. Available: http://www.avx.com

[2] P. N. Lee *et al*., "Design and modeling methodology of embedded passives substrate in a compact wireless connectivity module," 61st ECTC, May 31-June 3, 2011, FL USA, pp. 144-149.

[3] *Features and Applications of Polymer Thin Film Multi-Layer Capacitor PML CAP*, Rubycon Co., 2011. Available: http://www.rubycon.co.jp

[4] J. Andresakis *et al*., "Use of high Dk, low loss composite material as used for embedded capacitors in high frequency applications," 41st IMAPS, USA, 2008.

[5] R. Ulrich, L. Schaper, D. Nelms, and M. Leftwich, "Comparison of paraelectric and ferroelectric materials for applications as dielectrics in thin film integrated capacitors," *Inter. J. Microcircuits Electron Packag.*, Vol. 23, 2000, pp. 172-180.

[6] S. J. Monte, "Titanate Coupling Agents," in *Functional Fillers for Plastics*, 2nd ed., M. Xanthos, Ed. Germany: Wiley-Vch, 2010, pp. 91-114.

[7] J. H. Hwang *et al*., "High Dk Embedded capacitor Materials in organic packaging substrate," 12th Electronic Circuits World Convention (ECWC12), US100, Taiwan, 2011.

[8] J. Krupka *et al*., "Uncertainty of complex permittivity measurements by split post dielectric resonator technique," J. Europ. Ceram. Soc., Vol. 21, 2001, pp. 2673-2676.

[9] S. George et al., "Dielectric mechanical, and thermal properties of low-permittivity polymer-ceramic composites for microelectronic applications," Int. J. Appl. Ceram. Technol., Vol. 7, 2010, pp. 461-474.