Integrated Capacitors Using Polymer-Ceramic Composites for MCM-L

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Abstract

This paper discusses the use of polymer-ceramic composite materials in making thin film integrated capacitors for MCM-L based technology. Different combinations of fillers and matrix materials were chosen for their good electrical and physical properties. The effect of filler particle size (0.1 - 1.24 μm) on the dielectric constant of the composites was studied and its consequence on the film thickness is discussed. Thin film capacitors, from composites, were fabricated below 230°C to be MCM-L compatible. Their applicability as decoupling capacitors are demonstrated via high frequency (500MHz - 20GHz) measurements (S-parameter) carried out using a network analyzer. The dielectric constant required of the polymer and the ceramic to achieve high dielectric constant composites for decoupling capacitors for next generation of computers is also discussed.

Key Words: Composite Materials; Integrated Capacitors; Decoupling Capacitor; Photo-imageable; MCM-L; Lift-off.

1. Introduction:

MCM is one of the fastest growing segments of packaging technology and many type of MCM technologies exist today [1]. In order to achieve high density interconnects while maintaining low cost, thin deposited layers on PWB (MCM-LD) is currently the technology of greatest interest [2 - 7]. The infrastructure of Printed Wiring Board (PWB) industry is well established and thus the cost of MCM-L based technology is low.

There is also a drive towards integration of passives (resistors, inductors and capacitors) into MCM technology [8 - 13]. The advantages of integration over surface-mount include:

(1) Improved packaging efficiency.
(2) Improved electrical performance due to reduced parasitics.
(3) Elimination of a separate package for passives yielding low cost, and reduced profile and weight.
(4) No assembly to board and thus reduced cost.
(5) Improved reliability due to reduced solder joint failures.

The Packaging Research Center at Georgia Institute of Technology is working on a next generation of low cost single level integrated module (SLIM). The package will include embedded passives among other functions. The substrate of choice is the PWB for its cost benefits. This paper describes an on-going work towards the integration of capacitors in MCM-LD on a large substrate.

One of the biggest challenge to overcome in MCM-L based technology is the processing of subsequent layers on PWB at low temperatures. Many polymer materials are available in order to meet this requirement. Similarly, integration of passives in MCM-L-based technology requires low temperature processing.

Composite materials (Polymer Thick Films, PTF) are suited for making integrated capacitors in a MCM-L-based technology for their low temperature processing requirements. The processing temperature of the composite is determined by the curing temperature of the polymer matrix material. Many polymer materials exist that require low temperature curing (< 230 °C), a limitation imposed by most commonly used PWBs).

In this paper composite materials for integrated capacitors in MCM-L-based technology are discussed. Five major points are evaluated and discussed. They are:

(1) Dielectric constant as a function of particle size. This is done in order to determine the thinnest film achievable.
(2) Fabrication of capacitor structures using composite materials.
(3) Free standing capacitors (an alternative technique of integrating capacitors in MCMs).
(4) Applications (decoupling capacitors)

(5) Dielectric constant requirements of the polymer and ceramic material to satisfy the decoupling capacitor needs of next generation computers.

2. Background

Two types of composite material can be applied in making capacitors:
(1) Partially-conductive particle-filled (grain boundary capacitors) [14].
(2) High resistive ceramic filled [15 - 21].
The first approach uses the effective capacitance generated by bringing particles in close proximity to each other. The second technique gives an effective dielectric constant which lies between the dielectric constants of the two materials. The first approach has an inherent problem of high leakage current and also the possibility of low yield due to potential shorts generated when particles (partially-conductive) form a continous path from top to bottom electrode of a capacitor. Given these problems, our investigation foucsed on high-resistivity ceramic-filled polymers.

The electrical properties of randomly dispersed particle composite systems have been studied over the last fifty years and various models have been developed which predict their dielectric behavior. The modified Lichteneckers equation (Equation 1) gives a good fit to the randomly distributed filled composite system [17].

$$\log(\varepsilon_{eff}) = \log(\varepsilon_p) + (1-K)(V)\log(\frac{\varepsilon_c}{\varepsilon_p}) \quad \text{... (1)}$$

Where, ε_{eff} = effective dielectric constant
ε_p = polymer dielectric constant
ε_c = ceramic dielectric constant
K = constant
V = volume filled

It requires previous knowledge of the dielectric constant of both the materials. The effective dielectric constant of the material increases as a function of volume of high dielectric constant material (ceramic). To achieve high dielectric constant material a high dielectric constant ceramic and high dielectric constant polymer should be selected. It should be noted that composites with non-polar polymers show better temperature and frequency stability [16]. Where as, the degree of particle dispersion improves with the polarity of the polymer and lower dielectric constant values are typically achieved [18]. In general, the electrical conductivity of the composite is governed by the ceramic and the dielectric behavior is governed by the polymer material [15, 16]. Thus, a combination should be chosen to achieve the desired properties of high dielectric constant material with low loss.

3. Material Selection:

Electronic grade (low ion content) polymer materials requiring low curing temperature (< 230 °C) and having high glass transition temperature (>180 °C) were selected. Above the glass transition temperature (Tg) the tan-delta becomes high due to ionic conduction [21]. The polymers selected for making composites (used in the study of electrical properties) were:
(1) Non-photodefinable Benzocyclobutene (product of Dow Chemicals)
(2) Photodefinable pre-imidized Polyimide (Ultradel 7505, product of Amoco Corporation).

Table 1 lists the properties of the ceramic particles selected from different vendors. The particles were selected on the basis of different sizes and dielectric constants.The electrical properties given are for the bulk material. The dielectric constant in the powdered form is typically known to be lower than in the bulk form.

Table 1. Ceramic fillers used (at 25 °C).

Filler	Diel. Const.	tan-delta	Surface Area (m^2/g)	Av. size (μm)	Den. g/cc
BT	4,425	0.010	2.0 - 3.1	1.43	5.5
BT-6	~3,500	—	—	~ 0.1	—
BT-8	~3,500	—	—	~ 0.2	—
HPBT1	N/A	N/A	—	~ 0.7	5.38
HPBT2	N/A	N/A	2.9 - 3.9	1.24	5.38
LMT	17,800	0.015	1.65-2.65	1.10	7.8

BT: Barium Titanate (TAM Ceramics)
BT-6, 8: Barium Titanates >99.5% purity (Cabot Performance Materials)
HPBT: High purity Barium Titanates (TAM Ceramics).
LMT: Lead Magnesium Titanate (TAM Ceramics).

Mixing of the materials was carried out using a ball-mill (porcelain-balls) technique. Ceramic powders were dispersed in the polymer material and the viscosity of the material was controlled with the addition of solvents (recommended by the manufacturers). Typical mixing times used were above 100hrs (3RPM) at room temperature (RT). However, improved mixing techniques requiring only few hours can easily be implemented.

4. Processing/Characterization:

Thin films of composite materials (dielectric layer) were deposited using a spin coat technique. The viscosity of the material was controlled to achieve uniform particle dispersion and to achieve required film thickness. After spin coat, the film was first dried (removing solvent) at low temperatures (70°C for 15 min.). This was followed by 100 °C (15 min.), 130 °C (30 min.) and 225 °C (1.5- 2 hr.) curing on a hot-plate.

Characterization (at RT) of the dielectric material was carried out by making several parallel plate capacitors on a glass substrate. The bottom and top electrodes were deposited using an e-beam system. The bottom electrode was made common for all capacitors and the top electrode was patterned to several (0.42cm X 0.42cm) area electrodes. The dielectric layer was in the 5 - 10 µm range and the uniformity of the thickness was assured (a Tencor profilometer was used for thickness measurements). Figure 1 shows the structure of the capacitor used in low frequency measuremets.

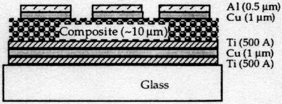

Figure 1. Layout of parallel plate capacitors used to characterize dielectric constant at low frequencies.

Figure 2 shows the dielectric constant of polyimide (PI) filled, 34%, with different types of particles. Dielectric constant was measured upto 25 MHz and was found to be stable over this range. The highest dielectric constant was obtained with LMT particles. Dielectric constant behavior as a function of volume filled is shown in Figure 4 for a PI-LMT system. From this it can be noted that the dielectric constant increases with volume filled as predicted by the modified Lichteneckers rule (Figure 4).

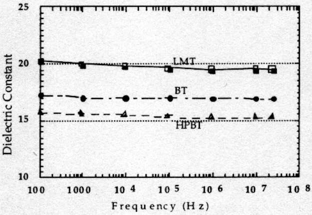

Figure 2. Dielectric constant as a function of frequency for composites made with different fillers.

Benzocyclobutene (BCB) was also filled with LMT particles at three different volumes and the results are given in Table 2. Similar to the polyimide-based material, the dielectric constant of the BCB based materials was found to be stable to 25MHz. The dielectric constant values achieved from BCB and PI based materials were fitted using the Lichtenecker rule. The constant (*K*) was determined to lie between 0.4 - 0.45 for all the systems containing LMT particles.

Table 2. BCB-LMT combination (100KHz).

Volume % Filled	Dielectric Const.	tan-delta
34	18	—
43	24	—
55	38	0.015

5. Applications:

Many applications of capacitors will require integration in high performance packages, including:

(1) Decoupling capacitors to reduce simultaneous switching noise (SSN).
(2) Filter applications
(3) Impedance matching (e.g., in high speed data bus)

Simultaneously switching noise is reduced by decreasing the inductance of the power lines and by incorporating decoupling capacitors near the switching devices (chip). Surface mount capacitors are not ideal because they can occupy 20 - 30% of the surface area of the boards. Thus, in order to attain high performance MCM-LD technology with high packaging efficiencies, integration of decoupling capacitors should be considered. Important characteristics of a decoupling capacitor are [11-13, 22]:

(1) High but controlled capacitance
(2) Low inductance between the chip and the decoupling capacitor (closely placed close to the chip)
(3) Low impedance (thin film with high dielectric constant) over a large bandwidth.
(4) Fabrication of capacitor structures for integration.

Most applications do not require the highest quality dielectric materials and some losses are acceptable. The performance requirements of decoupling capacitors exceed or meet those for most other capacitor applications; except active filters.

In order to evaluate composite materials for decoupling capacitor use, a small thin film capacitor (~4 µm) was made on a glass substrate using 49% LMT-filled. Two port S-parameter measurements were made by probing (using coplanar waveguide probes, G-S-G, connected with 50 Ω coax) at the diagonal points of a solid plane parallel plate structure (1.2mm X 1.2mm) using a HP8510 network analyzer. The measured S-parameters (S11, S12) are shown on the Smith chart in Figure 3. Low impedance of the decoupling capacitor is required, [22], and is demonstrated on the Smith chart. The insertion loss (S12) of the capacitor structure was determined to lie below -30 dB over the measured frequency range.

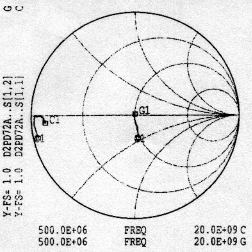

Figure 3. Measured S-parameters (2-port).

6. Particle Size Dependence:

Different particle sizes (average), ranging from 0.1 to 1.24 μm, of $BaTiO_3$ from different vendors (Tam Ceramics and Cabot Performance Materials) in combination with polyimide were studied. The resulting dielectric constant and loss-tangent are given in Table 3.

Table 3. Dielectric constant and tan-delta

Particles (size, μm)	Wt. %	Diel. Const.	tan-delta
BT-6 (~ 0.1)	89.7	30.78	0.013
BT-8 (~ 0.2)	88.42	24.7	0.014
HPBT-1 (~ 0.7)	91.34	32.95	0.019
HPBT-2 (~ 1.24)	91.22	31.17	0.018

From Table 3 it can be observed that high dielectric constants can be achieved using both small particles and larger particles (~1 μm range). The benefits of using smaller particles are that thinner films (~1um range) can be made to achieve high specific capacitance. Also, advantage of particle distribution can be taken for high volume filling to achieve high dielectric constant composite. Curing was done in air and thus high loss (tan-delta) is observed in Table 3.

7. Next Generation Requirements:

Most of the growth in MCMs is expected to be in desktop computers [1]. Decoupling capacitors with specific capacitance of 73 nF/cm^2 ($\varepsilon_{r,\ eff}$ = 165 for 2 μm thick film) are required by year 2005 for computers [11]. In order to determine the dielectric constant needed of polymer/ceramic to meet this requirement, dielectric constant as a function of volume was studied for the polyimide-LMT combination. Equation (1) was fitted to the measured values by varying the constant (K) value (Figure 4).

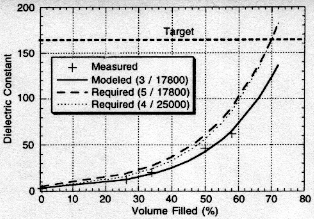

Figure 4. Measured and modeled dielectric constant as a function of volume filled. In parantheses are the polymer/ceramic dielectric constants.

Using the determined K value and using LMT (ε_r = 17,800) as the filler, a polymer material with dielectric constant of 5 will be required to achieve an effective dielectric constant of 165 for a volume loading of 70%. There exist many epoxy materials with dielectric constant near 4.0. However, polymers with higher dielectric constants (>5) and which are suited for capacitor applications in MCM-LD have not been reported. On the other hand, if a dielectric constant of 4 for the polymer is used then the dielectric constant of ceramic rshould be 25,000 (Figure 4).

The above predictions are based on 2 μm thick dielectric layer. However, thinner films can easily be achieved using smaller particles as discussed above. For a dielectric thickness of 1.25 μm ($\varepsilon_{r,required} \cong 100$), a dielectric constant of 2.5 will be required of the polymer material (in combination with LMT filler) and most polymers meet this criterion. Higher dielectric can be achieved with modification of the morphology of the fillers. Dielectric constant value of 154 for polymer-ceramic composites has been demonstrated for a 70% volume filled [20]. Therefore, based on the dielectric requirements, composite materials can satisfy the need of integrated capacitors in MCM technology. Three other challenges that will also need to be satisfied are: (1) Achieving defect free thin films (e.g., pin-hole free); (2) Achieving very low loss materials (tan-delta < 0.01) and (3) Low-cost. The loss-tangent of the composite is dependent on the loss-tangent of both the polymer and the fillers used, [17], and low loss materials should be selected.

8. Fabrication of capacitor structures:

In order to limit processing steps and obtain well controlled capacitor structures, a photo-imageable dielectric is desirable. Photo-processing of thick films has been used successfully by many authors, [23, 24], for low dielectric materials. However, no materials are commercially available for making capacitors on PWB. A feasibility study using highly filled composites was carried out using PD-PIs (Ultradel 7505 and PI 2621, products of Amoco and Du Pont respectively). Figure 5 shows thin line pattern of composite material in a 16 μm thick film. Figure 6 shows a capacitor structure with 50 μm vias in a 4 μm thick composite film (49% volume filled). Successful results were obtained using both types of polyimides.

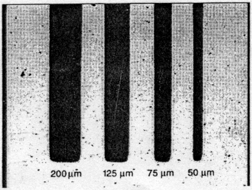

Figure 5. Thin line structures made from PD-PI based composite material (16 μm thick film).

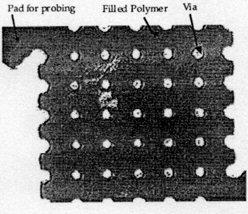

Figure 6. PD-PI based composite film (4 μm thick) with 50μm vias.

9. Free-Standing Capacitors:

Free standing capacitors are useful in integration within the PWB layers or attaching as a layer during MCM build-up. The benefit of this technique is that the capacitors can be tested and reworked if required before integration.

Processing steps for making free standing capacitors are outlined in Figure 7. For a thick layer of PI-2611 (> 10 μm), lift-off can be done by peeling off the films. For a thin layer of PI-2611 (~2 μm) adhesion at the PI-2611/glass interface can be weakened by submerging in PI-developers or photoresist-developers (~2 hr.). Films as large as 2.5cm X 2.5cm have successfully been made using this technique. Photo of a small free standing capacitor made using PD-PI/LMT is shown in Figure 8. Apart from glass, other temporary-substrates can be impelmented which show poor adhesion with PI or bottom electrode (e.g., steel for Cu electrodes) to make free-standing large size capacitors. Capacitors on a flexible substrate have been made using $BaTiO_3$ and Ta_2O_5 by ref. [9]. Composite films are very flexible and thus are more compatible with flexible substrates.

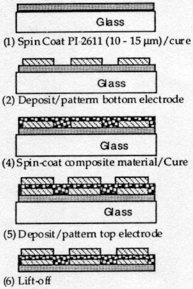

Figure 7. Fabrication of a free standing capacitor.

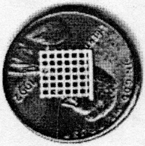

Figure 8. Free standing capacitor from PD-PI filled composite.

10. Conclusions:

Low temperature processing requirements make composite materials suitable for integrated capacitors in MCM-L based technology. Dielectric constant increases as a function of volume filled as predicted by the modified Lichteneckers rule. The dielectric constant of the composites (using Polyimide and Benzocyclobutene) made using different ceramic fillers was found to be stable over the measured frequency range (110Hz - 25MHz). High frequency results (S-parameters) indicate that thin film decoupling capacitors can be made from composite materials. Capacitor structures for integration can be made using photodefinable-polymer filled materials. Vias with 50 μm diameter have successfully been made using PD-PI based material. Based on the curve fitting using the modified Lichteneckers equation, a dielectric constant of ~5 and ~2.5 for polymer will be required to achieve a specific capacitance of 72 nF/cm^2 using a 2 μm and 1.25 μm thick dielectric layers, respectively. Comparable dielectric constant values were obtained using small as well as large particles, 0.1 - 1.24 μm range. Use of composite material in making thin film capacitors on a flexible substrate has been demonstrated.

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References:

[1] R. R. Tummala and E.J. Rymaszweski, Microelect. Packaging Handbook, ed., NY: Van Nostrand Reinhold, 1989.

[2] Y. Tsukada, S. Tsuchida, and Y. Mashimoto," Surface Laminar Circuitry Packaging," 42nd Electronic Components and Technology Conf., 1992, pp. 18 - 20.

[3] T. Miyagi, Y. Iseki, K. Higuchi, Y. Shizuki, T. Manawa, E. Takagi, M. Saito, K. Yoshihara and M. Konno, "MCM-D/L Using Copper/Photosensitive-BCB Multilayer for upper Microwave Band Systems," 46th Elect. Comp. and Tech. Conf., 1996, pp. 149 - 153.

[4] A. J. G. Standjord, P. E. Garrou, R. H. Heistand, and T. G. Tessier, "MCM-LD: Large Area Processing Using Photosensitive-BCB," IEEE Transactions on CHMT, Part B, Vol. 18, pp. 269 - 276, 1995.

[5] M. Nachani, L. Nguyen, J. Bayan and H. Takiar, " A Low Cost Multichip (MCM-L) Packaging Solution," IEEE 1993, pp. 464-468.

[6] A. Tanaka, H. Shinohara, K. Yamada, M. Honda, T. Hatada, A. Yamagiwa and Y. Shirai, " A CPU Chip-on Board Module," IEEE Transaction on Comp., Packaging and Manufacturing Technology Part-B: Advanced Packaging, Vol. 17, NO. 1 , pp. 115 - 118, Feb. 1994.

[7] Albert Pruitt, "Conversion of Memory Module from MCM-D to Laminate Base," International Conference on Multichip Modules, 1995, pp. 30 - 35.

[8] J. Y. Park and M. Allen, "A comparison of Micromachined Inductors with Different Magnetic Core Materials," 46th Electronic Components and Technology Conference, 1996, pp. 375 - 381.

[9] T. Lenihan, L. Schaper, Y. Shi, G. Morcan and J. Parkerson," Embedded Thin Film Resistors, Capacitors and Inductors in Flexible Polyimide Films," 46th Elect. Components and Tech. Conf., 1996, pp. 119 - 124.

[10] P. Chahal, R. R. Tummala, M. G. Allen and M. Swaminathan, "A Novel Integrated Decoupling Capacitor for MCM-L Technology," 46th Electronic Components and Tech. Conf., 1996, pp. 125 - 132.

[11] H. Schettler, "Passive-Silicon-Carrier Design and Characteristics," 40th Electronic Components and Tech. Conf., 1990, pp. 559 - 561.

[12] T. Takken, D. Tuckerman, "Integral Decoupling Capacitor Reduces Multichip Module Ground Bounce," IEEE Multichip Module Conference, 1993, pp. 79-84.

[13] R. Kambe, R. Imai, T. Takada, M. Arakawa, and M. Kuroda, "MCM substrate with high capacitance," IEEE Trans Compon Packag Manuf Technol Part B Adv Packag 18, pp. 23-27, Feb. 1995.

[14] S. L. Namboodri, H. Zhou, A. Aning and R. G. Kander, "Formation of Polymer/Ceramic Composite Grain Boundry Capacitors by Mechanical Alloying," Polymer V. 35, No. 19, pp. 4088 - 4091, 1994.

[15] D. K. Das-Gupta and K. Doughty, "Polymer-Ceramic Composite Materials with High Dielectric Constants,"Thin Solid Films, 158, pp. 93-105, 1988.

[16] D. Sinha and P. K. C. Pillai, "Polymer-Ceramic Composites as Potential Capacitor Material," J. Mater. Sci. Lett., Vol. 8, pp. 673 - 674, 1989.

[17] H. S. Nalwa,, Ferroelectric Poly.: Chemist., Physics, and Appl., ed. , M. Dekker Corp., chapt. 11, 1989.

[18] K. Nagata, S. Kodama, H. Kawasaki, S. Deki and M. Mizuhata, "Influence of Polarity of Polymer on Inorganic Particle Dispersion in Dielectric Particle/Polymer Composite Systems," Journal of Applied Polymer Science, Vol. 56, 1313 -1321.

[19] S. Simamoto, Y. Sakata, J. Kojima, N. Kumbe and Y. Tsujimoto, "Lacquered Polymer-Ceramic Composite Dielectric Film for Capacitors," IEEE International Symp. on Electrical Insulation, 1992, pp. 140 - 143.

[20] S. Asai, M. Funaki, H. Sawa, and K. Kato, "Fabrication of an Insulated Metal Substrate (IMS), Having an Insulating Layer with a High Dielectric Constant," IEEE Trans. Comp. Hybrids Manufact. Techn., Vol. 16, No. 5, pp. 499-504, August 1993.

[21] K. A. Klein, A. Safari, R. E. Newham and J. Runt, "Composite Piezoelectric Paints," Proceedings of the 6th Int. Symp. on Appl. of Ferro/, 1986, pp. 285 - 287.

[22] K. Lee and A. Barber, "Modeling and Analysis of Multichip Module Power Supply Plane," IEEE Transact. on Components, Packaging, and Manufact. Tech.- PartB, Vol. 18, No. 4, 1994, pp. 273 - 278.

[23] G. P. Shorthouse, L. Brickness, R. W. J. Russel, R. J. Morris, "High Density, High Speed Thick Film Interconnections Incorporating a New, Low Premittivity, High Resolution Dielectric," ISHM 90 Proceedings, pp. 216 -223.

[24] N. Hagan, J. F. Henderson, W. J. Nebe and J. J. Osborne, "High Resolution Thick Film Material System," The International Journal for Hybrid Mircroelect.," Vol. 12, No. 4, pp. 175 - 179, 1989.