# Embedded Decoupling Materials Characterization.

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## Abstract

The dielectric constant of the embedded capacitance materials was measured in the frequency range of 100 Hz to 5 GHz. The testing included evaluation of the capacitance density, leakage current, and the effect of environmental stress on the capacitance. The objectives of NIST involvement in this NCMS-led project was to develop and evaluate a test method suitable for dielectric permittivity of high-k polymer composite films that covers a broad frequency range including the microwave. A test specimen and corresponding testing procedure was designed for dielectric characterization of the embedded capacitance materials and to compare the dielectric constant of several high-k films that have recently been developed by the industry. The low frequency test vehicle consists of lumped elements for the permittivity in z and x-y directions. The high-frequency test vehicle was designed as a two-layer circuitry with a number of microstrip resonators, transmission lines and coaxial terminations. The testing procedure has been examined on films 40 μm to 100 μm thick with a dielectric constant ranging from 4 to 40. It has been determined that the upper frequency limit of the measurements decreases with increasing value of the dielectric constant from about 18 GHz for films with the dielectric constant of 4 to about 5 GHz for films with the dielectric constant of 50.

## Introduction

Polymer-based high dielectric constant films (high-k) can be used to construct embedded, discrete RLC circuits and decoupling power planes for wireless communication and high-speed electronics. The permittivity of the prospective materials should be high and determined with a high degree of confidence for operation at microwave frequencies. In order to develop and successfully commercialize such materials, the industry needs a suitable test method to measure dielectric properties and to assess the functional and reliability performance of these materials in planar, thin film configuration. Currently, there are no standard test procedures for evaluating the electrical properties of high dielectric constant films in the frequency range of practical importance viz., at low frequencies where charge storage is important, and at microwave frequencies where the discharge rates in the sub-nanosecond time frame are important. The available ASTM and IPC test procedures are only suited to a narrow frequency range, near 1 MHz (ASTM D150, D669 and D163)[1] or 8-12 GHz (ASTM 3380, IPC-TM-650, No.:2.5.5.5)[2] , and are designed for large samples. We employed several test patterns specifically designed to evaluate the dielectric properties of high-k polymer composite films that were used by the NCMS Embedded Distributed Capacitance Project. The dielectric constant of the embedded capacitance materials was measured in the frequency range of 100 Hz to 5 GHz. The testing also included evaluation of the capacitance density, leakage current, and effect of HAST[3] on the capacitance.

## Description of the test specimens

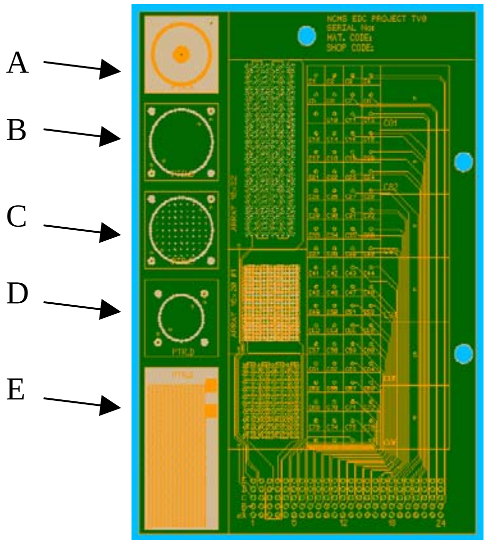

Fig. 1. Test patterns A-E for dielectric characterization of embedded capacitance films at DC and low frequencies

The layout of the TV0 test specimen is shown in Fig.1 It contains five patterns, *A-E,* which were designed to characterize the dielectric properties of films from DC to RF frequencies. Pattern *A* is a capacitive termination designed for the APC-7 coaxial air line at frequencies of up to 2.5 GHz. Patterns *B*, *C* and *D* represent a parallel plate capacitance for frequencies below 100 MHz. Pattern *E* was designed to assess electro-migration resulting from the residual charge impurity levels at the surface and in the bulk of the materials. A guard surface circuitry in patterns *B*, *C* and *D* minimizes the effect of the fringing field and can be used to measure the surface leakage current. The active area, $A_f$ of the pattern *B,* is 1.65 cm$^2$ ( 0.255 inch$^2$). The active area of pattern *D* is 0.79 cm$^2$ (0.122 inch$^2$), which is approximately half of the area of the *B* pattern. Pattern *C* has the back plane circuitry area and the active circuitry area perforated, $A_f$ =1.58 cm$^2$, which allows to evaluate the effects of moisture absorption and/or the manufacturing process on the materials nominal capacitance density $C_d = C_m/A_f$ , where $C_m$ represents the value of the measured capacitance. The test patterns *B* - *E* embedded inside the TV0 card can be electrically accessed via plated though holes. Characterization can also be performed on circuitized metal-clad cores to address the effects of manufacturing.

The high frequency test vehicle (HF-TV) shown in Fig.2 consists of microstrip lines, resonators and the corresponding co-planar terminations arranged in the three sections *A*, *B* and *C* having the line width of 400 μm, 200 μm and 125 μm respectively. The microstrip dimensions and coupling conditions were optimized to avoid overlapping of higher order modes and to achieve a low loading level at the resonance[4, 5]. In addition to the microstrip resonators and lines for the trough-reflection-line (TRL) measurements, there are five time-domain-reflectometry (TDR) sections for measuring permittivity based on a TDR response to a fast, 12.5 ps step voltage rather than on detecting the discrete, resonant frequencies. We have developed this technique specifically for thin films[6]. The TDR sections *A, B* and *C* contain coplanar capacitors and short terminations. The TDR section *D* is designed for the 7 mm APC standard while the dimensions of the TDR section D corresponds to the 3.5 mm APC standard, which is more suitable for films with the highest capacitance density.

Most of the difficulties in measuring the dielectric constant o high-k thin films at higher frequencies arise from the small thickness of the specimen. For such films, the desirable electrical parameters can be realized only with tiny patterns and highly conducting metal traces that are difficult to fabricate and evaluate. Since the width of typical traces in plastic packages is usually 200 μm or larger, the characteristic impedance of the thin film devices is rather low, causing the usual calibration standards (coaxial shorts, opens and

loads) to become unreliable. To improve the dynamic range of the measurements, we added to the test specimen non-coaxial terminations for insitu calibration verification.
In comparison to the currently available test methods, which are applicable to dielectric sheets thicker than 1.2 mm with the dielectric constant lower than 12, the new microstrip test pattern is appropriate for films as thin as 40 microns having a dielectric constant of 50 at frequencies of up to 5 GHz. For thinner films, such as the 3M C-Ply, we are investigating the applicability of the TDR method and the corresponding test patterns to

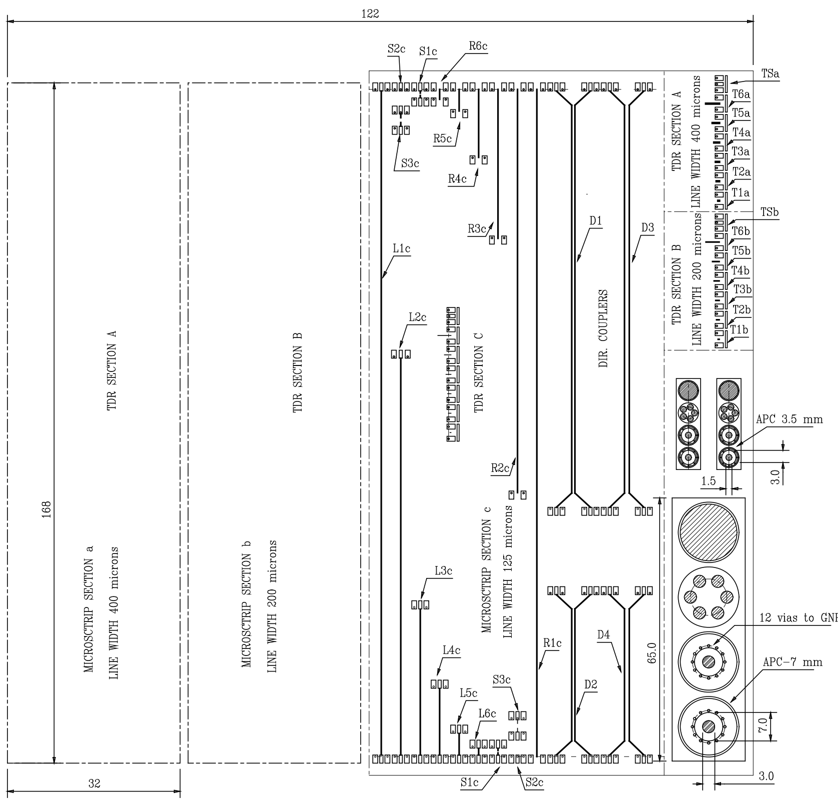


Fig.2 Schematic of the high frequency test vehicle

extend the frequency range of the data obtained from the microstrip resonators[7]. Unlike other techniques, TDR can provide information about the high frequency dielectric behavior from the total reflection in the presence of a large charging response associated with a large capacitance.

## Experimental

The low frequency measurements were carried out in accordance with the ASTM D-150 standard test method (ref. 1) using a HP 4274A / HP 4192 A Impedance Analyzer. The measurements were performed on TV0 patterns *B* and *C* and *D*. The relative uncertainty was expressed as a sum of uncertainties due to measurements of complex capacitance, geometrical capacitance (active area and film thickness), and fringing field. The effect of the fringing field was ignored since the electrical configuration included a guarding electrode. The relative instrumental uncertainty was within 1 %. The relative uncertainty of the geometrical capacitance was estimated to be about 4%. The reported low frequency

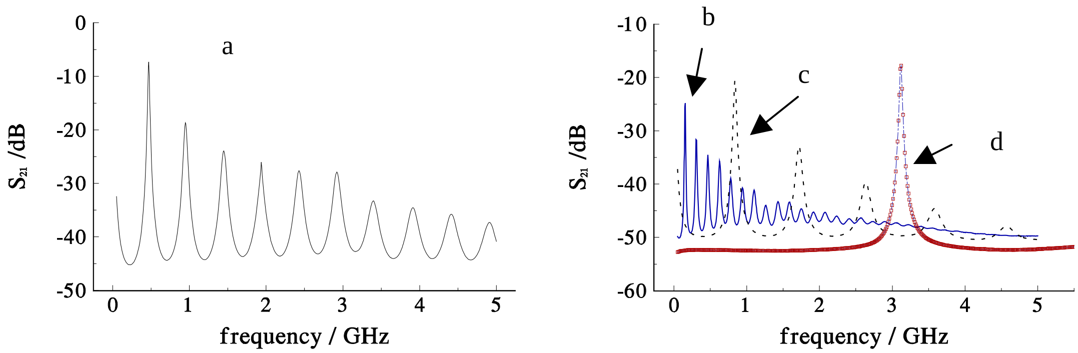


Fig.3. Measurement example using the microstrip test specimen. a) HADCO BC2000, the resonator length l=164 mm, $\varepsilon^1$ = 3.93 at 461 MHz, b) HADCO EmCap, l=164 mm, $\varepsilon^1$ = 36.3 at 151 MHz, c) HADCO EmCap, l=29.5 mm, $\varepsilon^1$ = 36.4 at 842 MHz, d) HADCO EmCap l=8 mm, $\varepsilon^1$ = 35.9 at 3.122 GHz

permittivities are accurate within 5%. Measurements in the high frequency range were performed using the high frequency test vehicle (HF TV, Fig. 2) on several microstrip test specimens fabricated to fine dimensions using photolithography. The resonant frequencies were detected by measuring the $S_{2,1}$ parameters using a HP 8720D Network Analyzer and Cascade ACP-40-W GSG probes. Example results are shown in Fig.3. The temperature-dependent measurements were carried out in the EC-12 Environmental Chamber from Sun Microsystems.

The relative dielectric constant, $\varepsilon_r$, was calculated from the following formula[4] :

$$\varepsilon_r = \frac{c^2}{f_{m,n}^2}\left\{\left(\frac{m}{2l}\right)^2 + \left(\frac{n}{2w}\right)^2\right\}$$

where $l$ and $w$ are the electrical length and width of the resonator, $m$ and $n$ are the mode integers. The dielectric loss was estimated from the width of the resonance peak, measured 3 dB below its maximum value.

The largest contribution to the uncertainty in this method comes from the coupling length, which affects the total length of the resonator. The relative uncertainty in the high frequency dielectric constant increases from about 2 % at 1 GHz to about 8 % at 5 GHz.

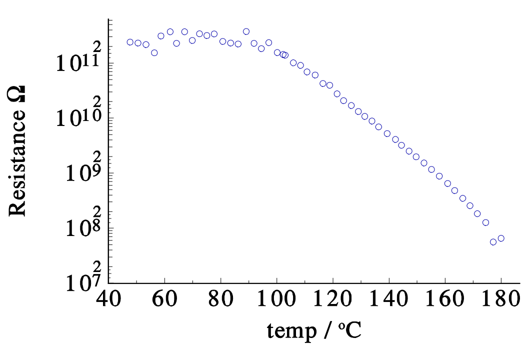


Fig.4. Insulation resistance of FR4 laminate under bias of 100V as a function of temperature

**Results and discussion**

The following thin film capacitance materials were evaluated: HADCO BC2000, HADCO EmCap, DuPont HiK Kapton, and 3M C-Ply. For comparison, data was also obtained for the FR4 fiberglass epoxy laminate in analogous conditions.

**FR4**

Figure 4 shows the DC insulation resistance of the FR4 laminate under 100 V bias as a function of temperature. The insulation resistance decreases from about $10^{11}$ Ω at 85 °C to 5 $10^7$ Ω at 180 °C, indicating an excellent electrical insulation

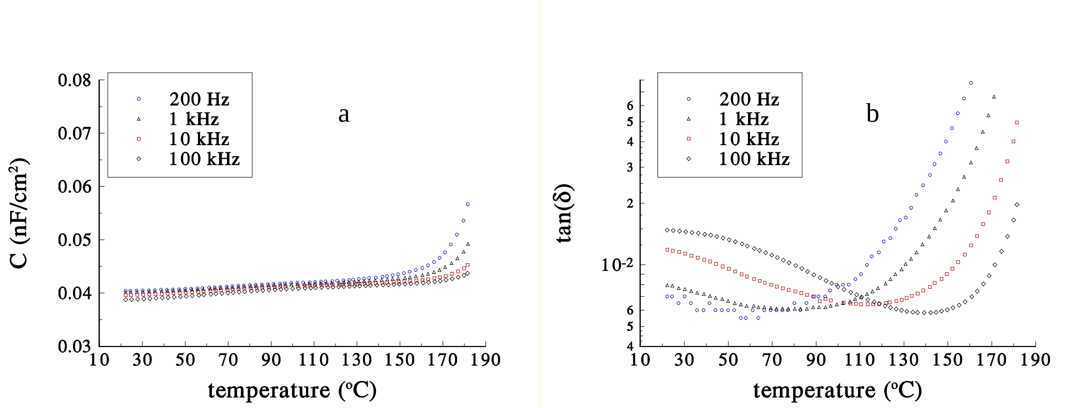


Fig.5. Capacitance density (a) and the dielectric loss tangent (b) of FR4 as a function of temperature and frequency.(TV0 / Merix, pattern B)

characteristic.

The capacitance density and the dielectric loss tangent of the FR4 material as a function of frequency and temperature are shown in Fig. 5. In the glassy state, below 125 °C, FR4 shows relatively insignificant dependence of capacitance on frequency, which reflects the behavior of the dielectric constant of he material (dielectric dispersion). Following the dielectric dispersion, the capacitance density slightly decreases with increasing frequency. In the temperature range of 20 °C to about 130 °C, the capacitance density is approximately 0.04 nF/cm$^2$. Above 130 °C, the FR4 resin starts to undergo a glass-rubber transition. The capacitance increases considerably due to liberation of segmental relaxation of the resin backbone. It should be noted however, that the low frequency loss tangent measurements can detect the beginning of the glass-rubber relaxation process typically 10 to 15 centigrades below the Tg temperature determined by the DSC or TMMA techniques. This molecular behavior is responsible for an increase in the dielectric loss tangent at temperatures approaching the glass-rubber transition. The 200 Hz plot in Fig 5b is basically a low temperature shoulder of the α-relaxation peak, which shifts to higher temperatures as the frequency increases. Thus, the dielectric loss at elevated temperatures appears to decrease as the frequency increases.

Tab.1 High frequency dielectric constant of FR4

| Frequency (GHz) | Dielectric Constant | Loss tangent |
|---|---|---|
| 0.450 | 4.13 | 0.023 |
| 0.924 | 3.92 | 0.021 |
| 1.398 | 3.85 | 0.02 |
| 1.874 | 3.81 | 0.018 |
| 2.348 | 3.79 | 0.017 |
| 2.822 | 3.78 | 0.017 |
| 3.290 | 3.78 | 0.016 |
| 3.771 | 3.78 | 0.015 |
| 4.226 | 3.79 | 0.015 |

HF TV, microstrip test pattern A, l=164 mm, w = 200 μm

In addition to the segmental α relaxation, FR4 also exhibits a local β-relaxation which strongly affects the dielectric performance of the material in the RF frequency range and in the microwave. A high temperature shoulder of the β-relaxation peak is seen on the

100 kHz plot as a decrease in the dielectric loss in the temperature range of 20 °C to about 140 °C. This peak shifts to lower temperatures with decreasing frequency.

Therefore, the room temperature dielectric loss in Fig. 5b appears to increase with

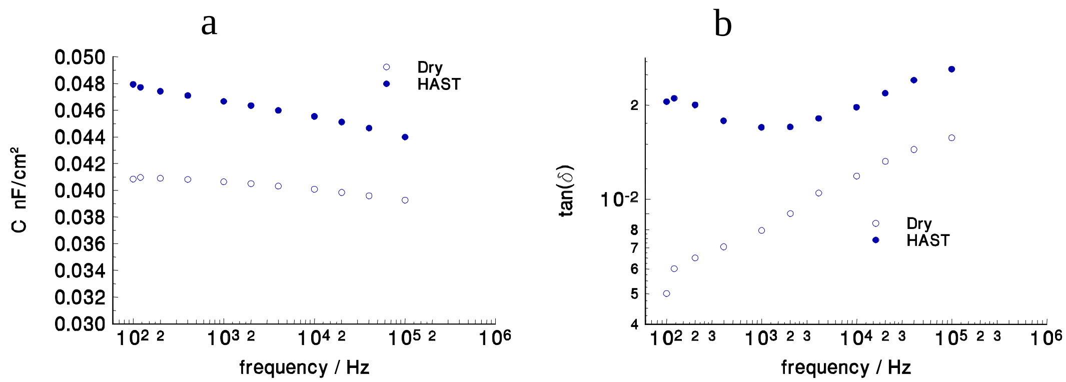


Fig.6. Capacitance density (a) and the dielectric loss tangent (b) of FR4 saturated with moisture d during HAST. (TV0 / Merix, pattern C)

increasing frequency. For typical FR4 resin, the room temperature dielectric loss tangent reaches a maximum of about 0.025 at 10 MHz. The loss due to β relaxation should decrease at higher frequencies (room temperature) though molecular defects, free radicals and other paramagnetic impurities may contribute to the dielectric loss mechanism, extending it into the microwave. The dielectric constant data in the high frequency range obtained for FR4 using the microstrip test pattern is given in Table 1.

Moisture absorbed during a highly accelerated stress test (HAST, 200 hours, 130 °C, 85% RH) increased the dielectric loss and the dielectric constant (capacitance density). The largest effect is seen at the lowest frequencies (Fig 6.) due to interfacial polarization. At 200 Hz, the change in capacitance after HAST is about 6 pF/cm$^2$. In comparison, the dielectric loss tangent increases considerably higher, from 7 $10^{-3}$ to about 2 $10^{-2}$. This indicates that the absorbed water may facilitate electromigration and compromise the reliability of the dielectric under DC bias or when carrying a digital ON/OFF signal.

**<u>BC2000</u>**

The DC insulation resistance of the BC2000 shows a thermally activated behavior similar to that shown in Fig. 4 for FR4.

The insulation resistance decreases from about $10^{11}$ Ω at 85 °C to $10^{7}$ Ω at 180 °C. A change in the activation energy of the conducting process takes place at about 125 °C due to glass-rubber transition of the resin. The capacitance density is about 0.08nF/cm$^2$ (0.5 nF/inch$^2$), approximately twice the measured value of FR4, which results from a decreased thickness of the dielectric. The capacitance density and the dielectric loss tangent plots shown in Fig.7 for BC2000 as a function of frequency and temperature are analogous to that of FR4 (Fig. 5).
The dependence of capacitance density (dielectric constant) on temperature is somewhat stronger than that of FR4, probably due to lower glass transition temperature. Consequently, both the segmental and local relaxations are more temperature dependent, which contributes to an increase in loss at RF and in the microwave range. The dielectric constant data in the high frequency range obtained for BC2000 using the microstrip test pattern is given in Table 2.

Tab.2 High frequency dielectric constant of BC2000 thin film capacitance material

| Frequency | Dielectric Constant | Loss tangent |
|---|---|---|
| 200 Hz* | 4.24 | 0.0055 |
| 1 kHz* | 4.21 | 0.0088 |
| 10 kHz* | 4.11 | 0.016 |
| 100 kHz* | 4.1 | 0.021 |
| 1 MHz * | 4.0 | 0.023 |
| 0.461 GHz** | 3.93 | 0.024 |
| 0.928 GHz** | 3.88 | 0.021 |
| 1.399 GHz** | 3.84 | 0.021 |
| 1.872 GHz** | 3.82 | 0.020 |
| 2.347 GHz** | 3.8 | 0.019 |
| 2.820 GHz** | 3.78 | 0.020 |
| 3.291 GHz ** | 3.78 | 0.016 |
| 3.774 GHz** | 3.75 | 0.016 |
| 4.225 GHz** | 3.79 | 0.015 |

* LCR Impedance Analyzer, TV0 pattern B.
**HF TV, microstrip test pattern A

Saturation with moisture during the 200 hours of HAST at 130 °C, 85% RH, increases capacitance density by about 3 pF/cm$^2$ from 0.081nF/cm$^2$ to 0.084 nF/cm$^2$. Moisture also contributes to an increase in the dielectric loss. The largest effects were similar to those shown in Fig. 6 for FR4 at lowest frequencies.

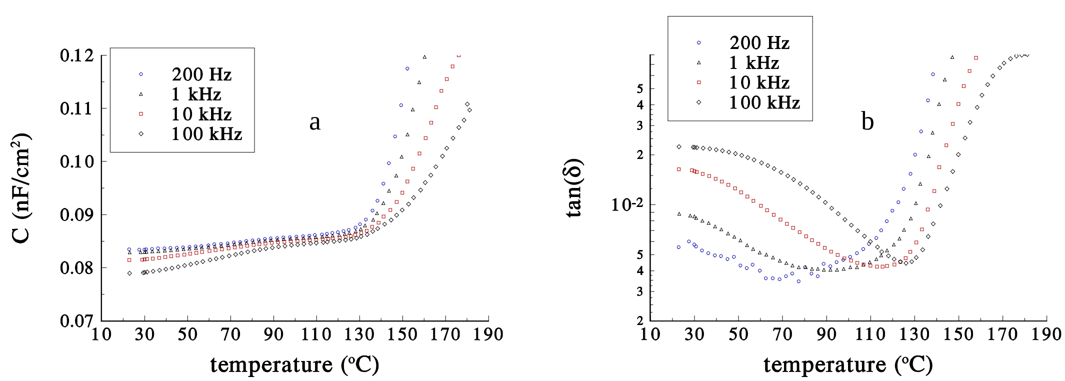


Fig.7. Capacitance density (a) and the dielectric loss tangent (b) of BC2000 as a function of temperature and frequency.(TV0 / HADCO, pattern B)

**EmCap**

The DC insulation resistance of the EmCap high-k film shows a thermally activated behavior similar to that seen in Fig. 4 for FR4. The insulation resistance decreases from about $10^{11}$ Ω at 85 °C to $10^{7}$ Ω at 180 °C. A change in the activation energy of the conducting process was detected at about 125 °C, which originated from the glass-rubber transition of the resin matrix.

The capacitance density measured at ambient temperature was about 0.33nF/cm$^2$ (2.1 nF/inch$^2$), which for films 100 μm thick corresponds to a dielectric constant of about 40. This is one of the highest dielectric constant values measured for an epoxy resin composite loaded with ferroelectric powder. Since the practically achievable loading level is about 50-volume % of the ceramic phase, the $BaTiO_3$ powder-epoxy composites may exhibit a dielectric constant of up to about 50. The capacitance density and the dielectric loss tangent plots at several frequencies are shown in Fig.8 as a function of temperature. A thermally activated increase in capacitance is seen above 130 °C (Fig. 8a). The character of the dielectric loss data is reminiscent of the epoxy resin matrix such as in FR4 laminates. It indicates that the dielectric loss is controlled by the dielectric behavior of the resin rather than the high dielectric constant ceramic ingredient. Thus, an increase in the dielectric loss with increasing frequency seen at room temperature originates from the local relaxation processes in the polymer backbone.

Tab.3 Dielectric constant and loss tangent of EmCap thin film capacitance material

| Frequency | Dielectric Constant | Loss tangent |
|---|---|---|
| 200 Hz* | 39.2 | 0.00774 |
| 1 kHz* | 38.8 | 0.0101 |
| 10 kHz* | 38.2 | 0.0151 |
| 100 kHz* | 37.9 | 0.0198 |
| 1 MHz* | 37.2 | 0.0212 |
| 99.98 MHz** | 36.6 | 0.0182 |
| 151.87 MHz** | 36.3 | 0.0168 |
| 414.32 MHz** | 36.3 | 0.0151 |
| 842.00 MHz** | 36.4 | 0.0132 |
| 1.729 GHz** | 36.0 | 0.0123 |
| 3.122 GHz** | 35.9 | 0.0114 |
| 7.921 GHz** | 36.0 | 0.0103 |

* LCR Impedance Analyzer, TV0 pattern B.
**HF TV, microstrip test pattern A

Table 3 lists the room temperature dielectric constant obtained for EmCap using the low frequency pattern B (200 Hz to 1 MHz) and the microstrip test pattern (100 MHz to 8 GHz).

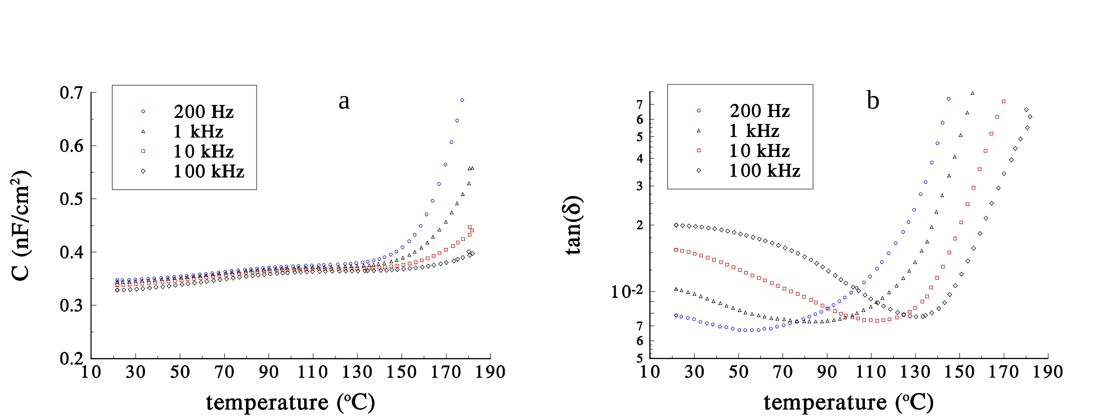


Fig.8. Capacitance density (a) and the dielectric loss tangent (b) of EmCap as a function of temperature and frequency.(TV0 / MERIX, pattern B)

Saturation with moisture during the 200 hours of HAST at 130 °C, 85% RH, increases the capacitance density noticeably. At 200 Hz, 25 °C the difference in capacitance density between the dry and moisture-saturated samples was measured to be about 70 pF/cm$^2$. Moisture absorption also contributes to an increase in the dielectric loss. The effect is somewhat larger than that shown in Fig. 6 for FR4.

**HiK Kapton**

The insulation resistance of the HiK Kapton decreases with increasing temperature exponentially from about 3 $10^9$ Ω at 85 °C to 5 $10^6$ Ω at 180 °C. In contrast to the epoxy based composites, which undergo glass-rubber transition at about 130 °C, the thermally activated DC conductivity of the HiK takes place in the glassy state following a single activation energy.

The capacitance density is about 0.25nF/cm$^2$, which corresponds to a dielectric constant of 12 for films of 41 μm thickness.

Figure 9 shows the effect of temperature on the capacitance density and the dielectric loss tangent at several frequencies from 200 Hz to 100 kHz. At ambient conditions the

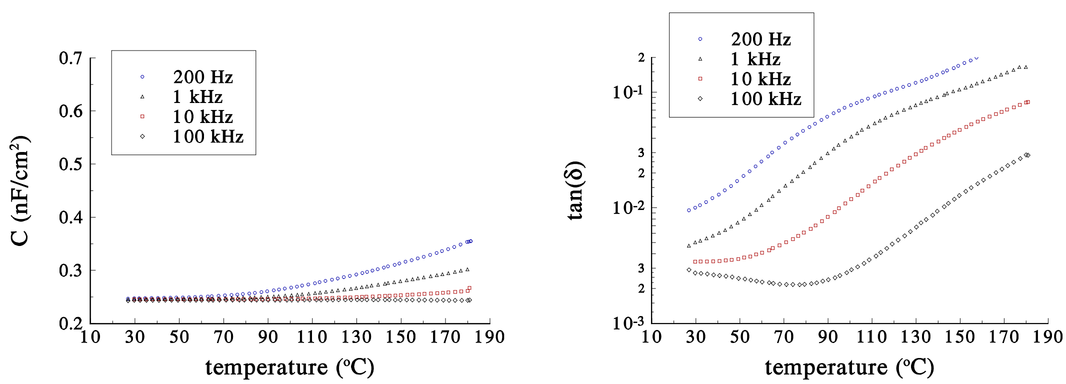


Fig.9. Capacitance density (a) and the dielectric loss tangent (b) of Hi K Kapton as a function of temperature and frequency.(TV0 /Raytheon-TI, pattern B)

capacitance density is about 0.25 nF/cm$^2$ (1.5 nF/inch$^2$) without noticeable dispersion i.e. frequency dependence. The capacitance density increases with temperature only at frequencies below 10 kHz. This behavior originates probably from the interfacial arrangement and polarization between separate phases in the composite rather than from polarization of the Polyimide backbone itself. It is seen that at higher frequencies, above 10 kHz, the capacitance density appears to be independent of temperature. This is in contrast to the epoxy-based composites, which typically show thermally activated increase in capacitance when the rubbery transition of the resin is approached. It is worthy to note that in contrast to the epoxy-based composites the dielectric loss tangent of HiK decreases with increasing frequency.

At room temperature, Fig. 9b, the dielectric loss tangent decreases from about 0.01 at 200 Hz to about 0.002 at 1 MHz (Tab. 4). In comparison, the epoxy-based composite films show an increasing loss in the analogous frequency and temperature conditions. The dielectric data of HiK kapton at higher frequencies is listed in Table 4, where the dielectric constant decreases from 12.5 at 200 Hz to about 11.6 at 6 GHz. An apparent increase in the dielectric loss tangent at frequencies of 265 MHz and above may be caused by electrical limitations of the microstrip test specimen (limited Q factor) at higher frequencies.

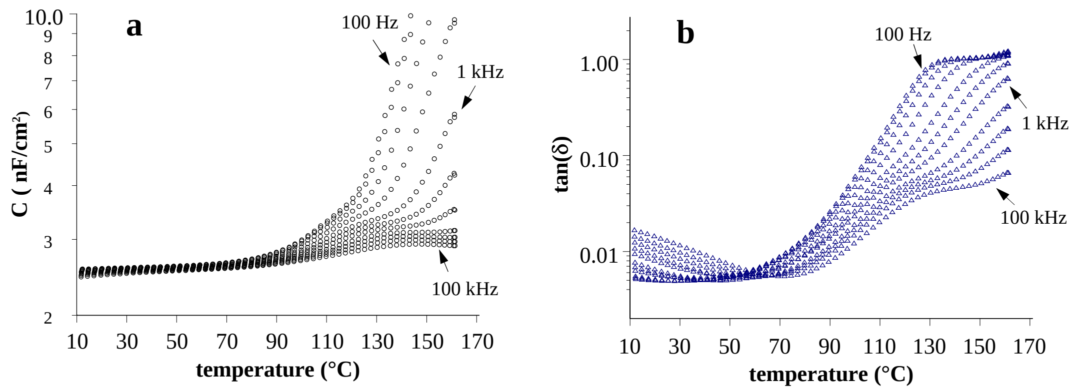


Fig.10. Capacitance density (a) and the dielectric loss tangent (b) of C-Ply as a function of temperature and frequency.(TV0 /3M, pattern B)

Saturation with moisture during the 200 hours of HAST at 130 °C, 85% RH increases capacitance density and loss of the HiK considerably. The effect is especially large at the lowest frequencies and likely due to interfacial polarization and accumulation of charge carriers between the Polyimide resin and the ceramic phases. At 200 Hz, 25 °C, the difference in capacitance density between the dry and moisture-saturated samples was about 120 pF/cm$^2$.

Tab.4 Dielectric constant and loss tangent of HiK Kapton thin film capacitance

| Frequency | Dielectric Constant | Loss tangent |
|---|---|---|
| 200 Hz* | 12.5 | 0.01 |
| 1 kHz* | 12.3 | 0.0048 |
| 10 kHz* | 12.2 | 0.0032 |
| 100 kHz* | 12.1 | 0.0031 |
| 1 MHz* | 11.9 | 0.0029 |
| 265 MHz** | 11.9 | 0.0082 |
| 757 MHz** | 12.1 | 0.011 |
| 1.0931 GHz** | 11.8 | 0.0098 |
| 3.0278 GHz** | 11.7 | 0.0122 |
| 3.6511GHz** | 11.7 | 0.011 |
| 5.9642GHz** | 11.6 | 0.011 |

* LCR Impedance Analyzer, TV0 pattern B.
**HF TV, microstrip test pattern D

**C-Ply**

The capacitance density of the 3M C-Ply, 8 μm thick films was measured to be about 2.5 nF/cm$^2$ (16 nF/inch$^2$) at ambient conditions. The material shows a disperssive behavior, similar to that of epoxy-based composites. The capacitance density and the dielectric loss tangent plots are shown in Fig.10 as a function of temperature at several frequencies. A thermally activated increase in capacitance is seen above 90 °C (Fig 10b).

The character of the dielectric data shown in Fig. 10 is reminiscent of a resin blend with the lowest glass-rubber transition temperature below 130 °C. Therefore, the dependence of capacitance density (dielectric constant) on temperature is stronger than of FR4 and as a result, both the segmental and local relaxations are more temperature dependent. This contributes to an increase in the dielectric loss. The dielectric constant at high frequencies, above 1 MHz, was measured using the TDR technique (Tab. 5) since the resonance measurements did not produced satisfactory results. Due to small thickness and large capacitance, the microstrip lines exhibited very low impedance, below 2 Ω, causing a large return loss ($S_{11}$) at the input reference plane. Therefore, the resonance peaks appeared rather small and difficult for analysis, especially at frequencies above 1 GHz. In contrast, the TDR method was more suitable for determination of the dielectric constant in spite of a large capacitance density. The results obtained at the ambient temperature are listed in Table 5. It is seen that C-Ply exhibits relatively low dispersion. The dielectric constant decreases from 23 at 200 Hz to about 21 at 2 GHz. The dielectric loss tangent increases from 0.005 to about 0.14 in the same frequency range. At 1 GHz, C-Ply exhibited the largest loss among the investigated materials.

**Summary**

Dielectric characterization of embedded capacitance materials has been performed at frequencies ranging from 200 Hz to 5 GHz. The measurements of the dielectric constant were performed in functional, thin film configuration using test specimens specifically designed for the embedded capacitance films. The test specimens were fabricated using standard copper circuitize and card lamination processes.

The largest dielectric constant was measured for the HADCO EmCap films. At 1 GHz this material showed a dielectric constant of 36. The capacitance density of a 100 μm thick EmCap was about 0.33 nF/cm$^2$ (2.1 nF/inch$^2$). The 3M C-Ply showed at 1 GHz a dielectric constant of 20. In comparison, the capacitance density of the 8 μm thick 3M C-Ply was about 2.5 nF/cm$^2$ (16 nF/inch$^2$) nearly 8 times larger than that of EmCap due to much smaller film thickness. At frequency of 1 GHz, the dielectric constant of the DuPont HiK Kapton films was about 11.8, while the capacitance density of 48 μm thick films was about 0.25 nF/cm$^2$ (1.5 nF/inch$^2$). The HADCO BC200 50 μm thick films exhibited the lowest dielectric constant and the lowest capacitance density among the evaluated materials, about 3.9 and 0.08 nF/cm$^2$ (0.5 nF/inch$^2$) respectively.

Tab.5. High frequency dielectric constant of C-Ply thin film capacitance.

| Frequency (GHz) | Dielectric Constant | tan(δ) |
|---|---|---|
| 200 Hz* | 23.2 | 0.00572 |
| 1 kHz* | 23.1 | 0.008510 |
| 100 kHz*z | 22.5 | 0.0135 |
| 1 MHz* | 22.4 | 0.0250 |
| 10 MH**z | 22.0 | 0.0387 |
| 100 MHz** | 21.5 | 0.0436 |
| 1.0 GHz** | 21.1 | 0.0810 |
| 1.5 GHz** | 20.8 | 0.133 |
| 2.0 GHz** | 20.5 | 0.141 |

* LCR Impedance Analyzer, TV0 pattern B.
** HF TV, TDR pattern D

In comparison to the FR4 laminate, the capacitance density of the tested materials increased in the following order:

FR4(1) > BC2000 (2) > HiK (6) > EmCap (8) > C-Ply (63), where the capacitance density of the C-Ply was 63 times larger than that of FR4.

During heating, the EmCap, 3M C-Ply and BC200 films showed a thermally activated increase in capacitance and dielectric loss, similar to that of FR4 epoxy resin approaching the glass-rubber transition temperature. In contrast, permittivity of the HiK Kapton films was much less temperature dependent, especially at higher frequencies.

The dielectric properties of all the tested thin film capacitance composites were found to be sensitive to moisture. Water accumulated during HAST (200 hours at 130 C, 75 % RH) typically contributed to an increase in the capacitance density and the dielectric loss tangent. The largest effect was observed at lowest frequencies due to moisture-activated conductivity and interfacial polarization.

The high frequency microstrip test pattern with 400 μm wide traces was suitable for testing high-k films thicker than 40 μm at frequencies of up to 5 GHz. Resonant frequency measurements on high dielectric constant films thinner than 10 μm were inconclusive. We continue investigating applicability of higher impedance traces (250 μm and 125 μm wide) for films thinner than 10 μm.

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**Disclaimer**
Certain materials and equipment identified in this manuscript are solely for specifying the experimental procedures and do not imply endorsement by NIST or that they are necessary the best for these purposes.

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