Recent Developments in Polyimide-Based Planar Capacitor Laminates

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ABSTRACT

The foundations of the electronic world are constantly evolving. To evolve with them circuit designs need to accomplish more, in ever decreasing spaces, at much higher speeds. An emerging technology assisting designers with this evolution is the move toward embedding passive functionality into the substrate of the printed wiring board. This paper discusses performance and reliability data of both unfilled and ceramic-filled polyimide-based thin core laminates for use as embedded planar capacitor layers. A short overview of a simulation tool's prediction of the impact of increasing the dielectric constant between power and ground will also be discussed.

I. Introduction

Publications describing the use of thin core laminates as embedded planar capacitors or low impedance power distribution planes in printed wiring boards began emerging in the mid 1980's. Since then, laminate core thickness has continued a downward trend. In addition to conventional FR-4, thin core polyimide and unreinforced epoxy laminates have come on the market. Now, thin core laminates filled with high dielectric constant powders are being used. The advantages of using laminates with thin dielectrics have been researched and presented in various venues. Fabrication experience has shown that thin laminates can be processed when attention is paid to panel handling through conveyorized equipment. Board design and production experience have demonstrated performance results of reduced EMI, reduced power bus noise and fewer surface mount capacitors.

It is difficult to make a very thin glass reinforced dielectric. Laminate dielectrics 25 microns and thinner are therefore generally non-reinforced, being either pure polymer or polymer containing a filler to raise the dielectric constant and increase the capacitance density. Both filled and unfilled thin core polyimide-based laminates have undergone a variety of electrical and environmental tests that demonstrate robustness for use as power and ground planes in rigid printed wiring boards.

II. Polyimide-based Laminate Construction

Unfilled Polyimide Laminates

Unfilled polyimide laminates come in dielectric thicknesses of 50, 25, and 18 microns and are supplied with ED or RA copper foils in a variety of copper thicknesses. They can even be made in asymmetrical constructions. These laminates are based on the same all polyimide platform that has been sold to the flex industry in high reliability applications (satellites, military, under hood automotive, disk drives etc) for a number of years and millions of square feet have been made. Because they are unfilled, they provide excellent over voltage protection and, unlike older flex laminate materials, moisture absorption is lower.

Filled Polyimide Laminates

Filled polyimide laminates are available in thicknesses of 25 and 14 micron. We will focus on the 14-micron thickness laminate since it has the highest capacitance density. The polyimide is filled with a ceramic filler that increases the dielectric constant. For comparison, the unfilled polyimide-based dielectric has a dielectric constant of 3.5 while the filled laminate has a dielectric constant of 11.

III. Electrical Characteristics of Thin Polyimide-Based Laminates

Both unfilled and filled laminates can be drilled and plated by processing through the normal electroless copper plating line ensuring solid electrical connections. Either plasma etching or the more common permanganate desmear chemistry may be used. Figure 1 shows cross-sections of two different boards containing two layers of 14 micron filled polyimide laminate. Each board was processed at a different manufacturing site through permanganate desmear chemistry in the electroless line. The cross-section photos show the condition of the through-hole plating.

Because these laminates are thin, they exhibit low power plane self impedance[1]. The effect of reducing the dielectric thickness is shown in Figure 2. In both graphs frequency in Hertz is shown on the x-axis and impedance in Ohms is shown on the y-axis. The graph on the left shows the behavior over the frequency range tested. As the dielectric thickness is reduced, the self impedance is reduced. The graph on the right shows an expanded view of the frequency range beyond the resonant frequency. At these frequencies the impedance to current flow is inductive rather than capacitive and exhibits

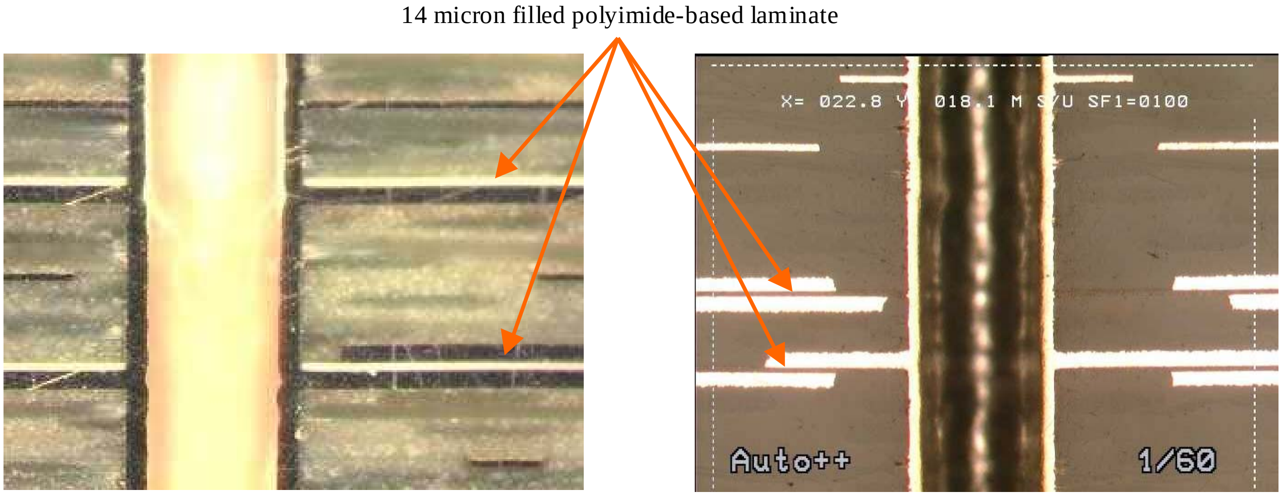


Figure 1 - Cross-sections of Through-hole Drilling and Plating of 14 micron Filled Polyimide-based Laminate

impedance spikes. As the dielectric becomes thinner the overall impedance is reduced and the magnitudes of the impedance spikes are reduced.

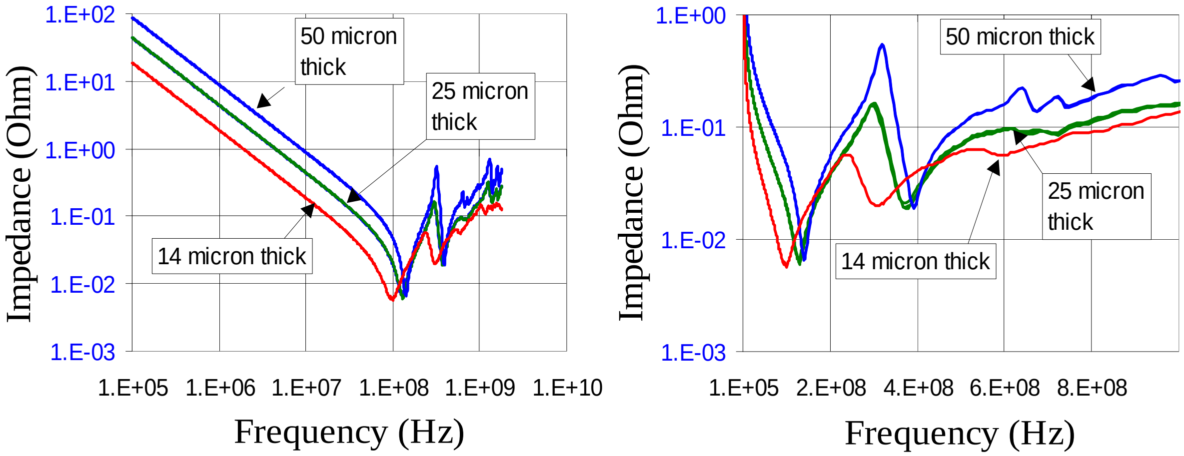
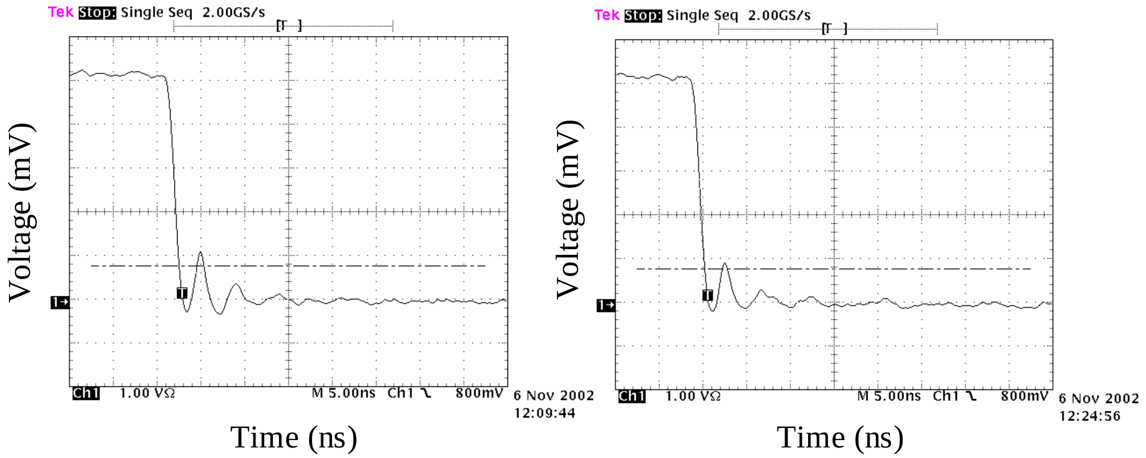


Figure 2 - Power Plane Self Impedance Characterization of Polyimide-Based Thin Core Laminates

Using thin core polyimide-based laminate as a planar capacitor in the multilayer board permits removal of surface mount capacitors. To illustrate this an existing high-speed video board design was built normally. This board was compared to a board redesigned with 2, 25 micron unfilled polyimide cores as layers 2/3 and (n-2)/(n-1). Although this board was redesigned in terms of the power and ground pairs, all the surface mount capacitor vias and pads were left in the design. The signal integrity of each of the boards was analyzed. Figure 3 shows one of the signal trace comparisons. Figure 3(a) shows the trace for the normal board. Figure 3(b) shows the trace for the redesigned board after removing over 400 SMT capacitors. The signal was still improved even though the vias and pads for the removed capacitors were present.

Capacitance also remains stable with respect to frequency[2]. Figure 4 shows capacitance measurements from 0.1 MHz to 100 MHz on a variety of planar capacitor laminates. Based on thickness and dielectric constant, these laminates had different absolute capacitance values. However, to compare them the results were normalized to show the percent change in capacitance of each of the materials. The polyimide-based laminates changed about 1% over the frequency range while the epoxy-based laminates changed about 10%. The sharp fall-off at the highest frequencies was a result of the measurement set-up and does not indicate an abnormality in the material behavior. Rather, the established trends would be expected to continue at even higher frequencies.



(a) (b)

Figure 3 - Comparison of Signals Between (a) Normal Board and (b) Board Containing 25 micron Polyimide Core with 400 SMT Capacitors Removed

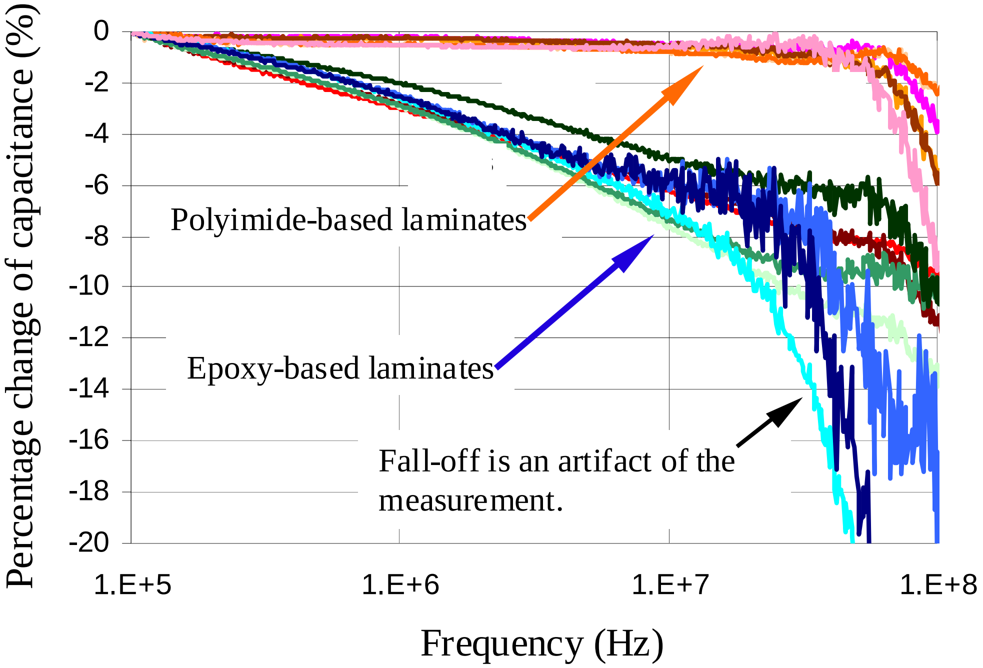
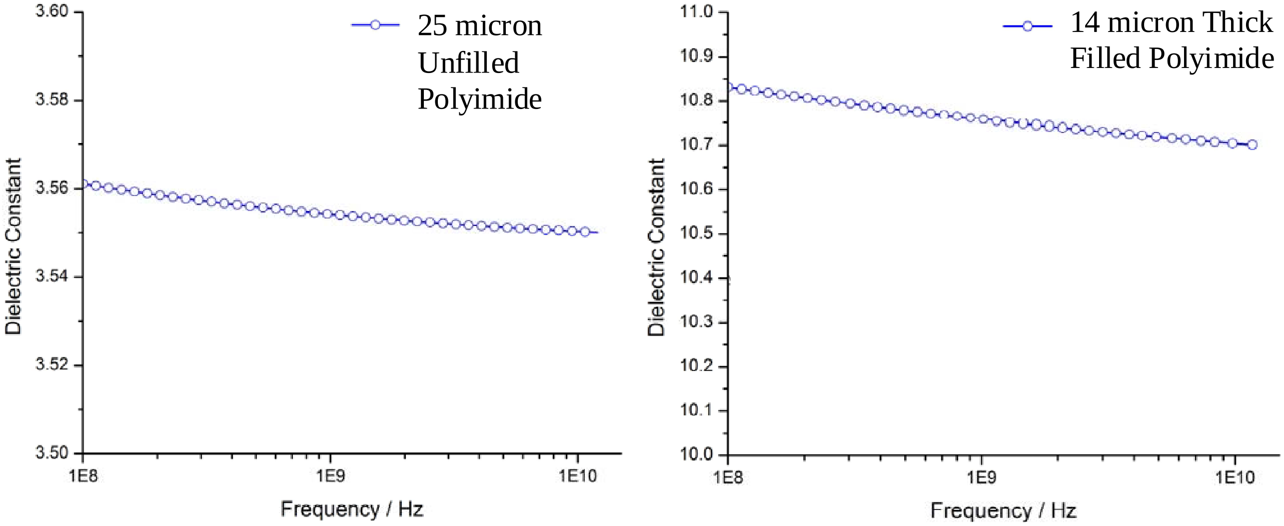


Figure 4 - Effect of Frequency on Capacitance of Filled and Unfilled Polyimide Laminates

The dielectric constant measured at even higher frequencies also shows the stability of polyimide laminates. Dr. Jan Obrzut of NIST has developed a test method for measuring dielectric constant and loss tangent at high frequency on very thin dielectric laminates. This procedure is an outcome of the IPC D37-D task group, “Embedded Passive Devices Test Methods Task Group,” which Jan chairs. Figure 5 shows the dielectric constants of filled and unfilled polyimide laminates spanning the range from 100 MHz to 10 GHz.

Intuitively, it would seem that having a higher dielectric constant and correspondingly higher capacitance density would be of value in an embedded planar capacitor layer. Unfortunately, mathematical analysis shows that the quantity of charge that can be accessed in time “t” from an embedded planar capacitor layer is independent of dielectric constant[3]. From this it would seem that there is no need for increasing Dk but are there other benefits that might accrue? In an effort to evaluate the impact of increased dielectric constant on input impedance Lucent Technologies, Inc. and Sigrity, Inc. conducted a simulation to compare low and high dielectric constant materials[4]. The basis of the simulation was a known board design where layers 2 and 3 were ground and power (3.3V) respectively separated by 25 microns of dielectric. Sigrity software was used to model



(a) (b)

Figure 5 - High Frequency Measurement of Polyimide Laminate Dielectric Constant

the input impedance for two cases. Case I was analyzed assuming a dielectric constant of 4.2 and Case II was analyzed assuming a dielectric constant of 10. The input impedance was modeled at a specific IC location on the board.

The plane size was about 320 x 190 mm resulting in parallel plane capacitance of 90 nF for Material I (Dk = 4.2) and 215 nF for Material II (Dk = 10). The board had the distribution of capacitors connected to the power plane shown in Figure 6. The analysis showed that leaving some capacitors on the high Dk board would be beneficial. Figure 7 shows the capacitors that were left on the board.

Decap Model	1 u	0.1 u	0.01 u	2700 p	1000 p	100 p	Total
Decap Number	1	279	20	4	107	6	417
Total Value of Capacitance	1 u	27.9 u	0.2 u	10.8 n	107 n	600 p	29.22 u

Figure 6 - Distribution of Decoupling Capacitors on Board Design Used for Simulation

	Decap Model	1 u	0.1 u	0.01 u	2700 p	1000 p	100 p	Total
Original placement	Decap Number	1	279	20	4	107	6	417
	Total Value of Capacitance	1 u	27.9 u	0.2 u	10.8 n	107 n	600 p	29.22 u
Some decaps removed	Decap Number	1	188	20	0	0	0	209
	Total Value of Capacitance	1 u	18.8 u	0.2 u	0	0	0	20.00 u

Figure 7 - List of Capacitors Left on Board for Simulation

The resulting input impedance comparison between Material I with all of the original capacitors in place and Material II with some capacitors removed is shown in Figure 8. The red line shows the input impedance of the board with Material I and all SMT capacitors in place out to 2 GHz. The Blue line shows the input impedance for Material II with all the capacitors in place. The green line shows the input impedance with only the partial complement of capacitors.

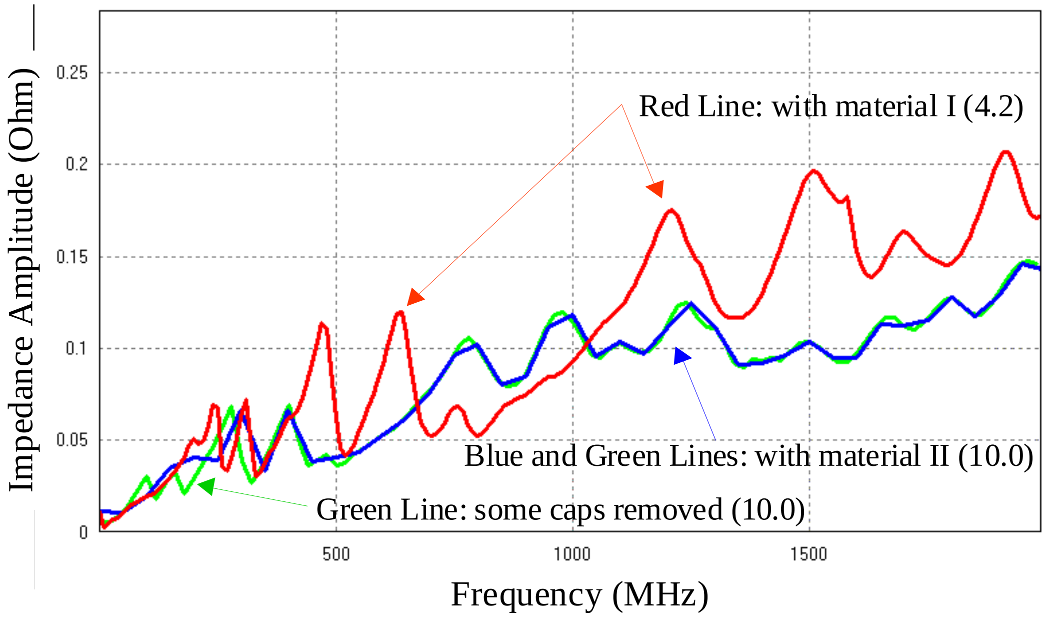


Figure 8 - Simulation Results Comparing Materials with Different Dielectric Constants

In this simulation the dielectric thickness of each of the two materials was assumed to be the same, 25 microns. The calculated input impedance for each was very similar up to about 400 MHz. Beyond this frequency the increase in dielectric constant from 4.2 to 10 showed overall lower input impedance, even with selected capacitors removed. Using the simulation software has revealed a potential benefit of using higher dielectric constant materials. It has also suggested the importance of using simulation software to evaluate a design when embedded planar capacitor laminates are being contemplated, particularly when the designer is uncertain about how many and which ones can be eliminated from the design.

IV. Environmental Characteristics of Thin Polyimide-Based Laminates

Polyimide-based laminates maintain high performance under accelerated aging conditions. In the case of the 14 micron filled laminate, peel strengths remained high after exposure to Highly Accelerated Stress Testing (HAST) for 96 hours. Peel strength also remained high after exposure to an 85°C / 85% relative humidity environment. Figure 9 shows these results.

The idea of using thin laminates in rigid printed wiring boards is scary to many. There is a concern that thin laminates may be susceptible to filament growth across the dielectric from one side of the laminate to the other when the planes are under bias voltage. Interestingly, flex circuits made with 25 and 50 micron dielectric thickness have proven that this concern is unfounded. In the case of polyimide-based laminates for use as power and ground, exposure to voltage bias, even at accelerated conditions, shows stable performance. To demonstrate this, 25 micron unfilled polyimide laminate was tested under both HAST and 85°C/85% RH conditions while under 100 VDC bias. Figure 10 shows the results for the 85°C/85% RH condition. HAST results were similar.

Unlike older polyimide-based flex laminates newer, all polyimide laminate technology has resulted in significantly reduced moisture absorption. Moisture absorption of these laminates ranges from 0.5 - 0.8% after exposure to 100% RH for 48 hours. This results in little influence of moisture on dielectric constant. Figure 11 shows a very slight increase in dielectric constant (Dk) when the laminate is exposed to high temperature and humidity conditions of 85°C and 85% relative humidity. This graph also shows that capacitance is stable into the GigaHertz range.

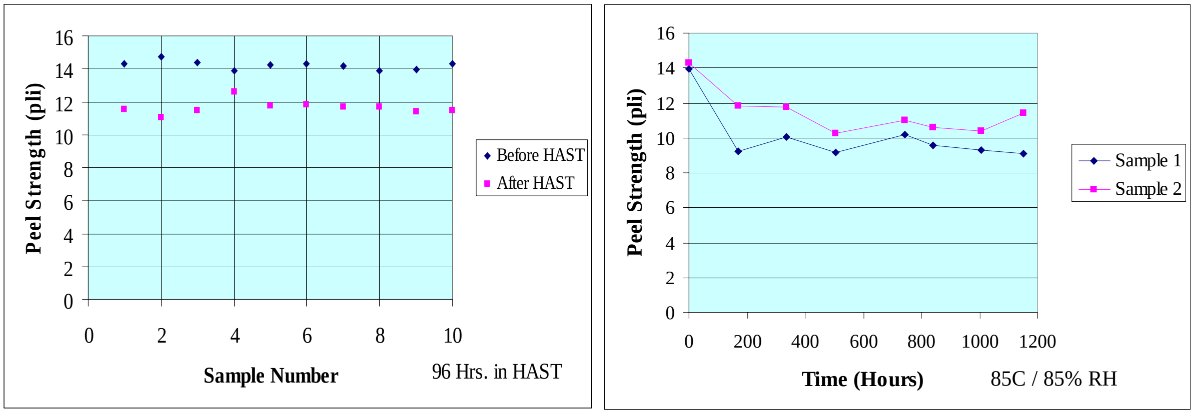


Figure 9 - Peel Strength of 14 micron Filled Polyimide Laminate After Accelerated Aging

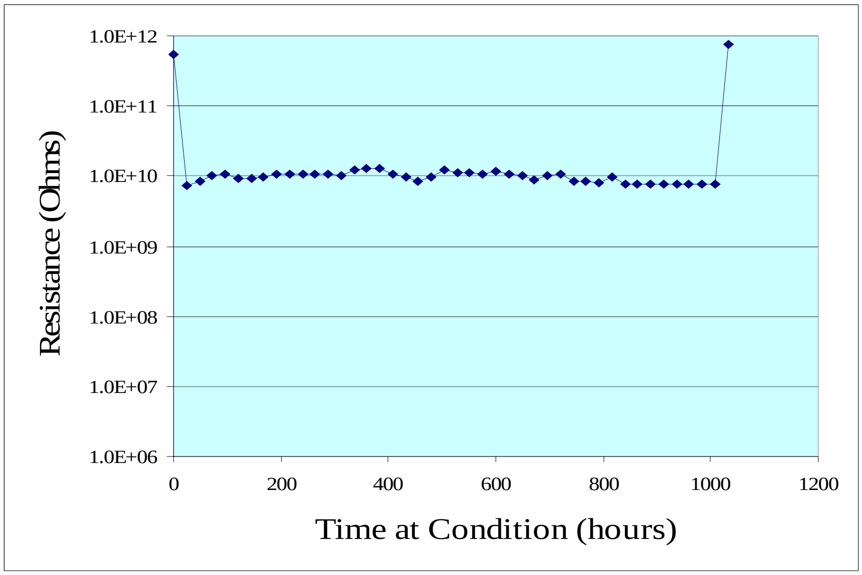


Figure 10 - 100 VDC Bias Test on 25 micron Unfilled Polyimide Laminate

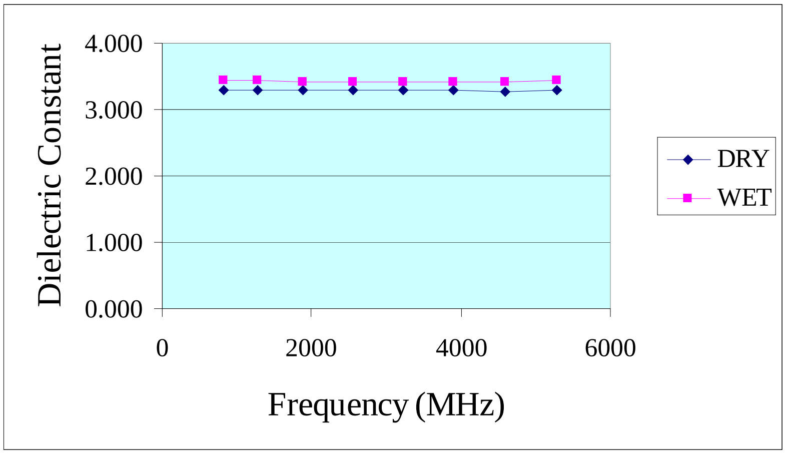


Figure 11 - Moisture Effect on Dielectric Constant of 25 micron Unfilled Polyimide Laminate

Polyimide-based laminates have excellent capacitance stability over a wide range of temparatures. Figure 12 shows the temperature coefficient of capacitance of a 25 micron unfilled laminate.

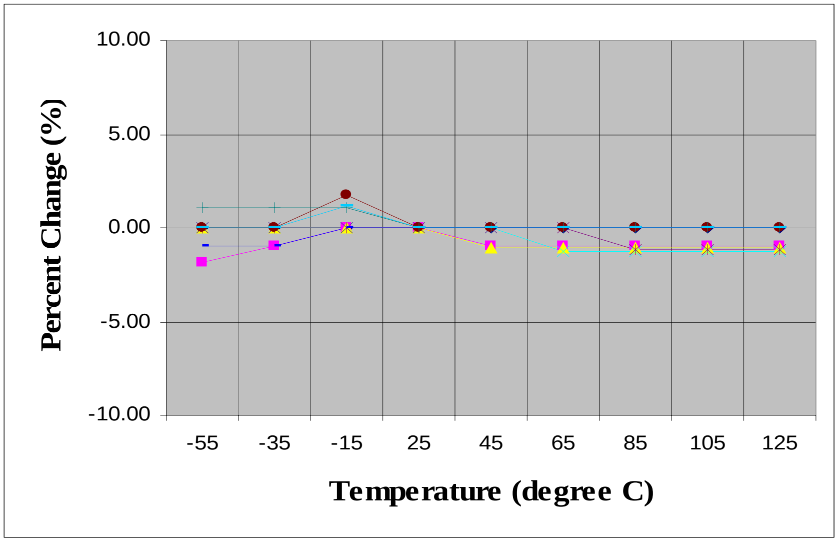


Figure 12 - Temperature Coefficient of Capacitance for 25 micron Unfilled Polyimide

Capacitance remains stable when exposed to accelerated stress conditions. Both filled and unfilled polyimide-based clads were subjected to HAST conditions. Capacitance was measured every 24 hours up to 96 hours. The results are shown in Figure 13. Results from samples tested for 1000 hours in an 85°C / 85% RH environments were similar.

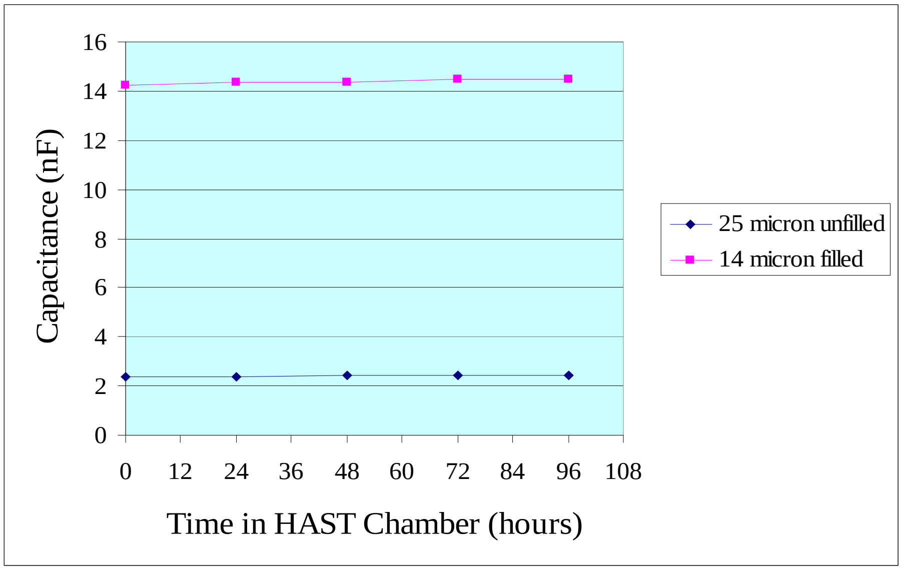


Figure 13 - Effect of HAST Conditions on Capacitance of Filled and Unfilled Polyimide Laminates

V. Summary

Commercial polyimide-based laminates are available for use for low impedance and embedded planar capacitance in printed wiring boards. These laminates are based on the same polyimide that has been used for many years in the flex industry. Recent developments have been discussed showing data to support the fact that thin core polyimide-based laminates have excellent electrical performance and are very robust when exposed to high stress, accelerated aging conditions. Thinner dielectric contributes to reduced power plane impedance and the ability to remove surface mount capacitors. Capacitance is stable when exposed to accelerated stress testing and is stable with increasing frequency. Filling polyimide with high Dk ceramic filler increases the dielectric constant. This appears, by way of simulation software analysis, to offer potential impedance reduction at high frequencies.

VI. Acknowledgements

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3. L. Shaper, R. Ulrich, D. Mannath, J. Morgan, K. Maner, “Decoupling with Anodized Ta,” IPC Printed Circuits Expo® SMEMA Council APEX® Designers Summit 04, February 23 - 27, 2004, Anaheim, CA.

4. Internal presentation by Sigrity, Inc. to Lucent Technologies, used with permission.