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Embedded Passives Become Mainstream Technology, Finally!

Joel S. Peiffer
3M Company
3M Center, MS: 201-1E-21
St. Paul, MN 55144
651-575-1464; 651-736-2947 (fax)
jspeiffer@mmm.com

Abstract

Embedded passives, especially embedded resistors and capacitors have been a hot topic since the mid-to-late 1990s. It is easy to understand why they have generated so much interest. Technology continues to be driven by performance, space and cost. Embedded passives offer potential significant advantages in each of these areas.

Embedded passives have far less parasitic inductance than discrete components, which enables electrical performance advantages (noise and EMI reduction), especially in high speed digital applications. Embedding passives saves surface real estate, which allows for board size reductions which is critical in space constrained designs such as military/aerospace and portable products. The incremental cost of embedding additional passive components is typically negligible; this offers the potential for system cost reduction in designs with high passive component counts. Embedded passives also offer additional advantages such as improved reliability and weight reduction due to the elimination of vias and solder joints.

However, even with all of their potential advantages, high performance embedded passive materials remained a niche market until the last couple of years. There were a number of reasons for this, including the typical fear of new technology, limited technical resources and funding, lack of successful case studies, lack of an experienced supply chain, lack of long term reliability data, very limited physical layout and simulation/modeling software tools, improvements in existing discrete passive products, the telecom bust, cost concerns and an insufficient knowledge of intellectual property and prior art.

After more than 10 years of large scale interest, high performance embedded resistors and capacitors have finally become mainstream technologies in many market segments. There are multiple suppliers of commercial thin film metal resistor materials and ultra thin embedded capacitor materials. A large number of PCB fabs across the globe have very significant experience in processing these materials in moderate to high volumes.

This paper will look at the above barriers to the implementation of high performance embedded passives, focusing on embedded capacitor laminate materials, and show how these barriers were overcome so that embedded passives could finally become a mainstream technology.

Intellectual Property and Prior Art

The foundation of embedded capacitance in printed circuit boards actually started as early as the late 1960s. In U.S. Pat. No. 3,519,959, the concept of embedded distributed capacitance (closely spaced power and ground planes for power supply decoupling) was disclosed. In the '959 patent, two layers of embedded distributed capacitance were used. Each embedded distributed capacitor utilized 0.0025" thick epoxy-glass and two ounce (0.0025") copper. The use of an even thinner and higher performance embedded distributed capacitance material is disclosed in U.S. Pat. No. 4,560,962 which was filed in 1983. In this case, one ounce (0.0014") power and ground planes separated by epoxy-glass dielectric as thin as 0.001" is disclosed.

It should be noted that both of these patents are expired and the teachings that are disclosed in them, such as the concept of embedded distributed capacitance, are now in the public domain and are able to be practiced broadly. This was important because many OEM designers and PCB fabricators had no awareness of the prior art in the area of embedded distributed capacitance as well as a poor understanding of patents. The combination of these two items was a significant impediment to the use of high performance embedded capacitor laminates in printed circuit boards prior to 2004 when the prior art in the area became widely shared and a better understanding of patents was achieved.

Lack of Technical Resources, Long Term Reliability and Successful Case Studies

The high interest in embedded passives and especially embedded capacitance took off in the mid-to-late 1990s. High speed digital products with large numbers of ICs switching simultaneously were seeing a combination of noise and EMI issues due their much faster rise times and lower operating voltages. Portable consumer products such as cell phones, digital still cameras and camcorders had a large need to reduce size and weight while still meeting EMI requirements.

Many military/aerospace had the combination of high performance requirements required by high speed digital products but also had the same space and weight needs as portable products. Since the drivers for military/aerospace products was primarily performance and space and not cost driven at that time, it is easy to see why military/aerospace products were some of the early adopters of the high performance embedded capacitor (and resistor) technology.

Some of this early interest in embedded passives resulted in an approved DARPA proposal by 3M in 1996. The goal of this project was extremely high capacitance densities which could be used in printed circuit boards and MCMs in military products. Both thin film metal oxides and ceramic filled polymers were studied over a four year period. However, it became apparent during the program that ceramic filled resins, especially barium titanate filled epoxies, offered the best combination of performance, reliability, and PCB fabrication compatibility as well as the quickest path to commercialization.

At about this same time, StorageTek was trying to organize an industry consortium of material suppliers, PCB fabricators and OEMs to study high performance embedded distributed capacitance materials. The industry consortia would mitigate the technical resources and funding required to study embedded capacitance in detail. This resulted in the NCMS Embedded Decoupling Capacitance (EDC) consortia. Five embedded capacitor materials including the 3M™ Embedded Capacitor Material were investigated as power-ground cores in multilayer rigid boards. One goal of the consortia was to confirm that embedded capacitor materials were compatible with all facets of the PCB manufacturing including design, fabrication and reliability testing. Another goal was to determine if the embedded capacitor materials would provide better electrical performance than surface mounted capacitors, and if so, how much.

The results of this consortium's work was presented to the industry in a final report issued in 2000. Here it was shown that most embedded capacitor materials, including the 3M Embedded Capacitor Material, were compatible with standard PCB processing, had similar reliability results to existing commercial thin, high Tg FR-4 laminates and required very minimal changes in the OEM design or in panelization of the design at the PCB fabricator. Additionally, ultra thin materials (4-8 um) with a high Dk (16) were shown to provide excellent electrical performance, much better than surface mount capacitors or the commercial 2 mil FR-4 material that was being used as a baseline (See Figures 1 and 2 below).

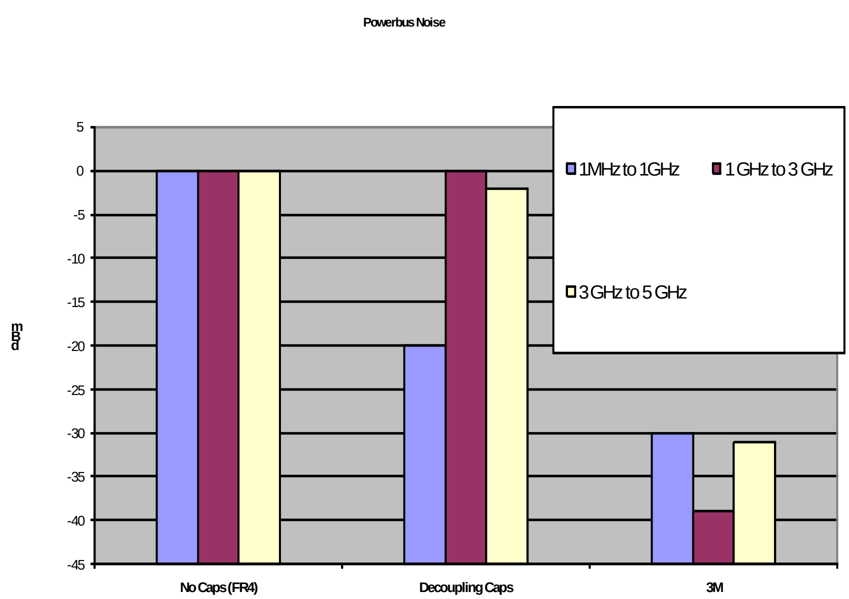

Figure 1 – Power Bus Noise
(Courtesy of University of Missouri at Rolla)

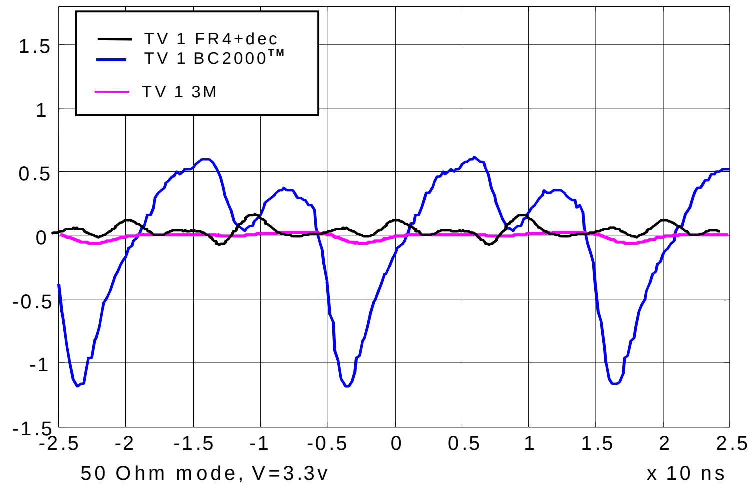

Figure 2 – Power Plane Voltage Fluctuation
(Courtesy of University of Missouri at Rolla)

The NCMS EDC consortia provided the initial performance and reliability data which significantly increased the interest in high performance embedded distributed capacitor laminates. The NCMS EDC consortia also paved the way for a larger follow up industry consortia on embedded passives. The NIST Advanced Embedded Passives Technology (AEPT) program started in 1999. The scope of this project was both embedded resistor and capacitor materials including capacitor functions beyond decoupling.

The PCB fabrication compatibility and reliability work done on the 3M Embedded Capacitor Material in the NIST AEPT program confirmed the earlier findings of the NCMS EDC consortia. Additionally, the NIST AEPT program looked at compatibility of the 3M material with non-standard (at that time) PCB fabrication processes such as laser drilling. The 3M material was found to be easily laser drilled and compatible with the microvia metallization process (see Figure 3 below).

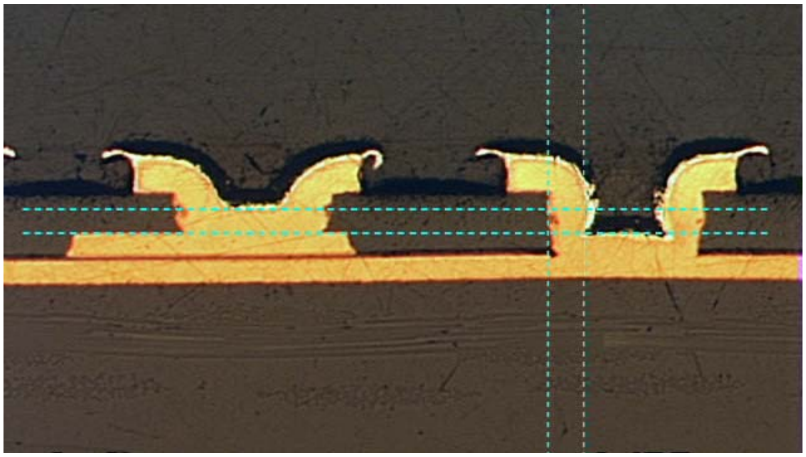

Figure 3 – Microvias in Test Board
(Courtesy of Merix)

Another important part of the NIST AEPT program was to ensure that high performance embedded capacitor materials could receive UL recognition at the desired levels. In 2001, the 3M Embedded Capacitor Material was the first high performance embedded capacitor material tested for UL recognition. It successfully passed this testing with results comparable to high Tg FR-4 laminates (94V-0 flame rating, 288C/30 sec solderability limits and 130C relative thermal index).

At the end of the program, all three OEMs involved built product emulators with the 3M Embedded Capacitor Material. The product emulators from Nortel, Compaq and Delphi were a 10 Gb optical transceiver module, a PDA and an engine control module (ECM) respectively. All three product emulators were successfully fabricated by the PCB fabricators in the consortia. All were found to be fully functional when tested at the system level even though a large number of discrete decoupling and/or filter capacitors had been removed from the board surface. A photo of the Nortel transceiver module, Compaq PDA and Delphi engine control module (ECM) board are shown in Figures 4, 5 and 6 below).

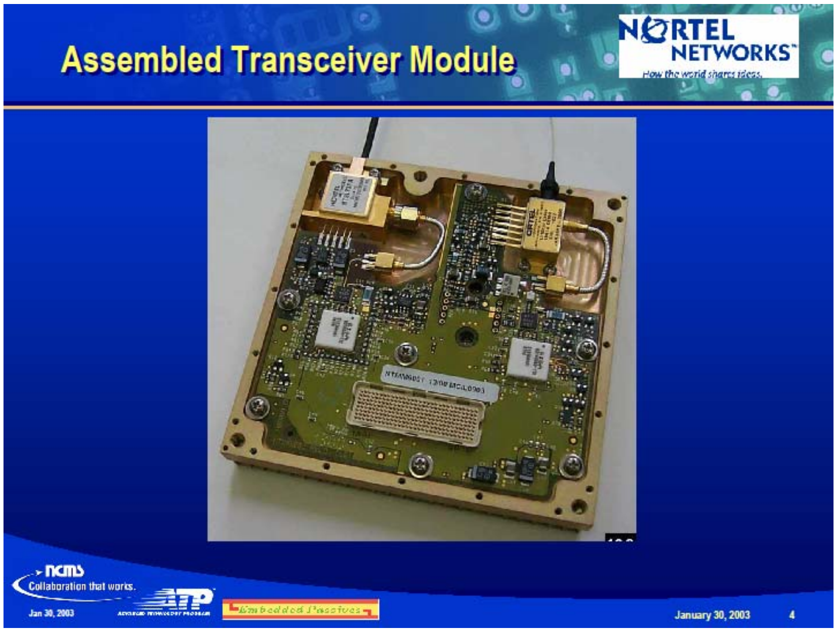

Figure 4 – Transceiver Module
(Courtesy of Nortel)

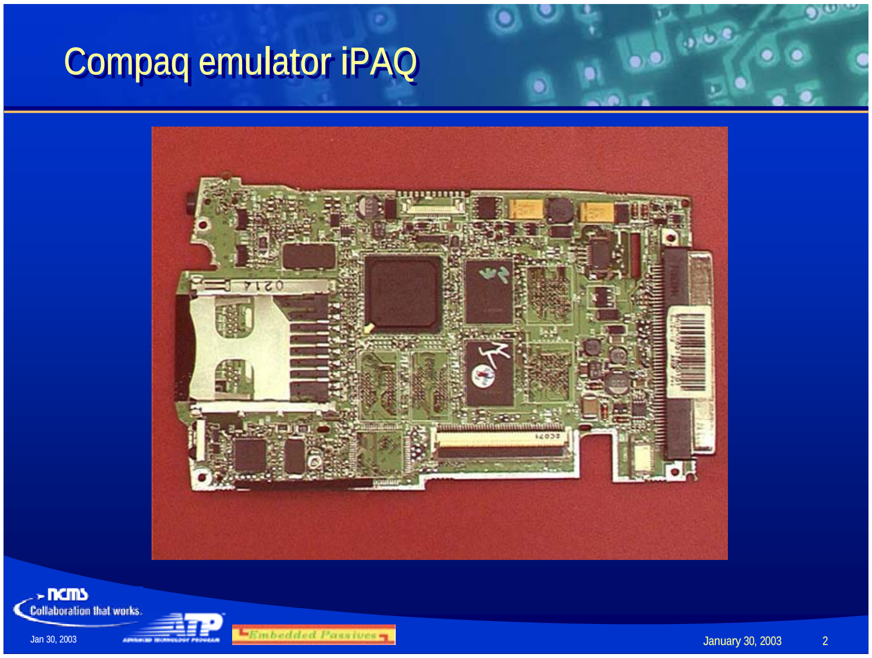

Figure 5 - PDA
(Courtesy of Compaq)

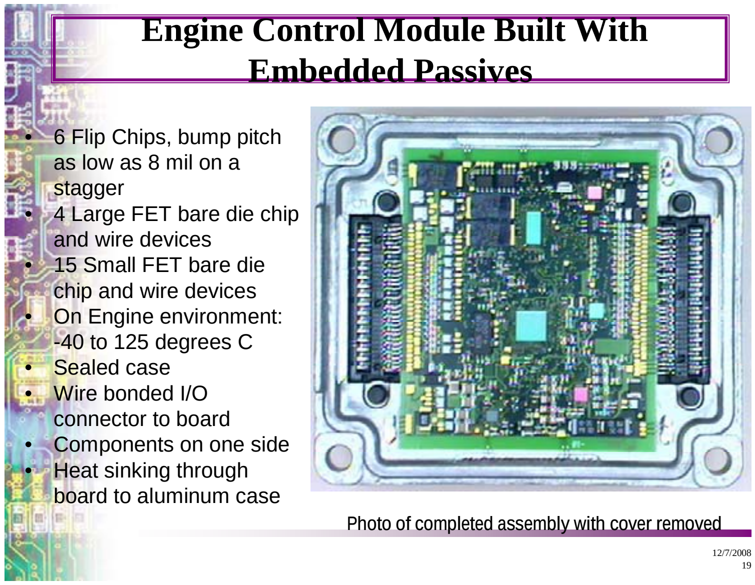

Figure 6 – Engine Control Module
(Courtesy of Delphi)

In the case of the Nortel transceiver module, the use of embedded capacitance (and resistance) was responsible for reducing the number of layers from 18 to 14 while improving signal integrity by 20%. In the case of Compaq, 74 discrete capacitors were removed from the board surface while still improving electrical performance. In the case of Delphi, it was shown that an on-engine ceramic module could successfully be replaced by an organic module with embedded capacitors (and resistors). The results of the product emulator testing and other test data of the NIST AEPT consortia were released in a final report to the industry in 2003.

Additional Successful Case Studies
One of the first OEMs to investigate embedded capacitance laminate materials outside of an industry consortia was Sun Microsystems. Over the period of ~1999-2003, Sun investigated a number of embedded capacitor laminate materials including the 3M Embedded Capacitor Material. Some of the testing included measuring the impedance versus frequency of a 5” X 10” test board which utilized different embedded capacitor materials for the power-ground cores. In Figure 7 below. the 0.3 mil (8 um) 3M Embedded Capacitor Material is compared to 2 mil (50 um) and 1 mil (25 um) FR-4 material.

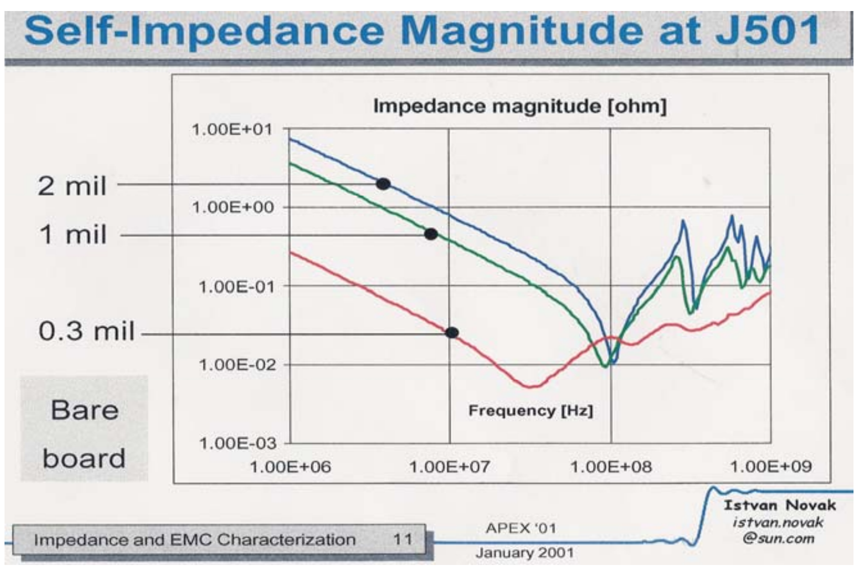

Figure 7 – Self-Impedance vs. Frequency
(Courtesy of Sun Microsystems)

At lower frequencies, it can be seen that the self-impedance of the ultra-thin laminate material is more than an order of magnitude lower than that of 1 or 2 mil thick FR-4. This is due to the much higher capacitance density of the ultra-thin material (~10 nF/in^2 vs. ~0.5 - 1 nF/in^2). At higher frequencies, the self-impedance of the ultra-thin dielectric material is also significantly lower than that of the 1 or 2 mil FR-4 laminate. This is primarily due to the significantly lower self-inductance of the ultra-thin material. Finally, in the 100 MHz to 1 GHz frequency range, both the 1 mil and 2 mil FR-4 laminates show very large impedance spikes caused by board resonances. These are very undesirable as the noise associated with these impedance spikes can trigger false switching, signal integrity and EMI issues. However, in the case of the ultra-thin dielectric, the board resonances are almost completely damped due to the high copper losses of closely spaced power and ground planes at high frequencies.

H.P. was another company that was a leader in testing of high performance embedded capacitor materials and sharing their internal results. In ~2002-2003, H.P. did a large amount of testing on boards that used the 3M Embedded Capacitor Material for power-ground cores. In one case, two board designs were compared. The first had a 3 mil FR-4 dielectric thickness between power and ground planes and the second board had an 8 um dielectric thickness (Dk of 16) between power and ground planes.

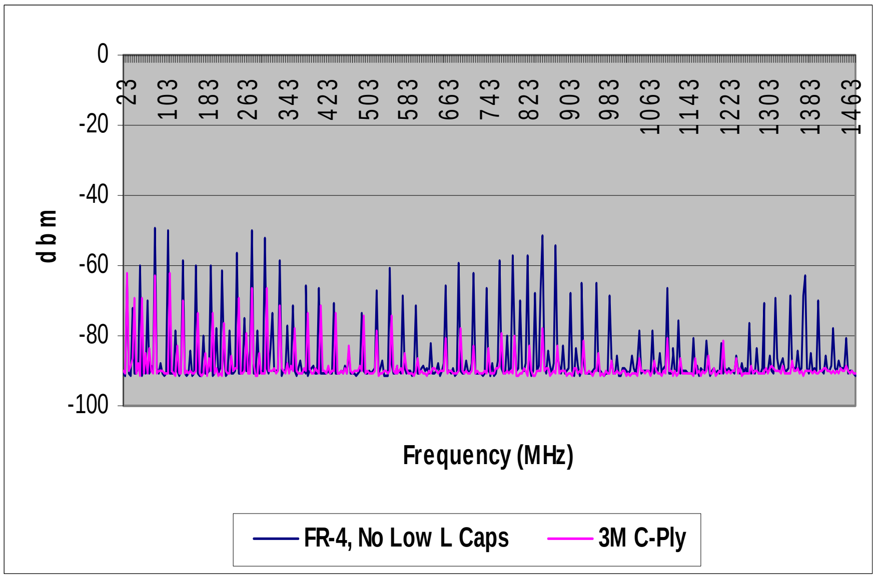

Figure 8 – Power Bus Noise vs. Frequency
(Courtesy of H.P.)

In figure 8, the noise versus frequency was measured on a fully assembled daughter board with an approximate size of 5” X 5”. The noise was measured on the 1.5 volt plane up to a frequency of ~1.5 GHz. The daughter card had a MIPS R14K processor running at 550 MHz and 9 secondary cache SRAMs running at 275 MHz.

As can be seen in Figure 8, the board with the ultra-thin dielectric had significantly less noise at all frequencies above ~50 MHz. At frequencies above 500 MHz, the board with the 3 mil FR-4 still had had a large amount of noise whereas the board with the ultra-thin dielectric had extremely effective noise dampening above 500 MHz. Over the frequency range measured, the board with the 8 um dielectric had 13.3 dB less noise than that of the board with the 3 mil FR-4 power ground plane.

The peak-to-peak voltage ripple was also measured on these boards. For the case of the board with the 3 mil FR-4 power-ground plane spacing, the peak-to-peak noise was 235 mV (15.7% of 1.5V). For the board with the 8 um power-ground spacing, the voltage ripple was 114 mV (7.6% of 1.5V), or slightly less than one-half of that of the 3 mil FR-4 board.

Lack of Experienced PCB Fabricators and Lack of High Volume Capability of Embedded Capacitor Material Suppliers

By 2004, the electrical performance, PCB fabrication compatibility and reliability work done by OEMs such as StorageTek, Nortel, Delphi, Compaq, Sun and H.P., UL, PCB fabricators and material suppliers such as 3M had confirmed the expected electrical performance results on active designs, proven that large number of discrete capacitors could be successfully removed from the board allowing large space reduction and had proven that embedded capacitor laminates had excellent long term reliability.

Also in 2004, the publication of the Printed Circuit and Design article on “The History of Embedded Distributed Capacitance” greatly increased the industries knowledge in the area of prior art. The combination of the above had mitigated most of the industries concerns regarding embedded capacitor laminate materials. However, at the start of 2004, the overall experience of the PCB fabricators, especially outside of North America was very limited. At this time, only 28 PCB board fabricators had any experience processing the 3M material. Approximately 25% of these were from their participation in the NCMS EDC and NIST AEPT consortia. Of the 28 board fabs, only 9 were from outside of North America, with 6 of this being in Asia and 3 in Europe.

The lack of experienced board fabricators started to change in 2004. During 2004 alone, an additional 18 board fabricators starting to use the 3M material including many in Asia. An additional 32 new board fabricators were added during 2005 and 2006 bringing the number of board fabricators who had processed the 3M material to almost 80. New board fabricators continue to be added on a regular basis. By the end of 2008, the number of board fabricators who have successfully processed the 3M material stands at approximately 100 with approximately 40% of these being in Asia, 40% in North America and 20% in Europe (see Figure 9 below).

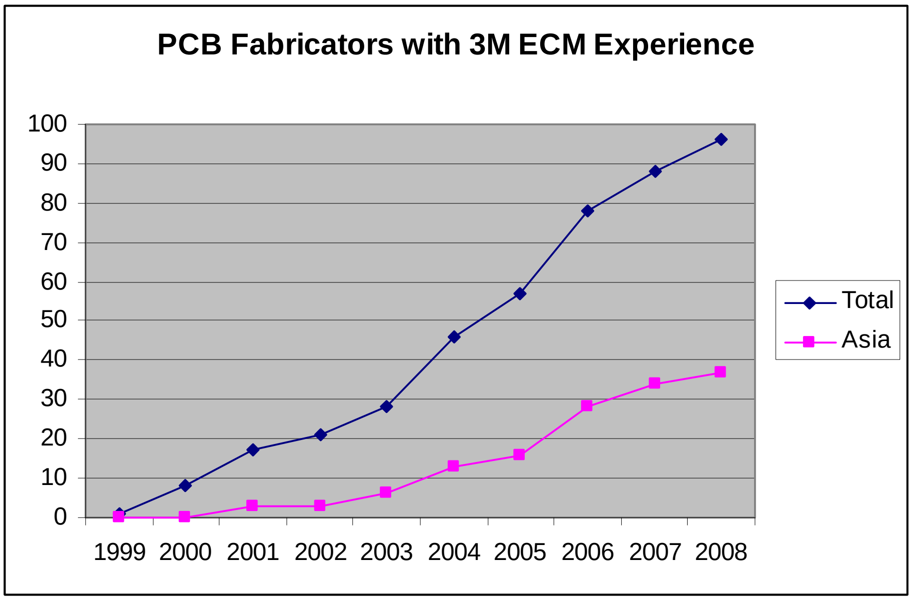

Figure 9 – PCB Fabricators using 3M ECM by Year

Lack of Physical Layout and Simulation/Modeling Software

The lack of physical layout and simulation/modeling software was not a large barrier initially for embedded capacitor materials because almost all applications only utilized embedded distributed capacitance. The physical layout was straight forward. Replace the existing thick, low Dk dielectric power and ground planes with very thin, high Dk dielectric power and ground planes of the same design.

If there was a need to determine how many decoupling capacitors could be removed with the use of embedded distributed capacitance, the typical route was to fully assemble the embedded capacitance board and start removing capacitors until you were happy with the performance and number of caps that were removed. This process was fine for implementing embedded capacitance on existing designs which was the standard practice when initially investigating the technology. However, as designers desired to implement embedded capacitance on next generation designs, there was a need for simulation/modeling tools to determine power integrity and how many decoupling capacitors would be needed as designers did not want to design in unnecessary SMT pads, traces and vias.

The very limited software tools available to designers for embedded passives was identified as a large gap early in the NIST AEPT program. Even though a couple of software providers were involved in the NIST AEPT program, not much progress was made during the course of the program. The EDA providers did not want to invest a large amount of resources and funding into the creation of software to support embedded passives until there was a known market. This created a chicken or egg scenario as the designers needed the EDA tools to scale up to large volumes.

In the course of the NIST AEPT consortia, much of the physical layout of the singulated embedded passives was done manually which was a slow and tedious process. Fortunately, as the use of embedded passives has steadily increased over the last 5 years, so has the number of available EDA providers and software tools. Today there are a number of both physical layout and simulation/modeling software tools that support embedded passives available from such companies as Ansoft, Cadence, Mentor, Sigrity and Zuken.

Telecom Bust, Improved Discrete Caps and Cost Concerns

Cost concerns are almost always a major hurdle in new technology commercialization and embedded passives were no exception. In 1998-2001, the costs of embedded capacitor bare boards were much, much higher than the cost of boards without embedded capacitors due to low volumes, low yields at the embedded capacitor material suppliers and lower yields on embedded capacitor boards during PCB fabrication. Of course this was expected as the technology was new and very few board fabricators had experience handling thin flexible materials.

However, even though embedded capacitance was initially a very significant cost adder, the products that really needed it such as military/aerospace and high end telecom/computing equipment could afford the technology and many OEMs went forward with qualifying the technology. Just as some of the telecom OEMs were ready to implement the 3M Embedded Capacitor Material into their designs, the telecom bust occurred. Programs that were slated to use embedded capacitance were either scrapped or only went forward with less expensive standard technology.

Also during this time, the discrete component manufacturers were not sitting idle. They could see that embedded passives were a serious threat. They continued to not only decrease the costs of discrete components but were able to package much more capacitance into the same volume. Additionally, they were able to fabricate smaller and smaller components to facilitate designers meeting their space requirements.

By 2003 a large percentage of the embedded capacitance market was no longer available due to cost pressures. Embedded passive material suppliers needed to improve their productivity and yields to become more competitive. The yields of embedded capacitance boards at the PCB fabricator also had to be comparable to standard product. Other market segments beyond military/aerospace, telecom and high end computing also had to be investigated.

Over the period of 2004-2006, the market for embedded capacitors was significantly increased by 3M offering a more cost-effective product. The cost of PCB fabrication also decreased significantly during this time due to increased experience, the increased use of thin core processing equipment, higher yields and off shore manufacturing. The cost reduction of offshore fabrication was so significant that boards manufactured in North America which used thin FR-4 could now be manufactured in Asia with the 3M material for similar or even lower costs. This made it possible to offer the OEM designer a significantly better performing product for the same or less cost.

During this time, the telecom and high end computing market came back somewhat and once again began to use high performance embedded capacitance materials in their rigid multilayer boards. However, this time, typically only the higher end products could justify the higher costs of embedded capacitance technology. These same companies also started investigating embedded passives in their high performance chip packages as well.

Also during this time, the use of high performance embedded capacitance materials significantly increased in military/aerospace products including backplanes and modules. Other market segments such as medical began to use the 3M material in higher volumes. In 2006, the 3M material was qualified into modules used in cell phones. More than a dozen cell phone manufacturers use the 3M product in their cell phone modules. In 2008, approximately 150-200 million cell phones were manufactured using the 3M material.

By 2008, the 3M material was being used or scaled up in moderate to high volume in essentially every market segment including handheld, military/aerospace, telecom, computing, medical, automotive and industrial. The high capacitance density of the 3M material is a very good fit for use in small modules. Use in modules has increased dramatically over the last couple of years and will likely continue to increase in the future.

The use of high performance embedded capacitance has continued to increase year after year. From 2003 to 2008, the CAGR of the 3M Embedded Capacitor Material was over 100%. This trend is expected to continue into the near future.

Summary

It has been a very long time coming, but high performance embedded passive materials have finally hit mainstream. Designers across the globe have specified it for use. PCB fabs in at least 14 different countries have successfully used the material. It has or is being used in backplanes, rigid, flex, rigid-flex, modules and chip packages. Wherever there is a strong need for improved electrical performance, space reduction, EMI reduction or reliability improvement, utilization of embedded passives will be found.

A recent survey conducted by Printed Circuit Design and Manufacture in late 2006 and published in January 2007 indicated that 11.1% of responders utilized embedded passive technology. Another finding of the study was that by 2008, 24.6% of the responders indicated they planned on utilizing embedded passive technology in their designs.

Having worked on embedded passives since 1996 and living through the slow, painful growth of the technology, I feel extremely proud to have been a part of the development, commercialization and scale up of high performance embedded passives technology. However, if it weren't for OEMs such as Compaq, Delphi, H.P., Nortel, Sun and StorageTek, PCB fabricators such as Litton Interconnect and Merix and material suppliers such as DuPont, MacDermid and 3M, it would have taken considerably longer.

3M has been committed to the development and advancement of high performance embedded passives materials for over 12 years and will continue to support embedded passive technology in the future.

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