Enhanced Embedded Passives Technology – From Distributed to Discrete

Douglas W. Trobough and Bob Greenlee
Merix Corporation
Forest Grove, OR

Introduction
Embedded passives are entering a new phase of improved product capability and enhanced processes. Thinner, higher capacitance embedded distributed capacitance (EDC) materials are coming to market. Alternate resistor forming and trimming technologies have recently been released, and discrete embedded capacitor technology is emerging. This paper will focus on embedded distributed capacitance and embedded resistor technology, with a brief discussion on embedded discrete capacitors and supporting technology.

Embedded Passives
Embedded passives provide multiple benefits, including improved electrical performance. This is achieved primarily by removing inductive delays. Reducing surface mount passives also increases the effective surface component density. Embedded passives may reduce the overall costs, particularly when a large number of surface mount passives are replaced. However, this is not common on system level boards.

Embedded Distributed Capacitance (EDC)
Embedded distributed capacitance (EDC) is the most commercially proven and utilized of the embedded passives technologies. Commercialization of distributed capacitance was driven by ZBC™. EDC is a very simple technology conceptually, creating one or more large capacitors utilizing the power and ground planes present in the printed circuit board.

Properties of EDC
A capacitor is formed when an insulative (dielectric) material separates two conductive layers. By applying different voltages to the conductive layers, energy is stored in the dielectric material, which can be released rapidly to system components. The amount of energy (capacitance) is proportional to the dielectric constant and surface area, as well as inversely proportional to the thickness of the dielectric material (see Figure 1.)

$$C = \frac{k\ A\ Er}{T},$$

where C = capacitance (pF)
k = 225 (constant)
A = area (in^2)
Er = dielectric constant
T = thickness (mils)

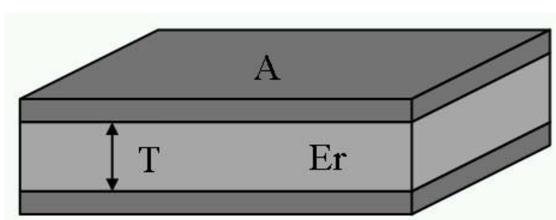

Figure 1 - Calculation of Capacitance

The performance of EDC differs from discrete surface mount capacitors significantly as the (AC equivalent) frequency of switching moves above 500 MHz-1 GHz. Key benefits are reduced switching noise, reduced power plane impedance, and improved EMI. The EDC materials can be grouped into three categories based on their relative benefits:

- Thin (25-50 µm) low Dk material (e.g. ZBC ™)
- Ultrathin (<25 µm) low Dk materials (e.g. Faradflex-Oak Mitsui, DuPont HK-4, others)
- Ultrathin (<20 µm) high Dk materials (e.g. 3M C-ply)

Processing impacts also differ by material type, as will be covered later in this paper.

Thin Low Dielectric Constant Materials
Thin (25-50 µm) low dielectric constant materials, such as ZBC ™, provide excellent EMI radiation reduction, and moderate improvement in plane self-impedance. Some node damping is seen, along with a moderate improvement in power bus noise. They also provide the ability to remove a significant number of capacitors.

Ultrathin Low Dielectric Constant Materials
Ultrathin (<20 µm) low dielectric constant materials, such as Oak-Mitsui's Faradflex, DuPont's HK-4, and others, provide a reduction in power-ground inductance, a large reduction in plane self-impedance, and significant node damping and shift to lower frequency. They also provide a large improvement in power bus noise, and allow large-scale removal of low value capacitors. The improvement in EMI is about the same as for the thin, low dielectric constant materials. Figures 2 and 3 illustrate the improvement in electrical properties for the FaradFlex ultrathin low dielectric constant material. Figures 4 and 5 show Cross sections of DuPont's HK-4 and Oak-Mitsui's FaradFlex materials. Figure 6 illustrates the manufacturing process for Oak-Mitsui's FaradFlex material.

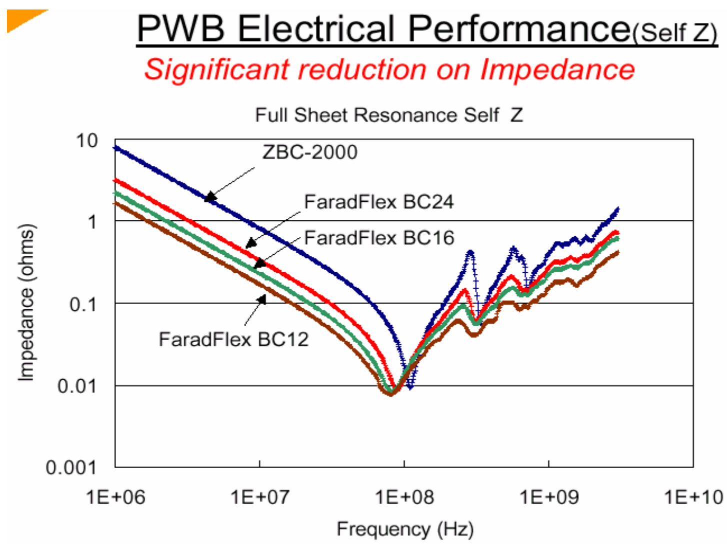

Figure 2 - Reduction in Board Self Impedance with Reducing Dielectric Thickness (Data Courtesy of Oak-Mitsui)

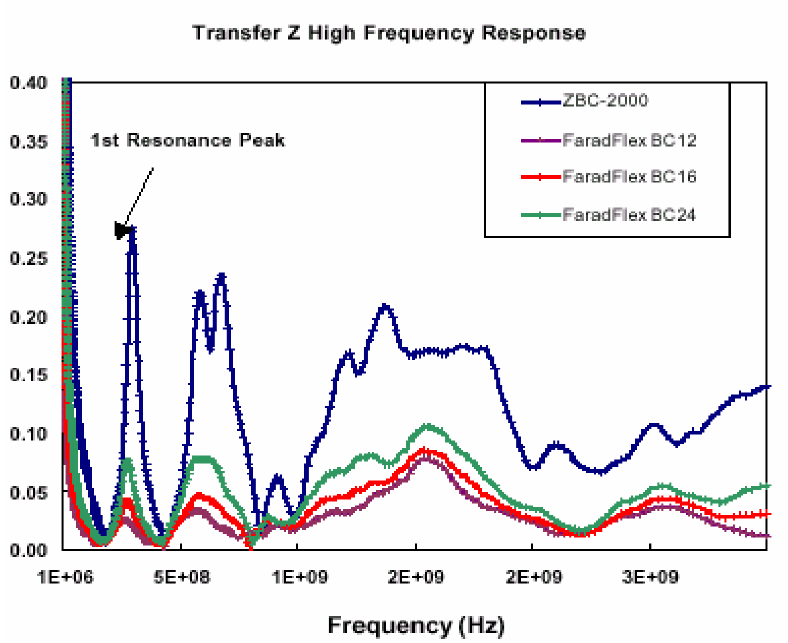

Figure 3 - Improved Node Damping with Reducing Dielectric Thickness (Data Courtesy of Oak-Mitsui)

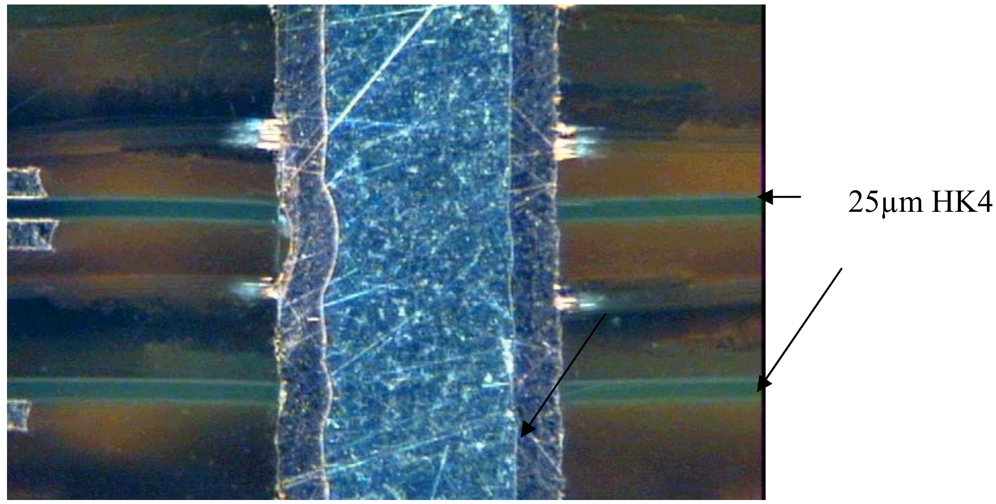

Figure 4 - Cross section of DuPont 25 µm HK-4 Material

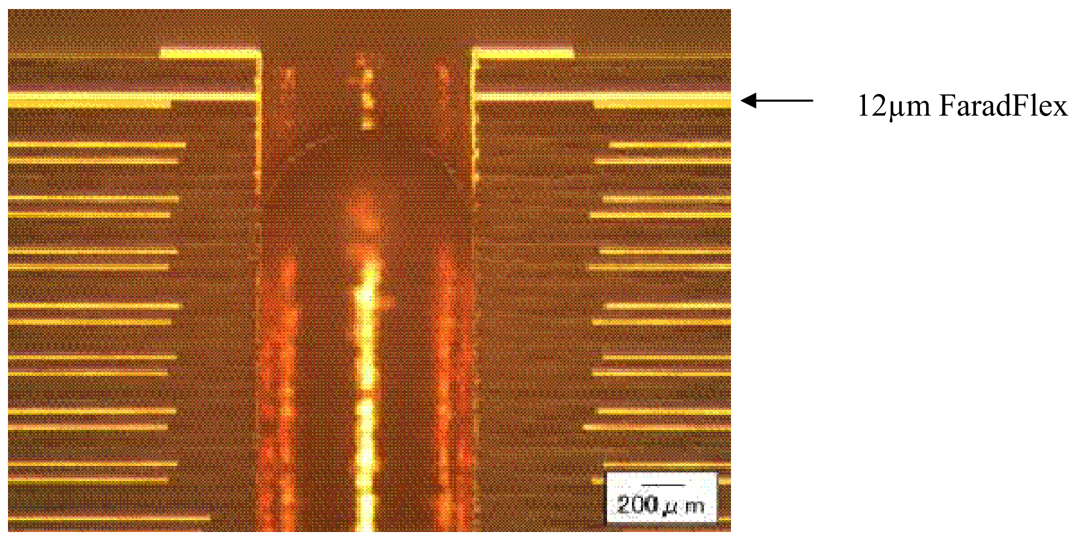

Figure 5 - Cross section of Oak-Mitsui 12µm FaradFlex (Photo Courtesy of Oak-Mistusi)

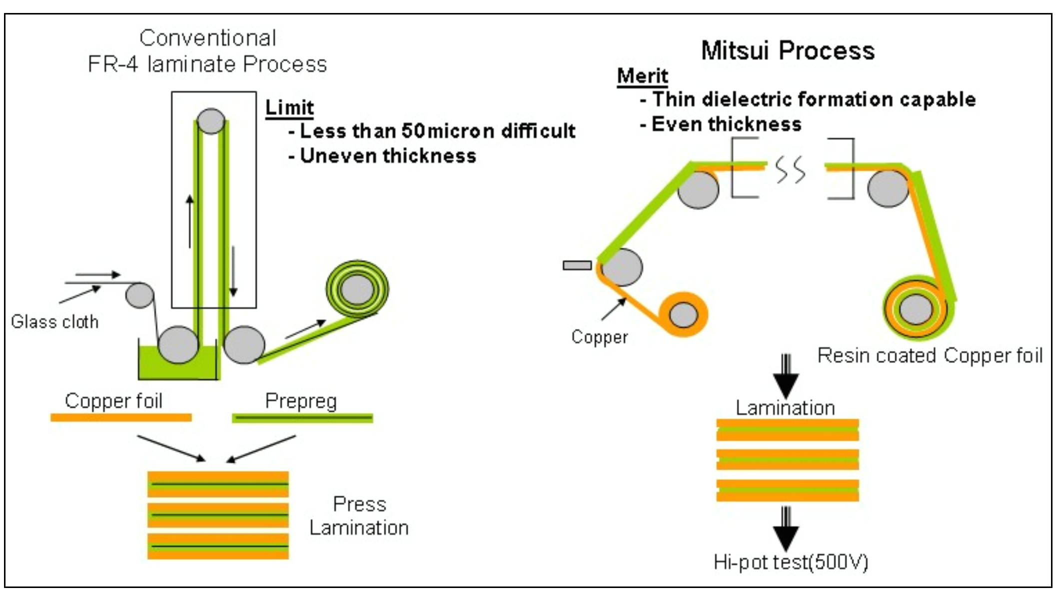

Figure 6 - Diagram of Standard Laminate Productions and Ultrathin Laminate Production (Courtesy of Oak-Mitsui)

Ultrathin High Dielectric Constant Materials

Ultrathin (<20 µm) high dielectric constant materials, such as 3M's C-Ply, also provide low inductance. In addition, the high dielectric constant makes the power-ground circuit look bigger. This creates another level of reduction in the plane self-impedance. The noise reduction is also enhanced as the increased 'size' leads to high frequency attenuation. Figures 7, 8, and 9 show the improvement in electrical properties for 3M C-Ply. Figures 10, 11, and 12 show Cross sections of boards made with 3M C-Ply.

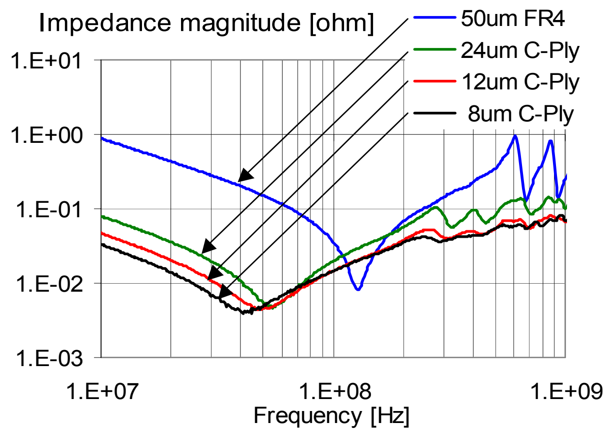

Figure 7 - Reduction in Power/Ground Self Impedance with Reducing Dielectric Thickness (Courtesy of Istvan Novak Sun Microsystems)

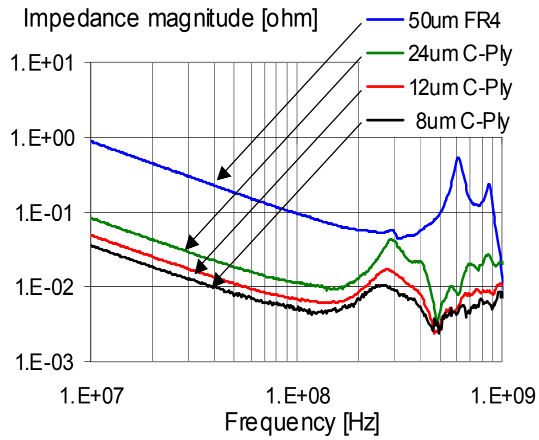

Figure 8 - Reduction in Power/Ground Transfer Impedance with Reducing Dielectric Thickness (Courtesy of Istvan Novak Sun Microsystems). Transfer Impedance (Courtesy of Istvan Novak Sun Microsystems)

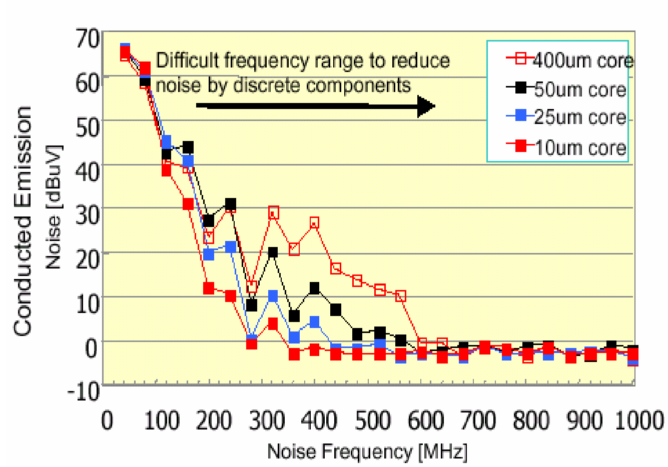

Figure 9 - Reduction in Electromagnetic Interference with Reducing Dielectric Thickness (Courtesy of Hitachi LTD)

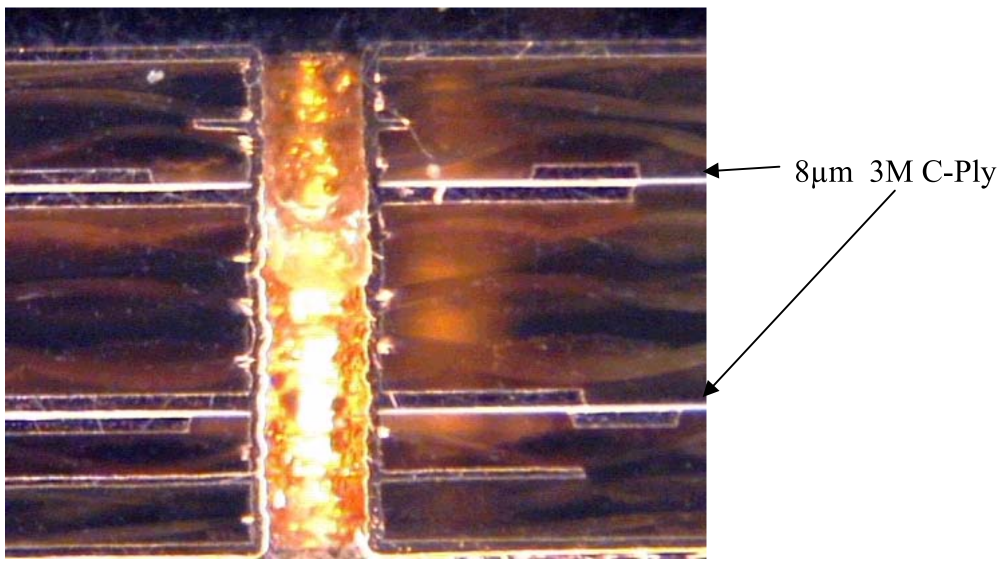

Figure 10 - Cross section of 3M 8 µm C- Ply™ Material

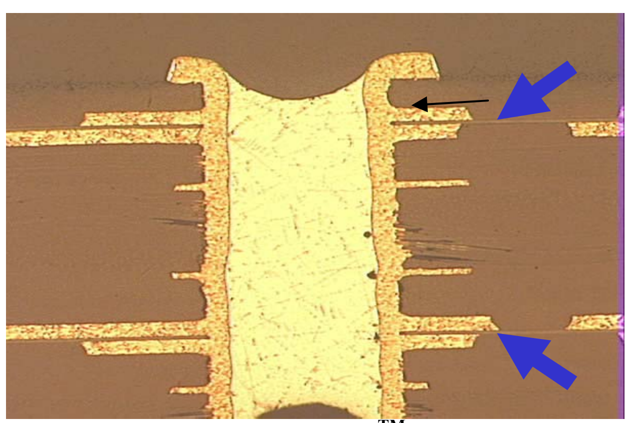

Figure 11 - Cross section of Two 3M 8 µm C- Ply™ Cores Separated by an FR406 core

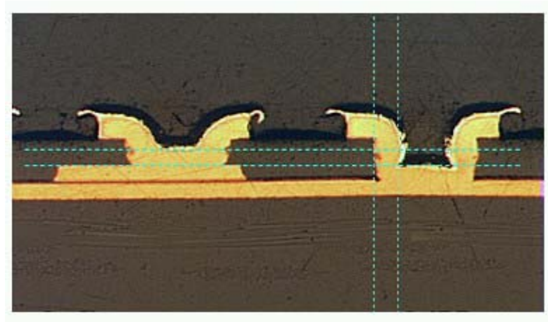

Figure 12 - Cross section of Microvias in 3M 8 µm C- Ply™

Process Impact of Embedded Distributed Capacitance Materials
For the thin (25-50 µm) low Dk material such as ZBC ™, there is very little process impact for thin core capable suppliers.

Ultrathin (<20 µm) low Dk materials such as Oak Mitsui's Faradflex and DuPont's HK-4, are similar to thin flex circuit materials and are normally "self supporting" materials, i.e., the dielectric material is strong enough to support itself through the PCB manufacturing process. However, excellent thin core handling capability is required by fabricator, and it is important to avoid areas clear of copper on the panel that might create folding lines. With some of these materials, the HiPot resistance may be reduced.

Ultrathin (<20 µ) High Dk materials such as 3M's C-Ply are normally not "self supporting", so that in addition to excellent thin core handling capability, these materials may require the development of special processing methods to manufacture the PCB.

Design Impact of Embedded Distributed Capacitance Materials
Many tests have been run showing that small value (fast response) decoupling capacitors can be entirely removed with ultrathin materials. However design rules need to be developed for specific system and processor speeds. The plane clearances need to be carefully considered when designing with the ultrathin low Dk materials, since making cross board plane splits in a line may create a folding issue which increases the chance of handling damage, and may hurt registration. This issue could be a significant cost driver. The special processes used on the ultrathin high Dk materials make it less susceptible to plane clearance design issues.

In general, one should not put high voltages across these materials, since there may be an increased chance of z-axis short formation. These are designed for less than 5-volt applications, and are particularly useful with high speed circuits. Also, it should be noted that these materials are intended for high capacitance, not controlled impedance or low loss.

Most, but not all, of the materials have good electrical properties. Impedance control across these materials will be reduced and conductor loss will be increased. High Dk materials will have negative impact on propagation velocity. Some of the materials are lossy, which is good for noise reduction, but very poor for transmission lines.

Embedded Resistors
Embedded discrete resistors are more complicated to implement than embedded distributed capacitors. The tolerance values can be quite large, and the costs vary widely. There are many types of technologies, and the power ratings vary depending on the material used. Also, more decision making is required by designer when using embedded resistors.

Embedded Resistor Types
There are three basic types of resistors:

- Metal based resistors, such as Ohmegaply™, Gould TCR™, MacDermid M-Pass™, Shipley InSite™ and others.
- Thick film resistors including many choices of resistive inks and pastes.
- Fired thick film resistors, such as DuPont's ceramic resistors technology.

Metal based resistors generally have highest power rating, and are normally limited to a single Ohm/square resistivity rating per layer. The tolerance as processed depends on the size of the resistor, but is typically ±10-20%. These resistors are laser trimmable, so that the tolerance can be significantly reduced. Metal resistors are generally very stable, and generally best for low value resistors (<1000Ω). Figure 13 illustrates Gould's method for vacuum metallization of resistive copper foil. Other approaches include MacDermid's selectively plated resistor and Shipley's combustion chemical vapor deposition (CCVD) resistors.

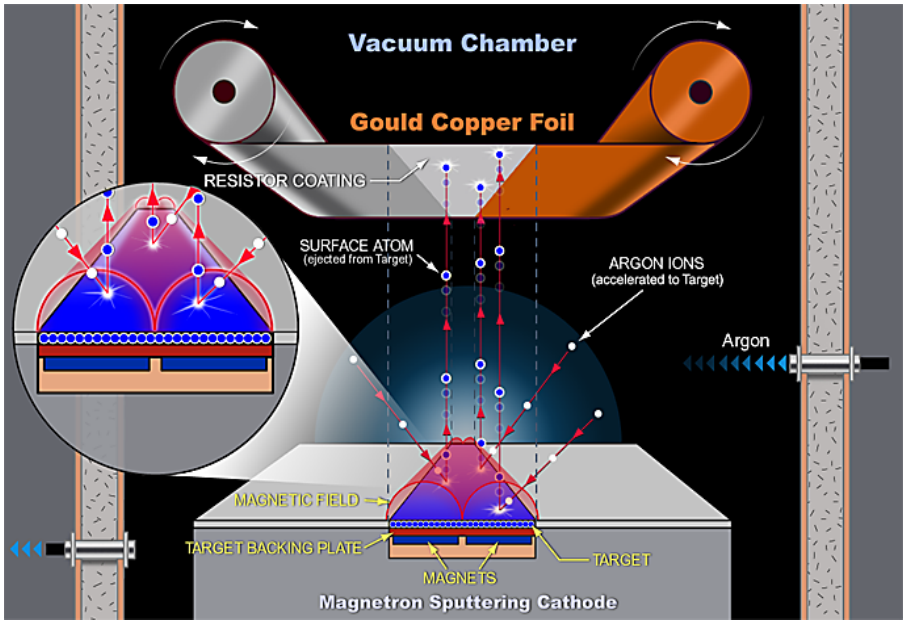

Figure 13 - Schematic Illustrating Vacuum Metallization (Courtesy of Gould Electronic Materials)

Recent process developments have resulted in significantly improved stability of thick film resistors. Their tolerance capability typically ±20-30%, and they are also laser trimmable. Thick film resistors permit a wide range of resistor values available on same layer, and offer a relatively low cost process.

The fired ceramic resistors developed by DuPont involve a new process similar to thick film resistors, but uses pastes based upon ceramic resistor technology. These are very stable and well-understood materials, with a wide range of resistor values. As with the standard thick film resistors, ceramic resistors are laser trimmable and potentially low cost.

Laser Trimming

ESI has developed very capable laser trimming equipment, which can trim resistors to ±0.5% with very fast trim times. Laser trimming is a cost adder, and trimming time and cost are extremely variable and design dependent. Using repeating resistor patterns minimizes probing issues and machine movement time.

Figure 14 shows before and after laser trim results for a carbon loaded polymer thick film. Figure 15 shows the laser trimmer probes contacting the resistor circuit. The resistor is measured while it is being trimmed. Post trimming resistor drift can increase spread of values 2 - 5% depending on the material. Likewise, the printed circuit lamination process often changes resistor values slightly and can introduce variation.

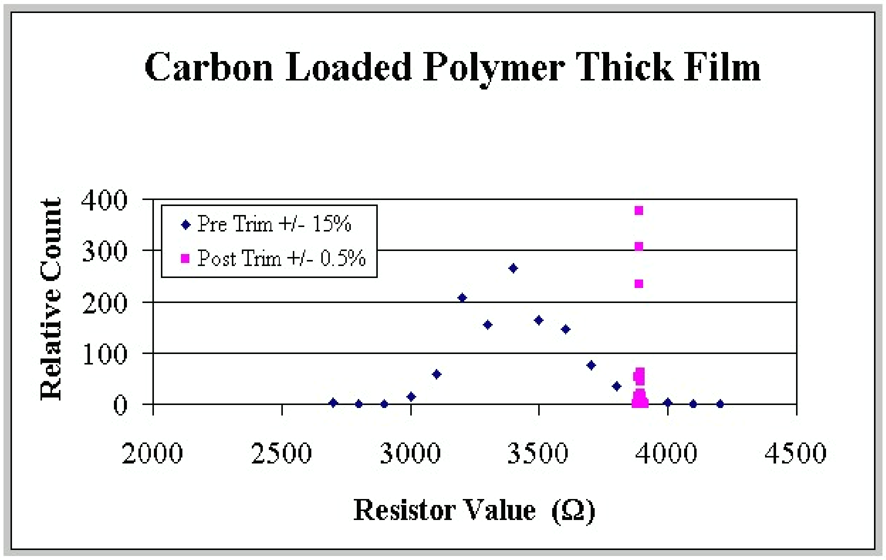

Figure 14 - Before and After Laser Trim Results from ESI Trimmer (Courtesy of ESI)

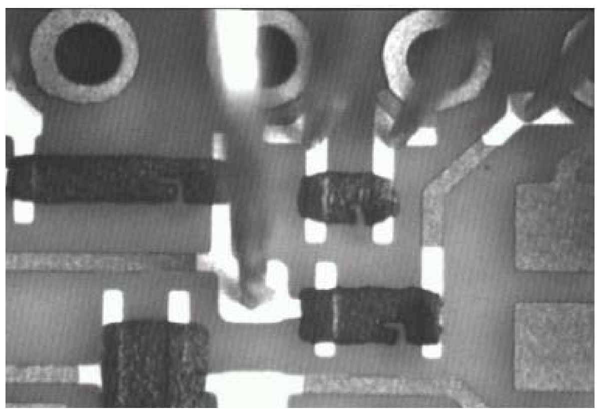

Figure 15 - Photograph of Laser Trimmer Probes on a Trimmed Circuit (Courtesy of ESI)

Design Impact of Embedded Resistors

The following guidelines are useful for determining whether and how to incorporate embedded resistors.

- Determine purpose for using embedded resistors
  - Cost reduction
  - High speed performance
  - Density improvement
- Understand capability of processes available for use
  - Values available
  - Cost drivers
  - Trimmed and untrimmed tolerances
  - Stability
  - Power rating
- Determine requirements of passives
  - Tolerance
  - Value
  - Power rating
  - Signal integrity requirements
- Determine if some resistors must be embedded
  - Certain applications may require embedded resistors for high speed functional performance. If so, consider using the resistor technology to its full extent, as the incremental cost will be low.
- Determine which passives can be embedded

    - Untrimmed
    - Trimmed
    - Values
- Choose resistor technology
    - Higher power, low value = metal based resistors
    - High value, large spread = thick film
    - Tight tolerance = laser trimmed
    - Evaluate if good design practices can be used for the trimmed resistors
- Evaluate for cost effectiveness
    - Determine embedded resistor cost
    - Determine surface SMT cost
    - Consider board size changes, impact on density

Although not a lot has been said in this paper about the use of embedded discrete capacitors, the decision path is identical with that of embedded resistors, substituting capacitor properties. Figure 16 shows a schematic of an embedded discrete ceramic capacitor. The manufacturing process for these is similar to that for ceramic resistors, and the range of ceramic capacitor values is from 150-300 nf/in^2.

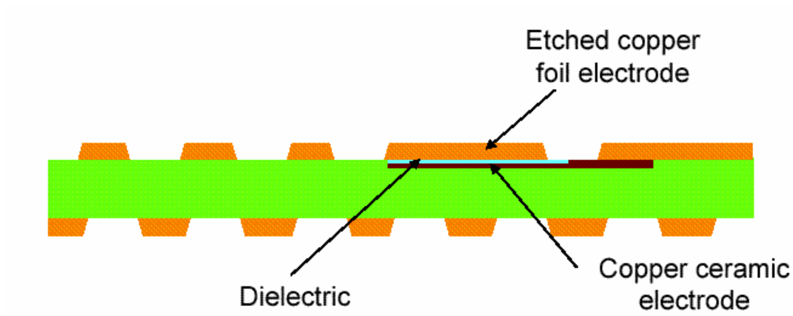

Figure 16 - Schematic of Embedded Discrete Capacitor (Courtesy DuPont, Coretec)

Conclusions

Embedded passive technology is well poised to support high-speed needs of future designs. Many of the newer technologies have already been proven to be reliable and stable in PCB use. However, embedded passive technology is a significant cost adder, and products with a large number of embedded passives are favored in pure economic analysis. Many large systems cards could see a net cost increase, which could be offset by a net increase in system performance. Today there exists significant momentum in technology development, and there are significant gains still to be made as the technology matures.

The NIST/AEPT Consortium work was performed with support of the U.S. Department of Commerce, National Institute of Standards and Technology, Advanced Technology Program, Cooperative Agreement Number 70NANB8H4025.

Bibliography

1. W. J. Borland and S. Ferguson, "Embedded Passive Components in Printed Wiring Boards, A Technology Review," CircuiTree, March 2001.
2. J. D'Ambrisi, D. Fritz, and D. Sawoska, "Plated Embedded Resistors for High Speed Circuit Applications," IPC Fall Annual Meeting, Orlando, Florida, October 2001.
3. J. Dougherty, et al., "The NEMI Roadmap Perspective on Integrated Passives," DesignCon2002, Santa Clara, California, January 2002.
4. J. Felten and S. Ferguson, "Embedded Ceramic Resistors and Capacitors in PWB Process and Design," IPC Printed Circuits Expo 2002, Long Beach, California, March 2002.
5. K. Fjeldsted and S. L. Chase, "Embedded Passives: Laser Trimmed Resistors," CircuiTree, March 2002, pp. 70-76.
6. K. Fjeldsted and S. L. Chase, "Trimming Embedded Passives: Cost of Ownership," CircuiTree, September 2002, pp. 8-14.
7. B. Greenlee, "Processing Thin Core Capacitor Materials," IPC Printed Circuits Expo 2002, Long Beach, California, March 2002.

8. R. Hilburn and B. Greenlee, “Manufacturing Embedded Resistors”, IPC Annual Meeting, November, 2002.
9. L. Marcanti and J. Dougherty, “Embedding Passive Devices Holds Promise for Improving Performance and Space Requirements,” Circuits Assembly, July, 2001, pp. 28 – 31.
10. D. R. McGregor, “Design Considerations Affecting the Measured Capacitance of Embedded Singulated Capacitors,” IPC Printed Circuits Expo 2002, Long Beach, California, March 2002.
11. P. Sandborn, B. Etienne and D. Becker, “Analysis of the Cost of Embedded Passives in Printed Circuit Boards,” IPC Fall Annual Meeting, Orlando, Florida, October 2001.
12. R. Sheffield, “New Technology Subcommittee Mission Statement,” IPC Cyber University, Northbrook, Illinois, December 2002.
13. R. C. Snogren, “A Novel Approach – Embedding Ceramic Thick Film Resistors and Capacitors into Printed Circuit Board Structures,” IPC Cyber University, Northbrook, Illinois, December 2002.
14. J. Zhou, J. D. Myers, and G. R. Dickinson, “Thermal Cycling and ESD Evaluation of Embedded Resistors and Capacitors in PWB,” IPC Fall Annual Meeting, Orlando, Florida, October 2001.
15. J. Zhou, J. D. Myers, and J. J. Felten, “Embedded Passives Technology for PCBs: Materials, Design, and Process,” IMAPS Advanced Technology Workshop, Ogunquit, Maine, June 2002.