PRINTED
CIRCUIT DESIGN

is published monthly by:
UP Media Group Inc.
2018 Powers Ferry Road, Ste. 600
Atlanta, GA 30339

Tel (678) 589-8800
Fax (678) 589-8850

Embedding Resistors and Capacitors

Putting passives in the board saves surface area, shrinks the board and cuts weight and thickness. So what's the hold up?

By Rolf Funer

Microvias have been called the third revolution in printed circuitry. Are embedded passives – resistors and capacitors buried in the board – the fourth, one with even greater potential to change the face of design? While microvia circuits enable higher densities, lighter weight and better performance, the board remains at its core just a bunch of wires. With passives built in, the board is a very different entity indeed.

Embedded passives are a relatively new concept. Why embed them? Lack of space on the board surface. In a typical assembly, components that cost less than 3% of the total price can take up 40% of the real estate! And it's getting worse. As we design boards with more functions, higher clock rates and lower voltages, more power and higher currents are required. Noise budgets go down with the lower voltages, and significant improvements in power distribution systems are needed. More passives are needed. This is why the use of passives is increasing at a greater rate than that of active components.

Placing passives inside the board is one big advantage, but there is another. Surface solder joints produce inductance. Embeddeds eliminate the solder joints, thus lowering inductance, which reduces power system impedance. So, embedding resistors and capacitors saves precious surface area, shrinks the board and cuts weight and thickness. And by eliminating solder joints, reliability is improved (solder joints are the leading failure mode of assembled boards). Embedded passives permit shorter leads and closer component placement, thus enhancing electrical performance.

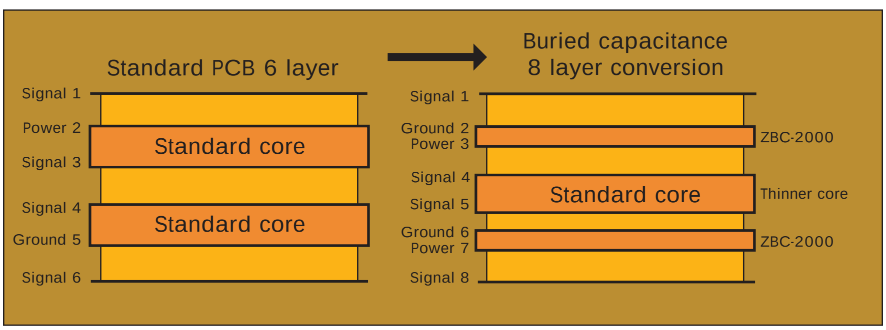

***Figure 1 –** Adding capacitance with thin dielectric power/ground planes*

Plane Capacitance

The most common method for using embedded capacitance involves a concept called distributed or plane capacitance. The starting material is a copper clad laminate with a very thin dielectric layer. This is fabricated into a power/ground pair. The very thin dielectric results in a very close spacing between power and ground. This capacitance can be accessed with conventional plated holes. Figure 1 shows a conventional board redesigned with buried capacitance. Basically, this builds a big parallel plate capacitor into the board.

The level of capacitance achieved depends on the thickness and dielectric constant of the dielectric layer and the size of the board:

$$C = ADkK/t$$

where C = total capacitance
A = area
Dk = dielectric constant
K is a constant
T = thickness

The only true commercial embedded product is BC 2000 (Sanmina-SCI Corp.). While capacitance is low, about 0.5 nF/in^2, it has found good use filtering capacitance. Plane capacitance is particularly valuable in high-frequency situations where the inductance of conventional discrete capacitors increases (see Figure 2).

Several companies are developing new products with higher capacitance. Some are distributed capacitor types; others are discrete embedded caps. DuPont and 3M are developing distributed capacitance products with much higher levels of capacitance by filling the dielectric with barium titanate, a high dielectric constant material. 3M's product, C-Ply, has an epoxy binder, while DuPont's HiK uses a polyimide binder.

Discrete embedded capacitors are created by printing a high dielectric constant paste onto one plate (usually a square of etched copper foil), curing it, and then printing or plating another plate on top. In one novel concept, DuPont prints and fires a high temperature capacitor material onto copper foil in the sizes and locations needed.[1] This is laminated into a circuit and the excess copper etched away. Because these dielectrics have such high dielectric constants (1,000+), high capacitance densities of 100 to 180 nF/in^2 are possible. Shipley's product has an even higher dielectric constant. Some of these newer materials and their properties are shown in Table 1. Not all will make it to commercial use, but some will.

The effect shown on powerbus noise for a test circuit for no caps, discrete decoupling caps and several different distributed cap materials is shown in Figure 3. Note that discrete capacitors lose effectiveness as frequency increases while the embedded ones remain effective up to 5 GHz.

Motorola employs buried capacitance in an interesting way.[2,3] It uses "mezzanine" capacitors made from an epoxy resin paste containing barium titanate. This material is coated onto the board, then discrete capacitors are made by photoimaging. Substrate cost is increased, but assembly cost is reduced so that final module cost is 12 to 14% less. Buried resistors are also used.

The revised design is smaller and lighter in weight, occupying 43% less space than its surface mount counterpart. The technology to make embedded passive circuitry is licensed to three PCB fabricators: AT&S, Wus Circuits and Ibiden. Motorola has built millions of GSM modules with embedded passives.

Embedded Resistors

Two methods are in use for burying resistors. Ohmega-Ply has been around for two decades. It is a bi-metal foil – copper foil with a thin plating of a nickel alloy that becomes the resistor element. This is laminated resistor side down to the substrate. Then by etching the copper and the nickel, patterns of nickel resistors with copper terminations are formed. These are laminated into an internal layer.

Ohmega-Ply has a limited resistance range – 25 to 250 ohms/square – but it is possible to make higher-value resistors by making long

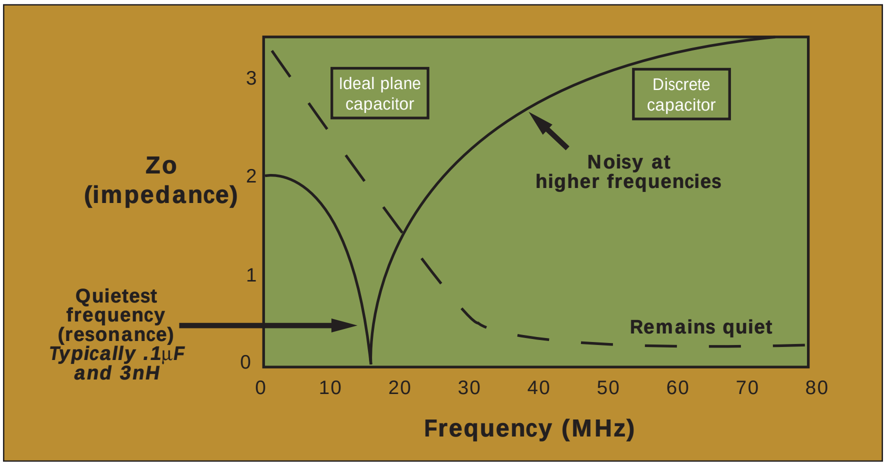

Figure 2 – Resonant discretes vs. nonresonant plane bypass capacitor impedance

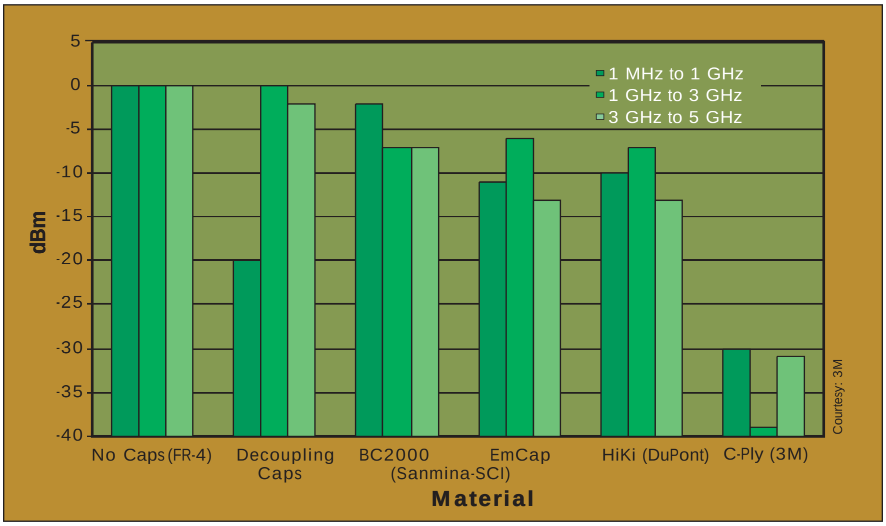

Figure 3 – A comparison of powerbus noise for a test circuit with no caps, discrete decoupling caps and several different distributed capacitance materials

Table 1 – Embedded material types and properties

Manufacturer	Sanmina	3M and licensees	DuPont	DuPont	Shipley
Product	BC2000	C-Ply	Interra	HiKI/HiKII	InSite
Type	Plane	Plane	Plane	Plane or discrete	Discrete
Dielectric	FR-4	$BaTiO_3$ in epoxy	Sintered ceramic on foil	$BaTiO_3$ in polyimide film	Ceramic on foil
Capacitance (nF/in^2)	0.5 - 0.9	5 - 30	150 - 600	1 - 14	>1000

meander patterns (high length to width). The material has been used in communications equipment such as satellites, base stations, medical electronics, avionics and computers. Like embedded capacitors, the resistors save space and weight, and can reduce size. They can also improve electrical performance. For example, see **Figure 4.** This probe card has over 100 resistors and six different values. Note that they are placed directly under the component leads to reduce the signal path to the resistors. **Figure 5** depicts a camera circuit in which the resistors form a rheostat type of pattern. What is noteworthy about this application is that each resistor changes value gradually and, for precision, they are laser-trimmed to +/-1%.

A second way to embed resistors uses resistor pastes. These are resins with conductive carbon or graphite as fillers, screen-printed onto terminations, cured and finally laminated into the board. Connections to components are made with plated holes or microvias. Pastes have been around for a long time and were generally limited by high tolerances and poor environmental resistance, which limited them to consumer applications. A new generation of paste products with better properties has been developed, however, and are finding their way into more sophisticated applications.

One example is Siemens' Simov, a carbon-based resistor paste with a resistance range of 20 to 150 ohms/square and a tolerance of +/-25% at values under 100 ohms and a tolerance of +/-40% at values greater than 100 ohms. It has been used for automotive applications. It is produced by InBoard, a board fabricator owned jointly by Siemens and Sanmina-SCI.

Another paste product, this one developed by Asahi Chemical,[4] has a range of 35 ohms to 1 megohm/square. Motorola has overcome a key limitation of pastes: resistor drift due to corrosion at the copper/carbon interface. Motorola developed a stability promoter that reduces resistance drift to less than 10% after exposure to 85%RH/85°C for 500 hrs. This change is reversible when baked, so it is not indicative of device performance in real operating conditions. The resistors are stable to high temperature as well. Exposure to 5X reflow (peak temperature: 220°C) followed by 500 cycles of liquid-to-liquid thermal shock results in less than a 4% change. Motorola uses these resistors in GSM phone modules.

Pastes have made progress but still have wide tolerances. Are better systems on the horizon? Several emerging materials and processes are in various stages of development (**Table 2**). DuPont[5] prints and fires patterns of high temperature resistor pastes onto copper foil. This sheet is then laminated component side down to an FR-4 core. Photoresist is applied to the copper, exposed, developed and then etched to form circuitry complete with ceramic resistors.

These are similar to the thick-film resistors DuPont sells for copper hybrid circuits with a resistance range of 10 to 100 kΩ/square and temperature coefficients of resistance (TCR) of less than 200ppm/°C. They can be trimmed to +/-1%. Despite its excellent properties, high-temperature nitrogen firing is a new process to fabricators, and will require a major capital investment. Registration of the foil is also a challenge, particularly with HDI and other fine feature boards.

Shipley's Insite is composed of a thin film of doped-platinum deposited directly onto copper foil by chemical vapor deposition (CVC).[6] This foil is laminated, resistor side down, to an FR-4 prepreg. Three etchings are used to remove most of the copper and the excess resistor material, and finally to remove copper to expose the resistors, leaving only the pads and traces. High

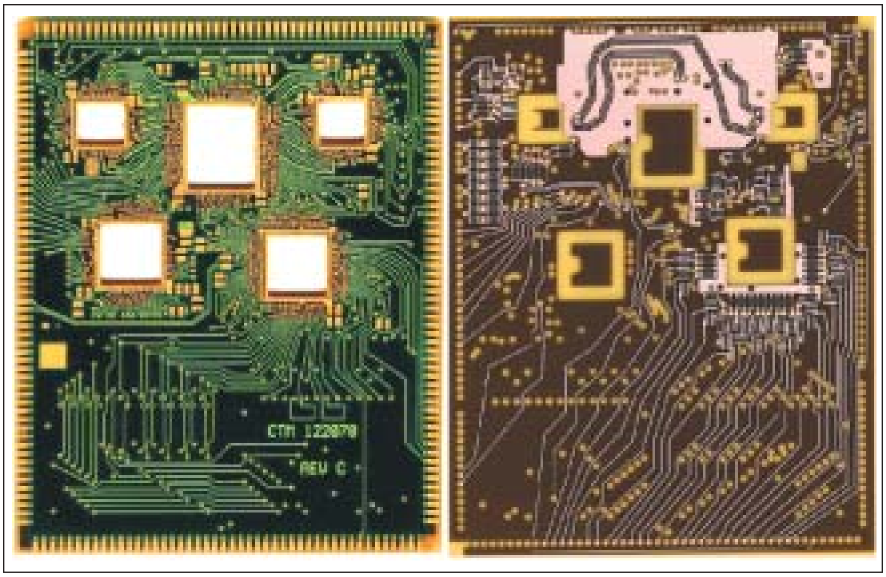

***Figure 4 –** Outer- (left) and innerlayer (right) of a probe card with buried passives. To reduce signal path, resistors are placed directly under component leads*

Table 2 – Embedded resistor products

Manufacturer	Ohmega	Siemens/Sanmina	Asahi Chemical	Shipley	DuPont	MacDermid
Product	Ohmega-Ply	Simov	TU-00-8	InSite	Interra	M-Pass
Resistor Material	Nickel alloy foil	Carbon paste	Carbon paste	CVD Pd alloy	Sintered ceramic	Plated nickel alloy
Range (ohms/ square)	25 - 250	25 - 150	35 - 1meg	25 - 1meg	10 - 10k	25 - 100
Tolerance (untrimmed)	10%	25 - 40%	20%	10 - 20%	5 - 10%	10 - 15%

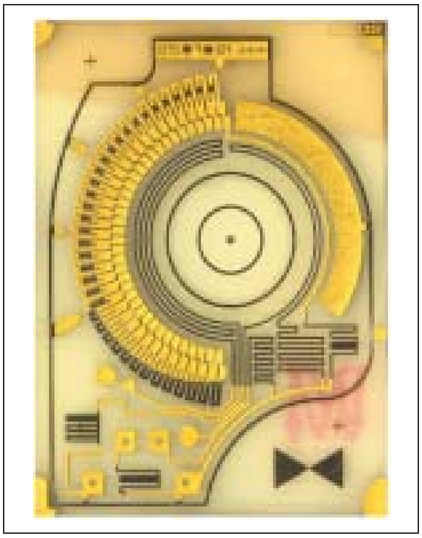

Figure 5 – *Circuit for a camera, with resistors forming a rheostat type of pattern*

sheet resistivity of 1,000 ohms/square with excellent tolerance is reported.

Finally, MacDermid is working on plated resistors. This involves sensitizing the FR-4 surface in the sizes and locations desired, then plating a nickel metal alloy directly onto the sensitized areas. The resistors have a low and narrow range (25 to 100 ohms/square) meaning long patterns are required to get to high values. They are also difficult to plate to tight tolerances though this can be achieved through laser trimming.

CAD Tools Need Work

Much needs to be done to develop design and test for embedded passives. The commercial products, BC2000 and Ohmega-Ply, are well supported. Ohmega-Ply has a particularly useful design guide. CAD software for virtually all the new systems is still under development, as are modeling and simulation tools. But board shops are set up for testing opens, shorts and impedance. For embeddeds, new test equipment and procedures are needed.

Testing of embedded resistors is currently done at both the innerlayer stage and on the finished board. The innerlayers are tested to ensure that the resistors are in value before proceeding to lamination. This is done using a bed-of-nails fixture, but one has to take care that the measuring current does not exceed the rated current. Test must be performed again at the finished board stage to ensure that the resistors have not been damaged during the lamination process.

In testing for embedded capacitors, the coupled power/ground plane must be "high pot" tested to ensure no shorts have developed in the thin dielectric. Capacitance is usually not tested after final fabrication. The development of better design tools and test methods is an integral component for broad use and acceptance of embedded components.

Cost is a complex issue. Compared to discrete devices, embeddeds are more expensive. But for a more accurate picture, the benefits of design improvements (smaller size, fewer layers, lighter weight), assembly savings (switching from double-sided to single-sided assembly), and possible performance improvements must be taken into account. As processes improve, volumes increase and competitive forces emerge, and costs are sure to drop. Microvia boards evolved this way.

A rule of thumb: the more passives, the better. Embedded passives are made by "mass formation," in which all passives are formed at once. Whether a design has one or 1,000 passives, the cost will be about the same. The most cost-effective designs have high passive counts (at least 5 to 10/in^2). Up to a 30% cost benefit is documented when all cost elements are included.[2]

Are they ready for wide use? The short answer is not quite yet. BC2000 is in fairly broad use. Same goes for Ohmega-Ply. The newer materials show promise, but will be subject to the standard "shake out." Fabricators need embedded experience. Design tools, testing, quick prototyping and the rest of the infrastructure are just not here yet. But because the benefits are huge, the change will come. And now is a good time to prepare.

References

1. J. Felten, et. al., "Embedded Ceramic Resistors and Capacitors in PCB: Process Performance," IPC Printed Circuits Expo Proceedings, March 2002.
2. John Savic, et al., "Embedded Passives Technology Implementation in RF Applications," IPC Printed Circuits Expo, March 2002.
3. Robert Croswell, et al., "Embedded Mezzanine Technology for Printed Wiring Boards," IPC Printed Circuits Expo Proceedings, March 2002.
4. Isao Morooka, "Developments in Polymer Thick Films," *EP&P*, January 1993.
5. William Borland. et. al., "Embedded Passive Components: A Technology Review," *CircuiTree,* March 2001.
6. Percy Chinoy, et. al., "High Ohmic Value Embedded Resistor Material," *CircuiTree,*, March 2002.

Rolf Funer is the principal consultant for Funer Associates (Greenville, SC). He has over 20 years of experience in interconnect materials development and fabrication and will be speaking on this topic at PCB West and HDI Expo 2003 in March.