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"Built-In-Trace" Resistors

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Abstract
The newly developed Ohmega-Ply "Resistor-Built-in-Trace" technology uses low-ohmic resistive materials for embedded resistors congruent to the circuitry in a multilayer PCB or HDI substrate. High frequencies and miniaturization has created the need for miniature resistors. Until now, the paradigm of the shape of an embedded resistor was the same as an SMT resistor, a discrete-like component having a definite width and length and occupying space. The new "built-in-trace" technology uses the signal path itself for the resistor and, therefore, requires no additional board area, thereby enabling higher I/O and component densities and reduced form factors. A "virtual component" is created by the gap in the conducting trace crossed only by the thin-film low ohmic resistive layer. No terminating conductive pads are required, the trace merely continues along its path. The CAD layout is simplified by the elimination of the resistor footprint. Low ohmic materials of 10 ohms per square or less yield tight tolerance of 3% or less so that the tolerance of the resistive element is equal to or better than the tolerance of the characteristic impedance of the circuit trace thereby improving signal integrity. The equivalency of the resistor width and trace width tolerances means that any manufacturing process capable of producing a controlled impedance PCB will be capable of producing the built-in-trace resistors to the required tolerance without resistor trim.

Introduction
Requirements for improved signal integrity and high-density designs drive the need to embed terminating resistors beneath and within BGA arrays. Increasing I/O densities increase pin counts faster than the number of channels available for the signals to escape the array. Parallel terminating resistors embedded in an existing voltage plane become the preferred embedded passive design. However, reductions in the BGA pitch reduce the channel width between pads to the point where there is insufficient space for standard planar resistor designs. Under present design constraints, resistor terminations and resistive elements within the footprint of a microBGA can be no wider than the circuit trace itself.

The "Resistor-Built-in-Trace" technology also called ORBIT resistors[1] (referred hereafter to as "built in resistors") was developed to accommodate the new design requirements and was based on the recognition that resistor "built-in-trace" designs are best achieved through the use of a congruent print and etch trace technology (i.e. do one at the same time as the other). The result is the abandoning of the paradigm of the discrete-like planar resistor in favor of a new paradigm of planar resistors built into conductive circuitry and congruent to the circuit trace itself. This reverses the trend toward high sheet resistivities for the short discrete-like embedded resistors. Narrow widths mean higher aspect ratios (length to width ratios) so that sheet resistivities are driven down. The resistive material used in the following design has a sheet resistivity of ten ohms per square.

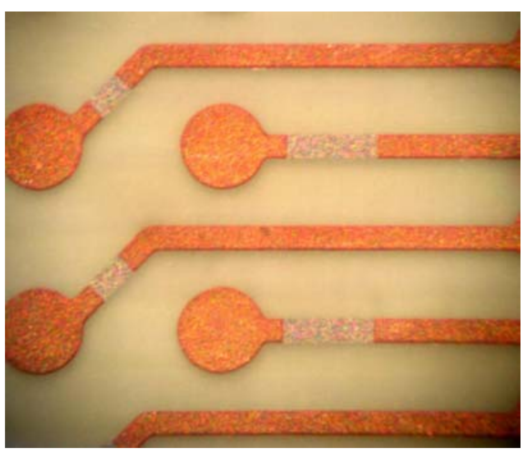

Figure 1 – Built-in-Trace Resistors

Matching the Characteristic Impedance Z_0

High-speed digital electronics requires terminating resistors for impedance matching. The characteristic impedance (Z_0) of the transmission line is a function of inductance and capacitance. For the purposes of this discussion, the characteristic impedance will be considered in relation to the circuit trace width. The ohmic value is inversely related to the trace width (the narrower the trace, the higher the impedance) as expressed by formulas well known to the industry.

The ohmic value of any resistor (R_n) used to terminate a high-speed digital signal is a function of the device impedance (Z_n) and/or the characteristic impedance of the circuit (Z_0) as shown,

a. Parallel Termination, $R_n = Z_0$
b. Series termination, $R_n = f(Z_0, Z_n)$

PCB processes must be capable of producing a circuit trace within the required width tolerance to achieve the required characteristic impedance tolerance. An existing algorithm for planar resistor technology defines the resistance in ohms as a function of the sheet resistivity (Rs) in ohms per square times the number of squares (ratio of length to width). The variation in the resistive element geometry (length versus width) is defined as an "etch factor tolerance" (T_f). The material percent tolerance and etch factor tolerance is used to compute the minimum element size necessary to hold a specified resistor tolerance.[2]

The resistance (R) and the etch factor tolerance (T_f) are expressed algebraically as shown:

$R_{ohms} = Rs \times N$ where $N = L/W$ (eq.1)
$T_f = f_1/W + f_2/L$ see below (eq.2)

Where f_1 and f_2 is the variation attributed to the first etch and second etch, respectively, and L and W are the length and width of the resistive element. For miniature planar resistors, the width and length becomes very small and the etch factor T_f becomes large increasing the percent tolerance of the planar resistor.

For the embedded resistors, the resistor width equals the trace width and the length becomes so long relative to the etch factor tolerance that the second term f_2/length approaches zero. Tolerance will be a function of the width with that width being identical to the circuit trace width and the resulting tolerance lower than that of a standard planar resistor. For precision PCB manufacturing, photolithography replaced silkscreen processes years ago and is doing so again to achieve tight tolerances for controlled impedance and embedded passives. Tolerance requirements for miniature resistors require tighter material tolerances than the five percent industry standard. The built in resistive material tolerance is three percent.

It should be noted that the built in resistor tolerance will be equal to or better than the characteristic impedance tolerance because variations in the dielectric constant, dielectric thickness or trace thickness affect the ohmic values of the characteristic impedance but have no effect on the ohmic values of the resistors. The elimination of series inductance and the inductive reactance of the SMT resistor make a 10% planar resistor better than a 1% SMT resistor.[3]

Design Methodology

A built in resistor test pattern was designed on a single layer modeled on an existing layer of a PCB design with a 1.25mm BGA footprint and five mil lines and spaces. Terminating resistors had ohmic values of 22, 50 and 100ohms. No design changes were made to the original layout and routing. Because the built in resistors follow traces, some of the resistors included features such as 45° bends in the resistor elements. The identical gerber data was used for the built in resistor layer as was for the original SMT design. The only modification of the design was the creation of a second print photo mask ("resistor define" artwork). The second print and etch steps create the gaps in the traces needed to produce the resistor elements. The CAD layout was simplified by holding the trace widths constant and by the elimination of the resistor pads and the attendant design rules. There was no component library. A "parametric design" method was followed wherein the resistor ohmic values and tolerances were entered into an EXCELL spreadsheet program that, based on the aforementioned equations one and two, calculated the resistor lengths to be defined by the second print artwork. The composite of the two artwork patterns is shown in Figure 2.

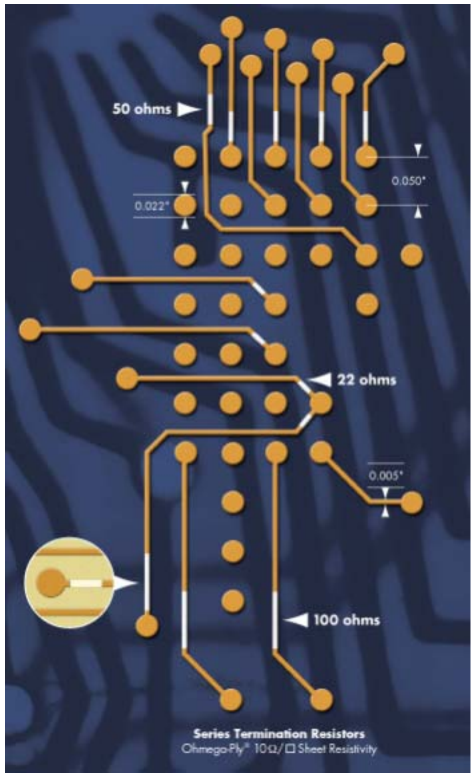

Figure 2 – "Built-in-Trace" Series Terminating Resistors

Materials and Processes

Analysis of the BGA pitch, pad diameters, spacing and traces widths indicated an ideal sheet resistivity of 10 ohms per square (e.g. a 50ohm resistor in a five mil trace has a resistive element twenty-five mils long). Target tolerances of +/-5% to +/-10% for untrimmed resistors require a starting thin film material tolerance no greater than three percent. The ten ohm per square sheet resistivity was achieved using a standard nickel-phosphorous layer electrodeposited one micron thick on 17 micron ED copper foil. The thicker deposit enabled tighter tolerances. Lower and upper 3-sigma statistical process control limits were set at 9.75ohms to 10.25ohms to achieve a sheet resistivity of 10 ohms +/-2.5%. The built in resistor material was bonded to a high Tg epoxy substrate. No change in the sheet resistivity occurred during lamination. The laminate met the resistor specification tolerance of +/- 3.0%. The laminate was supplied to a qualified PCB manufacturer along with gerber data for the built in resistor film set and the first and second print artworks. For the purposes of this experiment, the trace widths were increased to seven mils. No other change was made to the original design. The CAM operators panelized and edited the design and added eight coupons. Forty PCBs with built-in-trace resistors were placed on an 18" by 24" panel. The panels were printed and etched using standard PCB photolithographic processes and submitted for testing.

Electrical Test Results

We measured the resistor arrays on each of several PCBs on each core. The resistors were seven mils wide by twenty-four mils long. A total of 144 resistors were electrically tested using a digital ohm meter and an HP Data Acquisition System. The overall percent tolerance was +/- 6%. Optical measurement of resistors at the maximum and minimum ohmic values indicated that almost all of the variation could be attributed to line width variation. For statistical analysis, we measured arrays of straight (three-square) resistors only, however, a small number of resistors with 45° bends were tested. The results showed that the bends had no effect on the resistance value (serpentine resistors with 90° bends exhibit a "corner effect" that reduces the resistance of the corner square by a factor of 0.56 squares. No such effect was detected on the 45° bends). The purpose of the coupons was to detect resistance variation due to material and process variation independent of the resistor etched width and length, however, the test coupons showed a sheet resistivity almost identical to the original resistive material, 10.3 ohms per square +/- 3.0%. The means that the PCB manufacturing processes had almost no effect on the low-ohmic material other than those effects induced by changes in geometry (width and length variation).

Reliability Testing

The next step was to make test panels for reliability testing. An "L Pattern" was selected in which the length to width aspect ratio set at 10:1 (10 squares) is kept constant while the resistor size increases. The resistors met or exceeded the performance and reliability specifications for thin-film planar resistors. The improvements are attributed to the thicker resistive layer. Comparative results are shown on Table 1.

Table 1 – Reliability of Resistors

OHMEGA-PLY® RCM PROPERTIES AND SPECIFICATIONS						Remark and Condition
Sheet Resistivities	10	25	50	100	250	
Material Tolerance	+/-3	+/-5	+/-5	+/-5	+/-10	
Load Life Cycling Test (Δ R%)	<0.4 (after 1000 hrs)	<5	<5	<5	0.5 (after 1000 hrs)	MIL-STD-202-108I Ambient Temp: 70C On Cycle: 1.5 hrs Off Cycle: 1.5 hrs Length Of Test: 10000 hrs
Current Noise Index in dB	<-16	<-15	<-15	<-15	<-15	MIL-STD-202-308 Voltage Applied: 10 ohm/sq.: 53.2V 25 ohm/sq.: 5.6V, 100 ohm/sq.: 7.9V
Short Time Overload (Δ R%)	0	0	0	0	0	MIL-R-10509 Method 4.6.6 Power:2.5 X Rated Time: 5 sec
Resistance Temperature Characteristic(RTC) PPM/°C	20	50	60	100	100	MIL-STD-202-304 Hot Cycle: 25°, 50°,75° 125°C Cold Cycle: 25°, 0°,-25°, -55°C

Power Loading

The resistor power rating and power density was determined by standard "short term load" step-to-failure tests in which the applied power was increased until the resistors became unstable or opened.[4] As expected, reducing the sheet resistivity by increasing the resistive film thickness resulted in higher power densities. The results were plotted on Figure 3.

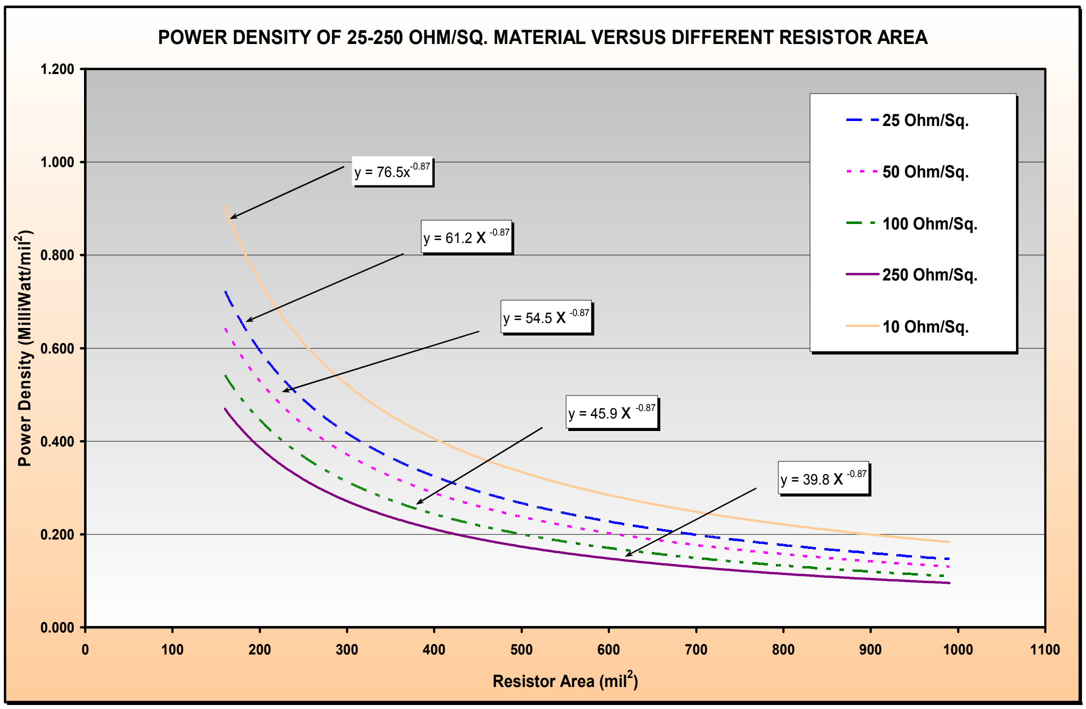

Figure 3 – Power Density of Resistive Materials

Significance of Findings

The significance of the built in resistor technology is found in its size, accuracy and simplicity. The experiment shows that reliable miniature resistors can be embedded in a microBGA footprint by following the circuit path. An example of this, for a telecom switching card, can be seen in Figure 4. The simplicity of the CAD design is due to the elimination of the resistor pads and the predicted accuracy with which the resistors can be made. The target value of a terminating resistor corresponds to the characteristic impedance. The equivalency of the "built-in-trace" resistor and circuit trace width tolerances means that any manufacturing process capable of producing a controlled impedance printed circuit board or high density interconnecting substrate will be capable of producing "built-in-trace" resistors of the required tolerance. Standard embedded planar resistor yield estimation is taken from process capability charts and tables based on tolerances and line widths. Because length variations have little effect on "built-in-trace" resistor tolerances, yield estimates based on resistor tolerances and trace widths should be predictable.

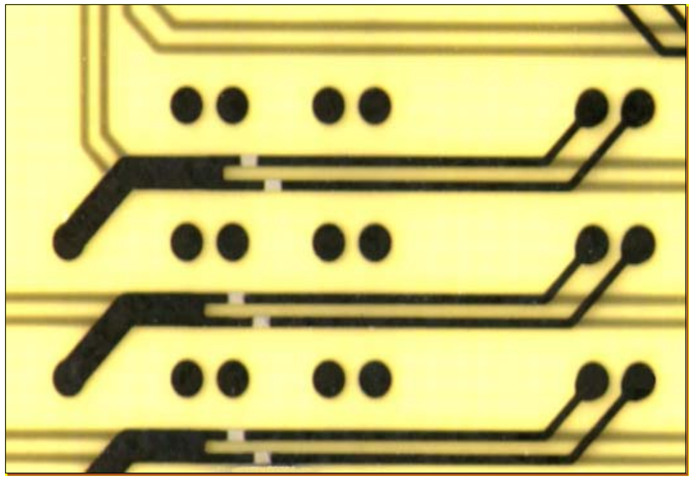

Figure 4 – Series Terminating Resistors in a Telecom Switching Card

Conclusion

Built in resistor technology is a reliable method for embedding tight tolerance resistors for BGAs or other high-density applications where channel widths constrain the resistor size. The increased thickness of the low-ohmic resistive materials results in tighter tolerances and greater stability than conventional higher ohmic resistive materials. The effect due to process variations is negligible hence there should be a high correlation between the laminate sheet resistivity and the ohmic value of the etched resistors. Built in ("embedded") resistors can achieve tight tolerances with high yields with few or no design iterations and meet planar resistor thin-film performance and reliability requirements.

Acknowledgement

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References

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