Designing Resistors to Embed

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Abstract
Embedding resistors right into the printed circuit board substrate is not new, but it is gaining momentum as a rapidly emerging and pivotal technology for the PCB industry, perhaps preceded only by the plated thru hole in the 50s and microvias in the 80s.

Embedding resistors requires designing resistors. Designing resistors requires understanding the resistor manufacturing process. Resistor materials are available in a wide range of values and technologies. This paper is written from a design for manufacturing perspective and includes guidelines for designing resistors with commercially available materials and manufacturing technologies to embed directly into the PCB substrate.

Background
Dr. Richard Ulrich[1] states "Integrating passive components directly into the circuit board is a well-established idea but an immature practice". This is true. The reality is that embeddable resistor materials and processes have been around since the late 60s. Early on, most applications used the resistors on the surface of the PCB. Within the last few years, the resistor materials have moved inside the PCB. Today there are only two basic material technologies for embeddable resistors, thin-films and thick-films. Thin-films, by definition, are less than 1µ thick and typically are metal and may be as thin is 0.05µm Thick-films, therefore, would be greater than 1µm thick and typically are polymers or ceramics in the range of 10 to 25µm. Although ceramic thick-films (CTF) have been in use in the hybrid industry, in harsh environment applications, for over 25 years and processes have been developed[2 3] to incorporate these materials into the PCB substrate, as of this writing, they are not commercialized. This leaves us with thin-films and polymer thick-films (PTF). These are viable, commercially available, mature materials and processes. Properties of these materials as embedded resistors are summarized in Tables 1 and 2.

Manufacturing Embedded Resistors
<u>Thin-film materials</u> – These materials come to the PCB manufacturer as a laminate clad on one side with the copper/resistive element and on the other with copper foil. Other than their label, they look just like any other standard copper clad laminate used to manufacture inner-layers of a multi-layer-board (MLB). Resistive elements are deposited on one side of the copper foil by electroplating NiP, nickel phosphorous,[4] vacuum deposition nickel chromium or nickel chromium aluminum silicon[5] or sputtering doped platinum.[6] Another thin-film process utilizes an electroless deposition of nickel phosphorous[7] directly on the etched and masked PCB inner layer. This process is not

Table 1 – Properties of Thin-Film Resistors in PCB Substrates

Resistance	Sheet resistance tolerance	CV (coefficient of variance)	TCR (temperature coefficient of resistance)	Solder float	Temperature exposure	Humidity exposure
(Ω/ÿ nominal)	(%)	(%)	–65^0 C to +125° C (ppm/^{0}C)	(%Δ R) after 20 sec @ 260°C	(%ΔR) after 1000 hrs @ 70°C	(%Δ R) after 240 hrs.@ 40°C and 95% RH
10	+/-3	+/-3	+/-5	-0.02	NA	0.25
25	+/-5	+/-5	-50 to 110	0.5	0.5	0.5
50	+/-5	+/-5	-60	0.75	0.75	0.75
100	+/-5	+/-5	-80	1.0	1.0	1.0
250	+/-10	+/-10	100	0.5	1.0	2.0
500	+/-10	NA	100	NA	NA	NA
1000	+/-10	NA	100	NA	NA	NA

Note: Properties vary depending on the resistive material, foil used, resistor value range, aspect ratio, type of substrate, termination design, and other manufacturing conditions. Reported data is limited. The above is a summary extracted from technical articles and vendor data sheets [4,5,6,7]

Table 2 – Properties of Polymer Thick-Film Resistors in PCB Substrates

Resistance range	Sheet resistance tolerance	CV (coefficient of variance)	TCR (temperature coefficient of resistance)	Solder dip	Temperature exposure	Humidity exposure	Humidity exposure
(Ω)	(%)	(%)	-30^0 C to $+100^0$ C (ppm/°C)	(%Δ R) after 3X260°C	(%ΔR) after 1000 hrs @ 100°C	(%Δ R) after 1000 hrs.@ 40°C and 90% RH	(%Δ R) after 500 hrs.@ 85°C and 85% RH
10 to100	+/-10	2 to 6	+/-250	-2 to 2.5	0 to -2.5%	0 to 2%	-3 to 5%
10K to1Meg	+/-10	2 to 8	+/-750	-5 to 2.5	0 to -5%	0 to 5%	0 to 5%

Note: Properties vary depending on the material source, resistor value range, thickness, aspect ratio, cure, type of substrate, termination design and finish, and other manufacturing and design conditions. Reported data is limited. The above is a summary extracted from several technical articles and vendor data sheets.[8, 9, 10]

chromium aluminum silicon[5] or sputtering doped platinum.[6] Another thin-film process utilizes an electroless deposition of nickel phosphorous[7] directly on the etched and masked PCB inner layer. This process is not yet commercially available. The thin film process is very similar, except for the chemistry of the etchant required to remove the unwanted resistive material. Figure 1 illustrates the basic resistor print and etch process. Note that the resistive element stays under the remaining copper. Also, there is a variation for one material where the resistive element in (Figure 1a) is removed simultaneous with the primary copper etch using a cupric chloride etchant. The second copper etch (Figure 1d) requires the use of an ammoniacal etchant.

Termination: If the process sequence is as shown in Figure 1, the relationship between the resistor element and the termination is virtually perfect. Etch tolerance does have an affect on resistor value or tolerance. Figure 2 illustrates the compensations that the PCB manufacturer makes to the design artwork and the resultant copper feature tolerance. For half ounce copper, most commonly used with embedded resistors, the etch tolerance is +10 µm to –0.5 µm.

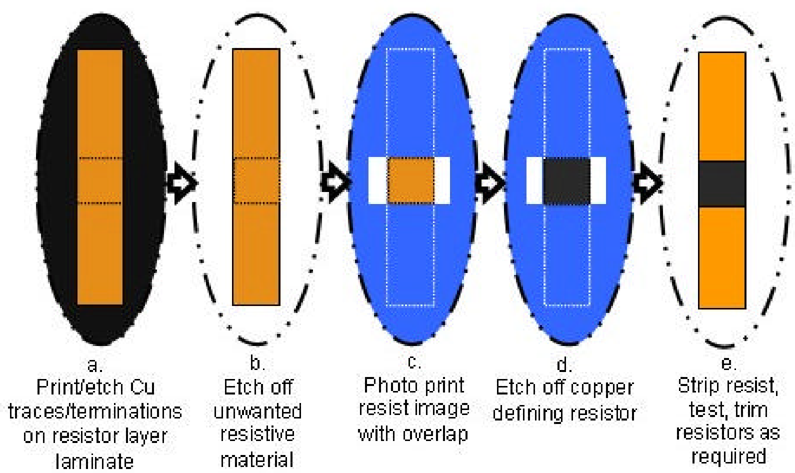


Figure 1 - Thin-film photo print and etch process

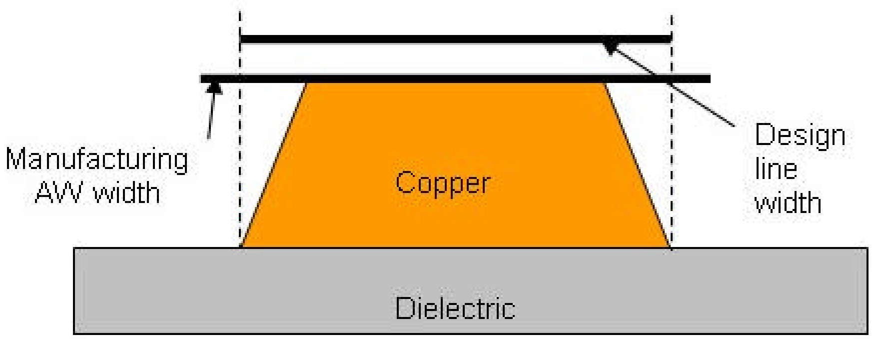


Figure 2 - Etch tolerance
(+10 µm to –5 µm for 17 µm Cu)

This tolerance applies both to the resistor length and width, since they are both controlled by the copper etching process. However, there are two etch processes, one controlling the length and one the width. They are performed at different times and the odds are that the direction of the tolerances will vary. In addition to the etch tolerance, the raw material tolerance must be considered. Table 1 gives the raw material tolerances for different materials and they range from 3% to 10%. Tables 3 and 4 show the affects of aspect ratio and resistor size resistance tolerance. Bigger is better in terms of tolerance.

Table 3 - Effect of Etch and Sheet Resistance Tolerance

Resistor width and length vs resistance and tolerance range for a nominal 50 ohm thin-film material								
Length (mm)	Width (mm)							
	0.1		0.25		0.5		1.0	
	R (ohms)	Tol range (%)	R (ohms)	Tol range (%)	R (ohms)	Tol range (%)	R (ohms)	Tol range (%)
0.1	50	41	20	32	10	29	5	28
0.25	125	31	50	23	25	20	12.5	18
0.5	250	28	100	19	50	16	25	15
1.0	500	27	200	18	100	15	50	13

Table 4 - Effect of Square Size on Tolerance of a 50 ohm thin-Film Resistor

Size vs. tolerance		
Square resistor size (mm)	Total tolerance (%)	Etch contribution only (%)
0.10	41.0	29.4
0.25	22.5	11.9
0.50	16.3	6.0
1.00	13.1	3.0
2.50	11.3	1.2
5.00	10.6	0.6
10.00	10.3	0.3

Polymer Thick-Film Materials

These materials come to the PCB manufacturer in plastic containers or pails. They are commonly called inks or pastes and are applied to the etched inner layer by a screen printing process and cured. Inner layers are manufactured in the conventional manner. Layer scaling may be slightly different to accommodate the dimensional changes of the laminate during cure of the resistor paste. The manufacturing process is relatively simple (see Figure 3). Virtually all PCB fabricators screen print legend and some other materials, yet the precision screen printing art has been lost over the years. Shops wanting to screen print resistors have to basically relearn their precision process. Not difficult, but must not be overlooked.

Barrier plating: For most applications, a barrier plating, typically immersion silver, is applied to the termination area to stabilize the resistance between the resistor element and the copper termination. The contact resistance mechanism was studied with electrically conductive adhesives by Lu et. al.[13] He suggests that galvanic corrosion is the dominant mechanism for a metal oxide formation and the resultant unstable contact resistance between conductive adhesives and non-noble metals. Motorola expanded on this notion and added a noble metal (electroless silver plate) between the copper and the PTF resistor element resulting in a very stable interface after environmental stress.

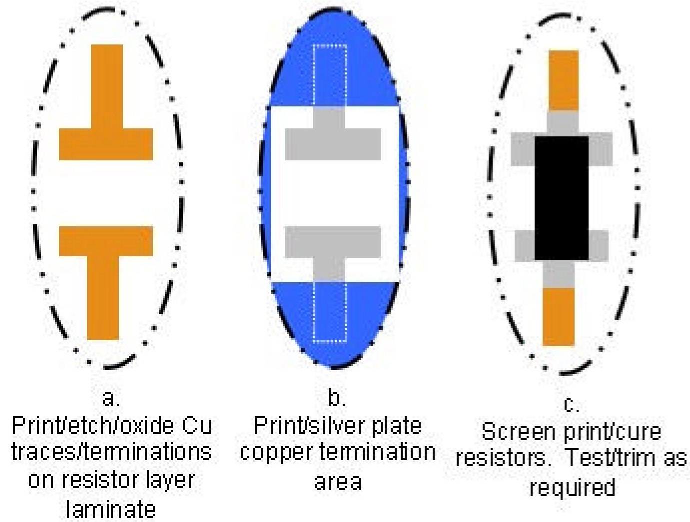


Figure 3 - Polymer thick-film print process

Termination: Another key issue is termination. As the inner layer fabrication process has its own set of manufacturing tolerances, so does the screen printing process. When the PTF image is printed on the previously imaged inner layer, there must be sufficient tolerance designed in both the layer and the resistor pattern to accommodate the merging of these two processes. Simply, the terminations must be wider than the resistor and the resistor must be longer than the space between terminations. (See Figure 4). T_E is the terminal extension beyond the resistor element. L_E is the resistor pattern length extension beyond the termination.

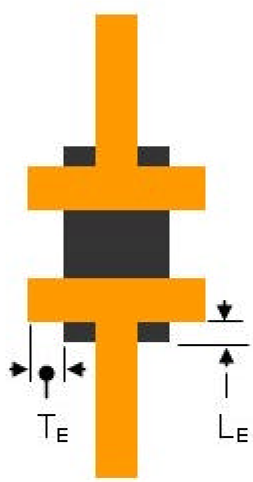


Figure 4 - Resistor terminations, critical manufacturing tolerance

Tolerance: The tolerance of PTF resistors is affected by many factors including variations within the resistor paste, lot-to-lot, within a lot, and within a print. Further, the consistency of the screening process is affected by the squeegee durometer, angle, pressure, and rate of travel; screen snap-off distance, screen material, mesh, tension, age and ink build-up; and the quality and durability of the emulsion. These variables affect the geometry of the resistor and the quality of the print. The termination pattern also affects the tolerance. The resistor length is established by the etch tolerances. The width and thickness result from the artwork, screen, and the screen print process, all of which affect the resistor geometry and tolerance.

The resistor size and termination have a tolerance affect as well. The cross section of the resistor is not a neat and tidy rectangle. See Figure 5. The edge definition is also not neat and tidy. See Figure 6. The larger, longer or thicker the resistor, the less effect these dimensional variations affect the resistance variation. Conversely, the smaller the resistor the greater the affect of the dimensional variations. Although we use ohms/square and squares to design resistors, the concept is not absolute due to the variations. In addition to these variables there is the geometry of the termination and standard variations in copper etch which affect the resistance path. The finished tolerance for etched features on 17 µm copper is +10 µm to –0.5 µm. We are dealing with a space rather than a line, yet the tolerance is still the same for the space. For a 250 µm long resistor that can contribute 6% to the tolerance variance, however, if the resistor is 1.5 mm long the variance drops to 1%. Wider is also better, the affect of edge irregularities diminishes with increased width. Motorola has also studied the affects of thickness on resistor value[11] and has demonstrated that beyond a thickness of approximately 80 µm, resistance is virtually insensitive to small thickness variations.

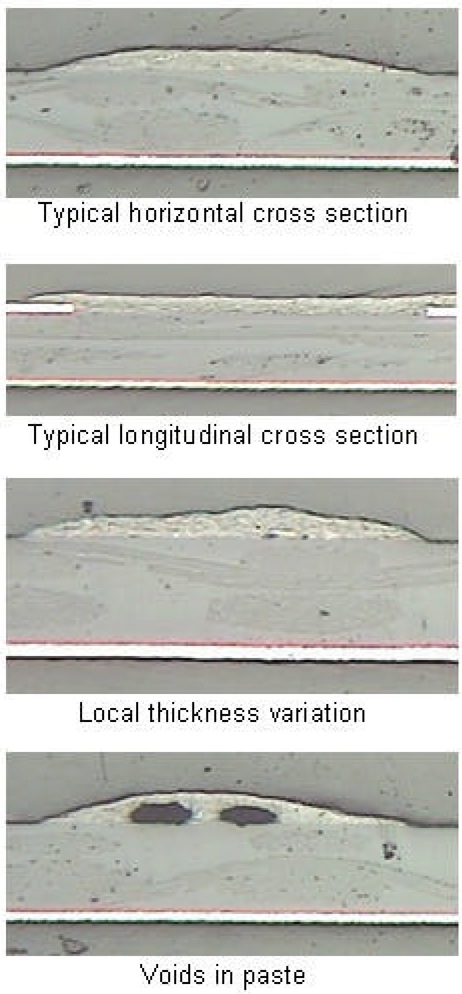


Figure 5 - PTF Resistor Cross Sections showing Variations

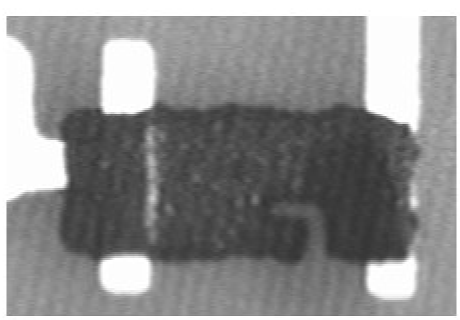


Figure 6 - PTF Resistor Surface View showing Irregular Edges, Laser Trim Cut, and Silver Terminations

Number of resistor values and number of prints: Every additional resistor value on a given layer reduces the PCB manufacturer's ability to achieve a consistent tolerance. Adding multiple prints to a given layer further reduces the resistor consistency.

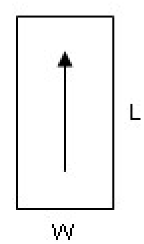
Designing Resistors to Embed

In addition to design tools, which is not the topic of this paper, untrimmed resistance tolerance, termination registration, orientation, size, and power handling are the top design issues for embedding resistors. None of these are showstoppers – all of these have logical rules. Since thin-film and PTF materials have different considerations, we will address these issues separately for each material type.

Motorola, more than anyone else, has commercialized embedded PTF resistors in high volume cell phone and other hand held applications. As a result, they and their suppliers have gained a wealth of experience, which they continue to share with our industry.[11, 12]

Untrimmed Resistance Tolerance

Thin-film materials: As mentioned earlier and illustrated in Tables 3 and 4, resistance tolerance is dependent on the raw material sheet resistance tolerance plus the manufacturing etch tolerance. The sheet resistance tolerance is reported in the supplier literature and should be a requirement of material specifications. The etch tolerance depends on the individual PCB manufacturer and that information is readily available for the asking. Using the following relationships, it is easy to create a spreadsheet calculator to predict the final resistor tolerance. Using a simple resistor element as shown in Figure 7, the arrow is the current flow, W is the width at the termination, and L is the length between terminations.



R = resistance in ohms

$R = A \times S_R$ where:

A = aspect ratio = L/W

S_R = sheet resistance

Figure 7 - Resistor Element

The maximum resistance will occur when the etch tolerance causes the smallest W and the largest L. Conversely, the minimum relates to the largest W and the smallest L. When this is determined, simply add the sheet resistance tolerance resulting in the manufacturable tolerance. To do better than that total tolerance requires trimming. If trimming is to be used, then the resistor element pattern must be designed where W is approximately 30% larger than the calculated nominal resistance required. This allows for trimming the resistor "up" to the specified value.

PTF materials: The only general rule we can make is that untrimmed PTF resistors will be in the range of +/-40%. Less than that is possible. Boards are manufactured today, in volume, at +/-20%.[11] In some applications, tolerances of +/-15% have been achieved with limited success (low yields). Again, size is a factor and although "bigger is better", the trend is to "smaller", which complicates achieving the lower tolerances. It is essential to work with a PTF resistor material supplier and PCB manufacturer in the design stage, if tolerances less than +/-40% are required. Material and process tests must be performed to characterize the process and determine the tolerance achievable for a particular design and material set.

Termination Registration

Thin-film materials: Figure 4 illustrates termination registration. For thin-films, the registration of the termination and resistive element are virtually perfect, therefore T_E and L_E are zero. One cautionary registration note is that the pattern for the second etch (Figure 1c and 1d) must be wide enough to assure that the desired copper is removed, however, it must not interfere with the adjacent circuits or new resistors will be formed that are not in the design. A good rule of thumb is to extend the etch opening mask 100 µm both sides of the termination and to keep it at least 100 µm away from adjacent copper.

If your design has a 100 µm wide in-line resistor on a 100 µm trace with 100 µm space, the above rule won't work unless you have a row of resistors parallel to each other and the mask can extend across a larger area. If this is not the case, then it is critical to work with your PCB manufacturer to assure that you create a design that is producible.

PTF materials: Figure 4 illustrates termination registration. T_E and L_E should be +/-100 µm to +/-200 µm, depending on the precision of the PCB manufacturers screen printing process.

Orientation

Thin-film materials: Where tolerance and TCR are critical considerations, it is important to orient the direction of the resistors consistently. The substrate material has an X and Y coefficient of thermal expansion (CTE). Except for known isotropic materials, such as those using mat or random fiber reinforcement rather than woven fabric, laminates are anisotropic. Our most common laminate, FR-4 for example, typically will have a 12 to 14% difference in expansion rate between the X and Y axis. It is also possible to orient resistors on a 45 degree bias to compensate for the CTE variation. Regardless of the orientation, consistency is the rule.

PTF materials: To assure the maximum uniformity of the screening process, the termination bars of the resistor must all be oriented in the same direction. During the process, the squeegee must run perpendicular to the long axis of the termination.

Size and Power

Thin-film materials: Previous discussions have illustrated the relationship between resistor size and resistance tolerance, where bigger is better. Unfortunately for the designer, in today's market "bigger" is not in our vocabulary. The drive is for smaller. Size then is a trade off. When power handling becomes an issue, size is a major consideration. All thin-film manufacturers have guidelines for power handling.

PTF materials:

The PTF suppliers have not published as many guidelines as the thin-film suppliers, however the rules will be basically the same.

Another way:

We can also treat resistor power handling like we treat conductors. Resistors are conductors (only they are poor conductors). There are rules and standards for conductor sizing based on current. The IPC has an ongoing initiative to refine and update these rules and guidelines for conductors, by considering the PCB construction and incorporating the notion of power density and the PCBs ability to dissipate that power. Regarding resistor power requirements, there are concerns for the fact that typically the PCB designer is given a bill of materials including resistors, package sizes, tolerance and power rating. Typically, the designer is not given the current associated with the resistor, so it is not possible to size the resistor based on current, power density, board construction and heat dissipation. Modeling, test and verification work is in progress to refine this concept for embedded resistor power handling based on current, power density and the PCBs composite construction and it's ability to dissipate heat.

Conclusions

This paper has not discussed testing and trimming. Both are rather intense topics. Both are possible and can be done very effectively. From a design perspective, this author believes that it goes without saying that testing is mandatory. With today's flying probe test technology, the product can be tested easily, both at the inner layer and finished stages. For trimming, however, there are design considerations. ESI has done considerable work on this topic. There are many publications available. Refs 14 - 16 are a just a few of numerous articles.

Without trimming, there are tolerance realities. It is important to clearly understand these from both the raw material and PCB manufacturing perspectives. Perform preliminary testing and evaluate your resistor design and requirements to determine the tolerance capability and if possible performance requirement before committing to the final design.

The final conclusion simply stated is that embedded resistor technology is real and it is here now. The design process, although not fully automated, is not difficult. The primary condition for a successful embedded resistor experience is for the project management, project engineering, design engineering and the PCB designer, to work with the PCB fabricator and the material supplier as a team to design a product including embedding resistors that will be manufacturable and meet the desired cost and performance requirements.

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