Manufacturing Embedded Resistors

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Abstract
Increasing component density and the requirements of higher performance electronic devices are driving the development of embedded passive devices in the printed circuit board (PCB). The benefits of embedded passives are that they free surface space for active devices, improve performance and signal quality by lowering inductance and reduce overall system cost. Embedded passives also yield a more reliable printed circuit board by reducing the number of solder joints.

A resistor is an important passive device in an electric circuit. To enable high performance devices, an embedded resistor must achieve a tolerance that allows the PCB design to meet electrical timing and circuit signal quality requirements. The tolerance of embedded resistors is not only determined by the uniformity of the resistor material but also by the PCB manufacturing process which forms them, especially when the sizes of the embedded resistors are small. The stability of the material when subjected to typical printed circuit board processes will also affect the final tolerance of embedded resistors.

Gould has developed a thin-film NiCr alloy resistive layer sputtered onto rolls of copper foil for embedded resistor applications. Nickel-chromium alloys possess high electrical resistivity, good electric performance and high thermal stability. The thin film is very uniform, and is capable of forming resistors with tolerances that meet the requirements of high performance PCBs.

Merix Corporation is involved in the NIST Advanced Embedded Passives Technology (AEPT) consortium, and has built test vehicles for the consortium and customer prototypes using Gould's thin-film alloy resistor foil. This paper reviews data from the material manufacturer on the effects of specific processing factors on the overall tolerance of the resistor, and describes the board fabricator's process development for reducing resistor variation and improving yields.

Introduction

The increase in component density and the requirement for higher performance electronic devices is driving the development of electronic systems with passive devices embedded in the PCB or IC package[1]. The benefits of embedded passives are the freeing up of surface space for active devices, improving performance with lower inductance and improved signal quality. Embedded passives yield a more reliable printed circuit board by reducing the number of solder joints and reduce overall cost. There are two main technologies for embedded resistors: thin film and thick film. The thin film technology has many advantages over thick film because thin film technology uses vacuum deposition, such as sputtering, which gives excellent coating consistency and thickness uniformity[2]. TCR™ is one of the integrated thin film materials for embedded resistor application, which is made by sputtering a thin layer of nickel-chromium alloy onto copper foil. Nickel-chromium alloys possess high electrical resistivity, good electric performance, high thermal stability, and are a well-known chemistry.

Resistors are important passive devices in an electric circuit. To enable high performance devices an embedded resistor must achieve a tolerance that enables the PCB design to meet electrical timing and circuit signal quality. A thin film embedded resistor usually is formed by a series of etching steps to define the resistor's width and length, followed by other printed circuit board construction processes. All these processes will have an impact on the resistive material, which in turn causes resistance change. Therefore, what the final resistive value is and how to improve or control the final resistor tolerance is critical for the manufacturer.

Material Uniformity

Material tolerance is determined by the resistive material coating uniformity and the surface roughness uniformity of the substrate, copper foil. Electrodeposited (ED) copper foil has a unique matte side, which has an isotropic uniform surface roughness. It is a perfect surface on which to deposit a thin film resistive material because the surface roughness provides an increased sheet resistivity and enhanced peel strength to laminate resins. The other side of the copper, called the shiny side, has a smooth surface. This surface can also be treated to have a nodular surface in order to improve the bonding for the multilayer board process. The treated copper foil is called reverse treated copper foil (RTC) and the non-treated copper foil is called standard copper foil (STD).

The thin film NiCr alloy is deposited on the copper substrate by a sputtering process utilizing a roll-to-roll process. The sputtering technique provides a manner to deposit a thin film with uniform thickness and consistent chemical composition. Both composition and thickness characteristics are critical to sheet resistance variation for resistive foil. By installing proper shielding and controlling sputtering parameters, a tight resistance tolerance material can be manufactured. Figure 1 shows a sheet resistance map across a 24" foil web. The resistance variation is less than ±2%. Figure 2 shows statistical results of 440 sheet resistance measurements sampled across the web and down a 500 ft production roll. Note that the total sheet resistance variation is within ±3%. Therefore, the material resistance tolerance is ±3%. Currently, most embedded resistive material available on the market has a resistance tolerance of at least ±5%. As the material tolerance is included in the final resistor tolerance and cannot be compensated for, the tolerance of resistors made from ±5% material tolerance can be improved by laser trimming.

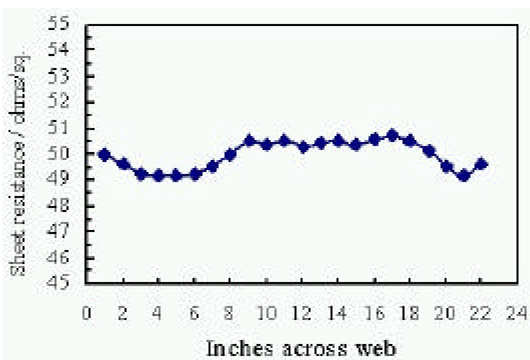

Figure 1 - Sheet Resistance Across a Resistive Foil Web - NiCr, 50ohm/sq. on 1/2oz Reverse Treated Foil

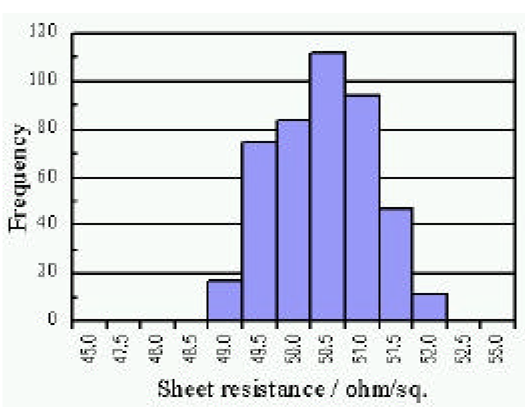

Figure 2 - Statistic Results of 440 Sheet Resistance Measurements on a 500ft Production Roll - NiCr, 50ohm/sq. on 1/2oz Reverse Treated Foil

The isotropic roughness uniformity is also critical to enable resistors oriented in different directions in the printed circuit board to have the same resistance. Table 1 shows statistical results of two test boards with resistors oriented in three directions. No orientation dependence of resistance is observed.

Etching Effect on Resistance Change

The resistance value of a thin film resistor is determined by its geometric dimension, the length and width. An embedded thin film resistor is formed by a series etching process to define the resistor's width and length. Many process factors could impact the final etched resistance tolerance, for example, phototool accuracy, photoresist resolution, and etching control etc. In addition, the copper thickness and its surface treatment on the side opposite the resistive layer (nodular or smooth) will also affect the dimensional accuracy of the etched resistor.

An etching test was performed to examine the effect of these factors on the variation of the etched resistors. During the etching test, defined resistors were exposed to the resist strip chemistry. Variation induced by sensitivity of the resistive layer to the alkaline resist strip solution is included in the total resistance variation. It was not separately quantified. The test panel had 135, 254 um (10 mil) wide by 381 um (15 mil) long resistors. The dimension of each resistor was measured under microscope after every image and etch step. The results are listed in Table 2. First, it can be seen that the artwork itself is not as accurate as it should be. The standard deviation of the artwork dimension reflects the actual size variation and the measurement variation. After imaging and developing, the photoresist dimensions are very close to the dimension of the artwork. Both width and length are about 12 um (0.5 mil) larger than the artwork dimensions. There is slightly higher standard deviation value for reverse treat foil compared to that of the standard foil. However, significant over-etching was evident. Especially, for the second step selective copper etching, more than 25 um (1 mil) over-etching of copper was evidenced for both smooth and nodular treated surfaces. After etching, the standard deviation value and variation percentage also increase significantly, which supports the etching process is a major resistance variation contributor.

If an etching process (DES process) is under control, the amount of copper over-etching should be consistent and can be compensated by adjusting the artwork. However, the variation of the etched resistor dimension, represented by the standard deviation of the width and length, is not able to be compensated for, and should be included into the final resistor tolerance. The etching tolerance after compensation can be written as:

$$t_f = \left|\frac{\Delta l}{l}\right| + \left|\frac{\Delta w}{w}\right| = \left|\frac{3\sigma_l}{l}\right| + \left|\frac{3\sigma_w}{w}\right|$$

Table 3 summarizes the resistance of square resistors with different sizes. The sheet resistances of the resistive foils were 25 ohms/sq. As the resistor's size reduces, the resistance value of the resistor becomes larger than the sheet resistance value because of copper over-etching.

The standard deviation value (resistance variation) also increases as the resistor size is getting smaller. This can be attributed to the non-perfect straight etched copper and resistive edges (Figure 3).

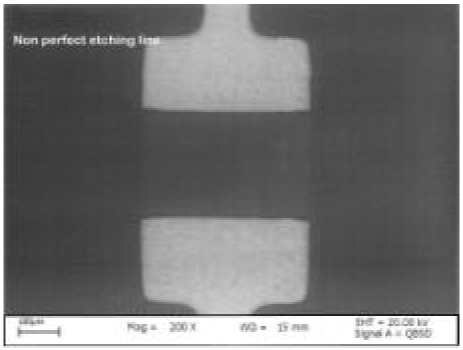

Figure 3 - Resistor Image Shows Non-Perfect Straight Etched Copper and Resistive Edges

Although the amount of the dimension change caused by this edge irregularity is small, it becomes significant when the resistor size is compared to it, resulting in a large resistance variation. The resistors made from smooth resistive foil have slightly tighter standard deviation value than that made from nodular resistive foil because of better etch definition with the smooth surface.

It was interesting to find from the etching test that the actual resistance of the resistor is higher than that calculated based on the measured resistor dimension and sheet resistance. This phenomenon is common for all the thin film resistive foils when used to form small resistors by the etching process. For example, the average etched 50 ohm/sq NiCr resistor is 1.79 squares (From Table 2, for STD copper), calculated resistance should be 89.5 ohm; however, the average resistance of these resistors is 111.88 ohm, which is 25% higher than calculated value. This phenomenon can be explained by interfacial undercut between copper and resistive layer during etching (see Figure 4).

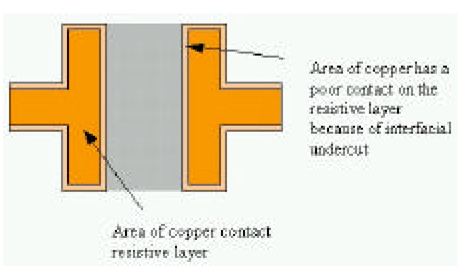

Figure 4 - Illustration of Interfacial Undercut Between Copper and Resistive Layer During Etching

Because of a slight etching solution attack on the interface between copper and resistive layer near the copper edge, the edge of the copper pads have a poor contact to the resistive layer which causes the actual length of the resistor to be longer than the apparent length. Since it is caused by etching solution attack it is very difficult to avoid. However, if the etching process is under control, especially for the second copper removal step, the amount of the resistor's actual length increase should be consistent. By doing an etching test, the compensation amount of the length that includes copper over-etching and interfacial undercut can be calculated by the following equation.

$$Rw = R_s \Delta l + R_s l$$

Where R is the resistance of the resistor, R_s is the sheet resistance, w is the resistor width, l is the resistor length, and Dl is the compensation amount of length.

In the equation, the interfacial undercut along the resistor width direction is not taken into account because its impact on the resistance change is negligible if $l >= w$. By plotting Rw vs. l, the Dl can be calculated from the slope and the intercept of the straight line. Figure 5 shows an example. The data for the plot is from Table 2, smooth foil. Rw shows a good linearity to the resistor length, l. The calculated total amount of resistor length compensation is 68 um (2.66 mil), which means the resistor length on the artwork should be 68 um (2.66 mil) shorter than theoretic length.

$$l_{artwork} = l_{theoretic} - \Delta l$$

Since the Dl is predictable, it should not affect the final resistor tolerance if it is compensated. Only the dimension variation due to irregular resistor edge which is reflected by the standard deviation of the resistance of the resistor will contribute to the final resistance tolerance. The smaller the resistor, the higher the etching variation and the higher the resistor tolerance.

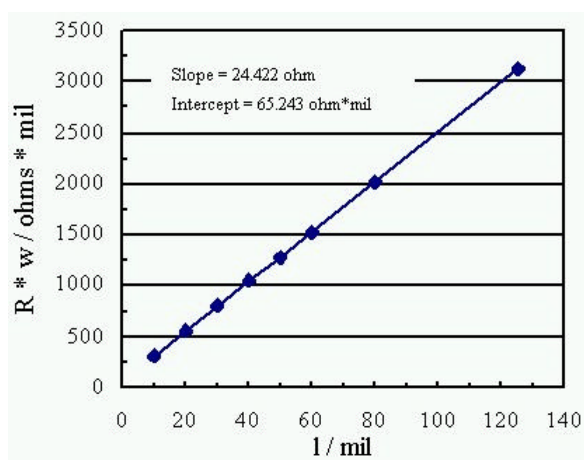

Figure 5 - *Rw* vs. l Plot to Calculate the Total Amount of Resistor Length Compensation - Data are from Table 2, STD Foil - Calculated Total Amount of Resistor Length Compensation is 2.66mil

Table 1 - Statistic Results of Resistor with Different Orientation NiCr on 1/2oz STD Foil, Resistor Size: 10mil x 15mil

	Test panel #1			Test panel #2		
Direction	0°	45°	90°	0°	45°	90°
Average	114.78	114.53	114.23	115.35	115.50	115.88
STDEV	1.89	2.70	2.11	4.09	4.67	4.42

Table 2: Etching Test Results 50ohm/sq, 1/2oz Standard Resistive Foil (STD)

	Width/mils			Length/mils		
	Artwork	**Photoresist**	**Etching**	**Artwork**	**Photoresist**	**Etching**
Average	9.270	9.864	9.387	15.699	16.148	16.766
STDEV	0.201	0.206	0.291	0.151	0.148	0.271
Variation %	6.495	6.252	9.300	2.885	2.753	4.851

	Artwork squares	Photoresist squares	Etched squares	Resistance/ ohm
Average	1.69	1.64	1.79	111.80
STDEV	0.04	0.04	0.05	4.80
Variation %	7.10	7.32	8.38	12.88

100ohm/sq, 1/2oz Reverse Treated Resistive Foil (RTC)

	Width/mils			Length/mils		
	Artwork	**Photoresist**	**Etching**	**Artwork**	**Photoresist**	**Etching**
Average	9.270	9.493	8.312	15.699	16.003	17.433
STDEV	0.201	0.248	0.222	0.151	0.168	0.209
Variation %	6.495	7.828	8.003	2.885	3.155	3.603

	Artwork squares	Photoresist squares	Etched squares	Resistance/ ohm
Average	1.69	1.69	2.10	240.30
STDEV	0.04	0.05	0.07	7.50
Variation %	7.10	8.88	10.00	9.36

Table 3 - Etching Test Results with 25 ohm/sq. NiCr

	Size/mil	125	80	60	50	40	30	20	10
STD foil	Average	25.0	25.2	25.4	25.6	26.0	26.7	27.6	31.9
	STDEV	0.16	0.29	0.21	0.17	0.41	0.45	1.05	1.94
	Variation%	1.92	3.45	2.48	1.99	4.73	5.05	11.4	18.24
RTC foil	Average	24.8	25.1	25.5	25.5	26.0	26.5	28.6	32.9
	STDEV	0.44	0.52	0.46	0.29	0.37	0.74	0.88	2.31
	Variation%	5.32	6.21	5.41	3.41	4.27	8.38	9.23	21.1

NIST AEPT Test Boards

In conjunction with the NIST Advanced Embedded Passives Technology consortium, TV1-R test boards were manufactured using 50 ohms/square resistor material. Figure 6 shows the innerlayer resistor core, and Figure 7 shows the finished board.

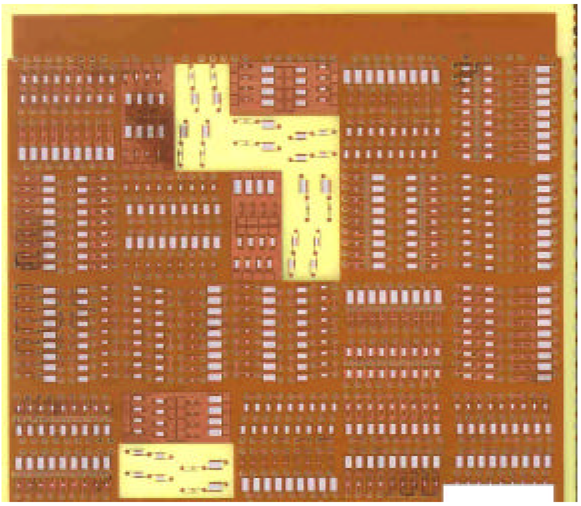

Figure 6 - NIST AEPT TV1-R Resistor Test Vehicle made with 50 ohms/square Resistors - Individual Resistor Sizes Range from 0.005" Squares to 0.055" Squares

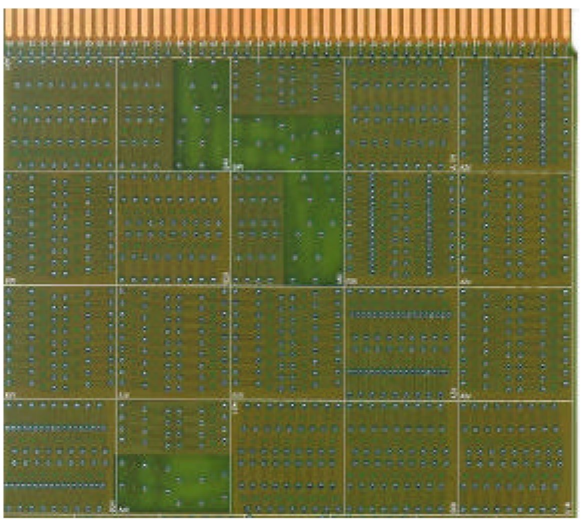

Figure 7 - NIST AEPT TV1-R Finished Board

The resistors were formed in two etching steps: first the innerlayer circuitry was etched using standard cupric chloride etcher to remove both the copper and the NiCr, then the resistors were formed using an ammoniacal etchant to remove the copper and exposing the NiCr resistor material underneath the copper. Figure 8 shows a flow diagram of the process.

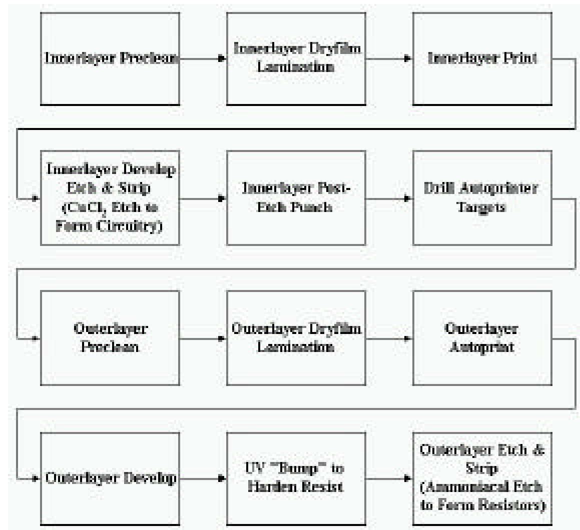

Figure 8 - Flow Diagram Showing Process for Forming Resistors with TCR Material

TV1-R Test Data

After etching the resistors, we laminated the cores into finished boards and measured the resistance values. Table 4 shows the average, standard deviation, and variation for each resistor size. Note that the resistor artwork film was not modified to compensate for the lateral etching in the alkaline etcher, so the resistances were consistently higher than the nominal value of 50 ohms.

Table 4 - Summary of Resistor Data for NIST AEPT TV1-R Test Boards Based on 10 Boards (Approximately 6,660 resistor measurements)

Resistor Size on Artwork (mils)	**5**	**10**	**20**	**30**	**40**	**50**	**55**
Average Value on Test Board (ohms)	97.5	71.8	60.4	56.7	54.9	53.9	53.7
Standard deviation, s (ohms):	11.0	5.2	2.0	1.4	1.1	1.0	1.1
% Variation (3 s/Average)	38%	22%	10%	7%	6%	6%	6%

Projected Yield

As the data suggests, the expected yield will depend on the size of the resistor, the target value, whether or not the artwork is modified to center the resistors on the target value, and the customer's specifications. For example, if the customer specified a tolerance of +/- 15% on a 20 mil resistor centered on the average of 60.4 ohms, the resistor yield on the TCR resistor material will be nearly 100% (see Figure 9).

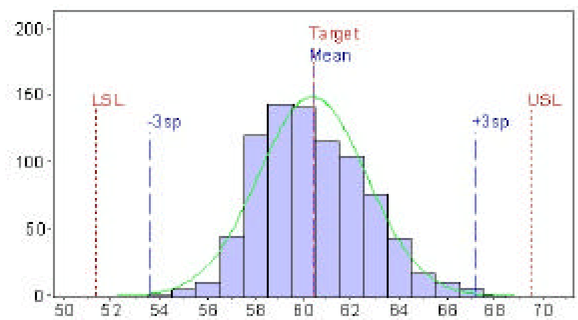

Figure 9. 20 mil Resistor Data Compared to a Target of 60 ohms - Predicted Yield is Greater than 99%

On the other hand, if the target is 50 ohms and no effort is made to scale the resistor to match the target, the resistor yield will only be about 10% (see Figure 10). Clearly, it will be necessary to scale the resistors in order to compensate for the shift introduced by the print, develop, and etching steps so that the distribution will be centered on the target value.

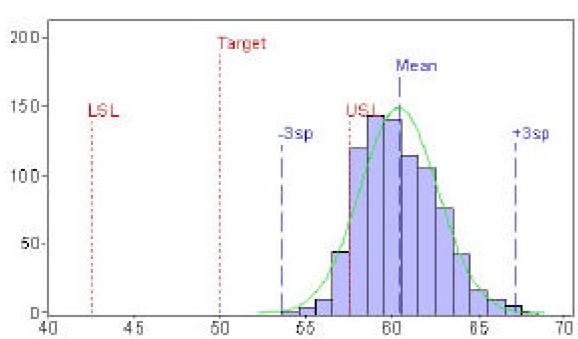

Figure 10. 20 mil Resistor Data Compared to a target of 50 ohms - if no Attempt is Made to Scale the resistors, the Predicted Yield is Only about 10%

TV1-R Predicted and Actual Tolerances

There are several approaches to calculating resistor variation, including simply summing the errors for resistivity, thickness, and the resistor and copper geometries[3]. Peter Sandborn has developed a more rigorous variation analysis, which he uses in his cost modeling for embedded resistors. His tolerance calculations are based on the variation in resistor length, width, and material thickness[4].

Glen Walther presented a similar approach which can easily be used to predict the maximum resistance expected for a given resistor size, based on the resistor material tolerance and the tolerances of the two etching steps[5]. A resistor with a width of w and a length of l made from a resistive material with a resistivity of R_S has a maximum resistance R_{max}

$$R_{\max} = (R_S)\left(1 + \left|\frac{\Delta R_S}{R_S}\right|\right)\left(\frac{l + |\Delta l|}{w - |\Delta w|}\right)$$

where

$\left|\frac{\Delta R_S}{R_S}\right| = t_m$ is the relative sheet resistivity variation

Δl is the resistor length variation

Δw is the relative resistor width variation

This equation can be used to form an expression for the resistor tolerance:

$$t = \frac{|\Delta R|}{R} = \frac{R_{\max} - R}{R}$$

By substituting the previous expressions for R and R_{max} and rearranging:

$$t = \frac{R_S\left(1 + \frac{\Delta R_S}{R_S}\right)\frac{(l + |\Delta l|)}{(w - |\Delta w|)} - R_S\frac{l}{w}}{R_S\frac{l}{w}}$$

Simplifying and substituting t_m for the material tolerance, t_l for the length etching tolerance, and t_w for the width etching tolerance gives this simple expression for the total resistor tolerance:

$$t = \frac{t_m + t_l + t_w + t_m t_l}{1 - t_w}$$

where:

$\left|\frac{\Delta l}{l}\right| = t_l$ is the relative resistor length variation

$\left|\frac{\Delta w}{w}\right| = t_w$ is the relative resistor width variation

The difference between this tolerance calculation and simply summing the material and etching tolerances is only significant for the smaller resistor sizes. As an example, suppose that a resistor material with a +/-5% tolerance is used to make a 10 mil square resistor. If both the copper etch and the resistor etch steps are accurate to within +/-0.5 mil, t_l and t_w will also be +/-5%, and the total tolerance will be:

$$t = 0.05 + 0.05 + 0.05 = 0.15 \text{ (or +/-15\%)}$$

(or +/-15%).

The tolerance calculation based on Walther's equation is slightly higher:

$$t = \frac{0.05 + 0.05 + 0.05 + 0.05 \times 0.05}{1 - 0.05}$$

$$t = 0.16 \text{ (or +/-16\%)}$$

(or +/-16%).

For 5 mil resistors, the calculation gives a variation of about +/-28%, compared with +/-25% if the tolerances are simply summed together. Our experience with the variation of the 5 and 10 mil resistors on the TV1-R boards was significantly higher than this (see Table 5).

As noted above, we did not use an etch compensation factor for the resistors in this test, so that the resistor lengths were longer than nominal. Also, as noted above, there may be some interfacial undercut between the copper and resistive layer during etching contributing to the higher resistance values.

Process Challenges

For the most part, we found that creating resistor cores using the outerlayer equipment was relatively simple. There are a few processing challenges that are worth noting, and additional opportunities for process improvements to reduce the resistor variation.

Because the resistor etch step takes place after the innerlayer circuitry is etched, conformance of the dry-film photoresist to the panel can be an issue. If the dry-film does not conform adequately to the innerlayer traces, the alkaline etchant may overetch the resistors and increase their resistance. Although using a vacuum laminator is recommended in order to improve the conformance over the traces, we used both a vacuum laminator and an autolaminator to apply the dry-film, and found that both gave comparable results in the test boards.

We registered the resistor image to the etched innerlayer circuitry by drilling tooling holes and either pinning the film to the panel and printing on a manual printer, or aligning the film to the panel with an autoprinter. An autoprinter, which uses cameras to align film targets with drilled holes in the panel, provides the best registration. However, thin resistor cores can be a challenge for the autoprinter, particularly if they are curled, so a manual printer may be preferred in some cases.

Another challenge to forming resistors with the resistor material is that it requires processing thin innerlayer resistor cores with equipment designed for thicker multilayer boards. Attaching leader boards to the resistor panels ensured that they did not jam up in the outerlayer developer, etcher, or stripper.

Table 5 - Summary of Predicted and Actual Resistor Variation for the TV1-R Resistors - Actual Variation is Calculated as Three Times the Resistor Standard Deviation Divided by the Average Resistance

Resistor Size	Innerlayer Etch Tolerance	Outerlayer Etch Tolerance	Predicted Resistor Variation	Actual Resistor Variation (3 s/ave)
5 mils	+/- 0.5 mils	+/- 0.5 mils	+/- 28 %	+/-33 %
10 mils	+/- 0.5 mils	+/- 0.5 mils	+/- 16 %	+/-22 %
20 mils	+/- 0.5 mils	+/- 0.5 mils	+/- 10 %	+/-10 %
30 mils	+/- 0.5 mils	+/- 0.5 mils	+/- 9 %	+/-7 %
40 mils	+/- 0.5 mils	+/- 0.5 mils	+/- 8 %	+/- 6%
50 mils	+/- 0.5 mils	+/- 0.5 mils	+/- 7 %	+/- 6%
55 mils	+/- 0.5 mils	+/- 0.5 mils	+/- 7 %	+/- 6%

Because of its elevated pH (>8.5), the alkaline etcher tends to attack polymer dry-film photoresists. In order to minimize the resist breakdown and subsequent contamination of the etcher, we hardened the dry-film photoresist after developing the resistor windows by "flood" exposing it on a manual printer at the same exposure as the resistors were originally printed with.

We also found that there was a significant difference in the resistor edge definition between two of our dry-film photoresists. This was particularly evident with the smaller resistors, and appeared to be related to a difference in developing of the resistor "windows".

Next Steps

The initial results from building test boards with the 50 ohms/square resistor material were quite encouraging. Processing is straightforward, and the material is much more uniform than thick film resistor technologies, so that this material could be used without laser trimming for applications such as termination resistors.

Further work is needed to reduce the variation of the smaller resistors. Many applications will require embedded resistors to be small enough to fit close to or below the surface mount chip package. Our goal is to reduce the variation on 10 mil resistors to +/- 15%. There are several areas we can focus on to reduce the process variation:

- Optimization of the print exposure, developer breakpoint, and etch speeds.
- Better understanding of the pH dependence of alkaline etch profiles, and tighter tolerances on the pH and temperature controllers for the alkaline etcher.
- Develop a process to etch the resistors first, then etch the innerlayer circuitry. By etching the resistor windows first, the edges of the resistors should be straighter, and handling and printing through the outerlayer processes should be improved, leading to reduced variability.

Conclusions

The final tolerance of a resistor formed by etching thin film resistive foil is determined by material uniformity, etching process and other thermal processes, such as lamination, solder reflow etc., involved in the manufacturing process. The resistance change caused by these processes is consistent and predictable; therefore, can be compensated by adjusting the phototool. Knowing the variation in each step of the process is critical so that the phototool compensation will yield the final resistance required. For small resistors, the material uniformity and the etching control are the major contributors to the final resistor tolerance. For larger resistors, the etching effect may not be as important; the resistor tolerance is mainly determined by material tolerance. In any case, the final resistor tolerance will not be better than the material tolerance used. If tighter tolerances are required than the material and/or the process will allow, laser trimming may be required.[6]

Acknowledgement

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