

# Stress Effects on Thin Film Nichrome Embedded Resistor Tolerance

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## Abstract

Electronic devices with high performance are becoming smaller and lighter. The passive components required to enable high performance consume premium space on the surface of the printed circuit board. Integrating the resistor function into the laminate substrate frees up the PCB surface area consumed by the discrete component, enabling increased device functionality by the placement of more active components. When the typical 5 to 20 % tolerance of embedded resistors can be allowed, the resistors satisfy the device requirements. The resistive materials and the PCB fabrication processes used to fabricate the resistors are currently not able to achieve precision of 1 % or less.

Laser trim technology achieves < 1 % tolerance on thin film embedded resistor panels. The resistive material has an effect on the efficacy the laser trim. Thin resistive films are laser trimmed to a high degree of precision. Thin film alloys of nickel and chromium, due to the good thermal stability of the alloy, are trimmed to high accuracy at high speed.

The printed circuit board manufacturing processes may induce a shift in the resistor value as well as widen the tolerance. Environmental stress during use may also widen the tolerance. The resistance value and tolerance of laser trimmed thin film nickel-chromium alloy selective etched embedded resistors was measured after PCB process steps, and after environmental stress tests. Thin film embedded resistor tolerance is quantified after multilayer lamination, humidity exposure, convection reflow, solder heat, and thermal cycles.

## Introduction

As electronic devices increase in functionality and complexity, the timing and integrity of the electrical signals becomes more critical. In high speed digital transmission discrete resistors are used to terminate interconnects to avoid reflections and inter- signal interference.<sup>1</sup> It is becoming increasingly difficult to place the discrete resistors in close proximity to the active component. Embedding the resistor in the printed circuit board in close proximity to the component pin should improve signal quality, provide better board reliability by reducing the number of solder joints, as well as reduce the overall cost.

Embedded passives are receiving attention and considerable development efforts to enable electronic devices with higher performance. Higher performance is achieved by creating a device able to perform more functions in a fixed package size. Embedded passives accomplish this by moving discrete passives from the surface of the printed wiring board and placing them in the printed circuit board. This frees up the surface space for the placement of more active components that increase functionality.

Resistors in high performance devices are required to be at specified values within tight tolerance levels and to remain within tolerance during the lifetime of the device. Applications in which the tolerances can be relaxed to the 5 to 20% level use embedded resistors successfully. This tolerance range is typical of present day as-fabricated embedded resistors. The printed circuit board (PCB) fabrication process and the resistive starting materials do not presently achieve the 1% tolerance required for high tolerance applications.<sup>2</sup>

The PCB process induced drift in resistance can be compensated for by changing the artwork as demonstrated by Wang, et al.<sup>2</sup> Artwork compensation changes the dimensions of the resistor. The average values of the resistors arrayed across the panel respond to the dimension change. The process induced resistance changes must be consistent and predictable for artwork compensation to be a useful tool. Artwork compensation does not improve the tolerance of a group of resistors across the board and from board to board.

The average resistance and tolerance of an array of resistors on a PCB can be adjusted by laser trimming.<sup>3</sup> A better than 1% tolerance on large panels is achieved consistently and reliably with laser trim systems. Thin film resistors are trimmed at sufficiently low laser power that underlying damage to the polymer dielectric support does not occur.

Laser trim is not the final process step for a resistor that is embedded in a PCB. The resistor is exposed to process chemicals and is packaged by embedding it into the multilayer laminate. The embedded resistor also encounters

environmental stresses during the device's lifetime. Both the packaging and environmental stresses can change the value and tolerance of an embedded resistor. This work examines the effects of these process and environmental stresses on the ability of laser trimmed embedded thin film nickel-chromium alloy resistors to maintain value and tolerance.

### **Manufacture of Thin Film Nichrome Resistors**

The thin film nickel-chromium alloy resistors examined in this work were fabricated by a print and etch process. The methodology of this procedure was described previously.<sup>4</sup> Resistive layers of nickel-chromium alloys are sputtered reel-to-reel onto 0.5 oz/ft<sup>2</sup> electrodeposited copper foil in a vacuum chamber. The copper foil has a distinctive matte surface morphology which offers enhanced bond strength to laminate resins and higher sheet resistance. The sputtering process offers the deposition advantages of consistency, uniformity, flexibility, and environmental friendliness.

The resistive layer on the copper foil sheet was laid against FR4 glass/epoxy prepregs (2 sheets with 1080 style glass) and placed in a lamination press. The lamination condition was 360°F, 300 psi, for 100 minutes. A 0.5 oz copper foil was simultaneously laminated to the other side of the prepreg to balance the construction. The dielectric thickness was 5 mils after pressing.

The print and etch process utilizes the selective etchability of nickel-chromium alloys versus that of copper. Acidic etch steps are utilized to remove both resistor and copper from selected locations on the surface of the dielectric. An alkaline ammoniacal etchant is used to remove only copper to uncover the thin film Nichrome alloy. The inner layer core formed by this method has conductive copper traces connected by thin resistor elements atop the dielectric.

The variation in resistance of resistors from their nominal value is a function of the uniformity of the starting material, the etching process, and other thermal processes, such as lamination, solder reflow etc., involved in the manufacturing. The PCB process effects become especially significant as the size of the resistor decreases. For larger resistors, the etching effect may not be as important; the resistor tolerance is mainly determined by material tolerance. The technology to laser trim resistors becomes critical for determining the finished value and tolerance of small resistors.

Panels with thin film resistors on the surface in this study were made with nine types of resistive materials. Two nickel-chromium alloys, an 80:20 nickel: chromium and Nichrome alloyed with small amounts of aluminum and silicon were examined. Three sheet resistances of 25, 100, and 250 ohm/square were tested. The sheet resistances were fixed by controlling the thickness of the sputtered alloy layers in the ranges from 100 to 500 Angstroms. The copper surface on the side of the copper foil opposite the resistor was either shiny smooth copper or rough nodular copper. A nodular rough copper surface is exposed on contact pads when the resistor layer is applied to a double treated copper foil. A smooth shiny surface is exposed when a standard copper foil is used. These surface treatments are in contact with electrical probes during the laser trim.

Each panel had 156 resistors. It has 24 one square resistors in the size of 10, 20, 30, 40, 50, 60, 80, 125 mil, 18 resistors of 20 mil wide and 0.5, 1, 2, 4, 8, 12 square, and 18 resistors of 40 mil wide and 0.25, 0.5, 1, 2, 4, 6 square. Eight duplicates of each panel type were fabricated.

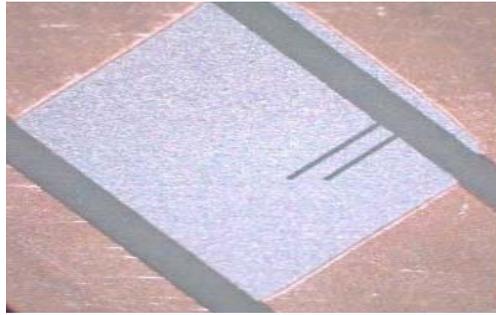
### **Laser Trim of Nickel-Chromium Alloy Resistors**

The panels with etched resistors were sent to GSI Lumonics of Waltham, Massachusetts for laser trim. The resistors were trimmed on the EP1000 machine. The technical considerations important for trim and the methodology employed to laser trim the test panels are discussed by Mabboux.<sup>3</sup> The machine supports automatic panel alignment with step and repeat probing capability and is equipped with an Nd: YAG laser at a wavelength of 1064 nm. Ohmic measurements were performed using the 4 wire, forced voltage, current nulling GSI Lumonics V900 bridge. The resistors were trimmed using a double plunge cut. Electrical power used during measurement and trim was varied from 1mW to 10mW.

Figure 1 shows a resistor trimmed with a double plunge cut. The thin film resistive layer is cleanly ablated without modification of the underlying glass/epoxy substrate.

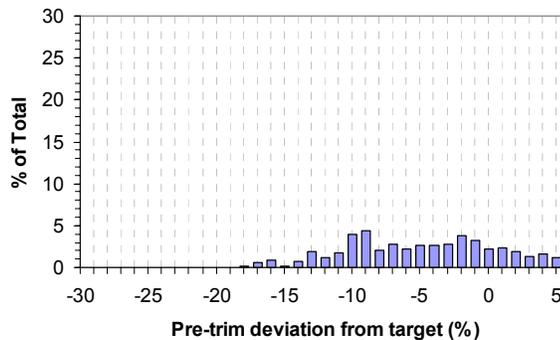
During the laser trim, resistance was measured using full-Kelvin probes. The beryllium-copper probe tips were overdriven by 375  $\mu\text{m}$  to ensure good electrical contact. To examine the effect of the copper surface treatment, shiny

or rough, 1284 resistors each were trimmed to the same resistance value. The copper surface treatment had no effect on the post trim average resistance or the 3-sigma standard deviation with the overdrive.



**Figure 1 - Double Plunge Cut in an 86 ohm/square Nickel-chromium Resistor on FR4 Glass/Epoxy Substrate. (Courtesy of GSI Lumonics)**

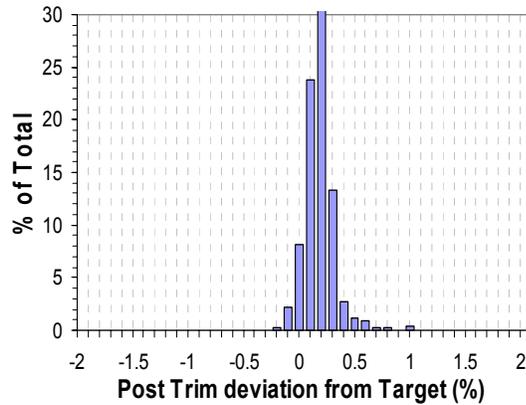
The pre-trim resistance values of 1,248 resistors from eight panels made with 100 ohm/square NiCrAlSi alloy were measured. The resistor size ranged from 10 mil x 10 mil to 0.125" by 0.125". The resistance values ranged from 25 ohm to 2,400 ohm. The variation in resistance value plotted in Figure 2 shows a large deviation from the target. The as-etched variation is intentionally high to test laser trim capability. No effort was made to optimize each of the wide range of resistor sizes to the low variation levels demonstrated in.<sup>2</sup> The trim and measurement system accuracy was confirmed by offline measurement of select resistor values using a high precision Hewlett-Packard digital multimeter.



**Figure 2 - Pre-trim Resistance Deviation from Target with 100 ohm/sq NiCrAlSi Alloy on Plain Treated Copper Foil**

The post trim resistance target was set 20% higher than the nominal as-etched resistance value. Distortion of the artwork caused approximately 30% of the as-etched resistors to be higher than the post trim target value. These resistors were not trimmed and were excluded from the post-trim data analysis. The above the target resistors were the smaller resistors on the boards. The same measure and trim technique applied to the other eight resistance layer/copper foil configurations yielded results that had a quite similar tolerance distribution.

The same resistors measured prior to trim in Figure 2 were remeasured after laser trim. The post-trim values plotted in Figure 3 shows a tight tolerance distribution with all trimmed resistors being within a  $\pm 1\%$  absolute of the target value. The 3-sigma standard deviation was calculated to be 0.39% for this lot of material. The other eight lots were trimmed to the same high level of precision. After trimming the panels were sent to Gould Electronics to undergo performance tests that simulate printed circuit board production processes and lifetime usage of an electronic device.



**Figure 3 - Post Laser Trim Resistance Deviation from Target Value with 100 ohm/square NiCrAlSi Resistive Alloy on Plain Treated Copper Foil**

**PCB Process and Lifetime Simulations**

The tests performed to simulate effects of PCB process and lifetime usage were (1) Humidity test: 40°C, 95 % relative humidity for 240 hours, (2) Solder reflow: carried out per EIA/JEDEC 22-A112-A with preconditioning at 30°C, 60% RH for 192 hours, then run the convection reflow 10 times at a maximum temperature of 220°C, (3) Thermal Cycles: MIL-STD-883, Method 1010.7, Condition C, -65 to 150°C, 1000 cycles, and (4) repeated epoxy FR4 lamination cycles at 360°F, 300 psi, for 100 minutes. Prior to the test, the resistance was measured manually on the trimmed resistors with the multimeter (Keithley model 2000) used to measure resistance after the test. The average value from a panel was in close agreement with the average from the trim machine. A slightly wider distribution of values was observed from the manual measurement than from the full-Kelvin probe measurement in the trim machine.

Prior to the stress test, the resistors were embedded in a 140 °C T<sub>g</sub> FR4 glass/epoxy. The embed lamination step employed two sheets of FR4 prepreg, 1080 glass, atop the etched, trimmed resistor. A Tedlar® release sheet was place between the prepreg and the stainless steel press plate. Lamination was carried out at 360°F, 300 psi, for 100 minutes. The dielectric thickness atop the resistor layer after pressing was 5 mils.

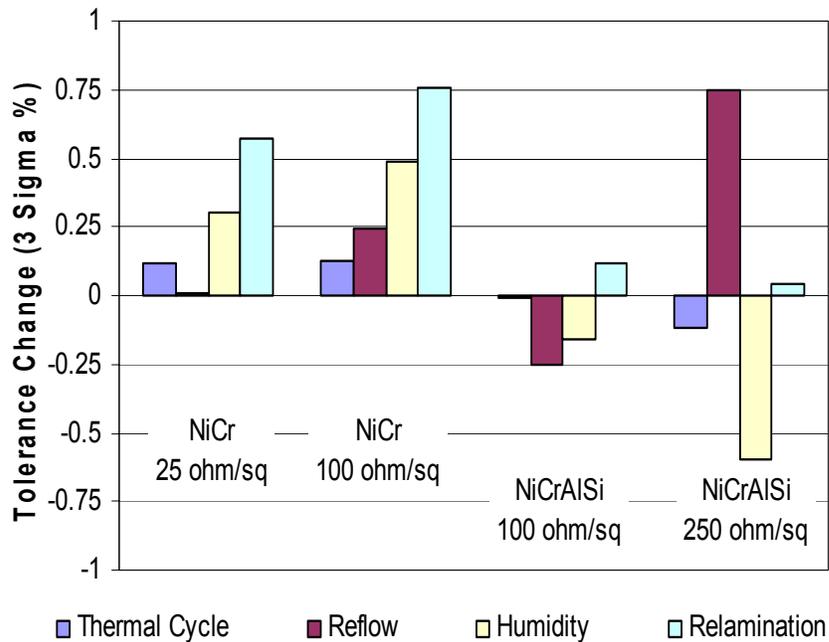
The resistance was measured after the embed lamination and after the stress test. Electrical connection with the embedded resistor was established by grinding through laminate with a Dremel tool to copper contact pads. The pads were large and well removed from resistor to minimize mechanical stress to the resistor and contributions to changes in the resistance. Data analysis of the 11,076 resistors was simplified by measuring only the 1 square trimmed resistors.

The change in tolerance of the resistors arrayed across the panel and from panel to panel induced during the tests is summarized in Table 1 and plotted in Figure 4. The stress tests induce a small change in tolerance, typically less than 1 %. The 100 ohm/square NiCrAlSi alloy performs particularly well, changing less than 0.25% in all the tests. This is in part due to the good thermal stability of this alloy. The negative values in the data indicating the tolerance appears improved after the stress test is likely due to small measurement inaccuracy.

Rigid epoxy laminates are used in electronic applications that require excellent chemical, mechanical, and thermal stability. These attributes contribute to the good performance of the embedded Nichrome resistors. Low x-y axis expansion contributes to good performance in the 10X reflow and thermal cycle tests. A portion of this stable performance is believed to be due to the ability of the glass/epoxy to be an effective potting compound for the resistor, being able to block intrusions of moisture and block transfer of thermo-mechanical stresses to the encapsulated resistor.

**Table 1 - Tolerance Change of Laser Trimmed One-square Thin Film Resistors on an FR-4 Substrate after PCB and Environmental Stress Tests**

Stress Test	Resistive Layer Alloy	Sheet Resistance	Tolerance Change
		Ohm/square	3-Sigma (%)
1000 Thermal Cycles per MIL STD 883	NiCr	25	0.12
		100	0.13
	NiCrAlSi	100	-0.01
		250	-0.12
10X Solder Reflow per EIA/JEDEC 22-A.112-A	NiCr	25	0.01
		100	0.24
	NiCrAlSi	100	-0.25
		250	0.75
Multilayer Relamination	NiCr	25	0.57
		100	0.76
	NiCrAlSi	100	0.12
		250	0.04
Humidity, 40°C, 95 % RH, 240 hours	NiCr	25	0.30
		100	0.49
	NiCrAlSi	100	-0.16
		250	-0.60
Embed Lamination	NiCr	25	0.97
		100	1.25
	NiCrAlSi	100	0.89
		250	2.29

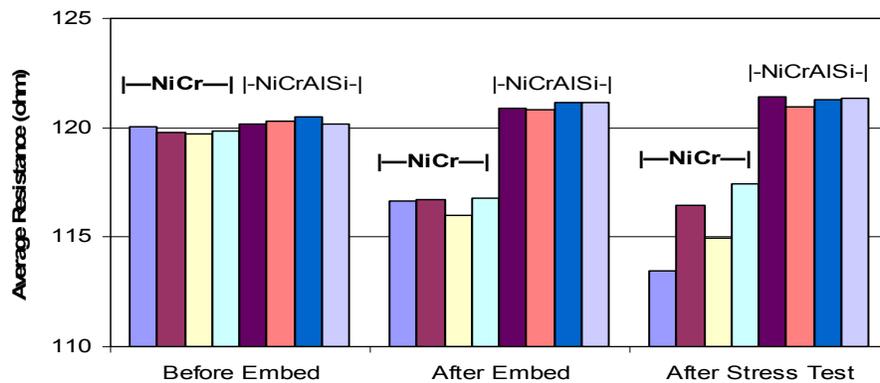


**Figure 4 - Tolerance Change of Laser Trimmed One-square Thin Film Resistors on an FR-4 Substrate after PCB and Environmental Stress Tests**

The embed lamination process induces the most stress on the resistor and produces the most tolerance change. The embed lamination increases tolerance by more than 1 %, Table 1. The variation change during first lamination process may be due to a surface scuff or chemical and mechanical interaction between resistive layer and resin. In separate experiments a “kiss” lamination cycle was applied during the embed lamination step. The “kiss” cycle ramps the press temperature to high value prior to the application of the final pressure. This cycle induced a smaller increase in the tolerance than the immediate simultaneous application of high pressure and temperature at the beginning of the cycle.

The resistance values plotted in Figure 5 show the change in the average values induced by the stress tests. The 1 square, 100 ohm/square materials were laser trimmed to 120 ohm. The resistance of the nickel-chromium-aluminum-silicon alloy changes less than the nickel-chromium alloy. The nickel-chromium alloy's resistance changes to a lower value while the nickel-chromium-aluminum-silicon alloy's resistance changes to a slightly higher value. These changes in average value can be accounted for by artwork compensation as explained by Wang, et al.<sup>2</sup> The changes in tolerance given in Table 1 are not compensated for by artwork modification.

Resistors are 1 square, 100 ohm/square laser trimmed to better than 1 %, 3 sigma tolerance. The tests in each group of four are from left to right thermal cycles, solder reflow, relamination, and humidity.



**Figure 5 - Average Resistance of Thin Film Nichrome Alloy Embedded Resistors after Process and Environmental Stress Test Simulations**

### Conclusions

Etched resistors composed of thin film nickel-chromium alloy layers are readily laser trimmed to a high tolerance. Laser trimming does not damage the underlying glass/epoxy substrate.

The Nichrome alloy with aluminum and silicon changes less in average resistance and has better tolerance than NiCr. The aluminum silicon alloy is more thermally stable.

The embed lamination process causes the most drift in average resistance value and change in tolerance of laser trimmed resistors.

Laser trimmed thin film Nichrome resistors embedded in an FR4 epoxy substrate exhibit small changes upon exposure to printed circuit board production process steps and to environmental stresses. The small changes imply that laser trimmed embedded resistors have the potential to be manufactured into a finished multilayer board with finished tolerance less than 1 %.

### Acknowledgement

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### References

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