Thin Film Embedded Resistor Processing in Sequential Lamination Printed Circuit Manufacturing

Rocky Hilburn, Jiangtao Wang Ph.D.
Ticer Technologies, 2555 West Fairview St., Chandler AZ 85224
David Parsons, Suixin Zhang Ph.D.
Coretec, 2020 Ellesmere Road, Toronto, Ontario M1H 2Z8 Canada

Abstract
New interconnect technologies continue to shrink feature size, increase routing complexity and component density in multilayer rigid and rigid-flex printed circuits. Printed circuit fabricators have choices on the technology required to build the multilayer circuits based on the level of the technology required. One innovative technology is sequential lamination where multilayer boards are formed by laminating together plated double-sided or multilayers with blind and buried via interconnections. The sequential lamination manufacturing technique can yield even more significant benefits in performance and circuit processing when combined with embedded resistor features within the printed board. Embedded passive technology allows the resistors to be placed on the same layer as the routed traces reducing the need for microvias. This technology also enables resistors to be placed at an optimum location to reduce the inductance impact of pads, stubs, and coupling. The sequential lamination process in combination with thin film embedded resistors requires a different processing sequence than conventional multilayer manufacturing with thin film embedded resistors.

Materials for embedded resistor can be either stand-alone resistor foil or a resistor laminate. For sequential lamination applications copper foil with a resistive alloy is preferred rather than a resistor laminate material. The copper/resistor foil has very low profile, and small circuit features can be achieved. Consequently, resistors can be fabricated in signal or power ground layers with multiple resistor values and good finished tolerances. The resistor alloys are robust and have low thermal coefficient of resistivity. The resistors maintain their initial values and reliability through the multiple lamination steps and subsequent thermal excursions required by the sequential lamination process.

Introduction
The need for higher performance and low signal losses in electronic devices continues to drive the development of electronic systems with passive devices embedded in multilayer PCBs. To enhance high performance devices an embedded resistor must achieve a specified value and a tolerance that enables the PCB design to meet electrical timing and circuit signal quality. Including embedded resistor in printed circuit designs allows the resistors to be placed more optimally in the circuit. This shortens the stub length and lowers overall inductance. The number of surface mounted resistors can also be reduced, typically improving escape routing, and allows more outerlayer area to be used for active devices. Embedded passives, in general, yield a more reliable printed circuit board by reducing the number of solder joints, reduce rework on the assembly, and lowers total system cost.

TCR® is an integrated thin film resistor foil for embedded resistor applications. It consists of a low profile copper foil with a thin layer of nickel-chromium alloy (NiCr or NiCrAlSi) sputtered onto the matte side of the copper. When this material is patterned appropriately, the resistive layer serves as the embedded resistor element. NiCr alloys possess high electrical resistivity, low parasitics, high thermal stability, and low temperature coefficients of resistivity in the range of -20 to 100 ppm/C^{o} [1].

The base copper foil has a low profile and the surface topography is isotropic. The uniform resistor layer enhances not only the fabrication of resistors with tight tolerances but also has improved transmission loss properties when compared to standard electrodeposited copper foil [2].

The manufacturing of PCBs with multiple subassemblies, multiple layers of buried resistors, buried microvias on high performance laminate systems can be challenging. The formation of the thin film embedded resistor element is done in a series of etching steps to define the resistor's width and length and represents just a small subset of process steps for the PCB. Understanding the materials, processing, chemistries, and their interaction is imperative to high-yielding, robust printed circuits with accurate resistor values.

In this paper, the processing sequence and benefits of thin film embedded resistors in sequential build-up constructions are presented.

Materials

The embedded resistor layers of the multilayer PCB can start with the cores having one thin film resistor foil laminated to one side in place of standard copper foil. The specific dielectric of the cores can be called out as part of the design or chosen by the PCB fabricator in order to meet the electrical requirements of the finished product. The thin film resistor foil has good peel strength and sheet resistivity values in combination with many of the high T_g, lead-free systems that are commercially available. Copper foil thickness for the resistor foil is 18 or 35 microns. TCR thin film resistor foil is commercially available in sheet resistivities from 25 to 250 ohms/square. The thickness of the alloy ranges from 150 to 1300 Angstroms depending on the desired sheet resistivity. Resistor foils are available in laminate form in standard dielectric thicknesses from major laminate suppliers.

An alternate and equally viable method of manufacturing the subassemblies is to use the thin film resistor foil as the cap-layer. This is the method of choice when the subassemblies have the resistor layer as the outermost layer. The resistor foil is supplied in unsupported (free-standing) sheet or roll form or as a supported sheet i.e. attached to a metallic carrier.

The NiCr alloys of TCR have several advantages that help minimize processing steps and contribute to the robustness of the finished embedded resistors. TCR resistor alloys are not attacked by alkaline solutions like photoresist strippers so the resistor values won't change when processing through these chemistries. Also, laboratory tests show that NiCr alloys have excellent resistance to value shift through multiple thermal excursions. This is particularly important to the resistors staying on the target value and the NiCr not degrading through PCB lamination and assembly processes.

Fabrication

The fabrication process discussed is specific to a multilayer printed circuit with multiple subassemblies. The subassemblies will have the resistor layers as outerlayer of the subassembly. Figure 1 shows the stack up of the multilayer PCB with three subassemblies and multiple embedded resistor layers. For clarity reasons the plated-through holes of the subassemblies and PCB in the figure are not shown.

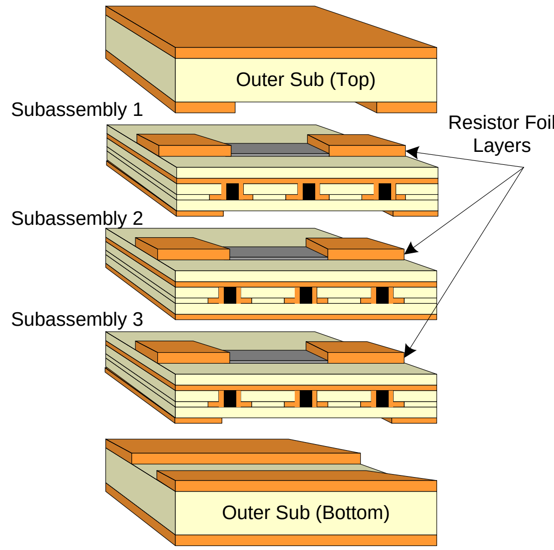

Figure 1: Stack up of multilayer PCB with subassemblies and multiple embedded resistor layers.

1. Subassembly Innerlayers, Lay-up and Lamination

The innerlayers of the subassemblies follow the steps of a standard single lamination multilayer printed circuit board. Since the resistor layer will be the outermost layer of the subassembly, the lay-up will start with the resistor foil either free-standing or supported. The pre-preg is layed down onto the exposed resistor side of the foil. Care should be taken not to slide the prepreg over the resistor surface thus avoiding damage to the surface.

The lamination and subsequent laminations have minimal effect on the sheet resistivity and the resistor values in the finished PCB. The resistors are also robust through the thermal excursions experienced in post-lamination PCB processing as well as thermal shock testing and assembly reflow processing [3].

2. Dry Processes

After lamination the subassemblies will be processed through the typical multilayer printed circuit processes of flash rout, bevel, and spotface. The subassemblies are x-rayed, drilled and deburred before being sent to wet processing.

3. Activation, First Image, and Copper Deposition

Electroless copper or alternative hole/via activation is applied. Photoresist is then applied and the subassembly is imaged and developed with a dot pattern. The dot pattern ensures that only the holes and vias are exposed for copper electrodeposition.

Copper is electrodeposited inside the holes/vias to the standard thickness, typically 25 microns. Coupons from the subassembly panel are microsectioned for quality assurance.

The subassemblies can be planarized to eliminate variability in the height of the plated button. This step is particularly important as layers counts increase in PCBs with stacked vias.

Finally the photoresist is stripped and the copper surface prepared for a second circuitization step.

4. Defining the Circuitry

At this stage a print and etch process is used to define the circuit pattern. Photoresist is laminated onto the subassembly, and a negative of the circuit pattern is imaged. Alternatively, laser direct imaging (LDI) can be used for the circuit pattern. Figure 2 shows the processing sequence to form the circuits and resistor elements. Once the photoresist is developed the subassembly is ready for etch.

Cupric chloride ($CuCl_2$) is the preferred etchant for NiCr alloy. The concentration of HCl should be greater than 60 g/L for optimum etching on the NiCr layer. The $CuCl_2$ will etch the copper and the underlying resistor background layer in one pass without adjusting the machine speed for the resistor material. If $CuCl_2$ with lower HCl concentration or ammoniacal etchant is used, then the background NiCr resistor layer can be removed by processing through an acidic permanganate solution and neutralizer [4]. TCR with the NiCrAlSi resistive layer also requires additional etch processing to remove the background resistor layer.

Typically the second or non-resistor side of the subassembly is imaged and etched at the same time as the first.

After etch measurements of line widths are compared to the nominal required value. These measurements can be recorded to determine if adjustments in the artwork or etching for the resistor pattern are required.

5. AOI and Electrical Test

Once photoresist is stripped the subassemblies can be processed through AOI and electrical test. AOI is performed at this step in the process because the AOI system isn't scanning the resistor elements. If this were not the case, false calls could arise due to the sharp transition from copper-to-resistor element and/or difference in color between copper and resistor alloy.

Electrical test can be done at this point in the process. Alternatively electrical test can be performed after the resistors are etched in order to determine resistor values.

6. Defining the Resistors

Photoresist is laminated to the subassembly. Good conformance of the photoresist is required to assure the resistor pattern has well defined transitions at the copper to resistor interface. One material suggested to ensure good conformance is a photoresist thick enough to fill between the circuit patterns defined in the previous etch step. A photoresist lamination process that utilizes a vacuum blanket helps to ensure good conformance as well.

The second side of the subassembly is also laminated with photoresist and completely exposed. The photoresist protects the second side etched circuit pattern through the next steps of selective etching of the resistor elements.

The resistor pattern image is printed or can be defined by LDI. LDI has the advantage of making on-the-fly adjustments to the resistor length if the circuit width is less than optimal.

Once photoresist is developed the subassembly is ready for selective etch.

7. Selectively Etching the Resistor Elements

Ammoniacal etchant is the preferred etchant for selectively etching the exposed copper to relieve the NiCr resistor elements. Typically, the most uniform etching occurs on the side of the panels that run face down through the etcher. It is preferred that the resistor image side is processed down. First articles should be evaluated for etch definition of the resistors and determining of the proper etch speed for the balance of etched subassemblies. A well defined copper-to-resistor transition will yield resistor values at nominal with good tolerances.

After etch, the photoresist is stripped, exposing the copper circuitry and the resistors. It should be noted that the NiCr alloys are very tolerant of strippers with high pH which results in resistors that don't change in value through this process.

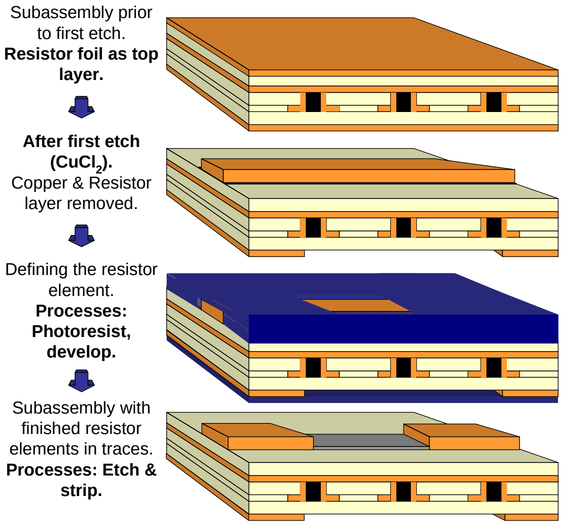

Figure 2: Processes for Defining Resistor Elements

8. Checking Resistor Values – Electrical Testing

Resistor values can now be checked on an AQL basis, 100% through electrical test, or tested and laser trimmed. AQL testing with a multimeter can be done on the actual resistor pattern. However, selectively placed coupons representing the in-board resistor dimensions are preferred so the exposed resistors are not damaged by the probes during testing.

If testing and laser trimming, the initial resistor values are targeted 30-40% lower than nominal so they can be laser trimmed up to the finished value.

With 100% electrical test, programming must take the entire net into consideration for the correct resistor value. The nets now include the additional circuitry of the electrically connected circuits of the subassembly and may have multiple resistors in series or parallel depending on where the net is tested. Also, the resistance of the copper traces must be considered. Long copper traces can add enough resistance to the net to effectively make the resistor value read higher than nominal.

9. Final Lamination

The subassemblies are processed through oxide/alternative oxide and bake. The resistor elements are exposed during these steps so care should be taken to eliminate handling damage to the resistors.

Different manufacturers' alternative oxide chemistries will microetch copper at different rates depending on their concentrations and operating parameters. The copper etching effectively lengthens the resistor element, increasing its resistance value. Variation in etching rates will increase resistor values minimally for resistors greater than 150 x 150 microns and will have much greater impact with smaller form factors. Etch factors can be determined and compensations made in the resistor definition artwork. The target resistor value should be slightly lower than nominal to compensate for copper etching occurring in this process.

The subassemblies are now layed-up and laminated into the finished PCB.

10. Completing the Multilayer PCB

Once the subassemblies have been laminated together the resistor elements are no longer exposed. The laminated PCB can now be processed through the standard sequence of drill, plate, image, etch, surface finish, soldermask, rout and electrical test.

At final electrical test the considerations for resistor values discussed earlier must be revisited to ensure the value measured in the net is correct. As with 100% electrical test at the subassembly level, smarter netlist data will yield a better electrical test program and fewer issues during test.

Conclusions

The processing sequence and benefits of thin film embedded resistors in sequential build-up constructions has been presented. NiCr thin film resistor foil can be incorporated into multilayer printed circuits requiring subassemblies with minimal additional processing and little or no additional chemistries or equipment.

Some unique features of the processing of subassemblies with embedded resistor should be noted. The addition of resistors in the subassembly circuitry requires processing steps to plate holes and vias while allowing for the additional process steps to selectively define and etch the resistor elements in the circuit pattern. Also, AOI is performed earlier in the process and consideration for the resistor values must be included in subassembly and final electrical test. Last, care must be taken to ensure the exposed resistors are not damaged by handling prior to final lamination.

Advantages of TCR thin film resistor foil in manufacturing sequentially laminated PCBs with embedded resistors are also worth noting. NiCr alloys are resistant to attack of alkaline chemistries and therefore the resistor layer can be processed through high pH solutions without need for compensation. Also, etching the circuitry using $CuCl_2$ with HCl concentration greater than 60 g/L etches both the copper and the background resistor layer in one process step. Last, NiCr alloys have a low thermal coefficient of resistance and can be processed through PCB manufacturing processes requiring multiple lamination cycles and the thermal excursion required for testing with very little effect on the resistance of the resistors.

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References

1. "TCR, TCR copper foil with integrated thin film resistor data sheet," Internet: http://ticertechnologies.com/tech_lit.html.
2. G. Brist, S. Hall, S. Clouser, T. Liang, "Non-Classical Conductor Losses due to Copper Foil Roughness and Treatment", Electronic Circuits World Convention 10, Anaheim, February, 2005; S19-2.
3. J. Wang, R. Hilburn and S. Clouser, "Stress Effects on Thin Film Nichrome Embedded Resistor Tolerance", Proceedings of the IPC Annual Meeting, Minneapolis, Minnesota, September 28-October 2, 2003, pp. S05-6.
4. T. Bergstresser, R. Hilburn, and J. Wang, "Adhesion and Etching of Nickel-Chromium Tiecoat on Adhesiveless Flexible Laminate", Paper presented at the IPC Second International Conference on Flexible Circuits, Chip Scale and Bare Die Packaging, January 6 – 8, 2004, Tempe, AZ, IPC, 2004.