

# Single Step Metallization Process for the Filling of Through Holes with Copper

Richard Bellemare, Don DeSalvo, Ron Blake, Carmichael Gugliotti, Andy Oh

MacDermid Alpha Electronic Solutions

227 Freight Street, Waterbury, CT 06702

[richard.bellemare@macdermidalpha.com](mailto:richard.bellemare@macdermidalpha.com)

## ABSTRACT

As designers continue to increase the functionality of electronic devices, printed circuit board substrate fabricators have been forced to develop new fabrication techniques to accommodate the miniaturization and densification of circuitry and the unique requirements that come along with it. This has resulted in the need for new design features utilized in the printed circuit board such as extremely fine lines and spaces with critical trace profiles and coplanarity for controlled signal impedance, the use of filled blind microvias and through holes for vertical signal routing to maintain short signal distances for maximized clock speeds, and thermal vias for the management of the heat concerns associated with more tightly packed, heat generating electrical components. These new design features have required the development of novel metallization chemistries capable of meeting the stringent needs of these new substrate architectures in terms of capability, versatility, and reliability.

This paper will discuss a copper plating process capable of filling through holes with solid copper, in one step, for applications such as core layer through hole filling with minimal surface copper build up for HDI technologies and thermal management of heat sensitive electronics. The advantages of the single step filling process benefit both the technology and the fabricator. In the copper through hole filling for core layer applications, the ability to fill a variety of aspect ratio holes, void free and flat, with reduced surface copper, provides improved fine line resolution for HDI and IC substrates. For thermal management of closely packed, heat generating sources, the presence of a solid copper structure offers tremendously enhanced thermal conductance versus conventional technologies to draw heat from the operating devices and dissipate it throughout the printed circuit board. From a processing standpoint, the single step copper filling technology is capable of filling various through holes in a fraction of the time compared to conventional copper plating technologies, greatly increasing potential throughput. In certain applications, the copper filling technology can eliminate complete processes, greatly simplifying the manufacturing process.

This paper will discuss in detail, the various aspects of the single step copper filling chemistry and the advantages this technology can provide versus conventional systems. Presented will be the current capabilities and limitations of the process as well as design guidelines that can affect the process.

## Need for Through Hole Filling

The through hole has long been a means of electrical interconnect between layers of a printed circuit board, both as a stand-alone feature and as a base upon which to build further layers (i.e. buried via). As a stand-alone feature the through hole would be plated with a copper deposit sufficient enough to provide the necessary strength and electrical performance to survive the rigors of assembly and usage. In designs where further build up layers are necessary, the through holes would first be plated with copper as above but then require filling to convert the open through hole into a solid base upon which to build further layers.

Filling is accomplished in a separate process by forcing a conductive or non-conductive resin, typically epoxy based, into the plated through hole followed by curing and planarization of the epoxy plug. This plug is then plated over with electroless copper before further build up. With the advent of HDI (High Density Interconnect) and the continued evolution towards circuit miniaturization and densification, drawbacks to resin filling of through holes become evident.

As through holes decrease in size, it becomes much more difficult to get the resin into the through holes to fill them completely, resulting in a weakened structure on which to build further layers. In addition, finer line circuitry with smaller features requires much tighter dimensional tolerances for proper registration making mechanical planarization of the plugged through holes much less desirable. From a reliability standpoint, the coefficient of thermal expansion mismatch between the resin plug and surrounding copper and the smaller contact areas for metallic bonding between layers in these smaller features can result in higher rates of mechanical failure during thermal excursions.

As more and more high power, heat generating components are packed more tightly onto a circuit board, thermal management becomes an issue. Heat from these devices must be drawn away and dissipated in order to increase the efficiency and life of the electronic components. Though various techniques of heat management exist such as copper coining, these techniques become difficult with circuit miniaturization. The plugging of plated through holes with thermally conductive pastes containing copper or silver has been used but offers limited thermal conductivity as well as the drawback of filling small holes.

## Copper Through Hole Filling

The ability to completely fill through holes with copper using electrolytic plating offers the PCB manufacturer a fabrication process with many advantages including:

- Robust, stable structure for further build up
- Increased thermal conductivity versus conductive pastes
- Elimination of plugging process
- Integration into standard plating processes

A filled copper through hole provides a very strong, stable structure upon which to build further layers. The copper cylinder resulting from through hole filling has little to no tendency to crack under thermal stressing and the low coefficient of thermal expansion of the copper

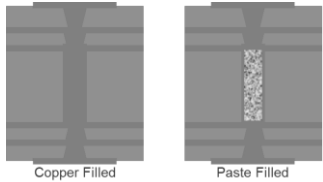


Figure 1. Copper Filled versus Plugged Through Hole

versus the epoxy plugging material (1.7 versus 4.4 – 8.8ppm/C) induces much less stress on the entire structure. In addition, all interfaces are metal to metal bonds representing the strongest possible layer to layer bonding strength. See Figure 1.

Another advantage to the copper filling of through holes is the increased thermal conductivity of the solid copper structure available

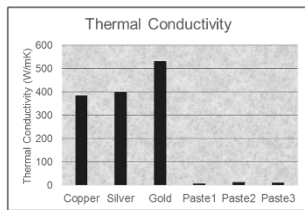


Figure 2. Relative Thermal Conductivities of Metals versus Pastes

to draw heat away from electrical components. The thermal conductivity of conductive pastes is a fraction of the solid copper (See Figure 2) thus limiting the conductance of heat energy to the thin copper layer plated on the side walls for electrical connection between layers.

From a fabrication standpoint, copper filled through holes can eliminate manufacturing processes such as plugging, curing, and planarization. The filling of through holes with copper is done using electrolytic deposition from an acid sulfate based system, a well established process familiar to many in terms of bath composition, additives, analysis, and control. Equipment design and requirements are similar to those typical of many existing plating lines simplifying equipment modifications for implementation of copper through hole filling processes.

## State of the Art

The filling of through holes is currently done in several ways:

- Direct current plating of laser drilled X-vias
- Two step bridge and fill plating

In the direct current plating of laser drilled X-vias, core layers are laser drilled from each side resulting in holes with a tapered middle. Panels are then processed utilizing standard type acid copper chemistries. The tapered hole wall allows the copper deposit to thicken in the middle of the hole to the point where the two sides of the hole wall meet and grow together, consequently filling the remainder of the hole.

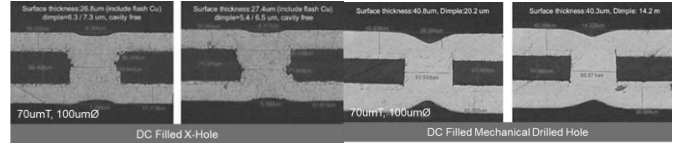


Figure 3. DC Filling of Laser and Mechanically Drill Holes

One drawback of this process is the limitation to only being able to fill laser drilled X-vias as mechanically drilled through holes tend to form cavities if aspect ratios are too high or fail to bridge if the aspect ratio is too low. DC plating leads to high thicknesses of plated surface copper requiring large amounts of etching that negate any fine line and space capabilities, large dimples, and extremely long plating times that can be as high as tens of hours. DC plating of through holes is therefore relegated to panel thickness of less than 0.2mm.

The second method of copper filling is a two-step bridge and fill where two separate plating solutions are used. One solution is a pulse periodic reverse (PPR) acid copper plating solution that utilizes specific waveforms that cause the deposition in the middle of the hole to “belly out” forming a copper bridge across the hole while minimizing the amount of surface copper for fine line applications. The second solution is a DC copper viafill solution that fills the two blind microvias formed by the bridge. This process is much more capable than the DC filling process.

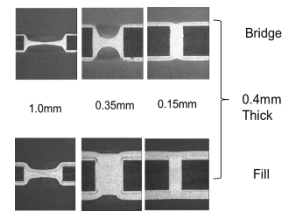


Figure 4. Two-Step Bridge and Fill

The two-step process can accommodate a much wider variety of panel thicknesses, hole diameters, and drilling methods as each solution can be finetuned for its intended purpose. The drawback is that it is a two-solution process requiring separate tanks and increased tank maintenance. Another potential drawback is that the two-step process introduces an additional interface between the bridge and fill layers which might or might not present an opportunity for reliability failure.

## One Step Through Hole Filling

The one step through hole filling process is a hybrid, panel plating process combining changes in electrical output over a plating cycle with specially designed additives that are resistant to breakdown under these conditions while able to perform their function as necessary. The objective of the plating process is to completely fill either X-vias or mechanically drilled through holes without cavities while maintaining a flat profile upon which to stack further layers with controlled surface

copper for fine line applications. See Figure 5. A further objective is to completely fill a through hole with copper for use in heat dissipation applications.

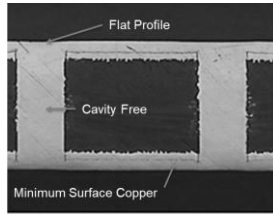


Figure 5. Hole Filling Requirements

The solution chemistry consists of copper sulfate, sulfuric acid, chloride ion, a wetter for suppression, a brightener for acceleration, and a leveler for secondary suppression. See Figure 6. During the first part of the plating cycle, specialized PPR waveforms are used to accelerate the deposition rate in the center of the hole to form the copper bridge without interference from the additives. During this phase of the plating cycle, the PPR controls the surface buildup of copper to a minimum in order to maintain fine line capabilities.

Component	Nominal	Range
CuSO <sub>4</sub> · 5H <sub>2</sub> O	240 g/l	230-260 g/l
Sulfuric Acid	90 g/l	80-100 g/l
Chloride Ion	80 ppm	70-90 ppm
Wetter	28 mL	25-35 mL
Brightener	0.85 mL	0.7-1.1 mL
Leveler	1.5 mL	1.2-1.8 mL
Current Density	2-4 ASD	1-7 ASD
Temperature	25° C	23-27° C

Figure 6. Typical Solution Composition

Once bridging is complete, rectification is changed within the same solution to more traditional DC. At this point, bridging ceases and through the normal mechanisms of additive adsorption, via filling



Figure 7. Hole Filling Progression

occurs. See Figure 7. The advantage of switching from PPR to DC within the same solution is the elimination of an interface and the potential for reliability failure due to copper oxidation between steps. Figure 8 illustrates a typical focused ion beam photograph of the grain structure within the filled copper feature. There is no interface

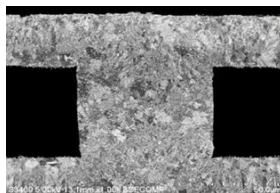


Figure 8. FIB Image of Grain Structure

observed. Depending upon the waveform and current densities used during the plating process, transitions in grain structure might be observed.

## Factors Influencing Through Hole Filling

There are a number of factors that influence the ability to fill through holes with electroplated copper that a designer should be

aware of when laying out a panel for through hole filling for further buildup or thermal management. Among these are hole diameter, panel thickness, aspect ratio, hole pitch, and density of holes. The hole diameter is critical to the ability to form a bridge at the center of the hole for cavity-free filling. If the diameter of the hole is too narrow, the bridging portion of the cycle will tend to form multiple bridges

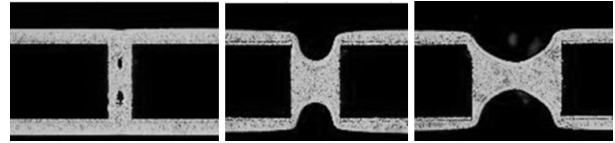


Figure 9. Effect of Hole Diameter (Bridge Only)

resulting in a double cavity effect as illustrated in Figure 9. Typically, this will become prevalent in hole diameters of less than 0.15mm. Though the process is able to bridge across a substantial distance, a realistic limit to hole diameter is approximately 0.45mm. Above this, the size of the blind microvias formed are too large to adequately fill without exorbitant amounts of surface copper.

The panel thickness and aspect ratio of the hole, in conjunction with the hole diameter, play a large role in the through hole filling process. As panel thickness and aspect ratios increase at lower hole diameters, the bridging portion of the cycle will tend to form multiple bridges resulting in cavity formation as described above. See Figure 10 for 0.10 and 0.15 diameter holes in 0.4 and 0.6mm thick panels. As

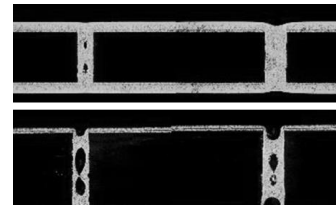


Figure 10. Effect of Aspect Ratio (Bridge Only)

panel thickness and aspect ratio increase, one needs to consider the volume of the through hole cylinder that needs filling. One must also consider the size of the blind microvia formed after bridging and its ability to be filled with a minimal dimple. This will require additional surface copper and plating time. As the panel thicknesses approach 0.5mm or more with hole diameters from approximately 0.15 – 0.35mm, plated surface copper to fill the through hole can be greater than 100um. Figure 11 contrasts the surface copper needed for through holes 100um diameter x 250um deep and 250um diameter x 600um deep. A general rule, therefore, would be panel thicknesses up to approximately 400um in thickness with aspect ratios of less than 4:1.

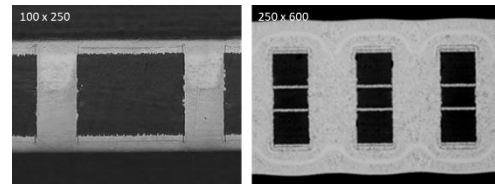


Figure 11. Effect of Panel Thickness and Hole Size on Surface Copper

The hole pitch and the density of holes within a certain area can also affect the through hole filling process. Tight pitches and very high hole densities result in a highly localized increase in surface area. This highly localized surface area creates a relatively lower apparent current density area that can slow the through hole filling process including both the bridging and via filling steps. See Figure 12.

Typically, adjustments to the plating cycle can compensate for this difference to some degree.

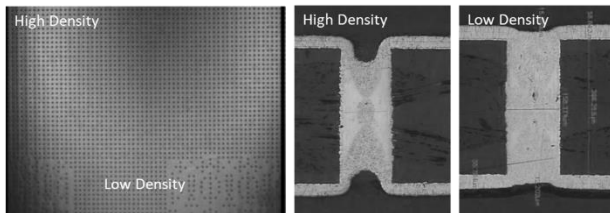


Figure 12. Effect of Pitch and Hole Density

## Summary

A single step copper through hole filling process is presented that offers the PCB or IC substrate design engineer another tool for the fabrication of next generation technologies. The process can be used for the filling of a variety of features including laser drilled X-vias and mechanically drilled through holes used in thin cores for the buildup of subsequent HDI layers. See Figures 13 – 15.

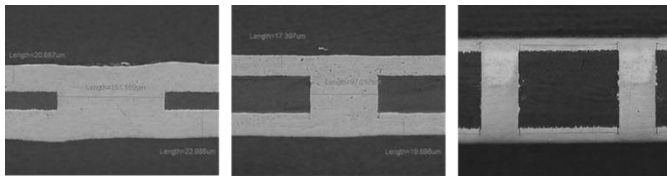


Figure 13. Various AR Holes in Core Materials

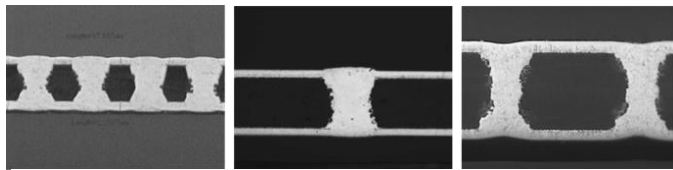


Figure 14. Various AR X-Vias in Core Materials

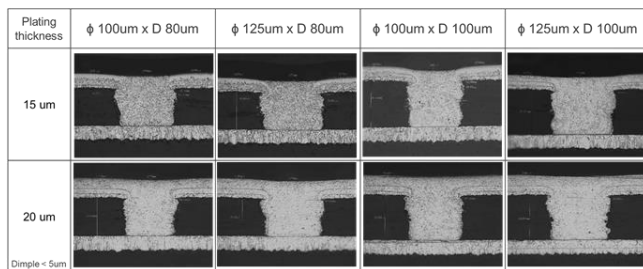


Figure 15. Various Blind Microvias

The process provides a solid copper structure with a flat profile for controlled thickness of thin dielectrics and stacking of microvias with minimal surface copper for fine line HDI capabilities. The excellent thermal conductivity of the filled copper through hole can be used for cost effective thermal management of PCB's.

An understanding of the factors that influence the through hole filling process will enable the designer to incorporate copper filled through holes into his designs for next generation technologies. At present, the capabilities of the one step through hole filling process

are summarized in the table of Figure 16. Further experimentation will continue to further extend the capabilities of the system.

Hole Diameter (mm)	Panel Thickness (mm)															
	0.06	0.07	0.08	0.10	0.15	0.20	0.25	0.30	0.40	0.50	0.60	0.80	1.00	1.20	1.40	1.60
0.10	X	X	X	X	X	X	X	X	X							
0.15	X	X	X	X	X	X	X	X	X	X	X					
0.20	X	X	X	X	X	X	X	X	X	X	X					
0.25						X	X	X	X	X	X					
0.30						X	X	X	X	X	X					
0.35						X	X	X	X	X	X	X				
0.40						X	X	X	X							
0.45						X										
0.50																
Surface Copper (um)	10	10	10	15	20	20	25	30	35	100	150	160				

Figure 16. Through Hole Fill Capabilities

## References

- [1] Wolfgang E.G. Hansal, *Pulse Plating*, Bad Saulgau: Eugen G. Leuze Verlag KG, 2012, ch 2, pp. 33-50.
- [2] R. Bellemare, C. Gugliotti, "The Effect of Board Design on Electroplated Copper Filled Thermal Vias For Heat Management", *Proceedings of SMTA International* March 2017
- [3] William H. Safranek, *The Properties of Electrodeposited Metals and Alloys*, Florida: The American Electroplaters and Surface Finishers Society, 1986, ch 1, pp 1-19.