Electronic Materials

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Copper Electroplating for HDI and IC Substrate Through Hole Fill

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ABSTRACT

Established methods for filling through holes in core layers of HDI and IC substrates are labor intensive, multistep processes that rely on mechanical filling with epoxy or paste after conformal through hole metallization, planarization, and a cap layer of electrodeposited copper before subsequent build-up of additional dielectric layers. Additionally, the mechanical strength and thermal conductivity properties of current epoxy or paste materials used to fill through holes are sub-optimal. With recent advances in copper electroplating technology, it is now possible to completely fill through holes in build-up core layers with planar, void-free solid copper electrodeposits, while simultaneously improving mechanical and thermal properties. The use of a single copper electroplating process eliminates the separate filling, planarization and capping steps, shortening the circuit board manufacturing process. This paper describes a novel pattern-plate, Direct Current (DC) copper electroplating process designed for filling core layer through holes in HDI and IC substrates. Copper through hole fill performance for a variety of substrate thicknesses and hole diameters as a function of chemical parameters, processing variables and electroplating equipment design is discussed.

INTRODUCTION

Miniaturization and portability of consumer electronics is driving the ever increasing circuit density of today's printed circuit designs. Thin core material, reduced line widths and smaller diameter through and blind vias are key attributes of build-up construction for High Density Interconnects and IC substrate package fabrication.

The use of electrolytic copper filled through holes is a recent development. Prior to the development of copper through hole filling, only blind microvias were completely filled by copper electroplating. Plugging of through holes in conventional build-up core layers had to be done after conformal plating with conventional electrolytic copper, using an epoxy fill, followed by planarization, re-metallization and processing through an electrolytic copper capping process prior to dielectric build-up. [1]

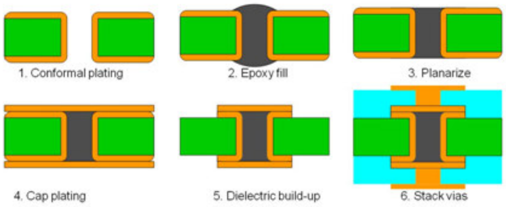


Figure 1. Build-up process using conventional epoxy hole plug

With the advent of electrolytic processes capable of completely filling through holes with copper, several problematic manufacturing steps are eliminated. The copper fill through hole process has many advantages over a conventional epoxy plug process, including improved reliability, higher thermal and electrical conductivity, increased productivity and reduced overall costs.

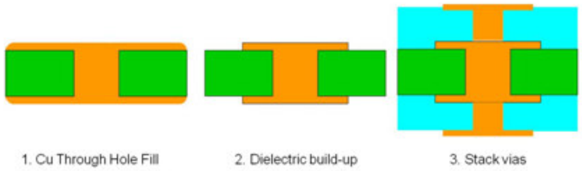


Figure 2. Build-up process using electrolytic copper through hole fill

COPPER THROUGH HOLE FILL DEVELOPMENT

A development program for an electrolytic copper through hole fill process was initiated in the Dow Electronic Materials research labs in Marlborough, MA. Product development objectives focused on maximizing through hole filling, while minimizing thickness variation across the substrate surface. In order to be commercially viable, a filling process must demonstrate a combination of void-free and high filling performance, low dimple depth and uniform surface distribution.

While the exact target values for these metrics will depend upon specific application and end-user requirements, for purposes of benchmarking development progress, the following initial targets were used:

- Hole Diameter : 75 – 100 µm
- Substrate Thickness : 100 – 200 µm
- Current Density : 10 – 20 A/ft^2
- Dimple Depth : ≤ 10 µm
- Surface Copper : ≤ 25 µm
- Substrate Metallization : Electroless Cu
- Compatible with insoluble anodes
- All organic components analyzed by CVS

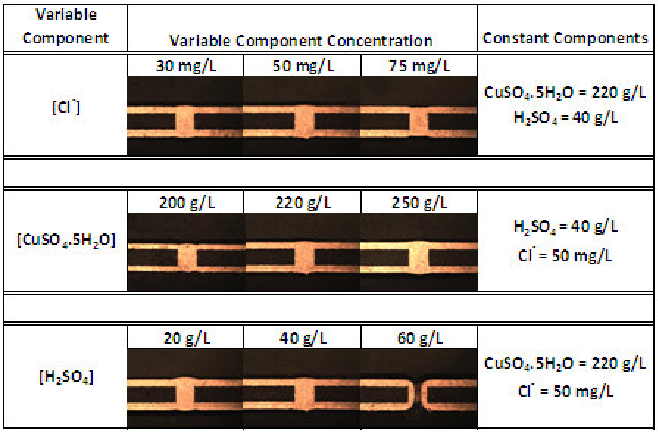
During the development program extensive screening was conducted of various classes and combinations of additives, carriers and levelers for through hole filling performance. Promising candidate materials were further optimized over a range of inorganic chemistry component concentration. Test vehicles included panel and patterned substrates, featuring through holes ranging from 75 µm to 150 µm diameter and panel thicknesses of 100 µm and 200 µm.

Copper Electroplating

The vast majority of copper electroplating baths for use in PCB fabrication are based on electrolytes consisting of copper sulfate and sulfuric acid. Combining low cost and convenient operation, these sulfate based systems are a well established technology, having now been used in the PCB industry for over 50 years.

Inorganic Components

A typical acid sulfate system contains copper sulfate (the primary source of cupric ions), sulfuric acid (for solution conductivity) and chloride ion (as a co-suppressor). Of these components, sulfuric acid concentration has the most significant impact on through hole filling performance.



Variable Component	Variable Component Concentration			Constant Components
$[Cl^-]$	30 mg/L	50 mg/L	75 mg/L	$CuSO_4.5H_2O$ = 220 g/L H_2SO_4 = 40 g/L
$[CuSO_4.5H_2O]$	200 g/L	220 g/L	250 g/L	H_2SO_4 = 40 g/L Cl^- = 50 mg/L
$[H_2SO_4]$	20 g/L	40 g/L	60 g/L	$CuSO_4.5H_2O$ = 220 g/L Cl^- = 50 mg/L

Figure 3. Through hole fill as a function of inorganic component concentration, 100 µm diameter x 100 µm thick, 15 A/ft^2

As evident from Figure 3, filling performance decreases with increasing sulfuric acid concentration. Insoluble anode systems require copper replenishment to the plating bath, with the most common being copper oxide (CuO) powder. This is problematic for through hole filling electrolytes using sulfuric acid concentrations below 40 g/L, due to low copper oxide solubility at such low acid concentration. For this reason, an electrolyte with a nominal 40 g/L sulfuric acid content offers a good balance of filling performance and CuO solubility.

Roll of Organic Additives

Acid copper sulfate systems operated without additives typically yield deposits of poor physical properties. Proprietary additives are used to refine deposit characteristics and facilitate through hole filling behavior. Organic additives are employed to improve grain refinement, throwing power, leveling and brightening of the deposit.

Generally there are three basic types of additives used in acid copper plating: Carriers, Brighteners, and Levelers.

Carriers, also referred to as suppressors, are typically large molecular weight polyoxy-alkyl type compounds. Carriers are adsorbed at the surface of the cathode and in concert with chloride ion act to suppress the plating rate. Brighteners, also referred to as accelerators, are typically organo-sulfur compounds that increase the plating reaction by displacing adsorbed carrier. [2,3] Brightener compounds may exist in several forms in electrolytic working baths.

Levelers are typically nitrogen bearing heterocyclic or non-heterocyclic aromatic compounds that act by displacing brightener species in high current density sites (protrusions). Adsorption of these additives at protrusions reduces the plating rate in those regions.

The organic additives play a key role in through hole filling. Of particular importance is the interaction between brightener and leveler. Leveler is preferentially adsorbed at areas of local high current density, such as the entrance of the hole. Leveling behavior is also affected by mass transfer and thus filling behavior is strongly influenced by convection. The competitive adsorption between the brightener and leveler results in a concentration gradient along the hole wall, with the leveler-rich corners effectively inhibited relative to the brightener-rich center, resulting in the non-uniform plating rate necessary for through hole filling.

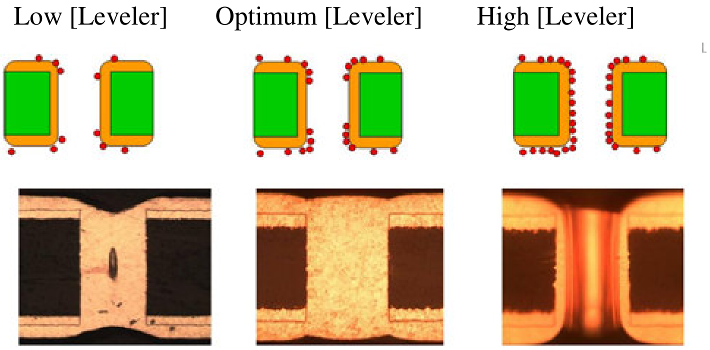


Figure 4. Effect of leveler concentration on through hole fill

Low leveler will cause a lack of inhibition at the entrance of the hole, with the result being excessive plating at the knee, rather than the center of the hole. Excessive leveler concentration will prevent selective inhibition of high current density areas, resulting in a conformal deposit.

The ratio of brightener to leveler, as well as the actual concentration of each component, must therefore be controlled for consistent through hole filling.

THROUGH HOLE FILL EVOLUTION PROFILE

Figure 5 (below), illustrates the fill evolution of a through hole filling process at 15 A/ft^2 for 100 µm and 150 µm dia holes in a 100 µm thick substrate. The fill evolution proceeds through three distinct regimes: 1) initial induction regime of conformal deposition; 2) butterfly or bow-tie deposition regime, where the plating rate is significantly accelerated in the center of the hole relative to the hole corners and substrate surface; 3) the final regime of blind microvia bottom-up filling, once the center of the hole has closed.

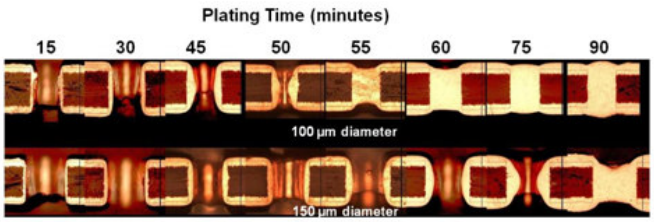


Figure 5. Through hole fill evolution as a function of plating time, 100 µm diameter (top) and 150 µm diameter (bottom) on 100 µm thick substrate, 15 A/ft^2

Figure 6 shows the copper plating thickness as a function of time, for the substrate surface, corner of the hole, and in the center of the hole. The plating rate on the substrate surface increases linearly with time, while the corner of the hole is locally suppressed. The accelerated plating in the center of the hole becomes apparent after approximately 50 minutes, corresponding to approximately 15 µm of copper surface plating.

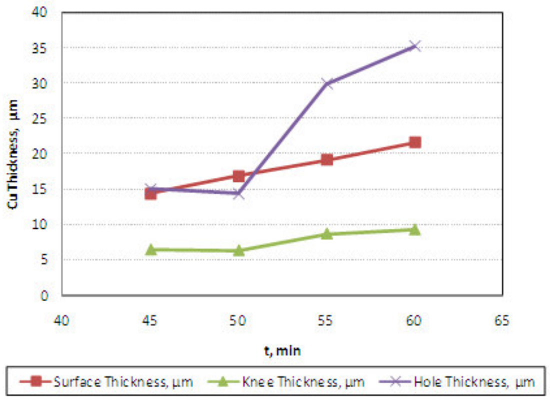


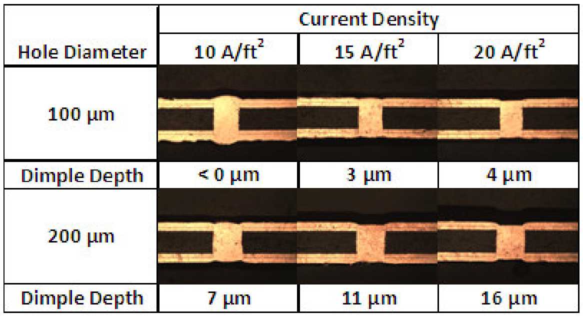
Figure 6. Copper thickness as a function of plating time for surface, hole corner and hole center, 100 µm diameter x 100 µm thick substrate, 15 A/ft^2

Impact of Mass Transport and Current Density

Mass transport and current density have a significant impact on through hole filling capability. In general, lower levels of solution flow were found to improve through hole filling performance, particularly in larger diameter holes (> 100 µm). However, this improvement comes at the price of increased risk of improper fill in smaller diameter through holes (≤ 75 µm) and on thicker substrates (> 100 µm). Improper fill may lead to defects such as “seams” and voids within the plated deposit. The consequence of this behavior is that solution flow must be carefully chosen to achieve the best balance between levels of fill and plating quality for the specific applications being run.

Convection was further studied by comparing through hole filling performance for conventional air agitation and jet impingement systems. A well designed jet impingement system was found to simultaneously reduce the incidence of voided through holes and increase filling uniformity across the panel.

The effects of current density are somewhat less complex. Lower current density will enhance through hole filling (i.e., smaller dimples) and also produce product with lower levels of voiding. As with solution flow, the effects of current density depend on the through hole dimensions. In general, lower aspect ratio through holes can tolerate a higher applied current density than higher aspect ratio holes.

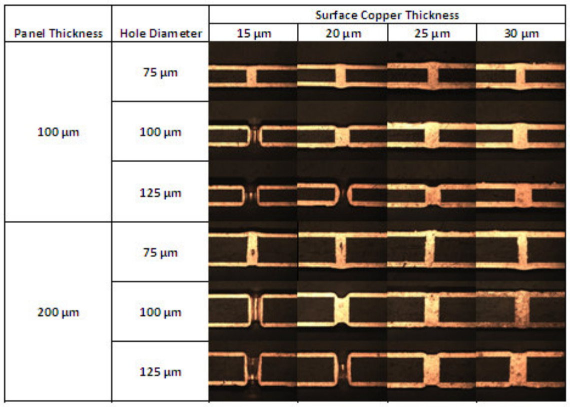


Hole Diameter	Current Density		
	10 A/ft^2	15 A/ft^2	20 A/ft^2
100 µm			
Dimple Depth	< 0 µm	3 µm	4 µm
200 µm			
Dimple Depth	7 µm	11 µm	16 µm

Figure 7. Through hole fill of 100 µm and 200 µm diameter x 100 µm thick as a function of current density (25 µm copper thickness)

PLATING THICKNESS AND HOLE SIZE

The amount of copper deposited on the surface required to give a dimple depth below 10 µm varies with substrate thickness and hole diameter. For thin substrates (≤ 100 µm) with small diameter holes (< 100 µm), as little as 15 µm of surface copper is necessary to achieve complete through hole fill. As the hole diameter and substrate thickness increase, the amount of copper must also be increased to provide equivalent through hole fill performance. For hole diameters greater than 125 µm in substrates 200 µm thick or greater, more than 30 µm of copper is required to completely fill the through holes, while maintaining a dimple depth below 10 µm.



Panel Thickness	Hole Diameter	Surface Copper Thickness			
		15 µm	20 µm	25 µm	30 µm
100 µm	75 µm				
	100 µm				
	125 µm				
200 µm	75 µm				
	100 µm				
	125 µm				

Figure 8. Fill performance as a function of surface copper thickness in 75 µm, 100 µm and 125 µm diameter holes in 100 µm and 200 µm thick substrates, 15 A/ft2

COPPER THROUGH HOLE FILL EQUIPMENT DESIGN

A wide variety of system design features that further enhance through hole filling performance may be incorporated in both batch and continuous conveyorized plating equipment. These include anode materials and engineered fluid delivery devices, such as eductors or nozzles, designed to create impinging flow on panel surfaces. A wide variety of different factors influence process selection for copper through hole filling and careful design and selection of plating equipment for new process chemistries can provide the end user with high process capability and an attractive equipment cost.

The following factors should be considered, when comparing the advantages and disadvantages of different types of copper electroplating processes for through hole filling:

- Plating uniformity
- Thin core material handling
- Throughput / yield
- Equipment cost, complexity and footprint

Copper electroplating process equipment can be generally placed in two broad categories: vertical batch or continuous conveyorized. In conventional vertical batch electroplating systems, a number of panels are mounted on a single flight bar and processed in a single vertical plating cell for the full duration of the plating cycle. In conveyorized electroplating systems, the panels are dynamically transported through a series of plating cells.

Whether used in batch or continuous electroplating equipment, the ability of a well engineered jet impingement system to deliver uniform solution flow across an entire substrate surface is critical to enhanced through hole filling performance.

ANODE MATERIALS

Copper anodes, also referred to as soluble anodes, are typically solid bars of copper, or alternatively balls or nuggets encased in titanium baskets. The anodes are phosphorized to control dissolution and to avoid excessive polarization. Copper anodes are typically surrounded by porous anode bags, to prevent particulates from entering the plating bath. As a copper anode dissolves in a plating bath, the overall anode surface area changes, affecting both anode current density and deposit uniformity. [4] The use of soluble copper anodes may restrict productivity as the anode current density must be limited to approximately 30 A/ft^2, above which the anode polarization increases, ultimately leading to passivation.

Insoluble anodes, usually a mixed precious metal oxide (MMO) coated titanium mesh, address many of the issues associated with soluble anode operation. Insoluble anodes can operate at significantly higher current densities, and remain dimensionally stable, thus offering both higher deposition rates and more consistent deposit uniformity.

The electrochemical reaction at the insoluble anode is the decomposition of water into oxygen and hydrogen ions (acid):

$$H_2O \rightarrow 1/2O_2 + 2H^+ + 2e^-$$

Insoluble anode systems require copper replenishment to the plating bath. Several methods are available, with the most common being copper oxide (CuO) powder. Copper oxide dissolves in the plating solution, maintaining acid concentration:

$$2H^+ + CuO \rightarrow Cu^{2+} + H_2O$$

It is well known that brightener species generate by-products during operation. This behavior is common to all organo-sulfur brightener species used in commercially available acid copper plating baths. These by-products are formed both chemically, during idle time, through interaction with Cu(0), and electrochemically, during deposition. A number of different by-product species can be formed. While by-products generated by anodic oxidation are generally inert and do not affect plating performance, brightener reduction by-product species are known to be electrochemically active and can degrade the deposit quality and filling performance. [5] Copper through hole filling performance is sensitive to brightener by-product concentration.

Given that brightener species can be reduced through direct reaction with copper metal surfaces, forming active by-product species, it is not surprising that insoluble anode systems have proven less susceptible to the generation of harmful brightener by-products than copper anode systems.

Summary

A novel and enabling electrolytic copper through hole fill process has been developed for consistent and reliable through hole (and simultaneous high blind microvia filling) performance over a wide range of hole diameters and substrate thicknesses. Chemical and operating process parameters have been fully characterized, to allow the end user the flexibility to tailor the process to their specific needs.

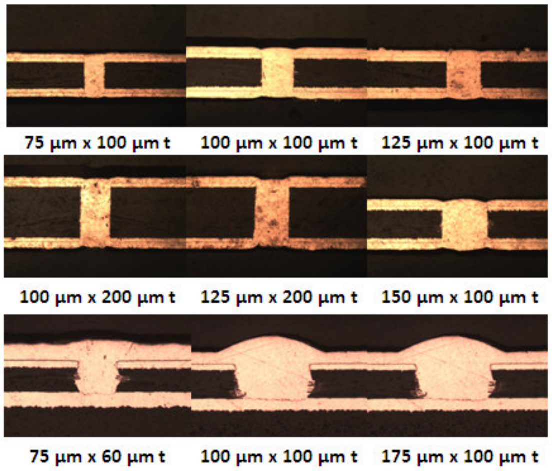


Figure 9. Through hole and blind microvia fill performance over a range of hole diameters and substrate thicknesses

While electrolytic copper through hole fill processes are in the early stages of commercial application, it is anticipated that there will be substantial adoption of this technology to enable a variety of current and future HDI and IC substrate package designs.

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