Copper Electroplating Technology for Microvia Filling

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Abstract
This paper describes a copper electroplating enabling technology for filling microvias.

Driven by the need for faster, smaller and higher performance communication and electronic devices, build-up technology incorporating microvias has emerged as a viable multilayer printed circuit manufacturing technology. Increased wiring density, reduced line widths, smaller through-holes and microvias are all attributes of these High Density Interconnect (HDI) packages.

Filling the microvias with conductive material allows the use of stacked vias and via in pad designs thereby facilitating additional packaging density. Other potential design attributes include thermal management enhancement and benefits for high frequency circuitry. Electrodeposited copper can be utilized for filling microvias and provides potential advantages over alternative via plugging techniques.

The features, development, scale up and results of direct current (DC) and periodic pulse reverse (PPR) acid copper via filling processes, including chemistry and equipment, are described.

Introduction

The continuing trend of portability and increasing functionality of electronic devices has driven the miniaturization and increased wiring density of printed circuit boards (PCBs) [1,2]. Conventional multilayer PCBs with through hole interconnect vias are not really a practical solution to satisfy these density requirements. This has driven the introduction of alternative approaches for high density interconnects (HDI) for example sequential build up (SBU) technologies incorporating microvias. A number of differing SBU/microvia technologies are employed however a common feature is the achievement of increased densification.

Utilizing conductive filled microvias enables yet further package densification by facilitating via in pad and stacked vias designs. Electrodeposited copper via filling offers several potential advantages over alternative via plugging techniques:

- Solid copper via plugs are inherently reliable and have higher conductivity than organic or conductive pastes.
- Gains are realized in manufacturing productivity as densification and electrical connectivity is established in one step.
- Copper electroplating is a technology already well known and extensively used in PCB fabrication.

All of these features ultimately lead to higher reliability lower cost circuit densification. A program was therefore embarked upon to develop copper electroplating as a viable via filling technique.

Copper Via Fill Development

The program for copper via fill process development was initiated in the Shipley research labs in Omiya, Japan. Product development objectives focused on maximizing via filling while minimizing thickness variation across the substrate surface. Filling ratio, a quantifiable measure of via filling, was used to compare capability of candidate formulations and is described in the schematic below:

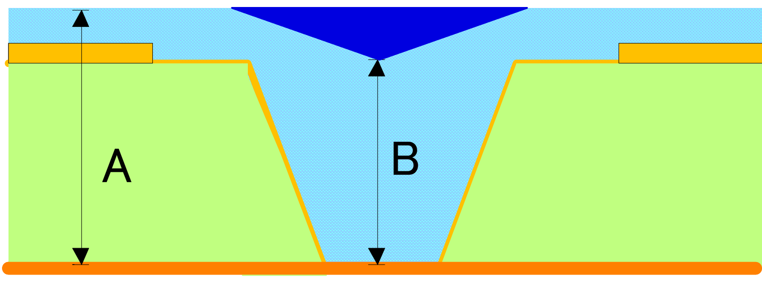

Figure 1, Via Filling Ratio Definition

Initial target performance was to obtain a filling ratio > 80% for via diameters from 80µm to 120µm on 50µm - 80µm deep laser ablated vias at a nominal 25µm deposit thickness**.**

Copper Electrolytes

It is apparent that for the achievement of via filling the plating rate in the via trench should be higher than on the surface and as such the copper electrolyte characteristics would be of fundamental importance in creating such differential plating rates.

There are several general classes of electrolytes used for electrolytic copper deposition, defined by the predominant copper counter ion, including: cyanide, fluoroborate, pyrophosphate and sulfate based systems

[3]. Sulfate based systems are most commonly used in PCB manufacturing owing to their low cost, convenient operation, safety and ease of waste treatment [4]. Development of an electrodeposited via fill process was therefore focused on acid copper sulfate systems. The acid copper sulfate system typically consists of copper sulfate, sulfuric acid, chloride ions and proprietary organic additive(s).

Inorganic Components

- Cupric (Cu^{2+}) ions
- Sulfuric acid
- Chloride

Copper sulfate is the initial source of copper ions in solution. The copper content in solution is maintained by a coulombic equilibrium set up between the cathode, where plating occurs, and the anode. The anode is typically made of the same metal as is being plated, in this case copper and acts as an ion source.

Sulfuric acid contributes to the overall solution conductivity, reducing anode and cathode polarization.

Chloride ions work in conjunction with the carrier to suppress deposition and help refine the deposit morphology.

Organic Components
Proprietary additives are used to further refine deposit characteristics. An acid copper sulfate system operated without additives typically yield deposits of poor physical properties. 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 [5-7]:

- Carriers
- Brighteners
- 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 are typically small molecular weight sulfur containing compounds that increase the plating reaction by displacing adsorbed carrier. 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). The plating rate in effect is suppressed at these protrusions.

Via Fill Mechanism
In direct current (DC) plating the mechanism for accelerated via filling (i.e. bottom up filling) is largely due to the role of the organic additives. The brightener (accelerator) concentration effectively increases in the via as the surface area becomes smaller. This localized increase in brightener concentration results in accelerated deposition in the via compared to the surface [8]. In order for this accelerated bottom up filling to occur, the additive package must operate in balance with each other and be maintained within specific parameters.

Pulse periodic reverse plating (PPR) in combination with organic additives can also provide a route to the differential plating rates required for via filling. In direct current plating, only current (or voltage) is controlled while a pulse periodic reverse current wave form, three parameters can be varied independently: on time, off time and current density, resulting in more intimate control of deposition. Additionally, different PPR waveforms can be chained together to form complex waveforms. These variables affect adsorption and desorption phenomena, allowing control of these variables otherwise unavailable with conventional DC plating [9,10].

Organic additive selection
During the development program extensive screening was conducted of various classes and combinations of additives, carriers and levelers for via filling efficacy. Candidate materials were further optimized with inorganic chemistry component concentration. Test substrates included CO_2/UV laser ablated micro vias from 80µm to 130µm dia in RCC and LDPP dielectric materials form 50µm to 80µm thick.

This optimization was done in conjunction with rectification type resulting in distinct via fill products for use with DC and PPR waveforms.

Process Parameters – Chemical Effects
During the development of the respective DC and PPR via fill systems, the effect of inorganic component concentration on via filling was determined. The following constituents were studied for their effect on via filling performance.

- Copper sulfate
- Sulfuric acid
- Chloride

Of these the copper sulfate concentration was found to have the principal influence. The effect of copper concentration on filling ratio is shown in Figure 2

Copper sulfate	130g/L	150g/L	180g/L	200g/L	250g/L
Sulfuric acid	190g/L	150g/L	120g/L	100g/L	50g/L
Chloride ion	50mg/L	50mg/L	50mg/L	50mg/L	50mg/L
70um Φ/80umt					
Void/Hole	29/102	40/126	18/68	0/105	8/103
100um Φ/80umt					
Void/Hole	18/190	7/186	0/110	0/103	0/112

Figure 2, Effect of Copper Sulfate Concentration on Via Filling

Process Parameters – Physical Effects

- Physical process parameters studied included:
- Current density
- Agitation
- Plating thickness
- Temperature
- Rectification (DC and PPR) and waveform (PPR)

The major effects are described below.

Current Density – The relationship between current density and filling ratio is for a specific via type is shown in Figure 3. In general lower current density improves via filling capability.

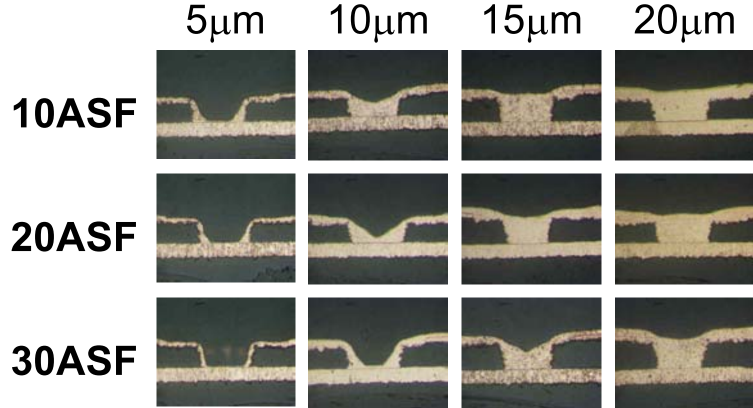

Figure 3, Effect of Current Density 100µm dia x 80µm deep

Solution agitation – This was found to play a key role in copper via filling. Figure 4 compares the effect of air agitation with jet or impingement plating on via filling. As is evident, jet plating significantly improves via fill capability and uniformity of via fill across the panel compared to air agitation alone.

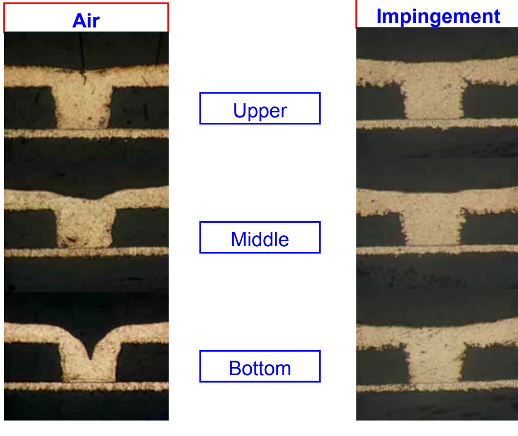

Figure 4, Effect of Agitation on Filling Uniformity

Plating thickness - The effect of copper thickness has a significant effect on via filling ratio. As via diameter is increased, more copper is required to maintain fill.

Optimized process parameters – Based on the aforementioned development program optimum process parameters were derived. These are given for DC and PPR via fill processes in Tables I - II:

Table I, DC Via Fill Process Parameters

Parameter	Target	Range
$CuSO_4.5H_2O$	200 g/l	190 – 210 g/l
H_2SO_4	100 g/l	90 – 110 g/l
Cl	50 ppm	40 – 60 ppm
VF A	2.0 ml/l	1.5 – 2.5 ml/l
VF B	20 ml/l	15 – 30 ml/l
Current Density	1.5 A/dM^2	1.0 – 2.0 A/dM^2
Temperature	23°C	22 – 25°C

Table II, PPR Via Fill Process Parameters

Parameter	Target	Range
$CuSO_4.5H_2O$	130 g/l	120 – 140 g/l
H_2SO_4	190 g/l	180 – 200 g/l
Cl	50 ppm	40 – 60 ppm
VF PPR A	1.0 ml/l	0.5 - 1.5 ml/l
VF PPR B	5.0 ml/l	4.0 – 8.0 ml/l
Current Density	2.0 A/dM^2	1.0–3.0 A/dM^2
Forward:Reverse Current	2:1 A	
Forward:Reverse Time	10:1 msec	
Temperature	20°C	18 – 23°C

Scale Up

To further explore process capability scale up was undertaken in pilot plant then production scale electroplating equipment and the following elements were studied and optimized:

- Idle time
- Bath Age
- Substrate effects
- Consistency and uniformity
- Reliability

Idle time – This is simply non-plating time, where no current is applied and no deposition occurs. It is known that idle time can be detrimental to plating performance in acid copper systems. It is also known acid copper performance can degrade with age and usage [12].

In Figures 5 - 6, the effect of idle time and bath age seen initially on via filling performance is shown.

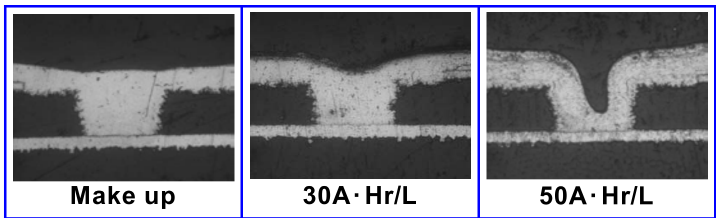

Figure 5, Effect of Bath Age

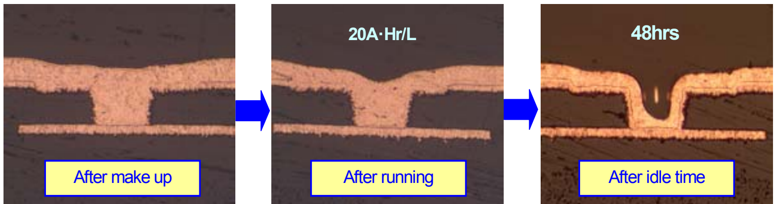

Figure 6, Effect of Idle Time

It was postulated that much of the degradation in performance due to idle and aging effects could be attributed to organic byproducts, primarily from the brightener, which accumulate in the bath. These byproducts are formed both chemically during idle time and electrochemically during deposition. Most byproducts are inert and do not affect plating performance, however some brightener byproducts are known to be electrochemically active [13,14]. To determine whether brightener byproduct was responsible for loss of via fill capability, extensive studies were conducted.

In Figure 7, a known electrochemically active brightener byproduct was added in increasing amounts to a new bath. As is evident, filling ratio was significantly compromised as concentration increased.

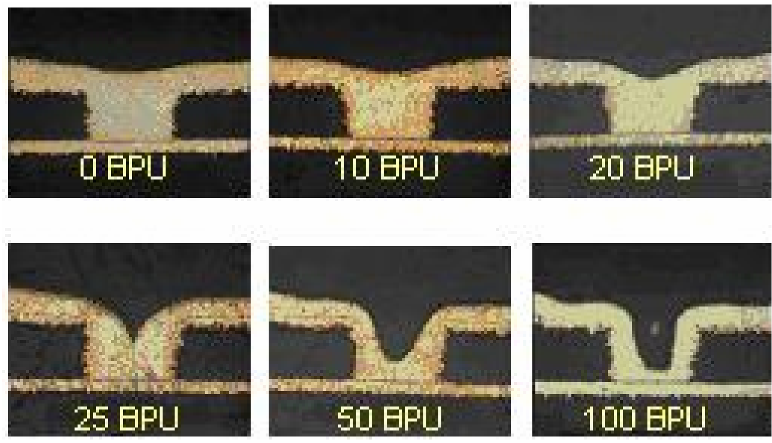

Figure 7, Effect of Brightener Byproduct Concentration

Clearly to maintain viafill performance it would be necessary to manage and minimize the generation of byproduct. Previous research activities within the organization had established techniques that could

scavenge such byproduct. This methodology was therefore investigated in the viafill process with very positive results

Figures 8 - 9 provide the results of idle and running time on via fill when operated with byproduct scavenging methodology.

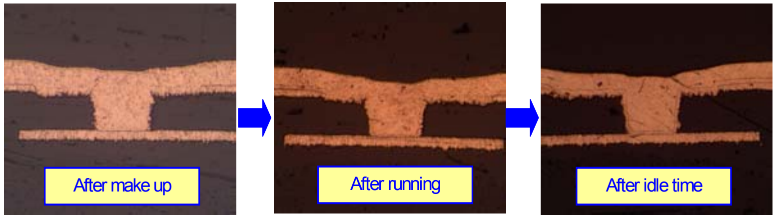

Figure 8, Effect of Idle Time Using Byproduct Scavenger

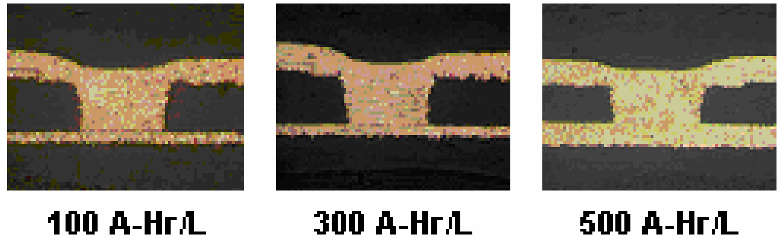

Figure 9, Effect of Bath Age with Byproduct Scavenger

This clearly confirmed that byproduct species were indeed responsible for the loss of viafill however the scavenging technique was fully effective in preventing the degradation in performance.

Substrate Influence

The ability to reliably and completely fill a via is dependent on several factors beyond via diameter and depth. It was determined that the condition of the substrate also has a significant effect on via fill ability. These factors include via profile, thickness and uniformity of electroless copper coverage, degree of surface oxidation, and dielectric material. Each of these factors was investigated and the findings are summarized as follows.

The via profiles shown in Figure 10 demonstrate a range of shapes that can be filled. The profiles on the left are harder to fill than those on the right.

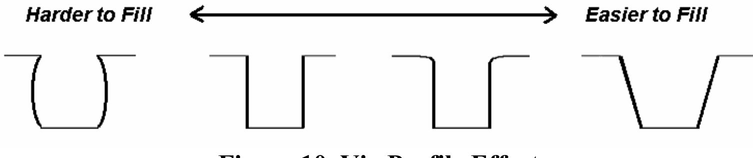

Figure 10, Via Profile Effects

The thickness, uniformity of coverage and age of the electroless copper influence copper via fill. Thin or discontinuous electroless copper will not fill as reliably as a thick uniform deposit. Generally a uniform electroless copper thickness > 0.3μm is required for reliable filling.

Oxidation of the electroless copper can also adversely effect via fill. To demonstrate this, substrates were Processed through electroless copper and annealed at 120℃ for 5 hours prior to via fill. After copper via fill electrodeposition, no characteristic bottom-up fill was seen. Storage time and environment also play a role via fill ability. Panels stored in a non humidity controlled environment for 3 weeks were shown to exhibit poor in fill compared to identically processed panels with fresh electroless copper. Panels stored in a controlled environment for similar times lost via fill at a slower rate than the uncontrolled environment.

The dielectric material has an influence on via fill capability. Non-glass reinforced materials are generally easier to fill than glass reinforced materials. Note the presence of heavy glass protrusions into the via can have an adverse effect on electroless copper coverage. Figure 11 shows the effect of glass reinforcement after laser ablation and copper via fill.

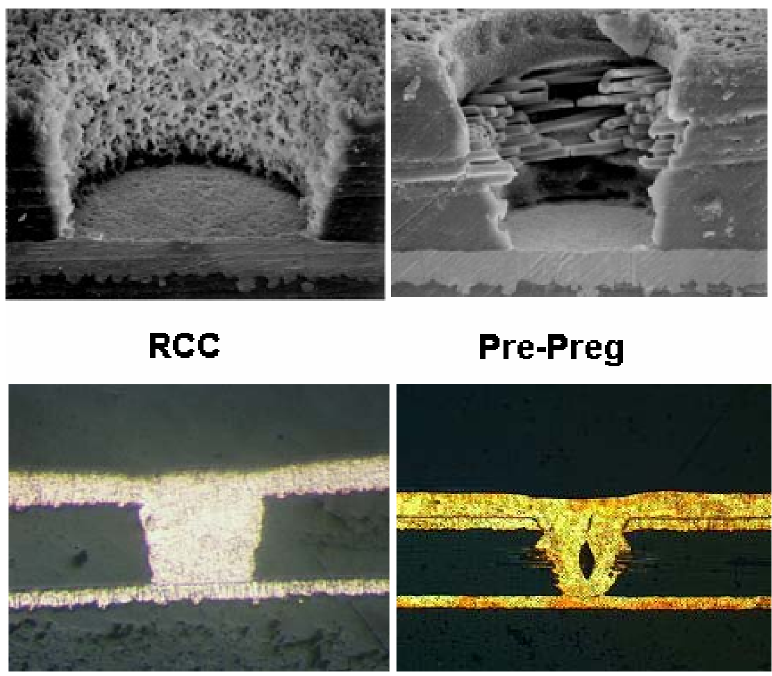

Figure 11, Effect of Glass Reinforcement After Laser Ablation (top) and Copper Via Fill (bottom)

Reliability and Physical Properties

Copper filled vias exhibit excellent reliability. A solid plug of copper is inherently robust. Table III below shows the interconnect reliability of plated through holes and blind microvias from a production copper via fill process. Table IV summarizes the tensile and elongation values obtained with copper via fill as a function of current density.

Table III, Interconnect Reliability

	Solder Float (288℃/5cycle)		*Hot oil (260℃/100cycle)*	
Bath Age	***Blind Via***	***Through Hole***	***Blind Via***	***Through Hole***
64 A-hr/L	***0/70***	***0/10***	***0/35***	***0/10***
133 A-hr/L	***0/70***	***0/10***	***0/35***	***0/10***
202 A-hr/L	***0/70***	***0/10***	***0/35***	***0/10***
255 A-hr/L	***0/70***	***0/10***	***0/35***	***0/10***
284 A-hr/L	***0/70***	***0/10***	***0/35***	***0/10***
Stacked Via	***0/70***	-	***0/35***	-

Table IV, Physical Properties

Current density	Tensile strength	Elongation
$1A/dm^2$	$307.7N/mm^2$	22.8%
$2A/dm^2$	$323.6N/mm^2$	27.9%
$3A/dm^2$	$314.7N/mm^2$	25.3%

Process Capability

The through hole throwing power from the DC and PPR via fill processes are given in Figure 12. At higher panel thickness and current density, the advantage in throwing power of the PPR over DC system is evident. Conversely, the trend is reversed at low current density and the DC system provides an advantage. At panel thickness more typical of SBU construction there is little difference in through hole throwing power between the 2 systems.

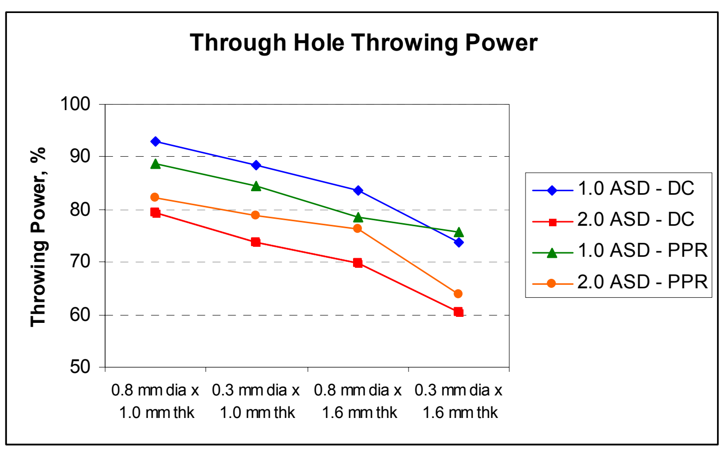

Figure 12, Copper Via Fill Through Hole Throwing Power

Substrates comprised of three unique test patterns were used to compare the surface Cu thickness distribution of the DC and PPR via fill systems for pattern plate operation. Results are shown graphically in Figure 13. Figure 14 compares the characteristic trace profile obtained from DC and PPR via fill processes. In general, better pattern surface distribution with a more desirable shape is obtained with the PPR via fill system.

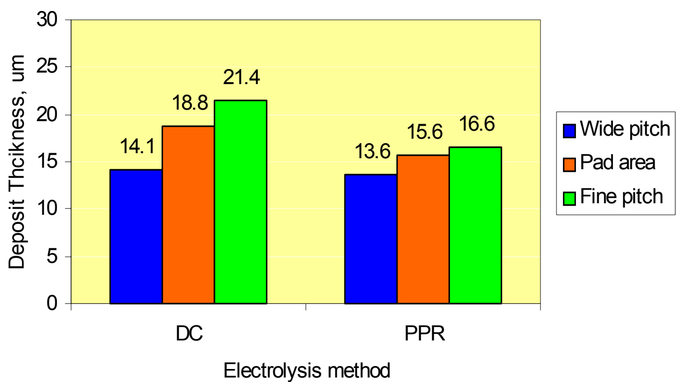

Figure 13, Comparison of DC and PPR on Pattern Surface Distribution

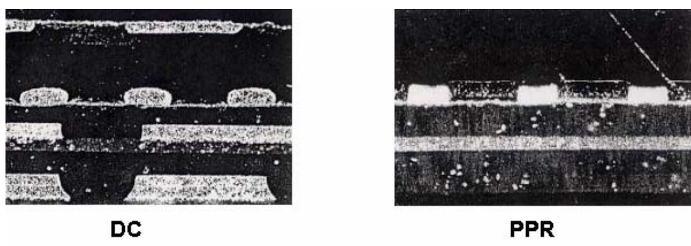

Figure 14, Comparison of DC and PPR on Pattern Shape

The capability of the processes to fill vias of various shapes, and dimensions is an ongoing activity in both laboratory and commercial scales. At present we find that the PPR via fill system is capable of filling a broader range of via dimensions than the DC system.

Comparison of DC and PPR Systems

The relative pros and cons of the DC and PPR via fill systems are given below in Table V.

Table V, DC and PPR Pros and Cons

DC Via Fill	PPR Via Fill
Pros	Pros
• Conventional rectification	• More capable via fill
• Ease of operation	• Greater potential through waveform mediation
Cons	• Higher PTH throwing power
• Lower PTH throwing power	• Better pattern plate surface distribution and profile
• Worse pattern plate surface distribution and profile	Cons
	• PPR rectifiers
	• More sensitive substrate to condition
	• Requires more control

For pattern plate via fill applications that include thick panels with plated through holes, the PPR via fill system may be more appropriate. Conversely for panel or pattern plate applications with uniform feature

distribution and no plated through hole requirement (e.g. packaging application), the DC system may be more appropriate.

Plating Cell Design

A key element of the copper via fill process is the engineering design of the specialty plating cell. This has led to a plating cell design that incorporates specific elements to enhance via fill capability and uniformity with process consistency. A side view of the cell design is shown in Figure 15.

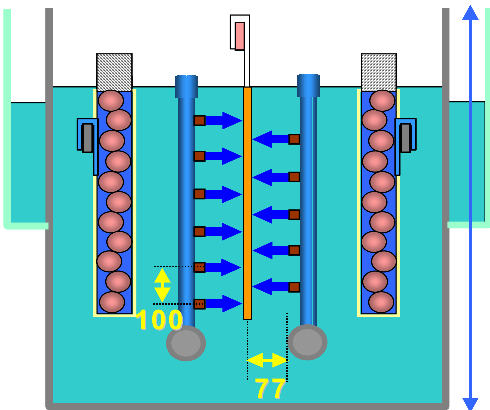

Figure 15, Side View of Via Fill Plating Cell

Conclusions

Novel and enabling copper electroplating DC and PPR via fill systems have been developed for reliable and consistent blind via filling. Each system has distinct attributes and offer the end user the flexibility to select a via fill process best tailored for their application. These processes are currently seeing commercial applications and it is anticipated that there will be substantial adoption of this technology to produce features such as shown in Figure 16.

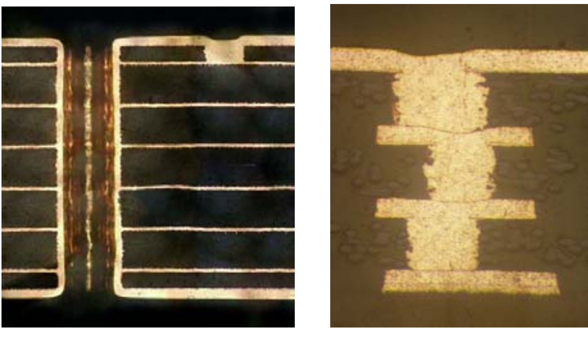

Figure 16, Examples of Copper Filled Vias

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