FILLING THROUGH HOLES AND BLIND MICRO VIAS WITH COPPER USING REVERSE PULSE PLATING AND INSOLUBLE ANODES

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ABSTRACT
This paper presents systematic investigations on complete through hole filling for cores using a Cu electroplating process as an alternative to the common paste plugging process [1]. This technology is targeting at both HDI production and also at the packaging level [2].
This electro plating process consists of two steps, a first process to merge both centers of the through hole walls (X-plating) followed by filling up the resulting blind micro vias. Processes and manufacturing technology are described as well as current limitations and requirements. Complete filling of through holes is achieved by reverse pulse plating, RPP.
Examples of filling of mechanically drilled through holes and also the extension of the technology to laser drilled through holes is shown.
In detail the influence of electrolyte agitation, current density, reverse pulse parameters, redox mediators ($Fe^{2+/3+}$) and temperature on the filling performance are described and discussed for each step of the process. The separate discussion for the two steps mechanism allows a deeper insight and thus a significant process improvement

Key words: Through Hole Filling, Pulse Reverse Plating, Cu Plating

INTRODUCTION
Through Hole filling by RPP offers a viable alternative to the standard paste plugging for core processing in substrate manufacturing. Current core manufacturing requires a paste plugging after Cu galvanization for through holes so that subsequent build up layers can be produced by sequential lamination, the flat core surface is essential for stacked via and also via in pad technology.
Instead of plating only a conformal Cu barrel into the through via it is now possible to completely fill it with Cu and thus eliminate the need for the plugging process reducing significantly the number of overall process steps and thereby the overall cost.
Moreover, it offers certain advantages such as potentially higher reliability in accelerated aging tests and an improved thermal management as the thermal conductivity of a completely copper filled through via is significantly higher than a paste plugged through via.
Today's challenges in the so called Through Hole Filling process are represented by through holes with a high aspect ratio. Voids after X-Plating occur easily for smaller through hole diameter and higher board thickness. In addition, depending on design, varying hole pitch on one board increase the difficulty to achieve an acceptable plating uniformity. To understand the limitations of the process our investigations aimed at identification of the key parameters.
As there are two steps in the through via filling process we divided our experimental work accordingly. The 1st section will give an overview over the process itself (fig 1), the 2nd section will concentrate on the formation of the X (merging through via walls) and the 3rd section will deal with electrochemical filling of the resulting blind vias.
Most of the tests have been conducted in a single board cell (volume 400 l) i.e. each plating cell is handling exactly one 18" by 24" sample board. Different test panels have been used and are described within the experiment itself. All panels have been electroplated in the so called panel plating mode i.e. there were no dry film patterns on the board during plating. This panel plate technology is being used in standard production processes by applying the resist and the conductor pattern in a subsequent step.

GENERAL DESCRIPTION OF THROUGH VIA FILLING
Table 1 describes the process flow of the electrochemical through via filling technology

Electrochemical Cu Through Via filling
1. Drilling
2. Seed Layer Deposition (E'less Cu 0.2 -0.5 µm)
3. Galvanic reinforcement (2-5 µm Cu)
4. Galvanic Cu Filling -X-Plating (5-10 µm) -Via filling (10-15 µm)
5. Dry Film Application and subsequent Structuring

Table 1: Process steps characterizing the electrochemical Cu through via fill technology

The plating process is described in fig 1 showing the two main plating processes of step 4.

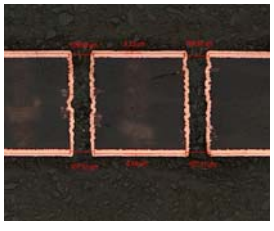
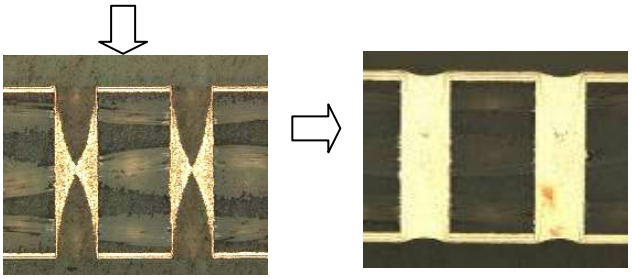


Fig. 1: Plating steps to a complete fill of a through via with Cu, starting from a conformally plated layer (top). 2nd plating step is the formation of the X, resulting in 2 blind

vias on both sides of the panel which are then completely filled in the next step.



As an alternative electrochemical route one could consider a slow purely conformal growth of copper on the side walls to give a complete fill. That process has several disadvantages such as being slow (less productivity) and a higher risk for voids (see fig 2.).

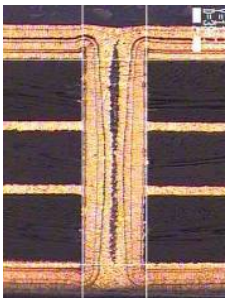


Fig. 2: Conformal Cu growth to a complete fill may end up in producing a long ribbon like void depending on aspect ratio.

Moreover, this conformal technique may require excessive Cu on the surface (approximately ½ hole diameter) whereas the above mentioned X-formation offers the possibility to significantly reduce the Cu overburden. That is achieved by applying a combination of reverse pulse plating and etching in one electrolyte. The electrolyte contains not only Cu but also Fe^{2+} and Fe^{3+}. This Inpulse system is described for a better understanding schematically in Fig 3.

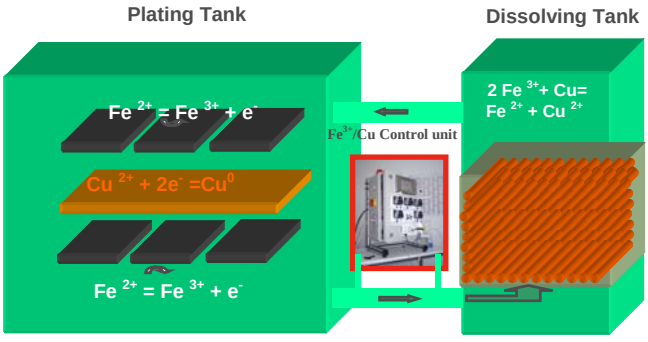


Fig. 3: Inpulse electrolyte system containing Cu and Fe.

Cu is deposited as usual on the cathode (panel) whereas the Fe^{2+} ions are used to carry the current at the dimensionally stable anodes and prevent oxidation of organic additives. The oxidation product Fe^{3+} is used to dissolve the consumed Cu chemically in a second compartment filled with pure Cu balls and reduced again to Fe^{2+}. However the Fe^{3+} cannot only be used to replenish Cu but also to reduce the Cu deposition on the panel surface. The electrochemical reactions at the cathode in the Inpulse system with corresponding potential are given below (I) and (II) as measured against standard hydrogen electrode.

$Cu^{2+} + 2e^- \rightarrow Cu$ E = 0.340 mV (I)
$2\ Fe^{3+} + 2e^- \rightarrow 2\ Fe^{2+}$ E = 0.771 mV (II)

Reaction (II) is electrochemically favored against (I) and thus the amount of Fe^{3+} reduces and determines the amount of copper deposited onto the cathode A control unit between the plating and dissolving tank regulates the exchange between both compartments and can control the amount of Fe^{3+} within a range of ±0.1 g/l which is a prerequisite for a good process control which has been proven in production scale. The exchange of electrolyte is much stronger on the surface than in a via so that this effect is mainly observed on a surface and not in vias and especially not in blind vias.
With this technology we were able to reduce the amount of Cu overburden for a 100 µm thick core from 50 µm down to now 13 µm (see fig 4).

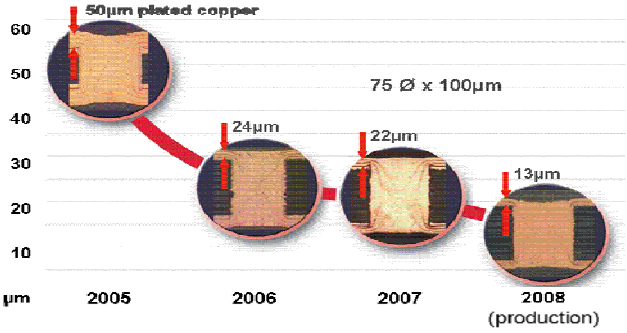


Fig 4. Development of through Via filling technology: reduction of Cu overburden for a 100µm thick core

This reduction was a prerequisite for a production scenario since the surface plated copper thickness determines in the end the achievable lines and spaces in the circuitization process of approx. 2 x Cu overburden: i.e. 13 µm plated surface can be etched to give 26 µm line and space.
Nevertheless, the main core thickness for IC substrates is thicker than 100 µm; most of today's products have cores of 400 µm thickness or more. These are extremely difficult to fill without void formation and require a long plating time at a low plating current density.
The aim of the work described in this paper was to expand the filling technology to higher aspect ratio cores by determining main parameters and improve each step of the process.

EXPERIMENTAL

Various reverse pulse plating parameters are described in the following chapters and for clarity a short explanation of the notation used is given below,
Example: 5/40 80/2 →
5 = Forward or cathodic current density (ASD)
40 =Reverse or anodic Current density (ASD) -
80 = Cathodic plating time (ms)
2 = Cathodic plating time (ms).

This means 5/40 80/2 is an 80 ms cathodic pulse at 5 ASD followed by a 2ms anodic pulse at 40 ASD

X- Plating

As there were a large number of parameters we started a first series of experiments in a small lab tool to determine which of the following parameters might have a significant influence. We used a small 20 litre test cell, 400µm thick core panels with 100µm hole through holes and varied in a series of several small DOEs the key parameters. We found that the parameters in *italic* showed a significant influence determined by statistical software tools and set up further experiments in a production tool on 400µm panels with through hole of 100µm diameter.

- *Current density and pulse parameters*
- *Fe^{3+} concentration*
- *Temperature*
- *Cu concentration*
- *Cl –concentration*
- *Electrolyte agitation*
- Fe^{2+} concentration
- Sulfuric acid concentration
- Brightener (accelerator)
- Leveller (inhibitor) concentration

The nature and type of additive has a big influence on the plating performance but in this specific case within the chosen ratio of brightener and leveller a significant influence was not seen.

We also investigated the influence of the **panel design** on the X- formation as it turns out that isolated and clustered through holes (small pitch, many neighboring through holes) may show different results as depicted in Fig 5.

Fig. 5: Difference between isolated and clustered through holes. Left: isolated, right clustered TH with 200 µm pitch, middle through holes a the edge of such a cluster

Parameters for this experiment at 40°C were

Cu :	25 g/L
H_2SO_4 :	200 g/L
Fe^{2+}:	15.0 g/L
Fe^{3+}:	0.5 - 1.0 g/L
Cl- :	100 mg/L
RPP:	1.5/40 – 80/4

Commercially available Inpulse additives according to data sheet.

The differently located through holes need different plating times to form the bridge in the middle. So the minimum time to form the X is always determined by the clustered through holes.

Electrolyte Flow

The difference between these clustered and isolated THs could be minimized by increasing the electrolyte flow onto the panel. The flow direction was 90° (perpendicular) to the surface. Doubling the flow rate resulted in a homogenous X–formation with little difference.

The effect of Fe^{3+} is even stronger as can be seen from Fig. 6. Here, we varied the Fe^{3+} concentration only from 0.5 g/l up to 1.0 g/l. The other key electrolyte parameter was copper 50 g/l. The result is that with a higher ferric concentration a much slower X- formation was observed.

Both experiments were conducted under identical parameters. The consequence of this result is that the control of ferric ions is extremely important for handling the process. Therefore a control unit was installed between the plating and the dissolving tank so that the ferric ion concentration could be controlled to within ±0.1 g/l.

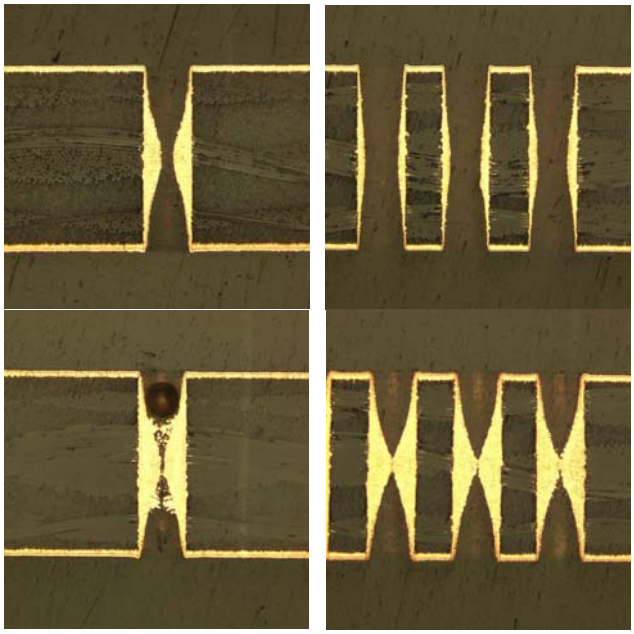


Fig 6: Effect of ferric ions on the X- formation: top:1.0 g/l and bottom 0.5 g/l ferric . Left isolated and right clustered through vias

The effect of copper concentration on the X-formation is different to the usual Blind Via filling: In contrast to the latter process a lower Cu concentration turned out to be beneficial. The influence is significant both for the x-formation and for the distribution of the X between the isolated and clustered TH. An additional test run with 18g/l and 32g/l Cu on very thick panels (3.2 mm with 0.3 mm hole diameter) confirmed the result. With these panels it is not possible yet to achieve through via filling but we did not aim at a complete X- formation since differences between experiments can better be evaluated before the X- is finally formed. We stopped plating after a certain time period (55 min) and measured the thickness in the middle of the hole compared to the surface. With the 18 g/l we increased the Cu thickness in the middle of the hole by a factor of 1.9.

The same effect had the increase of temperature from 20°C to 40°C.

Summarizing our findings for the optimization of X-formation results in the following:

- Use strong reverse pulse: 5/50 80/4 for 15 min leads to closure of the X- formation on 400 µm cores with 100 µm diameter.

- Use lower Cu concentrations of 25 g/l for regular distribution.
- Use higher Cl- concentration 90 instead of 60 mg/l
- Use a strong electrolyte flow to minimize differences between clustered and isolated TH
- Use low ferric concentrations (0.5 g/l)

Above mentioned parameters were used to plate a 400 µm/100 µm core as depicted in fig 7. Additional parameters were 240 g/l sulfuric acid and 5 g/l Fe^{2+} added as ferrous sulfate

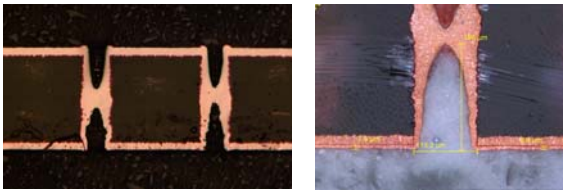


Fig 7: 400 µm thick core with 100 µm TH plated within 15 min. Right detail showing 9 µm plated Cu on the surface while > 50 µm Cu plated in the middle of the via

Blind Via Filling

Most of the following experiments were performed with boards having three different BMVs with a depth of 40 µm and width of 75, 100 and 125 µm. These sample boards were chosen because of their well defined and reproducible via structures. Information gathered on these boards are then applied on through vias to achieve the best possible result. All tests have been conducted with an Inpulse electrolyte system (Cu/Fe) with the same commercially available additive system

Following parameters have been investigated:

- Reverse and Forward Pulse time and current
- Temperature
- Electrolyte Flow
- Fe^{3+} concentration

The Cu concentration has not been investigated in this series due to the fact that its effect is already well known: A high Cu concentration is beneficial for Via filling.

Reverse and Forward Current: The standard 5/40 80/2 parameter set has been chosen as a start point. Fig. 8 shows the influence of the reverse time on the remaining dimple for the 3 different blind vias. The electrolyte was set up with 50 g/l Cu, 150 g/l Sulfuric Acid, 63 mg/l HCl with Inpulse brightener (accelerator) and leveller (inhibitor) and plated at 45°C.Increasing the reverse time has a significant effect on the filling performance as it changes from a deposit with a recess of a few µm into one with a convex dome on top of the via. As expected, the smaller vias are easier to fill than the larger ones. Shortening the cathodic pulse while keeping the anodic pulse constant leads to a similar result. This effect is in line with the explanation that via filling is mainly achieved by a changing ratio of accelerating and inhibiting additives in a via and surface. As described in [3] the Cu accelerating agents are depleted during a reverse cycle mainly on the surface but not in a via. In the via a net accumulation and thus acceleration and copper filling is observed. Net accumulation of accelerator in a via compared to the surface can be achieved either by intensifying the depletion rate from the surface (stronger anodic pulse) or by increasing the frequency of the anodic pulse.

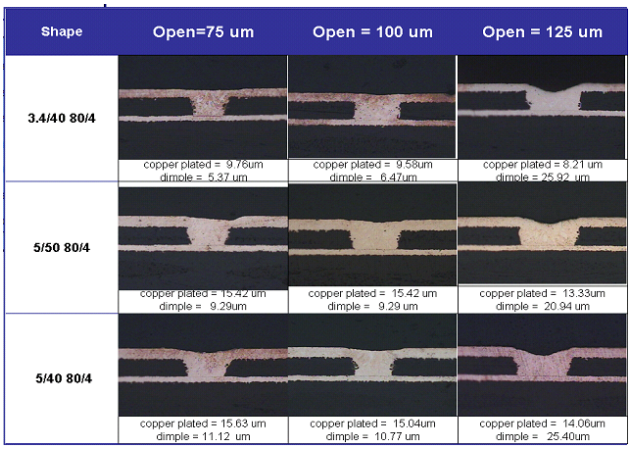


Fig. 8: Influence of the reverse (anodic) time (last no in left column in ms) on via filling. Filling performance significantly improves with reverse time

The effect of the forward and reverse current density on the dimple is shown in fig. 9 for the same electrolyte. Best results are achieved with lower forward current densities as expected. From via filling experiments in pure DC mode it is well known that lower current density usually leads to a better filling performance. This effect is also seen under reverse pulse conditions.

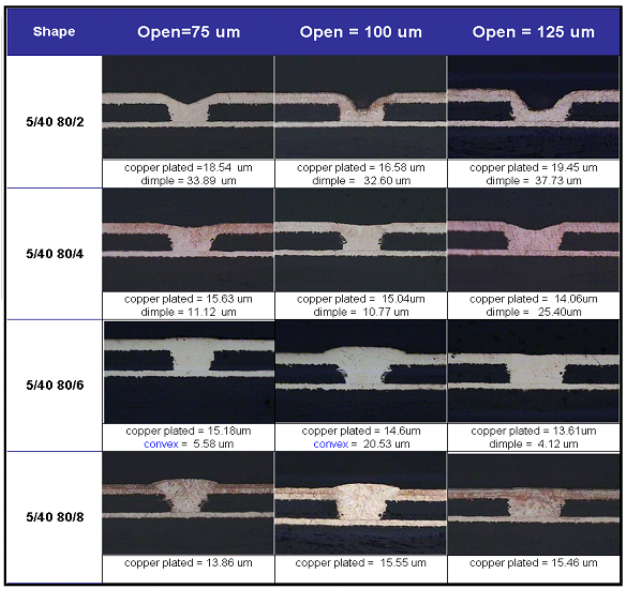


Fig. 9: Influence of the forward and reverse CD (1st and 2nd no left column in ASD) on via filling. Filling performance significantly improves with lower forward CD

Electrolyte Agitation

The influence of electrolyte agitation on the filling performance has been investigated by using frequency controlled pumps which feed the spray bars. The electrolyte is pumped through nozzles directly onto the board (90° angle). We used the same electrolyte set up as before. The frequency is then changed during the plating procedure, as it turned out that this procedure gave the best performance. At first, a thin protecting Cu layer with moderate pulse parameters is deposited and then followed

by the modification of the electrolyte agitation. The higher the pump frequency the higher the agitation rate, at the end of the cycle again a moderate pulse layer is plated to achieve a smooth surface.
In general, one can observe with lower agitation rates a better Via filling performance (fig 10). With increasing pump frequency significant dimples are observed so that the best results are achieved with low agitation rates.

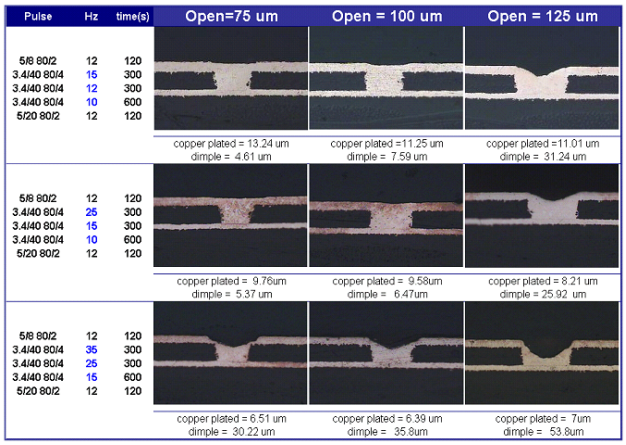


Fig.10 Influence of agitation on filling performance. Higher pump frequencies in blue relate to higher electrolyte agitation. Low agitation (top) improves filling performance

Temperature Effects Since the dimple performance is depending on the adsorption/desorption ratio between accelerator and inhibitor one would expect a certain influence of the temperature. Therefore, we varied the temperature over a range from 25-50°C under the same electrolyte setup as before and used the best pump frequency program (top experiment in fig 10).
As it turns out there is an optimum temperature of about 35°C but the influence of this parameter is not as strong as both aforementioned ones, pulse and agitation.

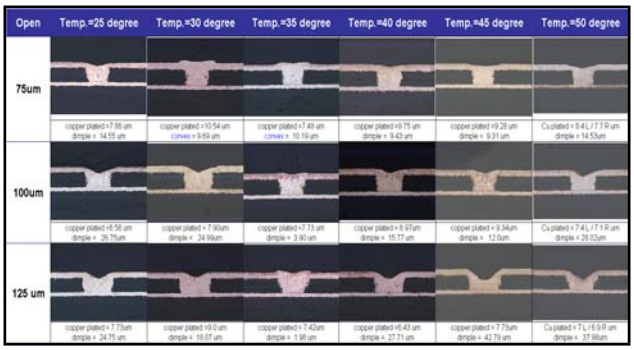


Fig. 11: Influence of temperature on Via filling
The panel surface is also affected. The surface becomes rough below 35 °C and very smooth above 40 °C, so that depending on requirements a compromise has to be found between good via filling and surface appearance.
Fe^{3+} Influence: It can be expected from equation (I) and (II) that the overall yield for the copper deposition is strongly affected by Fe^{3+}. Fig. 12 depicts this very strong dependency. This current yield is measured by weight difference against the theoretically possible Cu mass of 100%. A lower current yield than 100% usually needs to be counterbalanced by additional plating time. This is not necessarily the case for the via filling application since the amount of plated Cu on the surface is not equivalent to the amount in a via. The relevant parameter is the dimple not the amount of plated Cu on the surface. Hence the amount of plated Cu can vary with the Fe^{3+} concentration to achieve the best performance.

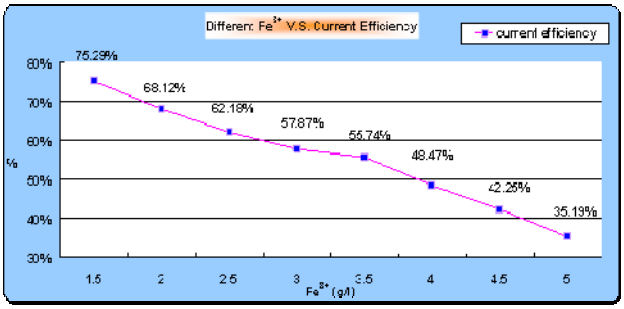


Fig. 12: Yield in copper deposition as a function of Fe^{3+} concentration
The experiments shown in graph 13 were conducted with aforementioned electrolyte, pulse and pump parameters and at 45°C.

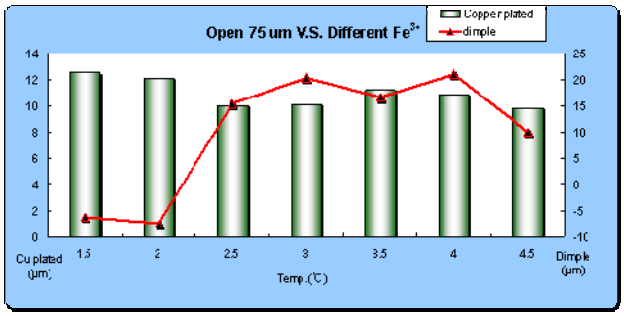


Fig. 13: Plated Cu thickness (columns) and dimple (red line) as a function of Fe^{3+} concentration for 75µm diameter and 40µm deep BMVs .
The results shown that the dimple is lowest for lower ferric concentrations, however again the surface appearance of the boards is the critical parameter. The surface becomes smoother with increasing ferric concentrations, again a compromise between dimple performance and surface appearance has to be found.
Summarizing the optimization experiments to fill blind vias leads to following results

- Apply CD of approx. 3 - 4 ASD cathodic and apply stronger reverse parameters to decrease the dimple (depending on required surface roughness): Best compromise 3.4 /40 80/ 4. Via filling is achieved within 24 mins.
- Decrease electrolyte agitation for a smaller dimple.
- Apply low Fe^{3+} concentrations, depending on required surface roughness
- Work at 35- 40°C to achieve best dimple.

OVERALL PERFORMANCE – SUMMARY AND OUTLOOK

The aim of the optimization experiments presented was to identify the best possible parameter sets for copper filling and to combine them to achieve filling for through vias thicker than 100µm with target for 400 µm thick cores. For some parameters a compromise between dimple and surface roughness had to be chosen.

The test series showed that for a successful fill of thicker core at 400µm a split into different electrolyte types is necessary with very different parameter sets.

Table 2: Process parameters for both TH Fill steps.

Parameter	**X- formation**	**Via fill**
Pulse Parameter	Strong reverse	Strong reverse
Overall current density	3-4 ASD	3-4 ASD
Temperature	40°C	35-40°C
Cu^{2+}	Low 20-30 g/l	High > 40 g/l
Fe^{3+}	Very low 0.5g/l	> 1.5 g/l
Electrolyte agitation	Strong	Low
Time	Approx 15 min	40-60 min

At this moment the process can successfully plate and fill through vias for cores with thickness up to 300 µm with plating time less than an hour and without voids, some examples are shown in microsection in fig 14,

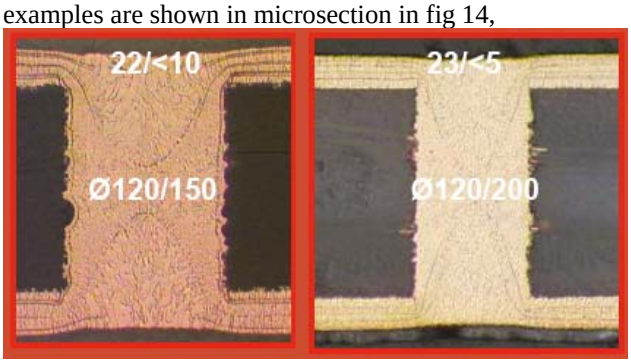


Fig 14: Filled through vias: 150 µm and 200 µm cores which have been plated with 22 µm Cu for the 150µm thick core and 23 µm Cu for the 200 µm thick core to achieve void free filling and less than 10µm or in the case of the 200µm core less than 5µm dimple

However 400 µm cores show still some voids which are usually small, 10µm or less as shown in an example in fig 15.

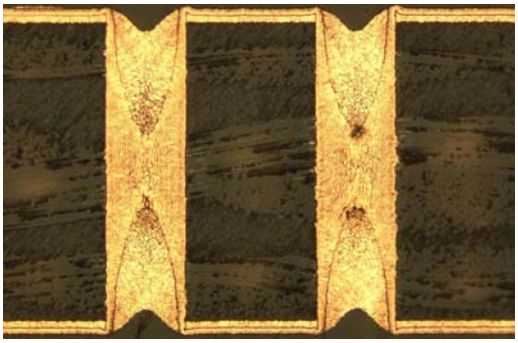


Fig 15: Copper filled 400µm core with 100µm diameter holes showing small voids.

Investigations on the effect of these voids are being made and especially reliability measurements will be performed which should show whether the voids will lead to any failure or if the void can be isolated within the plated copper as they appear to be perfectly encapsulated.

A further extension to the technology is the copper filling of laser drilled through vias, figure 16 shows the through hole filling of a laser drilled through hole. The core is 200µm thick which would at first investigation suggest an easier filling process due to the lower volume to be filled however the nature of the drilled hole wall with "V" shape and potential for protruding glass fibres requires specific optimization of the filling process which is now in the process of being made in production scale testing. In particular the electrolyte flow rate towards the core has been increased by use of special pumps and flow nozzles to ensure void free copper filling.

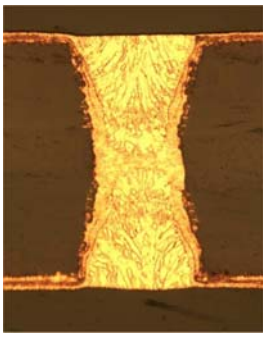


Fig 16: 200µm core with 100µm laser drilled through holes

Whether the through hole filling technology can be expanded over 400 µm cores is still unclear. There is a great potential for completely filled Cu vias for use as thermal vias since the thermal conductivity of Cu is several magnitudes higher than any paste but the greatest hurdle for this application is the use of very thick panels (> 1mm) which would require very large amounts of copper and thus long process times at low plating current densities.

ACKNOWLEDGEMENT

This paper describes work some of which was originally published in the Proceedings of the SMTA International Conference, Fort Worth, Texas, October 16 - 20, 2011 however the work has been extended to cover the copper filling of laser drilled through holes as described.

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