The Influence of Fluid Dynamics on Plating Electrolyte for the Successful Production of Blind Micro-Vias: Laboratory Investigations Leading to Optimised Production Equipment

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Abstract
Successful copper plating of blind micro-vias is very strongly dependant on the effective mass transport of copper ions into the vias. This mass transport limitation is demonstrated by a rough or even in extreme cases at high aspect ratio or high applied current densities, a burnt appearance of the copper deposit at the base of the via. The poor quality of deposited copper has an obvious impact on productivity and also on the feasibility of filling the blind micro-vias required for highest packaging density.

This paper describes the methods used to evaluate solution flow in micro-vias carried out in controlled laboratory conditions. The subsequent successful implementation of improved solution flow in simulated production equipment and also in full-scale production is shown. Results are included from horizontal and also vertical processing; in both cases using production equipment operating with reverse pulse plating and insoluble dimensionally stable anodes.

Introduction

With the increase in interconnect density the use of blind micro-vias has become the essential technology to achieve the required circuit line and space tolerances. This development has been particularly driven by the demands from mobile telecommunication applications. The technology is also being used in packaging applications where components are directly bonded to the micro vias; in this case the requirements are for blind micro-vias completely filled after copper plating.

Currently equipment is producing circuits for mobile telecommunications applications using pulse plating with insoluble, dimensionally stable anodes achieving good results in copper plating at up to 9 A/dm² effective current densities and with blind micro-vias of aspect ratio up to 1:0.75. This equipment is most effective when used as part of a horizontal production line. As a comparison, for packaging applications the effective current density used is normally much lower, in the region of 1–2 A/dm² and the processing is usually carried out in vertical processing equipment due to the line and space requirements in the range of 30 µm.

However as the required packaging density increases, the via aspect ratio also increases so creating more difficulties in achieving good copper plating results. Essentially the deeper and narrower the via the more difficult it is to get the required minimum copper thickness of the required quality.

Figure 1 shows the effect of a decrease in the blind micro-via diameter on the copper plating results in an extreme example of blind via aspect ratio. The effect shown can be extrapolated to other more normal production cases; the vias all have the same depth, 160 µm but varying diameter as shown. The copper plating conditions were identical in each case.

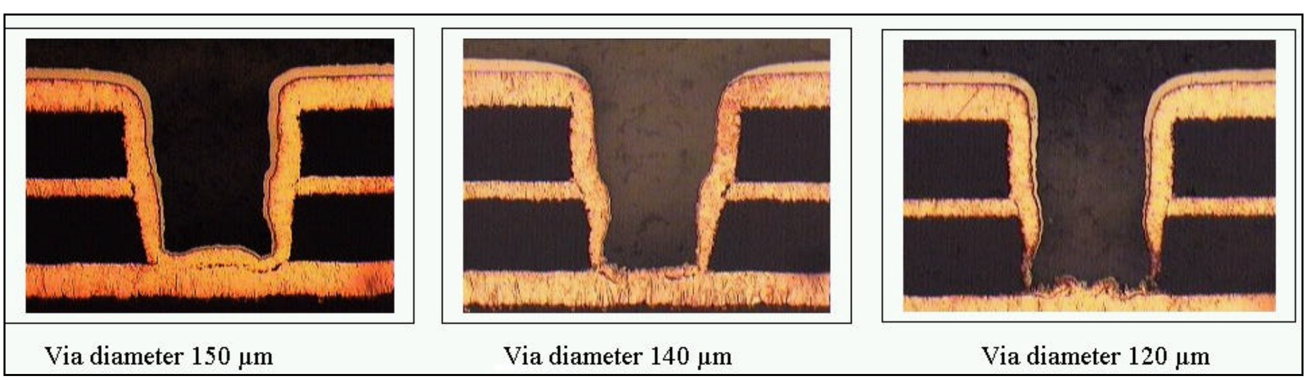


Figure 1 - Effect of the Increase in Blind Micro-Via Aspect Ratio on Copper Plating Quality

As can be seen in the first case with 150 µm via diameter the copper plating is smooth and has a good throwing power. In the second case the throwing power or the plating thickness on the capture pad is thinner and in the third case with a via diameter of 120 µm the copper plating is rough and the thickness will not meet the required specification. This rough plating sometimes appears as a "burnt" copper deposit and is caused by a restricted mass transport of copper ions into the micro-via due to a decrease in the diameter of 30 µm with a constant via depth of 160 µm. This change corresponds to an aspect ratio of 1:1.06 becoming aspect ratio of 1:1.3.

To improve copper plating there are a number of actions, which can be taken,

1. Increase the working temperature of the electrolyte.
   This will increase the copper mass transport but could have an effect on the plating equipment or the electrolyte additives. Also the scope for increase in temperature has restrictions.
2. Increase the copper concentration in the electrolyte.
   This will improve the copper plating result in the micro-via but will potentially reduce the copper throwing power in the through holes.
3. Reduce the plating current density.
   This will improve the copper plating result both in the micro-vias and in the through vias but will also reduce the process productivity.
4. In the case of pulse plating reduce the reverse plating current density.
   This will improve the copper plating in the through vias but will also reduce the throwing power in the through holes.
5. Increase the micro-via diameter.
   The essential cause of the problem is the fact that the via aspect ratio is too high, by reducing this then the copper plating will improve but the required line and space density cannot be achieved.

As described above there are possibilities to improve the copper plating performance in blind micro-vias but the basic problem, the solution flow into the via is not addressed in any of these.

This paper describes work carried out in laboratory conditions to explore the fluid dynamics of an idealized horizontal plating cell.

The techniques of laser Doppler anemometry (LDA) are used to gain data on solution flow patterns to optimize the solution flow over the whole surface of the panel.

The results have been used to modify small-scale production equipment and the plating results in blind micro-vias are shown.
The extension of the analysis to vertical plating equipment is discussed and production results achieved using Eductor technology to optimise solution flow are shown.

Laboratory Experiments

A simulated horizontal plating cell was constructed as shown in Figure 2; the cell has a transparent port through which measurements can be made. Figure 2: Side view of idealised horizontal plating cell. Experiments to assess solution flow in the cell were measured using the techniques of Laser Doppler Anemometry a schematic of the measurement system is given in Figure 3. LDA is an optical velocity measurement technique, which can be used to determine the localised speed and direction of particles. The measurement principle is based on the illumination of particles in a solution flow and the reflection of light from the particles, the illumination is carried out by laser light sources. The method has a number of advantages over use of measurement sensors inside the test chamber.

- Information is given on flow dynamics without influencing the flow; there is no physical contact with the medium.
- The method is especially effective for turbulent system analysis.
- The spatial and time resolution is high.
- The method can be used over a wide temperature range and even in burning gases.
- Areas of low and high pressure can be effectively measured.

Disadvantages of the system are that the medium must be transparent to the light source used and the measurement chamber must be optically accessible, the test cell was so constructed that an observation port was incorporated as shown in Figure 2.

The reflection of the light is made by use of a suitable particle, which must be transported by the medium without influencing its flow. The reflection particle moves through an interference pattern from two laser beams and reflections are detected by an optical sensor so giving information on flow direction and speed.

The choice of reflection particle is critical for successful analysis, this must:

- Follow the solution flow without being restricted this means a particle size of less than 10 µm is necessary.
- The particle must have good light reflection characteristics.
- The particle must be chemically inert.

- The particle should not contaminate the system for example with sludge.

For these experiments the particle used was titanium dioxide, particle size < 10 µm.

A number of experiments were carried out to investigate the flow patterns in the existing design of horizontal plating modules. Changes were made to the fluid delivery system to optimize the flow, the results from one of these experiments is given in Figure 4.

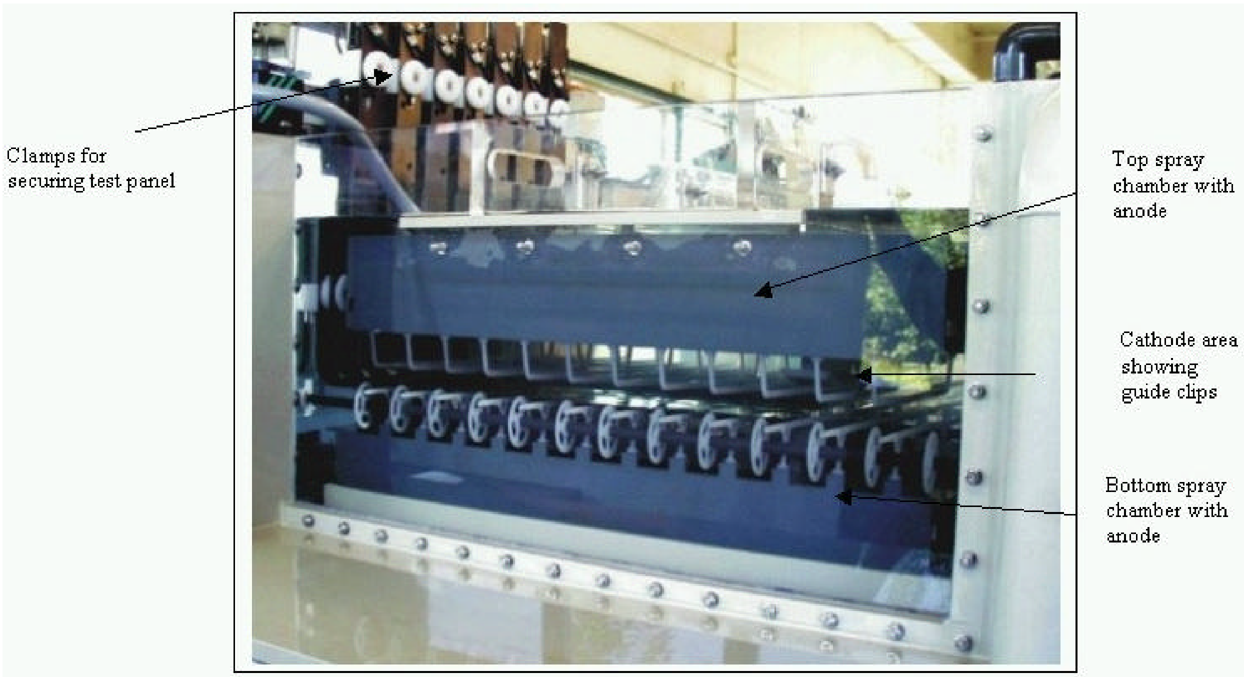


Figure 2 - Side View of Idealized Horizontal Plating Cell

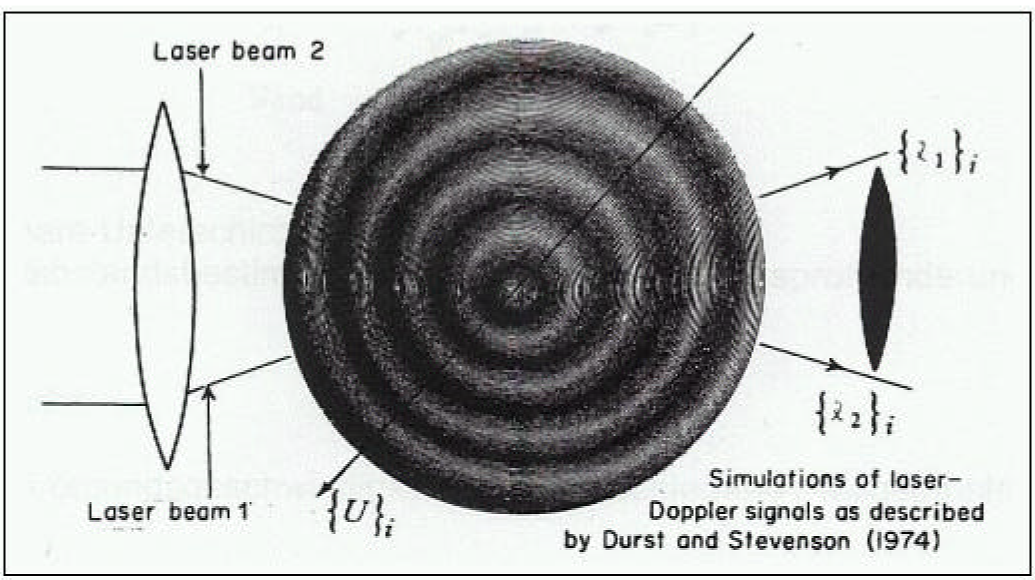


Figure 3 - Schematic Operation of an LDA Measurement System

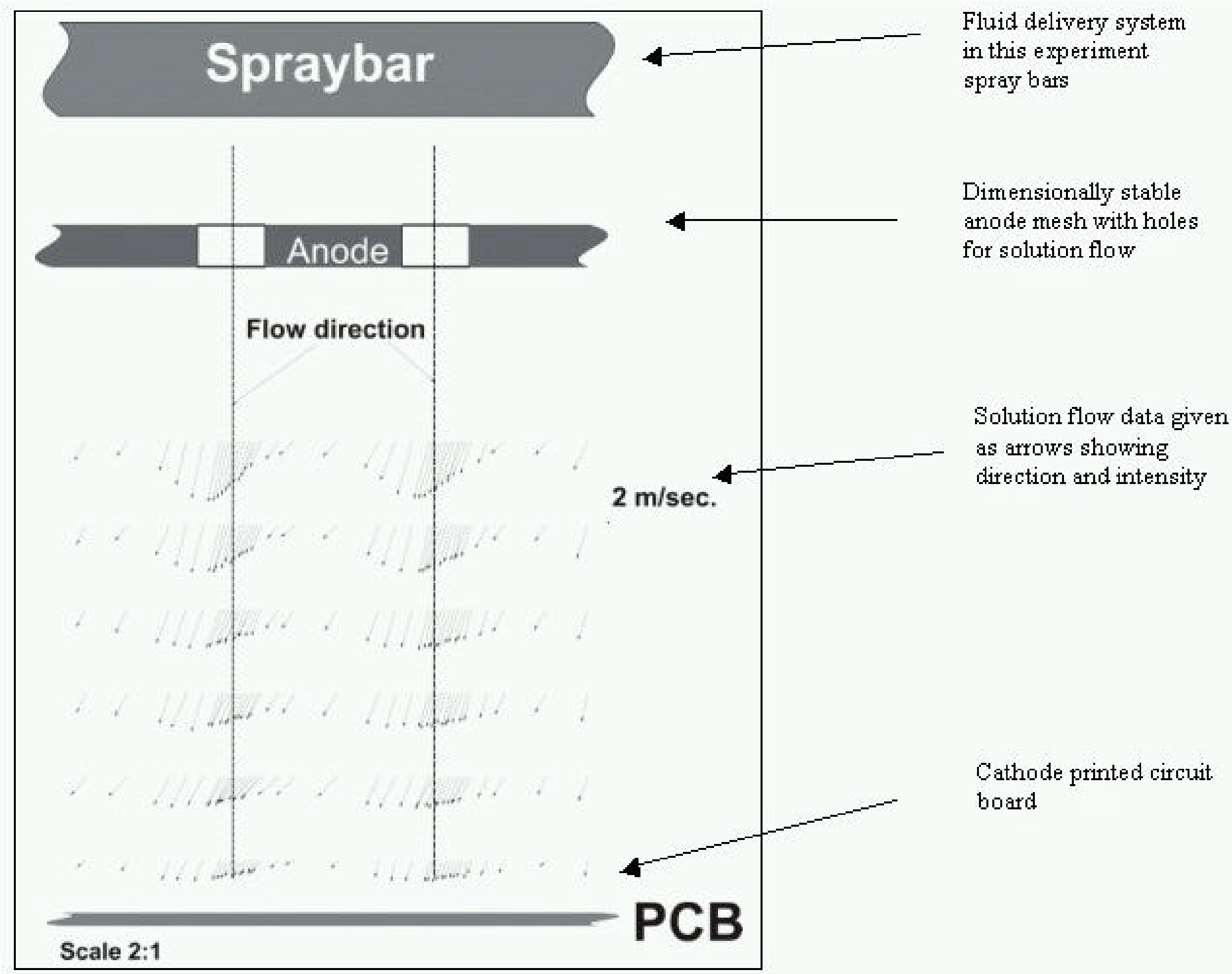


Figure 4 - An example of Results Obtained from a Flow Experiment

Unfortunately more complete results cannot at present be described due to the fact that this work is being completed as a joint venture investigation. However it was found that an increase in solution flow had a positive influence on blind micro-via plating results and because of this various spray delivery systems were designed and tested in a small scale production line.

Experiments in Small Scale Production Line Leading to Modified Production Line

A horizontal plating module was modified as a result of the flow tests carried out and the effect on the plating quality with blind micro-vias was assessed, the alternatives tested were as follows,

1. Conventional horizontal flooding system, spray bars with 1mm hole at interval on the bar.
2. Flat spray nozzle system with symmetrical nozzles set at 45° to the direction of panel travel.
3. Spray hood system.
4. Tangential flow system.
5. Flat spray nozzle system with symmetrical nozzles set at 90° to the direction of panel travel.

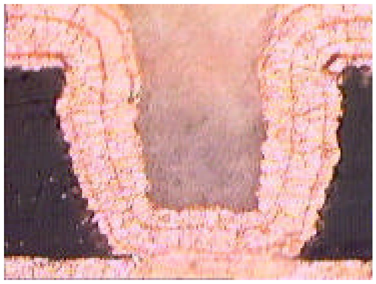
Micro-via plating quality in vias diameter 100 µm and with depth 75 µm was assessed, all other processing parameters were held constant.

Average current density 10 A/dm², reverse current density 40 A/dm², electrolyte temperature 30°C, the results are shown as a comparison of micro-section data.

The micro-sections were prepared using a copper protection coating applied under DC conditions to assist preparation.

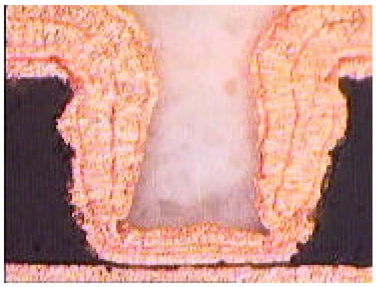
Small Scale Trial Line Test Results

1. Conventional flooding system, spray bars with 1 mm hole at intervals on the bar, this configuration serves as the standard for comparison purposes.



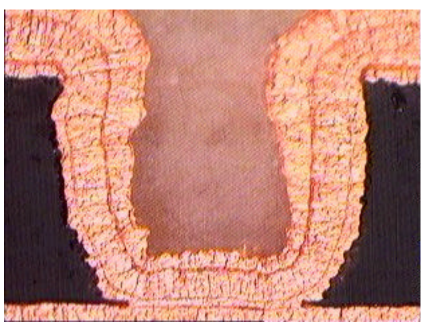
The result shows average throwing power with some rough copper plating

2. Flat spray nozzle system with symmetrical nozzles set at 45° to the direction of panel travel.



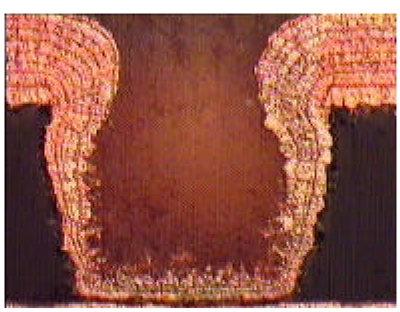
The result shows a reduction in the throwing power.

3. Spray hood system.



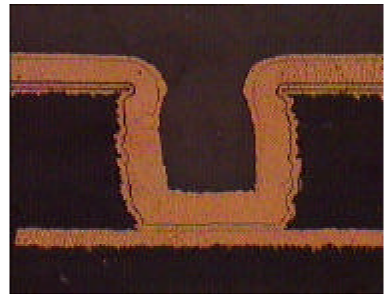
The result shows a similar throwing power to the conventional system.

4. Tangential flow system.



Very poor copper deposit showing typical mass transport limitations "burnt" copper plating.

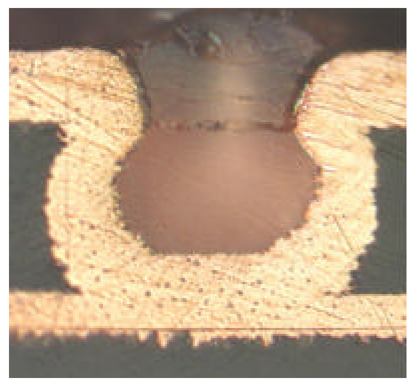
5. Flat spray nozzle system with symmetrical nozzles set at 90° to the direction of panel travel.



Very good even copper deposition at high current densities.

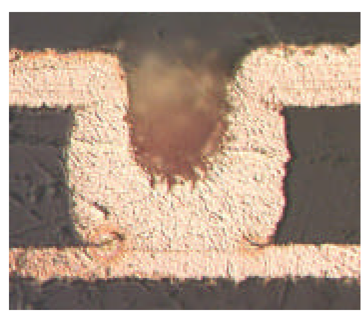
It can clearly be seen that the results from the spray system sat at 90° to the direction of panel travel show the best results. This configuration was used to modify a production line to confirm the results under production conditions. Modified production line test results:

1. Blind micro-via diameter 90 µm, depth 60 µm. Plating parameters 10 A/dm² average, 40 A/dm² reverse.



Plating result with production system showing good micro-via throwing power but some slight rough deposit at the base.

2. Blind micro-via diameter 90 µm, depth 60 µm.



Plating parameters 4 A/dm² forward, 30 A/dm² reverse. Via filling effect achieved by use of lower effective current density.

Optimisation of Solution Flow in Vertical Equipment

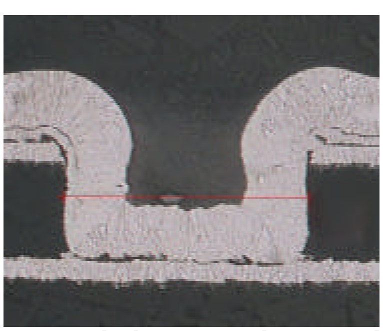
The extrapolation of the results of the flow experiments to cover vertical applications is limited by the design differences between vertical and horizontal equipment, vertical equipment design is not so flexible as horizontal and much work has been carried out in existing modified vertical lines. Vertical plating cells have generally a larger volume and the solution flow rate is much lower, associated with this is the use of generally lower current densities. In vertical cells traditionally air agitation is used which is less efficient in enabling good mass transfer into blind micro-vias. To improve agitation the use of Educators for airless agitation is becoming more popular not least because of the reduction in acid spray above plating tanks. Trials have been carried out using Educators to improve solution flow based on the experiments carried out on the flow dynamics of horizontal systems.

Figure 5 - Installation of Educators in a Plating Cell

The Educators are mounted in two separate pipes and can be rotated to give varied flow over the cathode. The return from the filter system can be seen running along the bottom of the tank between the Eductor feed pipes.

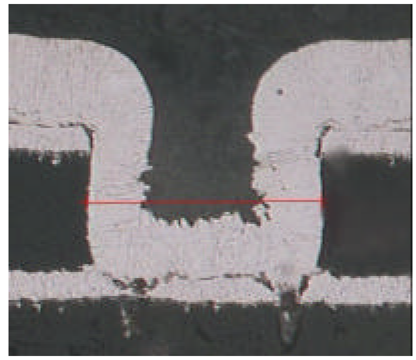
The plating parameters used were as follows:
forward current density 2.5 A/dm²,
reverse current density 6.25 A/dm², the plating results are shown as micro-sections.

1. Micro-via width 150 µm depth 100 µm.



The plating result shows smooth copper plating.

2. Micro-via width 100 µm depth 100 µm.



The plating result shows copper plating with the beginning of rough plating even at the relatively low current density used.

Further trials are being carried out with variation in the Eductor orientation and also use of smaller Educators more widely spread over the plating window to give a more uniform electrolyte flow.

Summary

The efficient plating of blind micro-vias is determined by copper mass transport limitations. This mass transfer is a function of the hydrodynamic conditions in the bulk solution and by the diffusion process in the micro-vias.

Initial optimization of horizontal plating cells has enabled improved plating results to be achieved at high current densities up to 10 A/dm² effective current density.

Further modification and optimization is being carried out to enable filled via technology in horizontal systems.

The experience in horizontal technology is being repeated in vertical systems. Here equipment design complicates the hydrodynamic conditions so making modifications time consuming. Initial results with Educators show possibilities to reach the same copper plating standard as in horizontal systems however at a much lower current density.