Via Filling: Challenges for the Chemistry in the Plating Process

Mike Palazzola
Nina Dambrowsky and Stephen Kenny
Atotech Deutschland GmbH,
Germany

Abstract
Copper filling of laser drilled blind micro vias (BMV´s) is now the standard production method for high density interconnects. Copper filled BMV´s are used as solder bump sites for IC packaging where the filling process enables the required interconnect density and provides the surface to ensure reliable solder attachment. For “smart phone” production use of multiple lamination and typically 10 layers of stacked copper BMV filling is now the preferred technology, this is also known as the “any layer” filling process.
Advances in filling processes are required to maintain the development in circuit miniaturization together with the reduction in overall processing costs and to meet the demand for ever more filled BMV´s on each plated layer. The required filling processes must provide void or inclusion free filling, a minimum of surface plated copper along with the capability to allow stacked filled structures.
This paper describes the function and principles behind BMV filling processes together with methods for non destructive testing of the filled structures. Production processes for BMV filling in vertical and horizontal production equipment with both soluble and insoluble anodes are presented together with a discussion of the plating parameters currently used in volume production. A comparison in filling performance of DC plating with that achieved in reverse pulse plating is also made.
The impact of specific processing parameters on volume production systems is discussed and in particular the use of fully automatic process control and the advantages of such systems in achieving uniform and reliable product quality.

Introduction
The copper filling of BMV´s is one of the enabling production processes in the drive for miniaturization of consumer electronics following the expectation of innovation and invention given by Moore´s Law. This is not a law of nature but “an expectation of continuity of innovation and invention; it is a promise of the innovation and creativity of our profession and industry” this drive for reduced cost and higher capability are discussed in [1]. BMV filling allows the use of via in pad technologies both in IC packaging and also in HDI applications which has allowed reductions in the absolute size of circuits.

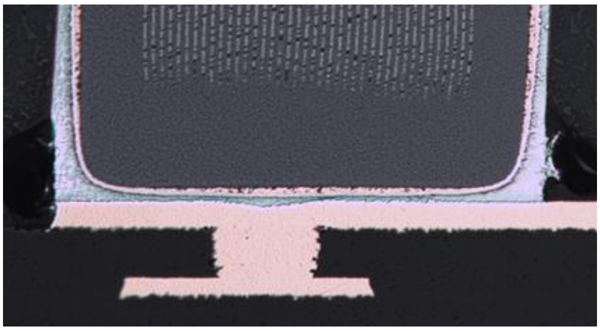

Figure 1 Filled BMV used as via in pad for solder mount of device for HDI application

The use of multiple stacked filled BMV´s is allowing circuit design to move into three dimensions whilst keeping the trend to reduction of the overall circuit size, this 3D circuit design has been described as a “More than Moore” development. For the production process the rapid increase in the number of BMV´s to be filled has placed increased demands on the uniformity of the process. For example in 2008 a standard size production panel could have up to 800 thousand BMV´s on the surface all of which must be uniformly produced and then copper filled, this number is increasing rapidly. In Figure 2 a microsection of a typical filled BMV in an IC package is shown. The BMV has been laser drilled in a homogenous build up material and then metalized and copper filled. The copper surface has been processed in soldermask to define the pad and then in electroless tin to give the final surface finish for attachment of the solder ball.

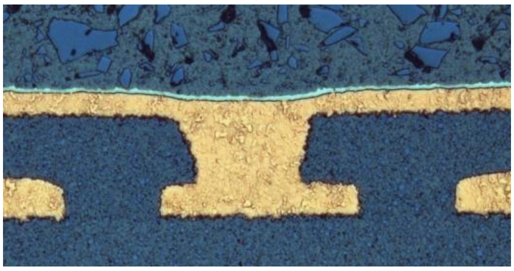

Figure 2 Filled BMV as solder bump site on substrate

Figure 3 shows a multiple stacked and filled structure as used in an HDI panel for a smart phone application. In this case the BMV is formed by laser drilling of glass reinforced material also with copper foil for the inner layers even as the final outer layer again is a homogenous material. This process variation places extra demands on the copper deposition as the via form may not be as uniform as desired.

Figure 3 Filled stacked BMV as used in smart phone application

The production of filled stacked BMV´s requires good uniformity particularly in the plated copper distribution over the surface of the panel and the need for a minimum dimple as the base for the next BMV. Repeated passes in processing equipment must give constant results otherwise the production yield will be low; this is one reason why conveyorized production solutions have gained market acceptance for volume production. Industry requirements are for low defect rates in volume production also with the trends to a reduction in the diameter of the via and an ever increasing number of vias per panel. Typical BMV´s may have a diameter of 70µm and aspect ratio 1:1 which need special treatment and equipment to ensure reliable wetting and copper plated throwing power both in metallization and electrolytic deposition.

BMV Filling Processes

Processes for the filling of BMV´s with electrolytic deposited copper can be described by three basic methods, the "normal" deposition, conformal deposition or the "bottom up" or in some cases "SuperFilling" method where minimum surface copper deposit is made. These three methods are summarized schematically in figure 4.

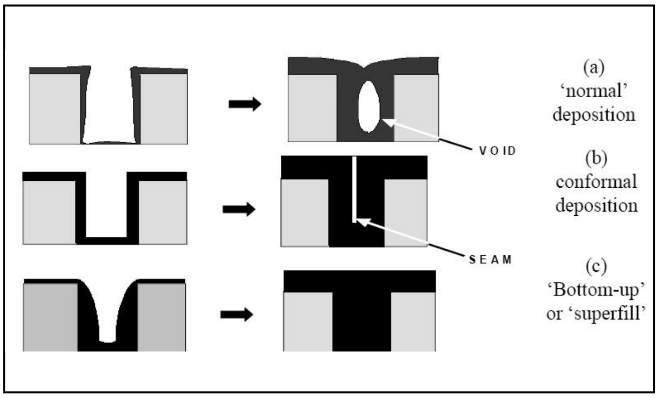

Figure 4 Schematic representation of BMV filling process

In the normal process copper is deposited until the via is closed however this will typically leave a void or inclusion in the centre of the structure depending on the dimensions of the BMV and the copper deposition parameters. Modifications to the process electrolyte can be made in particular to the organic additives so that the surface copper plating is inhibited and more copper is deposited into the BMV, this is shown in the conformal deposition process. The disadvantage of this system is however that the mass transport of the electrolyte becomes reduced due to the filling process increasing the aspect ratio of the BMV and this in itself will limit the filling. The result can be a BMV with a "seam" in the centre where copper deposition was not possible due to the increase in the aspect ratio. The third possibility is the bottom up method of BMV filling where the copper is deposited preferentially onto the base of the via giving in the ideal case a low dimple together with a minimum of plated surface copper. The bottom up method is also dependant on the organic additives used in the electrolyte and in particular the effective acceleration of the deposition. The accelerator or brightener used in the plating process is preferentially adsorbed onto the base of the BMV and the inhibitory additives are more concentrated onto the surface of the cathode. This will cause an increased deposition at the base of the BMV. Figure 5 shows a microsection through a plated BMV which has been processed in such a way that each step in the filling process can be seen; the preferential deposition on the base is clearly shown.

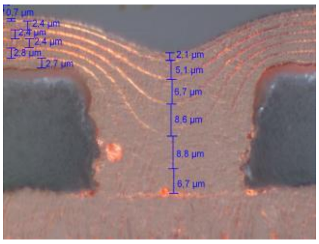

Figure 5 BMV filling with bottom up process

A production process which can fill the structures with a minimum of deposited copper has obvious advantages not least the cost of the deposited copper metal which has a large impact on the overall running cost of the filling process. At current copper metal costs a reduction of 15µm in deposit required to process the panel in the so called panel plating process can result in a cost reduction in the range of 2 US$ per m² of produced panel this cost only considering the metal consumed. The reduction in the surface plated copper also has a direct impact on the circuitization process, thinner plated copper may be etched to produce finer line and space structures which are required for the latest HDI production. One method of bottom up or SuperFilling utilizes the iron redox system of copper replenishment for production systems with insoluble anodes together with reverse pulse plating. Copper is deposited in the normal way in the forward cycle of pulse plating and at the same time oxidation of Fe^{2+} ions to Fe^{3+} takes place at the insoluble anode which prevents oxidation of the process additives in the electrolyte. The oxidation product Fe^{3+} is used to replenish the consumed copper chemically in a second compartment filled with pure copper balls and reduced again to Fe^{2+}. Additionally the function of the Fe^{3+} oxidation product is to reduce the amount of copper deposited onto the panel surface. The reduction of Fe^{3+} to Fe^{2+} at the cathode is electrochemically favored in comparison to the deposition of copper and so the concentration of the Fe^{3+} can determine the deposition rate of copper onto the surface of the panel. This system and the production results achieved are described in [2]. The combination and form of organic additives used is critical for the effective filling of BMV´s. Typical additives consist of brighteners or accelerators which in combination with chloride ions serve to reduce the activation energy necessary for the reduction process of Cu^{2+} to Cu^{0}, the deposition of copper metal. A high adsorption of accelerator at the base of the BMV is important to promote the preferential deposition of copper and can promote the SuperFilling method of BMV filling. Carriers or wetting agents are inhibitors which form a stable diffusion layer over the entire cathode surface and enable a uniform copper deposition. The leveler component is a strong inhibitor and works in neutralizing the action of the accelerator.

BMV Filling Quality Control

Quality control can be either destructive as in the micro-sections in figures 1, 2 and 4 or non-destructive analysis of dimple and presence of void or inclusions. Currently the confocal microscope is being used to scan the surface of the plated panel and to give data on the degree of filling or dimple. The system illustrated can scan up to 99 BMV´s in one hour with sufficient resolution to show the dimple distribution. Figure 6 shows a schematic of the operation of the confocal microscope and the actual unit in operation.

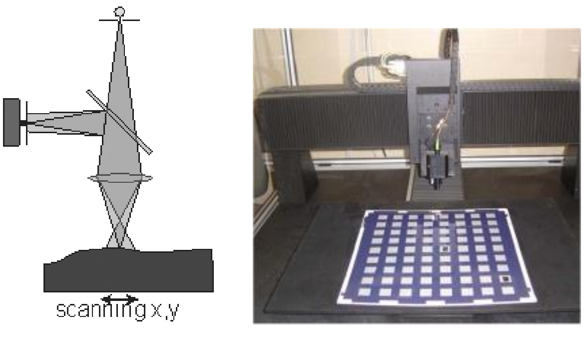

Figure 6 Confocal microscope

Investigation of inclusion or void in the filling process is normally made by microsection techniques however recent improvement in X-ray analysis now offer this method of non destructive quality control. Comparison of X-ray images with micro-section of void areas have been made to judge the capability of this method for quality control. In figure 7 data from such investigations is shown.

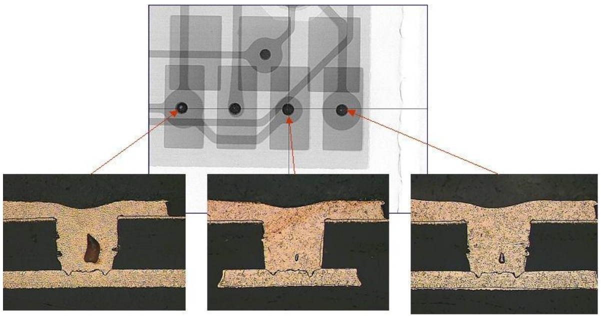

Figure 7 Correlation of X-ray analysis to microsection for voids in filled BMV

BMV Filling Production processes

HDI high volume production is currently made in conveyorized systems where the horizontal system with wet to wet metallization followed by BMV filling has gained widespread market acceptance. The metallization is critical to ensure that the copper filling can be made without any voids. Figure 8 shows examples of good coverage of electroless copper and strike plate despite poor adhesion of dielectric to copper capture pad after laser drill and desmear process. This good coverage of any gap or void is a prerequisite for reliable filling performance.

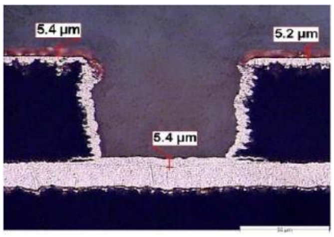

Figure 8a. Good coverage in BMV despite wedge at capture pad

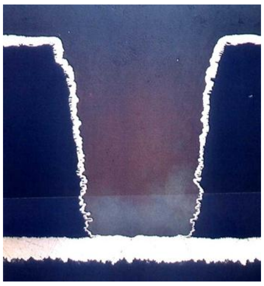

Figure 8b. Good metal throwing power in high aspect ratio BMV

Use of insoluble anodes in the electrolytic copper process ensures uniform plating results and in particular the surface distribution can be optimized and is not affected by any anode erosion. Insoluble anode systems require constant copper replenishment either by the use of solid copper oxide replenishment into the working electrolyte or by use of the iron redox system. Use of the redox system of copper replenishment has advantages in that no oxygen is evolved at the anode and the replenishment is a closed loop using pure copper metal. Pure copper is easily obtained in the correct quality and the running cost with this material is lower than the alternative use of solid copper oxide replenishment. Copper oxide replenishment is used typically for vertical conveyorized systems, copper is added according to the ampere hours plated by a mechanical device to feed the oxide into the electrolyte, this is normally carried out in a separate chamber where the oxide is dissolved and filtered prior to being added to the working tank.

Vertical BMV filling with soluble anodes

Soluble anode plating systems are generally used under DC pattern plating conditions with current densities in the range 0.8A/dm² up to 1.5A/dm². Such systems are commonly used for the production of the small volume BMV´s as found in IC packages with diameter approx 60µm and depth 30µm to 40µm as shown in Figure 1.

Use of soluble anodes is in theory more simple than insoluble anodes, extra systems for copper replenishment are not necessary but the process itself is less stable. Soluble anodes erode during the plating process causing deterioration of surface distribution, one of the critical factors for reliable BMV filling. Anode contacts are very important to ensure plated quality in all electrolytic systems and there is always the danger of a high contact resistance between copper and titanium used as anode baskets or contacts in soluble anode systems. In contrast insoluble anodes can be installed with direct cable contact to the rectifier and with current monitoring in each cable to ensure uniform plating conditions.

Vertical conveyorized BMV filling

Vertical conveyorized systems with insoluble anodes for BMV filling are operated in DC mode and normally with copper oxide replenishment. Current densities in the range 1.5A/dm² and up to 2.5A/dm² may be used depending on the aspect ratio of the BMV and the electrolyte flow capability of the equipment. The higher the electrolyte flow the better is the electrolyte diffusion into the BMV´s and the filling process can be more uniform. The filling process in DC mode is very dependant on the organic additives used in the electrolyte; a strong leveler is required to ensure good filling results however the plated copper thickness requirement is generally higher than that required for a similar structure using pulse plating in horizontal mode. Figure 9 shows a typical filled BMV produced with a current density of 2A/dm².

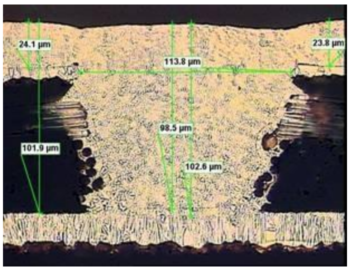

Figure 9 Filled BMV with vertical conveyorized line

The copper replenishment system using copper oxide has the disadvantage that the running cost may be higher in comparison to the use of pure copper as a raw material. The reason is that copper oxide of a sufficient quality and in particular with a low chloride contamination level is required and this can be relatively expensive. The use of inert anodes has advantages in plating uniformity and constant working conditions however the disadvantage with the copper oxide replenishment system is that oxygen is evolved at the surface of the anode. This will cause an increase in the consumption of organic additives depending on the equipment design and may require regular electrolyte purification depending on the additive components used.

Horizontal conveyorized BMV filling

Typical horizontal conveyorized systems in production are using reverse pulse plating and the iron redox system of copper replenishment; this is the Uniplate Inpulse process. The iron redox system has a number of advantages over the copper oxide replenishment system. There is no oxygen evolution at the anodes which means that the electrolyte is more stable in particular with respect to breakdown products, the source of copper ions is from pure copper clippings or pellets which is more readily available with sufficient purity than copper oxide. The overall running cost of the process is lower particularly when considering the plated copper deposition necessary to fill the blind micro vias. An example of current production for HDI is with BMV diameter and depth 70µm and this can be filled with a surface plated copper of only 13µm as shown in Figure 10. The plating system used in this case consisted of two working modules which offer the possibility to vary the working conditions in the two modules. The first module was operated at an average current density of 3A/dm² whilst the second module was set to 4.5A/dm²; this increase in current density was used to match the electroless copper metallization process and to ensure no etch of electroless copper with the pulse plating process.

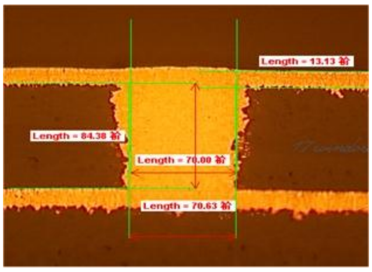

Figure 10 Filled BMV with horizontal production line

The electrolyte flow could also be adjusted in the two modules and this is critical for production of such BMV´s with aspect ratio 1:1 to ensure wetting and void free production. The electrolyte is circulated with frequency controlled pumps which allows correct flow parameters to be adjusted according to the size of the BMV´s and the thickness of the material. A further advantage of horizontal production with insoluble anodes is the capability for constant control of each insoluble anode segment which ensures the correct current flow and therefore copper deposition on the panel surface.

Process control systems

Fully automatic process control is necessary for high volume manufacturing with BMV filling. For copper plating systems with insoluble anodes the copper content of the working electrolyte is critical. Typically production electrolytes will be used at relatively high copper concentrations at up to 50 g/l however conveyorized systems have a high production loading so constant control is needed. In Figure 11 a control unit is shown which analyses the copper content and also the Fe^{3+} of the working electrolyte, the unit can be used to analyze three Inpulse production modules simultaneously. The analysis data is used by the equipment control system to set the copper and redox system in the working cell and thus to control directly the BMV filling quality.

Figure 11 Analysis unit for copper and redox system

The organic additives for electrolytic copper plating processes are analyzed using cyclic voltametric stripping techniques (CVS). This technique is now available as an on line system, to analyze and control plating processes depending on the equipment.

Summary

Copper BMV filling is a critical enabling process for the production of HDI panels and IC packages. The number of BMV´s found on a typical substrate is increasing and the dimensions are decreasing which is pushing the limits for the production process and at the same time there is the ever present demand for cost down. Filling is required with a minimum of surface plated copper to allow etching of fine line structures in HDI applications in panel plate mode and .to meet the demands for the smallest structures in pattern plating for IC packages. Treatment of homogenous base materials as well as glass reinforced materials both with and without copper foil is required. Production is now being made in a wide range of equipment, vertical hoist and conveyorized systems as well as horizontal conveyorized systems. Integration of metallization together with electrolytic copper plating in a wet to wet horizontal plating system has gained market acceptance for HDI production particularly for hand held devices. Such conveyorized systems offer the high volume production capability together with reduced panel to panel variation enabling increased yields and reduced processing costs.

References

[1] Bernd Appelt, *Heterogeneous Packaging: SiP based on 2.5D and 3D Integration*. Proceedings of the 2011 EMPC, Brighton, UK, September 12th to 15th, 2011.

[2] Bernd Roelfs, Ph.D., Nina Dambrowsky Ph.D., Christof Erben and Stephen Kenny, *New challenges for higher aspect ratio: Filling Through holes and Blind Micro Vias with Cu by Reverse Pulse Plating.* Proceedings of the SMTAI, Fort Worth, USA. 2011.