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Use of Ultrasonic Agitation for Copper Electroplating, Application to High Aspect Ratio Blind Via Interconnections

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Abstract
Using conventional PWB copper electroplating techniques (DC bath chemistry with air agitation), non-uniform deposition inside blind via features may arise when the vias have diameters less than 6 mils and aspect ratios greater than one. These observations result from two main causes: unfavorable solution hydrodynamics and the presence of air bubbles. Ultrasonic agitation (UA), well known for cleaning purposes, can provide a strong local agitation that "refreshes" the plating solution inside holes together with punching small trapped air bubbles. It has been demonstrated that UA greatly enhances the throwing power inside small blind via features. It must be pointed out that low UA power densities were used (2 to 8 W.gal^{-1}). The frequency was 40 kHz and air was bubbled during plating. Using a conventional DC plating solution at 15 ASF, throwing power was improved on average by 35.9 % for vias having a diameter of 6 mils and aspect ratio between 1.25 and 1.5. A more drastic 74.6 % throwing power improvement was noted for 4 mils blind vias having an aspect ratio of 1.9 and 2.4. Through ductility measurements, it has been also demonstrated that plated through hole reliability was improved using mild UA.

Introduction
The electronic interconnection industry today faces significant challenges. This industry is now looking for PWB's that could provide the required foreseen interconnect density at an acceptable cost. Multi-layered printed circuit boards are now using plated through holes (PTH) and blind vias or microvias (BVH) with high aspect ratios for high density interconnections. Using conventional techniques (DC bath chemistry, air agitation and side-to-side cathode motion), non-uniform copper plating inside blind via features may arise when the vias have diameters (*d*) less than 6 mils (150 µm) and aspect ratios (*AR*) greater than one. These observations result from two main causes: unfavorable solution hydrodynamics to transfer Cu^{2+} ions inside such holes and the presence of small air bubbles inside the holes.

Two main technologies[1-2] are already employed in the PWB industry to overcome such challenges: the use of complex DC bath composition as well as the reverse pulse technique, which also works with complex chemical bath compositions. To overcome the bubble presence problem mechanical board vibration (50 to 160 Hz) is a viable avenue,[3-4] but in this case throwing power was not significantly improved. To minimize the presence of air, the use of e-ductors is also a possibility.[5]

Mass transfer improvement using ultrasonic agitation (UA) is well known in eletrotroplating.[6] UA is also used for cleaning purposes in the PWB industry.[7] However few instances are found in the literature about the possible use of UA for enhancing throwing power (TP) inside PTHs and BVHs. A Russian team claimed that plating efficiency was enhanced inside PTHs using UA.[8-10] However, these authors did not establish any comparison between UA and other types of mixing, thus improvement in the plating rate was logical. Hsaio et al.[11] also studied the influence of UA upon copper thickness uniformity for PTHs, but no improvement was observed. Fournier et al.[3] studied the influence of board vibration in the near ultrasonic range (18 kHz) upon copper TP inside BVHs and they showed that no significant improvement was noticed. Finally it must be pointed out that some authors[12-13] studied UA to improve copper electroplating inside the very fine features of integrated circuits for the micro-electronic industry. In the Lai[12] patent, the preferable way to enhance copper plating was by ultrasonically vibrating the wafer.

The present work focuses on a new process utilizing UA of the plating bath to improve copper deposition throwing power inside BVH's having diameters less than 6 mils and *AR* > 1. To attain maximum reliability, throwing power inside such features must be close to 100 %.

Experimental
Standard PWB test panels (18 x 24 in., 0.053 in. (1.35 mm) thickness) made of six copper laminate layers separated by FR-4 glass reinforced resin type

layers were used for the plating experiments. Arrays of laser-drilled through holes and blind via holes, 4 < d < 10 mils, cover large areas of the panel. A conventional electroless copper and copper flash steps were performed prior to the electroplating step, which is described in Table 1. In fact the DC plating solution was a standard commercial one. The main tank (600 l) had a cathode side to side motion system, air agitation tubing system and the ultrasonic transducers were placed inside two externally anodized titanium cans which were inserted between anode baskets. Each ultrasonic can provided 500 W power at 40 kHz frequency. Current density, ultrasonic power and air agitation were the variable plating parameters.

Table 1 - Electroplating Procedure

Steps	Chemicals	Conditions
Cleaning	Phosphoric acid, Ethylene glycol	110^{o}F, 2.5 min
Microetch	Na Persulfate, H_2SO_4, 12 %	76^{o}F, 20 s
DC Plating	H_2SO_4, 200 g.l^{-1}, $CuSO_4$ 80 g.l^{-1}, Cl^- 50 ppm, Brightener and leveler	85^{o}F, side to side motion

Using cross-sections of BVHs, two parameters were determined to assess the coating quality inside the BVHs:

(i) *TP* (%) or Throwing Power coefficient
(ii) *VQ* (%) or Via Quality coefficient

$$TP = \frac{2}{3}\frac{\left(l_w^1 + l_w^2 + l_b\right)}{\left(l_t^1 + l_t^2\right)}\times 100 \qquad (1)$$

$$VQ = \frac{3\,l_{\min}}{\left(l_w^1 + l_w^2 + l_b\right)}\times 100 \qquad (2)$$

These two parameters were estimated by measuring different copper thicknesses, see Figure 1 and equations (1) and (2). In these two formulas, l_t and l_w represent the thicknesses at the top of the board (pad) and at the mid point inside the BVH cylinder respectively. l_b and l_{min} represent the copper thickness at the disk center in the BVH bottom and the minimum copper thickness inside the BVH respectively. *TP* estimates the throwing power inside BVHs by comparing the amount of copper deposited on the pad surface with that deposited inside the hole. A 100 % value for *TP* indicates that the deposition was very uniform.

The coefficient *VQ* assesses the copper deposition effectiveness or the absence of defects inside a given feature. A low *VQ* value indicates that a BVH has a thin copper thickness at a given location which may lead to poor reliability.

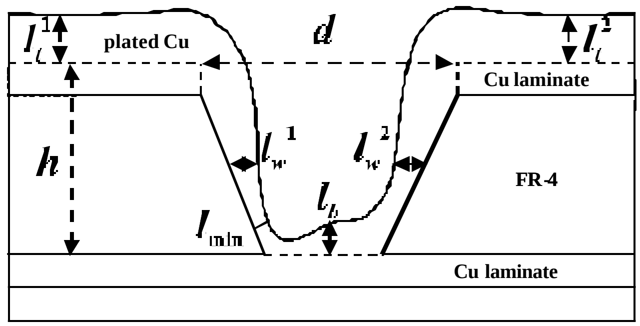

Figure 1 - Schematic Drawing of a Blind Via Cross-section with its Thickness Parameters

PWBs and UA, Why?

It has been demonstrated[3] that air bubbles trapped inside small BVHs (d < 6 mils for AR = 1) are not the only cause for poor throwing power. In that study mechanical vibration removed the air trapped inside the holes, but *TP* coefficients were not drastically improved. Therefore a proper mass transfer of Cu^{2+} cations inside such BVHs is an important requirement to reach high *TP*.

In fact, using the Faraday law, it is estimated that a BVH barrel (d = 4 mils and AR = 1) needs to be replenished approximately 532 times (1 time every 5 seconds) with new solution in order to plate 1 mil copper thickness at 15 ASF using the solution described in Table 1. Thus it is crucial to have a good mass transfer of copper ion species inside such features. Using simulation and mathematical modeling tools, some authors also found that for high *AR* holes[14] or trenches[15] aqueous solutions are recirculating upon themselves in the bottom part of a given feature under given (macro) flow condition (liquid circulation) and hole size. Bubbling air, side to side motion of the PWB as well as the use of e-ductors generate a macro agitation of the bulk solution. These techniques are very efficient as far as copper plating at the surface of the PWB (e.g., pad) or inside low *AR* BVHs and PTHs are concerned. However new agitation means are needed in order to disturb the flow pattern near and/or inside BVHs or microvias. In other words, the agitation must take place at the micro-level. Kadija et al.[16] used a system comprising very fine brushes which enhanced copper etching by locally modifying the liquid flow pattern near small circuitry lines having small width-to-depth ratios. In the present study the use of UA is proposed to generate micro agitation, like micro jets of solution, in order to enhance mass transfer inside microvias.

As described by Walker[6] mass transfer is improved during electroplating using UA. Each point in the liquid is subjected to alternating negative and positive pressure which creates cavitations bubbles and subsequently their implosion. This implosion creates a tiny but intense area of pressure and temperature, which reduces, locally, the diffusion layer (δ) of the electrochemical reaction as shown in Figure 2.

UA is widely used for cleaning purposes[7-17] in the plating industry and to a certain extent in the PWB industry. As mentioned by Fuchs,[7] frequencies from 40-45 kHz are reserved for applications on substrates susceptible to damage by intense cavitation (20-25 kHz range), and for cleaning and rinsing applications requiring enhanced penetration of complex surfaces. The same author estimates that for a 600 l (132 gallons) tank, 20 $W.gal^{-1}$ is the required ultrasonic power density used in typical cleaning applications. Since PWBs are considered as delicate substrates, because of the presence of fine polymer photoresist masks for instance, the frequency was chosen at 40 kHz and the ultrasonic power density was kept below 10 $W.gal^{-1}$.

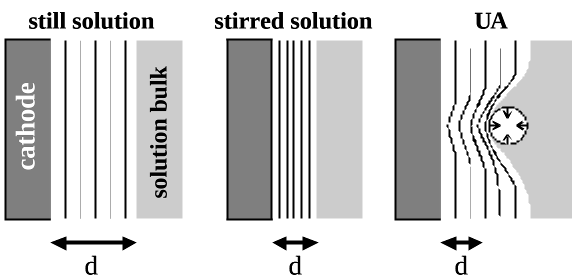

Figure 2 - Schematic Drawings of the Diffusion Layer Thickness Under Three Agitation Modes[6]

BVH Throwing Power Study

The average sizes of seven types of BVHs or microvias studied are presented in Table 2. Diameters varied from 4 to 7.5 mils and the aspect ratios from 2.4 to 0.8. The electroplating variable parameters are shown in Table 3. Air agitation was either switched on or off, UA varied from 0 to 8.3 $W.gal^{-1}$ and finally two current densities were studied (15 and 20 ASF).

Table 2 - Average Size of the Studied BVHs

BVH type / fig. symbol	*d* (mils)	*AR*
v1 / △	7.5	0.8
v2 / ○	5.5	1.15
v3 / □	7.5	1.15
v4 / □	6	1.25
v5 / ○	6	1.5
v6 / □	4	1.9
v7 / ○	4	2.4

Table 3 - Electroplating Variable Parameters

Exp #		Air Agit.	*UA* ($W.gal^{-1}$)	*J* (ASF)
v1-v3 series	A	ON	**OFF**	20
	B	**OFF**	4.1	20
	C	**OFF**	8.3	20
	D	ON	4.1	20
	E	ON	8.3	20
v4-v7 series	F	ON	**OFF**	15
	G	ON	2.1	15
	H	ON	4.1	15
	I	ON	8.3	15
	J	ON	2.1	20

BVHs v1 to v3 were copper electroplated using conditions A to E, while BVHs v4 to v7 were plated using conditions F to J. Due to their large diameter and their low *AR*, BVHs in the v1-v3 series were easier to copper plate than those in the v4-v7 series. Also, the BVHs within each of these two series (see Table 2) are ranked from the easier one to plate to the most challenging one. BVHs *TP* and *VQ* values (averaged values) versus condition A to E and F to J were plotted and are shown in Figures 3 to 8.

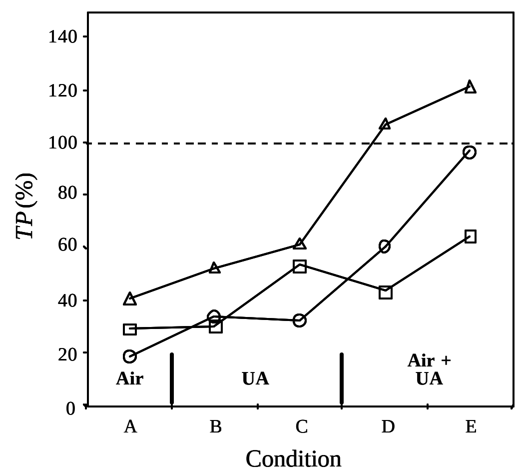

Figure 3 - BVH Throwing Power (*TP*) Assessment vs. Condition A to E BVHs Type: v1 (△); v2 (○) and v3 (□)

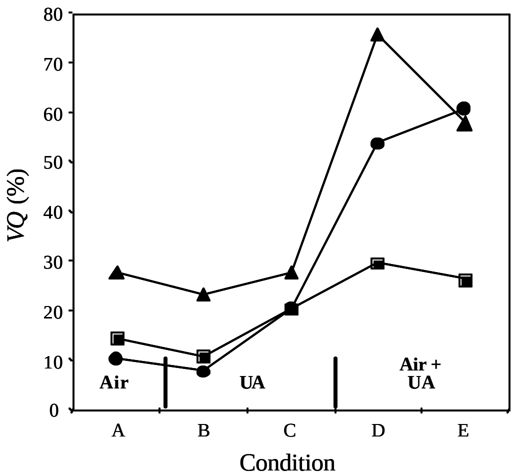

Figure 4 - BVH Coating Quality (*VQ*) Assessment vs. Condition A to E BVHs Type: v1 (▲); v2 (●) and v3 (■)

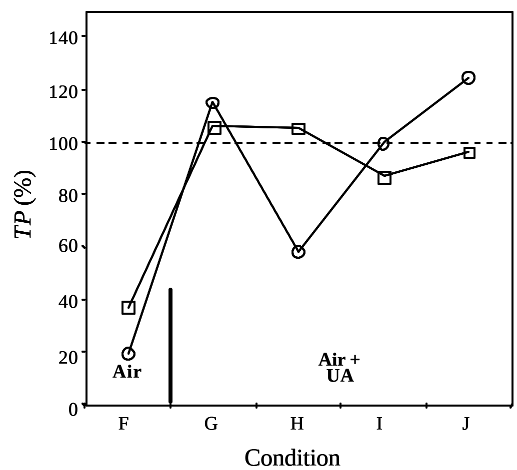

Figure 7 - BVH Throwing Power (*TP*) Assessment vs. Condition F to J BVHs Type: v6 (□) and v7 (○)

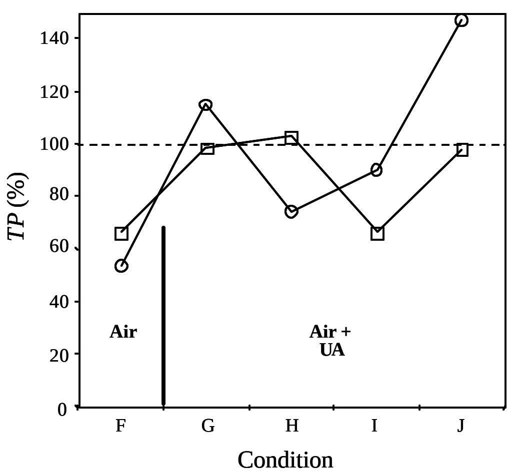

Figure 5 - BVH Throwing Power (*TP*) Assessment vs. Condition F to J BVHs Type: v4 (□) and v5 (○)

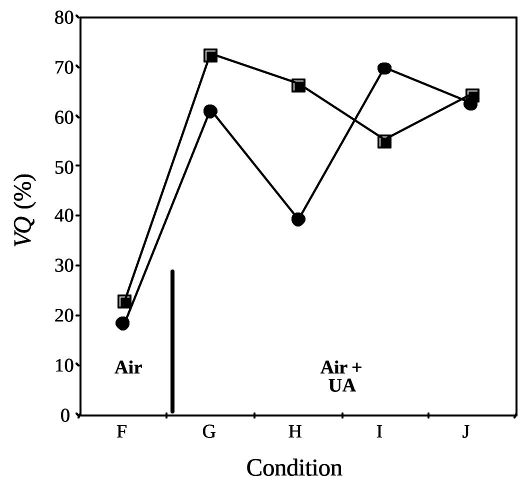

Figure 8 - BVH Coating Quality (*VQ*) Assessment vs Condition F to J. BVHs Type: v6 (■) and v7 (●)

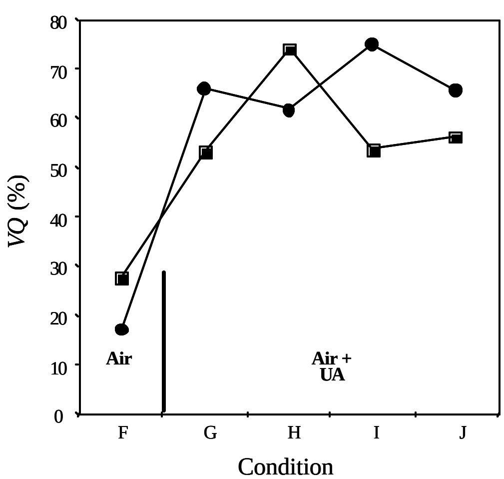

Figure 6 - BVH Coating Quality (*VQ*) Assessment vs. Condition F to J BVHs Type: v4 (■) and v5 (●)

Let us examine the influence of the two agitation modes by analyzing the corresponding *TP* and *VQ* values (see Figures 3 and 4 respectively) for the experiments A to E. The *TP* coefficients were improved by 20, 15 and 20 % when the solution was only agitated by ultrasonic means (condition C) compared to air agitation alone (condition A) for BVHs types v1, v2 and v3 respectively. On the other hand, *TP* coefficients were improved by 75, 78 and 32 % when the solution was agitated both by ultrasonic and air means (condition E) compared to air agitation alone (condition A) for BVHs types v1, v2 and v3 respectively. As far as the *VQ* factor was concerned (see Figure 4), improvements were not noticeable between the condition A and conditions B and C for three types of BVH. However, important rises in *VQ* factors were found when the solution was stirred both by ultrasonic waves and air (condition D and E) compared to the three other agitation modes (conditions A to C).

As expected, UA alone improved throwing power inside BVHs due to its micro-agitation nature. Although this improvement was significant, greater improvements in both *TP* and *VQ* were noticeable when both air and UA were used. In fact *TP* values close to or over the 100 % mark were found for v1 (conditions D and E) and v2 (condition E). Two main reasons can explain this behavior: macro agitation

Types of stirring, has the largest mass transfer enhancement factor (25 to 100). According to the same author UA has a low mass transfer enhancement factor (2 to 10).[18] However UA in the present study enhanced the local mass transfer (inside the BVHs). It must be pointed out also that no visible damage to the thin photoresist mask and to the other surface of the PWBs was seen for plating conditions D and E. However photoresist peeling was noticed when the air agitation was switched off (conditions B and C). The importance of bubbling air during plating is enhanced by the fact that UA distribution over the whole plating tank attenuated the aggressiveness of ultrasonic waves while improving the throwing power.

To study further the influence of UA upon copper electroplating inside BVHs, a new batch of PWBs was prepared which contain more difficult holes; see series v4-v7 in Table 2. Better care was taken with the drilling and electroless steps in order to be able to electroplate copper in geometrically well defined holes with their whole surface covered by a thin copper film.

Comparison of *TP* coefficients between condition A (v1-v3) and condition F (v4-v7) (see Figures 3, 5 and 7) shows that in spite of dealing with challenging holes, major improvements were noticed with the new v4-v7 series. Nevertheless *TP* values for the latter series remained well under the 100 % mark.

As far as the *TP* is concerned, independently of the applied current density (conditions G and J) and the UA power density (conditions G, H and I), values close to and over the 100 % mark were measured; see Figures 5 and 7. Major improvements can be noticed also for *VQ*, see Figures 6 and 8. Once again these improvements were independent of the different chosen UA power and current densities. Thus since no real relations between the three UA power densities and between the two applied current densities exist, the results were averaged and are displayed in Tables 4 and 5. These two tables also indicate standard deviation values as well as the number of the analyzed BVHs.

On average *TP* was improved by 35.9 % when UA was used for BVHs having a 6 mils diameter and aspect ratios of 1.25 and 1.5 (see Table 4). A bigger (air) is needed to stir vigorously[18] the solution bulk and the multiple air-solution interfaces represented by the air bubbles allowed a better distribution of the ultrasonic waves alongside the board surface. As mentioned by Fuchs[7] the air/liquid interface constitutes a near perfect reflector for the sound waves. As far as air agitation is concerned, Gabe[18] has shown that this one, among several other 74.6 % improvement was noticed for BVHs having a 4 mil diameter and aspect ratios of 1.9 and 2.4.

On average *VQ* was improved by 43.6 % when UA was used for BVHs having a 6 mils diameter and aspect ratios of 1.25 and 1.5 (see Table 4). A similar 42.6 % improvement was noticed for BVHs having a 4 mil diameter and aspect ratios of 1.9 and 2.4.

Table 4 - Average *TP* and *VQ* Coefficients, BVHs: v4 and v5

Agit. mode	BVHs analyzed	TP_{av} (%)	VQ_{av} (%)
Air	26	**61** +/- 13	**23.1** +/- 10.3
Air + UA	97	**96.9** +/- 33.4	**66.7** +/- 21.2

Plating was very efficient when the lowest UA power density was used (2.1 W.gal^{-1}); see conditions G and J in Figures 5 and 7 for the *TP* values and Figures 6 and 8 for the *VQ* values. The fact that low UA power densities can be used is important since no damage whatsoever must be done to the PWB surface. In the G and J conditions the UA power density used was 10 times lower than the standard density used for cleaning purposes. This low UA power density combined with the 40 kHz working frequency and air agitation minimize possible damage done to the PWBs.

Table 5 - Average *TP* and *VQ* Coefficients, BVHs: v6 and v7

Agit. mode	BVHs analyzed	TP_{av} (%)	VQ_{av} (%)
Air	14	**27** +/- 11.7	**20.2** +/- 12.8
Air + UA	60	**101.6** +/- 34.3	**62.8** +/- 16.5

Micro-section photographs, see Figures 9 to 12, show the uniform copper plating inside 4 different BVHs. The copper layer was relatively uniform even at the bottom of very challenging holes such as those of the v6 type shown in Figures 11 and 12. However some BVHs were difficult to copper plate like those of the v7 type shown in Figures 13 and 14. In the first of these two figures, one can notice that the electroless step did not cover the walls at the BVH bottom part. Although uniform copper plating occurred inside most of the BVH barrel, connection between the two copper layers was not achieved. Also the drilling step was just able to reach the inner copper layer giving place to an accentuated "V" shape form of the BVH. Like every other technology used to copper plate BVHs, the drilling and electroless steps should be as precise and effective as possible. The dogboning effect also had a bad effect on some vias, as shown in Figure 14, where the hole was literally plugged.

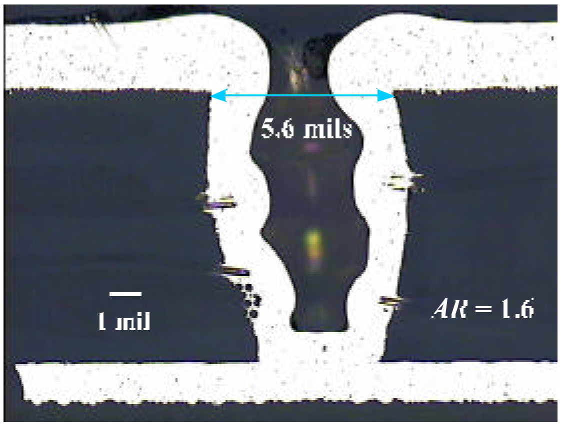

Figure 9 – BVH (v5 type) Cross Section, Plating Condition J (UA + air)

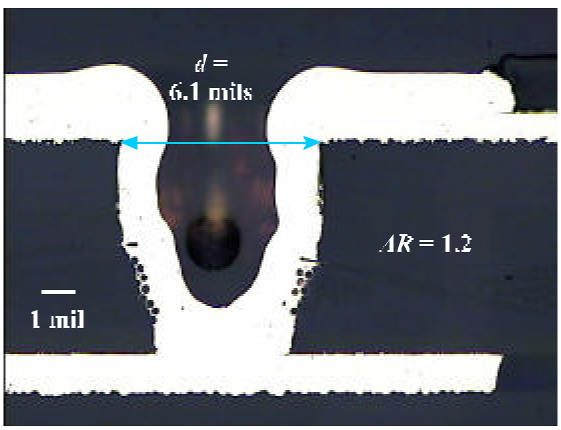

Figure 10 – BVH (v4 type) Cross Section, Plating Condition J (UA + air)

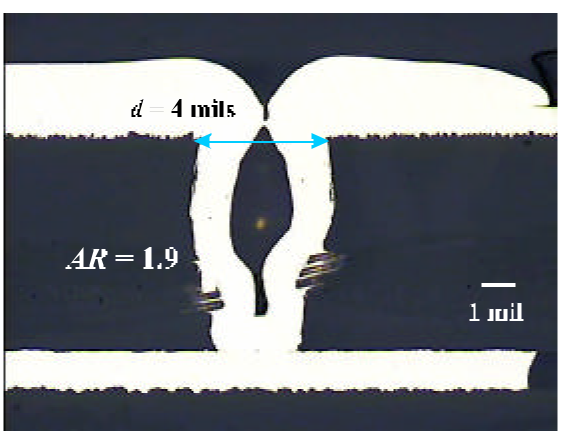

Figure 11 - BVH (v6 type) Cross Section, Plating Condition H (UA + air)

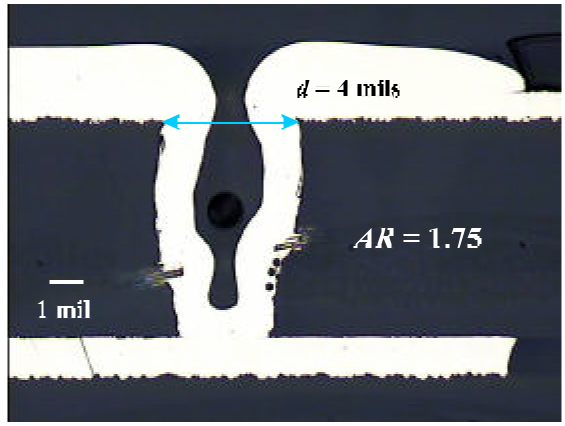

Figure 12 - BVH (v6 type) Cross Section, Plating Condition H (UA + air)

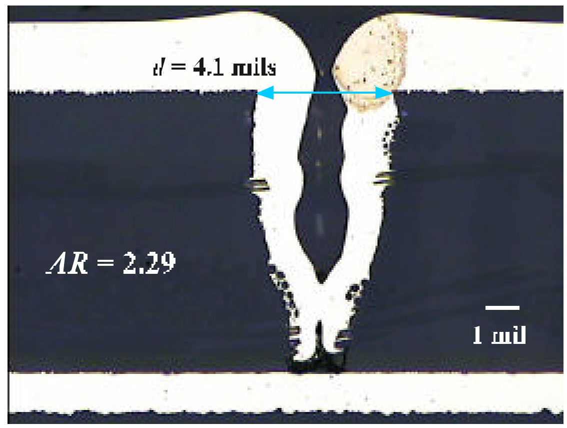

Figure 13 - BVH (v7 type) Cross Section, Plating Condition I (UA + air)

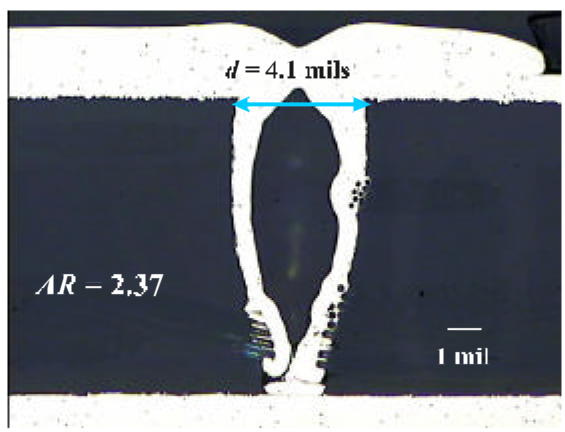

Figure 14 - BVH (v7 type) Cross Section, Plating Condition I (UA + air)

Time to time low *TP* and *VQ* values were found. This can be seen in Figures 5 and 7, where *TP* coefficients were relatively low (on average) for BVHs of the v5 and v7 series (condition H) and the v4 series (condition I). Overall this fact was quantified by calculating the different standard deviation values shown in Tables 4 and 5. The somehow wide dispersion of *TP* and *VQ* values show that issues related to the other steps of the whole process can have an adverse effect upon plating quality. Drilling and electroless steps remained important issues as shown in Figures 13 and 14. It has been demonstrated that UA is able to provide a good copper ion transfer into PWBs small features, but these one should be able to be plated and/or be free of air bubbles. Every steps of the plating procedure should be looked at carefully to obtain reliable PWBs.

Low *AR* BVH Plating Assisted with UA

Copper electrodeposition inside low *AR* (< 1) BVHs gave very interesting results in term of throwing power. As one can see in Figures 15 and 16, partial via filling is noticeable inside these two BVHs. No statistical studies were performed on this kind of BVHs, since copper filling was not reproducible. Nevertheless, it seems that UA should be considered or at least studied to perform copper via filling on microvias (*d* = 2 to 3 mils and *AR* = 1, for instance).

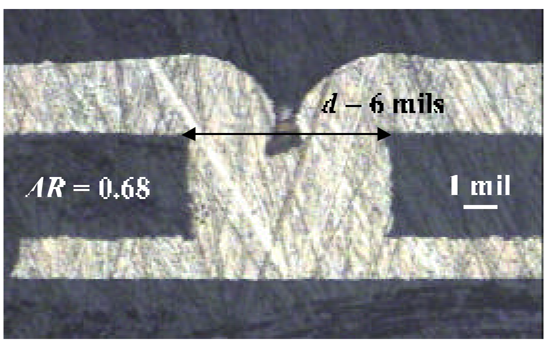

Figure 15 - Low *AR* BVH Cross Section, Plating Condition J (UA + air)

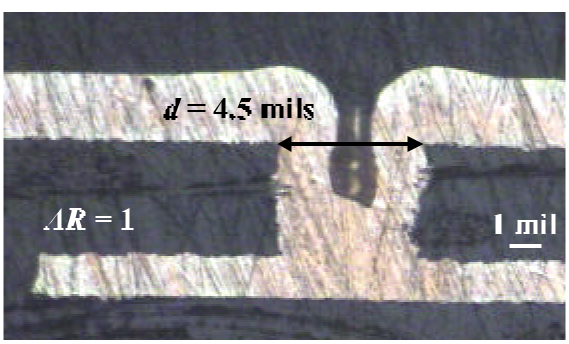

Figure 16 - Low *AR* BVH Cross Section, Plating Condition J (UA + air)

Plated Through Holes Reliability

The use of UA in electroplating can change the metal deposit morphology[6] and thus may modify its mechanical properties. Therefore it was important to check if the fatigue behavior of the deposits changed when UA was used during the electroplating step. Reliability assessment for PTHs is well detailed in the IPC-D-279.

PTH fatigue behavior can be described by equation (3).[19] This formula is very similar to the formula used to described metal fatigue behavior. The only difference is that the effective maximum strain range, $\Delta\varepsilon_{max}$(eff), (see equation (3)) for the PTH is replacing the total cyclic strain range ($\Delta\varepsilon$). No estimation of $\Delta\varepsilon_{max}$(eff) was found in the literature for BVHs. Meanwhile PTH fatigue behavior should give a rough estimation regarding UA influence upon BVH reliability and in any case PTHs and BVHs are both present in PWBs. Using a ductentiomat from Atotech, the fracture ductility D_f (%) and the tensile strength S_u (PSI) were measured for a copper foil electrodeposited on a mirror polished stainless steel mandrel.

$$N_f^{av\;-0.6} D_f^{0.75} + 0.9\frac{S_u}{E}\left[\frac{\exp\left(D_f\right)}{0.36}\right]^{0.1785\log\frac{10^5}{N_f}} - \Delta e_{\max}(eff) = 0 \qquad (3)$$

The other coefficients in equation (3) are: N_f^{av} the mean fatigue life, cycles to failure and E the modulus of elasticity (PSI). All the data are summarized in Table 6. Four different UA power densities were studied, see conditions F to I in Table 3. The results were computed and plotted for five mean cycles to failure (see Figure 17). According to Englemaier,[19] the mean strain ranges for computers (0.2 %) and for the automotive and military applications (0.95 %) are also indicated in Figure 17.

Table 6 - Variables used in the Fatigue Formula

Computed data	Measured data	Constant parameter
N_f^{av}	S_u (PSI)	$E = 1.2\ 10^7$ (PSI)
$\Delta\varepsilon_{max}$(eff) (%)	D_f (%)	

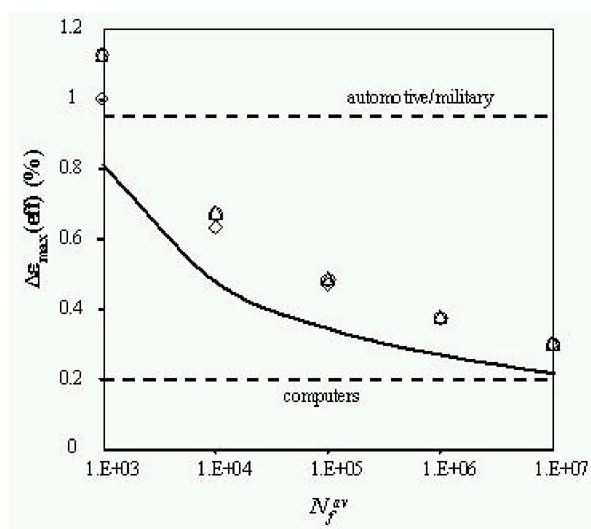

Figure 17 - PTH Fatigue Behavior (Solid line): Cond. F (no UA), (△): cond. G, (○) : cond. H and (◇) : cond. I

During electroplating, the use of UA at power densities lower than 10 $W.gal^{-1}$ did not increase the fatigue behavior of PTHs. In fact reliability was increased when UA was used. For instance, the estimated fatigue life was 4610 cycles for a mean strain range of 0.71 % (industrial environment[19]) using condition I. However, for the same strain range, the fatigue life was estimated to be 1590 cycles when electroplating was performed in standard conditions (F). To explain such encouraging results, relations between copper grain morphology versus reliability will be study in the future. Future work will also involve the BVH reliability issue.

Conclusions

It has been demonstrated that UA greatly enhances the throwing power inside small blind via features. It must be pointed out that mild UA power densities were used, which corresponded to up to one tenth of the power used for cleaning purposes. Air was bubbled during plating to improve throwing power and to minimize PWB surface damage. Using a conventional DC plating solution at 15 ASF, throwing power was improved on average by 35.9 % for vias having a diameter of 6 mils and aspect ratio between 1.25 and 1.5. A more drastic 74.6 % throwing power improvement was noted for 4 mils blind vias having an aspect ratio of 1.9 and 2.4. In each case the throwing power was close to the 100 % mark on average. Through ductility measurements, it has been also demonstrated that plated through hole reliability was improved using mild UA.

It has been demonstrated that UA is able to provide a good copper ion transfer into PWBs small features, but these one should be able to be plated and/or be free of air bubbles. Every other steps of the plating procedure (e.g. drilling and electroless) should be looked at carefully to obtain reliable PWBs.

UA for PWB copper electroplating may be an attractive solution to produce high throwing power copper plating.[20] UA is easy to implement, silent and robust. Conventional DC bath composition is needed.

Acknowledgements

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