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ABSTRACT

In this research experimental and simulated analysis investigates the influence of megasonic (MS; 1 ± 0.05 MHz) acoustic-assisted electroplating techniques, with respect to the fabrication of through-hole via (THV) and blind-via (BV) interconnects for the Printed Circuit Board (PCB) industry. MS plating of copper down THV and BV interconnects was shown to produce measurable benefits such as increased connectivity throughout a PCB and cost savings. More specifically, a 700% increase of copper plating rate was demonstrated for THVs of 175 μm diameter and depth-to-width aspect ratio (ar) of 5.7:1, compared with electrodeposition under no-agitation conditions. For BVs, a 60% average increase in copper thickness deposition in 150 μm and 200 μm, ar 1:1, was demonstrated against plating under standard manufacturing conditions including bubble agitation and panel movement. Finite element modelling simulations of acoustic scattering revealed 1st harmonic influence for plating rate enhancement.

1. Introduction

The Printed Circuit Board (PCB) industry is a critical stakeholder in the global manufacturing supply chain of electronic devices. PCBs sit at the heart of almost all electronic systems and structurally support a plethora of devices, including integrated circuits and discrete electronic components such as transistors, resistors and capacitors. Global demand for increased functionality of systems, along with increased battery life operation and reduced component footprint has led to an increase in the density of components on the surface of a PCBs. These trends are reflected in myriad of high value markets such as automotive, aerospace, space, defense, consumer goods, medical, networking and communications sectors. The global PCB market is expected to grow at a compound annual growth rate of 3% by 2020, with primary contributions to this growth coming from the internet of things (IoT) and wearables such as smart watches and smart eye ware [1].

Vertical Interconnect Access (vias) provide the required high density of interconnections from the top layer to inner layers or intermediate inner layers of a PCB, either as a Through Hole via (THV) or as a Blind Via (BV). The metal filling of high depth-to-width aspect ratio (ar) via is essential to ensure the efficient transmission of power and high frequency signals between components (> 1 GHz [2]) with transmission speeds over 25 Gb/s [3], whilst ensuring low bit error
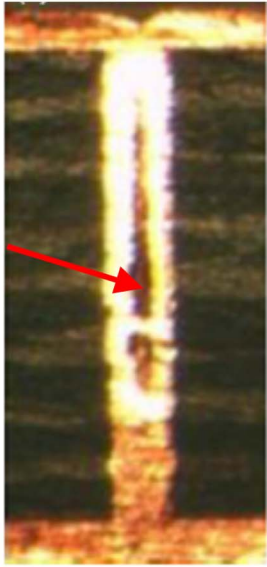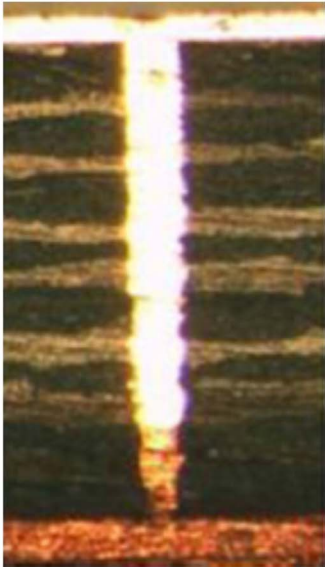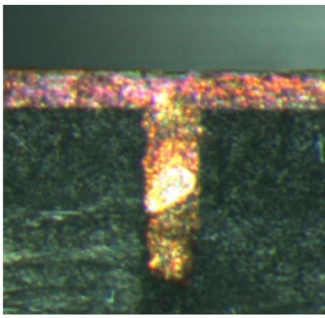
rates (10^{-18} at 10 Gb/s [4]). Additionally, small track feature sizes are desired to allow for large component densities on PCBs.

After an extensive review of recent advancements in electrodeposition, a critical process in PCB production, we explore improvements in electrodeposition of copper (Cu) vias within a PCB through the application of a high frequency, 1 MHz, megasonic (MS) streaming. The application of high frequency acoustics induces streaming mechanisms which have the ability to improve the transport of plating solution down microfeatures [5–7], improving the Cu plated thickness down vias over existing agitation techniques. A MS wave is used to deliver a uniform acoustic wave to the surface of the PCB, cathode, to investigate the influence of acoustic agitation within the electrolyte solution [8–12]. Increases in Cu deposition depth and improved uniformity of the Cu filling were obtained for high thickness-to-width aspect ratio (ar) vias, of the order of 8:1 and 3:1 for the THV and BV, respectively, as shown in Table 1. Both types of vias were uniformly filled using DC current without additional specialized filling chemistry. The interconnects obtained under laboratory conditions highlighted a vast improvement over existing industrial techniques, especially in the BV case whereby an ar of 1.2:1 can only be achieved using a single plating operation. Without MS assisted agitation, voids, indicated by red arrows in Table 1 are formed at the centre of the vias under standard plating conditions. The presence of such voids induces several

Table 1
Microsections showing plating outcomes obtained with the introduction of 1 MHz megasonic-assisted plating for a 1 A/dm^2 DC current density and non-filling chemistry. Voids highlighted by red arrows [11].

disadvantages, such as localised joule heating at high current densities, increased impedance, loss of data transfer and if processed further in high temperature (260 °C) reflow soldering operations, these voids would undergo expansion leading to cracks in the Cu and electrical opens [13].

Fabricating a PCB with interconnects containing 100% Cu fill and high *ar* would be extremely useful and profitable, notably the mobile phone market which currently employs Cu filled THVs of *ar* of 4:1, incurring high fabrication costs due to proprietary via-filling additives, long plating cycles and complex plating waveforms [14].

The quality of the MS plated Cu deposits was reported in [9]. For increases to MS plating power from 40 to 450 W, the roughness average (*Ra*), increased from 400 to 760 nm. This was attributed to unstable cavitation and an interference of the bath additives used for grain refinement. Due to the interference of bath additives cracks were observed on the surface deposit indicating a weakening of the plated structure. The drop in additive performance was attributed to standing wave acoustic interference effects. These interference effects can be negated by applying a phase shift [15] or a variation of the frequency [16] to the acoustic output and so, enabling improved via filling along with a high quality deposit.

In this paper we detail in Section 2 the physical phenomena responsible for the advanced agitation of the electrolyte solution provided by MS waves and the resulting waves in THV and BV, as well as their

mode of characterization. Section 3, a description of the observation metrics and methods, the experimental setup and the design of experiment is provided. Section 4, the results and analysis of the experiments and lastly, Section 5 outlines the primary conclusions of this investigation.

2. Phenomena responsible for the enhanced agitation of electrolyte solution

The agitation of an electrolyte solution is a critical factor for the plating of large deposits of Cu down high *ar* vias [17]. Metal ions in the vicinity of the surface to be metallised are depleted during plating and the solution requires continuous replenishing through fluidic streaming. If the replenishment rate is less than the deposition rate, the concentration of metal ions can decrease to a point where deposition of metal is impaired. This is especially important for plating down vias where the ability to transport electrolyte is hindered by viscous forces, limiting the techniques currently employed for fluid transport to the PCB - panel movement and sparge bubble agitation.

Acoustic streaming can be divided into categories described by the individual mechanisms behind their formation, with each displaying different velocities and magnitudes. It is beyond the scope of this paper to discuss the individual characteristics of these mechanisms and their relative importance to the observed fluid transport enhancements

witnessed down vias [9,10]. However, a summary of the acoustic streaming categories are as follows:

- Eckart streaming, which is streaming within bulk solution [18],
- inner layer boundary microscale streaming also known as Schlichting streaming [19],
- outer layer boundary microscale streaming also known as Rayleigh streaming [19],
- streaming induced due to the flexural motions of a rigid wall by a surface acoustic wave [20],
- streaming due to the implosion of microbubbles by cavitation [21,22] and
- cavitation microstreaming, which is streaming induced around microbubbles due to resonance induced motions [23].

Sonovoltammograms produced by 20 kHz ultrasound (US) agitation studies in [24] highlight that increases to diffusion mass transport occur by the thinning of the Nernst diffusion layer thickness. Here acoustic streaming in the close vicinity of the cathode surface reduces the distance over which ions diffuse, from 600 μm under silent conditions to 0.7 μm under US. This reduction enables the deposition of Cu at higher limiting current densities and therefore higher plating currents and faster plating rates. The Nernst diffusion layer thickness under MS agitation is approximated from rotating disc electrode studies in [25] as

$$\delta = \left(\frac{2v}{\omega \rho} \right)^{1/2} \tag{1}$$

where v is the Rayleigh streaming acoustic velocity, ρ is the density of the medium and ω is equal to $f/2\pi$; where f is the acoustic frequency. Using this approximation, increases to the acoustic frequency bring further reductions to the diffusion layer, improving the diffusion mass transfer of the Cu ions [12].

The Rayleigh streaming velocity was measured in [26], to increase between 100 and 500 μm/s, for increases of acoustic frequency between 1.5 and 3 MHz within a microcavity. The increases to the fluid streaming velocity coincide with enhancements to the convective forces within the microcavity. In relation to MS plating, this result indicates that, for higher acoustic frequencies, Rayleigh microstreaming increases which enable improved transport of electrolyte solution for the plating down vias.

With MS agitation, the two factors – reduction of the diffusion layer and enhanced electrolyte replenishment – support enhanced Cu deposition within vias of increased *ar*. The intensity of the individual mechanisms and thus the forcing of electrolyte solution for via plating, is influenced by the acoustic resonance established in the via cavity. MS studies have highlighted the formation of an acoustic standing wave formed within a THV cavity of size 0.8 mm diameter (*ar* 2:1), as measured from pressure distributions from a fibre optic hydrophone probe [27]. The probe measured increases and decreases in pressure, displayed in Fig. 1, occurring at fixed positions within the THV. These positions were separated by distances of half of the acoustic wavelength – 0.7 mm – of the applied 1 MHz agitation.

An acoustic standing wave is a superposition of an oncoming travelling wave meeting its reflection travelling in the opposite direct. A combination of these two waves within a THV lead to the formation of fixed regions of changing high and low pressure, and regions with zero change in pressure, which correspond to pressure anti-nodes and nodes, respectively. The formation of standing waves influences the acoustic streaming properties [19] and their formation shall be further considered in this paper through the use of the simulation software COMSOL Multiphysics®, which provides insight into the MS-assisted plating behaviour and the technological capabilities of the process.

The MS assisted plating performed in [11] was conducted with a continuous acoustic output. The introduction of a pause has been shown in [28,29] to increase cavitation and the presence of bubbles

occurring within the area sonicated, due to the 'recycling' of imploded bubbles after cavitation. The creation of microbubbles and cavitation has been attributed to enhanced mass transport [30]. Additionally, the introduction of a pause cycle during acoustic-assisted plating has been shown to assist the replenishment of electrolyte solution [31]. For these reasons the application of a pause cycle shall be considered for its impact on the MS plating of THV.

Another technique for the enhancement of mass transport for Cu electroplating, is the insertion of a supercritical carbon dioxide suspension into a plating solution, which is maintained under high pressures (2000 psi) during plating. This technique has been shown to alter the parameters of the plating solution which include reducing viscosity, increasing the diffusion coefficient and lowering surface tension, all of which contribute to an increased Cu ion transport [32]. Increases to the uniform filling of Through Silicon Vias (TSV) with Cu has been demonstrated in [33] through the use of this technique. Further enhancements to supercritical plating performance have been demonstrated in [34], by the application of 42 kHz US agitation during plating. The introduction of US has shown to improve the mechanical properties of the deposited coating and its surface roughness, due to a dampening of the damaging forces induced by unstable cavitation by the carbon dioxide suspension, termed soft cavitation [35]. Soft cavitation has also been attributed to improved mass transfer which could be explained by increases to cavitation microstreaming.

The application of higher frequency MS agitation rather than US results in the formation of smaller cavitation microbubble sizes [36]. The benefits obtained from US supercritical plating in [34] were pressure dependent, where increases to pressure reduced the size of the microbubbles. The highest plating quality obtained was for microbubble sizes closest to the Nernst diffusion layer size. With the inclusion of MS rather than US alongside supercritical plating, it could be possible that the microbubbles sizes could be reduced further, lowering the high pressures required to obtain a high quality deposit and thus the production costs.

US within a supercritical suspension has also been applied for the fabrication of large-scale graphene production to improve size and yield, which was possible due to exfoliation of the graphene sheets [37]. Effective exfoliation is obtained by a high degree of cavitation, which is determined by a fluid's cavitation threshold - where lower values produce more cavitation. Increases to acoustic frequency increase the cavitation threshold [38] and for this reason, MS over US agitation may not be suitable for this application.

3. Experimental procedures

Plating investigations were carried out on FR4 PCBs supplied by Ventec Ltd, (FR-481, Cu thickness 18 μm). The PCBs were drilled with THV and BV features using mechanical drills (Schmoll Maschinen GmbH). Prior to electroplating, the PCBs were uniformly plated with 1–2 μm of electroless Cu using the MacDermid Ltd process. The electroplating was performed in a medium size 500 L plating tank which used soluble Cu anodes with PCBs held 21.6 cm away from the anode basket for maximum plating uniformity across the boards [39]. The bath included an external fluid pump to filter the solution at a rate of 1000 L/hour. The transducer (Sonosys Ltd) was faced parallel to the front of PCBs surface at a distance of 4.5 cm, found to be the optimum distance between minimum electrical current thieving and maximum acoustic pressure. The transducer is a square-faced submersible composed of four rectangular piezo-transducers, of size 2.5 cm by 11 cm, embedded in a steel sheet of 1.03 dm² area. The transducer outputs a 1 MHz ± 0.05 MHz acoustic wave with a variable power, where at maximum electrical power, 500 W are converted to acoustic power output with a conversion efficiency of around 90%. In all setups the acoustic wave within the bath was unidirectional due to the small beam spread angle attributed to high frequency acoustics [40] and covered an area approximate to the area of the transducer face. MS plating
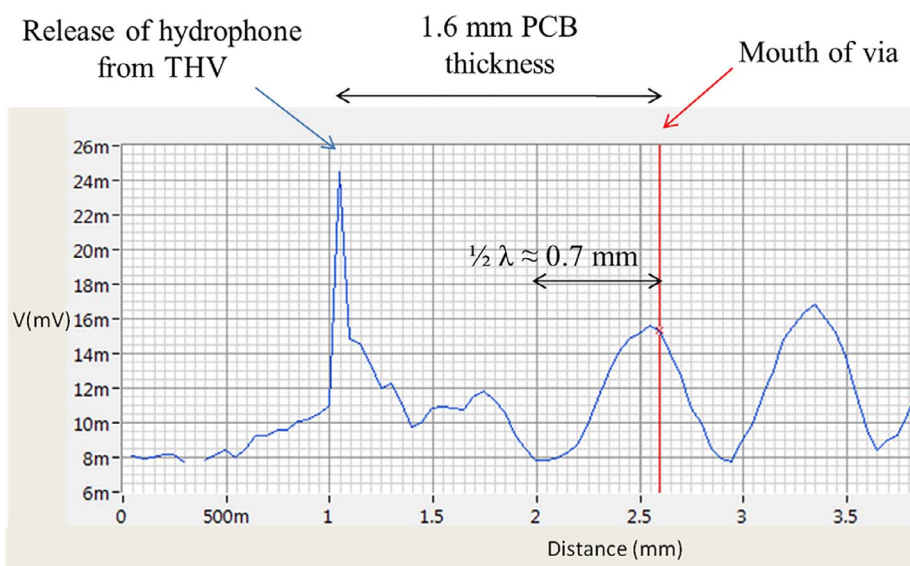
Fig. 1. A plot of the voltage response as measured from a 0.2 mm diameter hydrophone pressure probe as it was guided through a 0.8 mm diameter ar 2:1 THV, which received 1 MHz sonication at 20 W output. Average pressure 92 ± 13 kPa. Highlighted are high and low pressure peaks at fixed positions within THV cavity [27].

investigations were performed with the introduction of an acoustic pulse modulator, which periodically switches off the MS output (7 s on, 17 s off). The settings were chosen as similar pulse settings were applied in [31] for acoustic plating, which reported an increased electrolyte replenishment. The acoustic modulator consisted of a control PCB with an electrical connector, which was applied to the transducer power unit.

The Cu plating solution used, SLOTOCOUP CU110 (Schloetter Ltd), is formulated for direct current (DC) and reverse pulse (RP) plating. A bottom-up filling chemistry was not employed in BV trials due to the high costs of new insoluble anodes required. DC and RP plating were used with settings as indicated in Table 2. The durations of the forward:reverse pulses for RP were 10 ms and 0.5 ms, respectively. The RP plating magnitudes were varied depending on the experiment being performed. However, in most cases, a large forward to reverse ratio such as 1:3 was applied during the plating cycle to reduce the unwanted pinching effect occurring at the neck of vias at the expense of increased surface roughness of the Cu deposit. When operating under the recommended manufacturer's conditions, a high quality finish is produced, characterised as a fine grain and ductile deposit. The chemistry was comprised of 80 g/L copper sulphate, 100 mL/L sulphuric acid and 80 mg/L chloride. Chemical proprietary additives Cu 111 (5 mL/L) and Cu 114 (5 mL/L) were included in the solution.

COMSOL version 4.3b was used to model the hydro-acoustic behaviours of the MS within THV and BV.

3.1. Analytical techniques

The amount of Cu plated depends on the concentration of Cu ions at the surface of the PCB and the electrical current available for electrodeposition [41]. These factors are controlled through careful adjustment of the plating rectifier operational parameters and chemical composition of the electrolyte solution. When introducing MS agitation into the plating bath, changes to the Cu concentrations within via structures are altered due to the forcing of solution by acoustic streaming currents. The amount of copper down the vias was quantified by measuring the average plating rates and thicknesses obtained in the middle of THV and at the bottom of BV. The plating thickness was measured directly through the use of a microscope. Microsections of samples were performed by cutting out the area of interest, embedding sample in a thermoset resin FiaFix (Struers) and grinding edge of the sample to improve smoothness for feature resolution under microscope. A Nikon Labophot™, of 2.5 to 20-times magnification and resolution of 1 μm, was used to obtain images of the microsections.

3.2. Experimental conditions

Experiments were performed to investigate the plating thickness obtained down THV and BV with changes to THV diameter, transducer positioning, acoustic output, electrical current density, and DC and RP plating. These were complemented by simulations as listed in Table 2.

4. Results and discussion

4.1. Experiment 1: MS plating down THVs of different size

MS plating was performed on THVs of different sizes under settings outlined in Table 2. Typical plating behaviours show that smaller THV diameters produce a smaller deposition of Cu down the middle. Fig. 2 shows microsections of plated results for diameters 0.325 mm (A & B) and 0.475 mm (C & D). For THV of diameters larger than 0.30 mm the inner region contained little Cu. The Cu deposited after MS plating A & C, was characterised by variations in plated Cu thickness, unlike the case with standard agitation where a large build up is witnessed at the entrance of the THV with a thinner deposition towards the centre B & D, characteristic of a variation in the electrical field line distribution that altered the plating rates [41].

Periodic variations in deposit thickness and overall smaller deposition characterise the plating process using MS assisted agitation. Periodic changes in Cu thickness after MS plating have been observed previously on the surface of the PCB and are attributed to standing wave interference effects as reported in [9]. The variations inside the THVs were only observed under MS plating configurations and the separation distance between the thick/thin Cu deposits down the plated THV was approximately 650 μm, which is approximately half of the acoustic wavelength in solution.

Plating trials were performed down THVs of diameter 0.175 mm with aspect ratio, *ar*, of 5.7:1 and reported in [8]. This diameter was chosen as it is the minimum size for THVs on a PCB at this *ar* and so any improvements witnessed here would reflect an increase in PCB plating capability. These plating results are displayed in Fig. 3 with A, 225 W MS and B, with only solution agitation provided by the filtration pump of the bath. On the application of MS the plated thickness increased compared to plating without any agitation. Also the undulating Cu features were not present as observed when plating down THVs larger than 0.3 mm. The 0.175 mm features showed Cu 'pinching' at the ends of the THV, which was expected under DC plating conditions. The result additionally showed that MS plating enhancement was THV diameter size and board thickness dependent.

Table 2
A list of the four experiments performed with their parameters and simulation settings.

Experiment Number	Parameter altered	PCB Settings		Via diameter (mm ± 25 mm)	Plating Settings		Simulation Settings
		PCB thickness (mm)	PCB area (dm²)		Transducer (W)	Electrical waveform, Current Density & Duration	Cavity feature simulated
1 & 3	THV diameter	1.6	4.64	0.325	225	DC at 1.0 A/dm² for 16.5 h	0.30 mm by 1.60 mm THV
				0.475	225	DC at 1.0 A/dm² for 16.2 h	No simulation performed
				0.175	450	DC at 0.5 A/dm² for 15.5 h	0.15 mm by 1.00 mm THV
				0.5	225	DC at 2.0 A/dm² for 16.8 h	0.50 mm by 1.60 mm THV
2	Agitation settings: CW acoustic output, pulsed acoustic output & no agitation	1	4.64	0.175	450 Continuous output	DC at 0.5 A/dm² for 15.5 h	No simulation performed
					450 Pulsed acoustic output	DC at 0.5 A/dm² for 16.0 h	
					Not in bath	DC at 0.5 A/dm² for 16.0 h	
4	MS plating down BVs with RP and different ar	1.6	2.3	0.20 and 0.15, ar 1:1 and 2:1	450	RP at 1.0 fw 3 rv A/dm² for 12 h	0.2 mm by 0.2 mm BV
					No transducer, standard agitation		0.2 mm by 0.4 mm BV
					No agitation at all		0.2 mm by 0.6 mm BV

The orientation of the transducer was kept tangential to the surface of the PCB during the plating. At acoustic frequencies greater than 200 kHz acoustic streaming becomes highly directional [42]. On the application of MS for the cleaning of flat surfaces, the highest acoustic streaming is received on a surface when the transducer face is in a parallel alignment to a flat surface, so that the acoustic streaming propagates tangentially [43].

It is predicted that increases to the orientation beyond tangential will reduce the total acoustic energy coupled into the THV. A reduction of the acoustic energy coupled into the THV may, in the case of the 0.30 mm diameter *ar* 8:1 THV, result in an increase of plated Cu and for 0.15 mm diameter *ar* 5.7:1 THV, a decrease.

4.2. Experiment 2: MS plating down 0.175 mm THV with differing MS waveform

The MS wave induces high energy acoustic cavitation and thermal increases on the PCB surface which can induce damage to the PCB surface as highlighted in [9]. Introducing a pause in its output reduces the MS agitation reaching the surface, but has also been shown to influence the formation of cavitation and its energy released as shown in [28,44]. The impact on plating rate due to a pulsed MS output is uncertain and so an investigation was performed applying an acoustic pulse modulation of 7 s on and 17 s off. The ability to deposit Cu with a continuous acoustic output, pulsed and no agitation, was quantified by measuring the plating rates obtained in the middle of 0.15 mm diameter THVs. Plating trials were performed as outlined in Table 2.

The plated thicknesses measured under the different settings are shown in Fig. 4 and the evaluated average plating rates determined from ten measures of Cu thickness were plotted on Fig. 5 along with their standard deviations. Under no agitation, an extremely small plating rate was obtained. With MS the plating rate increased by approximately 700% inside the THV when compared with no agitation. This was due to enhancements to acoustic streaming forces through the THV. The results obtained when applying pulsed acoustics showed a reduced plating rate compared to MS plating, although it was approximately 400% thicker than under conditions of no agitation. This result shows that, with a non-continuous supply of acoustic agitation, the solution is stirred sufficiently to produce some enhancement to plating performance, although was not as effective as continuous agitation.

4.3. Experiment 3: Simulation of THV cavities

Acoustic scattering simulations were performed using the software package COMSOL™ to provide further insights into the relationship between standing wave acoustic distribution and Cu deposition. The simulation output was a pressure distribution with red, blue and white representing pressure maxima, pressure minima and nodes, respectively. The simulation was static in time and thus the red and blue regions correspond to pressure anti-nodes.

The plated result in Fig. 6A was a THV of diameter 0.5 mm and showed the undulating Cu pattern. The pressure distribution in B was a plot obtained for the setup, where Cu thickness was exaggerated in the simulation at the entrance of the THV to model Cu pinching. Under this condition, three pressure nodes are observed within the THV, the first inside the THV neck, the second in the middle and the third outside the THV. The asymmetrical positioning of the node into and out of the THV on either end, is due to the propagation direction of the acoustic wave, where, in the simulation, it is set up to travel from left to right. The extension of the pressure node outside of the cavity structure on the right is due to the end correction effect, which increases the separation distance between standing wave nodes outside of a cavity [45]. The simulated 0.5 mm diameter THV includes a pressure maximum / minimum region separated by half of the acoustic wavelength, which corresponds to a second harmonic wave formed within an open-ended
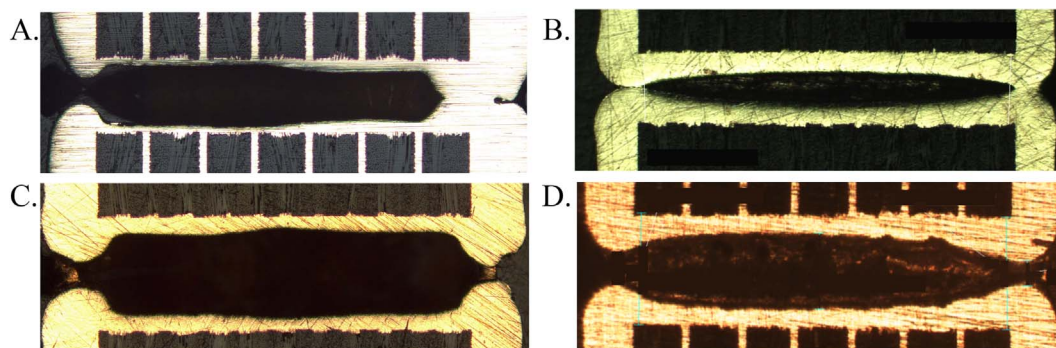
Fig. 2. Plating behaviour for THVs of size 0.325 ± 25 μm A) & B) and 0.475 ± 25 μm C) & D), formed with 225 W MS-assisted plating A) & C) and standard plating conditions B) & D).

cylinder [46]. Measures taken of the pressure wave formed within a THV are shown in Fig. 1 which provide further evidence for this harmonic formation. The undulating Cu features produced are not typical for the plating behaviour induced due to standard electrical field line attraction within the THV, as shown in Fig. 2. The undulation of the Cu in the THV appears such that the regions of minimum Cu deposition coincide with the pressure nodal regions and the thicker deposits with the pressure anti-node regions. The possible mechanism for the behaviour could relate to the formation of Rayleigh streaming vorticity within the THVs, whose localised microfluidic velocities vary dependent on the position within the MS standing wave [19]. Increases to fluid transport on the pressure node could result in the Cu peaks and transport reductions on the pressure anti-nodes, the thinner regions.

THVs of diameters larger than 0.30 mm show no enhancement to plating, producing results of a lower thickness that those obtained under standard agitation conditions. This outcome appeared to correlate with the appearance of a second harmonic standing wave. The formation of a standing wave between two parallel plates within a cavity filled with fluid will undergo zero mass transport [47]. In the THV a standing wave between the entrance and exit of the THV, hinders further transport into and out of the cavity. A greater understanding as to the formation of a standing wave in open ended pipes is covered in [48]. In MS THV plating, the prevention of electrolyte transport into the THV would hinder the deposition process and could account for the overall net effect observed. The plating enhancements witnessed in previous literature were reported on THVs smaller than 0.30 mm diameter and not the size plated here.

Simulations were performed modelling the pressure distribution in cavities of size 0.15 mm, which were an approximation of the THV in

Fig. 3. Results were plotted in Fig. 7 before any Cu had formed A, and, as the cavity closed up B. The distributions are different from the pressure distributions obtained for the longer and wider cavities. Instead of a 2nd harmonic, a 1st harmonic mode is observed, indicated by red as a single pressure anti-node formed within the cavity. In A the pressure nodes were situated outside of the THV and as the Cu thickness increased, the nodes are drawn in towards the entrances of the THV, confining the pressure anti-node. Unlike the 0.30 mm diameter cavities, plating was not hindered within the 0.15 mm diameter THV which also coincided with the formation of the 1st harmonic mode. The formation of the 1st harmonic would have altered the Rayleigh streaming vorticity motion within the THV and the hindrance of the fluid transport induced by the standing wave – witnessed at larger diameter cavities – did not take effect for the 0.15 mm cavity. The possible mechanism for this could be due to an interplay of microbubble streaming [23] and cavitation induced streaming within microscale cavities [49]. At this size plating enhancement with the MS plating agitation was obtained which was significantly larger than plating obtained under no agitation, although it was uncertain how this enhancement compared to the standard bath agitations as a plating result under this condition was not performed. This result needs performing along with further studies to determine the exact microstreaming mechanism behind the behaviour. A microfluidic chamber using 1 MHz transducer and fluorescent microbeads could be constructed like in [19,50] to visualise the transport mechanisms and would provide insight into the correct mechanism occurring here.
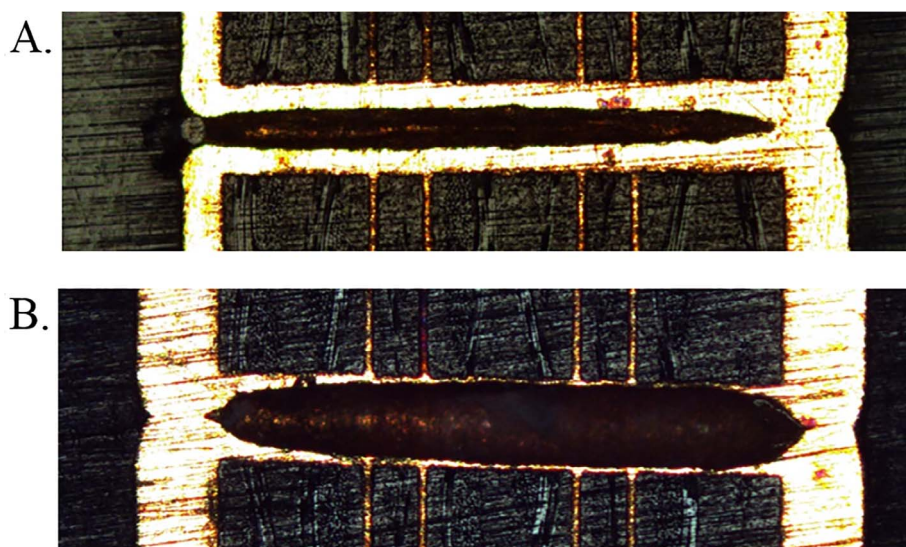

Fig. 3. Microsections of 175 μm diameter (ar = 5.7:1), THV interconnects on a PCB electroplated at 0.5 A/dm², for 15.5 h and showing A) with 450 W MS and transducer setup 4.5 cm tangential to PCB and B) plating with only solution movement by filtration pump. [8]
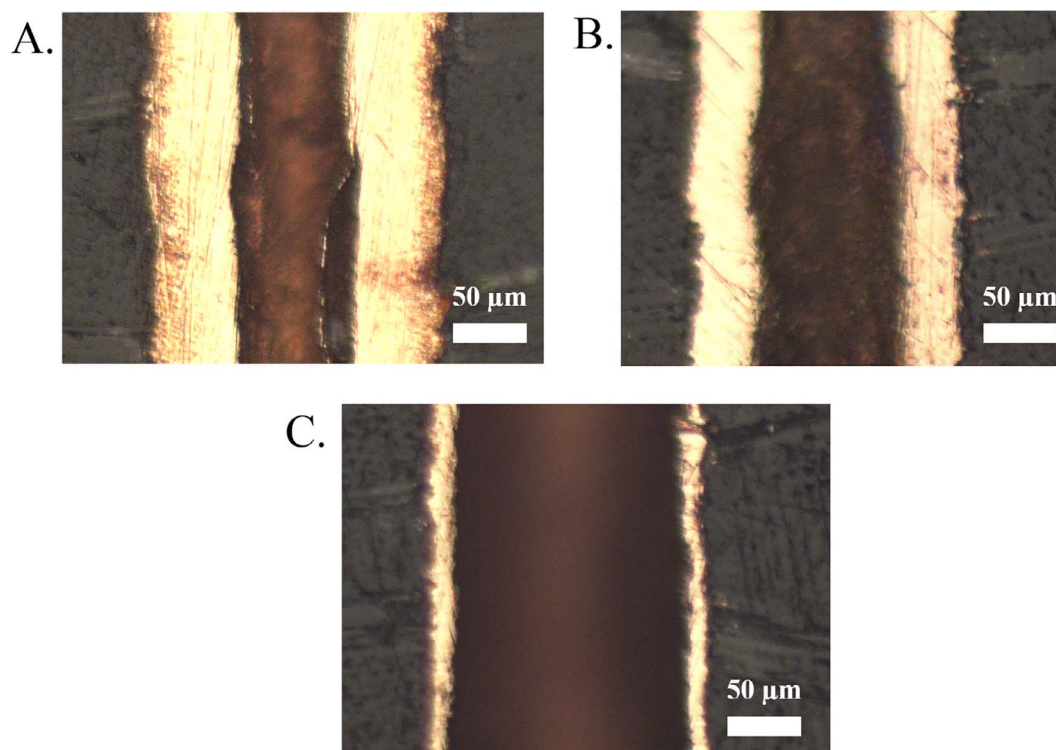
Fig. 4. Microsections of the Cu thickness in the middle of 0.175 ± 25 µm diameter, ar 5.7:1 THV, deposited at 0.5 A/dm² for 16 h under conditions of A) 450 W MS, B) Pulsed acoustic and C) no agitation.
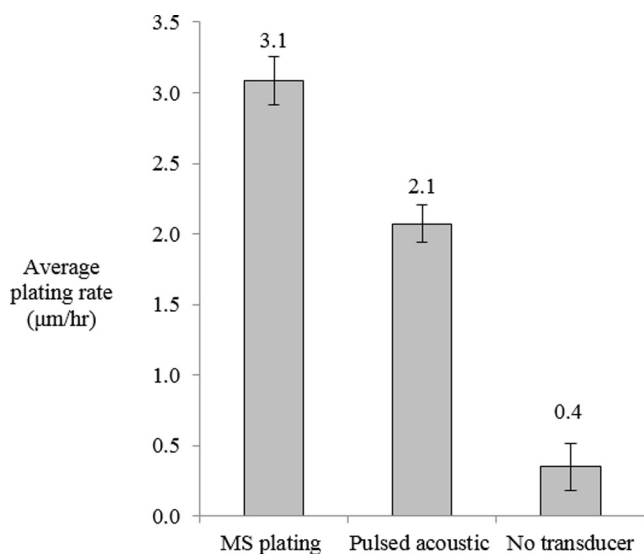

Fig. 5. Average plating rate evaluated from ten measures of Cu thickness taken in the middle of 0.175 mm diameter, ar 5.7:1 THV.

4.4. Experiment 4: Blind-via plating

The BV MS plating investigations in [10] reported a uniform filling of Cu down a 0.1 mm diameter, *ar* 3:1 BV. In an attempt to reproduce the previous literature findings and to reduce the variation in the measurement of the average plated thickness, MS–assistance plating trials were performed to plating conditions outlined in Table 2. MS plating trials were performed with no agitation, standard and 450 W MS. Microsection images of the plating results are displayed in Table 3 for a 0.20 mm diameter BV with *ar* 1:1 and 2:1. With no agitation, little Cu was deposited down the BV and the neck of the BV failed to close. With standard agitation, a larger thickness was deposited down the via

and the entrance of the BV closed. With MS agitation, a significant increase in Cu was observed within the BV, characterised by a minimum voiding in the centre of the BV. The results clearly highlight that with MS the plating, performance increases down the BV beyond the current capability. This was likely due to increased replenishment of electrolyte down the BV because of the enhanced forcing of solution by acoustic streaming mechanisms. The 1:1 *ar* BVs displayed voiding within the vias. This was expected due to the non-filling chemistries applied during the BV plating trials.

The plating behaviour was analysed down 2:1 *ar* BV plated under MS agitation. With MS, the amount of Cu deposited down the 2:1 BV increased, compared to the result obtained for the no-agitation setting. The Cu electroplating stopped in the BV at the point where the Cu seed layer failed to deposit in the electroless process prior to electroplating. For this reason, despite the enhancement to electrolyte replenishment observed with MS, plating failed to occur at the bottom of high *ar* BVs and was unable to reproduce results obtained in [10].

The plating thicknesses were measured in the bottom of the BV for different diameters and agitation settings and an average plating thickness was plotted on Fig.8 along with their standard deviations included as error bars. Statistical analysis was performed on the data. A Levene's test, performed to test for homogeneity, found the data to be nonhomogeneous despite logarithmic transformations being applied to it. The plated thickness was then compared with the different agitations settings and BV diameters by using the two-factorial Scheirer-Ray-Hare test [51].

The different agitation settings produced statistically significant results between the sets of data ($p = 3.9 \times 10^{-9}$) highlighting that a different plating response could be obtained when changing the agitation. There was no significant statistical difference ($p = .36$) between the different agitation settings and the different via diameters (plating agitation × blind via diameter), which indicated that via diameter had not had a significant effect on plating rate for the different agitation settings. The two BV sizes were comparatively similar, therefore the dynamics influencing deposition such as fluid circulation would not be
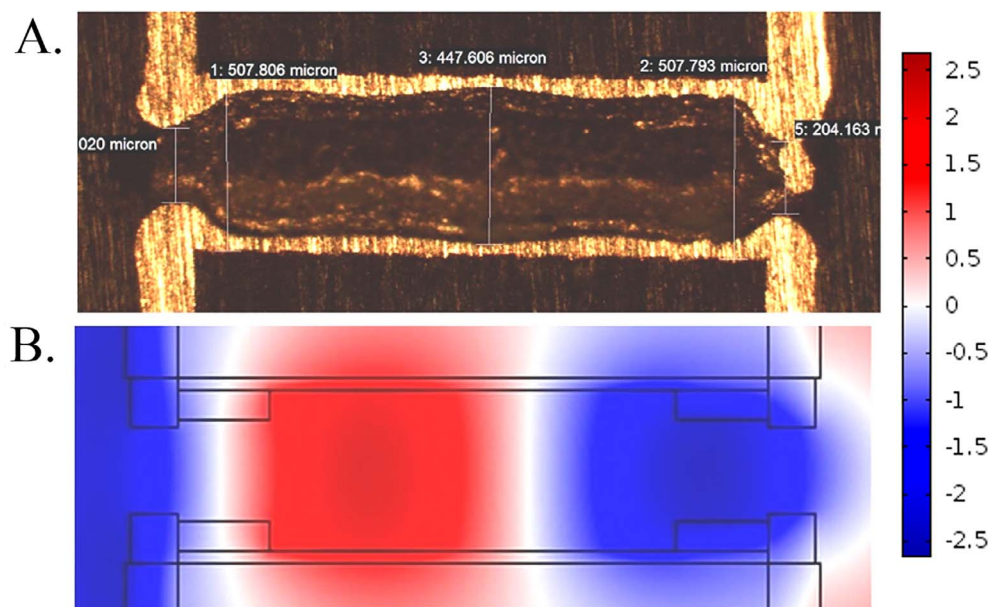
Fig. 6. A) 0.500 ± 25 μm diameter THV after MS plating and B) 2-D COMSOL simulated acoustic pressure distribution of cavity of comparable size. Scale bar for simulation showing normalised units of acoustic pressure.
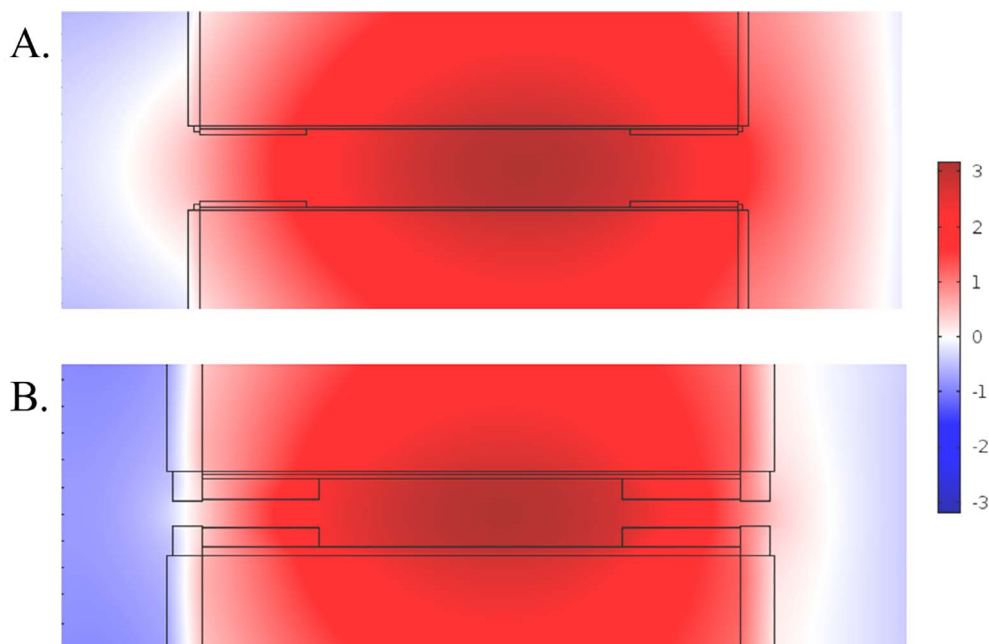

Fig. 7. COMSOL acoustic scattering simulations of 0.15 mm diameter, ar 5.7:1 for A) little Cu and B) thick Cu. Scale bar for simulation showing normalised units of acoustic pressure.

significantly altered, contributing to the effect observed.
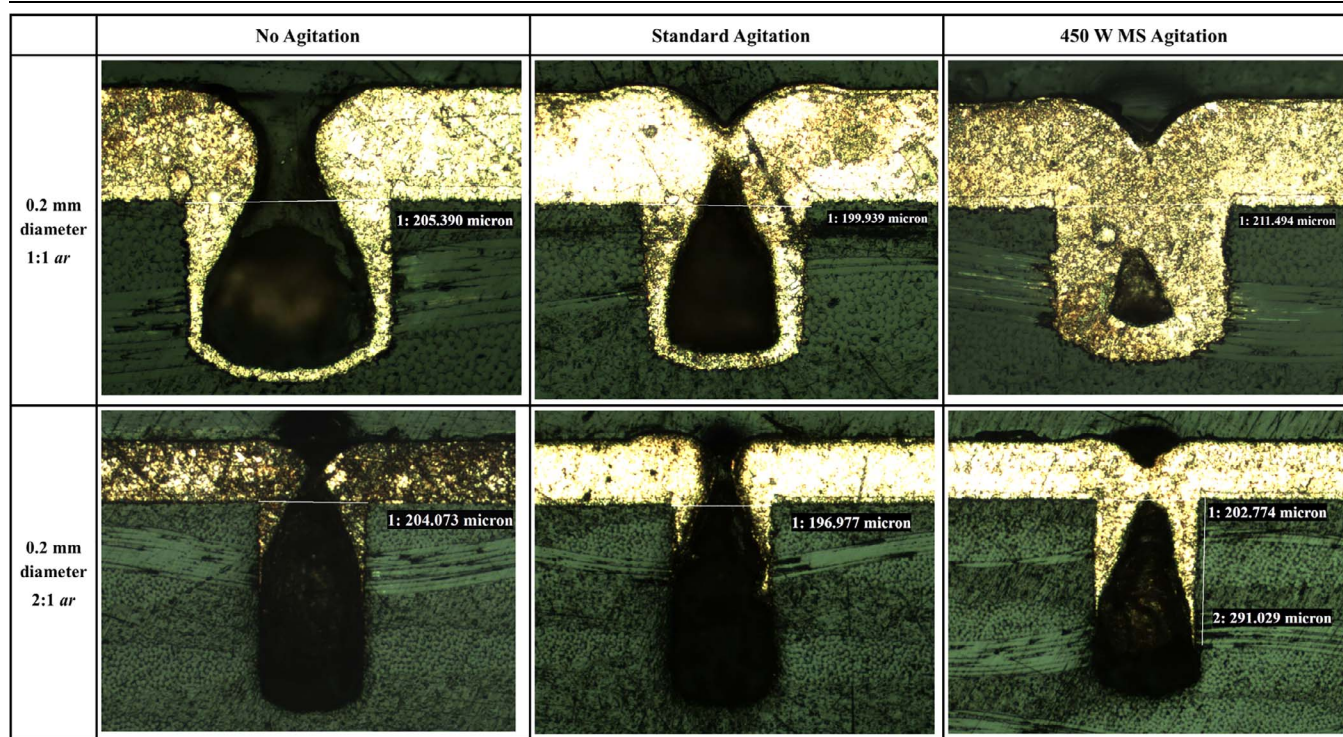
The data for the two diameters were averaged and the values displayed in Table 4 along with their standard deviation. These results show that the MS agitation increased the plating rate at the bottom of the BV by approximately 280% and 60%, compared with none and standard agitation settings, respectively. MS agitation enhances the replenishment of depleted electrolyte in the small microcavities compared to existing techniques. The replenishment is likely due to increased streaming forces. The exact mechanism behind the forcing of solution due to MS is uncertain. Evidence for standing wave undulating patterns were not observed within the BV cavity as in the THV cavity. Additionally, changes to the cavity diameter and depth did not appear to alter the performance, although the two sizes investigated were similar and so a vast change in plating behaviour would have been unlikely.

COMSOL simulations were performed down BV of diameter 0.2 mm for ar 1:1, 2:1 and 3:1 as displayed in Fig. 9. The simulation was set up

with the acoustic wave travelling from left to right into the BV. Within the ar 1:1 BV in B, a pressure antinode is formed. The harmonic of the acoustic mode is less distinguishable, as the entire cavity comprises of a pressure antinode - highlighted by a uniform blue colour. The harmonic modes formed within a BV should differ than the modes formed within the THV due to the geometry arrangements of the vias – the BV being a single-sided open tube and the THV being a double-sided open tube. For increases to BV depth the formation of a pressure node becomes more apparent within the centre of the cavity, which is clearly defined by white under the 3:1 ar in D.

The simulated results provide further evidence of the differing acoustic harmonics formed within vias of differing size. An enhancement to MS plating was obtained with the configuration highlighted in B. It is difficult to MS plate down BVs of higher ar due to the lack of an electroless Cu seed layer formed at the bottom of BV. The seed layer is not formed down high ar features using electroless plating, due to the effective viscous forces encountered in the microfeatures like in the

Table 3

Microsection images of 0.20 mm diameter BVs of different ar, RP plated at 1:3 A/dm^2 for 12 h, with different agitation settings.

	No Agitation	Standard Agitation	450 W MS Agitation
0.2 mm diameter 1:1 *ar*	1: 205.390 micron	1: 199.939 micron	1: 211.494 micron
0.2 mm diameter 2:1 *ar*	1: 204.073 micron	1: 196.977 micron	1: 202.774 micron / 2: 291.029 micron

electroplating process. For this reason further MS investigations are worthwhile for electroless Cu plating solutions to improve the Cu seeding of the BV. If successful, the likelihood of obtaining MS electroplating down BVs of *ar* 3:1 would be greatly increased.

5. Conclusions

Changes to the diameters and *ar* of PCB vias revealed a range of MS plating behaviours unique to MS processing. Down THV, for diameters larger than 0.3 mm, acoustic standing waves hindered the motion of fluid into the interconnect preventing Cu deposition from occurring. At smaller diameters, the plating behaviour altered and enhancement was

Table 4

The average plated thickness for plating settings.

Plating Setting	Average Plated (μm)	Population Standard deviation (μm)
No agitation	9.2	2.3
Standard agitation	21.3	2.8
MS agitation	35.2	8.9

witnessed. The result was attributed to changes in both the acoustic harmonics formed within the THV cavity and the microstreaming currents produced for the different harmonics. The 1st harmonic mode formed for an open-ended pipe was identified as the ideal configuration
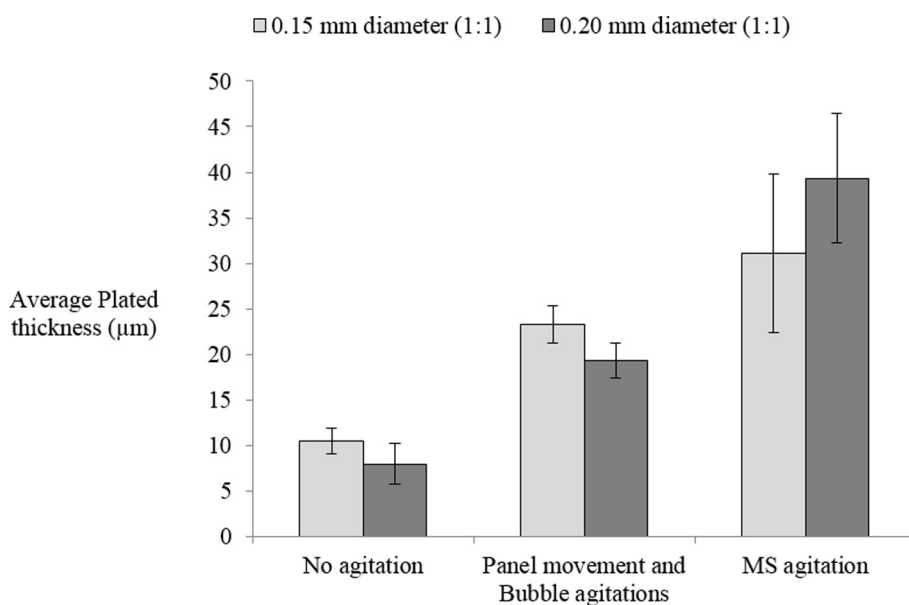
Fig. 8. Average plated thickness evaluated from ten thickness measures taken from the bottom of BVs after 12 h RP plating, under different agitation conditions.
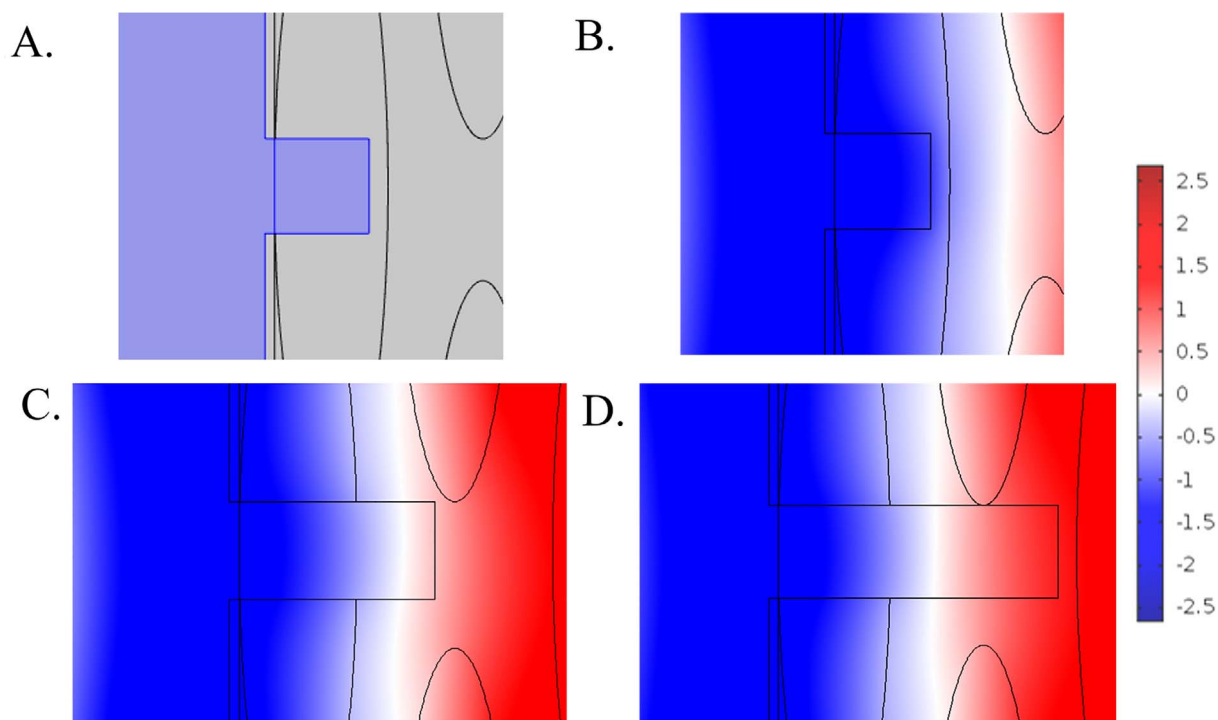
Fig. 9. A) 2-D schematic of simulated area with blue showing fluid region and gray PCB substrate with BV. Simulated COMSOL acoustic pressure distributions for 1 MHz acoustic wave induced left to right into BV cavity of diameter 0.2 mm and ar B) 1:1C) 2:1 and D) 3:1. Scale bar for simulation showing normalised units of acoustic pressure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

for MS-assisted plating. To successfully MS plate down any THV of particular diameter and *ar,* it is proposed that an acoustic frequency be introduced which forms a 1st harmonic within that THV. Simulations using COMSOL could be made to identify the required frequencies.

Plating enhancements beyond the current capability of a PCB manufacturer were obtained down BV interconnects of diameters 0.20 mm and 0.15 mm *ar* 1:1. Results obtained in laboratory settings were not reproduced on BV of *ar* 3:1 – although a method introducing MS-agitation into electroless Cu plating may lead to improved Cu seeding, providing the foundations for high *ar* BV MS plating. With these changes, the realisation of process cost savings and technological improvement to PCB interconnect density will be within closer reach.

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