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The penetration of acoustic cavitation bubbles into micrometer-scale cavities

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ABSTRACT

The penetration of acoustically induced cavitation bubbles in micrometer-scale cavities is investigated experimentally by means of high-speed photography and acoustic measurements. Micrometer-scale cavities of different dimensions (width = 40 μm, 80 μm, 10 mm and depth = 50 μm) are designed to replicate the cross section of microvias in a PCB. The aim here is to present a method for enhancing mass transfer due to the penetration of bubbles in such narrow geometries under the action of ultrasound. The micrometer-scale cavities are placed in a test-cell filled with water and subjected to an ultrasound excitation at 75 kHz. A cavitation bubble cluster is generated at the mouth of the cavity which acts as a continuous source of bubbles that penetrate into the cavity. The radial oscillation characteristics and translation of these bubbles are investigated in detail here. It is observed that the bubbles arrange themselves into streamer-like structures inside the cavity. Parameters such as bubble population and size distribution and their correlation with the phase of the incident ultrasound radiation are investigated in detail here. This provides a valuable insight into the dynamics of bubbles in narrow confined spaces. Mass transfer investigations show that fresh liquid can be continuously introduced in the cavities under the action of ultrasound. Our findings may have important consequences in optimizing the filling processes for microvias with high aspect ratios.

1. Introduction

Modern consumer electronics demand smaller, lighter and smarter devices which in turn implies that more and more components need to be placed on the printed circuit boards (PCB). In other words, the density of these components needs to be increased. The introduction of high density interconnection (HDI) technology has led to multi-layer packaging of the components on PCB's. This has caused a considerable increase in the number of electric connections that need to be handled. The electrical connectivity between the interconnects is accomplished by the so-called vertical interconnect access [1–4], or microvias. The major processes for creating microvias are laser drilling [5,6], mechanical drilling, photoimaging [7,4] and wet/dry etching [4]. Filling of microvias is one of the critical steps in the manufacturing of multilayer PCB's. With increasing demand for miniaturization the number of packaging layers has increased, thereby leading to manifold increase in the aspect ratio (height to diameter) of vias.

The most preferred technique for filling microvias is electrodeposition of metal (e.g., copper) from an electrolyte solution [8–12]. Generally, this is a two step process where a thin layer of copper is first seeded in the microvia by electroless copper deposition followed by electroplating in order to increase the thickness of the fill. However, as the aspect ratio increases, it becomes hard to ensure void-free and uniform deposition of copper seed layer by this method. In case of high aspect ratio microvias, the difficult hydrodynamic conditions and non-homogeneous distribution of current density at the mouth of the cavity lead to reduced convection in the electrolytic solution near the surface of the substrate. As a result, the ion concentration in the solution reduces within the immediate proximity of the microvia [13–15]. This leads to an increase in the Nernst diffusion layer [16] and reduction in the deposition rate of the metal. One of the approaches to overcome this limitation is to make use of inhibitors, accelerators and other chemical additives that enhance the deposition of cupric ions at the bottom of the microvias [17]. Another approach is to increase

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the convection by forcing flow of fresh electrolyte in the microvia. Kaufmann et al. [15] have used high frequency acoustic streaming at 500 kHz to increase agitation next to the surface of the microvia. They showed that this leads to a reduction in the Nernst's diffusion layer. Consequently, higher deposition rates and void-free filling can be achieved by megasonic agitation. Strusevich et al. [14] carried out numerical simulations to verify whether acoustic streaming is responsible for the improved ion transport into the micro via. Their findings show that although acoustic streaming does not take place within the micro-via, it enhances cupric ion transport in the immediate vicinity of the via. They could not conclude whether acoustic streaming is the only phenomenon accompanying megasonic agitation which leads to improved ion transport and thus mentioned the need to investigate other factors such as the effect of resonant bubbles, thermal effects, etc.

In the current work a method using ultrasound and acoustic cavitation has been proposed for improving the mass transfer in the microvias. The concept, as shown in Fig. 1, is that if the bubbles created due to acoustic cavitation are able to penetrate the cavities with higher aspect ratios, they would carry fresh liquid with them. In addition to penetration, these bubbles would generate a subtle microstreaming flow [18,19] in their vicinity. Thus the liquid next to the bubble would be set into motion. If this process takes place at the mouth of the cavity, this would lead to continuous replenishment of electrolyte containing cupric ions. If a bubble cluster containing large number of bubbles is formed at the mouth of the cavity, sufficient liquid recirculation may be induced as a combined effect of all the bubbles in the cluster.

A liquid contains many impurities in the from of microbubbles or fine particles. Similarly, air is trapped in the micro-cracks or crevices in the vessel containing the liquid [20–22]. When such entities are exposed to ultrasound radiation, they grow during the negative part of the pressure cycle and form cavities. At the given ultrasonic excitation frequency these cavities undergo nonlinear oscillations. These oscillations can be classified as stable or transient depending upon their lifetime. Stable bubbles oscillate around their equilibrium radius for multiple acoustic cycles, whereas the transient bubbles undergo a violent collapse within one acoustic cycle. Due to the violent nature of their collapse, the occurence of transient bubbles should be minimized. This is achieved by using higher ultrasound and lower power. At high frequencies, the time scales are so short that the bubbles do not have sufficient time to get larger and thus hardly reach the collapse phase.

The present work has been carried out in order to verify the hypothesis mentioned above that acoustic cavitation bubbles would enhance mass transfer in the microvias and thus ensure uniform filling with desired thickness. High speed visualizations have been carried out in order to understand the dynamics of acoustic cavitation bubbles in micrometer-scale cavities. Similarly, extent of penetration of these bubbles into the cavity has been studied along with the possible improvement in the mass transfer.

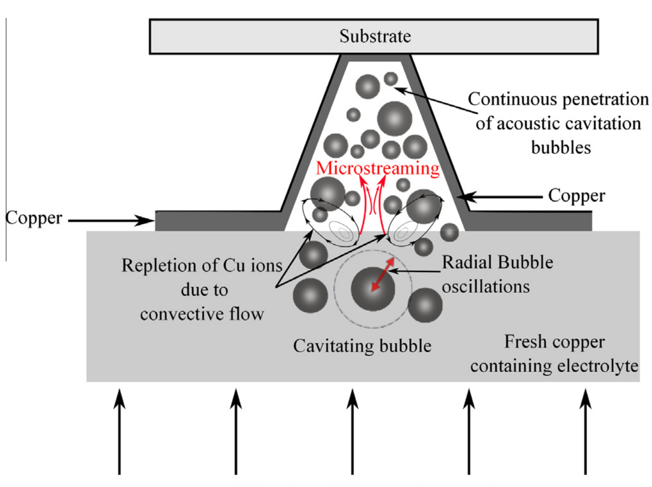

Fig. 1. Mechanism of improved convective flow due to ultrasound.

2. Materials and methods

2.1. Test setup for generating acoustic cavitation bubbles

The experiments were carried out in a transparent cylindrical Plexiglas cell with 50 mm inner diameter and a height of 100 mm. In order to get aberration-free images a piece of the curved surface was milled out as shown in Fig. 2 and a 1 mm thick Plexiglas sheet was glued instead. The details regarding the driving electronics, transducer input waveform and acoustic measurements using the hydrophone have been presented elsewhere [23].

2.2. Construction of the micrometer-scale cavities

In order to replicate the microvias, a simple construction was used here, as shown in Fig. 3(b). Thin stainless steel foils, 50 μm in thickness, and with laser-cut recesses of different widths as shown in Fig. 3, were placed between two microscope glass slides. The glass slides were then sandwiched between steel plates and fixed by screws, as shown in Fig. 3(b). Table 1 shows the dimensions of the micrometer-sized cavities which were used to replicate the microvias. For the sake of simplicity, there cavities were named as Cavity A, Cavity B and Cavity C respectively.

2.3. Driving parameters

A cylindrical piezoelectric continuous-wave Langevin-type transducer ($\phi = 25.4$ mm and height = 26 mm) with a resonant frequency of 75 kHz was used in the current work. Stably oscillating bubbles are created at this frequency. More details have been provided in our previous work [23].

2.4. Experimental conditions

The test-cell was filled with Ultrapure water (Conductivity $\leqslant 1.1$ μS/cm, Biochrom AG, Germany) and the micrometer-sized cavity arrangement was immersed in it as shown in Fig. 2. The size of the cluster varied with the water level in the cell as well as the position of the cavity. These parameters were chosen in such a way that maximum cavitation activity could be attained at the edge of the cavity. The size of the hemispherical cluster was used as an indicator for the cavitation activity.

2.5. Hydrophone measurements

The details of hydrophone measurements have been provided in our earlier studies [23]. The pressure distribution in the setup as well as the hydrophone characteristics have been described there. The micrometer-sized cavities were placed along the acoustic axis in the test-cell in such a way that their edges coincided with the position of maximum acoustic intensity. The bubble clusters were observed only at this position, with any further deviation leading to their disappearance.

2.6. High-speed imaging

Owing to the extremely small time-scales involved in the process, a high-speed IS-CCD camera (HPV-2, Shimadzu Deutschland