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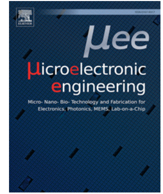

Research paper

Dynamics of filling process of through silicon via under the ultrasonic agitation on the electroplating solution

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ABSTRACT

Through-silicon-via (TSV) connection is a promising technology to provide more effective and faster data processing in integrated-circuit (IC) devices. In this study, via-filling processes with the direct ultrasonic agitation, the effects of additives (accelerator, suppressor and leveler) and different current densities are investigated. Microvias with a diameter of 20 μm and a depth of 65 μm is used in the electrodeposition process. The dynamic evolution of the via-filling process activated by ultrasonic under different current densities is obtained by scanning electron microscopy. It is found that the application of ultrasonic agitation can change the deposition rate of copper ion at the via and improve the filling process to obtain void-free TSVs. Under the action of ultrasonic agitation, the via-filling process under the condition of low, middle and high current density are explored to realize the "V" type filling, "U" type filling, void filling, respectively. In addition, the filling ratio and filling speed of copper in the vias under different conditions are also analyzed in this work.

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1. Introduction

In the next generation of IC packaging technique, three-dimensional (3D) integration has become a major focus for more effective and faster data processing in integrated-circuit (IC) devices. Three-dimensional integration is mainly achieved by interconnecting vertically stacked chips using through-silicon-via (TSV). In this process, Cu is considered as an excellent material due to its high electrical conductivity and cost-effectiveness. Nowadays, copper electroplating is widely practiced and plays an important role in the process of filling the microvias. Nevertheless, problems still exist in this approach, of which the most critical one is the existence of seams and voids during the TSVs filling process.

To avoid the possible reliability problem or unstable performance at high frequency caused by such micro defects, the via-filling process to fabricate void-free TSV is investigated [1–6]. It is known that superfilling (bottom-up filling) is an accepted filling performance to fulfill this purpose. To realize the superfilling, a common chemical method is to add additives into the plating bath to modulate the performance of the copper electrodeposition in vias. The additives such as suppressor, accelerator, and leveler, which are absorbed on the electroplating surface, are used to change the current density distribution in the vias to achieve the bottom-up filling [7–11]. In addition to adding additives, physical methods are also adopted in superfilling, such as using pulsed current [12–14], applying ultrasonic field to improve the filling process. The ultrasonic agitation improves mass transport [15] inside vias and decrease the concentration gradient of reactants within via to avoid the formation of voids or seams. Chen et al. investigated the copper electroplating with the assistance of ultrasonic agitation and found that, ultrasonic agitation has the potential to facilitate the formation of void-free TSV with a high aspect ratio [16]. Moreover, the fabrication of the nanostructures assisted by the ultrasound is studied by Phuruangrat [17]. So far, there are few reports about the effect of ultrasonic agitation combining the effects of additives on the filling process of TSV.

In this work, a novelty method for the TSV filling process with the direct ultrasonic agitation on the electroplating solution with additives is explored. With the same current density and plating conditions, the application of ultrasonic agitation can change the deposition rate of copper ion in the via, improve the TSV filling ratio, and realize bottom-up filling. Under the action of ultrasonic agitation, the dynamic via-filling process under the different current densities is explored. The “V” filling could be achieved at low current density (0.002 A/cm^2), and the “U” (conformal) filling can be achieved at middle current density (0.005 A/cm^2). At high current density (0.008 A/cm^2), the via is pinched off and a large void is formed.

2. Experimental

In this experiment, a small piece of silicon which is cut off from a silicon wafer containing micro-vias is used as a cathode fixed on the electrochemical platinum electrode clamp (Xuzhou Zhenghao Electronic

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Technology Co. Ltd.). The internal surface of the silicon wafer and the blind via is covered with a thin copper layer. The piece size is 1 cm in width, 2 cm in length. The diameter of the via on the piece is 20 μm and 65 μm in depth. A planar copper containing phosphorus with an area of 33 cm^2 is as an anode immersed in electroplating solution. The precision power (Agilent B2901A) is used to supply a direct current. The ultrasonic horn of the ultrasonic processor (Shang Chao Pai) is used to apply ultrasonic wave propagated by longitudinal motion to the plating bath. As shown in Fig. 1, the plating bath used in the experiment is Haring cell with 25 cm in length, 8.5 cm in width, 12.5 cm in height and 0.5 cm in thickness. The anode is fixed on one side of the plating bath, while the cathode clamp is fixed in the center of the bath and the distance between them is 5 cm. The distance between the cathode and the upper surface of solution is 1 cm. The ultrasonic horn through the middle bracket is fixed on the rod between the cathode and the anode. The ultrasonic horn's bottom is immersed in the solution with 4 cm in depth (The volume of plating solution is 1 L). In this experiment, the composition of copper electroplating solution contains: 195 g/L $CuSO_4 \cdot 5H_2O$ (Sinopharm Chemical, China), 49 g/L H_2SO_4 (Sinopharm Chemical, China), 0.05 g/L NaCl (Sinopharm Chemical, China), 0.01 g/L MPS (Mengde, China) as accelerator, 1.5 g/L PEG (Mw. 6000, Mengde, China) as suppressor, and 0.02 g/L PN (Mengde, China) as leveler. The reagents of the plating solution maintain the optimal concentration combination according to our previous experiments. The solvent is deionized water and the experiment is carried out at room temperature.

It is worth noting that before the experiment starts, the silicon wafer should be pretreated as the following process. Firstly, electrode holders are used to clamp the silicon piece containing blind vias and it is all immersed into deionized water in the beaker. Secondly, the silicon piece containing blind vias is put into a vacuum device for pumping vacuum processing. When the vacuum degree reaches −15 kg/cm^2, the condition is maintained for 5 min. At this point, bubbles are observed on the silicon wafer. Thirdly, an ultrasonic cleaning machine is applied to clean the silicon wafer for 5 s by immersing it in the deionized water to make the wafer surface free of obvious bubbles. The second and third steps are repeated for 3 to 4 times, until no bubbles can be found on the surface of the silicon wafer. At the beginning of the experiment, the silicon wafer with vias (cathode) is soaked in the electroplating solution for 15 min. The solute is diffused into the vias, which makes the solute concentration be relatively balanced in and out of the via. After the silicon wafer is fully soaked, the precision power and ultrasonic processor are switched on to supply power and ultrasonic wave, and the time is recorded. In this experiment, the current densities are set to 0.002 A/cm^2, 0.005 A/cm^2, and 0.008 A/cm^2; the ultrasonic power is set to 60 W; the frequency is set to 20 kHz. For different current densities, the corresponding electroplating time is also different. When the current density is 0.002 A/cm^2, the plating time is 0.5 h, 1 h, 1.5 h, 2.5 h, and 5 h, respectively. When the current density is 0.005 A/cm^2, the plating time is 15 min, 30 min, 45 min, 60 min, and 90 min, respectively. When the current density is 0.008 A/cm^2, the plating time is 10 min, 20 min, 30 min, 45 min, and 60 min, respectively. When the plating is completed, the silicon chip is sealed out by resin. Its surface is then cleaned with water and blown to dry immediately. After the solidification of the resin, a lapping and polishing machine is used to polish samples to obtain the maximum cross-section of vias. Then, the samples are immersed in alcohol and cleaned with the ultrasonic cleaning machine until no copper debris exists in the hole. Finally, SEM pictures of the samples are taken for further observation and analysis.

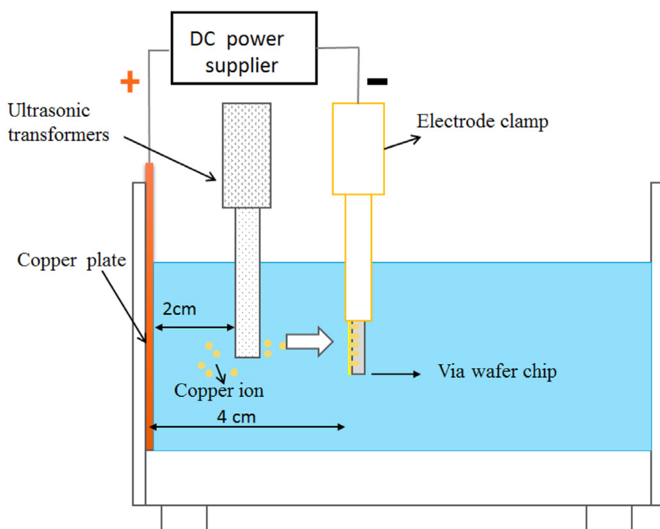

Fig. 1. Electroplating system with ultrasonic agitation.

After electron microscope image is obtained through SEM, the filling ratio is calculated by image processing technology. MATLAB is used to process the obtained data. In order to describe and analyze the experimental results accurately, the filling ratio and the filling growth ratio are defined as follows:

Filling ratio

$$M_i = B/(B_i + S_i) \quad (1)$$

Filling growth ratio

$$V_i = (M_i - M_{(i-1)})/(T_i - T_{(i-1)}) \quad i \gg 1 \quad (2)$$

where S_i is the unfilled area in vias and B_i is the filled area in vias as shown in Fig. 2.

3. Results and discussions

3.1. Comparing of TSV filling with and without ultrasonic

When no ultrasonic wave is applied during the filling process, the current density is set to 0.002 A/cm^2, 0.005 A/cm^2, 0.008 A/cm^2 respectively and the plating time is 5 h. The profiles of the filled TSVs using different current densities are shown in Fig. 3. When the current density is

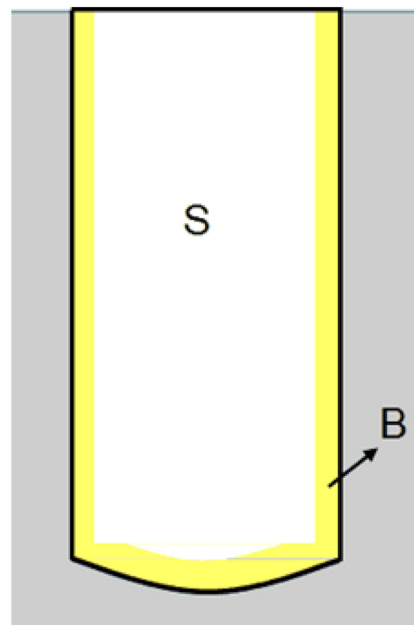

Fig. 2. Definition of the filled area "B" and the unfilled area "S" in cross-section of TSV filled by Cu.

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