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High-Speed Copper Filling within High Aspect Ratio Through Holes in Polymer Substrates

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In this work, we presented a "bottom-up" and a "two-step" electrodeposition formulas for copper filling within high aspect through polymer holes (TPHs), which are needed for integrating flexible bio-micro-electro-mechanical system (bio-MEMS) sensors with conventional CMOS circuits. By using the "two-step" electrodeposition formula, a void-free copper filling is successfully realized for TPHs with the diameter of 20 μm and height of 125 μm in a common plating solution. The void-free filling effect was attributed to the preformed "V" profile after the first-step deposition. The filling time is reduced by about 80% than that of the "bottom-up" filling formula. The results suggest that the "two-step" deposition mode can be a potential solution to the long time of the through polymer holes filling.

Keywords: Through polymer holes (TPHs); TSV; MEMS; 3D packaging; Electrodeposition; Hole filling.

1. INTRODUCTION

For the last two decades, polymer materials have been gaining more attention in micro-electro-mechanical systems (MEMS) technology for bio and medical applications, because their advantages over silicon material including lower stiffness and better biocompatibility for implantable applications, and excellent flexibility for applications where the MEMS devices are directly in contact with the elements, such as smart skins for tactile and flow sensing [1-5]. However, the integration of bio-MEMS devices with silicon structure and electronic circuits is still remaining an unsolved challenge. One major reason is that many bio-MEMS devices should be accessible for gases and even fluids. One important solution is to use through substrate via structure for achieving vertical electric interconnection but still keeping electronics circuits from outsides [6].

Three-dimensional integrated circuitry (3D-IC) with through silicon via (TSV), is a promising technology to obtain vertical electric interconnection and thus high packaging density, faster signal transmission, and lower power consumption [7-9]. Complicated high density interconnection (HDI) flexible polymer substrates are experiencing a strong demand for advanced applications such us implantable medical devices. To create such a flexible HDI circuit, a multilayer construction is needed, where each polymer film layer is aligned and bonded along Z direction [10]. Therefore, the through polymer holes (TPHs) technology is thought to be one solution for integrating the polymer-based bio-MEMS devices including those used in fluids with electronic circuits by the formation of vertical electric interconnection.

The holes density and aspect ratios of the TPHs are becoming higher because bio-MEMS sensors are becoming smaller and often used in array configurations. Similarly to the TSV technology, the metal filling of holes will be a core technique for the application of TPH. Although it is well documented for the metal filling of TSV, there are few literatures available for that of TPH structure especially with the diameter less than 30 μm and the aspect ratio of higher than 5. It is known that the effectiveness of the metal filling of holes or via hinges on the ability to generate a defect-free feature [11-14]. The successful filling experiences for through silicon holes (TSHs) by electrodeposition process could be proposed for the TPH [13, 15-18]. Among of them, a “bottom-up” electrodeposition mode was used to obtain a perfect void-free filling, where a conductive template was fabricated as seed layer at the bottom. The shortages of this process were the very low filling speed and the difficulty to remove the assisted template wafer. Recently, it was also reported that a void-free filling was obtained in the TSHs with a seed layer on sidewall by means of selective organic additive in solution [17-19].

In this work, we explored the void-free filling for the through polymer holes (TPHs) array using a common plating solution. A "bottom-up" deposition was performed using a simple and low-cost conductive template fabrication method. In contrast, a "two-step" deposition was developed to realize a void-free filling effect and a high filling speed.

2. EXPERIMENTAL

2.1 Fabrication of through polymer holes (TPHs)

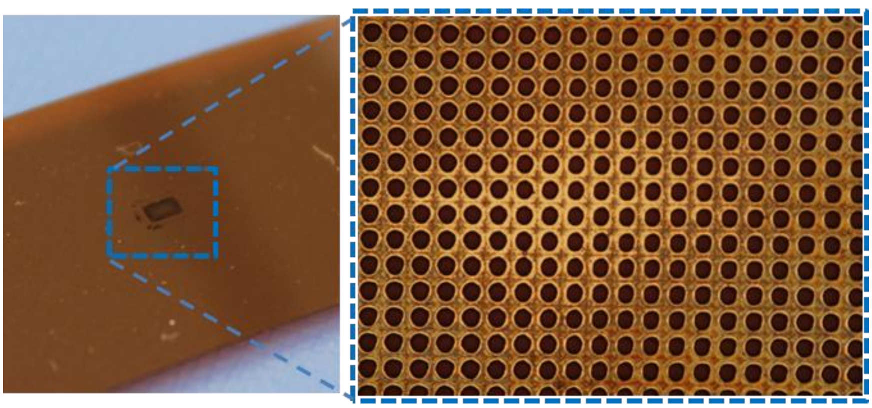

Figure 1. Through polymer hole unit fabricated by laser drilling.

Polyimide sheet with a thickness of 125 μm was used as the substrate. The through polymer holes were micro-fabricated by laser drilling process. Every unit consisted of the holes array of 20×30, in which the diameter of the hole was 20 μm and the pitch was 60 μm, as shown in Figure.1. The TPH unit was ultrasonically cleaned to remove the residues from fabrication process.

2.2 Two electrodeposition filling formulas

Two electrodeposition formulas were employed for filling TPH unit. One formula was defined as "bottom-up" filling mode, as illustrated in Figure.2.

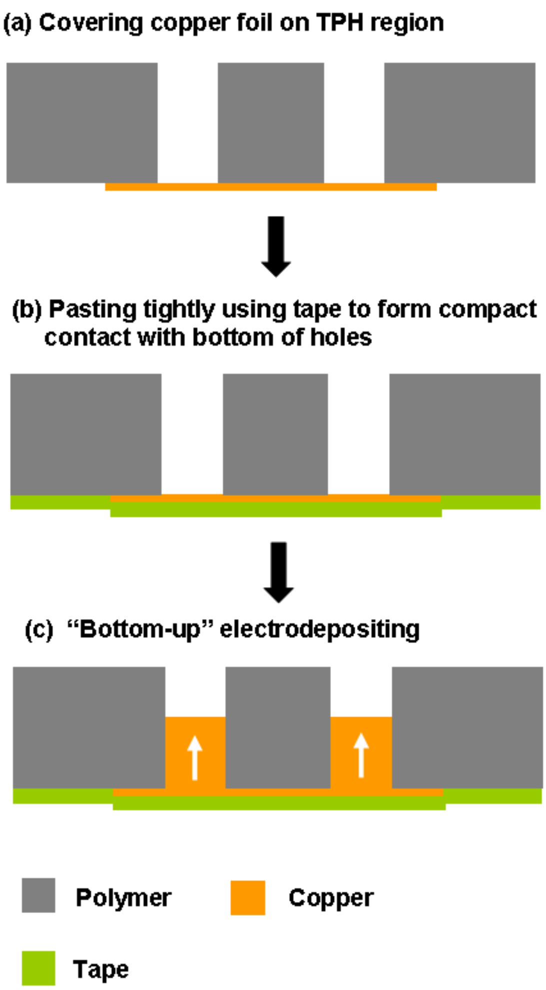

Figure 2. Schematic process of "bottom-up" electrodeposition for filling of through polymer holes (TPHs).

In this process, a commercial copper sheet with a thickness of 20 □m was selected as the metal template to cover the bottom of holes. Then the copper sheet was tightly pasted on the polymer substrate using a tape, so that the copper sheet had a compact contact with the bottom. The other formula was defined as "two-step" filling mode, as illustrated in Figure.3. A copper film of 0.2 □m thickness was sputtered on the back side and sidewall of the holes. Before the first-step deposition, the front holes were sealed by an insulated tape. The electrodeposition was firstly performed on the pre-sputtered side for 1 hours using a relatively higher current density until the holes entrances were completely blocked. Following that, the insulated tape on the front side was removed and the second-step electrodeposition was carried out on the front side for 2.5 hours using a relatively lower current density.

2.3 Electrodeposition and electrochemical evaluation

The electrodeposition was performed in a plastic bath with a magnetic stirring apparatus. The sample was placed at bath center as a cathode and a copper plate as anode was placed facing target side of the sample. For the “bottom-up” electrodeposition process, the direct current density was controlled to be $1A/dm^2$. During the “two-step” deposition process, the current density values were $3A/dm^2$ and $1A/dm^2$ for the first and second deposition process respectively. The plating solution was composed of 50g/L $CuSO_4$, 250g/L H_2SO_4, 50mg/L Cl^- and 2ml/L carrier. A rotating ring disk electrode (RDE) was used for electrochemical measure, where the work electrode was made of platinum, the counter electrode was made of a platinum foil, and the reference electrode was a saturated calomel electrode. The rotation disk speeds of the RDE were 0, 100, and 1000 rpm. The scanning rate was 1mA/s. After electroplating process, the cross sections of the holes were observed using optical microscopy (OM) and scanning electron microscopy (SEM) to determine the filling qualities.

3. RESULTS AND DISCUSSION

3.1 Filling through "bottom-up" electrodeposition mode

The “bottom-up” electrodeposition means that the metal deposition begins at the bottom of the hole and gradually grows upwards. The “bottom-up” electrodeposition process does not need a seed layer on sidewall, which can avoid non-uniform electrical current distribution. The core technique for the "bottom-up" electrodeposition was the fabrication of conductive template under the bottom of holes. A common method was that the wafer with holes was pasted on a seed layer deposited wafer using lithography resist, and then the seed at the bottom of hole was exposed after lithography and development process [13, 17]. But this method is not suitable for the present case because of the transparency of polymer film. The process illustrated in Figure.2 could successfully achieve such a purpose and was also relatively simple and low-cost.

Figure.4 shows the top surface morphology and cross-section microstructure of the TPH after “bottom-up” deposition. It is shown that the TPH was completely filled with copper without any void or defect. The copper growth was very uniform throughout the TPH unit. Although the sidewall surface of holes might be rough during laser fabrication process, there were not visible defects at these locations, indicating an excellent cohesive strength. However, it is noted that the deposition process spent 17 hours for this complete filling. When the higher electrical current was applied to improve filling speed, the voids tended to take place. These results demonstrated that the long time of this "bottom-up" deposition mode was a strong limit in practical application.

3.2 Filling through "two-step" electrodeposition mode

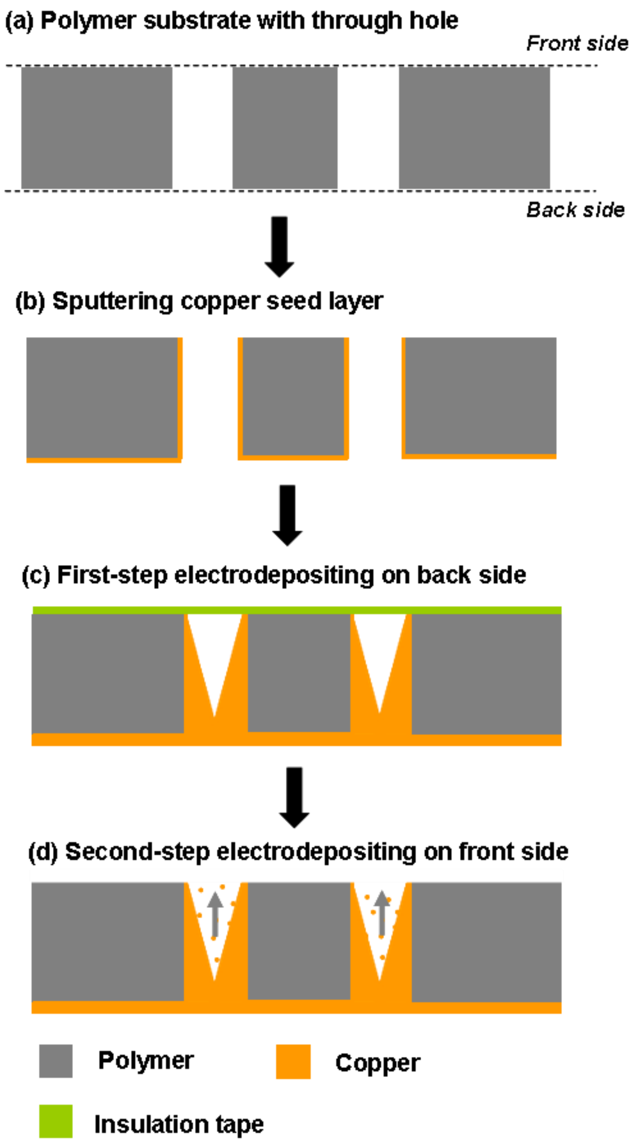

Figure 3. Schematic process of "two-step" electrodeposition for filling of through polymer holes (TPHs).

In the electrodeposition for TSV filling, the conductive seed layer was sputtered on the top surface, the sidewall and bottom surfaces of a blind via. However, the current distribution of via will be greatly non-uniform when the surface is covered with a conductive layer. The current density at the via entrance will be much higher than that at bottom. As a result, the large voids or hollow filling structure within a via will be formed before the entrance is completely sealed. This non-uniform current distribution will become severer when the aspect ratio of the hole exceeds more than 5 and opening size is below 20 μm.

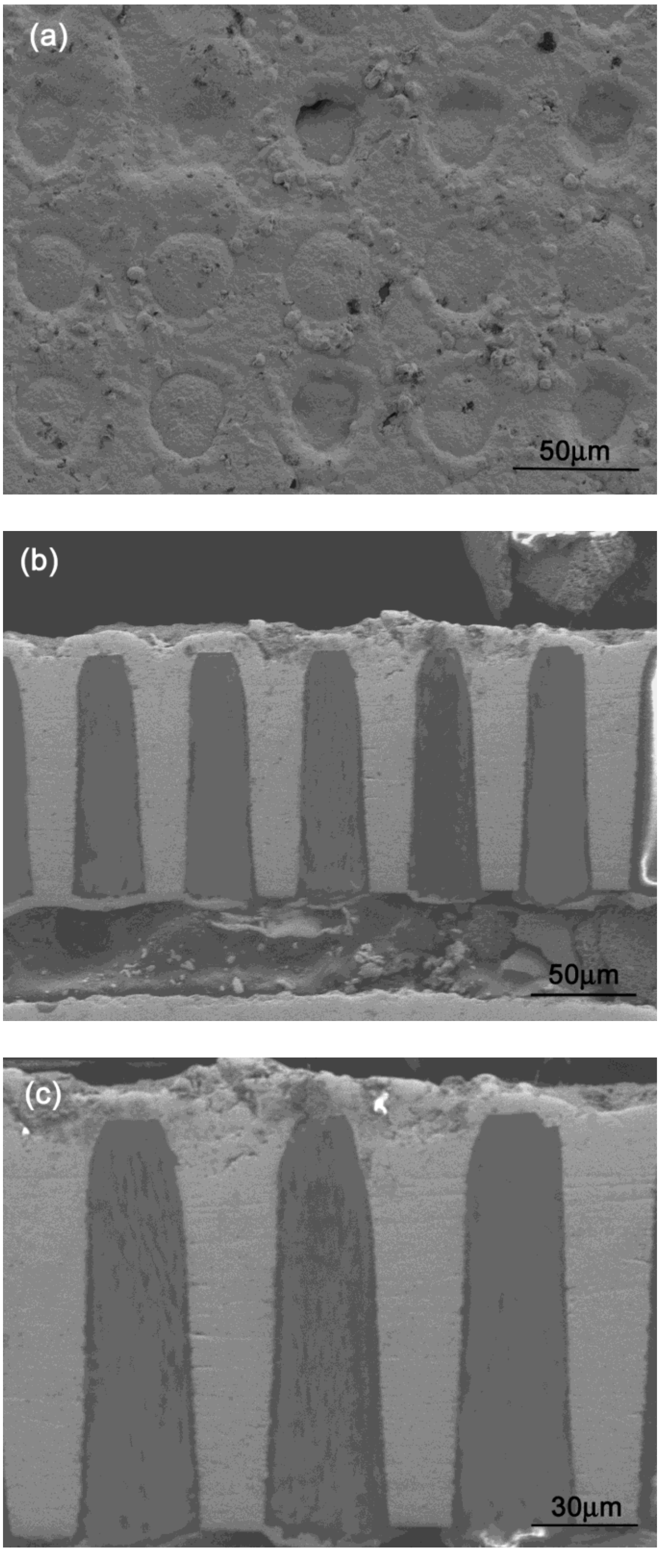

Figure 4. Surface morphology and cross-section image of copper filling after "bottom-up" deposition: (a) surface morphology, (b) cross-section image in lower magnification, (c) cross-section image in higher magnification.

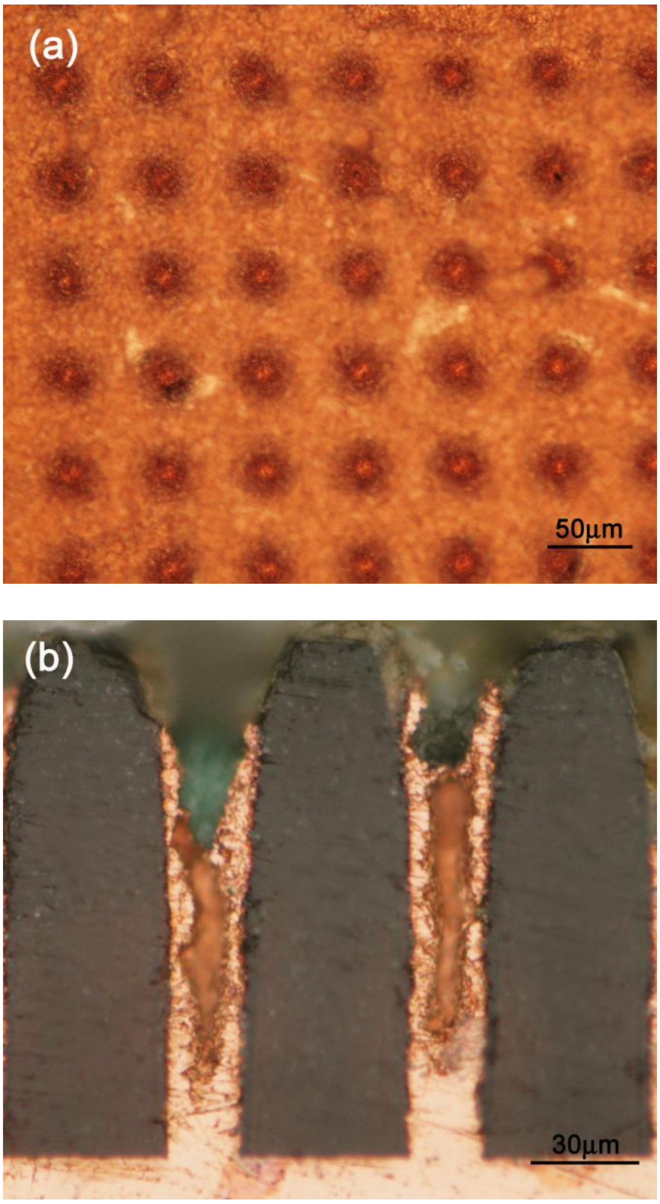

Figure 5. (a) Optical image of back side surface morphology and (b) formed "V" filling shape after first-step deposition.

For a perfect void-free filling of the via with a seed layer, the bottom-up deposition was pursued by the special additives in plating solution and the application of periodic reverse pulse current. This super-filling was often characterized with a "V" growth profile that meant that the growth speed at the entrance was suppressed and the speed at the bottom was accelerated. However, in a common electroplating process a reverse "V" filling profile will be obtained where the entrance of the via is sealed in advanced and the hollow structure is left.

As illustrated in Fig.3, a rapid deposition was performed on the back side for the below considerations. Firstly, the entrances at the bottom are blocked so that a TSV-like electrodeposition filling process can start at the front entrances. Secondly, a "V" growth profile was aimed to obtain, which is needed for a void-free filling. As expected, the highest current density occurred at the entrance and decreased from back to front side during the first-step deposition. Then a "V" filling profile was formed while the back entrance had been completely sealed, as shown in Fig. 5.

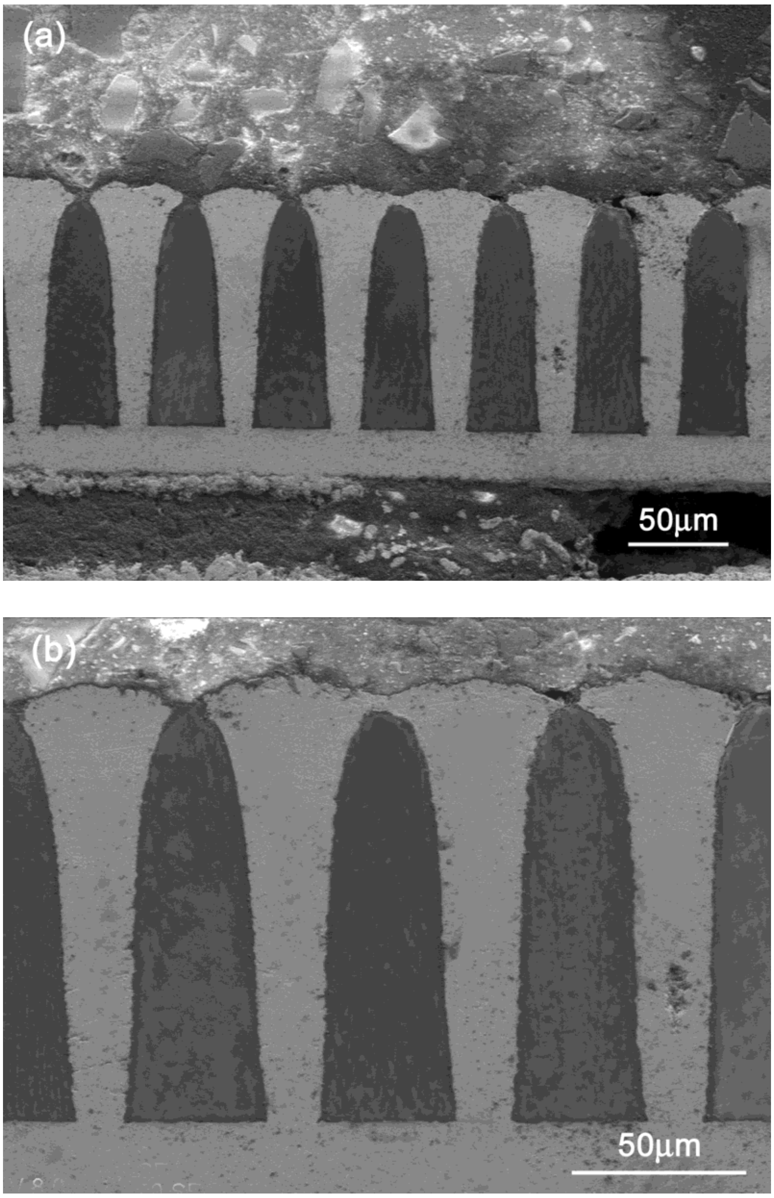

Figure 6. Cross-section image of copper filling after "two-step" electrodeposition: (a) image in lower magnification, (b) image in higher magnification.

In the electrodeposition filling process, the step coverage ratios was used as a reference value to evaluate the deposition performance [20], i.e, $r_{SC} = \frac{t_{btm}}{t_{neck}}$, where the t_{neck} and t_{btm} were the thickness near the entrance and bottom respectively. The higher value of the step coverage represents a closer bottom-up growth for void-free filling. In the second-step deposition, the formed "V" filling profile increased the step coverage value, which made it possible to fill completely at deeper location before the sealing of the entrance. Figure.6 shows the cross-section of the through polymer holes after the second-step deposition. A complete and void-free filling effect was obtained using this "two-step" deposition formula.

3.2. Electrochemical measurements

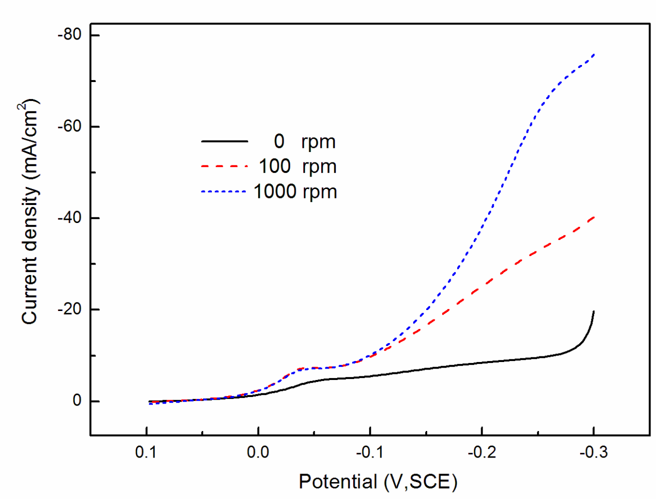

Figure 7. Potential-current density curves in plating solution at different rotation disk speeds.

The polarization curves at varied rotation speed are shown in Figure.7. The polarization curves were shifted to a much higher potential as the rotation speed increased, which suggested that the deposition speed was dominated by the ions diffusion mechanism. It can be assumed that the low rotation speed corresponds to the deeper position of the hole and the higher rotation speed corresponds to the position closer to the entrance. It is showed there is a weak suppressing effect at the entrance using this plating solution. It supports the result that the back entrances could be rapidly sealed and a "V" filling profile was formed when a large current was applied.

In the "bottom-up" electrodeposition mode, the low deposition speed could be resulted from the small contact area to the solution and the low iron diffusion rate toward the bottom. In comparison, the seed layer on sidewall greatly increased the contact area to the solution and also produced a higher irons diffusion rate toward the sidewall. As a result, the total plating time of the "two step" filling process was about 3.5 hours that is about 20% of that of the “bottom-up” filling process. The “two-step” formula can be a promising technique solution to the poor holes filling speed of traditional technique.

4. CONCLUSIONS

The "bottom-up" and "two-step" electrodeposition modes were proposed to filling the through polymer holes (TPHs). A simple and low-cost process for the "bottom-up" deposition could realize a void-free filling using a simple and low-cost conductive template fabrication process. The "two-step" deposition process used the seed layer on sidewall of holes and could realize a void-free filling in the common solution. Compared to the "bottom-up" deposition mode, the "two step" deposition reduced filling time by about 80%. During the "two-step" deposition process, the prior "V" filling profile after the first-step facilitated a void-free filling and the larger contact area to the plating solution improved the deposition speed.

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