During past decades, the fabrications of 3D microstructures and nanostructures have been attracting attention because of their applications in biosensors, gas sensors, thermal couples, and 3D integrated chips. Many processes have been proposed to produce 3D micro- and nanostructures, such as Lithographie Galvaniformung Abformung (LIGA), \(^1\) localized electrochemical deposition (LECD), \(^2\) mask projection micro-stereo lithography, \(^3\) track-etch method, and laser-assisted chemical vapor deposition (LCVD). \(^4\) Among these techniques, LECD has the advantages of being an inexpensive, mask-less, low-power, and easy-to-design technique. \(^5\)\(^-\)\(^12\) Furthermore, LECD can be applied to multiple materials such as metals, metal alloys, piezoelectric material, conducting polymers, and semiconductors. \(^13\)

New methods have been proposed to improve the performance of LECD; these include micro-anode-guided electroplating (MAGE), \(^14\) deposition-detection-withdrawal (DDW) control method, \(^15\) and real-time image-guided micro-anode electroplating system. MAGE has demonstrated that the micro-anode can be controlled to move in either continuous or intermittent mode to guide the progress of Ni-electroplating; \(^14\) hence, it influences the surface morphology of the electroplated microstructures. Although the resulting microstructures are less porous, their surface is rough and nodular. To improve the surface quality of microstructures by employing the MAGE process, C.S. Lin proposed a DDW control method, \(^15\) which could prevent the possible contact between the microstructures and the micro-anode. However, the resulting surfaces are not uniform because the deposition rate is not constant as it is affected by electric field that is applied on surface of the microstructures. \(^16\) Moreover, the variation of the electric field owing to the variation in the gap between the anode and microstructure cannot be controlled by employing the MAGE process or DDW control method. To address all these problems, a MAGE system with real-time image processing was proposed to create a steady electric field on the microstructure surface proposed. \(^17\) This system stabilizes the distance between the anode and the microstructure on the basis of measurements based on from real-time imaging, ensuring that the formed column structures are smooth with no pores, uniform, and straight. Moreover, the diameter of the microstructure can be controlled by adjusting different parameters, such as applied voltage and the distance between the anode and the microstructure. \(^18\)

Most previous studies \(^3\)\(^-\)\(^22\) mainly focused on the fabrication of 1D microstructures. In order to fabricate complex-shaped 2D and 3D microstructures, the factor for control the geometry of microstructure should be analyzed. In this paper, we show that the microstructure can be fabricated in different orientations by placing the tip of the microstructure away from the central axis of the micro-anode. By controlling this tip position and maintaining the offset distance, microstructures with different geometries can be fabricated, as shown in the experiment results in this paper.

The sections of this paper are organized as follows: the setup of the experiment equipment is discussed in Section 2, the image processing and position feedback control software are discussed in Section 3, the generation of the approximation curves and the approximation errors are discussed in Section 4, and the conclusion is presented in Section 5.

### Image-Guided Two-Dimensional MAGE System

The devices used in this research were classified into two subsystems: the image capturing system and MAGE system. Fig. 1 shows the schematic illustration of all systems, and Fig. 2 shows the actual experiment hardware. The traditional MAGE system included the DC power supplier, micro-stepping motor controller, PC-based controller, electrolyte, plating cell (A), pump (C), micro-stepping motors platform (D), copper substrate (E), and Pt micro-anode (F). The plating cell (40 mm × 40 mm × 70 mm) was made of polymethyl methacrylate (PMMA). The pump was used for electrolyte convection and for removing the bubbles formed due to electroplating. The electrolyte was a 1 × 10\(^{-3}\) m\(^{-3}\) freshly prepared solution containing 0.8 M CuSO\(_4\) - 2H\(_2\)O and 0.65 M H\(_2\)SO\(_4\). The Pt micro-anode was composed of a 127-μm-diameter Pt wire that was embedded in glass. The substrate was a cuboid (5 mm × 5 mm × 1 mm) pure-copper (99.9 wt%) sample mounted with epoxy resin. More details about fabrication of the anode and copper substrate were presented in reference 22.

The micro-stepping motors platforms included three straight-line platforms to move cell in three directions. The control program only drove two platforms to be moving simultaneously for experiments require. The step distance of micro-stepping motors platform was 0.1 μm. The other system was an image capturing system, including a CCD camera (Sony 97C) with magnifier 4 × lenses (B), a PC-based frame grabber (Matrox Meteor II), and a high-power LED module (G). The CCD cameras were installed in front of the cell. To increase illumination, the high-power LED module was installed behind the cell.

The continuous MAGE and experimental process could be divided to four steps: in the first step, the surface of the Cu substrate was cleaned by emery papers (grades 600–1200) and it was fixed on the plating cell. Then, the plating cell was fixed on the stage of the micro-stepping motors platforms and filled with the electrolyte. In the second step, the micro-anode was fixed on an immovable platform and one half of the anode was immersed in the electrolyte in the cell. Then, in the third step, the camera and magnifier lenses were setup to obtain images of the anode. In the last step, the pump was filled with the electrolyte, and the nozzle position and flow rate of the pump were adjusted to remove the bubbles generated during the electroplating process.
Figure 1. Schematic illustration of micro-anode-guided electroplating with real-time image processing.

Figure 2. Layout of the experimental setup: (A) plating cell; (B) CCD camera with magnifying lens; (C) pump; (D) micro-stepping motor platform; (E) Cu substrate; (F) Pt micro-anode; (G) high power LED module.

Image Processing Algorithm for Two-Dimensional Position Feedback Control

The image processing algorithm could analyze the positions of the micro-anode and the tip of microstructure. And, the results would be feedback to the controllers for adjusting the stepping motors. The block diagram of image feedback control process is shown in Fig. 3. The whole process could be completed in one sampling cycle, which lasts for 0.05 s.

The flowchart of image processing algorithm in Fig. 4 shows four major steps. The first step was to set the parameters for the experiments. The second one was to measure the center of the micro-anode by two scanned areas in the image, whereas the two scanned areas were selected by the operators. As shown in Fig. 5, the first scanned area in the image was processed with Sobel operation to find the boundaries of Pt-wire. From these boundaries, the central axis of the Pt wire was determined. In the second scanned area, as shown in Fig. 6, the horizontal height of the anode can be found. The image processing software can delimit the central of anode from the central axis and the horizontal height, which was considered to be the origin of the system.

The third step was to determine the position of the microstructure and maintain the relative position between the microstructure and micro-anode. The position of the microstructure could be determined by the position of top point of the microstructure. The top point of the microstructure could be measured on the second scanned area, as shown in Fig. 6. After this image was processed by the thresholding method, the image of microstructure became a white block and the top point of white block could be calculated and determined. With this calculated results, the relative position of the microstructure and micro-anode could be determined and be used to the relative distance
Experimental Results and Analysis

In order to examine the effect of the relative positions of the anode and the microstructure on the geometrical shape, we chose eight relative positions for experiments, as shown in Figure 7. The definite values of distance and results structure’s angle are listed in Table I. The electrical voltage was set at 3.4 V in all the experiments. The SEM images of the results are shown in Fig. 8.

The results show that the device and control software of Image-Guided MAGE System used in this research can fabricate two-dimensional microstructures. The top point of microstructure determined by the algorithm used in this research can be used in all experiments with reliability and reproducibility, and it has clearly definition on geometry even though this point has no chemical and physical properties. In addition, this algorithm has excellent image processing efficiency, which is very important on real-time control system.

The angles of microstructures are closely related to the relative positions of their tips with respect to the central axis of the anode. The angles progressively increased from A to F. For instance, the microstructure is a vertical cylinder when the tip of the structure was right below under the center of the anode. However, as the tip position of the structure gradually shifted away from the center axis of the anode, the angle increased. For instance, the resulting angle of the microstructure was 25.8° at position E, which was in line with the edge of the anode. Fig. 9 shows the angles of the microstructures for tip positions corresponding to position A to E. The tip positions of microstructures are under the anode cylinder. These angles can be approximated by a line as follows.

\[ \phi = 0.4184x \]  

Table I. parameters and results of 2D microstructure.

| Group | A  | B   | C   | D   | E   | F   | G   | H   |
|-------|----|-----|-----|-----|-----|-----|-----|-----|
| Relative X(μm) | 0.0 | 16.5| 33.0|49.5 |62.7 |82.5|89.1 |95.7 |
| Position Y(μm) | 39.6|39.6 |39.6 |39.6 |39.6 |36.3|26.4 |23.1 |
| Alpha (°) | 0° |29° |45° |55° |0° |29° |45° |55° |
| Resulting Angle(°) | 0.0°|11.0°|16.9°|19.0°|25.8°|35.2°|45.5°|51.9°|

Figure 5. Selected position of first area image and the result with sobel image process method.

Figure 6. Selected position of second area image and the result with thresholding image process method.

Figure 7. Schematic diagram shows relative positions of group A to F.

Figure 8. SEM images of the microstructures fabricated at positions A to H.
where $\phi$ (°) is the angle of the microstructure and $x$ (µm) is the position of the tip relative to the centerline of the anode.

If the tip position is not under the anode cylinder, the positions of microstructures at a constant distance from the edge of the cylinder, as at points F, G, and H. Experimental results show that the angles of the microstructures also increase from point E to H. For instance, the angle of the microstructure was 51.9° for the tip position at point H. The results are shown in Fig. 10, and the data are approximated by the curve as follows.

$$\phi = 0.0055x^2 + 0.179x + 25.741$$  \[2\]

where $\alpha$ (°), as shown in Fig. 7 and Table 1, is the acute angle between the vertical line and the vector from the bending point to the tip position of the microstructure.

Equation 1 and 2 can be used to manufacture the desired microstructures in diverse growth directions. By maintaining constant positions relative to the central axis of the anode, the angle of microstructure will be maintained as a constant. In addition, in SEM images, all surfaces of the microstructures are seen to be smooth and are symmetric to their axes.

**Conclusions**

By improving MAGE system with real-time image processing, we proposed a new fabrication of two-dimensional microstructures that can control geometry. Experimental results showed that microstructures in different orientations could be fabricated by adjusting the tip position of the microstructure relative to the anode center axis. The angles of the columns approximated by two different equations depending on the tip position relative to the anode center axis can be used predictions for new fabricating processes.

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