Fabrication of void-free submillimeter-scale nickel component by bottom-up electrodeposition

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Abstract
This study proposed and demonstrated the feasibility of adopting metallization method of bottom-up Damascene process (seed layer over entire patterned surface) in LIGA electrodeposition process to fabricate void-free submillimeter scale metallic components. Single additive (PEG of molecular weight, Mw 10,000) rather than complicated mixture of multiple additives is studied in order to simplify the additives concentration monitoring process. Hydrodynamic flow pattern and concentration distribution of additive in the electrolyte flowing across trenches of various aspect ratio were studied by using fluid kinetics simulation. Simulation results showed the shear flow of the agitated electrolyte across the top surface caused the formation of a concentration gradient of inhibitor (PEG) within the cavity, in which the concentration of inhibitor at the top surface was consistently maintained at a higher level as compared to the bottom part of cavity. The studies on the influence of PEG concentration on electrodeposition profile showed a relatively low concentration of 10 ppm has exhibited a remarkable difference in the electrodeposition rate at the top and inner surfaces of submillimeter cavity (bottom-up electrodeposition) which subsequently eliminated the formation of void/seam-like defects associated with conventional electrodeposition. Underfilling issue was identified and a two-step electrodeposition method was proposed to mitigate the underfilling effect. Nickel component electrodeposited by PEG-added electrolyte shows higher Vickers hardness of approximately 20% as compared to additive-free sample. Flat and thin surface layer that has been electrodeposited using this technique suggested a low risk of parts’ peel-off. This resulted in the simplified process of surface polishing, planarization and demolding. This approach provides an insight into fabrication techniques for void-free multilayer, millimeter-scaled components like watch parts.

1. Introduction
LIGA process (German acronym for Lithographie, Galvanoformung and Abformung) is widely used in the mass production of three dimensional and highly precise microcomponents with dimensions ranging from a few millimeters down to submicrometers for applications like microelectromechanical systems (MEMS) and ultralarge-scale integration (ULSI) [1–4]. Conventional LIGA process uses electrodeposition-through-lithographic mask method (also known as through-mask deposition or through-mask electroplating) [5–7] as illustrated in figure 1.

Through-mask electrodeposition is an ideal process for the fabrication of single level structure. For fabrication of multilevel or mushroom-shaped microcomponents for applications like MEMS sensor and actuator, repeated through-mask electrodeposition process is necessary [8]. The fabrication of multilevel microcomponent is very much dependent on factors which include overlay accuracy, uniformity of metal...
deposition thickness and bonding strength in between adjacent metal layers [9]. On top of the high accuracy of the alignment system, the requirement of planarization by lapping or polishing before every subsequent through-mask electrodeposition process makes the fabrication process complicated, time-consuming, and costly [10, 11].

The above-mentioned limitations of through-mask electrodeposition in fabricating multilevel microcomponent could potentially be overcome by depositing conductive seed layer after the completion of the entire patterning process of multilevel structure as illustrated in Figure 2. This seed layer depositing process is similar to that of Damascene process of copper electrodeposition for microelectronic interconnects [7]. However, there are some challenges associated with adopting the seed layer deposition method of Damascene process in through-mask electrodeposition (LIGA) process as discussed in the following section.

(1) Extended electrodeposition period is usually carried out in LIGA process to mitigate the effect of uneven local current distribution on metal filling in trenches, hence to ensure a complete filling of every cavities. Extended electrodeposition on seed layer deposited on entire substrate will incur an excessive yet uneven metal deposition on the top surface [12, 13]. Difference in topography height over substrate would induce variations in contact local pressure, therefore requires much delicate and longer planarization process to prevent peeling off or crumbling of parts due to high local pressures during planarization [14, 15].

(2) Formation of void/seam-like defect due to higher local current density and faster electrodeposition rate at the edges of trenches (edge effect) [16–22]. In Damascene process, a special mix of additives such as inhibitor, accelerator and leveller are used to achieve a void-free or ‘superfilling’ electrodeposition [3, 23, 24]. On top of the proper selection of additives, a successful bottom-up filling is very much dependant on the applied current density [25–27] and concentration monitoring to keep additives at the optimum...
concentration [28–33] in order to maintain a delicate balance between diffusion/adsorption rates, chemical and physical interactions between these additives [32, 34–38].

(3) Difference in trench sizes between Damascene and LIGA process may pose another challenge. Damascene process usually involves metal filling in nano- or microscale trenches which is typically smaller or of a similar order of magnitude as the thickness of additives diffusion layer as illustrated in figure 3. For instance, additive such as PEG has a diffusion layer thickness in the order of tenths of micrometer [39–44]). Concentration gradient induced by diffusion of additives was described as the key to a successful bottom-up electrodeposition in nano or submicron cavity [41, 42, 45–47]. This transport-limited leveling model may not be applicable in LIGA process involving submicrometer or even micrometer scale trenches as illustrated in figure 4.

M Takeuchi et al achieved bottom-up copper electrodeposition by using a single diallylamine-type copolymer additive [31]. B H Wu et al demonstrated void-free anisotropic deposition for copper IC interconnects with PEG as the single additive based on the concept of uneven adsorption distribution [48]. S–K Kim and Jungjin Han et al reported a successful bottom-up superconformal nickel metal deposition in submicrometer trenches [17, 49] and more recently, Josell et al reported on superconformal bottom-up nickel deposition in high aspect ratio of through silicon vias of 50 μm height and 5 μm width [50]. Several researchers studied the influence of forced convection agitation with air bubbles and demonstrated fluid dynamics being crucial in achieving a bottom-up via filling [33, 51–53]. However, these studies were focused on copper electrodeposition for printed circuit boards (PCB) with microscale features. More research is required to determine if Damascene process could be extended to electrodeposition of nickel in submilimeter trenches.

Figure 2. Schematic illustration of Damascene electrodeposition process: (A) Photoresist coating on plain substrate; (B) Patterning; (C) Seed layer deposition on the patterned photoresist (seed layer is deposited on the entire surface of patterned photoresist, after the completion of entire patterning process); (D) Electrodeposition; (E) Planarization.
In this paper, feasibility of adopting metallization method of Damascene process (seed layer over entire patterned surface) in LIGA process to fabricate submillimeter scale nickel components, is presented. Single additive (PEG of molecular weight, Mw 10000) rather than complicated mixture of multiple additives is studied to simplify the monitoring process of additives concentration. Fluid kinetic simulations were carried out to investigate the concentration mapping of additive across the submillimeter-scaled cavities of various aspect ratio under forced convection. Simulation results were verified by experimental results demonstrating bottom-up electrodeposition of nickel in submillimeter scale cavity using Damascene-like metalization method. Flat and thin surface layer that has been electrodeposited using this technique suggested a low risk of parts’ peel-off thus
simplifies the subsequent processes like surface polishing, planarization and demolding. Nickel component electrodeposited by PEG-added electrolyte shows higher Vickers hardness of approximately 20% as compared to additive-free sample. This approach provides an insight into fabrication techniques for void-free multilayer, millimeter-scaled components like watch parts.

2. Experiment

The patterned substrates used in this study were fabricated by a conventional ultraviolet (UV) lithography using SU-8 (MicroChem) as the photosresist. A seed layer, Au (200 nm)/Cr (50 nm) was sputtered over patterned photoresist of submillimeter scale rectangular trenches with 0.2 mm-depth and 1 mm-length. Three aspect ratio (height/width) of 1.0 (0.2 mm_width), 0.5 (0.4 mm-width) and 0.4 (0.5 mm_width) were investigated. The electrodeposition process was conducted with electrolyte composition and the conditions were shown in table 1. A semi-custom-designed, three-electrode electrodeposition system provided by Yamamoto-Ms Co., Ltd and a potentiostat (V3-200, Princeton Applied Research) was used along with an Ag/AgCl electrode in a saturated KCl solution as the reference electrode. A paddle agitation unit in which the paddle moved back and forth in a direction parallel to the substrate surface at an adjustable speed, with a moving distance of 30 mm (15 mm with respect to the substrate), was installed in the system.

EBSD analysis was conducted on EBSD analysis was conducted on the cross section polished specimen using JEOL JSM7600F scanning electron microscopy, equipped with Oxford AZtec Synergy system (for EDX and EBSD). The polished specimen was scanned at accelerating voltage of 20 kV (tilt angle of 70 degree) for phase identification and crystal orientations. Grain size analysis was computed from the acquired EBSD map with the software.

3. Numerical simulation

Simulations of the agitated electrolyte flow across submillimeter scale cavities were carried out by using two-dimensional, laminar and incompressible models of three different mesh sizes of 2.5 μm, 5.0 μm and 10 μm. The simulations were performed by discretizing the governing incompressible Navier–Stokes equations as shown in equations (1) and (2), using finite volume method (FVM) by commercial software ANSYS Fluent. In equations (1) and (2), \( V \) and \( \rho \) is electrolyte velocity vector and pressure respectively; \( p \) is the density and \( \mu \) is the viscosity.

\[
\nabla \cdot \boldsymbol{V} = 0
\]

\[
\rho \left( \frac{\partial V}{\partial t} + \nabla \cdot \nabla V \right) = -\nabla p + \mu \nabla \nabla V
\]

The second-order upwind method was used to increase the accuracy of spatial discretization for pressure-velocity coupling. Various velocity of 0.1 ms\(^{-1}\), 0.05 ms\(^{-1}\) and 0.15 ms\(^{-1}\) were assigned at the inlet and gauge pascal of zero pascal was set at both flow inlet and outlet. Stationary and no slip condition (zero velocity) was set at the walls.

Laminar flow with species transportation model was used in the simulation for concentration mapping of PEG species. Local mass fraction of species was calculated through the solution of a convection–diffusion equation (equation (3)), where \( \dot{Y}_i \) is the local mass fraction of species and \( R_i \) and \( S_i \) are the net rate of production of species and rate of creation by addition from the dispersed phase, respectively. \( \dot{J}_i \) is the diffusion flux of

| Table 1. Electrolyte composition and operating conditions for nickel electrodeposition. |
|-----------------------------------|---------------------------------|
| Ni(SO\(_3\)NH\(_2\))\(_2\)·4H\(_2\)O | 1.96 mol l\(^{-1}\)           |
| NiCl\(_2\)                        | 0.13 mol l\(^{-1}\)           |
| NiBr\(_2\)                       | 0.32 mol l\(^{-1}\)           |
| H\(_3\)BO\(_3\)                  | 0.49 mol l\(^{-1}\)           |
| Poly(ethylene Glycol), MW 10,000 | 0–5000 ppm                    |
| Temperature                      | 55 °C                          |
| Anode (counter electrode)        | Ni plate                       |
| Reference electrode              | Ag/AgCl in KCl saturated solution |
| Paddle agitation                 | 0 or 10 cm s\(^{-1}\) (linear speed) |
species, which arises due to gradients of concentration and temperature. Fick’s law was used to model mass diffusion due to concentration gradients, under which the diffusion flux can be written as shown in equation (4). In equation (4), $D_{m,i}$ is the mass diffusion coefficient for species in the mixture, and $D_{T,i}$ is the thermal diffusion coefficient.

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho \bar{v} Y_i) = -\nabla \cdot \vec{J}_i + R_i + S_i$$

(3)

$$\vec{J}_i = -\rho D_{m,i} \nabla Y_i - D_{T,i} \frac{\nabla T}{T}$$

(4)

The molecular weight and diffusive coefficient of PEG were set as 10000 kg kg$^{-1}$ mol$^{-1}$ and $5 \times 10^{-11}$ m$^2$ s$^{-1}$ respectively absorption [39]. The viscosity of the mixture of electrolyte and PEG was set as 1.57 mPa-s. Concentration of PEG at the inlet, outlet and top boundary (bulk solution) were set at a constant value of 10 ppm while zero PEG concentration was set at electrode surface (bottom boundary) by assuming a rapid adsorption on the basis of hypothesis of diffusion-controlled PEG absorption [39]. To simplify the simulation, negligible eddy effect of paddle reciprocating movement was assumed, considering the substrate is relatively small in dimension in comparison to paddle moving distance. The details of parameter setting and boundary conditions applied in simulation were shown in table 2.

### 4. Results and discussion

#### 4.1. Velocity mapping of electrolyte under forced convection

Simulation results of velocity-mapping of the electrolyte (figure 5) flowing through submillimeter trenches shows that hydrodynamic flow by forced convection can be divided into two distinct regions: high flow velocity region near the top of trench, the other being stagnant or low flow velocity region inside the trench. Simulation results of velocity of electrolyte flow in trenches (figure 6) shows that the amount of fresh electrolyte penetrate into a trench is inversely propotional to the aspect ratio of the trench. Velocity of less than 1.0 cms$^{-1}$ or stagnant at most of the inner region of trench suggests that circulation of electrolyte and replenishment of metal ions by forced convection is less effective in the trench of aspect ratio 1.0 as compared to 0.4 and 0.5. These simulation

| Parameter Setting | Boundary Condition (without agitation) | Boundary Condition (with agitation) |
|-------------------|----------------------------------------|-----------------------------------|
| Material          | Mixture of PEG and water                | Top Boundary                       |
| Viscosity         | 1.57 mPa                                | Pressure-inlet, PEG 10 ppm, gauge-pressure at 0 |
| Density           | 998.2 kg m$^{-3}$                       | Left Boundary                      |
| PEG concentration | 10 ppm                                 | Pressure-inlet, PEG 10 ppm, gauge-pressure at 0 |
| Temperature       | 55°C                                   | Right Boundary                     |
| PEG molar mass    | 10000                                  | Pressure-outlet, PEG 10 ppm, gauge-pressure at 0 |
| PEG density       | 1120 kgm$^{-3}$                        | Bottom Boundary                    |
| FEM               | Green-Gauss Cell-Based                 | Static wall, PEG 0 ppm, free-flux of PEG |
| Flow model        | Laminar flow with species transportation | Top Boundary                       |
|                   |                                        | Static wall, PEG 10 ppm, free-flux of PEG |
|                   |                                        | Left Boundary                      |
|                   |                                        | Velocity-inlet, fluid velocity of 10 cms$^{-1}$, PEG 10 ppm |
|                   |                                        | Right Boundary                     |
|                   |                                        | Pressure-outlet, PEG 10 ppm, gauge-pressure at 0 |
|                   |                                        | Bottom Boundary                    |
|                   |                                        | Static wall, PEG 0 ppm, free-flux of PEG |

Table 2. Parameter Setting and boundary condition in fluid simulation.
results concur with the flow pattern predicted from the general purpose finite element code named FIDAP, reported by Alkire and Deligianni [54].

Simulation results was verified with experiment using an additive free, conventional electrodeposition method. In the absence of inhibitor, nickel was initially deposited at the same growth rate over the entire substrate surface as shown in figure 7(A). However, as shown in the simulation result, continuous refreshment of electrolyte at the top of trench against stagnant electrolye (ineffective circulation) inside the trench caused a prominent discrepancy in nickel ion concentration, as well as the high current density at the edges of trench (edge effect as explained in figure 4) can be considered the main factors contributing to higher nickel deposition rate at the top of trench [18], resulted in the formation of 'void' as shown in figure 7(B). Void in a electrodeposited component is undesired, because it reduces the overall mechanical strength. Furthermore,
most mechanical calculations and structural designs were carried out without taking into consideration of void defect, and these 'unexpected' void formation would eventually lead to design inaccuracy.

Simulation of various level of forced convection (figure 8) suggested a limited effect in improving the circulation of fresh electrolyte into the trenches, especially smaller trench of aspect ratio 1.0 where the electrolyte flow in the trench remain stagnant even when the agitation speed was changed from 5 cms$^{-1}$ to 10 cms$^{-1}$ or even 15 cms$^{-1}$ as shown in figure 9. This simulation result was verified by the polarization curves measured by linear scan voltammetry using an additive free, conventional electrolyte (figure 10) which show no remarkable changes in electrodeposition characteristic when the electrolyte was agitated at different agitation speed. Instead of manipulating the level of forced convection or agitation, other method as discussed in the later session, is required to eliminate void formation in electrodeposited trenches.

**Figure 6.** Velocity (m s$^{-1}$) of electrolyte in the submilimeter features (mesh size = 2.5 μm) having aspect ratio of (A) 1.0 (0.2 mm_width x 0.2 mm_depth), (B) 0.5 (0.4 mm × 0.2 mm) and (C) 0.4 (0.5 mm × 0.2 mm). Depth is defined as 0 m at the top outer surface, 200 μm at the bottom of trench.

**Figure 7.** Optical microscope image of cross-section of submillimeter features electrodeposited at $-0.7$ V versus Ag/AgCl in basic electrolyte (Nickel sulfamate bath without additive for deposition times of 4 h (left) and 16 h (right), with agitation speed of 10 cms$^{-1}$. The aspect ratio of trenches are 1.0 (Left), 0.5 (Center) and 0.4 (Right).
4.2. Effect of concentration of inhibitor on electrodeposition characteristic

As compared to polarization curves by various agitation speed which show no significant change (figure 10), experiment results showed that polarization curves shifted cathodically when the PEG concentration in electrolyte increased from 0 ppm (PEG-free) to 5000 ppm (figure 11). This cathodical shift of polarization curves indicated that nickel desposition was indeed inhibited in the presence of PEG. A saturation point of PEG coverage was found between 100 ppm and 1000 ppm as only a slight shift in the polarization curves was observed between 1000 and 5000 ppm.

Cross-sectional images of submillimeter trench that were electrodeposited in electrolyte with 1000 ppm PEG (figure 12) indicates that nickel electrodeposition was excessively suppressed due to the saturated coverage of inhibitor. To avoid the saturation of inhibitor in electrolyte, a lower PEG concentration of 10 ppm with significant inhibitory effect (cathodically-shifted polarization curve) was considered.

Figure 8. Fluid kinetics simulation result of the velocity-mapping of an agitated electrolyte flowing through submillimeter features, under different agitation speed (Top: 5 cms\(^{-1}\), Middle: 10 cms\(^{-1}\), Bottom: 15 cms\(^{-1}\)).
Figure 9. Velocity of electrolyte in the trench of aspect ratio 1.0 (mesh size = 2.5 μm) when the agitation speed was changed from (A) 5 cms⁻¹ to (B) 10 cms⁻¹ and (C) 15 cms⁻¹ in simulation. Depth is defined as 0 μm at the top outer surface, 200 μm at the bottom of trench. Most of the velocity of electrolyte flow in the trench remained below 1.0 cms⁻¹ regardless of change in convection level.

Figure 10. Polarization curves measured by linear scan voltammetry using an additive free, conventional electrolyte. Results show no remarkable changes in electrodeposition characteristic when the electrolyte was agitated at different agitation speed.

Figure 11. Cathodic polarization curve measured at scan rate of 10 mVs⁻¹ for the electrolyte with various PEG concentrations (0–5000 ppm).
4.3. Effect of inhibitor in changing the deposition profile

Hydrodynamic flow pattern of conventional electrolyte (additive-free) under forced convection (top of trench: continuous circulation of fresh electrolyte, inner trench: stagnant) and edge effect are the main reasons behind the void formation in sub-millimeter trench. However, simulation result of concentration mapping of inhibiting species in a 10 ppm PEG-added electrolyte under forced convection as shown in figure 13, suggests that the adoption of electrodeposition inhibiting species (PEG) would turn the disadvantageous flow pattern to a favorable factor to eliminate the formation of void defect in nickel electrodeposition.

When electrodeposition is initiated (the electrode is polarized), incorporation of additive species into electrodeposited nickel surface will cause the concentration of additive to decrease and form a concentration gradient in the diffusion layer adjacent to the electrodeposited nickel surface. On top of the stagnant electrolyte at the inner area of trench as shown in previous simulation result (figure 8), slow diffusion rate of PEG (due to its long chain-like molecule structure) has as well contributed to the formation of a low PEG concentration zone within the trenches as shown in figure 13.

Simulation result was verified by the experimental result as shown in figure 14. In contrast to the conformal deposition (figure 7) using additive-free electrolyte, electrodeposition by PEG-added electrolyte changed the deposition characteristic to 'bottom-up' deposition, similar to that of LIGA process as illustrated in figure 1. Despite having a conductive seed layer all over the entire substrate surface, the circulation of fresh electrolyte (contain relatively high PEG concentration) causes a continuous suppression of nickel electrodeposition, therefore only a very thin nickel layer of 5 μm (growth rate of 1.25 μm h⁻¹) was deposited at the top surface.

![Figure 12](image12.png)

**Figure 12.** Optical microscope image of cross-section of trenches with aspect ratio of 1.0 (width: 0.2 mm, depth: 0.2 mm) electrodeposited at −0.7 V versus Ag/AgCl under inhibitor (PEG) concentration of 1000 ppm and electrodepositing time of 6 h, (A) with agitation and (B) without agitation. Deposition of nickel was excessively suppressed in both conditions.

![Figure 13](image13.png)

**Figure 13.** Fluid kinetics simulation result of concentration mapping for PEG species in an electrolyte contains 10 ppm of PEG, under agitation of 10 cm s⁻¹. Formation of a low PEG concentration zone can be observed in the trenches.
while thick nickel layer of 70 μm (growth rate of 17.5 μm h⁻¹) in the trench, a remarkable electrodeposition rate difference of approximately 1:14 (figure 15).

On the other hand, simulation of PEG concentration mapping without agitation, the above-mentioned concentration gradient was less significant (figure 16(A)) between both the top surface and the inner area of trench. Experiment result showed relatively conformal electrodeposition (figure 16(B)) with an excessive deposition at the edges which can be explained with the ‘edge effect’ phenomena; a relatively fast growth of
electrodeposition metal layer caused by the strong electric field at the edges of substrates [16, 17]. This results show that agitation plays an important role in changing the profile of nickel deposition by using inhibitor additive, to achieve void-free electrodeposition.

4.4. Effect of geometry of trench

Cross-section of submillimeter trenches electrodeposited at $-0.7 \text{ V versus Ag/AgCl}$ in an agitated, PEG-added electrolyte (figure 14(A)) showed different nickel growth rates in trenches, approximately $17.5 \mu \text{m h}^{-1}$, $13 \mu \text{m h}^{-1}$ and $9 \mu \text{m h}^{-1}$ in trenches with aspect ratio of 1.0, 0.5 and 0.4, respectively. After 20 h of electrodeposition, trench with aspect ratio of 1.0 was filled up to almost 95% but trenches with aspect ratio of 0.5 and 0.4 showed an underfilled profile by approximately 50% of the trenches were remained un-deposited (figure 14(B)). This underfilling phenomenon can be well explained by simulation results as trench with lower aspect ratio of 0.4 and 0.5 allow more electrolyte from the bulk solution penetrate into the trench (figure 8). This consequently caused the region of low PEG concentration to occur at a point lower than the top surface of trench, at which the nickel deposition was greatly suppressed (figure 13).

Polarization curves (figure 11) shows that inhibitive effect of PEG decreases significantly when the applied potential reach a particular value, for instance around $-0.75 \text{ V}$ for PEG-added electrolyte of 10 ppm concentration. Figure 17 shows the result of a two-step electrodeposition carried out by applying $-0.7 \text{ V}$ (potential of high PEG inhibitive effect) for the initial 2 h and $-0.8 \text{ V}$ (potential of low PEG inhibitive effect) for the subsequent 2 h. The result shows an improvement in overall nickel growth rate in trench of aspect ratio 0.4, from $9 \mu \text{m h}^{-1}$ (Single-step, $-0.7 \text{ V}_4 \text{h}$ as shown in figure 14(A)) to $27 \mu \text{m h}^{-1}$ (Two-step, $-0.7 \text{ V}_2 \text{h} \text{ plus } -0.8 \text{ V}_2 \text{h}$, as shown in figure 17). Although some process optimization is still required to achieved a
4.5. Effect of inhibitor on grain size and hardness of electrodeposited

Grain size data of nickel samples electrodeposited was collected by using electron backscattered diffraction analysis (EBSD). Inverse pole figure (IPF) map shown in figure 18 shows no significant changes in nickel crystal structure (mainly cubic face centered) but grain size of nickel varies from 3 μm down to 260 nm (average grain size of 800 nm) and from 1.4 μm down to 320 nm (average grain size of 500 nm) for nickel electrodeposited by additive-free and PEG-added electrolyte, respectively. Hardness measurement result (table 3) shows an approximately 20% of increment in Vickers Hardness (HV) from 360 HV (additive-free electrolyte) to 430 HV of component electrodeposited by PEG-added electrolyte, attribute to the grain size reduction as analyzed by EBDS.

5. Conclusions

We have demonstrated the feasibility of adopting metallization method of Damascene process (seed layer over entire patterned surface) in LIGA process for nickel metal filling in submillimeter scale trenches. Fluid kinetics simulation was conducted to study the flow profile of electrolyte passing through submillimeter trenches and concentration distribution of inhibitor species across the trenches. Void-free, submillimeter scale nickel structure was fabricated with bottom-up electrodeposition process by using single inhibitive additive PEG (molecular weight, Mw 10,000). Electrodeposition on the top surface was significantly inhibited by the circulating fresh bath solution containing high PEG concentration, resulting in a flat surface finishing at the top of the cavity. Nickel component electrodeposited by PEG-added electrolyte shows higher Vickers hardness of approximately 20% as compared to additive-free sample.
This electrodeposition technique demonstrates the feasibility of fabricating multiple levels or mushroom-shaped submillimeter components using a conventional LIGA process. Design and calculation inaccuracies due to void formation can be reduced, which enable products to be fabricated with enhanced quality and reliability. Furthermore, flat and thin surface layer electrodeposited with this technique, suggested a lower risk of parts peel-off. This, therefore, will simplify the process of polishing, planarization and demolding.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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