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TECHNICAL NOTE

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Technical Note

A single mask process for the realization of fully-isolated, dual-height MEMS metallic structures separated by narrow gaps

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Abstract
Multi-height metallic structures are of importance for various MEMS applications, including master molds for creating 3D structures by nanoimprint lithography, or realizing vertically displaced electrodes for out-of-plane electrostatic actuators. Normally these types of multi-height structures require a multi-mask process with increased fabrication complexity. In this work, a fabrication technology is presented in which fully-isolated, dual-height MEMS metallic structures separated by narrow gaps can be realized using a self-aligned, single-mask process. The main scheme of this proposed process is through-mold electrodeposition, where two photoresist mold fabrication steps and two electrodeposition steps are sequentially implemented to define the thinner and thicker structures in the dual-height configuration. The process relies on two self-aligned steps enabled by the electrodeposited thinner structures: a wet-etching of the seed layer utilizing the thinner structure as an etch-mask to electrically isolate the thinner and the thicker structures, and a backside UV lithography utilizing the thinner structure as a lithographic mask to create a high-aspect-ratio mold for the thicker structure through-mold electrodeposition. The latter step requires the metallic structures to be fabricated on a transparent substrate. Test structures with differences in aspect ratio are demonstrated to showcase the capability of the process.

Keywords: MEMS, single-mask, high aspect ratio, metallic structures, UV LIGA, dual-height, electrodeposition

(Some figures may appear in colour only in the online journal)

1. Introduction

Vertical actuators with large stroke have been shown to play an important role in optical and electrical applications [1, 2]. Various transduction mechanisms have been proposed to realize vertical actuation, among which, electrostatic [1] and magnetic actuators [3] most of which rely on vertically displaced electrodes (comb fingers) or magnetic poles. The electrodes/magnetic poles should be microfabricated in such a way that they are initially vertically misaligned, and as actuation occurs, they are snapped into alignment at the same vertical height level. Moreover, it is often optimal for the electrodes/magnetic poles to be separated by narrow gaps in order to enhance the actuation force [1]. This height difference in poles, together with the narrow gaps that separate them, normally necessitates multiple masks [1, 2]. In this technical note, we describe a process that addresses this challenge using a single mask to create fully-isolated, dual-height MEMS metallic structures separated by narrow gaps on a transparent substrate.

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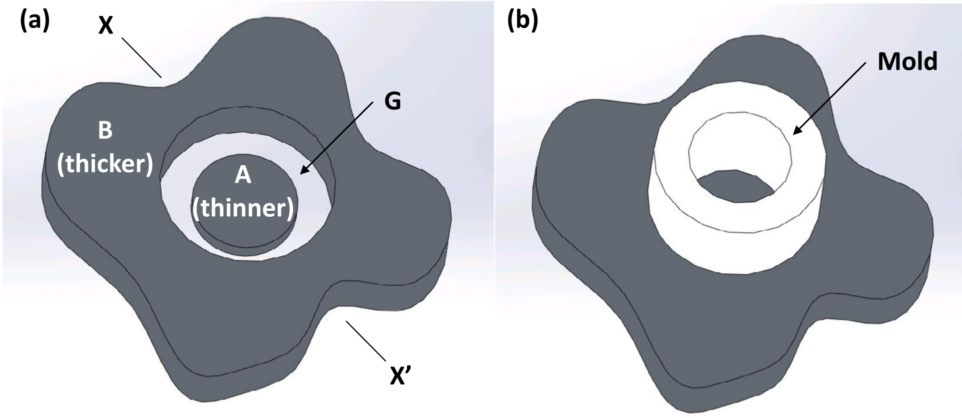

Figure 1. (a) 3D schematic of the exemplary dual-height structures after fabrication. Inner island A is the thinner structure, enclosed by a continuous white area *G*, the gap. On the periphery is the thicker structure. (b) Schematic of the structures during fabrication. The photoresist mold used for the through-mold electrodeposition is shown. The mold will be removed after plating, forming the continuous gap *G* of figure (a) between the dual-height structures.

2. Experimental details

2.1. Structure layout

The technology described here is capable of achieving dual-height MEMS metallic structures separated by narrow-gaps as long as four design considerations are met (see figure 1(a) for illustration): (1) the thinner structure (*A*) and the thicker structure (*B*) in the dual-height structures are fully isolated by a continuous gap (*G*); (2) the thinner structure resides inside of the gap forming an island whereas the thicker structure resides on the periphery; (3) the thicker structure always has identical materials with the thinner at the same vertical height level; and (4) a transparent substrate is needed for the dual-height structures to be built on. As will be discussed in detail in the following sections, the proposed fabrication sequence is a modified conventional through-mold electrodeposition: the gap area will be occupied by photoresist molds twice (figure 1(b)), whereas the remaining areas will be electroplated twice, forming the dual-height structures.

2.2. Substrate and seed layer preparation

The proposed process is a modified version of the conventional through-mold electrodeposition, where lithography-electroplating–lithography-electroplating (L-Ep–L-Ep) were sequentially implemented to define the thinner and thicker structures in the dual-height configuration. The process relies on two self-aligned steps enabled by the electrodeposited thinner structures: a wet-etching of the seed layer utilizing the thinner structure as an etch-mask to electrically isolate the thinner and thicker structures, and a backside UV lithography utilizing the thinner structure as a lithographic mask to create a high-aspect-ratio mold for the thicker structure through-mold electrodeposition.

A schematic of the fabrication is shown in figure 2. A soda lime glass slide (Corning) was cleaned using Piranha Solution (3:1 volume ratio of sulfuric acid and hydrogen peroxide) followed by an hour-long dehydration bake in a convection oven at 110 °C. A seed layer comprising copper (300 nm) sandwiched by titanium (30 nm) layers was then formed using DC sputtering (Denton Explorer14). The top titanium layer serves the purpose of (1) reducing possible oxidation of the copper seed layer on which the plated metallic structures grow; and (2) enhancing the adhesion of the photoresist mold to the seed layer. The bottom titanium layer enhances the adhesion of the structures to the glass substrate.

2.3. First lithography process

The glass substrate with Ti/Cu/Ti seed layer was then cleaned with solvent, followed by an O_2 descum (Technics RIE, 110 sccm O_2, 100 W, 30 s). This first lithography step was intended to create a photoresist mold for the first plated metallic layer that will functionally serve as a mask-equivalent for subsequent wet-etching and lithography steps, as well as structurally realize the entirety of the thickness of the thinner structure, and partially realize the thickness of the thicker structure. Both positive and negative photoresists are suitable for this lithography step, but one caveat is that due to the mask-equivalent nature of this layer, pattern non-idealities will propagate throughout subsequent process steps. Hence, in general, a straighter wall-profiled photoresist with a thickness larger than that of the desired first plated metallic layer is preferable for this step. For demonstration purposes, a chemically amplified thick positive photoresist AZ 40XT-11D (MicroChemicals) with nearly vertical resist wall profile [4, 5] was used for the first lithography step to create a 20 μm plating mold. The detailed process is as follows. The resist was manually dispensed onto the glass wafer bearing the seed layer. To achieve a 20 μm thickness, a two-step spinning procedure with a pre-spin of 500 rpm/10 s and a main-spin of 3000 rpm/30 s was used. In order to prevent the formation of bubbles in the resist film, a temperature-stepping soft bake (65 °C/60 s + 95 °C/60 s + 125 °C/300 s + 95 °C/60 s + 65 °C/60 s) on a contact hotplate was implemented.

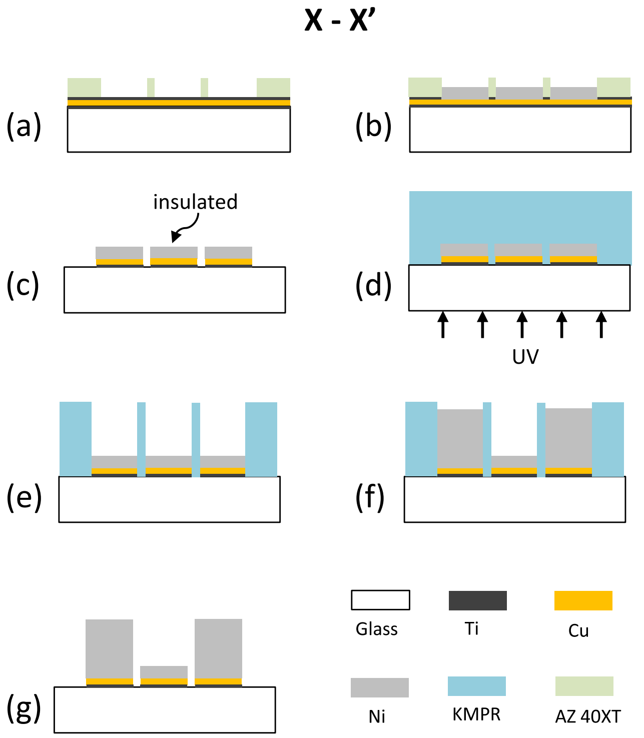

Figure 2. Fabrication sequence (side view, cross-section *X–X'* of figure 1). (a) Sputtering of Ti/Cu/Ti seed layer on glass substrate and patterning positive resist mold; (b) top Ti seed layer wet-etched and electrodeposition of Ni layer; (c) positive resist mold stripping followed by exposed seed layer wet-etching, electrically insulating the inner (thinner) structure; (d) negative resist spinning and backside UV exposure; (e) negative resist development, forming a self-aligned mold; (f) electrodeposition of Ni on the outer (thicker) structure only; and (g) negative resist mold stripping.

After soft baking, the resist was cooled down for 10 min to room temperature. The glass wafer was then exposed with a dose of 300 mJ (i-line) using a UV mask aligner (Karl Suss MA6) through a chrome mask in the vacuum contact mode. A post-exposure bake of 105 °C/100 s was carried out on a contact hotplate and let to cool down to room temperature. The exposed wafer was then developed in a dedicated resist developer AZ 726MIF (MicroChemicals) for 210–240 s at room temperature. This concludes the first lithography process as shown in figure 2(a).

2.4. First layer electrodeposition

Prior to electrodeposition, an O_2 descum process was carried out to remove any possible photoresist residue. The exposed top titanium layer in the Ti/Cu/Ti seed layer stack was wet etched in a diluted hydrofluoric acid solution (0.25% vol.) immediately before commencement of electrodeposition. Conventional through-mold electrodeposition (figure 2(b)) was implemented using a DC current source with current density of 10mA cm^{-2} in a nickel electrodeposition bath [6] consisting of 200 g l^{-1} $NiSO_4 \cdot 7H_2O$, 5 g l^{-1} $NiCl_2 \cdot 6H_2O$, 25 g l^{-1} H_3BO_3, and 3 g l^{-1} saccharin, with pH of 2.5–2.8. The plating rate was measured to be 6.5 μm h^{-1}. Plating occurred at room temperature with no agitation. The target thickness of this layer plating is the thickness of the thinner structure in the dual-height structures. After electrodeposition, the plating mold was subsequently stripped in acetone.

2.5. Seed layer etching

Using the previously plated nickel layer as a wet-etching mask, the copper conductive layer and bottom titanium adhesion layer in the Ti/Cu/Ti seed layer stack originally underneath the resist mold were selectively wet etched using diluted hydrofluoric acid (0.25% vol.) and a saturated solution of copper sulfate in ammonium hydroxide [7], respectively. After wet etching (figure 2(c)), the inner structure (i.e. the thinner of the dual-height structures) is electrically isolated from the outer structure (i.e. the thicker of the dual-height structures). Further, the gap between the structures has now become transparent due to the glass substrate. Upon this step, the plated Ni layer, along with remaining Ti/Cu/Ti seed layer essentially mimics a conventional chrome mask with the plated metal regions serving as the light-blocking pattern in a UV lithography mask.

2.6. Second lithography process for high-aspect-ratio (HAR) molds

A second lithography step is utilized to create a thick plating mold for the remaining thickness of the thicker metallic structure. By using the first plated metal pattern as an effective mask for the backside UV exposure, the second lithography process is automatically self-aligned to the first lithography step. It is worthwhile to point out that a conventional topside alignment registration is not practical when the dual-height structures have a large thickness difference, since when the photoresist gets thick, the simultaneous focusing on the upper and lower layer could not be easily realized in a conventional mask aligner [8]. Other benefits of backside exposure include [8] (1) avoiding underexposure at the bottom of the resist which might cause resist delamination after development and (2) bypassing the diffraction-related resolution reduction caused by the uneven contact of the thick resist to the mask (due to the potential thickness nonuniformity commonly seen in thick photoresists). By shining the UV light from the back as shown in figure 2(d), the thick negative photoresist could be patterned and cross-linked to create a HAR mold (figure 2(e)) that enables a HAR gap essential for multiple MEMS applications. The selection considerations of the photoresist in the second lithography step are threefold: (1) must be a negative photoresist; (2) the resist thickness should well exceed the thickness difference of the dual-height structures and, (3) for some applications where a fixed gap size is desired, a straight resist wall-profile is needed. A chemically amplified thick negative photoresist KMPR with HAR capability and straight wall-profile, has been reported as an SU8 alternative for UV LIGA process with improved removability [9, 10]. For demonstration purpose, KMPR 1050 (MicroChem) with 100 μm in thickness was used for the second lithography step. To avoid

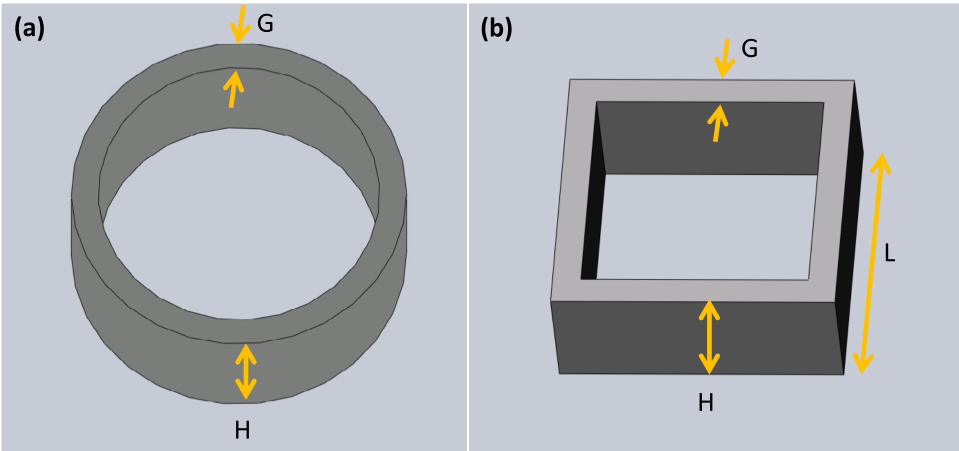

Figure 3. 3D schematics of the HAR resist molds that will define the dual-height test structures: (a) ring-like mold and (b) square-like mold. The height (H), length (L) and gap (G) are defined in the figure.

Table 1. Parameters of test structures.

Ring-like structures

H=100µm

G	10µm	20µm	30µm
H/G	10	5	3.3

Square-like structures

H=100µm

G \ L	350µm	100µm
10µm	35 / 10	10 / 10
30µm	11.7 / 3.3	3.3 / 3.3
85µm	4.1 / 1.2	N/A / N/A

in-plane aspect ratio: L/G (upper right of each cell)
H/G: out-of-plane aspect ratio (lower left of each cell)

poor adhesion of the KMPR resist mold to the glass substrate, adhesion promoters such as HMDS are highly recommended [11]. Prior to applying HMDS, standard surface treatments such as dehydration and descum steps outlined in sections 2.2 and 2.3 were utilized. The HMDS prime process was conducted in an HMDS prime oven (Yield Engineering Systems), followed by manual dispense of the KMPR1050 photoresist. The resist was dispensed over the wafer to cover all the prefabricated features. A two-step spinning was implemented to achieve 100 μm thickness with a pre-spin of 500 rpm/10 s and a main-spin of 1500 rpm/30 s. After edge bead removal, the glass wafer was left to sit on a leveled surface for 3 min to aid the planarization of the resist. The wafer was then soft-baked on a contact hotplate at 100 °C/30 min. After cooling down to room temperature, the wafer was flipped upside down and exposed with a 1500 mJ (i-line) dose along with a 360 nm long-pass filter. The application of the long-pass filter helps to obtain vertical sidewall profile as the wavelength below 360 nm shows a low transmittance similar to SU8 [9]. A temperature stepped post-exposure bake (65 °C/120 s + 95 °C/240 s + 65 °C/120 s) was carried out on a contact hotplate followed by cooling to room temperature. The wafer was then developed upside down in SU8 developer (MicroChem) for 7 min followed by an isopropyl alcohol rinse.

2.7. Second layer electrodeposition

After a typical descum process, the second layer nickel electroplating was carried out with the same parameters as outlined in section 2.4. The target height of this layer is the thickness difference between the thicker and thinner of the dual-height structures. The combined two-layer plating will finally achieve the desired thickness of the thicker structure. Again, since the thinner structure was electrically isolated from the current path, no electrodeposition occurred in the thinner structure region (figure 2(f)).

The HAR KMPR resist mold is stripped in an NMP solution (PG remover, MicroChem) at 80 °C for 90 min with sonication. Optionally, O_2 plasma could be used (225 W, 110 sccm) to remove any remaining residue. The resulting

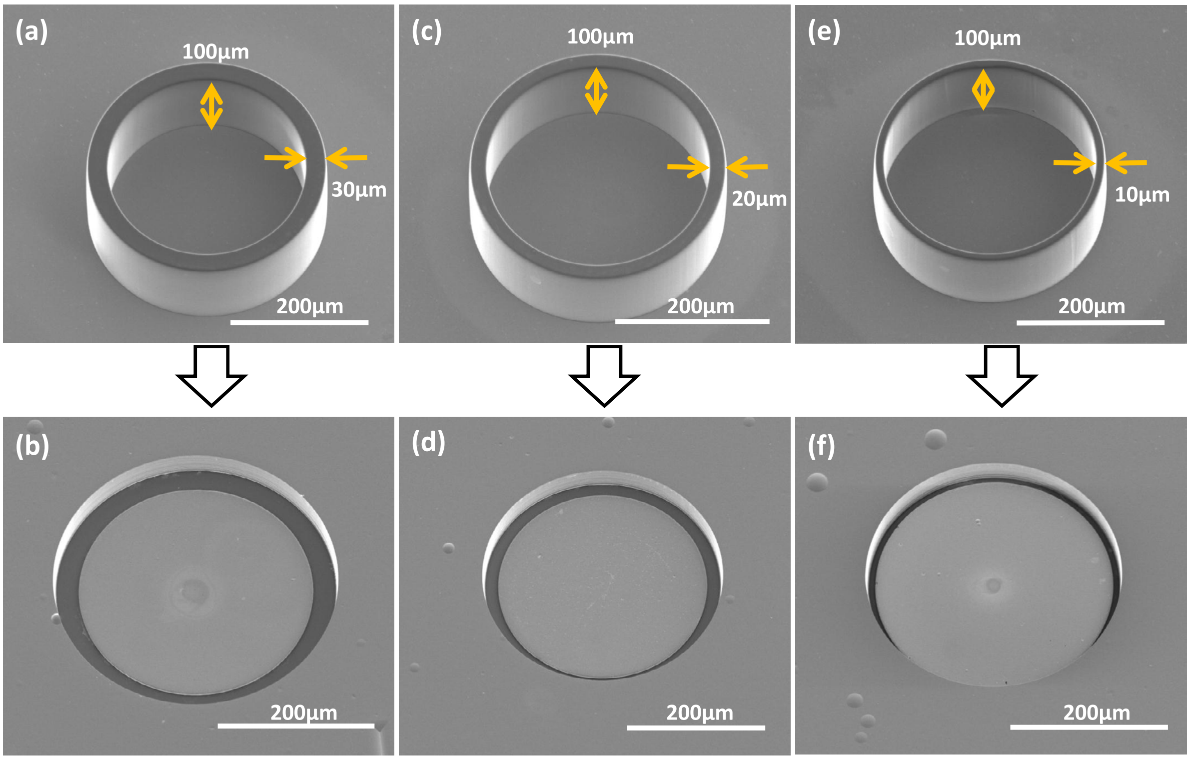

Figure 4. SEM images of microfabricated ring-like test structures. (top) HAR KMPR molds after the second lithography step, 100 μm in height and (a) 30 μm, (c) 20 μm and (e) 10 μm in gap sizes. (b), (d) and (f) show the corresponding dual-height (5 μm and 35 μm) structures after the second electrodeposition and mold stripping.

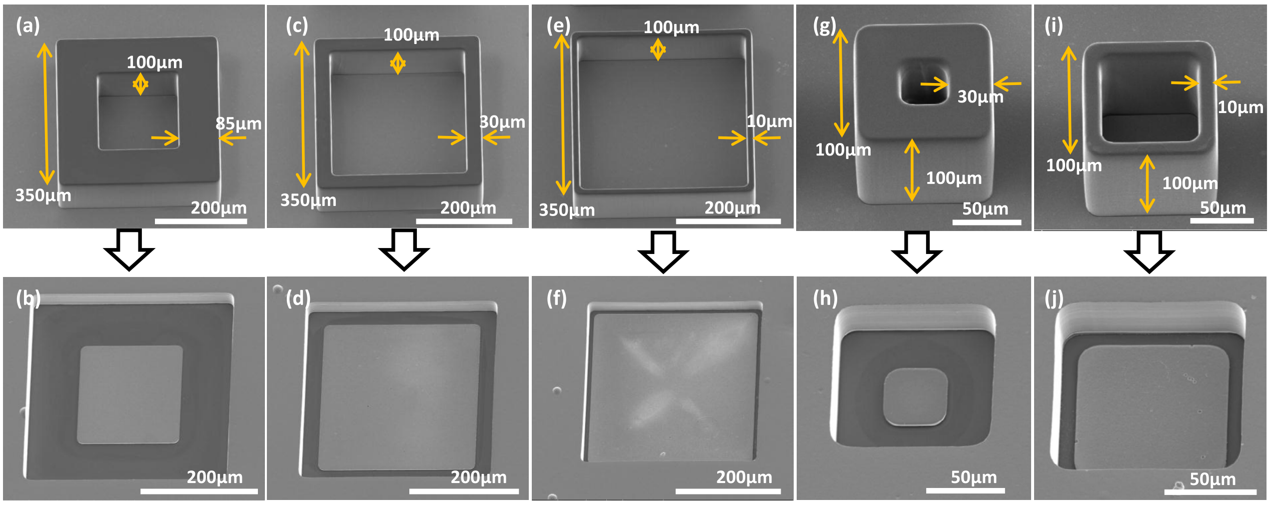

Figure 5. SEM images of microfabricated square-like test structures. (top) HAR KMPR molds after the second lithography step (a), (c), (e), (g) and (i); and the corresponding dual-height (5 μm and 35 μm) structures (b), (d), (f), (h) and (j) after the second electrodeposition and mold stripping.

dual-height structures, fully isolated by a narrow gap, are shown in figure 2(g).

3. Results and discussion

The most important process step in the proposed fabrication sequence is the HAR resist mold enabled by the backside exposure in the second lithography step through the plated first metallic layer. To evaluate the fabrication capability of the proposed process, two types of test structures, distinguished by the HAR resist mold shapes, are designed. As indicated in figures 3(a) and (b), one is a ring-like structure (with varying out-of-plane aspect ratio) while the other is a square-like structure (with varying in-plane and out-of-plane aspect ratio). The height (H), length (L) and gap (G) are defined in figure 3 and the corresponding parametric variations are listed in table 1 for both ring- and square-like test structures. The in-plane aspect ratio is defined as the ratio of L to G for square-like structures, whereas the out-of-plane aspect ratio is defined as the ratio of H to G

for both test structures. The resulting microfabricated test structure images obtained from scanning electron microscopy (SEM, FEI Quanta 600) with a 30° tilt angle for ring- and square- like structures are shown in figures 4 and 5, respectively. In all the test structures, for demonstration purposes, the thinner and the thicker dual-height structures are 5 μm and 35 μm in height, respectively. Figures 4(a), (c) and (e) demonstrate the ring-like HAR KMPR 1050 molds which are 100 μm in height and 30 μm, 20 μm and 10 μm in gap size by the second lithography step. Figures 4(b), (d) and (f) show the corresponding dual-height structures after the second layer nickel electrodeposition and mold-stripping. Similarly, figures 5(a), (c), (e), (g) and (i) demonstrate the square-like HAR KMPR 1050 molds and figures 5(b), (d), (f), (h) and (j) show the resulting dual-height metallic structures.

4. Summary

This work demonstrated a single-mask fabrication sequence to create dual-height metallic microstructures separated by a narrow gap which normally necessitates a multi-mask process. The proposed fabrication scheme takes advantages of two self-aligned steps, to create UV-LIGA type of structures. Dual-height test structures have been demonstrated to showcase the fabrication capability of this technology.

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