Experimental investigation of an embedded root method for stripping SU-8 photoresist in the UV-LIGA process

2004 J. Micromech. Microeng. 14 356

(http://iopscience.iop.org/0960-1317/14/3/007)

J. Micromech. Microeng. **14** (2004) 356–364 PII: S0960-1317(04)63500-5

Experimental investigation of an embedded root method for stripping SU-8 photoresist in the UV-LIGA process

Chien-Hung Ho and Wensyang Hsu

Department of Mechanical Engineering, National Chiao Tung University, 1001 Ta-Hsueh Road, Hsinchu, Taiwan 30010, Republic of China

E-mail: whsu@mail.nctu.edu.tw

Received 13 May 2003, in final form 8 October 2003
Published 17 December 2003
Online at stacks.iop.org/JMM/14/356 (DOI: 10.1088/0960-1317/14/3/007)

Abstract
In much previous research it has been popular to use SU-8 photoresist as a mold for electroplating, facilitating the production of low-cost microelectromechanical systems. However, the thickness of the electroplated structures standing on the substrate could only reach 50 μm or less due to the internal force and deformation of the photoresist in the final stripping process. In order to fabricate thicker structures, an embedded root method has been proposed to consolidate the adhesion of the metal structures to the substrate during the SU-8 removal process. In this paper, an experimental investigation of this method is conducted to characterize the relationship between the root depth, the linewidth and the achievable thickness of the electroplated structures. Some test patterns with embedded roots have been designed and fabricated to estimate the possible size of various structures associated with different depths of niches, which are completely defined through the SiO_2 masking and KOH etching processes. Based on the established relationship between the root depth and the geometric sizes, a three-dimensional Ni coil, with a thickness of 200 μm, a width of 80 μm and a root depth of 4 μm, is successfully released by the SU-8 mold, which has a height of 400 μm. This cannot be achieved by the standard SU-8 molding process. The process parameters presented herein may be applied to the fabrication of other thick metal microstructures with similar needs.

1. Introduction

A metal structure with vertical sidewalls and a high aspect ratio can enhance the output force of a microactuator, such as a magnetic or an electrostatic actuator. Also, a thicker structure will increase the toughness of the components and prevent the microdevices from cracking due to mechanical failure or stress concentration during long-term operation. In order to achieve this, the photoresist, NANO™ XP SU-8 (MicroChem Corp. (MCC)), announced by IBM, has served as a mold to electroform the required metal structures in the production of microelectromechanical systems (MEMS) [1]. On account of its superior optical transparency and contrast under near-ultraviolet (near-UV) light, several studies have been carried out on using this photoresist for the patterning of ultra-thick structures and molds with highly vertical profiles. Currently, in a single-layer spin-coating, more than 500 μm thick photoresist and an aspect ratio of 18 can be achieved reproducibly [2]. To implement a process for metal microstructures, Lorenz *et al* [3] and Lee *et al* [4] attempted to fabricate various metal components, including microgears and microcoils, using the UV-LIGA technique with these resist molds.

Although a 500 μm thick SU-8 mold can be realized, it is rare for the thickness of the released electroplated structure standing on the substrate to reach more than 50 μm [3–5]. During the mold stripping process, the SU-8 photoresist will swell and deform when it is immersed in the standard commercial remover provided by MCC. For thicker (>100 μm) electroplated microstructures, a significant internal force induced at the interface between the metal component and the mold results in failure, either due to

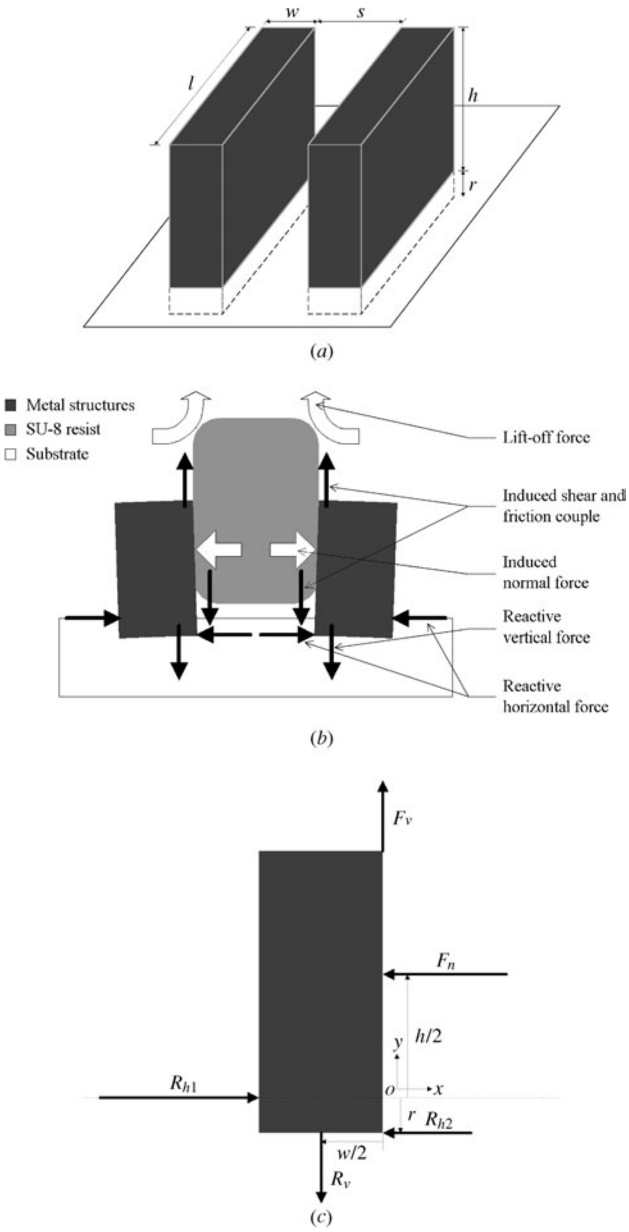


Figure 1. Illustration of the principles of an embedded root method for the removal of cross-linked SU-8. (*a*) Schematic diagram of the geometric arrangement of test metal structures. (*b*) SU-8 removal using a lift-off mechanism with commercial remover. (*c*) Free-body diagram of the metal structure.

resist remnant or structure ablation. In order to fabricate a thicker metal structure, which still adheres to the substrate after the mold removal, Ho *et al* [6] proposed an embedded root method to consolidate the binding of the electroplated microstructures with an underlayer. They also successfully applied this method to the fabrication of stators in an UV-LIGA micromotor. However, there has been no report on the relationship between the root depth and the achievable height of the electroplated structures.

Here, we conduct a detailed investigation of this method in order to characterize the relationship between the root depth, the linewidth and the reachable thickness of electroplated structures. Test patterns with various geometric linewidths were designed, and then thick SU-8 molds with patterned configurations were fabricated by near-UV lithography. Next, metal structures with various roots embedded in the wafer were electroplated to characterize the effects on reinforcing structural adhesion and sustaining internal force in the follow-up SU-8 removal process. The reference data that relate the linewidth to achievable thickness with different root depths can be established. Based on these reference data on the root depth and the achievable electroplated thickness, a three-dimensional (3D) Ni coil with a thickness of 200 μm was fabricated to demonstrate the feasibility and reliability of these reference data.

Table 1. Definition of symbols for the geometric arrangement of the test structures.

Symbol	Definition	Variety in size
r	Root depth of electroplated structure	0, 1, 4, 7 and 10 μm
l	Length of electroplated structure	1000 μm
w	Width (linewidth) of electroplated structure	20–200 μm at an interval of 20 μm
h	Height (thickness) of electroplated structure	240, 200, 160 and 120 μm
s	Space between two metal entities	20–200 μm at an interval of 20 μm
m	SU-8 mold thickness	300 μm

2. Principle of the embedded root method

Figure 1(*a*) and table 1 define the geometric arrangement of the test structures employed in this study. r denotes the depth of an electroplated root deposited in a niche constructed by SiO_2 masking and KOH etching processes. l, w and h denote the length, the width (i.e. the linewidth) and the desired height (i.e. the thickness) of the metal structure, respectively. s is the space, which is also the pattern width of the SU-8 mold, between two metal entities. The mold thickness (m, not shown here) is always kept constant at 300 μm in this study. To eliminate the size effect, the dimension of the pattern length l is designed to be at least five times longer than that of the pattern width w.

Compared to other approaches, such as chemical etchant [6, 7], O_2 plasma ashing [8] and excimer laser [9], applying the embedded root method to the removal of cross-linked SU-8 is a simpler resolution and is also compatible with the materials used in the UV-LIGA process. Figure 1(*b*) briefly illustrates the principle of the embedded root method and the SU-8 removal by a lift-off mechanism with a commercially available resist remover (the trade name is Remover PG), which is the standard remover provided by MCC. As shown in figure 1(*b*), when the hot remover is used, it detaches the cross-linked SU-8 photoresist from the surface of the wafer and provides a lift-off force to pull it off the substrate. However, the swell effect of SU-8 always generates extensive internal forces, including normal, shear and friction forces at the interface between the electroplated structure and the mold. With the root embedded in the substrate, a reactive force will be produced to withstand the internal force from the swollen resist. Hence, the SU-8 resist can be completely stripped in the lift-off process, and then the electroplated structure standing on the substrate can also be successfully released.

Typically, the lift-off force is particularly affected by the exposed sidewall height of the SU-8 mold. A thicker SU-8 mold m or lower metal structure h enables the remover to act on a relatively larger exposed area, which can make the stripping of the resist easier. In this study, therefore, the ratio of electroplated height to mold thickness (i.e. h/m) is assigned as the parameter for the characterization of the embedded root method. Experimental results will show that reducing the ratio h/m of the test patterns, either by decreasing the electroplated height or by increasing the mold thickness, may considerately facilitate the stripping of cross-linked SU-8 without resist remnant.

In addition to the thickness of metal structures and the SU-8 mold, the internal force may be dependent on the width of the cross-linked resist. A large internal force can result in the SU-8 being trapped in the gap between the metal structures when the standard remover is employed. Accordingly, the mold width s is also considered here as a parameter to evaluate the best achievable linewidth w of the metal structure.

On the other hand, the use of an embedded root is expected to provide a reactive force on the substructure to assist the electroplated microstructure to resist the induced normal, shear and friction forces. Figure 1(c) shows the front view of an electroplated entity, as illustrated in figure 1(a), in conjunction with forces acting on the sidewalls of the structure during the removal process of SU-8. For clarity, the distributed forces are simplified as forces concentrated at some given positions. From the free-body diagram in figure 1(c), three mechanical equations, according to elementary statics, can be obtained as

$$\sum F_x : R_{h1} - R_{h2} - F_n = 0 \tag{1}$$

$$\sum F_y : F_v - R_v = 0 \tag{2}$$

$$\sum M_o : F_n\frac{h}{2} + R_v\frac{w}{2} - R_{h2}r = 0 \tag{3}$$

where F_v denotes the shear and friction induced due to the lift-off mechanism, and F_n indicates the normal force generated by the swollen SU-8 resist. R_{h1}, R_{h2} and R_v are the reactive, horizontal and vertical forces exerted by the embedded root, respectively. In static equilibrium, the reactive forces can be expressed as

$$R_{h1} = \left(1 + \frac{h}{2r}\right) F_n + \frac{w}{2r} F_v \tag{4}$$

$$R_{h2} = \frac{h}{2r} F_n + \frac{w}{2r} F_v \tag{5}$$

$$R_v = F_v. \tag{6}$$

The relations obtained above show that, for a given electroplated height h and linewidth w, the root depth r dominates the strength of the reactive forces required to withstand the external forces F_n and F_v from the swollen SU-8 resist. From equations (4) and (5), we can see that a deeper root may reduce the necessary reactive forces against the internal forces. Therefore, a reasonable adjustment of the root depth r should be able to avoid structure ablation from the substrate during the mold removal process. In this investigation, various root depths r will be selected as another parameter to find the smallest linewidth w of the plated structure. For specific geometric dimensions (i.e. given l, w, s, and h/m) of the test structure, the root depth will vary in size; the five different sizes are 0, 1, 4, 7 and 10 μm in this investigation. The minimum root depth, which means the smallest root depth required among these five sizes to support the metal entity standing on the substrate without structure ablation, can then be determined. To obtain the optimum root geometry with better resolution, a finer interval in root depth needs to be further carried out.

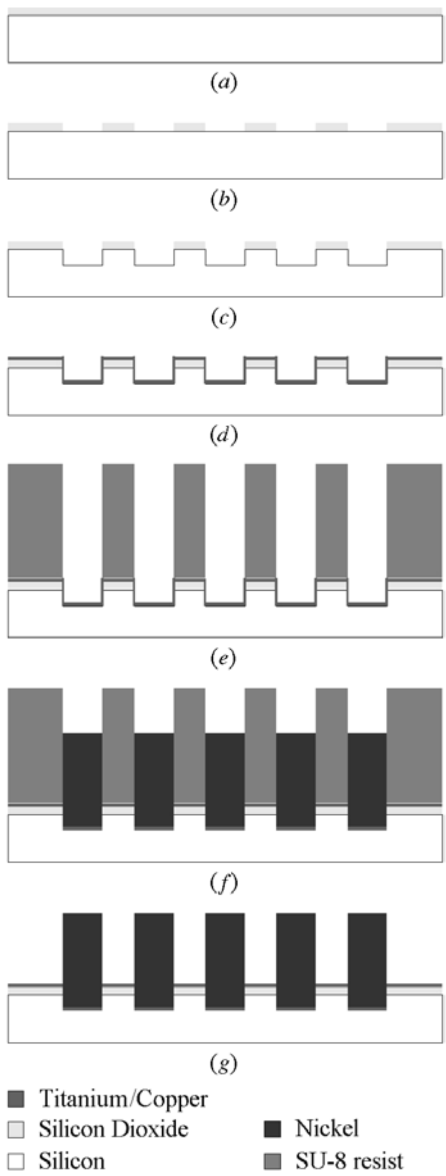


Figure 2. Fabrication processes of the UV-LIGA technique with root construction: (a) silicon dioxide layer formation; (b) oxide delineation as mask layer; (c) anisotropic etching in the silicon substrate; (d) adhesion/seed layer sputtering; (e) thick photoresist patterning and mold building; (f) metal structure electroplating; (g) mold removal in the final release.

3. Process design

Figure 2 shows a schematic diagram of the fabrication process of metal structures with embedded roots in this study. First, a (100) silicon wafer is thermally grown to produce a thick

Table 2. Parameter conditions of the UV-LIGA process with SU-8 mold.

Process step	Parameters	Equipment and chemical solvent
Thermally wet oxidation	1 μm thick1050 °C for 3.2 h	Quartz furnace
SiO_2 lithography	Standard recipe	FH 6400
SiO_2 wet etching	12 min immersion	BOE
Anisotropic etching	Root depths of 4, 7 or 10 μm 40% in weight, 80 °C 0.3 μm min^{-1} etching rate	Potassium hydroxide (KOH)
Seed layer deposition	Ti 500 Å, 0.23 Å min^{-1} Cu 5000 Å, 1.2 Å min^{-1}	Physical sputter

Table 3. Process conditions of NANO^{TM}XP SU-8 50 with a height of 300 μm.

Process step	Parameters	Equipment and chemical solvent
Dehydration bake	150 °C for 15–20 min	Vacuum oven No HMDS priming
Spin-coating	Spread: 300 rpm for 25 s Spin: 500 rpm for 45 s Acceleration: 100 rpm s^{-1}	Karl Suss GYRSET RC8 (Open)
Relaxation	0.5–1 min	
Mass measure	3.1–3.3 g	Precision balance
Soft bake	90 °C for 10 h	Hotplate
Relaxation	8 h	
Exposure	Dose 1350 mJ cm^{-3}	Karl Suss MJB3 Broad-band near UV
Post-exposure bake	90 °C for 20 min	Hotplate
Relaxation	24 h	
Development	20 min immersion	PGMEA from MCC Ultrasonic cleaner (optional)
Removal	70 °C for 12 h	Remover from MCC, Hotplate Ultrasonic cleaner (optional)

silicon dioxide layer (figure 2(*a*)). Notably, this layer is used as a shield mask for the later etching process to construct niches in the substrate. Following near-UV lithography, the insulation layer is patterned to expose the underlayer surface in the desired positions (figure 2(*b*)). The exposed places are the locations for the embedded roots. Next, an anisotropic etching process with a KOH solution is utilized to form the niches for subsequent electrodeposition of the root structures (figure 2(*c*)). The required depth of the embedded roots inside the substrate depends on the thickness of the electroplated structures, which will be discussed in section 4. To obtain conformal morphology of the root construction, an adhesive titanium layer and a copper layer are respectively deposited via sputtering (figure 2(*d*)). This bilayer serves as a conductive seed layer in the electroplating process. Then, SU-8 photoresist is spun over the seed layer using the near-UV-lithographic technique (figure 2(*e*)). The resist layer is delineated to build thick molds with niches in the substrate. This high-aspect-ratio mold is provided for electroplating desired Ni entities with roots within the niches (figure 2(*f*)). In the mold removal process, the standard remover is used to strip the polymerized resin (figure 2(*g*)). Fabrication results with different space, linewidth and root depth are then recorded to establish the reference data.

3.1. Parameter conditions

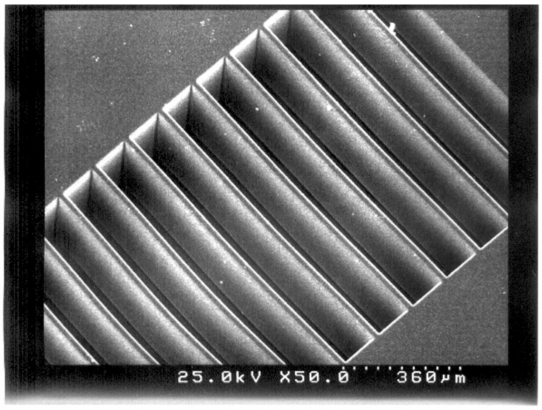
Table 2 displays the parameters used in realizing the UV-LIGA process with the SU-8 mold shown in figure 2. The thick silicon dioxide layer is 1 μm thick and needs to be isotropically wet etched for about 10 min in the standard buffered oxide etchant (BOE). In the niche construction, roots with a depth of 4 μm (1 μm SiO_2 + 3 μm Si), 7 μm (1 μm SiO_2 + 6 μm Si) and 10 μm (1 μm SiO_2 + 9 μm Si) are fabricated by hot KOH etchant (40% by weight, 80 °C). For the seed layer formation, Ti of 500 Å is sputtered on the substrate first, and then a 5000 Å thick Cu layer is superposed on this Ti layer.

Table 3 summarizes the process parameters and the related equipment in generating the 300 μm thick SU-8 molds. The resist molds are designed to be 20–200 μm in pattern width at intervals of 20 μm. Although the SU-8 photoresist has been widely employed in MEMS, recommended operational parameters differ in previous works [10–13]. As the SU-8 coating technique is yet not standardized, the process data depend not only on the fabrication facilities, but also on the structure geometry.

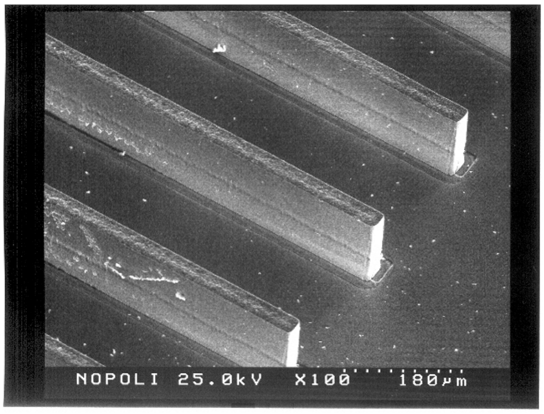
Following the niche construction and SU-8 mold preparation, samples are electroplated in a nickel–sulfamate-based solution. In this investigation, there are four types of Ni structure with different heights of 240, 200, 160 and 120 μm, respectively. Table 4 lists the bath conditions, including composition, pH and operational temperature.

4. Results and discussion

In this section we present the key results in the characteristic investigation of the embedded root method in the UV-LIGA process. Figures 3, 4 and 5 show some photographs of the

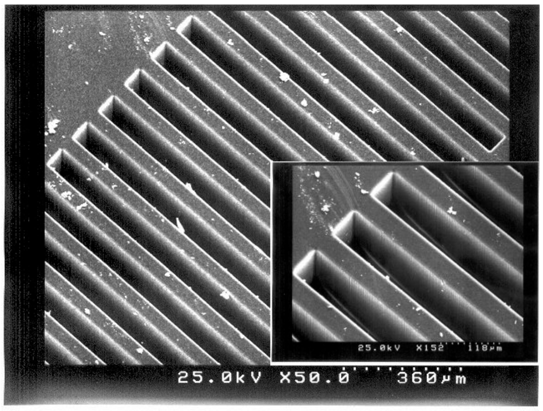


(*a*)

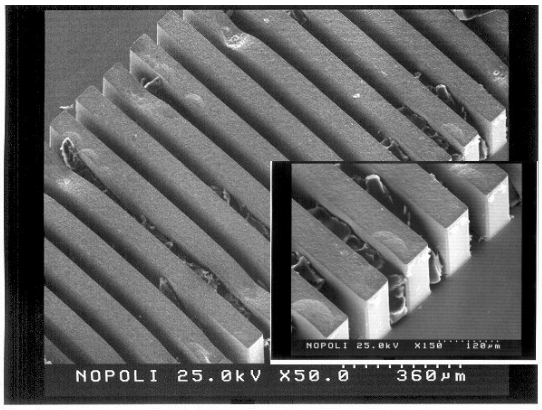


(*b*)

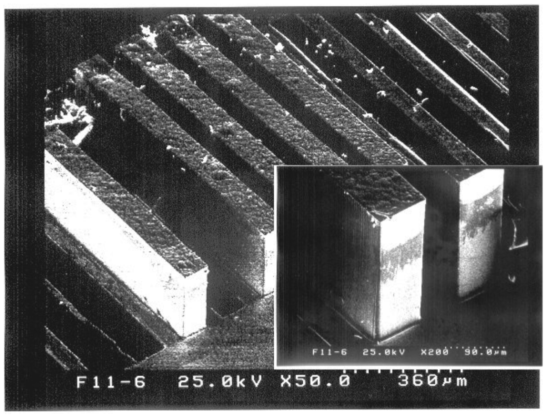
Figure 3. Achievable best resolution of SU-8 using the process conditions in table 3: (*a*) SU-8 molds, 300 μm in height h and 20 μm in resist space s; (*b*) Ni structures, 200 μm in height h and 40 μm in linewidth w.



(*a*)



(*b*)



(*c*)

Figure 4. SEM micrograph of SU-8 stripping via hot remover without embedded roots: (*a*) molds before electroplating; (*b*) SU-8 remnants after mold stripping; (*c*) SU-8 removal accompanied by ablation of metal structures.

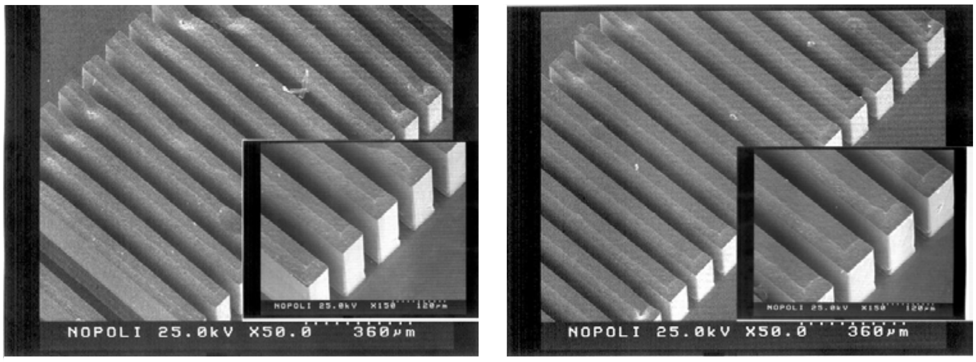
Table 4. Process conditions of the Ni electroplating bath.

Composition		Operational condition	
$Ni(NH_2SO_3)_2 \cdot 4H_2O$	450 g l^{-1}	pH value	4.6
$NiCl_2 \cdot 6H_2O$	3 g l^{-1}	Temperature	43 °C
H_3BO_3	35 g l^{-1}	Current density	1 A dm^{-2}
Wetting and leveling agent	a little	Flow of jet agitation	7 l m^{-1}

test microstructures, comprising SU-8 resist molds before electrodeposition and electroplated metal entities after the mold removal process. The experimental data pertaining to the relationship between geometric features and root structures are summarized in figure 6. These data will exhibit the limitations on reachable thickness of the electroplated microstructures with various root depths. Based on the established relationship, as shown in figure 7(*c*), a Ni coil with high aspect ratio is successfully fabricated, which cannot be achieved by the standard SU-8 molding process, as shown in figures 7(*a*) and (*b*).

4.1. SU-8 mold formation

Figure 3(*a*) shows a scanning electron microscopy (SEM) micrograph of the molds of the bar-shaped test structures made of SU-8 photoresist. In this study, the resist mold is fixed at the thickness of 300 μm (i.e. $m = 300$ μm) in all experiments. Using the lithographic parameters listed in table 3, we achieve an SU-8 structure with the best resolution of 20 μm in width and an aspect ratio of 15, where the resist width also represents the space s between metal entities, as shown in figure 1(*a*). However, with these given parameters, the smallest gap in the SU-8 mold is 40 μm, which will be the limitation on linewidth w of the electroplated metal structure. For w less than 40 μm, it is hard for the developer to flow into the deep trench of the



(*a*) (*b*)

Figure 5. Successfully released structures standing on the substrate: (*a*) structures with deep embedded roots (with a structure height of 160 μm, and root depth of 7 μm); (*b*) structures with height control in electroplated structures (with a structure height of 120 μm and root depth of 1 μm).

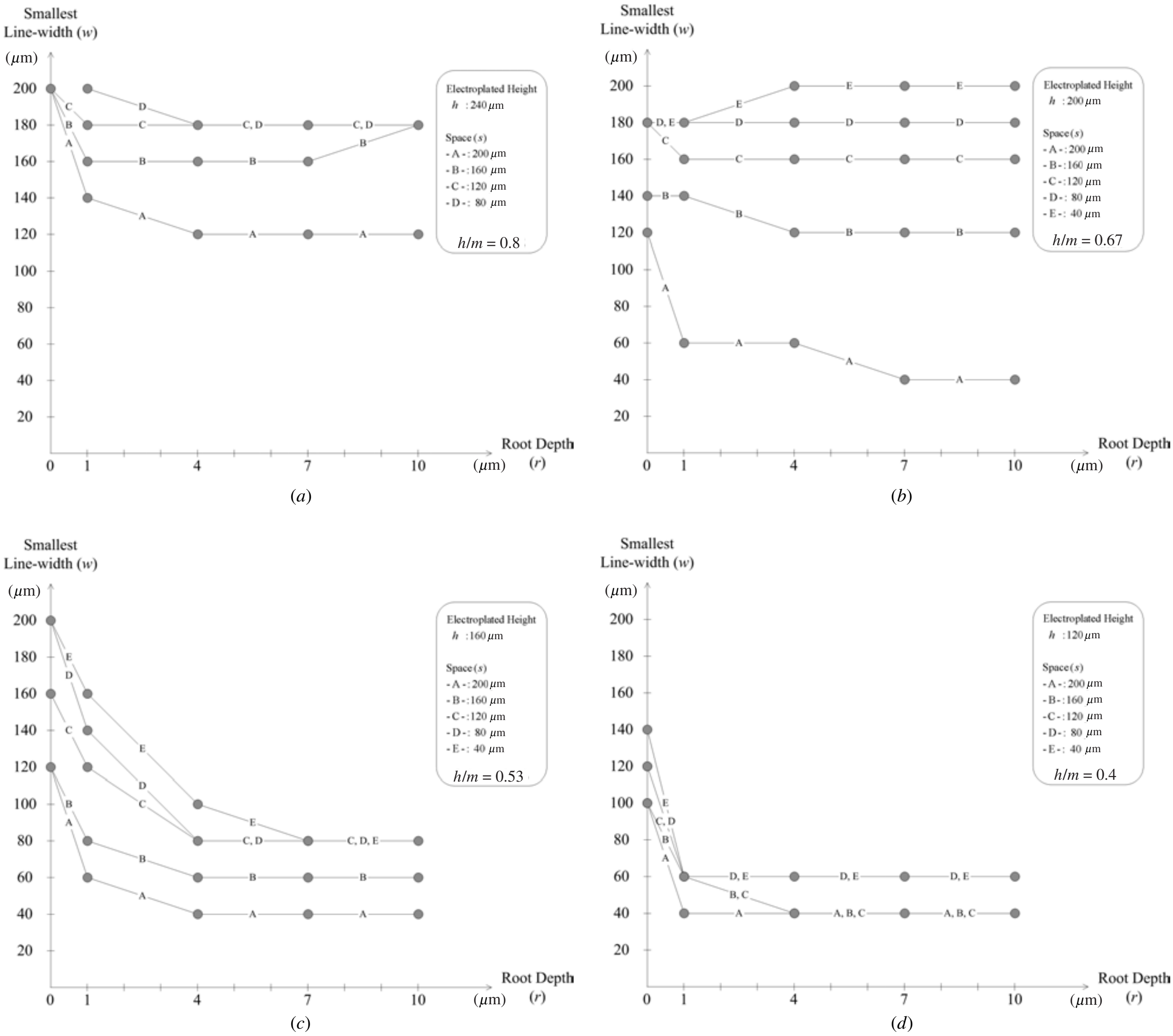
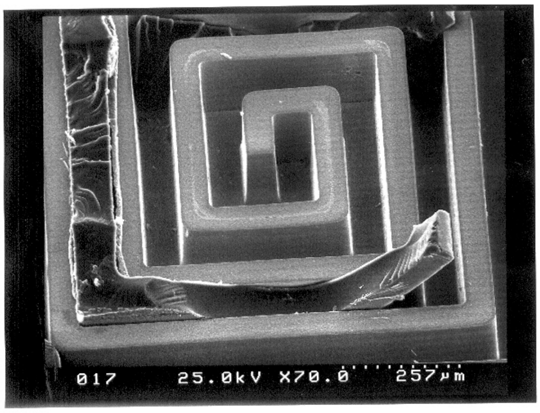
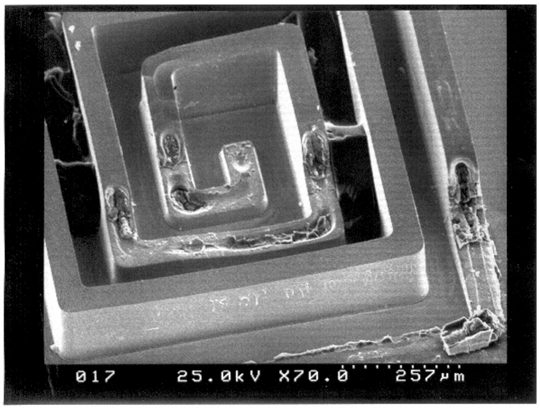


Figure 6. Relationship between root depth *r*, linewidth *w* and space *r* for electroplated structures with various heights *h*: (*a*) $h/m = 0.80$; (*b*) $h/m = 0.67$; (*c*) $h/m = 0.53$; (*d*) $h/m = 0.80$.

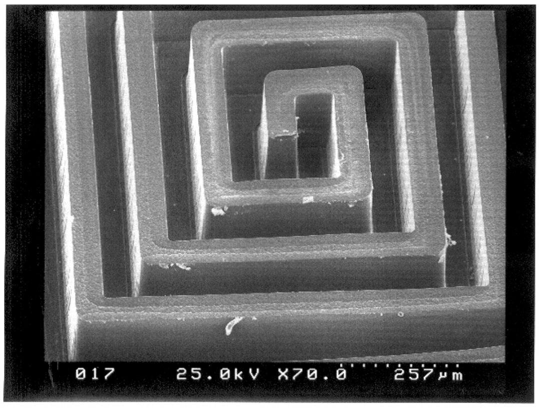
mold to completely clean the unexposed and uncross-linked SU-8 resist. Therefore, Ni metal cannot be deposited on the conductive Ti/Cu seed layer in the later electroplating process. Figure 3(*b*) exhibits the metal structures that are successfully



(*a*)



(*b*)



(*c*)

Figure 7. Fabrication of a Ni coil with an electroplated height *h* of 200 μm, linewidth *w* of 80 μm and space *s* of 80 μm: (*a*) photoresist residue; (*b*) structure ablation; (*c*) successful release by choosing h/m of 0.5 and *r* of 4 μm in the embedded root method.

electroplated in the mold with a linewidth *w* of 40 μm, after the final mold release process.

4.2. Structures without embedded roots

Figure 4 displays two typical problems when the cross-linked SU-8 mold is immersed in the hot remover for the stripping process. Figure 4(*a*) shows a mold, before electroplating, which is 40 μm in space *s*, 80 μm in width *w* and 300 μm in height *h*. After electroplating, the sample without the embedded root construction proceeds to the mold stripping process with the standard remover. For electroplated structures of 200 μm in height, segments of the photoresist are trapped in the substrate, particularly in the gap between two metal entities (figure 4(*b*)). This phenomenon may be caused by the horizontal and vertical internal forces, which are induced between the junctions of the seed layer, the Ni structure and the polymerized resist during the fabrication processes, such as lithography, electroplating and mold removal. Figure 4(*c*) presents another case that often appears when hot remover is employed to clean the cross-linked SU-8. Since the adhesion at the Ni/Cu interface cannot withstand the lift-off force, some electroplated metal structures (e.g. 160 μm in height, as in figure 4(*c*)) are also detached from the substrate when the mold is in the remover.

4.3. Structures with embedded roots

There are two key techniques to construct the electroplated structures while using SU8, including the embedded root method and using the height control in electroplating. During the SU-8 stripping process, swell and deformation of the photoresist induce significant stress on the electroplated structures. With roots embedded in the substrate, the electroplated structures become stronger at withstanding the stress from the swollen SU-8 resist. On the other hand, when the height of the electroplated structure is scaled down, the remover can reach more SU-8 resist to increase lift-off force. Simultaneously, the contact area between the photoresist mold and the electroplated structure also becomes smaller and, therefore, the resultant clamping force on the mold can be effectively reduced, which will help in the successful removal of the SU-8 resist in the lift-off process.

With the same size of SU-8 mold shown in figure 4(*a*), successfully released structures standing on the substrate are presented in figure 5. Figure 5(*a*) shows the electroplated entities, 160 μm in height and 80 μm in width, where a root, 7 μm deep, is embedded in the substrate. Using the root construction, the metal structures can endure the internal force from the swollen photoresist during the mold stripping with hot remover. Additionally, an ultrasonic vibration is also utilized to assist this removal process. For a non-rooted structure, the vibration of the ultrasonic cleaner makes the electroplated entity ablation more serious during the mold removal process since the adhesion between the structure and the substrate is weak. For a structure with an embedded root, this adhesion is now greatly improved and, therefore, the mold removal process assisted by an ultrasonic cleaner works excellently. Figure 5(*b*) illustrates the electroplated structures, 120 μm in height and 80 μm in width, with a root depth of 1 μm inside the substrate. A reduction in the electroplated thickness (e.g. 120 μm thick structures for 300 μm thick molds in this example) is shown to be helpful in the lift-off of SU-8. Consequently, only 1 μm of an embedded root is needed for stripping the cross-linked photoresist as well.

4.4. Relationship between root depth and geometric dimensions

Figure 6 summarizes the experimental results of the relationship between the root depth *r*, the linewidth *w*, the space s and the allowable thickness h of the electroplated structure. The gray circles in figure 6 represent the smallest linewidths achieved under specific dimensions (i.e. given r, w, s and h/m). In our mask design, each die with specific dimensions consists of 20 identical bar-shaped test samples. The presented plots are verified by at least two dies, where all 40 test samples firmly stand on the substrates without structure ablation or photoresist residue after the final release. During this experiment, the SU-8 mold m is fixed at a thickness of 300 μm, and the electroplated structures are varied with heights of 240, 200, 160 and 120 μm. As shown in figures 6(*a*)–(*d*), the experimental data are divided into four groups according to the parameter h/m.

For thicker metal structures, where the parameter h/m is 0.80 or 0.67 as illustrated in figures 6(*a*) and (*b*), the cross-linked SU-8 is very difficult to remove with hot remover, even with ultrasonic vibration. The stripping process chiefly fails because of residual resist wedged into the gaps between the structures. In h/m of 0.80, the smallest linewidth w that can be achieved is 120 μm when the space s is 200 μm and the root depth is at least 4 μm (curve A, figure 6(*a*)). Since a relatively large value of h/m will restrict the lift-off force applied to the mold and cause resist remnant, an increment in root depth r cannot effectively solve the SU-8 trapping problem. However, an enlargement of the space s is evidently helpful for linewidth reduction due to the decrease of the internal force F_n induced between the mold and the structure. As shown in figure 6(*b*), for example, in the case of metal structures 200 μm in height ($h/m = 0.67$), a larger space s can produce smaller linewidth w of the metal entities. Consequently, with a finite area (e.g. $w + s = \text{constant}$) of a substrate, the trade-off between the linewidth w and the space s is evident for thick structures.

For lower metal structures, where h/m is 0.53 or 0.40, as illustrated in figures 6(*c*) and (*d*), the stripping process primarily fails by structure ablation, when the mold is detached from the substrate. Accordingly, an increment in the root depth r will help the electroplated structure stand on the substrate and withstand the internal force from the swollen resist. Figure 6(*c*) shows the distinct effects between the linewidth w and the root depth r. For h/m of 0.53 ($h = 160$ μm), for example, when space s is 80 μm (curve D), the smallest metal structures have linewidths w of 200, 140 and 80 μm for root depths of 0, 1 and 4 μm, respectively. For the 4 μm deep root in curve D, the smallest linewidth is 2.5 times smaller than that without using the embedded root method. With larger spaces s of 160 and 200 μm, the smallest linewidth can be further reduced to 60 and 40 μm, respectively, at a root depth of 4 μm, as shown in curves B and A of figure 6(*c*), respectively. For a further lower ratio h/m, figure 6(*d*) indicates the characterization of the embedded root method with the electroplated height of 120 μm. Based on such low structural thickness ($h/m = 0.40$), the root depth just needs to be 1 μm for the smallest linewidth to be achieved at around 40–60 μm under SU-8 molds with various sizes of space. This means that for $h \leqslant 120$ μm, $s \geqslant 60$ μm and $m = 300$ μm, a root depth of 1 μm is sufficient to resist the internal force induced during the SU-8 mold removal process.

Referring to equations (4) and (5) in section 2, which imply a reduction in the necessary reactive forces against the internal forces by having a deeper root, although these forces are difficult to identify, the experimental data in figure 6 do verify this trend. For example, from figure 6(*c*), in the case of $h/m = 0.53$ ($h = 160$ μm, $m = 300$ μm) and $s = 200$ μm (curve A), without the root structure, the linewidth w of 60 μm cannot be achieved. When a root depth of 1 μm is constructed, the linewidth of $w = 60$ μm can be achieved. When a root depth of 4 μm is constructed, an even smaller linewidth ($w = 40$ μm) can be achieved. These results are consistent with equations (4) and (5). However, the embedded root method is not so effective in eliminating the trapping of photoresist residues between gaps. Therefore, in figures 6(*a*) and (*b*), when the electroplated metal structure height is closer to the SU8 thickness ($h/m = 0.80$ and 0.67, respectively), the improvements on the smallest linewidth by the embedded root method are not so evident since most of the failures are caused by the trapping of photoresist residues.

Table 5. Correlation and significance of r, s and w by statistical analysis. For $\alpha = 0.01$, significant thresholds are $CC_{\text{sign}(df=17)} = 0.575$ in h/m of 0.80 and $CC_{\text{sign}(df=23)} = 0.505$ in h/m of 0.67, 0.53 and 0.40.

Statistical analysis	Correlation coefficient	
	r versus w	s versus w
h/m	CC_{rw}	CC_{sw}
0.80	−0.324	−0.632
0.67	−0.114	−0.898
0.53	−0.666	−0.529
0.40	−0.612	−0.315

Further confirmation of the relationship among the parameters can be realized via a correlation estimation in statistical analysis [14, 15]. Table 5 lists the correlation and significance test of three key parameters r, s, and w at four h/m ratios. Under a level of significance α of 0.01, the correlation coefficient CC_{rw} exhibits significantly negative correlation between the root depth r and the linewidth w for h/m of 0.53 and 0.40. Similarly, referring to the correlation coefficient CC_{sw}, high negative correlation between the space s and the linewidth w is verified for h/m of 0.80, 0.67 and 0.53 by the significance test.

4.5. Ni coil fabrication

By properly using the ratio of the electroplated height h to the mold thickness m and the reference data in figure 6, Ni coils with various mold thickness and structure height have been fabricated to demonstrate the parameter selection in using the embedded root method. Figures 7(*a*) and (*b*) show the failed Ni coils due to photoresist residue and structure ablation, without embedded roots, and figure 7(*c*) shows the successfully released Ni coil using the embedded root method, where the height h of the Ni coil is 200 μm, the linewidth w is 80 μm, and the space s is also 80 μm. By patterning the SU-8 mold, with a thickness of 400 μm, the corresponding h/m becomes 0.5. Then according to curve D in figure 6(*c*), where s is 80 μm and w is 80 μm, a root depth of 4 μm is shown to be able to construct the Ni coil with the desired geometry.

5. Conclusions

In this paper, we have performed a characterization study of the embedded root method to establish useful reference data for the UV-LIGA process with SU-8 photoresist. Some test structures have been fabricated to investigate the relationship between the root depth, the linewidth and the feasible thickness of electroplated structures. Various niche depths are defined by SiO_2 masking and KOH etching processes. The metal structure is then electroplated with the root embedded in the substrate to reinforce structural adhesion and resist internal force in the subsequent SU-8 removal process. From the experimental results, it is found that, with a lower ratio h/m of 0.53 or 0.40, the embedded root method is particularly effective in solving the problem of structure ablation during the stripping of the cross-linked SU-8. Using these reference data, a Ni coil with an embedded root can be successfully released by choosing a proper root depth and the ratio of the electroplated height to the mold thickness. The electroplated Ni coil, at least 200 μm thick, 80 μm in width and with a root depth of 4 μm, can be achieved by an SU-8 mold with a thickness of 400 μm, whereas the traditional standard method can fabricate the same coil with a thickness of only about 50 μm. The techniques outlined here may help to avoid the problem of the hard-to-strip polymerized SU-8 resist and assist the fabrication of other microstructures with similar needs.

In fabrication, the embedded root method requires extra processing cost for root construction, which can be achieved easily using a standard wet or dry etching facility. However, the root-constructed process presented here belongs to the bulk-micromachining technique, in which it is necessary to etch the substrate. If an integrated circuitry is needed on the common substrate, the available area for the circuit will be reduced. In the future, a root-construction process based on the surface micromachining technique may be developed to form a thick passivation layer above the active area to protect the circuit and also to serve as the base for root construction.

References

[1] IBM Corp. 1989 US Patent No. 4 882 245

[2] Lorenz H, Laudon M and Renaud P 1998 Mechanical characterization of a new high-aspect-ratio near UV-photoresist *Microelectron. Eng.* **41–42** 371–4

[3] Lorentz H, Despont M, Fahrni N, LaBianca N, Renaud P and Vettiger P 1997 SU-8: a low-cost negative resist for MEMS *J. Micromech. Microeng.* **7** 121–4

[4] Despont M, Lorenz H, Fahrni N, Brugger J, Renaud P and Vettiger P 1997 High-aspect-ratio, ultrathick, negative-tone near-UV photoresist for MEMS applications *Proc. IEEE Micro Electro Mechanical Systems (MEMS)* p 518–22

[5] Chang H K and Kim Y K 2000 UV-LIGA process for high aspect ratio structure using stress barrier and C-shaped etch hole *Sensors Actuators* A **84** 342–50

[6] Ho C H, Chin K P, Yang C R, Wu H M and Chen S L 2002 Ultrathick SU-8 mold formation and removal, and its application to the fabrication of LIGA-like micromotors with embedded roots *Sensors Actuators* A **102** 130–8

[7] Dentinger P M, Clift W M and Goods S H 2002 Removal of SU-8 photoresist for thick film applications *Microelectron. Eng.* **61–62** 993–1000

[8] Chang S C and Kempisty J M 2002 Lift-off methods for MEMS devices *Mater. Res. Soc. Symp. Proc.* **729** 47–56

[9] Ghantasala M K, Hayes J P, Harvey E C and Sood D K 2001 Patterning, electroplating and removal of SU-8 moulds by excimer laser micromachining *J. Micromech. Microeng.* **11** 133–9

[10] Zhang J, Tan K L, Hong G D, Yang L J and Gong H Q 2001 Polymerization optimization of SU-8 photoresist and its applications in microfluidic systems and MEMS *J. Micromech. Microeng.* **11** 20–6

[11] Ling Z G, Lian K and Jian L 2000 Improved patterning quality of SU-8 microstructures by optimizing the exposure parameters *Proc. SPIE* **3999** 1019–27

[12] Eyre B, Blosiu J and Wiberg D 1998 Taguchi optimization for the processing of Epon SU-8 resist *Proc. IEEE Micro Electro Mechanical Systems (MEMS)* p 218–22

[13] Brunet M, O'Donnell T, O'Brien J, McCloskey P and Mathuns S C O 2002 Thick photoresist development for the fabrication of high aspect ratio magnetic coils *J. Micromech. Microeng.* **12** 444–9

[14] Fisher S R A 1970 *Statistical Methods for Research Workers* 14th edn (New York: Hafner)

[15] Odeh R E, Owen D B, Birnbaum Z W and Fisher L 1977 *Pocket Book of Statistical Tables* (New York: Marcel Dekker)