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Sensors and Actuators A 102 (2002) 130–138

SENSORS AND ACTUATORS A PHYSICAL

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Ultrathick SU-8 mold formation and removal, and its application to the fabrication of LIGA-like micromotors with embedded roots

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Received 5 April 2001; accepted 28 July 2002

Abstract

In this study, a novel method to completely remove crosslinked SU-8 without remnants of the resist or destroying the electroplated microstructures was utilized. The LIGA-like fabrication of a side-driven electrostatic micromotor was employed as an example to describe polymerized SU-8 resist removal. Using near-UV light, nickel components of the micromotor were electroplated 160 μm in a 300 μm-thick SU-8 mold. A comparison of various approaches based on a commercial remover was performed during the mold removal process. Experimental results showed that components having 1 μm-deep substructures embedded in the substrate could provide stronger structures to withstand the internal stress due to the photoresist deformation. In addition, when the height of the electroplated structure was below two-thirds of the photoresist mold thickness, the net clamping force on the resist could be effectively reduced to make the removal of SU-8 with heated remover successfully. The rotor and the stator with embedded roots were released cleanly and thereby, assembled to form a high-aspect-ratio micromotor. The technique of SU-8 removal and LIGA-like process presented herein can be applied to the fabrication of other high-powered microactuators.

Keywords: Microactuator; Micromotor; SU-8; UV-LIGA; LIGA-like; Root construction

1. Introduction

The actuation principle of movable devices in micro-electro-mechanical systems (MEMS) may be classified into many types, including magnet, heat, piezoelectricity, and static electricity. In these devices, three-dimensional micro-structure with a vertical sidewall of several hundred micrometers in height is preferred. For example, in the field of static electricity-driven microactuators, this higher structure will increase the toughness of the components and provides greater attractive force, if the capacitive plates are designed laterally.

Since 1988, many researchers have applied extended integrated circuit (IC) process to fabricate movable mechanical structures [1,2]. Numerous authors have developed micromachining technology to manufacture micromotors [3–6]. Utilizing surface-micromochining, Mehregany et al. [7] presented a detailed fabrication process of micromotors and related critical issues. To improve the micromotor's output torque, electrodeposition technique was applied to fabricate high-aspect-ratio rotors and stators to increase capacitive area [8–10]. In addition, as the thickness of micromotors has increased, assembly technology has been proposed recently to avoid the sacrificial layer preparation and the final etching process. Via Lithographie, Galvanoformung, and Abformung (LIGA) and deep reactive ion etching (DRIE) processes, Yasseen et al. [11] depicted an assembled rotary electrostatic micromotor that was 200 μm thick and had a 1 mm diameter. Samper et al. [12] demonstrated a multi-stator, LIGA-fabricated electrostatic micromotor which was realized with a nickel stator cylinder and was approximately 2.5 mm in diameter and 250 μm in thickness.

Although the X-ray LIGA and DRIE techniques have greatly improved the output torque of micromotors, advanced equipment as well as complicated fabrication procedures have become an evident burden to production cost. Hence, it would be ideal if traditional IC equipment and near-UV resist were adequate for manufacturing high-powered micromotors.

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PII: S0924-4247(02)00297-2

A new photoresist, NANO^{TM} XP SU-8 (MicroChem Corp. (MCC)), which was recently announced by IBM, can facilitate low-cost MEMS fabrication [13]. Using this photoresist, several studies have been conducted on the patterning of an ultrathick structure with a vertical sidewall. With a single layer coating, more than 500 μm-thick resist and an aspect ratio of 18 were achieved reproducibly [14]. With its superior aspect ratio, vertical sidewall, and stable characteristics within a nickel–sulfamate solution, SU-8 is also an excellent molding material for the electroplating process. To fulfill metallic structure's requirements, Lorenz et al. [15] and Lee et al. [16] electroplated various metallic-components, including microgears and microcoils, via an SU-8 mold and electrodepositon technique. However, effective methods to strip UV-exposed and thermal-crosslinked SU-8 have not been developed. In fact, limited information exists on mold removal technique, which successfully releases the electroplated components.

As SU-8 is an epoxy-typed, near-UV negative photoresist, such molecular structures will be cured in heat treatment to form a three-dimensional network, which is denominated curing or crosslink to describe the process that transforms one or more low molecular-weighted reactants into high molecular-weighted crosslinked networks [17]. So far there has been no effective wet etchant or stripper found out to normally dissolve the cured SU-8 mold as well as not to destroy structural entities. The utilization of Remover PG, which is provided by MCC, may remove the resist from the substrate by lift-off mechanism [18]. However, during this stripping process, the swelling effect of SU-8 always generates extensive internal stress at the interface, resulting in either resist remnant between structure gaps or structure ablation.

The purpose of this study was to investigate the removal process of the crosslinked SU-8 mold after electroplating during the manufacturing of a salient-poled, side-driven capacitive micromotor. Niches were initially defined on the substrate through the wet etching process. Then the SU-8 mold was constructed by the near-UV lithography technique. Via electroplating in a nickel–sulfamate-based solution, the stator and the bearing post were deposited gradually within the niches and the SU-8 mold. With the root of the electroplated component embedded in the substrate, our experiments demonstrated that a heated commercial remover could easily remove the crosslinked SU-8 mold. Consequently, with a released stator and rotor, a prototype of the LIGA-like micromotor was assembled successfully.

The remainder of this paper is organized as follows: Section 2 presents a detailed description of the methods adopted to fabricate the LIGA-like micromotor as well as to completely remove the crosslinked SU-8 photoresist. Section 3 provides experimental results and a discussion of SU-8 removal techniques, which are based on a commercial remover. Finally, Section 4 presents the conclusion of the work.

2. Method

Within a traditional electrodeposition process, microstructures are plated on a flat surface. Weak material bonding at the interface between two layers cannot sustain the

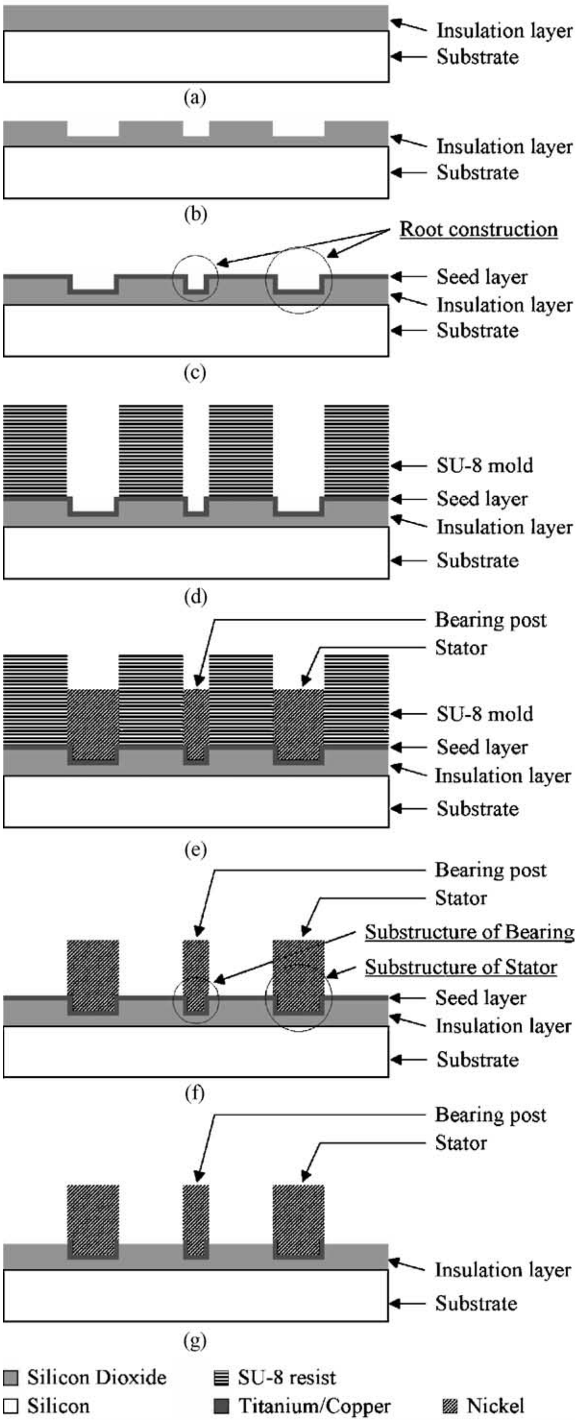

Fig. 1. Partial fabrication processes of LIGA-like micromotor with root construction. (a) Thermal oxidation. (b) Wet etching. (c) Seed layer sputtering. (d) Thick photoresist patterning, and mold building. (e) Stator and bearing electroplating. (f) Mold removal. (g) Selective etching and final release.

internal stress, and therefore, during subsequent SU-8 removal microstructures disjoin from the substrate easily. In the following section, procedures are proposed to facilitate crosslinked SU-8 mold removal and electroplated microstructure release. These procedures focus on root construction and substructure formation via electroplating.

2.1. Procedures to fabricate a micromotor and to remove a crosslinked SU-8 mold

The LIGA-like fabrication of a side-driven electrostatic micromotor was employed as an example to describe SU-8 removal procedures. Fig. 1 illustrates major steps for stator and bearing post fabrication and crosslinked SU-8 removal. To simplify, however, the processes to fabricate the insulation layer and the interconnection between the bonding pad and the stator have been neglected. The procedure illustrated in Fig. 1 is as follows.

First, an (1 0 0)-oriented silicon wafer was thermally oxidized to produce a 1.6 μm-thick silicon dioxide layer (Fig. 1(a)). Notably, this layer isolates the device from the substrate during high driving actuation voltage. Following UV-lithography and HF wet etching, the insulation layer was patterned 1 μm in depth in several places to form bowl-shaped cavities (Fig. 1(b)). These cavities will be electroplated in the later process to form the root structures of the stator and bearing post. To obtain conformal morphology of the root construction, first a 500 Å adhesive titanium layer and then a 5000 Å copper seed layer were deposited via physical sputtering. With good step coverage of Ti/Cu on the substrate, the root structures in niches can be constructed successfully (Fig. 1(c)). This bi-layer will also serve as a shield film and conductive electrode in later fabrication processes. Following Ti/Cu deposition, a thick SU-8 photoresist was spun over the seed layer via UV-lithography technique, which was then patterned to construct a 300 μm mold (Fig. 1(d)). Via Ni electrodeposition, this high-aspect-ratio mold was employed to electroplate the stator and the bearing structures (Fig. 1(e)). During the mold removal process, NANO^{TM} Remover PG removed SU-8 polymer resin completely (Fig. 1(f)). Since special substructures embedded in the niches consolidate Ni/Cu interface adhesion, the crosslinked SU-8 decomposes into several pieces easily when the commercial stripper is applied. Finally, after the seed layer was oxidized via the wet etching process,

Table 1
Process conditions of NANO^{TM} XP SU-8 50 for 300 μm in height

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 15 s; spin: 350 rpm for 30 s; acceleration: 100 rpm/s	Karl Suss; GYRSET RC8 (open)
Relaxation	0.5–1 min	
Mass measure	3.1–3.3 g	Precision balance
Soft bake	90 °C for 8.5 h	Hotplate
Relaxation	9 h	
Exposure	Dose: 1350 mJ/cm^3	Karl Suss MJB3; broad band near UV
Post-exposure-bake	90 °C for 20 min	Hotplate
Relaxation	48 h	
Development	20 min immersion	PGMEA from MCC; ultrasonic cleaner (optional)
Curing (optional)		
Removal	80 °C for 8 h	Hot REMOVER PG from MCC; Hotplate
Rinse	5 min	Acetone and DI Water; ultrasonic cleaner (optional)

Room temperature: 24 °C, humidity: 71%.

Table 2
Process conditions of Ni electroplating bath

Composition	Operational condition
$Ni(NH_2SO_3)_2 \cdot 4H_2O$ (450 g/l)	pH value (4.3–4.5)
$NiCl_2 \cdot 6H_2O$ (3 g/l)	Temperature (43 °C)
H_3BO_3 (35 g/l)	Current density (1 A/dm^2)
Wetting and leveling agent (a little)	Flow of jet agitation (5 l/m)

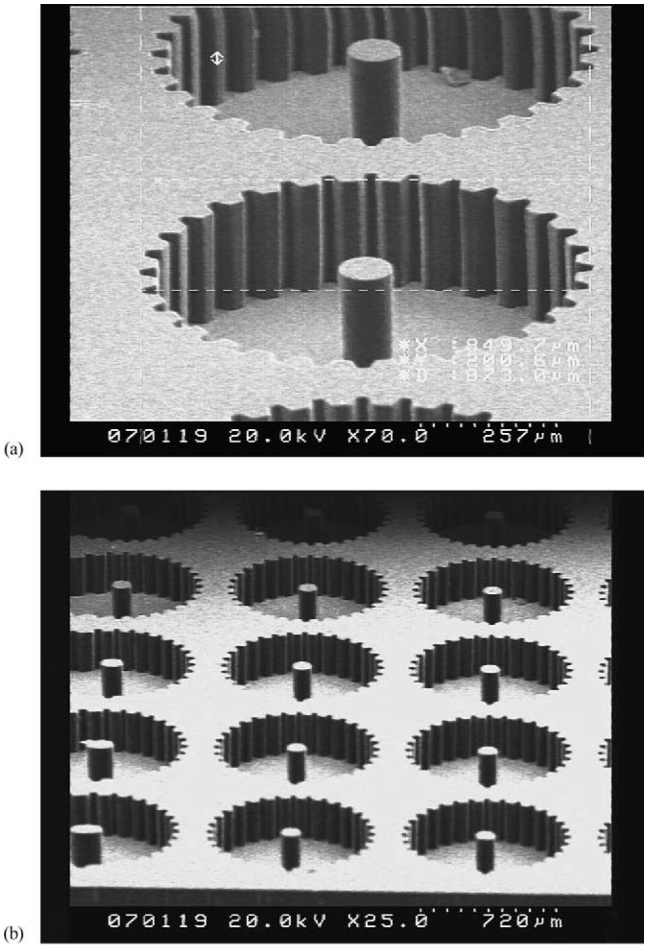

Fig. 2. Batch-fabricated microgear molds by SU-8 50. (a) SEM close-up of microgear molds. (b) An overall view of microgear molds.

the stator and the bearing post, with their roots embedded in the substrate, were released successfully (Fig. 1(g)).

2.2. Experimental conditions

Although SU-8 photoresist has been widely employed in MEMS recently, fabrication parameters differ in each published reference. As the SU-8 coating technique is yet not standardized, detailed fabrication conditions depend not only on the local experimental equipment, but also the geometrical structures. Table 1 presents the process parameters and the related equipment to create the 300 μm-thick SU-8 micromotor mold. In order to derive the precise baking time, the required quantity of SU-8 resist spun on the wafer was estimated by measuring the weight of the wafer both before and after coating. To promote resist reflowing and eliminate the edge bead, the coated wafer was left alone for 0.5–1 min during the first relaxation process. To prevent the solid resist film from thermal shock, the post-exposure-baked (PEB) wafer was placed on the hotplate to cool gradually to the ambient temperature. During the PEB process, crosslinking occurred effectively in only the regions with a photoacid catalyst that photochemical transformation produced. Moreover, to ensure absolute polymerization, a second relaxation, which continued for 48 h, was consistently performed following UV light exposure and the PEB process.

Following root construction and SU-8 mold preparation, the wafer was electroplated in a nickel–sulfamate-based solution. The bath condition, including solution composition, pH and operational temperature, can be referred to Table 2. The deposited height of nickel structures was fixed at half to two-thirds of the mold's thickness. In the mold removal process, the wafer was immersed in the 80 °C hot NANO^{TM} Remover PG. During this process, the crosslinked SU-8 broke into several pieces and was separated from the substrate without causing Ni structures ablation or mold remnants. Substructures embedded in the substrate enforced the adhesion of the Ni structures to the substrate and resisted interfacial stress between Ni structures and SU-8. Thus, due to this removal process, the mold was completely cleaned.

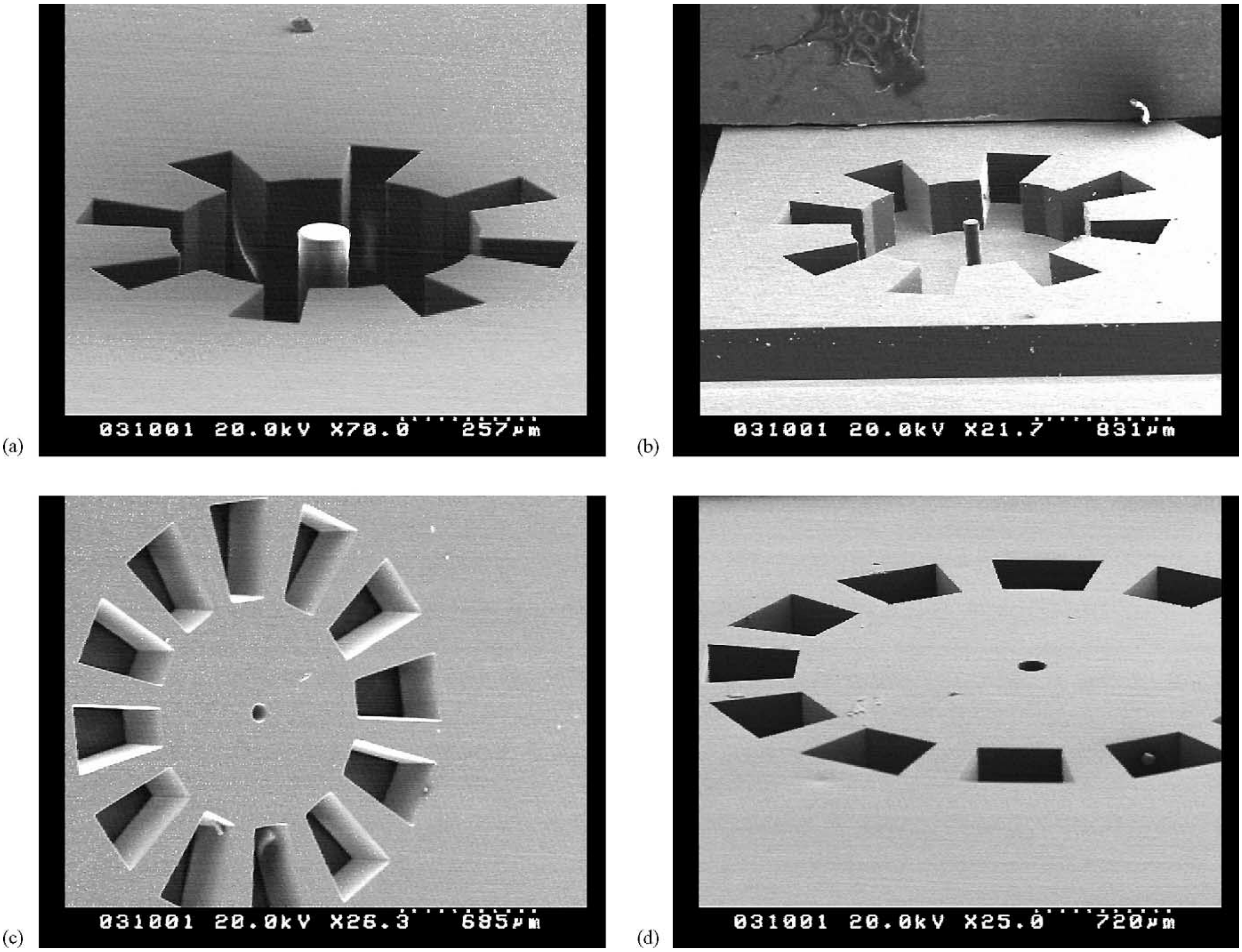

Fig. 3. Molds of rotors and stators for various scales that were patterned using SU-8 50. (a) A rotor's mold 500 μm in thickness and 980 μm in diameter. (b) A rotor's mold with a bearing post 90 μm in height. (c) A stator's mold 1 mm in inner diameter and central hole of 80 μm. (d) The smooth surface of a stator's mold.

In the selective etching and releasing processes, diluted nitride acid with HNO_3:$H_2O = 2{:}1$ was initially applied to react with the copper seed layer. Then, hydrofluoric acid of 5 vol.% etched away the exposed titanium adhesion layer. Finally, the released rotor and stator were successfully assembled under a microscope to form an integrated micromotor.

3. Results and discussion

In this section, high-aspect-ratio test structures and micromotor's molds comprised of SU-8 are first displayed to exhibit the potentials for this photoresist in MEM fabrication. Next, via an SU-8 mold, nickel structures of the stator and the bearing post are depicted to demonstrate the feasibility of the electroplating technique. Then, a comparison of the mold removal methods, which are based on NANO^{TM} REMOVER PG is investigated and discussed. Finally, a prototype of the assembled micromotor is presented.

3.1. SU-8 mold structures

Fig. 2(a) and (b) shows an SU-8 mold for test structures of batch-fabricated microgears. The mold was about 230 μm in height and Table 1 displays the process conditions. This experimental result proves that SU-8 is capable of producing microstructure with vertical sidewall and superior aspect ratio, and has stable characteristics to be the mold for the subsequent electroplating process.

Fig. 3(a) and (b) shows a scanning electron micrograph (SEM) of the rotor's molds of different sizes, which was created with SU-8 photoresist. The outer diameter of the rotor in Fig. 3(a) was 980 μm and the thickness in the figure measured nearly 500 μm. The slender cylinder located centrally within the mold would be the bearing hole after electroplating and was 90 μm in diameter (Fig. 3(b)). From the basic capacitance equation with two parallel conductive plates, the transversal force between the rotor and stator is proportional to the height of the components. Compared with the rotor developed by Mehregany et al. [7], this component is much higher and, therefore, may provide more output torque when driven by the same voltage. Fig. 3(c) displays the SEM of the stator's mold, which matched the rotor's mold of Fig. 3(a). The inner diameters of the stator and the central hole in the mold were 1 mm and 80 μm, respectively, and the thickness of this mold was identical to that of the rotor's. Notably, to ensure successful assembly the bearing hole on the rotor is slightly wider than the bearing post located at the center of the stator. The gap between the rotor and stator is 10 μm. Therefore, if the rotor tilts or wobbles during operating, approximately 5 μm of clearance exists between the two components. Also, in Fig. 3(d), the SU-8 mold has an extremely smooth surface. To acquire such a mirror-like surface, the photoresist spinner should maintain a level rotary vacuum chuck and a moderately long spin stage.

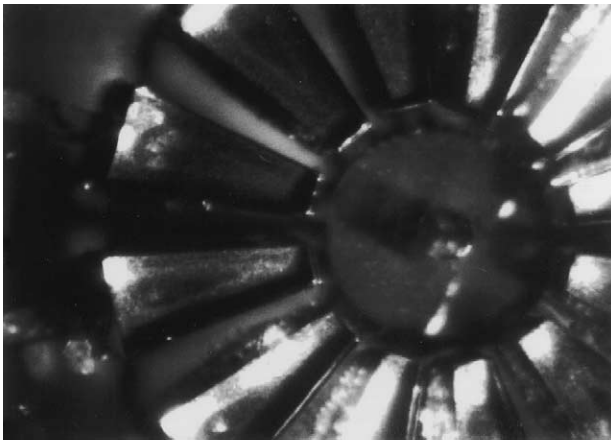

Fig. 4. An optical microscope micrograph of a Ni-electroplated stator before SU-8 mold removal.

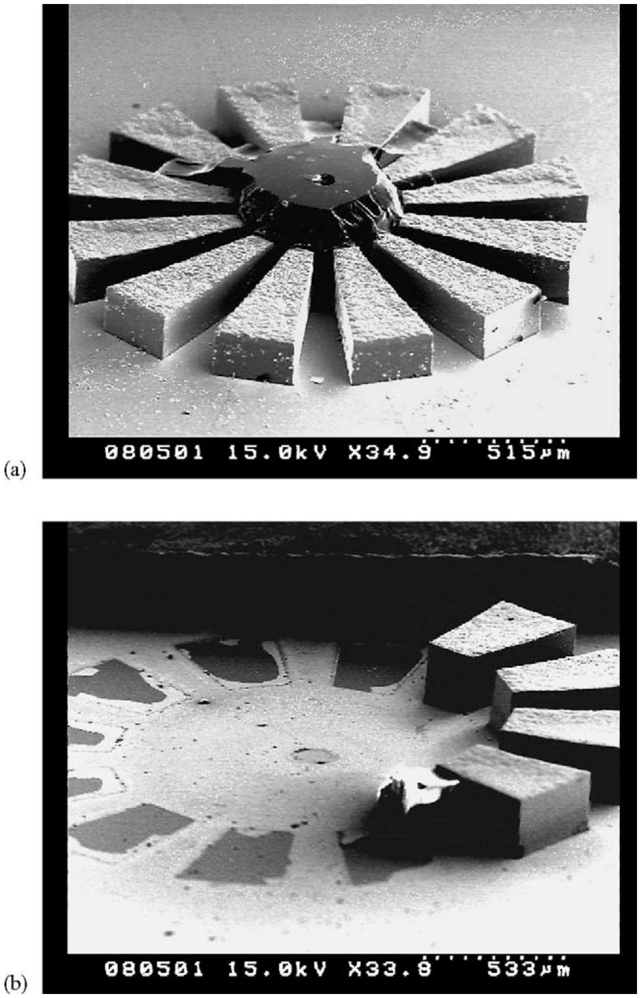

Fig. 5. SEM micrographs of the stator and bearing post following SU-8 stripping via hot remover. (a) SU-8 remnants in the central region and stator slots. (b) SU-8 removal accompanied with stator poles and bearing post ablation.

3.2. *The electroplated stator and bearing post*

Fig. 4 shows the nickel-electroplated stator and bearing post. Although non-uniform distribution of the current density resulted from the differences in area scales and geometric shapes of the pattern, to simplify fabrication, the stator and the bearing post were electroplated simultaneously. Consequently, the deposition rate of these two components occasionally appears to differ.

3.3. *Comparisons of experimental results based on the NANO^{TM} REMOVER PG*

Herein, three types of SU-8 mold removal experiments, which were based on the heated remover, are performed. These include (i) heated remover only; (ii) heated remover, followed by a wet etchant; and (iii) heated remover on the mold with embedded microstructure roots. The experimental results are compared and discussed in the following sections.

3.3.1. *Hot remover only*

Fig. 5 displays the SEM of the stator and bearing post after the SU-8 mold was removed by the commercial remover. Apparently, segments of the photoresist remained on the substrate, particularly in the clearance between two neighboring stator poles and at the central region between the bearing post and the surrounding stator poles (Fig. 5(a)). This phenomenon may have been caused by the accumulated internal stress, which was induced among the junctions of the seed layer, the Ni structure, and the polymerized resist during the fabrication processes, such as lithography, electroplating, and mold removal. Fig. 5(b) presents another problem that often occurred when hot remover was employed to clean a crosslinked SU-8. Since the adhesion at the Ni/Cu interface could not withstand the lift force,

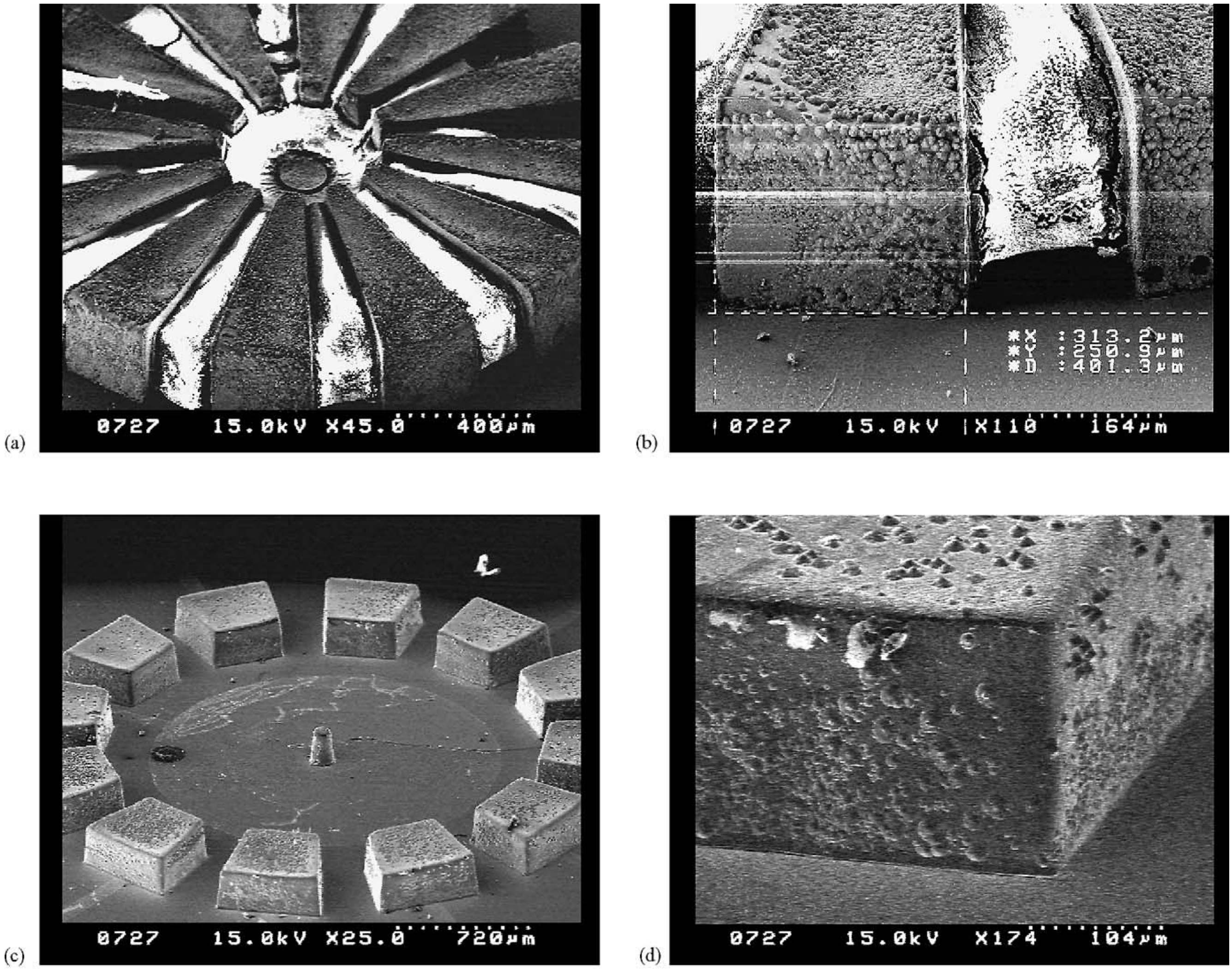

Fig. 6. SEM micrographs of the stator and bearing post following SU-8 stripping by hot remover and sulfuric acid–hydrogen peroxide. (a) Heaved SU-8 remnants wedged between two stator poles. (b) SEM close-up of suspended SU-8 remnants. (c) Deformed stator and bearing post released by modified etchant and bath temperature. (d) SEM close-up of the stator pole with rough surface.

some stator poles and bearing posts were also peeled while the mold was heaved in the remover.

3.3.2. Hot remover and etchant

If the mold is left bonding without immediate and adequate treatment, the crosslinked SU-8 is difficult to remove. Fig. 6(a) depicts a specimen of over crosslinked SU-8, which was primarily heaved and stripped in the hot remover and then etched by sulfuric acid:hydrogen peroxide (H_2SO_4:H_2O_2 = 3:1). Most wet etchants contain a strong oxidizing agent, such as H_2O_2, in this case, which decomposes organic impurities. However, the high cleaning temperature depletes the H_2O_2 concentration and renders the process difficult to control. Fig. 6(b) illustrates a close-up of side structures and the remnant resist, which wedged between stator pole gaps. During the wet process, the Ni surface also sustained serious damage. The etching and oxidizing processes, which was caused by H_2SO_4 and H_2O_2 simultaneously, produced this rough surface. Reducing the H_2SO_4, bath temperature or etching time may improve the surface roughness. In the experiment, the highest temperature (100–130 °C) of the etchant occurred at the beginning of mixing H_2SO_4 and H_2O_2. To obtain a better etching result, the piranha was diluted as H_2SO_4:H_2O_2:H_2O = 3:1:1, and then cool it to 60–80 °C for the resist cleaning process. Fig. 6(c) demonstrates the improved result by decreasing the operational temperature and the etchant concentration together. However, the surface morphology still exhibited partial deformation with noticeable surface pits and tips (Fig. 6(d)).

3.3.3. Microstructures with embedded roots

In this paper, there are two key techniques to construct the electroplated structures while using SU8.

3.3.3.1. Structures with embedded roots. During the SU-8 stripping process, swelling and deformation of the photoresist induced significant stress on the electroplated structures. With roots embedded in the substrate, the electroplated structures became stronger to withstand the stress from the swelling photoresist.

3.3.3.2. Height control in electroplated structures. When the height of the electroplated structure was scaled down, the contact area between the photoresist mold and electroplated structure also became smaller. Then the net clamping force on the mold could be effectively reduced. In other words, the force to hold the photoresist in the structure gaps became smaller, which resulted in successful removal of the SU-8 resist in the lift-off process by Remover PG.

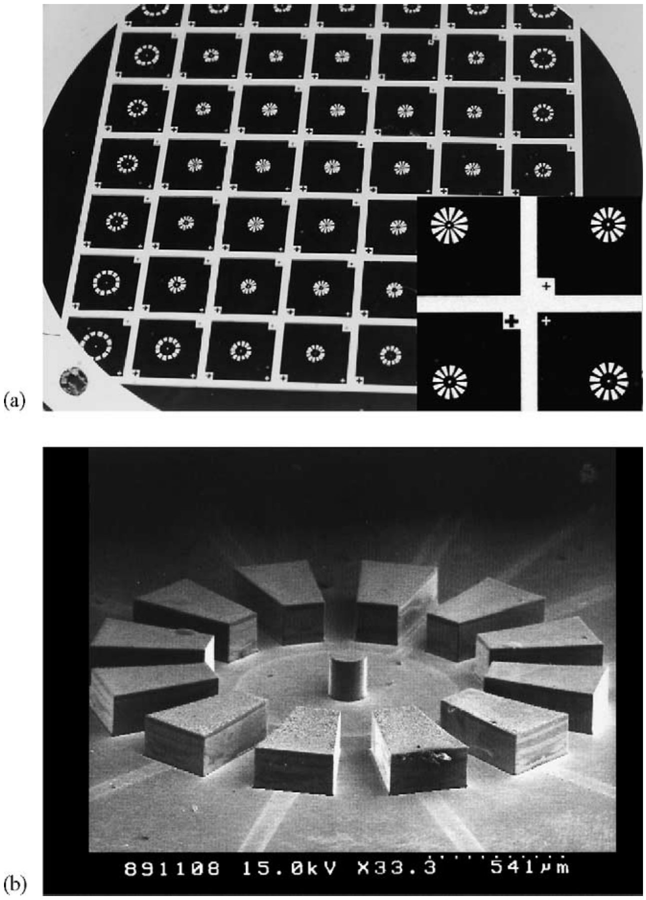

Fig. 7. An optical microscope micrograph and an SEM close-up of released stators with 1 μm-deep substructure embedded in the root construction. (a) Successfully released stators of various scales on a wafer. (b) SEM close-up of the successful released stator and bearing post.

Fig. 7(a) presents the entire image of 49 stator dies on a 100 mm wafer. Stator components with various scales were all stripped successfully without photoresist residue. In this study, to ensure complete removal of the crosslinked resist and to preserve the plated structure, the SU-8 mold was 300 μm-thick on the substrate and had defined niches (Fig. 1(d)). Subsequently, to form the micromotor components, Ni was electrodeposited on the Ti/Cu seed layer to roughly 160 μm in thickness. Consequently, the electroplated stator and the bearing post with substructures of 1 μm in depth were mounted on top of the root constructions, which the niches defined. Fig. 7(b) presents an SEM of the released stator and bearing post which were 1.2 mm and 160 μm in diameter, respectively. This empirical result demonstrates that even if the hot remover is used alone, when the structures are electroplated with roots that are embedded in the substrate and has a thickness of less than two-thirds of the mold's thickness, the crosslinked SU-8 can be removed entirely.

3.4. Micromotor assembly

The rotor and stator, which were fabricated separately, were then assembled under the microscope. Fig. 8 illustrates the integrated prototype of the salient-poled, side-driven electrostatic micromotor. The thickness of the stator was designed slightly greater than that of the rotor. This placement guarantees a lifting force, generated from electrostatic

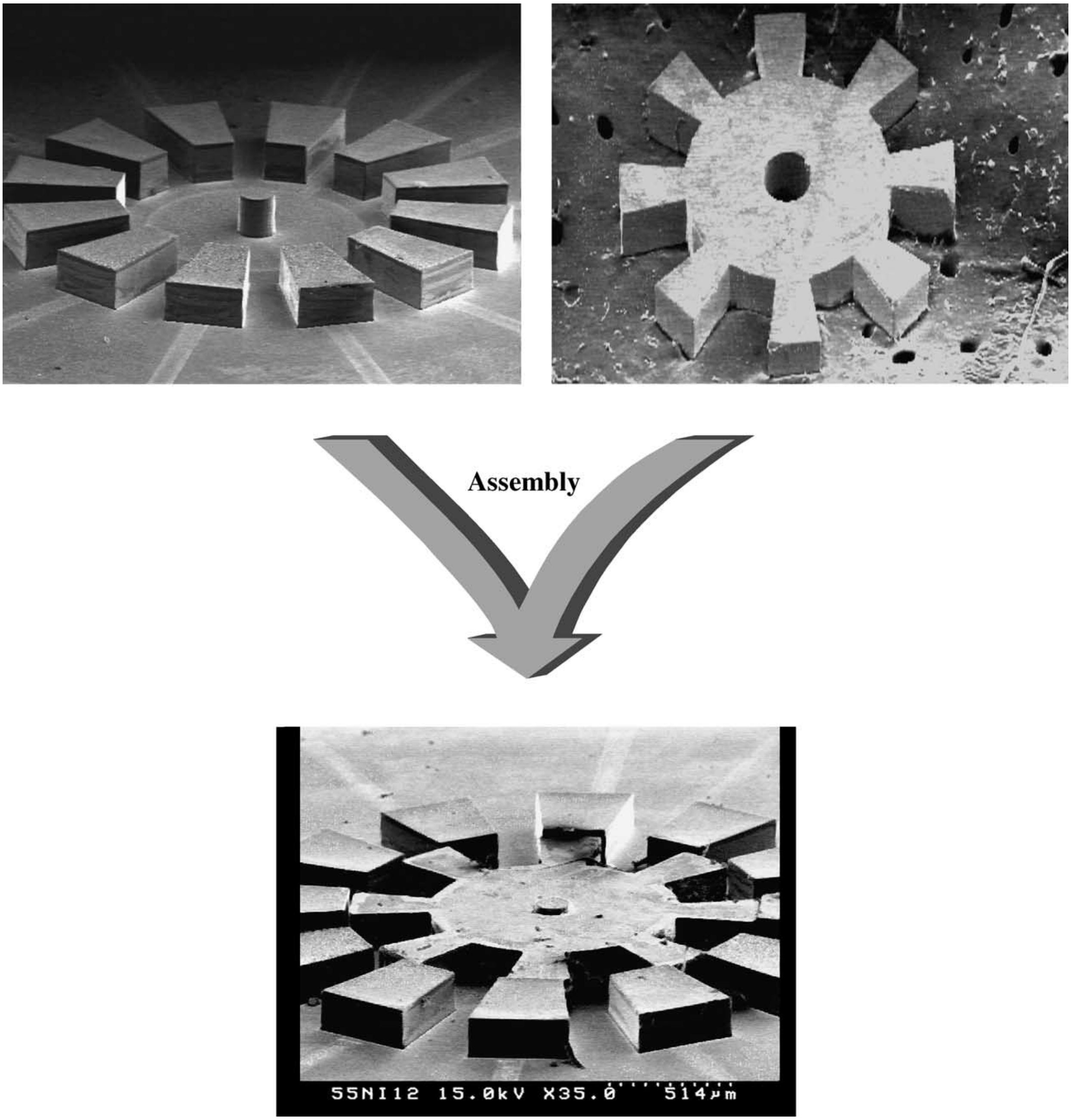

Fig. 8. Integrated prototype of the salient-poled, side-driven electrostatic micromotor fabricated by LIGA-like process and SU-8 photoresist.

attraction, on the rotor and, thereby, diminishes the contact friction between the rotor and the substrate.

4. Conclusion

In this investigation a novel method for the removal of crosslinked SU-8 was developed. Our experimental results demonstrated that when microstructures are electroplated with roots, which are embedded in substrate niches, polymerized SU-8 can be removed completely without remnants and structure ablation. The detailed removal process was presented via an example of a side-driven electrostatic micromotor fabricated with LIGA-like technique. The main advantage of this process is that plated components with 1 µm-deep roots will consolidate the adhesive force between microstructures and the seed layer. However, the experimental results also indicate that to reduce internal stress, structures should be electroplated less than two-thirds of the SU-8 mold in thickness.

The techniques outlined herein solve the notorious problem of the hard-to-strip polymerized SU-8 resist. Also, the LIGA-like process combined with the SU-8 removal technology presented in this work can be applied to simplify fabrication procedures and reduce the production costs of other integrated microactuators.

Acknowledgements

This paper is dedicated to the memory of professor Kan-Ping Chin. Dr. Chin was the first author's adviser who initiated this research, unfortunately, he passed away on 8 February 2002, due to pneumonia. Authors would like to thank professor Wensyang Hsu for his help in the article revision. They are also grateful to the National Science Council of the Republic of China (Contract No. NSC88-2218-E-009-007) and the Materials Research and Development Center of CSIST (Contract No. BV89H14P) for financially supporting this research. Ms. Jih-Wen Wang and Mr. Jeng-En Juang at the Microsystems Technology Center at Electronics Research Service Organization of Industrial Technology Research Institute are appreciated for their assistance in the electroplating. The staffs at the Semiconductor Research Center of National Chiao Tung University are also acknowledged for providing technical support.

References

[1] T.A. Lober, R.T. Howe, Surface-micromachining processes for electrostatic microactuator fabrication, IEEE Solid-State Sensor and Actuator Workshop, Hilton Island, SC, USA, 6 and 9 June, 1988, pp. 59–62.

[2] L.S. Fan, Y.C. Tai, R.S. Muller, Integrated movable micromechanical structures for sensors and actuators, IEEE Trans. Electron Devices 35 (6) (1988) 724–730.

[3] Y.C. Tai, L.S. Fan, R.S. Muller, IC-processed micro-motors: design, technology, and testing, IEEE Microelectro Mechanical Systems Workshop, Salt Lake City, UT, February 1989, pp. 1–6.

[4] T.C. Tai, R.S. Muller, IC-processed electrostatic synchronous micromotors, Sens. Actuators A 20 (1989) 49–55.

[5] M. Mehregany, S.F. Bart, L.S. Tavrow, J.H. Lang, S.D. Senturia, M.F. Schlecht, A study of three microfabricated variable-capacitance motors, in: Proceedings of the Fifth International Conference on Solid-State Sensors and Actuators and Eurosensors III, Switzerland, June 1989, pp. 173–179.

[6] M. Mehregany, Y.C. Tai, Surface micromachined mechanisms and micromotors, J. Micromech. Microeng. 1 (1991) 73–85.

[7] M. Mehregany, S.D. Senturia, J.H. Lang, P. Nagarkar, Micromotor fabrication, IEEE Trans. Electron Devices 39 (1991) 2060–2069.

[8] B. Frazier, J.W. Babb, M.G. Allen, D.G. Taylor, Design and fabrication of electroplated micromotor structures, Micromechanical Sensors, Actuators, and Systems, vol. 32, ASME, New York, 1991, pp. 135–146.

[9] J. Mohr, C. Burbaum, P. Bley, W. Menz, U. Wallrabe, Movable microstructures manufactured by the LIGA process as basic elements for microsystems, in: H. Reichl (Ed.), MicroSystems Technologies, 90 edition, Springer, Berlin, 1990, pp. 529–537.

[10] J. Mohr, P. Bley, M. Strohrmann, U. Wallrabe, Microactuators fabricated by the LIGA process, J. Micromech. Microeng. 2 (1992) 234–241.

[11] A.A. Yasseen, J.N. Mitchell, J.F. Klemic, D.A. Smitch, M. Mehregany, A rotary electrostatic micromotor 1X8 optical switch, IEEE J. Selected Topic Quantum Electron. 5 (1999) 26–31.

[12] V.D. Samper, A.J. Sangster, R.L. Reuben, U. Wallrabe, Multistator LIGA-fabrication electrostatic wobble motors with integrated synchronous control, J. Microelectromech. Syst. 7 (1998) 214–223.

[13] IBM Corp., US Patent 4 882 245 (1989).

[14] M. Despont, H. Lorenz, N. Fahrni, J. Brugger, P. Renaud, P. Vettiger, High-aspect-ratio, ultrathick, negative-tone near-UV photoresist for MEMS applications, IEEE Microelectro Mechanical Systems Workshop, January 1997, pp. 518–522.

[15] H. Lorenz, M. Despont, N. Fahrni, J. Brugger, P. Vettiger, P. Renaud, High-aspect-ratio, ultrathick, negative-tone near-UV photoresist and its applications for MEMS, Sens. Actuators A 64 (1998) 33–39.

[16] K.Y. Lee, N. LaBianca, S.A. Rishton, S. Zolgharnain, J.D. Gelorme, J. Shaw, T.H.-P. Chang, Micromachining applications of a high resolution ultrathick photoresist, J. Vac. Sci. Technol. 13 (6) (1995) 3012–3016.

[17] D.W. Johnson, MCC Technical Report, Advance Package Seminar, Taiwan, 1998.

[18] NANO^{TM} SU-8 Negative Tone Photoresists Formulations 50 and 100, MicroChem Corp.

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