Journal of Vacuum Science & Technology B

Enhancement on forming complex three dimensional microstructures by a double-side multiple partial exposure method

Junwei Chung and Wensyang Hsu

Citation: Journal of Vacuum Science & Technology B **25**, 1671 (2007); doi: 10.1116/1.2781527
View online: http://dx.doi.org/10.1116/1.2781527
View Table of Contents: http://scitation.aip.org/content/avs/journal/jvstb/25/5?ver=pdfcov
Published by the AVS: Science & Technology of Materials, Interfaces, and Processing

Enhancement on forming complex three dimensional microstructures by a double-side multiple partial exposure method

Junwei Chung and Wensyang Hsu[a)]
Department of Mechanical Engineering, National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu 300, Taiwan

(Received 1 May 2007; accepted 13 August 2007; published 17 September 2007)

This study presents a novel batch process based on standard lithography technology, called the double-side multiple partial exposure (DoMPE) method, which enhances the fabrication capability of three dimensional (3D) photoresist microstructures. By incorporating gray-tone lithography and double-side exposure techniques, the proposed DoMPE scheme extends the multilevel morphology on both the front side and back side of the suspended photoresist microstructures. Back-side gray-tone lithography is achieved by depositing various appropriate thicknesses of Ti film on glass substrate that acts as the gray-tone mask. The process parameters, including metal film thickness, developed depth, exposure dosage, development time, and soft-bake time, are experimentally characterized. Different 3D photoresist microstructures with multiple levels on the front and back sides are successfully fabricated and presented here to show the enhancement effect using the proposed technique, including a microinductor structure and a vertical comb drive structure that demonstrate potential applications even on electrically conductive devices. © *2007 American Vacuum Society.* [DOI: 10.1116/1.2781527]

I. INTRODUCTION

Fabrication technologies on batch process of integrated circuits (ICs) promote the rapid development of microelectromechanical systems (MEMSs). Recently, three dimensional (3D) microstructures have proved helpful in applications such as photonics,[1] chemical sensors,[2] data storage,[3] tissue engineering,[4] microfluidic systems,[5–7] and microelectronic devices.[8–11] To date, different approaches have been developed for constructing true 3D microstructures. Beyond the standard lithography technology, the microstereolithography process[12] and two-photon absorption (TPA) polymerization,[3,13–15] which are based on light-induced polymerization in photopolymerizable resin, have been proposed to create the 3D structures in arbitrary shapes. However, both approaches lack batch fabrication ability, which must be supported by the introduction of microtransfer molding for replicating master structures.[16] Another technique, called multibeam interference lithography (MBIL),[1,17] is a method for constructing 3D microstructures with highly parallel processing; however, only spatially periodic structures can be obtained using this technique. Even though microstereolithography, TPA, and MBIL provide specific approaches to construct true 3D or periodic microstructures, unlike the standard lithography, limited equipment availability always restricts their practical applications. Therefore, owing to the advantage of easy access to equipment compatible with IC standard lithography, expanding the fabrication capability of standard lithography technology to 3D microstructures still attracts considerable attention—even the IC fabrication scheme is basically a planar technology.

For the standard lithography technique, the development of thick photoresist technology makes fabricating the 3D microstructures increasingly feasible. First, the high aspect-ratio structures achieved by LIGA (German acronym for lithography, electrodeposition, and molding) or LIGA-like processes, which are often considered 2.5D techniques, enhance the performance of microcomponents.[18] By using the inclined and rotated UV lithography, the oblique or curved microstructures, which have been called the 3D microstructures, can be constructed with the negative photoresist SU-8 for the applications of microchannels, filters, mixers,[5] and optical mirrors.[19] However, the complexity of 3D microstructures is still quite limited when using either approach. Another important technique, which reportedly defines the photoresist in flexible shape, is the gray-tone lithography that changes the UV-light transmission through the mask, thereby modulating the exposure intensity on the substrate front side.[20–23] To generate the suspending microstructures, the back-side partial exposure scheme with glass substrate has been utilized to suspend photoresist microstructures, such as cantilevers and bridges,[6] without additional sacrificial material. However, the suspending space was restricted to one level because the back-side dosage could only be controlled by the exposure time.

Based on standard lithography equipment, this study presents a novel batch process called the double-side multiple partial exposure (DoMPE) method, which enhances the complexity of suspended 3D photoresist microstructures by incorporating a gray-tone mask on the back-side exposure. Here, the gray-tone mask is realized by controlling the thickness of the metal film.[23] The mergence of the gray-tone mask on the back side produces the possibility of carrying out partial exposure on the substrate front and back sides, and the photoresist can then be carved out to form increasingly

[a)]Author to whom correspondence should be addressed; electronic mail: whsu@mail.nctu.edu.tw

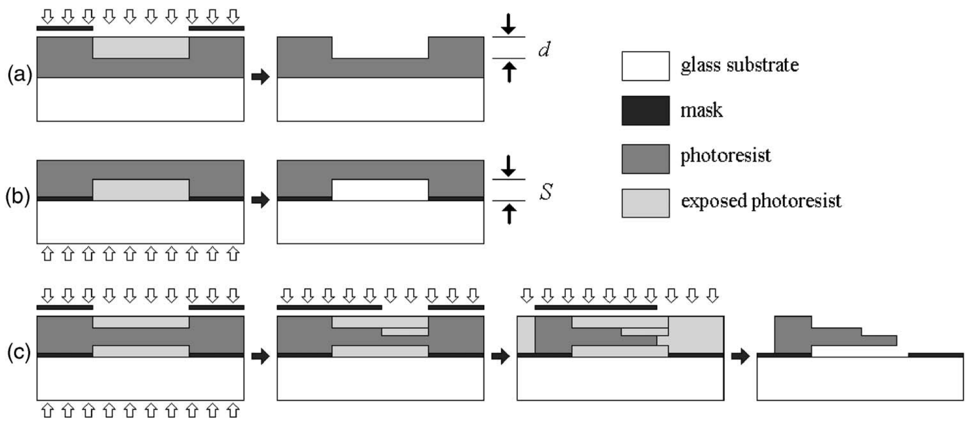


FIG. 1. Fabrication of photoresist microstructures with multiple levels on front side; (a) the grove with a depth of d created by front-side partial exposure, (b) the suspending bridge with a space of S created by back-side partial exposure, and (c) the suspended cantilever with three levels on the front side by front-side multiple partial exposures.

complex 3D microstructures. In this study, microstructures with up to four levels on the front and back sides generated via the DoMPE process are presented to demonstrate the enhancement effect when constructing complex 3D microstructures made of positive photoresist AZ9260®.

II. PROCESS DESIGN

To remove various thicknesses of positive photoresist on the front and back sides, multipatterning on the front side and gray-tone lithography on the back side are used to achieve the dosage control in each exposure step to generate a desired depth. When these exposure steps are complete, the development solution finally removes the exposed photoresist to obtain freestanding 3D photoresist microstructures without using a sacrificial layer and an additional release step. The proposed DoMPE method comprises front-side multiple partial exposure and back-side multiple partial exposure, and requires only standard IC-compatible equipment, such as a spin coater, mask aligner, and physical vapor deposition system. Process steps for fabricating multilevel microstructures are described as follows.

A. Suspended front-side multilevel microstructures

Figure 1 illustrates three examples of fabricating suspended photoresist microstructures with various levels on the front side through the double-side partial exposure techniques. A glass substrate is used for back-side exposure. The front-side partial exposure can utilize a standard front-side mask [Fig. 1(a)], where the photoresist is partially exposed to define the groove. In Fig. 1(b), partial exposure on the back side is realized through a patterned metal layer, which is previously deposited on the glass substrate as a back-side mask to create a suspending space. Groove depth d and suspending space S are mainly controlled by exposure dosage. When standard masks are used during front-side partial exposure, multipatterning can be implemented easily in the front direction by only changing masks with the dosage control; this process is called front-side multiple partial exposure. Via this method, a suspended photoresist cantilever with multiple levels on the front side can be fabricated after final development without an additional release step [Fig. 1(c)].

B. Suspended back-side multilevel microstructures

To generate multiple levels on the back side of microstructures, a proposed back-side gray-tone mask is utilized, since it is difficult to place and switch the mask for multipatterning the back side through the glass wafer in a standard aligner with precise linewidth control. The gray-tone mask is achieved by depositing various thicknesses of metal film on the glass substrate to modulate light transmitted through the glass wafer for back side multiple partial exposure. Figure 2 presents the fabrication process of a photoresist cantilever with multiple levels on the back side via back-side multiple partial exposure. First, a thicker metal film is deposited and patterned by a lift-off process as the opaque back-side mask [Fig. 2(a)]. A thinner metal film is also subsequently defined

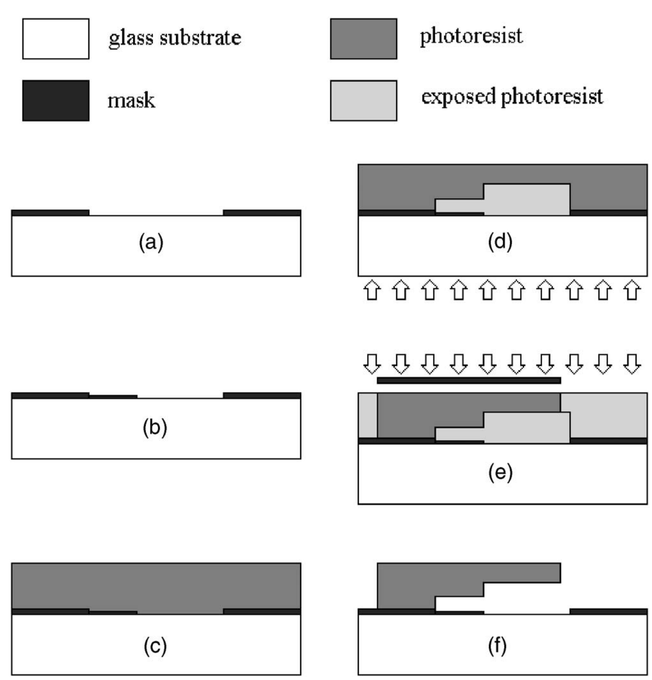


FIG. 2. Fabrication process of 3D photoresist microstructure with multiple levels on the back side; (a) defining the thick metal film as back-side opaque mask, (b) defining the thin metal film as back-side gray-tone mask, (c) coating thick positive photoresist, (d) completing back-side multiple partial exposure by one exposure, (e) front-side full exposure to define the overall area of structure, and (f) development and release.

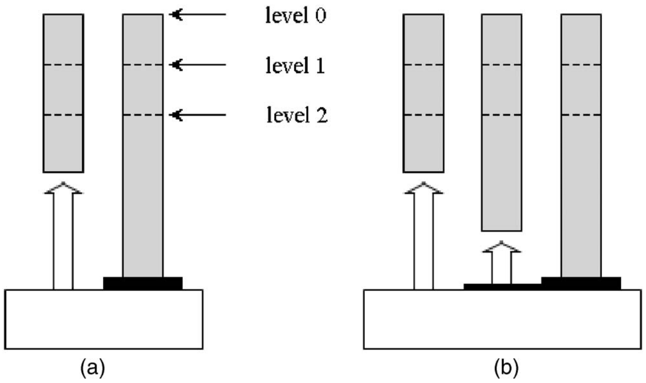


FIG. 3. Possible combinations of microstructures fabricated by the DoMPE process with three levels on the front side: (a) six combinations due to two levels on the back side and (b) nine combinations due to three levels on the back side.

at the desired locations by sputtering as the gray-tone back-side mask for modulating back-side exposure dosage [Fig. 2(b)]. Then, the thick positive photoresist is spin coated and soft baked [Fig. 2(c)]. After rehydration, back-side multiple partial exposure is carried out by one exposure [Fig. 2(d)], in which the photoresist on the back side is exposed with different dosages due to the gray-tone mask to create different exposure depths. Subsequently, front-side exposure on the proper area is applied to define overall shape of the microstructures [Fig. 2(e)]. At last, a cantilever with multiple levels on the back side can be obtained after final development [Fig. 2(f)].

By combining multiple partial exposures on the front and back sides, more complex 3D microstructures can be achieved using the proposed DoMPE method. For example, when three front-side levels are employed (levels 0, 1, and 2)—where level 0 indicates zero dosage—without the back-side gray-tone mask, i.e., two different metal film thicknesses [Fig. 3(a)], one partial exposure can produce two levels in the back-side direction; thus, six combinations of microstructure can be fabricated. By using the back-side gray-tone mask [Fig. 3(b)], three different metal film thicknesses can generate three levels on the back side. Thus, there are nine combinations. Expanding the multilevel fabrication capability on the back or front sides directly enhances the complexity of 3D microstructures.

III. RESULTS AND DISCUSSION

In this section, the relationships between development depth and process parameters, such as development time, exposure dosage, and soft-bake time, are first experimentally characterized. The thickness effect on the gray-tone mask for the back-side multiple partial exposure process is then investigated. Finally, different 3D microstructures are fabricated to demonstrate the capability and potential applications of the proposed technique.

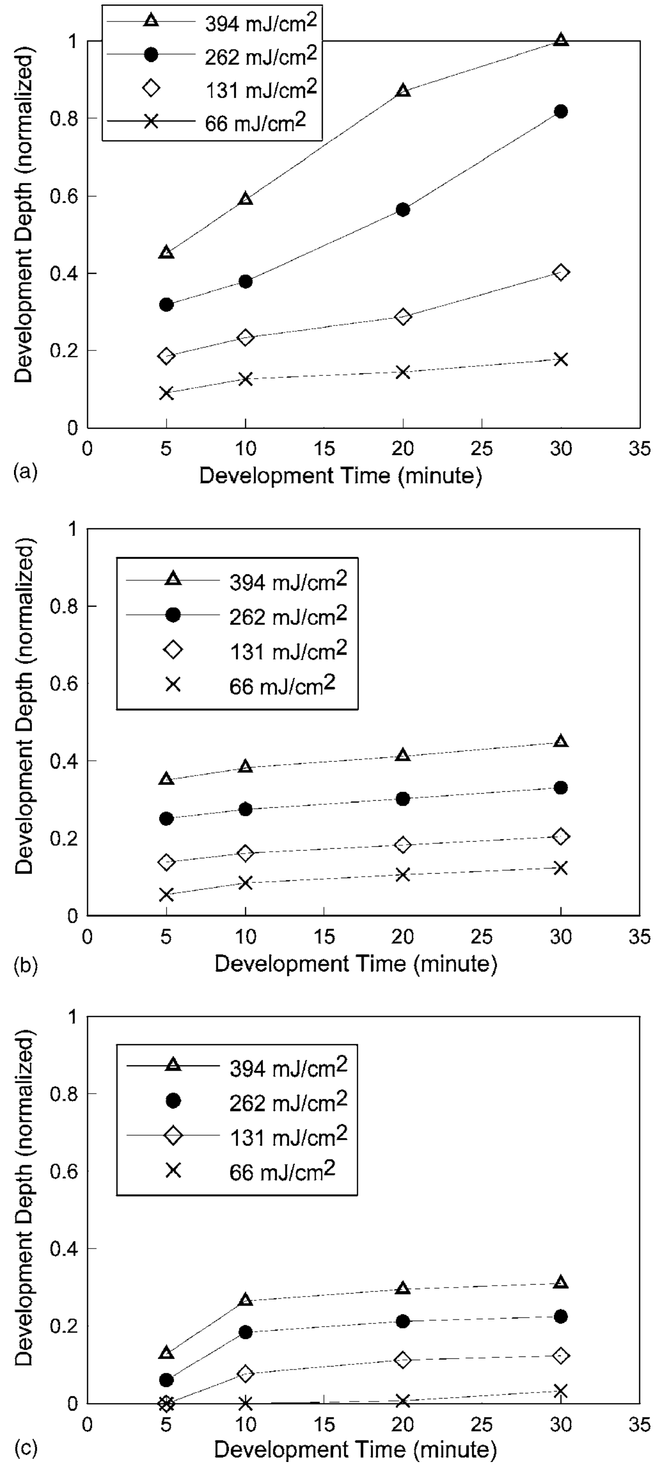
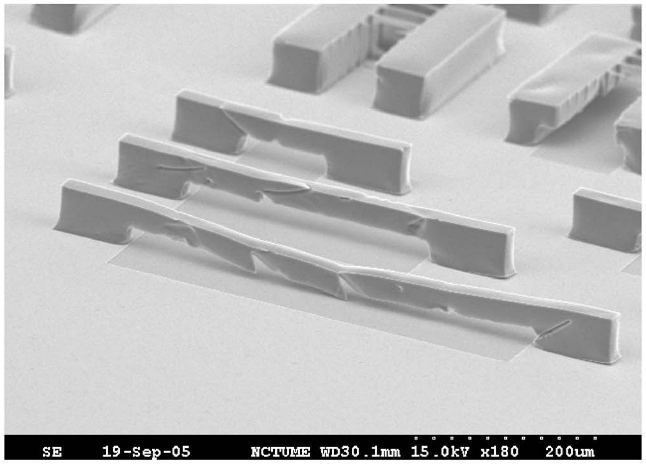


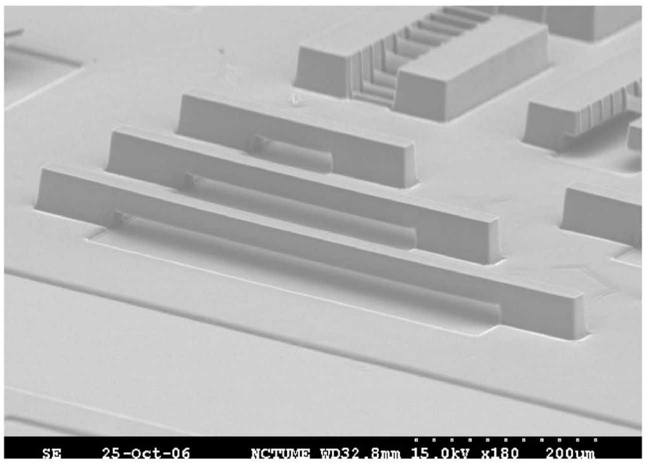
FIG. 4. Development depth under different development times and exposure dosages. Photoresist AZ9260® is soft baked at 90 °C for (a) 15 min, (b) 60 min, and (c) 90 min.

A. Photoresist processing

The commercially available positive thick photoresist (AZ9260®, Clariant) is used here. First, the photoresist with a thickness of 58 μm is spin coated and then soft baked at 90 °C. After rehydration for over 30 min, the photoresist is exposed to different dosages. Then, different development



(a)



(b)

FIG. 5. Bridges made of photoresist AZ9260® with soft-bake times of (a) 40 min and (b) 90 min.

times are applied using an AZ-400K developer diluted at a ratio of 1:4 with de-ionized water. Figure 4 shows the experimental results for development depths at development times of 5, 10, 20, and 30 min and exposure dosages of 66, 131, 262, and 394 mJ/cm^2, respectively, where the photoresist is soft baked for 15, 60, and 90 min, respectively. Development depths are normalized using the overall photoresist thickness of 58 μm. According to experimental results shown in Fig. 4(a), where soft-bake time is 15 min, a large exposure dosage or extended development time increases development depth. Furthermore, the comparison of development depths in Figs. 4(a)–4(c) clearly indicates that soft-bake time also plays an important role in this process. A longer soft-bake time increases stability and decreases development depth under different development times, especially at the high partial exposure dosages. When the soft-bake time is increased to 90 min, as shown in Fig. 4(c), the development depth is further decreased, especially for the development time of 5 min, indicating that the photoresist needs at least 10 min to reach the stable region. For the development time over 20 min, a soft bake of 90 min generates a consistent development depth, which is suitable for processes needing long development times. In addition to improved photoresist development, a long soft bake is also helpful for reliable fabrication of 3D photoresist microstructures. Figures 5(a) and 5(b) show fabrication results for photoresist bridges with soft-bake times of 40 and 90 min, respectively. The bridge collapses down after release due to insufficient soft-bake time, and the structure stands well on the substrate with sufficient soft-bake time.

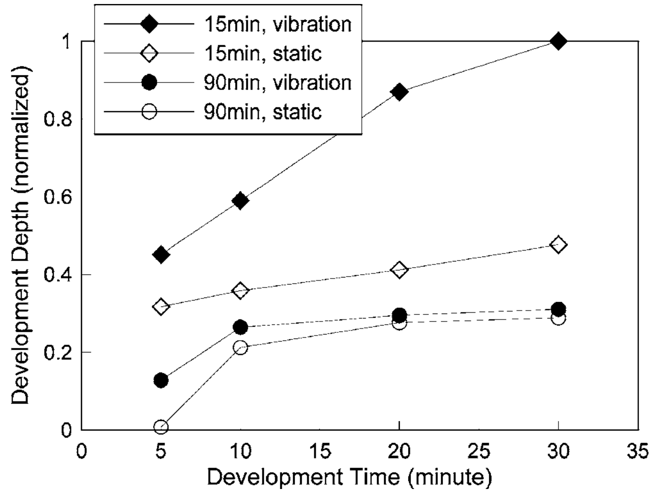


FIG. 6. Development depth at different development times with or without gentle vibration at two soft-bake times, where the exposure dosage is 394 mJ/cm^2 and the development depths are normalized by an overall photoresist thickness of 58 μm.

A gentle vibration to refresh the developer above the photoresist during the development may affect development depth, especially with short soft-bake times. Figure 6 shows the influence of vibration on the development depth under two soft-bake conditions with different development times, where the solid symbol indicates the development with gentle vibration while the hollow symbol presents the results obtained without any vibration. Experimental results show that the vibration markedly enlarges the development depth

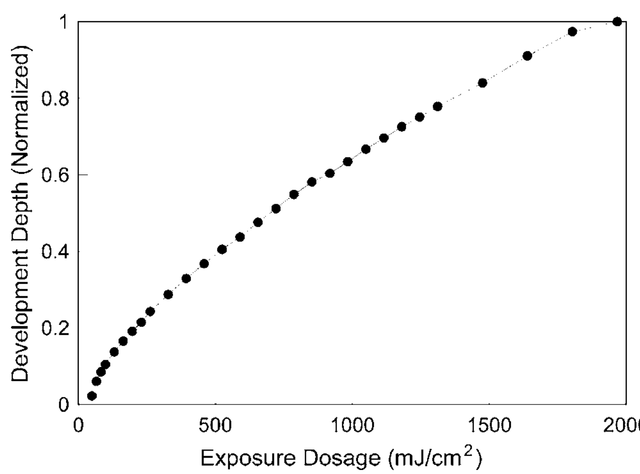


FIG. 7. Relationship between development depth and exposure dosage for photoresist AZ9260® at a soft-bake time of 90 min and development time of 45 min.

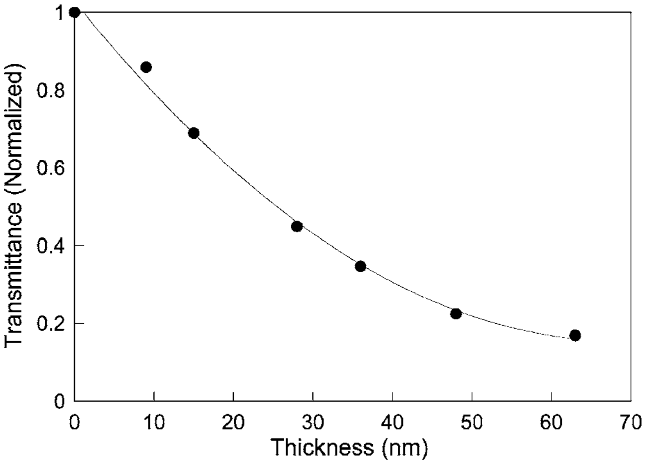


FIG. 8. Measured UV-light transmittance at different Ti film thicknesses.

when soft baked for 15 min, especially under long development times. For a soft bake of 90 min, the influence of gentle vibration on development depth is not obvious when development time exceeds 20 min. Figure 7 shows the detailed relationship between development depth and exposure dosage under soft-bake time of 90 min and development time of 45 min without the gentle vibration, where development depths are normalized by overall photoresist thickness of 58 μm. Experimental results indicate a stable but not quite linear increase to development depth by increasing exposure dosage.

B. Gray-tone mask

To achieve back-side multiple partial exposure, the modulation capability of the gray-tone mask realized by different thicknesses of metal film must be characterized. In this work, an opaque mask and gray-tone mask for back-side multipartial exposure are both formed by Ti film deposited by a sputtering system. With different thicknesses of Ti film deposited on the glass substrate, the transmittance of Ti film is measured by a radiometer with a spectral response of 310–515 nm and a peak response of 405 nm. Experimental results show (Fig. 8) that a thicker Ti film reduces transmittance. For example, a Ti film with thicknesses of 15 and 63 nm provides about 68.9% and 16.9% UV-light transmittance, respectively, where transmittance is normalized by the measured exposure intensity of 34.1 mW/cm^2 under the glass substrate without Ti deposition. Therefore, based on experimental data, the dosage distribution in the back-side multipartial exposure can be designed to fabricate various desired suspending gaps when Ti thickness is properly controlled. Figure 9 shows experimental verification of development depth under different Ti thicknesses with an exposure dosage of 616 mJ/cm^2, where the square symbol indicates calculated depth using experimental data (Figs. 7 and 8), and the triangle symbol indicates direct measurement results under different Ti thicknesses. Experimental results show that the dosage modulation of Ti film characterized by the radiometer agrees well with direct measurement results.

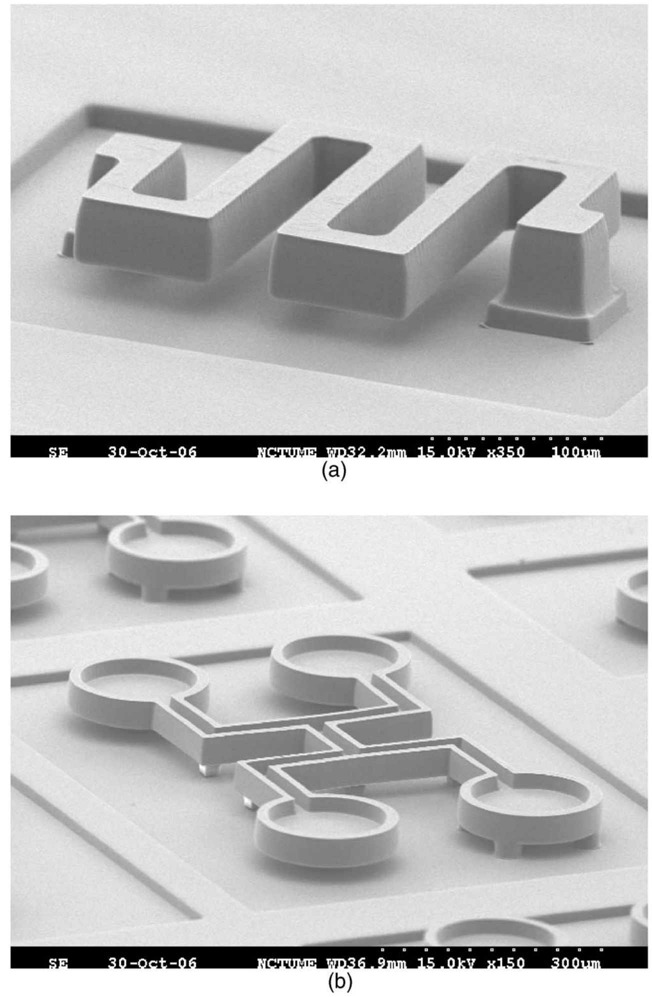


FIG. 10. 3D microstructures made of photoresist AZ9260® with two levels on the back side: (a) the suspending meander line with one level on the front side and (b) microchannel with two levels on the front side.

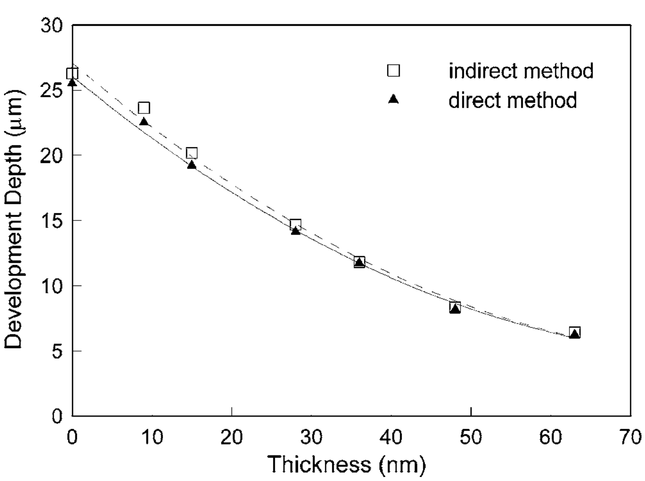


FIG. 9. Verification on the development depth vs Ti thickness with a photoresist of 58 μm that is soft baked for 90 min and developed for 45 min. Line with square symbol is obtained by calculating data in Figs. 7 and 8. Line with triangle symbol is obtained by direct measurements.

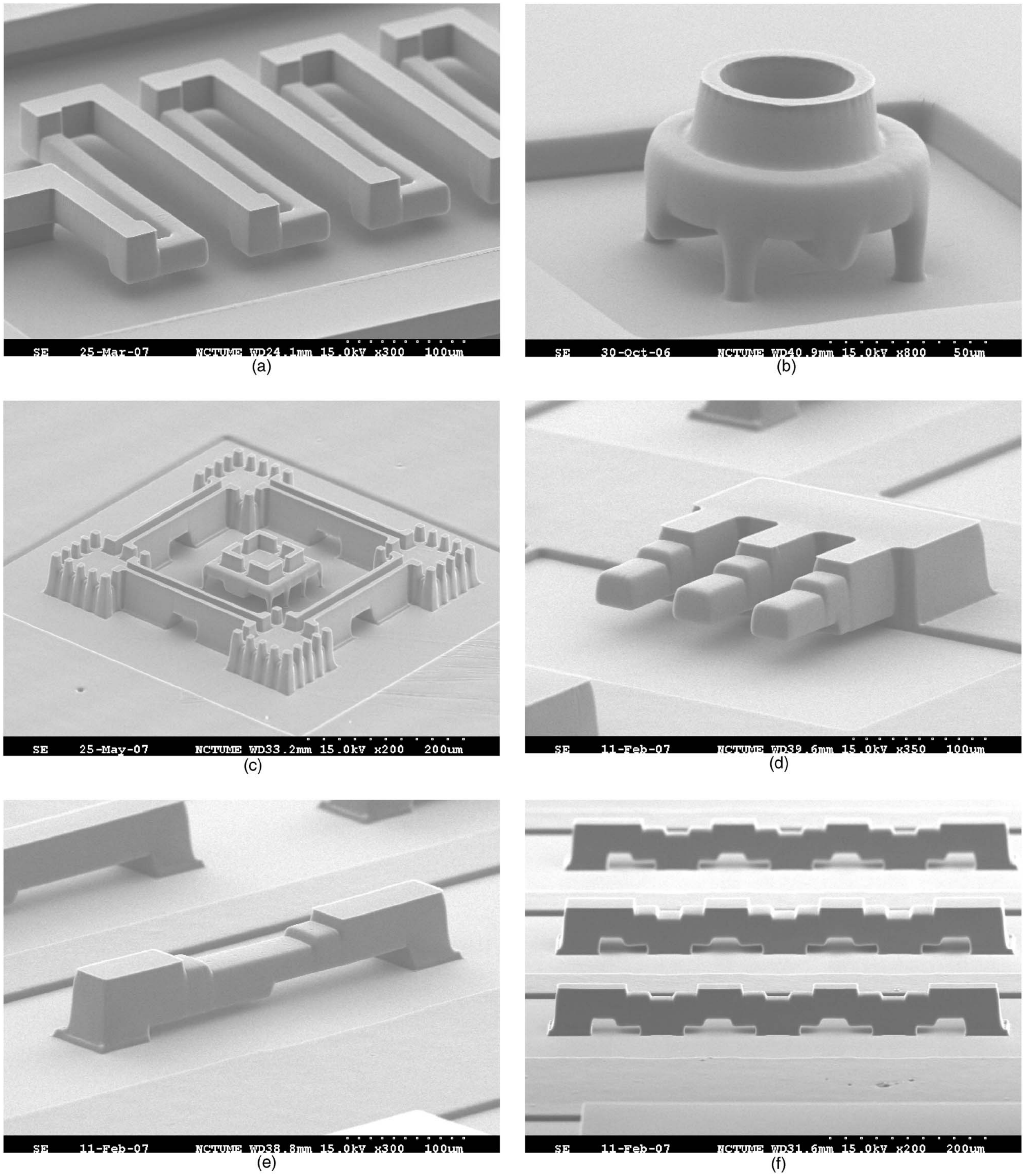


FIG. 11. 3D microstructures made of photoresist AZ9260® with three levels on the back side. For (a)–(c), two levels on the front side: (a) microinductor, (b) microstructure with round shape, and (c) minicastle. For (e)–(f), three levels on both the front and back sides: (d) cantilevers and (e)–(f) bridges.

C. 3D microstructures

After establishing the process parameters, different 3D microstructures made of AZ9260® are fabricated and presented to demonstrate the effectiveness of the proposed DoMPE process. The photoresist with a thickness of approximately 60 μm is spin coated and soft baked at 90 °C for 90 min. Figure 10 shows the structures with only two levels on the back side. For only one level on the front side, the meander with the linewidth of 30 μm is fabricated [Fig. 10(a)] and suspended 19 μm from the substrate with a back-side exposure dosage of 407 mJ/cm^2. By introducing two front dosages, the suspending channel has a depth of 20 μm [Fig. 10(b)], in which two levels exist on both the front and back sides.

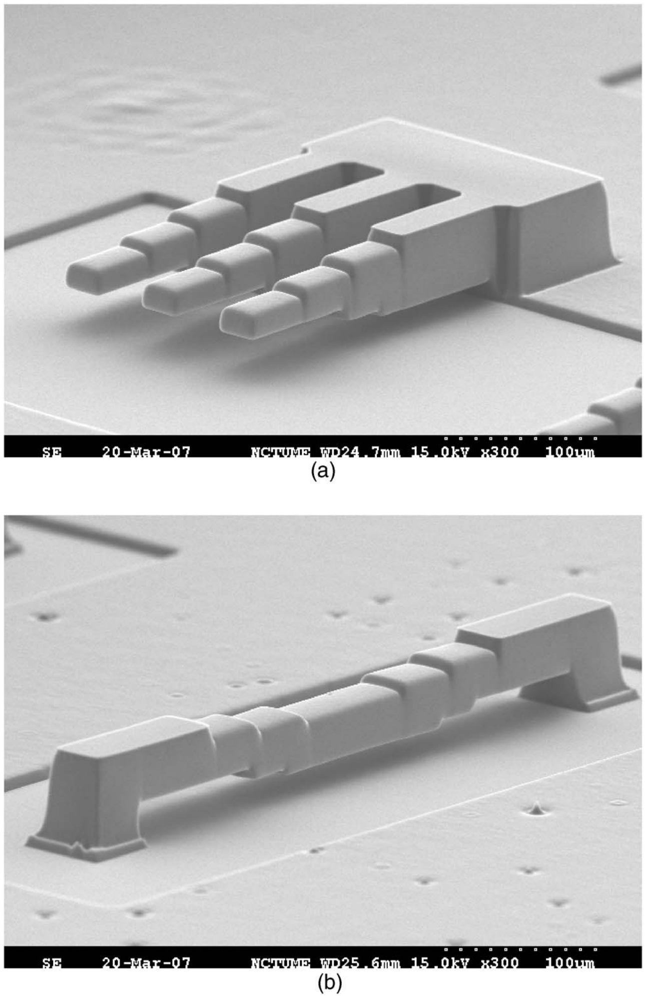


FIG. 12. 3D microstructures made of photoresist AZ9260® by the DoMPE process with four levels on both the front and back sides; (a) cantilevers and (b) bridge.

Figure 11 shows the microstructures fabricated by double-side multiple partial exposure, where the gray-tone mask creates three levels on the back side. With two levels on the front side, Figs. 11(a)–11(c) show a microinductor, a round 3D structure, and a minicastle with different suspending gaps, respectively. Figures 11(d)–11(f) show the cantilevers and bridges with uneven thicknesses and three levels constructed on both the front and back sides. Increased thickness variation on the gray-tone mask can provide additional levels on the back side. With an opaque mask formed by a Ti thickness of 160 nm and a gray scale formed by Ti thicknesses of 0, 28, and 48 nm, Figs. 12(a) and 12(b) show the fabricated cantilevers and bridges with four levels on both front-side and back-side directions. The 3D microstructure complexity is successfully enhanced by incorporating gray-tone lithography on back-side exposure. These photoresist 3D microstructures are useful for enhancing the complexity of 3D molds on forming 3D microchannels with polydimethylsiloxane,[6] or providing channel cross sections with increased flexibility while directly fabricating microfluidic components, such as embedded channels, filters, and mixers.[5,7]

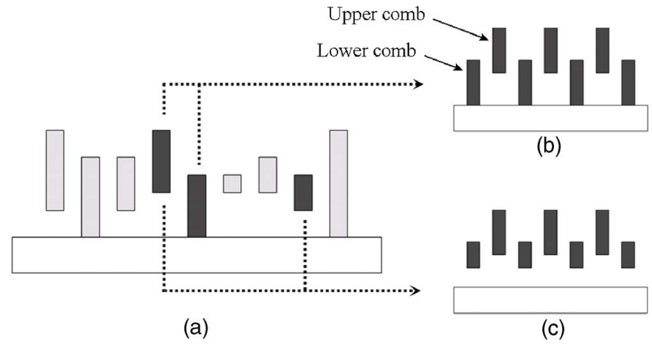


FIG. 13. Different beam structures can be fabricated with three levels on both the front and back sides for constructing vertical comb drives with different strokes by the DoMPE process; (a) nine various beam structures, (b) type I vertical comb structure design with fixed lower comb fingers, and (c) type II vertical comb structure design with suspended lower comb fingers.

Moreover, by incorporating metallization schemes, such as electroless[8] and physical vapor[9–11] depositions, polymer-based 3D microstructures have been demonstrated to extend to be electrical-conductive devices, such as microinductors,[9] electrothermal actuators,[9] accelerometers,[10] and comb drives.[11] Here, for example, with metallization by physical vapor deposition, a 3D microinductor by the DoMPE process is fabricated [Fig. 11(a)] instead of using the conventional layer-by-layer method. Figure 13(a) illustrates structures that can be fabricated using the DoMPE process with three levels on both the front and back sides. By selecting different pairs of structures, vertical comb structures with different strokes can be constructed. Figures 13(b) and 13(c) show two vertical comb structure designs with different working strokes. The scanning electron microscopy photographs in Fig. 14 present fabrication results made of photoresist AZ9260®. Figure 14(a) shows the design with fixed lower comb fingers, where the suspending space of upper comb finger is about 24 μm. Figure 14(b) shows the fabricated type II vertical comb structure with upper and lower comb fingers suspended at different gaps. By sputtering, a metal layer can be deposited on the structural surfaces to provide the desired electrical conductivity for these vertical comb drive structures to act as active devices.

IV. CONCLUSIONS

Using standard lithography equipment, the proposed DoMPE process enhances the complexity of suspended 3D photoresist microstructures by incorporating back-side gray-tone lithography and a partial exposure technique. Process parameters, including exposure dosage, development time, development depth, soft-bake conditions, and the Ti film thickness as gray-tone mask, have been characterized experimentally. Experimental results indicate that soft-bake time plays a significant role in the DoMPE process and affects development depth and fabrication stability. By increasing

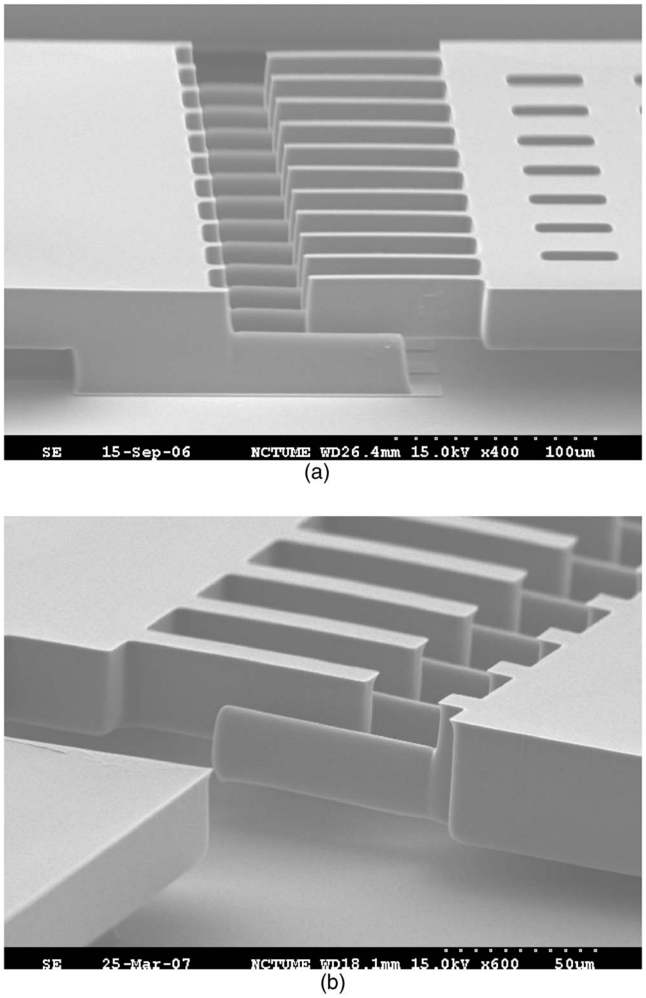


FIG. 14. Fabricated vertical comb structures: (a) type I with fixed lower comb fingers and (b) type II with suspended lower comb fingers.

the thickness variation on the gray-tone mask, complexity of 3D microstructures can be further enhanced. The DoMPE process can act as a basic platform that provides an affordable solution to construct flexible features in three dimensions for MEMS applications.

ACKNOWLEDGMENTS

This work was supported by the National Science Council of Taiwan, Republic of China under Grant No. NSC95-2218-E-009-023. The authors would also like to thank the staffs at the Nano Facility Center of National Chiao Tung University for providing technical support.

[1]C. K. Ullal, M. Maldovan, E. L. Thomas, G. Chen, Y.-J. Han, and S. Yang, Appl. Phys. Lett. **84**, 5434 (2004).
[2]Y. Y. Li *et al.*, Science **299**, 2045 (2003).
[3]B. H. Cumpston *et al.*, Nature (London) **398**, 51 (1999).
[4]A. Abbott, Nature (London) **424**, 870 (2003).
[5]M. Han, W. Lee, S.-K. Lee, and S. S. Lee, Sens. Actuators, A **111**, 14 (2004).
[6]B.-G. Kim, J.-H. Kim, and E. Yoon, Seventh International Conference on Miniaturized Chemical and Biochemical Analysis Systems, 2003 (unpublished), p. 627.
[7]Y.-J. Chuang, F.-G. Tseng, J.-H. Cheng, and W.-K. Lin, Sens. Actuators, A **103**, 64 (2003).
[8]R. A. Farrer, C. N. LaFratta, L. Li, J. Praino, M. J. Naughton, B. E. A. Saleh, M. C. Teich, and J. T. Fourkas, J. Am. Chem. Soc. **128**, 1796 (2006).
[9]N.-T. Nguyen, S.-S. Ho, and C. L.-N. Low, J. Micromech. Microeng. **14**, 969 (2004).
[10]S. J. Jeong and W. Wang, Proc. SPIE **5344**, 115 (2004).
[11]W. Dai, K. Lian, and W. Wang, Microsyst. Technol. **13**, 271 (2007).
[12]A. Bertsch, H. Lorenz, and P. Renaud, Sens. Actuators, A **73**, 14 (1999).
[13]S. Maruo, O. Nakamura, and S. Kawata, Opt. Lett. **22**, 132 (1997).
[14]S. Kawata, H.-B. Sun, T. Tanaka, and K. Takada, Nature (London) **412**, 697 (2001).
[15]T. Baldacchini, C. N. LaFratta, R. A. Farrer, M. C. Teich, B. E. A. Saleh, M. J. Naughton, and J. T. Fourkas, J. Appl. Phys. **95**, 6072 (2004).
[16]C. N. LaFratta, L. Li, and J. T. Fourkas, Proc. Natl. Acad. Sci. U.S.A. **103**, 8589 (2006).
[17]J. H. Moon and S. Yang, J. Macromol. Sci., Polym. Rev. **45**, 351 (2005).
[18]M. J. Madou, *Fundamentals of Microfabrication*, 2nd ed. (CRC, New York, 2002).
[19]K.-Y. Hung, H.-T. Hu, and F.-G. Tseng, IEEE Solid State Sensors, Actuators and Microsystems (Transducers'03), 2003 (unpublished), p. 821.
[20]Y. Oppliger, P. Sixt, J. M. Stauffer, J. M. Mayor, P. Regnault, and G. Voirin, Microelectron. Eng. **23**, 449 (1994).
[21]B. Wagner, H. J. Quenzer, W. Henke, W. Hoppe, and W. Pilz, Sens. Actuators, A **46–47**, 89 (1995).
[22]W. Däschner, P. Long, R. Stein, C. Wu, and S. H. Lee, J. Vac. Sci. Technol. B **14**, 3730 (1996).
[23]W. Däschner, P. Long, M. Larsson, and S. H. Lee, J. Vac. Sci. Technol. B **13**, 2729 (1995).