CURVED SU-8 STRUCTURE FABRICATION BASED ON THE ACID-DIFFUSION EFFECT

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ABSTRACT

This paper proposes a novel technology to fabricate 3D curved structures on SU-8 resist by a photo-acid-diffusion process. This technology deliberately modifies the standard SU-8 photolithography procedure and allows the diffusion of photo-acid released from UV-exposed regions into the adjacent unexposed resist regions, which would result in forming smooth 3D curved structures after cross-linking and development. The formation mechanism of curved SU-8 structure is demonstrated by experiments and numerical simulation.

INTRODUCTION

The fabrication of 3D microstructures with well- defined curved surface contours has been becoming more and more important for extending the flexibility of building 3D structures for MEMS applications. However, conventional microfabrication technologies including bulk micro-machining [1], surface micromachining [2] and the LIGA process [3] are not well suited for creating 3D curved structures due to limitations of these planar processes. Recently, several 3D fabricate technologies have been introduced for the formation of curved structures for MEMS devices, such as gray-scale lithography [4], 3D diffuser lithography [5], photoresist (PR) reflow method [6], interfacial free energy equilibrium method [7] and soft stamping method [8]. Gray-scale lithography and 3D diffuser lithography can make various curved 3D microstructures, but these processes need expensive photomasks or special apparatuses. 3D structures obtained by PR reflow method are seldom suitable for commercial MEMS devices due to the thermal and chemical instability of the positive PR. Interfacial free energy equilibrium method and soft stamping method provide very simple processes to form smooth curved surfaces on photoresist structures. However, these processes can create only some simple 3D curved structures in a narrow range of geometric dimensions (such as curvature and height) owing to constant surface tension coefficient of photoresist, which may limit their practical applications.

In this paper, a novel approach by employing photo-acid diffusion is proposed to fabricate smooth curved structures on SU-8 resist. The shape and curvature of the curved structures can be easily controlled by coupling the geometrical design with the photo-acid diffusion process. Compared to gray-scale lithography and 3D diffuser lithography, this approach is a simpler and more cost-effective process, suitable for mass production. Meanwhile the cross-linked SU-8 structure has better mechanical strength and chemical resistance than other commonly used polymers.

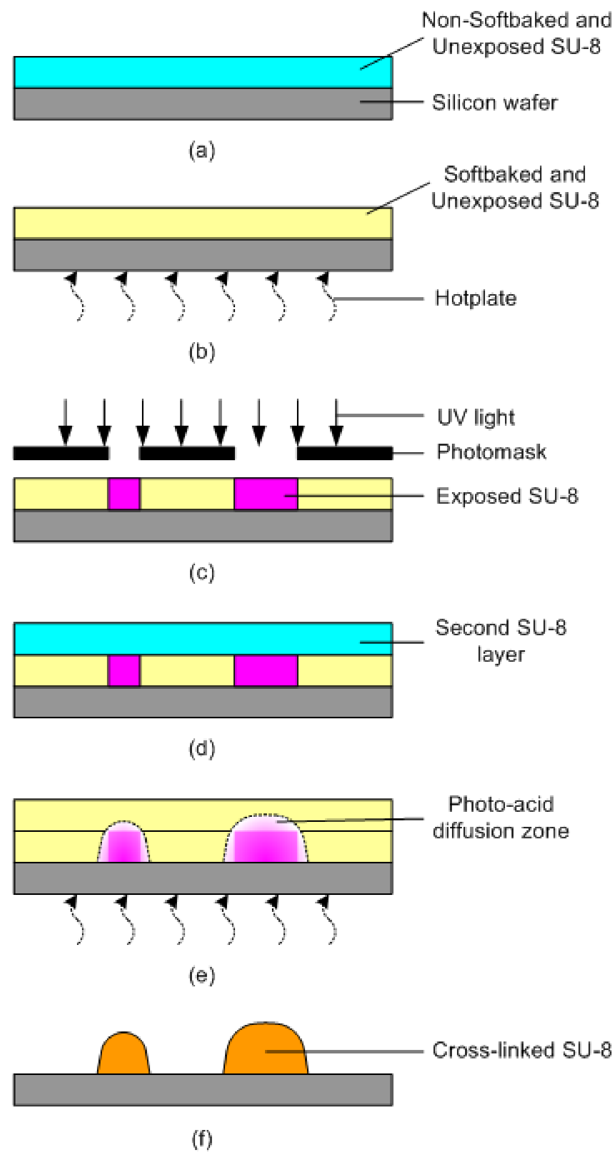

Figure 1: Process for formation of curved SU-8 structures based on the diffusion of photo-acid. (a) spinning the first su-8 layer, (b) softbaking, (c) exposure, (d) spinning the second su-8 layer, (e) post-exposure baking , (f) developing and hardbaking.

FABRICATION CONCEPT

The concept of fabricating curved SU-8 microstructures by the diffusion of photo-acid is illuminated in Figure 1.

First, a layer of SU-8 is spun onto a silicon wafer (Figure 1a), and then soft bake is performed to dry out solvent in the resist film (Figure 1b). Next, the coated wafer is exposed to the UV light through the pattern on the mask (Figure 1c). Upon exposure, in the standard SU-8 photolithography process, a post expose bake (PEB) must be followed to selectively cross-link the exposed portions of the PR film. However, this step is deliberately omitted in our experimental procedures. Instead, a second layer of SU-8 is immediately coated over the first layer that has been activated by the UV exposure (Figure 1d), and then the two-layer resist is stored in room temperature for a considerable period to allow diffusion of the solvent in the top resist layer into the bottom layer. The elevated solvent content in resist film will drastically enhance the thermal diffusion of acid generated from photo-acid generators upon UV-exposure. So an obvious diffusion of the photo-acid will occur between the exposed and unexposed zones if the entire bilayer SU-8 is subjected to a bake step. During the baking process, the photo-generated acid diffuses into the adjacent unexposed regions from the exposed regions, resulting in a partially cross-linked interfacial layer (Figure 1e). Subsequently, a development was performed to dissolve all uncross-linked SU-8 resist, leaving behind the curved structures (Figure 1f).

THEORY BACKGROUND

SU-8 is an epoxy-based, chemically amplified, negative photoresist and the main components are SU-8 monomers, organic solvent and a photo-acid generator (PAG). Conventionally, the deposition of the resist is followed by a soft-bake to remove the solvent. Then, the resist film is exposed to UV light through a pattern defined mask. During UV-exposure, a strong acid is generated by the photolytic decomposition of PAG. The photo-acid acts as a catalyst in the subsequent cross-linking reaction. Following exposure, a PEB is immediately performed to activate the exposed SU-8 resist for cross-linking. This bake is necessary because the reaction kinetic of the cross-linking mechanism is very slow at ambient temperature. The elevated temperature promotes diffusion of the photo-acid and increases the mobility of the SU-8 monomers, which allows for improved cross-linking. During the PEB step, the photo-acid would also diffuse into the unexposed area, which cause line width variation and reduce the resolution. However, the acid diffusion effect can normally be ignored because the resist film has been densified by soft bake and the exposed regions rapidly polymerize during the PEB which limits the migration of acid molecules.

In our experimental procedures, the PEB step of an exposed SU-8 was deliberately omitted. Instead, a second layer of SU-8 was immediately coated over the exposed SU-8 film, and this two-layer resist was kept in room temperature for 2 hours to allow diffusion of the solvent in the top SU-8 layer into the bottom exposed SU-8 layer. Some studies have indicated that the diffusion coefficient of the acid molecule is strongly dependent on the concentration of remaining solvent in the resist film [9]. So if the solvent concentration in the exposed resists is held in a high level before PEB, it is highly possible that some photo-acid diffuses into the adjacent unexposed areas from the exposed areas of the resist film to induce the cross-linking reactions in neighbor regions. Since the diffusion of photo-acid is nearly isotropic, 3D arc-shaped structures will be obtained after removal of all uncross-linked SU-8 by developer.

In order to demonstrate the formation mechanism of 3D curved SU-8 structures based on the diffusion of photo-acid, a numerical model was constructed to elucidate the photo-acid distribution in SU-8 resist matrix during PEB. Here, a model of solute transport in porous media was utilized for explaining the acid diffusion. It is assumed that the light intensity distribution upon exposure regions is uniform and the diffusion of photo-acid is isotropic in the resist. To model diffusion of acid molecules, the equations governing mass balance must be solved. The model equation in the modeled domain is formulated below:

$$\frac{\partial c}{\partial t} + \nabla \cdot (-D \nabla c) = 0$$

where c denotes concentration and D the diffusion coefficient of the species. The concentration initial conditions in the exposed regions and the unexposed regions are defined as $c=c_0$ and $c=0$, respectively. Finally, the model was solved with FEMLAB software, a commercial finite element package (COMSOL Inc. Burlington, MA). Figure 2 shows the cross-sectional spatial concentration of photo-acid in SU-8 after 15 min diffusion, which is originated from an exposed SU-8 region of width 100 µm and height 30 µm (infinite extent into the paper). The degree of local SU-8 cross-linking is proportional to the acid concentration, so the distribution of photo-acid will define the profile of cross-linked SU-8 resist.

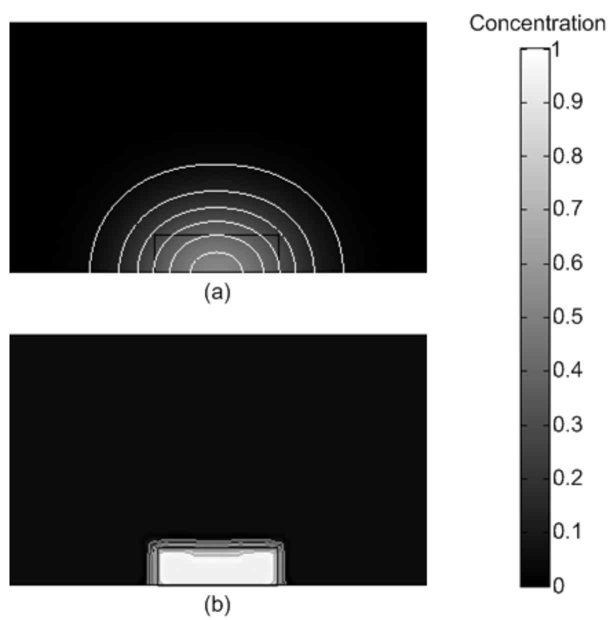

Figure 2: Simulated concentration profile of the photo-acid in the bilayer SU-8 resist matrix after 15 min diffusion. (a) no PEB for the first SU-8 layer, (b) PEB for the first SU-8 layer.

EXPERIMENT RESULTS

As above mentioned theory, the curved profile of SU-8 structures were defined by the concentration contour of the photo-acid. In order to investigate the effect due to the photo-acid diffusion, a comparative experiment of the standard SU-8 photolithography process and the proposed SU-8 photolithograhpy process was performed with SU-8 2050 photoresist. Figure 3a and 3b show the cross-sectional images of SU-8 line structures fabricated with the standard procedure and the proposed procedure, respectively. Figure 3a shows that, with baking the first exposed SU-8 layer before the addition of the second layer, the fabricated structures have nearly vertical sidewall profiles. On the contrary, the structures obtained with omitting the first SU-8 layer PEB step have rounded edges due to the diffusion of photo-acid (Figure 3b). The photo-acid diffusion effect has also a negative influence on the lithographic resolution. It can be found that the curved SU-8 structures is wider than the exposed pattern due to diffusion of the photo-acid, which leads to a loss of the resolution. However, through the appropriate geometrical compensation and diffusion control, précised fabrication of the 3D curved SU-8 structures based on the photo-acid-diffusion effect can be achieved. On the basis of this proposed method, we fabricated various 3D curved structures, including linear, circular, triangular, rectangular, annular, and star-shaped curved structures (Figure 4a~f). These results indicate that the photo-acid diffusion method can fabricate the complex 3D curved microstructures effectively with a simple, inexpensive and reliable process. The profile and curvature of the curved structure are determined by several factors, including exposure dose, diffusion time, baking temperature, resist thickness, and geometric dimensions. In order to precisely predict the shapes and sizes of the 3D curved structures, we will further investigate the effects of these factors in the future study.

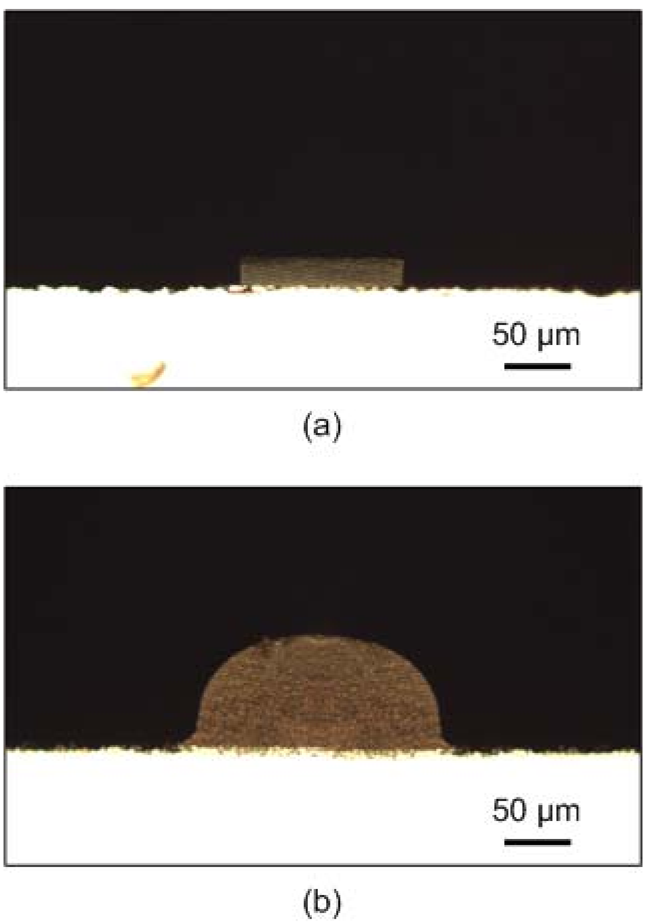

Figure 3: Cross-sectional micrograph of the fabricated SU-8 structures. (a) 15 min PEB for the first SU-8 layer, (b) no PEB for the first SU-8 layer.

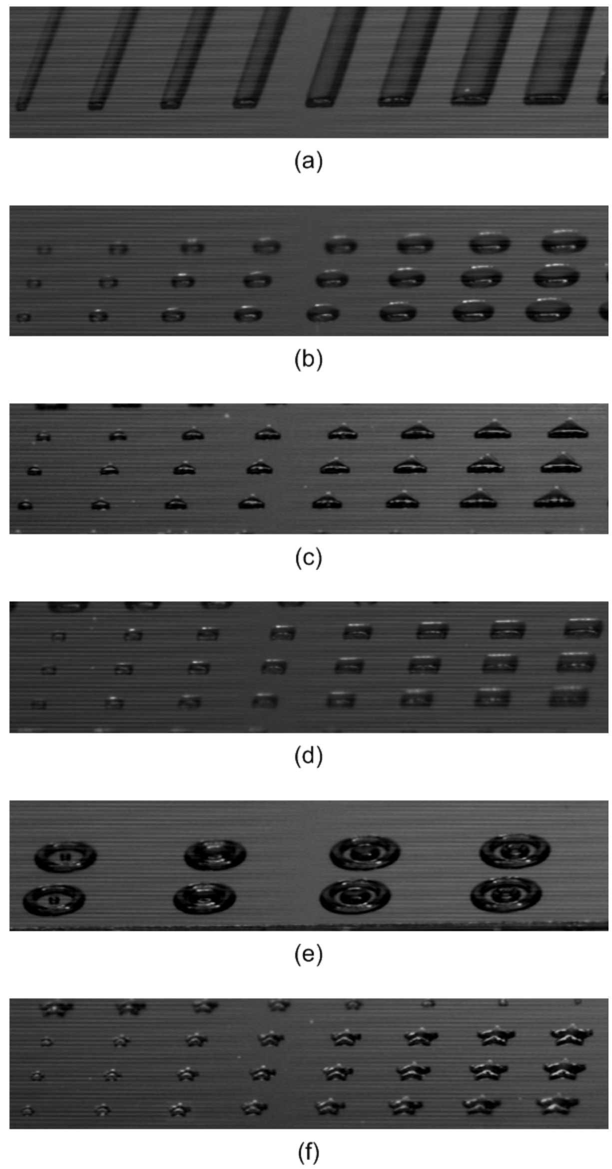

Figure 4: Optical micrographs of diverse-shaped 3D curved SU-8 structures. (a) semi-cylindrical structures, (b) dome-shaped structures, (c) triangular curved structures, (d) square curved structures, (e) annular curved structures, (f) star-shaped curved structures.

CONCLUSION

A novel technology to fabricate 3D curved SU-8 structures has been successfully demonstrated in this paper. This technology utilizes the isotropic nature of photo-acid diffusion to form smooth arc-shaped resist profile for 3D curved fabrication. The standard SU-8 photolithography procedure was modified by omitting a PEB step to increases the mobility of the photo-acid, which leads to cross-linked interfacial layers and forms curved structures. These structures were fabricated without the use of sophisticated equipment and could be integrated with the entire device within the same fabrication step. Through geometric design and diffusion time control, curved shapes with different curvatures and configurations have been successfully fabricated with this technology. Compared to traditional gray mask technologies, this method provides a simple and cost effective way to fabricate curved structures with reasonable surface smoothness. This technology combined with proper geometrical designs can generate many complex 3D structures suitable for the applications of optical MEMS or microfluidic systems.

ACKNOWLEDGEMENTS

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REFERENCES

[1] G. T. A. Kovacs, N. I. Maluf and K. E. Peterson, "Bulk micromachining of silicon" ,in *Proc. IEEE*, vol. 86, pp. 1536–1551, 1998.

[2] J. M. Bustillo, R. T. Howe and R. S. Muller, "Surface micromachining for microelectromechanical systems", in *Proc. IEE*E, vol. 86, pp. 1552–1574, 1998.

[3] H. Guckel, "High-aspect-ratio micromachining via deep x-ray lithography", in *Proc. IEEE*, vol. 86, pp. 1586–1593, 1998.

[4] Y. Oppliger, P. Sixt, J. M. Stauffer, J. M. Mayor, P. Regnault and G. Voirin, "One-step 3D shaping using a gray-tone mask for optical and microelectronic applications", *Microelectron. Eng.*, vol. 23, pp. 449–454, 1994.

[5] S. Chang and J. Yoon, "Shape-controlled high fill-factor microlens arrays fabricated with a 3D diffuser lithography and plastic replication method", *Opt. Express*, vol. 12, pp. 6366–6371, 2004.

[6] C. Lin, H. Yang, and C. Chao, "Hexagonal microlens array modeling and fabrication using a thermal reflow process", *J. Micromech. Microeng.*, vol.13, pp. 775-781, 2003.

[7] C. M. Cheng, K. Matsuura, I. J. Wang, Y. Kuroda, P. R. LeDuc, and K. Naruse, "Fabricating small-scale, curved, polymeric structures with convex and concave menisci through interfacial free energy equilibrium", *Lab Chip*, Vol. 9, pp. 3306-3309, 2009.

[8] C. Y. Chang, S. Y. Yang, L. S. Huang, and K. H. Hsieh, "Fabrication of polymer microlens arrays using capillary forming with a soft mold of micro-holes array and UV-curable polymer", *Optics Expres*s, Vol. 14, pp. 6253-6258, 2006.

[9] K. Asakawa, T. Ushirogouchi, M. Nakase, "Effect of remaining solvent on sensitivity, diffusion of acid, and resolution in chemical amplification resists", *J. Vac. Sci. Technol. B*, vol. 13, pp. 833-839, 1995.