고 형상비 UV LIGA 공정을 위한 낮은 내부응력의 SU-8 도금틀 제작

論 文
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SU-8 Mold Fabrication with Low Internal Stress and High Aspect Ratio for UV LIGA Process

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Abstract - This paper describes the research to minimize the film stress and maximize the aspect ratio of photoresist structure, especially about SU-8 for electroplating mold. UV LIGA process using SU-8 allows fabricating high aspect ratio polymer structures. However, it is hard to get fine patterns in the high aspect ratio structures because of high internal stress and difficulty of removing SU-8. The purpose of this paper is to set up the process condition for the obtainment of both low film stress and high aspect ratio and to find design rules that make the pattern be less dependent on stress problem. Firstly, the process of heat treatment and exposure of SU-8 are proposed. These two conditions control the amount of cross-linkage in polymer structure, which is the most important parameter of both pattern generation and remaining stress. Heat treatment is dealed with soft bake and post-exposure-bake. Temperature and time duration of each step are varied with heat treatment condition. Exposure time is varied with exposure condition. Some test patterns are fabricated to evaluate the proposed process. Nickel electroplating is performed with the mold fabricated through the proposed process to confirm the SU-8 as a good electroplating mold.

Key Words : SU-8, stress, UV LIGA, electroplating mold

1. Introduction

High aspect ratio in microstructure means many advantages for MEMS applications. The definition of aspect ratio is the ratio of height to the width or the gap size of structure. It is an important parameter especially in the case of the actuators driven by electrostatic force, such as comb drives. Figure 1 shows two kinds of aspect ratio.

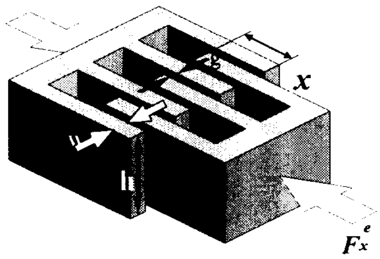

Fig. 1 Comb electrode

The aspect ratio of structure is given by

$$R_s = \frac{h}{w} \tag{1}$$

And the aspect ratio of gap is given by

$$R_g = \frac{h}{g} \tag{2}$$

From the Figure 1, electrostatic force can be calculated.

$$F_x^e = N\frac{\partial W^{e'}}{\partial x} = \frac{N}{2}\varepsilon_0\frac{h}{g}v^2 \tag{3}$$

We': electric coenergy

N : number of gap

ε_0: permitivity in vacuum

υ : driving voltage

Assumed that the system has a linear spring, the static displacement is expressed by

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$$x = \frac{N}{2k} \varepsilon_0 R_g v^2 \qquad (4)$$

k: mechanical spring constant

The equation 4 shows that the displacement is proportional to the value of aspect ratio of gap. High aspect ratios make it possible to increase the static displacement of the actuator. For the case of plating mold, the aspect ratio of mold structure means the aspect ratio of gap between metallic structure. So the aspect ratio of structure is also important in mold generation.

The processes have been researched in many ways to get the structure of high aspect ratio. Usually, polysilicon is used to fabricate the microstructures. The polysilicon process with reactive ion etching is useful in multi-layer generation. However, it is almost impossible to deposit thick layers more than 10㎛. Moreover, the process costs are very high. Recently, new process named TRP(Trench Refill Process) makes it possible to fabricate the structure of high aspect ratio over 30 with poly-silicon process[1]. Development of dry etch equipment encourages the dry etching process with single crystalline silicon[2]. Bulk silicon process by wet etching is also much improved. Electroplating is usually used to get the metallic structure of high aspect ratio. The most important parameter is the vertical profile of plating mold. There are several kinds of mold fabrication process. X-ray LIGA, which is known as the best process for high aspect ratio, uses X-ray accelerated by synchrotron to expose a mold to deep range without scattering. In addition, beams having characteristics of high transparency and low scattering, such as ion-beam, are used as an exposure method. However, they are high cost and low productivity processes. So the processes, using UV(Ultra Violet) LIGA process is briskly reported. The UV LIGA process uses UV light as exposure energy and performs electroplating. Therefore, the new material for mold application is vigorously investigated to overcome the limitation of aspect ratio.

Recently, SU-8 has been developed and researched for high aspect ratio molds in UV-LIGA process. SU-8 is an epoxy-based photoresist, designed for ultrathick photoresist structure with single layer coating[3,4]. Thicker than 100㎛ layer can be obtained by single coating, and much thicker layer can be achieved by multiple coating. In addition, SU-8 has very high transparency in near UV band. It is easy to expose to the deeper range with low scattering due to the high transparency of this material[4]. Therefore, structures having the aspect ratio over 10 have been fabricated[1,3]. These results show the possibility of SU-8 for high aspect ratio mold. However, they have some problems that matter seriously during LIGA-like process. Firstly, the high stress of SU-8 film is produced primarily by the difference between the linear expansion coefficient of the wafer and the resist during heat treatment. The stress is large enough to bow the substrate[5]. Secondly, it is hard to remove the SU-8 film with most kinds of solvent. Even with the commercialized remover for SU-8, it is almost impossible to eliminate the hard baked SU-8 film. Even with commercial SU-8 remover, it takes longer than 1 hour to remove 45㎛ film without semicuring. Moreover, the line width of fabricated structures are larger than 10㎛.

Therefore, the object of the paper is to establish the process condition to get the patterned SU-8 structure with low stress and high aspect ratio more than 20 in the scale of several micron order.

2. SU-8 Characteristics

As SU-8 is an epoxy based negative thick photoresist, the material has good properties that are helpful to MEMS applications. Main constituent is EPONR Resin SU-8. Organic solvent, GBL(gamma-butyrolacton), is added to control the viscosity of the photoresist, and a kind of photo-initiator is added[4]. Figure 2 is the chemical formula of EPONR resin SU-8.

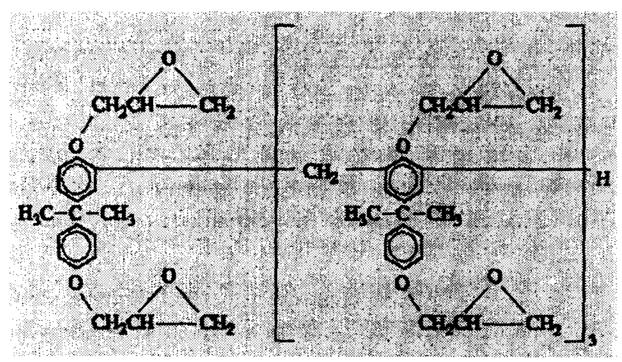


Fig. 2 Multifunctional Glycidyl Ether derivative of Biapanol-A Novolac(EPONR resin SU-8).

The most important characteristic is the high transparency in UV range. High transparency enables us to expose the photoresist up to much deeper range, comparing with other thick photoresists. Furthermore, it is possible to coat the material by conventional spin coater up to several hundreds of microns by single coating. Figure 3 shows the optical absorption curves of some conventional thick photoresists.

SU-8 is good to generate the fine pattern. Comparing with other negative photoresists, it is much more stable to get the pattern as designed. Most negative photoresists

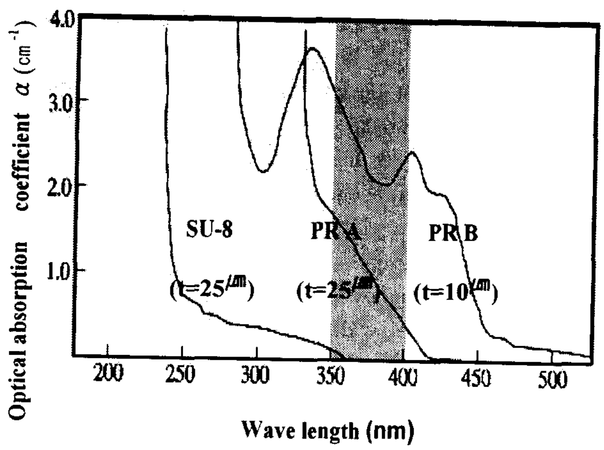


Fig. 3 Optical absorption
PR A: RISTON T-168
PR B: diazo resist

have different mechanism compared with positive ones. For the case of positive PR, during the exposure the linkage of exposed part is broken to give increase of the solubility in the developer. For the case of negative one, exposure energy let photoinitiator generate a strong acid, and the acid facilitates polymeric cross-linking during PEB(Post Exposure Bake). The molecular weight of the exposed part is increased to give reduction of the solubility in the developer. Therefore, negative PR is sensitive to the condition of PEB. The exposure generates a strong acid, and the acid diffuses before PEB. Therefore, the profile of pattern is affected by the time interval between exposure and PEB. SU-8 offers relatively stable results around the optimized conditions because it undergoes almost no diffusion of acid during the period.

SU-8 has a good endurance to the chemical and plasma. The characteristic enables us to have freedom in process design. A good adhesion with Si wafer and glass is another advantage of SU-8.

In spite of the advantages mentioned above, there are some problems at pattern generation. SU-8 has a large stress. If it is excessively cross-linked, the patterns are distorted and sometimes adhesion failure occurs. Figure 4 is the SEM(Scanning Electron Microscope) photograph of fabricated SU-8 mold for comb electrodes, which is an over cross-linked case. Figure 4 shows that the stress is large enough to cause adhesion failure during the development. Molds of comb electrode come off and stick to each other.

Figure 5 is another kind of stress effect. The figure shows the wrinkles in the pattern edge of mold for comb electrode. The phenomenon is easily found at corners of the patterns. This stress makes the pattern much more distorted as the film becomes thicker.

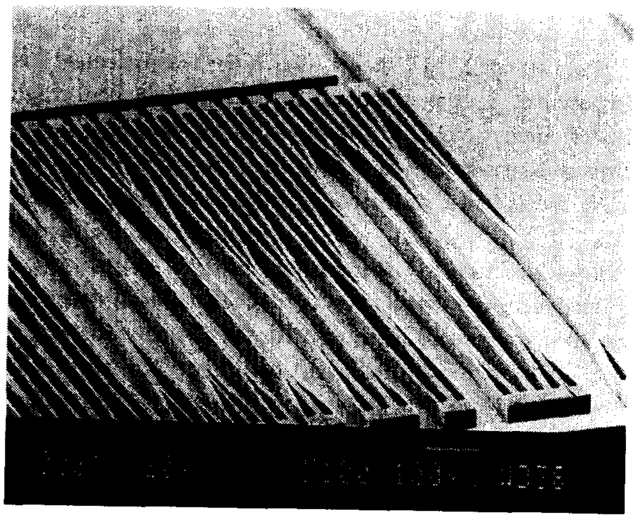


Fig. 4 Stress effect on pattern generation

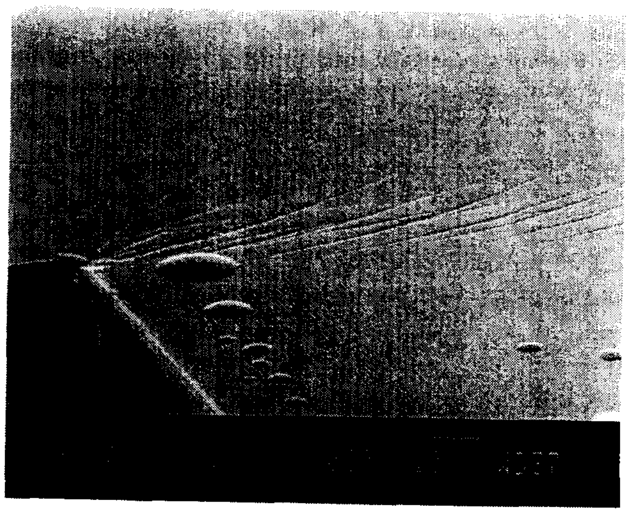


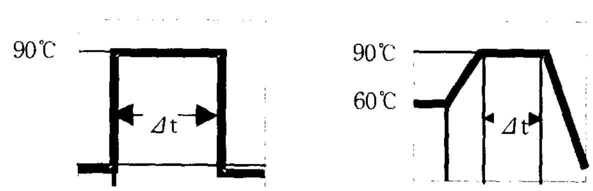
Fig. 5 Wrinkles on the pattern edge

Besides the stress problem, it is hard to remove SU-8 with a solvent after a whole process, especially including hard bake process. Even in the acid or alkali such as boric acid or HF or KOH, SU-8 film is not attacked. And even with the commercial remover for SU-8, it takes 1 hour to clean up the 45㎛ film. If the film is hard baked, it is almost impossible to remove except for using plasma asher.

3. Optimization Experiments

To establish the conditions, experiments are performed by varying spinning time and speed, soft-bake, develop and PEB (Post Exposure Bake) conditions. In order to get a vertical wall profile(high aspect ratio structure), the amount of exposure and heat energy should be increased. However, increasing exposure and heat treatment too much make the structure excessively cross-linked. The excessive cross-linkage increases the stress of SU-8 film. In other words, these two aspects are traded-off. Then, a fabrication process for low stress SU-8 film is proposed. The proposed process has two key factors. One is to control the stress by controlling amount of cross linkage by varying the time and temperature of PEB, and varying the time duration of exposure. The other one is to reduce the stress by changing the coating condition and heat treatment such as soft bake and post exposure bake.

Firstly, we use relatively low spin speed and have a sufficient relax time after coating to minimize the stress associated with the spin coat process. While most of the photoresists are coated at the speed of several thousand rpm, and there is no relaxing time before soft bake, as shown in Figure 6(a).



(a) (b)

Fig. 6 Heat treatment for soft bake and PEB
(a) Conventional heat trea60℃
(b) Proposed heat treatment

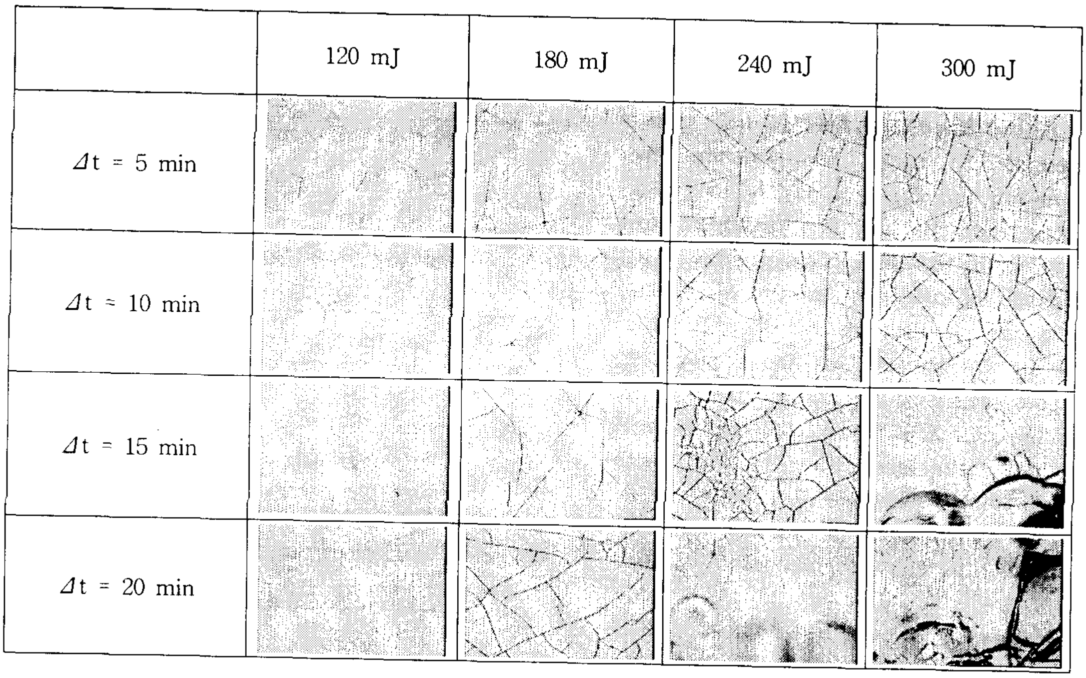
Additionally, a multi-step heat treatment for soft bake and post exposure bake is proposed to reduce the adhesion failure as well as cracking, as shown in figure 6(b). The initial lower temperature in heat treatment allows the much part of the solvent to evolve out of the film without causing deformation. Then, the temperature is slowly raised at the rate of 5 degrees per minute to about 100℃ and maintained at that temperature for several minutes. The substrate is cooled down slowly at the isolated plane to room temperature. The proposed multi-step heat treatment is useful to reduce the stress by suppressing the temperature shock.

Table 1 Comparison of conventional process and the proposed process

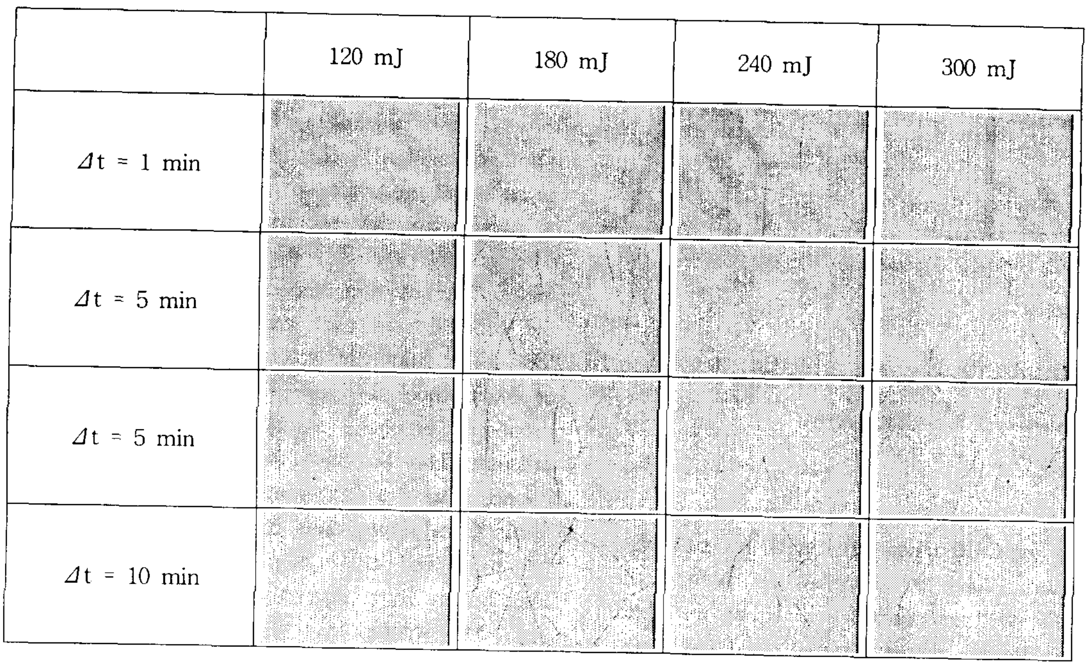
	Conventional process	Proposed process
Spin coating	low spin: 500 rpm high spin ≥ 2000 rpm spinning time: 25sec high viscosity SU-8	low spin: 500rpm ligh spin≤1000rpm spinning time≤15sec low viscosity SU-8
Relax	no relax time	more than 30min.
Soft bake	conventional heat treatment (single step) figure 6 (a)	proposed heat treatment (multi step) figure 6 (b)
Expose	sufficient time	prevent excessive cross-link
PEB	conventional heat treatment (single step) figure 6 (a)	proposed heat treatment (multi step) figure 6 (b)
Develop	no agitation≥30 min	gentle agitation≤20 min

The other conditions mentioned above, such as spinning time, spin speed and development are tested for the various thickness from 5 to 130㎛. Table 1 summarizes the difference between the conventional process and the proposed one.

To compare the results of film fabricated by using the conventional process and the proposed one, we observed the surface of film tested under various conditions. All the conditions in each experiment are the same, except for the conditions of exposure and PEB. The photographs of microscope in figure 7 show the improved result of proposed process, comparing with the conventional process. The thickness of the films are 20㎛. In any results from the conventional process, wrinkles are easily found from photographs in figure 7 (a). Exposure energy has to exceed 240 mJ/cm2 and the PEB time should be longer than 15 minute to fabricate the line narrower than 5㎛. **Δ**ts, written in figure 7 (a) and (b), mean **Δ**ts in figure 6 (a) and (b), respectively. As shown in figure 7 (a), the surfaces showed severe wrinkles at the conditions of larger than 240mJ/cm2 and 15 min. In the case of the proposed process, lines narrower than 5 ㎛are generated with more than 240 mJ/cm2 of exposure and more than 5min of **Δ**t instead of 15min in the conventional process.



(a) Results from the conventional process

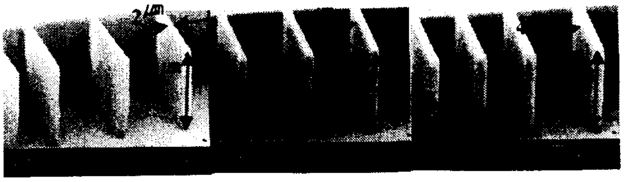


(b) Results from the proposed process

Fig. 7 Photographs of film surface tested varying exposure dose and PEB condition.

4. Micro Structures

To confirm the validity of the proposed process, several kinds of test pattern for determining the minimum line width and allowable gap size are fabricated. Some photographs of lines are shown in Figure 8. They are designed to test the narrow lines. The height of the structures in Figure 8 is 40㎛, and the widths are 2, 3, and 4㎛, respectively.



(a) (b) (c)

Fig. 8 Narrow line pattern
(a) 2㎛ lines, aspect ratio : 40/2=20
(b) 3㎛ lines, aspect ratio : 40/3
(c) 4㎛ lines, aspect ratio : 40/4=10

Figure 9 shows the fabrication results of 40㎛ high structure. Lines of 1㎛ width are come off from the substrate during development and rinsing. Line width is designed from 1㎛ to 100㎛. Gap size of each pattern is 40㎛, 20㎛, and 10㎛, respectively. For the case of 2㎛ lines in each pattern, the aspect ratio of structure is 20.

The same patterns are tested for much thicker layers. The thickness of tested structure is 130㎛. Figure 10 shows the result of 130㎛ high SU-8 structure. Fabricated minimum line width is 5㎛. The lines narrower than 5㎛ are come off during development. Therefore, the maximum aspect ratio of the structure is 26 and it is the maximum value all through the experiment. The sidewall of the structure is clean enough.

When these polymer structures are used as a plating mold, the shape of plated metal takes the reverse form of the polymer structure. In other words, a line width means a gap size of plated metal and a gap size means a line

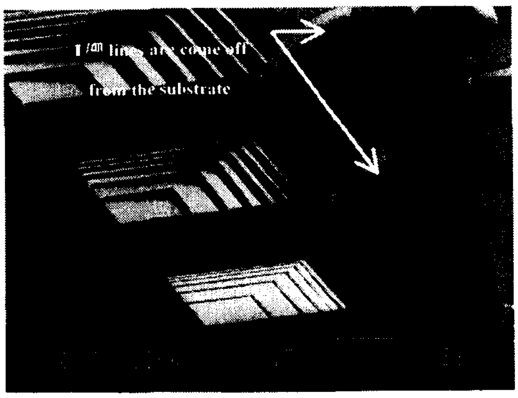


FIg. 9 Pattern of lines and spaces

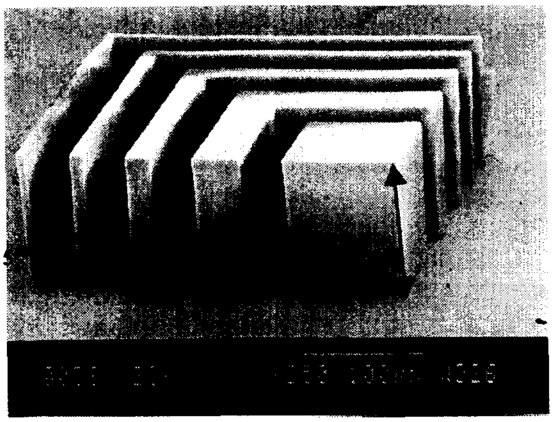
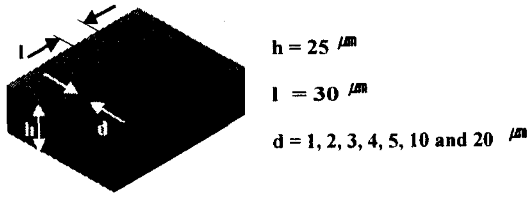
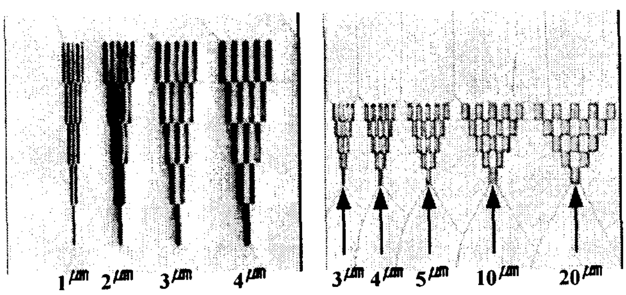


Fig. 10 Lines and spaces of 130㎛ high

width of metallic structure. In order to prove the usefulness for plating mold, fabrication of deep trench is also important. Figure 11 shows deep trenches fabricated. The width of trench is designed from 1㎛ to 20㎛ and the depth is 25㎛. For the case of 1㎛ trench the aspect ratio of gap is 25, and this tested the maximum aspect ratio of the gap.



(a)

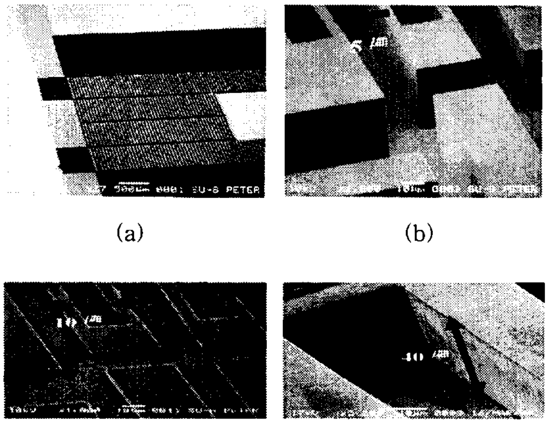


(b) (c)

Fig. 11 Narrow trench
(a) Perspective view of structure
(b), (c) Photographs of microscope

5. Electroplating

Nickel electroplating was performed with a successfully fabricated mold to show a usefulness of SU-8 structure as a mold. The thickness of PR mold is 45㎛ and that of plated nickel is 40㎛. As shown in figure 12, minimum line width of the mold is 5㎛. Nickel surfamate bath was



(a) (b)

(c) (d)

Fig. 12 Nickel electroplating with optimized fabricati process of mold
(a) Mold overview
(b) Magnified view of SU-8 mold
(c) After electroplating
(d) After mold removing

used as a electroplating bath. Plating rate is 0.25㎛ per minute when current density is 10 ㎃/㎠. In the electroplating bath, there contains some additives to improve the quality of electroplated nickel. Mechanical stirring of solution performed continuously during the electroplating. Figure 12 is the SEM photographs of each step: (a) is the overview of fabricated mold, (b) is the magnified view of (a), (c) is the shape after electroplating, (d) is a electroplated nickel structure after removing the mold with O2 plasma ashing.

6. Conclusion

In this paper, optimization experiments are described to minimize the stress of SU-8 structure as well as maximize the aspect ratio. Process conditions of mold fabrication for various thickness from 5㎛ to 130㎛ were settled. Stress problem is so reduced that pattern distortion or adhesion failure disappears. Stable results of aspect ratio over 10 are obtained and maximum aspect ratio of structure, obtained with the test patterns used, is 26. In the case of gap maximum value of aspect ratio is 25. With the mold, nickel electroplating was performed successfully.

7. Acknowledgment

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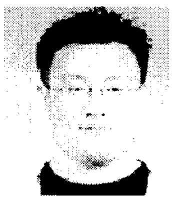

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