Study on Fabrication of Arbitrary 3-D Structures Utilizing Pixels Exposed Lithography

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Abstract

Research on the development of a method of fabricating three-dimensional microstructures that uses Synchrotron Radiation (SR) light is reported. Before now, some research on three-dimensional processing methods using SR lithography has already been reported. They have involved techniques of applying exposure energy distributions to resist surfaces. Complicated energy distributions need to be applied to resist surfaces to fabricate arbitrary three-dimensional structures. However, we devised a new method that made it possible to fabricate arbitrary three-dimensional microstructures which is not symmetrical and asymmetrically related by using a mask with pattern created function. The advantages of this method are that it is suitable for rapid prototyping and it reduces the fabrication time and cost since it is not necessary to fabricate conventional photolithographic masks. Our research involved a basic experiment on this method of fabrication where we succeeded in fabricating a free-form surface by exposing it through an overlapping array of pixels that created a single aperture. Moreover, the pixel size could be made smaller than the aperture size by overlapping adjoining pixels.

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1. Introduction

Microfabrication of three-dimensional structures represents a significant technology in producing various components for MEMS. Potassium hydroxide (KOH) anisotropic etching of silicon and laser machining[1] have been employed in fabrication using MEMS. Nanoscale three-dimensional microfabrication technology using Synchrotron Radiation (SR) lithography is possible with a high aspect ratio, which harnesses the characteristics of SR, and free-form structures with inclined sidewall surfaces can be fabricated. Some research on three-dimension processing methods using SR light has already been reported [2] [3] [4] [5] [6] [7] [8]. Each of these techniques has involved exposing an energy distribution onto the resist surface. Complex energy distributions need to be applied to the resist surface to fabricate complicated three-dimensional structures. Therefore, there have been techniques of using two or more masks and the gray-mask method to change the thickness of X-ray absorbers that have been used to apply complicated energy distributions. However, these techniques have involved complex processes, material processing has been difficult, and the structures that have been able to be fabricated have been limited.

Therefore, we examined methods that made it possible to apply complicated energy distributions to fabricate not only intricate structures but those with various arbitrary forms. Moreover, many existing methods have problems, such as complex processes and difficult material processing with masks, and a great deal of time and money are required to fabricate masks. Therefore, we examined new methods that took into consideration not only complicated energy distributions but that also simplified the processes for fabricating masks.

2. Method of 3-D Fabrication Based on Pixels Exposed Lithography

2.1 Outline of New Method of 3-D Fabrication

We devised a new method that made it possible to fabricate arbitrary three-dimensional microstructures by the mask with pattern created function. This method is outlined in Fig.1. SR light is shaped by the aperture, and the amount of exposure energy is controlled by opening and closing the aperture with an actuator. It is a technique of applying the energy distribution in a mosaicked shape as shown in the figure. As the advantage of this method, since there is no necessity of fabrication masks and it is suitable for rapid prototyping, reduction of fabrication time and cost is mentioned. The advantages of this method are that there is no need to fabricate masks, it is suitable for rapid prototyping, and it reduces the fabrication time and cost.

We first examined whether this method of exposure could be used when samples were exposed by SR lithography through a pixel array. When the three-dimensional processing method of others which SR light is used and has actually been performed to until is compared with this exposure method, in order for there to be no big difference by the mechanism of giving absorbed energy distribution to inside of the resist, it is thought that it is theoretical sufficiently possible. When other three-dimensional processing methods in which SR light had been used were compared with this method of exposure, no large differences due to the mechanism that applied absorbed energy distribution inside the resist were theoretically thought to be possible. Therefore, we determined that improving the three-dimensional processing itself could actually give an ideal energy distribution. Therefore, it was necessary to examine about the pattern to create an ideal energy distribution.

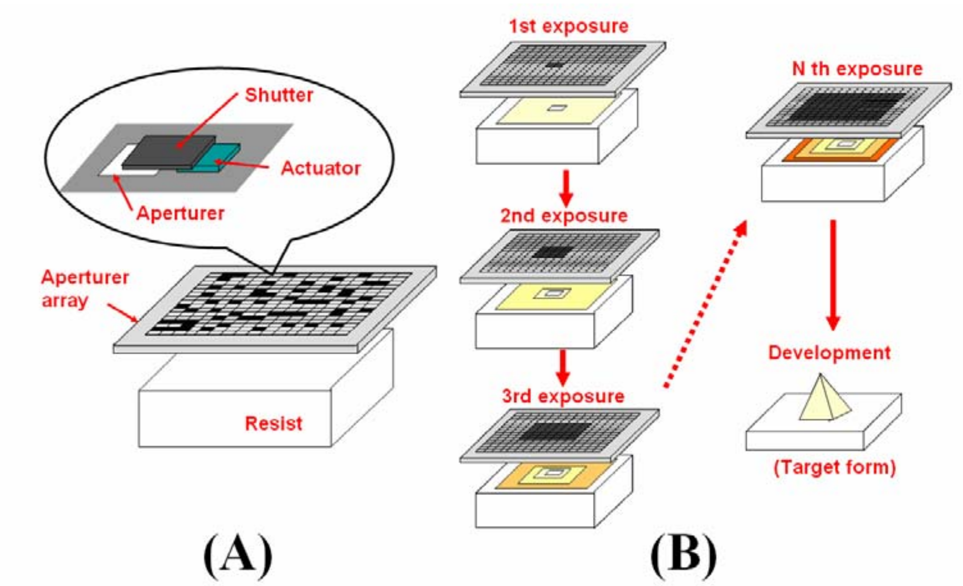


Fig.1 Outline of 3-D method of fabrication based on Pixels Exposed Lithography. (A) Concept underlying this method, using the mask with pattern created function where SR light is shaped by aperture, and amount of exposure energy is controlled by closing and opening aperture with actuator (B) Using the mask with pattern created function to apply mosaicked energy distribution to resist surface

2.2 Examination about Pattern Created for Giving Ideal Energy Distribution

The aperture to create the pattern needs to have an ideal energy distribution with a mosaicked exposure applied to Polymethylmethacrylate (PMMA) resists. An aperture requires two main features. First, the aperture needs to produce a high-contrast pattern and, second, it needs to be square or rectangular to produce very precise angles with smooth side walls. The energy to produce high contrast should be 1 or 0 (Fig. 2) in applying an ideal energy distribution with a mosaicked exposure to the opening and energy interception components of the aperture. Therefore, we need to use heavy metal with high absorptivity in the X-ray region for the aperture material. Moreover, to avoid non-exposed or double exposure on the boundary lines and boundary points, and produce very precise angles, the aperture for SR light needs to be rectangular or square and the plane roughness on the side surface needs to be low at the opening of the aperture (Fig. 3).

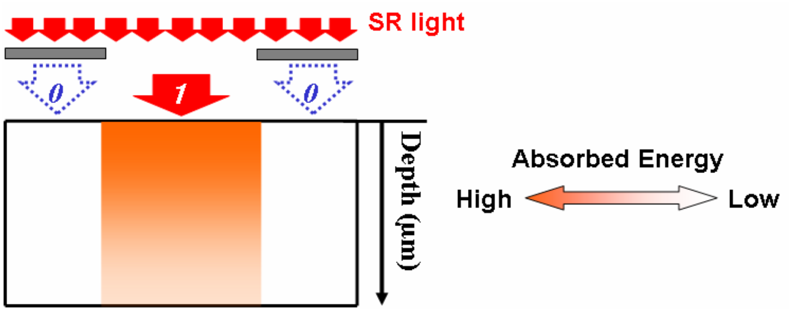


Fig.2 Absorbed energy distribution of resist cross section utilizing aperture. Shading indicates amount of energy

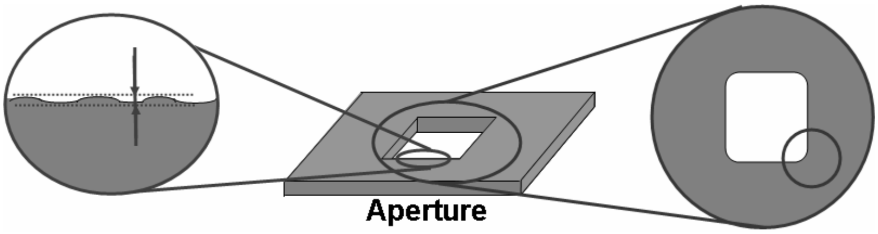


Fig. 3 Outline of aperture. Angle should be very accurate with smooth side wall

The thicker the aperture, the stronger the mechanical strength and absorptivity of SR light. However, if the aperture is too thick, SR light cannot be optimally shaped. As shown in Fig. 4, when the aperture is inclined and raised to the SR light with angle error in the pixel array, SR light is reflected from the sides of the opening for the aperture. The inclination of the aperture to the shaped SR light was set to a. θ[°], the aperture width, was set to D[µm] and the aperture thickness was set to t[µm]. The effective area, D'[µm], that received the exposure was determined by following formula.

$$D' = D \cdot \cos\theta - t \cdot \sin\theta \tag{1}$$

From Eq. (1), the smaller the aspect ratio of the aperture opening, the less it is influenced by angle error θ[°] in the pixel array. If the aspect ratio of the aperture opening is large, not only does the effective area of exposure decrease but it is also easy to increase the energy distribution since SR light is reflected from the sides of the opening (Fig. 5). When PMMA is exposed through a steel aperture with an aspect ratio of 20 (width 50 [µm] and thickness 1 [mm]), which can expose sufficient energies of 1 through the opening and 0 to the parts of the aperture that intercept energy, a curved surface is fabricated on the bottom surface after development as a result of the energy distribution (Fig. 5). The inclination of the aperture is arranged so that it is 0.1 degree or less.

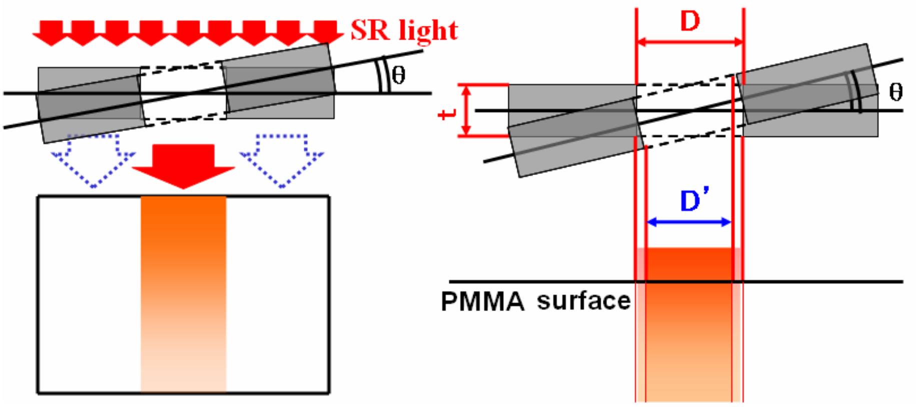
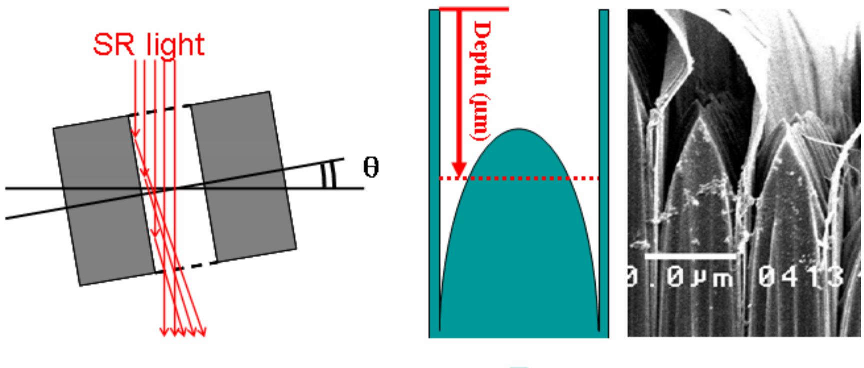


Fig.4 Decreased exposure area by inclining in arrangement



(A) **(B)**

Fig.5 Energy distribution and curved bottom. (A) SR light is reflected by inclined aperture (B) Curve begins at bottom

It is necessary to take into consideration not only the shape of the aperture but also the aspect ratio of the opening to distribute an ideal exposure energy on the PMMA surface. It is necessary to reduce the thickness of the parts of the aperture that absorb energy to reduce its size and eliminate non-exposed parts. However, if it is made thin, it will be hard to realize high contrast. However, if they are made too thin, it will be difficult to achieve high contrast. Therefore, there is a trade-off between minimizing the thickness of the aperture and achieving sufficient contrast. Moreover, if the aperture is too thin, it will bend easily. Therefore, it is necessary to not only take the absorptivity of energy into consideration but the quality of the material for the aperture including the coefficient of thermal expansion and Young's modulus.

3. Experimental Results

3.1 Experiment Condition

A number of experiments were carried out using beam line number 13 (BL-13) at the superconductivity compact SR source "AURORA", located at the SR center of Ritsumeikan University, Japan. The SR conditions at AURORA for the experiment were a minimum wavelength of 0.15 nm, an applied orbital radius of 0.5m, electron energy of 575 MeV, and a maximum storage current of 300 mA.

A wavelength between 0.2 and 0.5nm is optimal for X-ray lithography also in this wavelength domain. The reasons for this are to suppress the spread of secondary electrons due to Fresnel diffraction in the long-wavelength domain and suppress secondary electrons generated within the resist in the short-wavelength domain, as well as narrow the fabrication line width and improve resolution. The light from AURORA penetrates through two 200-μm Be windows, and uses light within the chamber that has a 0.15 to 0.95-nm wavelength. The exposure environment in the chamber was covered by helium gas at 1 atm to prevent the attenuation of X-rays by N_2 or O_2 gases and to prevent damage to the mask or resist by generated heat.

A PMMA sheet provided by Nitto Jushi Kogyo Co., Ltd. was used as the resist. Since PMMA has high resolution, the reproducibility of fine structures for molding could be enhanced in a further fabrication process [9]. The exposed PMMA structures gradually appeared during development with a GG developer (60 vol% 2-(2-butoxy-ethoxy) ethanol, 20% tetra-hydro-1, 4-oxazine, 5 vol% 2-amino-ethanol-1 and 15 vol% water) for 180 min. After that, stopper liquid (80 vol% 2-(2-butoxy-ethoxy) ethanol, and 20 vol% water) was used for 10 min followed by rinsing the sheet in water for another 10 min. All these processes were done at the exact temperature of 37ºC.

3.2 Fabrication of Arbitrary 3D Structures

To enable easy mosaicked exposure, the exposure energy was input into a two-dimensional array that was numbered in rows and columns. After that, the stage was programmed to automatically provide the necessary amount of exposure energy to the resist surface. Moreover, the smooth surface can be fabricated by making the adjoining pixels were overlapped [10]. Therefore, an algorithm that could determine the amount of exposure energy taking overlap into consideration was written to the target form to fabricate a three-dimensional structure that had an arbitrary shape [11]. Based on section 2.2, the aperture of 75μm × 80μm was fabricated, and various arbitrary three-dimensional structures were fabricated using this aperture and algorithm. We fabricated 3-D microstructures and its X-Y coordinates are expressed by Eq. (2), (3), (4), (5), (6), and (7). Each target forms and SEM photos of 3-D structures are shown in Fig. 6, 7, 8, 9, 10 and 11.

$$\text{Depth}(x, y) = -(40 \times \text{Sin}[x] \times \text{Sin}[y] + 45) \tag{2}$$

$$\text{Depth}(x,y) = -(5 \times e^{0.2x} \times \text{Sin}[y] + 45) \tag{3}$$

$$\text{Depth}(x, y) = -\left[100 \times x \times y \times (x^2 - y^2)/(x^2 + y^2) + 40\right] \tag{4}$$

$$\text{Depth}(x,\ y) = 60 \times \text{Arctan}[\ x/y] - 50 \tag{5}$$

$$\text{Depth}(x, y) = -(20 \times x \times \text{Cos}[y] + 100) \tag{6}$$

$$\text{Depth}(x, y) = 5 \times e^{x} \times \text{Sin}[y] - 40 \tag{7}$$

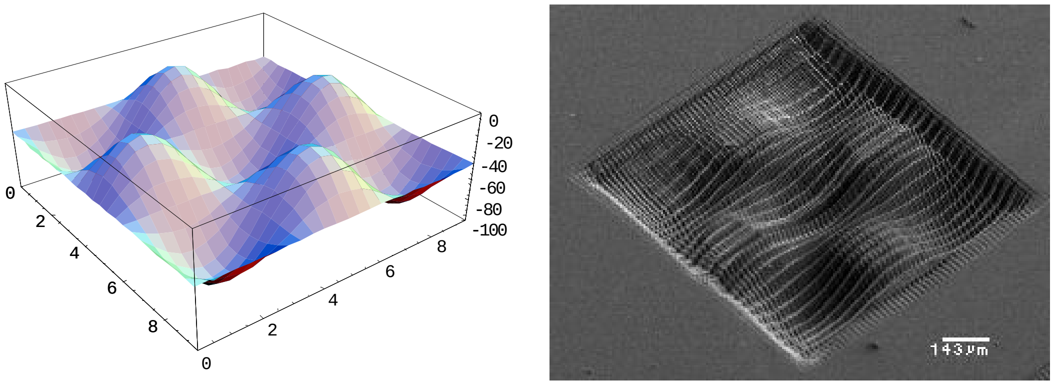


Fig. 6 Target form and SEM photo of 3-D structures derived with Eq. (2)

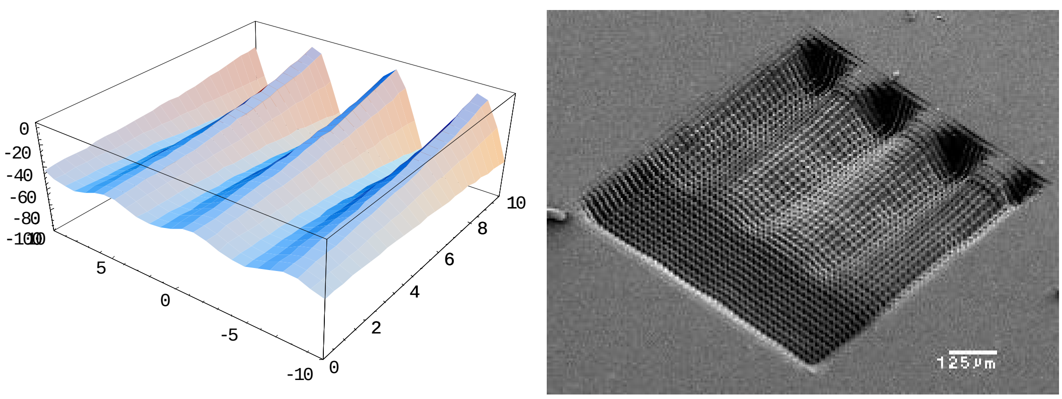


Fig. 7 Target form and SEM photo of 3-D structures derived with Eq. (3)

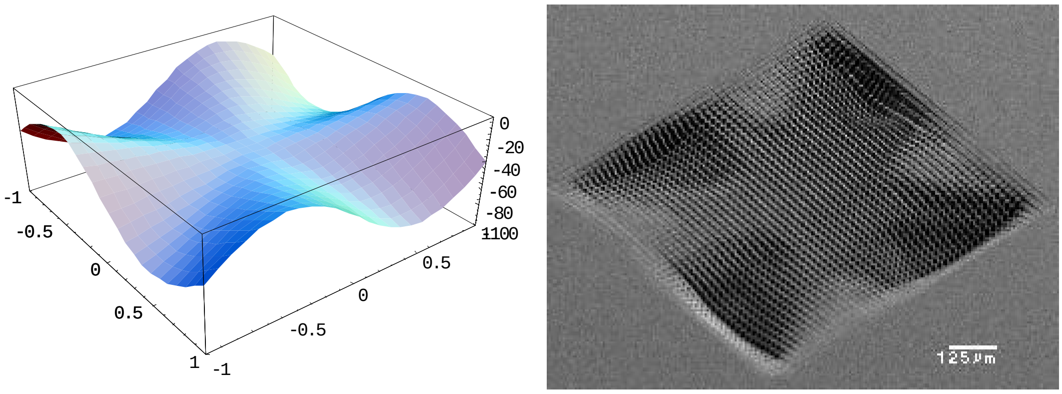


Fig. 8 Target form and SEM photo of 3-D structures derived with Eq. (4)

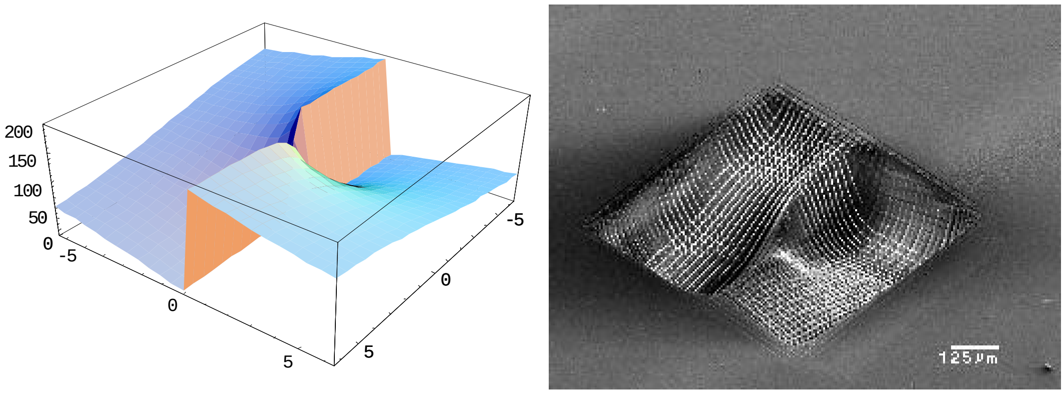


Fig. 9 Target form and SEM photo of 3-D structures derived with Eq. (5)

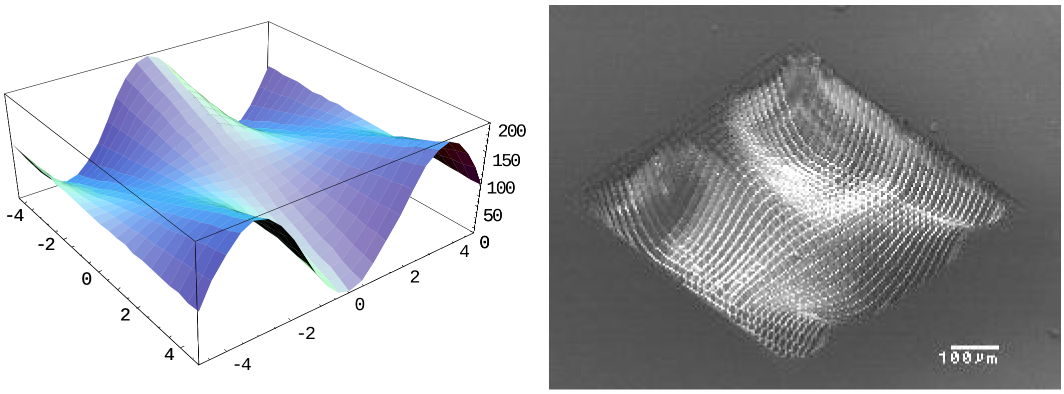


Fig. 10 Target form and SEM photo of 3-D structures derived with Eq. (6)

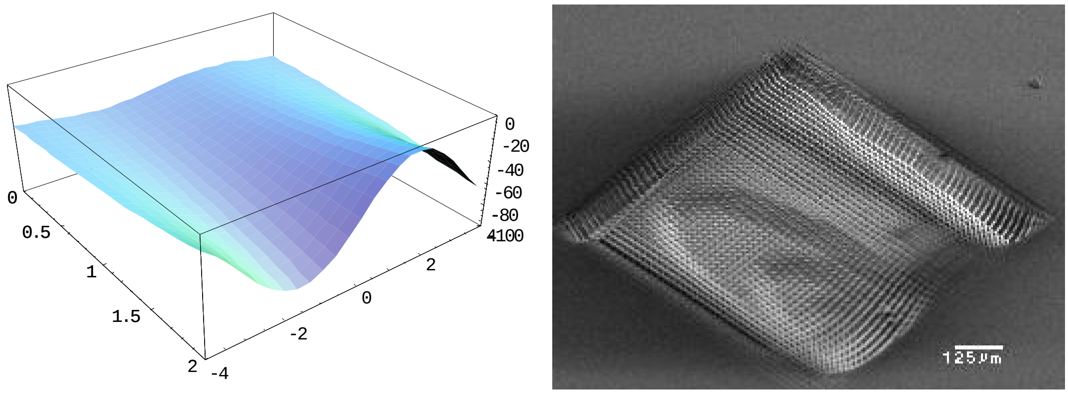


Fig. 11 Target form and SEM photo of 3-D structures derived with Eq. (7)

4. Conclusion

This research was aimed at the fabrication of arbitrary three-dimension structures. The problems with existing methods of fabrication needed to be solved and we proposed new method of lithography that made it possible to fabricate arbitrary three-dimensional microstructures by the pixels exposed lithography using the SR light. The advantages of this method are that it is suitable for rapid prototyping and it reduces the fabrication time and cost since it is not necessary to fabricate conventional photolithographic masks. We did basic research on this method of fabrication and succeeded in fabricating a free-form surface by exposing it through pixels that were overlapping. Moreover, an algorithm that could determine the amount of exposure energy that took overlap into consideration was written to the target form to fabricate a three-dimensional structure that had an arbitrary shape. It was possible to fabricate various arbitrary three-dimensional structures.

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