High-Aspect-Ratio Tapered Structures using an Integrated Lens Technique

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ABSTRACT

In this work, a fabrication approach for tapered column structures with high aspect ratio is presented, and its application to microneedle fabrication is discussed. Microlenses were fabricated on a glass substrate by chromium-masked isotropic wet etching. This substrate was subsequently coated with SU-8 negative epoxy resist and exposed from the back. The chromium acted in a self-aligned fashion to block light from the non-lens portion of the substrate, and the lenses acted to shape the beam through the epoxy to produce sharply-tapered structures. An extension of the technique allows for subsequent repetition of the structure through micromolding; solid biodegradable microneedles with a cone shape were fabricated in this manner. The microneedles have sharply tapered tips and are 1.5 mm in height. These needles were inserted into human skin and were demonstrated to be suitable for blood extraction.

INTRODUCTION

Recently there has been much interest in unconventional exposure techniques of thick photoresist (e.g., SU-8 epoxy) to inexpensively produce new and useful structures. Examples include fluidic filter and mixer structures using inclined exposures [1,2] and microchannel structures using double exposures [3]. Extending these techniques, advanced three-dimensional structures could be obtained by using microlenses to produce additional optical modification of the light path.

Several methods for microlens fabrication have been reported previously for other applications [4,5]. In this work, we introduce the use of an integrated lens substrate to produce unconventional exposure patterns in SU-8. Replication of the tapered structures using micromolding has also been demonstrated. An illustrative application of this approach is the fabrication of deep-tissue microneedles, that require both sharply tapered tips and lengths exceeding 1 mm, from materials such as biodegradable polymers.

CONCEPT

A schematic view of the process is summarized in Figure 1. An opaque chromium layer is deposited and patterned on a transparent substrate. Self-aligned isotropic etching of the substrate through the openings in the patterned opaque layer is then performed to create a concave pattern. Casting of negative-tone photosensitive resist on this nonplanar surface results in a film on the substrate with an underlying integrated microlens, due to the refractive index difference between the substrate and the resist. After soft-baking, the film is exposed from the bottom (through the substrate) using UV light. Due to the opaque layer on the substrate used to form the original lenses, the substrate is transparent only in the lens regions. The light passes through the lens area to give a latent image in the resist, predictable from a ray trace of the convex lens modulated by the thresholding nonlinearity of the resist. As an example, in the case of a circular lens, subsequent resist development leaves a tapered-cone-shape pattern. The geometry of the resulting cones can be controlled by controlling the lens diameter and curvature, as well as the refractive indices of the substrate and photoresist.

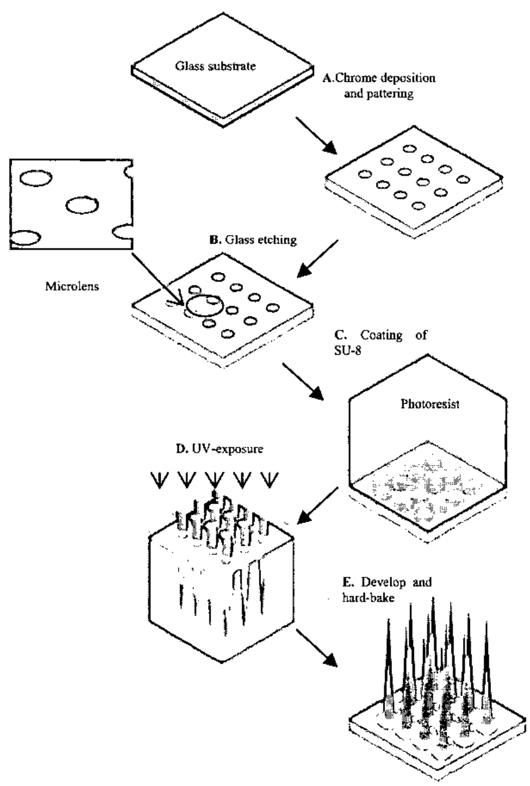
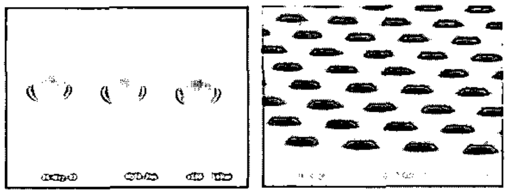


Figure 1 : Fabrication sequence for tapered structure



(a) (b)

Figure 2 : Scanning electron micrograph images of : (a) a portion of an array of glass lens; (b) an array of PDMS mold replicas copied from the glass lenses

EXPERIMENTAL

Figure 2a shows an example of the lens etched by a hydrofluoric acid (HF) based etchant for three hours. To ascertain the shape of the lens for subsequent raytracing analysis, a polydimethysiloxane (PDMS) copy of the lens was made and is shown in Figure 2b. The resultant hemispherical concave holes have 200 μm diameter, 70 μm depth and center to center spacing of 400 μm between structures. HF-based etches usually result in a rough surface, but the recipe consisting of 10 % HCl, 5 % Buffered Oxide Etchant (BOE) and 85 % D.I. water provides a smooth surface [6]. The lateral and vertical etching rates are approximately 0.28 μm/min and 0.39 μm/min, respectively. It should be noted that the final shape of the tapered structures will depend not only on the shape of the microlens, but also on the refractive index difference between the substrate and the photoresist.

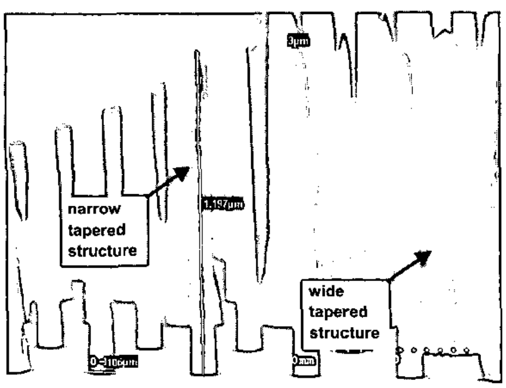


Figure 3 : Scanning electron micrograph images of a SU-8 tapered micro structure array

Figure 3 shows tapered microstructures created using the lens arrays of Figure 2a. The microlens-bearing substrate was soda-lime glass (refractive index of 1.51) and the resist material was a 1.2 mm thick SU-8 epoxy resist cast on the substrate. This combination results in a convex lens effect since the refractive indices of SU-8 and glass are known as approximately 1.7 and 1.5, respectively [1].

The geometry of the tapered structure is affected by the lens geometry. Long isotropic etch times can result in significant lateral underetch of the chromium, and subsequent chromium overhang. If this overhang is not removed, the light passes through only the original opening area in the chromium to form a narrow tapered structure according to the lens curvature as modified by the portion of the lens blocked by the overhanging chromium layer. In contrast, removal of the chromium overhang results in structures with wider bottoms and increased angle. In the case of the overhanging chromium layer remaining, the microneedles are 1.2 mm in height, 100 μm at their bases, and 5 μm at their tips. If the overhanging chromium layer is removed, they are 1.2 mm height, 200 μm at their bases, and 30 μm at their tips. The needles are positioned in a 20 by 10 array with a center to center spacing of 400 μm and 800 μm. An entire array occupies an area of 9 mm by 9 mm.

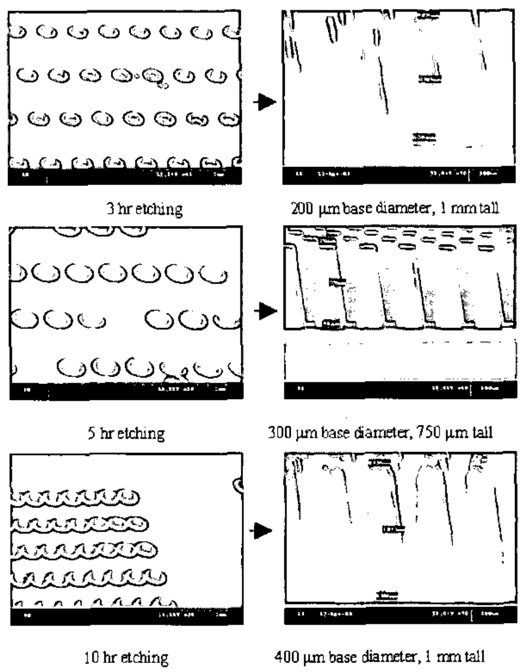


Figure 4 : Scanning electron micrograph images of glass lenses and the resulting SU-8 tapered structures

Figure 4 shows different lenses fabricated with various etching times and the resultant tapered microstructure arrays in each case. Longer etching times yielded larger radii of curvature, which resulted in structures with longer focal lengths, as expected. The resultant diameters of the microlens according to various etching time are summarized in Table 1.

Table 1 : Resulting diameter of the microlens with original diameter of 100 μm according to various etching time

Etching time [hr]	Diameter of the opening [μm]
3	184 (200*)
5	256
10	368

*stirring enhanced etching with 300rpm

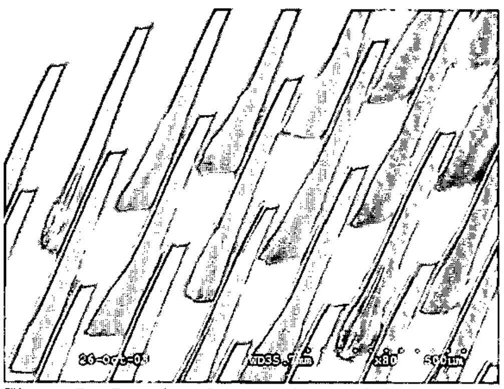


Figure 5 : Scanning electron micrograph images of an array of inclined conical columns

Figure 5 shows an inclined column array exposed through microlenses with 3 hours etching. The substrate was exposed at 45 degree of inclination from a horizontal plane in order to form the inclined structure [1]. Inclined conical shapes with 150 μm base diameter and 70 μm tip diameter have been obtained.

(a) (b)

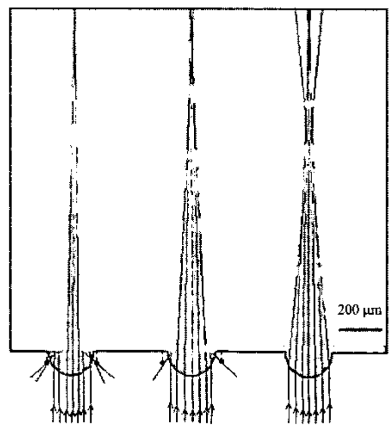
Figure 6 : Scanning electron micrograph images of an array of PDMS mold replicas copied from the glass lenses

The effect of stirring was also investigated. The glass substrate with 100 μm circular opening patterns is immersed in the described etchant for 3 hours in two experiments: without stirring and with 300 rpm stirring. The diameter of microlens openings without stirring was 184 μm and that of microlenses with stirring was 200 μm.

ANALYSIS

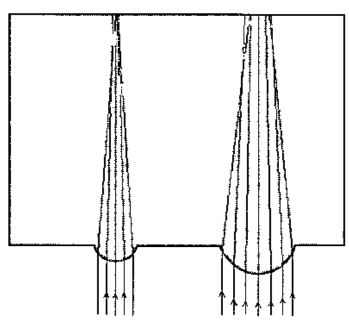
In order to better understand the patterns produced by exposure through integrated microlenses, a simulation is performed using optical ray tracing by means of a standard ray tracing simulator (IME software). Figure 7 shows the raytracing simulation as a function of differing lens openings. The refractive indices for the simulation of SU-8 and glass are 1.7 and 1.51, respectively. The light source used is 365 nm wavelength (i-line). The radius of the curvature for the microlens is 100 μm and the opening diameters are 100 μm, 150 μm, and 200 μm from the left to right in Figure 7, respectively.

The focal length of the lens with the radius of curvature 100 μm is 1.3 mm for the structure with 100 μm opening in Figure 7a, which agrees quite well with the fabrication results in Figure 3. Simulation results for differing radii of curvature, simulating the lens size effect resulting from different etching time, are presented in Figure 8.



(a) (b) (c)

Figure 7 : Ray-tracing simulation with different lens opening; diameter of (a) 100 μm, (b) 150 μm, and (c) 200 μm



(a) (b)

Figure 8 : Ray-tracing simulation with different radii of the lens curvature; radius of (a) 100 μm, and (b) 200 μm

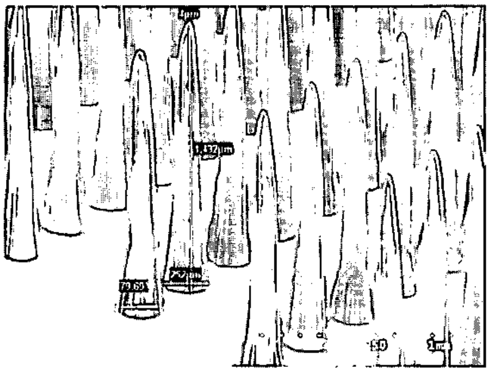


Figure 9 : Scanning electron micrograph images of a portion of an array of biodegradable polymeric microneedles

APPLICATION

To demonstrate the ability to create multiple copies of the micromold, biodegradable microneedles were fabricated from PDMS molds that were made from the tapered SU-8 masters [7]. Microneedles for insertion into soft tissues (such as skin) for applications such as body fluid or blood extraction should have sufficient height to overcome the flexible deformation of the skin [8]. Therefore, long needle molds were utilized. As shown in Figure 9, an array of 200 polyglycolic acid biodegradable microneedles was prepared by the above-described process. Each needle had a bottom diameter of 200 μm, tip diameter of 7 μm and height of 1.5 mm. These needles were successfully tested to show their ability to insert into human skin and extract blood, as shown in Figure 10.

CONCLUSION

Using an integrated lens technique, tapered column structures with high aspect ratio and continuously-varying three-dimensional shape were created. The geometries of the tapered column structures could be predicted using ray-tracing techniques, and controlled by controlling the geometry of the microlens. Biodegradable polymeric microneedles with sharply tapered tips 1.5 mm in height were created using a subsequent molding step. The long tapered microneedle was inserted deeply into skin and blood was extracted successfully.

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Figure 10 : Optical photomicrograph of blood on human skin (finger) produced by piercing of microneedles

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