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405 nm laser processing of thin SU-8 polymer film

Y.K. Cheong [a], W.H. Lim [a], S.H. Lee [a], C.H. Pua [b], W.Y. Chong [a,*], H. Ahmad [a]

[a] Photonics Research Centre, Physics Department, Science Faculty, University of Malaya, 50603 Kuala Lumpur, Malaysia
[b] Universiti Tunku Abdul Rahman, Bandar Sungai Long, Selangor, Malaysia

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ABSTRACT

This paper presents a comprehensive study on the effect of laser fluence on a negative tone thin film resist, SU-8, using an all-fibre 405 nm laser direct writing technique. 405 nm Gaussian beam is delivered on the spin-coated SU-8 thin film using single mode fibre, followed by subsequent chemical developing process. Disc structure is formed where its dimension is affected by the laser fluence. We found that polymer processing using this technique can be categorized into three stages. In the first stage (fluence > 90 J/cm^2), lens shaped structure is formed with linear increase in diameter with logarithmic increase in laser fluence. In second stage (fluence > 600 J/cm^2), flat-top disc structure is formed and the increase in disc diameter slows down with increasing laser fluence. In the third stage (fluence > 49 kJ/cm^2), crater is formed at the centre of the disc due to laser ablation. Moreover, relatively large exposure fluence above the value required for complete polymerization has allowed collateral thermal-polymerization of the surrounding of the disc structure and reduced aspect ratio of the structure. Hence, by controlling laser writing fluence, different structures mentioned above can be produced. This understanding serves as a basis for polymer patterning using the proposed all-fibre laser direct writing technique, which finds potential application in micro-lens array, polymer optical waveguide, photomask and Lab-On-Chip fabrication.

1. Introduction

Photosensitive polymers were initially used as photoresist mask in photolithography processes for the production of semiconductor, optical waveguide, micro-electro-mechanical-system (MEMS), microfluidic and micro-optics devices. Over the years, polymers with high transparency have also been developed and used directly as the building materials for optical and MEMS microstructures. Various types of polymers such as PMMA [1], BCB [2], PDMS [3] and SU-8 have been used in the research and development of polymeric optical and MEMS microstructures. SU-8 formulated by Microchem Corporation is a popular candidate for polymer optical device development due to its high optical transparency and its ability to produce structures with high aspect ratio. The relatively low synthesis cost and process temperature of polymer-based devices also translate into low overall production cost with the possibility of electronics integration, which is itself a low temperature process [4,5]. Due to their high refractive index compared to silica, polymer-based optical devices have huge potential for application in photonic integrated circuits and micro-optics [6].

A number of techniques for the direct fabrication of polymer microstructures have been demonstrated. The first single mode planar optical waveguide structure fabricated using laser direct writing has been demonstrated by Eldada et al. in 1996 [7]. The laser used was an argon ion ultra-violet (UV) laser with laser lines between 333.6 nm and 363.8 nm. This technique produced laser-delineated straight waveguides with low propagation loss at 0.03 dB/cm at 840 nm. Since then, UV lasers with different wavelength have been used to fabricate Y-branch and directional coupler structures [8,9]. Fabrication of micro-ring resonator and Mach-Zehnder interferometer was also demonstrated using direct electron-beam [10], followed by the recent definition of microdisk resonator using proton beam writing in 2013 [11]. These techniques have proven to yield high quality polymeric structures with dimensions smaller than 10 μm. However, the requirement of large gas lasers and vacuum environments in electron-beam and proton beam writing elevates the cost and complexity of the entire fabrication process.

Laser direct writing using optical fibre as light delivery medium instead of free-space optics have been demonstrated by Feng Tian et al., where sub-micron structures have been defined on a 120 nm thick photoresist using a tapered fibre [12]. Furthermore, micro-axicon structures have been defined using Bessel field created by an axicon shaped fibre tip [13]. Both reports used blue laser sources with low writing power coupled with long exposure duration to

* Corresponding author. Tel.: +60 3 79674119; fax: +60 3 79674146.
E-mail address: wuyi@um.edu.my (W.Y. Chong).

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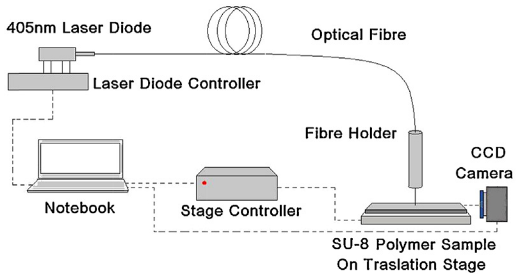

Fig. 1. Experimental setup of the fibre-coupled laser direct writing system.

produce the above-mentioned structures. Though a comprehensive study of the effect of fluence on photolithography defined SU-8 microstructures has been undertaken by Keller et al. [14], the availability of high power single mode fibre-coupled laser diode operating at 405 nm makes it possible to study the effect of laser writing fluence to the shape and dimensions of the fabricated microstructures.

In this paper, the effect of the 405 nm laser fluence on the processing of SU-8 polymer thin film coated on CR39 substrate will be studied. The change in the microstructure profile and its dimensions with different laser writing fluence was measured and analyzed.

2. Methodology

SU8-2002 photoresist was diluted with cyclopentanone with 3:1 dilution ratio (SU-8: cyclopentanone) and then spin-coated at 3000 rpm for 2 min onto CR39 substrate to achieve 1.4 μm coating thickness. The substrate was then soft-baked at 80 °C for 3 min to allow the evaporation of excess solvent. Absorption spectrum of pre-exposure SU-8 can be found in [15].

The laser direct writing setup is illustrated in Fig. 1. Sample was placed on a 3-axis high precision (0.1 μm step size) translational stage (Suruga Seiki D220) controlled by a computer using LabVIEW programming. The fibre output of the 405 nm laser diode from QPhotonics (QLD-405-20S) was spliced to a SM-300SC single mode fibre with smaller mode field diameter (MFD). The MFD was calculated to be ∼2.5 μm with a numerical aperture of 0.12. The laser diode was driven using a laser diode controller connected to a function generator to allow precise control of the exposure power and duration. Laser power measured at the fibre tip can be controlled between 0.5 mW and 6 mW, while exposure time is set using function generator in the range between 20 ms and 1000 ms. The minimum gap between the fibre tip and the sample surface was maintained at 5 μm to prevent damage to the fibre tip as well as the sample surface. As a result, the spot of illumination on the sample surface with $1/e^2$ of the maximum intensity will have a diameter of ∼3.1 μm, which translates into a laser intensity between 5.52 kW/cm^2 and 66.25 kW/cm^2 at the irradiation spot. A Thorlabs DC1545 CMOS camera (50× magnification) is mounted near the sample holder and parallel to the plane of sample to provide real time monitoring of the distance between the fibre tip and sample surface.

Fluence of laser irradiation was varied from 16 J/cm^2 to 164 kJ/cm^2 by controlling the laser power and exposure duration. After the direct writing process, post-exposure-bake of the sample was undertaken at 80 °C for 15 min using hotplate and then allowed to cool down to room temperature. It was then subject to chemical developing for 15 s to remove the unexposed SU-8. The sample was then dried by a jet of nitrogen gas. Finally, it was hard baked at 80 °C for 4 h in an oven. The height of the SU-8 discs was measured using a Dektak D150 surface profiler and the disc diameter was obtained from analysis of the microscope images. Scanning Electron Microscope images were also obtained to study the profile of the SU-8 disc produced using different laser fluence.

3. Results and discussion

SU-8 structure was first observed on the substrate using a laser writing fluence of 90 J/cm^2. SEM images of the SU-8 structures are shown in Fig. 2. Three distinct structures have been observed, starting with a lens-like structure when the laser writing fluence used was between 90 J/cm^2 and 600 J/cm^2. Diameter of the structure increased linearly with increasing laser writing fluence. From 600 J/cm^2 to 49,000 J/cm^2 (or 49 kJ/cm^2), the produced SU-8 showed a flat-top disc structure and the increase in disc diameter slows down with increasing laser fluence. When the laser writing fluence was increased beyond 49 kJ/cm^2, a crater-like feature was observed at the centre of the disc structure where its size also increased when higher laser writing fluence was used. We believed that these observations can be explained by the spatial distribution of the Gaussian laser irradiance.

The fluence of laser irradiance on the sample is the product of irradiance intensity and exposure time,

$$F = I(r, z)t \tag{1}$$

Since the fibre output is single modal, the corresponding irradiance can be represented using a Gaussian function [16], where its peak irradiance depends on the laser power, P, beam radius at distance z, $W(z)$, radial distance from the centre of the beam, r and wavelength, λ,

$$I(r, z) = \left[\frac{2P}{\pi W^2(z)}\right] \exp\left[\frac{-2r^2}{W^2(z)}\right] \tag{2}$$

where

$$W^2(z) = W_0^2 + \left(\frac{z\lambda}{\pi W_0}\right)^2$$

W_0 is the mode field radius (MFR) of the single mode fibre, which is about 1.25 μm at 405 nm. Distance between fibre tip and substrate, z is fixed at 5 μm. By including exposure duration into (1), the fluence can then be rewritten as:

$$F(r, z, t) = \left[\frac{2Pt}{\pi W^2(z)}\right] \exp\left[\frac{-2r^2}{W^2(z)}\right] \tag{3}$$

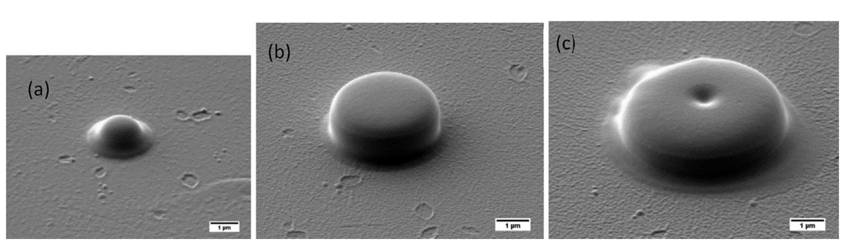

Fig. 2. SEM images of polymerized SU-8 structures produced using laser writing fluence of (a) 164 J/cm^2, (b) 8197 J/cm^2 and (c) 82 kJ/cm^2.

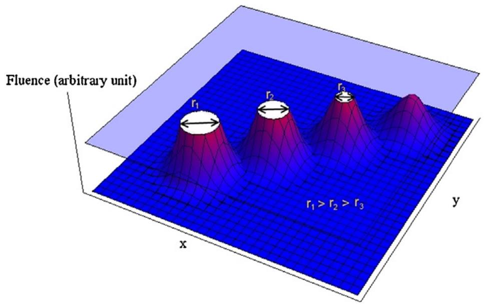

Fig. 3. Spatial profile of laser fluence of a Gaussian laser beam at a distance of 5 μm from fibre tip.

By controlling the laser power and exposure time, the spatial distribution of the laser writing fluence can be obtained from Eq. (3), as shown in Fig. 3. The upper transparent plane indicates the level of threshold fluence, F_{th}. When laser fluence is increased (in this case, by 50% from the smallest Gaussian curve on the right) from right to left, the cross sectional diameter of each profile that exceeds F_{th} increase. This diameter represent diameter of SU-8 disc formed. The change of SU-8 disc diameter and change of crater diameter with fluence can then be simulated by solving Eq. (3) for the disc radius, r,

$$r^2 = -\left[\frac{W^2(z)}{2}\right] \log_e \left[\frac{F_{th}\pi W^2(z)}{2Pt}\right] \tag{4}$$

Thus, we can predict the diameter of disc, $2r$ from P, t, and z. F_{th} is the minimum threshold fluence where the SU-8 disc was produced on the substrate, which is 90 J/cm^2. On the other hand, the value of 49 kJ/cm^2 was used as F_{th} to calculate the change of the crater diameter. Both simulated results and measurements using image analysis of optical micrographs are shown in Fig. 4. The effect of laser writing fluence can be discussed in three separate stages according to the produced SU-8 structural profiles.

3.1. Stage 1

The beginning of this stage is characterized by the threshold fluence of SU-8 structure formation on the substrate where SU-8 structure first appeared after chemical developing process. The fluence for all the discs formed within this region ranged from 90 J/cm^2 to 600 J/cm^2. Within this range, the diameter of the SU-8 discs depends on the diameter of the irradiated region where laser fluence exceeds F_{th}, and the diameter increases linearly with logarithmic increasing of fluence. The disc diameters produced were smaller than 3.1 μm, which is the laser irradiated diameter on the sample. Since the Gaussian beam used in the writing is characterized by peak intensity at its centre which falls off quickly over the radial distance, laser writing fluence at the centre of the irradiated region is relatively higher compared to the edge. Therefore, at this stage, the centre of the SU-8 disc will be exposed with sufficient laser writing fluence to form structures on the substrate surface while the region further from the centre where the fluence is lower than F_{th} will experience underexposure and will not form any polymerized structures. As the laser writing fluence was increased, regions further from the centre will be sufficiently exposed and therefore SU-8 structure with large diameter was formed.

It was also observed that the SU-8 structure formed in *stage 1* is not a cylindrical-flat-top profile, but a lens-like profile where it is thickest at the centre and the thickness gradually reduced towards the edge, as illustrated in Fig. 2a. This observation is the result of the combination of Gaussian laser irradiance during the writing process and chemical developing process. At this stage, the SU-8 was not completely polymerized and cross-linked and hence the bonding between the polymer chains and between the polymer and substrate are relatively weak. Upon chemical developing, the upper portion of the SU-8 will be removed by the chemical developer, resulting in the formation of lens-like structures. The deviation between the prediction of our model and experimental data can be attributed to error in width measurement, where there is no clear boundary of the lens-like SU-8 structure produced in this stage.

3.2. Stage 2

Stage 2 is characterized by the formation of flat-top SU-8 disc structure as shown in Fig. 2b. This happened within fluence range from 600 J/cm^2 to 49 kJ/cm^2. The diameter of the discs becomes larger when higher laser writing fluence was applied.

The formation of flat-top disc structure indicates complete polymerization of the SU-8 polymer. As the laser writing fluence increases, larger diameter of the irradiated region will be exposed to sufficient fluence for complete polymerization, resulting in the increase of the SU-8 disc diameter. However, the maximum diameter obtained via photopolymerization is limited by the laser irradiated region. Therefore, there exists an upper limit to the maximum disc diameter formed within this stage and the increase in disc

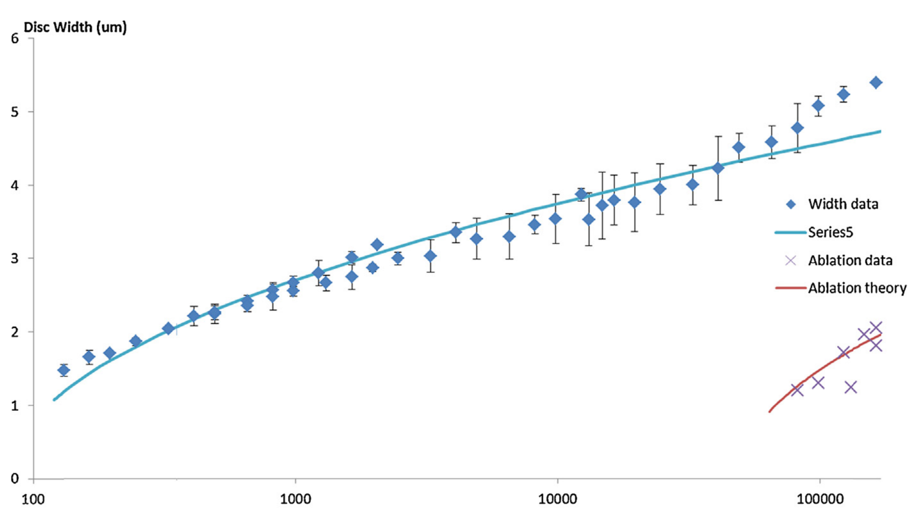

Fig. 4. Relationship between laser writing fluence and diameter of SU-8 disc structures. Solid lines were calculated from Eq. (4).

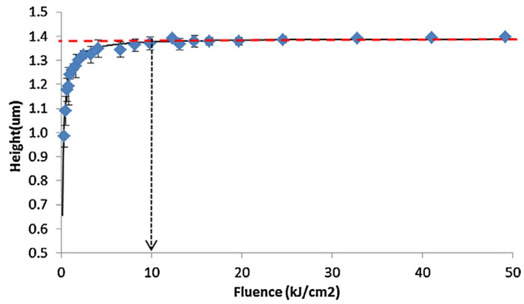

Fig. 5. Relationship between fluence and maximum height of the discs.

diameter with increasing fluence slowed down when higher laser writing fluence was applied. Note that the threshold fluence for SU-8 polymerization and complete polymerization is different. The irradiated area that exceed polymerization threshold will adhere to the substrate, while exceeding complete polymerization threshold will form flat top pattern.

3.3. Stage 3

If the laser writing fluence is increased beyond 49 kJ/cm^2, the produced SU-8 discs showed a diameter larger than the prediction of the model used, which only considered photopolymerisation due to exposure to the writing laser. The larger-than-predicted disc diameter is believed to be the results of other effects not considered by the current model such as thermal-polymerization by heat generated due to excess laser irradiance. Heating effect at this fluence level becomes significant, and causes collateral thermal-polymerization in region surrounding the laser irradiated circumference, resulting in the formation of SU-8 disc with larger diameter.

The excess laser writing fluence also caused the formation of craters at the centre of the SU-8 disc as shown in Fig. 2c. The crater diameter created with different laser fluence was measured and is found to increase when larger laser fluence was used. We suspect there exists a laser fluence level where the SU-8 will start to be removed through localized thermal ablation, similar to the phenomenon reported by Cheong et al. [17]. By substituting F_{th} in Eq. (4) with 49 kJ/cm^2 to calculate the crater diameter, it is found that the experimental measurements fit relatively well with the calculation results as shown in Fig. 4.

Analysis of the height of SU-8 disc produced using different laser writing fluence revealed a different observation. The maximum height of the SU-8 disc produced using different laser writing fluence was measured using surface profiler and the results shown in Fig. 5. It can be seen that the maximum height of the SU-8 disc increases with increasing laser writing fluence, and reached the maximum height of 1.4 μm – equivalent to the initial SU-8 film thickness – when the laser writing fluence exceeds 10 kJ/cm^2. Although a flat-top disc structure was produced using laser writing fluence as low as 600 J/cm^2, we suspect that when the laser writing fluence was below 10 kJ/cm^2, polymerization and cross-linking of the SU-8 is still not complete. Weakly linked SU-8 chains at the top will be removed during chemical developing process. Therefore, the height of the SU-8 discs formed using laser writing fluence below 10 kJ/cm^2 is smaller than the initial SU-8 film thickness. This information is useful when precise control of the height of the produced microstructure is required.

The observation of three distinct structural profiles, corresponding to three different range of laser writing fluence has provided more understanding of the processing of SU-8 polymer using 405 nm laser. The three different structures can be used in different applications. The lens-like structure produced at low laser writing fluence (90–600 J/cm^2) has potential in the fabrication of microlens arrays. On the other hand, a concave structure is produced on the SU-8 disc structure when the laser writing fluence used is larger than 49 kJ/cm^2. SU-8 cylindrical disc structure can be produced using laser writing fluence between 600 J/cm^2 and 49 kJ/cm^2. This large tolerance in laser writing fluence that produces structure with consistent width and height is desirable in the fabrication of optical waveguides and microfluidic channels. Using equation for calculation of dynamic laser writing fluence provided in [18], combination of a typical laser power of 5 mW and writing speed as fast as 420 mm/s can be used to achieve a laser writing fluence of 600 J/cm2, which in turn produces microstructures with steep sidewall.

4. Conclusions

A comprehensive study on the effect of 405 nm laser fluence on SU-8 polymer processing has been carried out in terms of the irradiated spot diameter and the height profiles of the discs formed. Three distinct structures have been produced using different laser writing fluence ranges, namely lens-like structure, cylindrical disc structure and crater. Gaussian intensity distribution of the fibre output power was used to model the SU-8 structure diameter written at different laser writing fluence. The change in diameter of the produced structure agrees well with the experimental results. Cylindrical disc structure with consistent dimensions can also be produced over a wide range of laser writing fluence, which is essential in producing high quality optical waveguide structures and microfluidic channels. The ability to produce different structures by controlling the laser writing fluence enables the proposed technique to be used for the fabrication of various micro-optics, optical waveguide and microfluidics devices.

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