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Fabrication of curved PDMS microstructures on silica glass by proton beam writing aimed for micro-lens arrays on transparent substrates

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ABSTRACT

Polydimethylsiloxane (PDMS), a type of silicone rubber, has excellent material properties such as flexibility, optical transparency and biocompatibility. Therefore, it can offer possible applications in the field of microfluidics as flexible micro-optical components, when they can be formed on transparent materials such as silica glass. We performed proton beam writing (PBW) (with 1.0 MeV beam) on PDMS microstructures with curved surface on silica glass. We found that 13-μm thick PDMS films on silica glass are sensitive only for proton fluences above 600 nC/mm^2 in contrast with the sensitivity of 4.0 nC/mm^2 when using a silicon substrate. Based on the hypothesis that the effective sensitivity was lower due to the electric charging of silica glass surface during PBW, we coated the silica glass surface by Au sputtering. As a result, we were able to observe the formation of PDMS on the Au-coated silica glass at a much lower fluence of 2.0 nC/mm^2. Arrays of curved PDMS structures with a height of 13 μm and diameter of 40 μm have been fabricated on a semi-transparent Au-coated silica glass.

1. Introduction

Among various lithographic techniques, proton beam writing (PBW) is a unique technique for 3D micro-fabrication by direct writing using a focused beam of MeV protons. The PBW has been reported to be useful for the fabrication of high-aspect-ratio micro-structures and prototyping of devices; moreover, it is applicable to a wide range of materials [1–3].

In recent years, there has been strong demand for 3D micro fabrication techniques for optical components in integrated circuits and packaging technology. Also, device flexibility is an important issue in order to achieve high-density packaging and range of applications. Particularly, flexible micro-optical components are required for microfluidic systems, which enable variable transport and sensing operation on liquids. Further application areas including biochip readers require micro-lens arrays, which are completely tunable and beam shaping for optical switching [4,5].

Polydimethylsiloxane (PDMS) is a flexible silicone rubber with good transparency and biocompatibility. The PDMS has widely been used as a basic material in the field of microfluidic devices [6]. The use of siloxane type resists such as hydrogen silsesquioxane, (HSQ, Fox-16, Dow Corning) [7] or spin-on-glass (SOG, ACCUGLASS 512B, Honeywell) [8] have been reported and originally developed as thin (<1 μm) inter layer dielectrics for microelectronics. On the other hand, the PDMS can be formed as a thick layer (>10 μm) patterned by PBW using compaction [9] or by PBW and subsequent wet etching process [10]. In the latter technique, the PDMS behaves as a negative resist with a feature suitable for a grayscale lithography, where the thickness of the exposed and developed PDMS gradually increases with fluence. The grayscale lithography technique has also been reported when using PBW in other resists (SU-8 and ma-N resists) [11].

Using a superior feature of PDMS as an optical material, several reports have been published on micro devices made of PDMS such as lenses, waveguides, or microfluidics devices using UV lithography, [12–15] or PBW [10,16–19]. Fabrication of convex lenses [16,17] using compaction of the PDMS has been reported using PBW with relatively high fluences up to 1.5–2.0 μC/mm^2 of 2.0 MeV PB. Other techniques to form the curved surfaces involve a lithography and subsequent processing steps such as reflow by heating [13], or replication using an electroplated Ni mold [18], an AZ4620 mold by UV proximity printing [14,15], and a SU-8 mold by PBW [19]. Since we can control the curvature of the PDMS micro lenses by just changing the proton fluence within relatively low values [10], the present results provide us with more rapid and flexible means to obtain micro-lens arrays on various substrates, when comparing with other previously reported techniques.

For applying this PDMS feature to the production of micro-lens arrays integrated into micro-channel devices, we must form the PDMS microstructures on a transparent substrate such as silica

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glass, which is another basic material for microfluidics. Therefore, the formation of the PDMS structures on transparent substrates should be further investigated.

In this study, aiming at application of the PDMS microstructure by PBW as optical components integrated to microfluidics, we studied the formation of PDMS structures on various substrates with different properties such as silica glass, silicon and thermal oxide on silicon. We also report fabrication of PDMS curved surface structures on silica glass for micro-optical components such as micro-lens arrays.

2. Experimental procedures

PDMS materials can be obtained through the commercially available Sylgard 184 kit (Dow Corning) by mixing its base polymer and crosslinker in a volume ratio of 10:1 and cured at 125 °C for 20 min [20]. However, we have used only the base component of the Sylgard 184 that was spin coated for 60 s at 8000 rpm onto various substrates those including silica glass, low-resistivity (100) silicon (1.0–20 Ohm cm), or 100-nm thick thermal oxide on silicon substrate. In our PBW process no curing process was needed neither before nor after the development, since the PDMS prepolymer was crosslinked just by irradiation of PB [10]. The thickness of the PDMS film on silicon was estimated to be 13 μm by a spectroscopic reflectometer (Nano Calc-2000, Mikro Pack). The curved surface of the micro-lens was measured using a confocal laser microscope (OLYMPUS, LEXT OLS4000).

The PBW was performed using a proton beam writer (Kobe Steel Corp., MB-S1000) at beam energy of 1.0 MeV with a beam size of 1.0 × 1.0 μm and beam current of 1.5 pA. After exposure to the 1.0 MeV proton beam, the PDMS films were developed with a solution of THF–CH_3CN (8:2) for 2 min. at temperature of 60 °C. The PDMS surface was observed by a scanning electron microscope (SEM, Shimadzu, SSX-550).

3. Result and discussion

3.1. Comparison of the PDMS sensitivity to PBW on various substrates

Fig. 1 shows a SEM image obtained for PDMS films on silica glass, which was scanned with 4 × 6 arrays of 10-μm squared patterns with proton beam (PB) at various fluences from 470 to 700 nC/mm^2 in steps of 10 nC/mm^2. The squared pattern was not visible at fluences lower than 600 nC/mm^2. Above this threshold, PDMS film thickness gradually increased up to 13 μm with increasing PB fluence.

To compare the PDMS sensitivity with PBW, the PDMS thicknesses obtained on silica glass, silicon and 100-nm-thick thermal oxide on silicon substrates were plotted as a function of the PB fluence (see Fig. 2). The result shows a clear difference between these substrates. The PDMS on silicon substrate was produced at fluence above 4.0 nC/mm^2. The PDMS on thermal oxides on silicon started to be formed at similar fluence as well, with thickness gradually increasing up to 600 nC/mm^2. From these observations, it is clear that the silica glass or the thermal oxide (SiO_2) on silicon substrates affect the sensitivity to PBW. Since both substrates are typical insulators they are easily charged when subjected to high energy particles such as electron beam (EB) [21] and PB, we can here assume that the effective sensitivity of the PDMS is determined by the surface conductivity of the substrate. Actually, charging effects in EB lithography are well known to produce errors in the patterning placement [22].

3.2. Behavior of PDMS on Au coated silica glass substrate

In order to test the hypothesis of the above mentioned charge effect, we examined the behavior of the PDMS during PBW on silica glass substrates sputter coated with different Au thicknesses from 5.7 to 13.5 nm. Fig. 3 shows a SEM image obtained for PDMS films with 13.5-nm thick Au coating, which was scanned with 6 × 6 arrays of squared patterns with PB at beam energy of 1.0 MeV by changing PB fluence from 1.0 to 36 nC/mm^2 in steps of 1.0 nC/mm^2. The results demonstrated that squared patterns were produced with fluences above 2.0 nC/mm^2 and that the thickness of PDMS structures gradually increases with increasing fluence. This indicates that the PBW fluence at which the negative type reactions occurs is reduced from 600 to 2.0 nC/mm^2 just by adding a conductive Au coating on the silica glass surface.

In principle, the sensitivity of the material cannot be affected by the substrate, since the cross-linking of the PDMS should occur by the energy deposition of the 1.0 MeV protons when traveling through the 13-μm thick PDMS film. Therefore, we consider that the effective sensitivity changed due to the charging of the insulating silica glass substrate. Fig. 4 shows the thickness of the obtained PDMS structures plotted as a function of the 1.0-MeV PB fluence for

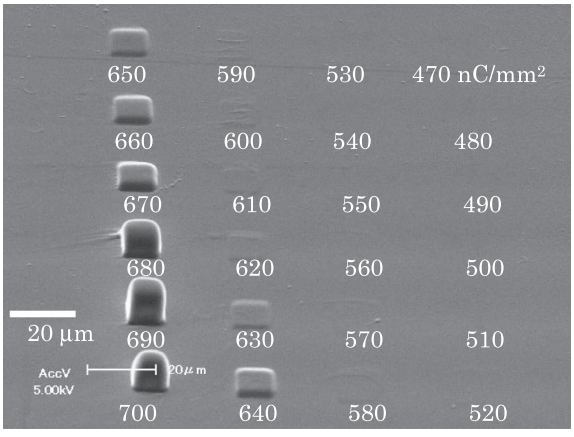

Fig. 1. A SEM image of a PDMS film on silica glass after development which was scanned with 4 × 6 arrays of 10-μm squared patterns by proton beam fluence from 470 to 700 nC/mm^2.

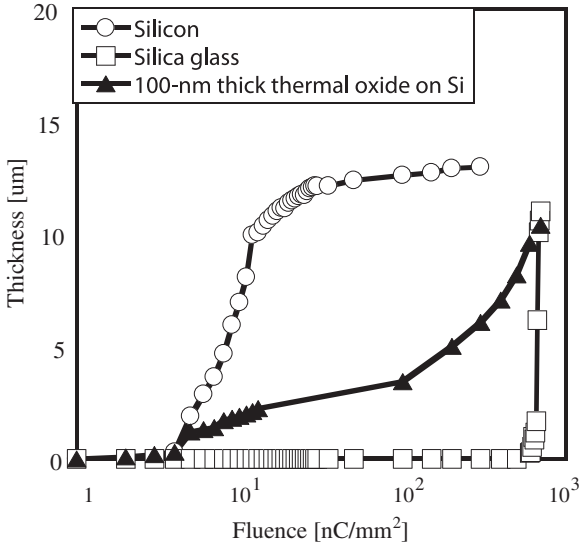

Fig. 2. Remaining PDMS thickness as a function of a fluence of PB at 1.0 MeV and after development obtained for different substrates such as silica glass, silicon substrate, and 100-nm thick thermal oxide on silicon.