Fabrication of Polymeric Photonic Structures using Proton Beam Writing

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Abstract. Proton Beam Writing is a direct write lithographic process that has been developed at the Centre for Ion Beam Applications, National University of Singapore. The technique utilizes a beam of MeV protons focused down to a spot size typically less that 1 μm and scanned in a predetermined pattern over a sample, usually a polymer. The fabrication technique can be utilized for various applications including for microphotonics, microfluidics, lab-on-a-chip technology and for making stamps and moulds for nanoimprinting. Proton Beam Writing allows one to both pattern and modify the optical properties of a material at the submicron scale making it well suited to making microphotonic structures.

1. Introduction

Polymeric materials have some unique properties that make them particularly useful for applications in microphotonics. Polymers can be easily coated on almost any substrate making it possible to easily integrate polymeric structures with existing optical devices made in other materials like silicon, silica and $LiNbO_3$. The optical properties of polymers can be engineered to give the desired refractive index, loss, transparency or electro-optic coefficient. This makes it possible to manufacture both passive and active components such as high bandwidth modulators [1] and optical interconnects [2]. New and emerging lithographic technologies like nanoimprint lithography (NIL) [3] are well suited to low cost mass production in polymer. It is therefore desirable to have manufacturing tools that can easily and rapidly prototype micro-optical structures in polymer, or to make stamps and moulds that can be used to replicate such structures.

Proton Beam Writing (PBW) is a lithographic technique that is well suited to the fabrication of micro and nano structures in polymer, and for making stamps and moulds for NIL. In this paper we show some examples of the type of microphotonic structures that can be made in polymer using the PBW technique including microlens arrays, gratings and waveguides.

2. The Proton Beam Writing system

PBW is a direct write lithographic technique that utilizes a highly focused beam of MeV protons to pattern or modify various types of substrates [4]. At the Centre for Ion Beam Applications (CIBA), National University of Singapore, the proton beam writing technique has been developed and utilized for various applications over the past 6 years. The system that was developed consists of a high brightness 3.5 MV Singletron™ accelerator from High Voltage Engineering Europa and a home built beam-line and end-station dedicated to proton beam writing. The end-station consists of a set of new generation compact (OM52) quadrupole lenses (Oxford Microbeams Ltd.) configured in a high excitation triplet configuration, mounted on an optical table. The target vacuum chamber houses three computer-controlled piezoelectric translational stages (*Burleigh TSE-150HV Integral Encoder Stage*) in an *x-y-z* configuration [5]. Each stage has a 25 mm travel stage driven by a compact *Inchworm® Motor drive* (containing piezoelectric ceramics) with an integral 0.02 µm resolution encoder. In order to calibrate and normalize the fluence delivered to the samples, an annular surface barrier detector is mounted in the chamber giving a solid angle of approximately 62 msr at a scattering angle of 170 degrees. To allow for rapid beam focusing at relatively low beam currents (<1pA), a Channel Electron Multiplier (CEM) detector (Amptek MD502) is also mounted in the chamber. A photograph of the Proton Beam Writing end-station is shown in figure 1.

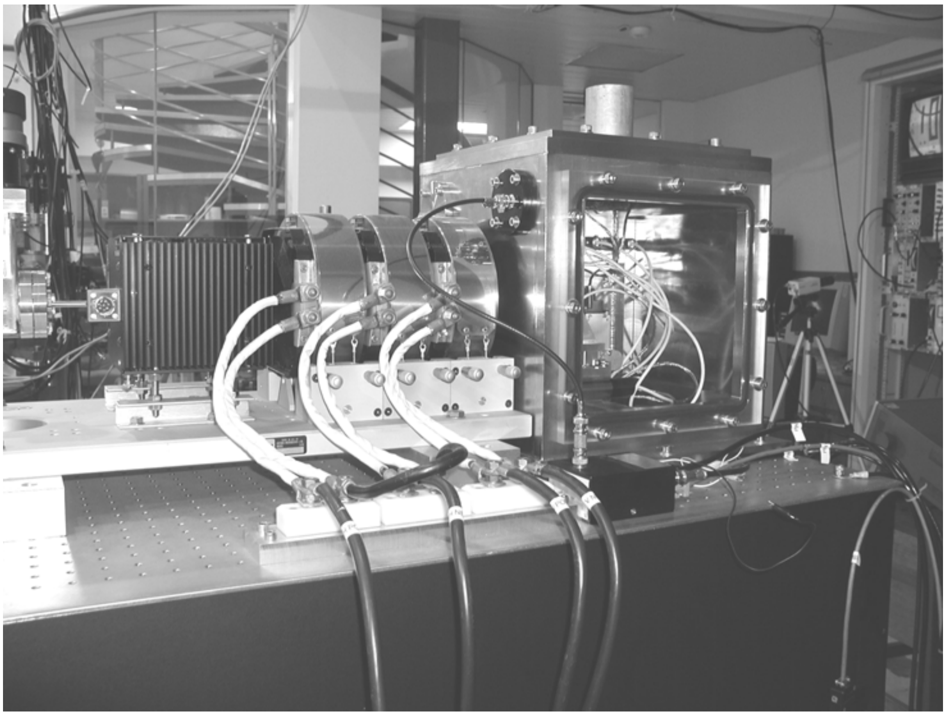

FIG. 1. The Proton Beam Writing End-station at the Centre for Ion Beam Applications, National University of Singapore.

Using the PBW facility at CIBA, structures can be fabricated in polymer coated wafers (up to 6 inch) using a step and repeat process. Each scan field can be up to 800 µm in size and positioned anywhere within a 25 × 25 mm region in the centre of the wafer. The ability to mount smaller samples is also possible. The beam resolution is routinely better than 200 nm with a best recorded beam spot resolution being 35×75 nm [6]. For the fabrication of large linear structures like waveguides or microfluidic channels, the stage can also be scanned at a maximum speed of approximately 1500 µm/sec.

3. Applications

Proton beam writing being a direct write technique, offers some unique opportunities for the rapid prototyping of microphotonic devices in polymers. The minimum feature size and the overall length scale best suited for microphotonics is perfectly matched to the capabilities of the proton beam writing technique (100 nm - 1μm resolution with overall lengths of 1-2 cm). There are two fabrication routes that can be followed using proton beam writing. The first involves the direct micromachining of the microoptical components, usually in polymer. This method may typically require some post irradiation processing like resist development, additional coating steps or thermal treatment in order to make the final device or component. The second route that can be followed involves ion beam modification of the material to form a region with a different refractive index from the bulk. This is the method of choice when using bulk polymers. Various microphotonic components fabricated using Proton Beam Writing are now discussed in detail.

3.1 Microlens arrays

Microlens arrays can be used for various applications including for enhancing the light collection efficiency of CCD detectors [7], for optical interconnects [2] and for lab-on-a-chip devices [8,9]. Several fabrication techniques have been employed in the past to fabricate microlens arrays [10]. The method used in our study is known as the thermal reflow technique. In this technique a sample is initially prepared by spin coating a resist layer with the desired thickness on a substrate. If the structure is to be used directly, then typically a transparent substrate like glass or quartz is chosen. If on the other hand the structure is to be replicated in metal for stamping applications [11], then the resist layer is spin coated on a silicon wafer that is first coated with a metallic seed layer for plating. The electroplating seed layer is typically comprised of an adhesion layer of 20 nm Cr followed by a seed layer (typically 200 nm of Au). After preparation of the sample, the microlens arrays are fabricated using a lithographic process, in our case proton beam writing is used to define the circular diameter of the lenses. Positive resists like polymethyl methacrylate (PMMA) and polydimethylglutarimide (PMGI) are usually more suitable for the reflow technique because the lens is unirradiated and hence the optical properties are left unaltered by the lithographic process. Once the microlens array is patterned using proton beam writing, the sample is chemically developed to remove the exposed regions leaving behind an array of cylinders on a substrate. In order to form the hemispherical lenses, the sample is heated to a temperature above the glass transition temperature of the polymer in an oven or on a hotplate. As the polymer melts, surface tension will shape the polymer cylinders into hemispheres. If you assumes that the volume of material in the cylinder remains unaltered by the reflow process, a simple expression can be derived that allows one to predict the shape of the lens and hence its focal length. If the thickness L, refractive index n and diameter D of the microlens is known, one can make an estimate of the focal length f and radius of curvature R_c using the equation [12]

$$R_c = (n-1)f = \frac{D^2}{4L} \tag{1}$$

Figure 2a shows an optical image of several microlenses fabricated using a layer of PMGI spin coated on a glass substrate. The thickness of the spin coated layer was measured to be approximately 13 µm. A step profilometer was then used to measure the profile of the lenses after reflow at 280 degrees for 10 minutes in an oven, shown in figure 2b. The data points are plotted along with the equation of a circle of best fit showing a good agreement between the measured and theoretical values. The image in figure 2a also shows a number of bright spots at the centre of each lens. These spots are produced by placing a point light source behind the lens array. The approximate focal length of the lens array can be measured by adjusting the focus of the optical microscope and comparing the position where the lens surface is in focus, and the point light source image is in focus.

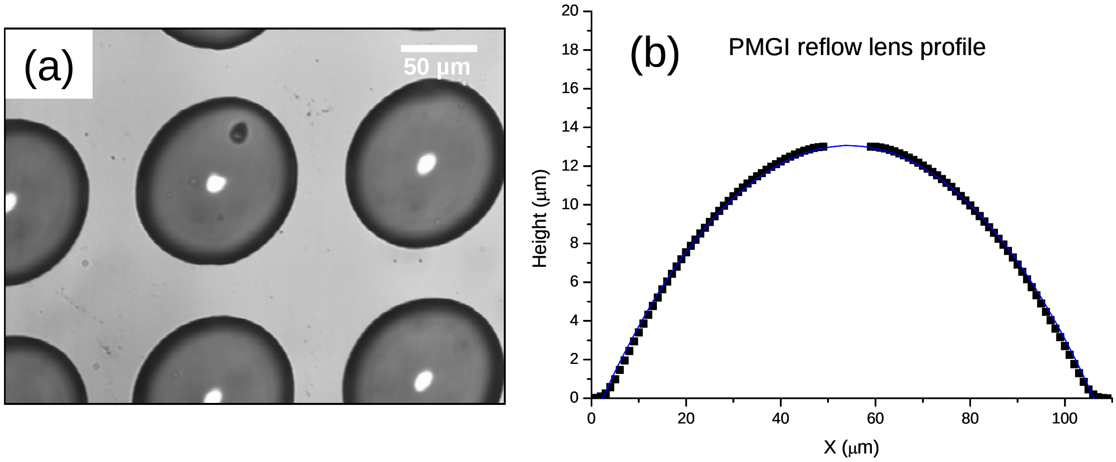

FIG.2. (a) Optical Image of a microlens array fabricated in a 13 µm layer of PMGI resist spin coated on a glass substrate. (b) Profile of one of the lenses along with a circular fit showing that the structure can be approximated by a hemisphere.

3.2 Gratings

There are two main types of gratings that can be fabricated using PBW, short period gratings and long period gratings. An example of the application of PBW for the fabrication of long period fiber Bragg gratings is discussed in reference [13]. The more technically challenging grating to fabricate is the short period grating. Short period Bragg gratings that operate in the visible to near infra-red wavelengths typically need to have a periodicity between 100 nm up to a few microns. This places some stringent requirements on the accuracy with which one knows the proton beam dimensions since the minimum feature size can be sub-100 nm.

The fabrication of high density structures like gratings require a precise control of beam conditions like fluence and scanning signal noise in order to correctly expose the desired structures and to avoid any unevenness. A good knowledge of the development conditions is also required since it is almost impossible to observe under an optical microscope if the structures are fully developed. An example of the types of gratings that can be fabricated using PBW is shown in figure 3. This grating was fabricated in a layer of 2 µm PMMA spin coated on a Si wafer with a Cr (20 nm)/Au (200 nm) seed layer. The metallic seed layer in these samples is typically used for subsequent electroplating, and it also assists in the adhesion of the PMMA to the Si substrate. The whole grating structure is 100 μm in length with a width of 30 μm. The gaps are 320 nm across and the lines (unexposed region) are 260 nm across. Typically these gratings are fabricated by setting the beam spot size to the desired gap width and repeatedly scanning the beam for 6-10 loops in order to improve the line edge roughness. The extremely low line edge roughness can be easily observed in these images indicating that higher density lines and spaces are possible with the proton beam writing technique.

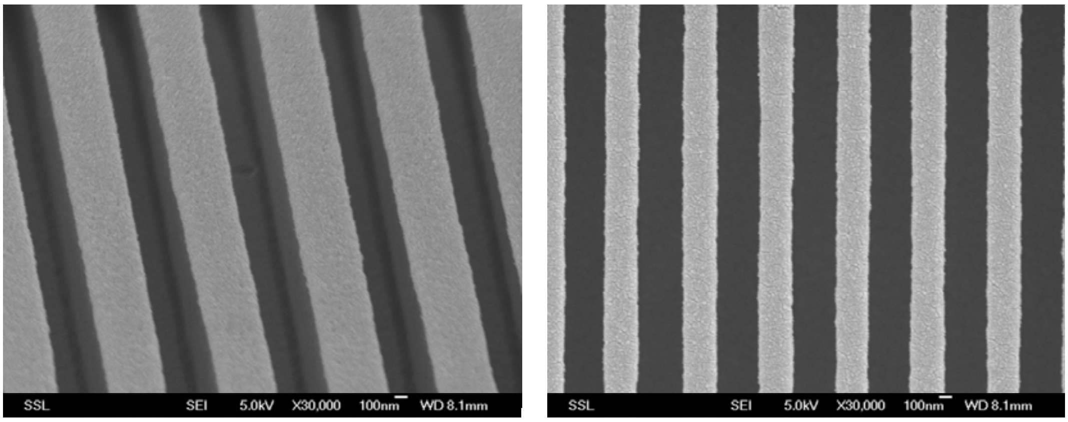

FIG.3. Gratings fabricated in a 2 µm layer of PMMA spin coated on a silicon wafer. The width of the gap in between the PMMA lines is 320 nm, the lines themselves are 260 nm across.

3.3 Wavguides

Optical waveguides are one of the basic building blocks of many microphotonic devices ranging from optical amplifiers, optical switches and ring resonators. There are two basic types of waveguiding structures that can be fabricated in polymer using PBW. Waveguides can be fabricated in a single step if PBW is used to modify the refractive index of the target material. The fabrication technique relies on the fact that the energetic (MeV) ion impinging on a sample will loose most of its energy in a region adjacent to the end of range. This energy loss process is either due to the interaction of the energetic ion with target electrons (electronic energy loss) or interaction with target nuclei (nuclear energy loss) resulting in atomic displacements. The ion beam induced damage causes a volume change at the end of range that can result in a densification of material giving rise to a localized increase in refractive index. In order to achieve weak guiding of light, a refractive index contrast of about 10^{-4} – 10^{-3} is usually sufficient depending on the material being used. The refractive index change can easily be observed using differential interference contrast optical microscopy, an example is shown in figure 4a. These structures were fabricated in a thick PMMA sheet (3 mm) that was obtained from Röhm (*GS233).* A beam of 2 MeV protons was used to make these structures approximately 60 µm below the surface of the material. In order to avoid problems with sample damage during the irradiation, the beam current needs to by kept below 1 -2 pA. The fluence required to make these structure typically ranges from 25 – 160 nC/mm^2 [14].

The second type of waveguide structure that can be fabricated using PBW involves patterning the polymer directly to form the high refractive index core of a waveguide. An example of a y-branch fabricated in a 5 µm layer of SU-8 spin coated on a Pyrex® substrate is shown in figure 4b. After fabricating the core, a cladding material (usually a polymer) needs to be chosen with a refractive index lower than the core material and closely matched in order to reduce propagation losses. Using this fabrication procedure the core size and refractive index contrast of the waveguide can be easily controlled by choosing an appropriate polymer combination, and spin coating the desired cladding thickness. This procedure is therefore useful for making both single mode and multimode waveguides in polymer. The cladding layer chosen for the SU-8 waveguides fabricated using PBW was NOA-88, a UV curable polymer that has a refractive index of 1.555 at a wavelength of 632.8 nm [15]. The refractive index of the SU-8 core (1.596 at 632.8 nm) and the Pyrex® substrate (1.470 at 632.8 nm) were measured using a Metricon prism coupler system. This fabrication procedure enabled us to fabricate waveguides that had a measured propagation loss of 0.19 dB/cm at 632.8 nm, measured using a scattering technique [15]. The extremely low loss is due to the smoothness of the sidewalls of the fabricated structure. The typical sidewall root mean square roughness of the SU-8 waveguides was measured using an AFM and shown to be approximately 4 nm [16].

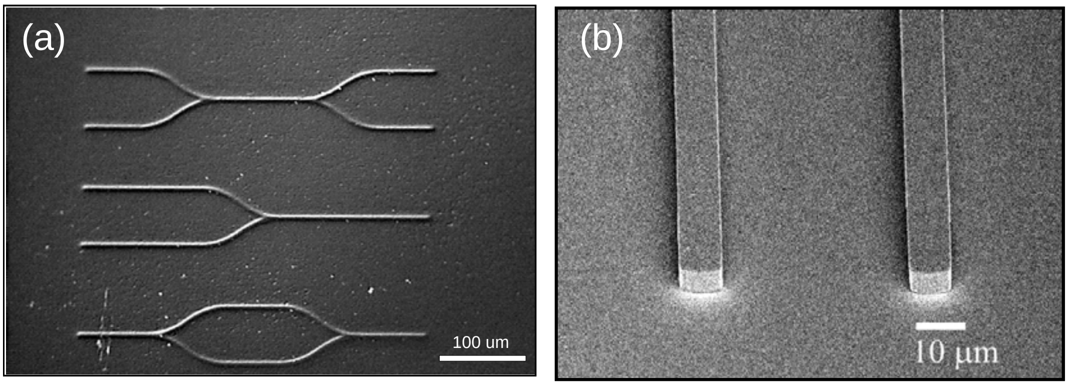

FIG.4. Optical waveguides fabricated using proton beam writing by (a) ion implantation in PMMA and by (b) direct patterning in SU-8 photoresist.

4 Conclusion

The ability to produce arbitrary structures in various materials using the flexibility of a direct write process like PBW is important for developing and prototyping microphotonic structures. The added ability to be able to selectively modify the refractive index of a material makes PBW a powerful tool that is capable of making integrated optical devices. Examples of microlens arrays, gratings and waveguides have been demonstrated in the paper. If PBW is combined with new and emerging mass production lithographic techniques like nano imprint lithography, PBW has the potential to make an impact on the microphotonics industry in the future.

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