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Nuclear Instruments and Methods in Physics Research B 231 (2005) 364–371
NIM B Beam Interactions with Materials & Atoms
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A progress review of proton beam writing applications in microphotonics

A.A. Bettiol [a,*], T.C. Sum [a], F.C. Cheong [b], C.H. Sow [b], S. Venugopal Rao [a], J.A. van Kan [a], E.J. Teo [a], K. Ansari [a], F. Watt [a]

[a] *Centre for Ion Beam Applications, Department of Physics, National University of Singapore, Singapore 117652, Singapore*
[b] *Colloid Lab, Department of Physics, National University of Singapore, Singapore 117652, Singapore*

Available online 7 April 2005

Abstract

The proton beam writing technique is a direct write lithographic technique that is being actively developed at the Centre for Ion Beam Applications, National University of Singapore for microphotonic applications. The technique utilizes a highly focused beam of MeV protons to pattern or modify the refractive index of various materials including polymers, glasses and other inorganic crystals. The technique has been applied to the fabrication of several different types of microoptical components including waveguides, gratings, microlens arrays and colloidal crystal templates. In this paper we give a review of the progress made thus far by our group and other workers in the field of microphotonics using proton beam writing.

PACS: 07.78.+s; 42.79.Bh; 42.79.Dj

Keywords: Proton beam writing; Photonics; Waveguides; Gratings; Microlens arrays

1. Introduction

Proton beam writing is a direct write lithographic technique where a highly focused beam of protons is used to pattern various types of substrates. The technique has been actively developed in the last 5 years or so at the Centre for Ion Beam Applications, National University of Singapore [1] where a dedicated beamline and end station has been commissioned [2]. Recently several other proton beam writing facilities have come online at various laboratories around the world [3,4]. The main application areas for proton beam writing thus far include microfluidics, tissue engineering substrates [5], fabrication of stamps for nanoimprint technology [6] and microphotonics [7,8].

* Corresponding author. Tel.: +65 6874 4138; fax: +65 6777 6126.
E-mail address: phybaa@nus.edu.sg (A.A. Bettiol).

0168-583X/$ - see front matter
doi:10.1016/j.nimb.2005.01.084

Proton beam writing being a direct write technique, offers some unique opportunities for the rapid prototyping of microphotonic devices in a range of materials including polymers, semiconductors and glasses. 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–1 μm 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 micro-optical 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. Surface relief gratings, microlens arrays, photonic crystal templates and waveguide cores are all fabricated using this method. 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 non-polymeric materials; however it is also possible to apply it to polymers. In this paper we review the work to date in applying proton beam writing to the fabrication of devices for microphotonic applications.

2. Applications

2.1. Waveguides

Optical waveguides are one of the basic building blocks of many microphotonic devices ranging from optical amplifiers, optical switches, ring resonators and various interferometers that can be used for applications in biological and chemical sensing [9]. There are two types of waveguiding structures that can be fabricated using proton beam writing. The first type of structure involves direct micromachining of the high refractive index core followed by the coating of a lower refractive index cladding layer. Using this fabrication procedure (shown schematically in Fig. 1(a)) 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. An example of a *y*-branch fabricated in a 5 μm layer of SU-8 spin coated on a Pyrex® substrate is shown in Fig. 1(b). The cladding layer chosen for this application was NOA-88, a UV curable polymer that has a refractive index of 1.555 at a wavelength of 632.8 nm [10]. 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 [10]. The propagation loss of these waveguides is about 0.19 dB/cm at 632.8 nm, measured using a scattering technique [10]. 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 [11].

Waveguides can also be fabricated in a single step if proton beam writing is used to modify the refractive index of the target material. Ion beam modification is by far the most exploited proton beam writing method used for the fabrication of waveguides in many different types of materials [12,13]. A review of the optical effects of ion beam modification and the various materials used for waveguide formation can be found in [14]. 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. This refractive index contrast corresponds to a proton fluence of 10^{14}–10^{15} ions/cm^2 for fused silica [13] and 10^{11}–10^{14} ions/cm^2 for polymers [15]. A schematic of the ion beam irradiation process and an example of some arbitrary waveguide structures

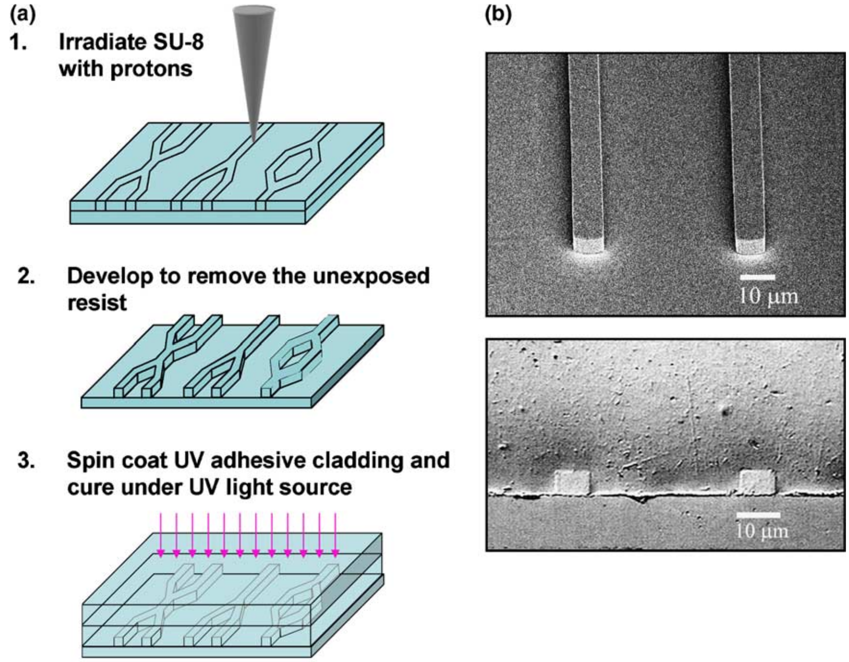

Fig. 1. (a) Fabrication procedure for ridge type waveguides fabricated in SU-8; (b) SEM images of an SU-8 Y-branch made using proton beam writing, before and the cladding layer is added.

made in PMMA using 2 MeV protons is shown in Fig. 2. The proton beam writing technique has also recently been applied to the fabrication of buried channel waveguides in phosphate glass that has been co-doped with Er^{3+}–Yb^{3+}. The fabricated waveguides have been used as optical amplifiers

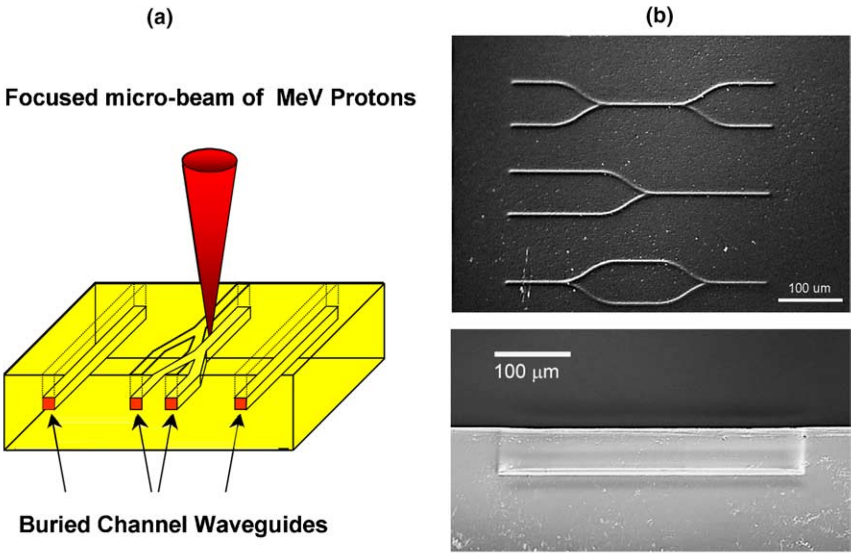

Fig. 2. (a) Schematic of the irradiation procedure, and (b) and optical image of some waveguides fabricated in 3 mm thick PMMA.

with a maximum net gain of 1.72 dB/cm measured at 1.534 μm [16].

2.2. Gratings

The fabrication of surface relief gratings using proton beam writing in polymer has some unique processing challenges. 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. 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. Furthermore, a good knowledge of the development conditions is required since it is almost impossible to observe under an optical microscope if the structures are fully developed. Two examples of gratings fabricated using proton beam writing are shown in Fig. 3. The grating in Fig. 3(a) 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 whole grating structure is 100 μm in length with a width of 30 μm. A second example of a grating fabricated with a large cut away region along one edge is shown in Fig. 3(b). This grating was fabricated in an 800 nm layer of 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 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. For both of these grating structures, the beam was repeatedly scanned for 6–10 loops in order to improve the line edge roughness. Fabrication of long period gratings is also possible using proton beam writing.

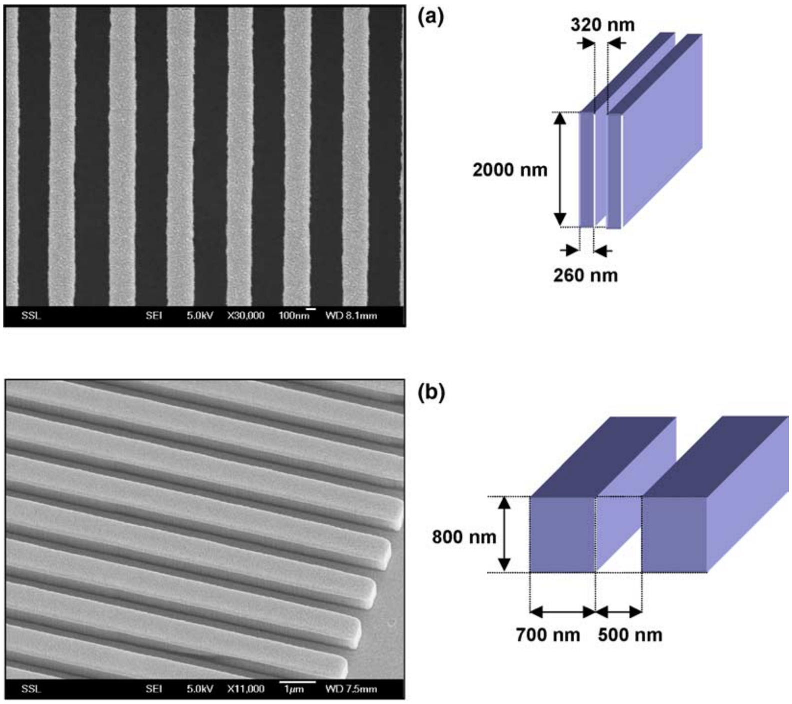

Fig. 3. SEM images of two surface relief gratings fabricated in a (a) 2 μm and a (b) 800 nm layer of PMMA spin coated on a Si wafer with a Cr (20 nm)/Au (200 nm) seed layer.

Von Bibra et al. reported the use of proton beam writing for the fabrication of long period Bragg gratings in non-photosensitive optical fiber [17]. In order to fabricate the Bragg gratings, a proton energy of 2.4 MeV was chosen so that the end of range exactly corresponded to the depth at which the fiber core was located.

2.3. Microlens arrays

Microlens arrays are increasingly finding applications in many types of photonic devices including optical interconnects [18], lab-on-a-chip technology [19,20] and for improving the efficiency of CCD camera sensors [21]. Several methods of fabricating microlens arrays that use high energy protons in polymer have been reported. Ottevaere et al. [22] have been able to produce high quality microlens arrays in PMMA using MeV protons irradiated through a high aspect ratio non-contact metal mask. Free radicals formed in the irradiated regions reduce the average molecular weight of the PMMA. Subsequently, MMA vapor is diffused into the irradiated regions resulting in a volume expansion, and the formation of micro lenses. Plastic micro-optical interconnection modules for data communication applications have been produced using this method [18]. Direct write methods, such as proton beam writing offer the flexibility to fabricate microlens arrays in almost any shape or pattern without the need for a high aspect ratio mask. The technique used for microlens array fabrication with proton beam writing is known as the thermal reflow process [23]. The fabrication steps for the thermal reflow technique are shown in Fig. 4(a). Initially a layer of photoresist is spin coated onto a transparent substrate like a glass slide or coverslip. The photoresist is then patterned using proton beam writing and subsequently developed to leave behind an array of cylinders with a diameter corresponding to that of the final lens required. The sample is then placed onto a hotplate or in an oven and heated to a temperature well above the glass transition temperature of

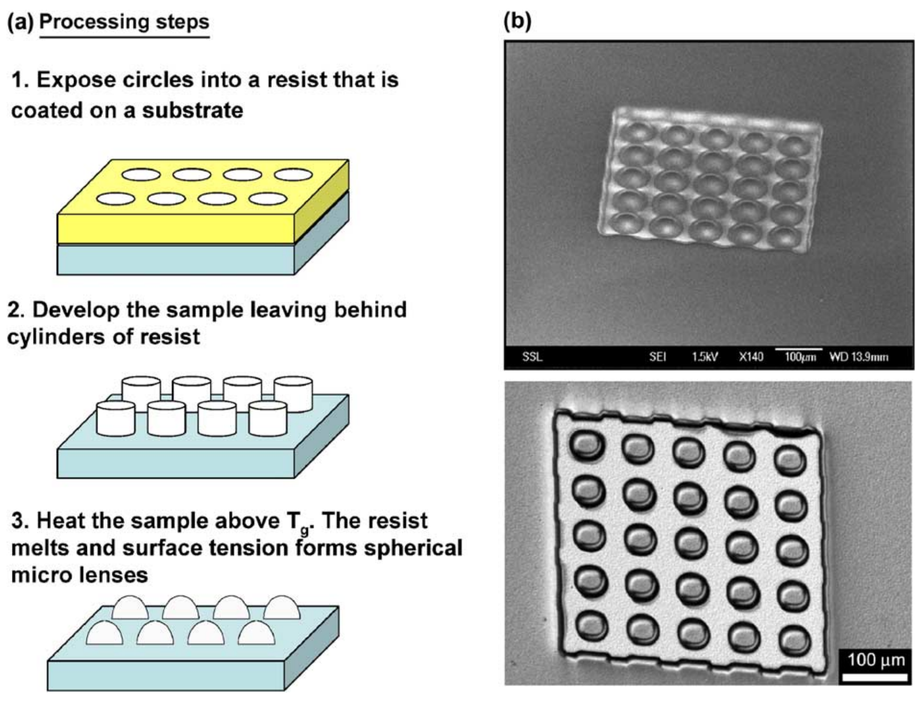

Fig. 4. (a) Processing steps and (b) SEM images of a microlens array fabricated using proton beam writing and a thermal reflow technique.

the polymer, but below the disintegration temperature. During the heating process the polymer will flow and the surface tension will form a hemispherical surface on the substrate. Knowing the thickness L, refractive index n and diameter D of the microlens, one can make an estimate of the focal length f and radius of curvature R_c from the equation:

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

Fig. 4(b) shows an optical image and an SEM image of some microlens arrays fabricated in 950 K molecular weight PMMA photoresist from Microchem using the thermal reflow method. These arrays were fabricated in a 12 μm PMMA layer that was coated onto a Si wafer with a Cu metallic seed layer using a reflow temperature of 200 °C for 30 min. The 12 μm PMMA thickness was achieved by spin coating a 4 μm layer at 900 rpm and then baking the wafer at 180 °C for a few minutes before repeating the coating step two more times. Microlens arrays fabricated on metallic substrates like this are used for making metallic replicas that can be utilized for mass production using nanoimprint lithography. Microlens arrays fabricated on glass slide coverslips using proton beam writing and thermal reflow have been used to make multiple spot laser tweezers that can be incorporated into a fluidic cell [24]. In a laser tweezer, the light at the focal point of the microlens is transmitted through microbeads with higher refractive index, undergoing refraction. The momentum change of the light results in a net attractive force pulling the microbeads towards the optical axis of the light cone and thus giving rise to trapping.

2.4. Colloidal crystal templates

The discovery by Yablonovitch [25] and John [26] that electromagnetic radiation interacting with a periodic dielectric structure with a lattice constant of the order of the wavelength of the radiation exhibits behavior that is analogous to electrons in a crystalline material, has revolutionized research in micro-optical systems. The ability to control light in three-dimensions has opened up numerous applications in the field of opto-electronics and micro-photonics. These structures, known as photonic crystals, can be used to make waveguides with 90° bends, enhance the emission from light emitting diodes [27], and optical fibers that have air as a core material [28].

There are basically two methods currently employed for making photonic crystal structures, micromachining and self-assembly. Using micromachining to fabricate photonic crystals utilizes the existing semiconductor industry infrastructure and MEMS technology to make periodic structures. These structures are typically made in silicon, with a lattice constant of the order of half a micron or less. This method has the advantage that it is relatively straight forward to design any structure and even to introduce defects into the periodic structure to create localized levels. Furthermore, semiconductors typically have sufficient refractive index contrast to open up a full photonic band-gap. The main disadvantage of this method is that fabricating a truly three-dimensional photonic crystal requires several processing steps, making it costly and time consuming. The second approach used to make photonic crystals utilizes the crystallization of a mono-disperse colloidal system to create a three-dimensional lattice of micro and nano-spheres. The silica and polystyrene spheres used in this approach do not have the refractive index contrast required to produce a full 3-D photonic band gap. In order to achieve this, the crystal structures are back filled with high refractive index material such as Titania, then the original crystal backbone is etched away to form an inverse opal structure. This approach has the advantage that it is relatively cheap and easy to form a multilevel three-dimensional structure. The main disadvantage of this approach is that the types of structures that can be produced are limited, and it is difficult to introduce a desired defect. More recently researchers have employed a method known as directed self-assembly [29]. This method utilizes patterned substrates that are typically made in silicon by conventional photolithography to 'control' the self-assembly process. Directed self-assembly is an attempt to exploit the advantages of both self-assembly and micromachining to give more flexibility in the way in which photonic crystals are fabricated.

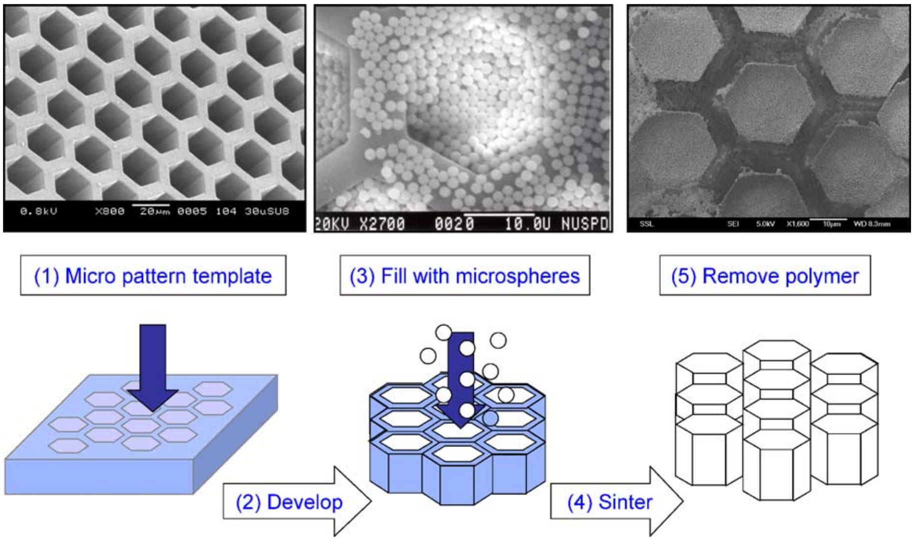

Fig. 5. SEM images of SU-8 colloidal crystal templates. The templates are filled with silica microspheres to form free standing colloidal crystals several tens of microns across on a silicon wafer substrate.

Proton beam writing is a useful tool for the fabrication of polymeric templates for directed self-assembly. The high aspect ratio structures that can be machined using proton beam writing can be used to support more layers than are otherwise possible with standard colloidal crystallization techniques. Examples of structures that have been fabricated using SU-8 photoresist as a scaffold for colloidal self-assembly is shown in Fig. 5. Also shown are the processing steps used to make these self-supporting colloidal crystal structures. The templates were initially fabricated on a 30 μm SU-8 layer spin coated on a silicon wafer. The Silica micro-spheres with a diameter of 1.6 μm were then deposited in the scaffold via sedimantation after which the structures were sintered and the polymer template removed. This process allows us to selectively deposit colloidal crystals anywhere on a silicon substrate thus making it easy to integrate the structures with any pre-existing devices.

3. Conclusion

Examples of waveguides, microlens arrays, gratings and colloidal crystal templates fabricated using the proton beam writing facility at the Centre for Ion Beam Applications, National University of Singapore has been demonstrated. The ability to produce arbitrary structures in various materials using the flexibility of a direct write process like proton beam writing is important for developing and prototyping microphotonic structures. The added unique ability to be able to selectively modify the refractive index of a material makes proton beam writing a powerful tool that is capable of making integrated optical devices. These devices can find applications in bio and chemical sensing, as well as other areas of photonics. Coupled with new and emerging mass production lithographic techniques like nano imprint lithography, proton beam writing has the potential to make an impact on the microphotonics industry.

Acknowledgments

This work was supported by a Defence Innovative Research Program grant from the Defence Science and Technology Agency, Singapore, and a grant from the Agency for Science Technology and Research, Singapore.

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