Direct measurement of proton-beam-written polymer optical waveguide sidewall morphorlogy using an atomic force microscope

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Proton-beam writing (PBW) is a direct-write micromachining technique capable of fabricating low-loss single-mode polymer waveguides with straight and smooth sidewalls. Recently, the sidewall morphologies of such proton beam written polymer waveguide structures were directly measured using an atomic force microscope (AFM). Statistical information such as the rms roughness and the correlation length of the sidewall profile obtained from the AFM scans allows us to quantify the quality of the sidewalls and optimize the fabrication parameters using PBW. For structures fabricated using a stage scanning speed of $\sim 10\ \mu\mathrm{m/s}$, a rms roughness of 3.8 ± 0.3 nm with a correlation length of 46 ± 6 nm was measured. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1784035]

The fabrication of waveguides with low optical losses is one of the important considerations for any waveguide fabrication technique. Optical losses in waveguides arise due to the material absorption and scattering losses from the sidewalls. The former is intrinsic to a particular material while the latter is attributed to the lithographic process. One solution to reducing the intrinsic absorption loss in polymer waveguides is to design polymers in which the highly absorbing C–H groups are replaced with very-low-absorption loss fluorocarbon groups (C–F).[1] In the case of the scattering losses, it has been proposed[2–4] that such losses from an imperfect sidewall are proportional to Δn^2 $(=n^2_{\mathrm{core}} - n^2_{\mathrm{cladding}})$. To minimize the optical losses due to sidewall scattering, the waveguide fabrication process must be optimized.

Proton-beam writing[5] (PBW) is an emerging lithographic technique which uses a focused submicron beam of high-energy protons to direct-write on suitable photoresists, such as SU-8 and poly-methylmethacrylate. The latent image formed is chemically developed. Three-dimensional (3D), high aspect ratio (HAR) micro-components with straight and smooth sidewalls have been produced using this "rapid-prototyping capable" technique.[6] Recently, sub-100 nm HAR microstructures[7] and optical waveguides[8,9] have been fabricated using this technique. One of the ways to fabricate optical waveguides involves a combination of magnetic scanning and stage scanning where SU-8 waveguides with propagation losses of (0.19 ± 0.03) dB/cm at 632.8 nm were fabricated.[9] The rms surface roughness, R_q of the spin-coated SU-8 resist is very low (~ 0.32 nm). Unlike the sidewall profile, the top surface does not significantly contribute to the scattering losses in a waveguide. The contributions of the sidewall morphologies in PBW may be attributed to: (a) the dimensions of the proton beamspot, (b) the beam intensity variation which could be due to the energy stability of the accelerator or stray sources of alternating current electromagnetic fields, and (c) the parameters for the magnetic scanning and stage scanning such as the update time and stage scanning speed. Stage scanning involves a mechanical translation of the stage and the sample. The sidewall roughness may increase due to the stage vibrations if it is moving too fast. Accurate statistical information about the sidewall morphologies of the fabricated structures will allow us to quantify the quality of the microstructures and optimize the parameters for PBW of optical waveguides.

Atomic force microscopy (AFM) studies on the sidewall roughness of InP/InGaAsP optical waveguides fabricated using inductively coupled plasma reactive ion etching were reported by Jang *et al.*[10] Martin *et al.*[11] reported on the application of specially fabricated HAR boot-shaped AFM tip to characterize the sidewall profile of a photoresist line. Hosomi *et al.*[12] used the AFM to measure the sidewall profile of ridge waveguides by mounting the sample at a tilted angle. But, a complicated calibration routine is required to correct for the tilt in the AFM scans. In the case of polymer structures, there are few and limited published studies on their sidewall morphologies.[13,14] Most ridge-type optical waveguide structures typically have a low aspect ratio (i.e., height to width ratio of $\leqslant 3$) and near vertical sidewalls. Hence, direct imaging of their sidewall roughness with an AFM using commercially available Si cantilevers is extremely challenging. The scanning electron microscope (SEM) is another popular noncontact measurement technique which was also used to study the roughness of a sidewall profile.[15,16] However, in uncoated polymeric structures, even when low voltages are used,[13] charging effects makes it very difficult to obtain high-resolution images of the profile. Coating of the polymers with a thin conductive layer is not desired as it may alter the morphology. Hence, tapping mode AFM is ideal for the direct measurement of sidewall surface morphology provided the probe can access the region of interest.

In this letter, we report on the direct measurement of proton beam written polymer waveguide sidewall morphology using a tapping mode atomic force microscope (AFM). The typical cross section of the proton-beam-written SU-8 waveguides is $5 \times 5\ \mu\mathrm{m}^2$. From Stopping and Range of Ions in Matter[17] simulation, 2.0 MeV protons have a range of $\sim 60\ \mu$m in SU-8. The protons penetrate the 5 μm SU-8 resist with very little lateral straggle. The energy loss mechanism is dependent only on the type of material and not the thickness. The amount of lateral straggle of the protons in

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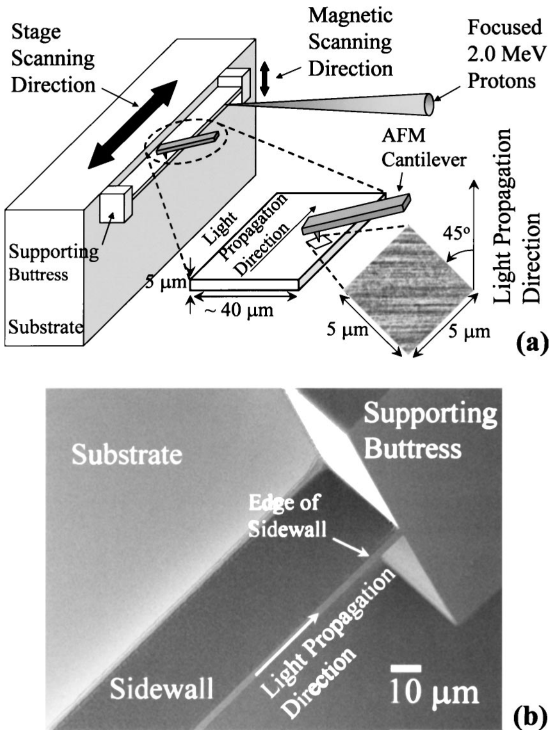

FIG. 1. (a) A schematic of the proton beam written structure and a typical AFM image of its sidewall morphology. The relative orientations of the magnetic and stage scanning directions used in the proton beam writing are indicated. (b) A SEM image of the fabricated structure.

SU-8 will be the same at a particular depth, regardless of the total sample thickness. In this study, a much thicker SU-8 resist ($\sim$40 μm) was spin-coated on a glass substrate to allow sufficient clearance for the AFM probe to approach and assess the sidewall directly. Such direct measurement is possible because of the characteristics of the ion beam and its interaction in the polymer.

PBW was carried out at the Centre for Ion Beam Applications (CIBA)[18] using both stage and magnetic scanning.[9] A beam of 2.0 MeV protons with a spot size of $\sim$0.3 μm along the magnetic scan direction and 1.0 μm along the stage scanning direction was used. The 2.0 MeV protons penetrate the 40-μm-thick SU-8 resist layer, stopping into the glass substrate. With a dose of $\sim$30 nC/mm^2 and the same magnetic scanning parameters [i.e., 256 pixels with a pixel dwell time of 40 μs/pixel (over the 5 μm width)], structures were fabricated close to the sample edges using stage scanning speeds of $\sim$10, 20, 50, and 90 μm/s. Typically, four stage scanning loops (i.e., two loops each in the forward and reverse directions) were used to ensure an even dose distribution along the entire length of the structure. A loop is defined as the pathway taken such that the proton beam irradiates all the pixels along the whole length of the sample once. Supporting buttresses were fabricated to enhance the adhesion and stability of these 1.5-mm-long structures. All the fabrications were performed in a single experiment on the same sample to minimize effects such as the size of the beam spot and the beam intensity variations of the accelerator which may be present for different experimental runs on different days. The structures were chemically developed after PBW.[9]

Tapping mode AFM (Digital Instruments Dimension™ 3000 SPM) was used to image the striations on the sidewalls. The probe was an etched Si cantilever with a nominal tip radius of curvature of $\sim$5–10 nm. A schematic of geometry

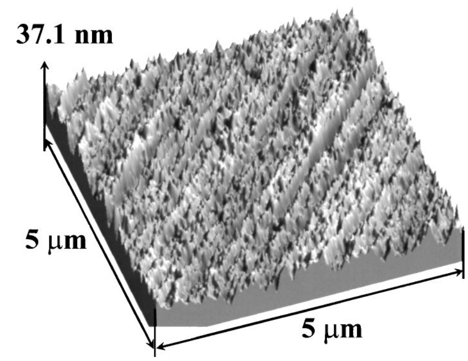

FIG. 2. A 3D AFM image of the sidewall morphology over a 5×5 μm^2 scan area. Structure was fabricated using a scanning speed of $\sim$10 μm/s.

of the proton beam writing direction and orientation of the sample is given in Fig. 1(a) and a SEM image of one of the structures is shown in Fig. 1(b). The cantilever was scanned at 45° relative to the direction parallel to the direction of light propagation for better sensitivity. The 5×5 μm^2 AFM scans (512×512 pixels) were taken $\sim$2–3 μm away from the sidewall's edge. Figure 2 shows a typical AFM image of the sidewall surface morphology for one of the samples. The AFM images were flattened using a low order polynomial fit.[8] The R_q of the sidewall (averaged over five independent measurements) for each of the structure were determined and plotted in Fig. 4. The uncertainty in the R_q is estimated from the standard deviation of the five measurements. The data reveal that the R_q of the sidewalls for the structures fabricated using a speed of 10–50 μm/s are comparable to one another (i.e., $\sim$3.7 nm). For structures fabricated with a speed of 90 μm/s, an increase in the rms roughness was measured. It is believed to be caused by the excessive stage

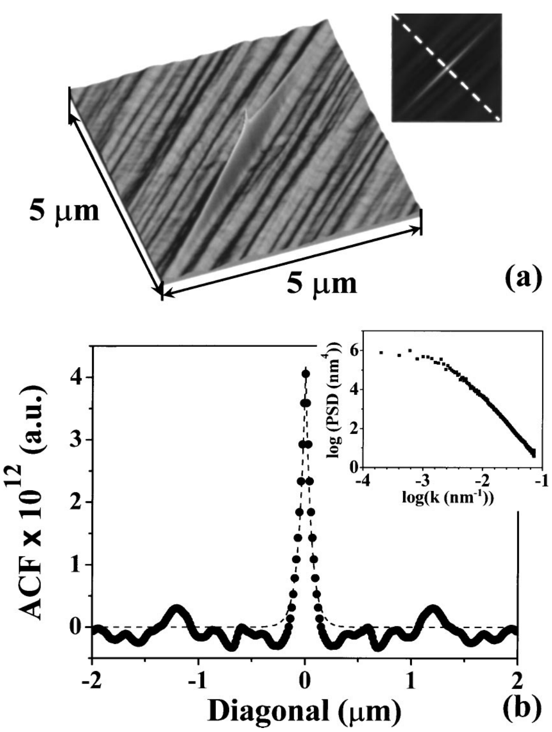

FIG. 3. (a) A 3D view of the 2D ACF of the AFM surface shown in Fig. 2. The inset shows a planar 2D view of the same function. (b) An exponential fit of the extracted 1D ACF (i.e., extracted diagonally across the 2D ACF, orthogonal to the undulations as indicted by the dotted diagonal line in (a) inset). The inset shows the corresponding power spectral density function.

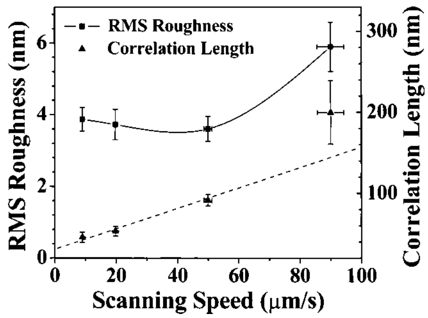

FIG. 4. A plot of the rms roughness (■) and a linear fit of the correlation lengths (▲) as a function of the stage scanning speeds.

vibrations during the scanning. The R_q alone is insufficient to quantify the sidewall profile. It must be complemented with the correlation length of the striations.

From the AFM data, two-dimensional (2D) autocorrelation functions (ACF)[19] were calculated. By extracting a diagonal line profile across the 2D ACF as shown in Fig. 3(a), a one-dimensional (1D) ACF is plotted in Fig. 3(b). A best fit of the 1D ACF is obtained using an exponential function[4,20] ($f_z(r)=|A|\exp(-|r/L_z|)$), where $|A|$ refers to a normalization constant and L_z to the correlation length. The average L_z of the striations were determined and plotted as a function of the stage scanning speed as shown in Fig. 4. As the scanning speeed increases, the L_z increases linearly for speeds up to 50 μm/s. The deviation from linearity for the speed of 90 μm/s is attributed to the excessive vibrations from the stage. From the data, it can be deduced that the criteria for fabricating polymer structures with low R_q and small L_z is that the stage scanning speed must be <90 μm/s. For structures fabricated using a scanning speed of ~ 10 um/s, an R_q of 3.8 ± 0.3 nm with a L_z of 46 ± 6 nm is measured. The R_q is comparable to that reported by Reynolds *et al.*[13] ($\sim$3 nm), Jang *et al.*[10] ($\sim$3.45 nm), and Yamaguchi *et al.*[14] ($\sim$2–3 nm); and better than that reported by Lee *et al.*[21] ($\sim$10 nm). The correlation length is comparable to that reported by Lee *et al.*[21] ($\sim$50 nm) and Yamaguchi *et al.*[14] ($\sim$50 nm); and lower than that reported by Jang *et al.*[10] ($\sim$160 nm).

In conclusion, the sidewall morphologies of proton-beam-written polymer waveguide structures fabricated with different stage scanning speeds were directly measured using an atomic force microscope (AFM). In our PBW facility, the optimal stage scanning speed for fabricating polymeric structures with low sidewall roughness and small correlation lengths must be <90 μm/s. Sidewall profile with a R_q of 3.8 ± 0.3 nm and a L_z of 46 ± 6 nm for the striations was measured for structures fabricated using a stage scanning speed of ~ 10 μm/s. This is one of the lowest reported correlation lengths for the striations on a sidewall profile. Further work on the study of the relationship between waveguide losses and waveguide parameters are currently in progress.

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