Direct measurement of proton-beam-written polymer optical waveguide sidewall morphology 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 ≈ 10 μm/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.

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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 waveguides are is an emerging lithography using a tapping mode atomic force microscope.17 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 microstructures and optimize the fabrication 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 ≈ 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 × 5 μm². From Stopping and Range of Ions in Matter17 simulation, 2.0 MeV protons have a range of ≈ 60 μm 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
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, 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) using both stage and magnetic scanning. A beam of 2.0 MeV protons with a spot size of ~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 ~30 nC/mm² 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 ~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.

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 ~5–10 nm. A schematic geometry 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 μm² AFM scans (512×512 pixels) were taken ~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. The roughness of the sidewall (averaged over five independent measurements) for each of the structure were determined and plotted in Fig. 4. The uncertainty in the roughness is estimated from the standard deviation of the five measurements. The data reveal that the roughness of the sidewalls for the structures fabricated using a speed of 10–50 μm/s are comparable to one another (i.e., ~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 scanning time.
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)\textsuperscript{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\textsuperscript{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 speed increases, the $L_z$ increases linearly for speeds up to 50 $\mu$m/s. The deviation from linearity for the speed of 90 $\mu$m/s is attributed to the excessive vibrations from the stage.

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 $< 90$ $\mu$m/s. Sidewall profile with a $R_q$ of $3.8 \pm 0.3$ nm and a $L_z$ of $46 \pm 6$ nm for the striations was measured for structures fabricated using a stage scanning speed of $\sim 10$ $\mu$m/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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\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig4.png}
\caption{A plot of the rms roughness (■) and a linear fit of the correlation lengths (▲) as a function of the stage scanning speeds.}
\end{figure}

19 D. J. Whitehouse, Handbook of Surface Metrology (IOP, Bristol, 1994), Chap. 1, p. 49.