Reflow of Deep UV Resist for Line Edge Roughness Reduction in InP Membrane Waveguides

J.P. van Engelen, J. Bolk, M.K. Smit, K.A. Williams, J.J.G.M. van der Tol, Y. Jiao

Photonic Integration Research Group (PhI), Institute for Photonic Integration (IPI), Eindhoven University of Technology, Netherlands

A reflow process for photoresist is described that aims to reduce propagation loss and static phase error in InP membrane waveguides. We demonstrate that vacuum UV exposure followed by exposure to acetone vapor smoothens the resist and significantly reduces the line edge roughness.

Introduction

The InP-membrane-on-Silicon platform consists of a 300 nm thick InP layer (membrane) bonded to a silicon substrate using 2um thick BCB. The high index contrast between the InP waveguide core and BCB cladding allows for compact devices due to the tight optical confinement. Many devices demonstrated in the InP-membrane-on-Silicon platform have sub-micron dimensions: 400 nm waveguide width, 300 nm pitch gratings and photonic crystal holes of 110nm [1]. Up to now these features have been realized with electron beam lithography (EBL). In the past we have described a method for smoothening the resist pattern from EBL [2] which reduced the propagation loss in waveguides. However EBL is not suitable for exposing large areas due to long writing times. Recently we demonstrated low-excess-loss AWGs using an ArF deep UV lithography process for generic InP integration with few-micron waveguide dimensions [3]. Here we use a similar process to pattern the small features of InP membrane devices. However, these small features show significant line edge roughness (Fig. 1, left). Inatomi et al. [4] showed that developed resist can be smoothened with vacuum UV (VUV) exposure and subsequent exposure to solvent vapor. In this paper we describe how this technique is adapted to reduce line edge roughness, which relates to propagation loss and static phase error in InP membrane photonic circuits.

Acetone vapor reflow process

As demonstrated in [4] a solvent atmosphere can be used to smooth resist patterns of ArF deep UV lithography. The solvent penetrates the exposed edges of the photoresist, surface tension then

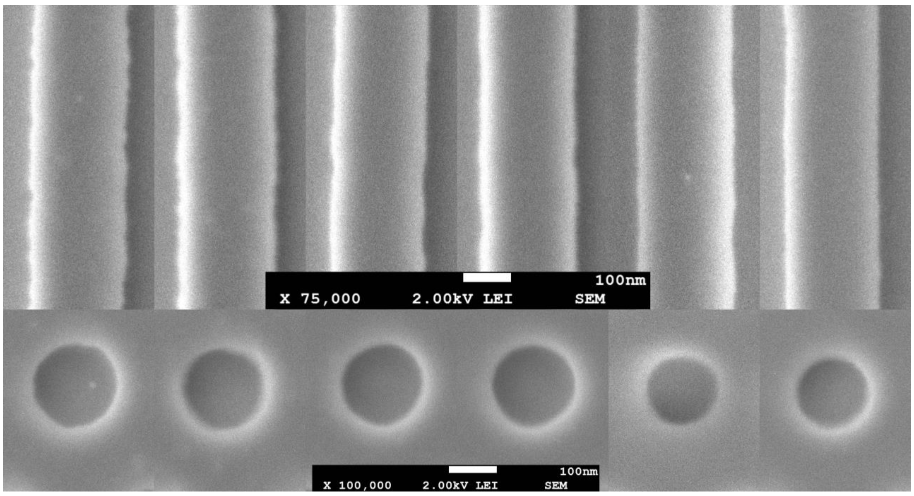

Figure 1: Pattern in silicon nitride of 200 nm line (above) and 150 nm hole (below). From left to right is shown the smoothing effect of applying the acetone vapor for a longer times (from 0 to 10 minutes in 2 minute increments).

smoothens the edge. When the solvent atmosphere is removed the photoresist dries out and the smoothened edge remains.

The samples used in our experiment are first covered by a silicon nitride layer that serves as a hard mask. The samples then undergo standard lithography process of coating, exposure, development and hard baking. For the reflow process the developed and baked sample is exposed to vacuum UV (VUV) and the photoresist is reflown by putting the sample in a chamber with an air and acetone vapor atmosphere. This atmosphere is created by pouring a small amount of acetone into the chamber and closing it. The sample is suspended above the acetone. Part of the acetone evaporates into the atmosphere (air) of the chamber, the evaporation reaches an equilibrium defined by the vapor pressure. After a period of time the chamber is opened and the sample is taken out. The photoresist pattern is then transferred to the silicon nitride layer by a dry etching process. The photoresist is then removed with an oxygen plasma and the sample is dipped into a dilute HF solution to remove reaction products of the dry etching process. Finally the pattern in the silicon nitride is inspected in a scanning electron microscope (SEM). The following patterns are inspected: 120 nm; 200 nm; 300 nm; 400 nm lines and spaces (120 nm line-space corresponds to 240 nm pitch grating), and 150 nm wide holes in a hexagonal grid of 300 nm pitch.

Exposure to VUV prior to exposure of acetone vapor significantly speeds up the photoresist reflow process. VUV breaks certain bonds in the photoresist that lead to a higher solubility of organic solvents [4]. A developed wafer can be put into an acetone vapor atmosphere for several minutes at room temperature without any noticeable effect on the pattern. When the wafer is exposed to VUV first, we observe that the patterns are completely removed after only 30 s. Therefor in all our experiments the chamber is chilled to 2 °C to lower the acetone vapor pressure and slow down the reflow process.

Line edge roughness improvement

The effect of time duration in this chamber is shown in Fig. 1. It is clear that the line edge roughness improves significantly with longer time duration, while the small holes remain open. A comparison of samples with and without 8 minutes acetone vapor exposure is shown in Fig. 2. The acetone vapor exposure improves line edge roughness for all investigated structures.

Fig. 3a shows the measured line edge roughness (LER, defined here as 3 times the standard deviation from a straight line) as a function of time in the acetone vapor chamber. In this figure the reduction in line edge roughness is especially pronounced in the 200 nm and 300 nm line-space pattern, while the change is more pronounced in the 120 nm line-space pattern in Fig. 2. Furthermore, the data for the 200 and 300 nm line-space pattern displays a threshold characteristic: between 4 and 6 minutes most of the change in the LER occurs. Exposure longer than 6 minutes does not improve LER further. It should be noted that only one sample per time duration was measured, and the LER of 8 edge lines is averaged to create Fig. 3a. Ideally multiple samples per time duration are prepared and measured to better understand repeatability of the reflow process.

The measured critical dimension loss (CDL, defined here as the change in the average measured width of the line relative to the measured width on the sample without reflow) is shown in Fig. 3b. It is clear that the reflow process has little influence on the CDL. However, the reflow process was performed on samples of several cm^2 each, one sample per time duration and the width of 4 lines are averaged to create Fig. 3b. In the future we will investigate if this reflow process provides uniform LER and CDL over a full 3” wafer.

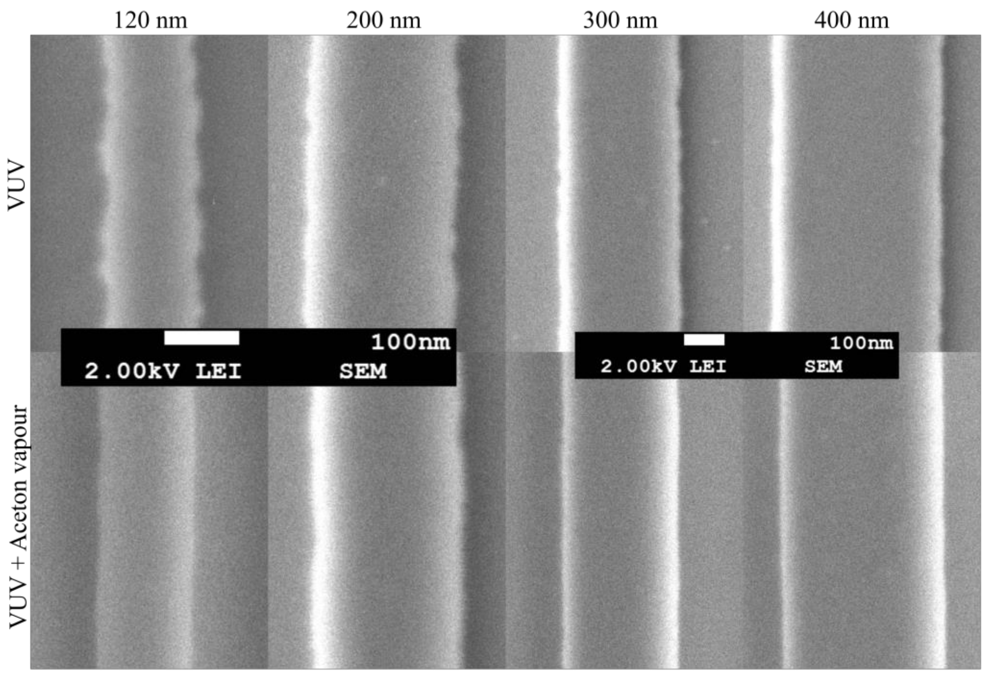

Figure 2: Pattern in silicon nitride of 120nm, 200nm, 300nm and 400nm line space structures. The top row only has VUV applied to the photoresist pattern, the bottom row was also exposed to acetone vapor for 8 minutes. It is clear that line edge roughness is significantly reduced for all shown features.

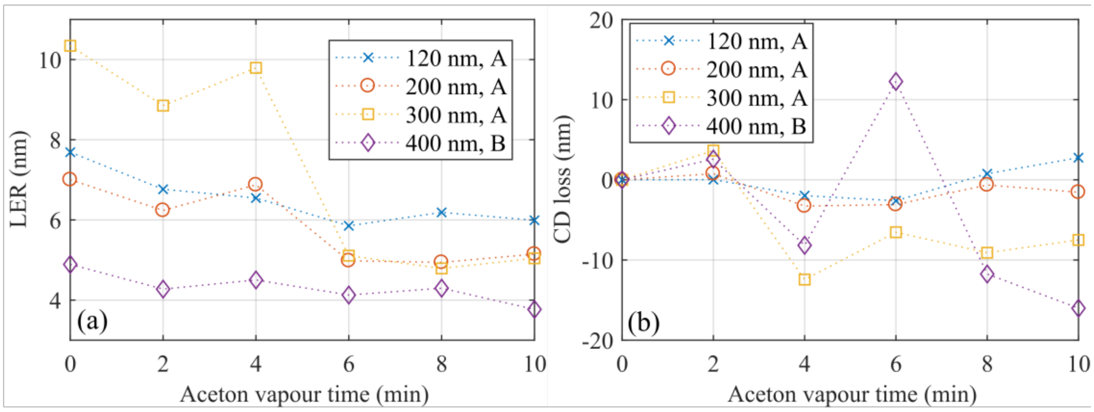

Figure 3: Effect of time in the acetone vapor atmosphere on the photoresist's line edge roughness (a) and critical dimension loss (b).

Conclusions

A reflow process is developed for ArF deep UV lithography photoresist. Significant reduction in line edge roughness is demonstrated with little impact to the critical dimension of the pattern. It is expected that propagation loss and static phase error will be reduced due to the line edge roughness improvement.

References

[1] J. van der Tol, Y. Jiao, L. Shen, A. Millan-Mejia, V. Pogoretskiy, J. van Engelen, and M. Smit, "Indium Phosphide Integrated Photonics in Membranes", IEEE Journal of Selected Topics in Quantum Electronics, vol. 24, paper no. 6100809, 2018.

[2] Y. Jiao, J. Pello, A. Millan Mejia, L. Shen, B. Smallbrugge, E.J. Geluk, M. Smit, and J. van der Tol, "Fullerene-assisted electron-beam lithography for pattern improvement and loss reduction in InP membrane waveguide devices", Optics Letters, vol. 39, no. 6, 1645-1648, 2014.

[3] J. Bolk, H. Ambrosius, R. Stabile, S. Latkowski, X. Leijtens, E. Bitincka, L. Augustin, D. Marsan, J. Darracq, and K. Williams, "Deep UV Lithography Process in Generic InP Integration for Arrayed Waveguide Gratings", IEEE Photonics Technology Letters, vol. 30, no. 13, 1222-1225, 2018.

[4] Y. Inatomi, T. Kawasaki, M. Iwashita, "LWR reduction in ArF resist pattern by resist smoothing process", Proc. SPIE 6153, Advances in Resist Technology and Processing XXIII, 2006.