Arrayed waveguide grating in InP membrane on silicon patterned by 193-nm deep UV lithography

Arrayed waveguide grating in InP membrane on silicon patterned by 193-nm deep UV lithography

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

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

We demonstrate an almost twofold improvement in insertion loss, crosstalk and channel non-uniformity of AWGs in InP membranes by using 193-nm deep UV lithography compared to our previous EBL results.

Introduction

Recently we demonstrated significant improvement of AWGs in ridge-waveguide photonic ICs using deep UV lithography [1]. In InP membranes, critical dimension control across dense photonic structures, like AWGs, remains challenging. This is due to the long scattering distance of electrons (30 µm in silicon substrates) in electron beam lithography (EBL). Proximity error correction of the exposure dose is unable to fully correct the background electron dose.

Optical lithography does not suffer from the electron scattering problem which improves critical dimension control. However state-of-the-art optical lithography tools are needed to pattern the small feature present in InP-membrane-on-Silicon (IMOS) devices. In this paper we demonstrate that key performance parameters of AWGs in InP membranes are improved by almost a factor of 2 by patterning with 193 nm deep UV lithography.

First the proximity error in EBL lithography is discussed and the 193-nm deep UV lithography is presented. Second the fabrication process of IMOS passive devices is discussed. Finally the performance of an AWG fabricated by deep UV lithography is presented and compared to our previous results that used EBL.

Proximity error correction in EBL lithography

The EBL photo resists that are used during the processing of IMOS samples rely on electrons with 2-3 keV energy to change the solubility of the resist. Previously we have used a 100 keV EBL to pattern IMOS features. The 100 keV electrons lose energy through collision with other electrons transferring momentum. As is shown in Fig. 1a photoresist up to 30 um away (in case of silicon substrate) from the shot location receive a significant background dose. This is problematic in dense structures like the arrayed waveguides in AWGs where the background dose differs between the waveguides near the edge and center. This creates a difference in width and therefor effective index, and introduces static phase error between the arrayed waveguides.

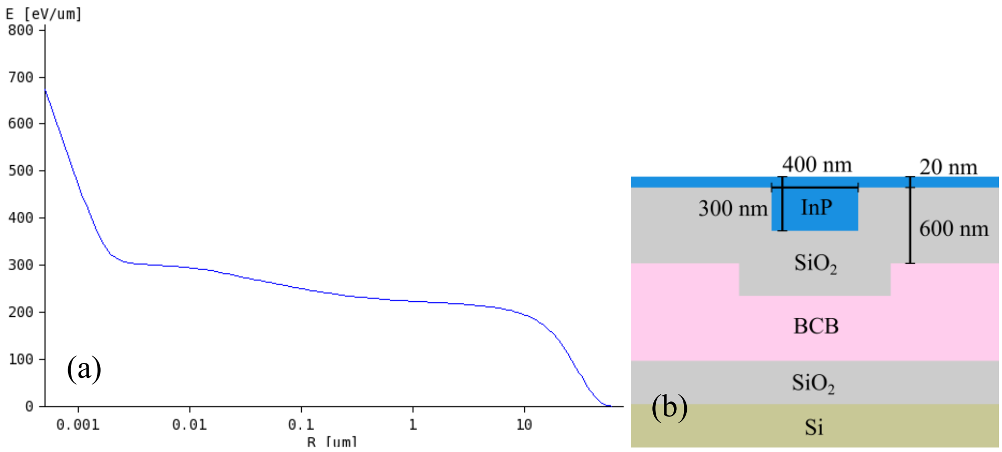

Fig. 1a: Cumulative energy deposited into the photoresist as a function of distance to the electron beam shot. This simulation shows that resist up to 30 um is exposed for a typical IMOS sample after bonding. Fig. 1b: cross-section of an IMOS waveguide.

There are several ways to correct for this background dose to ensure that the designed dimensions are achieved. The method that is used for the EBL result presented later in this paper is dose proximity error correction. This method compensates the dose of each shot for the expected background dose. Unfortunately we experience that dose proximity error correction on ZEP520A for arrayed waveguide gratings is challenging. There appears to be a tradeoff between achieving dose-to-clear and uniform waveguide dimensions in the center versus edge of the arrayed waveguides. Furthermore it is challenging to find settings that work for both dense (AWGs) and sparse features (isolated waveguides) which are often used in the same circuit.

193-nm deep UV lithography for IMOS

Recently we demonstrated significant improvement of AWGs in ridge-waveguide photonic ICs using deep UV lithography [1]. The NanoLab@TU/e cleanroom offers access to a modified ASML PAS5500/1100 tool that, to our knowledge, is the only scanner in the world to pattern features down to 100 nm with 15 nm overlay at high speeds on 3” InP substrates. Furthermore we recently demonstrated significant improvement [3] in the propagation loss of passive IMOS waveguides over previous EBL results [4].
Proximity errors also need to be taken into account when using 193nm optical lithography. However we find that this only matters for features that are much closer together (<1 um, e.g. in photonic crystals) compared to EBL (<30 um). As the distance between the arrayed waveguides is approximately 10 um we find that there is no appreciable difference in the dimensions of the center and the edge of the arrayed waveguides when using 193 nm optical lithography.

Fabrication process of IMOS passive circuits

A silicon nitride hardmask is deposited on a 3” InP wafer a with 300 nm InP and 300 nm InGaAs epi-stack. A photoresist is applied and exposed. Transfer of the pattern into the hardmask is done using a RIE process, after which it is etched into the 300 nm InP waveguide layer using a single step RIE process [4]. An etch depth of 120 nm is used for gratings. The hardmask is removed and the above process repeated to pattern the waveguide trenches which are etched to 280 nm depth, leaving 20 nm of InP in the trenches. The wafer is then bonded to a 3” silicon wafer using BCB with the wafer top

surfaces facing each other. Lastly the InP substrate and InGaAs layer are removed using selective wet etchants. A cross-section of the resulting waveguide is shown in Fig 1b.
In the past we used EBL to expose gratings and waveguide trenches for IMOS circuits using a ZEP520A photoresist. In this paper we demonstrate for the first time an IMOS

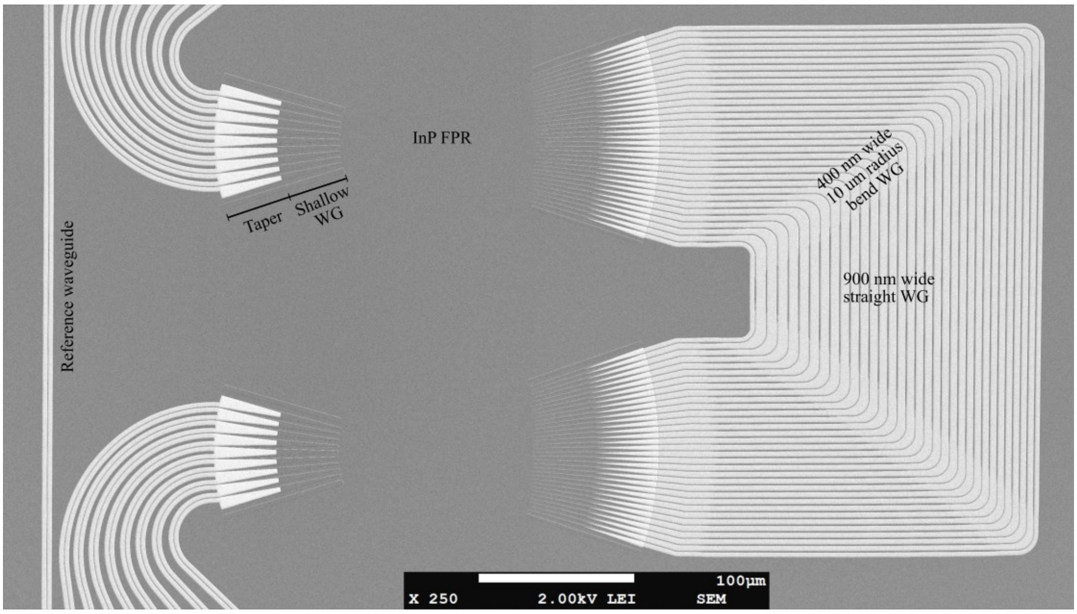

Fig. 2: The AWG presented in this paper during fabrication.

AWG using 193 nm deep UV lithography. The process is kept the same as described above, and only the lithography and subsequent steps to transfer the pattern into the hardmask are changed [1]. The wafer is then exposed using the modified ASML PAS5500/1100B scanner introduced earlier.

Significant AWG performance improvement over EBL

The 8x8 cyclic AWG was designed with a 4 nm channel spacing. A SEM image of the AWG during fabrication is shown in Fig. 2. Fiber grating couplers are used to couple the light to the input and output waveguides but these have a strong wavelength dependence. To separate out the effect of the grating couplers a reference waveguide next to the AWG is measured and the AWG spectrum is normalized to this reference waveguide. The measured transmission spectrum from input 4 to all output ports is shown in Fig. 3. The insertion loss, uniformity and crosstalk are discussed for the eight channels closest to design center wavelength of 1550 nm.
The insertion loss is 3.7 dB and is an improvement over our previous results of 5.7 dB using EBL. It is still higher than expected as the propagation loss of a 400 nm wide waveguide is measured to be 1.5 dB/cm on the same die. The high insertion loss may be caused by the poor patterning of the shallow etch in the free propagation tapers because this exposure is optimized for 300 nm pitch distributed Bragg reflector gratings whereas the teeth are only 100 nm wide.
The insertion loss uniformity is found to be 1.6 dB and is a two-fold improvement over the 3.1 dB achieved with EBL. This may be improved upon by optimizing the width of the FPR couplers.
The crosstalk is measured to be -15.3 dB and is a two-fold improvement over the 7.1 dB achieved with EBL. Any slight non-uniformity in the arrayed waveguides, such as

dimension variations, result in a different propagation constant in each arm of the arrayed waveguides. This causes non-uniform phase errors at the end of the arms. This leads to poor imaging of the field on the output which causes crosstalk. To improve the crosstalk better control over the dimensions and sidewall roughness is required. Recently we demonstrated improved roughness using a photoresist reflow technique [5].

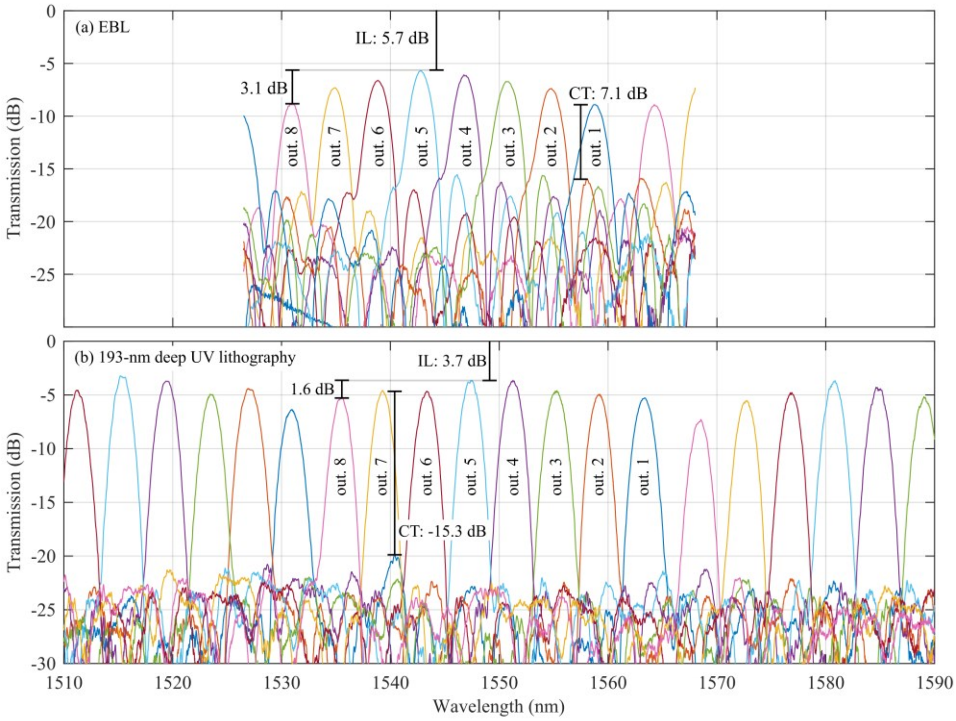

Fig. 3. Measured transmission spectrum from the center input waveguide to the 8 output channels for an 8x8 cyclic AWG with 4 nm channel spacing patterned using (a) EBL and (b) 193-nm deep UV lithography.

Conclusion

We demonstrate an almost twofold improvement in insertion loss, crosstalk and channel non-uniformity of AWGs in InP membranes by using 193-nm deep UV lithography compared to our previous EBL results. In a cyclic 8x8 AWG with 4 nm channel spacing fabricated using 193-nm deep UV lithography we measured an insertion loss of 1.6 dB, insertion loss channel non-uniformity of 1.6 dB and crosstalk of 15.3 dB.

References

[1] J. Bolk et al., "Deep UV lithography process in generic InP integration for arrayed waveguide gratings," IEEE Photonics Technology Letters, vol. 30(3), 2018.

[2] X. Zhang et al., "Reflecting AWG by Using Photonic Crystal Reflector on Indium-Phosphide Membrane on Silicon Platform," IEEE Photonics Technology Letters, vol. 3(13), 2019.

[3] J.P. van Engelen et al., "Low loss InP membrane photonic integrated circuits enabled by 193-nm deep UV lithography", Compound Semiconductor Week (CSW), 2019.

[4] Y. Jiao et al., "Vertical and Smooth Single-Step Reactive Ion Etching Process for InP Membrane Waveguides", Journal of The Electrochemical Society, 162(2), E90-E95, 2015.

[5] J.P. van Engelen et al., "Reflow of deep UV resist for line edge roughness reduction in InP membrane waveguides", Proc. of the 23rd Annual Symposium of the IEEE Photonics Society Benelux Chapter, p. 165-168, 2018.