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Low Loss InP Membrane Photonic Integrated Circuits Enabled by 193-nm Deep UV Lithography

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Abstract—For the first time we demonstrate the application of 193 nm optical lithography to InP-Membrane-on-Silicon (IMOS) passive nanophotonic integrated circuits. A record low propagation loss of 1.3 ± 0.1 dB/cm is demonstrated in a Mach-Zehnder interferometer (MZI) circuit and a microring resonator Q-factor up to $62 \cdot 10^3$ with 4 nm FSR is measured.

Keywords—photonic integrated circuit; propagation loss; Mach-Zehnder interferometer; microring resonator

In silicon photonics low surface roughness and excellent uniformity are achieved by state-of-the-art 193 nm optical lithography [1]. Recently we demonstrated low-excess-loss arrayed waveguide grating on a microphotonic InP platform [2]. We expect that the same methods will have a high impact on InP nanophotonics, where so far the losses have been limited to 2.5 dB/cm [3]. Silicon-on-insulator (SOI) waveguides with comparable dimensions and mode confinement typically achieve 1.5 dB/cm [4]. In this work for the first time we evaluate the use of 193 nm scanner lithography for InP nanofabrication by fabricating a test-cell for propagation loss analysis in the IMOS platform [5].

For the fabrication a 300 nm InP waveguide layer and a 300 nm InGaAs etch-stop layer are grown epitaxially on a 3" InP substrate. A silicon nitride hardmask is deposited and a tri-layer photoresist stack is spun. The wafer is then exposed with an ASML PAS5500/1100B scanner lithography tool. This lithography tool is modified to be, to our knowledge, the only scanner in the world to expose features down to 100 nm with 15 nm overlay accuracy on 3" InP substrates at high speeds [2]. The pattern is first transferred to the silicon nitride hardmask, then to InP using a RIE process [3]. This forms 120 nm deep fiber coupler gratings. The hardmask is removed and the above process repeated to pattern 280 nm deep waveguide trenches. A 600 nm thick silicon oxide layer is deposited and the InP wafer is bonded to a Si wafer using BCB. The substrate and etch-stop layer are removed in a wet-chemical process. The resulting cross-section is shown in Fig. 1. Using this process MZI (Fig. 2) and microring resonators (Fig. 3) measurement structures are fabricated. The measurement results of these structures are discussed next.

MZI structures with 400 nm waveguide width and different path length differences are measured. The transmission spectrum of a structure with $\Delta L = 1774 \mu\text{m}$ is shown in Fig. 4. The transmission spectra of the MZI structures are fitted to an analytical model and the resulting propagation loss α is shown in Table 1. The average propagation loss is 1.3 ± 0.1 dB/cm which, to the knowledge of the authors, is the lowest reported to date for InP nanophotonic waveguides of these dimensions.

Microring resonators with 450 nm waveguide width, 24 μm radius and different bus-to-ring spacing are measured. The radius corresponds to a free spectral range (FSR) of 4 nm. The transmission spectra around resonance are shown in Fig. 5. These spectra are fitted to an analytical model of the rings [6] and the propagation loss can be isolated from the self-coupling coefficient by measuring identical rings with different bus-to-ring spacing. The propagation loss α is shown in Table 2 for the different rings. It is not clear why the ring with 300 nm spacing has significantly higher propagation loss. We suspect that this is caused by a fabrication defect. The average propagation loss of the other rings is 1.8 ± 0.1 dB/cm. This is higher than in the MZI even though the waveguide is wider. Higher overlap of the mode with the sidewall due to the curvature and the smaller feature size in the coupling region are suspect. The Q-factor is derived from the full width half maximum (FWHM): $Q\text{-factor} = \lambda / \text{FWHM}$ and shown in Table 2 for the different rings. The ring with the largest spacing (400 nm) achieves a Q-factor of $62 \cdot 10^3$.

In conclusion, we have demonstrated for the first time the application of 193 nm lithography to InP passive membrane nanophotonic ICs. Propagation loss of 1.3 ± 0.1 dB/cm and microring resonator Q-factor up to $62 \cdot 10^3$ with 4 nm FSR were demonstrated.

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Fig. 1. Schematic cross-section of the InP membrane waveguide used in this publication. The waveguide width is 400 nm in the MZI and 450 nm in the microring resonators.

Fig. 2. Overlapped SEM images of the silicon nitride hardmask for the waveguide trenches of the fabricated MZI.

Fig. 3. Tilted SEM image of the silicon nitride hardmask of the waveguide trenches of the fabricated microring resonator.

Fig. 4. Transmission spectrum of MZI structure with a path length difference in the arms of 1774 μm.

Fig. 5. Transmission spectrum of microring resonators with different spacing between the ring and the bus waveguide. The measurement points (dots) are fitted (lines).

Table 1. Propagation loss of MZI structures with different path lengths.

ΔL (μm)	α (dB/cm)
1345	1.31
1774	1.15
2202	1.40

Table 2. Propagation loss and Q factor of rings with 24 μm radius and 450 nm waveguide width and varying spacing between ring and bus waveguide.

Spacing (nm)	α (dB/cm)	Q-factor (-)
250	1.79	$10 \cdot 10^3$
300	3.04	$19 \cdot 10^3$
350	1.68	$40 \cdot 10^3$
400	1.84	$62 \cdot 10^3$