Thin-film Lithium Niobate Photonic Devices on 8-inch Silicon Substrates

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Abstract: Thin-film lithium niobate photonic devices are first demonstrated on 8-inch silicon substrates. The fabrication is done in a commercial semiconductor foundry. A waveguide propagation loss of 0.47±0.09 dB/cm is achieved at 1550 nm wavelength. ©2022 The Author(s)

1. Introduction

Lithium niobite (LN) has been widely used in optoelectronic devices for decades for its remarkable electro-optic, acousto-optic and non-linear properties. In recent years, breakthroughs in the manufacturing of LN on insulator (LNOI) wafers and the LN fabrication processes open up a revolutionary area of thin-film LN photonics [1-5]. Featured with low-loss waveguides, compact device size and wide transparent window from visible to mid-infrared, thin-film LN photonic devices show promise in a variety of areas, e.g. optical communication, distance measurement and quantum technologies [6-9]. Although progress has been made in various thin-film LN photonic devices, the fabrication processes are mainly chip-level. With the technology advances, wafer-scale fabrication becomes increasingly important for mass-production of thin-film LN photonic integrated circuits (PICs). Research works of thin-film LN devices fabricated on 3- to 6-inch wafers have been reported [10-15].

It is worth noting that the current mainstream semiconductor foundry platforms are for 8-inch or larger wafers. The 8-inch fabrication process brings the following advantages. Firstly, the advanced optical lithography tools, such as 193 nm ArF scanner, can be used, which is hardly available in the platforms for smaller size wafers. This enables not only a smaller line-edge-roughness (LER) of the waveguide, but also a smaller critical dimension (CD) which is important for nanophotonic devices in visible wavelengths. Secondly, it could leverage on the wafer-level metrology and optical characterization infrastructures well-developed in the Si photonics platforms. Thirdly, by matching the size of 8-inch microelectronic wafers, wafer-level packaging between the thin-film LN PICs and the electronic ICs becomes possible. To the best of our knowledge, however, thin-film LN photonic devices on 8-inch substrates have not been demonstrated yet.

In this work, we report the first demonstration of thin-film LN photonic devices on an 8-inch Si substrate, as shown in Fig. 1. The device fabrication was done in a commercial 8-inch semiconductor foundry. The LN ridge waveguide shows a propagation loss of 0.47±0.09 dB/cm at 1550 nm wavelength. The waveguide performances at the entire C-band are also characterized.

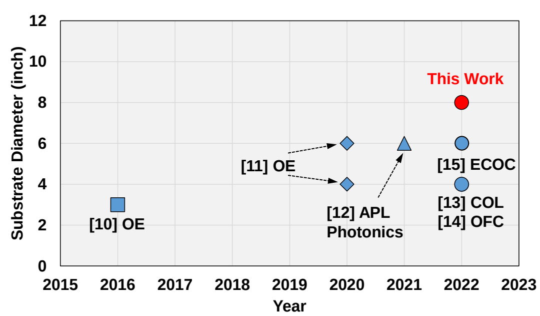

Fig. 1: Progress on the wafer-scale thin-film LN photonic devices on substrates with different diameters.

2. Device Fabrication

The fabrication process was done in a commercial 8-inch semiconductor foundry. As it is still challenging to manufacture a full 8-inch LNOI wafer using current technologies, a 6-on-8 inch LNOI wafer (commercially available from NANOLN) was used in this work. Nevertheless, the fabrication process developed in this work can be directly used for full 8-inch LNOI wafers once they are available in the future. The wafer consisted of a 400 nm thick X-cut LN thin film, a 3 μm thick buried oxide (BOX) and a 725 μm thick high-resistance Si substrate. The diameters of the LN thin film and the Si substrate are 6-inch and 8-inch, respectively.

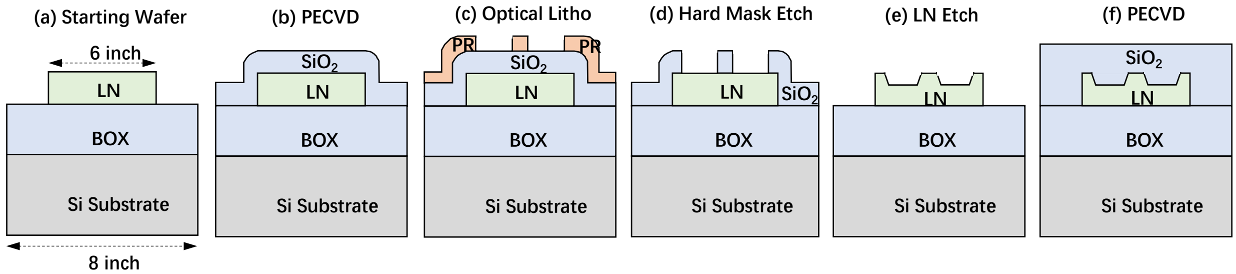

Fig. 2: Key fabrication steps of the thin-film LN photonic devices: (a) the starting 6-on-8 inch LNOI wafer, (b) SiO_2 deposition by PECVD, (c) waveguide patterning by i-line optical lithography, (d) SiO_2 hard mask dry etching, (e) LN partial dry etching and wafer cleaning and (f) SiO_2 cladding by PECVD.

The key fabrication steps of the LN photonic devices are illustrated in Fig. 2. A SiO_2 film was deposited on the entire wafer by plasma-enhanced chemical vapor deposition (PECVD). After that, an i-line optical lithography stepper was used to form the device patterns. It should be noted that the i-line lithography tool was used only for preliminary device demonstrations. It is foreseen that the device performance could be enhanced by using advanced deep UV (DUV) lithography tools, which will be subjects of our future works.

After lithography, a fluorine-based SiO_2 dry etching process is applied to form the hard mask. Subsequently, a dedicated argon ion etching process was developed to realize the LN ridge waveguide. Wet cleaning processes were then utilized to remove the remaining hard mask. The device fabrication was completed by depositing a SiO_2 upper cladding for the LN devices. It should be noted that the above-mentioned fabrication process is relied on standard 8-inch fabrication tools without customization, showing promise in wafer-scale mass production of thin-film LN PICs.

3. Results and Discussion

A photography of the wafer (under yellow-light condition) during fabrication is shown in Fig. 3(a). The die size is 20 mm by 20 mm. The wafer comprises 30 full dies, within which a variety of thin film LN photonic devices, e.g. waveguides, grating couplers, ring resonators, are fabricated. In this paper, we focus on the characterization of waveguide performances. LN ridge waveguides with lengths (L_{wg}) of 2.21, 5.23, 11.49 cm are designed for propagation loss measurements. The waveguide width is fixed at 1 μm. Figure 3(b) shows a microscopy image of the spiral waveguide with L_{wg} = 11.49 cm. By cleaving the wafer at the spiral region, a cross-sectional scanning electron microscopy (XSEM) inspection is carried out to measure the ridge height and the sidewall angle, as shown in Fig. 3(c). It is observed that the LN etching depth is around 100 nm and the sidewall angle is around 70°.

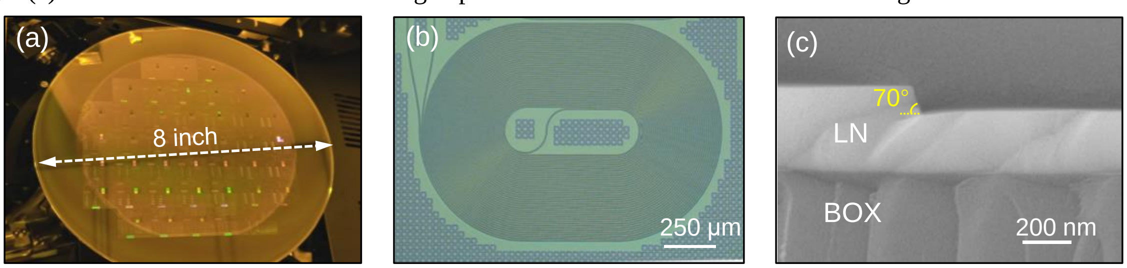

Fig. 3: (a) Photography of the LNOI wafer during fabrication process. The image was taken in a yellow-light cleanroom. (b) Optical microscopy image of a spiral LN waveguide with a propagation length of 11.49 cm. (c) XSEM image of the LN ridge waveguide.

The waveguide propagation loss is characterized by the cut-back method. A fiber-coupled tunable laser is used as the light source. Grating couplers are used to couple light in and out between fiber and the photonic chip. Five groups of testing structures are used for the loss measurement. The only difference between each group is the grating coupler design (the groups are hereinafter named as GC-1 to GC-5). The total optical power loss as a function of L_{wg} at λ = 1550 nm is plotted in Fig. 4(a). The black dotted lines are the linear fitting curves of the data points by the least square method. A waveguide propagation loss of 0.47±0.09 dB/cm are thus obtained by extracting the slopes of the fitting lines.

Next, the wavelength dependency of the waveguide propagation loss is characterized at the entire C-band (1530 nm to 1565 nm). The total optical power loss spectra of the group GC-1 with various L_{wg} are plotted in Fig. 4(b). The black arrow indicates the direction of decreasing L_{wg}. The waveguide propagation losses at different wavelengths can be thus obtained by the cut-back method discussed above. The results are presented in Fig. 4(c). It can be seen that the propagation loss spectrum at C-band is relatively flat, with loss values at the range of 0.4 to 0.6 dB/cm. This indicates that the LN waveguide realized in this work are suitable for C-band photonic integrated circuits.

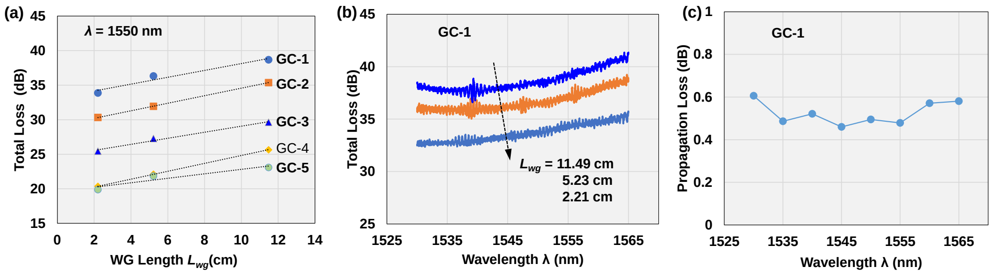

Fig. 4: Optical characteristics of the LN ridge waveguide. (a) The total optical power loss of five groups of testing structures at λ = 1550 nm. The propagation loss could be extracted by linear fitting of the data points, which yields a loss value of 0.47±0.09 dB/cm. (b) The total optical power loss of waveguides at C-band. The black arrow indicates the direction of a smaller L_{wg}. (c) Propagation loss of the waveguide at C-band.

The wafer-scale thin film LN photonic devices reported in literatures are benchmarked in Table 1. In this work, an 8-inch substrate for thin-film LN devices enables the possibility of using the mainstream Si photonics foundry infrastructures. In addition, the optical lithography and dry etching processes ensure the short process time and high-repeatability in mass production. In spite of a narrower waveguide width of 1 μm, a decent waveguide loss of 0.47 dB/cm is realized at 1550 nm wavelength. The loss should be mainly originated from the sidewall scattering effect, as the i-line lithography tool may not be able to provide a small enough LER for the 1 μm wide waveguide. Therefore, one possible approach to suppress the waveguide propagation loss is to use an advanced lithography tool, e.g. 193 nm ArF scanner, which is hardly available for wafers less than 8-inch diameter.

Table 1. Benchmark of wafer-scale thin-film LN photonic devices.

Reference & Year	Substrate Size (inch)	Key Process	Waveguide Width (μm)	Wavelength (μm)	Propagation Loss (dB/cm)
[10] 2016	3	Optical Litho, Dry Etch, Bonding	3.5	1.55	1
[11] 2020	4	Optical Litho, Dry Etch	2	1.59 to 1.6	0.27
	6	Optical Litho, Dry Etch	N. A.	N. A.	N. A.
[12] 2021	6	EBL, Dry Etch	1.3	1.56	<0.5
[13] 2022	4	Optical Litho, Wet Etch	1.3	1.55	0.2
[14] 2022	4	Optical Litho, Dry Etch	1.5	1.55	0.23
[15] 2022	6	EBL, Dry Etch	1.5	1.55	<0.14
This Work	**8**	**Optical Litho, Dry Etch**	**1**	**1.55**	**0.47**

4. Conclusion

In this work, we report the first demonstration of thin-film LN photonic devices on 8-inch Si substrates. The fabrication processes are developed in a commercial semiconductor foundry using standard 8-inch fabrication tools without any customization. A propagation loss of 0.47±0.09 dB/cm is achieved for the LN ridge waveguides at 1550 nm wavelength. In addition, the characterization of waveguide performance at the entire C-band is performed. This work paves the way for the wafer-scale mass production of thin film LN photonic integrated circuits.

5. Acknowledgements

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6. References

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