Lithium Niobate-On-Insulator (LNOI): Status and Perspectives

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ABSTRACT

As optical components continue to replace electronics in ultrafast signal processing applications, a growing interest in further miniaturization and integration of photonic devices on a single chip is observed. Therefore, optical waveguides of high refractive index contrast of core and cladding materials are developed since a couple of years. They can have a very small cross section and also bending radius, enabling the development of ultra-compact photonic integrated devices and circuits. Silicon-On-Insulator (SOI) waveguides ("photonic wires") and devices are the most prominent examples.

A corresponding technology for Lithium Niobate-On-Insulator (LNOI) waveguides is still in its infancy, though LN offers - in contrast to SOI - excellent electro-optic, acousto-optic, and nonlinear optical properties. Moreover, it can be easily doped with rare-earth ions to get a laser active material. Therefore, LNOI photonic wires will enable the development of a wide range of extremely compact, active integrated devices, including electro-optical modulators, tunable filters, nonlinear (periodically poled) wavelength converters, and amplifiers and lasers of different types.

The state-of-the-art of LNOI films as platform for high-density integrated optics is reviewed. Using a full-wafer technology (3" diameter), sub-micrometer thin LN films are obtained by high-dose He^+ ion implantations, crystal-bonding to a low-index substrate (preferably SiO_2) and cleaving by a special annealing step ("ion-beam-slicing"). Various LNOI structures, also combined with metallic layers, are presented. Based on such platforms, photonic wires and micro-photonic devices are developed using different micro- and nano-structuring techniques. To be specific, the fabrication and characterization of LNOI photonic wires with cross-section < 1 μm^2, and periodically poled LNOI photonic wires for second harmonic generation are reported in detail.

Keywords: Lithium Niobate, photonic wire, periodic poling, nonlinear integrated optics.

1. INTRODUCTION

Optical waveguides of high refractive index contrast enable ultra-small waveguide cross-sections below 1 μm^2 (photonic wires) and bending radii smaller than 10 μm, facilitating the development of ultra-compact photonic integrated devices and circuits [1]. For lithium niobate ($LiNbO_3$, LN), a favorable high-refractive-index-contrast structure is a thin single crystal LN film on a SiO_2 layer deposited on a LN-substrate with a refractive index difference of 0.7. Such a structure is named Lithium Niobate-On.Insulator or LNOI to emphasize the analogy to SOI. However, in contrast to SOI, lithium niobate has excellent electro-optic, acousto-optic, and nonlinear optic properties, and is transparent also in the visible spectral range.

Photonic wires based on LNOI will enable the development of a wide range of active integrated devices. They comprise electro-optical modulators, tunable filters, and amplifiers and (tunable) lasers of different types. In particular, periodically poled LN (PPLN) photonic wires are ideal candidates for efficient nonlinear optical devices for wavelength conversion and all-optical signal processing [2]. Due to high mode intensities even at moderate optical power levels, devices of high efficiency can be expected.

A well-known technology to prepare thin single crystal films from bulk material is called “smart cut” [3]. This technology includes ion implantation, direct wafer bonding, and thermal splitting. It is widely used for the fabrication of SOI wafersand can also be used for the fabrication of LNOI. Due to the large thermal mismatch between LN and SiO_2, bulk SiO_2 cannot be used as substrate. However, the sandwich structure of LN film/SiO_2 layer/LN substrate reduces significantly the thermal mismatch problem. According to modeling results for 1.5 μm wavelength, the SiO_2 layer should be thicker than 1.1 μm, to form an optical barrier to avoid coupling of a guided mode to the substrate. Since the smart cut process was disclosed, several variants of this method have been studied for the exfoliation and transfer of different ferroelectric thin films. Free-standing LN films were fabricated by ion slicing and some optical devices were demonstrated [4, 5]. Crystal slicing was combined with direct bonding to fabricate LN films on SiO_2 [6]. Using benzocyclobutene (BCB) as cladding layer, electro-optical tunable micro-ring resonators were reported [7]. Also photonic crystal waveguide structures based on LNOI were already developed [8]. Moreover, free-standing LN micro-rings coupled to GaN channel guides on a sapphire substrate were demonstrated [9]. Recently, the fabrication of 3-inch LNOI wafers was reported [10]and high quality LNOI photonic wires could be developed [11].

We report in this paper our recent progress towards LNOI materials and devices, including the fabrication of LNOI wafers and waveguide structures. In the second chapter the development of LNOI wafers is presented. The fabrication and the optical properties of LNOI photonic wires are reviewed in the third chapter. Different approaches to realize periodically poled (PP) LNOI photonic wires will be shown and results of Second Harmonic Generation (SHG) experiments are presented in the fourth chapter. The last chapter gives some conclusions and perspectives.

2. WAFER-SCALE LNOI

The full wafer process to fabricate LNOI by ion slicing and crystal bonding is schematically shown in Fig. 1. At first, a Z-cut LN wafer of 3`` diameter was implanted by 250 keV He ions with a dose of 4×10^{16} ions/cm^2 forming an amorphous layer at about 760 nm underneath the surface. The amorphous layer defines a “cleavage plane”. Another Z-cut LN handle sample was coated by a SiO_2 layer of 1.3 μm thickness by plasma enhanced chemical vapor deposition (PECVD). The stress between SiO_2 and the LN substrate can be controlled by the parameters of the PECVD process. The SiO_2 layer was annealed at 450 ^{o}C for 8 hours to drive off the trapped gases. With a chemical mechanical polishing (CMP) process, the SiO_2 surface roughness was reduced from 6 nm to 0.35 nm to enable direct wafer bonding. The bonded pair of samples was then annealed (165 ^{o}C, 16 hrs; 190 ^{o}C, 6 hrs) to improve the bonding strength. By a further annealing procedure at 228 ^{o}C for 2 hrs, a thin LN layer of 760 nm thickness split along the He implanted layer and remained on the SiO_2/LN substrate. The sample was then annealed at 450 ^{o}C for 8 hours to increase the bonding strength further. By another CMP process, the roughness of the LN-air interface was reduced to 0.5 nm. Direct wafer bonding is a very versatile process. It was also used to fabricate various sandwich structures with a thin metal electrode either underneath the SiO_2 layer or underneath the LN film. These structures should enable electric field induced ferroelectric poling or electro-optic control of light propagation. Also a LNOI wafer with a MgO-doped LN film has been developed [10].

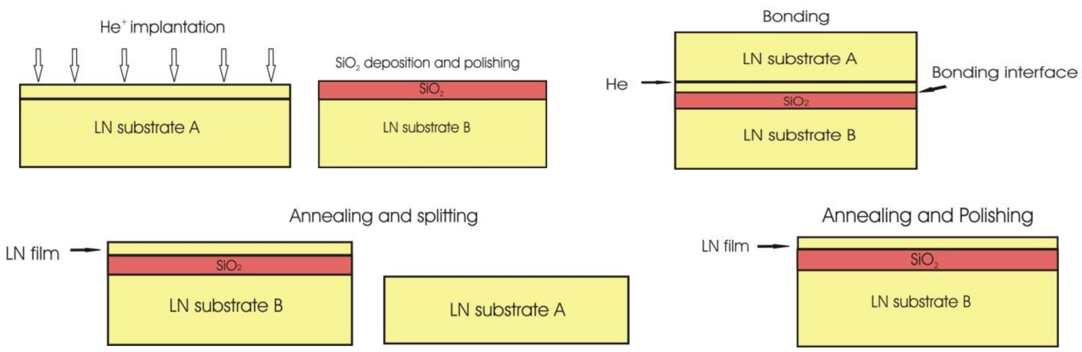

Fig. 1. Fabrication scheme of LNOI wafers of 3`` diameter: a "smart cut" single crystalline LN film of sub-micrometer thickness is directly bonded to a SiO_2 / LN substrate.

Fig. 2 shows an LNOI wafer. The homogeneity of the interference colors demonstrates the excellent homogeneity of the thickness of the LN layer of 6 % only, measured independently by a step profiler.

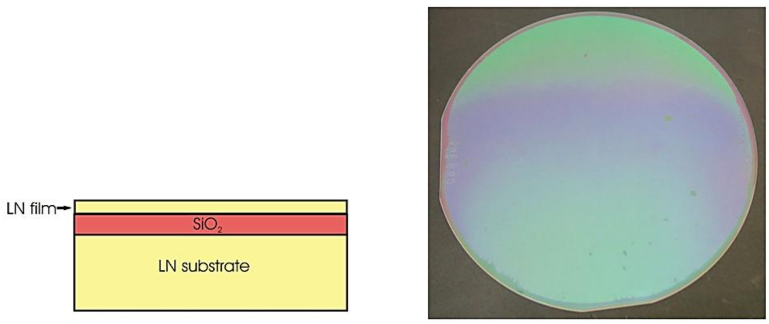

Fig. 2. Schematic cross-section (left) and photograph (right) of a LNOI-wafer of 3" diameter after splitting, consisting of a 760-nm thick single crystalline LN film crystal bonded on a 1.3-µm thick SiO_2 layer deposited by PECVD on a LN substrate.

3. LNOI PHOTONIC WIRES

Photonic wires are important basic structures of integrated optics. They are channel waveguides of high index contrast and very small cross-section dimensions leading to strong light confinement. LNOI was used as starting material for the development of photonic wires employing two different methods for the micro-fabrication of LN channels: Ar milling and focused ion beam (FIB) etching.

3.1 LNOI photonic wires fabricated by Ar milling

The LNOI sample usedconsists of a 730 nm thick single crystalline LN layer bonded to a 1.3 µm thick SiO_2 layer. Photoresist stripes of 1.7 µm thickness and 1 - 7 µm width were defined by photolithography on the LNOI surface as etching masks. Ar milling was performed in an Oxford Plasmalab System 100 with 100 W RF power inductively coupled into the plasma and 70 W RF power coupled to the sample table. The temperature of the sample was carefully controlled during the etching process to avoid a shrinking of the photoresist mask or a deformation. The etching depth was 430 nm. Fig. 3 shows a scanning electron microscope (SEM) picture of a photonic wire of 1 µm top width. The dark stripe underneath is the SiO_2 layer. On both sides of the ridge, etched trenches can be observed, resulting from additional etching by ions reflected by the angled walls of the ridge [11]. Finally, the end faces of the sample were polished to enable efficient end-fire coupling of light.

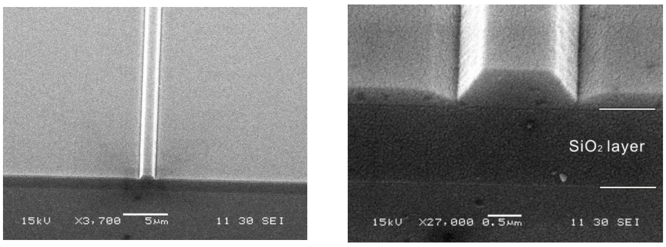

Fig. 3. SEM micrographs of a photonic wire of sub-micrometer cross-section dimensions (~1 µm top width). The trenches on both sides of the ridge nearly reach the surface of the SiO_2 buffer layer.

For the optical characterization of LNOI photonic wires, a laser diode was used tunable around 1.55 µm wavelength. The light was coupled to the waveguides by a 60 X / 0.8 objective, and a 100 X 0.9 objective magnified the near field distribution of the guides mode at the output side and formed an image on the camera. Fig. 4 shows on the left the measured mode distribution (quasi TM-polarization) of a photonic wire of 1 µm top width;on the right the corresponding theoretical distribution is shown calculated by a finite difference method. The calculated mode size is 0.4 μm^2 (product of FWHM in horizontal and vertical directions), more than one order of magnitude smaller than the mode size of about 16 μm^2 in a conventional Ti-indiffused strip guide of 7 µm width. Therefore, such photonic wires are ideal candidates to develop nonlinear devices of high efficiency.

Fig. 4. Measured (left) and calculated (right) intensity distribution of the fundamental mode in a LNOI channel waveguide of 1 µm top width (qTM-polarization; $\lambda = 1.55$ µm). The profile, used for the simulations, is indicated (right).

The propagation losses were measured by the Fabry-Perot method [12]. The end face reflectivity needed to evaluate the loss coefficients was obtained by a 3-dimensional finite difference time domain (FDTD) simulation. A qTE-propagation loss of 6.3 dB/cm was evaluated for the 2-µm wide channel; for qTM polarization, the loss is 7.5 dB/cm. In the 1-µm wide photonic wire the qTM propagation loss was determined to be 9.9 dB/cm; for qTE polarization, the loss is 12.9 dB/cm. The loss mainly results from scattering by the residual roughness of the etched walls of the photonic wires (see Fig. 3). The roughness might be reduced by an improved photolithography or an advanced etching process, such as FIB, which will be discussed in the next section.

The group index and the phase index play an important role determining pulse transmission and phase matching in photonic wires. The waveguide mode dispersion is determined by the material dispersion of core and cladding materials and by the waveguide dimensions. Fig. 5 shows the measured and calculated group index in a photonic wire of 1 µm top width. Due to the high index contrast of photonic wires and their small cross section dimensions, the effective index of refraction n_{eff} varies considerably as function of the wavelength between the bulk index of LN and that of SiO_2. The group indices for mode propagation are substantially larger than for light propagation in bulk LN, reflecting the influence of the small waveguide dimensions. They even allow adjusting a group index dispersion close to zero in the 1.5 µm wavelength range, which is of interest for optical communication devices [11].

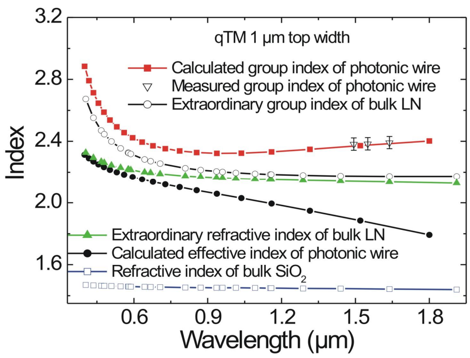

Fig. 5. Calculated effective and group indices for the fundamental modes of qTM polarization in photonic wires of 1 µm top width versus the wavelength. The measured group indices of photonic wires, the calculated group indices of bulk LN, and the refractive indices of bulk LN and SiO_2 are shown as well for comparison [11].

3.2 LNOI photonic wires fabricated by FIB

FIB etching is a very precise and controllable method to define sub-micron structures. In our experiments, a SII SMI3000 system was used to process a LNOI sample of 530 nm LN thickness. The photonic wires were milled with a focused beam of Ga ions accelerated to 30 kV. In order to minimize unwanted charging effects during the ion beam milling, samples were covered with a 20-nm thick Au layer and electrically connected to the grounded sample holder. After the milling process, the Au layer was removed by chemical etching. Two grooves of 1.2 µm separation, 6 µm width and 1.2 µm depth were etched to define a 4 mm long photonic wire and to separate it from the surrounding. According to modeling results, a width of 2 µm is sufficient to minimize the optical coupling to the remaining LN layer. Fig. 6 (left) shows a SEM picture of the photonic wire fabricated by FIB etching. It seems that the etched walls are somewhat smoother than those of Ar milled samples. Fig. 6 (middle) also presents an optical micrograph with a top view of a photonic wire. Moreover, a micrograph of the end face of the sample is presented in Fig. 6 (right), when light of a He-Ne laser (λ = 633 nm) is (mainly) coupled to the photonic wire. The bright spot in the center results from light guided in the photonic wire. The bright stripes besides the spot result from light guided in the remaining LN layer which forms planar waveguides. The determination of propagation losses is still in progress.

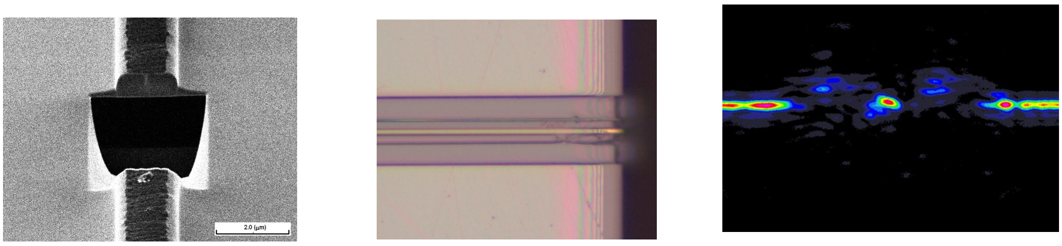

Fig. 6. Left: A hole was etched by FIB in a 1.2-µm wide photonic wire to show the cross section. Middle: Optical micrograph with a top view of the photonic wire defined by FIB etching. Right: Sample end face with light (λ = 633 nm) guided in the photonic wire (center) and in the remaining LN thin film on both sides.

4. PERIODICALLY POLED PHOTONIC WIRES

For efficient second order nonlinear optical interactions, (quasi-) phase-matching (QPM) is required. It can be achieved by a periodic ferroelectric do¬main inversion. Periodically poled LNOI (PPLNOI) photonic wires are ideal candidates to develop efficient nonlinear optical devices for wavelength conversion and all-optical signal processing. However, direct electric field poling of LNOI samples or of photonic wires was hard to realize. We assume that implantation-induced defects in the LN layer lead to electrical breakdown before domain inversion was achieved. Therefore, as alternative, conventionally poled bulk PPLN was used as starting material and processed by smart cut technology as described above. In this way, a periodically poled LNOI film was obtained and used for the fabrication of PPLNOI photonic wires by Ar milling. In this way, periodically poled photonic wires with 9.0 µm periodicity were realized designed for third order QPM SHG with 1064 nm fundamental wavelength (see inset of Fig. 7 (middle)) [13]. Modelling results showed that type I QPM SHG should be possible with a domain grating of 3 µm periodicity. Therefore, in a photonic wire with a 9 µm grating, a third order QPM process can be expected at the expense of a reduced efficiency. As only a section of 100 µm length of the 3mm long waveguide was successfully poled, uncritical quasi phase matching should be possible with a spectrally broad phase matching characteristics (see Fig. 7 (left)). In the corresponding experiments, light of 1064 nm wavelength from a narrow-band laser diode of up to 40mW output power was coupled to a PPLNOI photonic wire of 9 µm periodicity. SHG was successfully observed; the insets of Fig. 7 (left) show the intensity distributions at the end face of a photonic wire at 1064 nm and 532 nm wavelength, respectively. Due to the broad phase matching characteristics, SHG could also be observed in waveguides of 2 - 7 width. The SH output power was detected by a photomultiplier which is sensitive at the SH and blind at the fundamental wavelength. The dependence of the generated SH power on the input fundamental power is presented in Fig. 7 (middle); a parabolic dependence is observed.

Domain gratings of 3.2 µm periodicity have been fabricated in the surface of bulk Z-cut LN by the over-poling technology [14]. They can have a depth of several micrometers, sufficient for the fabrication of planar PPLNOI waveguides by the smart cut process. At first, a photoresist grating with 3.2 µm periodicity was fabricated by holography on the surface of bulk LN. A liquid electrode, covering the photoresist grating, allowed applying an electric field modulated by the resist structure. Using carefully

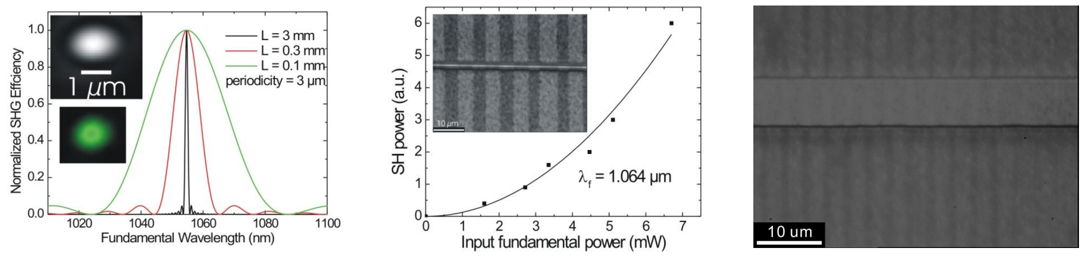

Fig. 7. Left: Calculated (first order) quasi phase matching characteristics for SHG with different (interaction) lengths L. Upper and lower insets: photographs of TM-polarized modes of the fundamental (λ = 1064 nm) and the SH mode (λ = 532 nm), respectively. Middle: measured (dots) and theoretical (fitted parabola, straight line) SH power versus input fundamental power (measured in front of the coupling lens). Inset: optical micrograph of a PPLN photonic wire of 1 µm top width and 9.0 µm periodicity. Right: Photonic wire of 7 µm width with periodicity of 3.2 µm.

selected poling parameters, the whole sample is domain inversed with the exception of a thin layer underneath the surface, where a grating of original domain orientation remains. By the following smart cut process, a planar PPLNOI film was fabricated. Finally, photonic wires of 1- 7 µm width were defined by Ar milling. Fig. 7 (right) shows an optical micrograph of a 7 µm wide PPLNOI photonic wire with 3.2 µm domain periodicity. It allowed observing first order QPM SHG at the fundamental wavelength of 1064 nm. Unfortunately, the efficiency of the nonlinear process was very weak, what we attribute to unperfect QPM and a weak overlap of fundamental and SH modes.

5. CONCLUSIONS AND PERSPECTIVES

The recent development of high-refractive-index contrast "lithium niobate on insulator" (LNOI) has been reviewed. Single-crystalline 3-inch LNOI wafers were fabricated by ion implantation and direct bonding technologies. LNOI might become a new platform for high-density active integrated optics due to the excellent electro-optic, acousto-optic, and nonlinear optical properties of LN. Moreover, it can be easily doped with rare-earth ions to get a laser active material. LNOI photonic wires with cross section < 1 µm^2 have been developed by Ar milling or FIB etching. The dispersion properties of photonic wires can be adjusted by the waveguide dimensions alone in a wide range. Periodically poled LNOI photonic wires were realized with domain periods of 9.0 µm and 3.2 µm enabling third and first order QPM SHG. Due to their small mode size, PPLNOI photonic wires have a great potential for nonlinear optical devices of unprecedented efficiency. They are ideal candidates for a wide range of nonlinear wavelength converters and devices for all-optical signal processing. In particular, sub-micrometer ferroelectric domain structures would be attractive enabling devices with backward nonlinear coupling. The growing activities and the great potential of LNOI based devices will lead to novel concepts and architectures of a high-density integrated optics with highly efficient electro-optical, nonlinear-optical, and laser/amplifier devices.

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