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Argon plasma inductively coupled plasma reactive ion etching study for smooth sidewall thin film lithium niobate waveguide application

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ABSTRACT

Lithium Niobate (LN) exhibits unique physical properties such as remarkable electro-optical coefficients and it is thus an excellent material for a wide range of fields like optic communications, lasers, nonlinear optical applications, electric field optical sensors etc. In order to further enhance the optical device performance and to be competitive with silicon photonics, sub-micrometric thickness lithium niobate films are crucial. A big step has been achieved with the development of LN thin films by using smart cut technology and wafer bonding and these films are nowadays available in the market. However, it is a challenge to obtain the requirements of the high quality thin LN film waveguide. In this letter, we show smooth ridge waveguides fabricated on 700 nm thickness thin film lithium niobate (TFLN). The fabrication has been done by developing and optimizing three steps of the technological process, the mask fabrication, the plasma etching, and a final cleaning wet etching step in order to remove the lithium niobate redeposition on the side walls. We have obtained single mode propagation with light overall losses of only 5 dB/cm.

1. Introduction

In the field of photonics, several disciplines like electro-optics, acousto-optics, optoelectronics, nonlinear optics, optical telecommunications and lasers are combined. One of the most suitable materials for the development of multifunctional photonic components is lithium niobate. Indeed, its intriguing electro-optical, acousto-optical and nonlinear responses among others, make of lithium niobate the perfect candidate for the fabrication of photonic chips integrating hundreds of different optical functions.

However, in the last few years, strong efforts have been made in order to develop silicon based photonic chips [1]. This growing interest in silicon photonics is mainly due to the fact that this field of research has profited considerably from the availability of large size silicon-on-insulator (SOI) wafers for micro and nanostructuring of photonic devices.

The equivalent technological progress in lithium niobate could represent a breakthrough in photonics [2] since, LN, unlike to SOI, offers excellent electro-optic, acousto-optic and nonlinear properties [3] and therefore, miniaturized LN photonic components like active integrated devices, ultrasensitive electric field sensors, electro-optical modulators, tunable filters and nonlinear wavelength converters could revolutionize photonics technology.

The key feature in order to make LN photonic platforms a reality is to be able to easily produce micrometric size optical waveguides with small optical losses. Two main ingredients are needed; thin film single crystal lithium niobate wafers and, secondly, a reliable dry etching process and mask fabrication capable of fabricating high index contrast waveguides. As far as the first requirement is concerned, single crystal sub-micrometer thickness lithium niobate films on SiO_2 are now commercially available [4]. They are obtained with crystal ion slicing technique and subsequently wafer bonding [5,6].

Buried optical waveguides such as Titanium in diffusion [8] and proton exchange (PE) waveguides [9,10] have been used in lithium niobate in order to create classical functions like electro-optic modulators [11]. These waveguides guarantee good optical confinement and extremely small optical losses of 0.01 dB/cm but the price to pay is that they sustain modes with sizes of several micrometers. The way to increase the light confinement is to use a ridge structure. The large index contrast due to the surrounding air leads to a stronger guiding of the mode in the lateral direction. In comparison to waveguides fabricated with Titanium-in-diffusion or proton exchange methods, the ridge geometry enables the use of smaller curvature radii, resulting in general in much smaller devices.

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The development of lithium niobate confined ridge waveguides has been studied for over 30 years in order to enhance the electro-optical interactions in comparison to standard waveguides, thereby reducing the control voltages while promoting the wide bandwidths. Nevertheless, the ridge waveguides developed in the 1980s and in the following decades showed significant roughness, resulting in important propagation losses compared to standard waveguides. The fabrication of ridge waveguides of micrometric dimension in lithium niobate is still nowadays a challenging task. Indeed, lithium niobate is a hard and relatively inert material, hence quite difficult to etch [7].

The realization of lithium niobate ridges can be approached by several types of solutions. Ion implantation assisted hydrofluoric acid (HF) wet etching method [12] and fluorine-containing gases (like CF_4, SF_6, and CHF_3) plasma etching on proton-exchanged LN [13,14] have been reported. The requirement of the ion implantation and PE treatment increases the complexity of the fabrication process and additionally LiF redeposition due to the use of fluorine-containing gases non-vertical and rough sidewalls. Fluorine gases are indeed generally used for $LiNbO_3$ plasma etching due to the good volatility of fluorinated niobium species at temperature around 200 °C. However, the major problem is the formation and re-deposition of lithium fluoride (LiF) that results in a decrease in the etching rate, in non-vertical sidewall profiles and in an increase of the sidewall roughness. In the last two–three years, extremely good optical quality waveguides in LN have been developed using new fabrication methods. Ion-beam enhanced etching, using argon and helium to break the crystalline structure at specific depths on LN followed by hydrofluoric acid wet etching has been utilized to create LN nanowires for second harmonic generation. Results show an enhancement of the second harmonic signal at the expense of quite high optical losses around 61 dB/cm [15,16].

An alternative way of producing ridge waveguides if one needs simple geometries of several micrometers width uses ultra-precision micromachining and brings the possibility of having extremely high aspect ratios and curved geometries [17–19].

In order to eliminate the LiF negative impact on the waveguide quality and to simplify the fabrication process, we propose an alternative method by using Argon gas Inductive coupled plasma (ICP) reactive ion etching (RIE) etching. Argon plasma etching is often used as the plasma cleaning treatment and it is performed by ion bombardment and by physical ablation process. As a difference with LN etching using fluride-based gases the chemical reaction between Li ion and the F does not take place and, as a consequence, the production of LiF is completely eliminated. Argon plasma etching with electron-cyclotron resonance reactive ion etching has been proposed in [20]. Microdisks resonators on thin film lithium niobate of 300 nm thickness have been fabricated with this alternative etching technology.

In this paper, a systematic fabrication study of ridge LN has been performed. We have put our efforts in three steps of the process: the mask fabrication, the plasma chemistry with a systematic study of the different etching parameters for reactive ion etching and inductively coupled plasma etching (ICP–RIE) and, finally, a chemical cleaning final step to remove the etched redeposited material on the side walls on the ridge structures. Mask fabrication and Argon plasma parameters have been studied in ICP–RIE configuration. Due to the high cost of the thin film wafer the parametric study has been performed on chips of 1.1×1.2 cm^2 area on X-cut 500 μm thickness lithium niobate. Once the fabrication parameters have been optimized on bulk, we have fine-tuned them in order to create ridge waveguides on LN thin films. A 3 inch X-cut 700 nm thickness LN layer film was provided by NanoLN [4]. The thin film is bonded onto a LN substrate via a sandwiched 2 μm SiO_2 layer.

As a proof of concept, optical characterization of the ridge waveguides in TFLN is performed showing single mode propagation and overall optical losses of only 5 dB/cm. Argon etching of photonic wires has been previously demonstrated [21] with propagation losses of 7.5 dB/cm, and 9.9 dB/cm for both light polarizations.

2. Fabrication process

2.1. Mask fabrication

As we have said before, LN etching is particularly hard. Masks with thicknesses superior to 1 μm are required in order to etch several microns of LN. This can be accomplished with metallic masks. Due to its good resistance to fluorine-based plasma etching, electroplated Ni has generally been chosen to make high-aspect ratio metallic masks. However, we can notice (Fig. 1) that the electroplated Ni mask presents significant roughness, probably due to the intrinsic columnar structure of the Ni. The electroplated layer is indeed here composed of cones of 100 nm in diameter which are revealed by the etching process. However, the mask side walls are rough and the roughness is directly transferred in the plasma etching to the LN producing waveguides of poor optical quality as shown in Fig. 1. Indeed, we can clearly see on the SEM image that the Ni mask defects are then transferred on the sidewalls of the ridge waveguides.

In this paper, UV lithography has been employed in order to fabricate the mask since, compared with other techniques, it guarantees neat edges and smooth sidewalls. The global process fabrication is schematically presented in Fig. 2.

A 2.8 μm-thick S1828 positive resist is firstly spin-coated and patterned by UV-lithography (70 mJ/cm^2) (Fig. 2(a)). After photoresist development, we performed a hard baking of the photoresist in order to increase the thermal, chemical, and physical stability of the mask to better resist the LN plasma etching and to improve the etching selectivity. Hard baking can improve the etching resistance and therefore the etching selectivity. Care must be taken on the temperature since hard baking produces mask deformation and one must be restricted to low baking temperatures. Our experimental results reveal that the optimal hard baking temperature and baking time for the S1828 photoresist is 80 °C for 60 min duration. The pattern is then transferred to the substrate using Argon (Ar)-based plasma chemical etching processes (Fig. 2(b)). The remaining photoresist mask layer is etched away using wet etching solution (Fig. 2(c)). Finally the $LiNbO_3$ etched redeposited material

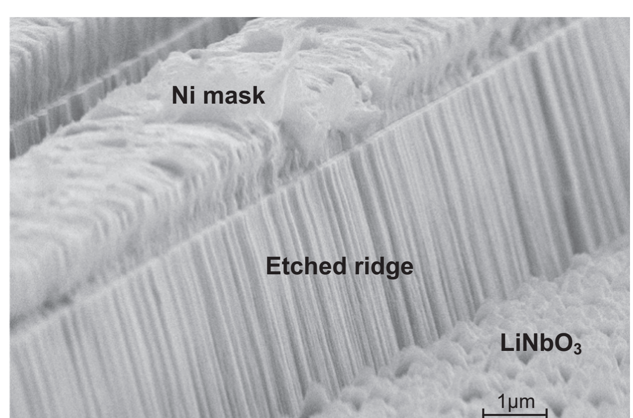

Fig. 1. SEM observation of the sidewall after fluorine-based plasma etching with electroplated Ni mask.