Ferroelectric Microdomains in Plasma-Etched Ridges on X-Cut Lithium Niobate

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Abstract. *The fabrication and investigation of (periodic) microdomains in the body of a ridge on X-cut Lithium Niobate (LN) is demonstrated. A 3-dim investigation with a non-linear Confocal Laser Scanning Microscope (CLSM) reveals a strong contrast of inverted and non-inverted sections of the ridge.*

Introduction

To enhance the efficiency of nonlinear interactions in optical waveguides, smaller cross section and higher index contrast are required leading to a stronger enhancement of the guided mode intensity. Therefore, "photonic nanowires" are currently developed [1]. If ferroelectric materials like Lithium Niobate (LN) are considered, a periodic domain inversion is required to enable quasi phase matching (QPM) for second order nonlinear processes. Ridge waveguides represent a first step towards photonic nanowires; they can be fabricated with excellent properties on Z-cut LN by chemical etching [2].
In this contribution we report the fabrication of ridges also on X-cut LN, using inductively coupled plasma (ICP) etching. Moreover, periodic domain inversion, localized in the body of the ridge only, is demonstrated - similar to the recent work of Généreux et al. [3]. The resulting domain structure is investigated in three dimensions using a nonlinear confocal Laser Scanning Microscope (LSM) [4]. It reveals a strong contrast between inverted and non-inverted sections of the ridge; however, the origin of this contrast has still to be explored.

Ridge fabrication and electrode definition

A Cr film of 220 nm thickness was deposited by sputtering on the –X face of a LN substrate of 1 mm thickness. Using optical contact lithography with an e-beam written mask and wet etching with a Cerium Sulfate solution, Cr stripes of 10 μm width were defined. The Cr stripes served as etch mask for the successive ICP (inductively coupled plasma) etching of LN with an etching ratio of 1:10. It was performed in an Oxford Plasmalab System 100 with an ICP 180 plasma source. The etching gas was a mixture

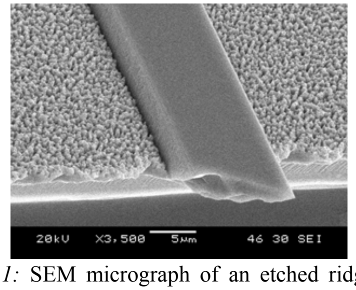

Fig. 1: SEM micrograph of an etched ridge of 2.4 μm height and 9.0 μm width on X-cut LN.

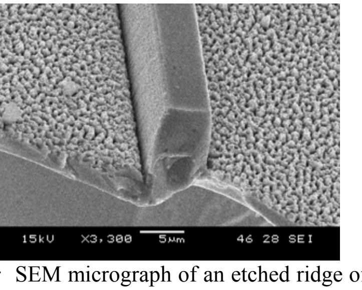

Fig. 2: SEM micrograph of an etched ridge of 5.8 μm height and 5.0 μm width on X-cut LN.

of 15 sccm C_4F_8 and 15 sccm He. After 4 minutes, the sample was taken out and cleaned in SC-1 solution (70% H_2O, 20% H_2O_2, 10% NH_4OH) for 1 minute to remove a brown layer, probably carbon polymers; then the etching was continued. This process was repeated 5 times until the etching depth was ~ 2 µm. Finally, the remaining Cr stripe was removed by a Cerium Sulfate solution and the sample was carefully cleaned. By using thicker Cr stripes, higher and smaller ridges could be fabricated with a height of up to 5.8 µm and a width of 4.0 µm. They can be doped by Ti to get optical guiding also in the depth [5]. Figs. 1 and 2 show SEM micrographs of etched ridges on X-cut LN of 2.4 µm (5.8 µm) height and 9.0 µm (5.0 µm) width, respectively.

A scheme of the poling configuration for a ridge on X-cut LN is depicted in Fig. 3. Comb like electrodes are placed on the Z-faces of the ridge enabling to generate periodic microdomains in the body of the ridge only. To fabricate such electrodes of 16.6 µm periodicity, we used lift-off lithography of a vacuum-deposited, 100 nm thick Ti layer. Fig. 4 presents a top view of the electrode structure on both sides of a 2.0 µm high ridge of 10 µm width. However, it turned out that the electrode fingers on both side walls were not as perfect as desired; only on one side the ridge wall was coated by the electrode fingers. On the other side, they terminated just in front of the ridge on the X-face of the substrate. Therefore, the electric field is higher at the bottom of the ridge; consequently, domain inversion should start here before growth to the top of the ridge, but also deeper into the substrate sets in.

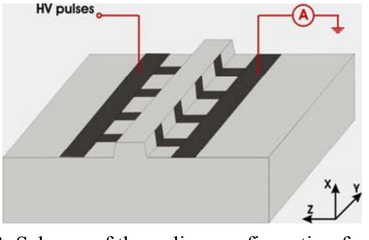

Fig. 3: Scheme of the poling configuration for a ridge on X-cut LN.

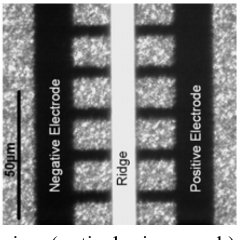

Fig. 4: Top view (optical micrograph) of the electrode structure of 16.6 µm periodicity on both sides of a 10 µm wide ridge.

Electric field assisted poling

In order to simulate the electric field distribution generated by the electrodes, the static electric potential distribution was calculated in the cross section of the ridge between the electrodes using a finite difference method. Afterwards, a numeric derivation was made on a non-uniform grid of 512x512 points in an area of 60x50 µm around the ridge, yielding as result the profile of the relevant component (E_z) of the electric field distribution. Fig. 5 presents as example lines of constant E_z in a ridge of 2.0 µm height and 10µm width, assuming 1 V applied to the left electrode. As the coercive field is ~ 20 kV/mm or 20 MV/m, respectively, the applied voltage should approach 200 V to start domain inversion. The highest field and, therefore, first nucleation are expected at the edges of the ridge assuming a symmetric field distribution as sketched in Fig. 5 (but see the comments given above).

The poling experiments have been done in an oil bath to maintain a high resistance between the two electrodes and to avoid any surface currents. Rectangular high voltage pulses have been applied for poling. The accumulated charge for each pulse was calculated and plotted as function of the pulse number. Fig. 6 shows as an example the

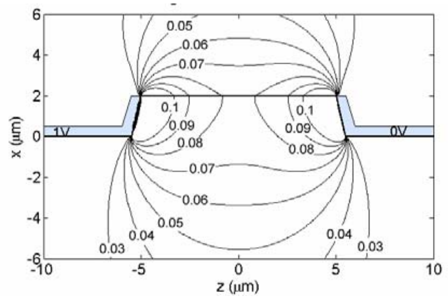

Fig. 5: Calculated lines of constant E_z (in MV/m) in a ridge of 2.0 µm height and 10 µm width, assuming 1 V applied to the left electrode.

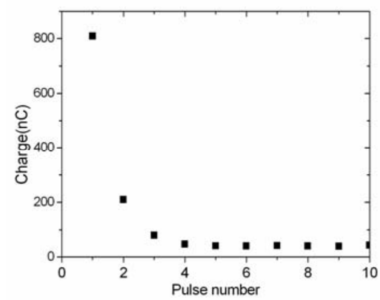

Fig. 6: The accumulated charge per rectangular poling pulse of 270 V as function of the pulse number.

charge evolution for a peak voltage of 270 V. The pulse duration was 10 ms and the interval time between consecutive pulses was 100 ms. We observe that the largest charge is accumulated during the first pulse; it decreases fast with increasing pulse number indicating that most of the domain inversion has been achieved by the first pulse alone. Such a behavior has already been observed previously [6].

Characterization by nonlinear confocal laser scanning microscopy

Preferential chemical etching, linear and nonlinear confocal laser scanning microscopy (CLSM) have been used to investigate the domain inverted structures. Etching with $HF:HNO_3$ (20 min.) attacks the -Z-face(s) of the ridge only; in case of a successful periodic domain inversion a corresponding pattern should become visible also from top. Therefore, we studied the processed ridge at the surface with a CLSM operated in the linear optical reflection mode; however, only a slight indication of a periodical modulation of the edges of the ridge is observable (Fig. 7, left). It might be that the domains did not grow up to the surface though expected from the calculated (ideal) electric field profile. However, operating the CLSM in the nonlinear (Second Harmonic Generation, SHG) mode with the polarization parallel to the Z-axis, a periodic pattern of strong contrast became visible at the surface of the ridge (Fig. 7, right). We were also able to observe the domain structure as function of the depth in the ridge down into the substrate; the pattern became weaker and broader in both dimensions with signatures under the electrode positions as well, before it completely disappeared in a depth of ~ 7 µm. The (nonlinear) CLSM was operated with a Ti-sapphire laser (λ_c = 800 nm, 20 fs pulses @ f_R= 80 MHz) with a depth resolution of ~1.0 µm. The generated SH-signal was detected in backward direction by a single photon counting module (avalanche photo diode) [4].

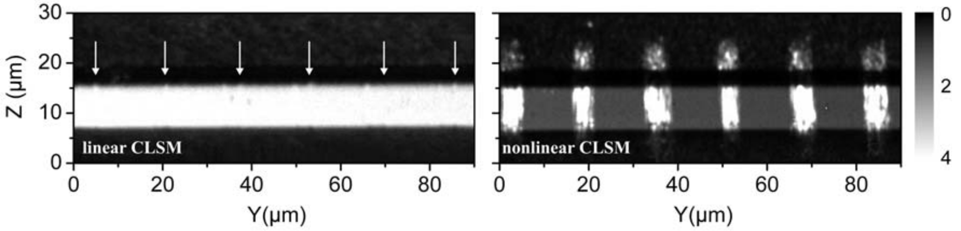

Fig. 7: Linear CLSM image of the X-face of a 10 µm wide ridge of 2.0 µm height; the faint periodic edge modulation is indicated (left). SH-signal generated by the nonlinear CLSM from the same surface (right). A grey scale of both, the fundamental- and SH-intensities, is given on the right.

Discussion

As already shown by Flörsheimer et al. [7], a relatively strong SH-signal can be expected from an X-face of LN, if the polarization is oriented parallel to the Z-axis. And domains of antiparallel orientation should yield the same SH-intensity, which drops to zero, if the focus of the LSM is shifted deeper into the substrate. The domain boundaries should become visible as fine dark lines at the surface and as bright lines in the bulk [7]. However, the behaviour we observe is quite different. Though the surface of the ridge gives a SH-signal in the non-inverted sections, which drops to zero in the depth, a much stronger signal is observed from the inverted sections (Fig. 7, right). The difference to [7] is that the investigated domain has a finite depth of several micrometers only. At the moment we can only speculate, why such a high nonlinear contrast arises. It might be due to the second nonlinear interface in the volume (or underneath) of the ridge. Or it might be due to a strong filamentation of the ferroelectric domains, which seem to be uniform, but might consist of many (not resolved) needle-like inverted filaments as already indicated in [7]. This could lead to an enhanced nonlinear contribution of the larger number of domain boundaries. By investigating cross sections of the ridges and by corresponding theoretical modelling we hope to be able answering this question.

Conclusions

ICP-etching allows fabricating ridges and ridge waveguides of good quality also in X-cut LN. By depositing electrodes on the side walls of the ridge, a fabrication of (periodic) microdomains in the body of the ridge becomes possible. In this way relatively low voltages of ~270 V are sufficient for ferroelectric domain inversion. A 3-dim investigation of the periodically poled ridge structure with a nonlinear CLSM reveals a strong contrast of inverted and non-inverted sections within the ridge. The origin of this contrast has still to be explored.

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