Fabrication of Lithium Niobate nanopillars using Focused Ion Beam (FIB)

Final report for "Nanofabrication with Focused Ion and Electron beams" course (SK3750)

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1- Introduction

Thanks to its high intrinsic nonlinearity and wide transparency spectra, Lithium Niobate ($LiNbO_3$, LN) has been widely studied and used in telecom and frequency conversion applications. Quadratic nonlinear optical processes such as Difference- and Sum-Frequency Generation and Second Harmonic Generation (SHG) are commonly employed frequency conversion processes to create light in frequency ranges where it is difficult to find available optical sources. These processes can also be used in telecom applications such as all-optical switching and quantum optics.

However, guidance and confinement of optical signals is essential in all aforementioned applications in order to realize integrated optical devices, which yield compact optical components and more efficient nonlinear processes. LN waveguides have been widely studied and commercially available, which benefit from some commonly used fabrication techniques such as proton exchange and Titanium diffusion, wet etching, Reactive-Ion Etching (RIE) and dicing LN substrates to realize ridge waveguides. Nevertheless, as an inert and relatively hard material, it is difficult to fabricate sub-micron low-loss LN devices with close-to-vertical sidewalls, which if fabricated, will result in higher confinement of light in LN waveguide and thus higher nonlinear efficiency and gain. Attempts have been performed to fabricate sub-micrometric LN devices such as rib waveguide realized in LN-on-Insulator (LNOI) substrate and plasmonic LN ring resonators. Recently fabricated LN nanocones (using Electron Beam Lithography and RIE) and nanowires can even be used in bio-sensing applications such as single molecule fluorescence microscopy and single cell endoscopy.

Here, fabrication of LN nanopillars (NPs) using FIB has been reported. The fabricated single- and arrayed-NPs can be used e.g. as local bio-sensing probes or as SHG sources with modified properties. Effects of different fabrication parameters such as aspect ratio, ion beam scan method and dwell time have been studied.

2- Experimental method

Since LN is a highly insulating material, it is essential to avoid local charging effects during pattern-writing (FIBing) process, which if not compensated, will yield drifting of the ion beam and thus a non-desired pattern on the sample. Hence, prior to FIBing, a ~ 40 nm-thick Cr layer has been deposited on top side of LN samples, subject to ion milling. This side was also grounded during the FIB process, for further assurance of minimizing charging effects. In all cases, a beam current of 30 pA was used to assure smooth and good quality sidewalls of the NPs.

A *FEI Nova 200 dual beam system* was employed to make NPs. In this system, an ion beam (for FIBing) and an electron beam (for SEM imaging) column are at an angle of 52° with respect to each other. The goal was to fabricate LN nanopillars with ~ 1 µm height, hence the NPs were embedded inside wider trenches. Thus, doughnut-shaped patterns were made using the software GUI (outer diameters of 2.8 µm and varying inner diameters) and exposed to realize single NPs. For fabrication of arrayed NPs, bitmap (.bmp) files with desired patterns were created according to instructions given in manuals, which were later imported by the software GUI.

3- Fabrication of single NPs

There are some technical details to be considered in order to create a FIBed structure, close to desired one, which is acceptable for further experimental purposes. Here, some of these considerations are studied and their effects on the quality of fabricated pattern are presented.

a) Pattern aspect ratio

It has been seen that if the pattern aspect ratio (defined as the structure height divided by openings in the pattern) is high, the fabricated structure will no longer be flat at the bottom surface, and will instead have a V-groove shape at the bottom. As a rule of thumb, a maximum aspect ratio of 2 can be remembered. Fig. 1 shows how a FIBed pattern with a high aspect ratio may look like.

b) Scan type of the beam

There are two types of beam scanning routines for beam patterning: “raster” and “serpentine” scanning. If raster scanning is chosen for a pattern, the beam proceeds along each scanning line in same direction, then blanks at the end of scanning line and retraced to the starting point of the next scanning line. In contrast, the serpentine scanning, the beam scans in opposite directions between each pair of adjacent scanning lines, which means that

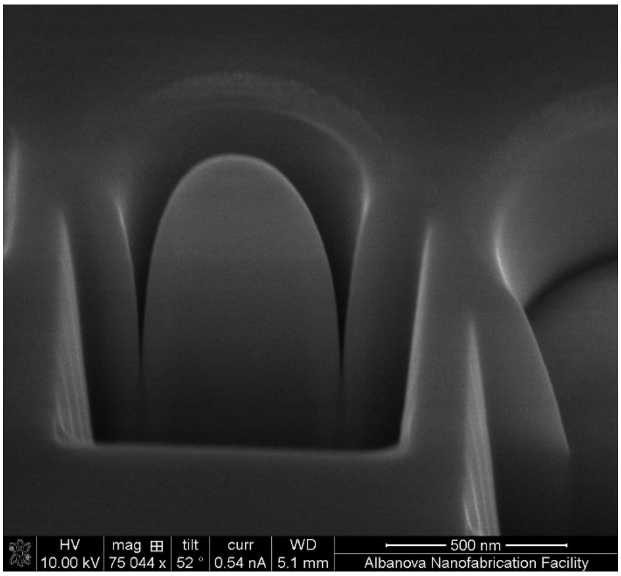

Fig. 1. Cross-section view of a V-groove shaped pattern resulted from a high aspect ratio.

retracing is not needed and beam does not need to be blanked. The proper choice of scanning method can affect quality of fabricated structure. However, depending on the structure used and material type, one scanning method may be more efficient compared to the other. In case of single LN nanopillars with circular geometries, the raster scanning method resulted in closer to vertical sidewalls of the NPs. Fig. 2 compares two NPs with diameters of 200 nm fabricated with the two aforementioned methods.

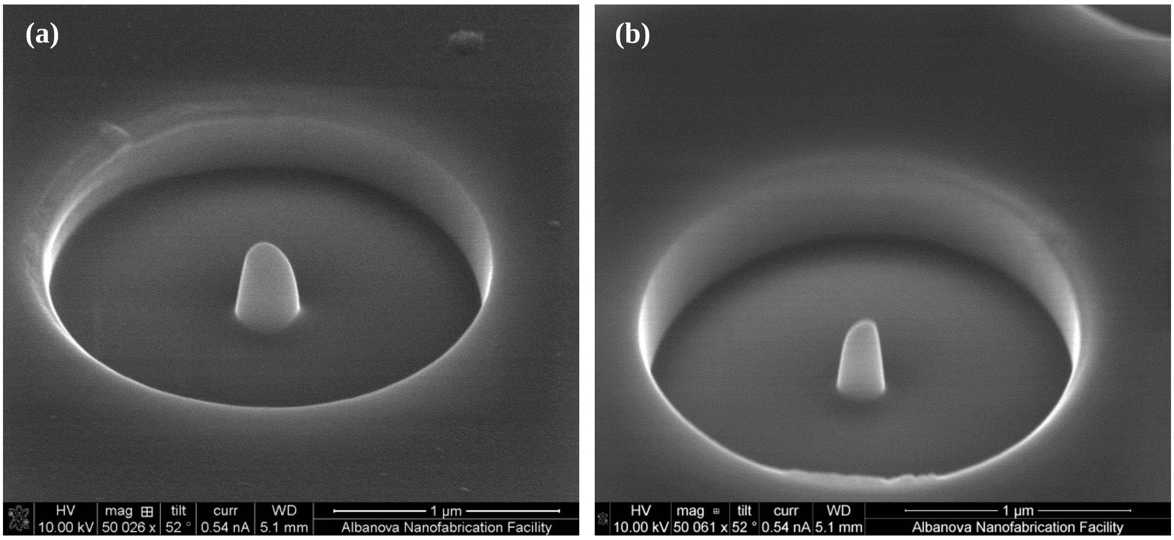

Fig. 2. 200 nm LN nanopillars FIBed using (a) serpentine and (b) raster scanning.

c) Dwell time

The dwell time can also affect the quality of the fabricated patterns. During fabrication process, it was observed that in case of small NPs, some of the fabricated NPs became shorter ones with sloped sidewalls, if a dwell time of 1 µS was used. This problem was encountered much less if a dwell time of 5 µS was chosen. Fig. 3 shows two examples of such NPs.

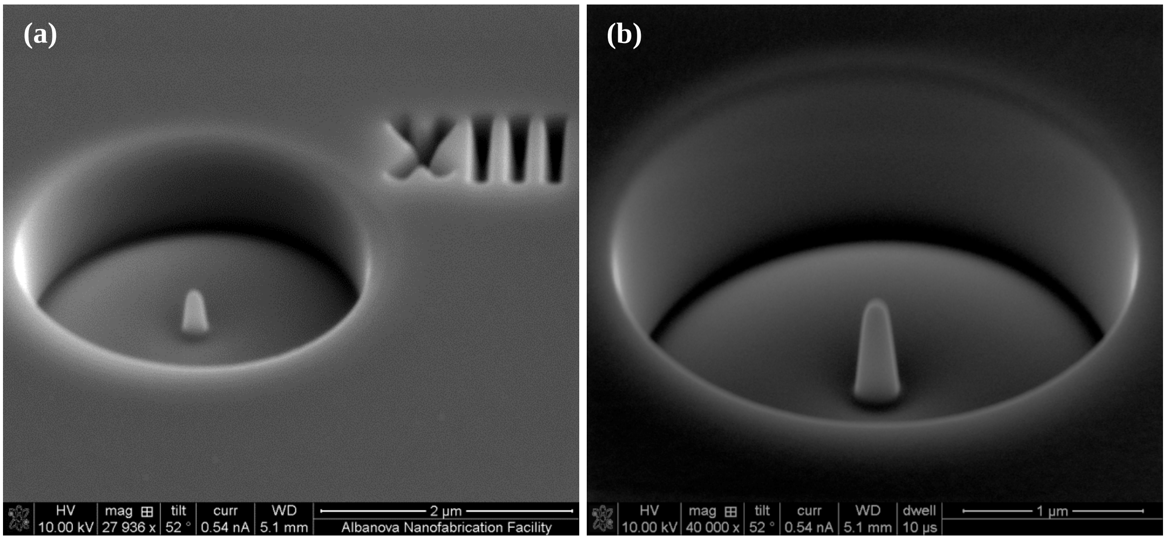

Fig. 3. Two NPs with diameters of 150 nm fabricated with: (a) dwell time of 1 µS, and (b) dwell time of 5µS.

4- Fabrication of arrayed nanopillars

Since there is no pre-defined arrayed pattern in GUI, a .bmp file with desired pattern needs to be created and imported by the GUI. A more detailed discussion of the file structure and preparation will be presented later.

a) Beam scan method

Similar to the case of single NPs, it was seen that raster scanning method suits better for our desired pattern and material. Fig. 4 compares two arrays of 200 nm NPs with center-to-center spacing of 400 nm, fabricated by raster vs. serpentine scanning styles.

b) Dwell time

According to the manuals, the file should be saved as a 24 bit RGB bitmap. The red (“R”) components of the pixels are not used, and hence can have any value between 0 and 255. However, the choice of green (“G”) and blue (“B”) components commands the operation of ion beam. G = 0 turns off the ion beam, while values other than 0 for “G” turn on the beam.

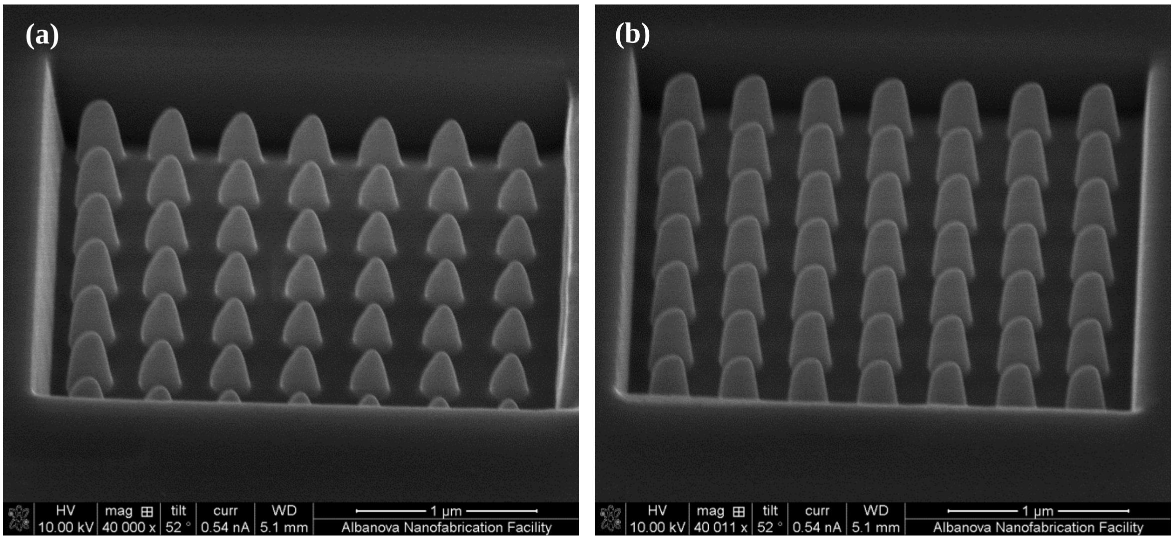

Fig. 4. 7×7 arrays of NPs fabricated with (a) serpentines, and (b) raster scanning method.

The “B” part determines swell time of the beam per pixel. If “B” = 0, the dwell time is set to 100 nS, and if “B” = 255 the maximum allowed value for dwell time is chosen. The dwell time for values between these extremes is linearly divided into steps of 100 nS.

According to the above instructions, different bitmap files corresponding to different NP sizes and spacing and with various choices of dwell times were created. However, similar to the case of single NPs, it was observed that higher dwell time results in better quality of the NP arrays. Fig. 5 illustrates some bitmap files created for patterning LN, while Fig. 6 presents some examples of fabricated arrays.

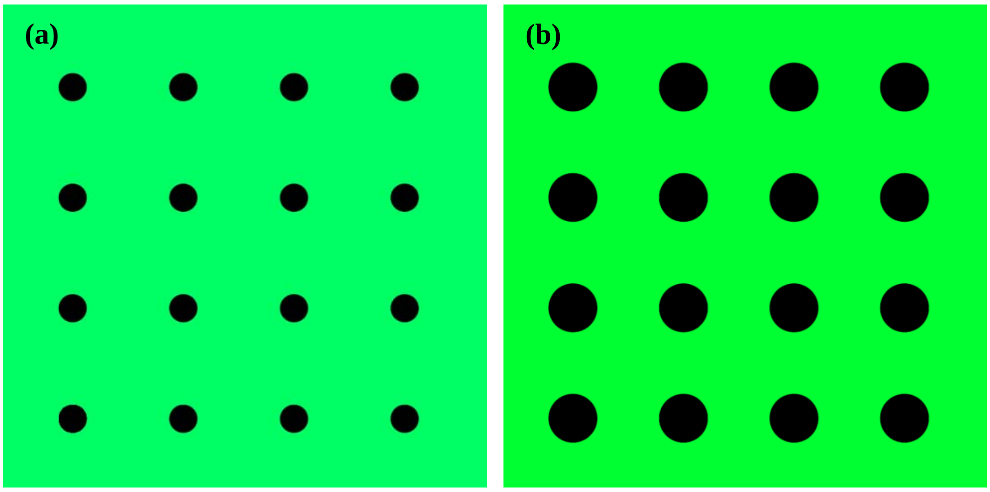

Fig. 5. Bitmap files for patterning 4×4 arrays of NPs to be embedded into 3.5×3.5 μm^2 trenches: (a) 200 nm diameter with 800 nm period and dwell time of 10 μS, and (b) 350 nm diameter with a period of 800 nm and dwell time of 5 μS. the changes in the color is due to the different choices of “G” part inside pattern, to change dwell time.

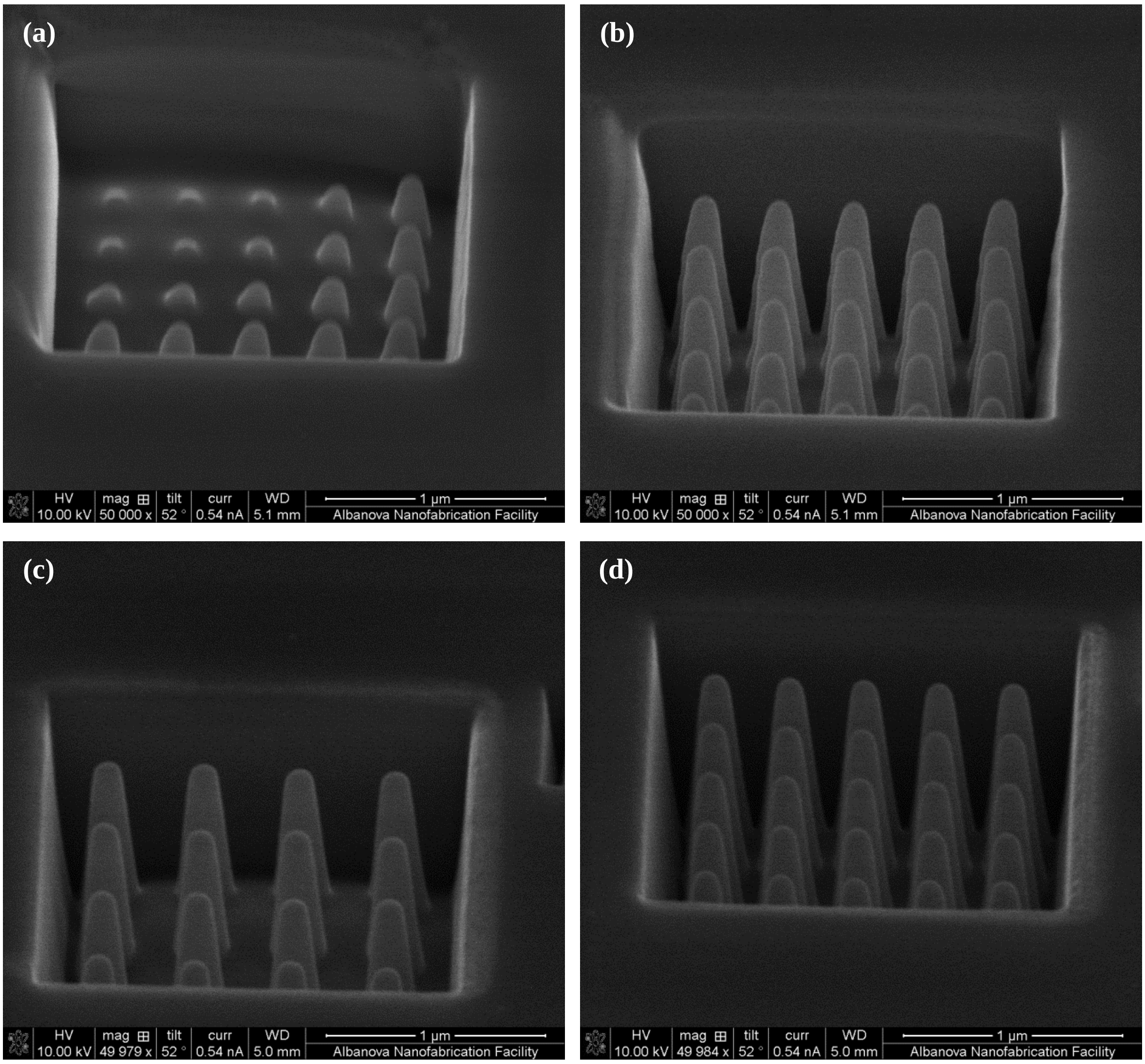

Fig. 6. Effect of dwell time on quality of fabricated arrays on 150 nm NPs: (a) dwell time of 1 µS, (b) dwell time of 2 µS, (c) dwell time of 5 µS, and (d) dwell time of 10 µS.

5- Conclusions

Single and arrayed Lithium Niobate nanopillars have been fabricated using FIB technique, and effects of different parameters on the quality of fabricated NPs have been studied. Experimental results show that raster scanning suits better the material and structure used in this study, and a dwell time of 5 or 10 µS yields more vertical sidewalls of the fabricated NPs.

Acknowledgements

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