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MICROFLUIDIC CHANNEL FABRICATION IN LITHIUM NIOBATE USING FOCUSED ION BEAM

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ABSTRACT

Microfluidic channels are fabricated in lithium niobate (LN) by Focused Ion Beam (FIB) milling. 127.68° axis rotated Y-cut (SAW grade) and Z-cut LN wafers are used. Material removal rate is $0.34 \pm 0.02 \mu\text{m}^3/\text{nC}$ for Y-cut sample and $0.30 \pm 0.02 \mu\text{m}^3/\text{nC}$ for Z-cut sample. Experimental results show that the material removal rate decreases at high ion doses and high aspect ratios due to the increased significance of material deposition at these conditions. We also demonstrate the suitability of FIB-milled nanochannels for micro/nanofluidic applications.

INTRODUCTION

Lithium niobate (LN) represents the most common piezoelectric material used in radio frequency telecommunications including mobile phones, television, and wireless transmitters. Machining lithium niobate, an interesting and commonly used piezoelectric material, is difficult, and although Focused Ion Beam (FIB) milling [1-3] has been used to machine LN in the past, all previous works have focused on the development of photonic devices [4-5]. In recent years, piezoelectrically generated acoustic energy using LN [6] has been found to be extremely useful for microfluidics.

In this paper, we investigate the use of FIB milling for fabricating a wide range of structures and show that FIB milling of nanochannels on lithium niobate can move microfluidics towards

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the next level of nanofluidics, where fluid transport in structures of feature sizes in the order of 100 nm could be easier than previously assumed.

EXPERIMENTAL

127.68° axis rotated *Y*-cut (SAW grade) and *Z*-cut LN wafers were obtained from Roditi International Corporation and diced into approximately 10 mm × 10 mm square samples. The LN samples were then coated with a thin layer (~ 25 nm) of Au by thermal evaporation to avoid charging effects and facilitate ion milling and scanning electron microscopy (SEM).

FIB milling experiments were conducted on the LN samples using a FEI Helios NanoLab 600 Dual-Beam FIB-SEM, which is an excellent machine for FIB milling. Ga⁺ ions were emitted with an accelerating voltage of 30kV at normal incidence to the sample surface. The ion beam overlap was fixed to the default value of 50% for all experiments, i.e. the beam was moved through the mill area in steps equal to half the beam diameter at a particular current, to minimize the effect of the Gaussian profile of the ion beam on the profile of the milled channels. All channels were first milled, in triplicate, sequentially using the FIB, cross-sections were then cut using the FIB with a lower ion beam current than the current used to mill the channel, and finally, the milled channels were imaged and the dimensions were measured using the SEM *in situ*.

RESULTS AND DISCUSSION

Channels with six different volumes varying from 50 μm³ to 250 μm³ were milled in triplicate using the FIB in both *Y*- and *Z*-cuts LN samples. Each milled channel was cross-sectioned using the FIB, and the dimensions of the milled channels were measured using the SEM. Figure 1 shows a SEM image of the cross-section of a typical FIB-milled 2 μm wide and 600 nm deep channel. Due to the Gaussian nature of the ion beam generated by the FIB system, some of the Au conducting layer surrounding the channel also appeared to have been sputtered away during the milling process, as is evidenced by the thin gray halo region around the milled area. The step structures that are visible in Figure 1 are standard features created during the process of cross-sectioning the channel by the FIB system. The volume of each of the milled channels was then calculated by using the measured dimensions and plotted against the total Ga⁺ charge incident on each channel for both the *Y*- and *Z*-cuts samples, as shown in Figure 2. As expected, the volume of LN that is sputtered away varied linearly with the number of Ga⁺ ions incident on the surface of the sample for both *Y*- and *Z*-cut samples.

The gradient of a linear fit through each set of data points gives us the value for the material removal rate for each cut of LN. Using this method, we obtained an experimental material removal rate of $0.34 \pm 0.02 \mu\text{m}^3/\text{nC}$ for *Y*-cut samples and $0.30 \pm 0.02 \mu\text{m}^3/\text{nC}$ for *Z*-cut samples. Thus, we observed that there is no significant dependence of the material removal rate using the FIB on the surface orientation of LN. For a given channel width, we observed

that the milled volume varied linearly with total incident dose at ion doses less than 100 nC and in good agreement with the material removal rate obtained from SRIM simulations. The material removal rate then tapered off at ion doses greater than 100 nC due to the effect of material redeposition at high ion doses.

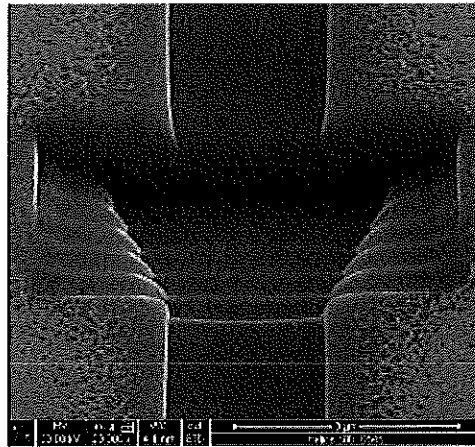


Fig. 1: SEM Image of the Cross-section of a Typical FIB-milled Channel in LN. Milled Channel was 2 μm Wide and 600 nm Deep

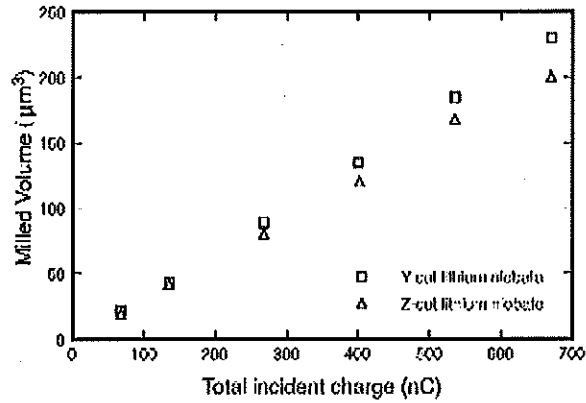


Fig. 2: Plot of Average Milled Volume of Microchannels as a Function of Total Incident Ga^+ Charge for Y- and Z-cut LN Substrates

Furthermore, we investigated the effect of material redeposition on the material removal rate of LN by milling a series of channels with varying aspect ratio, defined as the ratio of

depth to width of the milled structures, while keeping the total volume of milled material constant. Figure 3 shows the plot of material removal rate observed in the FIB as a function of the aspect ratio of milled channels.

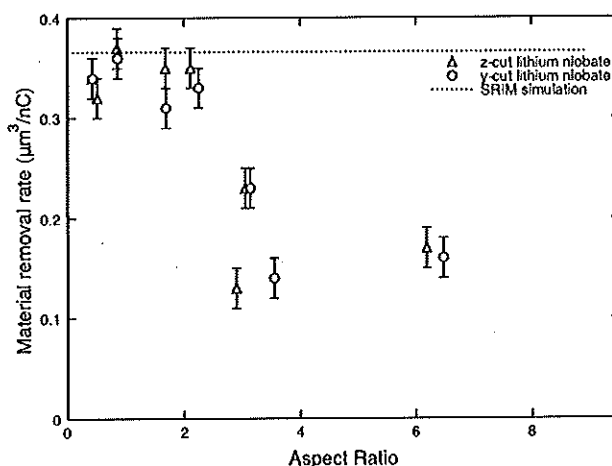


Fig. 3: Material Removal Rate as a Function of Aspect Ratio of Milled Channels for Y-cut and Z-cut LN

From Figure 3, we observe that the material removal rate in the FIB is in good agreement with the theoretical value obtained from our SRIM simulation for low aspect ratio structures. This is because material redeposition is not a significant factor in this regime. We also observe that the material removal rate decreases as a function of aspect ratio of the milled structures, decreasing to approximately 50% of the initial material removal rate at aspect ratios greater than 4. The reason for this decrease in material removal rate at high aspect ratios can be attributed to material redeposition. It becomes more and more difficult to remove material from a deep yet narrow (i.e. high aspect ratio) structure because the material has to be expelled a long way to escape the top surface of the substrate, and there is a high probability that the material will be redeposited along the sidewalls within the structure itself.

Lastly, we milled a nanochannel (W 100 nm, D 100 nm, L 100 μm) directly onto a LN sample and carried out preliminary experiments of imaging fluid inside such a FIB-milled nanochannel. Figure 4 shows a confocal microscope image of 22 nm fluorescent nanoparticles suspended in deionised water inside a FIB-milled nanochannel. The fluid appeared to fill slightly more than half the length of the nanochannel through capillary action, and illustrates the suitability of FIB-milled channels for micro/nanofluidic applications.

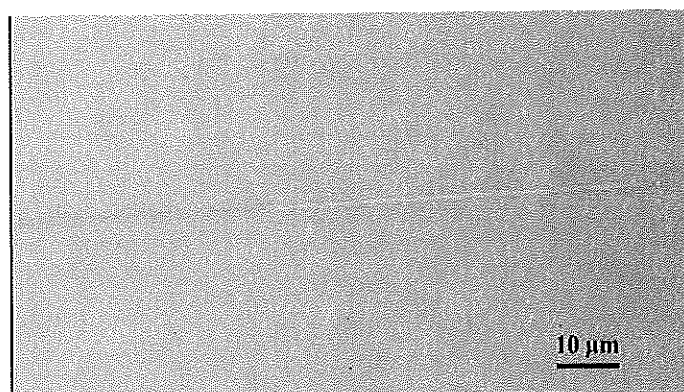


Fig. 4: Confocal Microscope Image of 22 nm Fluorescent Nanoparticles Suspended in Deionised Water Inside a FIB-milled Nanochannel.

CONCLUSIONS

Microfluidic channels in LN have been fabricated by FIB milling. Material removal rate is $0.34 \pm 0.02 \mu\text{m}^3/\text{nC}$ and $0.30 \pm 0.02 \mu\text{m}^3/\text{nC}$ for Y-cut and Z-cut LN, respectively. Experimental results have shown no significant dependence of the material removal rate on the surface orientation of LN. The suitability of FIB-milled nanochannels for micro/nanofluidic applications has been demonstrated experimentally.

ACKNOWLEDGMENTS

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