Characterization of Lead-Free $LiNbO_3$ Energy Harvesters

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Abstract

We present $LiNbO_3$ (LN) as a solid alternative for vibrational piezoelectric energy harvesting. The geometrical parameters and crystal orientations of the piezoelectric element are investigated in order to improve the piezoelectric response. LN single crystal layer is implemented in the micro-fabrication process in form of a cantilevered beam on silicon. The effective piezoelectric coefficient measured was $e_{23} = 2.9$ C/m². Finally, voltage response and expected power density are reported.

State of the art

Much effort has been done in order to implement lead-free piezoelectric materials in energy harvesting field. Non-ferroelectric AlN and ZnO, or ferroelectric $K_{1-x}Na_xNbO_3$ (KNN) and $BaTiO_3$ (BTO) are intensively investigated to replace $PbZr_{1-x}Ti_xO_3$ (PZT). $LiNbO_3$ (LN) represents a promising material, which exhibits high chemical stability and Curie temperature (1198°C) combined with high electromechanical coupling. Superior quality 6-inch single crystal wafers can be purchased for relative low price, allowing mass production of custom orientation cuts. Moreover, the possibility to obtain differently oriented LN thin epitaxial films on various substrates by MOCVD technique was reported [1]. The implementation of LN as energy harvesting transducer was originally investigated in thickness mode [2], while in this work a piezoelectric cantilever based on single crystal LN thick film is presented.

Description of the system

Low capacitance, therefore, high internal impedance of the piezoelectric layer can be induced by low permittivity of LN ($\varepsilon r = 30$ [3]), making the electronic interfacing challenging. To overcome this issue, the thickness of the piezoelectric layer was designed to be in the μm range. In order to improve the piezoelectric response, (YXl)/36° orientation was chosen. In this configuration polarization is along Y-axis and the strain along Z-axis, exploiting e_{23} piezoelectric coefficient in transverse mode. SiO_2/Si substrate was used in the fabrication process. SiO_2/Si wafer was Au-Au bonded to LN crystal using EVG bonding machine. The piezoelectric layer was subsequently polished down until the required thickness (Figure 1). Aluminum electrodes were fabricated by using UV lithography, E-beam evaporation and lift-off processes. Finally, samples were diced in order to obtain the cantilevers (Table 1).

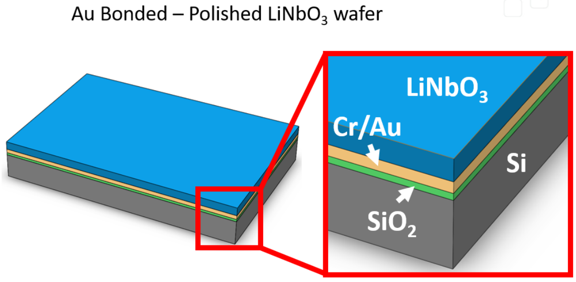


Figure 1: Schematic representation of the structure.

Table 1: Details of device geometry.

Length cantilever (mm)	*Length electrodes (mm)*	*Width electrodes (mm)*	*Thickness Si (µm)*	*Thickness LN (µm)*
20	*10*	*4.6*	*350*	*30*

Experimental Results

The effective piezoelectric

coefficient measuring setup consisted of a single-laser beam interferometer coupled with an aixACCT® TF2000 setup [4]. The clamped beam was excited by a large signal input, while the tip displacement was measured by the interferometer. At the frequency of 160 Hz, the piezoelectric effective coefficient was e_{23} = 2.9 C/m², proving that the chosen orientation improves several times the performance, compared to Z-cut [3]. The maximum tip displacement for different electric field magnitude can be observed in Figure 2, showing the expected linear behavior, with relative error of 6%.

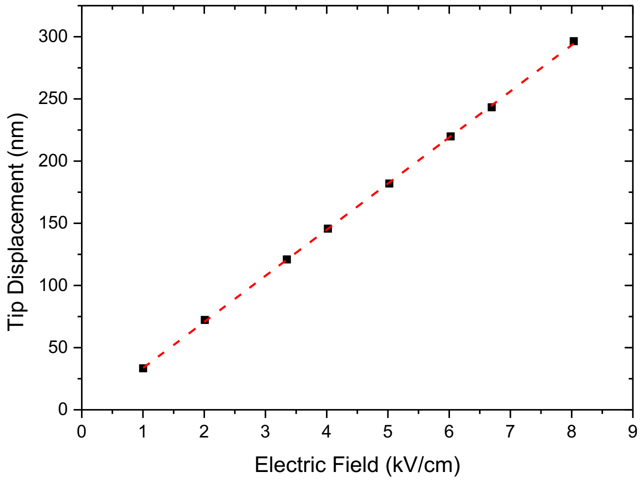
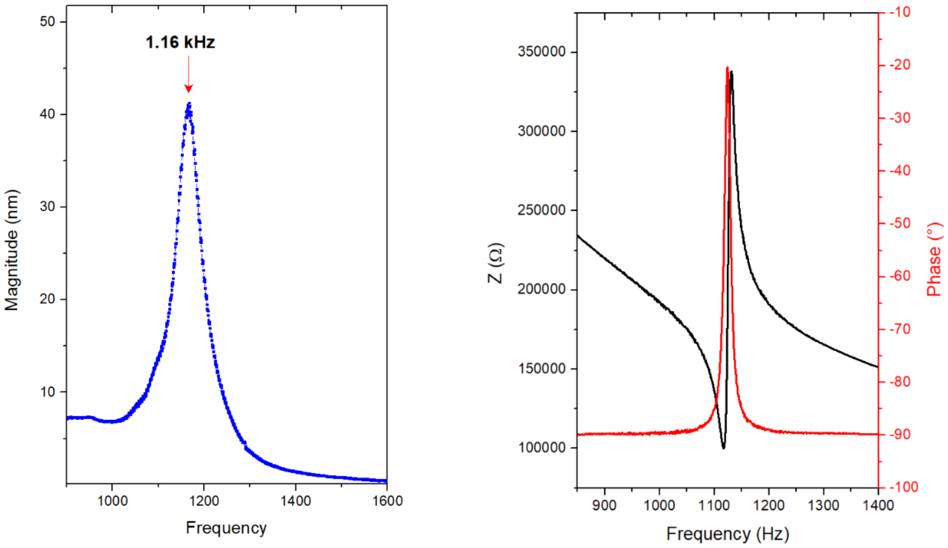


Figure 2: Tip displacement of cantilever in converse mode. The values of displacement show linear behavior as expected for a single crystal.

Optical vibrometer was used to study frequency response. The bending resonance frequency, observed at 1.16 kHz, was investigated by exciting the cantilever with chirp method (Figure 3 (a)). High frequency level observed can be attributed to the stiffness of the silicon cantilever. The parameters of equivalent circuit at resonance were investigated by impedance analyzer (Figure 3 (b)). The samples showed very small losses (<1%), confirming the good quality of the single crystal, and a capacitance of 0.8 nF. The quality factor Q = 21 and the structural coupling k² = 0.011 values were obtained from the equivalent circuit.



(a) *(b)*

Figure 3: (a) Bending resonance frequency obtained by vibrometer measurements; (b) impedance and phase response at resonance frequency.

Finally, we investigated the voltage response at resonance frequency (Figure 4). We measured 35.2 V peak-to-peak, at 3.4 g. Acceleration levels were chosen taking into account the stiffness of the substrate. From this value we simulated the power from constant acceleration, achieving a maximum of 54 µW/cm²/g².

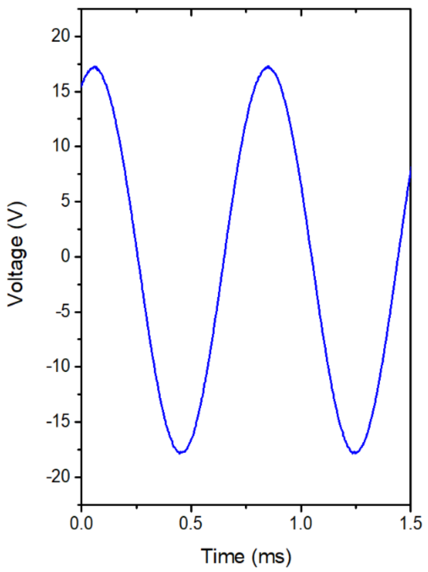


Figure 4: Voltage response at resonance.

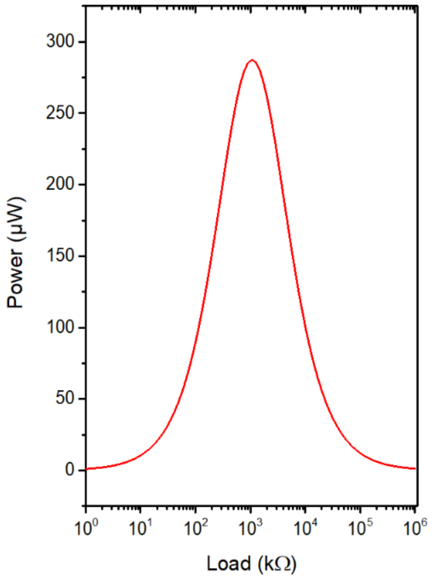


Figure 5: Simulated power after half-bridge rectification circuit.

This value is considerably high for a lead-free material [5]. The structural coupling and piezoelectric coefficient can be optimized by improving the design of the structure.

Summary

After the optimization of the material properties through the study of orientation of $LiNbO_3$ wafer cuts, it was possible to fabricate a prototype of piezoelectric cantilever. The device showed resonance bending frequency at 1.16 kHz, and 35.2 V peak-to-preak voltage response, with 0.8 nF capacitance. From these results we could estimate a power density of 54 $\mu W/cm^2/g^2$, that is comparable to both lead and lead-free current devices. Structural coupling and frequency response can be optimized integrating more flexible substrates and improved design.

Acknowledgements

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