Lead-free $LiNbO_3$ Films for Piezoelectric Energy Harvesting

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***Abstract*—With this paper we present $LiNbO_3$ as a solid alternative for vibrational piezoelectric energy harvesting. The geometrical parameters and crystal orientations of the piezoelectric element are investigated in order to maximize the figure of merit. A $LiNbO_3$ single crystal layer is implemented in the micro-fabrication process in form of a cantilevered beam on silicon substrate. Finally voltage response and expected power density are presented along with the structural properties.**

I. INTRODUCTION

Much effort has been done in order to implement lead-free piezoelectric materials in energy harvesting field. In particular non-ferroelectric AlN and ZnO, or ferroelectric $K1\text{-}xNaxNbO_3$ (KNN) and $BaTiO_3$ (BTO), among other materials, are intensively investigated to replace Lead Zirconate Titanate (PZT). Lead-free Lithium Niobate ($LiNbO_3$) represents a solid candidate due to its high chemical stability, high Curie temperature (1198°C) and high electromechanical coupling. Even if $LiNbO_3$ (LN) has been extensively studied in optics and surface acoustic wave field, little investigations have been done concerning its application for energy harvesting. High quality 6-inch single crystal wafers can be purchased for relative low price, allowing mass production of custom orientation cuts. Moreover, LN can be found in ions slide film on silicon, grown epitaxially by MOCVD with different orientations [1]. Because of low dielectric permittivity, for energy harvesting application we implemented successfully thick films in order to scavenge energy from vibrations. The purpose of this paper is to present the design, fabrication and testing of a piezoelectric cantilever beam device, based on single crystal LN thick film.

II. THEORETICAL ASPECTS

In order to harvest energy from vibrations, the piezoelectric effect can be exploited in transverse mode, hence in cantilevered beam configuration. $LiNbO_3$ has a trigonal structure R3c, its piezo and pyroelectric properties are strongly anisotropic and are represented in tensor form. The value of these tensors are well documented [2]. In order to optimize the piezoelectric response, we consider a (YXl)/36° LN rotated wafer cut, obtaining polarization along Y (or '2' in the following notation), and strain along Z ('3'), so that eventually we could use the piezoelectric coefficient d_{23}. The strain and electrical field are related then by the constitutive relations (Eq. 1):

$$\begin{cases} S_3 = s_{33}^E T_3 + d_{23} E_2 \\ D_2 = d_{23} T_3 + \epsilon_{22}^T E_2 \end{cases} \qquad (1)$$

where S is the strain tensor, s^E is compliance fourth order tensor at constant electric field, T is the stress tensor, d is the third order piezoelectric tensor, E is the electric field vector, D is the dielectric displacement vector and ϵ^T is the permittivity at constant stress. Here, charges are collected in transverse excitation mode with top-bottom electrodes. The coupling factor k_{23} is the efficiency of transduction from mechanical to electrical energy, and for transverse mode it is described by (Eq. 2):

$$k_{23} = \sqrt{\frac{d_{23}^2}{s_{33}^E \epsilon_{22}^T}} \qquad (2)$$

In transverse excitation mode, from the given rotation of the piezoelectric tensor by 36° around X-axis ('1'), we calculated $d_{23} = -18$ pC/N, and a coupling factor of $k_{23} = 0.3$, that are higher than the case of a regular Z-cut LN.

III. MICROFABRICATION PROCESS

The fabrication process consisted in using as initial substrate, a silicon wafer with SiO_2 insulation layer. The silicon and LN wafers were then sputtered with a thin layer of chromiuim and gold (250 nm) on one side, in order to bond them together via EVG wafer bonding machine. The piezoelectric layer was subsequently polished down until we reached the required thickness.

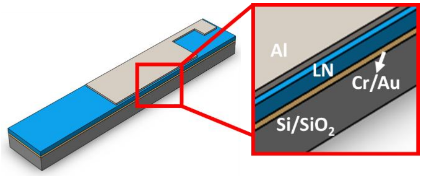

FIGURE 1. SCHEMATICS OF $LiNbO_3$ CANTILEVER BEAM.

Aluminum electrodes of 300 nm thickness, were then structured through UV lithography, evaporation deposition and lift-off. Finally, the samples were diced in cantilever shape.

In Figure 1 is presented a schematic view of the final prototype, while Table 1 summarizes the geometrical properties of the cantilever.

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

TABLE 2. GEOMETRICAL PROPERTIES OF CANTILEVER BEAM.

IV. EXPERIMENTAL RESULTS

The fabricated cantilever beam was characterized using an optical vibrometer to study displacement and mechanical response. The bending resonance frequency was found at 1.16 kHz, and it was investigated exciting the cantilever with chirp method, using 1 V input signal (Fig. 2A). Such high level of frequency is due in large part to the stiffness of the silicon cantilever, but with the aid of a tip mass it could feasible to decrease and tune the response to the resonance of the system.

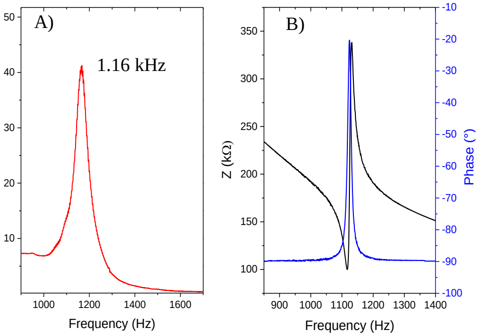

FIGURE 2. A) FREQUENCY RESPONSE OF CANTILEVER. B) MEASUREMENT OF IMPEDANCE AND PHASE.

Through an impedance analyzer we investigated the parameters of equivalent circuit at resonance, in order to deduce the properties of the piezoelectric element and the structural coupling of the device. In Figure 2B we can see the data measured for the clamped cantilever, in terms of impedance and phase. The losses were very small (<1%), confirming the good quality of the single crystal. Due to the low permittivity of LN, the piezoelectric layer could have high internal impedance, making the electronic interfacing challenging. To overcome this issue, the thickness of the layer was designed to be in the µm range. A sample with these features, showed 0.8 nF capacitance. From the values of the equivalent circuit was then possible to evaluate quality factor $Q = 21$, and structural coupling $k^2 = 0.011$. The structural coupling can be optimized with an improved design of the structure.

Clamping the prototype to a shaker, we investigated the voltage response at resonance frequency (Fig. 3). The value measured was 32 V peak-to-peak, with 3.4 g excitation level. We used such acceleration levels because of the stiffness of the substrate. From this value we could expect after rectification, a power of 308 µW.

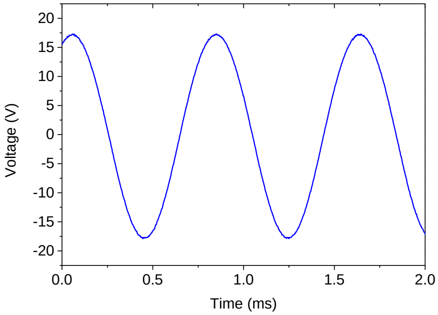

FIGURE 3. VOLTAGE RESPONSE AT RESONACE FREQUENCY.

V. CONCLUSION

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 32 V peak-to-preak voltage response, with 0.8 nF capacitance. From these results we could estimate a power density of 6.7 µW/mm^2, that is comparable to both lead and lead-free current devices [3]. Structural coupling and frequency response can be optimized integrating more flexible substrates and improved design.

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