High Performance Lithium Niobate Energy Harvester

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***Abstract*—In this paper we present a high performance (YXl)/128° $LiNbO_3$ on silicon device and its integration with standard electronic interface. The sample showed an effective coupling, k_{eff}^2, of 2.8 % and it had a rectified power output of 41.5 µW at open circuit resonance frequency (105.9 Hz) for an input acceleration of 0.1 g. The normalized power density (NPD = 965 µW/cm²/g²) is among the best for a Pb-free material and comparable to commonly used PZT ceramics.**

I. Introduction

Recently the implementation of piezoelectric materials for vibrational energy harvesting has become more prominent, as well as the need of finding an alternative to Pb-based ceramics for industrial upscaling. Piezoelectrics, such as $PbZr_{1-x}Ti_xO_3$ (PZT), are the most common and used in this field but do not respect REACH and RoHS regulation. Among Pb-free materials, AlN represents the most mature for CMOS technology, but it is limited by thin films integration constraints. Also, $K_xNa_{1-x}NbO_3$ (KNN) ceramics are still far to be considered an alternative to PZT, due to their challenging industrial upscaling. Among these materials, the well-known $LiNbO_3$ has not been consistently explored in energy harvesting, even though it is available in form low-priced and high-quality single crystals. The main reason is that its electro-mechanical properties are very dependent on the orientation of the crystal cut [1], therefore their careful choice can result in optimized performances. Some recent results [2] showed the potential of using $LiNbO_3$ in order to power small RF sensors and attained a similar normalized power density (71 µW/cm²/g²) to other MEMS.

II. Theoretical backgorund

In order to optimize the performances of the vibrational harvester, we have to consider the electro-mechanical coupling of the piezoelectric materials of choice. Typically, the electro-mechanical coupling is the ratio between the stored electrical energy and the input mechanical energy. For piezoelectric materials in transverse mode is commonly defined as:

$$k_{ij} = \sqrt{\frac{{d_{ij}}^2}{{s_{jj}}^E {\varepsilon_{ii}}^T}} \quad (1)$$

where d_{ij} represent the strain piezoelectric coefficient, s_{jj}^E the elastic compliance at constant field (E), and ε_{ii}^T the dielectric constant of the material at constant stress (T). In table 1 we present a comparison of the chosen crystal cut of $LiNbO_3$ (YXl)/128° and other piezoelectric materials.

TABLE 1. K_{31} for different Piezoelectric Materials.

Material	s_{11}^E *(pm²/N)*	$\varepsilon_{33}^T/\varepsilon_0$	d_{31} *(pC/N)*	k_{31}	*Ref.*
AlN	3.5	9.5	2	0.12	[3]
KNN	8.2	496	51	0.27	[4]
$LiNbO_3$ (YXl)/128°	6.9	50.5	27	0.49	[1]
PZT-5H	15.9	3935	320	0.44	[5]

Although AlN is showing very low dielectric constant, its piezoelectric coefficient is limiting the electromecahnical conversion. KNN has the highest piezoelectric coefficient among Pb-free materials, but also higher dielectric constant. Differently, PZT has the highest piezoelctric coefficient, but also extremely high dielectric constant. Eventually, $LiNbO_3$ (YXl)/128° has the highest transverse coupling (k_{31} = 0.49) compared to other common Pb-free and Pb-based materials, thus it represents a suitable choice for a cantilevered beam energy harvester. If now we consider the piezoelectric cantilever resonating near one of its resonance frequencies, we can model it as a single degree of freedom oscillator. Thus, the structure can be approximated as a spring-mass-damper system dynamically excited by an external force, and generating a voltage V from the deformation displacement x. Such system is described by the following set of dynamic equations:

$$\begin{cases} F = M\ddot{x} + C\dot{x} + K_E x + \alpha V \\ I = \alpha\dot{x} - C_0\dot{V} \end{cases} \quad (2)$$

where F is the external force, K_E the open-circuit stiffness of the system, M the dynamic mass, α is the electromechanical force factor, I the current, C the viscous damping and C_0 the clamped capacitance. With this formalism we are able to estimate the structural electromechanical coupling of the device, ${k_{eff}}^2 = \frac{\alpha^2}{C_0 K_E + \alpha^2}$, and quality factor $Q = \frac{\sqrt{KM}}{C}$.

III. Experimental Details

A commercial 500 µm thick (YXl)/128° $LiNbO_3$ wafer was used to fabricate the piezoelectric thick film on Si substrate. $LiNbO_3$ and Si wafers were bonded by means of mechanical thermo-compression of Cr/Au layers. The $LiNbO_3$ wafer was subsequently thinned by polishing and lapping steps to an overall thickness of 30 µm.

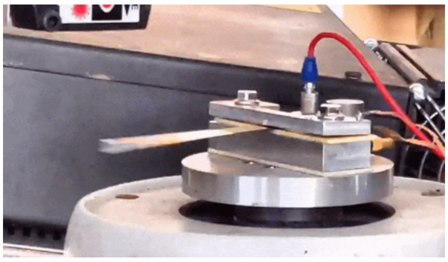

FIGURE 1. (YXl)/128° LiNbO3/Si energy harvester.

Cr/Au electrodes were structured on the $LiNbO_3$ surface by lift-off process using UV lithography and evaporation deposition technique. An additional step of Si etching was carried on the backside of the sample, leaving a tip mass of 500 µm. The cantilevers were diced mechanically by means of a dicing saw, resulting in an active surface of 430 mm². The samples were first tested with spectrum analyzer in order to investigate the capacitance and electromechanical coupling of the fabricated cantilevers. Afterwards, dynamic tests were carried on with an electrodynamic shaker operated by an amplifier and a National Instrument acquisition card. A picture of the sample is presented in Fig. 1 where the cantilever is excited around its resonance frequency. To investigate the harvesting capabilities of the specimen, a full bridge rectification circuit with four diodes was used in order to convert the sinusoidal voltage, *V,* in rectified voltage, V_{DC}, using a smoothing capacitor, C_r (12 µF) and a variable resistive load, R_l. Eventually we estimated the rectified power as $P = \frac{V_{DC}^2}{R_l}$.

IV. Discussion

The impedance and phase spectra were analyzed using a BVD equivalent circuit, in particular, the coupling k_{eff}^2, and the quality factor, *Q*, were estimated from measured resonance and

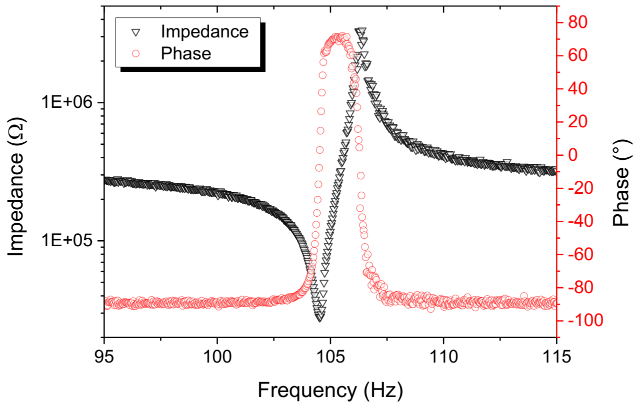

FIGURE 2. Impedance and phase spectra for (YXl)/128° LiNbO3/Si energy harvester.

anti-resonance frequencies (Fig. 2). The measured short- and open-circuit frequencies were 104.5 Hz and 105.9 Hz, respectively. From these values we obtained a coupling of k_{eff}^2 = 0.028 and a Q = 396, indicating that the sample was highly coupled. Furthermore, the dielectric losses were very small (tanδ = 0.0024), due to the high quality of the $LiNbO_3$ single crystal. The clamped capacitance measured at 2 kHz was C_0 = 5.8 nF, and it was chosen in order to achieve optimal impedance matching with the electronic interface. The harvesting tests were carried on with an input acceleration of 0.1 g while varying the resistive load, obtaining at open-circuit resonance a rectified power of 41.5 µW.

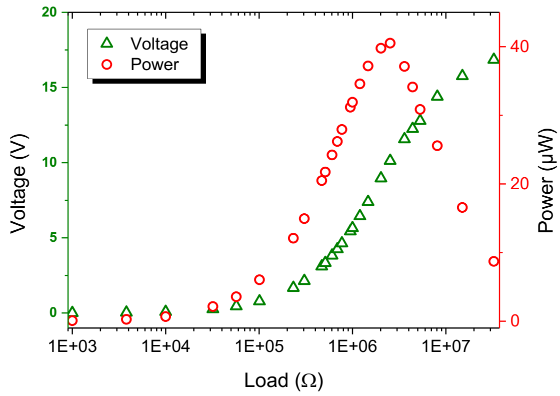

FIGURE 3. Voltage and power output for 105.9 Hz @ 0.1 g.

V. Conclusion

With a new improved design and $LiNbO_3$ (YXl)/128° single crystal cut, we attained low resonance frequencies (104.5 Hz - 105.9 Hz) and a rectified power of 41.5 µW. Finally, considering the low input acceleration level (0.1 g), we obtained a high normalized power density (NPD = 965 µW/cm²/g²), which is among the highest values reported in literature for a Pb-based and Pb-free energy harvesters. Reliability and robustness can be further improved by integrating metal substrates along with suitable packaging.

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