MINIATURIZED MULTI-BEAM (K,Na)NbO$_3$-BASED ENERGY HARVESTER

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Abstract: In this study, we developed an energy harvester with multi-beam configuration employing (K,Na)NbO$_3$ (KNN). The harvester was fully fabricated by micromachining technologies. Four KNN beams were integrated with a quatrefoil shaped proof mass to increase the energy density. By shaking the harvester with the frequency of 1412 Hz and the acceleration of 15 m/s^2, the maximum harvested power of 640 nW was obtained at the load resistance of 1 MΩ.

Keywords: Potassium sodium niobates thin film, lead-free piezoelectric, energy harvester, wide band

INTRODUCTION

Today, wireless sensor network which consists of autonomous sensor nodes is employed to many applications such as structural health monitoring or environmental observation. In these applications, since a large number of wireless nodes are distributed to the environment, an energy source with high power density is an important issue to achieve a maintenance-free system.

One of the promising solutions was a vibration type energy harvester employing Pb(Zr,Ti)O$_3$ (PZT). However, this harvester contains Pb, and is not suitable due to the environmental concerns.

Recently, a lead-free (K,Na)NbO$_3$ (KNN) material, which is environment-friendly, has gathered attention as a PZT substitution. This material can provide a high electromechanical coupling coefficient, compared with the conventional PZT [1]. The high quality KNN film could also be obtained by conventional deposition methods [2-5]. However, applications of the KNN-film to micromachined structures have not been reported well [6][7].

Micromachining is a key technology to enhance the power density and reduce the cost and size. In this study, the KNN-based energy harvester integrated with micromachined multi-beam structure was developed and verified.

STRUCTURE AND FABRICATION

We designed the multi-beam KNN-based energy harvester, which was constructed by the vibration-sensitive structure and electromechanical transducers. The structure was a Si proof mass suspended by four KNN beams as shown in Fig.1. In this device, electrical energy was harvested by utilizing d$_{31}$-mode of KNN piezoelectric material.

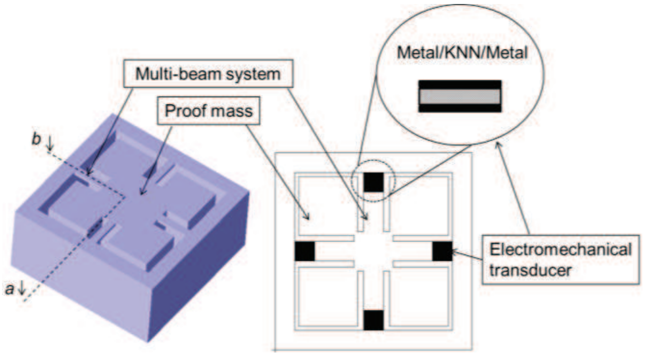

Figure 1: Illustration of multi-beam structure for KNN energy harvester

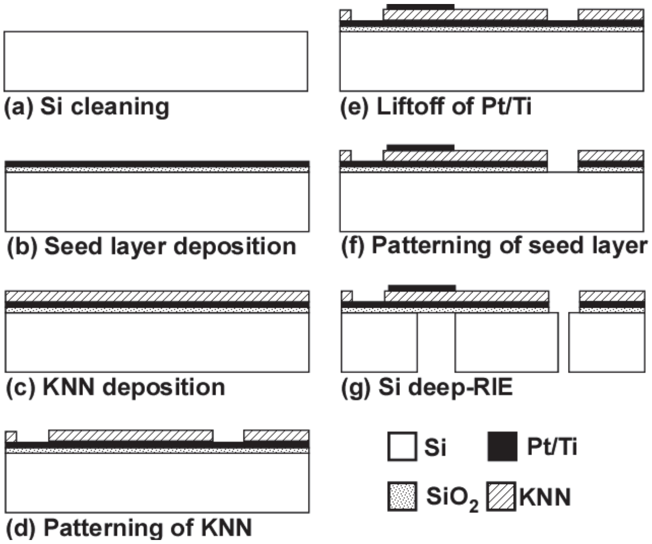

Figure 2: Fabrication flow of the multi-beam KNN energy harvester

In order to decrease the resonant frequency and increase the amplitude of vibration, proof mass and thickness of the beams were maximized and suppressed, respectively. The beams had a sandwich structure of KNN/metal and the top electrode in the electromechanical transducer area. Their length, width and thickness were designed to 1500 μm, 500 μm, and 2 μm, respectively. The weight and volume of a quatrefoil shaped proof mass were 6.6 mg and 1.4 mm^3, respectively.

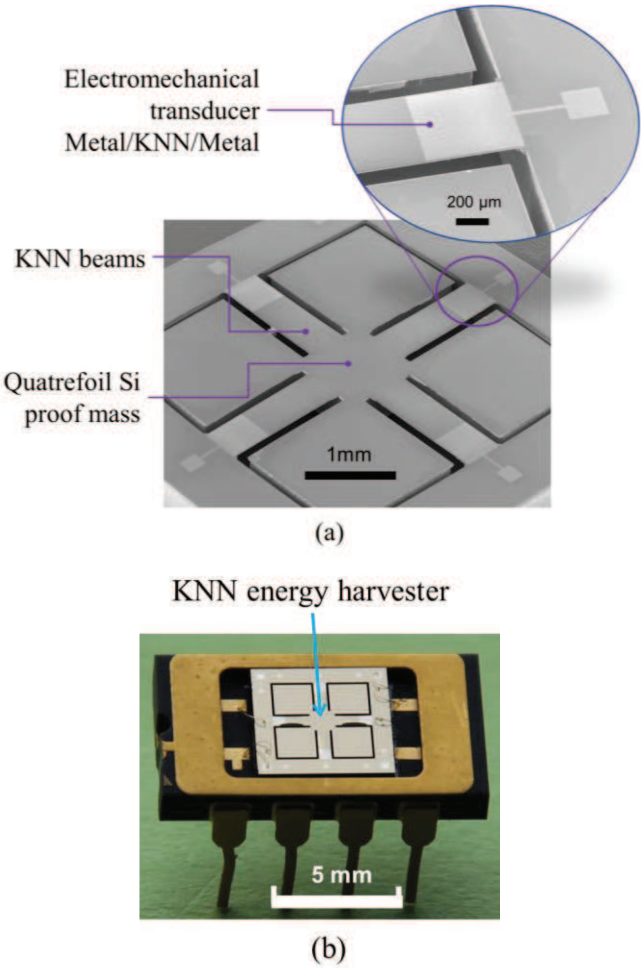

Figure 3: Fabricated multi-beam KNN energy harvester: (a) SEM images of the harvester, (b) wire-bonded harvester

The multi-beam KNN-based energy harvester was fabricated by bulk micromachined technologies. The fabrication flow was shown in Fig. 2. The silicon substrate was cleaned by RCA cleaning process (Fig. 2a). The seed layer for the KNN, which was Pt/Ti/SiO_2, was deposited (Fig. 2b). Thickness of Pt/Ti and SiO_2 were 200 nm, respectively. KNN film was deposited to 2 μm by RF magnetron sputtering (Fig. 2c). Its molar ratio Na/(K+Na) was optimized to 0.55. The KNN beams, the front shape of proof mass, and the contact hole for the bottom electrode were patterned by dry etching (Fig. 2d). In this step, fast atom beam etching (FAB) and reactive ion etching (RIE) were used alternatively to achieve the smooth surface and high selectivity against the Pt film. And then, top electrode of Pt/Ti was fabricated by lift-off process (Fig. 2e). The Pt/Ti/SiO_2 films were removed physically except the contact via by Ar ion milling (Fig. 2f). Lastly, Si substrate was etched from backside with deep RIE to form the quatrefoil shaped proof mass (Fig. 2g).

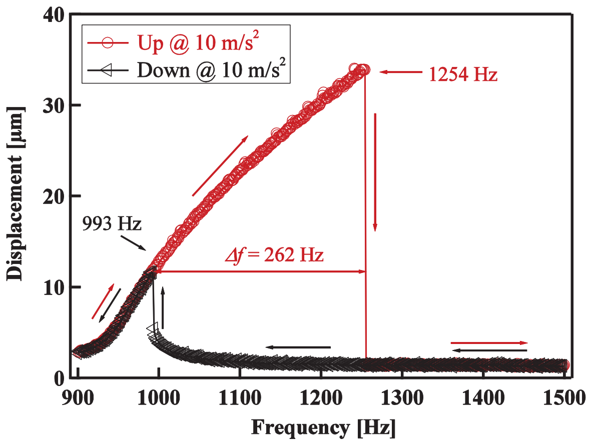

Figure 4: The relationship between the displacement and frequency at input acceleration of 10 m/s^2

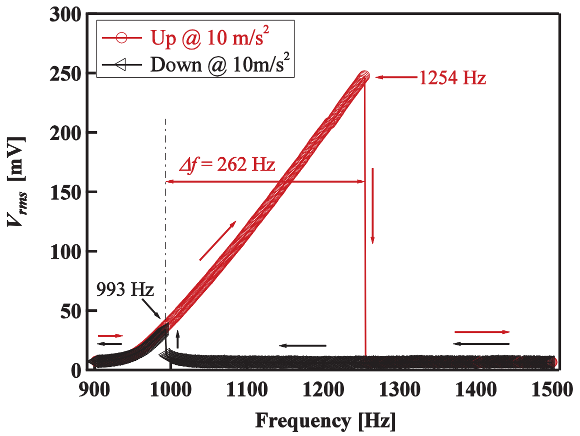

Figure 5: The relationship between the V_{rms} and frequency at input acceleration of 10 m/s^2

Figure 3a shows a scanning electron microscopic (SEM) image of the harvester. The fabricated havesterer was wire-bonded on the ceramic carrier to evaluate as shown in Fig. 3b.

EXPERIMENTAL RESULTS

We evaluated the amplitude of the displacement against the frequency. The fabricated device was shaken with acceleration of 10 m/s^2. Figure 4 shows the amplitude of the proof mass when the frequency ramps up and down.

From this result, the nonlinear hard spring effect could be observed clearly. As the frequency goes up, the displacement keeps increasing up to 1254 Hz (the jump-down frequency f_{down}). As the frequency goes down, the displacement lifts up at 993 Hz (the jump-up frequency f_{up}). Defining the Δf as the deviation between the f_{down} and the f_{up}, the Δf of our KNN energy harvester was 262 Hz.

Figure 5 and 6 shows output voltage V_{rms} and power from the single beam against the vibration frequency. In this measurement, acceleration of 10 m/s^2 and load resistance of 1 MΩ were used. The maximum V_{rms} and power at 1254 Hz were 250 mV and 63 nW, respectively. As increasing the input acceleration by 15 m/s^2, the power and Δf enhanced up to 160 nW and 412 Hz, respectively, as shown in Fig. 7.

Figure 8 shows the variation of the maximum harvested power and the Δf against the input acceleration. From this figure, it was confirmed that the Δf and the power had monotonically increasing relations against the acceleration.

There were four electromechanical transducers in the multi-beam KNN energy harvester. Therefore, the total harvested power can be enhanced to 640 nW with the acceleration of 15 m/s^2.

In this study, it was observed that large Δf due to the nonlinearity. External force induces two types of deformations of the beam, which are bending and stretching. According to Ref. 8 and 9, for outputting the power, stretching has higher nonlinearity than bending. Our energy harvester had metal/KNN/metal sandwich structure and was symmetry for the thickness direction. Due to this symmetry structure, electrical output by the bending becomes negligibly small, and stretching deformation determines the characteristics of energy harvesting. Therefore it was interpreted that large Δf of the harvester was induced by the stretching of the beam.

CONCLUSION

In this study, we developed an energy harvester with multi-beam configuration employing (K,Na)NbO$_3$ (KNN). The harvester was fully fabricated by micromachning technologies. Four KNN beams were integrated with a quatrefoil shaped proof mass to increase the energy density. By shaking the harvester with the frequency of 1412 Hz and the acceleration of 15 m/s^2, the maximum harvested power of 640 nW were obtained when the load resistance of 1 MΩ (open circuit). The harvester indicated the intense nonlinearity due to the symmetrical structure of the beam for thickness direction. Band width expanded by the nonlinearity was proportional to the acceleration, and reached to 412 Hz when the acceleration was 15 m/s^2.

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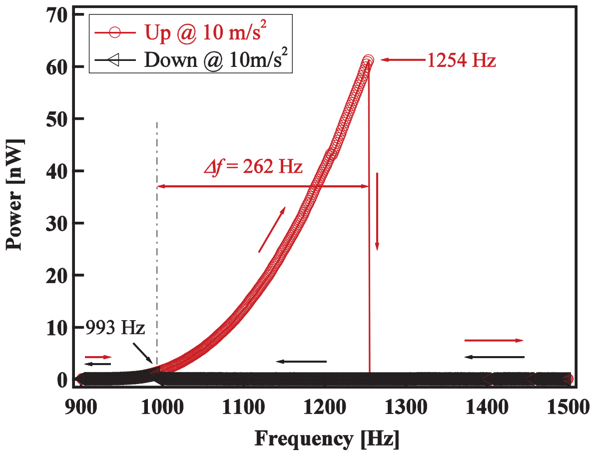

Figure 6: Relationship between the output power and frequency at input acceleration of 10 m/s^2

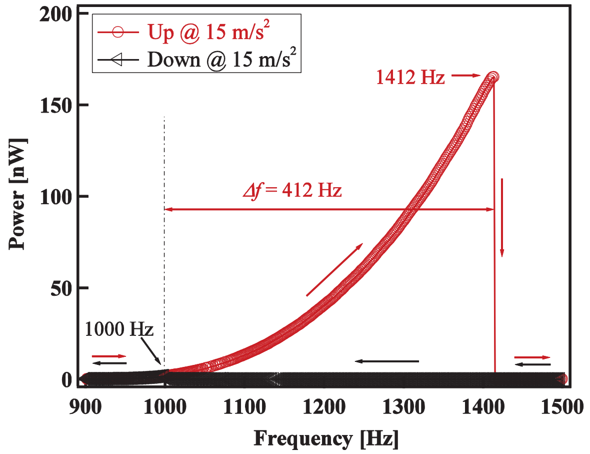

Figure 7: Relationship between the output power and frequency at input acceleration of 15 m/s^2

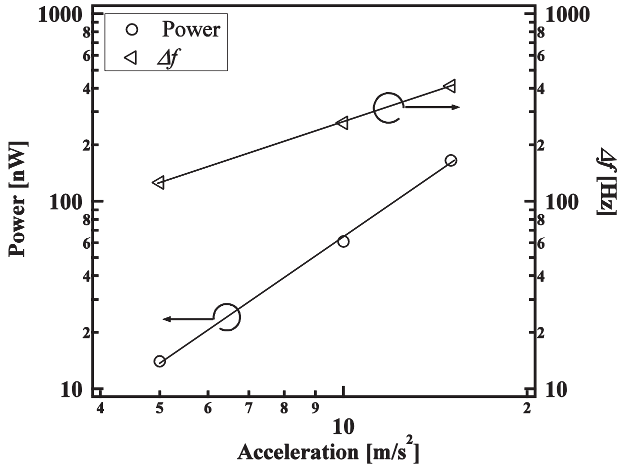

Figure 8: The maximum harvested power and the Δf *against the acceleration*

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