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Micro-fabricated flexible PZT cantilever using d_{33} mode for energy harvesting

Hyunok Cho, Jongcheol Park and Jae Yeong Park*

Abstract

This paper presents a micro-fabricated flexible and curled PZT [$Pb(Zr_{0.52}Ti_{0.48})O_3$] cantilever using d_{33} piezoelectric mode for vibration based energy harvesting applications. The proposed cantilever based energy harvester consists of polyimide, PZT thin film, and inter-digitated IrO_x electrodes. The flexible cantilever was formed using bulk-micromachining on a silicon wafer to integrate it with ICs. The d_{33} piezoelectric mode was applied to achieve a large output voltage by using inter-digitated electrodes, and the PZT thin film on polyimide layer has a remnant polarization and coercive filed of approximately $2\boldsymbol{P_r} = 47.9\ \mu C/cm^2$ and $2\boldsymbol{E_c} = 78.8$ kV/cm, respectively. The relative dielectric constant was 900. The fabricated micro-electromechanical systems energy harvester generated output voltages of 1.2 V and output power of 117 nW at its optimal resistive load of 6.6 MΩ from its resonant frequency of 97.8 Hz with an acceleration of 5 m/s^2.

Keywords: Flexible, PZT, Cantilever, MEMS, Energy harvesting

Background

Vibration-based energy harvesters have been considered as a promising power solution for wireless sensor nodes due to their sustainability and reliability in harsh environments and because vibration energy has a higher power density than other forms of wasted energy. Especially, piezoelectric energy harvesters have been actively studied due to their easy integration with micro-electromechanical systems (MEMS) and integrated circuit (IC) technologies [1–3]. In a typical piezoelectric energy harvester, a piezoelectric material is attached to a rigid structure, such as a silicon cantilever, and a proof mass located at the free end of the cantilever is coupled with an induced vibration. The transducer combined with a mechanical resonator converts the kinetic energy of the proof mass to electrical energy via the piezoelectric material [3–7]. However, the typical rigid-body based cantilever type energy harvester has a large resonance frequency due to its high spring constant. Thus, it is not for harvesting energy from human activity or low frequency ambient vibration. Polyvinylidene fluoride (PVDF) is probably the most popular material for flexible energy harvesting applications. However, PVDF has lower dielectric and piezoelectric properties than ceramics such as PZT. For flexible piezoelectric films based on ceramics, several approaches have been reported. Nunes-Pereira et al. reported a piezoelectric fiber composite based flexible energy harvester for wearable applications. Piezoelectric fiber composite (PFC) based devices presented a larger output than PVDF based ones [8]. Lin et al. presented a ZnO nano wire array based flexible nano generator by employing polydimethylsiloxane (PDMS) [9]. Do et al. and Park et al. also demonstrated a ceramic based flexible piezoelectric film. The laser annealing lift-off technique was utilized to transform the piezoelectric ceramic layer into a flexible substrate [10, 11]. Although the feasibility of using flexible piezoelectric films for energy harvesting applications has been well established, the fabrication process has limitations in terms of its integration with integrated circuits (ICs), such as the rectifying or boost-up converter in the interface circuit of the energy harvester. In this paper, a flexible piezoelectric energy harvester has been proposed and developed using low temperature process and silicon bulk micromachining technique for the formation of proof mass to compatible with integrated circuit fabrication process without

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any complex fabrication process such as laser annealing lift-off process. The proposed harvester also utilized a polyimide based flexible cantilever with low spring constant for harvesting energy from human activity or low frequency ambient vibrations.

Design and fabrication

The proposed vibration energy harvester consists of a flexible and curled piezoelectric cantilever and proof mass, as shown in Fig. 1. The flexible cantilever has the advantage of low spring constant which allows it to be excited by low frequency vibrations. Figure 2 presents the simulated spring constants of the proposed cantilevers for energy harvesting by using CoventorWare. The spring constants of rectangular shaped silicon cantilever, rectangular shaped polyimide cantilever, and trapezoid shaped polyimide cantilever are 35, 4.85 and 3.64 N/m, respectively. The oscillation of the proof mass at the end of the cantilever results in changes of the curvature of the piezoelectric layer, thus inducing a strain on it. Thus, the proposed energy harvester generates electricity from ambient vibration [12]. In order to improve the output voltage of the energy harvester, the piezoelectric d_{33}-mode was utilized by using inter-digitated electrodes, as shown in Fig. 1. This configuration is more sensitive to the excited vibration than the d_{31}-mode and also has an advantage in terms of the forward bias of the rectifying diode circuit [6].

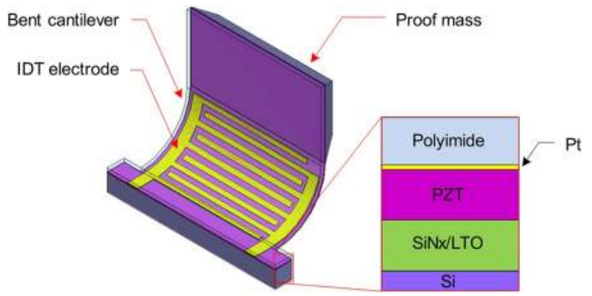

Fig. 1 Schematic drawing of the proposed piezoelectric d_{33}-mode MEMS power generator using a flexible and curled PZT cantilever

Figure 3 shows the fabrication process of the proposed flexible cantilever device. Firstly, LPCVD SiNx and LTO were deposited on Si wafers with thicknesses of 0.8 and 0.2 μm, respectively. $PbTiO_3$ and $Pb(Zr_{0.52}Ti_{0.48})O_3$ thin films with thicknesses of 0.2 and 1 μm, respectively, were sol–gel spin coated and annealed at 650 °C under oxygen ambient consecutively. A 0.1 μm layer of sputtered IrO_x was deposited on the PZT thin film as the electrodes. The annealing process at 650 °C under oxygen ambient was performed to crystallize the films as a perovskite structure. The IrO_x layers were patterned by the inductively coupled plasma (ICP) dry etching technique and the PZT thin film was wet-etched using $HF:HNO_3:HCl:H_2O$ at a ratio of 1:3:5:32 as the etchant at room temperature. In order to define the cantilever geometry, a 18 μm film of photo-definable polyimide (HD4100, HD MicroSystems) was spin-coated and structured by photolithography as an elastic layer. The cantilever device was released by wet-etching and dry-etching of the bulk silicon. The back side of SiNx defined by RIE etching was utilized as a mask-layer for KOH wet-etching to form the Si proof mass. Most of the bulk silicon was carefully etched using KOH wet-etching and the remaining silicon with a thickness of 20 μm was etched using XeF_2 etching. Finally, the cantilever device was released by RIE etching of the front side of the SiNx/LTO layer. As shown in Fig. 4a, trapezoid and rectangular geometries were designed and fabricated for the flexible cantilever based energy harvesters. The trapezoid and rectangular shaped piezoelectric energy harvesters utilized the flexible and curled cantilevers with the length of 2000 μm and the width of 3000 μm, respectively. In the case of trapezoid geometry, the width of cantilever becomes narrow toward the proof mass. The proof mass has the length of 2000 μm, width of 3000 μm

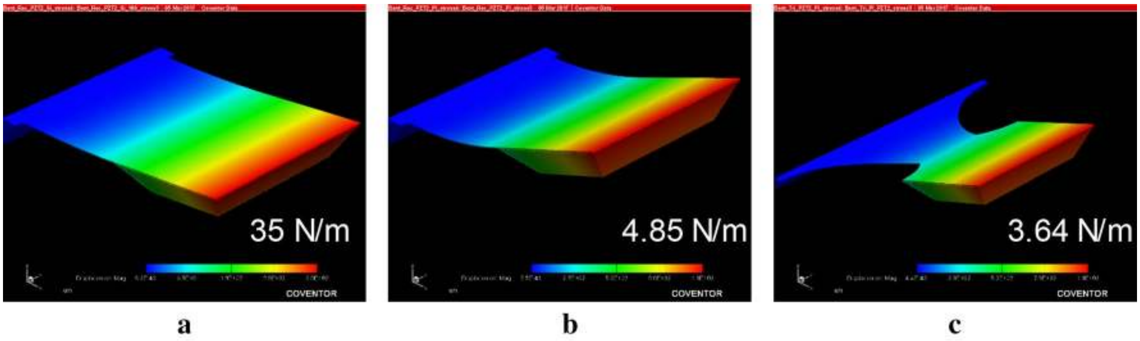

Fig. 2 Simulated spring constants of the designed cantilevers: **a** rectangular shaped silicon cantilever, **b** rectangular shaped polyimide cantilever, and **c** trapezoid shaped polyimide cantilever

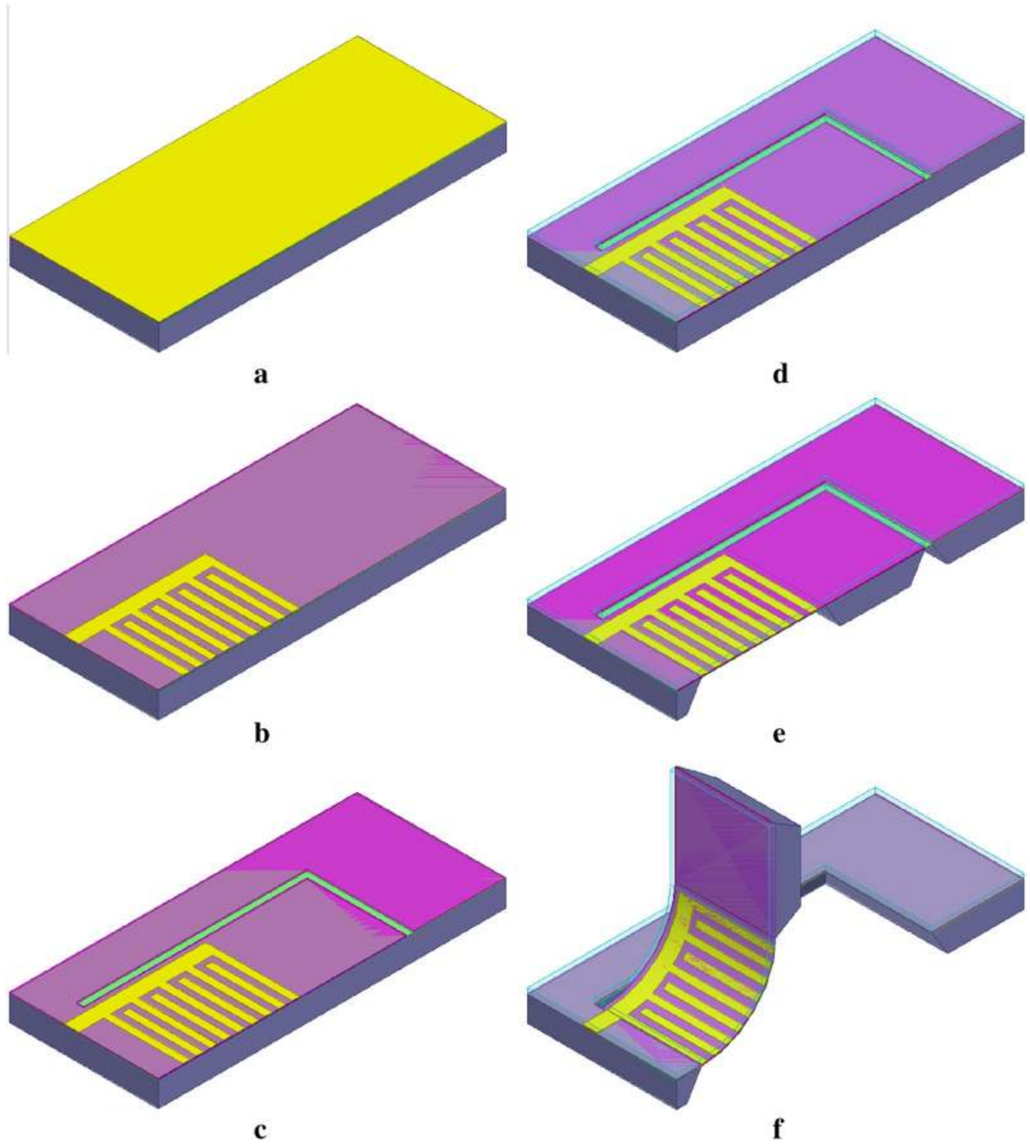

Fig. 3 Fabrication of flexible PZT based energy harvester: **a** deposition of SiNx/LTO, PZT/PbTiO3 and Pt on Si wafer, **b** Pt etching for IDT electrodes, **c** PZT wet etching, **d** depositing and defining the cantilever by using photo-definable polyimide, **e** KOH wet etching to form the proof mass, **f** SiNx/LTO etching by RIE for release

and thickness of 525 μm. The fabricated cantilevers undergo bending deformation, due to the internal elastic stress, and have radii of curvature of 1.2 and 1.4 mm for the trapezoid and rectangular geometries, respectively. Figure 4b just shows how much the fabricated PZT cantilever is flexible visually and Fig. 4c shows the IDT electrodes using IrO_x. Figure 5 shows the polarization properties of the PZT thin film on the rectangular shaped flexible polyimide cantilever characterized by polarization voltage measurements using a Radiant Precision LC system. A well-defined PE hysteresis curve was obtained and the measured results were $2\boldsymbol{P_r} = 47.9\ \mu\text{C/cm}^2$ and $2\boldsymbol{E_c} = 78.8$ kV/cm. The capacitance measured using an HP4194A is 0.23 nF and the extracted relative dielectric constant is 1243.4. In order to measure the dielectric properties, the effective area for the IDT electrodes was calculated as the product of the length of the comb fingers and the thickness of the PZT thin film [13, 14].

Experimental results and discussion

Figure 6 shows the frequency responses of the fabricated energy harvesters using the polyimide based PZT cantilever. They have resonant frequencies of 97.8 and 121 Hz and corresponding Q-factors of 51.4 and 57.6

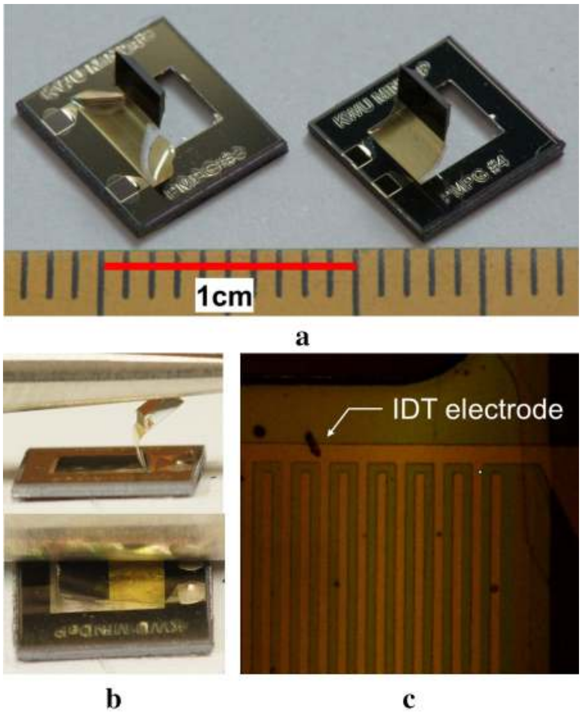

Fig. 4 Photograph of the micro-fabricated flexible PZT cantilever based energy harvester: **a** trapezoid (*left*) and rectangular (*right*) shaped cantilevers, **b** visual inspection of flexibility in the fabricated polyamide/PZT cantilever, and **c** inter-digitated electrodes for piezoelectric d_{33}-mode operation on the rectangular shaped cantilever

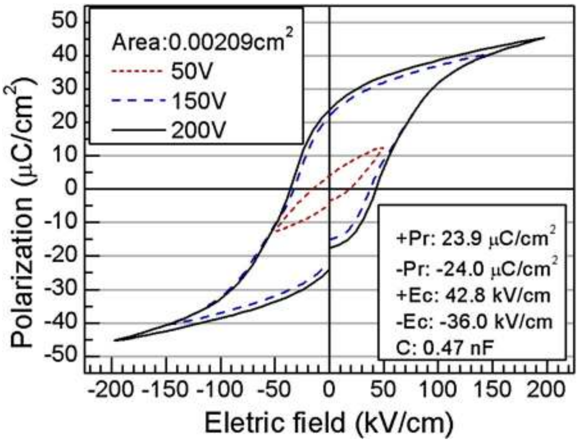

Fig. 5 Polarization curve measured by Precision LC system of the PZT thin film with IrO_x inter-digitally shaped electrodes formed onto the rectangular shaped Polyimide cantilever

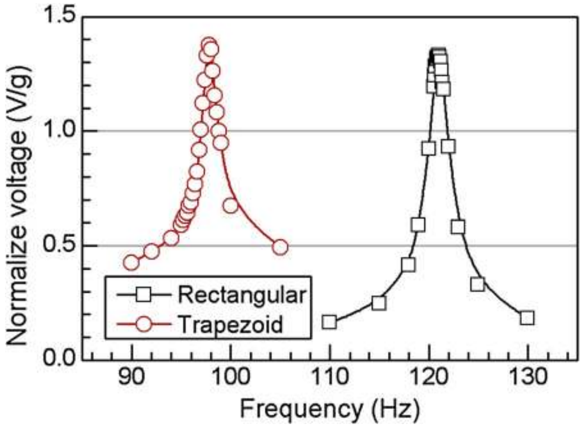

Fig. 6 Normalized open circuit voltage of the micro-fabricated curled cantilever based energy harvester under vertically induced vibration

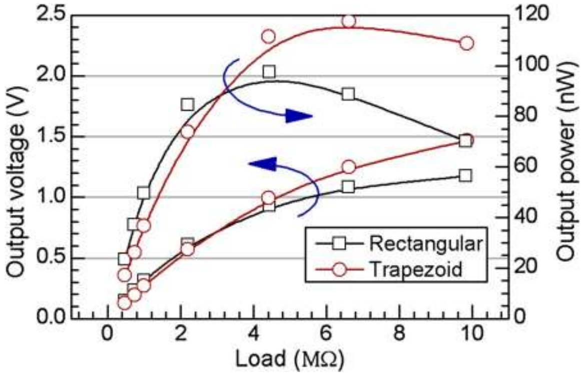

Fig. 7 Measured output voltage and power with different loads under an acceleration of 5 m/s² at their resonant frequencies of 97.8 and 121 Hz for the trapezoidal and rectangular shaped cantilever devices, respectively

from an input acceleration of 5.06 m/s² for the trapezoid and rectangular geometries, respectively. The resonant frequency of the polyimide cantilever devices was lower than that of the previously reported devices with similar geometrical dimensions, due to their low elastic modulus of approximately 3.4 GPa [4, 7]. Furthermore, the trapezoid geometry has a lower resonant frequency than the rectangular one because the trapezoid geometry has narrow width of cantilever than the rectangular device resulting in lower spring constant, as shown in Fig. 6. Maximum output powers of 117 and 97 nW were generated for load resistances of 6.6 and 4.4 MΩ from vertically excited vibration, respectively, as presented in Fig. 7. The higher output voltage than d_{31} mode PZT curled cantilever based energy harvester of Park et al. could be generated by d_{33} piezoelectric mode by using inter-digitated electrodes. In comparison of trapezoid and rectangular shaped geometries, the trapezoid geometry exhibited higher output voltage than the rectangular one as shown in Fig. 7. Since the induced stresses of the two ends of cantilever do affect to the output voltage. In case of rectangular geometry, stress is just concentrated at the anchor of the cantilever. On the other hand, in case of trapezoid geometry, stress is concentrated at both two ends (anchor and free end) of the cantilever.

Conclusion

A flexible PZT cantilever operating in d_{33} piezoelectric mode with an inertial mass located at its free end was presented for energy harvesting applications. The proposed energy harvester was fabricated using a multi-layered polyimide/PZT cantilever and bulk-micromachining. The fabricated PZT cantilever is flexible and generates electricity from low frequency vibration by using an inter-digitated electrode for d_{33} piezoelectric mode. The thin polyimide film used for the elastic layer of the cantilever layer was highly effective because of its flexibility and ability to lower the resonant frequency of the harvesting device. In addition, the proposed process is applicable to mass-production and integration with ICs, unlike the previously reported ceramic based flexible PZT films.

Authors' contributions

HO participated in the design and fabrication of the piezoelectric energy harvester in this study. JC participated in the design and measurement of the study. JY conceived of the study, and participated in its design and coordination and helped to draft the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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