WIDE-BANDWIDTH MEMS-SCALE PIEZOELECTRIC ENERGY HARVESTER

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Abstract: A wide-band resonating thin film PZT MEMS energy harvester has been designed, modeled, fabricated, and tested. It harvests energy from parasitic ambient vibration with a wide range of amplitude and frequency via piezoelectric effect. Contrary to the traditional designs based on high-Q cantilever beams which use the bending strain, the new design utilizes the tensile stretching strain in doubly-anchored beams. Our design exploits the nonlinearity of the stretching beam that enables a wide-band resonance and thereby a robust power generation amid the uncertainty of the input vibration spectrum. The device is microfabricated by a combination of surface and bulk micromachining processes. Released devices are packaged, poled and electromechanically tested to verify the wide-bandwidth nonlinear behavior of the system.

Keywords: Piezoelectric, Energy Harvesting, MEMS, PZT, Nonlinear, Wide-Bandwidth, Stretching Strain

INTRODUCTION

Piezoelectric energy harvesting has a high theoretical power density compared to other harvestable environmental energy sources and is considered as a new attractive option. Several piezoelectric energy harvesters have already been developed. They are based on a simple cantilever beam with a heavy proof mass at the end [1-2].

Subjected to the external vibration, the beam also vibrates and deforms as a result of inertial force exerted from the proof mass. The bending strain in PZT layer, originated from the beam's deflection, generates electrical charge in the form of an oscillating AC signal. In order to maximize the power, low-damped high-Q designs with a natural frequency matched to the excitation frequency have been desired and pursued.

There are some intrinsic problems associated with this approach. Having a constant and known frequency spectrum of ambient vibration as input to the harvester is only a valid fact in rare cases like the vibration from electrical motors. Q-factor of an oscillator is inversely proportional to its bandwidth; consequently, robustness is sacrificed to iprove the power by increasing the Q of oscillator. and the generated power will drastically drop for a small deviation in the input vibration spectrum.

Furthermore, reported harvested power densities are orders of magnitude lower than the maximum theoretical power density of PZT. Bending of a thick cantilever beam generates much smaller strain than the maximum allowable values in PZT. In this work, we are trying to address these issues by presenting a totally new design.

The MEMS-scale pie-shaped design aims to generate the maximum allowable power density in a broad range of vibration frequency and amplitude by employing the stretching strain in doubly-clamped structures. Unlike bending strain, stretching strain is almost uniform across the structure and boosted rapidly for very small deflection levels. Furthermore, it results in additional nonlinear stiffness that acts like a negative feedback to keep the system close to resonance amid a wide range of frequency and amplitude. Therefore, we harness the maximum theoretical power density from the piezoelectric material without sacrificing the bandwidth.

DESIGN

Conventionally, simple cantilever structures with a proof mass have been used in piezoelectric energy harvesting devices (Fig. 1). There is a layer of piezoelectric material (e.g. PZT) mounted on top of the beam. The ambient vibration will be transferred to the device as the oscillating motion of its base. Consequently, the beam will be forced to vibrate as a result of the base excitation.

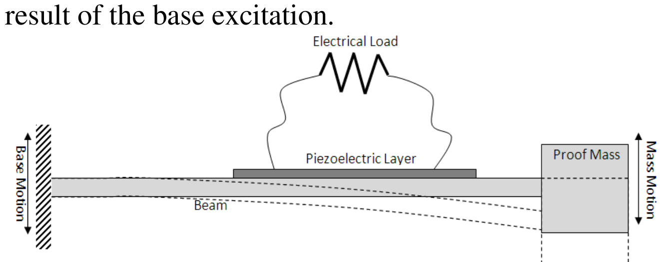

Fig. 1: Traditional design based on cantilever beams

The beam bending results alternating strain between tension and compression in the PZT layer. As a result, the PZT layer generates oscillating charge which should be rectified before collected from the electrodes. We have introduced a new pie-shaped design that employs trapezoidal beams forming the perimeter of a common central proof mass (Fig. 2). This design is a huge departure from the conventional design in that it exploits doubly-clamped beams instead of simple fixed-free cantilever beams as the resonating structure [3]. Unlike the bending strain which oscillates between tension and compression, this design gives always tensile stretching strain which is a key feature especially in large deflections.

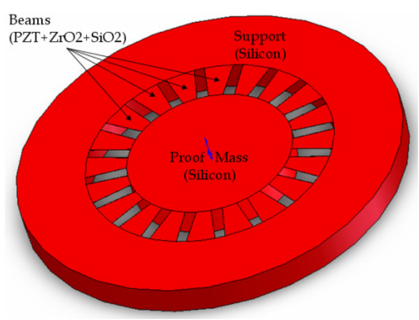

Fig. 2: Schematic structure of wide-bandwidth MEMS-scale piezoelectric energy harvesters.

ANALYSIS

Consider the large deflection of the proof mass in a simple model with only two beams as shown in Fig. 3. The symmetry of the beams around the proof mass prevents any lateral and rotational motion of the proof mass other than its main translation motion. In case of pure bending (shown in red), the tip of each beam should have a deflection perpendicular to the proof mass motion to preserve the beams length. However, this lateral motion is not allowed by the proof mass and a stretching force is applied to the beams to compensate their length increase. Consequently, we should include two sources of strain for large deflection of the proof mass: bending strain, S_B, and stretching strain, S_S [4].

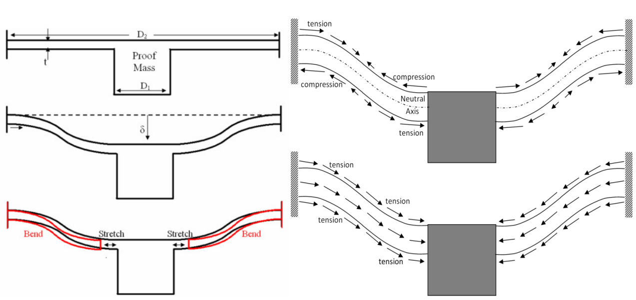

Fig. 3: Bending vs stretching

When the proof mass deflects, it generates nonuniform bending strain that varies across the beams' length and thickness with opposite sign in reverse motion. Contrarily, the stretching strain is always tensile and almost uniform across the length and thickness for both upward and downward motion.

We can use variational methods [4] to get an approximate large-amplitude load deflection relationship of the system:

$$\left(k_B + k_{\sigma_0}\right) z + k_S z^3 + C\left(\dot{z}, I_{Load}\right) + m_{pm}\ddot{z} = -m_{pm} A_{ex} \sin \omega_{ex} t \quad (1)$$

in which

$$k_B = \left(\frac{\pi^5}{24}\right)\left[\frac{\left(Y_{Si_3N_x} t_{beam}^3 + 3Y_{PZT} t_{beam}^2 t_{PZT}\right)\left(D_{out} + D_{in}\right)\eta_f}{\left(D_{out} - D_{in}\right)^3}\right] \quad (2)$$

is a linear stiffness due to the bending strain in the beam. D_{in}, D_{out}, η_f, Y_{Si3Nx}, Y_{PZT}, t_{beam}, t_{PZT} are inner and outer diameter of the device, filling factor, Young's modulus of the beam and the PZT layer, and the thickness of beam and PZT, respectively. Moreover,

$$k_{\sigma_0} = \left(\frac{\pi^3}{4}\right)\left[\frac{\left(\sigma_{Si_3N_x} t_{beam} + \sigma_{PZT} t_{PZT}\right)\left(D_{out} + D_{in}\right)\eta_f}{\left(D_{out} - D_{in}\right)}\right] \quad (3)$$

is another linear stiffness term due to the initial residual stress in the beam and is much bigger than k_B in thin-film structures like our case. Nevertheless, there is a nonlinear stiffness,

$$k_S = \left(\frac{\pi^5}{16}\right)\left[\frac{\left(Y_{Si_3N_x} t_{beam} + Y_{PZT} t_{PZT}\right)\left(D_{out} + D_{in}\right)\eta_f}{\left(D_{out} - D_{in}\right)^3}\right] \quad (4)$$

, resulted from the stretching strain in the beams. It can be modeled as an amplitude-stiffened Duffing spring that transfers the traditional linear dynamic model of the system into a nonlinear Duffing equation. Moreover, C represents all the damping forces which includes mechanical damping (mainly structural and aeroelastic) and also electrical damping (piezoelectric effect in PZT layer).

m_{pm} is the system's proof mass which is concentrated in the central silicon mass. Finally, the right side of the equation shows the excitation force coming from the base vibration at specific amplitude and frequency of A_{ex} and ω_{ex}, respectively.

To estimate the effect of nonlinear terms, we model the nonlinear stiffness and damping with equivalent linear stiffness and damping that stores and dissipates equal energy in one cycle, respectively and obtain a cubic equation with respect to δ^2 as a function of other terms:

$$\frac{9}{16}k_s^2\delta^6 + \frac{3}{2}k_s\left(k_B + k_{\sigma_0} - m_{pm}\omega_{ex}^2\right)\delta^4 + \left[c_{eq}^2\omega_{eq}^2 + \left(k_B + k_{\sigma_0} - m_{pm}\omega_{ex}^2\right)^2\right]\delta^2 - m_{pm}^2A_{ex}^2 = 0 \quad (5)$$

which can be solved and subsequently lead to the calculation of stretching strain that is always tensile and proportional to the square of the deflection.

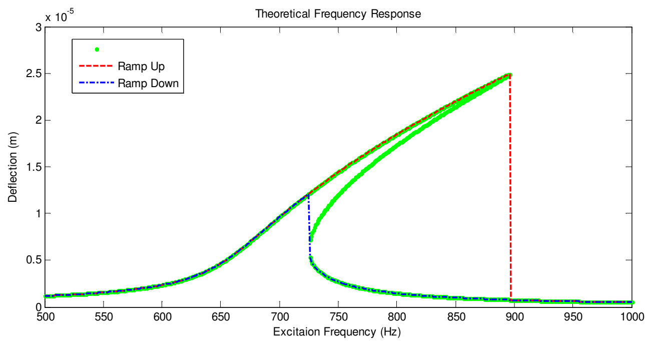

Fig. 4: Theoretical frequency response

A typical frequency response of linear system shows a sharp peak proportional to the Q-factor of the system at the natural frequency. Nevertheless, the bandwidth of the system is extremely small. However, as shown in Fig. 4, the frequency response of the nonlinear system is extremely different from that of a linear system due to the strong nonlinearity. Red and blue graphs show ramp-up and ramp-down responses, respectively. The sharp peak in linear system is skewed to the right. This provides us a wide bandwidth and large amplification simultaneously. Technically, the nonlinear Duffing stiffness act like a negative feedback by changing the natural frequency in such a way that keeps the system always slightly below the natural frequency amid changes in the excitation frequency and amplitude.

FABRICATION

Device fabrication includes a combination of surface micromachining steps to form the active layer and also bulk micromachining to build the structure (Fig. 5). LPCVD nitride has been used as a low-stress and high quality structural material to form extremely thin and long doubly-clamped beams that should hold the proof mass and withstand large strain during the device fabrication and performance.

To develop the structural layer, initially 200nm of thermal silicon oxide is grown on the RCA-cleaned silicon wafer. Subsequently, the wafer is immediately transferred to a low pressure chemical vapor deposition (LPCVD) vertical thermal reactor that deposits 2um of silicon nitride as the main structural layer. Finally, 200nm of PECVD oxide is deposited on top of the nitride layer to get a symmetric structure.

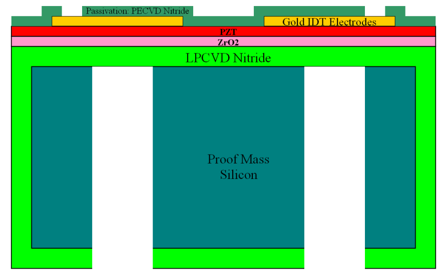

Fig. 5: Schematic cross-section of the device

First, the ZrO_2 solution developed by Mitsubishi Material is coated, dried, and pyrolyzed at 80ºC (150secs), 200ºC (150secs) and 380ºC (300secs), respectively and then cooled down to room temperature on hot-plates to obtain about 50nm of ZrO_2 for each coat. The process is repeated twice to reach the thickness of 0.1-0.2um as the diffusion barrier and seed layer for PZT. The ZrO_2 layer is difficult to be etched after annealing and therefore is patterned and wet etched in BHF after pyrolysis and before annealing. Finally, cleaned wafer is annealed at 700ºC for 3 hours in box furnace.

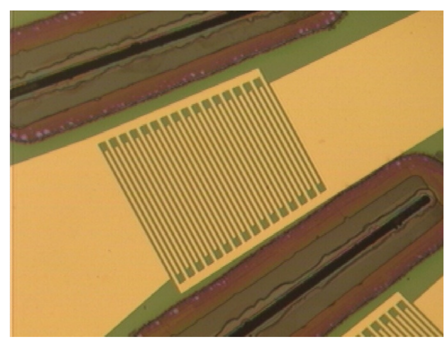
Fig. 6: Schematic cross-section of the device

A thin layer of PT followed by three layers of PZT is spin-coated to create a thick layer of PZT (0.2-0.3um). The same pyrolysis, cooling, patterning, wet-etching and resist-stripping procedures like that of the zirconium oxide are utilized. Finally, the patterned PZT is rapid-thermally annealed at 700ºC for 60secs.

Instead of top and bottom electrodes, top interdigitated electrodes are employed in d_{33} mode to collect the generated electrical charge generated in the PZT as a result of strain. 2000Å of Platinum on top of 200Å of Titanium as adhesion layer are e-beamed and patterned by lift-off method.

Electrical shortage has been a serious challenge that can dramatically reduces the yield rate of pie-shaped energy harvester. To address this issue, we added a passivating layer on top of active layer that electrically and chemically passivates the electrodes and the PZT layer throughout the fabrication and testing steps. Passivating layer consists of 150nm thick PECVD silicon nitride followed by 150nm thick PECVD silicon oxide which are dry etched to pattern vias for wire-bonding and packaging. Deep reactive ion etching (DRIE) from top and back of the wafer patterns the nitride beams and the silicon proof mass and finally a XeF_2 etching of silicon fully releases the device (Fig. 6).

Subsequently, the released devices are super glued to ceramic Pin Grid Array package which acts as the vibration base for the beams and transfer the ambient vibration to the device. Device pads are gold wire-bonded to the package's pads. The packaged devices are poled at 180kV/cm and 100ºC for 30mins. XRD crystallography and P-V measurements show a high quality perovskite PZT (Fig. 7).

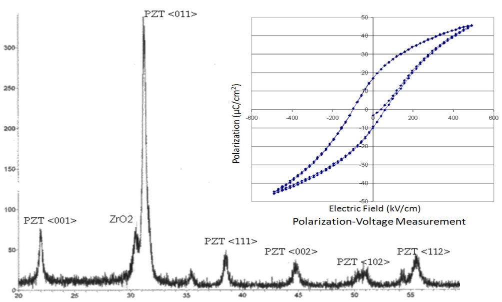

Fig. 7: XRD crystallography and P-V curve

RESULTS

Electromechanical testing is performed on the packaged device at the Gas Turbine Laboratory. Device is excited by a B&K electrostatic shaker type 4809 which is controlled by Prema ARB 1000 signal generator through a Crown DC-300A Series II power amplifier. Motion of the central proof mass and the base is measured remotely by Polytec PSV-300H doppler-effect laser vibrometer.

The base of the pie-shaped energy harvester is subjected to a sweeping vibration at 0.5g acceleration level that first ramps from 500Hz up to 1000Hz and subsequently ramp down back to 500HZ and the proof mass deflection with respect to the base is measured by the laser vibrometer in multipoint scanning mode. The maximum sweeping time, which is limited by the software's spectrum analyzer, is used to ensure quasi-static measurement, Unlike linear systems, totally different responses (shown in Fig. 8) are measured in ramp-up (red graph) and ramp-down (blue) that obeys the theoretical prediction shown in Fig. 4. Ramping up the frequency slowly, holds the nonlinear stiffness active as a negative-feedback that keeps the system slightly below the resonance and a large deflection is materialized in a wide range of frequency (720-855Hz). The drops rapidly at 855Hz to very small amplitude in a phenomenon called jump effect. Ramping down the system shows another stable region of the nonlinear system that jumps up below 770Hz by activating the negative feedback. Total ramp up-down response shows a hysteresis-like graph which cannot be seen in linear systems.

Currently, the power generation test is in progress and the results will be reported in near future.

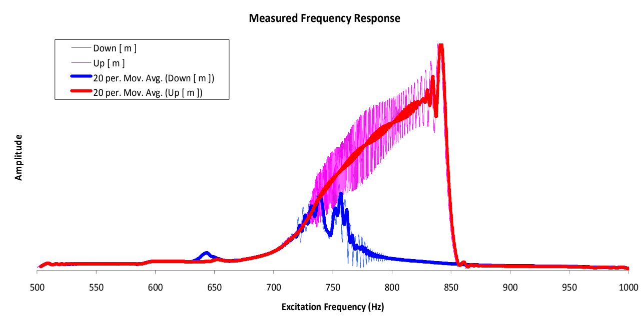

Fig. 8: Measured frequency response of the device

CONCLUSION

A novel piezoelectric pie-shaped MEMS-scale energy harvester has been designed, analyzed, fabricated and tested. The tensile stretching strain in thin doubly clamped structures in large deflection was suggested to achieve a wide bandwidth and high power density piezoelectric energy harvesting. A nonlinear electromechanical model of the nonlinear device was developed to verify the design. A MEMS device was microfabricated to have a thin-film PZT on a pie-shaped SiNx membrane. A much wider-bandwidth resonance of the excited beam has been measured which matches very well to the theoretical model.

This study was supported by the DARPA Grant HR0011-06-1-0045 and Hewlett Packard.

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