Analysis and design of a self-powered piezoelectric microaccelerometer

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ABSTRACT

Power consumption is a critical concern of many sensors used in diversified applications, especially where the replacement of batteries is impossible or inconvenient. Strain energy harvesting technique is an attractive approach to solve this problem using piezoelectric materials. The feasibility of a self-powered piezoelectric microaccelerometer system using lead zirconate titanate (PZT) thin film is studied in this paper. Since the electromechanical coefficient d_{33} of PZT is larger than d_{31}, and the transverse (33 mode) mode is also easier to fabricate, our design and analysis are focused on the transverse mode in constructing the PZT-based self-powered microsystem. The PZT-based cantilever structure with interdigitated electrodes and silicon seismic mass at the free end are designed to have specific resonance frequencies ranging from tens to thousands of hertz. The capability of energy storage and acceleration sensitivity in the proposed microaccelerometer are concurrently evaluated. A trade-off exists between these two major functions and the desirable operating frequency of the proposed system, i.e., the compromise depends on the demands of particular applications.

Keywords: self-powered, piezoelectric sensor, microaccelerometer, energy harvesting, remote sensing

1. INTRODUCTION

Piezoelectric thin films have been widely used in various electronic devices such as ferroelectric random access memory (FRAM), surface acoustic wave (SAW) delay line, acoustic imaging array, etc. Due to its large electromechanical coupling coefficients, temperature stability, and high electric impedance, interests in utilizing lead zirconate titanate (PZT) or polyvinylidene fluoride (PVDF) thin films in micro-electro-mechanical systems (MEMS) applications are currently high. A piezoceramic accelerometer has already been proposed as a substitute for the mechanical switch for air bag deployment [1]. Current efforts on piezoelectric MEMS accelerometers are motivated by the trend of miniaturization because PZT-based MEMS accelerometers can potentially offer high quality, high output impedance, and low damping [2].

Nowadays, low-voltage and low-power operation has become a key issue in the system design with the performance improvement in microelectronic integrated circuits (ICs), which is achieved by reducing transistor size and increasing its packaging density. Power source is a critical concern of many sensors in their diversified applications, especially where the replacement of long-life batteries is impossible or inconvenient, such as the wireless sensor networks for monitoring long span bridges [3]. Various energy harvesting techniques have been investigated, such as electromagnetic vibration-to-electricity converters [4-5], and an electrostatic MEMS design [6], with output energy in the range of several to hundreds of μW per cubic centimeter. Using piezoelectric materials is also an attractive approach to solve this problem due to the potentially larger output energy. Pioneering work to harvest environmental energy employed macroscale piezoelectric power generators (PZT dimorph and PVDF stave) can be found [7]. Recently, a MEMS piezoelectric power generator using PZT thin film was reported by Sood at al. [8], which could generate 7.4 μW-h/mm^2 at kHz range. It was claimed that the frequency of this MEMS device can be decreased to increase the power generation. Hence, potentially realistic vibration source applications such as large industrial equipments, office building floors, and automobiles, can utilize self-powered motion sensors as studied in this paper.

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Merging the characteristics of piezoelectric sensing and power generation, a PVDF-based self-powered mechanical strain energy sensor was reported [9]. By our group in 2004, we have demonstrated a feasible *macroscale* self-powered PZT-based sensor [10]. In this paper, a *microscale* self-powered piezoelectric accelerometer is proposed. The feasibility of the cantilever beam-based PZT microaccelerometer powered through scavenging vibration energy from environment will be studied, focusing on the concurrent evaluation of the capabilities of energy storage and sensing of acceleration.

2. MODELING AND DESIGN

In a piezoelectric accelerometer, the mechanical structure deforms when subjected to acceleration; stresses are then induced in the piezoelectric material and electric charge is generated. Storing this kind of parasitic energy through capacitors or rechargeable batteries, a self-powered system can be built ideally. For a multilayered structure with given geometry, the mechanical sensitivity with cantilever boundary condition is higher than those in membrane and bridge conditions. Therefore, the cantilever beam-type piezoelectric accelerometer is considered in our present analysis.

For one-dimensional state of stress for PZT, two modes of 33 and 31, i.e., the transverse and vertical modes with respect to the polarization direction are most popularly used. The electromechanical coupling coefficient d_{33} of PZT is 2-3 times larger than d_{31}, so a cantilever structure in 33 mode with interdigitated electrodes is considered to obtain higher electrical output for sensing function. In addition, the equivalent capacitance of the PZT structure, which affects the output voltage and yields the design of energy storage circuits, becomes more flexible by varying the electrode gap. This is because the relationship between the capacitance and the thickness of PZT film in 33 mode is different from that in 31 mode where the piezoelectric material is coated by electrodes on both top and bottom surfaces. Meanwhile, the transverse mode also eases the microfabrication process as only one electrode deposition is needed.

In this paper, to construct PZT-based microstructure, a thin $PbTiO_3$ (PT) film is employed as a buffer layer to get better adhesion with the substrate. The proposed PZT-based microsystem is thus focused on the PZT/PT/SiO_2/Si cantilever structure with interdigitated electrode, where the Si is designed as the seismic mass (see Figure 1). Cases with and without silicon seismic mass at the free end are scaled to have specific resonance frequencies of hundreds of hertz with comparison to tens of kilohertz, as the fairly representative vibration source frequency is around 60 Hz in the environment and the typical frequency range of the accelerometer using ±5% as accuracy requirement is lower than $\omega_n/5$ (ω_n : natural frequency) in actual applications [1, 11].

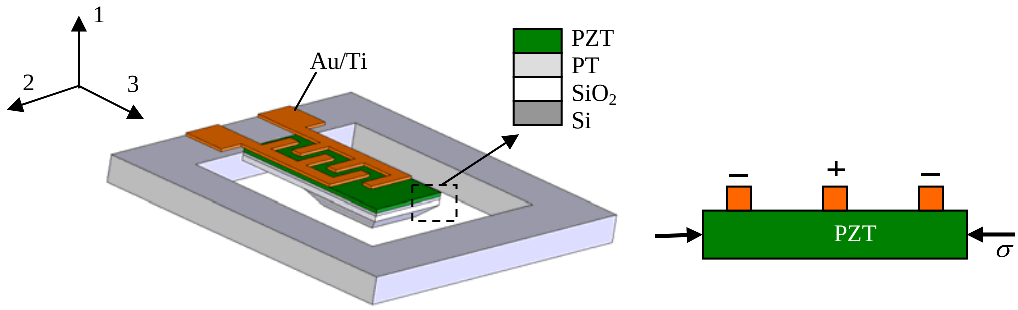

Figure 1: Schematic of the proposed microaccelerometer utilizing 33 mode of piezoelectric effect.

2.1 Sensing properties of piezoelectric microaccelerometer

The main properties of an accelerometer are the sensitivity and the operating frequency range. The sensitivity is defined as the ratio between the electrical output (charge or voltage) and the mechanical input (force or acceleration). The band where the sensitivity keeps practically unchanged defines the operating frequency range. The accelerometer is upper limited by the first resonance frequency of the device.

For a multilayer cantilever piezoelectric structure (width: w, length: l), Weinberg derived its working equations in 31 mode as both sensor and actuator [12]. Our analysis is mostly based on his derivation for evaluating the acceleration sensitivity, except working in 33 mode.

Given an input acceleration a, the charge generated between the electrodes is derived as:

$$Q = d_{33} E_3 C_M M (z_M - z_i) wl \tag{1}$$

where C_M is the curvature under unit torque applied at the free end, z_M denotes the neutral axis and z_i is measured from a reference to the center of each layer (subscripts $_1$, $_2$, and $_3$ refers to SiO_2, PT, and PZT, respectively). Define $Z_i = z_i - z_M$, when the reference is selected as the bottom surface of the composite beam, C_M can be calculated by

$$C_M = \frac{\sum E_i A_i}{\sum E_i A_i \sum E_i (I_i + A_i Z_i^2) - (\sum z_i E_i A_i)^2} \tag{2}$$

The total torque M acted on the beam can be considered as the sum of the torque M_1 induced by the beam mass and the torque M_2 induced by the seismic mass. To simplify, $M_1 = al^2 \sum \rho_i t_i w / 2$, $M_2 = M_s al$, where M_s is the seismic mass which is formed by anisotropic etching and designed to have the same width as the cantilever beam. ρ_i and t_i are the mass density and thickness of each layer, respectively.

The charge sensitivity S_q (unit: C/g, g is the acceleration of gravity) can thus be written as

$$S_q = d_{33} E C_M wl (z_M - z_i) \left[M_s l + l^2 \sum \rho_i t_i w / 2 \right] \tag{3}$$

Consequently, the voltage sensitivity S_v, i.e., the output open voltage per acceleration of gravity (unit: V/g) is $S_v = S_q / C$, where C is the equivalent capacitance between the electrodes and is estimated to be $C = \varepsilon b t_3 / d$ when neglecting the strain effect (ε: dielectric constant of PZT, b: transversely overlapped distance between two electrodes, d: electrode gap). It can be found that larger electrode gap results in larger voltage sensitivity.

The first natural resonance frequency of a cantilever beam structure is $f_n = \frac{1}{2\pi}\sqrt{k/m}$, where m is the equivalent mass and k is the equivalent spring constant. Here, $k = 3EI / l^3$; the total EI of the multilayer cantilever can be calculated by $EI = \sum E_i (I_i + A_i Z_i^2)$, where E_i and I_i stand for Young's modulus and area moment of inertia of each layer, and A_i is the cross-sectional area. The relationships between geometric dimensions, natural frequency and acceleration sensitivity in the case of PZT/PT/SiO_2/Si (0.5/0.1/1/10 μm) with 3 pairs of interdigitated Au electrodes and 10 μm thick silicon seismic mass are plotted in Figure 2(a) and 2(b), respectively. It is shown that the sensitivity is lower for the device scaled down to have higher resonance frequency. For example, the voltage sensitivity is about 0.5 V/g for 10 kHz turns to be more than 100 V/g for that with lower frequency 1 kHz.

2.2 Power generation of piezoelectric microaccelerometer

Considering the proposed piezoelectric accelerometer, the energy output within one period can be calculated by $\int_0^T \frac{1}{2} CV^2 dt$, where T is the period of the input stimulus (i.e., external acceleration), V is the terminal voltage and C is the capacitance of the PZT layer. For comparison, the power output is evaluated at the natural resonance frequency of the microstructure, i.e., $P = \frac{1}{2} CV^2 f_n$. For a given acceleration a, $P = \frac{1}{2C} S_q^2 a^2 f_n$. The scaling effect on the generated power density is plotted in Figure 2(c). It can be clearly observed that the power generation is higher for lower frequency. Scaled down to have the first resonance frequency of 10 kHz, energy density generated in the PZT cantilever (e.g., ~100 μm × 200 μm) will be less than 0.01 μW/mm^2/g. However, when the frequency is decreased to 1 kHz, the energy density

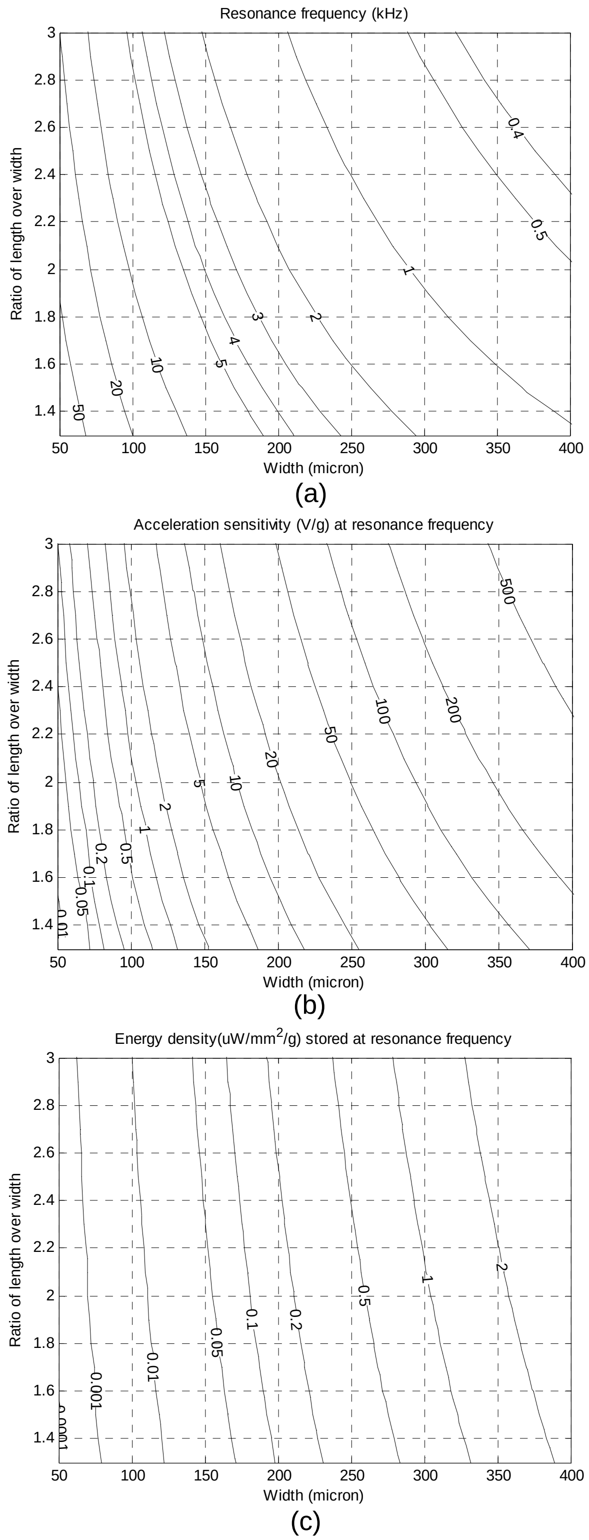

Figure 2: Scaling effects of PZT/PT/SiO_2 micro cantilever with 10µm Si seismic mass:
contour plots showing isolines of (a) natural frequency, (b) acceleration sensitivity, and (c) output power density.

turns to be more than 2 μW/mm^2/g. We can conclude that lower frequency device has the capacity for getting higher power output as well as larger acceleration sensitivity from the above analysis.

2.3 Mechanical limitation

Because the induced strain in the microstructure should be within the PZT film's strain ability (roughly 10^{-3} for PZT ceramic), the application range for the device should be considered in the design. The relationship between the tip displacement and the acceleration within a small range of motion can be linearized to $h = \frac{l^2}{6EI} M$. The induced strain in the PZT thin film is estimated to be $(z_3 - z_M) C_M$.

The overall relationship among the acceleration sensitivity, power generation and natural frequency for cantilever structure with PZT/PT/SiO_2/Si (0.5 μm/0.1 μm/1 μm/10 μm) is plotted in Figure 3, where three pairs of the interdigitated electrodes are calculated. Certainly, the number of interdigitated electrodes and their gap distance, as well as the individual thickness of each structure layer also play important roles in the device performances by affecting either mechanical or electrical properties. These effects will be further investigated in the future.

As shown in Figure 3, it is obvious that a trade-off exists between the acceleration sensitivity, power generation and desirable frequency. The compromise in the frequency needs to be made based on the demands of particular applications. Targeting to harvest the circumstance vibration energy in this paper, the PZT/PT/SiO_2 cantilever structure with interdigitated electrodes and silicon seismic mass at the free end are designed to have specific resonance frequencies of hundreds of hertz.

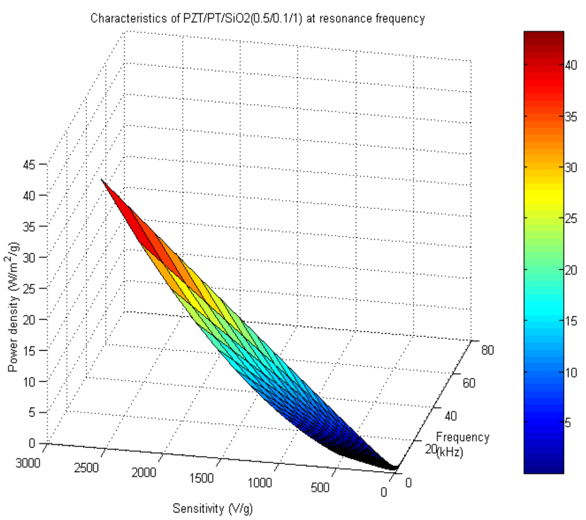

Figure 3: Characteristics of the PZT/PT/SiO_2/Si (0.5μm/0.1μm/1μm/10μm) cantilever-structured microaccelerometer.

3. DEVICE FABRICATION

In our preceding analysis, the seismic mass was designed to employ silicon block which will be composed of highly doped area in the silicon substrate and formed by anisotropic etching. For given geometry, the performances of the above device without seismic mass are generally degraded. Their first resonance frequency becomes higher, and both the acceleration sensitivity and output power decrease. For example, a PZT cantilever with dimensions of 100 μm × 200 μm has acceleration sensitivity about 0.3 V/g and output power density 0.001 μW/mm^2/g. However, the working range can be increased due to its higher 1st resonance frequency (~15 kHz). The magnitude difference between cases with and without seismic mass is roughly within one order. Therefore, we will consider the case without seismic mass in the preliminary fabrication as below before we can precisely control the fabrication of the PZT cantilever with the seismic mass.

3.1 Preparation of piezoelectric thin film

Sol-gel method is a low-cost and widely utilized thin film preparation method. In this paper, sol-gel technique was employed to prepare a PZT piezoelectric thin film. Stoichiometric ratio of 52/48 of zirconate/titanate is used to get high electromechanical coefficients of PZT. The flow to spin-coat one layer of $PbTiO_3$ or PZT is shown in Figure 4. Thicker film can be obtained by repeating the spin-coat of the precursor solution and prebaking before annealing in oxygen atmosphere.

Precursor solution spin-coating

↓

Prebaking at 450°C for 5 mins

↓

Annealing at 550°C for 10 mins, O_2 atmosphere

Figure 4: Process flow of PZT thin film by sol-gel method.

3.2 Fabrication process

Microcantilevers with various geometric dimensions will be fabricated on 4-inch (100) silicon wafers of 400 μm thickness. The process flow is described below. After thermal oxidization and backside patterned, the wafers are coated with ~0.1 μm of PT and then ~0.5 μm of $Pb(Zr_{0.52}Ti_{0.48})O_3$ on the wafer front sides, both by sol-gel technique. PT layer is a buffer layer for the upper PZT layer to have better adhesion with the substrate. The PZT and $PbTiO_3$ layers are then patterned using conventional photolithography and wet etching. Interdigitated gold electrodes with a thin titanium layer are then sputtered and patterned by lift-off. A protective SiO_2 will be followed by sputtering and patterned in order to release the structure by wet etching using TMAH solution or dry etching by DRIE eventually. The process flow with 4 masks is shown in Figure 5.

A fabricated microstructure (400 μm wide and 800 μm long) without seismic mass before release is shown in Figure **6**. As for the case with seismic mass which will be formed by highly-doped silicon, the fabrication is still ongoing as well. After fabrication, the resultant chips will be scribed and diced. Devices will then be poled by applying DC voltage and wire bonded for testing and characterization.

4. CONCLUSIONS

In this paper, a piezoelectric microaccelerometer is designed, analyzed and being fabricated in order to study the feasibility of a self-powered motion sensor that harvests the vibration energy at the available source frequency. The concurrent capabilities of the energy storage and sensing of the acceleration are theoretically evaluated with respect to the first resonance frequency. A trade-off exists between operating frequency and these two major functions. The compromise relies on the frequency and depends on the demands of particular applications. Experimental characterization on the performances under the exciting frequencies of environmental vibration sources will be investigated in the near future.

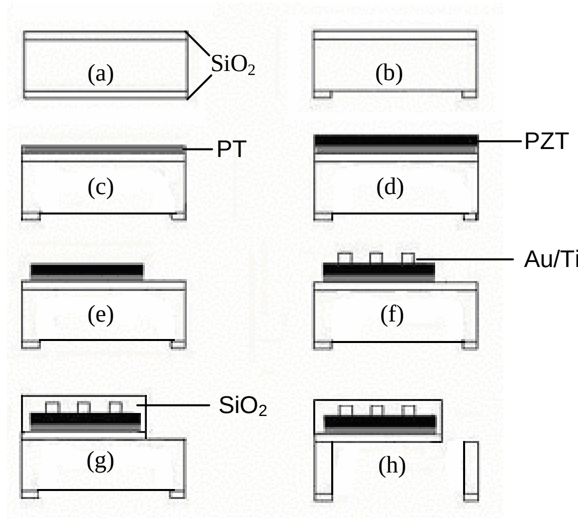

Figure 5: Fabrication process flow of PZT microcantilever (without seismic mass): (a) Thermal oxidization of Si wafer. (b) Backside SiO_2 patterned. (c) Deposition of PT layer on front side. (d) Deposition of PZT layer on front side. (e) Wet etching of PZT and PT films. (f) Deposition and lift-off of gold electrode with a thin titanium layer. (g) Deposition and patterning of a protective SiO_2. (h) Removal of Si to release the structure.

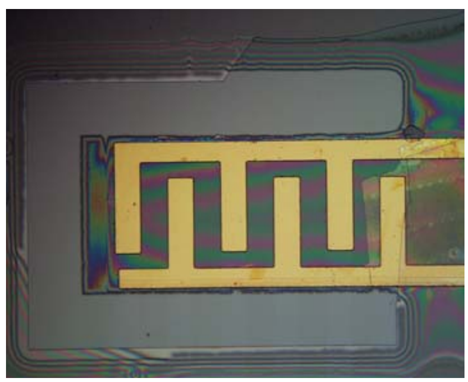

Figure 6: Microscopic picture of a fabricated microstructure before release, 400μm ×800μm.

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