Thin Film Piezoelectric Energy Scavenging Systems for an On-Chip Power Supply

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Abstract

For small, inexpensive, ubiquitous wireless sensors to be realized, all constituents of the device, including the power source, must be directly integratable. For long term application the device must be capable of scavenging power from its surrounding environment. An apparent solution lies in conversion of mechanical energy to electrical output via the growth and direct integration of piezoelectric thin films unimorphs with the wireless electronics.

Keywords: energy scavenging, piezoelectric, thin film

1. Introduction

The integration of piezoelectrics on silicon has been a widely explored topic. In recent years the growth of epitaxial ferroelectric films on silicon have paved the way for the integration of this films in microelectromechanical systems[2,4]. The fabrication procedure of the thin film form of most piezoelectrics (sol-gel, sputtering, etc.) employs a high temperature growth environment or annealing step which results in large scale residual stresses in the film making them virtually impossible to use. Several techniques have been utilized to combat this problem, more often than not several buffer layers are placed between the piezoelectric and silicon substrate typically resulting in complex fabrication procedures and reduced piezoelectric coefficients[5]. Alternative approaches include applying a mechanical force on the structure[6] and using an inter-digitated electrode pattern to apply an initial input voltage[7]. For applications that require large piezoelectric coefficients, such as vibrational energy scavenging, it is essential that the films be grown epitaxially to ensure high piezoelectric activity. Piezoelectric materials are perfect candidates for vibrational energy scavenging as they can efficiently convert mechanical strain to an electrical charge without any additional power[2]. This paper will explore the use of thin film piezoelectric microelectromechanical systems as vibrational energy scavenging systems.

2. Conversion design

The energy conversion from mechanical vibration into electrical power can be described using the elements of linear spring mass system with electrical and mechanical damping terms (Eq. 1).

$$m\ddot{z} + (b_e + b_m)\dot{z} + kz = -m\ddot{y} \qquad (1)$$

Where z is the output tip displacement, y the base displacement, m the lumped mass, k the spring constant, b_m the mechanical damping coefficient, and b_e is the electrical damping coefficient[6].
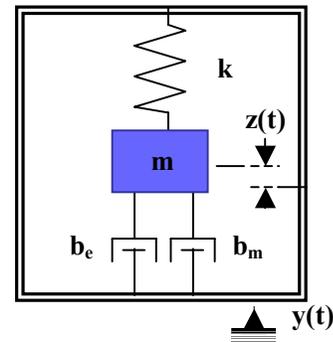

Figure 1- Schematic of generic vibration converter

Using this simple model the power output of this system at resonance is

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$$P = \frac{m\xi_e A^2}{4\omega(\xi_e + \xi_m)} \qquad (2)$$

Where $b=2m\xi\omega_n$ and represents the relative damping ratio, A the acceleration input of the input vibration, and ω the operation frequency. The system should be designed so that they mechanically resonate at a frequency tuned with ambient vibration. A study done by Roundy et al.[2] shows that most of the available environmental vibrations are at lower frequencies. Therefore in order to maximize the power output the energy scavenging device should resonate at a frequency lower that 1 kHz.

3. Piezoelectric Thin Film Fabrication and Characterization

The ultimate goal of energy scavenging devices is the realization of a completely integrated, microfabricated sensor node. To create an ubiquitous device of this nature requires careful consideration of a number of materials and processing difficulties, each of which predicate certain constraints on the materials selection and processing. Specifically, the concerns are: 1) the piezoelectric material must have sufficient material properties to produce a useable voltage under strain and have an intimate crystallographic and interfacial contact with the electrodes and growth substrate; 2) the growth, fabrication, and integration of the power source must consist solely of standard microfabrication processes; 3) the design of the energy scavenging device (with optimized piezoelectric layers) must be able to produce sufficient voltage under ambient vibrational excitation.

Although many piezoelectric materials exist and are commercially available as thin films (thickness on the order of 1 micron), few of them exhibit large enough piezoelectric coefficients to generate appreciable voltage while under strain. The $Pb(Zr,Ti)O_3$ (PZT) family of piezoelectrics in general have large piezoelectric coefficients and can be grown epitaxially with careful selection of growth substrate and electrodes (typically oxide electrodes, such as $SrRuO_3$ (SRO) which demonstrate usable conductivities when grown in thicknesses $\geq$ 50 nm). Epitaxial, or pseudo-single crystal, thin films are attractive because the piezoelectric coefficients, mechanical constants, and dielectric properties of the films can be an order of magnitude higher than polycrystalline films of the same composition.

A PZT ($PbZr_{0.47}Ti_{0.53}O_3$) film was grown on a Si/STO substrate via pulsed laser deposition.[8] Pulsed laser deposition was chosen for its ability to rapidly produce quality films. The quality of the piezoelectric films was determined through measurement of piezoelectric coefficient and remnant polarization. The d_{33} was determined using piezoforce microscopy and the results are

located in Figure 2. It can be seen that the d_{33} value of the film is approximately 160 pm/V which approaches the bulk value and is vastly superior to those the films grown on Pt electrodes. The polarization hysteresis curve identifies the saturation polarization and remnant polarization as 25 and 15 $\mu C/cm^2$ respectively. These values continue to increase
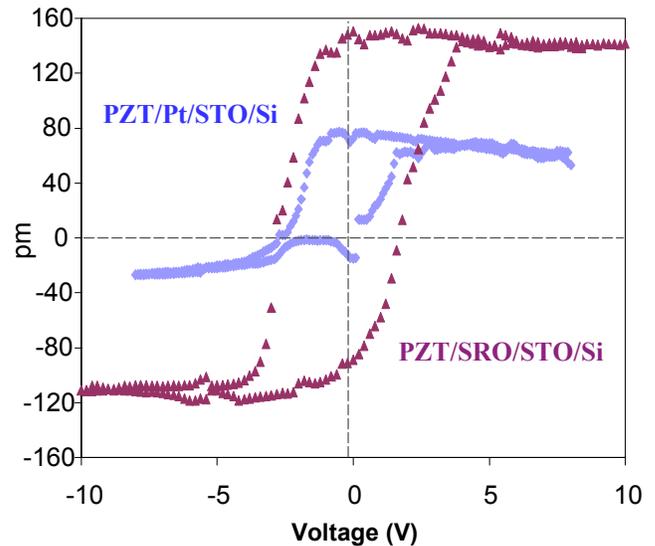

Figure 2 – d_{33} measurement

as the film fabrication is optimized. It should be noted the fabrication processes used to apply surface electrodes caused a significant amount of damage to the surface of the film, as seen by the leakage of the hysteresis curve, therefore care must be taken while fabricating the device structures.
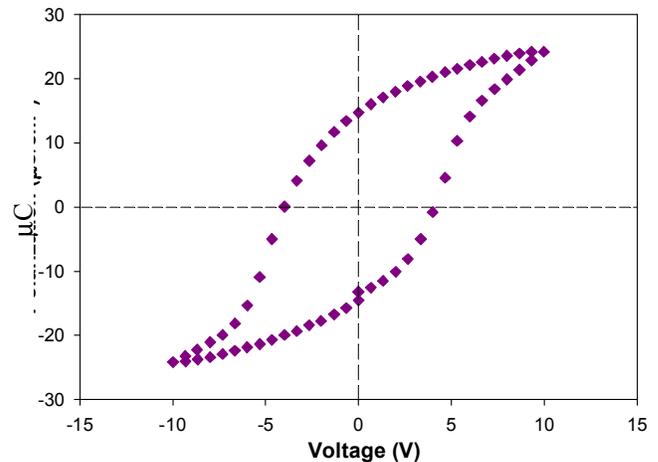

Figure 3- Polarization measurements

Recent studies by Beneyad et al. show the fabrication of epitaxial PMN-PT with thin film piezoelectric coefficients (d_{33}) in the range of 500 pm/V which mark a vast improvement of previously classes of piezoelectric materials.[9] Future fabrication attempts will include films of this stoichiometry.

4. 0 Design Considerations

The logical initial design would be one that is well known and characterized, has been shown to work in the past, and can be fabricated relatively easy with standard microfabrication processes, i.e. a simple heterogeneous bimorph or cantilever.

To effectively couple environmental vibrations, the structures must be designed to have a natural resonance that matches the environmental vibrations. The analytic model for the resonance frequency of a heterogeneous bimorph consisting solely of an elastic layer and a piezoelectric layer is shown as a function of length. It shows that small structures such as the microcantilever beams have relatively high resonance frequencies due to the $1/L^2$ dependency. This may be reduced through the addition of a small mass at the tip of the beam that is also helpful in driving the deflection of the cantilever under input mechanical vibration.

The constituent tensor equations for a heterogeneous bimorph were derived by Smits et al.[7], and can be solved to determine the voltage output resulting from an applied tip force. Although the model is very simplistic in nature, as it does not consider resonance, vibrational amplitude coupling, or power circuit coupling, it does give a decent approximation of how much power a single cantilever beam could be expected to generate.
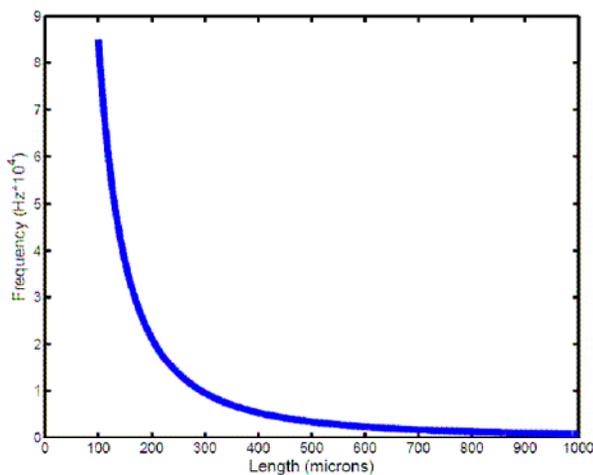
Figure 3 - Resonance frequency of cantilever

The analytical solution for power generation from an independent piezoelectric cantilever assuming capacitive circuit coupling has been calculated elsewhere[3]. Assuming an epitaxial PZT piezoelectric coefficient, cantilever dimensions with a calculated resonance frequency of 950 Hz, typical (not optimized) elastic/piezoelectric thickness and ratio, and simple capacitive circuit power coupling, we calculate that each microcantilever beam can generate approximately 5.5 nW (Figure 4). Considering cantilever dimensions, we arrive at an areal power density of 5 μW/cm^2 (using an interdigitated cantilever array configuration as shown in Figure 5), and an area projected volume power density of 80 μW/cm^3.
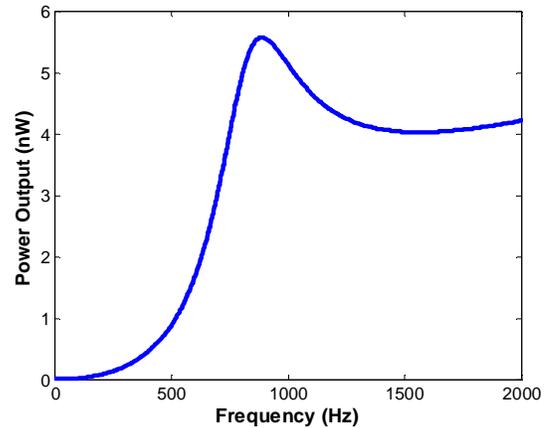
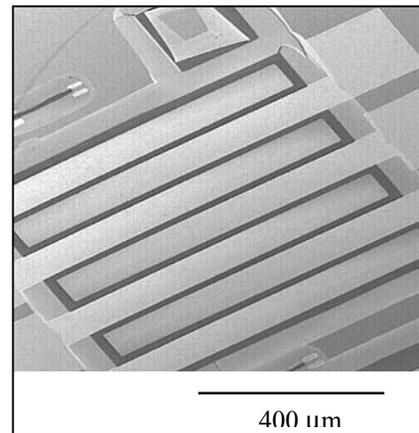**Figure 4 - Estimated power output per 800 μm cantilever beam**

Figure 5 - Interdigitated cantilever arrays for maximum power density

Although this calculated power density is at the threshold of the estimated required power for most low power radios, this model *may* be on the lower estimation side and is located in its entirety elsewhere[7]. Trapezoidal cantilever shapes would increase the area strained under excitation and may easily be fabricated to increase the generated power. The optimal elastic/piezoelectric

thickness and ratio were not used; instead, the dimensions and ratios that we are currently fabricating were used. Also, with slightly more elaborate, but still standard, microfabrication processes a proof mass may be added to the end of the cantilever beams to increase deflection and hence power output (Figure 6).
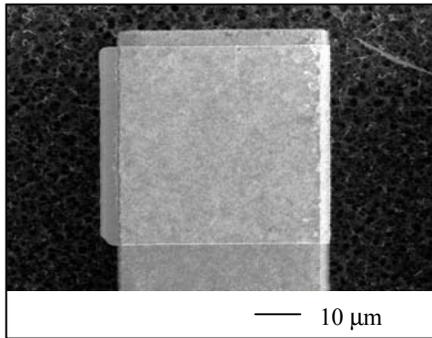

Figure 6 - Example proof mass on released cantilever

5.0 Initial Results

A cantilever beam 800 μm x 80 μm was grown using the following layered structure (Figure 7) and was released from the Si substrate using a gaseous XeF$_2$ etch.

Metal 500 nm
PZT 1000 nm
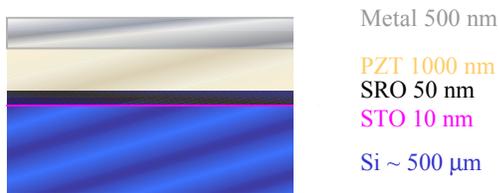SRO 50 nm
STO 10 nm
Si ~ 500 μm

Figure 7 - Film order and relative thicknesses

A proof mass 24.7 pg was applied to the tip of the beam to help drive the response. The resonant frequency of the beam was measured using Hewlett Packard Spectrum Analyzer 8560E. The resonant frequency was measured to be 967 Hz, the Q factor was roughly estimated to be 200 as there was significant background noise. The capacitance of the structure was 0.325 nF with and optimum load of 510 kΩ (Eq. 2).

$$R_L = \frac{1}{\omega C_o} \qquad (2)$$

The maximum output voltage per beam was 5 mV giving a power 24.5 pW per beam. This gives areal power output of 0.8 μW/cm^2 and total power density of 13 μW/cm^3.

6.0 Conclusions

Thin film PZT has been grown epitaxially on silicon with a limited number of oxide buffer layers. The film shows good polarization and switching capabilities. The residual stress that commonly plagues MEMS devices has been compensated for using a combination of metallic layers and careful processing techniques. Preliminary power modeling shows a minimum power density of 80 μW/cm^3, approaching the power requirement for most low power radios. Initial testing indicates the reduction of the resonant frequency with application of the proof mass. The output of the device was significantly lower than what was initially expected, however it was difficult to measure the output of the device due to small outputs per beam and relatively low operating frequencies. The next phase of the testing will give a better indication of what is occurring by observing the movement of the beam under input vibration using a laser doppler vibrometer (LDV).

7.0 References

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