Vibrational Energy Scavenging Via Thin Film Piezoelectric Ceramics

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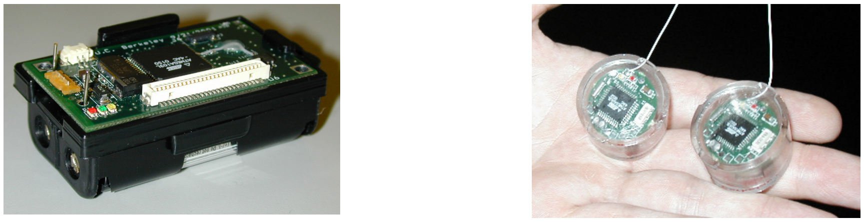
Abstract

This work focuses on constructing a vibrational energy scavenging device with a specific application to MEMS wireless sensor networks. The device utilizes vibrations produced by HVAC ducts, traffic in a room, and even wind hitting a window. The advantages of using thin film (~1 micron) PZT ($Pb_{1.15}(Zr_{0.47}, Ti_{0.53})O_3$) over a larger scale bimorph will be addressed. The thin films are grown using pulsed laser deposition (PLD) to deposit the film epitaxially on MgO. The PZT is then removed from the MgO and attached to a metallic shim, thus creating a usable bimorph. Discussion of the system will reflect that of an external force applied perpendicular to the beam at its tip. Characterization and material analysis will illustrate the effectiveness of this technique in creating an energy scavenging device.

Vibrational Energy Scavenging

Wireless sensor platforms are currently being used in preliminary experiments to monitor energy use in buildings, deflections of the Golden Gate Bridge, and the health of redwood trees in California forests. These self-contained sensor platforms, or motes, range from approximately 2 to 6 cm^3 in size and include the desired sensor(s), a small-integrated computer, a transmitter, and a battery (Figures 1a and 1b). The size and cost will need to be reduced as the research naturally evolves towards miniaturization. Complete sensor platforms utilizing complementary metal oxide (CMOS) fabrication and microelctromechanical (MEMS) devices have the potential of occupying volumes less than 1 mm^3. As “smart dust” they may eventually be spray-painted onto the walls of air-conditioning ducts, or integrated into the upholstery of furniture [1-3].



Figures (1a) and (1b): Wireless sensor “nodes” or “motes,” (b) practical size of 2 cm^3

The larger platforms depicted in Figure 1a can carry a supplementary sensor board for a range of sensors, while the meso-scale device shown in Figure 1b requires sensors permanently attached to the circuit board. A broad range of sensors are currently available including sensors for detecting and measuring temperature, humidity, light, motion, and particles. The large platforms have also been connected to conventional strain gauges and accelerometers for stress and vibration measurement. However, substantial obstacles exist for the practical deployment of such sensor platforms. Despite the small size of the electronics, the large battery volume dictates the final size of the wireless platform. Battery volume can be reduced by integrating a renewable power supply, thus reducing the total platform size. The potential and excitement of wireless sensor platforms has initiated research into discovering new energy sources to aid in miniaturization. The focus of this research is to construct both meso- and MEMS-scale energy scavenging (or harvesting) systems driven by ambient vibrations.

Batteries are a reasonable solution for short life sensor platforms (less than 1 year), but for industrial and commercial implementation an estimated 10-year life is required. Although research efforts focused on microbattery production for short term applications can be found in the literature [4-6], alternate solutions using photovoltaics and vibrational energy scavenging are more attractive for long term applications. Figure 2 charts the power density versus lifetime of various batteries and energy sources showing the lifetime limitations of batteries.

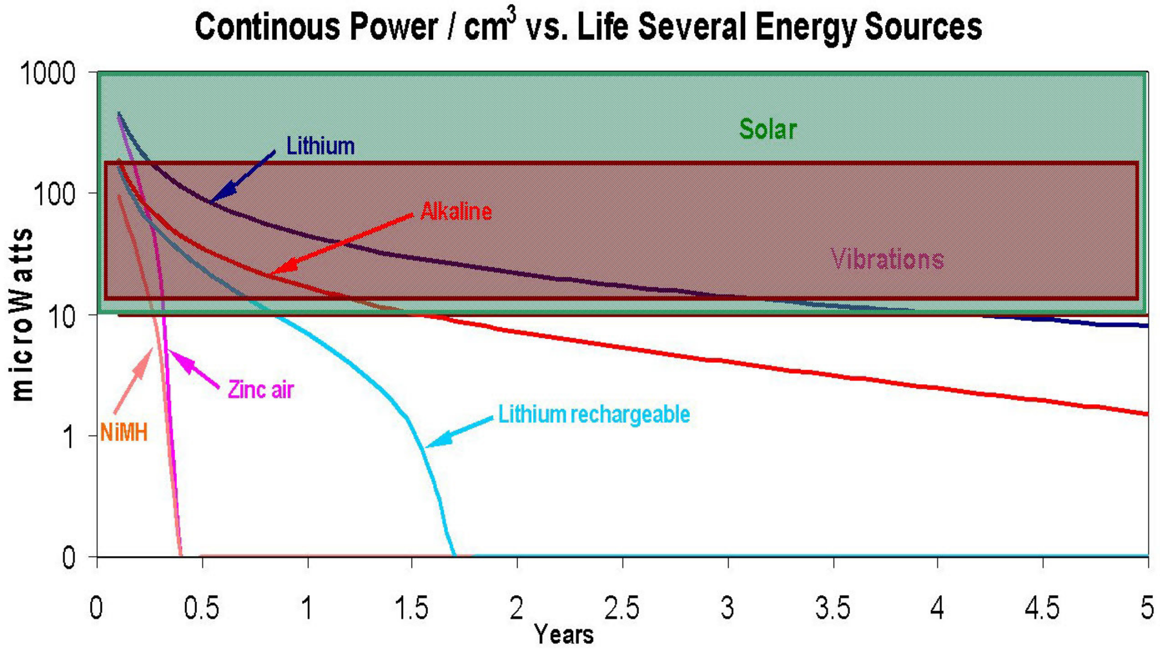


Figure 2. Power density vs. lifetime for various energy sources and batteries.

Photovoltaics offer excellent power density in direct sunlight, but in dim, or non-lit areas, they are inadequate [7]. Vibrational energy scavenging is one of the more promising alternative solutions due to the multitude of ambient vibrational sources and the relative ease of electromechanical conversion. The most common methods currently employed for intrinsic vibrational energy scavenging utilize electrostatic, electromagnetic, or piezoelectric devices [8-10]. Roundy *et. al.* [11] has analyzed frequency and acceleration output for various vibrational sources as tabulated in Table I. Effective vibrational energy scavenging devices must be designed around these readily available sources to be commercially viable.

Table I. Vibrational frequency and peak acceleration of various ambient vibration sources.

Vibrational Source	**Peak Acc. (m/s^2)**	**Freq. (Hz)**
Base of a 3 axis machine tool	10	70
Kitchen blender casing	6.4	121
Clothes dryer	3.5	121
Door frame just as door closes	3	125
Small microwave oven	2.25	121
HVAC vents in office building	0.2 - 1.5	60
Wooden deck with foot traffic	1.3	385
Breadmaker	1.03	121
External windows next to street	0.7	100
Laptop computer with CD running	0.6	75
Washing machine	0.5	109
2nd story of wood frame building	0.2	100
Refrigerator	0.1	240

The authors initial research efforts were aimed at designing piezoelectric devices optimized for ambient frequencies and accelerations. Piezoelectric power converters composed of a piezoelectric cantilever bimorph were constructed for electromechanical conversion. A bimorph consists of a long, thin, compliant bending element (usually stainless steel or brass) sandwiched by two piezoelectric layers. Additionally, a proof mass is attached to the end of the beam to increase deflection and power output. This configuration was utilized in the construction of the prototype as illustrated in Figure 3.

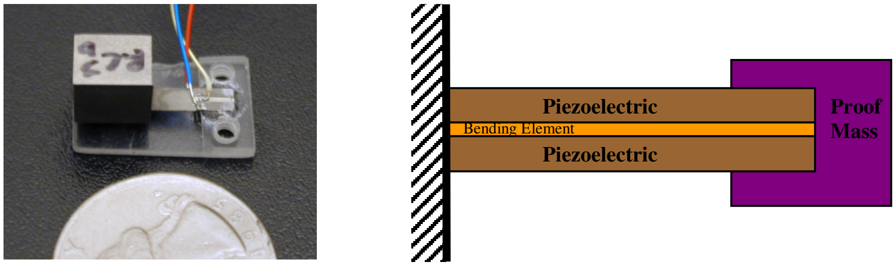


Figure 3. Picture and cross-sectional illustration of meso-scale piezoelectric bender.

The piezoelectric bimorph converts the input vibrations to usable power through the piezoelectric effect. The general model for power output of a piezoelectric bimorph was derived by Williams *et al* [8] and is given in Equation 1.

$$P = \frac{m\zeta_e A^2}{4\omega(\zeta_e + \zeta_m)^2} \qquad (1)$$

Where P is the power output, m is the oscillating proof mass, A is the acceleration magnitude of the input vibration, ω is the frequency of the vibration, ζ_e is the electrically induced ratio, and ζ_m is the mechanically induced damping ratio. William's model is only an approximation of the power output as it assumes the frequency of the driving vibrations are the resonant frequency of the scavenging system. While piezoelectric bimorphs are not always driven at resonance the model provides several important relationships between the power output and proof mass.

Additionally the model shows a critical relationship between the power output and ambient vibration amplitude and frequency.

Initial tests were conducted on a piezoelectric bimorph 4 cm long, 3.5 cm wide, and with a 0.7 g tungsten proof mass. The piezoelectric layers were 0.1397 mm thick and the brass bending element was 0.1016 mm thick. The tests were conducted at 50 Hz on a vibrometer so the input acceleration and frequency could be precisely controlled. The piezoelectric layers in the bimorph are laterally strained from the deflections caused from the input vibrations and generate a voltage. The generated AC (alternating current) voltage is measured through a resistive load attached to the piezoelectric bimorph. Figure 4 shows the voltage output and the vibrational input versus time.

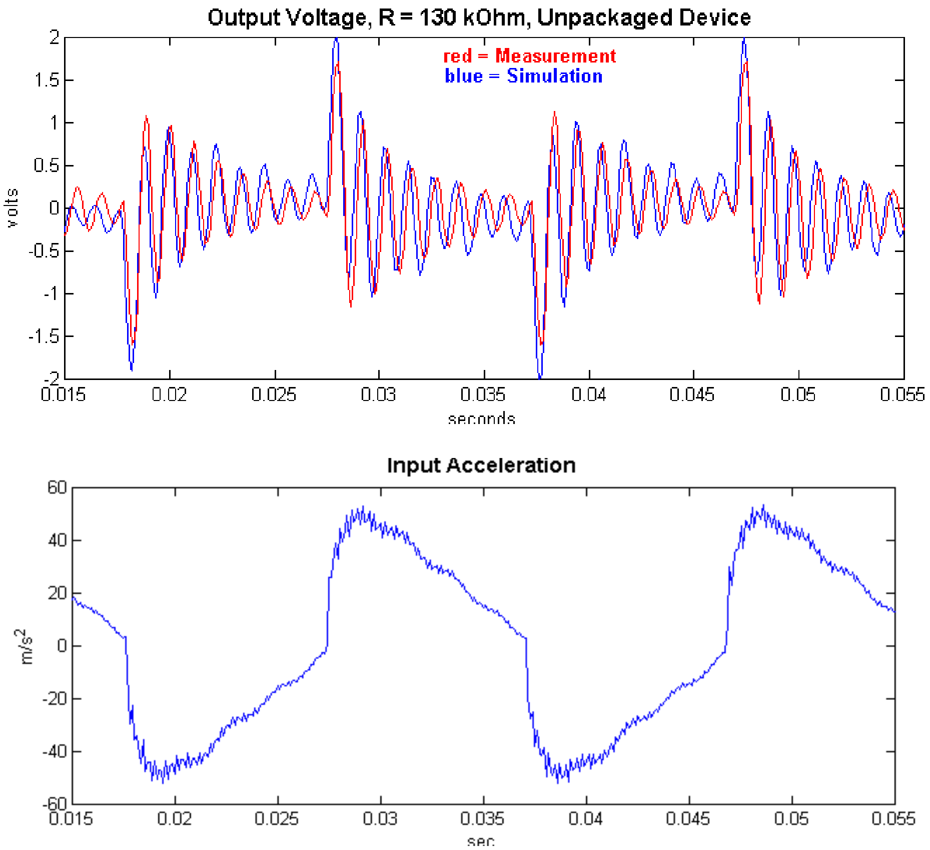


Figure 4. Input acceleration and output voltage for a piezoelectric bimorph.

The output voltage can be converted to power with Equation 2.

$$P = \frac{V^2}{2R} \qquad (2)$$

Where P is output power and V is the voltage measured across the load resistor, R. The power output of the bimorph in the range of the ambient acceleration amplitudes listed in Table 1 was on average ~200 μW [12].

To test the feasibility of these bimorphs for harsher working environments (e.g. inside car tires), a test bimorph was continuously subjected to vibrational amplitudes in excess of 80 m/s^2 until failure. The device lasted approximately 20 hours before succumbing to mechanical failure. The microstructure of the piezoelectric layer was analyzed and source of failure was determined to be due to intergranular fracture as depicted in Figure 5. Although mechanical failure was not observed with ambient vibrations, additional design considerations must be addressed for the meso-scale piezoelectric bimorphs to be effectively used in extreme vibrant environments.

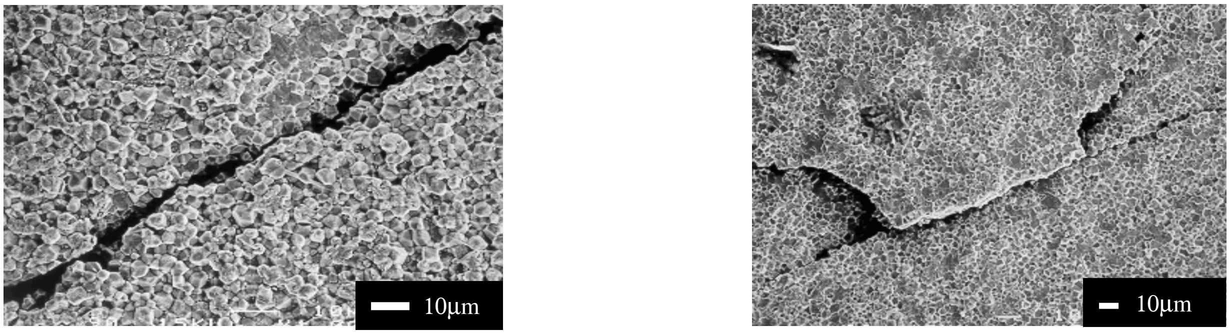


Figure 5. Scanning electron microscope images of the mechanical failure in the piezoelectric layer of the bimorph.

The extensive costs associated with purchasing piezoelectric benders and integrating them into wireless sensor platforms prohibits the mass production of an inexpensive wireless platform. The large size requirements of piezoelectric beams are also prohibitive to the reduced device scaling of wireless sensors. For small, inexpensive, ubiquitous wireless sensors to be realized, all constituents of the device, including the power source, must be directly integratable. The apparent solution lies in the growth and direct integration of piezoelectric thin film bimorphs with the wireless electronics. Piezoelectric thin films are commonly fabricated via rf sputtering, sol-gel processing, and pulsed laser deposition. The fabrication of piezoelectric films via pulsed laser deposition has significant advantages over the other methods. Deposition of the films by laser deposition allows the film composition and thickness to be precisely controlled without elaborate optimization experiments that are required with other methods to obtain quality films. In addition, the film can be grown epitaxially to the growth substrate; this can increase the piezoelectric properties of the film by over an order of magnitude compared to a comparable polycrystalline film [13].

The $Pb(Zr,Ti)O_3$ (PZT) compositional family was chosen for the MEMS scale piezoelectric element due to its large solid solution along its entire compositional range, and the large variability in the piezoelectric coefficients within the solid solution. $Pb_{1.15}(Zr_{0.47}Ti_{0.53})O_3$ was employed as the initial composition due to its good electromechanical coupling factor and high piezoelectric coefficients

PZT thin films approximately 1μm thick will be produced by pulsed laser deposition on (100) oriented single crystal MgO substrates as described in detail elsewhere [14]. Ferroelectric/dielectric test structures will be fabricated by first growing a 50nm thick epitaxial conducting $La_{0.5}Sr_{0.5}CoO_3$ (LSCO) film under identical conditions as the PZT film. The resulting films will be analyzed via scanning electron microscopy (SEM) to characterize the microstructure and x-ray diffraction for determination of crystalline orientation and quality. A standardized ferroelectric tester (Radiant Technologies RT66A) and low capacitance resonator (LCR) meter (HP4275A) will be used for ferroelectric and dielectric measurements. Once the piezoelectric thin films have been properly characterized and optimized, unimorphs consisting of a PZT piezoelectric element and a MgO bending element. Standard CMOS fabrication steps including wet and dry etching will be utilized to create said structure. Ultimately, elaborate heterogeneous integrations steps such as excimer laser lift-off (LLO) may be used to integrate the piezoelectric film with a stainless steel bending element [15].

Acknowledgements

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