Thin Film Piezoelectric Energy Scavenging Systems for Long Term Medical Monitoring

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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.

1. Introduction

The use of wireless sensor networks for long term medical monitoring and intervention devices represents a special set of challenges for the development of a renewable power source. The specificity of the medical application requires a power source that is virtually self sufficient and does not interact with its surroundings. Fixed-energy alternatives, such as batteries, are impractical for wireless devices with an expected lifetime of more than 10 years because the importance of the application of these devices precludes changing or recharging of batteries\(^1\). Current energy scavenging technology is highly focused on environmental phenomena such as solar and wind power, yet clearly these are not as applicable in the case of specialized monitoring devices. The body represents an excellence source of thermal as well as mechanical energy. Thermal gradients are present on the surface of the skin and may be used for external skin mounted sensors. However, for more ubiquitous monitoring, vibrational energy scavenging is a viable source of renewable energy.

Piezoelectric materials are perfect candidates for vibrational energy scavenging as they can efficiently convert mechanical strain to an electrical charge without any additional power\(^2\). Several bulk piezoelectric generators have been developed using the \(d_{31}\) piezoelectric mode\(^3-5\).

2. Conversion design

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

\[
m\ddot{z} + (b_e + b_m)\dot{z} + kz = -m\ddot{y}
\]

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](image)

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

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

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The constituent tensor equations for a heterogeneous bimorph were derived by Smits et al.\cite{Smits_2004}, 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 an array of
cantilever beams could be expected to generate.

Figure 2: Resonance frequency of thin film 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 800 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 3). Considering cantilever dimensions, we arrive at an areal power density of 5 μW/cm\(^2\), and an area projected volume power density of 80 μW/cm\(^3\).

Figure 3: Estimated power output

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 could easily be fabricated and would increase the generated power and cross-hatching would result in a more efficient use of the area. 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.

4. Fabrication Process

The 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 4. It can be seen that the \(d_{33}\) value of the film is approximately 160 pm/V which approaches the bulk value. The polarization hysteresis curve identifies the saturation polarization and remnant polarization as 25 and 15 μC/cm\(^2\) respectively. These values continue to increase as the film fabrication is optimized. It should be noted the fabrication processes used to apply surface electrode causes a significant amount of damage to the surface of the film, as seen by the roundness of the hysteresis curve, therefore care must be taken while fabricating the cantilever structures.

Figure 4: \(d_{33}\) measurement
Thermal deposition of several thin Au/Pd layers (of varying thicknesses) functions to reduce the residual stress in the film as well as act as a top electrode layer. Arrays of varying length SRO/PZT/SRO cantilever beams were patterned and dry etched using standard microfabrication processes and released using gaseous XeF$_2$ etch. The structures have adequate robustness and can withstand vibrational accelerations on the order of several g’s. Testing is currently underway to determine output power at various input vibrations.

5. 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 $\mu$W/cm$^3$.

The initial fabrication attempts have been successful and work has begun to characterize power output and behavior of the devices. These devices represent an exciting advancement of the application of piezoelectrics in microscale energy scavenging.

6. References


