THINNED-PZT ON SOI PROCESS AND DESIGN OPTIMIZATION FOR PIEZOELECTRIC INERTIAL ENERGY HARVESTING

Ethem Erkan Aktakka, Rebecca L. Peterson, and Khalil Najafi
Center for Wireless Integrated Microsystems (WIMS)
University of Michigan, Ann Arbor, MI, USA

ABSTRACT
This paper presents the design, fabrication, and testing of a thinned-PZT/Si unimorph for vibration energy harvesting. It produces a record power output and has state-of-the-art efficiency. The harvester utilizes thinning of bulk-PZT pieces bonded to an SOI wafer, and takes advantage of the similar thermal expansion between PZT and Si to minimize beam bending due to residual stress. Monolithic integration of a tungsten proof mass lowers the resonance frequency and increases the power output. The harvester dimensions, including the PZT/Si thickness ratio and the proof-mass/total-beam length ratio, are optimized via parametric multi-physics FEA. Additionally, a fabrication process for hermetic packaging of the harvester is introduced. It uses vertical Si vias for electrical feed-throughs. An unpackaged harvester with a tungsten proof mass produces 2.74 µW at 0.1 g (167 Hz), and 205 µW at 1.5 g (154 Hz) at resonance (here, g = 9.8 m/s²). The active device volume is 27 mm³ (7 x 7 x 0.55 mm³). We report the highest power output, Normalized Power Density (N.P.D.), and Figure of Merit (N.P.D. x Bandwidth) amongst reported microfabricated vibration energy harvesters.

KEYWORDS
Harvesting, scavenging, power generation, energy, inertial, vibration, piezoelectric, bonding, thinning, PZT.

INTRODUCTION
Rapid advances in solid-state devices over the past several decades have resulted in an increased functionality and performance in sensor systems, in addition to a continual decrease in their power consumption. Energy harvesting technology offers a further technological leap the result of which will be the development of energy-autonomous wireless sensor systems. These systems are needed in applications where using finite-lifetime batteries are not suitable. In these applications battery maintenance is impractical, too costly, or simply dangerous.

There is an increasing interest in inertial energy harvesting due to commonly existing vibration sources in several sensor applications. However, there are various challenges involved in the fabrication of these harvesters. First, the harvesters need to operate at low frequencies (50 to 200 Hz), a difficult range to achieve with micro technology. Second, the energy conversion efficiency is generally lower in micro-scale devices as compared to other macro-scale implementations. This is due to limitations in the material properties of deposited thin-films. Finally, demonstrated resonant devices to date have mostly very narrow bandwidths (1-3 Hz), which limit their use in practical applications.

Fig. 1. A packaged thinned-PZT inertial energy harvester.

This paper presents the design, fabrication and testing of a thinned-PZT vibration energy harvester which operates at ~160 Hz with a record power density and has a large bandwidth (6 to 14 Hz) (Fig. 1). The harvester utilizes bonding of bulk PZT pieces to a silicon wafer and subsequent thinning of PZT (Fig. 2). Bulk PZT ceramics provide higher electro-mechanical coupling and harvesting efficiency than deposited piezoelectric films such as AlN or sol-gel PZT. Recently, we have also reported an efficient power management circuitry for these harvesters [2].

Fig. 2. Primary fabrication steps of the thinned-PZT process.

We previously reported an inertial energy harvester based on aligned solder-bonding and thinning of bulk PZT pieces on Si [1]. However, the PZT/AuIn unimorph cantilever beams fabricated using this process had a large residual stress due to the temperature coefficient of expansion (TCE) mismatch between the top PZT layer and the bottom AuIn layer. The resultant beam bending caused a large static tip deflection, affected the mechanical integrity, and prevented packaging of the harvester. Additionally, the tensile stress in the PZT layer caused a decrease in the piezoelectric coupling, and also reduced the yield stress. This paper uses Si (instead of AuIn) as the bottom layer of the unimorph structure to avoid beam bending (Table 1). This enables the compressive residual stress in the bond layer to be equally distributed through the beam thickness, and minimizes static beam bending.
THINNED-PZT ON SOI PROCESS

The fabrication process is detailed in Fig. 3. Bonding of the diced PZT pieces to the Si, adhering the tungsten proof mass, and the final packaging are all realized by low-temperature (200°C) AuIn transient liquid phase (TLP) bonding (Fig. 4a). The alignment of the PZT pieces prior to bonding is achieved by using a shadow mask. There is a +/-20 µm alignment tolerance that has to be accounted for during mask layout. The final intermetallic bond compound has a higher re-melting temperature than the original bonding temperature. This property of the TLP bond allows for subsequent processing at elevated temperatures (≥200°C). The details of this bonding technique are described in [3], where it is used to realize high-deflection actuators.

During mechanical thinning of the PZT, the silicon wafer surface is used as a stop/masking layer. This provides better control of the PZT thickness and wafer-level uniformity. Parylene is used as an insulation layer between the top and bottom electrodes (Fig. 4b). Parylene is preferred due to its stress-free conformal evaporation at room temperature, and very low Young’s modulus. The proof mass can be either silicon or a tungsten piece, which can be integrated by bonding at the die-level. This allows for higher mechanical coupling of the vibration energy, and lowers the resonance frequency to 100 – 200 Hz where most industrial and commercial applications are found.

Table 1. Layers of the stress-compensated unimorph PZT beam

<table>
<thead>
<tr>
<th>Material</th>
<th>Top Layer</th>
<th>Bond Layer</th>
<th>Bottom Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (µm)</td>
<td>20</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>TCE (µm/m/K)</td>
<td>4.0</td>
<td>14.2</td>
<td>32.1</td>
</tr>
</tbody>
</table>

Table 2. Volume and weight of fabricated devices.

<table>
<thead>
<tr>
<th>Device Type</th>
<th>Weight w/ Si Proof Mass</th>
<th>Weight w/ W Proof Mass</th>
<th>Volume (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Device</td>
<td>53 mg</td>
<td>328 mg</td>
<td>27.0</td>
</tr>
<tr>
<td>Unpackaged Die</td>
<td>96 mg</td>
<td>371 mg</td>
<td>48.7</td>
</tr>
<tr>
<td>Packaged Die</td>
<td>190 mg</td>
<td>465 mg</td>
<td>146.2</td>
</tr>
<tr>
<td>Packaged Die w/ IC &amp; SMD components [2]</td>
<td>425 mg</td>
<td>600 mg</td>
<td>&lt; 300</td>
</tr>
</tbody>
</table>

Die-level hermetic packaging of the harvester with the top and bottom cap pieces can be performed in a single bonding step using mechanical registration for die alignment (Fig. 5-6). The top surface of the packaged harvester can be used as a platform for the integration of a power management IC and additional surface-mount components [2]. A packaged harvester with a tungsten proof mass weighs less than 0.5 grams, and occupies less than 0.15 cm³ (Table 2).
**DESIGN OPTIMIZATION**

A multi-physics FEA tool is used to determine the piezoelectric beam dimensions. The PZT-to-Si layer thickness ratio is a critical parameter in the design optimization. If the total beam thickness is kept constant, our analysis shows that a PZT/Si thickness ratio of ~1 provides the optimum power output (Fig. 7). For a 45 µm beam thickness with a 5 µm thick bond layer at the center, the PZT layer should be 20 µm thick. Using a material other than silicon for the bottom layer would change this ratio because of the consequent position shift in the neutral axis.

Additionally, the proof mass length is optimized for a constant beam length and for a constant device volume (Fig. 8). A larger proof mass length enables higher mechanical coupling of the vibration energy and lowers the resonance frequency. However, after the optimum point, increasing stiffness due to decreasing released-beam length becomes the dominant factor, and this limits the dynamic deflection of the beam and thus the power output.

**TEST RESULTS**

The resonance frequency, bandwidth, and power output of unpackaged harvesters are measured at different vibration levels (Fig. 9-10). The half-power bandwidth increases at higher vibration levels due to a decreasing quality factor as the electrical and structural damping increases. The nonlinear change in the Young’s modulus (and thus the resonance frequency), and the loss in mechanical quality factor depend on the PZT material composition and the heat generation at high vibration levels [4].

The high voltage that results from the high piezoelectric coupling in the harvester enables easy rectification of the output. An unpackaged harvester with a W mass has demonstrated power outputs of 2.74 µW and 205 µW under 0.1 g (164 Hz) and 1.5 g (154 Hz) vibration input respectively. At higher vibration levels the optimum resistive load decreases due to an increase in the PZT dielectric constant and dielectric losses, both related to the high mechanical strain and high electric field in the material.

**PERFORMANCE COMPARISON**

The performance of reported inertial energy harvesters and their power densities are shown in Fig. 11. As seen, most of the previous research has focused on piezoelectric devices due to their high power densities and voltage outputs. The popularity of piezoelectric harvesters is also related to challenges involved with micro-fabrication and scaling of electromagnetic devices, and parasitic effects and initial charging of electrostatic implementations. Power output is normalized (N.P.D.) with respect to the vibration amplitude (Acceleration²) and the unpackaged active device volume (Beam Width x Total Beam Length x Die Thickness) [5]. Since the vibration energy is inversely proportional to the vibration frequency for a constant input acceleration, iso-ambient-energy lines are used to compare devices operating at different frequencies.

The test results of the thinned-PZT energy harvesters are summarized and compared with the state-of-art piezoelectric energy harvesters fabricated through various bulk microfabrication techniques (Table 3). Here, the Figure of Merit value (= N.P.D. x Bandwidth) is used to allow for fair comparison between harvesters.
Fig. 11. State-of-art in the vibrational energy harvesters operating at different frequencies and bandwidths. The thinned-PZT harvesters provide the highest power output (>200 µW), highest power density (3-10 mW/cm³/g²), and a larger bandwidth compared to other piezoelectric inertial harvesters reported to date. This high performance is enabled by the inherently large piezoelectric coupling and electrical damping in the integrated bulk PZT material, the introduced stress-balanced process technology, and the related harvester design optimizations.

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REFERENCES


CONTACT

* E.E. Aktakka, +1-734-272-3170, aktakka@umich.edu
K. Najafi, +1-734-763-6650, najafi@umich.edu

Table 3. Performance comparison between state-of-art piezoelectric inertial energy harvesters

<table>
<thead>
<tr>
<th>Reference</th>
<th>Piezoelectric Material</th>
<th>Proof Mass</th>
<th>Input Vibration g (0-Peak)</th>
<th>Resonance Frequency Hz</th>
<th>Power Output µW</th>
<th>Half-Power Bandwidth Hz</th>
<th>Normalized Power Density mW/cm³/g²</th>
<th>Figure of Merit mW-Hz/cm³/g²</th>
</tr>
</thead>
<tbody>
<tr>
<td>This Work</td>
<td>Thinned PZT</td>
<td>W</td>
<td>0.1</td>
<td>167</td>
<td>2.74</td>
<td>6.1</td>
<td>10.15</td>
<td>61.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.5</td>
<td>154</td>
<td>205.0</td>
<td>14.1</td>
<td>3.37</td>
<td>47.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.5</td>
<td>415</td>
<td>160.8</td>
<td>33.3</td>
<td>2.65</td>
<td>88.2</td>
</tr>
<tr>
<td>[1] Michigan</td>
<td></td>
<td>Si</td>
<td>0.1</td>
<td>263</td>
<td>0.15</td>
<td>4.2</td>
<td>1.22</td>
<td>5.1</td>
</tr>
<tr>
<td>[6] IMEC</td>
<td>Sputtered AIN</td>
<td>Si</td>
<td>1.75</td>
<td>325</td>
<td>85</td>
<td>3</td>
<td>0.97</td>
<td>2.9</td>
</tr>
<tr>
<td>[7] IMEC</td>
<td>Screen Printed PZT</td>
<td>Si</td>
<td>2.0</td>
<td>572</td>
<td>60</td>
<td>2</td>
<td>1.00</td>
<td>2.0</td>
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<tr>
<td>[8] DTU</td>
<td>Sol-gel PZT</td>
<td>Si</td>
<td>1.0</td>
<td>235</td>
<td>14</td>
<td>8</td>
<td>0.75</td>
<td>6.0</td>
</tr>
<tr>
<td>[9] Auburn</td>
<td></td>
<td>Si</td>
<td>2.0</td>
<td>461</td>
<td>2.15</td>
<td>1.2</td>
<td>0.82</td>
<td>1.0</td>
</tr>
<tr>
<td>[10] EPFL</td>
<td>PZT</td>
<td>Si</td>
<td>2.0</td>
<td>870</td>
<td>1.4</td>
<td>-</td>
<td>0.73</td>
<td>-</td>
</tr>
<tr>
<td>[11] IMEC</td>
<td>Aerosol PZT</td>
<td>Si</td>
<td>2.35</td>
<td>1800</td>
<td>40</td>
<td>1</td>
<td>0.39</td>
<td>0.4</td>
</tr>
</tbody>
</table>

CONTACT

* E.E. Aktakka, +1-734-272-3170, aktakka@umich.edu
K. Najafi, +1-734-763-6650, najafi@umich.edu

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