Vibrational energy harvesting microgenerators based on piezoelectric thick films and MEMS

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Outline

- Background of energy harvesting
- Introduction to InSensor® PZT thick film technology:
  - deposition and patterning techniques
  - available substrates and applications
- PZT thick film material for energy harvesting
- Experimental setup, test structures
- Wireless sensors
- Conclusions and summary
Introduction to energy harvesting
Background: Sensors everywhere!

- Smart House
- Smart Dust
- Distributed Wireless Sensor Networks

Integrate components:

- Sensors
- Energy source
- Microcontroller
- Radio

Ultralow power!

On humans:
An electronic patch

On fish:
Sensor system
Example: Condition monitoring
Challenge: Measure vibrations on expensive machinery

Defect bearing
Normal operation

Motor rotational frequency 49.4 Hz
Bearing outer race defect fundamental 155 Hz
Multiple harmonics of outer race defect
Powering Distributed Systems

Energy
- Conversion
- Storage
- Management

- DC/AC Generator
- Electrochemical Reaction
- Thermoelectric Element
- Induction Coil
- Antenna/Rectenna

- Water Flow
- Compressed Gasses
- Mechanical Vibration
- Wind
- Solar Radiation
- Artificial Lighting

- Thermal Reservoir
- Autophagous Structure-Power Combustion
- Autophagous Structure-Battery

- Capacitive Transducer
- Induction Coil and Magnet
- Piezoelectric Transducer

- Mechanical Vibration
- Radio Waves
- Microwave Radiation
- Solar Radiation

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Harvesting energy from vibrations

- **Vision:** Eliminate batteries by introducing energy harvesters enabling a new generation of distributed wireless sensing and control systems

- **Approach:** Harvest ambient vibrational energy using a *piezoelectric* transduction mechanism
Vibrational Energy Harvester

- Cantilever based
- Resonance frequency ≤ 200 Hz
- Acceleration < 1 g
- System: Small dimensions needed < 1 cm x 1 cm x 5 mm
- Resonance frequency
  \[ f_{\text{peak}} \propto \sqrt{\frac{H^3}{L^3}} \]

<table>
<thead>
<tr>
<th>Vibration Source</th>
<th>a [m/s²]</th>
<th>( f_{\text{peak}} ) [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car engine compartment</td>
<td>12</td>
<td>200</td>
</tr>
<tr>
<td>Base of 3-axis machine tool</td>
<td>10</td>
<td>70</td>
</tr>
<tr>
<td>Blender casing</td>
<td>6.4</td>
<td>121</td>
</tr>
<tr>
<td>Clothes dryer</td>
<td>3.5</td>
<td>121</td>
</tr>
<tr>
<td>Door frame just after door closure</td>
<td>3</td>
<td>125</td>
</tr>
<tr>
<td>Small microwave oven</td>
<td>2.5</td>
<td>121</td>
</tr>
<tr>
<td>HVAC vents in office building</td>
<td>0.2-1.5</td>
<td>60</td>
</tr>
<tr>
<td>Windows next to a busy road</td>
<td>0.7</td>
<td>100</td>
</tr>
<tr>
<td>CD on notebook computer</td>
<td>0.6</td>
<td>75</td>
</tr>
<tr>
<td>Second storey floor of busy office</td>
<td>0.2</td>
<td>100</td>
</tr>
</tbody>
</table>

- MEMS technology to control thicknesses
- Screen-printing of thick film PZT
  - InSensor® TF2100

PZT thick films – technology and applications
Integrated piezoelectric materials

- Higher integration
- Smaller size
- Lower cost
- Lower weight
- Less material
- Less processing

[Diagram showing the integration of piezoelectric materials from bulk ceramics to nano-tech, with corresponding technological advancements.]
Challenges and the solution

Compatibility challenges
- Bulk ceramic is sintered at 1250 - 1300 °C
- At these temperatures PZT will react with the substrate
- Mismatch between thermal expansion coefficients causes delamination

Solution:
- By introducing a sintering aid, the sintering temperature can be reduced significantly

Delamination effects

Densification at lower temperatures
Deposition techniques

Screen printing

Pad printing
PZT thick film compatibility

SUBSTRATES

Ceramics

Stainless steel

LTCC*

Silicon/MEMS**

*) in cooperation with Thick Film Microsystems Lab, Wroclaw Univ. of Tech., Wroclaw, Poland

**) in cooperation with DTU Nanotech, Lungby, Denmark
PZT thick films – areas of application

- Transducers
  - Medical imaging (high frequency, high resolution)
  - p-MUTs

- Actuators
  - Micro-valves
  - Micro-pumps
  - Micro-mirror positioning
  - Linear or angular positioning

- Sensors
  - Accelerometers
  - Strain gauges
  - Knock sensors
  - Pressure sensors
  - Hydrophones
  - Viscosity sensors

- Energy harvesting
High-performance PZT thick film for energy harvesting
High performance PZT thick films

The piezoelectric properties of the PZT thick film can be improved by using an additional processing of the green films in high pressure.

Micrograph of standard PZT thick film (on silicon)

Micrograph of PZT thick film (on silicon) modified using high pressure processing
Test structures

- Test structures, have been manufactured using InSensor® PZT thick films
  - Standard (STD) TF2100 (hard PZT based)
  - Modified (MOD) TF2100 (hard PZT based, high pressure treated)
- 30 µm thick film (both STD and MOD) has been deposited on 360 µm thick silicon substrate with dimensions equal to
  - 12.5x2 mm²
  - 12.5x3 mm²
  - 25x3 mm²
- Pt based bottom electrode served also as diffusion barrier layer during the PZT sintering process
- Top electrode has been deposited using evaporation technique (0.5 µm thick)
Experimental setup

- Before the measurements the devices were glued to PCB fixtures
- The whole fixture was mounted on a shaker, imposing a sinusoidal acceleration at the base of the cantilever
- A reference accelerometer was fixed to the vertical axis of the shaker, in order to measure the vertical acceleration
- Three different values of seismic mass have been used in the experiments (125 mg, 191 mg, 286 mg)
- The measurements were performed at around 1 m/s² acceleration

Test structures, bonded to PCB fixture (top), on the shaker with clamped-on seismic mass (bottom)
Measurement results – direct comparison

Standard PZT thick film
InSensor® TF2100

High performance PZT thick film
InSensor® TF2100
Results - continued

Normalised output voltage on sub-optimal resistive load

Output power at 1 m/s²
Structures on 12.5x3 mm² substrates
Summary of results

Output power $P_{\text{max}}$ of a vibration energy harvesting generator with a seismic mass $m$ can be expressed in the following way:

$$P_{\text{max}} \sim m a^2 / f_r$$

FoM = $P_{\text{max}} f_r / (m a^2)$ = $\{P_{\text{max}} / a^2\} f_r / m$

<table>
<thead>
<tr>
<th>Planar dimensions [mm x mm]</th>
<th>Piezoelectric thick film</th>
<th>Resonance frequency; $f_r$ [Hz]</th>
<th>Maximal measured output power, normalized; $P_{\text{max}} / a^2$ [$\mu$W s$^4$/m$^2$]</th>
<th>FoM</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5 x 2</td>
<td>TF2100 STD</td>
<td>493.2</td>
<td>0.95</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>TF2100 CIP</td>
<td>512.1</td>
<td>2.46</td>
<td>4.4</td>
</tr>
<tr>
<td>12.5 x 3</td>
<td>TF2100 STD</td>
<td>617.4</td>
<td>0.87</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>TF2100 CIP</td>
<td>612.6</td>
<td>1.71</td>
<td>3.9</td>
</tr>
<tr>
<td>25 x 3</td>
<td>TF2100 STD</td>
<td>191.2</td>
<td>4.18</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>TF2100 CIP</td>
<td>205.0</td>
<td>7.56</td>
<td>5.4</td>
</tr>
</tbody>
</table>

*) All values have been measured for seismic mass of 286 mg at matching resistive load
Complete wireless sensor system
From single harvester to a system

Energy harvester

Energy management and storage module

LOAD

Microcontroller module
Acceleration sensor
Wireless communication module
Practical implementation of wireless sensor

- Harvesters convert kinetic energy into electrical energy
- Electrical energy is stored and conditioned
- When sufficient electrical energy is available, the load is powered
- Microcontroller repeats acceleration measurement and performs intermittent data transmission
Characteristics of acceleration measurement

- 3D acceleration measurement performed
- Sampling frequency: 1600 Hz
- Resolution: 13 bits (38 mm/s² per LSB)
- Number of acquired samples for each axis: 60
- Acquisition time: 37.5 ms
Early prototype characteristics

- 3-4 harvesters excited at the same resonance frequency
- Resonance tuned adding extra mass ($f_{\text{res}} = 167$ Hz)
- Minimum RMS acceleration: 5 m/s$^2$
- Wireless data transmission demonstrated above 1 m distance
Conclusions (1): PZT thick films

- The properties of the PZT thick film can be substantially improved by high pressure processing.
- Modified PZT thick films show superior performance over the standard ones and allow to significantly increase the output power of energy harvesting devices.
- Figure of merit of the high performance based devices is approximately two times as high as one for the standard PZT thick film based devices.
- The presented technology is a very promising candidate for fabrication of integrated and miniaturized devices on silicon (MEMS) comprising both sensors and energy harvesting micro-generators.
- The high-performance InSensor® PZT thick films based MEMS devices can be manufactured at wafer-scale making it very attractive for high volume production.
Conclusions (2): energy harvester

- Power harvesters realised with silicon micromachining technology and screen-printed PZT thick films
  - Open-circuit voltage up to 4 V @ 5 m/s² peak
  - Maximum power range up to 14 µW @ 5 m/s² peak
- Self-powered wireless sensor prototype
  - Harvester resonance frequency tuned by adding mass ($f_{res} = 167$ Hz)
  - Intermittent data transmission
  - 3D acceleration measurement
  - Radio frequency data transmission demonstrated
- More work will be put in harvesting at lower frequencies
Acknowledgement

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Working principle

- Ambient mechanical vibrations accelerates the seismic mass which strains the piezoelectric cantilever beam.
- Energy is harvested by electrodes on the sides of the strained piezoelectric layer.
- Most effective at resonance:

\[ P = \frac{R}{(R + R_g)^2} V_g^2 \]

Power output:

\[ P \sim f(d_{31}, \varepsilon_{33}) g(Y, \nu) h(L, H, \ldots) \frac{Ma^2}{\omega} \]

- Electrical parameters
- Mechanical parameters
- Geometrical parameters
Modelling the resonance frequency

\[ \omega_0 = \frac{1}{2} \sqrt{\frac{H^3 W Y}{L^3 M}} \]

Real device

\[ \omega_0 = \sqrt[3]{7} \sqrt{\frac{H^3 W Y (20L^2 M^2 + 5ML_m (6LM + 3ML_m))}{L(5040L^4 M^3 + 3ML_m (5040L^3 M^2 + 7LM_m (945L^2 M^2 + 30ML_m (21LM + 6ML_m))))}} \]

Too naive 😞

Good approximation 😊
Modelling the resonance frequency

Point mass $M, L=L+L_m$

Full model

Point mass $M$ at $L$
Resonance frequency

\[ \omega_0 = \frac{1}{2} \sqrt{\frac{H^3WY}{(L + \frac{L_m}{2})^3 M}} \]

\[ = \sqrt{2} \sqrt{\frac{H^3Y}{L_m(2L + L_m)^3(H\rho_{PZT} + h_m\rho_{Si})}} \]

Does not depend on the width of the beam!