Evolution of MEMS based piezoelectric thick film technology for energy harvesting applications

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Outline

1. Company introduction
2. Objectives
3. PZT thick films for energy harvesting
4. Micro-generators
5. Conclusions
1 Company introduction
Meggitt - overview

» Provides high technology products and systems for the aerospace, defence and other specialist markets, including: medical, industrial, energy, test and automotive
» 60 years experience in extreme environment engineering
» Broad geographic footprint
» Annual sales (2012), £1,605.8 million, 10% growth in comparison to 2011
» Listed on London Stock Exchange (MGGT)
» FTSE100 company
A global presence

North America
Employees: 5,790
Locations: 31
USA, Canada and Mexico

Mainland Europe
Employees: 1,450
Locations: 7
Denmark, France, Germany, Spain and Switzerland

UK
Employees: 2,090
Locations: 13

Asia and RoW
Employees: 650
Locations: 8
Australia, Brazil, China, India, Singapore, UAE and Vietnam

Over 10,000 employees worldwide
Meggitt Sensing Systems Denmark

» Meggitt A/S is a manufacturer of piezoelectric materials, components, devices
» 2-3 million units produced annually
» Major markets
  - Medical ultrasound
  - Underwater acoustics
  - Acceleration sensors
  - Flow meters
  - Energy Harvesting
Development objectives
Development objectives

» Micro generators
  - Easy to integrate
  - Relatively small (millimeter scale)
  - Broadband
  - Energy from vibrations

» System
  - Low weight
  - Low duty factor
  - Energy autonomous
  - Wireless
  - Long life
  - Wide range of working temperatures
Sensor node architecture

» Harvesters convert kinetic energy in electrical energy
» Electrical energy is stored and conditioned
» When electrical energy is enough the load is powered
Technology evolution

- High yield unimorph and bimorph process
- Second generation unimorphs
- First generation bimorphs
- High lateral coupling films
- First generation energy harvesting devices
- PZT thick film technology
The basic technology
Design criteria for bending structures

» Optimal design of a bending structure should assure the neutral bending axis to be located at the interface between active (PZT) and passive (Si) materials.

» Typical device layer of an SOI wafer (20 μm) requires 30-40 μm of the active material (PZT).

\[
\frac{t_{\text{pzt}}}{t_{\text{Si}}} = \sqrt{\frac{Y_{\text{Si}}}{Y_{\text{PZT}}}}
\]

\[
t_{\text{pzt}} = t_{\text{Si}} \cdot \sqrt{\frac{Y_{\text{Si}}}{Y_{\text{PZT}}}} = 20 \, \mu\text{m} \cdot \sqrt{\frac{130 \, \text{GPa}}{43.6 \, \text{GPa}}} = 34.53 \, \mu\text{m}
\]

Y – Young’s modulus
\( t \) – thickness

The foundation - PZT Thick Film technology

Technology of piezoelectric thick films (InSensor™) – enabling deposition and integration of piezoelectric layers (10 to 100 µm in thickness) with high lateral resolution (100x100 µm)

Key futures of InSensor™ technology
- Capable of manufacturing miniaturized devices
- Low prototyping costs
- High volume production
- High lateral resolution
- High frequency
- High response
- Piezoelectric material can be deposited on a number of different substrates (compatible with MEMS)
Deposition - Screen printing

PZT dispersed in an organic vehicle
High coupling thick films – important step towards efficient micro-generators

» 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) processed using high pressure processing
High coupling materials

The following properties of both materials have been used in the FEM

<table>
<thead>
<tr>
<th></th>
<th>Piezoelectric coeff. (estimated) (d_{31}) [pC/N]</th>
<th>Relative dielectric permittivity (measured) (\varepsilon_r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STD TF2100</td>
<td>-50</td>
<td>584</td>
</tr>
<tr>
<td>MOD TF2100</td>
<td>-93</td>
<td>730</td>
</tr>
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</table>
4 Micro generators
First generation devices
Cambrian period

- Realized with silicon micromachining technology and PZT thick films deposited by screen-printing technique
- Single clamped cantilevers with a silicon proof mass at the free end
- Planar dimension 10x10 mm²
- Different cantilever shapes, and mass-beam length ratios (MBR)

Rectangular | Trapezoidal | Inverted trapezoidal

- MBR 30%
- MBR 50%
- MBR 70%
- MBR 80%
First generation devices – performance comparison

Power output @ 0.5 g at resonance
Second generation unimorphs

Process flow

Unimorph energy harvesting devices
Second generation devices - performance

Power output as a function of resistive load (at resonance) @ 0.5 g harmonic excitation (240 Hz)
Wafer scale process analysis leading to next generation devices

Wafer level distribution of capacitance (left) and open circuit voltage (right)
Comparative study of distribution of the properties

<table>
<thead>
<tr>
<th>Chip</th>
<th>$B W_{FWHM}$ [Hz]</th>
<th>$Q_{total}$</th>
<th>RMS Power [$\mu W$]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.5g</td>
</tr>
<tr>
<td>A6</td>
<td>5.00</td>
<td>65.9</td>
<td>12.5</td>
</tr>
<tr>
<td>G3</td>
<td>6.80</td>
<td>50.7</td>
<td>10.5</td>
</tr>
<tr>
<td>B4</td>
<td>6.80</td>
<td>49.7</td>
<td>9.6</td>
</tr>
<tr>
<td>B6</td>
<td>6.60</td>
<td>49.3</td>
<td>9.7</td>
</tr>
<tr>
<td>F5</td>
<td>8.20</td>
<td>40.1</td>
<td>6.7</td>
</tr>
<tr>
<td>D7</td>
<td>9.00</td>
<td>37.1</td>
<td>6.1</td>
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<tr>
<td>E6</td>
<td>8.50</td>
<td>39.2</td>
<td>5.5</td>
</tr>
<tr>
<td>C2</td>
<td>8.75</td>
<td>37.7</td>
<td>4.8</td>
</tr>
<tr>
<td>A2</td>
<td>8.20</td>
<td>38.4</td>
<td>5.1</td>
</tr>
<tr>
<td>C3</td>
<td>10.25</td>
<td>31.1</td>
<td>2.9</td>
</tr>
</tbody>
</table>
Third generation unimorph devices

DRIE replaced by KOH etch
Third generation - performance

Wafer level distribution of quality factor (left) and peak power output at optimal load and acceleration 0.5 $g$ RMS (average frequency 482 Hz)
Parallel evolution path - bimorphs

Process flow

Bottom electrode

PZT thick film

Proof mass

Middle electrode

Top electrode

Bimorph energy harvesting devices
Bimorphs - performance

Power output as a function of excitation frequency (at optimal resistive load)
Summary

PZT thick film technology for energy harvesting devices has gone through several iterations leading towards high yield process (> 93%) producing very efficient devices.

The evolution has been targeting two mutually supporting development directions: higher power output at lower excitation accelerations.

Current generation of devices is capable of generation of 30-40 μW of power at moderate accelerations of about 0.5 g in relatively wide range of frequencies, producing output voltage of 4-5 V.
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