Piezopaint for Piezomems – industrial low temperature technology for design and production of integrated multifunctional devices,
Wanda Wolny, Rasmus Lou-Moeller, Tomasz Zawada and Konstantin Astafiev Meggitt, Copenhagen, Denmark
Outline

• Meggitt company introduction
• Integration, motivation and existing technologies
• Applications
  • Energy harvesting
  • Accelerometer
  • High frequency transducer
  • SHM
• PiezoPaint™ technology
• PiezoPaint™ demonstrators
• Summary
Leading technology positions
Meggitt Strategic Business Units

<table>
<thead>
<tr>
<th>Aircraft Braking Systems</th>
<th>Control Systems</th>
<th>Polymers &amp; Composites</th>
<th>Sensing Systems</th>
<th>Equipment Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheels</td>
<td>Thermal management</td>
<td>Electro-thermal ice protection</td>
<td>Condition monitoring systems</td>
<td>Power systems</td>
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<tr>
<td>Carbon brakes</td>
<td>ECS</td>
<td>Ice protection controllers</td>
<td>High performance sensors</td>
<td>Actuators</td>
</tr>
<tr>
<td>Steel brakes</td>
<td>Fluid control</td>
<td>Composite structures</td>
<td>Turbine ignition</td>
<td>Air data computing</td>
</tr>
<tr>
<td>Electric brakes</td>
<td>Electronic control</td>
<td>Seals</td>
<td></td>
<td>Avionics</td>
</tr>
<tr>
<td>Brake control</td>
<td>Engine dressings</td>
<td>Fuel bladders</td>
<td></td>
<td>Specialty components</td>
</tr>
<tr>
<td>Gear control</td>
<td></td>
<td></td>
<td></td>
<td>Fire protection</td>
</tr>
<tr>
<td>Nose wheel steering</td>
<td></td>
<td></td>
<td></td>
<td>Defence systems</td>
</tr>
</tbody>
</table>
A global presence

North America
Employees: >6000
Locations: 31
USA, Canada and Mexico

UK
Employees: 2,090
Locations: 13

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

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

>10,000 employees worldwide
Meggitt - overview

- Provides high technology products and systems for the aerospace, defence and other specialist markets, including: medical, industrial, energy, test and automotive
- 150 years of engineering innovation
- Broad geographic footprint
- Annual sales £m 1606 (USD m 2500)
- Listed on London Stock Exchange (MGGT)
Integration motivation and technologies

Higher integration

Lower cost

Smaller size

Lower weight

Less material

Less processing
Thick film technology I

• Doped PZT ceramic on a substrate
  • Ceramic
  • Silicon
  • Stainless steel
  • LTCC

• Thickness: 10-100 μm

Electrode
Barrier
Substrate
PZT
## Integration motivation and technologies II

Evolution in screen printing of thick film

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Sintering temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramics incl. Alumina, pzt and others</td>
<td>1100-1250°C</td>
</tr>
<tr>
<td>Steel, silicon, LTCC</td>
<td>850°C</td>
</tr>
<tr>
<td>Polymer</td>
<td>150°C</td>
</tr>
<tr>
<td>Textile</td>
<td>100°C</td>
</tr>
<tr>
<td>Composites</td>
<td>&quot;</td>
</tr>
<tr>
<td>Laminates</td>
<td>&quot;</td>
</tr>
<tr>
<td>Paper</td>
<td>&quot;</td>
</tr>
</tbody>
</table>
## Typical Thick Film Properties

<table>
<thead>
<tr>
<th>Materials</th>
<th>Piezoelectric charge coefficient, $d_{33}$ (pC/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZ26 (bulk component)</td>
<td>290</td>
</tr>
<tr>
<td>TF2100 InSensor® (thick film)</td>
<td>200</td>
</tr>
<tr>
<td><strong>Lead free thick film</strong></td>
<td>150</td>
</tr>
<tr>
<td>Flexible thick film</td>
<td>40</td>
</tr>
<tr>
<td>Piezopaint™</td>
<td></td>
</tr>
<tr>
<td>PVDF (thin film)$^1$</td>
<td>-8</td>
</tr>
<tr>
<td>Copolymer P(VDF-TrFE)$^2$</td>
<td>-33</td>
</tr>
</tbody>
</table>

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Thick film technology II

Screen printing

PZT powder is suspended in an organic vehicle
Thick film technology III

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
TF2100 transducer

Ultrasonic image of the skin with anginoma.

With IPPT

Ultrasonic image of the skin cancer spinocellular carcinoma.
Energy harvesting

- Energy conversion unit
- Energy storage unit
- Load
- Energy management
Energy Harvesting micro-generators

- 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
- Unimorph configuration
- High yield (> 90%) using KOH wet etch in the last part of the fabrication process

_In cooperation with DTU Nanotech_
Energy Harvesting micro-generators - bimorph

- 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
- Bimorph configuration
- Higher voltage and power compared to unimorph
- Si/PZT fabrication + middle electrode + 2nd PZT layer + Si membrane removal

In cooperation with DTU Nanotech
Comparison of the structures

- Charge sensitivity up to 37 nC/g @ 0.5 g peak
- Open-circuit voltage up to
  - 3 V @ 0.5 g peak (unimorph)
  - 4 V @ 0.5 g peak (bimorph)
- Maximum power range
  - 10 μW ÷ 12 μW @ 0.5 g peak (unimorph)
  - 12 μW ÷ 20 μW @ 0.5 g peak (bimorph)
Accelerometer

http://chestofbooks.com/crafts/popular-mechanics

Π-MEMS projektet finansieret af højteknologifonden

I samarbejde med Nanotech DTU
The advantages of the use of piezoelectric:

1. More controlled temperature dependence
2. No need for a stable driving source
3. Better long term stability
4. Higher possible bandwidth

\[ S_q = C \cdot S_v = A^2 \cdot \bar{E}_3 \cdot \varepsilon_r \cdot \varepsilon_0 \]

\[ \text{Capacitance} = \frac{A^1 + A^2 \text{ piezo thickness}}{\varepsilon_r \cdot \varepsilon_0} \]

\[ \bar{E}_3 = [g][\sigma] \]

\[ S_3 : \text{Charge sensitivity} \]
\[ S_v : \text{Voltage sensitivity} \]
\[ C : \text{Capacitance} \]
\[ A : \text{Electrode area} \]

Therefore, in order to increase the sensitivity, the **dielectric constant** and the **voltage coefficient** should be higher.

Disadvantage (PZT):
- Over printing
- Low properties

PMN-PT accelerometer

PMN-PT paste substitute

PMN-PT
Fraunhofer IKTS

- Monolithic Integrated Piezoelectrics for Smart Microsystems

**On Top**

- Piezoceramic Thick Films

**Inside**

- LTCC/PZT Multilayer

- Teamwork of Substrate and Piezoceramic

**Substrate Material**
- $\text{Al}_2\text{O}_3$
- LTCC
- Silicon
- others

**Piezoceramic Material**
- PZT
- PMN-PT
- KNN
- Others

- Chemical Reaction
- Mechanical Interaction
- Thermal Mismatch
PZT thick film on LTCC

- **Deformable Mirror for Laser Beam Shaping**

- **Multilayer Setup**
  - LTCC material: DP 951
  - LTCC Membrane: \( t = 220 \, \mu m \)
  - LTCC Frame: \( t = 660 \, \mu m \)
  - Membrane Diameter: \( d = 34.7 \, mm \)
  - Thickness PZT Film: \( t = 100 \, \mu m \)
  - Thickness Cu Film: \( t = 150 \, \mu m \)

Dr. Sylvia Gebhardt

[Image of deformable mirror and multilayer setup]
PZT thick film array

- 2D Ultrasonic Transducer for Particle Manipulation

- 2D Array
  - 6 x 6 element 2D array
  - 2 mm element pitch
  - PZT thickness $t = \, 140 \, \mu m$

- Crossed Electrode Array
  - 30 x 30 crossed electrodes
  - 0.5 mm electrode pitch
  - PZT thickness $t = \, 140 \, \mu m$

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SHM – lamb waves

- Arrays mounted with flex PCB by soldering
- Two arrays glued to an aluminium plate
- Both arrays connected to a dedicated SHM electronics module
  - High-frequency excitation (bandwidth up to 2 MHz)
  - PULSECHO functionality (emission and reception on same piezoelectric patch)
  - 4 channels per daughter board
Flexible piezoelectric materials - PiezoPaint™

Low temperature flexible piezoelectric materials has been developed on the basis of commercially available piezoelectric PZT based ceramics and polymer materials.

- Ultra low processing temperature (100 °C),
- High piezoelectric activity ($d_{33} > 40$ pC/N) and low dielectric losses (no power dissipation – no unnecessary heating),
- Flexibility and compatibility with screen-, pad-, and stencil printing techniques,
- Low manufacturing cost and suitable for large scale production,
- Ability to adjust the properties, depending on the final application.
PiezoPaint™ - The substrates

Can be applied onto:

- Fabrics
- Textiles
- Composites
- Metals
- Plastics/polymers
- Laminates
- Ceramics
- Paper
- PCB
- Etc.

PiezoPaint™ on polymer

PiezoPaint™ on fabric

PiezoPaint™ on PCB
Properties of PiezoPaint™ materials can be adjusted, depending on the final application and customer requirements:

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
<th>$\rho$, g/cm³</th>
<th>$T_{\text{opt}}$, °C</th>
<th>$\varepsilon$</th>
<th>$\tan \delta$, %</th>
<th>$d_{33}$, pC/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVDF</td>
<td>Co-polymer</td>
<td>1.8</td>
<td>&lt; 90</td>
<td>10 – 12</td>
<td>-</td>
<td>-30</td>
</tr>
<tr>
<td>PP-30</td>
<td>PZT</td>
<td>4.9</td>
<td>&lt; 150</td>
<td>90</td>
<td>2.5</td>
<td>28</td>
</tr>
<tr>
<td>PP-50A</td>
<td>PZT</td>
<td>5.0</td>
<td>&lt; 150</td>
<td>100</td>
<td>2.5</td>
<td>40</td>
</tr>
<tr>
<td>PP-50B</td>
<td>PZT</td>
<td>5.2</td>
<td>&lt; 150</td>
<td>125</td>
<td>3.0</td>
<td>40</td>
</tr>
<tr>
<td>PP-50LF</td>
<td>Lead-Free</td>
<td>&lt; 4</td>
<td>&lt; 150</td>
<td>250</td>
<td>4.0</td>
<td>25</td>
</tr>
</tbody>
</table>

Properties are for semi-clamped samples, in the case of the films printed onto alumina substrates (cured).
Energy harvesting

Piezoelectric accelerometer / energy harvester:

» The sensor has good linearity and produces a peak output of nearly 60 mV which would be sufficient for a motion sensor detection system.

Courtesy of University of Southampton, UK
Piezoelectric buzzers

- Represents a simple structure, where the piezoelectric thick film is sandwiched between the top and the bottom electrodes,
- The entire structure can be encapsulated with PVC or UV curable dielectrics, available e.g. from DuPont,
- Flexible and can be applied on any structures, including lab coats or work wear.
Piezoelectric buzzers

Piezoelectric buzzer under test:

- Signal Generator and High Voltage Amplifier
  - 12V input voltage
  - ~350 – 450V output signal
  - Full square wave output: 100Hz – 7kHz (two modes: buzzer and chirp)
  - Short circuit protection – safe to use

High voltage driver generator:

- 12V input voltage, and 350 – 450V output signal (peak to peak)
- Full square wave output: 100Hz – 7kHz (two modes: buzzer and chirp)
- Short circuit protection – safe to use
Piezoelectric buzzer on textile:

- Up to 75 dB of sound pressure,
- Flexible and can be applied on any structures, including lab coats or work wear.
Piezoelectric active filter cleaner

Signal Generator and High Voltage Amplifier

12V

~350 - 450V

Filter fabric

Top electrode

Bottom electrode

PZT

Powder to filter

Filtering area

Top electrodes

Bottom electrodes

0s 8s 30s 40s
Piezoelectric motion sensor:

- Printed on lab coat’s sleeve,
- The sensor is connected to the work wear’s control system and sensing the bending of the sleeves.
Piezoelectric motion sensor

Piezoelectric motion sensor printed on Kermel fabric, Polycotton fabric, and lab coat sleeves:
Piezoelectric motion sensor

- Piezoelectric motion sensor
- Comparator
  + ~100 mV
  -
- Microcontroller
  - Texas Instruments MSP430F22 74
- Transmitter
  - Texas Instruments CC2500
- Reference source
- Wireless Antenna
  - Adjusting threshold voltage

- Wireless Antenna
- Receiver
  - Texas Instruments CC2500
- Microcontroller
  - Texas Instruments MSP430F22 74
  - LED
    - If “0” is received – no motion
  - LED
    - If “1” is received – sensor is under stress (bending)
Piezoelectric motion sensor

Transmitter

Receiver (USB stick)

Motion sensor

Receiver

Transmitter
Lab coat prototype

Piezoelectric buzzer

Piezoelectric motion sensor
Summary

- New technologies support
  - Miniaturisation
  - Integration
  - Resource, cost and energy reduction
  - Open for new applications
  - Implementation of piezoelectric lead free materials

- PiezoPaint™
  - New technology for low temperature processing
  - Compatible with several flexible substrates
Thank you for your attention

Questions?