This document and the information in it is proprietary and is the property of CTS | Ferroperm. It may not be copied or disclosed to a third party or used for any purpose other than that for which it is supplied without the express written consent of CTS | Ferroperm

Information contained in this document is subject to certain Export Control regulations, specifically of the (choose as appropriate) United Kingdom, European Union, other national jurisdiction and / or the United States International Traffic in Arms Regulations and / or Export Administration Regulations. Each recipient of this document is responsible for ensuring that transfer or use of any information contained in this document complies with all relevant Export Control Regulations.



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

Tomasz Zawada, Louise Borregaard, Ruichao Xu, Michele Guizzetti, Erling Ringgaard CTS | Ferroperm, Denmark

Anders Lei, Erik V. Thomsen Department of Micro- and Nanotechnology, Technical University of Denmark

18th March 2013, Les Arcs, France

Outline

1 **Company introduction** 2 **Objectives PZT thick films for energy harvesting** Micro-generators 4 Conclusions 5

1 Company introduction



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



OE 52% / Aftermarket 48%

- Civil aerospace
- Military
- Energy and other

CTS | Ferroperm Denmark

- » We are 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



2 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



- » Electrical energy is stored and conditioned
- When electrical energy is enough the load is powered

Technology evolution



3 The basic technology



Design criteria for bending structures

- » Optimal design of a bending structure should assure the neutral bending axis to be located a 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)



$$\frac{t_{pzt}}{t_{Si}} = \sqrt{\frac{Y_{Si}}{Y_{PZT}}}$$

$$Y - Young's modulus$$

 $t - thickness$

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

Source: Jesper Kenneth Olsen, Master Thesis, "Piezoelectric Components in Microfluidic Devices", DTU, 2007



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 microgenerators

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)



Technology evolution

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

	Piezoelectric coeff. (estimated) <i>d</i> 31 [pC/N]	Relative dielectric permittivity (measured) ε _r				
STD TF2100	-50	584				
MOD TF2100	-93	730				

Micro generators





First generation devices Cambrian period

- Realized with silicon micromachining technology and PZT thick films deposited by screenprinting 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)





First generation devices – performance comparison



Power output @ 0.5 g at resonance

Second generation unimorphs







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

	А	В	С	D	Е	F	G	[nF]		А	В	С	D	E	F	G	[V]
1		5.342	5.448	5.495	5.234	5.096		6	1		0.75	1.06	0.985	1.30	0.507		2.7
2	5.336	5.640	5.693	5.679	5.600	5.506	5.343		2	1.173	0.96	1.21	1.32	1.52	1.07	1.88	
3	5.139		5.799	5.769	5.636	5.564	5.398		3	2.40		1.08	1.41	1.07	1.27	2.08	
4	5.768	5.766	5.839	5.924		5.724	5.004	5.64	4	2.09	2.15	2.25	1.31		1.72	1.10	1.6
5	5.789	5.868	5.884	5.924	5.934	5.896	5.449		5	2.27	2.20	1.84	1.00	1.28	1.60	2.41	
6	5.765	5.958	5.671		5.779	5.615	5.588		6	2.70	2.07	2.11		1.55	1.99	1.83	
7			5.812	5.853	5.749	5.869		5	7			2.10	1.53	1.77	1.79		0.5

Technology evolution

Wafer level distribution of capacitance (left) and open circuit voltage (right)

Comparative study of distribution of the properties

Chin	BW _{FWHM}	0	RMS Power [µW]						
Chip	[Hz]	total	0.5g	0.75g	1g				
A6	5.00	65.9	12.5	25.0	39.3				
G3	6.80	50.7	10.5	22.1	35.0				
B4	6.80	49.7	9.6	21.3	35.8				
B 6	6.60	49.3	9.7	21.4	34.7				
F5	8.20	40.1	6.7	15.7	25.7				
D7	9.00	37.1	6.1	14.8	24.3				
E 6	8.50	39.2	5.5	13.1	22.5				
C2	8.75	37.7	4.8	11.1	17.9				
A2	8.20	38.4	5.1	10.9	15.3				
C3	10.25	31.1	2.9	7.2	13.3				

Third generation unimorph devices







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



Bimorph energy harvesting devices

Bimorphs - performance



28

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





Contributors

» CTS | Ferroperm Denmark Team

- Louise Borregaard
- Rasmus Lou-Moeller
- Dr Michele Guizzetti
- Karsten Hansen
- Lise Nielsen
- Dr Erling Ringgaard
- Dr Ruichao Xu
- » DTU Nanotech Team
 - Prof. Erik V. Thomsen
 - Anders Lei

Acknowledgments

Danish National Advanced Technology Foundation through the ELBA project [ELiminating BAtteries – energy harvesters for integrated systems] contract no. 036-2009-1





The information contained in this document is the property of CTS | Ferroperm and is proprietary and/or copyright material. This information and this document may not be used or disclosed without the express authorization of CTS | Ferroperm. Any unauthorized use or disclosure may be unlawful.

The information contained in this document may be subject to the provisions of the trade compliance regulations (including those regulations governing transfer to a dual national or third country national, export and re-export) of various countries; see the first page for specific requirements. The recipient acknowledges that licences from the applicable regulatory agency or agencies may be required before the recipient may further disclose such information to others, and that such licences may impose restrictions on further disclosure of such information. The recipient agrees to comply with all applicable governmental regulations as they relate to the transfer, export and re-export of information disclosed in this document.