Project no.:
229196

Project acronym:
piezoVolume

Project full title:
High volume piezoelectric thin film production process for microsystems

Collaborative Project targeted to a special group (such as SMEs)
Grant Agreement No.:

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D 5.7
Dissemination of results by publications and open seminars. Exploitation assistance package

Due delivery date: 2012-12-31
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Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential , only for members of the consortium (including the Commission Services)	

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Abstract

The results of the piezoVolume project will be disseminated to the piezoMEMS industry but piezoMEMS community in general. In particular developers and suppliers of electronic components and systems will be addressed, through open seminars, company seminars, publications and conference contributions and company seminars. An "exploitation assistance package", will be assembled that describes virtually the design of a new piezoMEMS product by giving an overview on the different steps of the manufacturing chain. It will also address the infrastructure available to the public, created within the project.

WP5 will also monitor the market situation for the results generated in the project.

Public introduction[1]

[1] According to Deliverables list in Annex I, all restricted (RE) deliverables will contain an introduction that will be made public through the project WEBsite

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1 SUMMARY OF PROJECT DISSEMINATION ACTIVITIES

1.1 List of dissemination activities

The dissemination activities in the M1 – M36 period are listed in the table below.

In total there have been:

- 11 contributions to 8 different exhibitions where project results have been presented.
- Around 1000 project flyers distributed at 6 different venues
- 6 posters at conferences
- 12 presentations at conferences
- 8 presentations to industry
- 4 published papers
- 3 submitted articles (published articles in next table)
- 2 international industrial workshops on piezoMEMS arranged
- 1 Market analysis

The contributions are available from the piezoVolume web page www.piezovolume.com

Table 1.1: piezoVolume dissemination activities

Nº	Type of activities	Main leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
2	Exhibitions	AIX	High volume piezoelectric thin film production process for microsystems	22.03.2010	Deutsche Physikalische Gesellschaft, Regensburg	Industry	1200	Mainly Europe, partly USA and Asia
12	Exhibitions	AIX	High volume piezoelectric thin film production process for microsystems	14.06.2010	Electroceramics XII, 13-16 June 2011, Trondheim, Norway	Scientific community (higher education, Research)	350	Focused piezo community worldwide
16	Exhibitions	AIX	High volume piezoelectric thin film production process for microsystems	09.08.2010	International Symposium on Applications of Ferroelectric, Aug. 9-12, Edinburgh, UK	Scientific community (higher education, Research)	400	piezo community worldwide
15	Exhibitions	SOS	piezoVolume - are you ready to revisit piezoelectricity?	19.10.2010	Semicon Europe 2010, Dresden 19-21 October 2010	Scientific community (higher education, Research) - Industry - Medias	4000	Europe, USA, Asia

18	Exhibitions	AIX	High volume piezoelectric thin film production process for microsy	15.03.2011	Deutsch Physikalische Gesellschaft, Dresden	Scientific community (higher education, Research)	1200	Mainly Europe, partly USA and Asia
28	Exhibitions	SOS	Piezoelectric MEMS - High volume deposition tools for high quality PZT thin films CSD coater	06.09.2011	Second International Workshop on Piezoelectric MEMS - EPFL, Lausanne, Switzerland	Scientific community (higher education, Research) - Industry	80	Europe, USA, Korea, Japan
29	Exhibitions	SOS	High volume deposition tools for high quality PZT thin films	12.10.2011	Semicon Europe 2011, Dresden	Scientific community (higher education, Research) - Industry - Medias	8000	Europe, USA, Asia
30	Exhibitions	AIX	DBLI for quality in-line inspection	12.10.2011	Semicon Europe 2011, Dresden	Scientific community (higher education, Research) - Industry - Medias	8000	Europe, USA, Asia
33	Exhibitions	AIX	aixACCT DBLI system for quality in-line	28.03.2012	Deutsche Physikalische Gesellschaft spring meeting, Berlin	Scientific community (higher	100	Europe

			inspection (new e31,f estimation)			education, Research)		
52	Exhibitions	AIX	High volume piezoelectric thin film production process for microsystems	29.05.2012	Ferroelectric meeting Japan, Kyoto	Scientific community (higher education, Research) - Industry	4000	Europe, Asia, Korea
41	Exhibitions	AIX	aixACCT DBLI system for quality in-line inspection (new e31,f estimation)	09.07.2012	ISAF - ECAPD - PFM - 2012, Aveiro Portugal, 9-13th of July 2012	Scientific community (higher education, Research) - Industry	700	world wide
46	Exhibitions	AIX	aixACCT DBLI system for quality in-line inspection (new e31,f estimation)	07.10.2012	2012 IEEE International Ultrasonics Symposium, Dresden, Germany, October 7 - 10, 2012	Scientific community (higher education, Research) - Industry	100	Europe
47	Exhibitions	AIX	aixACCT DBLI system for quality in-line inspection	09.10.2012	Semicon Europe 2012, 9-11 October, Dresden, Germany	Scientific community (higher education, Research) - Industry - Policy makers - Medias	4000	Europe, USA, Asia
48	Exhibitions	SOS	High volume deposition tools for high quality	09.10.2012	Semicon Europe 2012, 9-11 October, Dresden, Germany	Scientific community (higher	4000	Europe, USA, Asia

			PZT thin films			education, Research) - Industry - Medias		
36	Exhibitions	AIX	aixACCT DBLI system for quality in-line inspection	24.06.2021	Electroceramics XIII, June 24-27, 2012, Twente, The Netherlands	Scientific community (higher education, Research) - Industry	350	Europe, USA, Asia
6	Flyers	AIX	FP7 piezoVolume 2010—2013	18.05.2010	International Workshop on Piezoelectric MEMS - Materials, Tools, and Devices, May 18-19 2010, Aache	Scientific community (higher education, Research) - Industry	60	Europe, USA, Korea, Japan
10	Flyers	SIN	FP7 piezoVolume 2010—2013	14.06.2010	Electroceramics XII, 13-16 June 2011, Trondheim, Norway	Scientific community (higher education, Research)	350	Europe
12	Flyers	SOS	FP7 piezoVolume 2010—2013	19.10.2010	Semicon Europe 2010, Dresden 19-21 October 2010	Scientific community (higher education, Research) - Industry - Medias	4000	Europe, USA, Asia
23	Flyers	EPL	FP7 piezoVolume	06.09.2011	Second International Workshop on Piezoelectric	Scientific community	80	Europe, USA, Korea,

			2010—2013		MEMS - EPFL, Lausanne, Switzerland	(higher education, Research) - Industry		
34	Flyers	AIX	FP7 piezoVolume 2010 - 2012 (flyer revision 1)	24.06.2012	Electroceramics XIII, June 24-27, 2012, Twente, The Netherlands	Scientific community (higher education, Research) - Industry	350	Europe, USA, Asia
37	Flyers	SIN	FP7 piezoVolume 2010 - 2012	27.06.2012	COMS 2012, Tønsberg, Norway 24-27/6 2012	Scientific community (higher education, Research) - Industry - Policy makers - Medias	600	Europe, USA
20	Posters	SIN	piezoVolume 2010-2013	14.06.2011	COWIN event Helsinki	Scientific community (higher education, Research) - Industry	100	Europe
21	Posters	ISI	In-situ large scale deposition of PZT	25.07.2011	ISAF 2011, July 24th – 27th, 2011 in Vancouver, Canada	Scientific community (higher education, Research) - Industry	700	World wide

27	Posters	SIN	Modelling of piezoelectric micromachined ultrasound transducers (pMUT) for medical use	06.09.2011	Second International Workshop on Piezoelectric MEMS - EPFL, Lausanne, Switzerland	Scientific community (higher education, Research) - Industry	80	Europe, USA, Korea, Japan
31	Posters	EPL	Conception of an Interdigitated Electrodes Based Cantilever for Piezoelectric Energy Harvesting	15.11.2011	POWER MEMS 2011, Seoul, South Korea	Scientific community (higher education, Research) - Industry	100	Asia, USA, Europe
32	Posters	ISI	Influence of Platinum Bottom Electrodes on the Piezoelectric Performance of PZT Thin Films....	28.11.2011	2011 MRS Fall Meeting November 28-December 2, 2011, in Boston, Massachusetts	Scientific community (higher education, Research) - Industry	1000	USA, Europe, Korea, Japan
39	Posters	SIN	piezoMEMS - get more out of your MEMS	27.06.2012	COMS 2012, Tønsberg, Norway 24-27/6 2012	Scientific community (higher education, Research) - Industry - Policy makers - Medias	600	Europe, USA
3	Presentations	COV	Design and modelling of piezoMEMS -	18.05.2010	International Workshop on Piezoelectric MEMS - Materials, Tools, and Devices,	Scientific community (higher	60	Europe, USA, Korea, Japan

			Methodologies and case studies		May 18-19 2010, Aachen	education, Research) - Industry			
4	Presentations	AIX	Piezoelectric thin film material testing, process qualification, and reliability control	18.05.2010	International Workshop on Piezoelectric MEMS - Materials, Tools, and Devices, May 18-19 2010, Aachen	Scientific community (higher education, Research) - Industry		60	Europe, USA, Korea, Japan
5	Presentations	OER	Oerlikon PVD production solutions for piezoelectric materials	18.05.2010	International Workshop on Piezoelectric MEMS - Materials, Tools, and Devices, May 18-19 2010, Aachen	Scientific community (higher education, Research) - Industry		60	Europe, USA, Korea, Japan
7	Presentations	SIN	High volume piezoelectric thin film production process for microsystems	19.05.2010	International Workshop on Piezoelectric MEMS - Materials, Tools, and Devices, May 18-19 2010, Aachen	Scientific community (higher education, Research) - Industry		60	Europe, USA, Korea, Japan
8	Presentations	OCE	Piezo printhead analysis	19.05.2010	International Workshop on Piezoelectric MEMS - Materials, Tools, and Devices, May 18-19 2010, Aachen	Scientific community (higher education, Research) - Industry		60	Europe, USA, Korea, Japan
9	Presentations	SIN	Industrial fabrication of piezoMEMS	13.06.2010	Piezoinstitute training course at Electroceramics XII, 13-16 June 2011, Trondheim,	Scientific community (higher		10	Europe

					Norway	education, Research) - Industry		
11	Presentations	SIN	SINTEF moveMEMS - a standard process for piezoelectric microsystems prototyping	16.06.2010	Electroceramics XII, 13-16 June 2011, Trondheim, Norway	Scientific community (higher education, Research) - Industry	30	Europe
15	Presentations	AIX	Dielectric Meeting Japan	15.10.2010	Tokyo	Scientific community (higher education, Research)	100	Japan
19	Presentations	AIX	Worlds First DBLI for quality in-line inspection	30.05.2011	Milano, Italy	Industry	12	Italy, France, USA
24	Presentations	SIN	piezoVolume – High volume piezoelectric thin film production process for microsystems	07.09.2011	Second International Workshop on Piezoelectric MEMS - EPFL, Lausanne, Switzerland	Scientific community (higher education, Research) - Industry	80	Europe, USA, Korea, Japan
25	Presentations	OER	Oerlikon PVD production solution for in-situ large scale deposition	07.09.2011	Second International Workshop on Piezoelectric MEMS - EPFL, Lausanne, Switzerland	Scientific community (higher education, Research) - Industry	80	Europe, USA, Korea, Japan

26	Presentations	AIX	Qualification and Quantification of piezoelectric MEMS	07.09.2011	Second International Workshop on Piezoelectric MEMS - EPFL, Lausanne, Switzerland	Scientific community (higher education, Research) - Industry	80	Europe, USA, Korea, Japan
33	Presentations	ISI	Optimised Piezoelectric PZT Thin Film Production on 8" Silicon Wafers for Micromechanical Applicatio	18.06.2012	TechConnect World, June 18-21, 2012, Santa Clara, California	Scientific community (higher education, Research) - Industry - Medias		Europe, USA, Asia
36	Presentations	SIN	How to make an "old" material class the cutting edge - FP7 piezoVolume – High Volume Piezoelectric T	27.06.2012	COMS 2012, Tønsberg, Norway 24-27/6 2012	Scientific community (higher education, Research) - Industry - Policy makers - Medias	600	Europe, USA
37	Presentations	EPL	FP7 piezoVolume - High Volume Piezoelectric Thin Film Production Process for Microsystems	10.07.2012	ISAF - ECAPD - PFM - 2012, Aveiro Portugal, 9-13th of July 2012	Scientific community (higher education, Research) - Industry	400	Europe, USA, Asia

39	Presentations	COV	Novel Software Environment for design and simulation of piezoMEMS	20.09.2012	SMACD 2012, 19-21 September, Seville, Spain	Scientific community (higher education, Research) - Industry	600	Europe, USA, Asia
41	Presentations	VER	pMUT for High Intensity Focused Ultrasound	10.10.2012	2012 IEEE International Ultrasonics Symposium, Dresden, Germany, October 7 - 10, 2012	Scientific community (higher education, Research) - Industry	300	Europe, USA, Asia
1	Web sites/Applications	SIN	piezoVolume website	01.03.2010	www.piezovolume.com	Scientific community (higher education, Research) - Industry	1000	world
44	Web sites/Applications	SIN	Webpage for piezoMEMS competence centre	10.10.2012	www.piezomicrosystems.com	Scientific community (higher education, Research) - Industry		world
38	Publication	OER	Cooperating on PZT Films for MEMS	01.09.2012	CHIP Oerlikon Cumstomer Magazine	Industry - Medias	1000	Europe, USA, Asia
40	Publication	VER	pMUT for High Intensity Focused	07.10.2012	IEEE-UFFC Symposium 2012 Proceedings	Scientific community (higher		Europe, USA, Asia

			Ultrasound			education, Research) - Industry		
46	Publication	COV	A Novel Software Environment for Design and Simulation of piezoMEMS	15.12.2012	Proceedings of SMACD 2012	Scientific community (higher education, Research) - Industry		Europe, USA, Korea, Japan
2	Workshops	AIX	International Workshop on Piezoelectric MEMS - Materials, Tools, and Devices	18.05.2010	aixACCT Systems GmbH, Aachen, Germany	Scientific community (higher education, Research) - Industry	60	Europe, USA, Korea, Japan
22	Workshops	EPL	Second International Workshop on Piezoelectric MEMS - Materials, Tools, and devices	06.09.2011	EPFL, Lausanne, Switzerland	Scientific community (higher education, Research) - Industry	80	Europe, USA, Korea, Japan

1.3 Publications

In the M1 – M36 period 4 papers have been published:

№	D.O.I.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Date of publication	Relevant pages	Permanent identifiers (if available)
1	10.1109/ISAF.2011.6013981	In-situ large scale deposition of PZT films by RF magnetron sputtering	Martin Kratzer	Applications of Ferroelectrics (ISAF/PFM) 2011	24-27/7 2011	08.09.2011	1-4	http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=6013981
2	10.1109/ISAF.2011.6014133	Influence of platinum bottom electrode on the piezoelectric performance of hot RF sputtered PZT films	Dirk Kaden	Applications of Ferroelectrics (ISAF/PFM) 2011	24-27/2 2011	08.09.2011	1-4	http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=6014133
3	10.1557/opl.2012.450	Influence of Platinum Bottom Electrodes on the Piezoelectric Performance of PZT Thin Films Hot Sputtered in a High Volume Production Tool	Dirk Kaden	MRS Proceedings	Volume 1397	25.02.2012	13-31	http://journals.cambridge.org/action/displayAbstract?fromPage=online&aid=8502281
4		Optimised Piezoelectric PZT Thin Film Production on 8" Silicon Wafers for Micromechanical Applications	Dirk Kaden	Nanotechnology 2012: Electronics, Devices, Fabrication, MEMS, Fluidics and Computational (Volume 2)	Volume 2	01.10.2012	176-179	ISBN 978-1-4665-6275-2

1.4 Industrial workshops on piezoMEMS

Open seminars have been given from the very beginning of the project and this might be a major reason for the success of dissemination of knowledge off this project.

AIX and EPL have organized the first Workshop on Piezoelectric MEMS in May 2010 in Aachen. The idea for this open seminar was born in early February after the start up meeting of the project. It was quite short notice to the community but non the less with engagement and networking especially Paul Muralt and Stephan Tiedke could convince about 75 people to join this workshop and it has been a great success, because needs of this emerging field were mentioned by the .industry and piezoVolume could introduce its goals. Therefore right from the beginning the whole community was informed on the goals of the project and generated decisive interest in the project results. The combination of demand from industry and the goals of the project formed a “magic” symbiosis. Throughout the project runtime especially industry was deeply interested in any progress within the project and also gave ideas to the project partner where to look at in detail. Best example is comment of Thomas Metzger from EPCOS, Munich during this first open seminar. He was pretty much interested in a kind of material qualification of a thin film PZT, similar to what is published on bulk PZT e.g. from Motorola. In order to prepare such a specification it appeared that first test procedures for characterization and influence of poling had to be studied. This is one of the major contributions of the project to the community, which will be published during the third Workshop on Piezoelectric MEMS.
The second Workshop organized by Paul Muralt, EPL in Lausanne, September 2011 showed the progress that was achieved in the field and like during the first workshop all partners could present their results.

The great success of the project is that the established workshop within the piezoVolume project will continue even after the project has expired. It is the most important meeting especially for industry in this field. We had planned to have a third open seminar during the project runtime, but due to the date of the third workshop on piezoelectric MEMS in April 2013 and the number of presentations at ECC, Twente in June 2012, ISAF, July 2012 and UFFC, October 2012 the community felt well informed and the interest for an open seminar that we had planned to be organized around the final meeting of the piezoVolume project in December 2012 in Paris was fairly low. Especially European companies had already entered into contact with many of the piezoVolume partners for wafer sampling and demonstrations, discussions etc.

As a summary for the project we would use the following sentence:

There is no other project in the world which had such a decisive impact on the piezoelectric MEMS community worldwide as piezoVolume.

International Workshop on Piezoelectric MEMS - Materials, Tools, and Devices 2010
Key numbers
The first International Workshop on Piezoelectric MEMS workshop was organized by AIX and EPL and has 60 participants from Europe, USA and Asia. piezoVolume was presented by distribution of the project flyer as well an invited talk. The project partners contributed with additional 4 talks on more focused subjects.

4.1.1 Impressions

Thorsten Schmitz-Kempen (AIX), Klaus Prume (AIX), Paul Muralt (EPL) and Stephan Tiedke

Mareike Klee of Philips showed in her plenary talk the excellent performance of thin film devices and micromachined bulk devices, which is great news to the piezo-MEMS market.
Paul Muralt of EPFL, Susan Troiler McKinstry of Penn State, and Kenji Shibata of Hitachi Cable reported on AlN, PZT and KNN state of the art materials. All of them showed great progress in film performance, which already stimulated new product developments.
It was shown that the entire infrastructure for the piezoMEMS production is available today and various vendors introduced their deposition tools, etching and testing tools. EPCOS, EPSON and Siemens impressed with their successful market introduction of AlN and PZT based piezoelectric MEMS products.
The essence of the workshop was that piezoelectric MEMS are a mature technology which will enable further products in the near future and push the system integration to the next level. Piezo-filter and ink jet printer heads are currently the mass produced products, but particle detection, micro switches, tilted mirror arrays, and pressure sensors etc. will become future products based on this technology. PiezoMEMS offer many advantages including smaller driving voltages at the same mechanical displacement comparable to electrostatic MEMS and no static power consumption.

Susan Trolier McKinstry (Penn State Univ.) giving a talk on PZT films for MEMS devices

Here are a few comments from participants of the workshop:

- "Definitely one of the most interesting workshops of the last years, also because it was well focused..." Dr. Metzger, EPCOS AG, Germany
- "Very useful workshop, well organized, something worth repeating" Dr. Westland, OCÉ Technologies, The Netherlands
- "What a great meeting..." Dr. Jowoong Ha, INOSTEK Inc., Korea

Second International Workshop on Piezoelectric MEMS - Materials, Tools, and devices 2011

Key numbers
The Second International Workshop on Piezoelectric MEMS workshop was organized by EPL and had 80 participants from Europe, USA and Asia. piezoVolume was presented by distribution of the project flyer as well an invited talk. The project partners contributed with additional 2 talks on more focussed subjects as well as contributing to the workshop exhibition (AIX, OER and SOS). 1 Poster was also presented.

General impression
The market of piezoelectric MEMS is growing, indicated by the increasing number of participants. A second indicator is the number of industry contact that we had over the year 2011 and during the workshop. The third indicator for the opening of the market window is the tremendous development of tools during the last 14 month since the last workshop in 2010 in Aachen. The Workshop was organized really excellent and this with quite a small number of group members! Congratulations to Paul Muralt! A lot of industry presentations as well as scientific, but the number of industry participants clearly indicates the need for in industry focused meeting.

The large companies that start to produce piezoMEMS or intend to produce these MEMS in the next two years drive this technology. Panasonic, EPSON, Seagate, OCE, HP. Beside these big players also smaller companies Boeckler, Festo, Sonitor, Vermon and Silicon Foundry Service companies like Silex and SVTC pay attention to this technology. This is exactly what we have predicted during the workshop 2010. But this happens earlier than expected. Tool suppliers should invite potential customers for tool demonstration into their labs to demonstrate the technology. Maybe cooperation between deposition tool and testing tool suppliers are quite helpful to help potential buyers to do a kind of feasibility study easily.

The third meeting in the series will be held in April 2013 in Washington. In fact this means that project partners AIX and EPL have established a well-recognized meeting for industry people in the

1.5 Company Seminars

To disseminate the knowledge gained during the project, company seminars were given. Especially in Japan, were companies gather information first before they enter a new market, seminars are very welcome. Due to the FeRAM business which is based on PZT thin films, Japan had some advantage by entering this new emerging field. Companies like EPSON were already producing PZT FeRAM when they entered into piezoelectric thin films. Therefore, most of the activities are based in Japan.

Seminars were given by AIX during a meeting of the Physical Society Japan in October 2010, company seminars on progress of the piezoVolume meeting were given once per year. The list of companies visited is given above in Table 1.1. These dissemination activities have provided the chance to the system manufacturers of WP2 to get into contact to these companies.

2 EXPLOITATION OF RESULTS

2.1 Exhibitions

To introduced the infrastructure that was generated during the project runtime to a wider audience manufacturers of the deposition and test systems have been visiting exhibitions mainly in Europe and one exhibition in the USA. This allows drawing the attention of decision makers to this new technology at an early stage. E.g. if decision makers learn about the progress in performance of piezoelectric coefficient and learn about demonstrators that work, they can consider this emerging technology for future projects in their companies.

2.2 Demonstrations of tools

A more focused way of introducing the deposition and test systems to the known community of piezoelectric MEMS is to do LIVE demonstrations of the tool or WAFER SAMPLING. Both ways have been used within the project. Some of them are listed in table 2.1

2.3 Company seminars

An alternative way to give demos of tools and wafer sampling is to give seminars in companies. Especially in Asia and the USA it is a more common way to introduce a new technology. This has been done by the system suppliers of WP2 OER, AIX, COV and SOS. Companies were very much interested in status and results of the piezoVolume project, because this project is the most visible worldwide in this field

Table 1.2.1: Core part of customers driving the piezoMEMS technology into mass applications

Company	Continent	Industry Area	Estimated market entry
EPSON	Japan	Printermanufacturer	2011
SAMSUNG Mechanics	Korea	MEMS manufacturer	2013
TDK	Japan	HDD	2013
Seagate	USA	HDD	2014
Qualcomm	USA	Telecommunication	??
Rohm	Japan	Automotive	??
Murata	Japan	Telecommunication	??
EPCOS	Europe	Telecommunication	2015
AIST	Japan	National Research Lab	
Advantest	Japan	RF switches	2013
Mitsumi	Japan	MEMS manufacturer	??
Silex	Europe	Foundry service	2013
ST Mixcroelectronics	Europe	Foundry service	2013
Hitachi	Japan	Foundry service	2013
RICOH	Japan	Printer manufacturer	2014
HP	USA	Printer manufacturer	??
XAAR	Europe	Printer manufacturer	??
Fuji Dimatix	USA	Printer manufacturer	??
Mitsubishi Materials	Japan	Material Supplier	2012

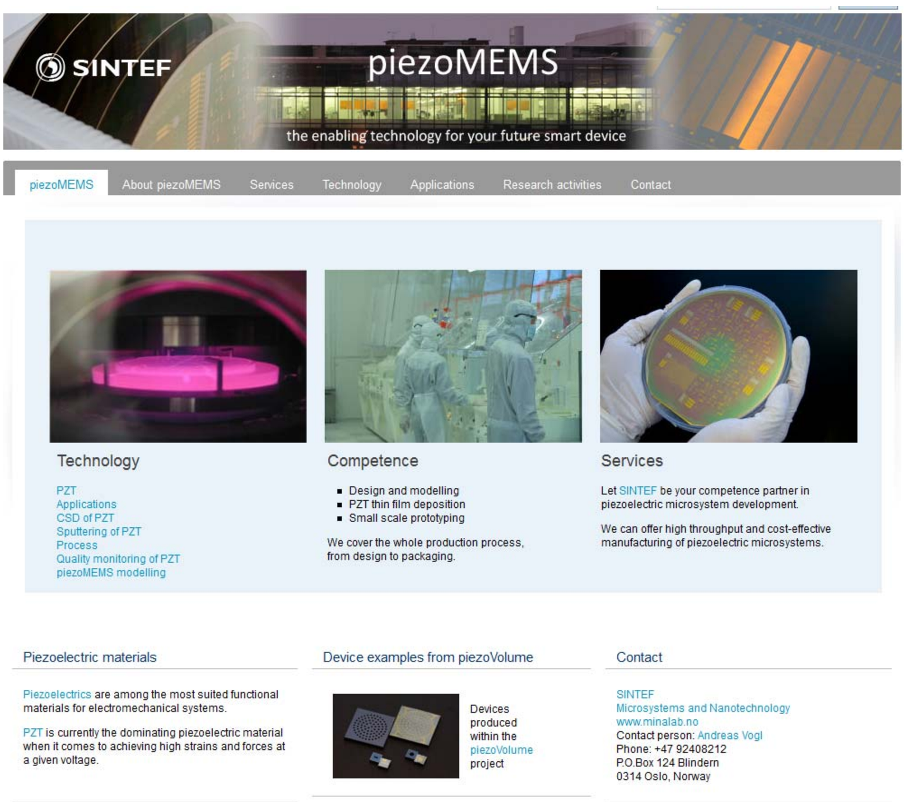
2.4 Competence centre

The Competence Centre (CC) created within the project is a perfect match to people who want to get started with Piezoelectric MEMS. This CC definitely cuts down time of feasibility study. People within the CC have worked with design, modelling, process development and fabrication of piezoeMEMS since 2002. The CC have a large network to infrastructure as well as experts in order to guide people through the difficulties of the first step with this new technology.

Some core benefits:

- Long experience in piezoMEMS (since 2002)
- Experienced project partner
- Deposition process and tools for high-performance PZT thin films on silicon wafers
- Modelling software specifically for piezoMEMS
- Modelling of device ideas and design assistance
- Evaluation of alternative processing routes
- Testing services and sophisticated testing equipment
- Manufacturing of prototypes
- Small scale production using 150 mm wafers (now) and 200 mm wafers (soon)
- Aims to have agreement with large MEMS fab for direct transfer to high volume production

Go to the Competence Centre web page:
www.piezomicrosystems.com

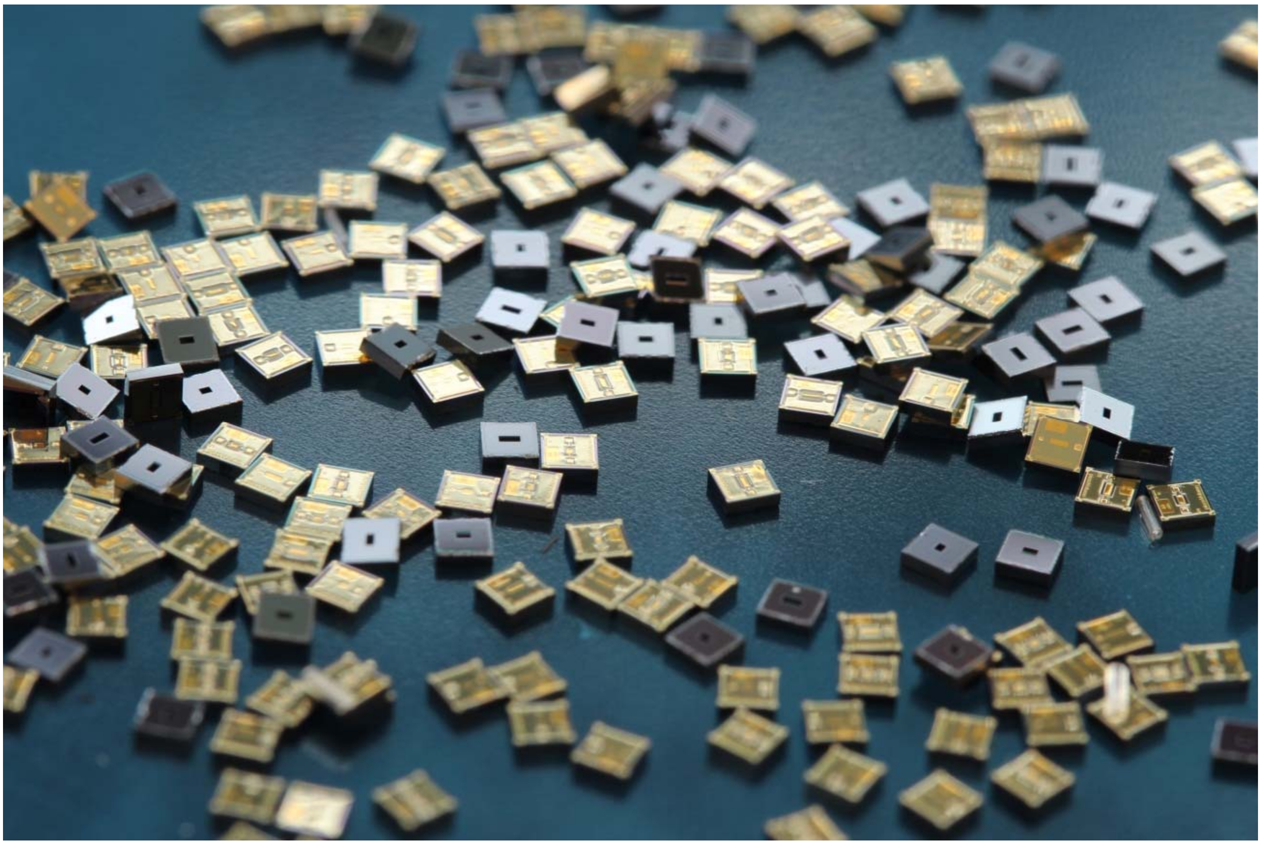


3 THE EXPLOITATION ASSISTANCE PACKAGE

piezoMEMS design and fabrication

A guidebook in how to enter into piezoMEMS technology

The piezoVolume exploitation assistance package
Editor: The piezoVolume consortium



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4 INTRODUCTION

The MEMS market is increasingly turning its attention to creating semiconductor-based devices that convert real-world non-digital as well as non-electronic information such as mechanical, thermal, acoustic, chemical, optical and biomedical phenomena to and from the digital domain. One particularly promising technology is the integration of piezoelectric thin films with silicon MEMS (Micro-Electro-Mechanical Systems). Piezoelectricity is the ability of some materials to generate an electric potential in response to applied mechanical stress. This may take the form of a separation of electric charge across the crystal lattice. The piezoelectric effect is two-way in the sense these materials both generates a charge when stress is applied (direct effect) and a strain when an electrical field is applied (converse effect).

PiezoMEMS have already demonstrated their potential for use in mass product applications like ink-jet print heads by EPSON and Matsushita. As of 2012 there are many others to come. Examples of known future applications are: RF switch, filters, gyro sensor, tilted mirror arrays, energy harvester, particle detection for biomedical applications and actuators for fine positioning in HDD. More market information can be found in 5.

Some advantages of piezoMEMS technology

One of the main advantages of piezoMEMS technology is the diversity of applications it can be applied for. Due to the two-way operation of piezoelectric materials going all the way from DC operation several tens of MHz piezoMEMS technology provides a pool of design opportunities. Fabrication technology for piezoMEMS can hence address a very wide window of opportunities.

Some application examples sorted on the operation mode is shown in Table 4.1:

Direct effect: sensors, energy conversion	Converse effect: linear actuators	Converse effect: with resonant ultrasound excitation	Both effects in resonance: resonant transducer
• **Vibration sensor** • **Accelerometer** • **Microphone** • **Photoacoustic sensors** • **Energy scavenging from vibrations**	• Vibration damper • Optical scanner • Optical switch • Micro and nano probes • Switch/relay, RF switch • Valve • Droplet ejector, inkjet	• Ultrasonic stator for micromotor • Liquid delivery	• **Thickness bulk waves:** ultrasonic imaging, RF filters, transformers • **Plate waves:** ultrasonic imaging, proximity sensors
Active damping			

Table 4.1: Classification of applications of piezoMEMS

piezoMEMS technology can also in addition to be a tool for pushing miniaturization and power consumption also be an enabling technology. One example is the use of piezoelectric actuators in MEMS. A piezoMEMS actuator using PZT is compared with other MEMS actuator technologies in Figure 4.1 and displays an unique combination of blocking force and displacement.

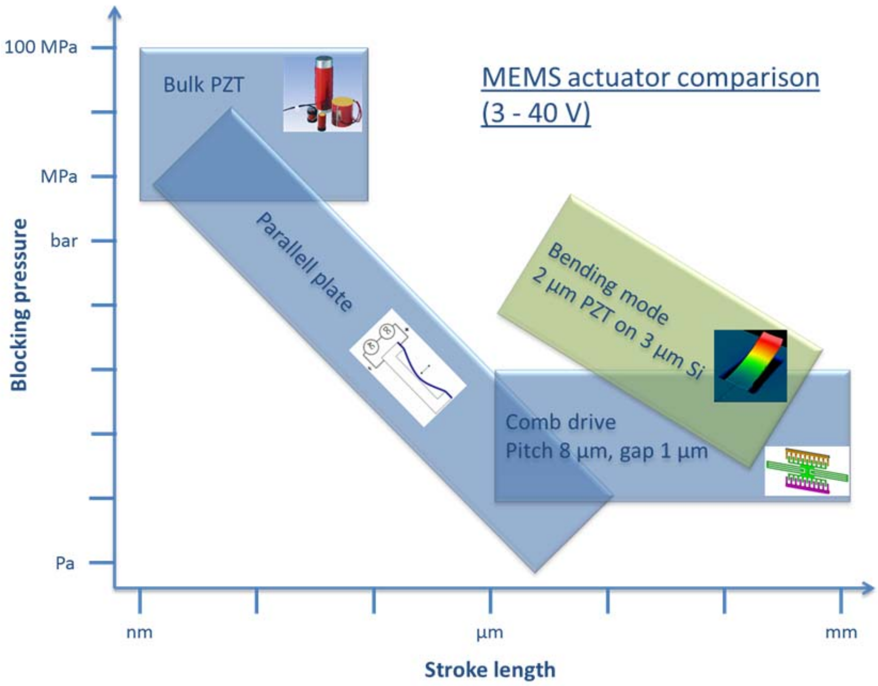


Figure 4.1: Piezoelectric thin film PZT provides a unique combination of stroke length and blocking force in MEMS

Such actuators can be used in RF MEMS switches. Compared to today's electrostatic switches a piezoMEMS switch would have two major advantages. Firstly, there would be no static power consumption and secondly the operation voltage can be reduced by circa a factor of four. The first advantage is very positive for mobile applications and for power consumption in general. The second advantage reduces cost in manufacturing, because the hybrid circuit that transforms the CMOS logic information into turning the switch ON and OFF will be less expensive.

The trend of adding complexity into chips is a driving force for piezoMEMS technology as well, if one application needs several features that can be realized in piezoMEMS technology, like RF switch, filter and gyro-sensor. Nowadays PZT material is already in use for buffer capacitors in integrated circuits. Taking all these facts together there is a clear cost advantage when using piezoMEMS technology.

Getting started

How can everyone evaluate this technology for his product idea? How does it work in general, when virtually a new product idea is going to be realized in piezoMEMS technology?

- First modelling with data that were derived within the project which are more accurate than literature data.
- Second device design and modelling of the design with available process data.
- Third, search for someone who can build deposit the piezoelectric film and someone who can build the prototype. But which manufacturing technologies are available and mature.
- From the deposited film and manufactured device we can derive material and device properties in order to optimize the model and to optimize the design and functionality.

Usually, the threshold for introducing a new technology is burdensome and time consuming. But piezoVolume has created infrastructure and know how to assist people who want to use this new technology in their products to perform feasibility studies. The Competence Centre (CC) created within the project is a perfect match to people who want to get started with Piezoelectric MEMS. This CC definitely cuts down time of feasibility study. People within the CC have their network to infrastructure as well as experts in order to guide people through the difficulties of the first step with this new technology.

5 PIEZOMEMS MARKET ANALYSIS

The first development and application spot will be driven by high volume users, mainly the printer industry and other big electronic companies. The driving forces for the printer industry to go to piezoMEMS are:

- True color printing
- Smaller printing holes for higher resolution
- Higher printing speed (10-30 kHz); lower mass to be moved

The current technology is either heating the ink for provoking ink ejection (HP) or using micromachined bulk piezo material in order to reach an activation voltage < 50 V for ink ejection (all other printer manufacturers).

In order to drive the PZT development very often an R&D Laboratory – industrial user pairing can be observed. Here are some examples:

R&D:	Industrial user:
Aist	various Japanese customers
CEA Leti	ST Microelectronics and other EU companies
Pennsylvania state Univrsity	US – Industry
FhG ISIT	OCE Printer NL
SINTEF	Silex
Oregon State University	HP-Corvallis
Internal R&D	Samsung

The needed clean room and tool invest is relatively high (5-6 M€) and can be only be stemmed by big users, mainly the printer industry.

There are a lot of other applications for PZT, mainly in the MEMS industry. By the nature of these emerging industries, companies are rather small and have not the ability to raise sufficiently fund for an own PZT production. A possible solution would be to create PZT foundry services, with a well-established production process, that delivers PZT layers (structured or unstructured) to the MEMS industry. PZT applications and the PZT market are just in front of the transition, going from high volume users to foundries.

Here some examples for potential markets:

MEMS Applications:

- **Printer industry:** This is clearly the biggest market and is partly already established today by some companies (2011 – 2012)
- **HDD read write heads adjustment:** The technology leader is TDK. The market break through is expected this year (2012)

- **Various telecommunication applications:** Depending on the application the markets will start from now to the next 2 years (2012 – 2014)
- **Automotive market:** telemetry sensors, like tire pressure measurement. They are power autarkic up to 300 µW/cm³. This market is estimated to come in the next years. (2015)
- **Small speakers:** To be integrated directly into MEMS.
- **Energy harvesting:** feeding power to small transmitters etc. This market is estimated to go faster than expected in the next years (2015)
- **Non ink printing applications:** This concerns mainly printing of electronic materials. This market is estimated to be even 9 times higher than the ink printing market. (2014)

Medical applications:

- **Particle detection:** Detection via resonance frequency change of a cantilever by mean of a particle load. Market will come soon (2013)
- **HF scanner:** Development of high frequency scanners (10-30 MHz) for skin cancer detection.
- **Cardiac pacemaker:** The development of cardiac pacemakers based on KNN (Potassium Sodium Niobate) needs still some amount of time due to the fact that the material needs to be developed further for use in MEMS and has to run through medical acceptance procedures.
- **KIST:** This is a **sensor pill** developed by a Korean company. The integrated camera can be set into focus be mean of a PZT layer.

Other Applications:

- **Buffer capacitors:** The permittivity of PZT materials of typically 200 $A \cdot s \cdot V^{-1} \cdot m^{-1}$ catches interest for creating capacitors beyond the typical MEMS applications. The value might be enhanced up to 400 and even 600.

6 PIEZOMEMS SPECIFIC TOOLS AND PROCEDURES

6.1 piezoMEMS design and modelling tools

6.1.1 Development of new piezoMEMS

PiezoMEMS enable an exciting broad range of new applications ranging from ultrasonic imaging transducers, positioning systems for handheld devices, sensors for pressure, flow and gas, micropumps and energy harvesters – just to name a few. In many cases the development of such new applications require new piezoMEMS devices or redesign of existing ones in order to fully meet the system specification.

As a first step in the product development process engineers usually imagine new concepts or new designs. These ideas need to be validated via a feasibility study. It is very important for the success of study that many design concepts are developed and evaluated simultaneously so as to offer enough choices for a successful product. In piezoVolume, Coventor[2] developed a development strategy that links design and manufacturing process by establishing systematic design methodology implemented into a common CAD framework. This design methodology offers not only the ability to create and evaluate several concepts rapidly and with confidence, but also to gain a deep understanding of the physical behaviour of the device. Compared to a "build and test" approach cost is reduced by limiting the number of expensive fab cycles, producing less waste and consuming less energy. As an overall result the product can be placed earlier in the market.

Conceptual Design Phase PiezoMEMS should be studied not only on device but also on the system level as the final aim is to optimize the system for targeted performances. The first step to any simulation is to create a device model.

From the very beginning the material and process data should be considered when modelling piezoMEMS devices. For this reason a design kit for piezoMEMS (MoveMEMS PZT technology from SINTEF) is provided together with Coventor tools that includes the essential technology data. Based on this design kit a model can be constructed in the system level modelling platform MEMS+. Here, the MEMS designer works in a 3D graphical environment to assemble a parametric model using high-order MEMS-specific finite elements (piezo-mechanical shells). Each element is linked to the process description and material database so that piezoelectric material properties are assigned automatically. The high-order elements provide a precise mathematical description of the device physics but using a lower number of degrees of freedom compared to traditional finite element techniques. This enables rapid, accurate simulation of the device physics and the ability to co-simulate the device with the conditioning circuit in Cadence Virtuoso or in Matlab/Simulink. For example, the designer can tune the piezoMEMS device dimensions to attain a maximum actuation displacement or a certain resonance frequency before simulating the device with different electronic circuits to compare the performance of each type.

6.1.2 Detailed Design Phase

Further detailed modelling can be undertaken using CoventorWare's multi-physics field solver to investigate details of the design. This analysis framework uses finite element and boundary element methods and includes a materials property database, a process and layout editors, a 3-D

[2] www.coventor.com

model and mesh generator, and electrostatics and mechanics field solvers, the latter with boundary conditions and features for PiezoMEMS. As the MEMS+ platform, it includes a process entry user interface with a ready to use library of foundry processes, e.g. the calibrated MoveMEMS SINTEF process for PZT piezoMEMS[3].

Both tools MEMS+ and CoventorWare can be combined. This so called hybrid approach has numerous advantages. For example, the design can be checked for high stress areas that may lead to breakage when the device is overloaded due to a shock. Gas damping coefficients can also be simulated and included in the MEMS+ model to accurately predict the Q-factor. An additional benefit is that simulation results from MEMS+ and CoventorWare can be verified against each other. Simulating piezoelectric harmonic analysis with a linear resistive load is one such example of a point of comparison between both tools.

6.1.3 Preparation for Fabrication

Once design is optimized, the next step is to prepare fabrication. Coventor's layout editor is used by designers to create masks and transfer them to the foundry for manufacturing. In this development phase new errors or uncertainties may arise. In addition to Design Rule Check on the 2D layout, design verification can be performed via virtual manufacturing SEMulator3D enables such virtual fabrication. The tool uses novel "voxel" technology (volumetric pixels) to build highly detailed, virtual 3D prototypes. Input is from 2D masks in industry-standard GDSII format, along with a calibrated description of the specific fabrication process. It offers a productive methodology that enables engineers to understand and communicate process flow and device design through interactive visualization and quantitative measurements. Areas of usage include process documentation, process modelling and optimization, process communications with foundry customers and piezoMEMS design verification prior to actual fabrication. It also includes a volume mesher to get a discretized model nearer reality which can be used then back into FEA tool like CoventorWare for final verification and testing. For examples, temperature influence or parasitic capacitances can be evaluated more precisely.

6.1.4 Recommendation

For low cost, efficient volume manufacture of piezoMEMS products, engineers should adopt a design methodology that incorporates details of the process through qualified and re-usable design kits containing both process characterization and material properties. Having reliable materials properties and process information available is important in enabling effective design and maximizing the probability of first pass success - reducing development cost and time. Looking forward, the success of any development approach for piezoMEMS will be measured by the ability to select the best design option. This will result in higher yield, and ramp-up to volume production in considerable shorter time scales than traditionally seen in the MEMS industry. One route to achieve this is to explore and exploit the many design possibilities quickly and accurately by leveraging proven electronic design automation (EDA) methodologies.

[3] SINTEF MoveMEMS: www.piezomicrosystems.com

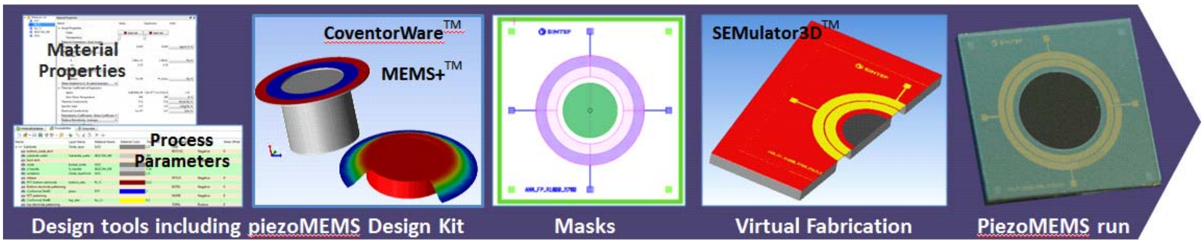


Figure : PiezoMEMS design flow from simulation through fabrication

6.1.5 Design tools

Different tools for the design and modelling of piezoMEMS have been developed by Coventor and are available. These software tools are calibrated to the PZT processes and enable engineers to simulate and optimize piezoMEMS designs before committing to build-and-test cycles. Coventor's MEMS+ and CoventorWare provide a design and simulation platform for MEMS designers, enabling them to simulate end-product performance specs such as sensitivity, linearity, frequency response, signal-to-noise, and temperature stability. SEMulator3D is a unique modelling tool for virtual fabrication, enabling them to review designs and detect process issues in advance of actual fabrication.

For mask layout any design tool which can generate a GDSII-file is appropriate, e.g. L-Edit. For L-Edit, also a piezoMEMS mask layer setup is available.

6.1.5.1 Design exploration and system-level simulation

The design platform MEMS+ allows to, quickly explore design alternatives, and to optimize performance with high accuracy. With Coventor's design flow the PZT technology comprising material and process data is already defined. To start with, a model of the piezoelectric device is constructed in MEMS+. Here, the MEMS designer works in a 3D graphical environment to assemble a parametric model using high-order MEMS-specific finite elements (piezo-mechanical shells). Each element is linked to the process description and material database so that piezoelectric material properties and electrodes are assigned automatically. The high-order elements give a precise mathematical description of the device physics using a low number of degrees of freedom. This enables rapid, accurate simulation of the device physics in Matlab/Simulink, and the ability to easily co-simulate the device with the conditioning circuit in Cadence Virtuoso. For example, the designer can tune the piezoMEMS device dimensions to attain a maximum actuation displacement or a certain resonance frequency before simulating the device with different electronic circuits to compare the performance of each type.

6.1.5.2 Design refinement and validation

Further detailed modelling can be undertaken using CoventorWare's field (or Finite-Element)) solvers to investigate details of the design. For example, the design can be checked for high stress areas that may lead to breakage when the device is overloaded due to a shock. Gas damping coefficients can also be simulated and included in the MEMS+ model to accurately predict the Q-factor. An additional benefit is that simulation results from MEMS+ and CoventorWare can be verified against each other. Simulating piezoelectric harmonic analysis with a linear resistive load is one such example of a point of comparison between both tools. Coventor's solution for piezoelectric devices combines MEMS+ and CoventorWare to provide hybrid solution that solves the coupled and multi-domain physics not addressed with traditional point tools.

6.1.5.3 *Virtual fabrication*

The 3D process modelling tool SEMulator3D enables virtual fabrication of piezoMEMS processes. Based on voxel (volumetric pixels) modelling technology, SEMulator3D has the ability to emulate complete process flows and build highly detailed, virtual prototypes. Input to the tool is only the 2D masks in GDSII format. Description of the calibrated PZT fabrication process is already available.

SEMulator3D offers a productive methodology that enables engineers to understand and communicate process flow and device design through interactive visualization and quantitative measurements. Areas of usage include process documentation, process modelling and optimization, process communications with foundry customers and piezoMEMS design verification prior to actual fabrication.

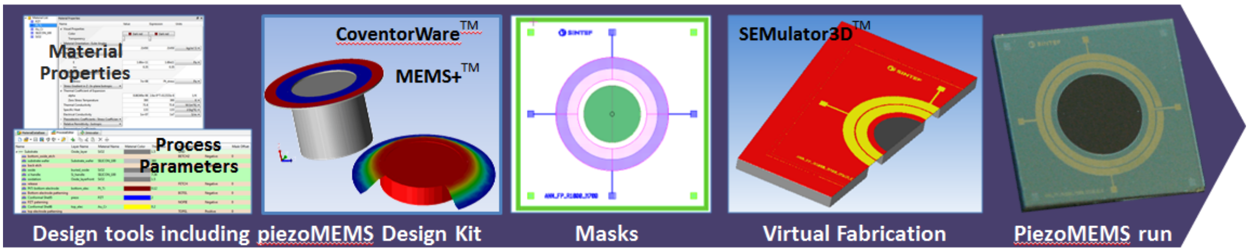


Figure 6.1: PiezoMEMS design flow integrating Coventor tools suite

All Coventor tools have process entry user interfaces that allow import of ready-to-use and calibrated piezoMEMS PZT technology template files, e.g. MoveMEMS SINTEF process.

6.2 piezoMEMS design rules

6.2.1 CMOS materials compatibility

PZT, Pt- and Au are materials that are not CMOS compatible. In many fabs the use of such materials must be strictly controlled to allow for simultaneous processing of components that need a CMOS compatible lab. For example, minute quantities of Pt or Au may contaminate both tools and clean wafer batches beyond repair.

Limitations on accepted materials vary between different labs and foundries and have to be addressed when planning the fabrication.

6.2.2 Material specifications

6.2.2.1 *Wafer specifications*

The process starts with a (bonded) silicon on insulator (SOI) wafers with an 8 µm device layer. The device layer of the SOI wafer defines together with the deposited layers the thickness of the resonating structures. 8 µm is found to be a good compromise between stiffness of resonators and mechanical strength during manufacturing. However, other thicknesses are available on demand.

Table 3.1: Example of wafer specification used for piezoMEMS

Device layer	**Diameter**	150 mm
	Type/Dopant	N/Phos
	Orientation	<100>
	Thickness	8 um
	Resistivity	1-10 Ohmcm
	Finish	Polished
Buried thermal oxide	**Thickness**	500nm
Handle wafer	**Type/Dopant**	N/Phos
	Orientation	<100>
	Resistivity	1-10 Ohmcm
	Thickness	500 µm
	Finish	Polished

6.2.2.2 PZT film specifications

The electromechanical properties of a film are different from those in bulk materials as the film is clamped to the substrate. The processing steps and in particular the thin film deposition process will also introduce a specific material quality. Deconvolution of real material coefficients often requires detailed knowledge of the elastic constants of the materials involved in the system, constants that may or may not be known. Hence, when dealing with thin film structures it is more convenient to operate with “effective” coefficients:

$$e_{31,f} = \frac{d_{31}}{s_{11}^E + s_{12}^E} = e_{31} - \frac{c_{13}^E}{c_{33}^E} e_{33}$$

$$d_{33,f} = d_{33} - \frac{2s_{13}^E}{s_{11}^E + s_{12}^E} d_{31}$$

With d_{xx} being the piezoelectric coefficient, e_{xx} the piezoelectric modulus, s_{xx} the elastic coefficient, c_{xx} the elastic constant in the direction given by the indices.

Films and devices are characterized electrically by measuring the electrical permittivity, CV, ferroelectric hysteresis and piezoelectrically by measuring the transversal piezoelectric charge coefficient $e_{31,f}$ with a 4-point bending measurement setup. Material parameters may vary according to the deposition method and level of defects.

Table 3.2: Parameters for the PZT film

Parameter	Value
E, Young's modulus	73 GPa
Poisson's ratio	0.288
Linear CTE	2.5 ppm
Density	7750 kg/m^3
Stress for non-poled PZT	30-160 MPa
Stress for poled PZT	50-200 MPa
Relative permittivity, , ε_r	1200 - 1600
Dielectric dissipation factor, tanδ	0.029
Breakdown field (typical)	> 300 kV/cm
$-e_{31,f}$ @ 1 Hz, zero bias	15-20 C/m2
$d_{33,f}$	110-125 pm/V

6.2.2.3 Breakdown field

There is no standard test for breakdown field. We apply a unipolar triangular waveform with increasing amplitude and intermittent measurement of $e_{31,f}$ coefficient.

The typical breakdown field is in excess of 325 kV/cm (65 V/2 µm), measured on test structures with standard electrode size.

6.2.2.4 Poling

For many applications, the ferroelectric PZT thin film material needs to be polarized. The material is generally poled at 150 kV/cm for 5-10 min at 100°C. Normally the bottom electrode is chosen to be negative.

6.2.2.5 Mechanical parameters for other layers than PZT

Mechanical parameters for the different layers are given in the table below. A full set of parameters is available as a part of the Process Development Kit from Coventor.

Table 3.3: Mechanical material parameters

Material	Young's modulus (GPa)	Built-in stress (MPa)	Mass density (kg/m^3)
Si	160	-	2331
SiO_2 (thermal oxide)	70	-300	2200
Pt	168	700	21450
Au	78	300	19300

6.2.3 Mask layer overview

The piezoVolume designs are of three basic types, based on end user specifications, design rules and processing limitations. The three processing routes available are:

A. Sensor-type with inter digital electrodes, without bottom electrode
B. Sensor-actuator types with bottom electrode
C. As B, including polymer isolating layer and two-layer top metal for routing

For more details about the processing routes, see chapter 6.3.

Some masks can be shared between the processing routes to reduce the mask cost during prototyping. As specified in Table 3.4 only some steps need an additional mask.

Table 3.4 Mask layer definition

Mask layer name	Description	Process type	Dark/Clear field
TOPEL_FINGER	This mask will contain the patterns for the top electrode	A	Clear Field
PASOPEN	This mask will contain the patterns for openings in passivating layer down to TOPEL	A	Dark field
METPAD	This mask will contain the patterns for pads down to TOPEL, might be lift-off	A	Clear field or Dark field
TOPEL	This mask will contain the patterns for the top electrode	B,C	Clear Field
NOPIE	This mask will contain the patterns for the PZT structures	B,C	Dark field
BOTEL-NOPT	This mask will contain the patterns for the bottom electrode	(B), C	Dark field
DIELOPEN	This mask will contain the patterns for opening of via-contacts to TOPEL and BOTEL through the isolating layer	C	Dark field
METAL3	This mask will contain the patterns for the bond pads and electrical contacts to TOPEL and BOTEL.	C	Clear Field
BACKOXIDE	This mask will contain the patterns to remove SiO_2 on the backside where the membranes will be	A,B,C	Dark field
BETCH	This mask will have square, circular or rectangular openings for the definition of the etching of membranes from the backside. This etch will stop on the BOX layer in the SOI wafers	A,B,C	Dark field
FETCH	This mask will have patterns for possible release etch of cantilevers etched from the front side (only necessary for release etch)	B,C	Dark field

6.2.4 Layout Rules

General layout rules:

- No pattern should be closer than 10 mm from the edge
- Standard bond pad size is $200 \times 200\ \mu m^2$

Table 3.5: Design rules for each mask layer

Mask layer name	Design rule
TOPEL and TOPEL_FINGER	Inter digital electrodes: minimum line width and spacing of 8 µm
	Conductor lines: minimum line width of 10 µm, 20-40 µm is preferred
	For process B bond pads should be considerably smaller than active area, but not smaller than 120x120 μm^2
NOPIE	Minimum overlap to TOPEL is 5 µm, 10 µm is preferred
	Minimum distance between openings is 20 µm
	TOPEL has to be removed everywhere where NOPIE is to be etched
BOTEL-NOPT	Minimum overlap to NOPIE 10 µm, 20 µm is preferred
	NOPIE has to be open everywhere where BOTEL-NOPT is open
PASOPEN	Minimum 50 µm to inter digital electrodes
METPAD	-
DIELOPEN	Openings only on top and bottom electrode (TOPEL and NOT BOTEL_NOPT). Minimum 6 µm to metal edge, 10 µm is preferred
	Minimum contact opening 60x60 μm^2
METAL3	Minimum overlap DIELOPEN 6 µm, 10 µm is preferred

	Metal pad should be larger than the opening in the DIELOPEN
	Conductor lines: minimum line width of 15 µm, 20-40 µm is preferred
BACKOXIDE	20 µm larger openings than BETCH
BETCH	Se chapter 6.2.4.1
	BACKOXIDE has to be open everywhere where BETCH is open
FETCH	-

6.2.4.1 Design rules for DRIE

Exposed Si should not exceed 20% of the wafer area, as this will reduce the etch rate considerably.

The minimum dimension of the smallest DRIE structure is in general 20 µm. The membrane size should preferably not be smaller than 50 µm. The largest dimension of the largest DRIE structure may be up to 5 mm.

Very large and very small DRIE structures together on the same wafer are a challenge. If the difference in dimensions is large, the etch profiles and etch depths will be significantly different even if the structures are placed far apart. Preferably each design should be revised by a RIE expert.

6.2.5 Design for manufacture

Design for Manufacturing (DFM) is an approach that considers manufacturability during the design process. Broadly, DFM includes organizational changes, systematic design principles and a common CAD methodology and framework for evaluating product designs (Ref 1).
The Coventor tool suite offers a platform dedicated to MEMS design starting from technology and manufacturing information. This design flow specificity enables a better integration of DFM principles into MEMS fabrication.

The Coventor Design kits include the material properties, process descriptions, layout templates and Design Rules Check (automatic or manual). Those are references and tools for the designer to create a device in a platform which includes manufacturing rules and limitations. Recent versions of piezoMEMS PZT design kits are available for all tools described in 6.1.5. In MEMS+ design kit, statistical data on fabrication steps (thickness or over-etch values for examples) given by the foundry can be added and used in simulations to run yield analysis or study performances of a random set of devices (e.g. Monte Carlo algorithm).

Virtual manufacturing with SEMulator3D allows checking masks prior to fabrication. Using the technology description, any layout can be built in 3D and the viewer enables direct and easy validation of each GDSII mask to be used in the clean room.
The last point relevant to DFM is covered by FEA tool CoventorWare. It concerns stress and reliability analyses. Knowing material characteristics the designer can run simulations for specific thermal or mechanical behaviour under boundary conditions applied during the fabrication process like accelerations, maximum temperature or pressure. These conditions may be specific to the foundry and a certain type of analyses can be then recommended. Some of these analyses may also be run in MEMS+ if statistical data (huge amount of calculation points requested) are used

6.3 piezoMEMS fabrication

This chapter gives an overview of the process, showing how the piezoVolume devices are manufactured according to a documented process chain. A more detailed description of the fabrication routes can be obtained by contacting the Competence centre.

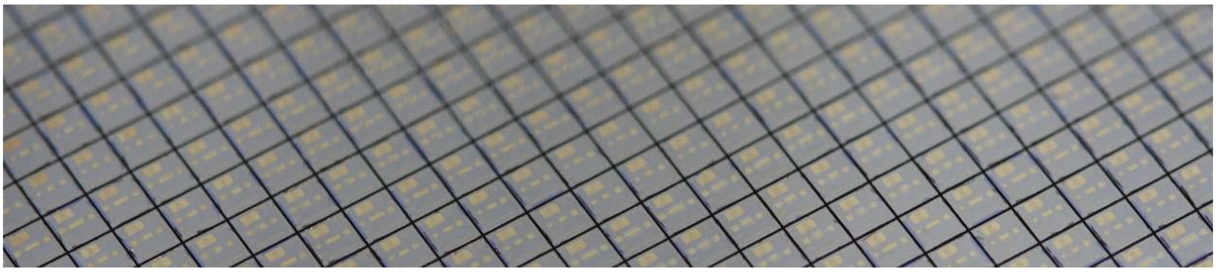


Figure 6.2: piezoVolume devices (also termed chips or dies) after the wafer has been diced.

A silicon-on-insulator (SOI) wafer is the starting point, where the buried oxide is employed as an etch stop for the back side bulk etch. Thermally grown SiO_2 serves as a barrier towards the Si, but also as a stress compensation layer as the compressive stress in the SiO_2 can be utilized to cancel the tensile stress in the later deposited layers (mainly from PZT).

The main processing routes are defined by the use of bottom electrode and top electrode or only top electrodes.

Three processing routes available are:

A. Sensor-type with inter digital electrodes and a barrier layer instead of bottom electrode
B. Sensor-actuator types with bottom electrode
C. As B, including patterned bottom electrode and a polymer isolating layer and two-layer top metal for routing

6.3.1 Process overview for type A –without bottom electrode

1. Thermal oxidation
2. Deposition of piezoelectric stack
    a. Barrier layer deposition
    b. PZT deposition
    c. Top electrode deposition
3. Back side patterning of SiO_2,
   MASK: BACKOXIDE
4. Patterning of top electrode
   MASK: TOPEL_FINGER
5. Deposition and patterning of passivation layer
   MASK: PASOPEN
6. Deposition and pattering of metal pads
   MASK: METPAD
7. Back side etch
   MASK: BETCH. It is in principle possible to use both DRIE and TMAH in this step but the device density is much improved by DRIE where you can avoid the angled sidewalls.

8. Dicing

6.3.2 Process overview for type B and C –with bottom electrode (B and C) and two-layer top metal (C)

1. Thermal oxidation
2. Deposition of piezoelectric stack
    a. Bottom electrode deposition
    b. PZT deposition
    c. Top electrode deposition
3. Back side patterning of SiO_2
   MASK: BACKOXIDE
4. Patterning of top electrode
   MASK: TOPEL
5. Patterning of PZT
   MASK: NOPIE

Now type B is finished except for back side etch.

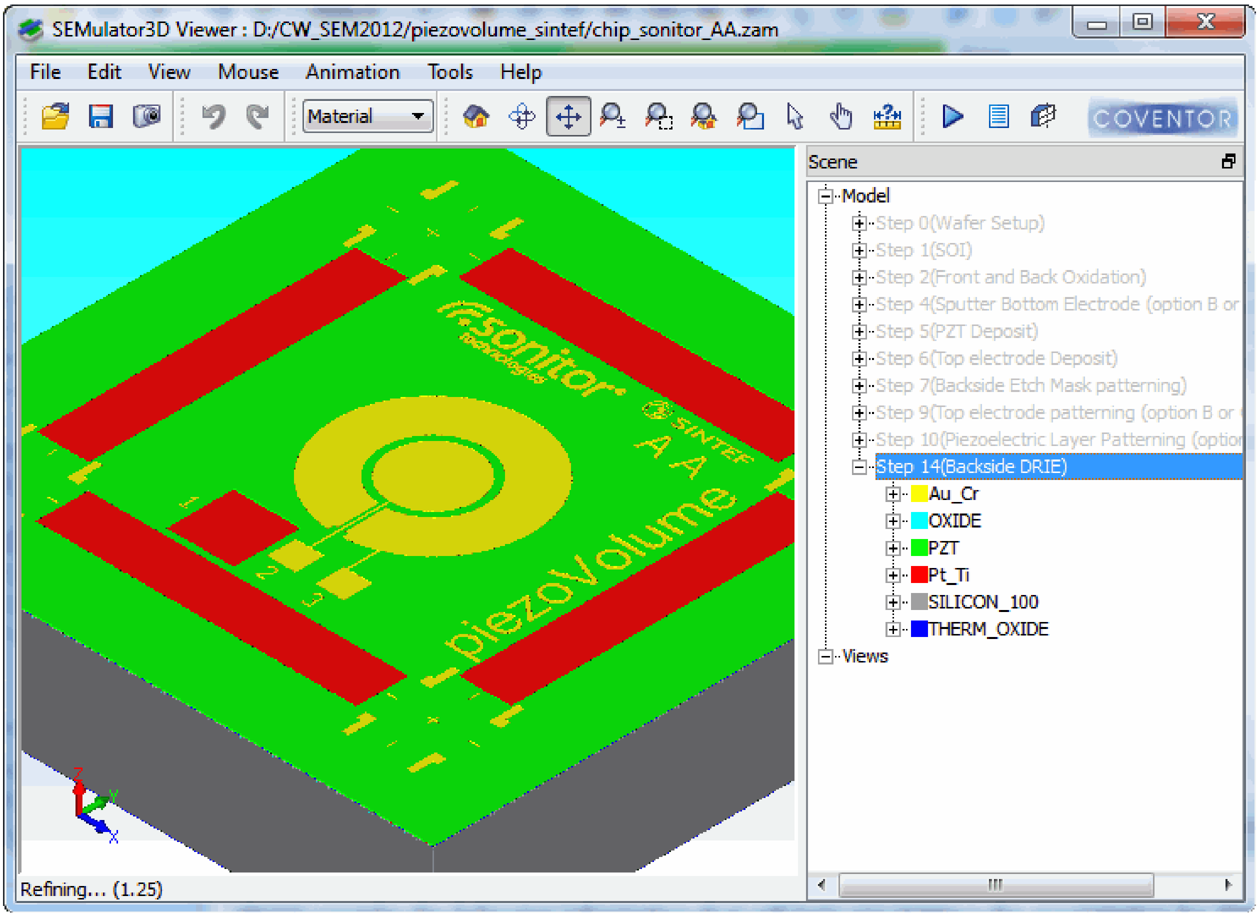


Figure 6.3: Device, process type B

6. (only C) Patterning of bottom electrode
   MASK: BOTEL-NOPT

7. (only C) Deposition and patterning of isolating layer
   MASK: DIELOPEN
8. (only C) Deposition and pattering of top metal
   MASK: METAL3
9. Back side etch,
   MASK: BETCH. It is in principle possible to use both DRIE and TMAH in this step but the device density is much improved by DRIE where you can avoid the angled sidewalls.
10. Dicing

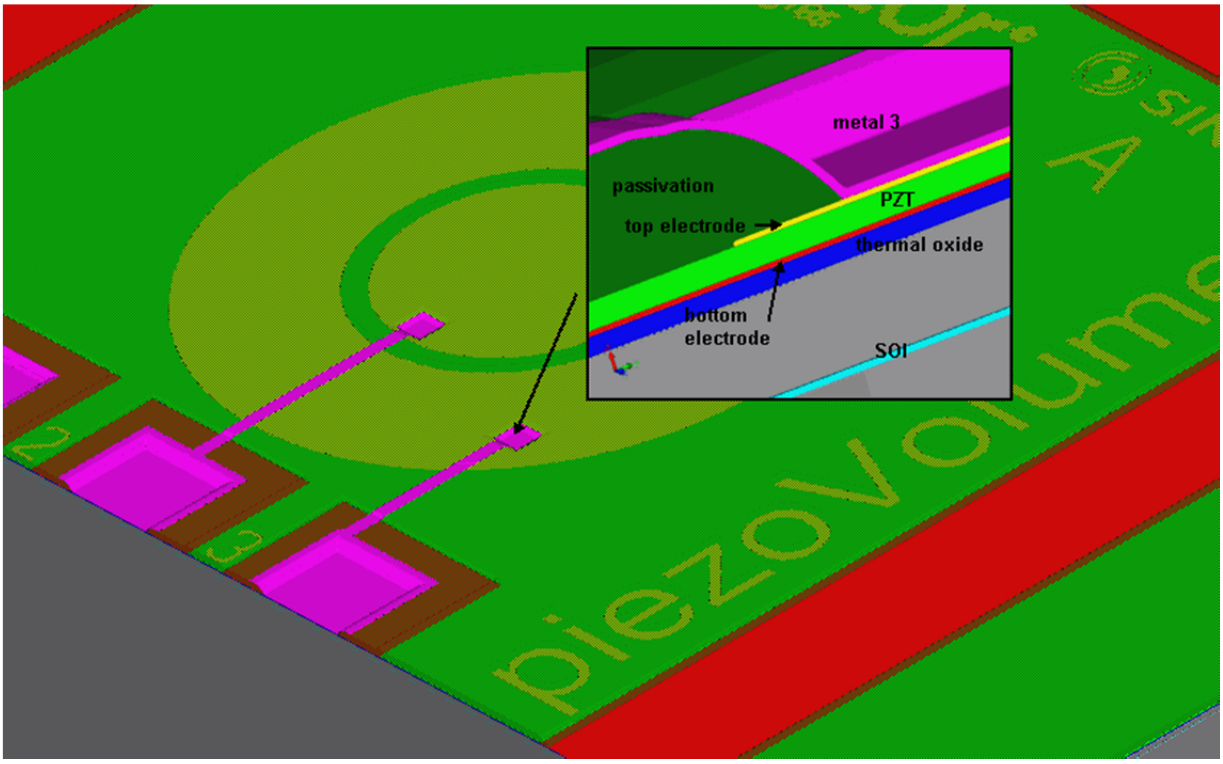


Figure 6.4: Device, process type C where passivation layer is set transparent (not in the zoomed cross section).

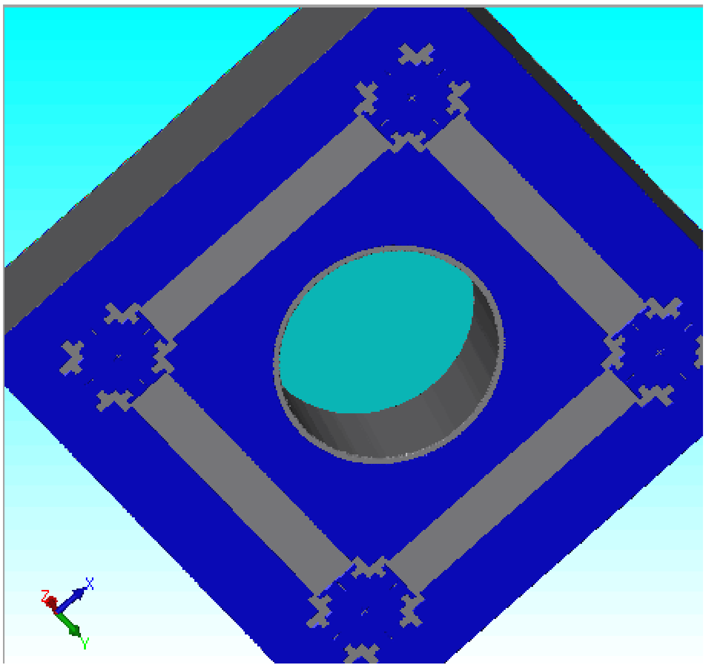


Figure 6.5: Backside of device with the backoxide etch (dark blue) and Silicon DRIE stopped at buried oxide (light blue)

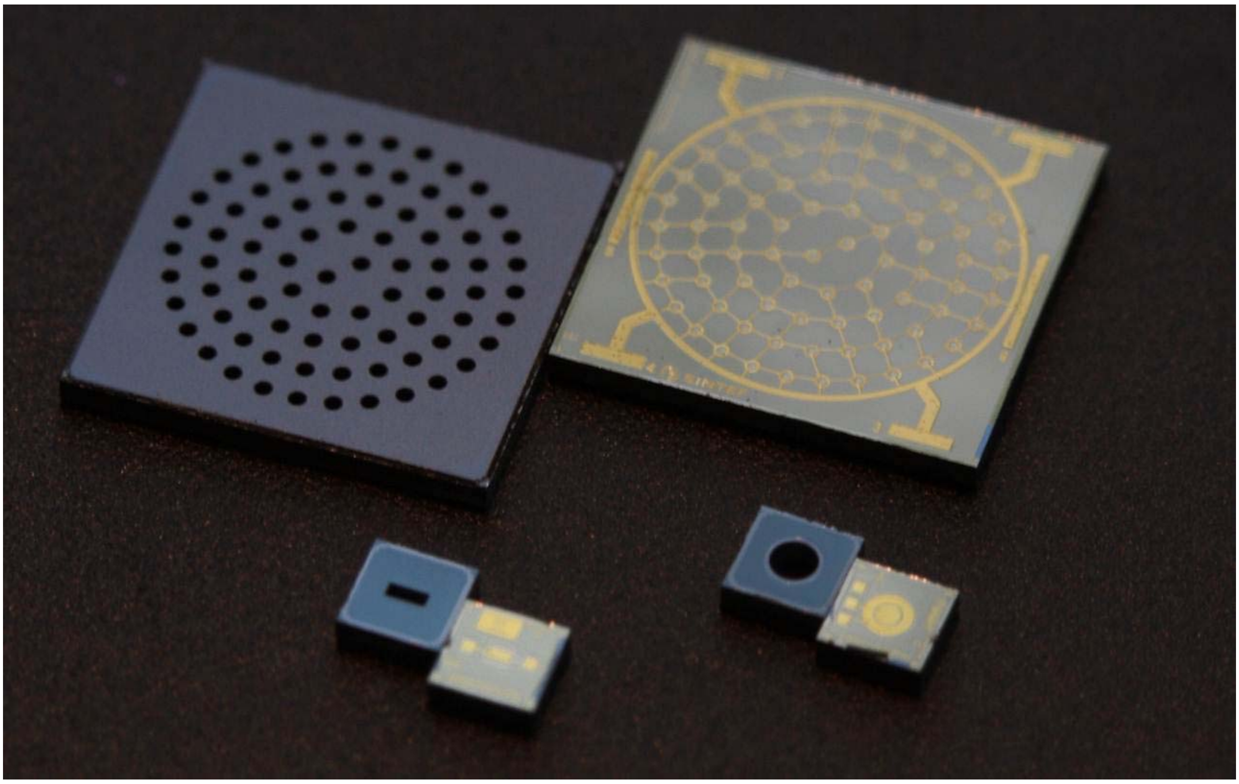


Figure 6.6: piezoVolume devices ready for packaging.

6.3.3 Fabrication strategy for CMOS compatibility

There can be several strategies to overcome this issue. One is to define parts of the cleanroom where additional materials are allowed and the wafers can be processed. All process steps that acquire CMOS-compatible equipment, such as thermal oxidation, must then be performed prior to Pt and PZT deposition.

6.3.4 Integration of piezoMEMS with higher level system and possible passivation

6.3.4.1 Wire bonding

One should preferable use thick (minimum 500 nm) Au-pads for wire bonding. It is preferred to have metal bond pads on bare silicon oxide and not on top of PZT.

6.3.4.2 Packaging for demanding environments

Direct exposure of the wafer's top side to various (conducting or chemically aggressive) fluids and gases requires additional process layers. Polyimide and Au may be used as additional barriers and packaging materials. One solution is to use additional layers of isolating/Au layers on top of the PZT stack.

As an example, processed 150 mm wafers could be bonded with a patterned glass wafer prior to dicing, for enhanced protection by encapsulating the fragile devices, see Figure 6.7. Advanced glass pattering can include TGV (through glass vias) and/or vias in Si as needed for e.g. acoustic coupling with the environment.

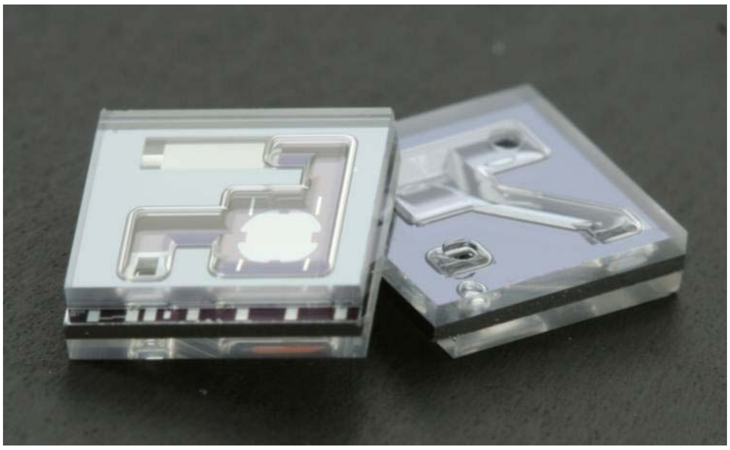


Figure 6.7: Flow sensor from MicroBuilder. A processed Si wafer has been bonded to two patterned glass wafers.

The backside of the processed wafers may be exposed to various exposures, e.g. water, under moderate pressures without further protection. The burst pressure of the membranes must be calculated. For other applications also the backside of the device can be protected by a bonded glass wafer- or by bonding directly to a ceramic or silicon substrate.

6.4 Infrastructure for piezoMEMS fabrication

The main goal of piezoVolume was to develop an integrated high-volume production process for piezoelectric microsystems. The developed platform covers the complete microfabrication process chain and the project has developed the tools and procedures within the 3 most significant bottlenecks within hardware and software to realize high volume fabrication of piezoMEMS:

1. High volume deposition tools for high quality piezoelectric PZT thin films

2. In-line testing and quality inspection of piezoelectric thin films on wafer level
3. piezoMEMS specific modeling and process emulation tools tailored to piezoMEMS

The piezoVolume process/fabrication chain is shown in Figure 6.8.

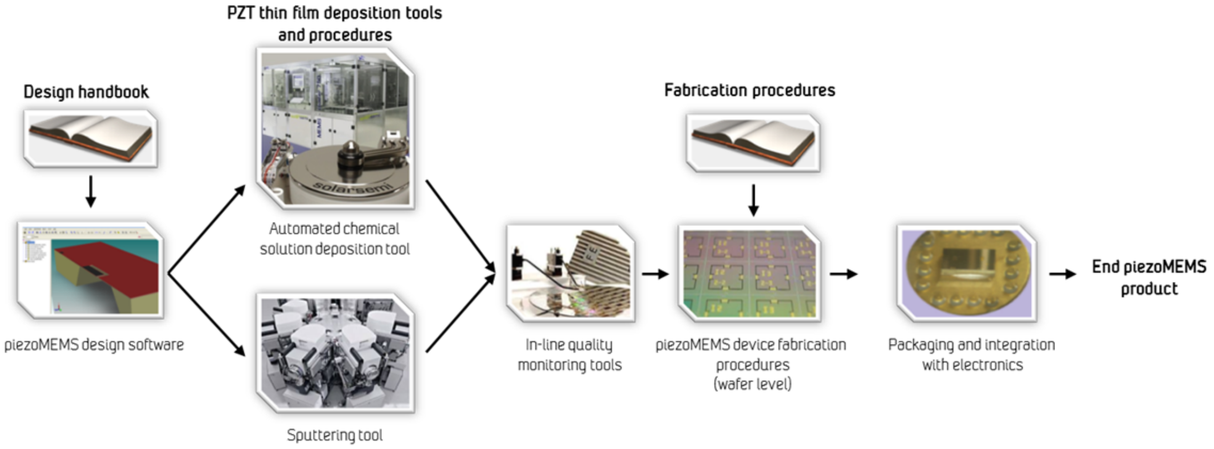


Figure 6.8: The piezoVolume process chain, from design to wafer level piezoMEMS device.

6.4.1 Pt sputtering

Pt is also a key process for piezoMEMS and the quality of the bottom electrode is important for the quality of the PZT. A layer stack of Ti / TiO_2 / Pt on top of an oxidized silicon wafer is recommended as the bottom electrode for PZT. The Pt-layer must be highly (111) oriented and the TiO_2 layer must act as an intact diffusion barrier.

6.4.1.1 Sputter tool for the bottom electrode

Among others both the Oerlikon sputter deposition tool LLS EVO II and the Cluster Tool CLN 200 II can be used. Both tools are industrial deposition tools which offer the required reliability and stability for providing consistent electrode quality. If an electrode post treatment process is not required the CLN200 II will be the preferred tool to produce both the electrode and the piezoelectric layer entirely without any vacuum breakage.

6.4.2 Tool for chemical solution deposition of PZT

6.4.2.1 CSD PZT

CSD PZT provides high quality PZT thin films with a high transversal piezoelectric coefficient, $e_{31,f}$ around -15 C/m^2. Depending on the precursor solution chemistry PZT films with thicknesses up to several microns can be deposited on 100 mm and 150 mm (4” and 6” diameter) wafers. The piezoVolume project also aims to qualify the process for 200 mm wafers, the subject of on-going work.

A cross section of a PZT thin film is shown in Figure 6.9. Here eight sequential crystallizations performed during the CSD process of PZT are clearly visible. For high volume production, the effort has been to automate and speed up the layer-by-layer deposition process.

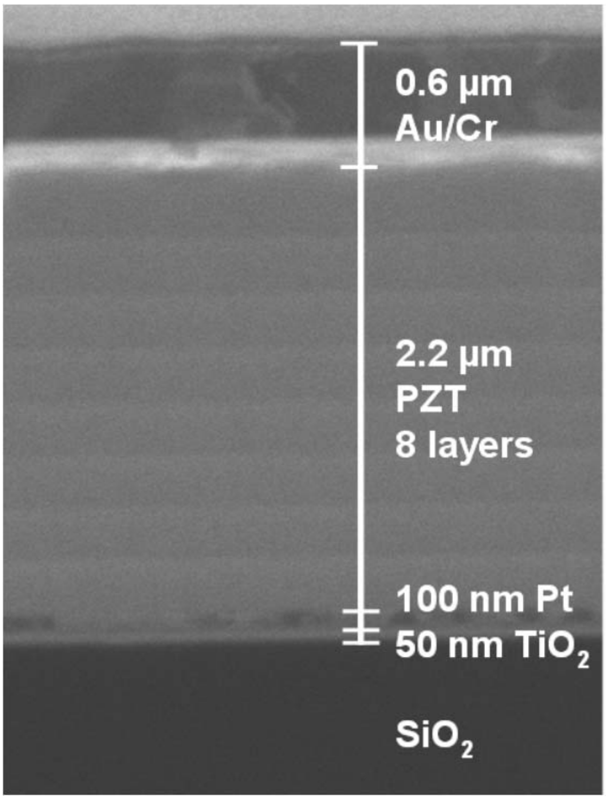


Figure 6.9: SEM image of a multimorph cross section milled by focused ion beam (FEI Company, The Netherlands).

6.4.2.2 Automated coating system for CSD

The coating system for CSD from Solar-Semi is based on an automated microcluster. Based on existing experience with spin-coaters, this high volume automation-line will be equipped with the following modules:

2 pcs. Spin-coating-modules including solution supply
2 pcs. Hotplates (for pyrolysis) / 2 pcs. Cool-plates
2 pcs. RTP units (for crystallization) (RTP = Rapid Thermal Processing)
1 pc. Handling system

Figure 6.10: Automated cluster tool

6.4.2.3 Performance

Using CSD it is possible to deposit high quality piezoelectric PZT films with a transversal piezoelectric coefficient $-e_{31,f}$ of 14-15 C/m^2 . The maximum thickness is ~4 µm.

Depending on the deposition tool and the amount of parallel processing which is implemented this method satisfies the throughput goal of 3,6 wafers/h*µm.

6.4.2.4 Integration

To integrate a CSD-cluster-tool into a wafer-fab, the following basic facility requirements should be available:

System dimensions	~ 3000 x 1500 x 2500 (W x D x H (mm))
System power supply:	3 x 400/230 VAC 50/60 Hz L1, L2, L3, N and PE
Power consumption:	Typically about 11 kW (without RTP)
Compressed air for pneumatics:	8 ± 2 bar, 5 µm filtered, dry, oil free
Vacuum for chuck and hotplate:	0.2 ± 0.1 bar
Nitrogen for tank-system, hotplate, RTP, etc.:	4.0 ± 0.5 bar
Oxygen for RTPs:	4.0 ± 0.5 bar
Different separate exhausts:	RTP/process/e-cabinet/hotplate/…

6.4.3 Tool for deposition of PZT by sputtering

Sputtering is a well known deposition technology providing high quality films for mass production at reasonable cost of ownership. The applications range from single metallic layer deposition of e.g. a reflective layer in optical storage technology to complex layer structures required e.g. for the magnetic storage or for devices in the semiconductor industry.
Fields of application for sputtering within the semiconductor business are e.g.

- Backside metallization

- Advanced packaging
- Solid state Lighting (LED)
- MEMS
- Antireflective coatings and waveguides
- BAW / SAW piezoelectric films, e.g. AlN
- Thin film read/write heads (magnetic storage)

6.4.3.1 Sputter tool for PZT

To get the best possible sputtered PZT, the perovskite phase has to be grown directly at a substrate temperature of about 600°C. The major obstacle to realize this process is that normal heater chucks in sputter equipment are not able to reach such temperatures. Therefore the standard hot chuck has to be exchanged by a so called very hot chuck where the heating of the chuck is done with a resistive coaxial heater with a maximum power of 2 kW and two control circuits to balance the heating at inner and outer diameter (Figure 6.11).

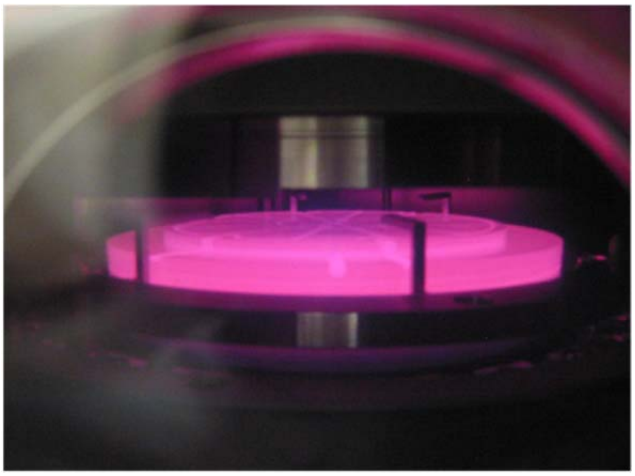


Figure 6.11: Very hot chuck for 150 mm wafer from Oerlikon.

The process also uses a single ceramic target which is sputtered by RF technology directly onto a very hot substrate. To increase the etch rate, the sputter performance is enhanced by a magnetron. This allows for balancing out the requirements for deposition rate, thickness and composition uniformity.

Either one can use one process module for manual single wafer handling or a complete Oerlikon cluster tool CLN200. This sputter equipment is commonly used in wafer processing industry and can be equipped with a maximum number of six modules.

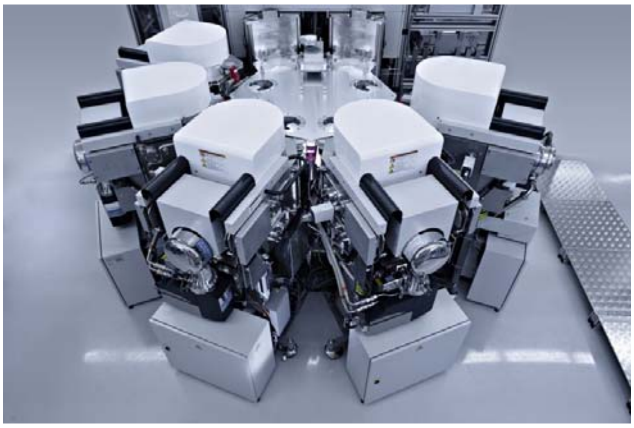


Figure 6.12: Oerlikon cluster tool

6.4.3.2 Performance

We have shown that it is possible to deposit high quality piezoelectric PZT films ($-e_{31,f}$ ~ between 15 and 20 C/m^2) onto up to 200 mm wafers. The actual throughput at this high film quality is up to 3 wafers/h µm with the potential of > 3.6 wafers/h at further process optimization. The thickness of the films is usually between 1 and 2 µm but if required films with a thickness up several microns can be deposited as well.

6.4.3.3 Integration

Usually the CLN200 I sputter tool is integrated into a wafer production to allow access to the cassette stations for wafer loading under clean room conditions where the sputter modules are a separated by a clean room wall and located in an area with a slightly higher contamination level (“gray room”).
To operate the system the facility installation has to meet typically the following requirements

System dimensions:	~ 3600 x 5000 x 2000 (W x L x H (mm))
Temperature range:	15 - 35°C
Relative Humidity:	40 – 60 %
Electrical data:	3 x 400/230 VAC 50/60 Hz L1, L2, L3, N and PE
Process gases:	Typically N_2, Ar, O_2, other on demand Purity 5 N or better Operating pressure: 1.4 – 4.0 bar
Compressed air:	5 – 7 bar, 5 µm filtered, dry, oil free
Cooling water:	Conductivity according to Oerlikon water specifications Temperature: 15 – 25°C Inlet pressure at maximum flow 7.5 bar Water consumption depending on configuration, typical range for a tool equipped with 6 module > 200 min-1
Exhaust:	Forepumps have to be connected to facility exhaust system

6.4.4 Tools for in-line quality monitoring of piezoMEMS wafers

Earlier during processing there could only be off-line tests for quality control, partly with dedicated test-wafers and/or test-devices/designs on device wafers. Dedicated test wafers may follow production batches through actual processing steps, but are not able to neither detect design specific problems nor fully map process problems with likely property distributions across wafers and for batch-to-batch control.

6.4.4.1 In-line quality monitoring system

aixACCT has developed a new high throughput in-line tool for quality control of the piezoelectric thin film (and electrode) properties. The tool, named aixDBLI, combines new and already existing hardware for 150 mm and 200 mm wafers. aixACCT's core technology of optical double beam laser interferometry is combined with a Cascade Microtech auto prober system.

Figure 6.13: In-line quality monitoring system from aixACCT.

The in-line tool enables a much improved process monitoring methodology as it will also allow keeping track of the production yield right after the deposition process. This will reduce production costs of the final MEMS device as the following cost intensive processing steps can be performed on already qualified films. This is also very useful for improving production designs with respect to increased yield through all production steps.

6.4.4.2 Performance

The fully automated aixDBLI system including a wafer robot allows the measurement of up to 10 wafers per hour using a piezoelectric small or large signal measurement on a 5 point wafer map. The measurement resolution is better than 1 picometer checked by X-cut Quartz measurements with a measurement repeatability better than 1%.

6.4.4.3 Integration
The aixDBLI system can be used either as a standalone measurement unit or it can be integrated into a wafer fab production process. This can be established by a standardized interface according to the SEMI standards SECS/GEM. These allow to control the measurement procedure and read-out system status and information.

6.4.5 Design tool integration

Coventor has developed a range of new design and modelling tools to improve the development of piezoMEMS. These MEMS specific software tools enable different levels of modelling, including manufacturing processes, device and system design. Interfaces to other standard design tools are available. Details on Coventor’s design tools for piezoMEMS are described in Chapter 6.1.5 below.

6.5 Application examples

6.5.1 Océ ink-jet actuator

Ink-jet actuators fabricated using processes B and C can be seen in Figure 6.14

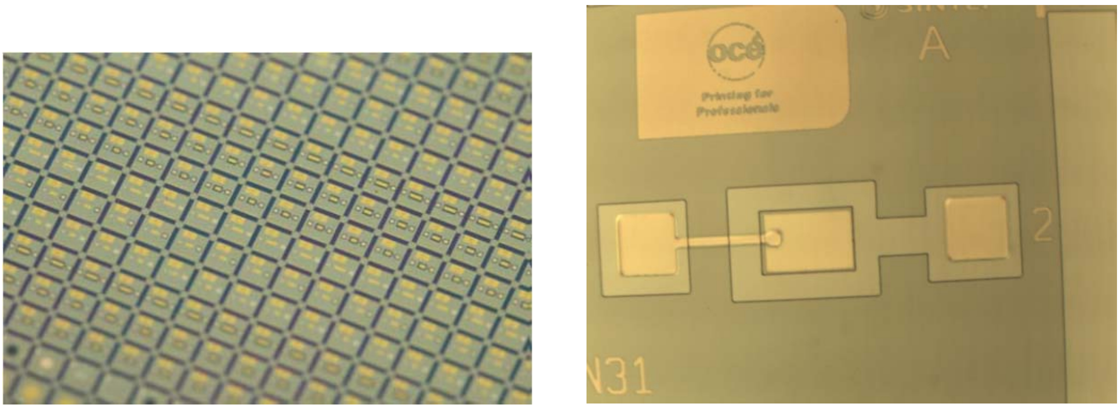


Figure 6.14: Ink-jet actuators fabricated using process C

6.5.2 Sonitor microphones

piezoMEMS microphones fabricated using processes A can be seen in Figure 6.15.

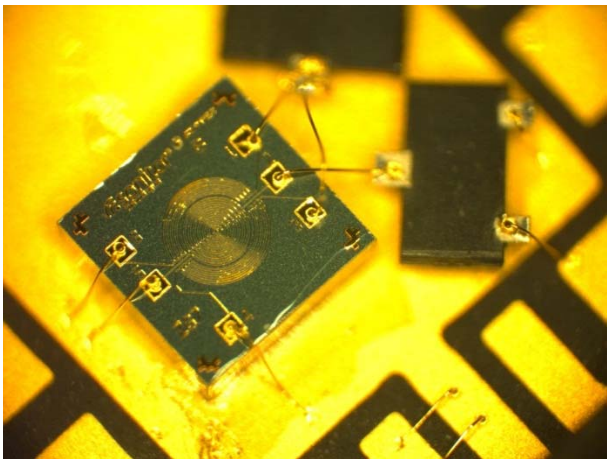


Figure 6.15 microphone chips glued on SOIC packet, and bonded for connection to the packet's pins.

6.5.3 Vermon pMUTs

Piezoelectric micromachined transducers (pMUTs) fabricated using processes C can be seen in Figure 6.16:

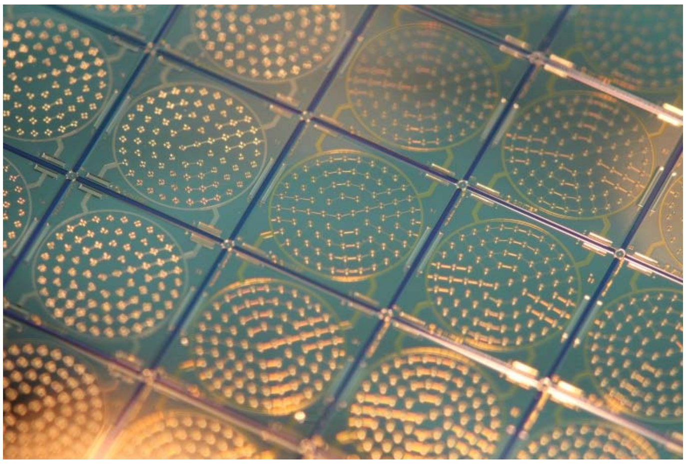


Figure 6.16: pMUTs fabricated using processes C

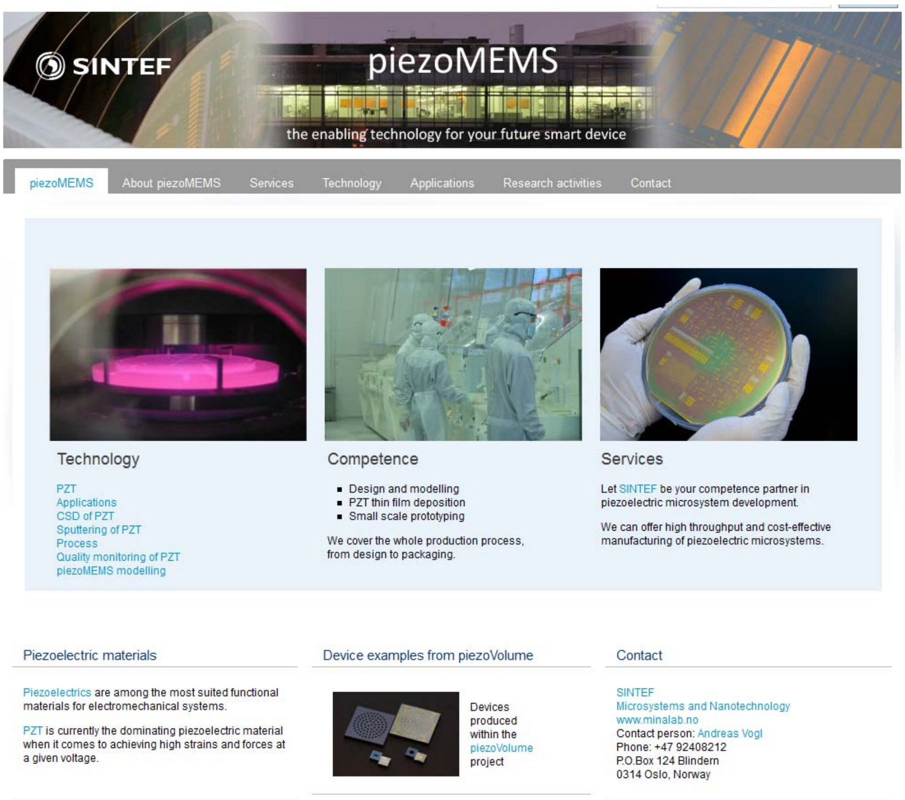
7 COMMERCIAL SERVICES

The Competence Centre (CC) created within the project is a perfect match to people who want to get started with Piezoelectric MEMS. This CC definitely cuts down time of feasibility study. People within the CC have worked with design, modelling, process development and fabrication of piezoeMEMS since 2002. The CC have a large network to infrastructure as well as experts in order to guide people through the difficulties of the first step with this new technology.

Some core benefits:

- Long experience in piezoMEMS (since 2002)
- Experienced project partner
- Deposition process and tools for high-performance PZT thin films on silicon wafers
- Modelling software specifically for piezoMEMS
- Modelling of device ideas and design assistance
- Evaluation of alternative processing routes
- Testing services and sophisticated testing equipment
- Manufacturing of prototypes
- Small scale production using 150 mm wafers (now) and 200 mm wafers (soon)
- Aims to have agreement with large MEMS fab for direct transfer to high volume production

Go to the Competence Centre web page:
www.piezomicrosystems.com



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