PROJECT FINAL REPORT

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Name of the scientific representative of the project's co-ordinator[1], Title and Organisation:

Dr. Frode Tyholdt, Senior Scientist

Stiftelsen SINTEF

SINTEF Materials and Chemistry

Forskningsveien 1

0373 Oslo

Norway

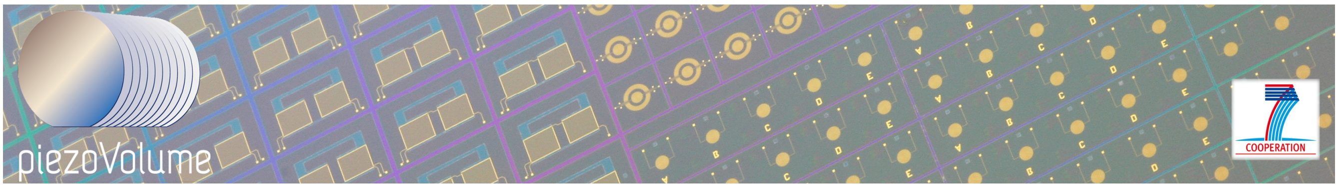
Tel: +47 91758274

Fax: +47 22067350

E-mail: frode.tyholdt@sintef.no

Project website[1] address: www.piezovolume.com

[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.



4.1 Final publishable summary report

4.1.1 Executive summary

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 modelling and process emulation tools tailored to piezoMEMS

The most important bottleneck has been to realize high volume deposition of PZT thin films with state of the art PZT thin film properties measured as the transverse piezoelectric coefficient $e_{31,f}$. In the project, deposition of PZT films both with chemical solution deposition and sputtering have been developed with this in mind and there have been remarkable developments. A world record level in $e_{31,f}$ of -20 C/m^2 was demonstrated by sputtering on 200 mm wafers.

In piezoVolume, the collaboration between large enterprises and SMEs in Europe was important to speed up the transfer of research to market. The consortium consisted of both technology providers and end-users. The SME aixACCT is currently a reference in testing equipment for piezoelectric thin films. In piezoVolume, aixACCT developed indirect extraction of $e_{31,f}$ from non-destructive $d_{33,f}$ measurements has been realized. This is a great leap forward in terms of wafer characterization during fabrication and the wafer quality monitoring tool developed in piezoVolume is already a product. The SME Coventor has improved their software products with new techniques for piezoMEMS. This includes specific improvements of Finite-Element-Methods (FEM) for piezoMEMS, system-level design allowing the combination of piezoMEMS with electrical circuit elements and virtual fabrication. Developed process design kits allow calibration with realistic process properties. The tools have been applied to piezoMEMS including mirrors, energy harvesters and membrane-based devices. There were also two potential SME end-users in the consortium.

The project has generated unique and many future activities worldwide on piezoMEMS will use either scientific or tool competence generated in this project. From a European perspective the project has strengthened European companies' position to supply of core components for piezoMEMS fabrication and also eased the access to European companies to this new market. This has been achieved in two ways. Firstly, a public Exploitation Assistant Package that describes the current market, the advantages of piezoMEMS and a walkthrough of design and fabrication has been made. Secondly, a piezoMEMS Competence Centre for piezoMEMS has been established at SINTEF which can act as a contact point for anyone needing design, modelling and prototyping services.

The results will enable high performing piezoelectric MEMS devices in many areas: inkjet printing heads, and further fluidic micro systems; active optic elements such as auto focusing lenses and optical displays and scanners; ultrasound transducers for proximity sensors, in room localization, and potentially also for medical imaging at high frequency (eyes, skin, artery walls, etc,).

Detailed information on the project results, the team and all public reports are available on the piezoVolume website www.piezovolume.com. The project was promoted as a success story by the Commission.

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4.1.2 Project context and objectives

The project has identified three bottlenecks have to be eliminated for successful high volume fabrication of piezoMEMS. Namely, PZT deposition, in-situ quality control and piezoMEMS specific design tools.

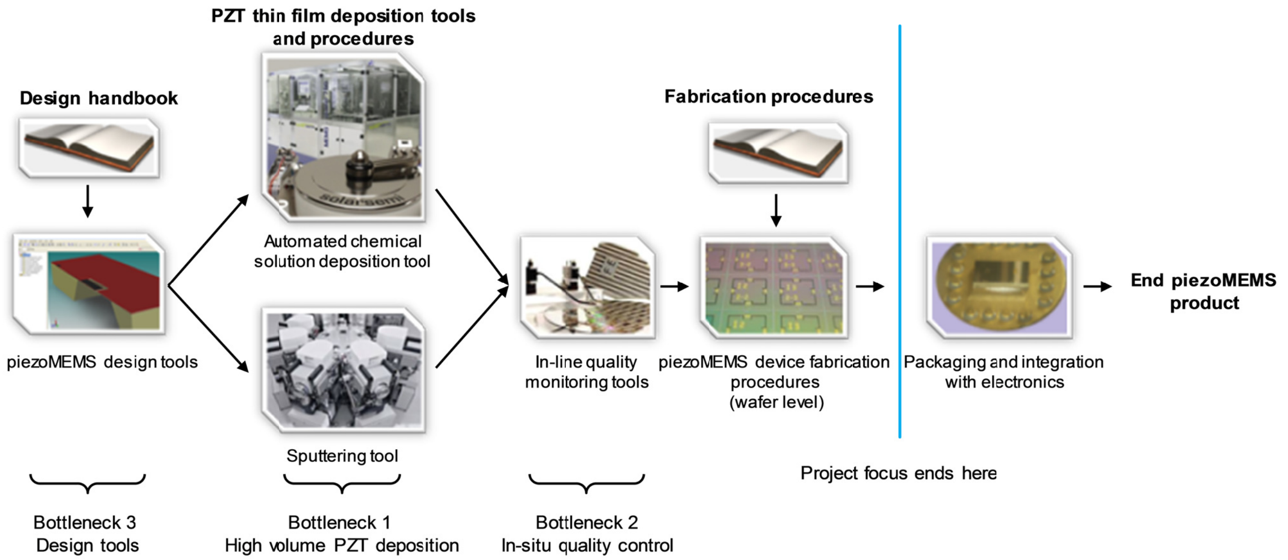


Figure 1: The piezoVolume process chain

WP1 - Process development and integration

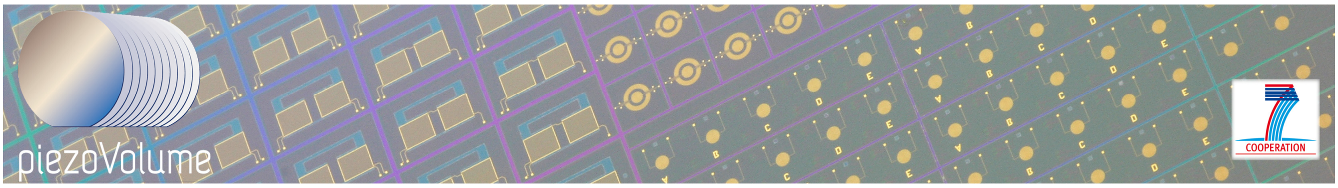
Today, it is not clear which method will be successful in realizing high volume deposition of PZT. CSD does as mentioned provide the best performance, but is a novel method for volume thin film deposition. Sputtering on the other hand is a very well known method in the semiconductor industry, but currently the piezoelectric properties are inferior to CSD. Hence, if CSD can be adapted to high volume deposition or the quality of sputtered PZT can be improved, bottleneck 1 will be eliminated. The process chain will be documented in terms of integration with existing silicon fabs, process steps and sequences, validated fabrication procedures and design rules for piezoMEMS. This information will be included in a design handbook.

WP2 - Tool development

The objective of WP2 is to create an infrastructure of critical tools that will be essential to bring piezoMEMS technology to a volume market. The infrastructure will comprise an automated high-volume deposition equipment for CSD and sputtering, automated quality monitoring system for piezoelectric properties and modelling tools and design kits specific for piezoMEMS. This infrastructure will be commercial production solutions open to clients after the project, allow keeping track of the production yield right after the deposition process, and remove the barriers to develop new designs and devices.

WP3 - Design and fabrication of device prototypes

The objective of WP3 is to demonstrate the capability of the total manufacturing process chain. To reach this objective, the end-users will develop specifications for three types of application-focused



devices. Based on the specifications, SINTEF will design the devices in cooperation with the end-users. Several design tools will be employed, including design rules developed in the project and elsewhere, and structural and dynamic modelling. The device prototypes will first be fabricated using state-of-the-art and manual methods. After assessment of this first generation, redesign of the devices will be considered. Finally, a second generation of the device prototypes will be fabricated by the automated processes developed in the project

WP4 - Testing and characterisation

There are currently no available tools or procedures for quality monitoring industrial deposition of PZT thin films. Characterization of dielectric and ferroelectric parameters has already been established for ferroelectric memories (main material is also PZT). But for piezoMEMS complete devices have to be fabricated and tested. This procedure is too slow and too costly when dealing with high volumes. aixACCT will develop a tool based upon a double beam laser interferometer (DBLI) too to meet the following testing needs: Early stage elimination of wafers with inferior quality films, wafer level $e_{31,f}$ "estimation, accelerated life time testing, device quality testing

WP5 - Dissemination and exploitation

To assure successful exploitation of the piezoVolume scientific and technical results, dissemination and exploitation activities will run in parallel with the coordination of the project. To maximise the likelihood of success, the project aims to provide customer-friendly access to the developed technology through the preparation of an "**exploitation assistance package**". The package will contain production procedures and design directions, application examples, infrastructure and IPR.

The piezoVolume partners intend to contribute actively to the development of **new industrial standards** in the field of piezoelectric MEMS.

4.1.3 piezoVolume main results

4.1.3.1 Process development and integration

Platinum electrodes

A layer stack of sputtered Ti/TiO_2/Pt on top of an oxidized silicon wafer has been selected as the consortium's preferred bottom electrode stack used for PZT deposition. Platinum is used for the bottom electrode because it has a reasonable good thermal stability and is chemically inert in the oxidizing conditions prevailing during PZT processing. To investigate also the influence of the bottom electrodes on the PZT quality a second approach has been pursued by ISIT using evaporated and annealed Ti/Pt electrodes for the PZT development on 200 mm wafers.

A schematic of the sputtered layer sequence is drawn in Figure 2. On top of the thermally oxidized substrate a 3 nm Ti layer is deposited to promote the adhesion of the subsequent layers and followed by 15 nm of TiO_2 which acts as a diffusion barrier. Finally, 110 nm of Pt (111) was sputter deposited on top of the substrates. Optionally a TiO_2 seed layer is deposited which promotes PZT growth with a preferred orientation.

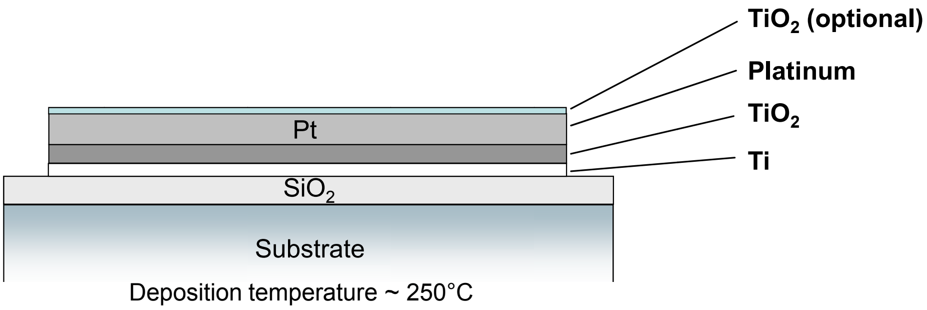
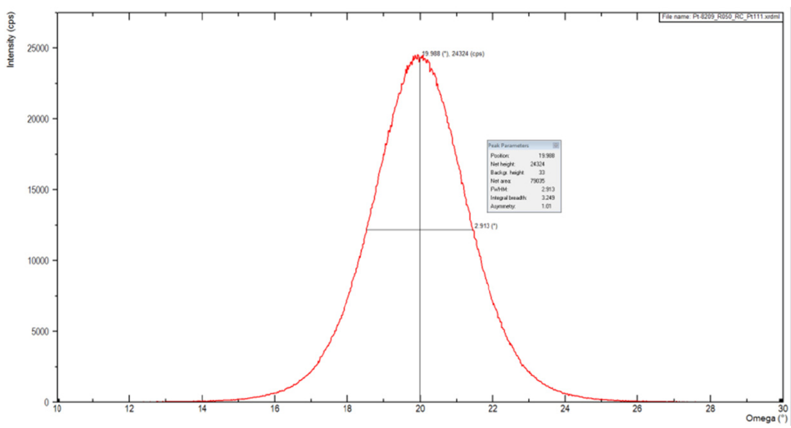


Figure 2: Bottom electrode layer stack

The Oerlikon sputter deposition tool LLS EVO II was the main source for bottom electrode depositions during the piezoVolume project. The LLS is an industrial well-proven deposition tool equipped with soft etch capability, pulsed DC processes for reactive sputtering and substrate heating. Further on it provides an easy conversion to different wafer formats (4", 150 mm, 200 mm) which have been used during the project.

The Pt electrode qualification has been successfully performed by applying a reference CSD PZT deposition process. Although qualified in the beginning of the piezoVolume project it has been found during the project that the maximum substrate temperature of approximately 250°C in the LLS tool was not sufficient to improve further the Pt film quality.



Therefore in the last year of the project an additional approach has been launched to utilize a cluster tool CLN200 for the Pt electrode deposition. The CLN tool enables the Pt deposition at much higher temperature up to 500 °C. This results in a further improvement of the Pt electrode as indicated e.g. by a reduction of the rocking curve FWHM from about 7° (LLS) to 3° (Figure 2).

In the final production solution for 150 mm and 200 mm PZT thin films both the Pt and PZT depositions are integrated in the CLN200 platform. This enables electrode stack and subsequently PZT film depositions without breaking the vacuum conditions and will result in an optimum interface quality.

Chemical solution deposition

The ideal situation would be to apply just one coating for a suitable thickness (e.g. 1 µm). However, the background for the repeated coating procedure is stress handling. As the applied solution is dried, and the solvent and organics escape, the film shrinks. However, since the film is clamped by the silicon substrate, only the upper part of the film is able to do so (Figure 4). Consequently, a stress gradient is formed in the thickness direction of the film, ultimately leading to cracking. This problem is currently circumvented by using the elaborate procedure described above in, which is not a problematic issue for small scale prototyping.

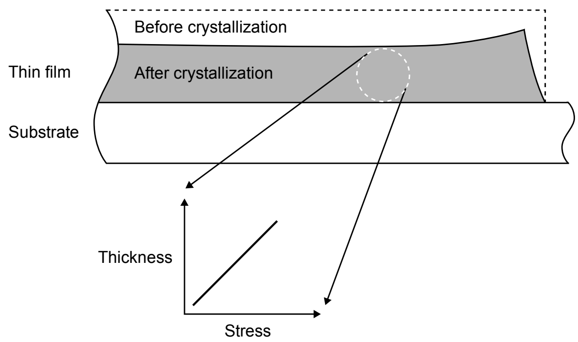


Figure 4: non-uniform shrinkage during drying of thin film layer

In the course of the piezoVolume project SINTEF (SIN) performed process developments to increase the throughput of the CSD process by increasing the coating thickness and at the same time minimize the time used for drying. The aim for total drying time in the project was 0.083 h/µm. By using the standard solution formulation the thickness per layer could be increased to 100 to 110 nm with a total drying time of only 0.074 to 0.105 h/µm by increasing the concentration to 0.6 M. However, such film could only be deposited crack free when the films had < 80 % (001) texture and is due to increased stress in highly oriented films. No benefits from increasing the pyrolysis time and/or temperature were found.

In order to facilitate deposition of thicker layer for highly oriented PZT the coating solution had to be modified. Using a modifier, highly (001) oriented, dense and crack free films with a thickness of 100 nm per layer could be obtained. A 2 µm film deposited using only 20 coatings is shown in Figure 5 along with a $d_{33,f}$ measurements.

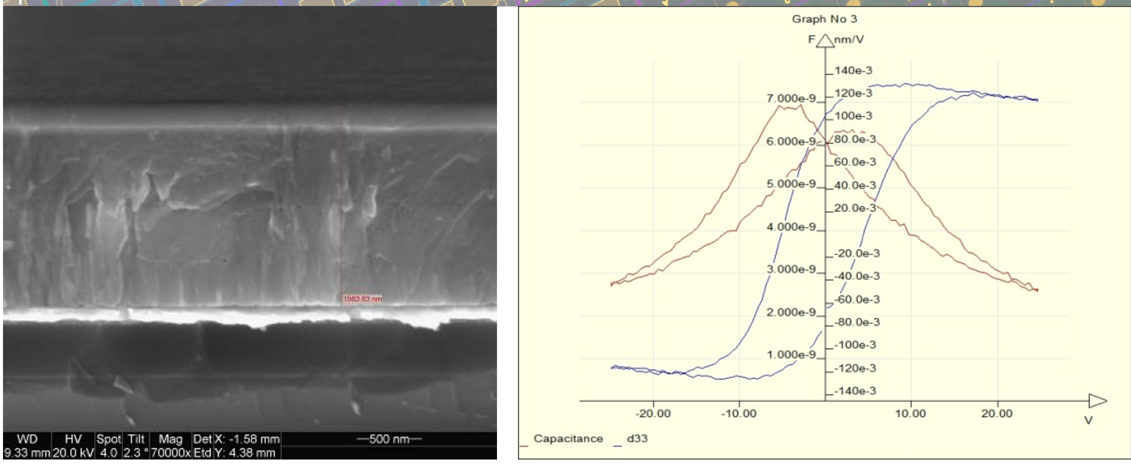


Figure 5: A 2µm PZT film deposited using a modified formulation and resulting high $d_{33,f}$ performance

In this work, the drying time for such films was 0.35 h/µm. However, it is expected that this can optimized down 50 % down to 0.18 h/µm. Such films are indeed very promising as they, in addition to decrease the number of needed RTPs, display piezoelectric performance comparable or even better than the state-of-the-art process (Figure 6). In the CSD process the RTP steps are rate limiting. Reducing the number of RTPs has a high positive impact on throughput. This formulation also made the deposition of 4 µm PZT films possible. The breakdown field of such films depend on the pad size and frequency. At 1 Hz and a pad size of 0,125 mm^2 breakdown was observed at 460 kV/cm (Figure 6).

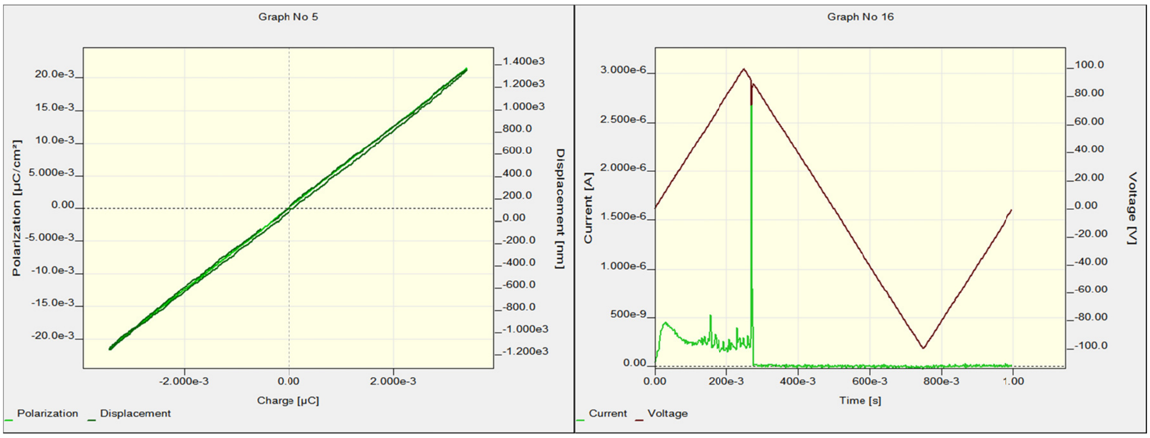


Figure 6: $e_{31,f}$: -15 C/m² at zero bias using modified coating formulation. Breakdown test at 1 Hz for small pad. Breakdown observed at 460 kV/cm.

Using another formulation, the heat treatment temperature was successfully reduced to 525 °C while maintaining a high d_{33} value and a very low non-uniformity over the wafer in Figure 7:

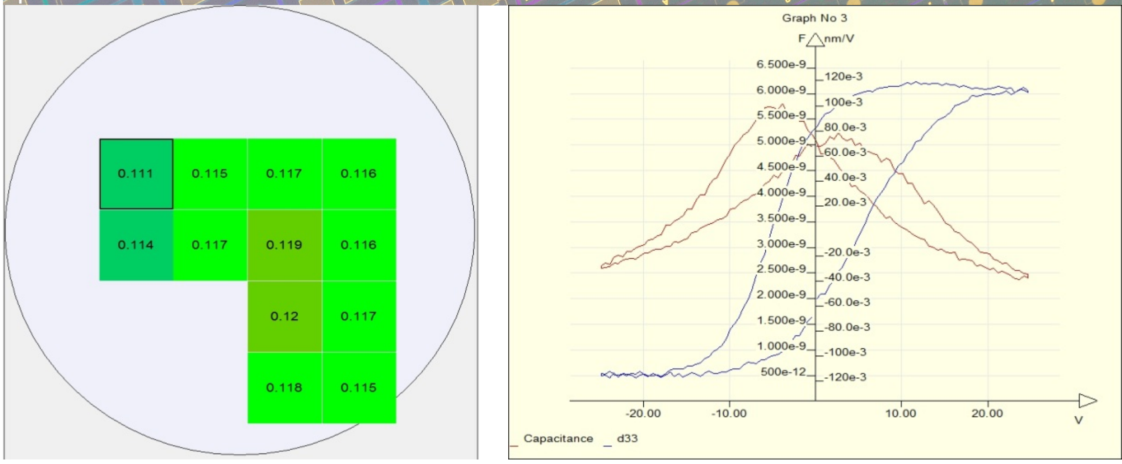


Figure 7: Wafer map of pV066 with distribution of $d_{33,max}$ over the wafer prepared by the low temperature route. The measured $d_{33,max}$ values are high and very homogeneous over the wafer.

To deposit high-quality PZT films on an insulating buffer layer of TiO_2 is needed when interdigital top electrodes is to be used. PZT was deposited on TiO_2 buffer layers using CSD resulting in a film with mixed (001) and (110) texture as shown in Figure 9:

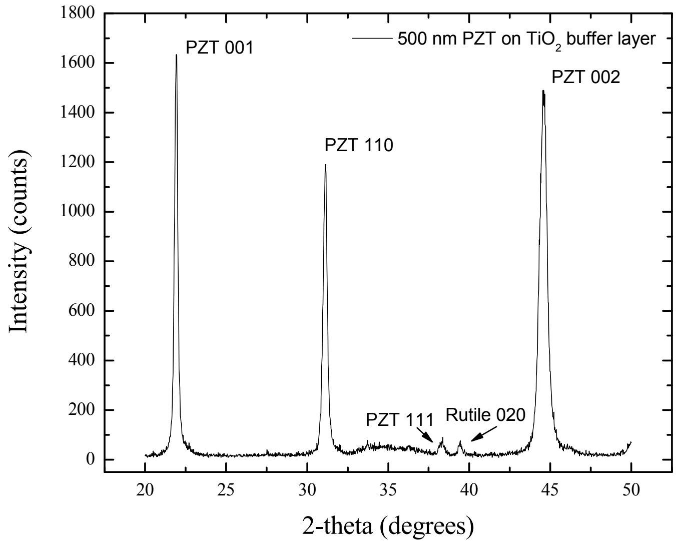
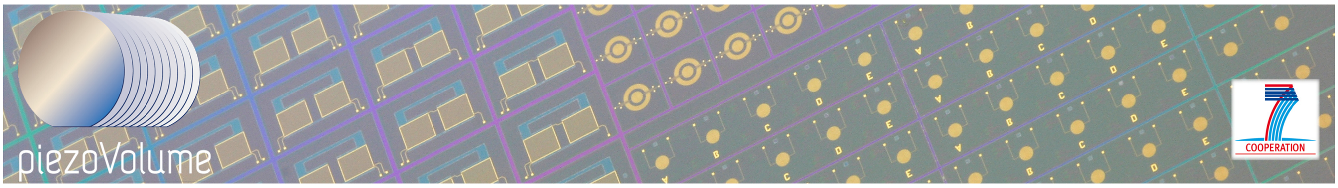


Figure 8: X-ray diffractogram of a 500 nm PZT thin film prepared deposited on the TiO_2 buffer layer.

In conclusion, the CSD process throughput has been increased by providing deposition of 100 nm layers with SOTA quality ($e_{31,f}$: -15 C/m²), low thickness non-uniformity and high breakdown field. The results show that CSD can be a competitive technology for high volume deposition of PZT.



In-situ sputtering

In piezoVolume the PZT sputtering process development was performed by the two institutions École Polytechnique Fédérale de Lausanne (EPL) and Fraunhofer Institute for Si-Technology (ISI). Both institutions have been supported by technical assistance of OERLIKON Balzers (OER) and an exchange of information and feedback regarding technological improvements, modifications and irregularities has been permanently maintained between the three partners.
EPL and ISI in general worked on sputtering platforms of differing complexity (Figure 9) for wafer sizes of 150 mm (EPL) and 200 mm (ISI) built-up by OER in the beginning of the project. Although both institutions pursued different processing routes, EPL as well as ISI achieved remarkable ferroelectric, piezoelectric and dielectric properties for their optimised in-situ sputtered PZT thin films.

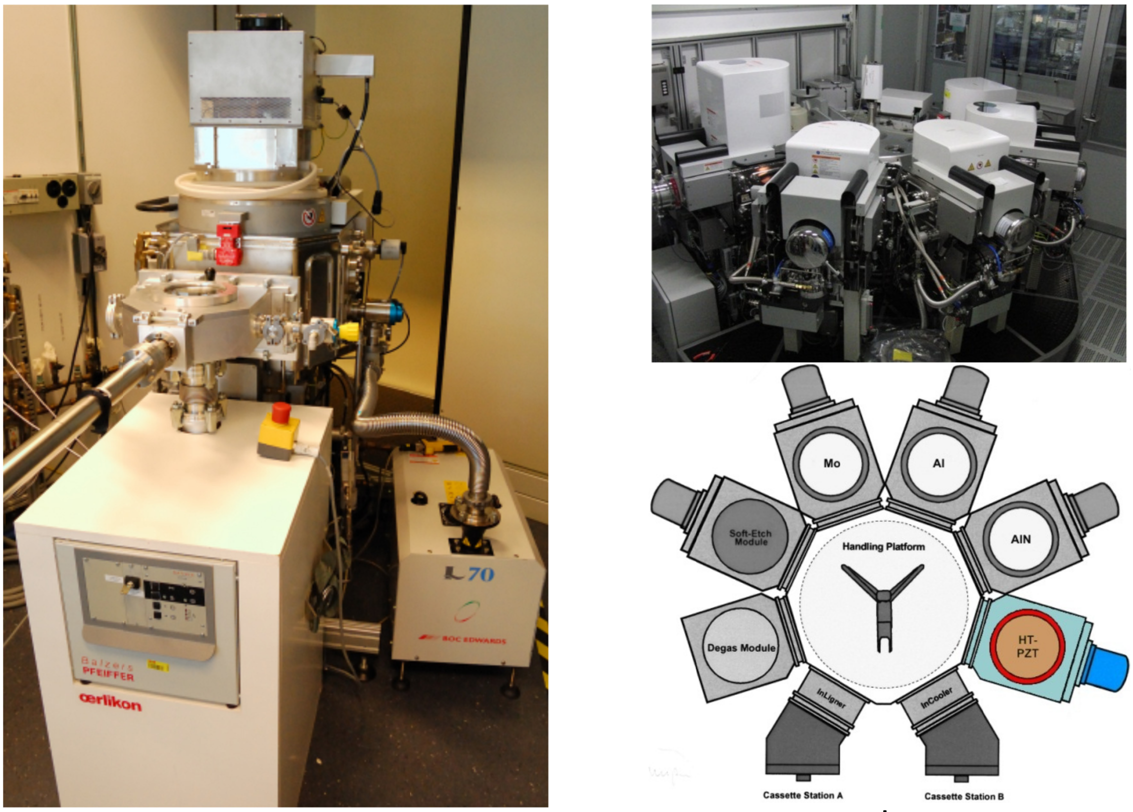


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Figure 9: The two set up PZT sputter deposition tools; a) 150 mm PZT module located at EPL; b) 200 mm PZT module integrated in a CLN200 cluster tool located at Fraunhofer ISiT

EPL investigated the influence of lead and non-lead based seeding layers for an improved nucleation and growth of subsequently sputter-deposited PZT films. Providing a suitable seeding EPL achieved highly textured, (100) oriented PZT thin films on 150 mm substrates with a deposition rate of 42.5 nm/min.

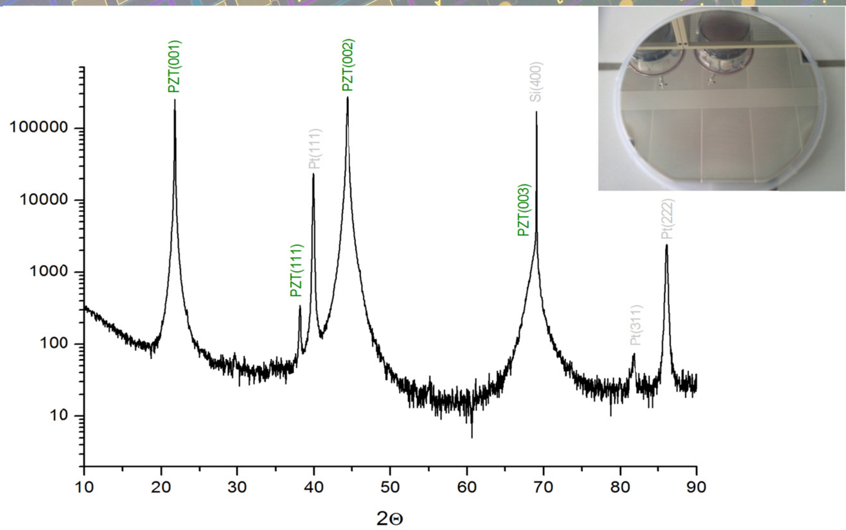

Figure 10: Crystallographic analysis of a 2 µm thick PZT film

XRD analysis on in-situ sputtered PZT films confirm a phase-pure perovskite film with only a minor content (visible only on logarithmic scale) of the (111) orientation (Figure 10). SEM pictures and TEM cross section reveal very compact and flat grain structures with the exception of some (111) grains.

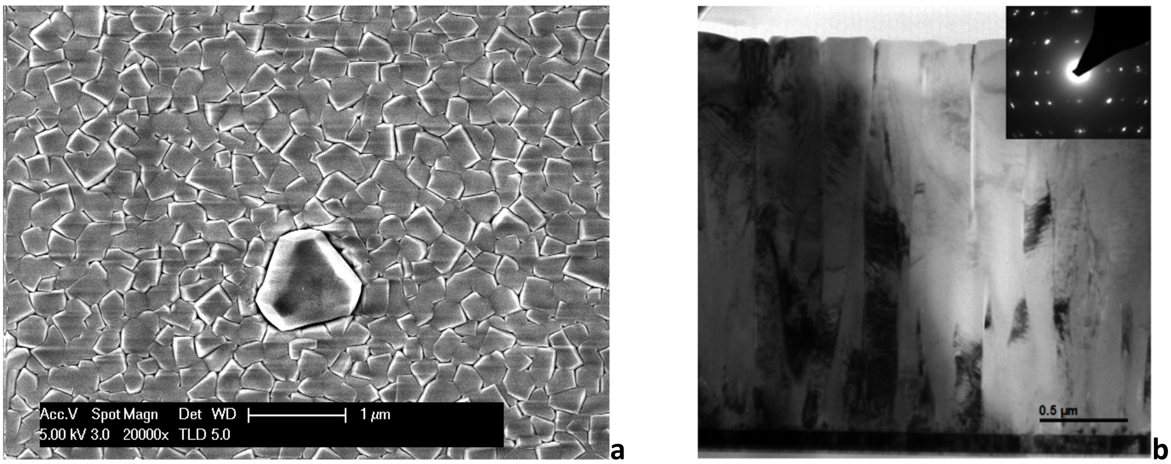

Figure 11: a) SEM surface analysis; b) TEM cross section

The high texture is also seen in the TEM diffraction pattern in Figure 11. The RMS roughness is less than 15 nm.

Such films exhibit a very good ferroelectric behavior with a maximum polarization of about 50 µC/cm^2 and a remanent polarization of about 20 µC/cm^2. Capacitance vs. DC bias loops show a relatively symmetric behavior with a maximum relative permittivity of about 1300 and a factor 3 tunability. Dielectric losses are very low even at high biases.

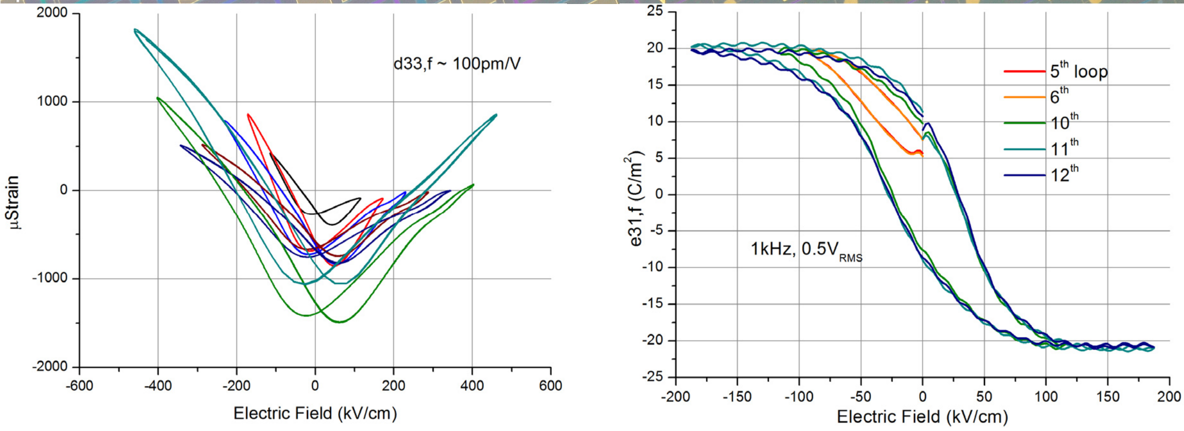

Figure 12: Determination of piezoelectric constant $d_{33,f}$ by Stain vs. E-field measurements under large signal excitation (left), Small signal $e_{31,f}$ vs. E-field measurements (right) for a 2 µm thick PZT film

The effective piezoelectric constant $d_{33,f}$ is about 100 pm/V for large signal measurements whereas for the small-signal $e_{31,f}$ a value of 20 C/m² under DC bias was obtained. The remanent value (at E=0) depends on poling conditions and can be as high as 15 C/m^2.

ISI's work focused on the development of an in-situ PZT sputtering process for 200 mm substrates and the integration of this process in a MEMS compatible production line as existent at Fraunhofer ISiT. The process and its integration was optimized taking into account factors like the pre-processing of substrates (cleaning, de-gas, soft-etch), different variants of substrates and also cost of manufacture in general. Therefore the PZT was directly sputtered on evaporated electrodes without use of an extra seed layer deposition process.

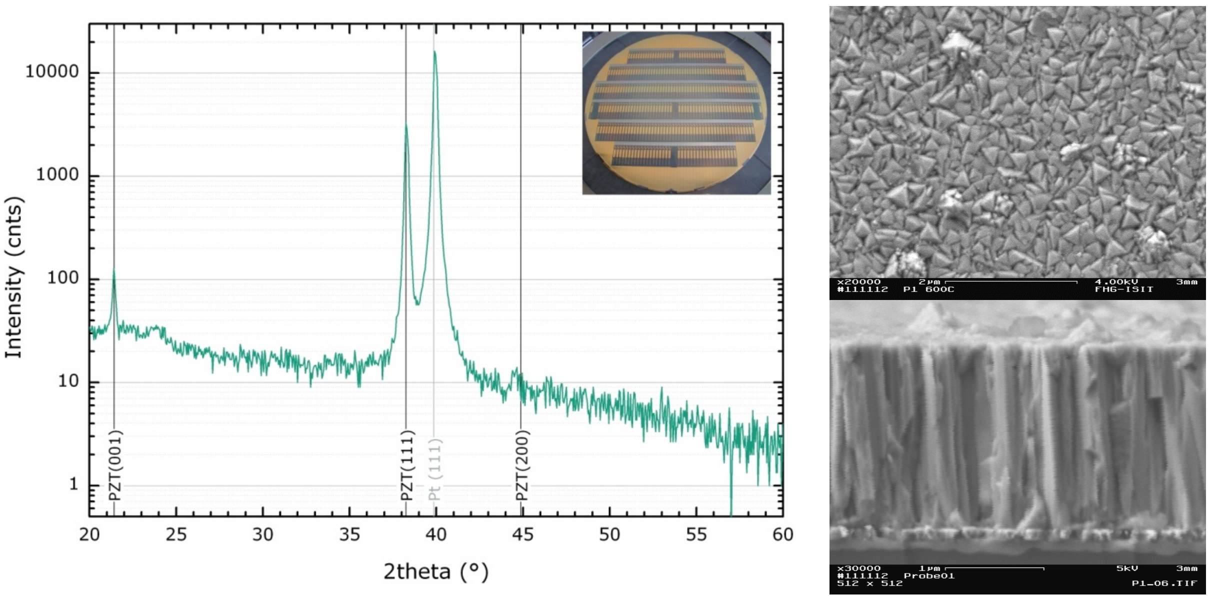

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Figure 13: a) XRD analysis of a 2 µm thick PZT film deposited on a 200 mm substrate, inset: patterned wafer used for ferroelectric, piezoelectric and dielectric characterization; b) surface and cross section of a PZT film

As shown in Figure 13a, the 200 mm PZT films show a pure perovskite phase with a preferred (111) orientation and without any signs of a non-piezoelectric secondary phase. The films are characterized by a columnar growth with triangular shaped grains (Figure 13b) and were deposited at a rate of about 45 nm/min.

Ferroelectric, piezoelectric and dielectric measurements (Figure 14) reveal a maximum polarization of about 60 µC/m², a maximum longitudinal displacement of about 4 nm at 25 V, piezoelectric constants $d_{33,f}$ and $e_{31,f}$ of about 110 pm/V and -20 C/m², respectively, and a maximum dielectric constant of about 1500.

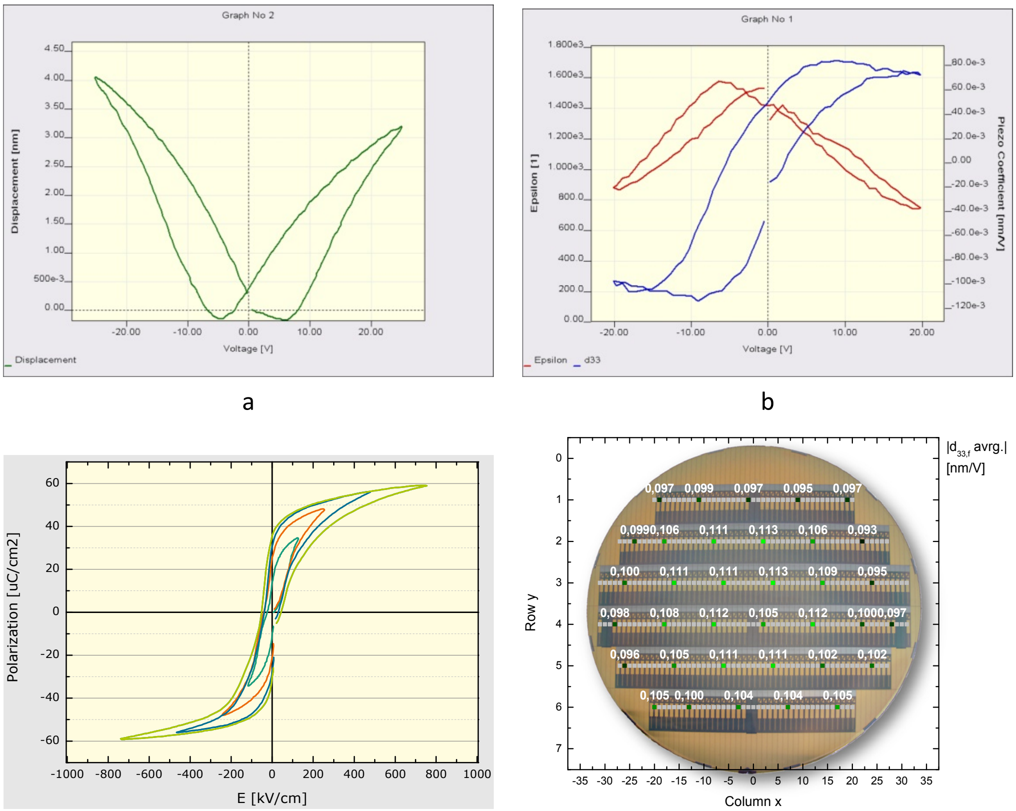
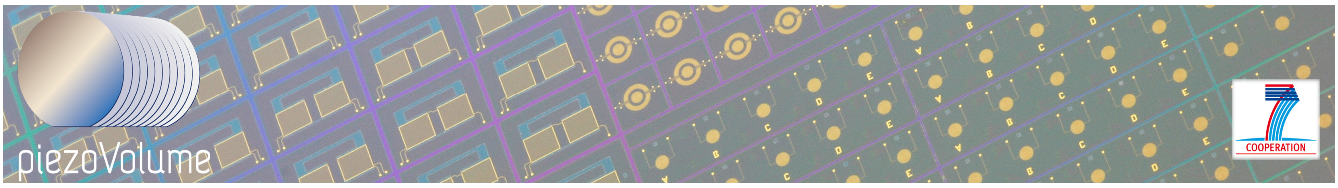


Figure 14: Piezoelectric response of PZT films of 2 µm thickness for large signal (a), small signal (b) excitation; c) measurements of ferroelectric hysteresis loops; d) $d_{33,f}$ mapping on a 200 mm substrate

A mapping for the piezoelectric constant $d_{33,f}$ across a 200 mm wafer revealed a mean value of about 100 nm/V with a range over mean of ±10%, Figure 14d. A summary of further characteristic values for a 1 µm and a 2 µm thick PZT film are given in Table 1.

Table 1: Characteristic ferroelectric, piezoelectric and dielectric values for 200 mm in-situ sputtered PZT films

		large signal excitation					small signal excitation		mechanical excitation
Film thickness	Film stress	P_{r+}	P_{r-}	P_{max}	V_{c+}	V_{c-}	$\lvert d_{33,f} \rvert_{max}$	max. rel. permittivity	$e_{31,f}$
nm	MPa	µC/cm²	µC/cm²	µC/cm²	V	V	pm/V	-	C/m²
1000	≈150	28,0	-20,6	62,4	5,5	-5,3	162,0	2040	-17,7
2000	≈100	35,4	-25,8	58,9	8,6	-10,4	114,0	1550	-21



In conclusion, the work of both institutions yielded in in-situ sputter-deposited PZT thin films of remarkable ferroelectric, piezoelectric and dielectric properties. The targeted piezoelectric values of $d_{33,f}$ > 100 pm/V and $|e_{31,f}|$ > 14 C/m² were achieved and exceeded on both 150 mm and 200 mm substrates. Some innovative processes have been developed for direct sputtering of PZT without need of an additional post-annealing treatment as well as for suitable seeding layers. In case of the 200 mm process the notable piezoelectric properties were achieved even without a supplemental seeding layer process.

piezoMEMS design and fabrication rules

The design tools, and in particular, the fabrication rules- will be subject to review when the processing tools are tuned in production. A "design handbook" will be available to the users of the piezoMEMS process. This is based on a public version of the piezoVolume report on integration, design and fabrication rules. Relevant information is available through the competence center piezoMEMS and piezoVolume web-sites.

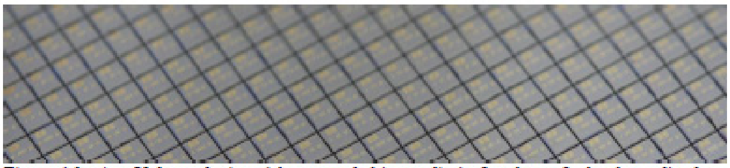


Figure 4.1: piezoVolume devices (also termed chips or dies) after the wafer has been diced.

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.

As mentioned in Chapter 3.3, the 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

Figure 15: Excerpt from (public) documentation on integration, design and fabrication rules.

The Coventor design tool PDKs are based on SINTEF's (manual) moveMEMS PZT process and will include updated/latest test data available on materials, specifications and design and processing/fabrication rules.

Process chain integration documentation

The design tools, such as the Coventor PDKs, the "Design handbook" and open web-based dissemination tools document the process chain for the fabrication of piezoMEMS devices. As yet a complete "fab" is still under development, the piezoVolume partners forming a virtual competence center. Most of the necessary tools have been installed at SINTEF MiNaLab, integrated through both process documentation and experience, in accordance with the ISO 9001 process certification. Tool development to enable volume fabrication of piezoMEMS devices has been our main project focus. The virtual tool to integrate all the "hardware/software" tools, the design handbook, will be made available as described above.

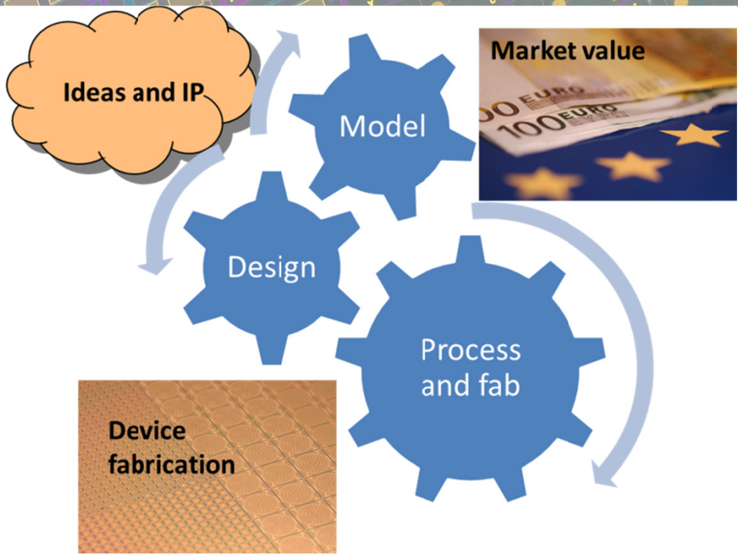


Figure 16: Full process chain illustrating inter-dependencies and important factors for device fabrication.

4.1.3.2 Development of piezoMEMS specific tools

Automated chemical solution deposition system

Solar-semi (SOS) has developed an automated CSD tool for the production of PZT thin films on up to 200 mm wafers. It consists of:

- RTP integrated into coating tool for PZT crystallization
- Optimization of RTP heat radiation through independent control of lamp arrays
- Wafer handling at the edges only to minimize thermal non-uniformity on coated PZT layers
- Hermetically closed cabinet permits operation under laminar flow conditions and prevents operators from coming into contact with toxic gases
- High temperature Hotplates (max. 450 °C) for pyrolysis
- Electrically controlled hotplates lifting pins permit arbitrary temperature profiles
- Three precision media pumps for coating solutions.
- The coater has either the SOS Covered Chuck Technology or option for open bowl operation
- Solvent saturated atmosphere in nozzle parking position

The final cluster tool incorporates improvements derived from SIN's experience with a prototype tool. Operation of the final cluster Tool (Figure 17) is greatly simplified through the ergonomically designed Human-Machine-Interface (Figure 18). Each module is represented by a self-explaining symbol and plain text messages guide the operator. The relevant parameters are displayed simultaneously giving excellent control over the running process.

Figure 17: Final CSD tool after installation at SINTEF

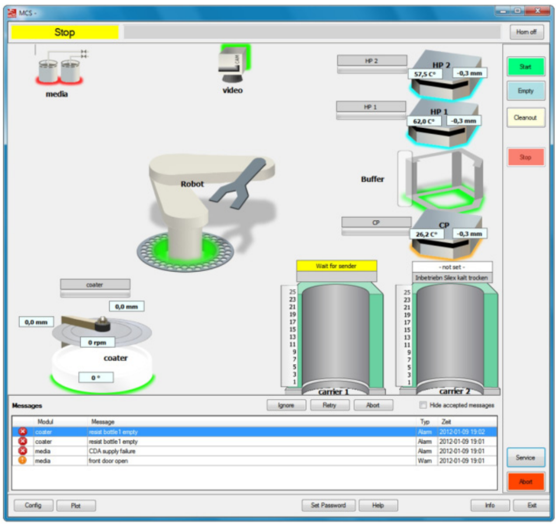


Figure 18: Human Machine Interface

The newly developed process with 100 nm per coated layer achieves 400 nm per RTP cycle and permits therefore a throughput of 3.2 wafer/h*µm (53 nm/min) using the tool in Figure 17. An up scaling of the PTZ tool to the tool platform MC 208 CSD with a robot that runs on a linear unit in the tool centre increases the throughput to 6.4 wafer/h*µm (106 nm/min) (Figure 19). Thicknesses from 100 nm to 4 µm can be realized.

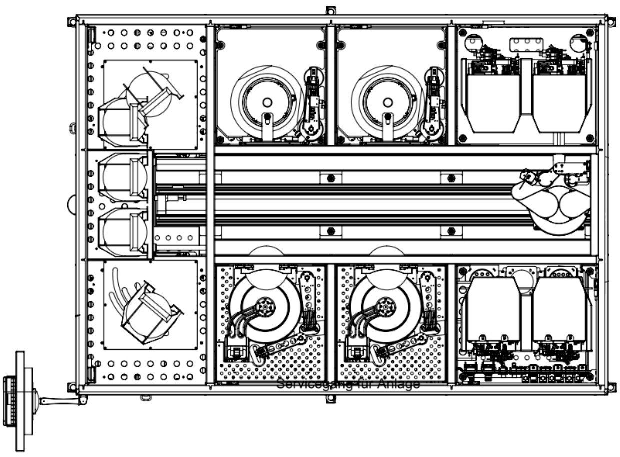


*Figure 19: Tool layout of the MC 208 CSD for throughputs of 6.4 wafers/h*µm*

A 200 mm wafer was coated using the final cluster tool. XRD analysis in Figure 20 show that the PZT is highly (001) oriented. Using a PZT powder as reference the film is 95,7 % (001) oriented which is very encouraging. The uniformity was measured using ellipsometry as shown in Figure 20. The data shows that the uniformity is very good with only +- 0.9 % thickness variation. An important development was a new more robust RTP process that eliminates problems with the high thermal mass of 200 mm.

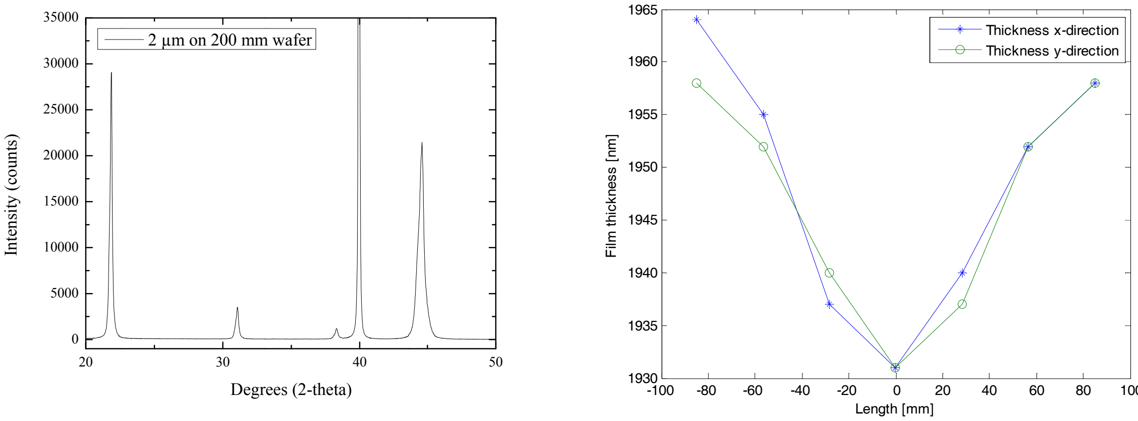


Figure 20: X-ray diffractogram of the center area of the 200 mm wafer and thickness uniformity measured by ellipsometry

The uniformity of $d_{33,av}^{+}$ using 16 measurement points and a combined C(V) and $d_{33,f}$ measurement for one pad are shown below in Figure 21. The $d_{33,f}$ performance is very good.

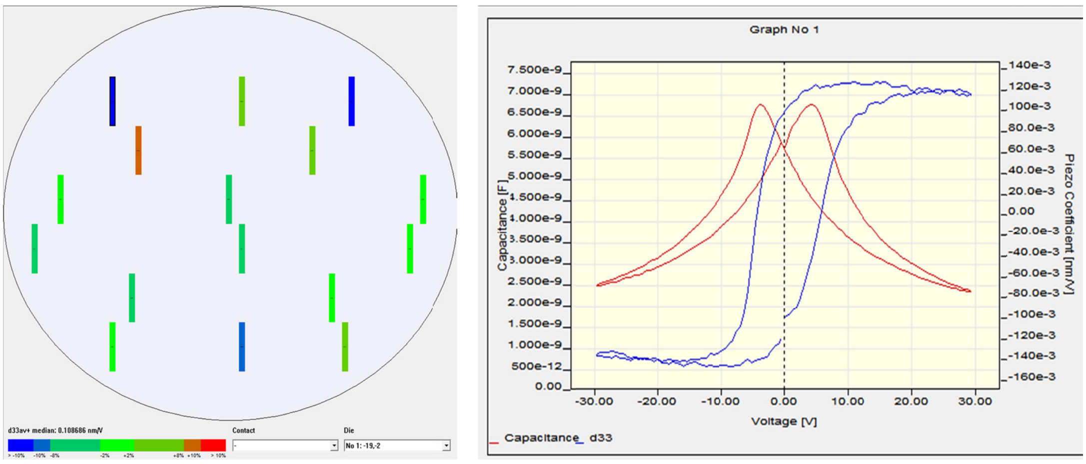
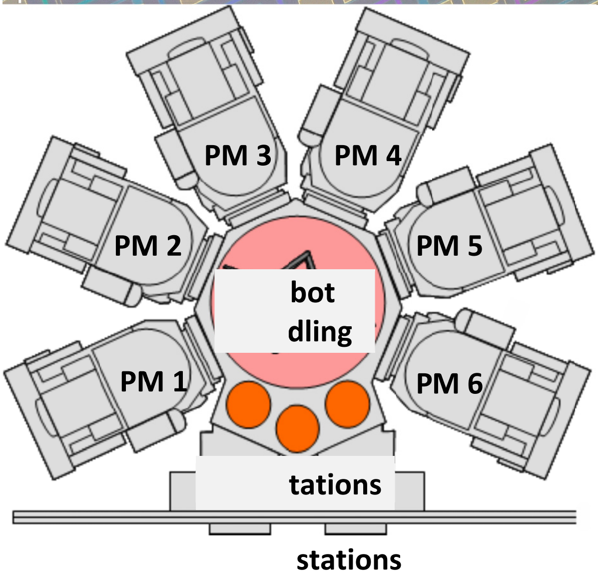


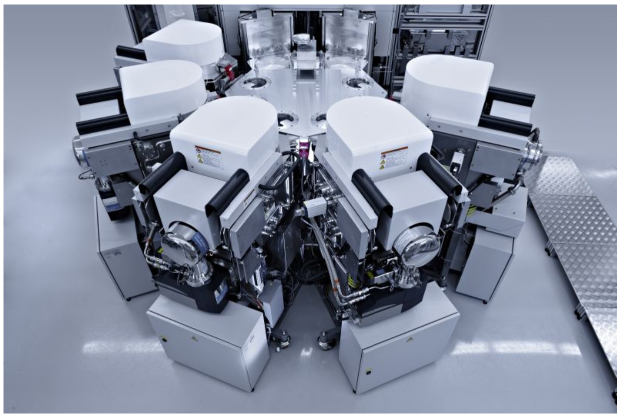
Figure 21: Uniformity of $d_{33,av}^{+}$ and a combined C(V) and $d_{33,f}$ measurement for one pad

SOS has developed a tool for the fully automated fabrication of piezo-ceramic films from chemical solutions. It consists of a specially adapter coater cluster, a RTP-furnace and the robotics for handling the wafers. For SMEs this provides a cost-conscious access to piezoMEMS production and the chance to implement innovative ideas.

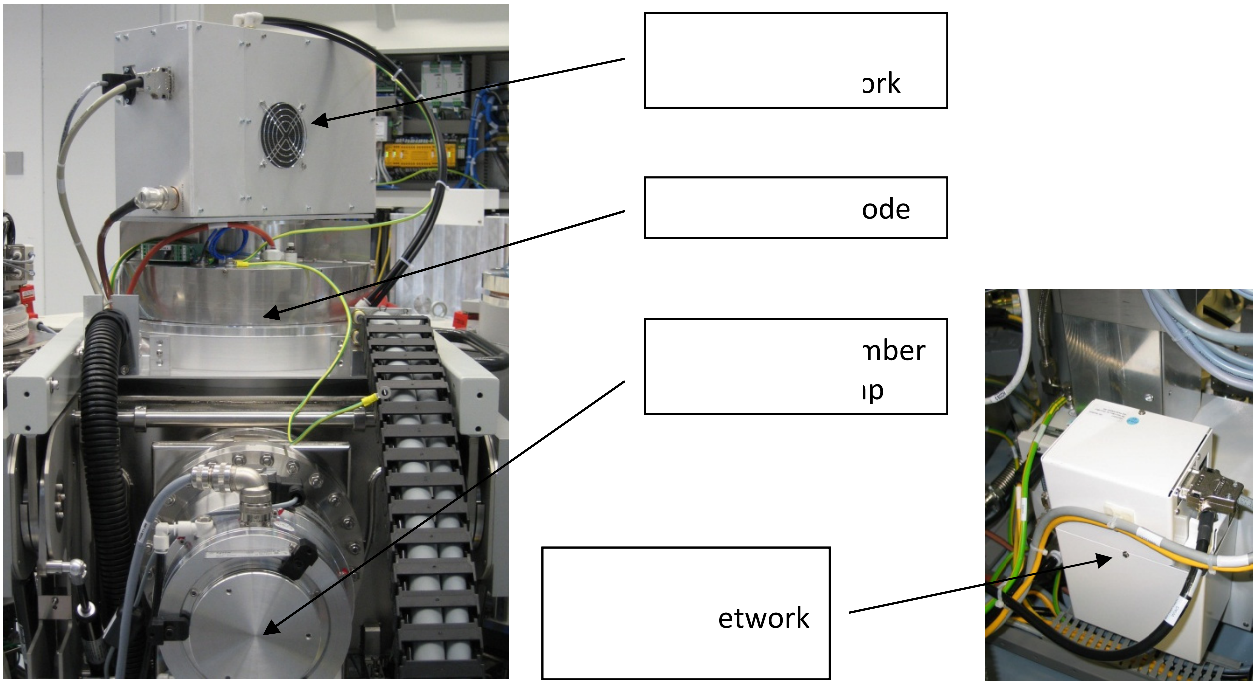
Automated high volume sputter deposition system

The sputter deposition tool for in-situ PZT deposition for both 150mm and 200 mm wafers is a Oerlikon cluster tool CLUSTERLINE 200 (CLN200). It consists of 2 load locks for wafer loading, a central robot for wafer handling and the sputter or etch modules for the depositions or the etching, respectively. Up to 6 process modules can be attached to the central robot handling and the tool can be optionally configured with 3 auxiliary stations (degasser, cooler and aligner) located close to the load locks. With this configuration complete PZT film stacks including bottom and top electrodes can be fabricated on 150 mm or 200 mm substrates in one run.

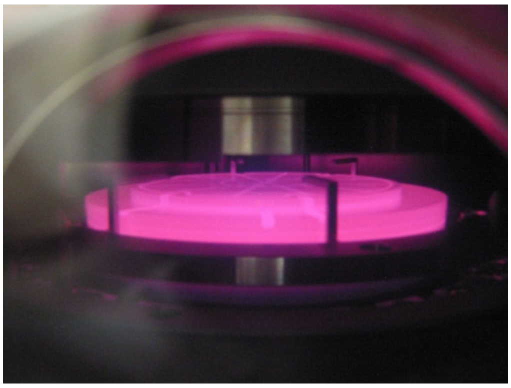


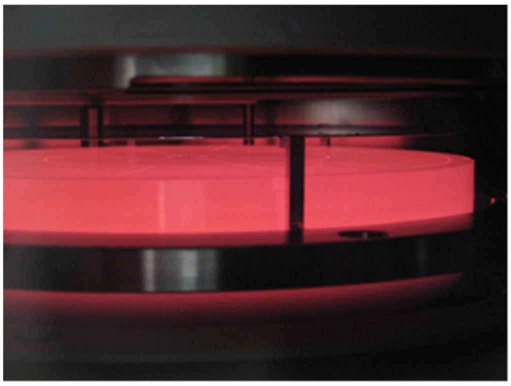


The sputter module to deposit PZT by RF magnetron sputtering on 150 mm or 200 mm wafer consists of a vacuum chamber equipped with a turbo pump, a RF sputter cathode with impedance matching network and a impedance matching network for application of RF bias to the substrate (Figure 23).



To reach the very high substrate temperature required for an in-situ PZT deposition process a so called Very Hot Chuck for 150 mm and 200 mm wafer formats was developed (Figure 24). Further on the special design of the anode allows a very homogeneous sputter gas distribution and finally the installed RF bias capability enables to tune the film properties.





A maximum temperature of more than 800°C is achievable with the very hot chuck which is well above the chuck temperature range of 550 - 700°C necessary for in-situ deposition of PZT. Therefore the very hot chuck can also be utilized to deposit other materials which need an even higher temperature to grow in-situ in the required crystal structure such as $BaSrTiO_3$ (BST).

Due to the separated heater circuits for the heating of the inside and outside area of the chuck and the design of the back gas inlet a very good temperature uniformity better than ± 2% could be achieved (Figure 25).

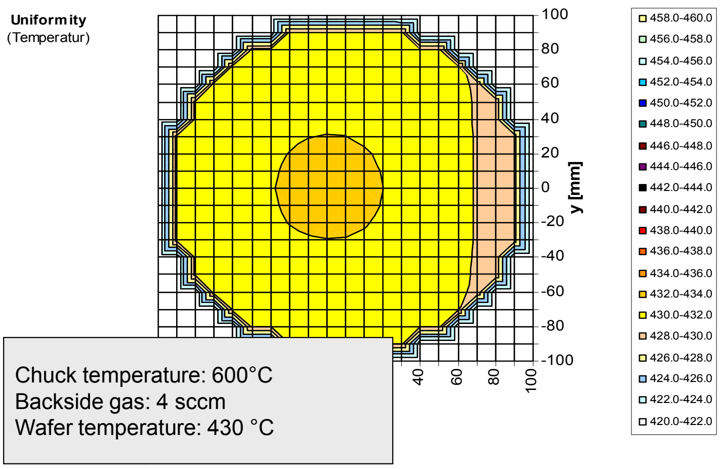


Figure 25: Temperature distribution on a sense array test wafer at heater set point 600°C.

With the actual magnetron design a film uniformity of ± 5% was achieved (Figure 26). At 3 kW RF load power the deposition rate is about 1.1 nm/s. Due to the design of the symmetric sputter gas distribution with 8 gas inlets the tangential uniformity is typically ~1% which means a very good value (graph insert).

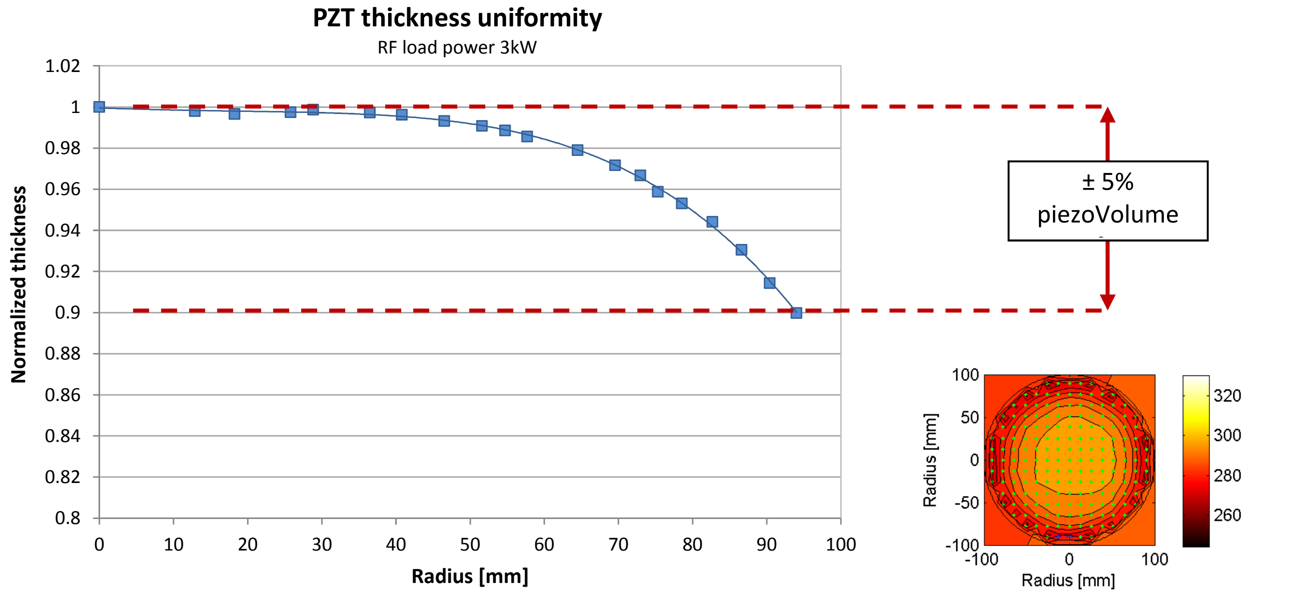


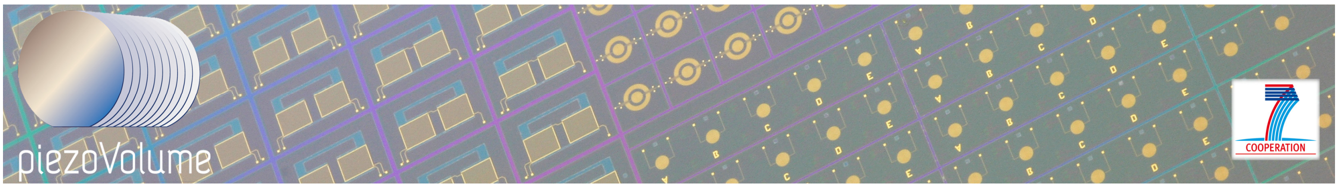
Figure 26: Thickness uniformity of PZT film deposited at 3 kW

Automated wafer level thin film in-line quality monitoring system (incl new testing methodology)

AIX has build up a double beam laser interferometer based on an automated wafer prober and has optimized the system in very detail especially in view of vibration sensitivity in order to guarantee 0.3 % accuracy on a reference x-cut quartz sample with an excellent stability. It is suitable for 8 inch wafer testing with ability to be extended by wafer robot handling and offers 1 pm resolution and proven 17 month stability of better 1 %, when measuring 100 pm displacement on an x-cut quartz reference sample (Figure 28). This is unique wordwide.

The system is operated through a touch screen Graphical User Interface with a recipe editor (Figure 27). The system is designed according to semi standards S2 and S8 and can be operated in a clean room envirnment and therefore is well prepared for the needs of piezoelectric MEMS industry.

Figure 27: Picture of the assembled aixACCT aixDBLI system with isolation vibration chamber and electronic rack with operation control unit.



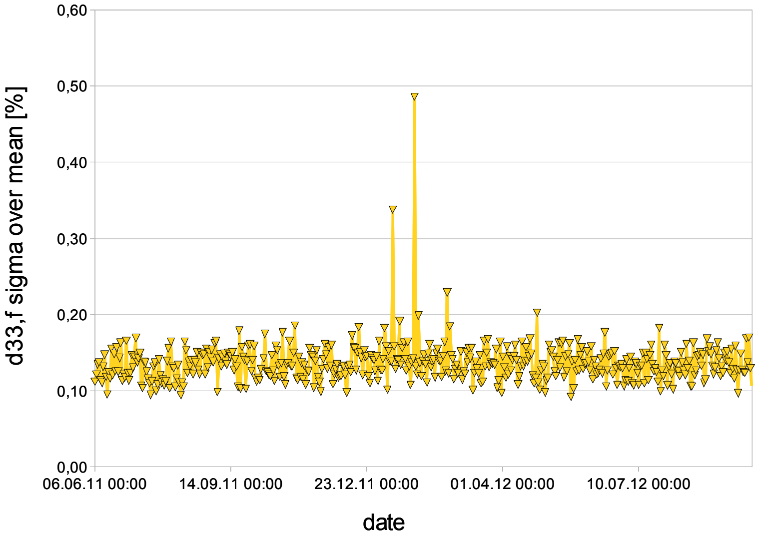


Figure 28: Sigma over mean data over 17 month of the aixDBLI system, which provides unique resolution and long term stability.

The system allows recording small and large signal response of electrical as well as electromechanical material properties. These data can be recorded on up to 8inch wafers. The important information out of these data is the wafer mapping information, which gives essential feedback for process optimization of the deposition process of the piezoelectric material. Furthermore, the software allows performing leakage current measurements as well as fatiguing measurements.

The recipe editor guides through the creation of a recipe, which is the core part of the system in order to operate this tool automatically (Figure 29). Due to this design concept the recipe is created by a super user in an office environment and the operator can simply select the recipe and perform all required tests automatically in clean room environment. The software can be operated even with gloves because of the touch screen concept.

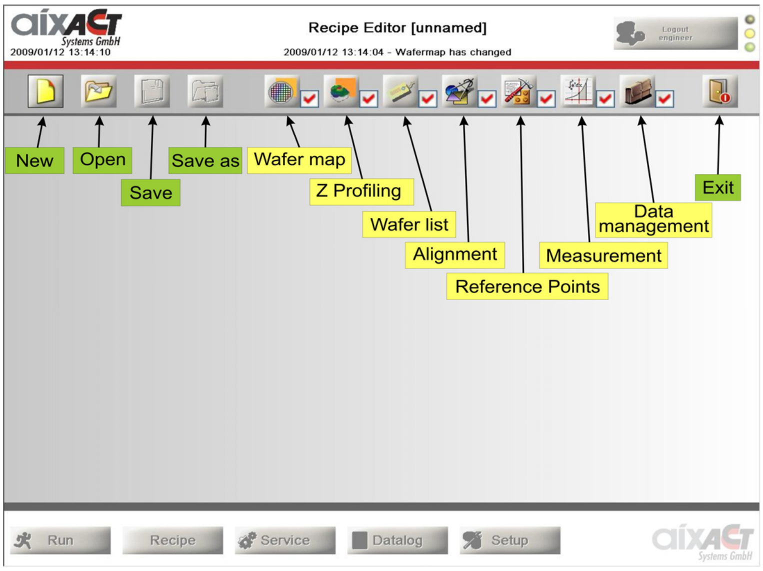


Figure 29: Screen shot of the Graphical User Interface of the aixDBLI system on touch screen basis.

New testing methodoloy has been developed to control the important piezoelectric coefficient $e_{31,f}$ which can not be measured on full wafer indirectly by means of piezoelectric coefficient $d_{33,f}$ and ε33 which can be measured on full wafers by the aixDBLI system. For this purpose we had to search for a solution quite long time and finally came to the conclusion to that we need to measure $e_{31,f}$ not without but versus bias voltage as it is done for $d_{33,f}$ and ε33. Since $e_{31,f}$ versus bias voltage was developed the correlation was quite simple to identify as the following figures show. The slope of the $e_{31,f}$ versus $d_{33,f}$ loop represents the mechanical compliance c13 (Figure 30).

This ends up in the conclusion that monitoring $d_{33,f}$ on wafer level plus monitoring the dielectric constant $\varepsilon 33$ is sufficient to predict the $e_{31,f}$ value without measuring this parameter. $\varepsilon 33$ monitors the density of the film precisely due to its high resolution measurement and therefore controlls the electromechanical in plane interaction of the film. If at the same time $d_{33,f}$ remains the same as usual we can predict that $e_{31,f}$ is the same as well. Changes in $\varepsilon 33$ or $d_{33,f}$ imply a change in $e_{31,f}$.

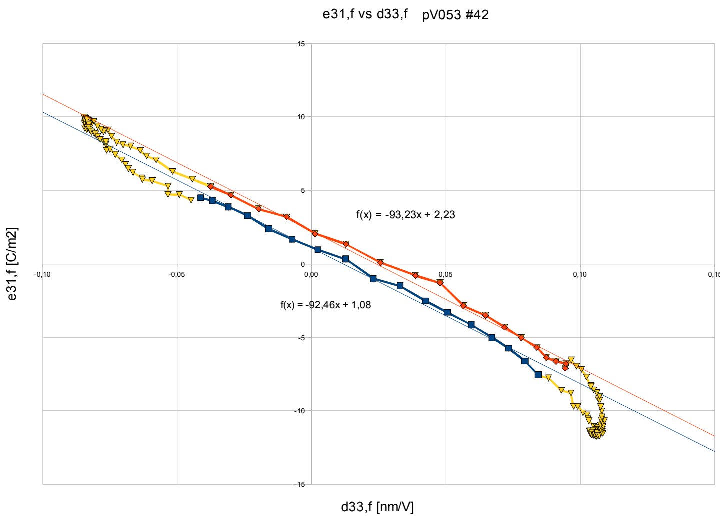


Figure 30: Correlation of $e_{31,f}$ and $d_{33,f}$ with slope of c_{13} enables indirect control of $e_{31,f}$ by monitoring $d_{33,f}$ and ε_{33}

piezoMEMS specific modelling tools and process design kits

Coventor developed design and modelling capabilities dedicated to piezoMEMS in order to improve the design of novel devices.

Development of new piezoMEMS specific models and modelling techniques

Finite-Element-Method (FEM) modelling techniques for piezoMEMS has been improved with new techniques. These new techniques allow modal harmonic analysis, for example, useful for piezoMEMS based resonators. Another development was carried out on including electrical circuit elements (resistors, capacitors, inductors and circuit nodes) into Coventor's FEM environment (tool CoventorWare). These simple circuits can be connected to piezoelectric materials. This is needed, for example, for energy harvesting applications.

Regarding high-order Finite Element models (tool MEMS+), a novel shell model with piezoelectric layer stack (conductor/piezoelectric/conductor) has been developed and integrated into the MEMS+ design platform based on 3D design entry and a component library of high-order Finite Element models. 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.

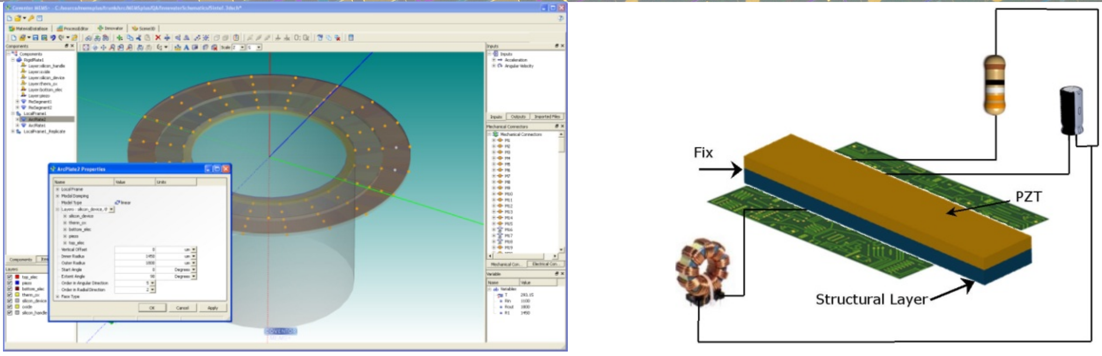


Figure 31: New shell model (left) and Schematic representation of a FEM cantilever including connection of simple circuit elements (via boundary conditions).

Development of piezoMEMS Process design kits (PDK)

These PDKs (one for each tool) have been created and integrated into the tools. They are based on Sintef's moveMEMS PZT process and include the latest data from Sintef. PDKs include processes, material information and examples layouts encoded into the Coventor's design environments enabling MEMS designers to easier and better design into an established process. The work included validation and further development of piezoMEMS library design elements.

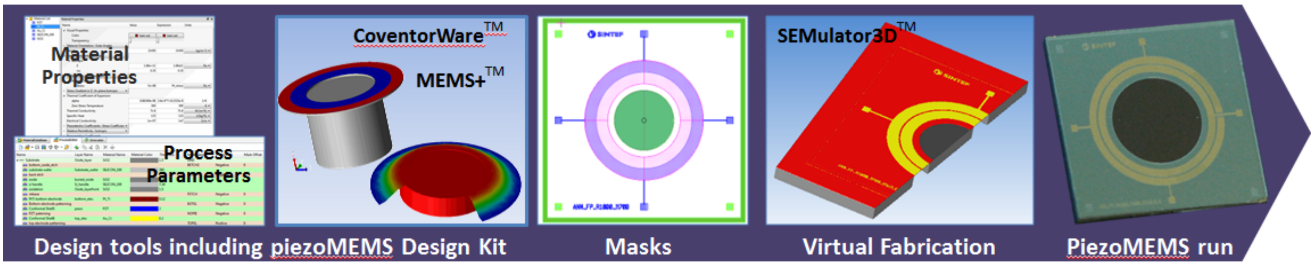
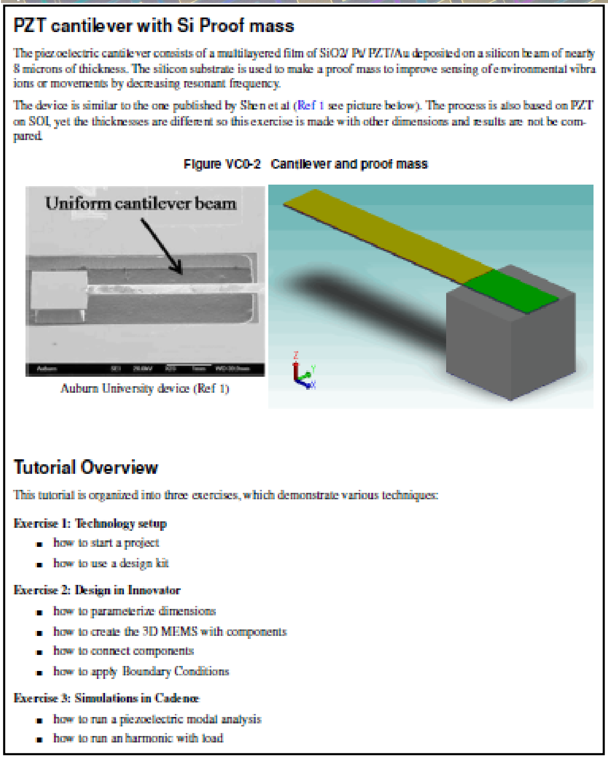


Figure 32: Design flow and modelling levels included in the PDK for MoveMEMS PZT.

Creation of piezoMEMS dedicated tutorials which explain how to use PDK to design piezoMEMS

Three tutorial materials have been done. The first one is a manual focused on Finite Element Analysis (EA) modelling with CoventorWare. It is made of a step by step description of procedures which allow users progressing and learning on their own on a reliable and secure way. The second one deals with modelling in MEMS+ high-order FE tool. It is less detailed and would require user investigation on how to do more analyses to stimulate user's autonomy. The third one concerns SEMulator3D virtual fabrication tool and is a live demonstration and exercises made of slide shows and support is needed to discover/explore the tool.



PZT cantilever with Si Proof mass

The piezoelectric cantilever consists of a multilayered film of SiO2/ Pt/ PZT/Au deposited on a silicon beam of nearly 8 microns of thickness. The silicon substrate is used to make a proof mass to improve sensing of environmental vibra ions or movements by decreasing resonant frequency.

The device is similar to the one published by Shen et al (Ref 1 see picture below). The process is also based on PZT on SOI, yet the thicknesses are different so this exercise is made with other dimensions and results are not be compared.

Figure VC0-2 Cantilever and proof mass

Uniform cantilever beam

Auburn University device (Ref 1)

Tutorial Overview

This tutorial is organized into three exercises, which demonstrate various techniques:

Exercise 1: Technology setup

- how to start a project
- how to use a design kit

Exercise 2: Design in Innovator

- how to parameterize dimensions
- how to create the 3D MEMS with components
- how to connect components
- how to apply Boundary Conditions

Exercise 3: Simulations in Cadence

- how to run a piezoelectric modal analysis
- how to run an harmonic with load

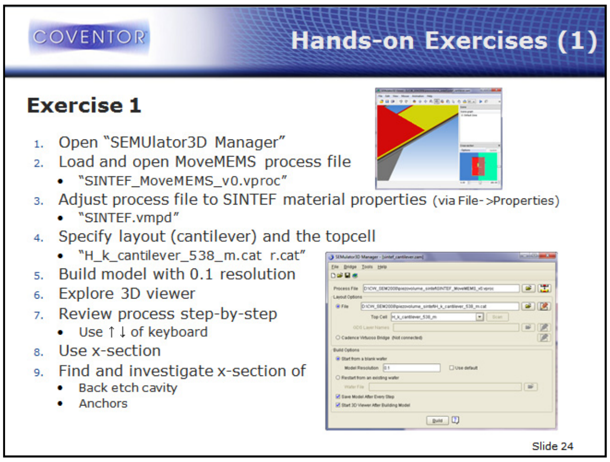
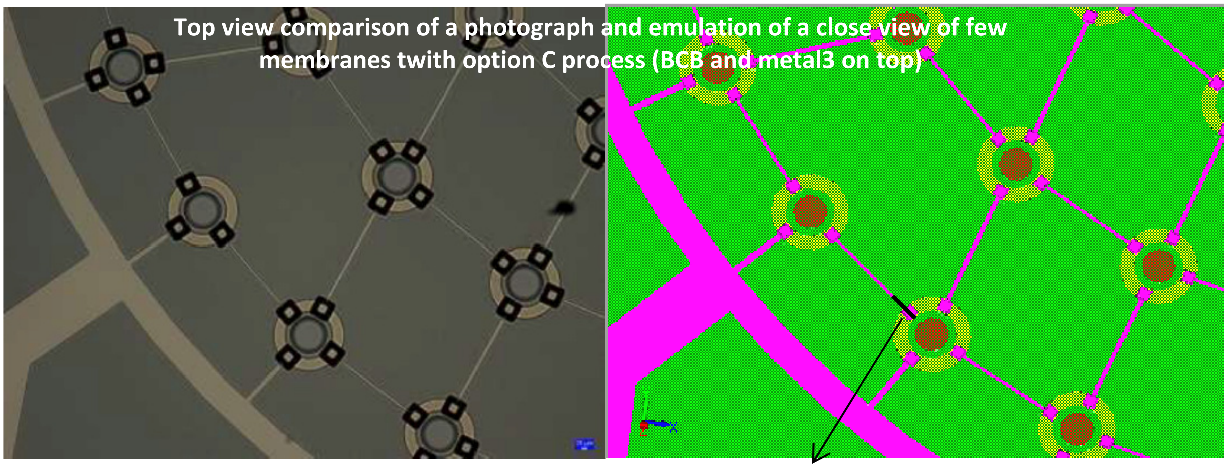


Figure 33: MEMS+ tutorial manual on Piezoelectric Vibration Energy Harvester overview and Slide show extract for SEMulator3D on MoveMEMS technology.

Creation of piezoMEMS dedicated Application Notes

Three application notes have been published on the usage of Coventor software tools for piezoMEMS design and modelling. First application note describes a cantilever vibration energy harvester. The second one deals with a piezoelectrically actuated piston micromirror. Both devices are studied with the complete set of tools ranging from system-level design (MEMS+) to verification with FEA (Coventorware). The third application note describes the use of virtual fabrication techniques applied to the demonstrators from Vermon (ultrasonic transducer) and Sonitor (microphone) based on Coventor's tool SEMulator3D. Those three notes are webpages available at http://www.piezomicrosystems.com/.



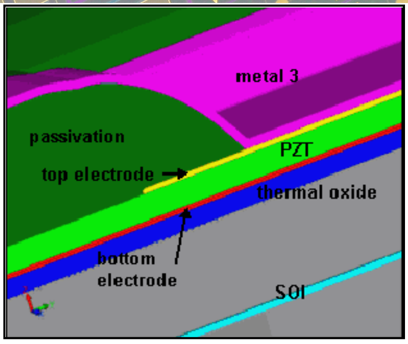


Figure 34: Ultrasonic transducer from Vermon generated by SEMulator3D with its comparison to a photograph and a cross section

4.1.3.3 piezoMEMS device prototypes

Device designs

In the piezoVolume project 2 different ultrasound devices and a test device for an ink-jet printer have been designed and have been manufactured. The ultrasound device requested by Vermon are intended for the use in therapeutical medical applications and the ultrasound device requested by Sonitor can be used for indoor positioning systems. The device requested by Ocè is a device for ink-jet printing. The first device will be only used as an actuator, the second will be used as both an actuator and a microphone and the third device is a fluidic actuator. The modelling is done with both analytical and numerical methods. For the numerical simulations the FEM-tool from Coventor (CoventorWare) is used. The material data is based on the material data base assembled in the piezoVolume project.

The modelling has been performed using both analytical and FEM models. Important parameters for the devices are especially the frequency of the first eigenmode, the capacitance (impedance) of the structures and the sensitivity (for the microphone). All devices are operated in bending mode. A typical set-up of the devices is shown in Figure 35. The d_{31} variant including a top and a bottom electrode is operated with an electrical field across the PZT ("3" direction) and the PZT will deform in a way so that the membrane bends ("1" direction). The d_{33} variant including only a top-electrode with circular "finger" shaped electrodes has both the electrical field between the electrodes (also here "3" direction) and the deformation in the same direction. This counts for both sensors and actuators.

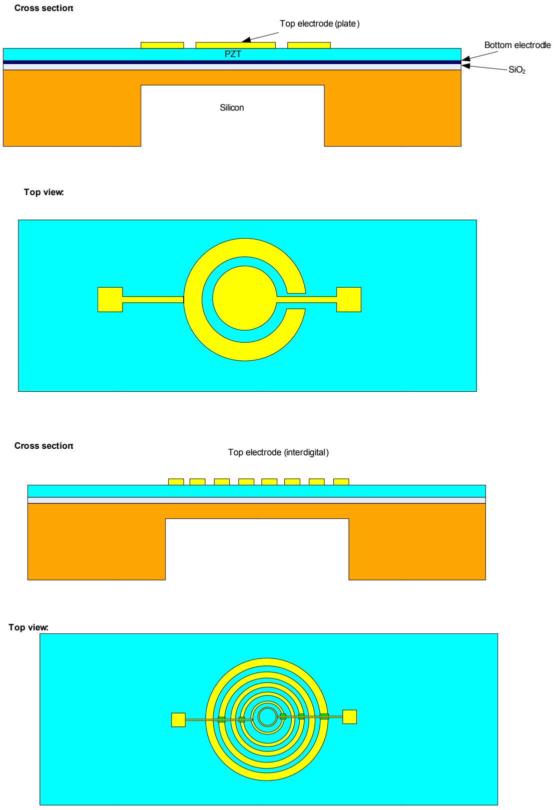


Figure 35: Cross-section of the two d_{31} and d_{33} variants for microphones/actuators, with and without bottom electrode.

The Vermon HIFU (High Intensity Focused Ultrasound) devices are piezoelectric micromachined ultrasound devices (pMUT) which can achieve large excitation amplitudes and high output power due to the advantages of this technology. The devices were designed by using both analytical and numerical (finite element analysis) methods. Figure 36 shows the results of the analysis of the eigenfrequency as a function of the membrane radius using both methods with somewhat varying geometry.

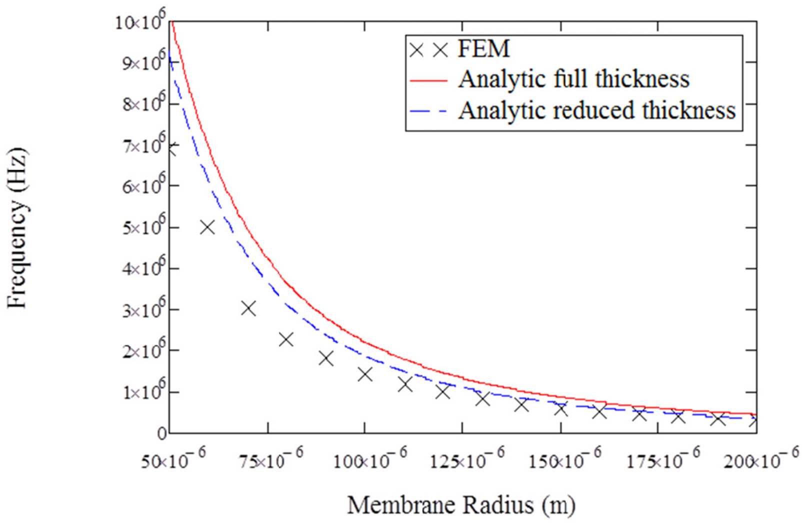


Figure 36: Resonance frequency as function of membrane radius. The red curve shows the analytical results based on the mass and flexural rigidity of the full stack, whereas the blue broken curve is based on the mass and flexural rigidity of the (Si-SiO2-Pt only).

Based on the modelling results a membrane diameter was chosen which corresponds to the eigenfrequency of 1 MHz for the first mode as intended for the application.

Sonitor's ultrasound microphone is an ultrasound sensor which has a similar set-up as the Vermon device, but is optimized for other frequency range and for high sensitivity. This device was modelled by the use of Coventorware for the eigenfrequency analysis (Figure 37) and analytical expressions for the sensitivity. The sensitivity has been calculated as a function of the membrane radius and is shown in Figure 38.

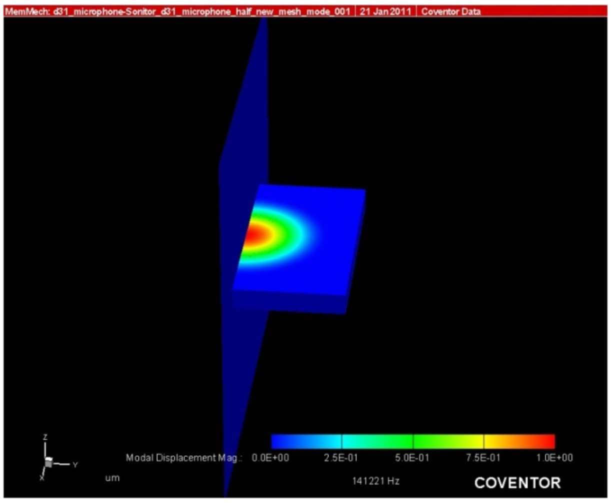


Figure 37: Coventor simulation results of the 3D eigenmode analysis with the frequency and shape of the first eigenmode.

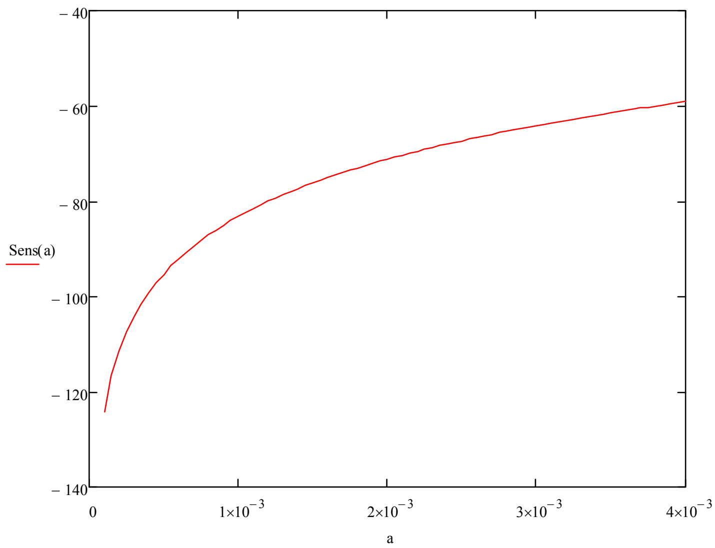


Figure 38: Sensitivity in dB (0dB is 1V/Pa) as a function of the membrane radius.

The ink-jet printing device from Océ is based on a rectangular membrane driven in the d_{31} mode. The main design goal was sufficient deflection of the membrane so that the necessary ink volume could be ejected.

Testing results

<u>Sonitor microphones</u>

One important advantage of piezoelectric MEMS over more conventional MEMS read-out technology such as capacitive sensing is the much reduced complexity of read-out electronics. Provided adequate sensitivity of the MEMS device, the readout can simply consist of a JFET acting as an impedance converter. This will provide a very large cost advantage over alternate MEMS solution.

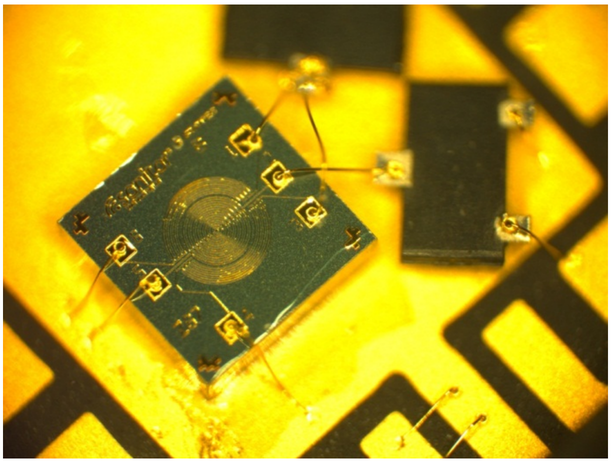


Figure 39: Microphone mounted with FETs for measurements

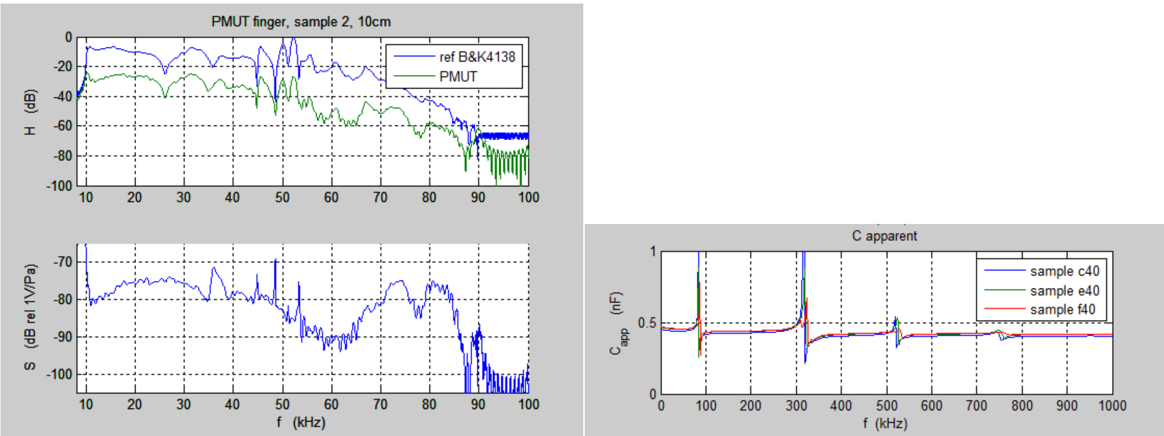
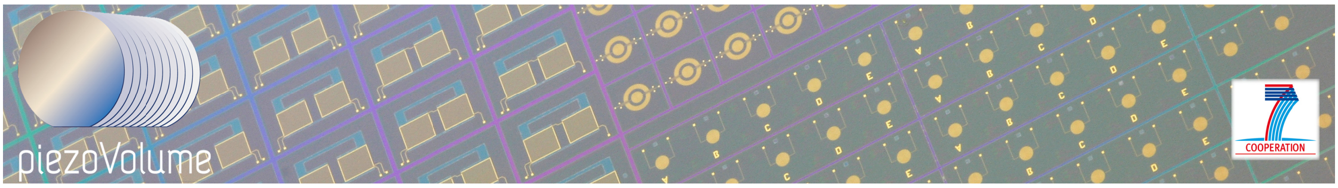


Figure 40: piezoMEMS microphone sensitivity measurements and frequency sweep showing resonance frequencies.

The main conclusions after testing the piezoMEMS microphones are:

- The piezoVolume microphone devices exhibited resonance features that are indicative of very high quality electro-mechanical coupling.
- The mechanical design limitations imposed by the multiple project wafer nature, imposes strong limitations on the sensitivity of the realized devices, limiting their sensitivity to -82 dB, at least 40 dB underperforming state of the art high volume microphones.

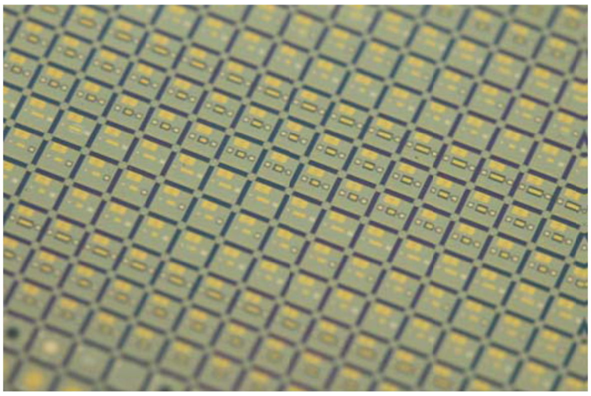


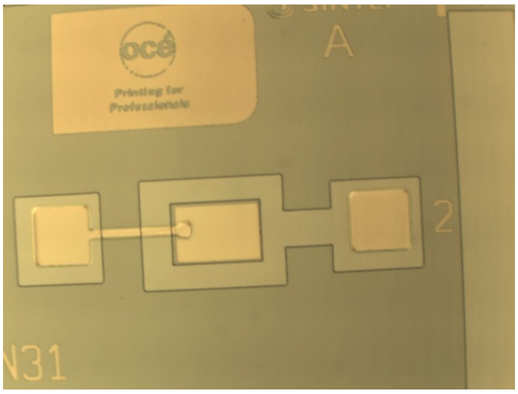
- Device sensitivity was too low to be able to use more conventional microphone characterisation approaches adapted from ECM characterization.
- Fatigue effects do not play a significant role in piezoMEMS based microphones due to the extremely low forces exerted by the acoustic excitation.
- Long term sensitivity of PiezoMEMS devices is of concern given the low temperature required to de-pole these devices.

<u>Oce inkjet actuator</u>

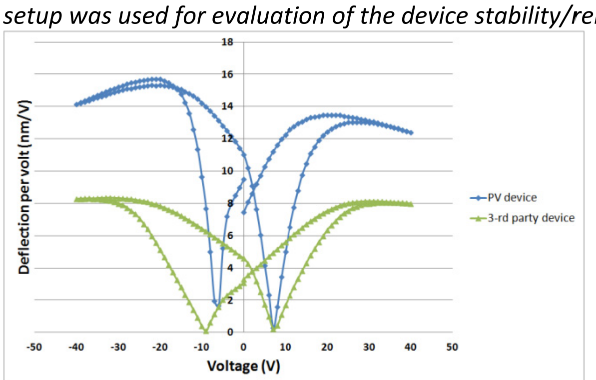
Recently, Océ has shifted its research focus to the possibilities of low-cost manufacturing of the piezoelectric print heads based on thin PZT films and MEMS technology. Successful actuator prototyping in combination with scaling and industrial validation of the CSD and sputtering methods for thin piezoelectric films within will open these possibilities. High performance thin PZT layers will allow further miniaturization of the actuator unit leading to print heads with high dpi resolution.

Several designs of inkjet actuators were realized within PiezoVolume project as prototype devices (see figure below).





Out-of-plane deflection was measured using Polytec SLV with MSA-400 optical measurement head. Additionally this setup was used for evaluation of the device stability/reliability.



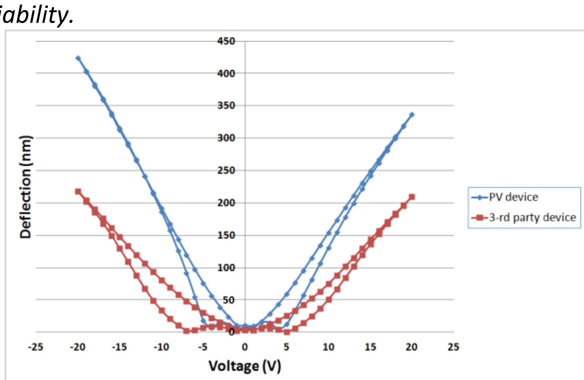


Figure above shows the small signal deflection (left), and large signal deflection (right). Blue lines represent the deflection measured on PiezoVolume devices while the red one corresponds to the deflection of the identical device but with the PZT layer from the third party. Clearly, PZT material developed with PiezoVolume project is twice more efficient than the material used in the previous experiments at Oce.

Device performance represents a satisfactory case. The deflection values are sufficient for the realization of the necessary volume displacement for droplet ejection. Unfortunately, we were not able to implement the PiezoVolume layers in the real demonstrator due to unavailability of wafers with PZT. This will be done after project completion.

Oce is planning to utilize thin PZT layers as an active material for inkjet actuator in the future. Despite several technical issues and the current absence of industrial source of "graded" PZT layers we believe that PiezoMEMS is the future technology for inkjet printing.

Vermon pMUT

Motivation : Vermon S.A. (France) is a major manufacturer of ultrasonic devices for medical and industrial applications, the application field in medical covers diagnostic, monitoring and ultrasound therapy (drug delivery or treatment by hyperthermia also called HIFU High Intensity Focused Ultrasound),. In the PiezoVolume project, Vermon is interested in testing pMUTs (piezoelectric micromachined ultrasonic transducers) with target to evaluating them for HIFU applications.

The transducer that was designed is a single element, disc-shaped, 6 mm diameter, 1 MHz emitter. Individual membranes were sized to match the desired working frequency and the transducer was realized as an assembly of such membranes, however with a large spacing between them imposed by process considerations.

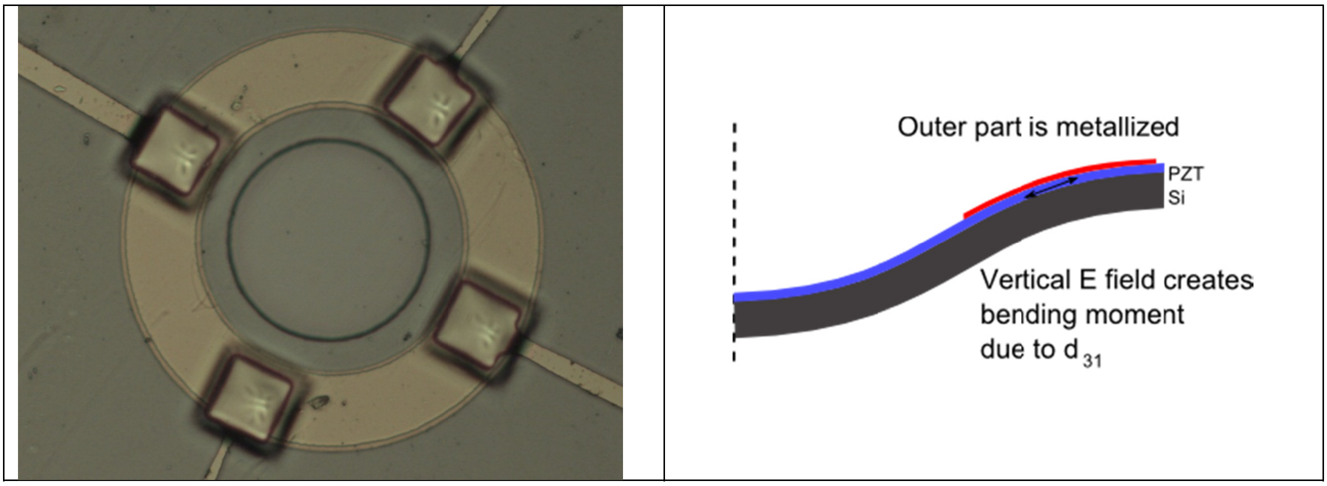


Figure 41: View of a Vermon pMUT device (left), and snapshot of the working principle of a pMUT membrane (below).

Two methods were used to characterize the devices : impedance measurements and laser interferometry. For both kinds of characterization, the pMUT samples were used with a small DC bias.

Figure 42 displays impedance measurement results, emphasis both the position of resonance peaks, and the very low values (compared to other transducer types) of impedance allowed by this technology.

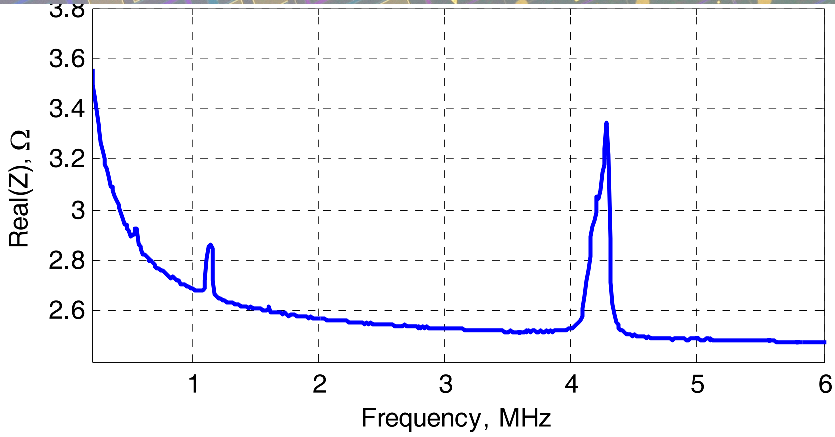


Figure 42: Impedance response (real part) of an element, displaying two resonance mode. The one used for ultrasonic transduction is around 1 MHz.

Figure 43 shows the displacement response of a pMUT membrane, measured at its geometric center in fluid immersion, for two different electric excitations (wide and narrow band).

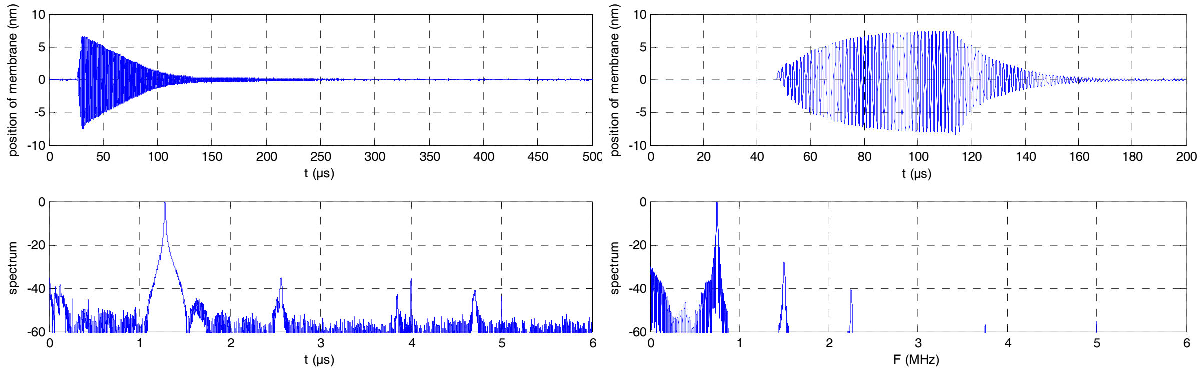


Figure 43: Results in air for a single 2.5 MHz pulse of 10 Vpp (left) 750 kHz, 20 Vpp, 50 cycles excitation in oil (right)

Displacement measurement provided an evaluation of the efficiency of pMUT design as a transducer:

1. Displacement is very linear (second harmonic is very low)
2. Displacement values at membrane center are surprisingly large : around 1 nm per volt of excitation at 1 MHz
3. However due to low filling factor of transducer surface with membranes, the emitted acoustic power remains small (a few milliwatts per cm²).

4.1.5 Potential impacts

4.1.5.1 Technological impacts

Fabrication rules and integration

New processes for deposition of PZT thin films on Pt electrodes, with state of the art PZT thin film properties (measured as the transverse piezoelectric coefficient $e_{31,f}$), optimized for high throughput have been developed. Moreover, new standards will be established concerning the important configuration of PZT deposited on an insulating buffer layer for interdigitated electrode systems. The results will enable high performing piezoelectric MEMS devices in many areas: inkjet printing heads, and further fluidic micro systems; active optic elements such as auto focusing lenses and optical displays and scanners; ultrasound transducers for proximity sensors, in room localization, and potentially also for medical imaging at high frequency (eyes, skin, artery walls, etc,).

A high volume fabrication solution for PZT thin films is indeed needed for a further innovation jump in MEMS devices and applications. Such innovation jumps related to new thin film materials are always a crucial period for thin film equipment manufacturers to have at the right moment the right process tools on the market. In case of oxide thin films the choice of the deposition method is not obvious. For PZT thin films, chemical solution deposition (CSD) is in competition with sputter deposition. Within the consortium we have both options.

piezoMEMS specific tools and processes

A high volume fabrication solution for PZT thin films is indeed needed for a further innovation jump in MEMS devices and applications. Such innovation jumps related to new thin film materials are always a crucial period for thin film equipment manufacturers to have at the right moment the right process tools on the market. We believe that the piezoVolume partners have managed to do just that. Two industrial partners, OER and SOS, will offer highly sophisticated production equipment (sputtering systems and automated CSD, respectively) to the global microelectronics fabrication market. Another industrial partner, AIX, is a world leader in testing of piezoelectric materials, and will offer testing services and sophisticated testing equipment. COV will offer modelling software specifically for piezoMEMS. Finally, the three application-specific industrial partners (SON, OCE and VER) will address their own specific markets for new piezoelectric MEMS products.

piezoMEMS device fabrication rules

The expected results are to show the viability of the total manufacturing process chain for the manufacturing of application specific devices as well as the applicability of the modelling tools. This will – if successful- have a direct potential impact on future products for the end-user partners. In a wider perspective it will make the developed technology more attractive for other users and, thus, also on future sales of the equipment/tool manufactures in the project. Therefore, the competiveness of the industrial partners will increase after a successful demonstration of the technologies.

Testing and characterization

As innovation leader for electrical thin film testing aixACCT Systems has extended the well approved double beam technique to the first commercially available Double Beam Laser Interferometer system for up to 8 inch wafer characterization with possibility to combine it with wafer robot system. The software allows performing small signal, large signal measurements as well as reliability tests in fatigue and DC creep. In one word, this system can acquire a full dataset of a piezoelectric film for characterization. The new methodology "monitoring $e_{31,f}$ by $d_{33,f}$ and ε_{33}" is a breakthrough in quality control for piezoMEMS film production.

4.1.5.2 Socio-economic impacts

It is in the interest of the project to actively pursue dissemination of the technology as to gain wider acceptance and larger product volumes, which will help to reduce cost. Therefore, most of the piezoVolume exploitation assistance package will be published openly. The full procedures and the design handbooks will however be kept confidential in order to maintain control of the distribution, but they will be made available to interested parties upon signature of a non-disclosure agreement.

The piezoVolume partners will exploit the results in many directions. The research partners (SIN, EPF and ISI) will utilize the academic potential in scientific publications and as basis for new research. The non-university research institutes (SIN and ISI) will offer product and process development, and production, to industries. Two industrial partners, OER and SOS, will offer highly sophisticated production equipment (sputtering systems and automated CSD, respectively) to the global microelectronics fabrication market. Another industrial partner, AIX, is a world leader in testing of piezoelectric materials, and will offer testing services and sophisticated testing equipment. COV will offer modelling software specifically for piezoMEMS. Finally, the three application-specific industrial partners (SON, OCE and VER) will address their own specific markets for new piezoelectric MEMS products.

The piezoVolume partners intend to contribute actively to the development of new industrial standards in the field of piezoelectric MEMS. This will greatly enhance take-up of the technology by industrial companies inside and outside the project. SIN, as a major European institute, has experience and is involved in the development of international standards in several research areas. AIX, as a specialist in testing of piezoelectric materials, is already involved in standardisation activities on European and international level.

From a European perspective the project has strengthened European companies' position for worldwide supply of core machines for the production of films of this technology. At the same time the project has also created an infrastructure for any European company to have access to this high tech technology in an easy and cost-effective way. To achieve this for the future the partners have assembled an Exploitation Assistant Package and even more important have established the competence centre for piezoMEMS at SINTEF.

4.1.6 Dissemination and exploitation

4.1.6.1 Dissemination

To promote the project to users and other stakeholders the piezoVolume partners attended a large number of international workshops and conferences. The contributions were given as oral presentation, posters, flyers, industry presentations, exhibitions and industry workshops. This resulted in:

- 11 contributions to 8 different exhibitions where project results have been presented.
- 1000 Project flyers distributed at 6 different venues in Europe and the USA
- posters at conferences
- 12 presentations at conferences
- 8 presentations to industry
- 4 published articles
- 3 submitted articles
- 2 international industrial workshops on piezoMEMS arranged
- 1 market analysis

Some of the venues for the dissemination activities are listed below:

- piezoMEMS workshop 2010, 18-19th of May 2010, Aachen
- ISAF 2011, Vancouver, Canada – July 24-27, 2011
- Electroceramics XII, 13-16/6 2010, Trondheim
- Power MEMS 2011, 15th – 18th November 2011, Seoul,
- Semicon Europe 2010, 19-21/10 2010, Dresden
- MRS BOSTON, USA 28. Nov-2nd Dec 2011
- piezoMEMS workshop 2011, 7/8th September 2011, Lausanne
- Semicon Europe, 11-13th of October 2011, Dresden
- Electroceramics XIII, June 2012, Twente Enschede
- COMS 2012, 24-27 July, Tonsberg, Norway
- ISAF July 2012, Aveiro
- SMACD 2012 Sept. 19th – 21st Seville, Spain
- Semicon Europe, 9-11th of October, Dresden
- UFFC October 2012, Dresden

Many of the presentations that have been given are available through the project website. There were also prepared project flyers. First a version at the beginning of the project, a revision after the first year and then a final version after 2,5 years. In total about 1000 flyers have been distributed at conferences in Europe (Semicon, Electroceramics, ISAF, DPG) and the USA (Semicon, US Navy Workshop) and during company seminars.

Industrial workshops on piezoMEMS

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 focussed subjects.

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

4.1.7 Impressions

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.

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

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.

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 field of piezoMEMS.

4.1.7.1 Exploitation

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. Some core industry partners that have been visited is given in the table below:

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

Table 2: Core part of customers driving the piezoMEMS technology into mass applications

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 at an early stage the attention of decision makers to this new technology. This is an important channel as company decision makers learn about the progress of piezoMEMS and demonstrators that work.

Figure 44: SOS and AIX booth at Semicon Europe 2011 in Dresden

Tool demonstrations

AIX had 15 demonstrations of their DBLI technology during the project runtime. OER has demonstrated PZT sputter technology by wafer sampling to at least 9 companies

Exploitation assistance package (EAP)

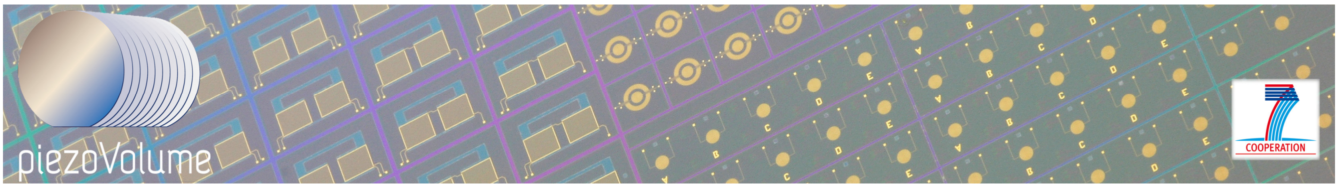
The EAP is a separate part of the public D5.7 report "Dissemination of results by publications and open seminars. Exploitation assistance package" and can be treated as a separate document. The EAP is a tool that the partners and potential customers can use to assist in exploring the potential of the piezoMEMS platform and the needed tools and procedures to enter into the technology. The EAP gives a summary of:

1. The piezoMEMS market
2. Design and modelling tools
3. Design rules
4. Fabrication routes
5. Infrastructure

The booklet should inform on the potential of this possible platform technology and ease the entry into this emerging technology. D5.7 and the EAP can be downloaded from the project web site.

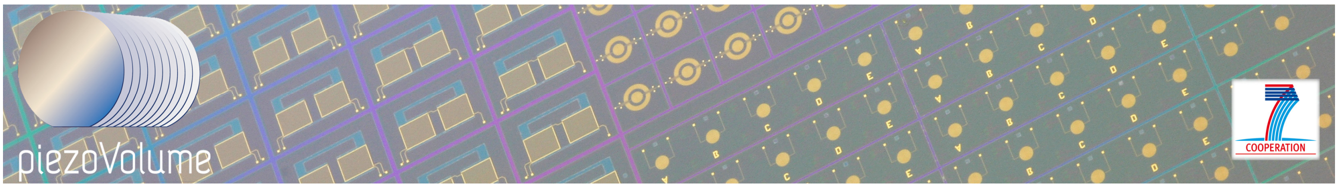
Market analysis

piezoVolume partners have had continuous contact in different kind of ways with the MEMS industry. From all these contacts, without disclosing confidential information the project partners assembled a detailed market analysis. The market analysis is a part of the public exploitation assistance package.



New standards

Standardization of the characterization of PZT and other piezoelectric thin films is highly needed. AIX as a specialist in testing of piezoelectric materials is involved in standardisation activities on European and international level and will propose a recommended method in 2013 through the European Committee for Standardization (CEN). A likely first step is making a CEN Workshop agreement (CWA), which is a standardization document developed in a CEN Workshop. The development of a CWA is fast and flexible, on average between 10-12 months.



piezoMEMS competence centre

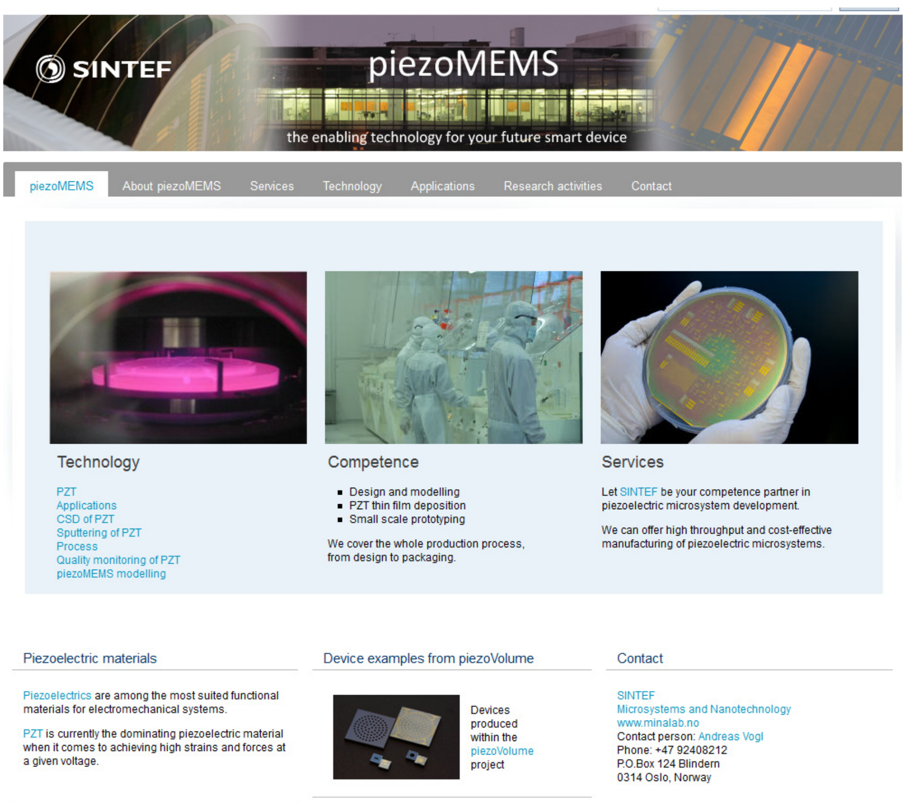
The Competence Centre (CC) created within the project is a perfect match to people who want to get started with Piezoelectric MEMS. This CC definitely cuts down time of feasibility study. People within the CC have worked with design, modelling, process development and fabrication of piezoeMEMS since 2002. The CC has 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



4.1.8 Contractors

The piezoVolume project has nine contractors:

- École Polytechnique Fédérale de Lausanne, EPFL
- aixACCT Systems GmbH
- Sonitor Technologies AS
- OC Oerlikon Balzers Ltd.
- Océ-Technologies B.V.
- Vermon
- Fraunhofer ISIT
- COVENTOR
- Solar Semi GmbH

Co-ordination contact details, public website and logo

piezoVolume co-ordinator:

Dr. Frode Tyholdt, Senior Scientist
SINTEF Materials and Chemistry
P.O.Box 124 Blindern, NO-0314 Oslo, Norway
Tel +47 917 58 274, fax +47 220 67 350

piezoVolume public website: www.piezovolume.com

piezoVolume logo: