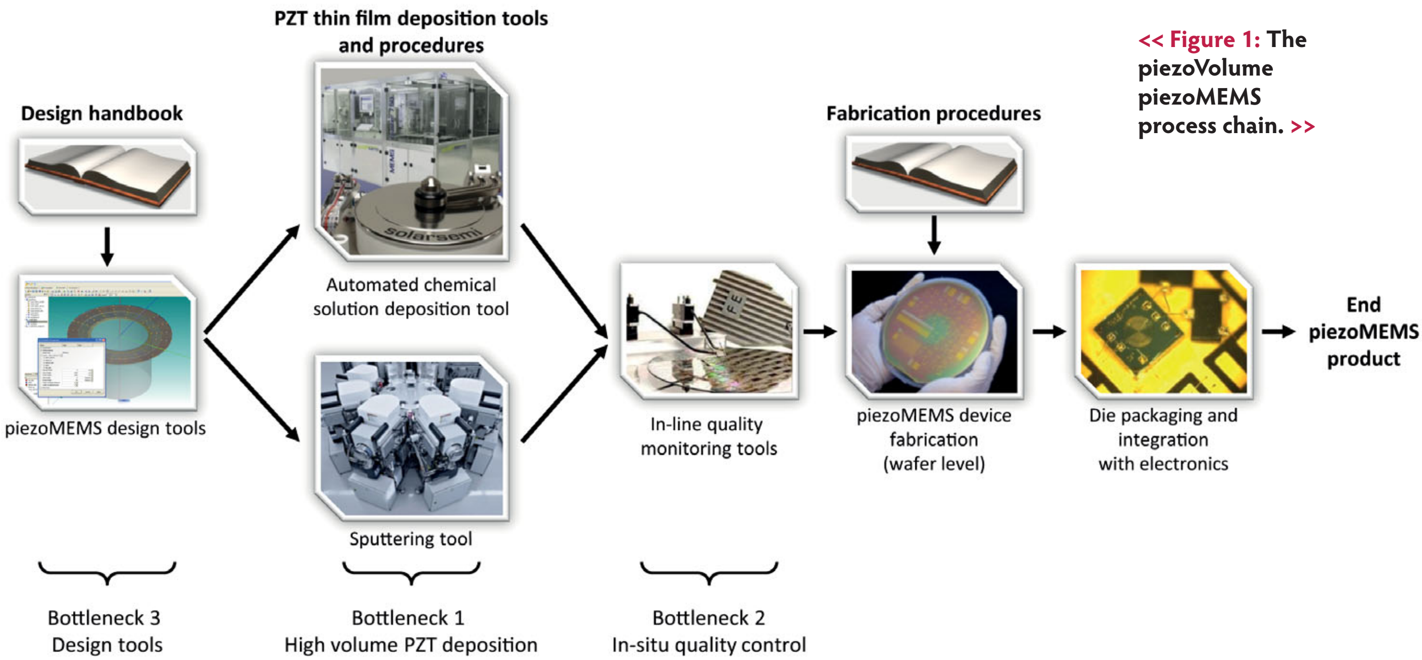

<< **Figure 1: The piezoVolume piezoMEMS process chain.** >>

FP7 piezoVolume —

HIGH-VOLUME PRODUCTION PROCESSES FOR PIEZOELECTRIC MICRO SYSTEMS

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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 to and from the digital domain. The information can be mechanical, thermal, acoustic, chemical, optical and biomedical phenomena. One particularly promising technology is the integration of piezoelectric thin films with silicon MEMS.

Piezoelectricity is the ability of some materials to generate an electric potential in response to applied mechanical stress. The piezoelectric effect is reversible in that materials exhibiting the direct piezoelectric effect (the production of electricity when stress is applied) also exhibit the converse piezoelectric effect (the production of stress and/or strain when an electric field is applied). This is what makes the piezoMEMS technology so versatile. Due to this two-way operation of piezoelectric materials, going all the way from DC operation to several tens of MHz, the piezoMEMS technology provides a pool of design opportunities.

A market analysis of the piezoMEMS market was recently performed by Yole. PiezoMEMS have already demonstrated its potential for use in mass product applications like ink-jet print heads by EPSON and Matsushita. As of 2013 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 actuator for fine positioning in HDD.

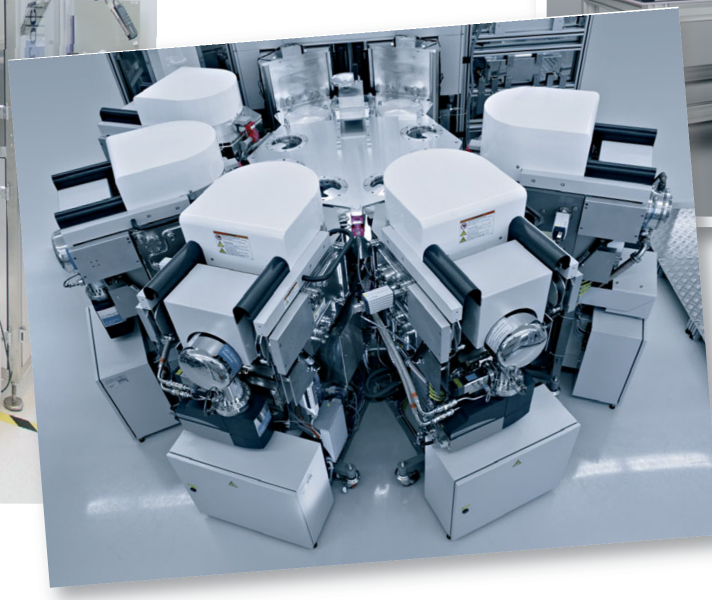
The main goal of piezoVolume (2010 – 2012) was to develop a full high-volume production process for piezoelectric micro systems. The platform should cover the complete micro fabrication process and develop the tools and procedures for the three most significant bottlenecks identified within hardware and software to realise high volume fabrication of piezoMEMS:

- High volume deposition tools for high quality piezoelectric PZT thin films
- In-line non-destructive quality control of piezoelectric thin films on wafer level
- piezoMEMS specific modelling and process emulation tools tailored to piezoMEMS

The most important bottleneck was indeed to realize high volume deposition of PZT thin films on 150 and 200 mm wafers with state-of-the-art PZT thin film properties (measured as the thin film transverse piezoelectric coefficient $e_{31,f}$) at throughputs needed in production. In the project, PZT deposition tools based both on chemical solution deposition (CSD) and

<< LEFT | **Figure 2:** PZT CSD cluster coating tool by Solar-semi. >>

<< BELOW | **Figure 4:** The aixACCT aixDBLI system for quality monitoring (Courtesy of aixACCT). >>



<< ABOVE | **Figure 3:** The Oerlikon CLN200II platform for PZT and electrode sputtering (courtesy of Oerlikon). >>

sputtering have been developed with this in mind and a remarkable development to show to. At the end of the project a world record level in $e_{31,f}$ of -20 C/m² was demonstrated by sputtering on 200 mm wafers.

In piezoVolume, we promoted collaboration between large enterprises and SMEs in Europe to speed up the development of the new technology and to enter into the market with piezoMEMS based product. The consortium consisted of both technology providers and end-users. This was a very successful match as new products based on the project developments were marketed and sold already before the project end. The following chapters will describe the new developments in more detail.

Design handbook and fabrication rules

It is important to realise that the rules used when designing and fabricating Si-MEMS often cannot be applied to piezoMEMS. A so-called white paper on tool integration, design and fabrication rules will be made available and may be used as a 'handbook', a rough guide for making MEMS using bulk micro machining. It gives an overview of the needed hardware and their integration in a fab. Relevant information is available through the SINTEF piezoMEMS competence centre and piezoVolume websites.

Deposition processes

CHEMICAL SOLUTION DEPOSTION (CSD)

The application procedures used for CSD are quite similar to what is used in the semiconductor industry for application of photoresist today, which is a proven high throughput process. The difference between the two processes is the number of coatings necessary to achieve the total film thickness and needed intermediate crystallisation steps using rapid thermal annealing (RTP). The throughput of a tool using one coater is around three wafers/h @ 1 µm (50 nm/min). However, an extended production tool with several coaters multiplies this figure. The method provides high thickness uniformity and a transversal piezoelectric performance, $e_{31,f}$, of around -15 C/m². Another benefit of this method is that the material composition can be switched easily via the coating solution.

SPUTTERING

Equipped with RF magnetron sputtering and a high temperature substrate holder (Very Hot Chuck), the CLUSTERLINE platform provides a very reliable high temperature deposition process with a high throughput capability of around 3.5 wafers/hour @ 1 µm (60 nm/min). One notable advantage is the remarkably high piezoelectric coefficient, $-e_{31,f}$, of — 18-20 C/m² that we have achieved — an outstanding result for PZT thin films. An additional benefit is that the full process, including bottom electrode, can be done in the same tool without breaking vacuum.

In-Line Quality Monitoring

Earlier during processing there could only be offline 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. 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

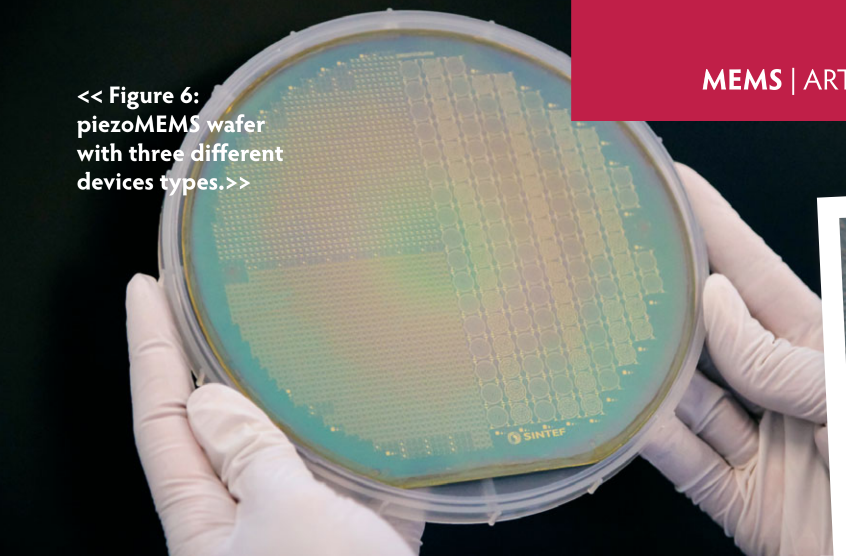
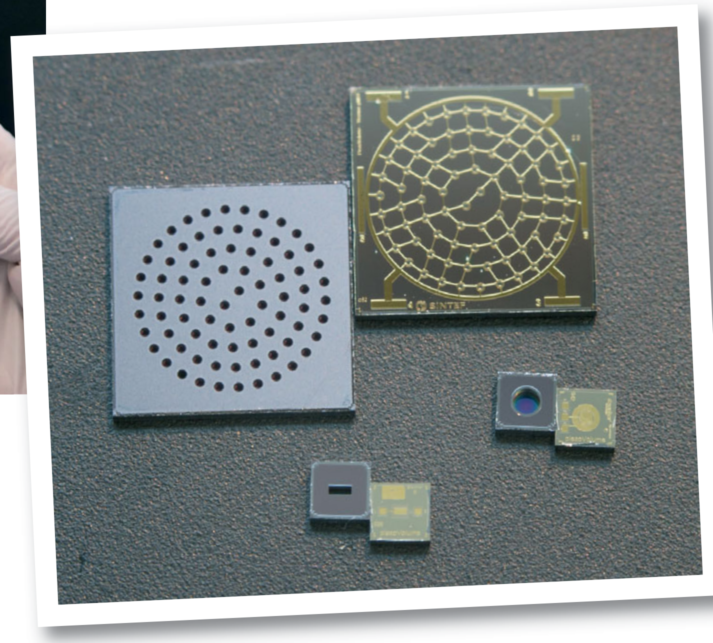

<< Figure 6: piezoMEMS wafer with three different devices types.>>

Figure 7: piezoMEMS devices in piezoVolume.



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. 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.

PiezoMEMS device modelling software
Coventor is a leading provider of 3D analysis and design automation software for the development of micro and nano scale devices and systems. 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 like Comsol are available.

These software tools are calibrated to real PZT processes, and enable engineers to simulate and optimise 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 you to review designs and detect process issues in advance of actual fabrication. That can be a real cost saver.

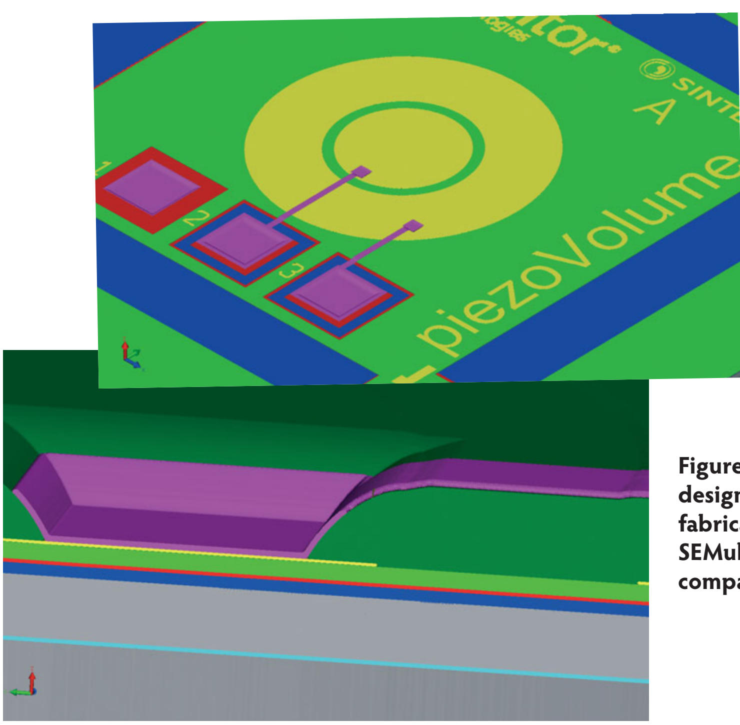


Figure 5: A microphone designed and virtually fabricated in SEMulator3D for the company Sonitor.

PiezoMEMS devices fabricated in the project
Prototype devices were designed and tested for three potential end-users of piezoMEMS technology using SINTEF's piezoMEMS processes based on bulk micro machining. These devices were ultrasonic microphones for the company Sonitor that has products within in-door positioning systems based on ultrasound, ink-jet actuators for Océ and its printing technology, and ultrasonic transducers for Vermon that develops ultrasonic transducers for the medical ultrasound market.

piezoMEMS Competence Centre
Usually, the threshold for introducing a new technology is burdensome and time consuming. The piezoVolume project has created infrastructure and know-how to assist potential users to integrate this new technology in their products and to perform feasibility studies. The piezoMEMS Competence Centre at SINTEF is a perfect match for small and medium size (fabless) companies that want to get started with piezoelectric MEMS based on PZT. The Competence Centre has a large network of infrastructure as well as experts able to guide users through the challenges with this new technology. The whole process from design to packaging including small-scale production of devices is covered. Experts within the Competence Centre have worked with design, modelling, process development and prototyping of piezoMEMS since 2002 and several successful projects have been completed. The unique experience that has been acquired reduces risk and time-to-market for our customers. Streamlined technology transfer from prototyping to high volume production is ensured through collaboration with independent MEMS fabs. The continuing research in material science and fabrication processes at SINTEF ensures access to state-of-the-art technology.
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