Nordic Innovation Centre

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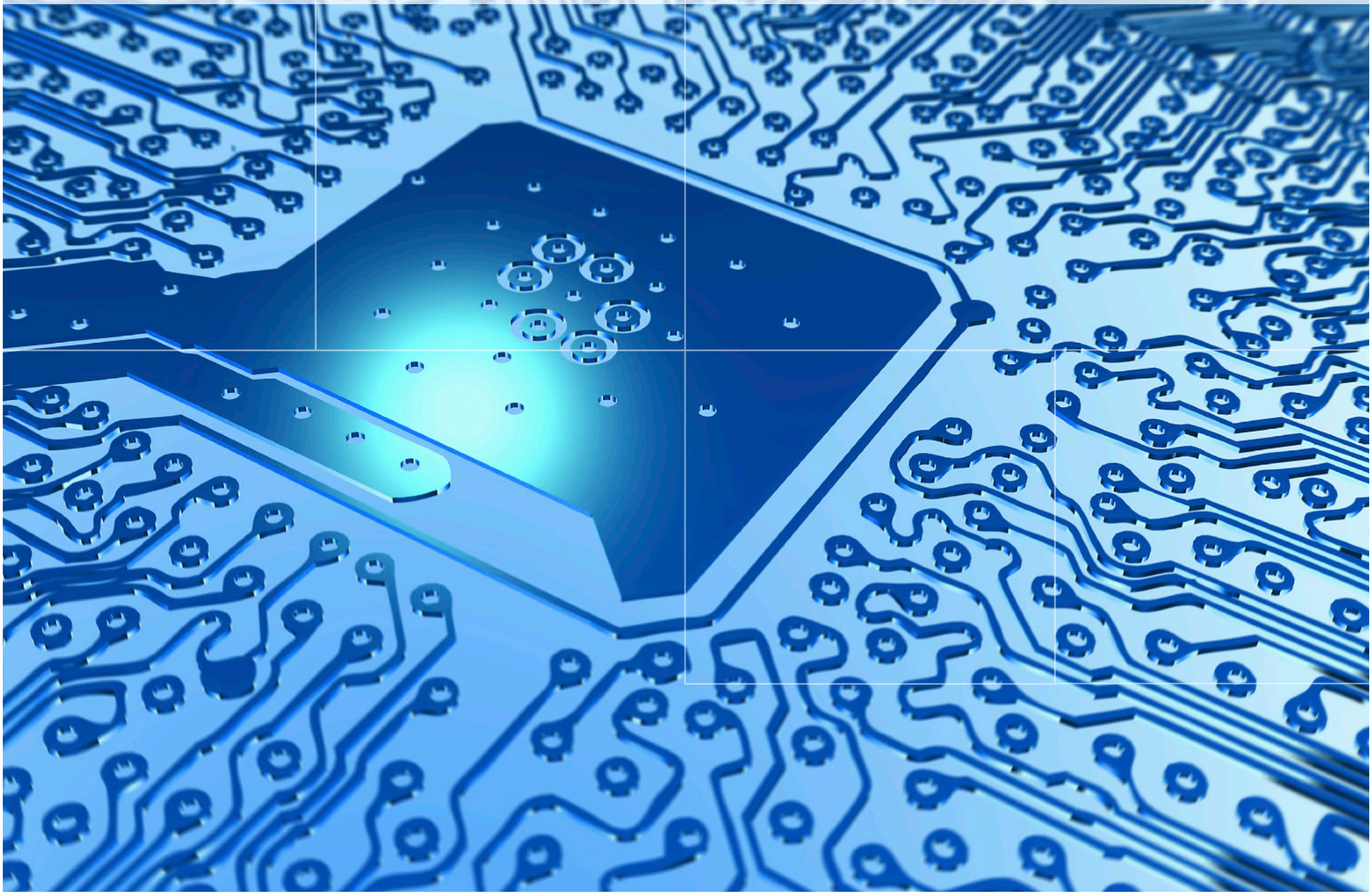
Piezoelectric micro-electromechanical systems for Nordic industry (NORD-pie)

- Open foundry service for prototyping and small scale production of MEMS with piezoelectric thin films
- Develop, produce and market new and competitive products
- Bridging the gap between process development and a qualified production route offered to the Nordic and European industry



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Title: NORD-pie – piezoelectric micro-electromechanical systems for Nordic industry	
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Abstract:
During recent years, the study of micro-electromechanical systems (MEMS) has shown significant opportunities for miniaturized mechanical devices based on functional thin-film materials and silicon technology. Microsystems, MEMS and MST are a quite mature range of technologies, but few industrial companies have the necessary know-how, financing and/or facilities available.

Many companies – in particular SMEs (Small and Medium Enterprises) – have come up with innovative ideas for new types of sensors, actuators and other products based on silicon MEMS (MicroElectroMechanical Systems) technology. However, the production of such systems is very demanding. Firstly, it needs substantial investments in clean-room infrastructure and equipment. Secondly, the interdisciplinary nature of these systems requires long experience in modelling, design, materials technology, materials processing and special micromachining in addition to normal microsystem processing technology. Thus, microsystem technology has in practice been unattainable for most companies. As a remedy the end goal of the NORD-pie project is to provide an open foundry service that allows for prototyping and small scale production of MEMS with piezoelectric thin films. This enables the partners to develop, produce and market new and competitive products. The technology will also be useful for large companies which often prefer to develop their own procedures and build their own production lines, due to the complexity and novelty of the process offered.

SINTEF and its NORD-pie partners have demonstrated the capability of the established piezo-MEMS process at SINTEF for device production to relevant companies in the Nordic countries. Feasibility studies of the present technology in relation to the companies present and future products will be carried out also in the near future. Demonstrators may thus be produced upon a set of design rules as defined in the design handbook that have been produced.

We see the need to bridge the gap between process development and a qualified production route- offered to the Nordic and European industry in this area. Hence, the project partners will continue to support Nordic companies in order to respond to the pressure for continuous technological innovation by providing reliable piezoelectric thin film technology the companies are not able to develop themselves. This support will continue through i.e. the European microBuilder project and services.

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Executive summary

The main aim of NORD-pie was to demonstrate:
- The availability of small scale and high quality industrial fabrication of piezoelectric MEMS devices to industry in the Nordic countries.
- The feasibility of piezoelectric micro-electromechanical systems for realizing new or improved products.

The fabrication process was based on the MEMS-pie process recently developed on European level by SINTEF and partners.[1]

The main objectives of the project were:
- To investigate the feasibility of piezoelectric MEMS based on selected geometries as cantilevers, membranes and bridges will be investigated in relation to suggested concepts from the partners. The companies could choose to investigate the possibilities in the technology for either present or future product concepts. Selected demonstrator designs were developed into commercial product concepts.

- NORD-pie aimed to combine the national Nordic activities in MEMS and packaging- to help industry gain access to the best available technology for product solutions.

- To function as a co-financed Nordic contact point (service) for generically qualified MEMS services including feasibility studies, design and production.

- To have a strong dissemination activity through visits, workshops and publications.

- To actively seek relevant industry partners through our existing and growing network of potential users. Regional (local) contact points are critical for successful industrial development.

The study has achieved these objectives by:
- Designing and fabricating device concepts proposed by the industry partners using a set of design and fabrication rules.

- Contributing to standardization of design and fabrication guidelines/rules necessary for realizing a multi user wafer approach. A design handbook that can be delivered to interested parties has been fabricated.

- Packaging and testing the fabricated device concepts. The results indicated that piezoelectric MEMS technology is suitable for entering several of the partners' product lines.

- Having a strong dissemination activity.

[1] MEMS-pie *Integration of piezoelectric thin films in micro-electromechanical systems, FP6, COOP-CT-2004-508219.*; www.sintef.no/mems-pie.

Method/Implementation:
The project was divided in 3 parts:

1. Ideas for piezoelectric MEMS devices were proposed by the partners. SINTEF proposed designs that could fulfil the requirements of the industrial partners and to successfully be able to carry out a feasibility study of the devices. Packaging of the devices was simultaneously considered by the packaging partner and provided feedback to the designers.

2. The devices were fabricated using SINTEF's piezoMEMS process and sent for packaging.

3. The feasibility of the packaged devices was tested by the respective partners.

In addition the project has had a strong dissemination activity.

Results and conclusions:
The following success criteria were listed in the project proposal:

1. *Deliver a design handbook and tools, which is a major project deliverable.*

A design handbook for fabrication of piezoelectric MEMS has been developed, describing the process steps, design rules, design guidelines and tolerances. The design handbook can be obtained by any interested party by signing a non-disclosure agreement. The NORD-pie process can either be based on a single silicon wafer, or be expanded to also include bonding of patterned glass wafers to the silicon wafer.

In order to be able to model piezoelectric MEMS is very important to lower the entry level in industry towards this new technology. We have carried out finite element modelling (FEM) of selected designs to qualify much simpler analytical models for calculating resonance frequencies.

Also, the company COVENTOR[2] will in cooperation with SINTEF provide a process access module for SINTEF's piezoelectric thin film process (MoveMEMS) in their MEMS design and modelling software. This means that the technology will be implemented in commercial software, which will generate significant publicity and increase the awareness in industry about the application possibilities.

The NORD-pie process is also included as an add-on (mixed technology) to microBUILDER[3] that has a special focus on microfludic systems (Figure 1). This service has partners such as Tronics[4] and SensoNor[5] which already offer well known multi-project-wafer (MPW) fabrication of non-piezoelectric MEMS. These companies can guide any requests for piezoelectric technology to the NORD-pie process and will greatly improve the publicity of the process. The microBUILDER design handbook, which contains the NORD-pie design handbook, can be requested at the microBUILDER web page.

[2] COVENTOR, (www.coventor.com)
[3] microBUILDER, (www.microbuilder.org)
[4] Tronics, (www.tronics.eu)
[5] Infineon Technologies SensoNor, (www.sensonor.no)

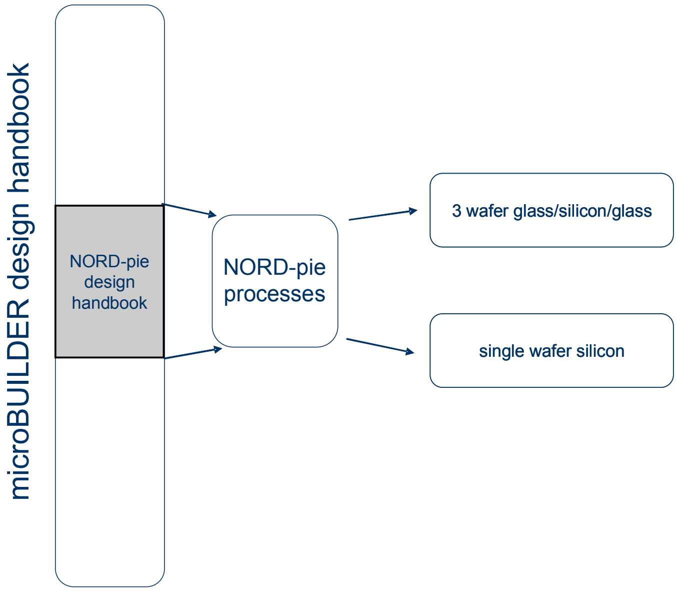

Figure 1: Relationship between the NORD-pie and microBUILDER design handbooks.

2. *At least 2 major technology companies will offer continued support ultimately leading up to financed pre-production prototyping within approximately 2 years*

The project has carried out feasibility studies of 4 different types of devices that were identified as interesting for the industry partners. Of these, 3 industry partners have explicitly communicated that piezoelectric MEMS technology has proved to be very viable for their product range and will carry out additional investigations and developments after the project. Likely by means of more targeted projects. The prototyping and fabrication service at SINTEF will be an important tool in this process.

3. *At least 6 feasibility studies will be carried out, resulting in at least 2 novel, patentable product concepts*

In the project 5 different devices (one per industry partner) was designed and fabricated. Of these, 3 device concepts will be developed further by the respective partners. It will be up the project partner if patent protection of the device concept is desired and possible. The general device fabrication process used in NORD-pie is not patentable.

4. *In addition, the project "service-activity" should result in a number of design and processing quotations, contacts and a few targeted visits.*

SINTEF experiences increasing interest in piezoelectric MEMS technology and the design handbook has already been transferred to interested parties.

5. *Improved Nordic networking and positioning in the European Research Area, industry and markets.*

The network within piezoelectrics in the Nordic countries has in recent years largely been concentrated to the EU FP5 thematic network POLECER.[6] Even though this have

[6] POLECER-network, *European Thematic Network on Polar Electroceramics, FP5, G5RT-CT-2001-05024* (www.polecer.rwth-aachen.de).

strengthened the networks towards Europe, the inter-Nordic connections have after our understanding been fewer. This is particularly true in the field piezoelectric MEMS. NORD-pie has contributed to establish a network in this field in the Nordic countries as well, bringing together industry and research institutes.
The NORD-pie partners have also been invited to join SINTEF in two FP7 project proposals.

The awareness of the project and the technology has been increased by a strong dissemination activity:

- A project flyer that has been distributed at conferences
- A web page that summarizes the project.[7]
- 1 newspaper article.[8]
- 1 article to be published mstnews.[9]
- 1 company visit
- 2 workshops on piezoelectric MEMS was arranged.[10,11]
- An invited conference talk.[12]
- An invited talk at local pMUT/CMUT seminar, Oslo 2007
- Dissemination of project results at the conference Electroceramics XI.[13]

6. *Strengthen and secure continued market position for the major technology companies involved, and to create viable start-up technology companies across the Nordic region- and into Europe.*

The market for microsystems-enabled products is expected to grow rapidly over the coming decade, with some forecasts projecting growth rates similar to those seen in the microelectronics industry in the past decades. We expect that piezoelectric MEMS will be part of this growth.
Due to the complexity of design and fabrication of piezoelectric MEMS it is crucial to have successfully established a platform technology that combines design, high-performance piezoelectric materials, integration and packaging, with a capability of making prototypes. The technology must also be accessible to relevant companies, including start-ups and SMEs. We believe that we have come a long way towards reaching this goal through the NORD-pie project.

Accessibility will render piezoelectrics as a major technology also for MEMS. As piezoelectric materials now also become included in design tools new ideas and designs will trigger more and more activity in this area, both in larger companies and individuals wanting to make a start-up.

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[7] NORD-pie web page (www.sintef.no/nord-pie)
[8] Kaleva (http://www.kaleva.fi/plus/index.cfm?j=667801)
[9] mstnews (www.mstnews.de)
[10] "Piezoelectric and magnetostrictive MEMS – from the laboratory to production", Oslo December 8th 2006
[11] "Piezoelectric MEMS", Copenhagen May 21-22 2008
[12] International Conference on Chemical Solution Deposition, Berchtesgaden, Germany June 2007 (http://www.iwe.rwth-aachen.de/iefs/)
[13] Electroceramics XI, Manchester, UK, September 2008, (http://www.electroceramics11.co.uk/)

7. *Increased competence, processing and application know-how and market position and potential among all project partners.*

NORD-pie has increased the awareness and competence of both the industry partners and the packaging partner regarding piezoelectric MEMS. Several of the partners have decided to continue the development of the device fabricated for them in NORD-pie. This is a very positive outcome and, if successful, Nordic Industry will be very early out in utilizing piezoelectric MEMS in commercial products.

Recommendations:

The feasibility of piezoelectric micro-electromechanical systems for realizing smaller and more energy efficient devices has been positively demonstrated. In our opinion, the highly developed piezoelectric and MEMS technologies that are now existing in the Nordic countries represent a real business opportunity.

When considering commercialization of piezoelectric MEMS devices it is imperative that they can be fabricated at a competitive cost. Currently, if industry finds a particular piezoelectric MEMS device suitable for their product line, the fabrication costs are still very high. SINTEF is a research organization not optimized for production cost having mainly research scientists. Thus, one scenario is to establish a spin-off company that can streamline fabrication of piezoelectric MEMS. Examples of other spin-offs from SINTEF are e.g. Presens AS[14] and Nacre AS.[15]

At the same time, the introduction of piezoelectric MEMS devices in more complex systems, where the micromechanical structures e.g. are stacked with microelectronics, should be pursued.

[14] Presens AS, (www.presens.no)
[15] Nacre AS, (www.nacre.no)

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Preface

The NORD-pie project has demonstrated how valuable Nordic collaboration is. Indeed, in this age of globalization we must not forget establishing and taking care of our closest networks.

The SINTEF NORD-pie team thanks all the partners for contributing so enthusiastically to the project. Managing this project with people from industries and a University from four different countries has been a pleasure.

You have been great.

Oslo, April 30th 2008

Frode Tyholdt

Frode Tyholdt
Project Leader

Introduction

In recent years, we have witnessed the emergence of an increasingly diverse area of microelectronics that goes beyond the boundaries of Moore's law (the number of transistors that can be inexpensively placed on an integrated circuit increases exponentially with time), into the area of "*More than Moore*", one of the six defined areas of nanoelectronics (Figure 2). From a technology perspective, "More than Moore" refers to all technologies based on, or derived from, silicon technologies without simply scaling with Moore's law (Error: Reference source not found). A typical example is the on-going integration of passive components such as inductors, capacitors and resistors onto silicon in order to meet the integration requirements of today's multi-band multi-mode mobile phones.[16] From an application perspective, "*More than Moore*" **enables functions equivalent with the eyes, ears, noses, arms and legs of human beings, along with the brain provided by microprocessor and memory subsystems**.

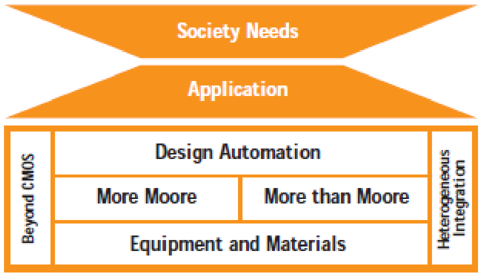
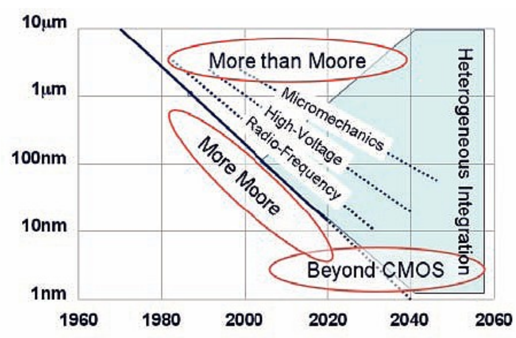


Figure 2: The six proposed areas of future nanoelectronics.Error: Reference source not found



relates to Moores's law.Error: Reference source not found

NORD-pie has been concentrated on one particularly promising technology that is categorized as "More than Moore", namely integration of piezoelectric films with silicon MEMS (Micro-Electro-Mechanical Systems). This technology can fulfil many of the requirements of sensors and actuators in tomorrow's smart systems, as a result of the large displacements, high sensing functionality and high energy densities that can be obtained, compared to pure Si-MEMS. As a consequence, they are very attractive for industries like automotive, aerospace, medical, telecom and consumer electronics. Examples of applications are given in Table 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 1: Classification of applications of piezoelectric MEMS

[16] Strategic Research Agenda: European Nanoelectronics Initiative Advisory Council (ENIAC) (2006).

The market for microsystems-enabled products is expected to grow rapidly over the coming decade, with some forecasts projecting growth rates similar to those seen in the microelectronics industry in the past decades. E.g. fresh market analysis reports suggest:

- MEMS gyroscopes and accelerometers market increased by 55% from 2005 to 2006 to reach US$ 232 M last year. An average of 35% Compound Annual Growth Rate (CAGR) for the 2006-2011 period is expected.[17]

- RF MEMS switching products are expected to generate US$ 390M market in wireless handset applications in 2011.[18]

- The MEMS microphone market is estimated to have reached 117M$ in 2006. The 2005-2006 period has shown a 90% volume increase and forecasts a 43% volume CAGR over the 2006-2011 period. The MEMS microphone opportunity is clearly one of the fastest growing applications within the MEMS industry.[19]

For Nordic industry to take part in these growth rates it is crucial to successfully establish a technology platform that enables prototyping and even small scale production of piezoelectric MEMS. Hence, one of the goals of NORD-pie is to establish a foundry service that offer manufacturing services to third parties. Here expertise on microsystem design and fabrication will be concentrated.
Due to the high costs of fabricating microsystems, the foundry service will be based on a multi-project wafer (MPW) system where the costs are shared between the customers. Normally, a customer will pay a certain price per wafer area.

The NORD-pie project is the first MPW run of the fabrication service, including feasibility studies of the technology by Nordic industry and a considerable dissemination activity.

[17] *World Inertial Sensors Markets: Accelerometers and Gyroscopes for Consumer Applications* (Electronics.ca Publications, 2007)
[18] *RF MEMS Switch Market* (Electronics.ca Publications, Sept. 2007).
[19] *Silicon Microphone Market 2007* (Electronics.ca Publications, Sept. 2007).

1. Selection of devices and design

1.1 Hök Instrument AB and Infineon Technologies SensoNor AS

Hök Instrument AB has produced acoustic gas sensors under the brand name Q-AIR for almost ten years. The sensors are being used for indoor air quality control, based on the fact that CO_2 concentration is an adequate variable closely connected to our subjective notion of air quality. Acoustic gas sensors are basically advantageous over the predominating infrared technology concerning power consumption.

Infineon Technologies SensoNor AS is located in Horten, Norway, and develops, produces and sells sensors and microsystems for high-volume applications worldwide. The company has delivered more than 35 million airbag crash sensors to the automotive market and is now in high-volume delivery position with its new tyre-pressure sensor product line. The company is a world-wide market leader in this new automotive sensor area. In addition the company has developed and currently produces angular rate sensors for automotive safety applications. The company became a wholly-owned subsidiary of Infineon Technologies AG in 2003.
The background for SensoNor's achievements in the sensor market dates back to industrial research on silicon devices in the early 70's in Norway. The first micro-machined silicon beam devices were developed in the 60's and silicon micro-machined diaphragm pressure sensors in the 70's. Research on silicon micromachined accelerometers began in 1982 and SensoNor was established as a company in 1985 to commercially exploit this work. In the meantime SensoNor has grown to more than 230 employees, including approximately 100 graduate engineers. The R&D group (counting more than 40 persons) is engaged into the following technical areas: Front-end technology development, Back-end technology development, ASIC development, microsystem simulation and modelling, design, and prototyping as well as energy harvesting. SensoNor's technology platform consists of a modern, well-equipped waferfab (150 mm) with state-of-the-art process equipment, and an advanced back-end production line featuring automated leadframe assembly of sensors and ASICs, epoxy-molded encapsulation and testing.

In the MASCOT[20] project involving SensoNor, SINTEF and Hök Instrument, MEMS implementation of an acoustic gas sensor was demonstrated for the first time ever. The project extended from 2002 to 2004. The demonstrator devices were designed and implemented using one of SensoNor's process lines only slightly modified. The process line results in stacked glass-silicon-glass structures, with several micromachining steps. Generation of acoustic power was accomplished by pulsed heating and detection by piezoresistive elements.

The MASCOT devices successfully demonstrated that acoustic gas sensors could be implemented by MEMS technology, at potentially very low cost. The devices were not aiming at a particular application, but it was indicated that automotive climate control, medical diagnostics and monitoring, could be useful areas besides indoor air quality control. Significant improvement of the sensing properties would, however, be necessary.

The MEMS-Pie project was conducted 2004-2007 with SINTEF as coordinator with two research institutes and five SMEs as partners, including Hök Instrument. This project was

[20] MASCOT (Micro Acoustic Sensor System for CO2 Tracking), EU FP5 (IST-2001-32411)

focussed on the technology of piezoelectric microstructures, and resulted in highly improved fabrication processes and characterisation tools.

Our objective in the NORD-Pie project was to obtain ‘proof of principle’ concerning the performance of piezoelectric MEMS structures as sensing elements for gas sensors.

1.1.1 Basic principles and equations

In an ideal gas, the velocity of sound c is given by

$$c = \sqrt{\frac{RT\gamma}{M}} \tag{1}$$

where R is the general gas constant = 8.314 J/mol K, T the absolute temperature [K], γ is the ratio of specific heat at constant pressure and volume, and M is the molecular mass of the gas.

More specifically, in a binary gas mixture with molecular masses M_0 and m, the resulting average molecular mass M is determined by the concentration x of the constituent m:

$$M(x) = mx + (1 - x)M_0 = M_0(1 + \frac{m - M_0}{M_0})x \tag{2}$$

In a binary gas mixture it is thus possible to determine the concentration x by measuring the velocity of sound, provided that temperature is measured independently, or controlled. The influence of γ is generally of minor importance.

The binary mixture approximation is applicable to the monitoring of a pollutant in air, if the molecular mass of the pollutant differs significantly from the average of air. This is the case for CO_2 (m = 44 compared to M_{air} = 28.9) and natural gas (M = 17-20). Compensation techniques must, in general, be employed to take care of undesired dependencies, due to e g temperature, humidity etc.

The velocity of sound may be monitored in an acoustic resonator, in which the resonance frequency is dependent on the velocity of sound. This is the case of the Helmholtz resonator, being modelled as a compliant (bottle) and an inertial (neck) lumped element combination, exhibiting a resonance frequency:

$$f_{rH} = \frac{c}{2\pi}\sqrt{\frac{A}{\ell \cdot V}} \tag{3}$$

V is the volume of the bottle, and A, ℓ are the neck area, and length, respectively – all dimensions being assumed to be considerably smaller than the acoustic wavelength. The resonance frequency is a linear function of sound velocity c. By choosing suitable sizes for V, A and ℓ it is possible to define the working frequency range of a certain sensor. The sharpness of the resonance peak is governed by inevitable power dissipation, mainly determined by friction or viscous loss within the neck area, and quantified by the quality factor Q. Helmholtz resonators exhibit moderate Q factors of only 5-10 at ultrasonic frequencies.

In another type of resonator the acoustic wave properties are being employed. A simple example is Kundt's tube with sound-reflecting walls at both ends:

$$f_{rKN} = \frac{N \cdot c}{2L}, N = 1,2,3,... \qquad (4)$$

The first resonance occurs when the tube length is equal to half the wavelength. The tube width is assumed to be smaller than the length. Standing waves are built up in the tube at this frequency, and at all octaves above it (N = 2,3,…). The Q factor of this type of resonator can be considerably higher than lumped element resonators, up to 100.

Resonators having more complex geometries than Kundt's tube are, of course, possible, but operation at higher modes restricts the measuring range which becomes limited by hopping between modes.

A preferable mode of operation is to match the resonance frequency of the acoustic resonator to that of a mechanical resonator including piezo elements for transduction to and from the electrical and mechanical domains. In the NORD-Pie project, cantilever beams and diaphragms are being used as such resonators. The resonance frequencies of these elements are given by equations (5) and (6):

$$f_{rCB} = k_i \frac{h}{l^2}\sqrt{\frac{E}{\rho}} \qquad (5)$$

k_1 = 0.162 and k_2 = 1.01 are constants for the first and second vibration modes of a cantilever. E denotes Young's modulus of elasticity [N/m^2], ρ the density [kg/m^3], h the thickness and l the length of the beam. The NORD-Pie structures are actually lamellar with silicon as the base, and including PZT + electrodes. A weighted average of E and ρ should therefore be used in precise calculations. It should be noted that the structure is otherwise completely determined by the thickness and length.

$$f_{rD} = \frac{2.56h}{\pi a^2}\sqrt{\frac{E}{3\rho}} \qquad (6)$$

The expression (6) for a clamped circular diaphragm is subject to the same limitation concerning the E/ρ ratio as the cantilever beam structure, and is otherwise determined by the thickness h and radius a. The NORD-Pie diaphragm structures include a sealed cavity on the backside of the diaphragm, and the seal is performed at elevated temperature. Therefore, at room temperature, the diaphragm will be bent and stretched. This is expected to result in an increase of the resonance frequency.

1.1.2 Application areas

The following application areas are being considered as potentially interesting:

1. Indoor air quality control
2. Automotive climate control
3. Medical diagnostics and patient monitoring

4. Hydrogen sensors for process control
5. Gas alarm systems.

The first three areas were subject to intense investigations during and after the MASCOT project. The IAQ area was the main topic of the MONTIE project which aimed at disseminating knowledge and experience in the field to companies within the Nordic region and elsewhere. In fact, this project led to several EU project proposals, however, none of them having yet been implemented.

By our company, special attention has been directed towards areas 3-5. This is mainly due to the fact that potential industrial partners have been identified, with possibilities to go ahead towards product development.

SINTEF, Laerdal and Hök Instrument jointly investigated possible medical applications, mainly in the field of anesthesia and intensive care. The investigation pinpointed the need to cover a relatively large range of molecular mass due to the use of heavy anaesthetic agents.

One interesting medical application is a *life sign monitor*, potentially useful in emergency situations, catastrophe sites, and the like. The product vision is a small device including both sensor and display, to visual the vital condition by means of respiratory activity. The sensor would respond to the variations of gas composition resulting from human embolism (O_2 in, CO_2 out). Our partner is a small startup company, Cap Safe Sweden AB. The market potential is quite large in the long term; however there is a need for identifying short term niches which could start the launching process.

Hydrogen is used in fuel cells and as an *additive to natural gas*. The use of acoustics as sensing principle is basically attractive for reasons of signal quality (high resolution, fast response) and safety (low power consumption reducing the risks for fire and explosion). We have been approached by the American company Hythane to design and build prototypes for hydrogen sensors.

Recently, SINTEF has patented the use of acoustic sensors in an *innovative system solution for gas alarm*. A collaborative prestudy has been started to explore the possibilities.

The efforts to map possible application areas and find industrial partners are essential to the project. A general finding is that most applications are "slow starters", each single one having small possibilities to carry the investment costs of MEMS implementation. Therefore, the formation of a consortium of several partners in different complimentary business areas joining forces to develop the technology platform, could be one route to proceed. However, to form such a consortium and keep it together, is a major, and high-risk venture. Alternatively, a more long term perspective is adopted, allowing a first product generation using commercially available bulk devices to be implemented. When market forces are strong enough, the willingness for technology investment may be more favourable.

1.1.3 Design of demonstrator devices

In view of our objective to obtain 'proof of principle', the major design considerations were:

- Choose element size matching the acoustic wavelength according to the outlined rules of the type of acoustic resonator (more specifically: frequency range should be 30-60 kHz corresponding to a wavelength of approximately 5-10 mm).
- Use a mechanical resonating structure with adequate acoustic coupling to the gas cavity, e g a cantilever beam combined with (see fig 1) a Helmholtz resonator defined by the cavity underneath the beam and the slit.
- Use a pair of such structures on a single chip, and cover with a lid forming a Kundt tube with length adapted to half the wavelength. Glass was chosen as material for the lid structure.
- As alternative to the cantilever beams, diaphragms at corresponding positions were tested.
- As alternative to the lid structure, the possibility of using the sensor package for defining the resonator was considered.

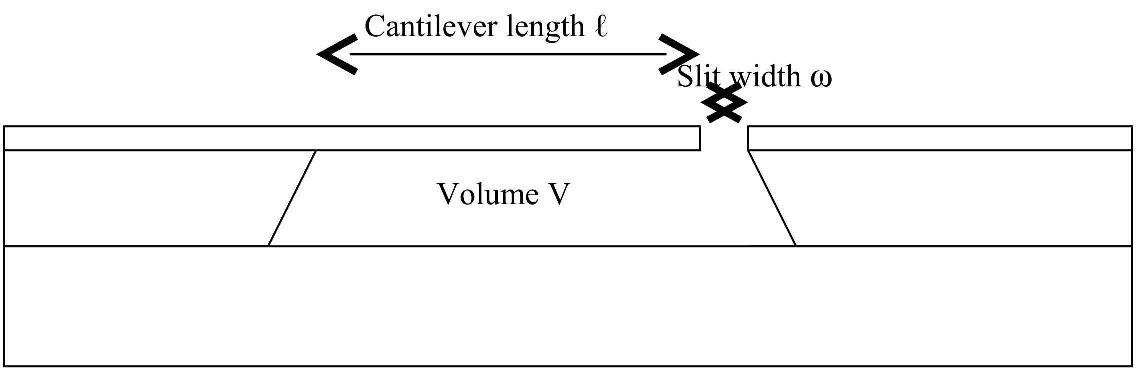


Figure 4: Cantilever beam with Helmholtz resonator.

The actual design of the NORD-Pie structures was performed by SINTEF, who also performed the fabrication of prototype devices. The glass-lid devices were wire-bonded and packaged by SensoNor/MicroComponent, and Mandalon performed the corresponding task on devices for specific packaging.

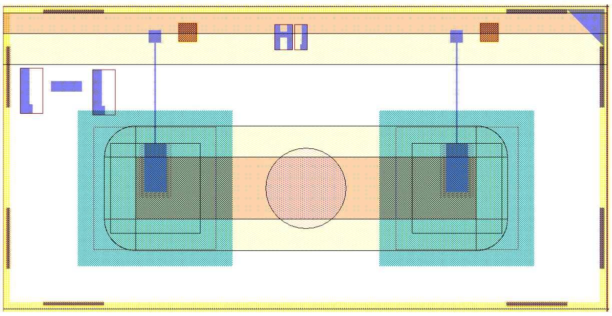


Figure 5: Die design of Hök gas sensor

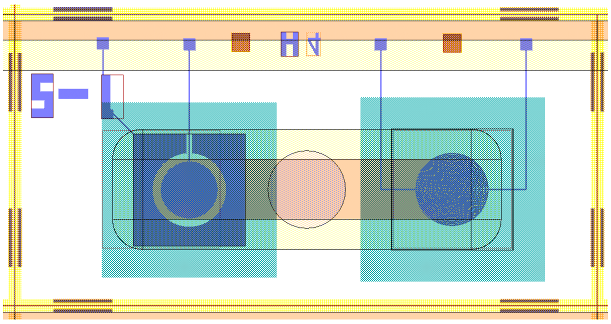


Figure 6: Die design of SensoNor gas sensor

1.2 Insensor A/S

InSensor A/S was formed in 2004 as a spin-off from Ferroperm Piezoceramics A/S. The objective of InSensor is to develop and manufacture piezoelectric thick films for specialised applications and the two main areas are ultrasonic transducers for medical imaging and various sensors. The application chosen for the NORD-Pie project was a piezoelectric MEMS accelerometer (for measurement of vibration), which could be manufactured with either thin film or thick film technology.

The design of the accelerometer was provided through InSensor's collaboration with DTU Nanotech, a department of the Technical University of Denmark specialising in MEMS and nanotechnology [Hindrichsen *et al.*, 2006]. The principle is seen from the sketch in Figure 7. The central part of the silicon structure acts as a seismic mass, which is released by means of etching from the external frame, so that it is suspended by four beams only. When the device is subjected to acceleration, the seismic mass will move with respect to the frame, which causes stresses in the beams. These stresses are converted into an electrical signal through the piezoelectric effect of the PZT film that is deposited on each of the beams. Since charges of opposite signs are generated in the two halves of the PZT pad, a signal is only collected from one half (the left part of the beam shown in the detail of Figure 7, covered by a top electrode).

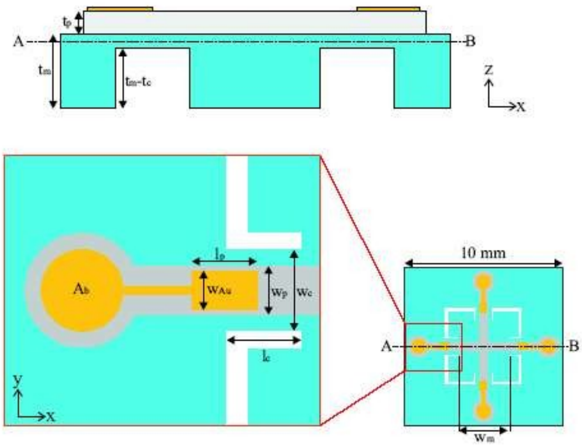


Figure 7: A draft of the accelerometer design. The PZT film (grey) is deposited onto the silicon structure (green) either by screen printing (thick film) or chemical solution deposition (thin film). A central seismic

mass is suspended by four beams, each with one top electrode (orange rectangle) connected to a bonding pad (orange circle). [C.C. Hindrichsen, 2006; used with permission]. [21,22]

The actual layout of the accelerometer on the wafer was carried out by SINTEF and the result is shown in Figure 8:

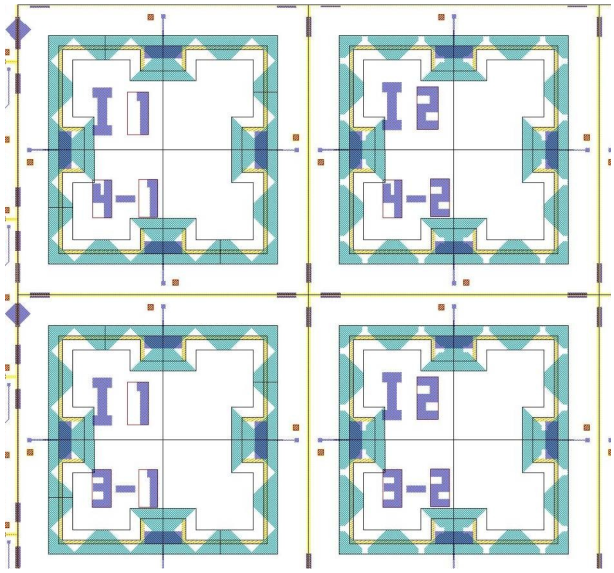


Figure 8: Die designs of accelerometers. Four full devices are seen.

1.3 Sonitor Technologies Inc.

Sonitor is a supplier of real-time indoor positioning systems based on ultrasound signaling. Such systems have a wide application area, including hospitals, assisted living for elderly, industrial plants and teleconference systems. To improve the spatial accuracy of the systems, Sonitor consider applying microphone arrays operating in the low ultrasound frequency range, around 40 kHz. By operating the microphones as phased arrays, directional information can be obtained.

Microphones with flat amplitude and phase response between 35 and 45 kHz are required. This means that any mechanical resonance of the structure should lie well clear of this band: e.g. all resonances should be above 90 kHz. To increase the microphone sensitivity we decided to explore the possibility for an interdigital electrode structure. Bondpads should lie well clear of the membrane opening. Parasitics due to electrode routing and the bondpad should be kept to a minimum.

The microphone arrays were designed to consist of 5 elements arranged along the same line at separation distances of 3 mm. The individual elements should have identical electrode arrangements. SINTEF and Sonitor designed the microphone arrays based on these criteria (Figure 9). Each array measured 3 x 15 mm. Each microphone had two top electrodes in a circular interdigital pattern.

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[21] C.C. Hindrichsen, R. Lou-Møller, T. Bove, E.V. Thomsen (2006): MEMS Accelerometer with Screen Printed Piezoelectric Thick Film, 5th IEEE Conference on Sensors, 1477-1480.
[22] C.C. Hindrichsen (2006): MEMS Accelerometer with Screen Printed Thick Film PZT. M.Sc. Thesis, Dept. of Micro and Nanotechnology, Technical University of Denmark

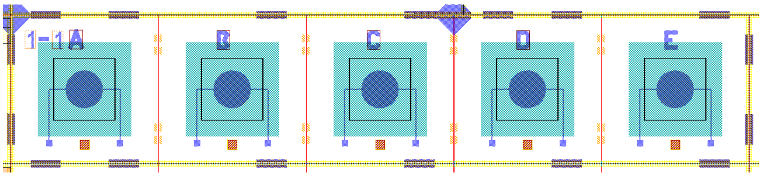


Figure 9: Sonitor phased array microphone

1.4 Star-Oddi

Founded in Iceland in 1985, Star-Oddi has become recognized as one of the world´s leading manufacturer of technology for researches on the oceans and its living resources. Since 1993, Star-Oddi has manufactured and developed the Data Storage Tag also known as archival tag, which is a miniature data logger designed for fish tagging but can be used for other marine animal tagging applications as well. We put high emphasises on developing equipment which can be used to protect, restore and manage the coastal and ocean resources through ecosystem-based management.

In NORD-pie, Star-Oddi wanted to explore the feasibility of miniaturized ultrasonic distance measurements in water.

The design of Star-Oddi is 1 and 4 MHz membrane transducers for water operation. To maximize the sound pressure level an array had to be made. As the package will be submersed in water the wiring must also be water proof.

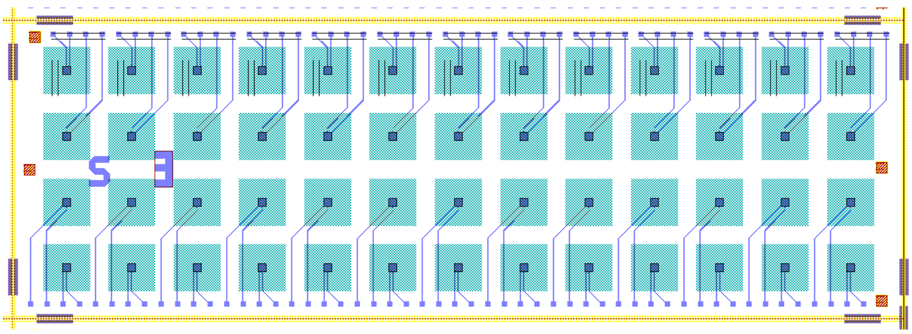


Figure 10: Star-Oddi 4 MHz membrane transducer array.

1.5 Wafer design

The goal of NORD-pie is to provide a multi-project wafer (MPW) approach to fabrication of piezoelectric MEMS devices. This means that all devices must be designed within the one and same design room.

Device and wafer design was performed by SINTEF according to process and design rules described in the NORD-pie design handbook.[23] The wafer layout can be seen in Figure 11. The wafer was divided into 4 quadrants carrying the different types of devices according to size and dicing pitch. Variants of the Star-Oddi ultrasonic transducers were placed in quadrant 1, Insensor accelerometers were placed in quadrant 2, Sonitor ultrasonic microphones were placed in quadrant 3 and Hök and SensoNor acoustic gas sensors were placed in quadrant 4.

[23] NORD-pie design handbook. Contact SINTEF for details.

The design was adapted to the use of 100 mm wafers.

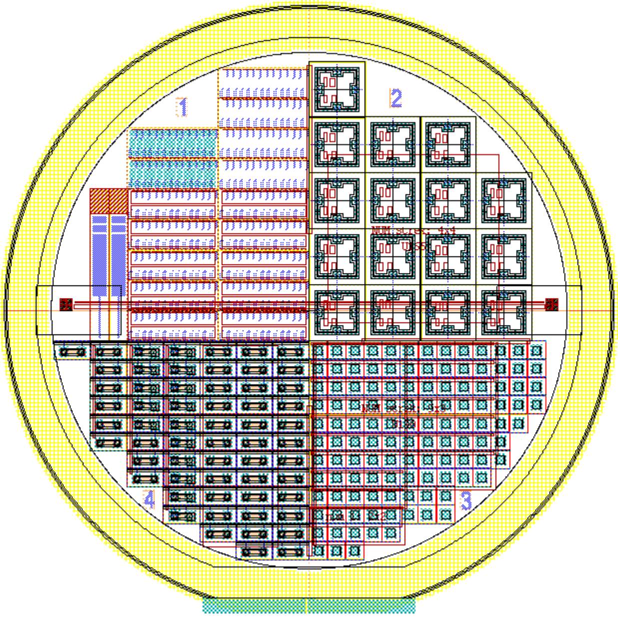


Figure 11: Layout of the 100 mm NORD-pie wafer

2. Fabrication

The prototype devices were fabricated using a qualified procedure for integrating piezoelectric PZT ($Pb(Zr,Ti)O_3$) into silicon MEMS.[24,25] Details can be found in literature or at the MEMS-pie web page (www.sintef.no/mems-pie). 100 mm silicon-on-insulator wafers were used and 8 wafer copies were made.
Pictures of a nearly finished wafer before it was diced into devices are seen in Figure 12. Moreover, pictures of the different device dies after dicing is shown in Figure 13.

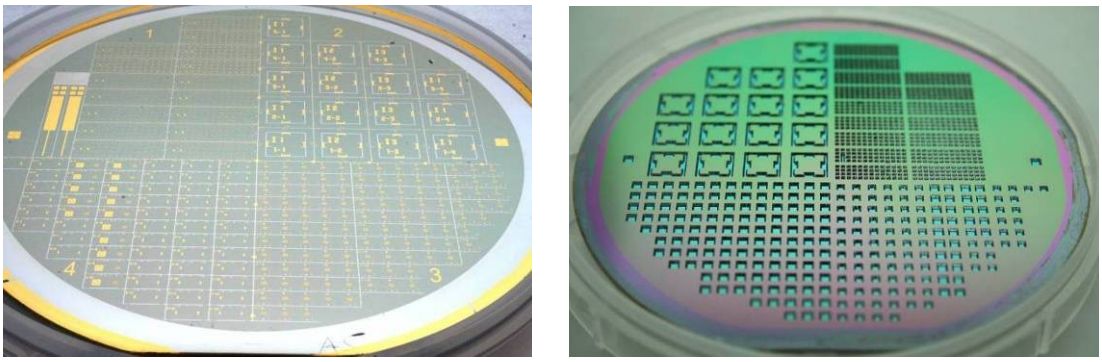


Figure 12: Finalized wafer (front side and back side) before dicing of the devices

[24] MEMS-pie *Integration of piezoelectric thin films in micro-electromechanical systems, FP6, COOP-CT-2004-508219.*; www.sintef.no/mems-pie.
[25] Raeder, H.; Tyholdt, F.; Booij, W.et al. *J. Electroceram.* **2007**, *19*, 357-362.

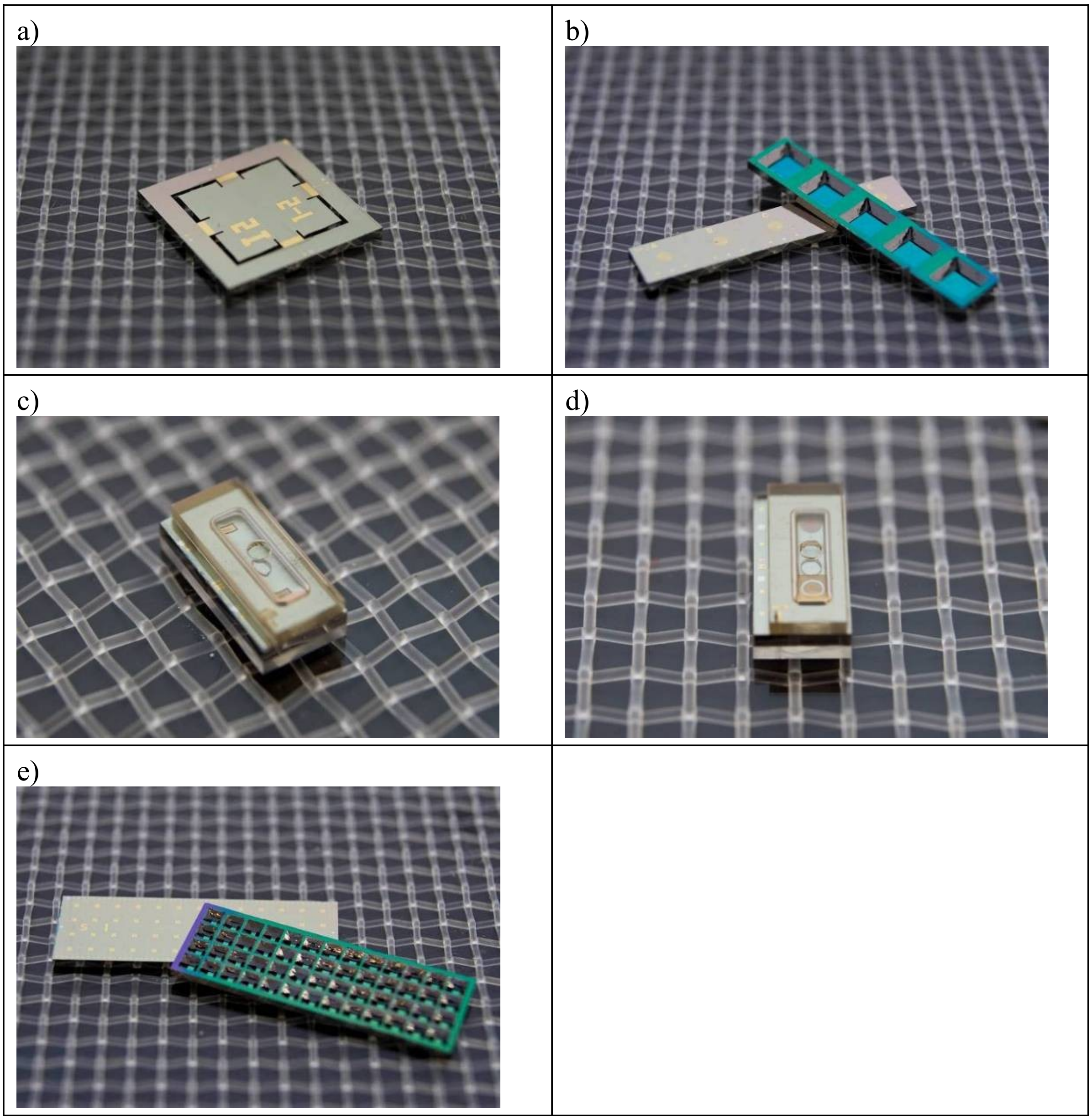


Figure 13: The NORD-pie device dies after dicing. a) Insensor Accelerometer, b) Sonitor microphones, c) Hök acoustic gas sensor, d) SensoNor acoustic gas sensor, e) Star-Oddi ultrasonic transducer arrays

3. Modelling

3.1 Software and hardware

The following modelling software packages were used:

1. ATILA 5.2.4 (ISEN, France) with
   a. Environment : complete 2D + 3D
   b. Materials : elastic, piezoelectric
   c. Solvers : static, harmonic, modal, transient
2. FEMLab 3.4 (Comsol AB, Sweden) with
   a. Structural mechanics module
   b. Acoustics module
   c. MEMS module

The modelling was carried out with Pentium 4 (3.4 GHz) with 3 GB RAM

3.2 ATILA FEM modelling

Modelled structures:

1) Piezoelectric resonators for Star-Oddi
2) Piezoelectric cantilever resonator for Hök

3.2.1 Star-Oddi circular resonator structure (in air) by analytical and ATILA FEM modelling

Material parameters (Table 2) and equations from Muralt et al. were used to calculate resonance frequencies of circular resonator:[26]

Material	Thickness [µm]	Young's modulus [GPa]	Poisson's ratio	Density [kg/m^3]
Si	9	130	0.278	2330
SiO2	1.2	70	0.3	2220
Pt	0.1	136	0.42	21000
PZT	2	76	0.288	7700

Table 2: Material properties used in ATILA models to calculate resonance frequencies.

[26] Muralt, P., Ledermann, N., Baborowski J., Barzegar A., et al. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **2005**, 52, 2276-2288.

The schematic cross-section of Star-Oddi resonator is presented in Figure 14.

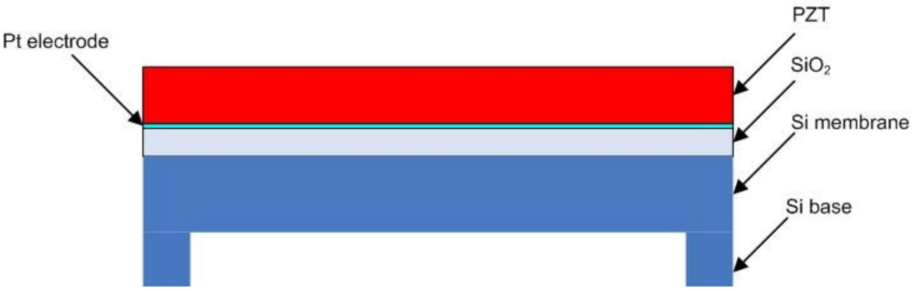


Figure 14: Schematic cross-section of the Star-Oddi circular resonator structure.

Resonance frequencies for different membrane radius and mesh density in FEM models with and without electrodes were modelled with ATILA (Table 3). Results were compared to the results obtained by Matlab calculations showing slightly lower resonance frequencies in air for FEM models.

1st resonance frequencies in air

Membrane radius (µm)	*ATILA (coarse mesh, no electrodes)*	*ATILA (coarse mesh, with Pt electrode)*	*ATILA (dense mesh, with Pt electrode)*	*SINTEF calculations*	*Difference*
300	0.36 MHz	0.37 MHz	0.36 MHz	0.37 MHz	-3 %
200	0.83 MHz	0.81 MHz	0.80 MHz	0.84 MHz	-5 %
150	1.43 MHz	1.41 MHz	1.39 MHz	1.49 MHz	-7 %
100	3.05 MHz	2.99 MHz	2.95 MHz	3.34 MHz	-12 %
80	4.57 MHz	4.49 MHz	4.39 MHz	5.23 MHz	-16 %
50	10.07 MHz	9.90 MHz	9.66 MHz	13.38 MHz	-28 %

Table 3: Resonance frequencies of ATILA and Matlab models.

Subsequently, the resonator structure was modified to obtain the first resonance at 3 MHz and 5 MHz with updated material parameters (Table 5) and dimensions. The results of ATILA FEM and Matlab models are shown in Table 4 exhibiting only 1-2 % difference for structure shown in Figure 15.

	Resonance frequency 3 MHz	**Resonance frequency 5 MHz**
Membrane radius by analytical model	105.6 µm	81.8 µm
Membrane radius by ATILA model (in air)	107.6 µm	81.1 µm

Table 4: Membrane radiuses for 3 MHz and 5 MHz resonance frequencies obtained by ATILA and Matlab models.

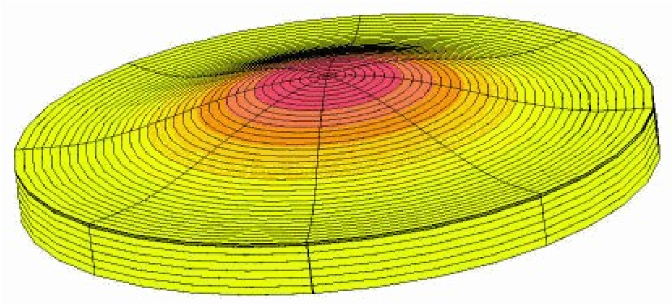


Figure 15: Modelled Star-Oddi circular resonator structure under excitation.

3.2.2 Hök cantilever resonator (in air) by FEM modelling

Modal analysis was used also for the cantilever resonator (Figure 16). In order to decrease calculation time, only the membrane and the cantilever (not the bulk Si) were modelled and the backside opening area was used for clamping (Figure 17).

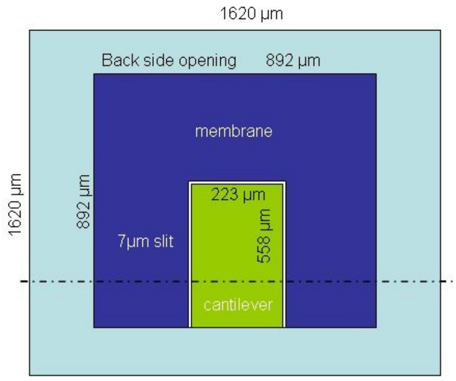


Figure 16: Top view of cantilever resonator design.

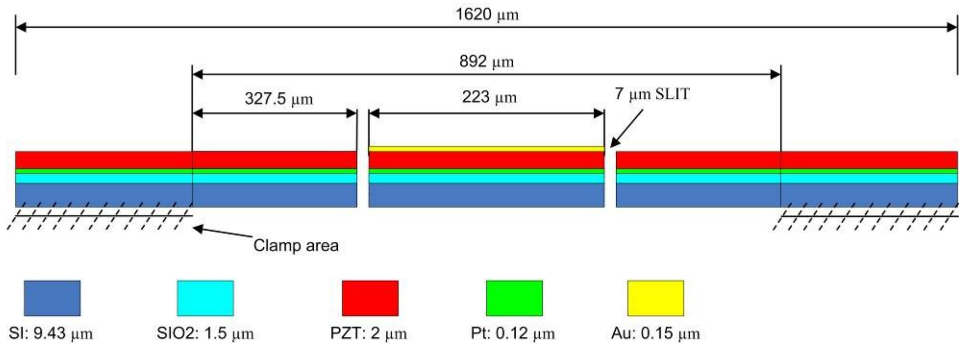


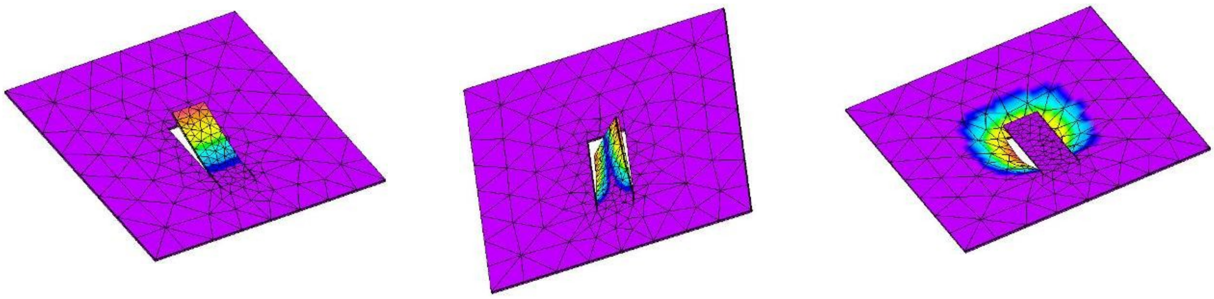
Figure 17: Cross section of cantilever resonator

Material parameters used for the modelling are shown in Table 5, colour coding refers to each layer of Figure 17.

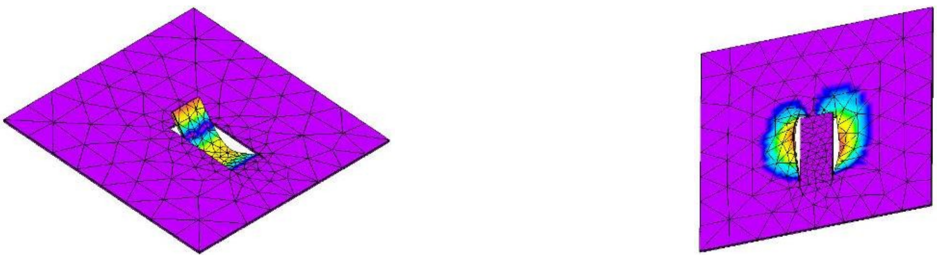
Material	Thickness [nm]	Young's modulus [GPa]	Poisson's ratio	Density [kg/m^3]
Si	**9430**	**166**	**0.278**	**2330**
SiO2	**1500**	**70**	**0.3**	**2200**
Pt	**120**	**168**	**0.38**	**21090**
PZT	**2000**	**110**	**0.28**	**7750**
Au	**150**	**78**	**0.42**	**19300**

Table 5: Material parameters used in modelling.

Different modes of the cantilever resonator were modelled in order to check possible interfering movement of the membrane (like in 3rd resonance in Figure 18c) around operating frequency (1st resonance frequency in Figure 18a). Interference of the membrane was not detected in the model.



a) 1st resonance: 44.2 kHz b) 2nd resonance: 214.2 kHz c) 3rd resonance: 254.0 kHz



d) 4th resonance: 275.7 kHz e) 5th resonance: 322.6 kHz

Figure 18: Different resonance frequencies and modes of the cantilever resonator structure.

Cantilever length was fitted to match 40 kHz resonance (1st resonance in air) → length of 588 µm (analytical model 558 µm).

3.2.3 FEM modelling of Star-Oddi resonator structures

The desired operation of this device is to emit 1 and 4 MHz ultrasound in water thus requiring FEM modelling also in fluids. First different electrode configurations were evaluated by modelling their performance, i.e. membrane deflection, in air. The resonance frequency using the top electrode design in Figure 19 and structures in Figure 20 and Figure 21 was modelled with and without losses.

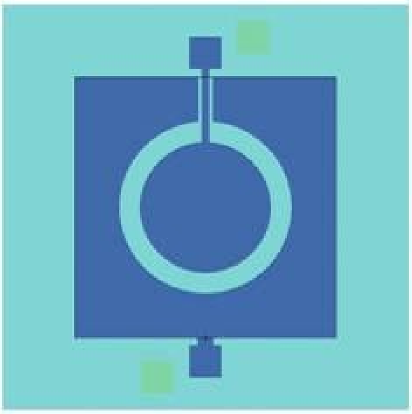


Figure 19: Circular two electrode layout

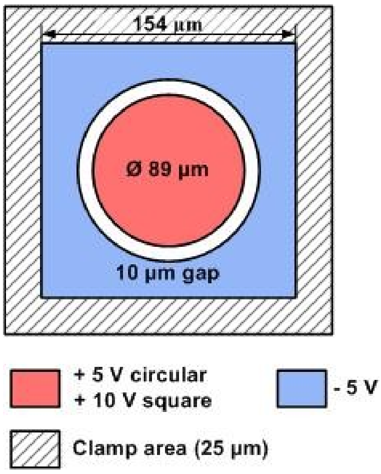


Figure 20: Modelled circular 2 electrode design.

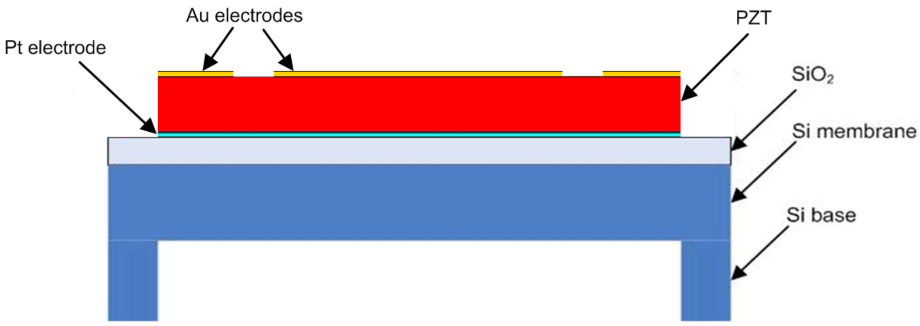


Figure 21: Cross-section of modelled 2 electrode design.

First resonance of circular 2 electrode design (Figure 21, circular area +5V, square area -5V) appeared at ~5.407 MHz in air without losses (Figure 22a). Introducing the 0.03 losses for all materials in Table 5 displacement of ~2.1 µm was obtained at 5.192 MHz i.e. at first resonance in air (Figure 22b).

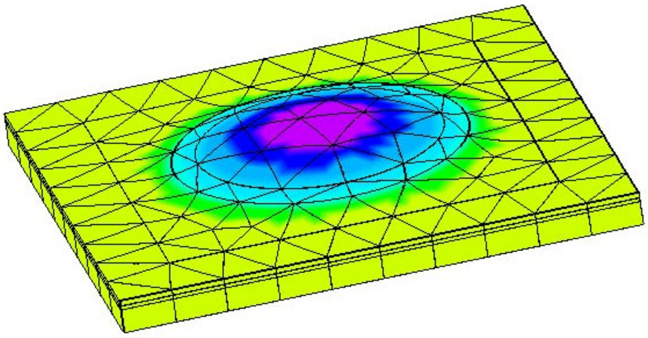


Figure 22: Displacement distribution at 5.407 MHz without losses and b) displacement as a function of frequency with losses (0.03) of the circular 2 electrode design.

3.3 FEMLab FEM modelling

Modelling of Star-Oddi resonators was also realised by FEMLab with acoustics module in air and water.

3.3.1 Frequency response (in air and water)

The harmonic analysis was used to calculate the frequency response of the Star-Oddi resonator structures with FEMLab. Dimensions of the resonators, (shown in Figs. 24 a and b), were further revised by SINTEF (earlier design in Fig. 21) to match first bending mode resonance at 1 MHz and 4 MHz frequencies in water. Voltages of +5 V and -5 V were used in the models (Figure 23).

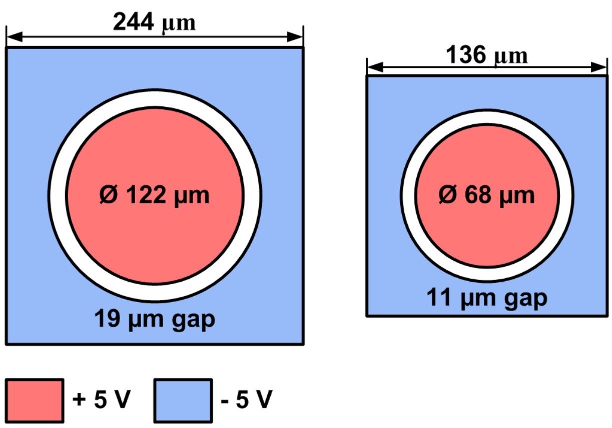


Figure 23: Modelled 2 electrode designs for a) 1 MHz and b) 4 MHz resonance frequencies.

For the modelling, 3D structures were created by extruding the 2D designs in Figure 23. Material parameters and thicknesses presented in Table 5 were used, except for the Au and Pt electrode layers, which were ignored to avoid problems with the meshing. The frequency response was first calculated in air (for reference) following the models in water.

3.3.2 The 4 MHz resonator models

The 4 MHz resonator design was clamped from the edges (movement in x-, y-, and z-axis directions = 0) as shown in Figure 24 and other boundary conditions were not used in air models.

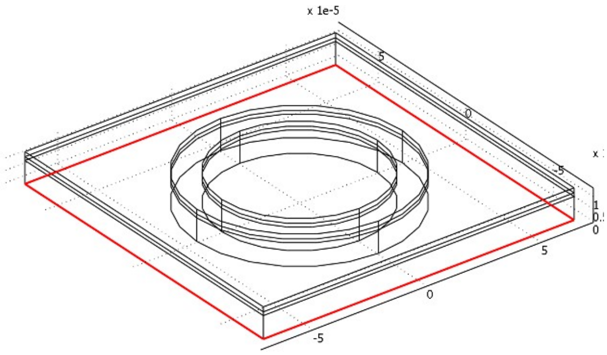


Figure 24: Clamping of the Star-Oddi resonator in the FEMLab, in air model.

As can be seen from Figure 25, the resonance of the 4 MHz design in air is ~5.5 MHz with a displacement of ~0.27 µm with loss factor of 0.03. Close correspondence in resonance frequency was obtained with models made by ATILA (5.192 MHz). When losses were increased, the displacement behaviour slightly changed but the peak frequency value (resonance frequency) remained the same (Figure 25).

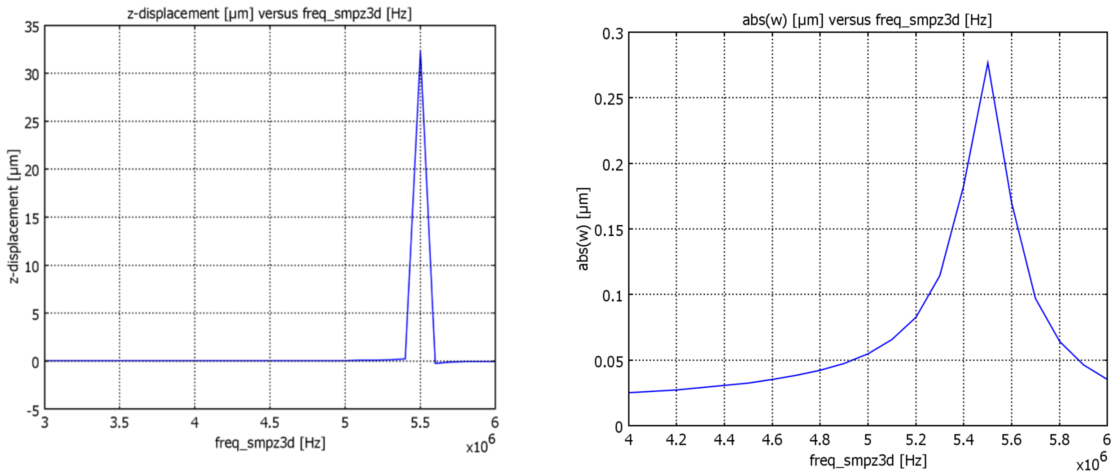


Figure 25: The frequency response of the 4 MHz design in air a) without material losses and b) with 0.03 mechanical losses for all materials.

Clamping of the resonator in the in water models were done similarly as in the in air models (Figure 24) and additional water layer was added under the resonator as shown in Figure 26. The boundary conditions of the outer walls of the water domain were specified as a radiation boundary so that the sound waves created by the piezo would go through the "walls" with minimised reflections. By this particular boundary condition information about the behaviour of the sound waves in the water (for example the pressure patterns) and the effect of damping are more reliable (no interfering reflections).

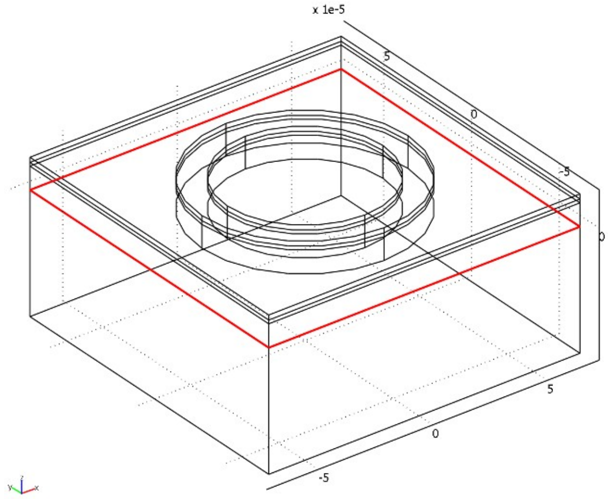


Figure 26: Clamping of the Star-Oddi resonator in the FEMLab water model.

All in water models were calculated using 0.03 losses in all solid materials. The density and speed of sound of the water was set to 1000 kg/m^3 and 1500 m/s, respectively. General damping with attenuation factor of 0.1 (general attenuation factor for pure water) was used. Different mesh densities in the water block were tested as well as two different sizes of the water domain i.e. 50 µm and 100 µm thick (Figure 27). As can be seen, the mesh density had relatively small impact for the displacement behaviour of the resonator, however, the water block thickness had more significant effect for the displacements due to near-field effects. It should be noted that change in water thickness also shifted the resonance peaks slightly to the left thus decreasing the frequency.

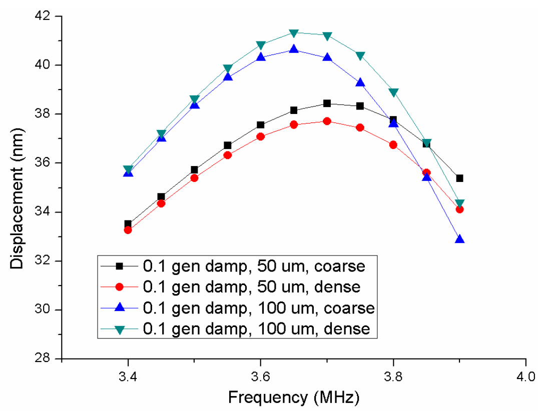


Figure 27: The frequency response of the 4 MHz resonator in water with 0.1 general damping.

According to the results presented in the Figure 27, the resonance frequency of the structure in water was ~3.65 MHz while targeting for 4 MHz. In addition, the displacement decreased from 270 nm in air to 41 nm in water. Regarding to displacement the pressure pattern and behaviour of the sounds waves generated by the resonator were simulated. The pressure patterns of the 4 MHz resonator in water at 3.65 MHz can be seen in Figure 28.

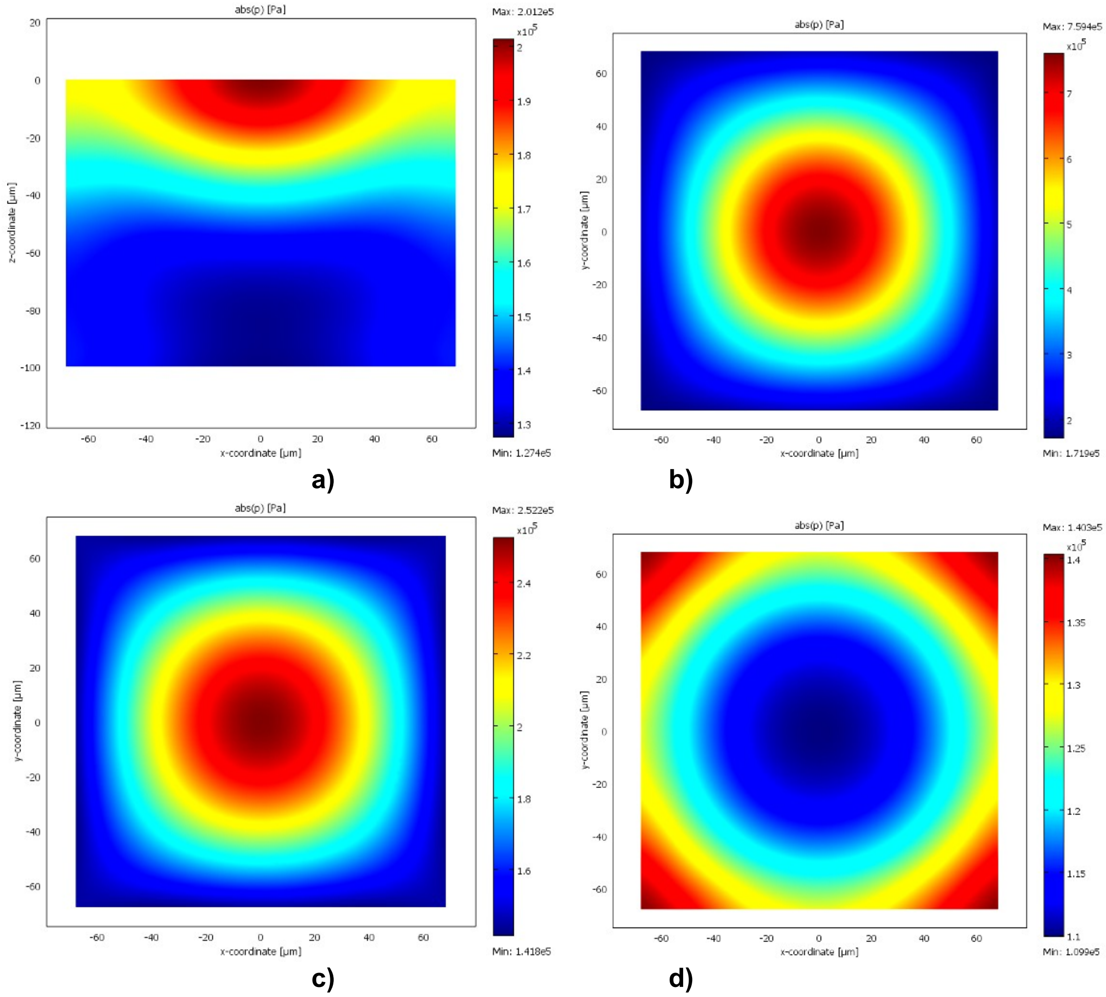


Figure 28: The pressure patterns of the 4 MHz resonator at resonance (3.65 MHz) from a) sidewall of the structure b) top, c) centre and d) bottom of the water

As can be seen from Figure 28, the pressure generated by the sound wave is rapidly attenuated and also pressure differences are greatly reduced at the bottom of the water block. According to Figure 28d and Figure 28a (although not very clearly) the pressure at the bottom is larger in the corners than in the centre although the displacement is the largest at the centre. Thus output sound wave of the resonator approaches to plane wave (Figure 28a) and differences between minimum and maximum pressure is about $\sim 0.3 \cdot 10^5$ Pa (Figure 28d) in contrast to more spherical wave where difference is $\sim 5.9 \cdot 10^5$ Pa (Figure 28b). The pressure of the sound wave was simulated also as a function of frequency from the centre of the water block along the line shown in Figure 29.

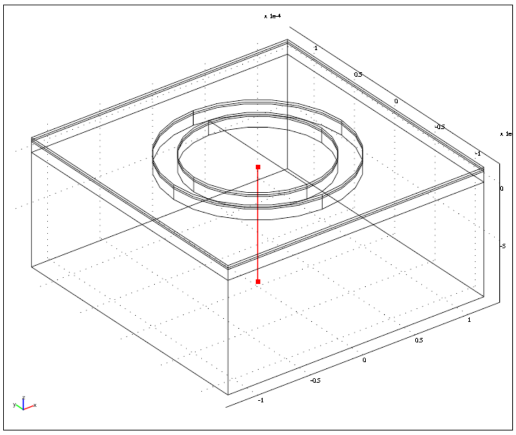


Figure 29: The centre line (red) in the water block where the pressure curves were calculated.

The pressure curves shown in Figure 30 display the absolute pressure along the centre line of the water block depth (z-coordinate, 0 = top, -100 = bottom) with different frequencies. As expected, the maximum pressure occurred around the resonance frequency at the top of the water (~ $8.0 \cdot 10^5$ Pa) and diminished along the line towards the bottom of the water.

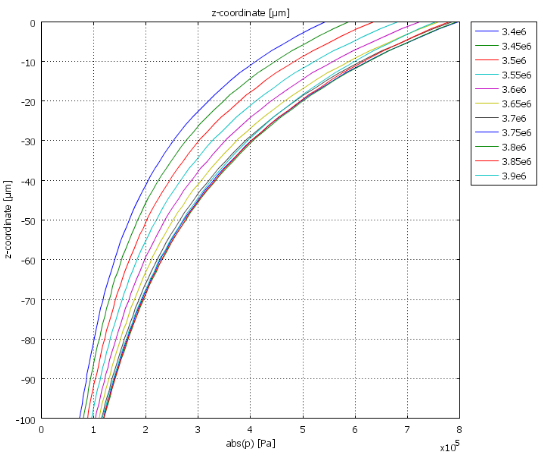


Figure 30: Pressures of the 4 MHz resonator along the centre line with different frequencies (3.4 – 3.9 MHz).

External pressure was also applied to the bottom of the water block in order to study the performance of the resonator under different pressures. As can be seen from Figure 31, the external "blocking" pressure is $3.0 \cdot 10^5$ Pa i.e. 3 bar. At this pressure level displacement of the resonator is zero and displacement above this point (shown in Figure 31) is generated from deformation of the membrane by external pressure. Note that absolute values of the simulated displacements were used in the Figure 31 and that earlier calculation in Figure 27 (displacement ~41 nm) were carried out with zero external pressure thus corresponding to the value presented in Figure 31.

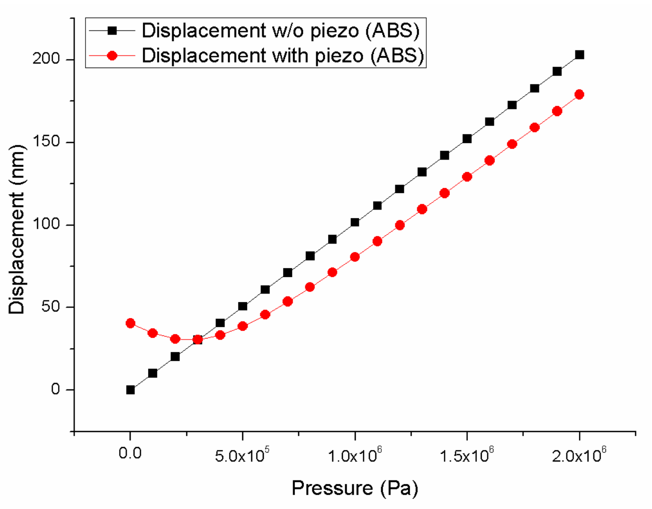


Figure 31: Performance of the 4 MHz resonator as a function of external pressure at the bottom of the water.

3.3.3 The 1 MHz resonator models

The modelling of 1 MHz resonator was started with the in air models and the first resonance appeared at ~1.79 MHz with a displacement of ~1.1 µm as shown in Figure 32. Loss factor of 0.03 was used for all solid materials in the calculations. Since the results with the 4 MHz models indicated that the mesh density was not a very critical factor (Figure 27), similar "coarse" mesh density was used. The calculation times were ~ 1-2 hour/model using the 0.01 MHz frequency steps thus computation time was increased by greater amount of nodes and degrees of freedom.

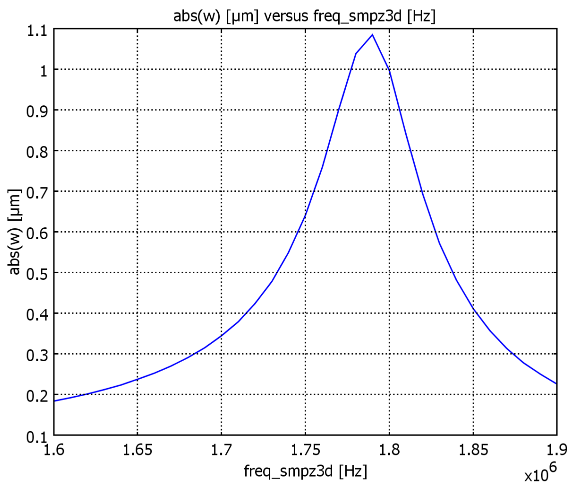


Figure 32: Frequency response of the 1 MHz design (in air) with 0.01 MHz step.

The frequency response of the 1 MHz resonator in water can be seen in Figure 33. The resonance frequency of ~1.01 MHz is closely matching with the designed frequency. The displacement of ~175 nm was generated with 0.03 loss factor of the solid materials and 0.1 general damping of water which was used also in 4 MHz models presented earlier.

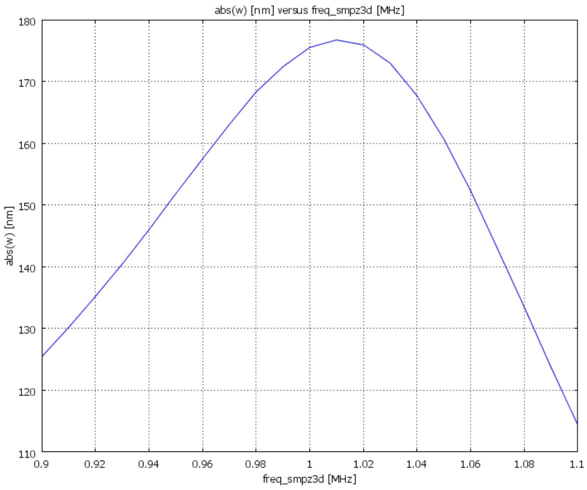


Figure 33: The frequency response of the 1 MHz resonator in water with 0.1 general damping.

The pressure patterns of the 1 MHz models from the sidewall, top and bottom of the water can be seen in Figure 34. The largest values of $4.6 \cdot 10^5$ Pa occurred near the surface of the water.

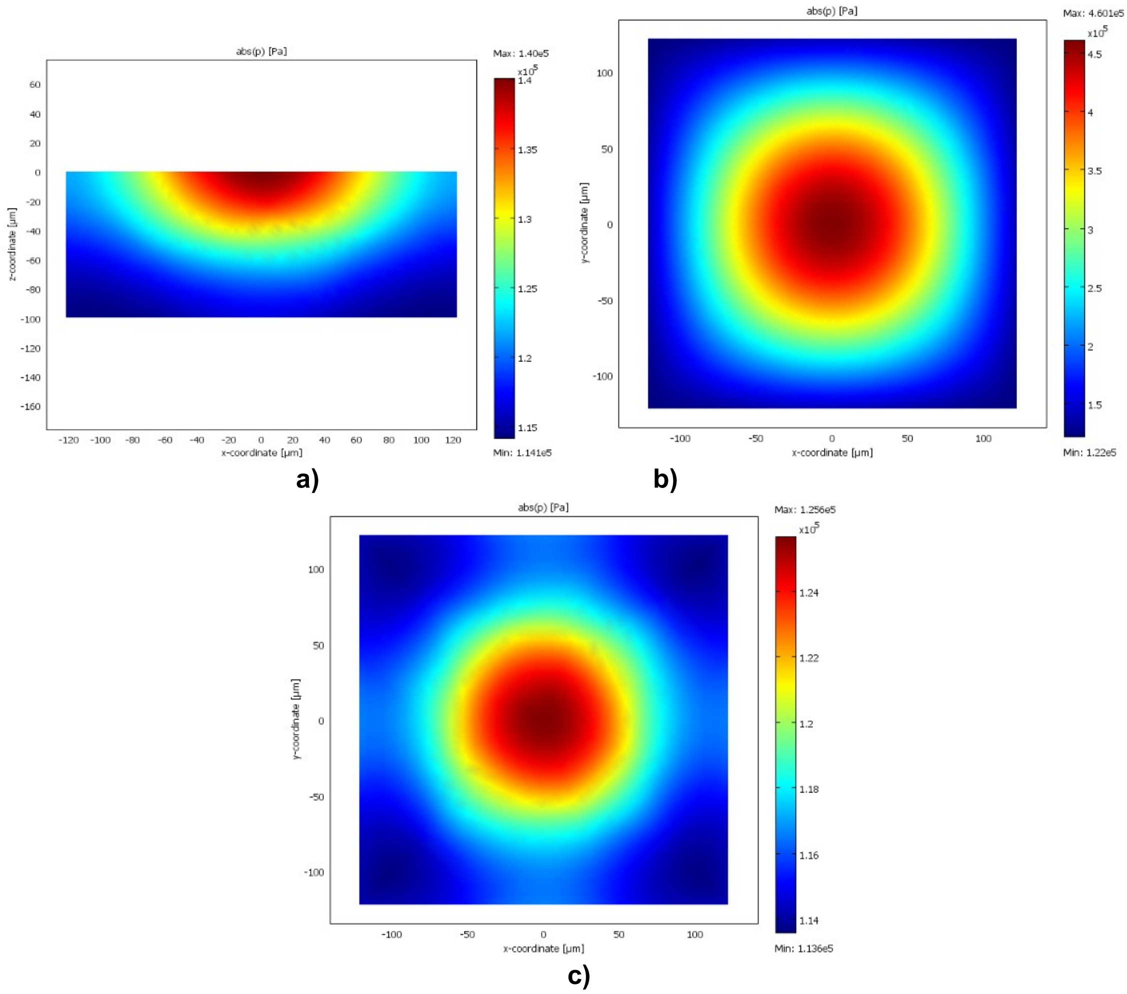


Figure 34: The pressure patterns of the 1 MHz resonator at resonance (1.01 MHz) from a) sidewall b) top of the water and c) bottom of the water.

The behaviour of the pressure pattern was similar observed with 4 MHz resonator, although more spherical pressure wave can be seen in Figure 34a in contrast to higher pressures on the edges in Figure 28a. Also in this case the output of the resonator showed greatly reduced pressure difference ~$0.12 \cdot 10^5$ Pa (Figure 34c) mainly due to lower initial pressure difference of ~$3.381 \cdot 10^5$ Pa (Figure 34b).

The pressure behaviour as a function of frequency was also simulated from the centre of the water block as presented in Figure 35. The maximum pressure occurred around the resonance frequency and at the top of the water. The pressure behaviour was similar as in the case of the 4 MHz resonator.

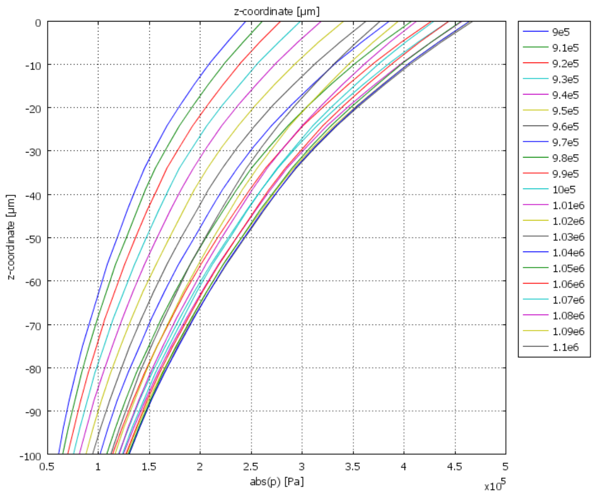


Figure 35: Pressures of the 1 MHz resonator along the centre line with different frequencies (0.9 – 1.1 MHz).

External pressure was applied to the bottom of the water block as in the case of the 4 MHz resonator models. As can be seen from Figure 36, the external "blocking" pressure is lower than in the 4 MHz resonator as a consequence of larger membrane hence reduced stiffness and area moment of inertia compared to the 4 MHz resonator. The blocking pressure occurred at ~$1.2 \cdot 10^5$ Pa i.e. 1.2 bar. The displacement of the resonator at zero pressure corresponds to the values presented in Figure 33 (displacement ~175 nm).

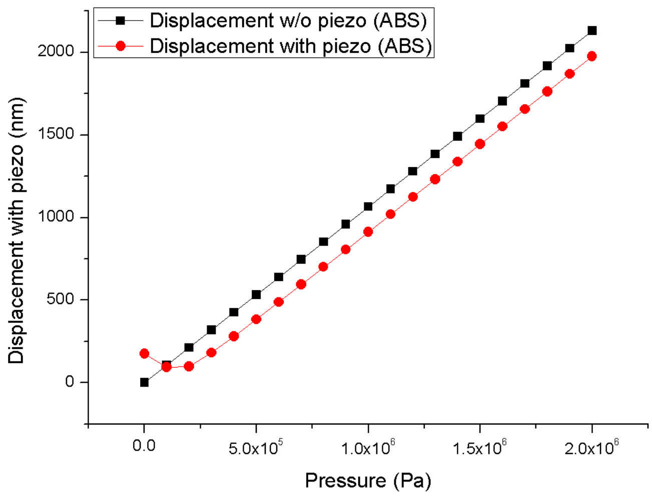


Figure 36: Performance of the 1 MHz resonator as a function of external pressure at the bottom of the water.

3.4 Concluding remarks

Numerous models and computations were realized by ATILA and FEMLab for different resonator structures and combinations of material parameters, boundary conditions and excitations. Even with the reasonable short calculation times (5-15 minutes mostly, with the 1 MHz resonator dense frequency step models ~1-2 hours), the designing and interpreting the results and computation in overall takes a considerable amount of time.

The clamping of the structures proved to be the most critical aspect of the in air models, however, the behaviour of in water models is more complex due to the surrounding geometry and other boundary conditions, for example "walls" of the water, which all played a significant role. In order to get the accurate modelling results correct material parameters for piezoelectrics and other materials including losses, knowledge of boundary conditions and exact geometry are all very critical aspects.

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4. Packaging

4.1 Introduction

Packaging was performed by Mandalon Technologies AB. Being the Packaging Partner in a scientific project such as NORD-pie meant involvement in the design phase from the start. If packaging of the structure is developed in parallel to the chip/sensor design, system integration issues will be solved at a much earlier stage. In this way “non-packageable” designs and negative effects on chip/sensor performance can be eliminated or reduced.

Therefore, at an early stage in the project, Mandalon visited all partner companies to gain insight in each partner’s specific need for packaging.

Four different structures were to be packaged during the project. Each package needed to be chosen or designed to fit the specific needs for each of the four structures.

4.2 Packaging Solutions – Technical Achievements

4.2.1 Package for Star-Oddi Ltd

Structure: Resonator matrix, 4 * 13 per chip

Problems to be considered:
Water sealed, water high pressure on membrane, relatively high number of I/O’s

Solution:
First prototype was based on a ceramic 300LGA package together with an object glass. The chip was bonded unmounted and after that glued tilted 90˚ on the ceramic. Half the chip was connected with 53 cables. To get a more production like design we chose a LTCC solution. This enabled a customised package that would meet the requirements mentioned above.

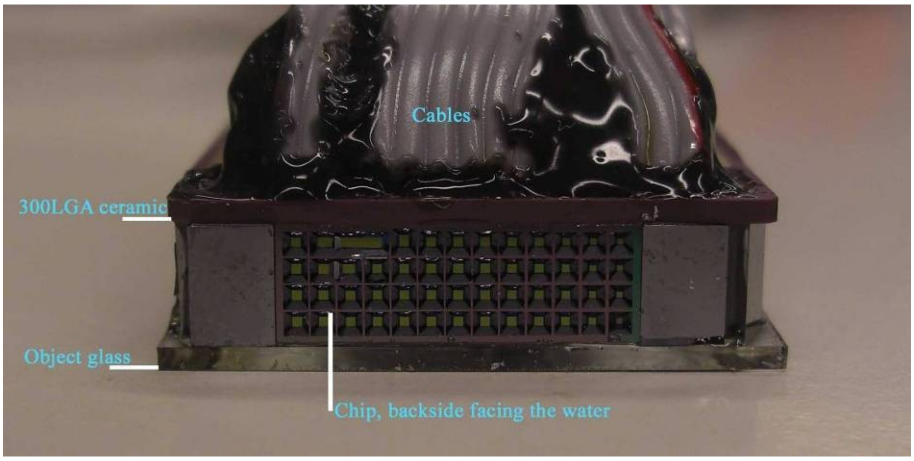


Figure 37: Star-Oddi first prototype showing mounted chip backside facing the water. This "box package" is open at the other end.

4.2.2 LTCC package for Star-Oddi resonators

The LTCC package was designed in co-operation with University of Oulu, Mandalon Technologies AB and Star-Oddi Ltd for the device to be tested in real environment. The package was realised at Microelectronics and Materials Physics Laboratories together with representative of the Mandalon. The Layout of the two primary conductor layers is shown in Figure 38:

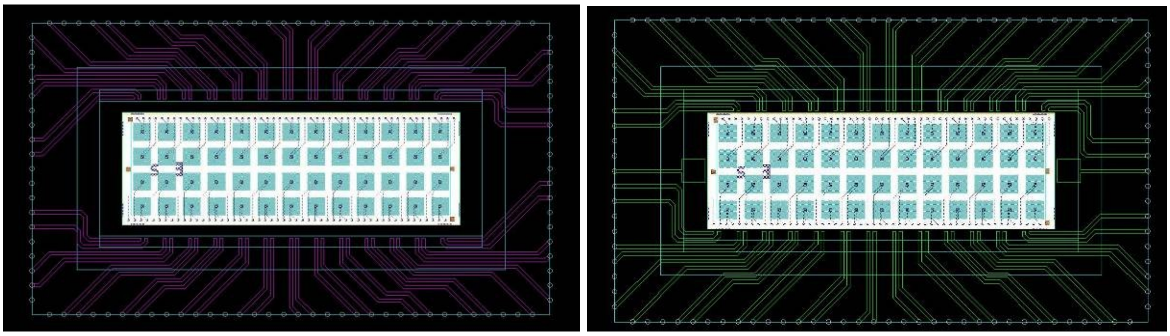
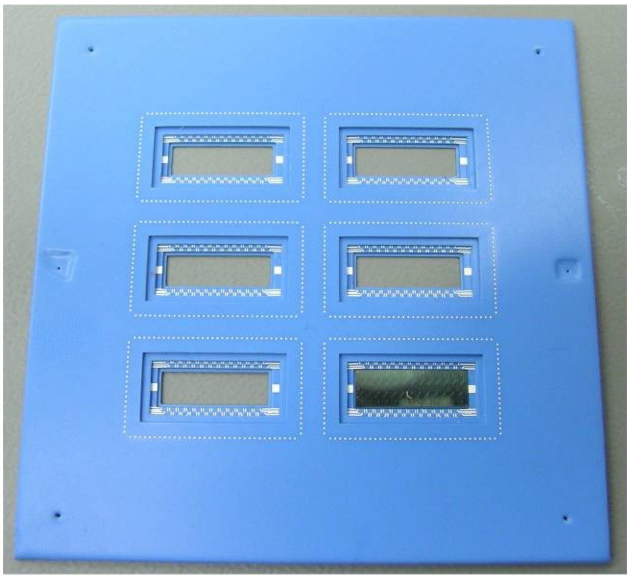


Figure 38: Layout of the electrodes on a) upper layer b) lower layer of the package.

Manufactured design consists of 10 layers of DuPont 951 with 200 µm green layer thickness producing 1.9 mm total fired thickness. The fired panel, individual package and chip of the resonator matrix in the package are shown in Figure 39. The lid of the package is manufactured from the same LTCC material. Diced LTCC packages will be sent to Mandalon for the finalisation of the packages i.e. electrical connections, assembly of the chip and lid.



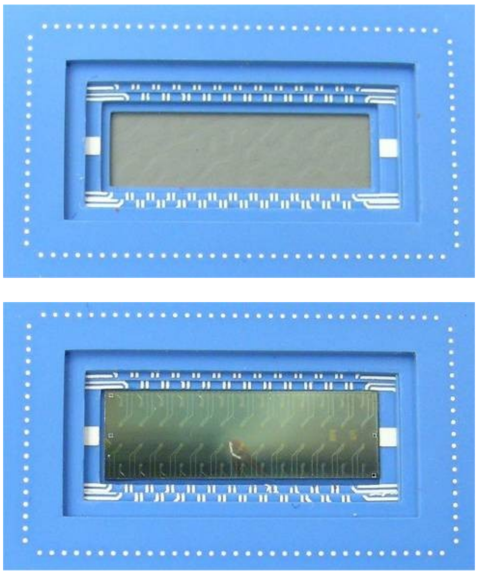


Figure 39: LTCC panel consisting 6 packages and LTCC package b) without and c) with chip of resonator matrix.

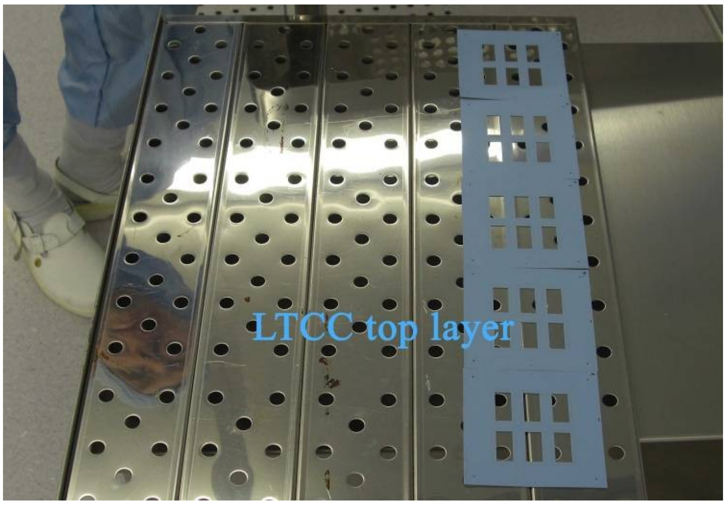


Figure 40: Star-Oddi package version 2.0, LTCC package is designed and the fabrication is in progress. It replaces the first prototype.

4.2.3 Package for Sonitor Technologies AS

Structure: Resonator array, 5 resonators

Problems to be considered:
In order to get a high number of measurement data the package needed to be exchangeable

Solution:
A thin PCB was used which directly fitted into a normal socket. On this PCB the chip was inserted into a hole in order to shield off the sound from front to back side.

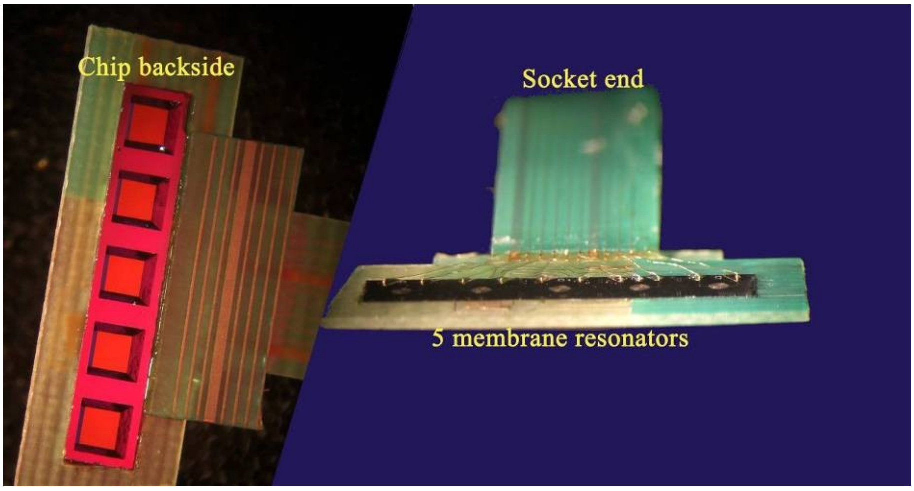


Figure 41: Final design of PCB package for testing of Sonitor phased array microphone

Result: The chip performances varied and proved to be very good on a number of samples.

4.2.4 Package for Insensor A/S

Structure: Accelerometer

Problems to be considered:
The problem was mainly to transport the bare chip until it was packaged.

Solution:
A TO-8 header with four glass pillars centred under each side of the chip was chosen.

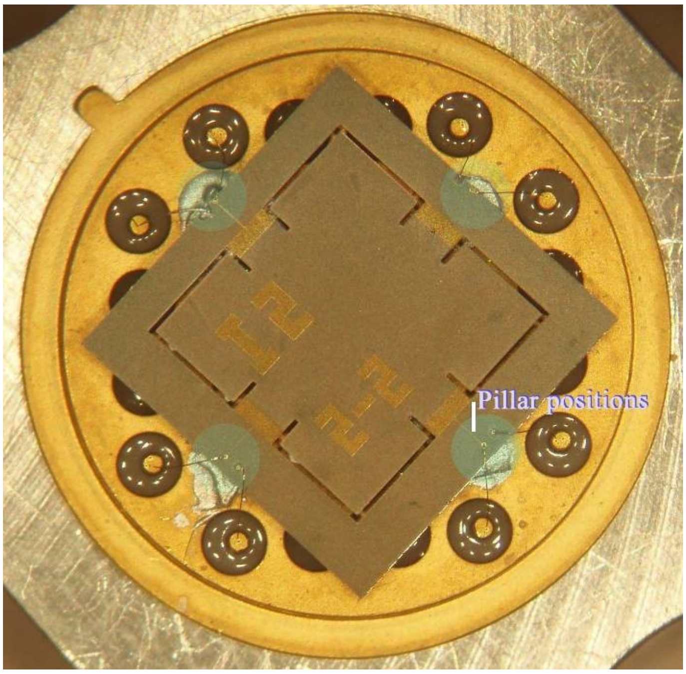


Figure 42: Insensor accelerometer mounted and wire bonded in a TO-8 canister

Result: In practice, the mass of the TO-header interfered too much with the measurement results and needs to be revised.

4.2.5 Package for Hök Instrument AB

Structure: Gas sensor cantilever resonator pair

Problems to be considered:
How to implement a fine tuning of the gas volume inside the package

Solution:
Use of a TO-8 header with a standard metal can. The can was to be customised with an adjustable top inside.

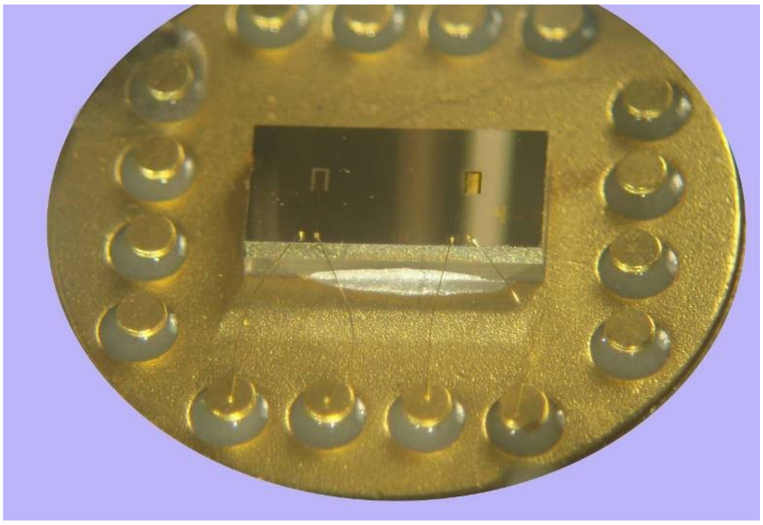


Figure 43: TO-8 header with the two-cantilever chip.

Result: Packaging is put on hold until the physical properties of the chip gives the desired resonating space of 4 mm above the resonator cantilevers

4.3 Conclusions

Four different structures were packaged during the project. Each package was developed to fit the foreseen specific needs of each of the four structures. For some structures the design had to be reconsidered. Three out of four structures has been tested and the preliminary results are promising.

In addition to the good results of the packaging within this project, for Mandalon this project has also been very valuable in terms of developing competence, networking and new business contacts. Emphasis has been on developing knowledge of the LTCC process.

5. Testing and characterization

5.1 Hök Instrument AB and Infineon Technologies SensoNor AS: Acoustic Gas Sensors

5.1.1 Experimental results

We received 16 samples from SensoNor/MicroComponent and one sample from Mandalon. The samples were first characterised by capacitance measurements, and then some devices were selected for poling and further characterisation.

For poling the devices, a simple adapter to a soldering iron was constructed in order to control the device temperature during the poling procedure. Voltage, temperature and time settings were originally following the recommendations from SINTEF: 20 V, 150 ˚C, and 10 minutes. Due to failure of one device at these settings, we chose to decrease voltage and temperature to 15 V and 130 ˚C, respectively.

The devices chosen for further experiments were – after poling – tested for resonance in the frequency range 20 kHz – 2 MHz. During this experiment, a series resistor of 100 kΩ was connected to the element, and the impedance variation with frequency was monitored on an oscilloscope. After detection of resonance, the frequency was noted, and the Q factor was measured according to standard procedure.

The devices with two resonators were then tested for resonant coupling, using one element as transmitter and the other as receiver. Again, resonance frequency and Q factor were measured, along with the signal coupling (peak ratio between output and input voltage).

Devices with detectable coupling were tested for gas sensitivity in a sealed chamber in which gases – CO_2 or helium, were added in controlled doses. The response to gas exposure was recorded in terms of shift of resonance frequency. Response time was recorded by exposing the device (in free air) to a “gas impulse” from a syringe.

Sample ID	*8-5*	*9-2 first mode*	*9-2 second mode*	*10-4*
Poling (voltage V, temp ˚C, time min)	20 150 10	15 130 10	15 130 10	15 130 10
Capacitance (pF)	580	610	610	1230
Resonance frequency (kHz)	44.6	33.2	193.7	71.6
Q factor	100	100	150	100
Signal coupling (V_{out}/V_{in})	-	$2*10^{-3}$	0.07	$3*10^{-3}$
Gas sensitivity (Hz/%CO_2)	ND	ND	-50	ND
Response time (sec)	ND	ND	20	ND

Table 6: Summary of measurement results performed on NORD-Pie structures.

In Table 6, the results of our measurements on NORD-Pie structures are summarised. The samples 8-5 and 9-2 were cantilever beam structures with glass lid, whereas, sample 10-4 was a diaphragm structure.

Sample 8-5 did not survive the poling procedure (one of the two devices exhibited only stray capacitance after poling), and its coupling characteristics could therefore not be measured. The other two devices were consequently poled at somewhat lower temperature and voltage. In each of them, coupling between transmitter and receiver could be measured.

Capacitance values were reproducible and stable. Minor changes could be observed after poling but were not investigated further. Signs of depoling after prolonged resonant excitation were observed in corresponding to results reported from the MEMS-Pie project.

The resonance frequencies of the cantilever beams corresponded well with expected values. Note that the nominal length of device 8-5 was 490 μm, whereas device 9-2 had a length of 535 μm (according to SINTEF).

In device 9-2 the signal coupling of the first resonance at 33 kHz was relatively weak, and it was not possible to detect any significant shift even at high concentrations of other gases (CO_2 or He). However, when exciting the second resonant mode at 193 kHz, the signal coupling was more than an order of magnitude higher, and the resonance frequency shifted by approximately -50 Hz/%CO_2. Frequency shift of opposite sign was observed (as expected) when the device was exposed to He or methane.

The response time of the device 9-2 was approximately 20 seconds, probably limited by the hole of the glass lid.

The diaphragm device 10-4 exhibited a signal coupling of the same order of magnitude as the cantilever device in its first resonance mode, and no gas sensitivity could be detected.

	Bulk	***MASCOT***	***NORD-Pie***
Size (mm)	12	2.3	2.7
Resonance frequency (kHz)	40	40	200
Q factor	30	10	150
Signal coupling (V_{out}/V_{in})	0.4	$3*10^{-6}$	0.07
Sensitivity (Hz/%CO_2)	-30	-110	-50
Resolution (ppm CO_2)	5	200	20
Power consumption (W)	10^{-4}	1	$5*10^{-4}$

Table 7: Comparison of properties: Bulk, MASCOT and NORD-Pie acoustic sensing devices.

In Table 7, the characteristics of the NORD-Pie device (element 9-2 operating in the second resonant mode) compared to commercial bulk elements and MASCOT devices are being compared.

For comparing the size of the devices, a characteristic dimension, (device volume)$^{1/3}$ has been used. The NORD-Pie device is marginally bigger than the MASCOT, and considerably smaller than the bulk device (a tubular structure with 10 mm diameter and 20 mm length).

The high operating frequency of the NORD-Pie device is a matter of circumstance, rather than anything. Performance is likely to be further improved if it can be brought down to the 40 kHz regime. The high Q factor may indicate that mechanical coupling predominates.

The most dramatic changes between the MASCOT and NORD-Pie devices are manifested by the signal coupling, and the power consumption. The electrothermal excitation and piezoresistive detection of the MASCOT devices were extremely inefficient compared to the piezoelectric solutions of the bulk and NORD-Pie devices.

The sensitivity and resolution of the NORD-Pie device also represents a significant improvement compared to the MASCOT devices, and is approaching that of bulk piezoelectric devices.

Response time was not included in the list of properties in Table 7, since it is depending on the device package, rather than the sensing elements.

5.1.2 Conclusions, further work

SensoNor, SINTEF and Hök formed a partnership through the MASCOT project (EU project: IST-2002-32411) and resulting patents, to develop a novel MEMS-based sensor suitable for air quality/environment (IAQ/IEQ) monitoring, respiratory health care and related applications. This partnership also formed a basis for the NICe-co-sponsored project MONTIE[27] primarily aimed at possible system providers and end-users of such IEQ sensors and technologies in general. The technology demonstrators produced through the NORD-pie project have now shown a proof of principle which will hopefully help prove to put these sensors to actual, industrial use.

The critical performance of the NORD-Pie device represents a significant improvement compared to the MASCOT devices, and is approaching that obtained with bulk piezoelectric devices.

The search for application areas and potential industrial partners is slowly proceeding along several parallel lines. The recent SINTEF invention related to gas alarm systems is particularly promising.

Further work along the following lines is suggested:

- Improved *theoretical modelling* of the devices
- Tests of *incremental design changes*, such as varying the slit width of the cantilevers, and acoustic resonator length could hopefully lead to nearly optimised design
- *Electronic design* to optimise performance, including power consumption
- *Packaging* will be crucial to cross-sensitivities and response time.

[27] MONTIE 04083 (http://www.nordicinnovation.net/prosjekt.cfm?id=1-4415-215)

5.2 Insensor AS: Accelerometer

5.2.1 Processing

Two processing routes was used for the accelerometer, one based on thin films like all the other applications in the project and one based on thick films. The details of the former route are described in the report of SINTEF, and two photos showing various stages are shown in Figure 44. It should be pointed out that the devices prepared by this route have PZT thin film (2 µm) deposited on the entire Si area. Furthermore, in this design the top electrodes cover the full width of the beams and the connections to the bonding pads are narrower.

A B

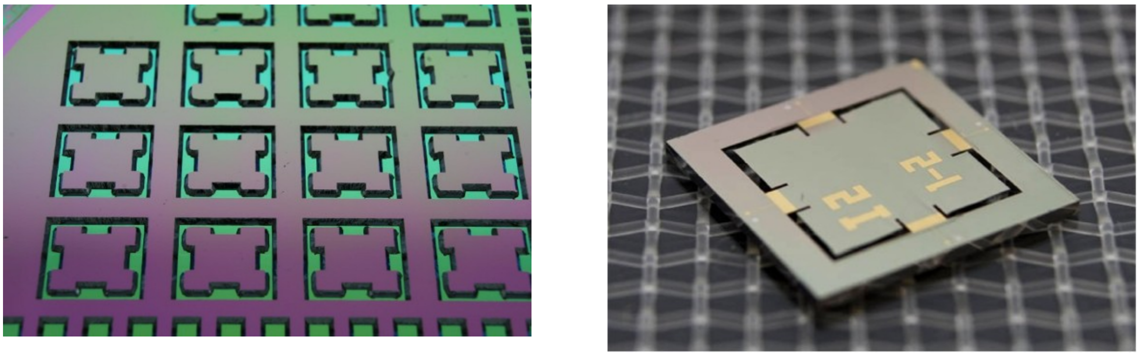


Figure 44: Stages in the thin-film processing of the accelerometer. (a) Part of a wafer with the seismic masses of the accelerometer seen from the back side. (b) A single accelerometer after the release etch, front side.

In the other processing route, the wafer is not covered with PZT thin film in the clean room. Instead, a ~20 µm thick PZT layer is screen printed onto the wafer in a pattern where the frame and the beams of each accelerometer are covered (i.e., not the seismic mass), cf. Figure 45. Unfortunately, the process used for preparing the wafers in NORD-Pie proved not to be compatible with the thick-film process where the final sintering is carried out at 850 ºC. As seen from Figure 45b, a large area of the wafer is discoloured, indicating reaction between PZT and Si, and the adhesion of the PZT is very poor, causing the film to peel off. In previous work carried out by InSensor, a Pt layer was deposited as a bottom electrode and barrier layer between the Si substrate and the PZT thick film and the results were quite good in terms of adhesion and piezoelectric sensitivity. However, the NORD-Pie process uses a thinner layer of Pt, which is clearly insufficient in this case. Subsequent experiments with sintering at only 750 ºC or an additional layer of Pt showed less reaction but still insufficient adhesion. The experiment with the thicker Pt seems to indicate some difference in the quality of the Pt layer between the clean-room processes used here and previously.

As a consequence of the reaction problems encountered here, it has not been possible to make a direct comparison within NORD-Pie of the performance of accelerometers based on PZT thin and thick films. However, in the near future thick-film accelerometers from the Danish project Π-MEMS will be tested in a similar manner.

A B

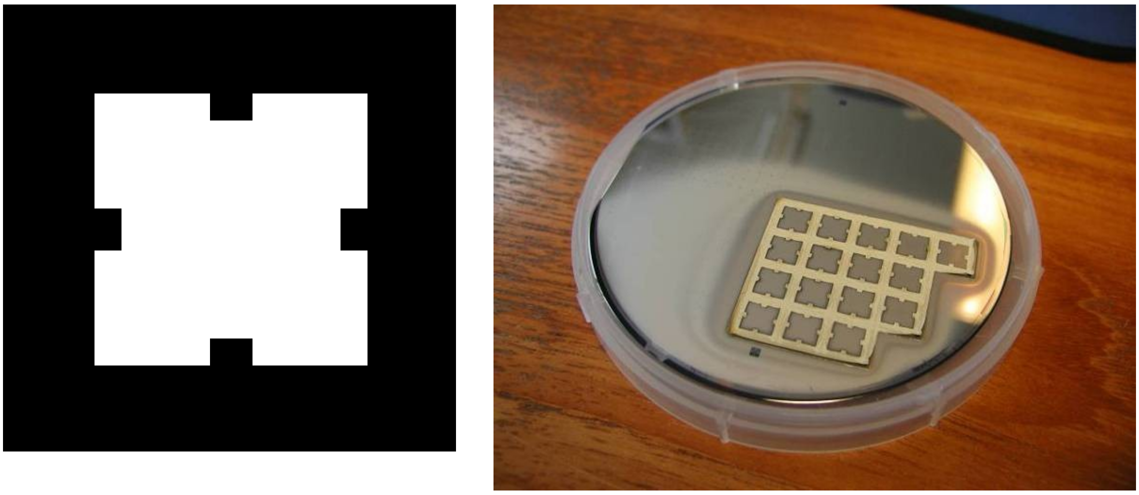


Figure 45: (a) PZT pattern (in black) for a single accelerometer in the thick-film route. (b) Example of wafer with scren-printed PZT (light-yellow pattern). Unfortunately, severe delamination occurs after sintering of the PZT.

5.2.2 Packaging

A packaging solution for the accelerometer was developed for NORD-Pie by Mandalon Technologies AB, see Figure 46a. After down-scaling the dimensions of the accelerometer by ~ 10 % with respect to the original design, it proved possible to use a standard electronic package called TO-8, which has metal cap and 16 pins for connections. The bonding and sealing processes were carried out by Mandalon after receiving the single accelerometer chips from SINTEF (only thin-film based, as mentioned in the previous section).

The handling and especially packaging of the accelerometer chips were made difficult by the dimensions of the accelerometer causing it to be very fragile. The thickness of the beams was only 10 µm Si + 2 µm PZT, which should be compared with 20 µm Si + 20 µm PZT in the original thick-film design. If a new design of the accelerometer was to be made specifically for the present SOI process, the mechanical properties of the beams should be optimised by adjusting the Si and PZT thicknesses, and furthermore the size of the seismic mass should be diminished in order to take into account the rather thin beams. However, out of the accelerometer chips that were intact after release etch and shipping, three survived packaging (and only one accelerometer made it all the way to vibration measurement).

A B

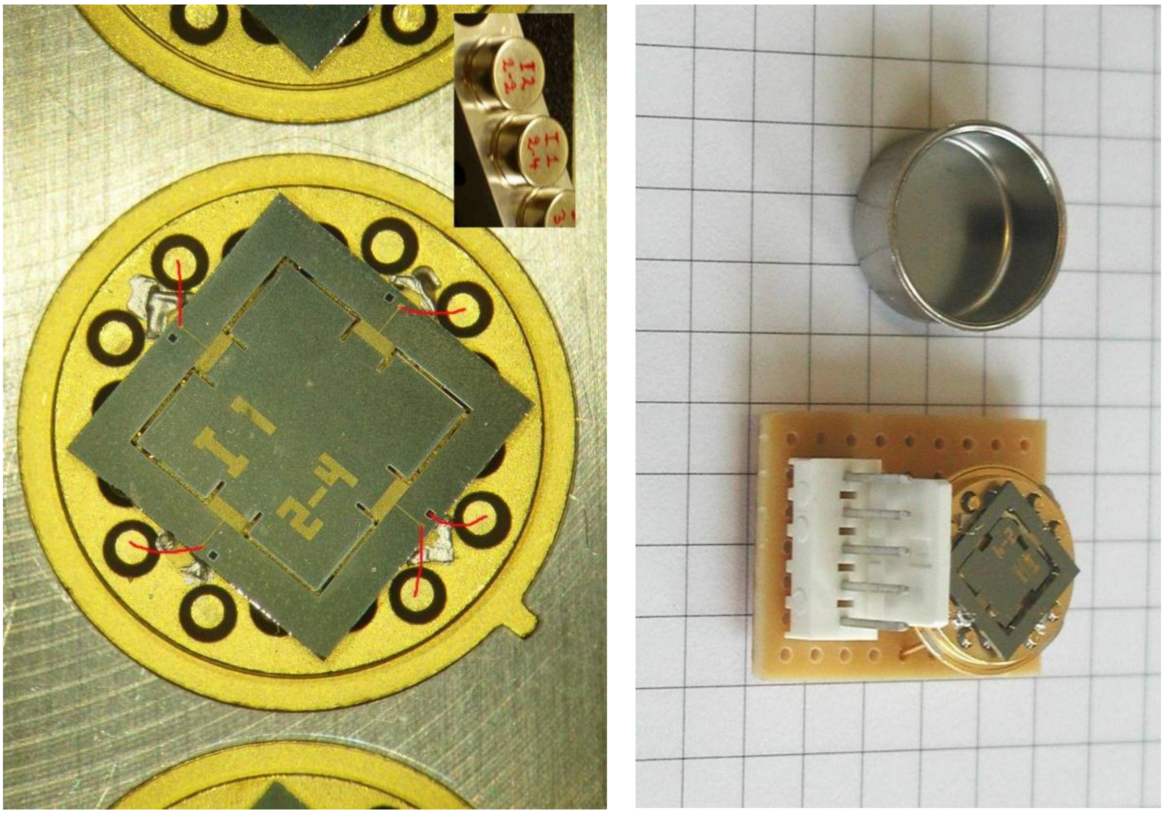
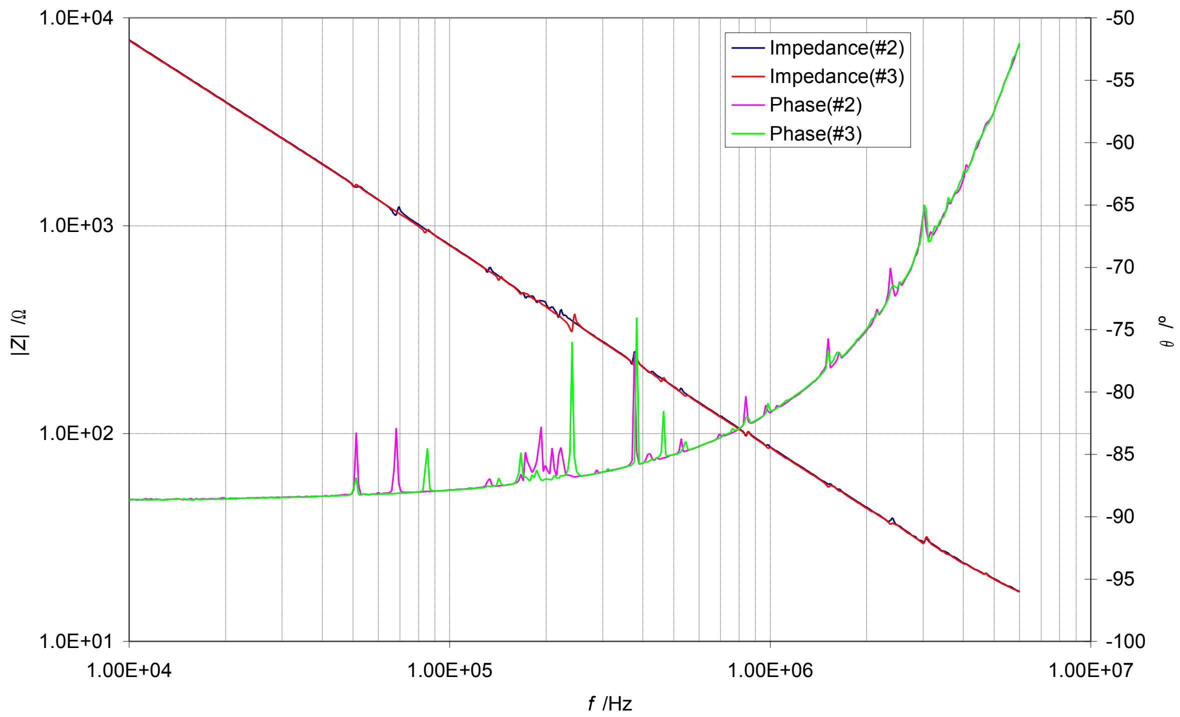


Figure 46: Packaging of the accelerometer. (a) Packaging by Mandalon. A standard TO-8 package is used where five of the 16 pins are connected for the output of the device, as indicated by the red lines. The inset shows 3 devices with the lids on. (b) Mounting on a PCB for vibration measurements on a shaker (discussed in characterisation section). The connector used is a 5-pin Molex header. On the device shown here, the four beams holding the seismic mass broke during mounting.

5.2.3 Poling and characterisation

InSensor received a total of three intact, packaged accelerometers, which were then poled at standard conditions: T = 150 ºC, U = 20 V (i.e., E = 10 kV/mm), t = 10 min. One of these broke during poling (a rattling sound indicated that the seismic mass broke off the four suspending beams). An overview of dielectric measurements is given in Table 8. For many piezoceramic materials, there is a characteristic change in capacitance measured before and after poling, but as seen from Table 8 this seems not to be the case here.

The piezoelectric activity of the two poled accelerometers has been verified by measuring the impedance spectra as seen in Figure 47. The accelerometer chip is a relatively complex mechanical structure and a number of resonances are seen, showing various bending modes. The thickness resonance of the beams (let alone that of the thin films themselves) is not seen by this measurement as the corresponding frequency is well above 100 MHz. As for the low-frequency end it is interesting to note that the behaviour is different for the two accelerometers. Sample I1_2-4 shows some weak resonances in the range 30 kHz to 40 kHz, whereas sample I2_2-2_feb has a more clear resonance close to 50 kHz, but nothing significant below. Also in the frequency range 100 kHz to 1 MHz, there are significant differences between the spectra of the two chips, but the spectra are generally too complex for mapping of the resonance modes. Furthermore, when comparing two beams of the separate accelerometers (especially I1 2-4), there are deviations between resonance frequencies, which seems to indicate some asymmetry in the structures.



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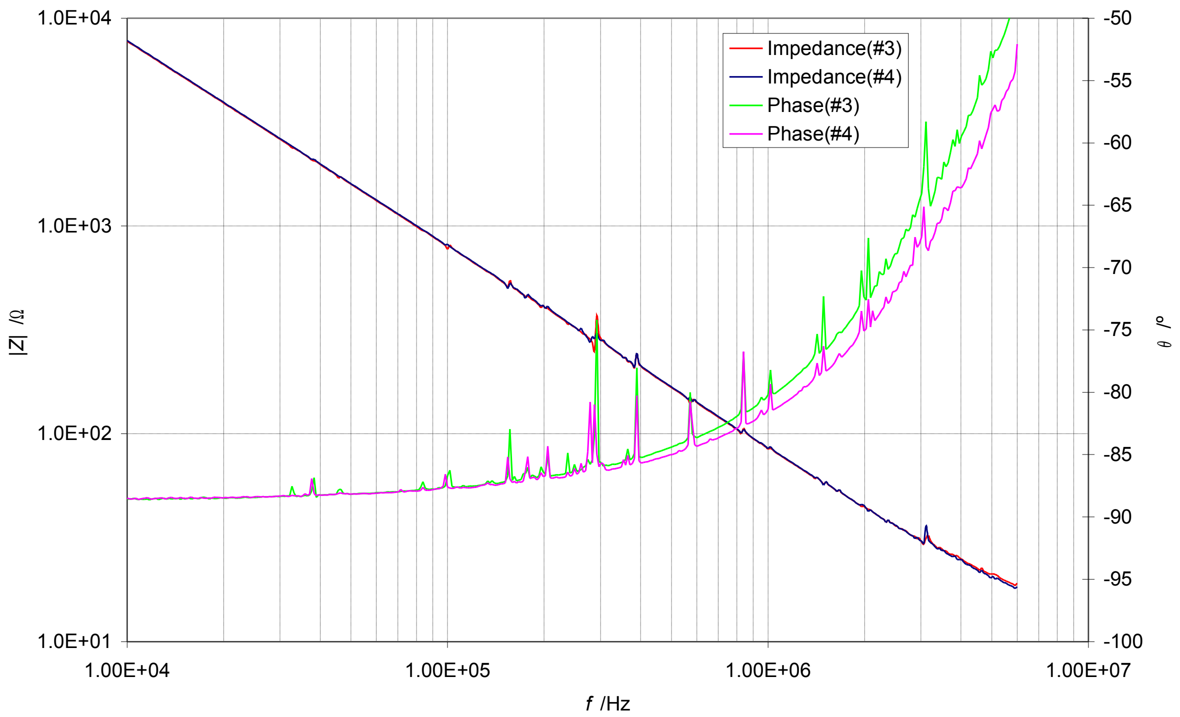

b

Figure 47: Impedance and phase spectra for the poled accelerometers, measured on two different beams for each. (a) Sample I1_2-4. (b) Sample I2_2-2_feb. The resonances (most clearly seen on the phase) is a clear indication of piezoelectricity, i.e. successful poling. Some characteristic differences between the two devices are seen, and even between the beams of each. The apparent increase in phase angle with frequency is a measurement.

ID	C_{unp} (nF)	tan δ	C_{pol} (nF)	tan δ	ΔC
I1_2-4 #1	2.36	0.037	2.34	0.041	-0.8%
#2	2.37	0.036	2.37	0.041	0.0%
#3	2.37	0.036	2.33	0.048	-1.7%
#4	2.35	0.036	2.35	0.040	0.0%
<#1-#4>	2.36	0.04	2.35	0.043	-0.6%
I2_3-2 #1	2.41	0.038			
#2	2.44	0.038			
#3	2.43	0.038			
#4	2.42	0.038			
<#1-#4>	2.43	0.04	0.775		
I2_2-2_feb #1			2.32	0.032	
#2			2.37	0.034	
#3			2.30	0.033	
#4			2.37	0.039	
<#1-#4>			2.34	0.034	

Table 8: Dielectric measurements carried out on the packaged accelerometers before and after poling. #1 to #4 are the output pins connected to each of the four beams. The sample I2_3-2 broke during poling and the sample I2_2-2_feb was not characterised prior to poling.

For measuring the performance of the accelerometers it was necessary to mount the packages on a mechanically stable structure with easy possibility of making electrical connections. InSensor's solution is shown in Figure 46b. Unfortunately, one of the two surviving accelerometers broke in the mounting process, when the lid of the TO-8 package came off. The last device was sent to Vibro-Meter SA, a Swiss manufacturer of accelerometers, for vibration measurements in an industrial shaker set-up. An acceleration level of 5 *g* was used at a frequency of 120 Hz.

The results are listed in Table 9. The sensitivity variation of beams 1, 2 and 4 seems quite acceptable, but the sensitivity for beam No. 3 is ~ 20 % lower than the mean value. According to Vibro-Meter, the general sensitivity of the NORD-Pie thin-film based accelerometer could be sufficient for some commercial applications, depending on other specifications such as maximum temperature of operation. Commercial accelerometers for maximum temperatures up to 300 ºC typically have sensitivities in the range 20 pC/*g* to 100 pC/*g*. The size and especially the thickness of the MEMS accelerometer would be another important competitive parameter, since it could be a very compact device if a dedicated package was developed.

Beam No.	Sensitivity (pC/*g*)
1	13.2
2	13.9
3	9.8
4	12.9
Mean	12.5
Std.dev.	1.6

Table 9: Characterisation of the sensitivity of the packaged accelerometer I2_2-2_feb using a mechanical shaker. The acceleration used was uniaxial and perpendicular to the plane of the chip so the sensitivity of each of the four beams should be nominally the same. Measurement conditions: $a = 5\ g$, $f = 120$ Hz.

5.2.4 Conclusions

Within the relatively short time frame of the NORD-Pie project, it proved possible to make a MEMS accelerometer using PZT thin film and to verify the functionality. For practical reasons and for the sake of comparison, the design was taken with only slight adjustments from a MEMS accelerometer with PZT thick film, and consequently the device was very fragile and not mechanically optimised. Nevertheless, InSensor together with SINTEF and Mandalon managed to get one device all the way through to performance characterisation and the sensitivity proved to be useful if not quite competitive with the state-of-the-art. Unfortunately we did not succeed in the other part of the objective, which was to make similar devices using PZT thick film and to compare the performance. There was a reaction between the thick film and the Si substrate causing very poor adhesion and attempts of adjusting processing conditions or improving the barrier layer were not successful. However, for InSensor it will be quite interesting in the future to compare the NORD-Pie accelerometer with an almost similar one based on PZT thick film.

In the course of the project we have gained a useful insight into SINTEF's SoI-based process for manufacturing MEMS and it was very relevant to get a chance to work on the packaging of the device together with Mandalon. Furthermore, it was quite interesting to meet the other Nordic end-users in the consortium and hopefully it will be possible to continue the collaboration in future project.

As for the development in InSensor's field, the integration of piezoelectric materials in micro-systems will certainly continue. Due to low effective volume of PZT in the thin films used in NORD-Pie, that technology will probably mainly be used for sensing applications. The plans of InSensor are to continue with the thick-film technology, which has certain advantages in terms of technology (simple, in-house deposition), flexibility of geometry (e.g., possibility of curved substrates) and large active volume, making it useful for active applications as well.

5.3 Sonitor: Ultrasonic microphone arrays

Phased array microphones were fabricated by SINTEF using an interdigital top electrode pattern (Figure 48). Five microphones were placed on each die.

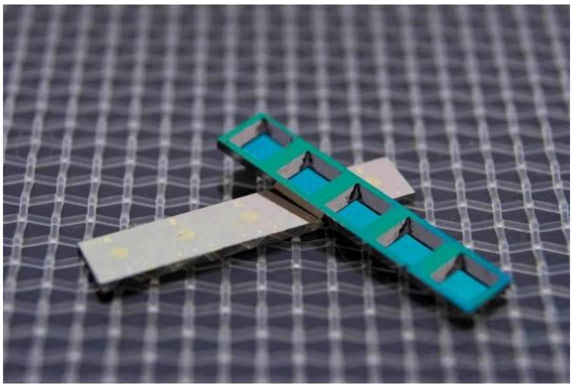


Figure 48: Two phased array microphones prior to mounting (left) and interdigital top electrode pattern (right)

5.3.1 Mounted Microphones

The arrays were mounted on printed circuit boards (PCBs) and contacted by gold wires by Mandalon AB. 11 mounted arrays were prepared. The arrays were aligned parallel or perpendicular to the PCB. This report shows the results from testing of one of them, microphone B1.

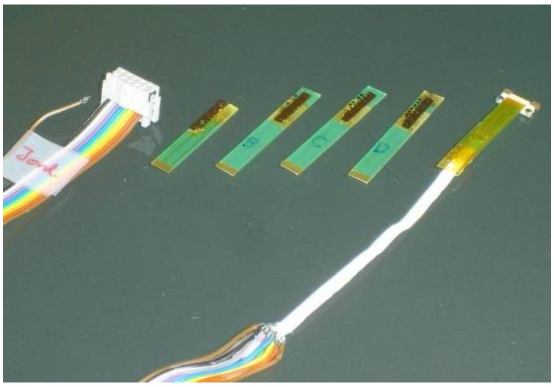
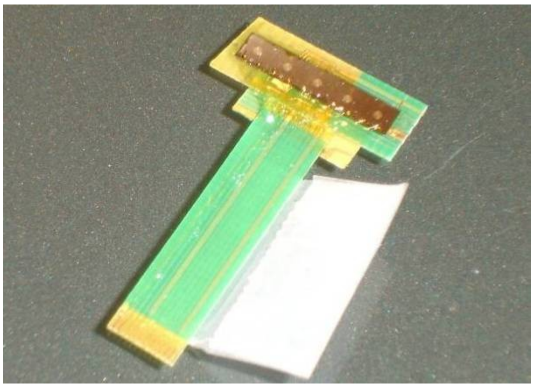

Figure 49: Some of the phased array microphones mounted on PCBs with socket and flat cable for connection (left); sample B1 (right).

5.3.2 Measurements and Results

5.3.2.1 Capacitance

The capacitance was measured for each microphone of array B1 using a conventional multimeter:

Microphone	Capacitance
A-B	0,45 nF
C-D	0,46 nF
E-F	0,46 nF
G-H	0,48 nF
I-J	0,47 nF

5.3.2.2 Poling

The microphones were poled by applying 25 V at 85 °C for 10 minutes. The positive pole of the voltage source was coupled to electrodes B, D, F, H and J.

5.3.2.3 Measurement set-up

The array and a standard Murata MA40S4S piezoelectric ultrasound transducer were placed 143 mm apart and 19,6 degrees off-line in a 16 x 16 x 16 cm^3 chamber with a spongy lining for damping. The box was also fitted with a Brüel & Kjær calibrated microphone for measurement of sound pressure. An 8 V peak-to-peak, 40 kHz sine signal was applied to the transducer.

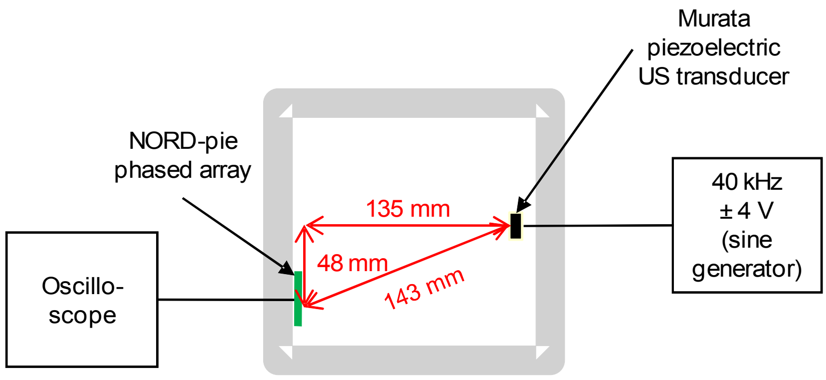

Figure 50: *Measurement set-up*

5.3.2.4 Sound pressure level

A Brüel & Kjær calibrated microphone and amplifier (NEXUS 2690 series) was used to measure the sound pressure at the same location in the box as the array. The sound pressure level (SPL) was **119 dB**, corresponding to **17,8 Pa** according to the relationship:

$$\mathrm{SPL\ (dB)} = 20 \log (P/P_{ref}), \quad P_{ref} = 20 \cdot 10^{-6}\ \mathrm{Pa}$$

5.3.2.5 Reference microphone

An electret condenser microphone from Panasonic (WM-61B) was mounted in the box in the same location as the array and exposed to the same sound pressure. It gave a **77 mV** peak-to-peak signal at 40 kHz.

5.3.3 Results

Peak-to-peak voltages of the signals produced by each microphone were recorded by the oscilloscope. The frequency was adjusted around 40 kHz to obtain maximum performance:

Microphone	Peak-to-peak signal strength mV	Sensitivity mV/Pa
A-B	9,1	0,5
C-D	19,8	1,1
E-F	50,3	2,8
G-H	150,0	8,4
I-J	32,7	1,8
Panasonic WM-61B	77,0	4,3

The frequency response over a broader frequency range was recorded using a Fostex FT17H tweeter as ultrasound emitter. It has a very flat response curve between 5 and 50 kHz.

The middle microphone (E-F) of array B1 was measured. It showed very low sensitivity below 34 kHz and above 43-44 kHz. In these measurements, the sound emitter and the microphone were placed in line.

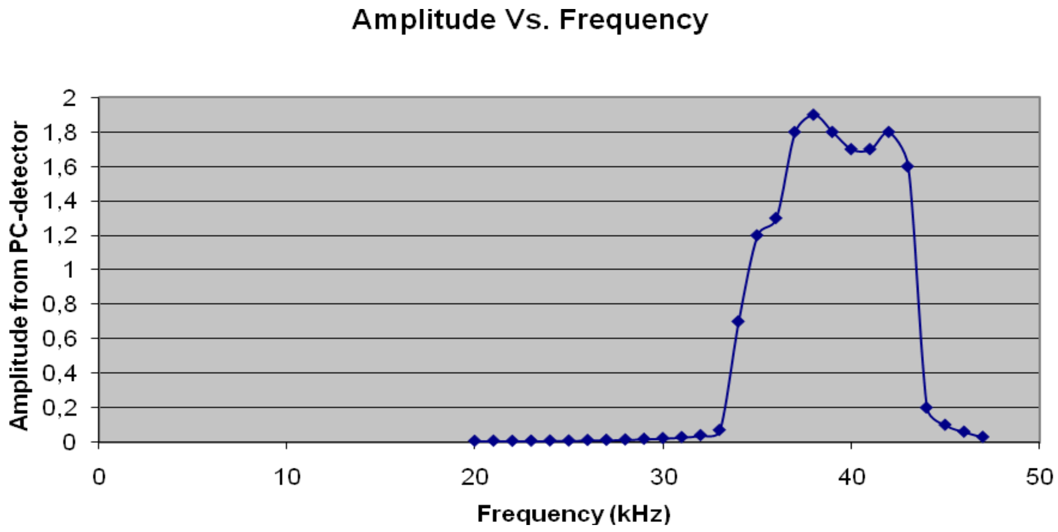

Figure 51: Sensitivity curve for the middle microphone of array B1. The amplitude scale shows arbitrary logarithmic units.

5.3.4 Conclusions

From the results we may draw the following conclusions:

- The microphones showed very high sensitivities in the relevant frequency band. Sensitivity up 8,4 mV/Pa at 40 kHz was observed, which is nearly twice the sensitivity of a standard commercial condenser microphone.
- However, the sensitivity varied considerably between the different microphones.
- The sensitivity was low outside the frequency range 34-44 kHz, which agrees well with the design specifications.

There is a high potential for optimization of the performance, especially to assure similar performance of all the microphones in one array, and of many arrays. It is still unclear whether interdigital top/top-electrodes or conventional top/bottom-electrode configuration will give the best performance.

5.4 Star-Oddi: Ultrasonic transducer array

To be able to use the MEMS sensor in water we covered the connectors with latex material at first and then we closed it with epoxy. To free the sensor from any contact except from water we used a plastic tube. Our setup is shown in Figure 52.

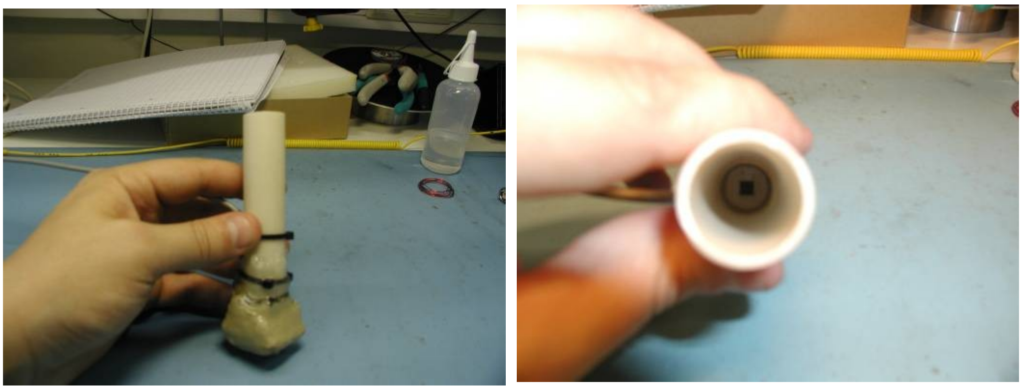

Figure 52: Sealing of the MEMS chip.

To be able to measure ultrasonic wave with the MEMS we produced a wave of 1MHz sinus as a burst and then followed by a silent for a 10mSek. This wave was transmitted as ultrasonic sound wave to the water with a Piezoceramic transducer and then received with the MEMS. The transmitted wave is shown in Figure 53.

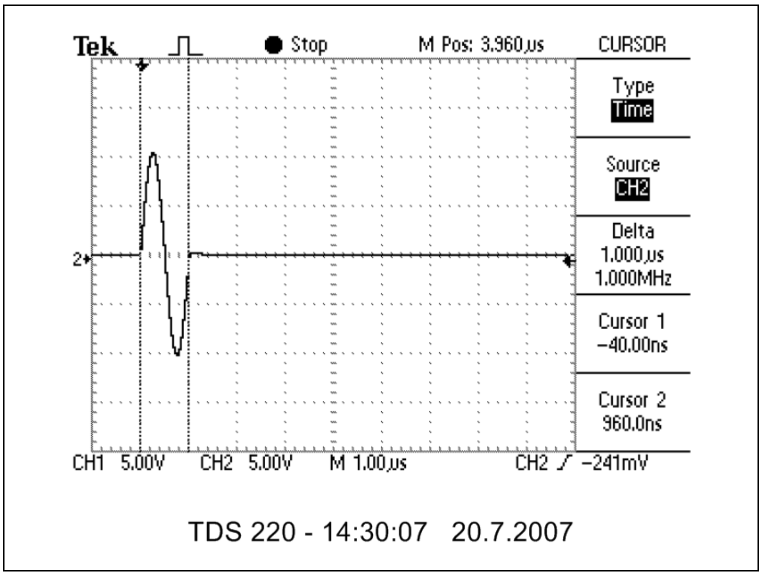

Figure 53: Pulse of a 1MHz burst which was transmitted to the water.

To get as much sensitivity as possible we connected nine of the MEMS sensors together and tried to receive a signal which was sent by the piezoceramic transducer. The MEMS was connected to amplifier giving amplification of 50dB (gain 350 times), the amplifier contained also a band-pass passive filter from 250 kHz to 1 MHz. The distance between the MEMS and the Piezo was approximately 6cm. As seen in Figure 54 the time between signal sent and received is approximately 43 µs which is calculated to be a distance a 6,5 cm, if calculated with the speed of sound in water as 1500m/s, which can be taken as a good result (well with in all tolerances).

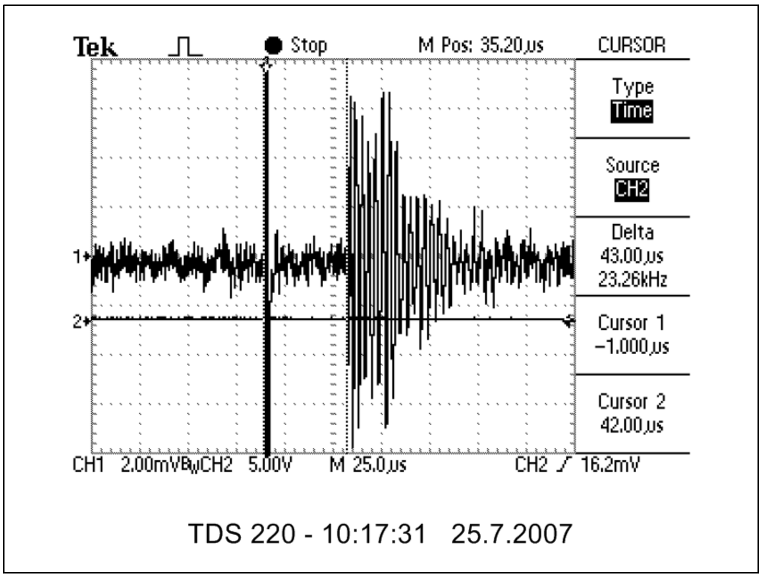

Figure 54: sent signal as channel 2 and received signal as channel 1

5.4.1 Analysis of signal amplitude:

As seen in Figure 54, the amplitude of the received signal is 12-13 mV max and if we look at the fact that we use amplification of 350 times then we can assume that the signal before amplification is approximately 34 µV max. If we compare it to a piezoceramic receiver then we see that the signal received from the MEMS is much lower then for the reference piezo sensor. The received signal with the piezo sensor is shown Figure 55.

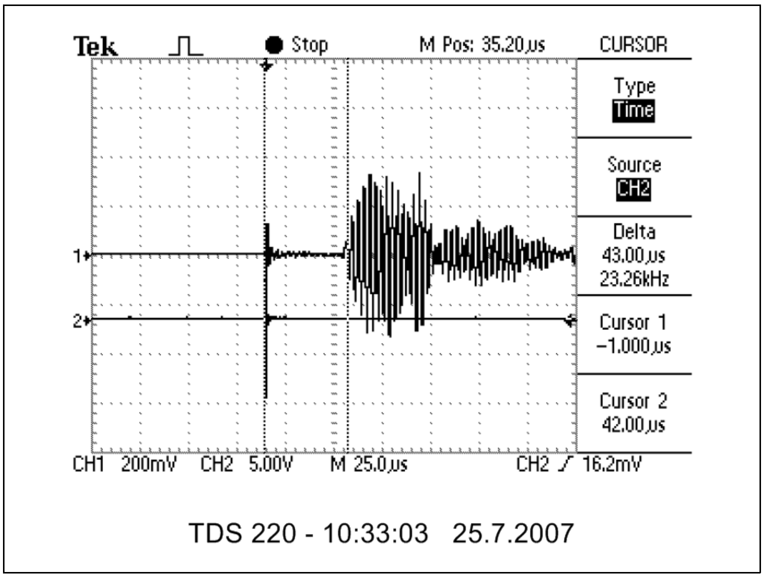

Figure 55: received signal with Piezo at a distance of approximately 6cm.

Max amplitude received with piezo is about 600 mVpp compared to approximately 12mVpp using MEMS. The MEMS needs to be able to transmit with higher ultrasonic power to be able to obtain the same signal level as for piezo sensor.

The Piezo sensor used in this test is shown in Figure 56:.

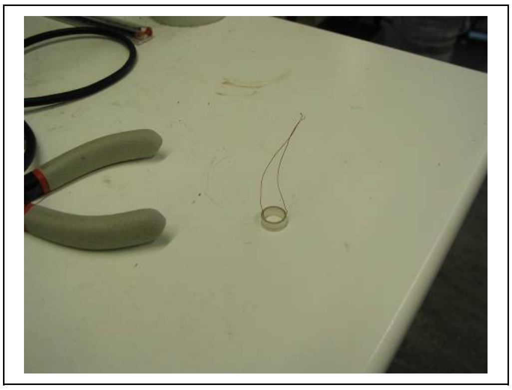

Figure 56: Reference piezo sensor used in test.

Ringing was not observed in the MEMS sensor as was in piezo, which can give opportunities for MEMS sensor. Ringing is a mechanical vibration of the material after signal has been exposed to it and can limit measurements for small distances.

5.4.2 Conclusions

There are advantages and disadvantages compared with existing available solutions with MEMS:

- The MEMS can be used underwater at very small depth for measuring distances, thereby partly fulfilling our target.
    - Receiving sensitivity is lower then for piezo, I still room for development
    - Transmission efficiency is lower then for piezo, the transmitter needs more power for same output signal level compared with piezo, there is still room for development.
    - There is need to develop the sensor so that it can interface to water, especially if the sensor is going to be used under high water or liquid pressure.
- The MEMS does not seem to have so called mechanical ringing in transmission, which might make it possible for the MEMS to measure, with high precision, very short distances or small movements.

With further improvements, the MEMS can likely me modified to operate underwater for receiving and transmitting acoustic signals under depth.

6. Conclusion and recommendations

NORD-pie has increased the awareness and competence of both the industry partners and the packaging partner regarding piezoelectric MEMS. Several of the partners have decided to continue the development of the device fabricated for them in NORD-pie. This is a very positive outcome and, if successful, Nordic Industry will be very early out in utilizing piezoelectric MEMS in commercial products.

The project has carried out feasibility studies of 4 different types of devices that were identified as interesting for the industry partners. Of these, 3 industry partners have explicitly communicated that piezoelectric MEMS technology has proved to be very viable for their product range and will carry out additional investigations and developments after the project. Likely by means of more targeted projects. The prototyping and fabrication service at SINTEF will be an important tool in this process.

A design handbook for fabrication of piezoelectric MEMS has been developed, describing the process steps, design rules, design guidelines and tolerances. The design handbook can be obtained by any interested party by signing a non-disclosure agreement. The NORD-pie process can either be based on a single silicon wafer, or be expanded to also include bonding of patterned glass wafers to the silicon wafer.

The NORD-pie process is also included as an add-on (mixed technology) to microBUILDER[28] that has a special focus on microfludic systems (Figure 1). This service has partners such as Tronics[29] and SensoNor[30] which already offer well known multi-project-wafer (MPW) fabrication of non-piezoelectric MEMS. These companies can guide any requests for piezoelectric technology to the NORD-pie process and will greatly improve the publicity of the process. The microBUILDER design handbook, which contains the NORD-pie design handbook, can be requested at the microBUILDER web page.

The company COVENTOR[31] will in cooperation with SINTEF provide a process access module for SINTEF's piezoelectric thin film process (MoveMEMS) in their MEMS design and modelling software. This means that the technology will be implemented in commercial software, which will generate significant publicity and increase the awareness in industry about the application possibilities.

[28] microBUILDER, (www.microbuilder.org)
[29] Tronics, (www.tronics.eu)
[30] Infineon Technologies SensoNor, (www.sensonor.no)
[31] COVENTOR, (www.coventor.com)

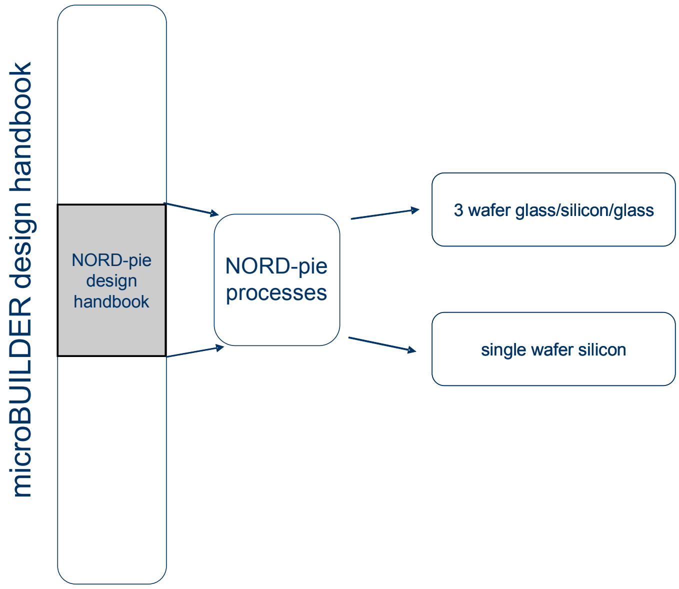

Figure 57: Relationship between the NORD-pie and microBUILDER design handbooks.

The network within piezoelectrics in the Nordic countries has in recent years largely been concentrated to the EU FP5 thematic network POLECER[32] and the EU FP6 Network of excellence MIND.[33] Even though this have strengthened the networks towards Europe, the inter-Nordic connections have after our understanding been fewer. This is particularly true in the field piezoelectric MEMS. NORD-pie has contributed to establish a network in this field in the Nordic countries as well, bringing together industry and research institutes.
The NORD-pie partners have also been invited to join SINTEF in two FP7 project proposals.

The awareness of the project and the technology has been increased by a strong dissemination activity:

- A project flyer that has been distributed at conferences
- A web page that summarizes the project.[34]
- 1 newspaper article.[35]
- 1 article to be published mstnews.[36]
- 1 company visit
- 2 workshops on piezoelectric MEMS was arranged.[37,38]
- An invited conference talk.[39]
- An invited talk at local pMUT/CMUT seminar, Oslo 2007
- Dissemination of project results at the conference Electroceramics XI.[40]

[32] POLECER-network, *European Thematic Network on Polar Electroceramics, FP5, G5RT-CT-2001-05024* (www.polecer.rwth-aachen.de).
[33] MIND FP6 NoE, (www.mind-noe.org)
[34] NORD-pie web page (www.sintef.no/nord-pie)
[35] Kaleva (http://www.kaleva.fi/plus/index.cfm?j=667801)
[36] mstnews (www.mstnews.de)
[37] “Piezoelectric and magnetostrictive MEMS – from the laboratory to production”, Oslo December 8th 2006
[38] “Piezoelectric MEMS”, Copenhagen May 21-22 2008
[39] International Conference on Chemical Solution Deposition, Berchtesgaden, Germany June 2007 (http://www.iwe.rwth-aachen.de/iefs/)
[40] Electroceramics XI, Manchester, UK, September 2008, (http://www.electroceramics11.co.uk/)

The market for microsystems-enabled products is expected to grow rapidly over the coming decade, with some forecasts projecting growth rates similar to those seen in the microelectronics industry in the past decades. We expect that piezoelectric MEMS will be part of this growth.
Due to the complexity of design and fabrication of piezoelectric MEMS it is crucial to have successfully established a platform technology that combines design, high-performance piezoelectric materials, integration and packaging, with a capability of making prototypes. The technology must also be accessible to relevant companies, including start-ups and SMEs. We believe that we have come a long way towards reaching this goal through the NORD-pie project.

Accessibility will render piezoelectrics as a major technology also for MEMS. As piezoelectric materials now also become included in design tools new ideas and designs will trigger more and more activity in this area, both in larger companies and individuals wanting to make a start-up.

Nordic Innovation Centre

Nordic Innovation Centre

Nordic Innovation Centre (NICe) is an institution under the Nordic Council of Ministers facilitating sustainable growth in the Nordic economies.

Our mission is to stimulate innovation, remove barriers and build relations through Nordic cooperation. We encourage innovation in all sectors, build transnational relationships, and contribute to a borderless Nordic business region.

We work with private and public stakeholders to create and coordinate initiatives which help Nordic businesses become more innovative and competitive.

Nordic Innovation Centre is located in Oslo, but has projects and partners in all the Nordic countries.

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