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PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential , only for members of the consortium (including the Commission Services)	

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Author(s)		
Name	**Organisation**	**E-mail**
Aurélie Cruau	COV	acruau@coventor.com
Gerold Schropfer	COV	gschropfer@coventor.com

Abstract

This document presents three application notes on the usage of Coventor software tools for piezoMEMS design and modelling. First application note describes an energy harvester. The second one deals with a piezoelectrically actuated piston micromirror. Both devices are studied with the complete set of tools ranging from system-level design (MEMS+) to verification with finite element analysis (Coventorware). The third application note describes the use of virtual fabrication techniques applied to an ultrasonic transducer and microphone based on the Coventor's tool SEMulator3D.

Public introduction[1]

This document presents three application notes on the usage of Coventor software tools for piezoMEMS design and modelling. First application note describes an energy harvester. The second one deals with a piezoelectrically actuated piston micromirror. Both devices are studied with the complete set of tools ranging from system-level design (MEMS+) to verification with finite element analysis (Coventorware). The third application note describes the use of virtual fabrication techniques applied to an ultrasonic transducer and microphone based on the Coventor's tool SEMulator3D.

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

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1 PIEZOELECTRIC VIBRATORY ENERGY HARVESTER DESIGN AND SIMULATION

MEMS Energy harvesters show great potential to provide almost perpetual power to small systems. Applications span the medical, consumer electronics, automotive and environmental market. Examples include Tire Pressure Monitors, ID tags and Wireless Sensor Networks (WSN). WSN, such as the one shown below are of particular interest for in-situ environmental, health and habit monitoring, where batteries are hard (or impossible) to replace.

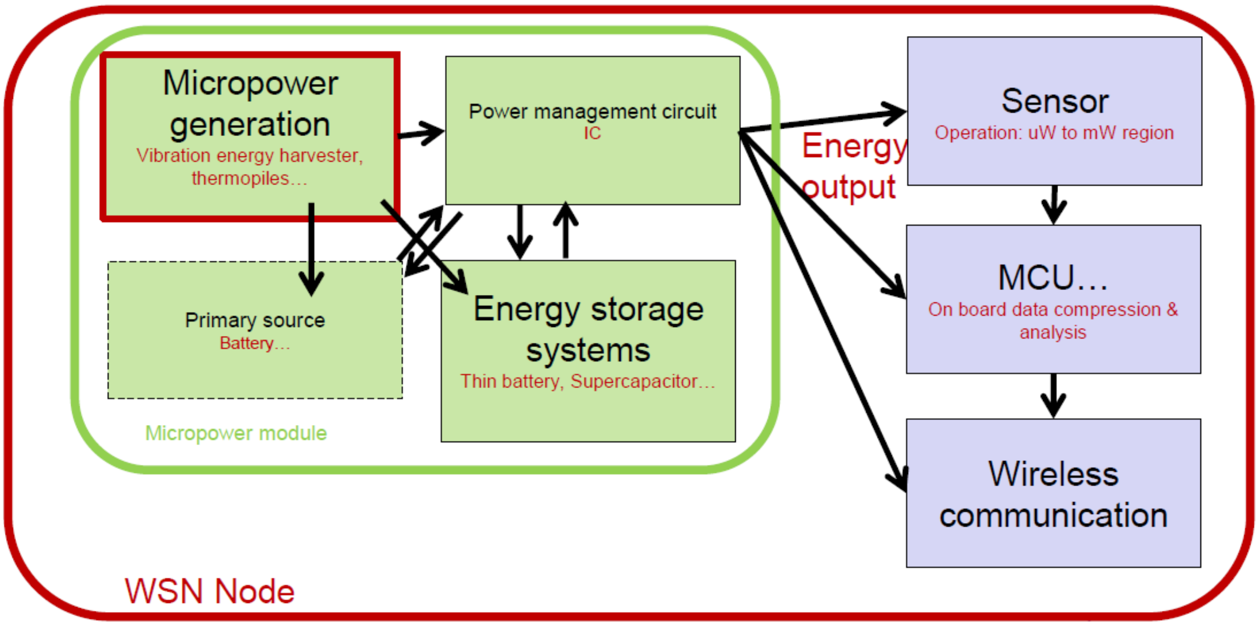


Figure 1.1 A typical WSN node (Yole Development, dMEMS Conference April 2012)

Among the family of harvesters available, the piezoelectric vibratory energy harvester is one of the most promising technologies, due to the power level generated and the ease of integration with the surrounding system. To be successful, Engineers have to offer innovative solutions to address the design of the harvester and surrounding systems and circuits, whilst avoiding time-consuming build and test methodologies.

1.1 Design Challenges

Three key criteria that need to be considered when designing a piezoelectric energy harvester are the frequency of operation, power generated and power transferred to the management circuit. The frequency of operation can be obtained running a standard Finite Element Analysis. However, the power generated and transferred to the storage system is highly dependent on the power management circuit. This means that a design platform capable of simulating both coupled piezo-mechanics and electronics is mandatory in order to simulate and optimize the complete design.

1.2 New Hybrid-Design Methodology

1.2.1 Rapid MEMS Design Exploration

Using Coventor's MEMS design flow shown in Figure 1.2 Coventor Design Flow for Energy Harvesters, a foundry technology comprising material and process data is first defined. A Design Kit for piezoMEMS (MoveMEMS PZT technology from SINTEF) is provided together with the MEMS+ platform. More information on the PZT technology is available via the piezoMEMS Competence Center, www.piezomicrosystems.com.

Next a model of the piezoelectric vibratory harvester is constructed in MEMS+. Here, the MEMS designer works in a 3D graphical environment to assemble a parametric model using high-order MEMS-specific finite elements (piezo-mechanical shells). Each element is linked to the process description and material database so that piezoelectric material properties and electrodes are assigned automatically. The high-order elements give a precise mathematical description of the device physics using a low number of degrees of freedom. This enables rapid, accurate simulation of the device physics in Matlab/Simulink, and the ability to easily co-simulate the device with the conditioning circuit in Cadence Virtuoso. Furthermore, by using high-order finite elements, there is no need to generate reduced order models from FEA and/or analytical equations.

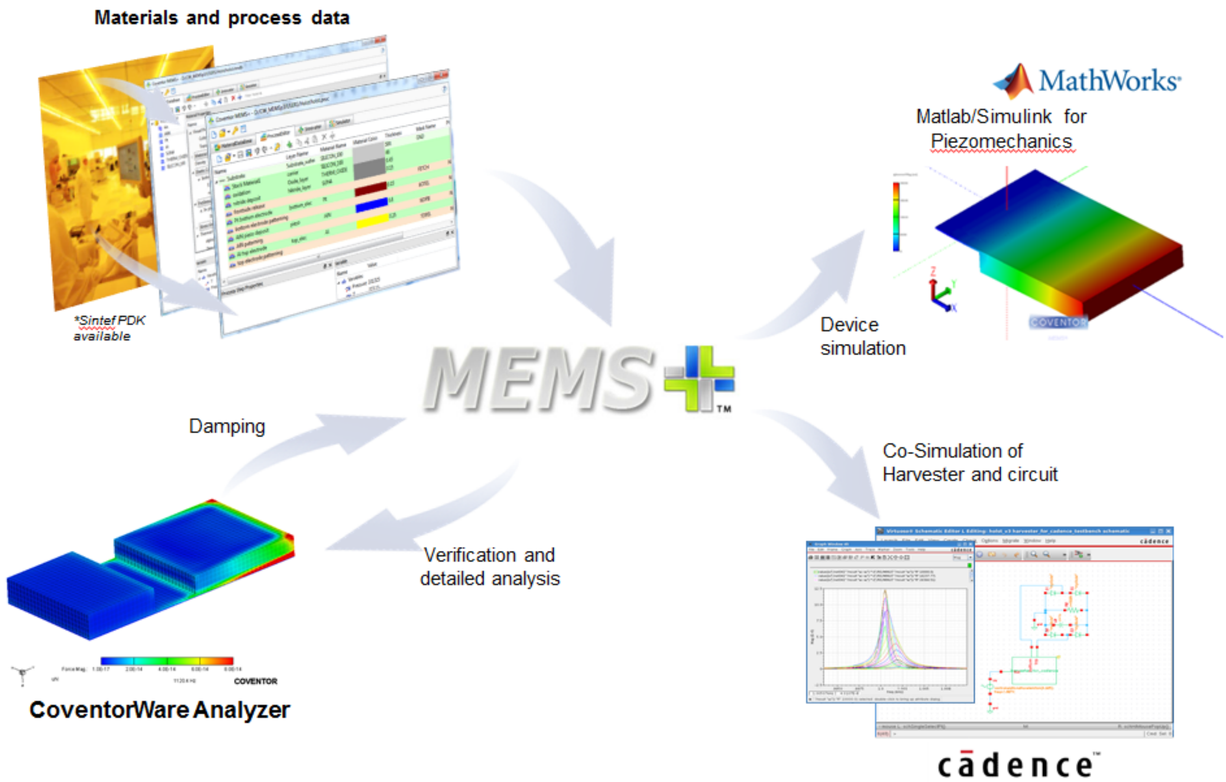


Figure 1.2 Coventor Design Flow for Energy Harvesters

1.2.2 Power Management and Circuit Design with Cadence

To model the harvester together with the conditioning circuit, the harvester model is imported directly from MEMS+ into Cadence Virtuoso. Electronic components are then added from the Cadence electronics libraries to complete the design. Both the harvester design parameters and circuit parameters can then be selected to attain an optimum device performance. For example, the designer can tune the harvester dimensions and resistive load to attain a maximum power transfer from the harvester to the conditioning circuit. Different circuits can be also simulated to compare the performance of each type.

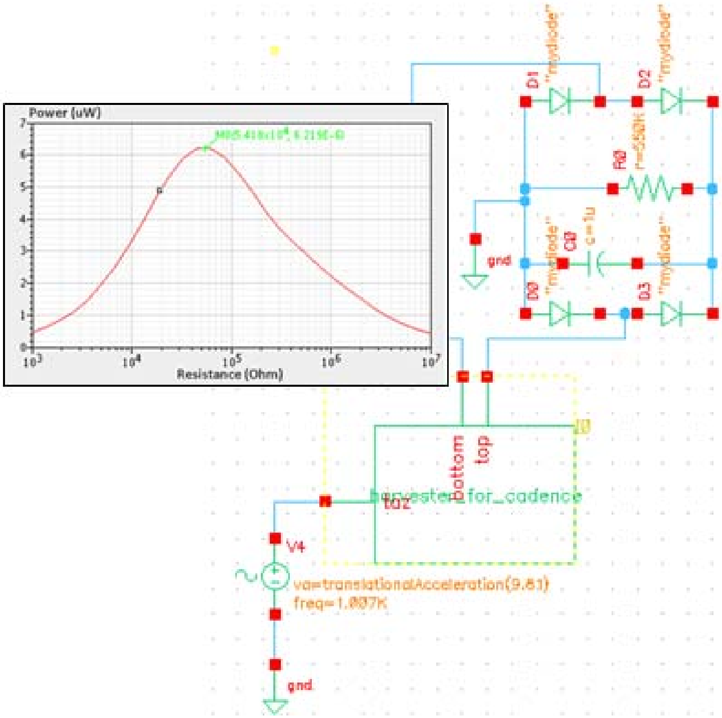


Figure 1.3 Cadence Virtuoso circuit and Spectre analysis with a graph showing power transferred to the bridge load-resistor with resistor value

1.2.3 Design Refinement and Validation with FEM/BEM solvers

Further detailed modeling can be undertaken using CoventorWare's field solvers to investigate details of the design. For example, the design can be checked for high stress areas that may lead to breakage when the device is overloaded due a shock. Gas damping coefficients can also be simulated and included in the MEMS+ model to accurately predict the Q-factor. An additional benefit is that simulation results from MEMS+ and CoventorWare can be verified against each other. Simulating piezoelectric harmonic analysis with a linear resistive load is one such example of a point of comparison between both tools.

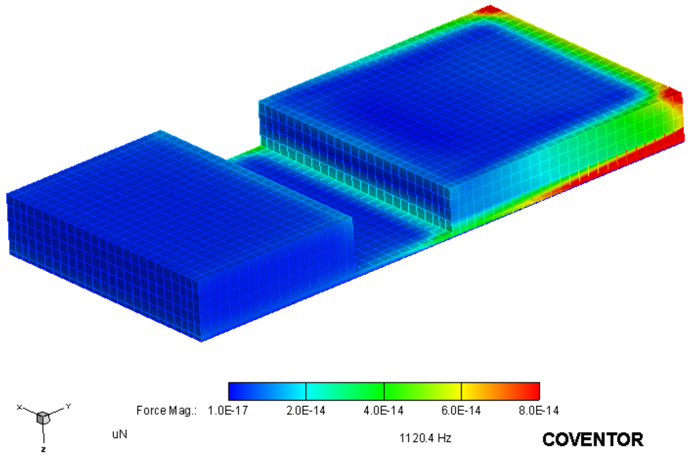


Figure 1.4 Simulation in CoventorWare Analyzer showing air damping forces acting on the vibrating harvester.

1.3 A Complete Platform

Coventor's solution for piezoelectric energy harvesting combines MEMS+ and CoventorWare to provide hybrid solution that solves the coupled and multi-domain physics not addressed with traditional point tools. This hybrid approach is has several advantages. First, it allows the co-design and co-simulation of harvesting device *and* conditioning circuit together. Second, as the models are parametric, rapid exploration of design and process changes can be immediately realized to optimize the system. Third, there is no need to create reduced-order models from FEA data and/or analytical expressions, a process which is typically time consuming and prone to error.

Utilizing a platform that integrates with best-in-class simulators like Cadence Spectre and/or Matlab/Simulink provides designers the best combination of accuracy and capacity. As Cadence and the Mathworks make speed and capacity improvements to their algorithms, these get automatically multiplied by the additional algorithm improvements and functionality made by Coventor.

1.4 More details and Contact

www.coventor.com
www.piezomicrosystems.com

2 PIEZOELECTRIC PISTON MICROMIRROR

Infrared absorption spectroscopy is well established in gas analysis. Today's systems require a set of different narrow bandpass filters to match the characteristic absorption bands and get a broad measurement channel. The increasing demand in collecting more and more spectral information, reducing cross sensitivities, making measurements faster and all this with tiny systems makes the MEMS spectrometer a challenging technology. In this family of devices, piston type micro mirrors integrated into Fabry Perot interferometers are promising. They can include tunable cavities enabling wide wavelength ranges thanks to large deflections of one movable mirror.

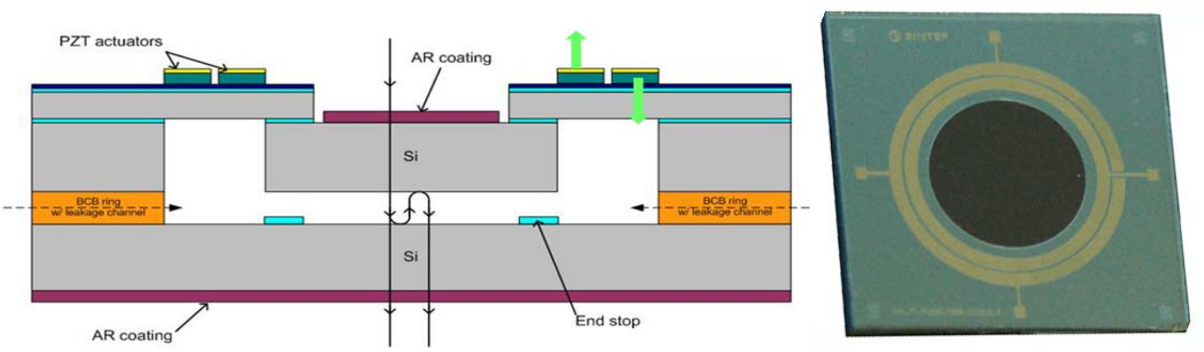


Figure 2.1 Tunable Fabry Perot interferometer cross section and piston mirror fabricated with MoveMEMS technology.

Piezoelectric actuators provide the advantages of long stroke at low voltages combined with low power consumption. Furthermore the large forces generated by the piezoelectric film make the structure stiffer and more robust while the crystal silicon surface of the mirror has very good planarity. The known limiting factor for the widespread use of piezoelectric actuators was the availability of high-quality thin films which can be monolithically integrated with silicon MEMS. Thanks to a new high-quality lead-zirconate-titanate (PZT) technology provided by the piezoMEMS Competence Center, www.piezomicrosystems.com, thin film providing large electromechanical coupling compatible with large volume manufacturing is available.
Other potential applications for this type piezoelectrically actuated micromirrors are laser beam steering or Fourier transform infrared spectroscopy (FTIR).

2.1 Design Challenges

The device studied here has been made using this PZT technology called MoveMEMS developed by SINTEF. The design of **Error! Reference source not found.** has a double stroke capability as two top ring electrodes are used to actuate up and down the central mirror. The important parameter for the mirror is the maximum deflection obtained with a minimum actuation voltage.

2.2 New Hybrid Design Methodology

2.2.1 Rapid MEMS Design Exploration

The first step in Coventor's MEMS design flow is to define a foundry technology comprising material and process data. We provide a specific design kit for piezoMEMS (MoveMEMS PZT technology from SINTEF) together with the MEMS+ platform.
Once the technology chosen, the design is made in the 3D graphical environment to quickly assemble a parametric model of the piston micromirror using high-order shell elements which includes mechanical and piezoelectric physics. When adding the elements, the layers are selected from the process and the stack of a piezoelectric material between two conductive ones is recognized. The high-order elements give a precise mathematical description of the device physics using a low number of degrees of freedom. This enables rapid, accurate simulation of the device physics.

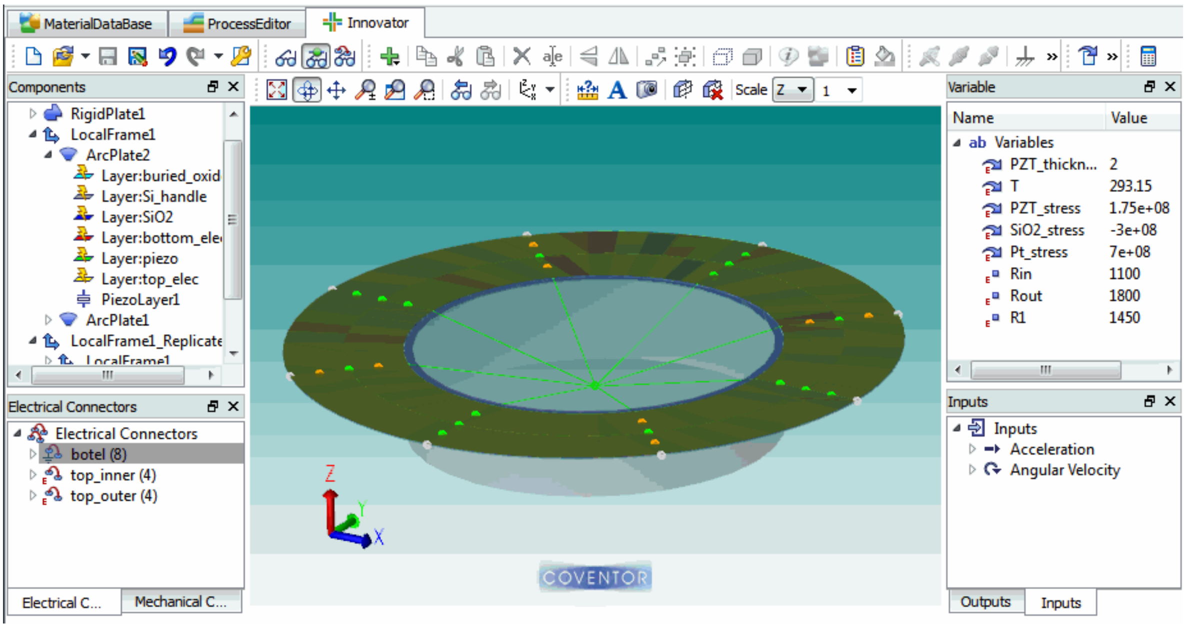


Figure 2.2 MEMS+ modelling of the PIMP mirror showing parameters on the top right and composition in the components tree on the left.

The model uses shells for piezoelectric outer and inner rings, and a rigid plate for the central mirror made of the substrate silicon. Shells are made of the piezoelectric stack (Pt - PZT - Au) and the silicon handling stack (oxide - Si - oxide). The number of connectors can be adjusted in the angular and radial directions to improve the precision of the model.

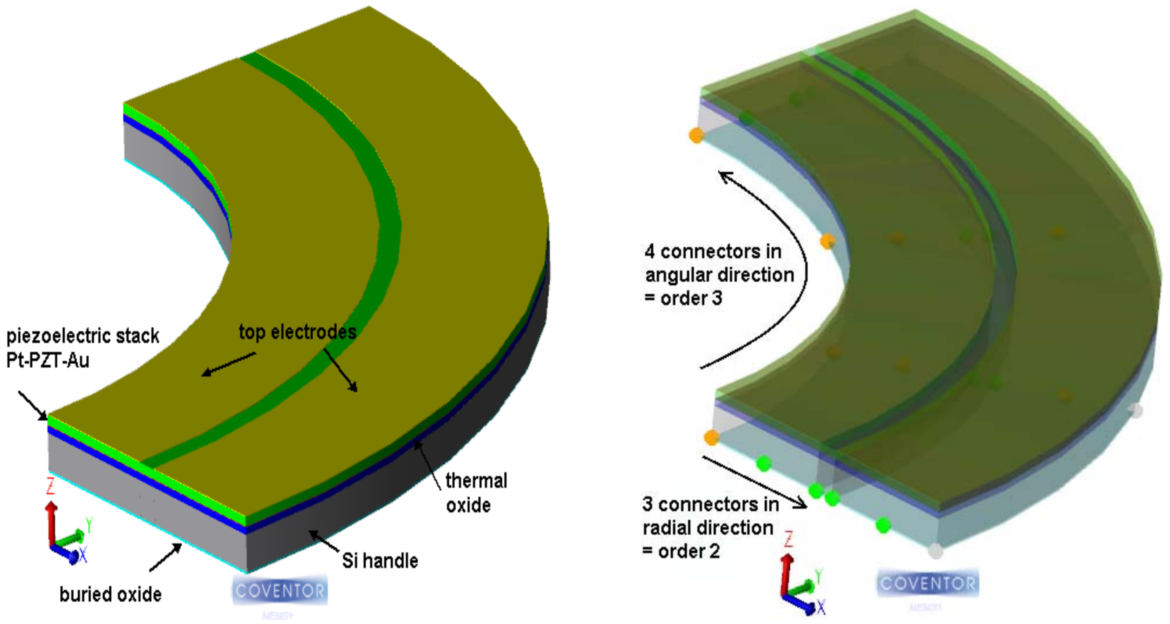


Figure 2.3 Quarter of the membrane actuating the mirror and meshing of mechanical connectors for a quarter.

2.2.2 Device optimization with established CAD tools

In traditional design flow the MEMS design is either split from the circuit design and combination of both is checked at the prototyping step at the high risk of loss of performances, or the MEMS model is reduced to be integrated with system or circuit CAD tools at the cost of uncertainties and unattended behavior.

MEMS+ model is integrated to Cadence or Mathworks established solvers. When creating a control circuit in Virtuoso or system in Simulink the MEMS block imported from MEMS+ is part of the netlist which runs into Spectre or Matlab. Its parameters, as well as the circuit relevant ones can be tuned to find an optimum for the maximum deflection and establish the best MEMS mirror dimensions. Simulation results are then visible into MEMS+ platform like the one given below:

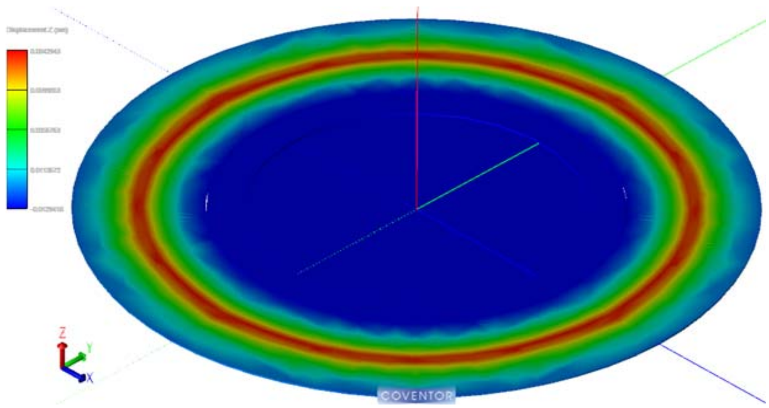


Figure 2.4 Deformation of the membrane due to residual stress simulated in Spectre with the MEMS+ model of the piston micromirror.

With the parameterized models created in MEMS+ platform, tuning can be done on parameters to explore device behavior and find optimum values. In the example below, the influence of residual stress value in the PZT layer on the deflection. Minimum stress is preferred for maximizing displacement.

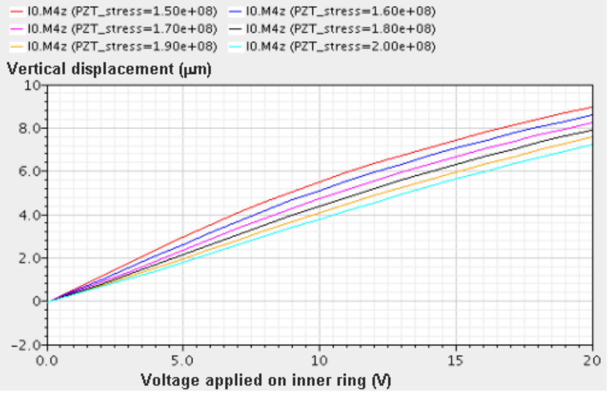


Figure 2.5 Deflection vs Voltage for PZT layer stresses from 150 MPa to 200 MPa.

2.2.3 Verification and Refinement with FEM-BEM solvers

To validate the results given by the MEMS+Cadence simulations, CoventorWare field solvers are used to model a more detailed 3D device including design tails and check assumptions for system modeling match FEA. Running piezoelectric mechanical analysis is a way to get a point of comparison between both tools inside the same platform. As shown below, results from FEA are comparable to MEMS+ simulations which validate the simplification made on the electrodes shape.

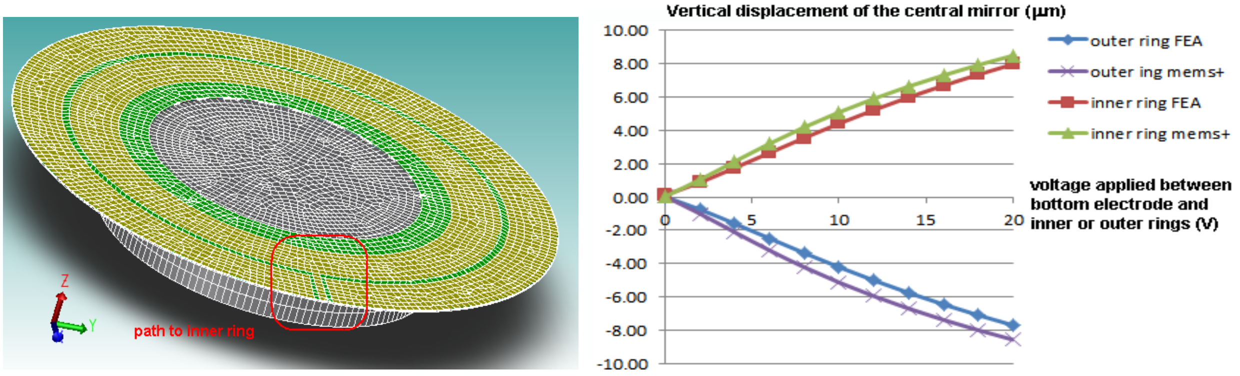


Figure 2.6 FE mirror mirror with real electrode design and mirror deflection with voltage.

2.3 A complete platform

Coventor solution for piezoelectric piston micromirror combine its two simulation tools, MEMS+ and CoventorWare, to get the most accurate results with a reasonable designer time and energy consumption.

This hybrid approach enable first to quickly design a piezoMEMS based micromirror by optimizing directly the device considering the technological constraints but also the different options available through design modifications and parameters tuning. The level of refinement is then increased to have a deeper understanding of side effects or to model more realistic systems.

Using this platform a company benefits from established and regularly improved simulators with broad application range as Cadence Spectre or Matlab/Simulink and Coventor's expertise in MEMS design with MEMS+ and CoventorWare.

2.3.1 Reference

1 A novel Ultra-planar, long-stroke, and low-voltage piezoelectric micromirror, T. Bakke, A. Vogl, O. Zero, F. Tyholdt,I-R. Johansen, D. Wang, Journal of Micromechanics and Microengineering, V20, N 6, 2010

2.4 More details and Contact

www.coventor.com
www.piezomicrosystems.com

3 PIEZOMEMS VIRTUAL FABRICATION

Virtual fabrication with SEMulator3D enables visualization of complex MEMS structures and process flows. This tool addresses realistic versus ideal geometry approaches to process development. It can accurately and quickly model a manufacturing process and effects of modifications. This enables fast validation of process assumptions, and visualization of the complex interrelationship of design and process.
The rapid evolution of MEMS applications places significant constraints on MEMS technology development. There is tremendous pressure to accelerate process development to keep pace with current demand while also innovating for the next generation. The ability to model new process flows, verify designs, and document process decisions with SEMulator3D offers a compelling advantage for process engineers facing these challenges.

3.1 Process development

Process engineers often know what to expect from a single deposit or etch step and can predict its effect on device geometry. But when known steps are combined into novel sequences, the final geometry can be hard to predict. With SEMulator3D, engineers can emulate new process sequences step-by-step and capture critical information about interactions between steps without running costly test wafer runs.

3.2 Design Verification

MEMS manufacturing design rules are typically enforced using 2D design rule checks (DRC) on the device layout. However, some types of design and layout mistakes are not obvious in two dimensions, making it difficult to fully verify manufacturability and device performance. With SEMulator3D, engineers can catch these mistakes before building test wafers with virtual manufacturing test runs to verify that a device design is compatible with the manufacturing process.

3.3 Documentation

Documenting processes with cross sections that are hand drawn is difficult and labor-intensive to maintain, especially when process changes require them to be completely re-drawn. SEMulator3D uses smart automation techniques that enable faster, more efficient creation of process documentation. Because SEMulator3D understands the process sequence, changing a deposit thickness or etch depth takes just a few mouse clicks.

3.4 SEMulator3D flow description

SEMulator3D takes into account the 2D geometry dimensions given by a GDSII layout, materials and process flow information stored in the process description when automatically building the model. The build takes just minutes. Its engine uses a unique, voxel-based modeling approach. A voxel is a 3D pixel, by specifying its size the user choose the spatial resolution of the resulting model.

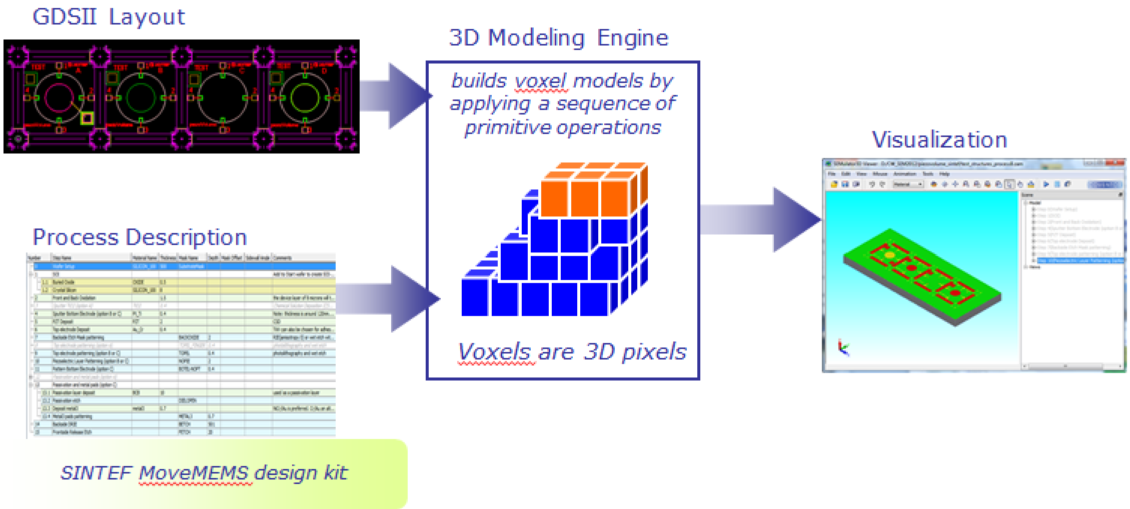


Figure 3.1 SEMulator3D flow

This 3D model can be visualized in SEMulator3D's Viewer, which allows the user to view complex structures, to rotate, zoom, pan, scale and slice the model to better visualize and eventually verify and optimize the design as well as the process flow. More options allow viewing electrical and mechanical connectivity, taking precise measurements, creating dynamic/interactive cross sections, creating animations, and even more.

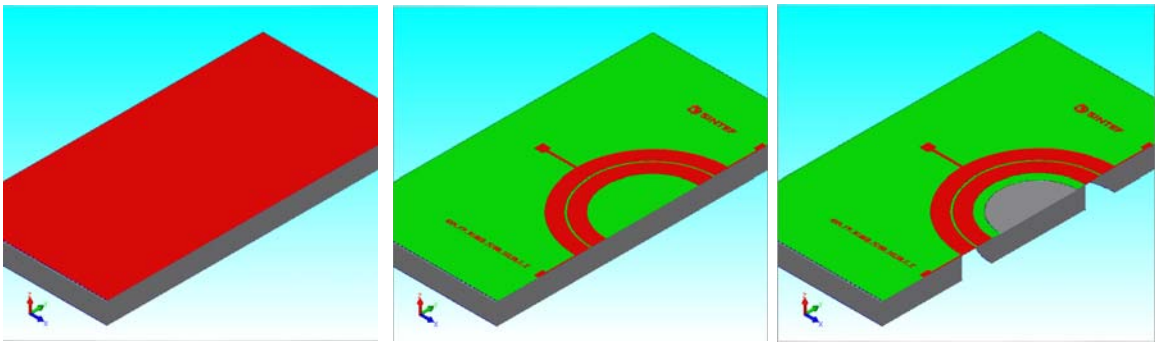


Figure 3.2 Animated gif of the fabrication of the piston micromirror of section 2

3.5 Virtual Fabrication of piezomems demonstrators

The examples demonstrated here are ultrasonic transducers and microphones fabricated with SINTEF MoveMEMS Technology for piezoMEMS.
The process uses a Silicon On Insulator wafer oxidized as a substrate for the piezoelectric stack deposit. This stack is done with Platinium bottom electrode, PZT for the piezoelectric material and a gold electrode on top. After all deposit the layers are etched to pattern the piezomems device.

The models can be viewed as 3D objects which can be manipulated thanks to the SEMulator3D reader downloadable immediately from the page:
http://www.coventor.com/products/semulator3d/semulator3d-reader/
This tool allows devices and process information sharing with control on what is published and what is kept confidential.

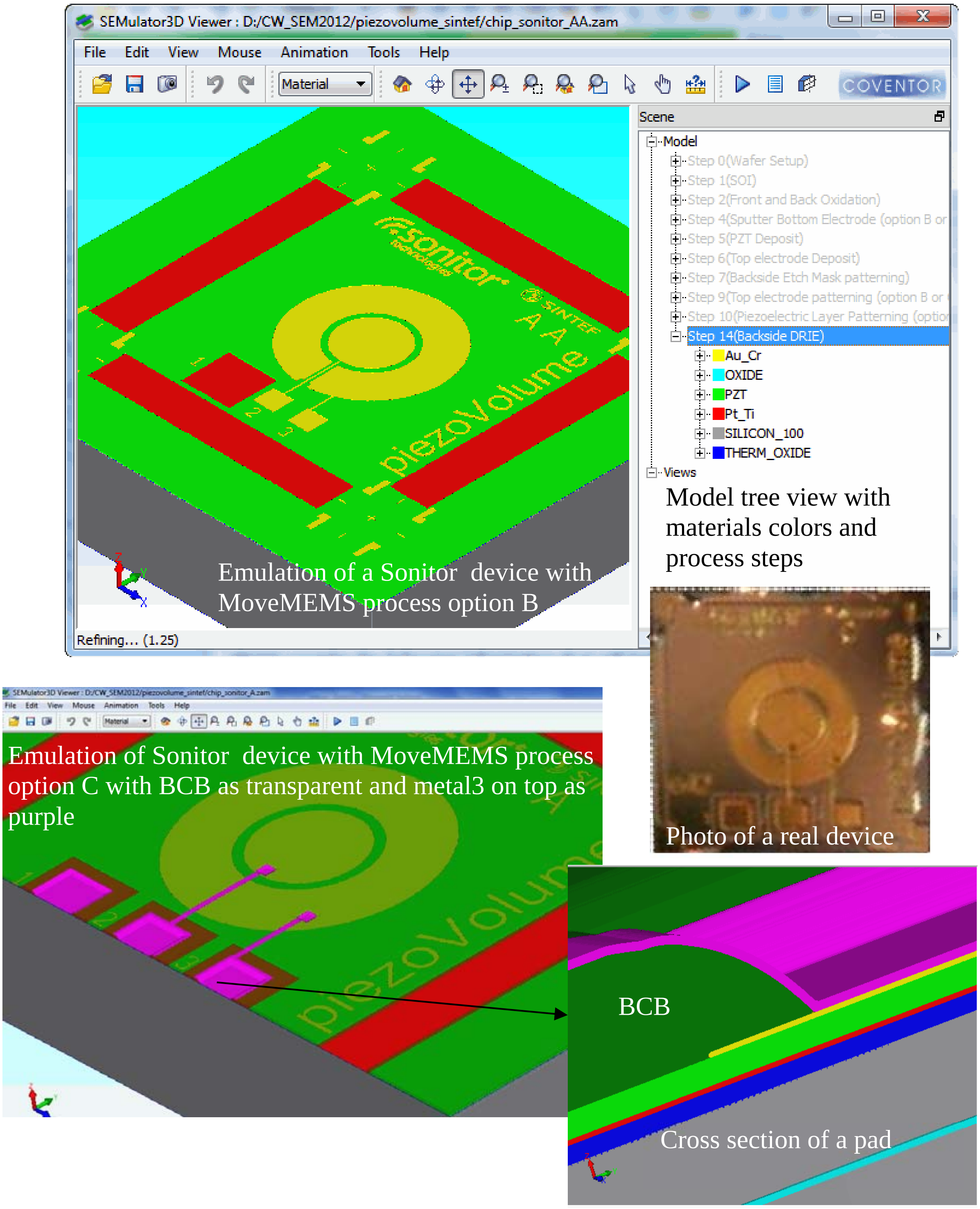
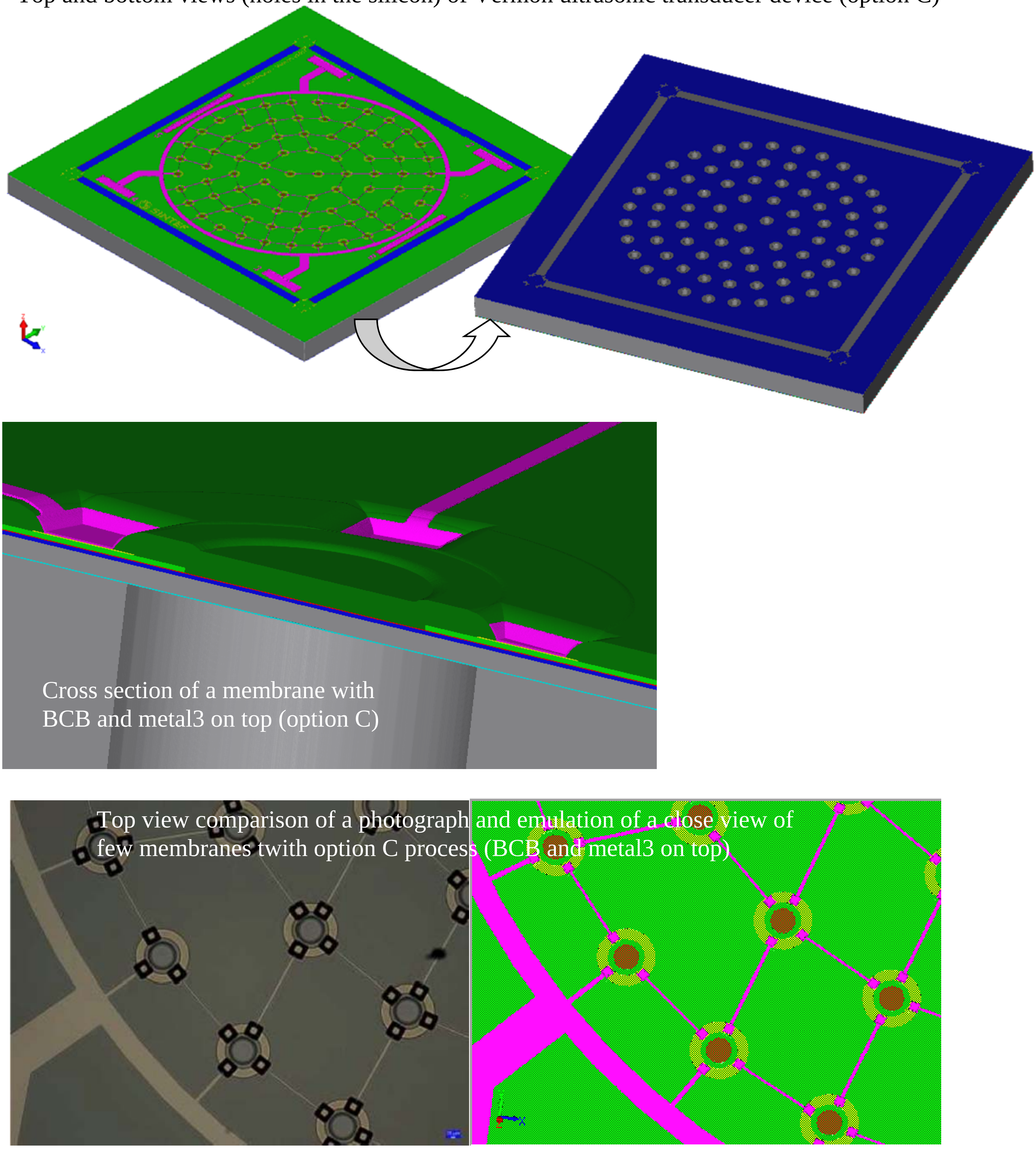


Figure 3.3 Different views of microphone devices from Sonitor made with SINTEF Movemems technology

Top and bottom views (holes in the silicon) of Vermon ultrasonic transducer device (option C)



Cross section of a membrane with BCB and metal3 on top (option C)

Top view comparison of a photograph and emulation of a close view of few membranes twith option C process (BCB and metal3 on top)

Figure 3.4 Ultrasonic transducer from Vermon generated by SEMulator3D with different views and comparison to photograph

3.6 More details and Contact

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