High volume piezoelectric thin film production process for microsystems

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SINTEF
Background

- Small and medium companies/Universities have ideas where PZT thin film technology is needed
  - But, often no means to develop/produce piezoMEMS

- Companies are looking for high volume solutions
  - Prototyping
  - Deposition
  - Fabrication

- Reliable deposition/fabrication solutions will increase the interest in piezoMEMS technology even more
FP7 piezoVolume (2010 – 2012)
High volume piezoelectric thin film production process for microsystems
5,14 M€ project

- PZT thin film deposition tools and procedures
  - Automated chemical solution deposition tool
  - Sputtering tool

- Fabrication procedures
  - In-line quality monitoring tools
  - piezoMEMS device fabrication procedures (wafer level)

- Packaging and integration with electronics

- End piezoMEMS product

Bottlenecks:
- Bottleneck 1: High volume PZT deposition
- Bottleneck 2: In-situ quality control
- Bottleneck 3: Design tools
"Dear cleanroom manager. I want to process PZT in your lab"
piezoMEMS design and fabrication rules

- Tool integration in lab
  - CMOS compatibility can be obtained

- Material specifications and design guidelines
  - Material parameters
  - Design guidelines and process limitations
  - Basic definition of lithographic masks

- Most of it public
The piezoVolume base processes

- Starting point: Silicon-on-insulator wafer (SOI)
- Backside opening by wet etch
- Pt bottom electrode by sputtering
- Piezoelectric layer by CSD, sputtering or PLD
- Au/Cr top electrode by vapour deposition and lift off patterning
- Patterning of piezoelectric layer by wet etch
- Back side cavity by wet etch
- Release by reactive ion etch

3 electrode configurations

- Standard
- Interdigital
- Cross-routing enabled
piezoMEMS specific design and modelling tools

- **Lower entrance barrier** and become productive more quickly, focusing on your MEMS design instead of your software
- Develop MEMS devices at a **lower cost**
- Efficiently design new MEMS products, moving them quickly from development into production
- Rapidly **explore and optimize** design and process options
- **Adapt** existing designs and processes to new markets
- Efficiently accommodate customer-requested **design changes**
- **Save fab cycles** during development and improve yield
piezoMEMS specific design and modelling tools

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**Key Features**
- 3D parametric library of standard (piezo)MEMS components
- Integration with traditional ICs and MEMS
- Integration with FEM software
- Material parameters included in process design kit (PDK)

See poster P10
piezoMEMS design platform – MEMS+
CoventorWare

- Complete software with 4 main packages
  - Architect3D
    - behavioural modelling
  - Designer
    - process specific design
    - Export of litho masks
  - Analyzer
    - FEM modelling
    - Visualization
  - Integrator
    - Extraction of linear/non-linear behavioural models
Virtual manufacturing of piezoMEMS – SEMulator3D

- 2D masks + description of fabrication process to create a voxel based 3D solid model.

- **Save Money** by finding problems before fabrication.
- **Enhance communication** with highly detailed, interactive 3D models.
- **Reduce time-to-market** and gain a competitive advantage.
- **Improve documentation** and reduce document creation effort.
- **Enhance Yield** through improved design rules and defect modelling.
piezoMEMS process design kit (pdk)

- Design Kits for SINTEF MoveMEMS PZT-based process including:
  - Material Databases storing relevant physical properties of materials meaningful for simulation and/or virtual fabrication
  - Process files describing the major fabrication steps stack
  - Implemented and documented in the latest releases of COV tools.
Software tutorials

Energy Harvester design in **CoventorWare**
Step by step manual

Energy Harvester design in **MEMS+**
Advanced user manual

Cantilever virtual fabrication in **SEMulator3D**
Slide show and live exercises

**Tutorial Overview**

**Exercise 1: Technology creation**
- how to use a design kit

**Exercise 2: Design in Innovator**
- how to parameterized dimensions
- how to create the 3D MEMS with components
- how to connect components
- How to define boundary conditions

**Exercise 3: Simulations in Cadence**
- how to run a modal analysis
- how to run a DC sweep
- how to build a circuit around the MEMS and run harmonic simulations

All materials are available for distribution
Deposition of PZT thin films in 2008-2009

<table>
<thead>
<tr>
<th>Method</th>
<th>$-e_{31,f}$ [C/m²]</th>
<th>Relative permittivity, $e_r$</th>
<th>Dissipation factor, tan $\delta$</th>
<th>Main bottleneck for high volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSD</td>
<td>12-18</td>
<td>1100-1600</td>
<td>~0.03</td>
<td>Throughput</td>
</tr>
<tr>
<td>Sputtering</td>
<td>-4-10</td>
<td>700-900</td>
<td></td>
<td>Quality</td>
</tr>
</tbody>
</table>

- **CSD:** High quality, throughput must be ensured by automation

- **Sputtering:**
  - Multi target DC reactive sputtering: low throughput
  - Single oxide target RF sputtering: higher throughput, but still too low quality
Deposition of PZT thin films in 2011

<table>
<thead>
<tr>
<th>Method</th>
<th>$\varepsilon_{31,f}$ [C/m²]</th>
<th>Relative permittivity, $\varepsilon_r$</th>
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</thead>
<tbody>
<tr>
<td>CSD</td>
<td>&gt;14</td>
<td>1100-1600</td>
<td>-0.03</td>
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<tr>
<td>Sputtering</td>
<td>&gt;14</td>
<td>700-1400</td>
<td>-0.03</td>
</tr>
<tr>
<td>PLD</td>
<td>&gt;14</td>
<td>same</td>
<td>same</td>
</tr>
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</table>

Status PiezoMEMS 2011:
- $\varepsilon_{31,f}$ jumping up.
- Very high influence from measurement and poling procedure

A new standard for characterization of PZT thin films is needed
Deposition tools – sputtering

- New hot chuck sputtering add-on for Oerlikon’s Clusterline 200 II for in-situ sputtering of PZT

- Throughput goal
  - 3.6 wafers/h·μm (60 nm/min) on 200 mm wafers

- Performance goal
  - $e_{31,f} \approx -14$ C/m²
  - Thickness uniformity < ± 5%
Sputtering – progress on 150 mm

- $d_{33,f} = 100 \text{ pm/V}$
- $e_{31,f} = -7 \text{ C/m}^2$ after poling for 20 min at 150 °C under a field of 170 kV/cm
Sputtering – progress on 150 mm

\[ \varepsilon = 1500 \]
\[ e_{31,f} = -7 \text{ C/m}^2 \]
Sputtering – progress on 150 mm

Ar = 60 sccm
2100 nm

2.09 μm

1 μm
Properties of sputtered PZT on 200 mm

![Graph showing properties of sputtered PZT](image)

**e31,f measurement (ISIT)**

<table>
<thead>
<tr>
<th></th>
<th>ISIT-Pt</th>
<th>OER-Pt sample</th>
<th>OER-PtTiO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>e31,f</td>
<td>11.8</td>
<td>13.8</td>
<td>17.6</td>
</tr>
</tbody>
</table>

**d33,f measurement (aixACCT)**

<table>
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<th>ISIT-Pt</th>
<th>OER-Pt sample</th>
<th>OER-PtTiO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>d33,f</td>
<td>99</td>
<td>101</td>
<td>121</td>
</tr>
</tbody>
</table>
Sputtered PZT on bufferlayer for IDT electrodes

- Fresh result from last week
- $e_{\text{IDE}} = 7 \text{ C/m}^2$  See poster P6
Deposition tools – CSD

- Adaptation of Solar-semi cluster coater tool
- Throughput goal
  - 4 wafers/h μm on 200 mm wafers (67 nm/min)
- Performance goal
  - $e_{31,f} \sim -14 \text{ C/m}^2$
  - Thickness uniformity < ± 5 %
PZT deposition – CSD PZT quality

- Device run finished now in Sept. 2011
  - 2 μm PZT is 99.8% (001) oriented on Pt electrode
    - ICSD #90700 as reference
  - Rocking curve of PZT 001 with FWHM of only 3.6 degrees.
  - PZT deposited on insulating buffer layer for interdigital electrodes

- New CSD processes
  - Thicker coating layers
  - Crystallization down to 500 - 550 °C

- New RTP process developed to accommodate increased thermal masses of thick wafers
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Improved orientation

Increased stress

Cracking
CSD PZT – lowering crystallization temperature

![Graph showing intensity vs. 2θ (°) for different PZT orientations and solutions]
Automatic CSD tool development

Rotating covered chuck and media arm

Wafer on chuck with media arm
Coater module

• **Dynamic Balanced System** (Patent pending)
  – eliminates substrate vibration, for best uniformity and process control

• **RTTC Features**
  – Solvent saturated atmosphere
  – No turbulence around the substrate
  – Eliminates rotational corner effects
  – No contamination on the rotating cover from coating solution
  – Self cleaning basic-chuck by “Venturi”-effect
  – Chuck rotation after closing rotating cover
  – 100 % sealed process chamber assures best coating uniformity
  – Cover plate laminated with Teflon to keep away external particles
Spin-coating-module incl. RCCT

Rotating Covered Chuck Technology

- Media arm
- Inlay
- Basic chuck
- Process bowl
- Lift pins
- Rotating cover
- Wafer handling Booster
- Process bowl rinsing
How to do quality monitoring?

<table>
<thead>
<tr>
<th>Method</th>
<th>Information retrieved</th>
<th>Suitability for high volume piezo thin film quality monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-situ XRD</td>
<td>Structure/texture/morphology</td>
<td>No 1:1 correlation between e.g. rocking curve and piezoelectric performance</td>
</tr>
<tr>
<td>Ellipsometry</td>
<td>Thickness/refractive index</td>
<td>Only thickness</td>
</tr>
<tr>
<td>Electromechanical</td>
<td>Piezoelectric coefficients/(\varepsilon_r)</td>
<td>Wafer must be processed to extract the coefficients</td>
</tr>
</tbody>
</table>
In-line quality monitoring

• Indirect estimation of $e_{31,f}$ from $d_{33,f}$ and $\varepsilon$
  – Needed resolution for thin films <10 pm
  – Laser interferometry

• Accuracy
  – Better than 4% of real $e_{31,f}$

• Throughput
  – 10 wafers/h

• Automation of measurements through electrode mask layout
  – Parameter/coefficient tracking
Measurement stage

- DBLI/SBLI automatic change between both modes automatically
- Air damping and active damping system have been evaluated according to vibration environments
- Design of the machine according to semi standard
New chuck design allows to switch easily between 150 mm and 200 mm wafers
Measurement software
piezoVolume end users

- **Sonitor**
  - Microphones for ultrasonic indoor positioning

- **Océ Technologies**
  - Ink jets

- **VERMON**
  - pMUT for medical ultrasound
piezoMEMS processing

- Océ ink-jets
- Sonitor microphones (Interdigital electrodes)
- Vermon pMUT device
piezoMEMS devices – dielectric insulation and cross routing

- Patternable dielectric layer
  - Reduction of stray capacitances
  - Enable cross routing

Standard design

Design enabling routing over dielectric
2D micromirror for laser beam scanning

- Static tilt possible (non-resonant)
- High frequency (~10kHz)
- Planar (~10nm peak-to-valley)

Thor Bakke et al., SINTEF MiNaLab
piezoMEMS competence centre

- The competence centre aims to act as contact point for interested parties and covers the whole production process for piezoelectric microsystems
  - Long experience
  - Experienced project partner

- Deposition process and tools for high-performance PZT thin films on silicon wafers
- Modelling software specifically for piezoMEMS
- Modelling of device ideas and design assistance
- Evaluation of alternative processing routes
- Testing services and sophisticated testing equipment
- Manufacturing of prototypes
- Small scale production using 150 mm wafers (now) and 200 mm wafers (soon)
Project status

• Project started Jan 1st 2010

• Modelling tools
  – piezoMEMS PDK for Coventorware available from COVENTOR
  – Further developments in 2011 – 2012

• Deposition tools
  – Very promising results. Much more to come in 2011 – 2012

• In-line quality monitoring tool
  – Tool qualification finished
  – Further developments in 2011 – 2012
Check status at www.piezovolume.com
Acknowledgements

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Thank you!