Industrial fabrication of piezoMEMS

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SINTEF
Outline

Background
- Current market situation
- Current situation regarding fabrication

What is needed for up-scaling of piezoMEMS fabrication
- Modeling
- Fabrication
- Tailored quality monitoring for piezoelectric thin films

Conclusions
Current market situation – AlN

- Several commercial actors use AlN for GHz filters
  - TDK-EPC (EPCOS)
- Filters main market for AlN but several other markets emerge. e.g.:
  - FBAR biosensors
  - Energy harvesting
- Production of AlN piezoMEMS is integrated into existing MEMS labs
  - Deposition by sputtering
  - AlN is CMOS compatible
  - Some MEMS foundries offer AlN
Current market situation – PZT

- Some large companies are working with PZT piezoMEMS
  - Ink-jet print heads
  - High frequency ultrasonic transducers (medical)

- Small and medium companies/Universities have ideas where piezoelectric PZT technology is needed
  - Need access to PZT based piezoMEMS foundry

- Companies are looking for high volume production solutions for PZT
  - Prototyping
  - Deposition
  - Fabrication
How can my company access piezoMEMS production technology?

• Low volumes (prototyping)
• Production
Current situation regarding low volume prototyping

In Europe there are a few Universities/Institutes that offer piezoMEMS feasibility studies:

- Cranfield University (UK), PZT
- SINTEF (NO), PZT
- EPFL (CH), AlN and PZT (research)
- Fraunhofer ISIT, AlN (DE)
- IMEC, AlN (BE)

Only SINTEF has a predefined process with design guidelines and fabrication procedure (moveMEMS)

Multi-project piezoMEMS wafer from SINTEF
There are 3 main bottlenecks for high volume fabrication:

- **High volume deposition**
  - AlN process already commercial (sputtering)
  - Commercial PZT process being developed now (2010)

- **Quality monitoring tool (piezoelectric coefficient)**
  - being developed in 2010

- **piezoMEMS design and modelling tools (+procedures)**
  - being developed in 2010
A piezoMEMS high volume fabrication process

Design handbook

piezoMEMS design software

Thin film deposition tools and procedures

Automated chemical solution deposition

Sputtering

Bottleneck 3
Design and modelling software

Bottleneck 1
High volume deposition process

Bottleneck 2
In-situ quality control

Fabrication procedures

In-line quality monitoring

piezoMEMS device fabrication procedures (wafer level)

Packaging and integration with electronics

End piezoMEMS product
AlN piezoMEMS

- The deposition process for AlN has been commercial for several years.
  - Big companies have it in-house (FBAR filters)

- Not so much focus on AlN piezoMEMS for actuation (low $e_{31,f}$). Mostly sensing.
  - MFI (http://www.memsfoundry.de)
  - IMEC (www.imec.be)
  - EPFL (lc.epfl.ch) (research)

- Some use ZnO as well, but AlN has similar properties.
The moveMEMS process (PZT)

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
- Au/Cr top electrode layer
- PZT or AlN piezoelectric ceramic
- Pt/Ti bottom electrode layer
- SiO₂
- Si

Release etch of piezoMEMS wafers
Material specifications and design guidelines

- Material parameters
- Design guidelines and process limitations
- Definition of lithographic masks
piezoMEMS modelling tool

- 3D parametric library of standard piezoMEMS components
- Integration with FEM software
- Material parameters included in process design kit (PDK)

Process emulation (virtual manufacturing)
- 2D masks + description of fabrication process to create a voxel based 3D solid model.

Virtual manufacturing
- **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.

*Virtual manufacturing of MEMS bond pads and comb drive. Courtesy X-FAB Semiconductor Foundries, AG.*
Process design kit (PDK)

- A Library of process emulation files (*.proc) define foundry-specific processes

- Material property database (*.mpd) provides process-specific values associated with materials

- Layout template file (*.cat, *.gds) contains geometric and process descriptions for pre-defined MEMS elements

- Library of parametric and non-parametric elements support schematic and physical design (optional)

- Link to design handbooks including validated MEMS design rules, detailed process information and design case studies are available upon request

Process Flow of the piezoVolume PZT process represented in CoventorWare
Coventor architect and designer

3D model of piezoelectric cantilever in MoveMEMS PZT

- Piezoelectric actuators and sensors included (SINTEF moveMEMS) from version 2008.010

ZOOM: MoveMEMS PZT layers

PZT plate model for schematic design
Implementation in CoventorWare

<table>
<thead>
<tr>
<th>Number</th>
<th>Step Name</th>
<th>Layer Name</th>
<th>Material Name</th>
<th>Thickness</th>
<th>Mask Name</th>
<th>Photore sist</th>
<th>Depth</th>
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<td>0</td>
<td>Substrate</td>
<td>Substrate_Wafer</td>
<td>SILICON_100</td>
<td>300</td>
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<td>Silicon-On-Insulator (SOI)</td>
<td>Burred_Oxide</td>
<td>SI02</td>
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<td>1.1</td>
<td>Thermal Oxidation</td>
<td>Si(Handle)</td>
<td>SILICON_100</td>
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<td>2</td>
<td>Wet Oxidation</td>
<td>Oxide_layer</td>
<td>SI02</td>
<td>1.5</td>
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<td>3</td>
<td>Oxide Etch Backside</td>
<td>BETCH</td>
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<td>Oxide Etch Fronside</td>
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<td>Sputtering Bottom Electrode</td>
<td>Bottom_electrode</td>
<td>PI_Ti</td>
<td>0.12</td>
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<td>6</td>
<td>PZT Chemical Solution Deposition</td>
<td>PZT_piezoelectric</td>
<td>CSD_PZT</td>
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<td>7</td>
<td>Lift-off Top Electrode</td>
<td>Top_electrode</td>
<td>Au_Gr</td>
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<td></td>
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<tr>
<td>7.1</td>
<td>Metal Deposition</td>
<td>Top_electrode</td>
<td>Au_Gr</td>
<td>0.2</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>7.2</td>
<td>Patterning</td>
<td>TOPEL</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Step Name: Grow Crystal Silicon
Action: Stack Material
Layer Name: Si_Handle
Material: SILICON_100

Comments:
At start of process the Silicon handle layer is 8000 ± 500 nm. However, after oxidation the layer is reduced to approx. 7340 nm.
Implementation in CoventorWare

Material Property Database

- Material: CSD_PZT
- Elastic Constants: Elastic-Isotropic
- Density (kg/m^3): 7.750000e-015
- Stress (MPa): Anisotropic
- TCE Integral Form (1A): Constant-Scalar
- Thermal Conductivity (W/mK): 0.000000e+000
- Specific Heat (J/kgK): 0.000000e+000
- Electric Conductivity (S/m): 2.500000e-001
- Dielectric: PiezoElectric-Strain
- Viscosity (kg/m/s): 0.000000e+000
- Piezoresistive Coeffs (1MPa): Constant_Scalar
- Custom Properties File: Piezoelectric_constant_for_SINTEF_CSD_PZT

Piezoelectric Constants:
- D1: 0.000000e+000 0.000000e+000 -1.360000e-004
- D2: 0.000000e+000 0.000000e+000 -1.360000e-004
- D3: 0.000000e+000 0.000000e+000 2.720000e-004
- D4: 0.000000e+000 0.000000e+000 0.000000e+000
- D5: 5.000000e-004 0.000000e+000 0.000000e+000
- D6: 0.000000e+000 5.000000e-004 0.000000e+000
- Dielectric: 1.300000e+003 1.300000e+003 1.200000e+003
Choice of PZT deposition method

<table>
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<tr>
<th></th>
<th>$-e_{31,f}$ [C/m²]</th>
<th>Relative permittivity, $e_r$</th>
<th>Dissipation factor, tan δ</th>
<th>Current main bottleneck for high volume</th>
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</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>~4-8?</td>
<td>900?</td>
<td></td>
<td>Quality</td>
</tr>
</tbody>
</table>

- **CSD**: High quality, but low throughput (manual deposition ~1 wafer/h μm)

- **Sputtering**:  
  - Multi target DC reactive sputtering: low throughput  
  - Single oxide target RF sputtering: higher throughput, but still too low quality

- **PLD** also coming up as candidate
Production deposition tools for PZT – CSD

- Adaptation of Solar-semi cluster coater tool

- Throughput goal
  - 4 wafers/h·µm (65 nm/min) on 200 mm wafers using new automatic CSD tool (15,000 wafers/y @ 43 % uptime)

- Performance goal
  - $e_{31,f} \sim -14$ C/m²

- Deposition cost
  - 10-20 €/wafer·µm due to consumables and equipment depreciation @ 43 % uptime
  - 4-8 €/cent per 1x1 cm die using 200 mm wafers

- Will be optimized for PZT but can also be used for other oxides

43 % uptime = 12h/day and 6d/week
Production deposition tools for PZT – sputtering

- Development of 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 (11.000 wafers/y @ 43 % uptime)

- Performance goal
  - $e_{31,f} \sim -14 \text{ C/m}^2$

- Deposition cost
  - 10-20 €/wafer·µm due to consumables and equipment depreciation @ 43 % uptime
    - 4-8 €/cent per 1x1 cm die using 200 mm wafers

43 % uptime = 12h/day and 6d/week
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 4 % of real \( e_{31,f} \)

- Throughput
  - 10 wafers/h

- Automation of measurements through electrode mask layout
  - Parameter/coefficient tracking

- Operations cost
  - 4 €/wafer due to equipment depreciation @ 43 % uptime
piezoMEMS competence centre

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

- World-class piezoelectric thin films (PZT). $e_{31,1} \sim -14 \, \text{C/m}^2 @ 10 \, \text{Hz}$
- 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

www.piezovolume.com
Conclusions

- There is a high focus on establishing production technologies for piezoMEMS (PZT)

- Low volume prototyping
  - AlN are offered by some MEMS foundries
  - PZT are offered by some commercially by a few institutes

- High volume fabrication
  - AlN already at high volumes in companies
  - PZT deposition processes currently under development
    - High volume deposition tools
    - Chemical solution deposition (piezoVolume)
    - Sputtering (piezoVolume)
    - PLD (SolMates)

- Process specific design and modelling tool

- Quality monitoring tool