Design and Characterization of a Novel High-g Accelerometer

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OUTLINE

- Introduction: Novel High-g Accelerometer
  - Accelerometer design and functional principle

- Extension of COMSOL material model

- Wafer-level characterization
  - Electro-mechanical characterization
  - Thermal characterization

- Summery and outlook
EMI Accelerometer
Design and Functional Principle

- Main components:
  - Flexural plate (spring-mass system)
  - Self-supporting piezoresistive (PR) elements
  - Rigid frame

- Functional principle:
  - Inertial forces cause deflection of plate
  - Straining of piezoresistive elements
  - Change in resistance is measurement signal
Use of COMSOL for Accelerometer Development

**Geometrical domain**
- Piezoresistiv-element (~µm)
- Die (~mm)
- Wafer (~cm)

**Physical domain**
- Mechanical
- Electrical
- Thermal

**Utilization**
- Design
  - Sensor
  - Experimental Setup
- Characterization
- Prediction

FEM COMSOL
Use of COMSOL for Accelerometer Development

**Physical domain**
- Mechanical
- Electrical
- Thermal

**Geometrical domain**
- Piezoresistive-element (~µm)
- Die (~mm)
- Wafer (~cm)

**Utilization**
- Design
- Sensor
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**FEM COMSOL**
Extension of the COMSOL Material Model
For Single Crystal Silicon

- Material: single crystal silicon

- Implemented properties in COMSOL:
  - Anisotropy
  - Basic mechanical-, electrical-, thermal-behaviors
  - Coupling of the physical domains (e.g. thermal expansion)

- Needed description of:
  - Temperature dependence of thermal expansion
  - Temperature depended PR-effect
  - Doping dependence of the PR-effect

implemented in this work
Wafer-Level Characterization

- Wafer-level Characterization of the PR-elements on
  - Static straining of the elements
  - ... and heating of the elements

- Advantages:
  - Easy handling of many sensors
  - Large number of measurements in a short time
Electro-Mechanical Characterization
Generation of Linearly Rising Stress

- Characterization of PR-elements on wafer-level

- Idea:
  - Generate mech. stress by bending
  - Stress in bent wafer rises linearly with bending curvature
Electro-Mechanical Characterization
Generation of Linearly Rising Stress

- Design of bending mold based on COMSOL simulation

- Setup only possible with wafer-level characterization

- Simple measurement with prober

![Image of test set-up showing a Wafer, Clamp, and Bending mold with a COMSOL simulation graph showing arc length x and von Mises stress in MPa. The fracture region is marked in the graph.]

Surface: von Mises stress [Mpa]
Electro-Mechanical Characterization
On-Chip Characterization of the PR-Elements

- Analytic calculation:
  \[ \frac{\Delta R}{R} \approx \sigma_l \cdot \pi_l \]
  (neglecting transverse tensions)
  - \( \sigma_l \): mech. stress \( \to \) from COMSOL
  - \( \pi_l \): PR-coefficient \( \to \) from literature

- Resistance change as expected
- Slight deviation from the theoretical value
Electro-Mechanical Characterization
On-Chip Characterization of the PR-Elements

- Significant deviation of the smallest elements

- Possible cause: "Giant piezoresistance effect"

- Effect could be used
  - But large scatter of data

Giant piezoresistance effect?
(R.He, P.Yang „Giant piezoresistance effect in silicon nanowires“; Nature Nanotechnology; Vol. 1; Oct. 2006)

![Graph showing relative resistance change vs. bending stress]
Thermal Characterization
Influence of Thermal Effects on the PR-Effect

- Examination of thermal influences on the PR-elements
- Use of the expanded material model for single crystal silicon
  - Thermal expansion
  - Temperature dependence of resistivity and PR-coefficients

\[
\begin{pmatrix}
\Delta \rho_{xx} \\
\Delta \rho_{yy} \\
\Delta \rho_{zz} \\
\Delta \rho_{yz} \\
\Delta \rho_{xz} \\
\Delta \rho_{xy}
\end{pmatrix} = \rho_0 \begin{pmatrix}
\pi_{11} & \pi_{12} & \pi_{12} & 0 & 0 & 0 \\
\pi_{12} & \pi_{11} & \pi_{12} & 0 & 0 & 0 \\
\pi_{12} & \pi_{12} & \pi_{11} & 0 & 0 & 0 \\
0 & 0 & 0 & \pi_{44} & 0 & 0 \\
0 & 0 & 0 & \pi_{44} & 0 & 0 \\
0 & 0 & 0 & 0 & \pi_{44} & 0
\end{pmatrix} \begin{pmatrix}
\sigma_{xx} \\
\sigma_{yy} \\
\sigma_{zz} \\
\tau_{yz} \\
\tau_{xz} \\
\tau_{xy}
\end{pmatrix}
\]
Thermal Characterization
Simulation of Thermal Effects

- Numerical simulation of thermal effects
  - Resistivity
  - Piezoresistive coefficient

→ Significant influence on sensor sensitivity expected

- Simulation confirmed by measurements

- Strange behavior of smallest elements
Summery and Outlook

- Extension of the COMSOL silicon material model with temperature and doping dependences
- Successful use of COMSOL during the development and characterization of a novel high-g accelerometer, e.g.
  - Generating defined mechanical stresses by bending
  - Prediction of thermal influences on sensitivity
- Good agreement between numerical and experimental data

Outlook
- Parameter optimization of sensor design with parameter-sweep capabilities of COMSOL
  - Implementation of the giant piezoresistance effect
Thank you for your Attention!

Questions?

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