Modeling and Design-driven Simulation of Integrated Piezo-resistive Pressure Measuring Systems

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Outline

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Motivation

Functional Principle:
Pressure related modulation of the specific resistance of integrated piezo-resistive elements

Criteria:
Sensitivity, stability, linearity, hysteresis, bursting strength and manufacturing yield

Aims:
Optimisation of the mechanical properties as well as investigation of drift effects, parasitic effects and technological variations
Stability Problem (Unstressed Bridge)

desired

undesired
Parameters of the Measuring System

Dimensions:
- Edge length 5.3 mm
- Diaphragm diameter 3.2 mm
- Diaphragm thickness $(30 \pm 2) \mu m$

Piezo-resistive elements:
- $R = 4.5 .. 5 .. 5.6 \, k\Omega$
- Width 6 $\mu m$
- Length 2 x 120 $\mu m$

Typical sensor parameters:
- $p_{\text{nom}} = 100 \, \text{mbar}$
- Sensitivity $> 10 \, \text{mV/V}$
- $p_{\text{burst}} = 6 \, \text{bar}$
- Stability $> 5 \, \mu \text{V/V}$
Principal Model Structure

Pressure sensor

Network model

Modeling with consideration of
- Layout and structure assembly of the sensing elements
- Doping profile, process sequence, ...
- Application, circuitry, supply voltage
- Thermo-mechanical interactions
- Parasitics (e.g. reverse currents, parasitic field effect)
Modeling

What?

• Behavioral Model of the bridge resistors (MAST, VHDL-AMS)
• Later on development of a Spice model (if possible)

How?

• Deriving the model using results of ANSYS-simulations for thermo-mechanical effects
• ATLAS-calculations of device electronics
• Measurement results for parameter extractions

Steps

• First step:
  Analysis of the impact of pressure and temperature on the bridge elements
• Later on:
  Modeling with considering further effects
**Modeling Flow**

- **ATLAS**
  - Process Simulation
- **System**
  - Distribution of Mechanical Stress in the Piezo-resistor
- **ANSYS**
  - Structural Mechanics
  - Mechanical Stresses
  - Current Density, Resistance
  - Power Loss
  - Thermo-mech. Calculations

**Structure of the Sensing Elements**
- (Position, Dimensions)

**Spec. Resistance Distribution**
- \( \rho = \rho(x, y, z, \theta) \)

**Distribution of Mechanical Stresses in the Piezo-resistor**

**Thermal Related Mechanical Stresses in the Piezo-resistor**
Relative resistance variation due to mechanical stresses
\[ \frac{\Delta R}{R_0} = \pi_{11} \bar{T}_1 + \pi_{12} \bar{T}_2 + \pi_{16} \bar{T}_6 \]

„unstressed“ resistor
\[ R_0 = \frac{L}{Bd} \frac{1}{\kappa_0} \]

Average conductivity
\[ \bar{\kappa}_0 = \frac{e}{d} \int_0^d \mu_p (N_A(z)) N_A(z) dz \]

Piezo-resistive coefficients according to the position of the sensing elements
\[ \pi_{11}, \pi_{12}, \pi_{16} = f(\pi'_{11}, \pi'_{12}, \pi'_{44}) \]

(\( \pi' \) - piezo-resistive coeff. in crystallographic coordinations <100>)
Basic Model of the Resistance Modulation (2)

Relative resistance variation due to mechanical stresses

\[ \frac{\Delta R}{R_0} = \pi_{11} \bar{T}_1 + \pi_{12} \bar{T}_2 + \pi_{16} \bar{T}_6 \]

Average mechanical stress

\[ \bar{T}_1 = \frac{1}{BL} \int_0^B \int_0^L \sigma_x dx dz \quad \bar{T}_2 = \frac{1}{BL} \int_0^B \int_0^L \sigma_y dx dz \quad \bar{T}_6 = \frac{1}{BL} \int_0^B \int_0^L \sigma_{xz} dx dz \]
Bridge Elements with Parasitic Resistors

- From layout to network architecture
- Parasitic elements
- Parametrisation - function in terms of $\varrho$, $p$, geometry, $u$, $i$
- Komplex network
Simulation of Doping Profile using ATLAS

Above:
Cross section

Below left:
Section into the depth at x=3µm

Below right:
Section parallel to the Si surface from x=9µm to x=17µm

2D doping profile of a resistance line with Sb implantation
Lock-In Thermography

Max. resolution: <1mK

„Stressed“ with I = 2mA:

- Chip heating about ca. 0.8K for 20min
- Comparisation of the 4 piezo-resistors: ΔT ca. 0.1K
2D-ANSYS-Simulation of the Stress Distributions

Deformed structure (not full-scale)

Stress distribution $\sigma_x$ in the region of the sensing elements

- radially positioned
- tangentially positioned (inside and outside)
Stress Distributions of the Radially Positioned Element

**Lateral components:**

- Component $\sigma_y$ upright to sensor’s surface:
  - About factor $10^4$ smaller than $\sigma_x$ and $\sigma_z$, respectively
  - Will be neglected

- Component $\sigma_{xz}$ diagonal to sensor’s surface:
  - Not available in the 2D model
  - 3D model necessary in the next step
Determining the Average Mechanical Stresses $T_1$, $T_2$ and $T_6$ of the Radially Positioned Sensing Element

$$\sigma_{xz} = 0 \ (2D)$$

$$\bar{T}_1 = \frac{1}{BL} \iint \sigma_x dx dz$$

$$\bar{T}_2 = \frac{1}{BL} \iint \sigma_z dx dz$$

$$\bar{T}_6 = \frac{1}{BL} \iint \sigma_{xz} dx dz$$

$\bar{T}_6 = 0$
Assignment of the Average Stress Components to the According Bridge Elements

rad - radially positioned
ti - tangentially pos., inside
ta - tangentially pos., outside
Results of the Behavioral Simulation (Saber)

Transient pressure increasing from 0 to 6 bar, supply voltage = 5 V

Distribution of the voltages at the bridge nodes and the acting pressure

Bridge voltage as a function of the acting pressure
3D-FE-Model of the Sensor (Quarder and Full Model)

3D Model enables among others:
- Feed in of a local power loss
- Computation of stresses, which are not in the cross section (e.g. $\sigma_{xz}$)

Temperature distributions
Summary

• Development of a **physically founded model** of the piezo-resistive resistance modulation due to acting pressure
• Implementation of a **behavioral model** (Saber) of integrated sensing elements
• **Simulations** of the pressure measuring system for dedicated load cases
• **Measurements** of temperature distributions and long time stability
• **3D-model** of the pressure sensor in ANSYS (determining shear stresses, thermo-mechanical reactions)
• Enhancement of the behavioral model
  • **Consideration of parasitic effects** (reverse and leakage current)
  • **Temperature dependency** of important parameters and parasitics
  • **2D-lateral effects** of the electric flow field in the sensor
• Proving the **seamless modeling flow**
Example: Sensor Resistor with Parasitic Reverse Current and Geometry Factor

Sensor resistor

\[ R_{w/2} = \frac{R_{0_w}}{\sqrt{1 + 2 \cdot \frac{R_{0_w}}{R_{w_{sub}}}}} \cdot g_w \cdot \Omega_w \]

unstressed resistor

\[ R_{0_w} \]

Geometry factor

\[ g_w = g \left( \frac{L_w}{B_w}, \Delta B_w \right) \]

Reverse resistance to substrate

\[ \bar{R}_{w_{sub}} = \frac{U_w + \bar{U}_{D_w}}{\bar{I}_{sp_w}} \]

Average reverse current

\[ \bar{I}_{sp_w} = I_{sp_w} \left( U_w, T_{9_w} \right) \]

Piezo-resistive factor

\[ \Omega_w \left( T_{9_w} \right) = 1 + \hat{\pi}_{11_w} \left( T_{9_w} \right) \cdot \bar{T}_{1_w} + \hat{\pi}_{12_w} \cdot \bar{T}_{2_w} + \hat{\pi}_{16_w} \cdot \bar{T}_{6_w} \]

(Reverse) voltage

\[ U_w \]

Average diffusion voltage

\[ \bar{U}_{D_w} \]
Calculation of the Resistance Modulation (1)

Determining

\[ \pi'_{\mu \nu} = \pi'_{\mu \nu} \left( \mu_1 / \mu_1, N_A, T \right) \]

based on the band structure

Effective mass determines the carrier mobilities

\[ \mu_{\nu p, n} = \frac{e}{2 \cdot m_{\nu \text{eff}}} \cdot \tau_{p, n} \]

\[ m_{\nu \text{eff}} \propto \left( \frac{d^2 E(\mathbf{k})}{d k_\nu^2} \right)^{-1} \]

Inversely proportional to the bending of the band structure

Piezo-resistor (unstressed)
Calculation of the Resistance Modulation (2)

Determining

\[ \pi'_{\mu\nu} = \pi'_{\mu\nu} \left( \mu_1 / \mu_1, N_A, T \right) \]

based on the band structure

Effective mass determines the carrier mobilities

\[
\mu_{\nu p, n} = \frac{e}{2 \cdot m_{\text{eff}}} \cdot \tau_{p, n}
\]

\[
m_{\text{eff}} \propto \left( \frac{d^2 E(k)}{dk^2} \right)^{-1}
\]

Inversely proportional to the bending of the band structure