Impact of process variability on a frequency-addressed NEMS array sensor used for gravimetric detection

MARTIN Olivier ¹, COLINET Eric*, SAGE Eric, DUPRE Cécilia, VILLARD Patrick, HENTZ Sébastien, DURAFFOURG Laurent and ERNST Thomas

CEA-Leti, Minatec Campus, 17 rue des Martyrs, 38054 Grenoble Cedex 9, France
* APIX Technology, Grenoble, France

¹ olivier.martin@cea.fr
Contents

- Introduction
  - State of the art & applications for NEMS used as gas sensors
- The « Crossbeam » NEMS
  - Presentation & fabrication
  - Gravimetric detection
  - Readout of such NEMS by frequency tracking
  - Arrays of NEMS
- Impacts of the process variation
- Measurements and results
  - Open loop
  - Optical control
- Conclusion
Contents

- Introduction
  - State of the art & applications for NEMS used as gas sensors
- The « Crossbeam » NEMS
  - Presentation & fabrication
  - Gravimetric detection
  - Readout of such NEMS by frequency tracking
  - Arrays of NEMS
- Impacts of the process variation
- Measurements and results
  - Open loop
  - Optical control
- Conclusion
NEMS resonators

[1] Capacitive A/D, metal, BE – University of Barcelona (UAB)


Applications

- Air quality
- Industrial process monitoring
  - Petrochemical industry, ...
- Volatile organic compounds (VOC) identification
  - TEOX (Toluene, Ethylbenzene, Octane, Xylene)
- Security
  - chemical warfare agents detection
- Promising biomedical applications
  - Early diagnosis of illness (lung cancer, ...)

Contents

- Introduction
  - State of the art & applications for NEMS used as gas sensors
- The « Crossbeam » NEMS
  - Presentation & fabrication
  - Gravimetric detection
  - Readout of such NEMS by frequency tracking
  - Arrays of NEMS
- Impacts of the process variation
- Measurements and results
  - Open loop
  - Optical control
- Conclusion
The « Crossbeam » - NEMS resonator

- In-plane motion of the beam
- Differential electrostatic actuation
- Piezoresistive detection by nanowire gauges
Process of fabrication (LETI)
The « Crossbeam » as a mass sensor

- Equation of the beam flexion:
  \[ H(\omega) = \frac{y(\omega)}{F(\omega)} = \frac{1}{M_{\text{eff}}} \frac{\omega^2}{\omega^2 - \Omega_1^2 + j \frac{\omega \Omega_1}{Q}} \]

- Effect of mass loading:
  \[ \Delta f = -\frac{\Delta m}{2M_{\text{eff}}} f_1 \]
Frequency tracking readout (FLL)

- **Principle:**
  - Phase shift of 90° @ resonance frequency
  - Input/Output phase shift comparison
  - Controller feeds a VCO which actuates @ the new resonance frequency

![Diagram of FLL principle]
Parallel NEMS array integration scheme

- Collectively addressed resonator
  - Same resonance frequency
  - Better SNR proportional to $\sqrt{N}$
  - Global Q depends on process fluctuation
  - Same load needed on each NEMS

- Frequency addressed resonator
  - Each NEMS is read independently around its resonance frequency
  - Limits: frequency bandwidth / Q
Contents

- Introduction
  - State of the art & applications for NEMS used as gas sensors

- The « Crossbeam » NEMS
  - Presentation & fabrication
  - Gravimetric detection
  - Readout of such NEMS by frequency tracking
  - Arrays of NEMS

- Impacts of the process variation

- Measurements and results
  - Open loop
  - Optical control

- Conclusion
Impact of the variations (I)

- Resonance frequency:
  \[ \Omega_1 = \sqrt{\frac{EI}{\rho S} k_1^2} \]

- Dependence of the geometrical parameters
  \[
  \begin{align*}
  \frac{\partial \Omega_1}{\partial W_b} &= \frac{(2.1178)^2}{2 L_b^2} \sqrt{\frac{E}{3 \rho}} \\
  \frac{\partial \Omega_1}{\partial L_b} &= -\frac{(2.1178)^2}{L_b^3} \sqrt{\frac{E}{3 \rho} W_b}
  \end{align*}
  \]

  With \( L_b > 15 - 20. W_b \)

  \( W_b \) is 10 times more impacting than \( L_b \)

- \( E \): Young’s Modulus of elasticity (169 GPa)
- \( \rho \): the density of the silicon (2330 kg/m³)
- \( S \): the cross-section of the lever beam
- \( k_1 = \frac{2.1178}{L_b} \): the wave vector (anchorage)
- \( I \): the bending moment of inertia

\[
I = \frac{(T_{si_b}.W_b^3)}{12}
\]
Impact of the variations (II)

- Resonance frequency shift:
  - For NEMS resonating at 20 MHz, 40 MHz and 60 MHz
  - With a 10 nm width fluctuation error
    - Downshift of 1.21 MHz, 2.46 MHz and 3.63 MHz respectively

- Bandwidth of the NEMS:
  \[ \Delta \Omega_1 = \Omega_1/Q \] with \( Q \approx 100^* \)
    - 500 kHz for a 50-MHz resonance frequency NEMS

- A 6% variation on the width leads to a 6% downshift of the resonance frequency

* In air
Contents

- Introduction
  - State of the art & applications for NEMS used as gas sensors
- The « Crossbeam » NEMS
  - Presentation & fabrication
  - Gravimetric detection
  - Readout of such NEMS by frequency tracking
  - Arrays of NEMS
- Impacts of the process variation
- Measurements and results
  - Open loop
  - Optical control
- Conclusion
Measurement setup (I) – Open Loop

- First bench:
  - Frequency control
  - Open loop
  - Lock-in Amplifier: SR 830
  - Sources: Agilent 81160A (Double)

Measurement (I) - Results

- Dispersion on the width below 10 nm
Measurement setup (II) – Optical

- **Second bench:**
  - **Morphology** of each NEMS characterized by **SEM** (Scanning Electron Microscopy)
  - Characterization of:
    - \( L_b, W_b, g \)
  - **Exemple of** \( W_b \) **for a 40 MHz NEMS:**
    - \( \sigma_{\Omega_1} = 1.83 \text{ MHz (cf Bench 1)} \)
    - \( \sigma_{W_b} \) should be 7 nm (Bench 1)
    - Results: 6.55 nm

![Diagram](image)
Contents

- Introduction
  - State of the art & applications for NEMS used as gas sensors
- The « Crossbeam » NEMS
  - Presentation & fabrication
  - Gravimetric detection
  - Readout of such NEMS by frequency tracking
  - Arrays of NEMS
- Impacts of the process variation
- Measurements and results
  - Open loop
  - Optical control
- Conclusion
Conclusion

- Process variations impact on a new NEMS device was studied
- Most impacting parameters are indentified
- Toward VLSI sensors with a better capture area
- Design of frequency-addressed NEMS arrays
  - Without overlap of frequencies
  - More robust
  - With a maximum of density
Thank you for your attention

_olivier.martin@cea.fr_