Reliability aspects of microsystem resonators: X-ray based packaging strain analysis and radiation tolerance

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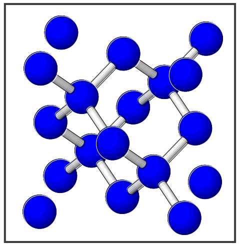
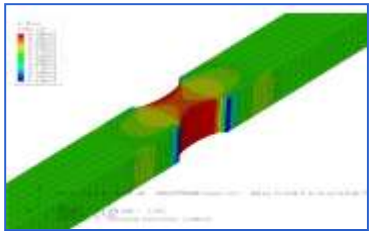
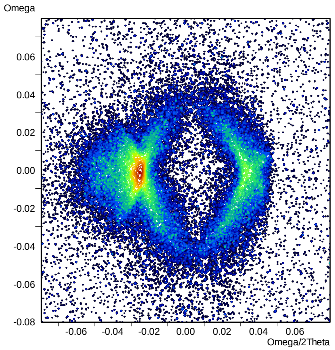
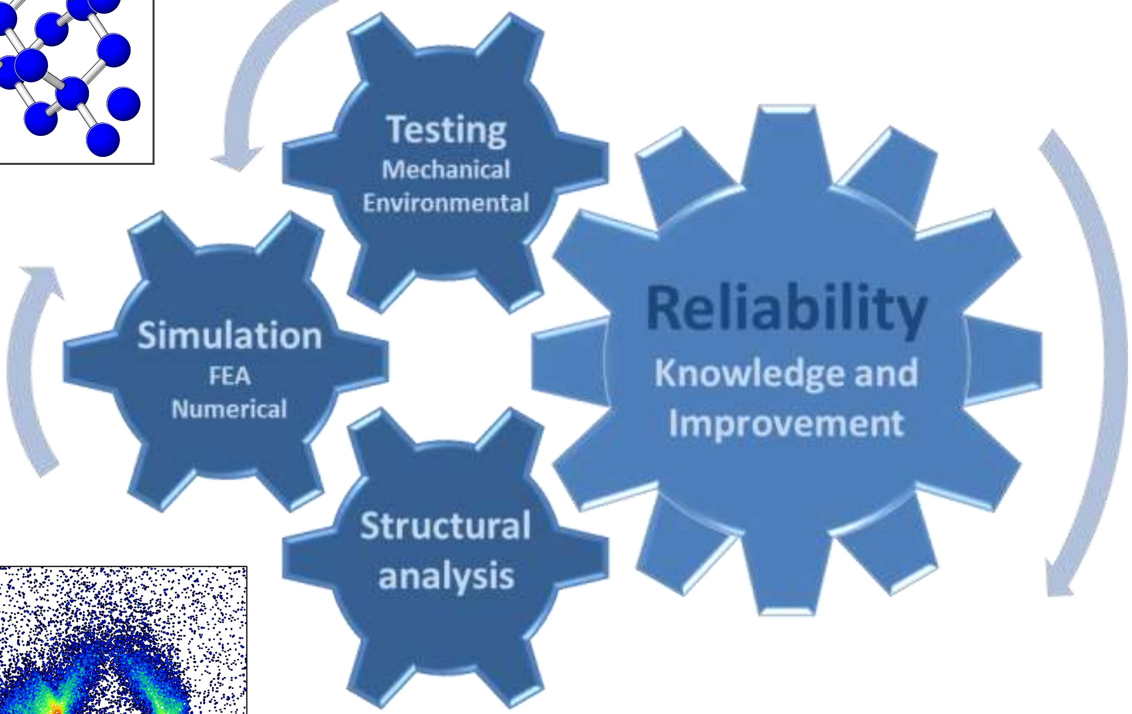
9th ESA Round Table on Micro and Nano Technologies,
12.06.2014

Reliability of MEMS





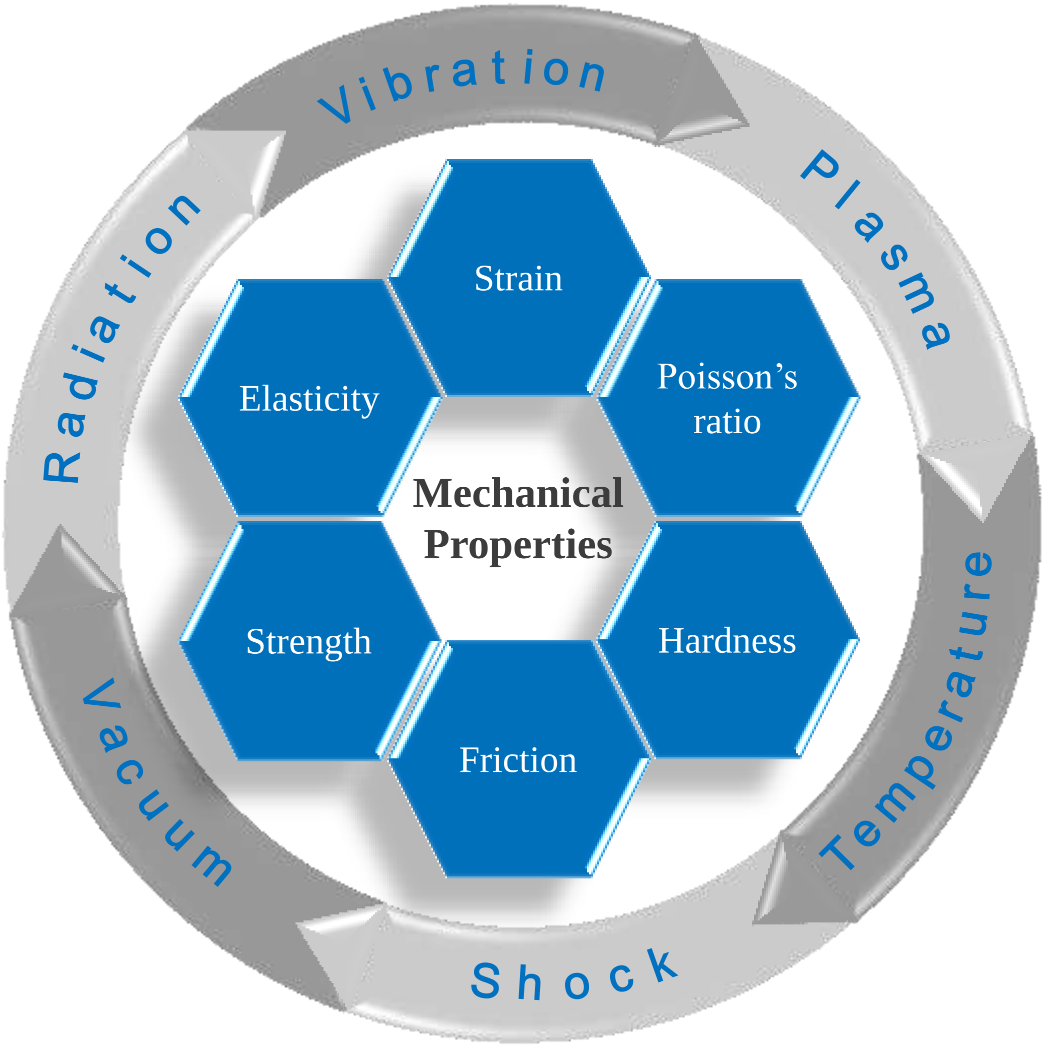




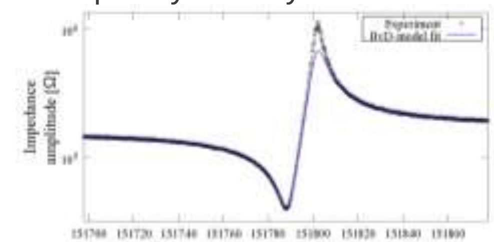
Use a combination of tools to investigate the reliability of MEMS

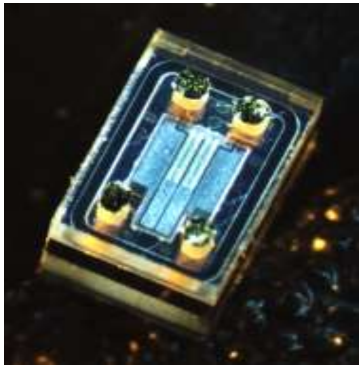
→ Focus on mechanical properties of MEMS structural materials

Environmental effects on mechanical material properties

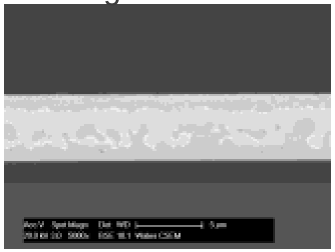


Frequency stability





Bonding

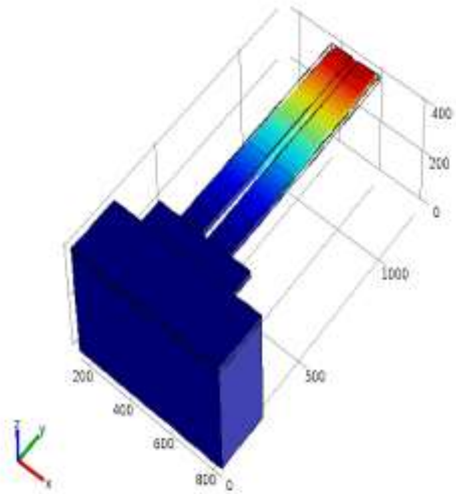


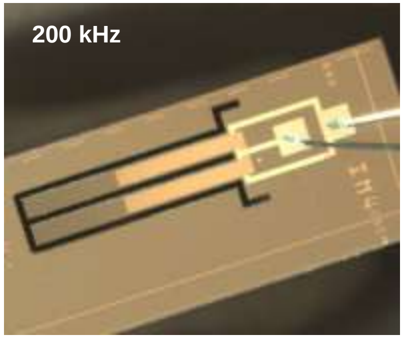
Importance of Young’s modulus in resonant structures

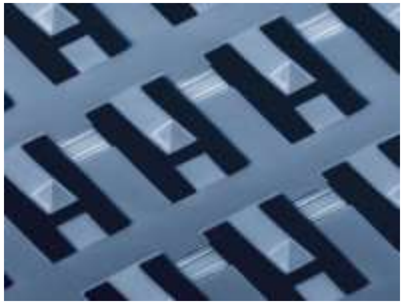
Harmonic oscillation of a resonator:

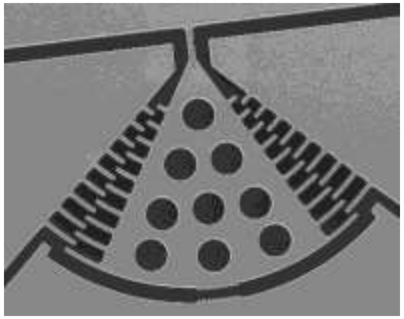
$$f = \frac{k_n^{\;2}}{2\pi} * \frac{b}{L^2} \sqrt{\frac{E}{12\rho}}$$

$$\Delta f / f = \tfrac{1}{2} \Delta E / E$$









→ Resonant MEMS require high stability of the mechanical properties of its materials (often on the ppm level)

→ Resonators are suitable structures for sensing changes in Young’s modulus.

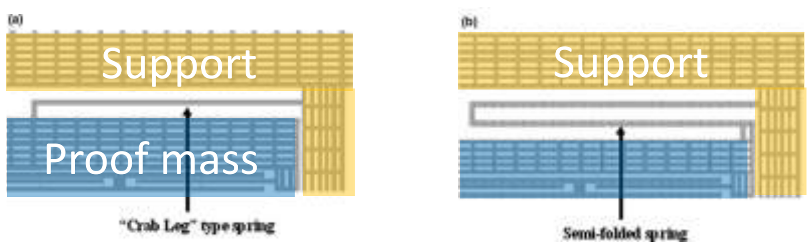
Packaging strain in microsystems

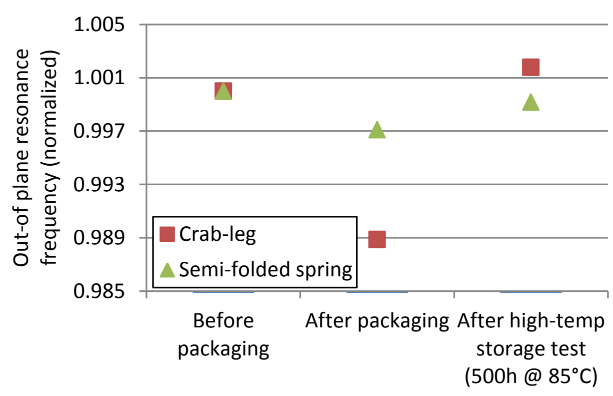
Bonding stress analysis

→ Influence of strain on device performance

→ Influence of residual stresses on aging

Example: Effect of packaging and geometry on the resonance frequency of a gyroscope



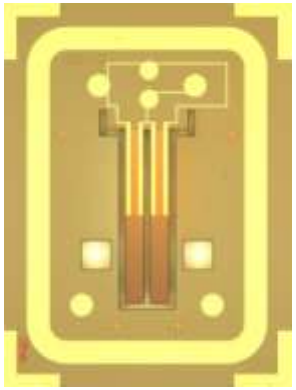


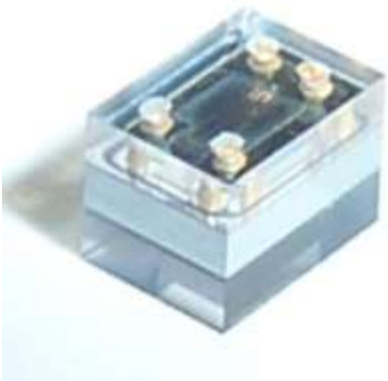
S. H. Choa, *Microsyst. Technol.*, **11** (2005)

Piezoelectrically activated silicon microresonators

Applications

- Pressure sensing
- Signal filtering
- Timekeeping

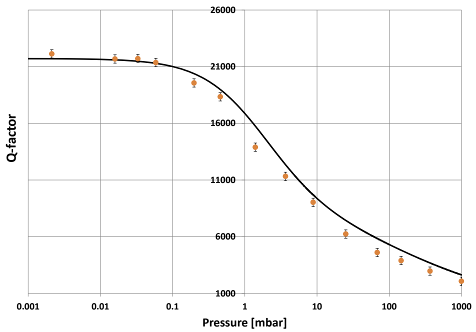


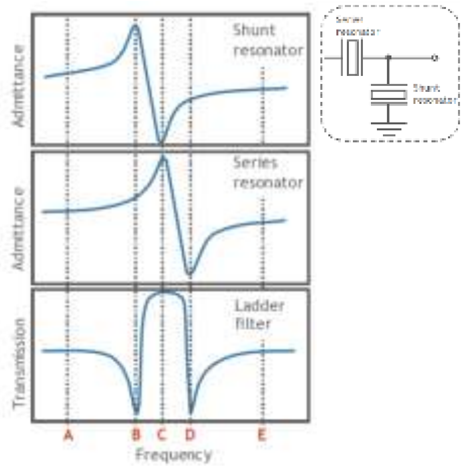


Tested device:

- Silicon resonator actuated by AlN thin film
- Pressure sensor for small cavities (nl)
- Resonance frequency: 150 kHz
- Quality factor of ~20000 in vacuum and 2000 in air

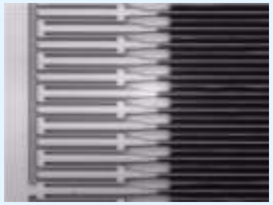
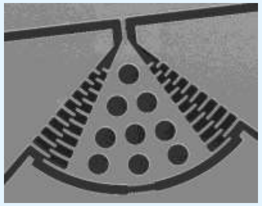
Timefreq.com





Kaajakari, VTI Technologies (2011)

High Resolution X-ray Diffraction (HRXRD) in MEMS reliability:

Design:
- Components
- Devices
- Packaging level

→ Fabrication → Assembly → MEMS → Product

<u>Components characterization:</u>

- Structural analysis:
  phases, texture, strain, …
- Defect and strain analysis related to MEMS parts in fabrication processes

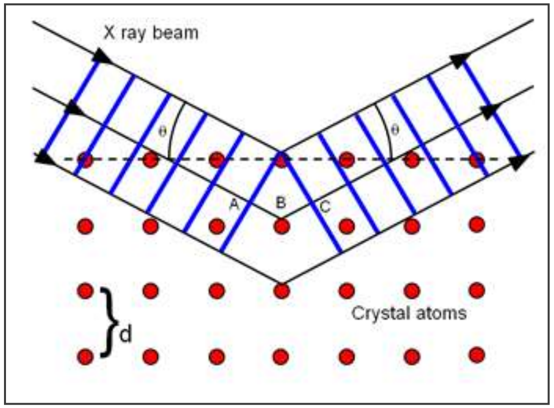
<u>Packaging:</u>

- Defect + strain analysis

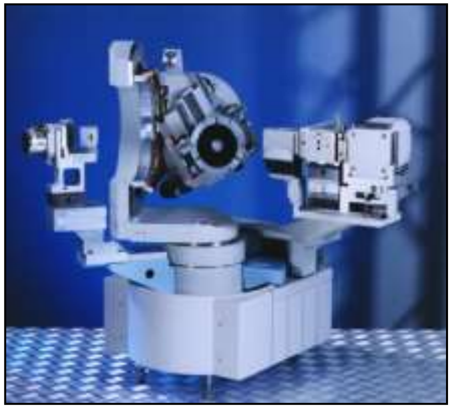
<u>Strain dynamics and mobility of Defects by XRD:</u>

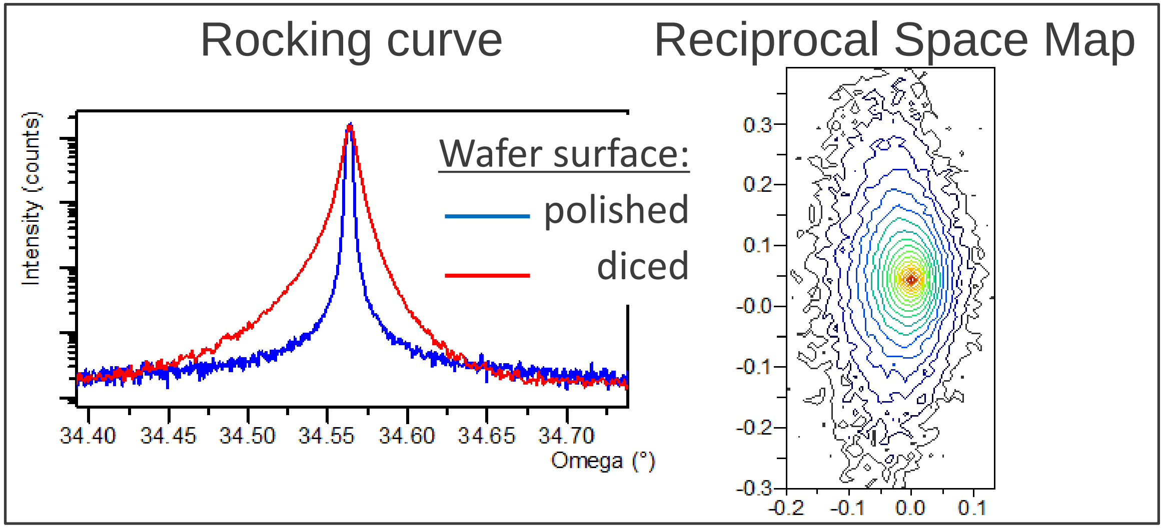
- In-situ testing:
structural + mechanical
- Aging studies:
T, radiation, high cycle fatigue

High-resolution X-ray Diffraction



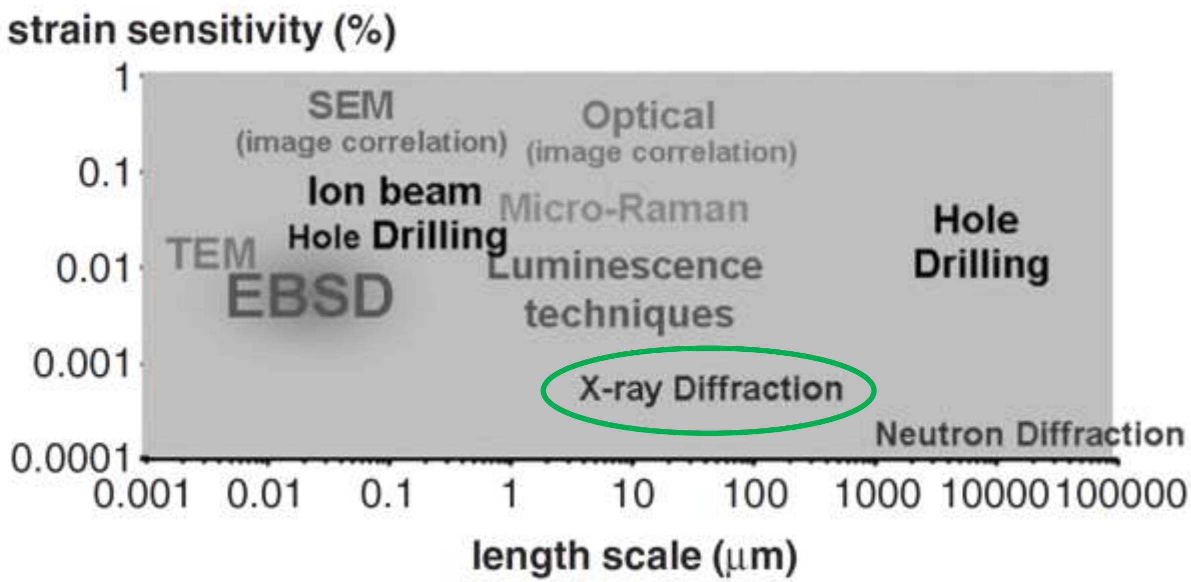
$$\boxed{n\lambda = 2d\sin(\alpha)}$$





1. Strain
2. Curvature
3. Defects from diffuse scattering

X-ray diffraction for strain measurement



From: D.J. Dingley et al., *J. Electron Micr.*, 59 (2010)

- Excellent strain sensitivity
- Spatial resolution limited by beam size and penetration depth (~100um in Si)

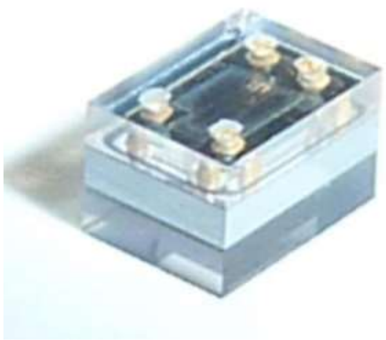
  But: Non-destructive measurement of sub-surface structures possible

→ Combination of finite element simulations with XRD:

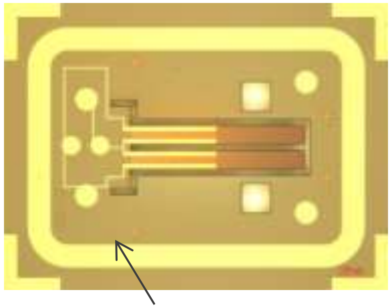
Turn limitations into strengths

Packaging strain in microsystems

- AuSn eutectic bonding technology
- Bonding stress analysis

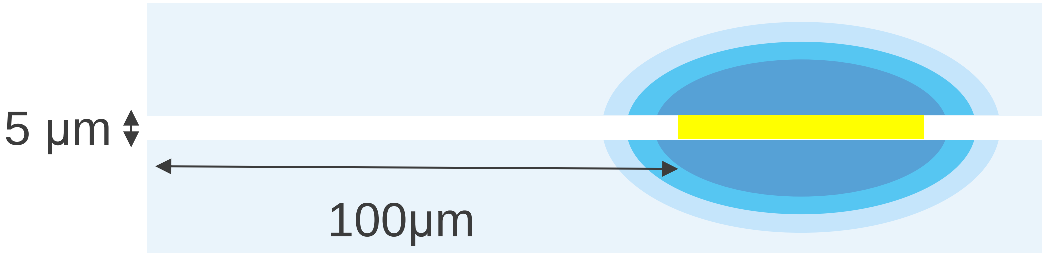


Top view

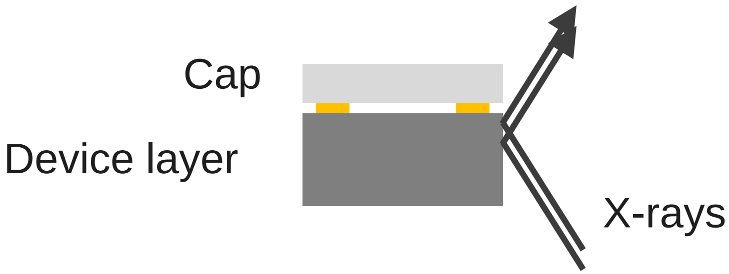


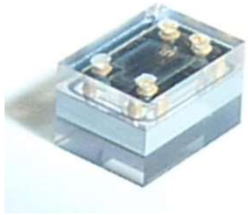
Sealing ring (width 100 µm)

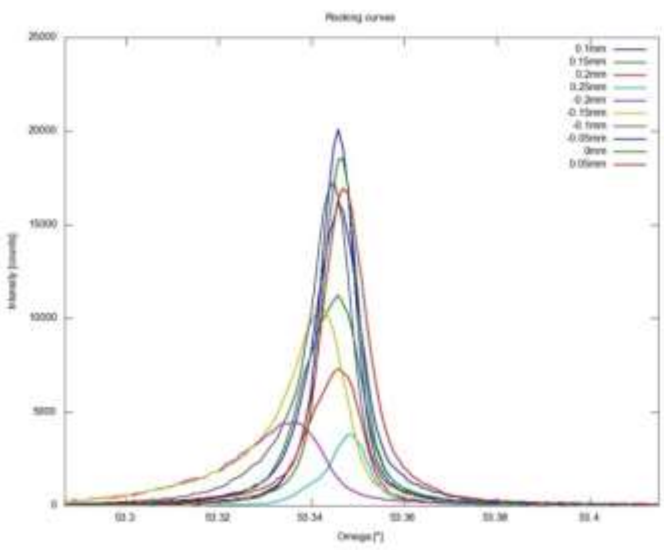
Cross section geometry:

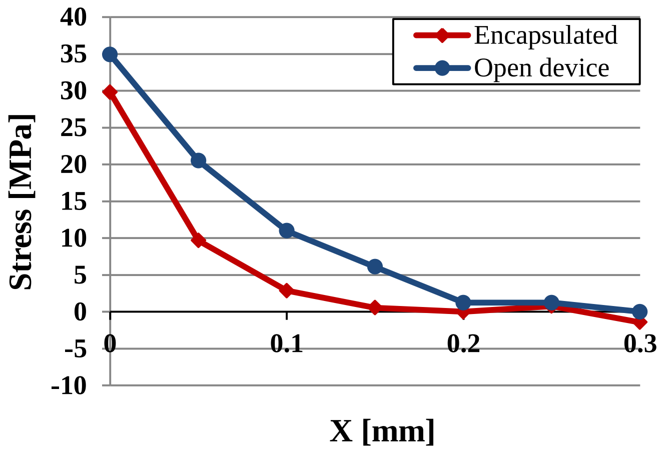


Bonding stress analysis – Bulk wafers (no resonators)

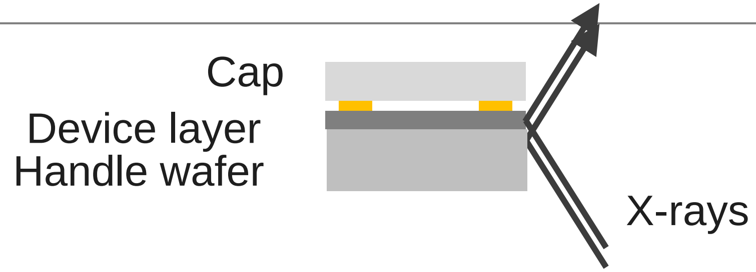




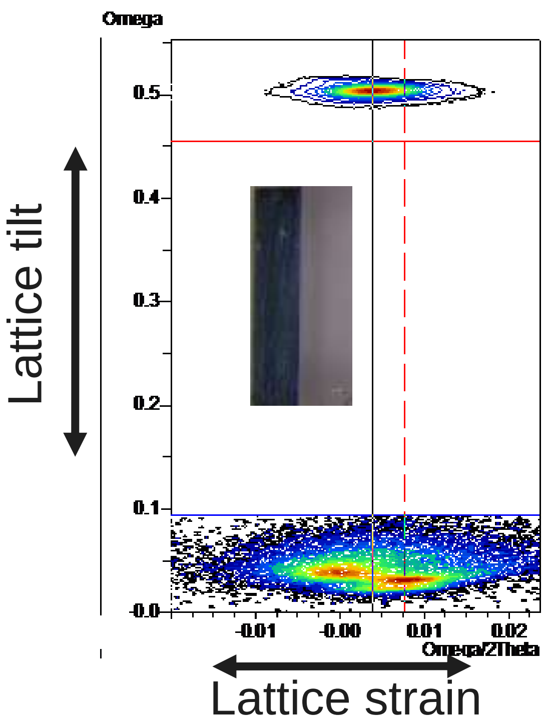




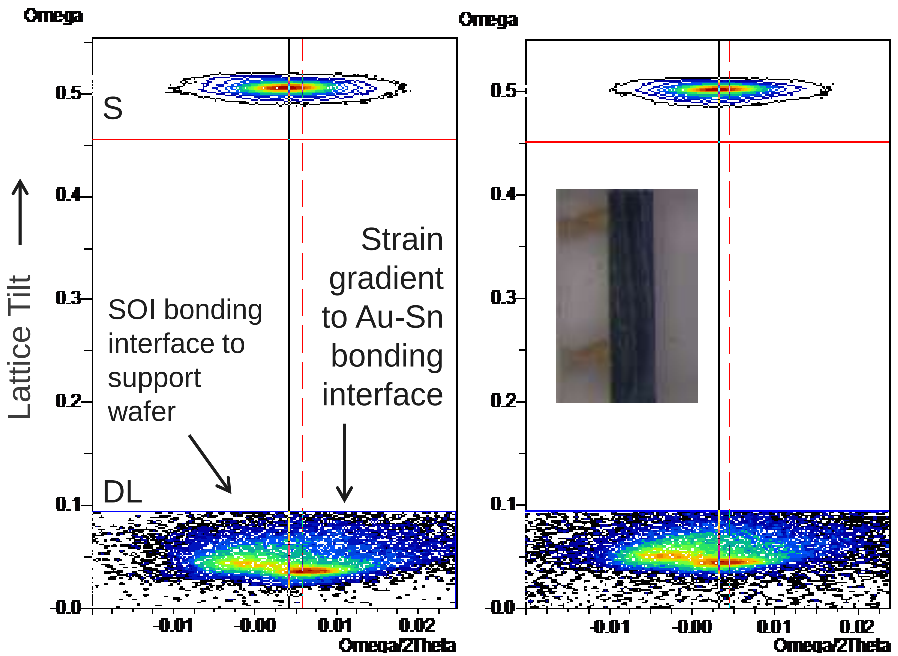
HRXRD investigation of bonding stress



Device without cap



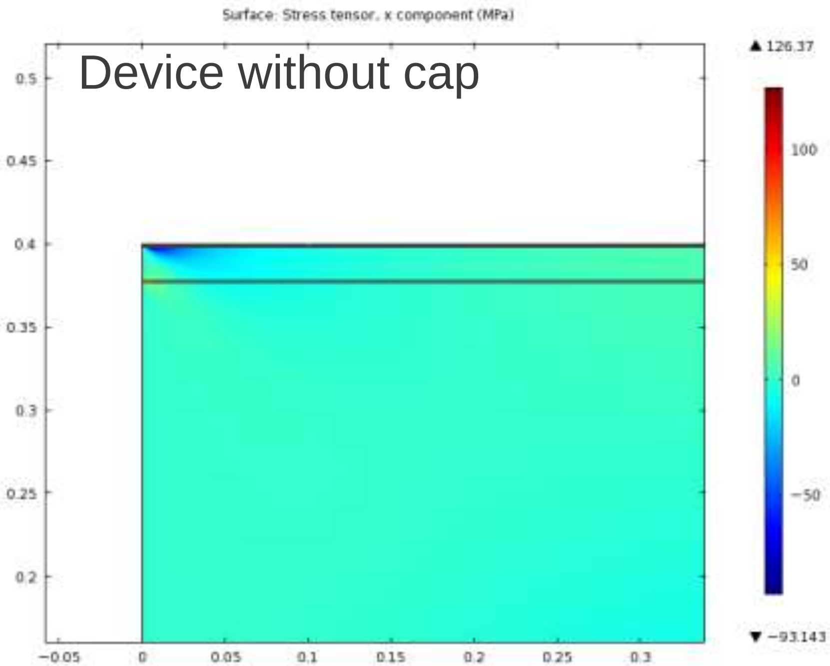
Packaged

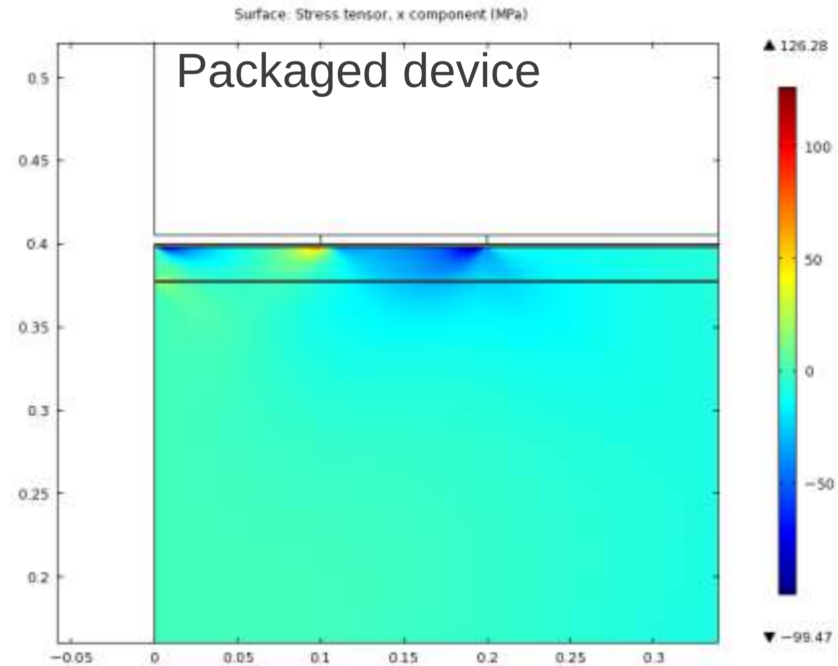


Finite element simulation

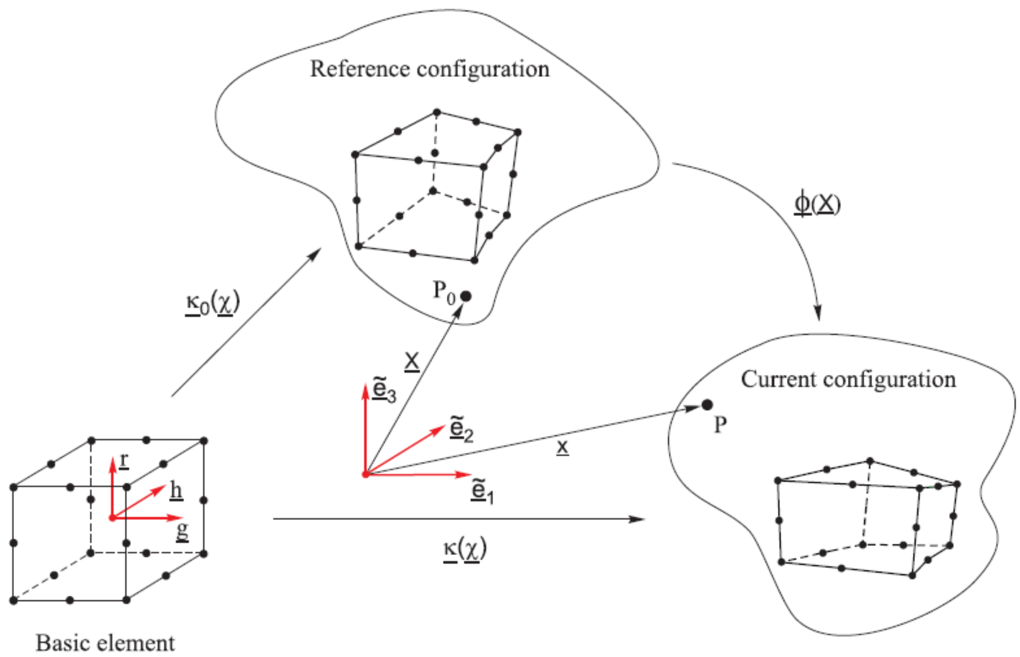
- Simplified 2D model
- ΔT = -260°C (melting point of eutectic AuSn → RT)

X-component of Stress in the silicon

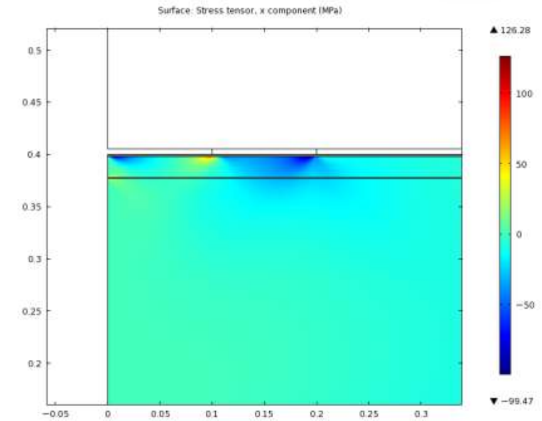


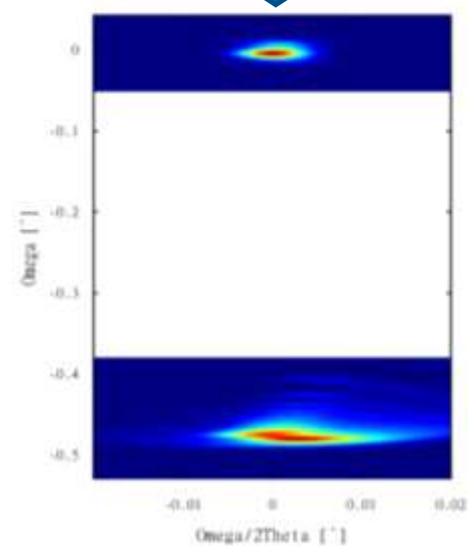


Simulation of Reciprocal Space Map



A. Schifferle, PhD Thesis, ETHZ, 2011





For every lattice node the strain and tilt components are calculated based on the deformation gradient.

→ Scattering vector

Radiation tests

Gamma-ray test: ESA Co-60 facility @ ESTEC (NL)

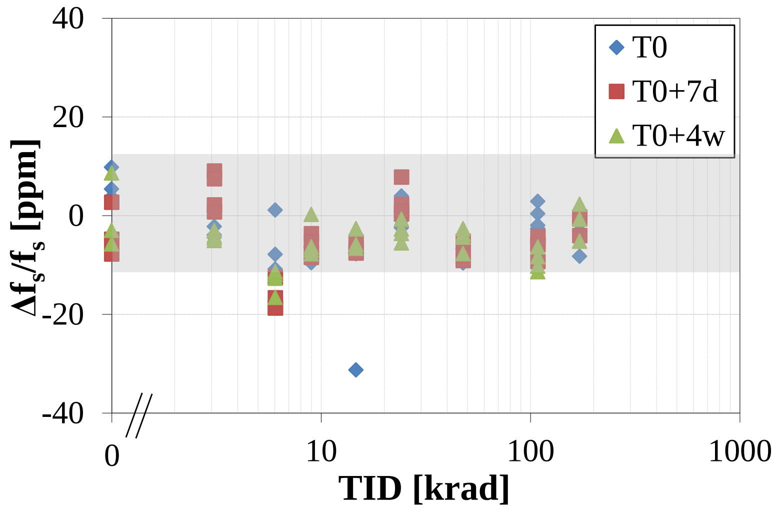
- Total ionizing doses **3 - 170 krad(Si)**.
- Dose rate 1 krad(Si)/h.

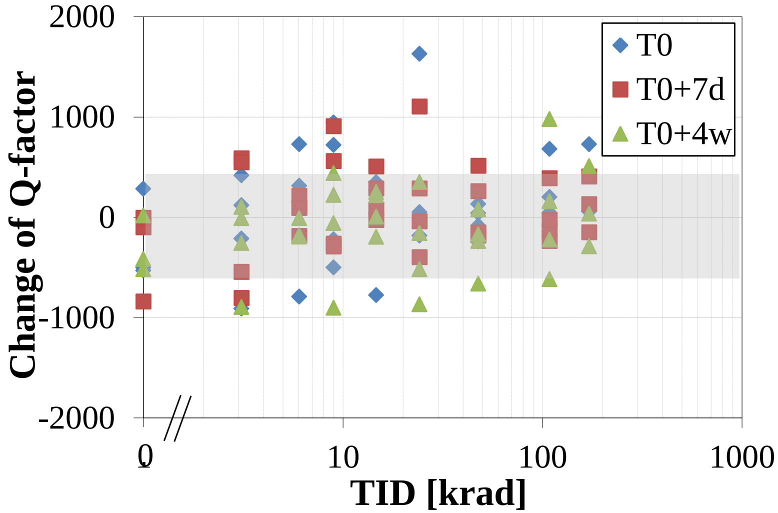
Proton irradiation: Paul-Scherrer Institute (CH)

- Proton energy: **50MeV.** Ensures full penetration of device.
- Total dose **10-150 krad(Si)**
- Proton flux of 1×10^8 p cm^{-2} s^{-1} ≙ ~15 rad(Si)/s

Results of ^{60}Co Gamma-ray test

- 28 devices were irradiated at doses of between 3 krad and **170 krad**.
- No significant change of the resonance frequency and the Q-factor.
- Possibly a higher variance in the Q-factor of the irradiated devices.

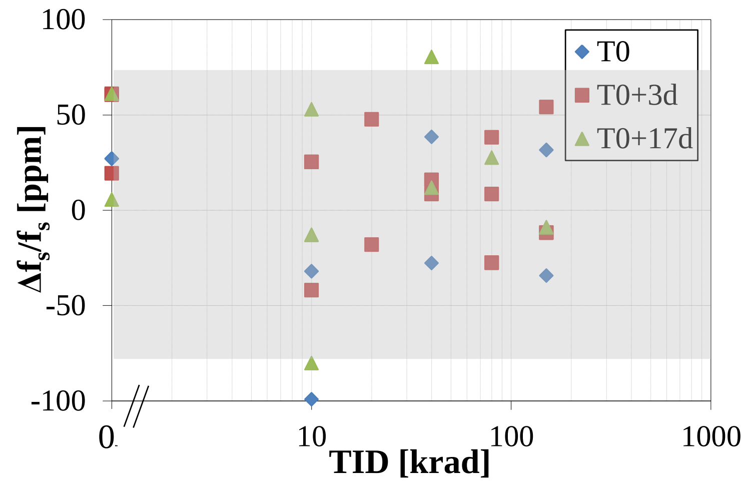


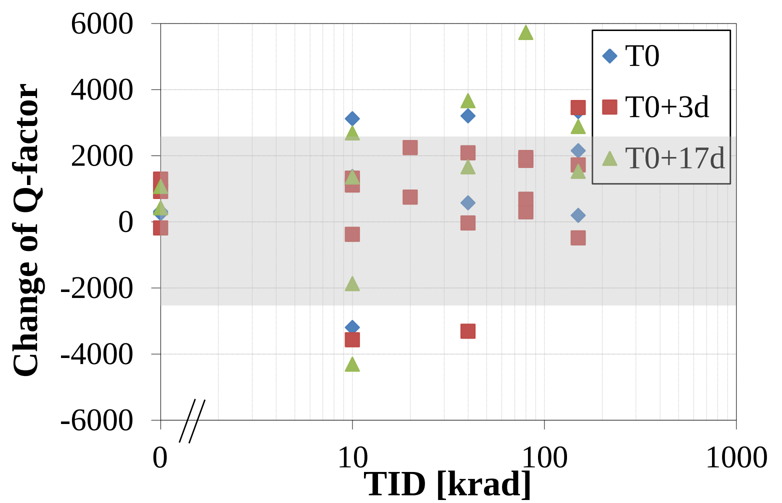


Proton irradiation test results

- 19 devices were irradiated at doses of 10 krad to 150 krad using 50 MeV protons.
- No significant change of the resonance frequency and the Q-factor observed.
- Possibly a higher variance in the Q-factor of the irradiated devices.

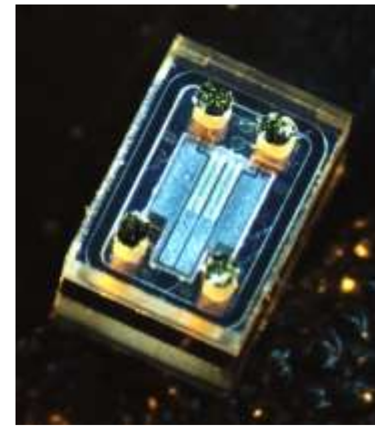
→ The elastic constants of silicon and AlN are highly resistant to radiation damage at space-relevant doses.

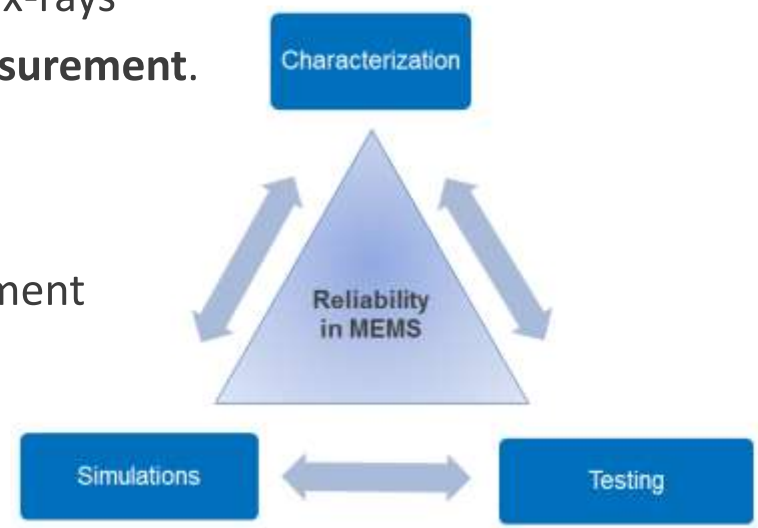




Conclusions

- Investigation of mechanical properties of MEMS materials
  Resonance characterization → Young's modulus
  HRXRD → Strain distribution
- The **elastic constants of silicon and AlN are highly resistant to radiation damage at space-relevant doses**.
- **HRXRD** was used to the investigate strain distribution in a MEMS package. The high penetration depth of x-rays **allows non-destructive sub-surface strain measurement**.
- Finite element simulation of strain distribution and calculation of reciprocal space maps
  → Direct comparison of simulation and experiment
  → Validation of modeling approach





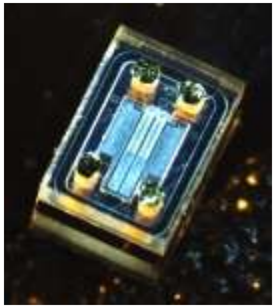
Outlook

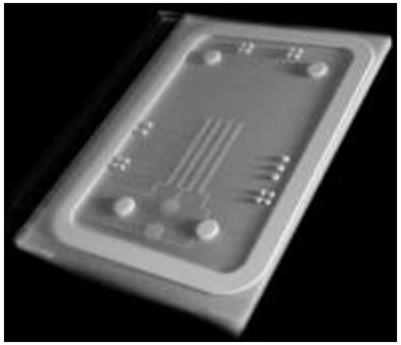
→ Higher radiation levels
- Nuclear power reactors (displacement damage)
- Missions near Jupiter's radiation belt

→ Improve experimental uncertainty of frequency measurement.

→ Improve the x-ray absorption modeling
- The current model considers photoelectric absorption
- Include dynamical absorption effects (extinction/re-diffraction)

→ In-situ heating for measuring thermal strains at non-ambient conditions





Thank you for your attention !

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Sylvain Jeanneret (now Patek Philippe Technologies S.A.)
Claude Muller (formerly CSEM)
Alex Dommann (now at Empa)

esa

Research funding (ESA-NPI)
Laurent Marchand
Nicolas Saillen