Radiation tolerance and reliability of piezoelectrically activated silicon resonators

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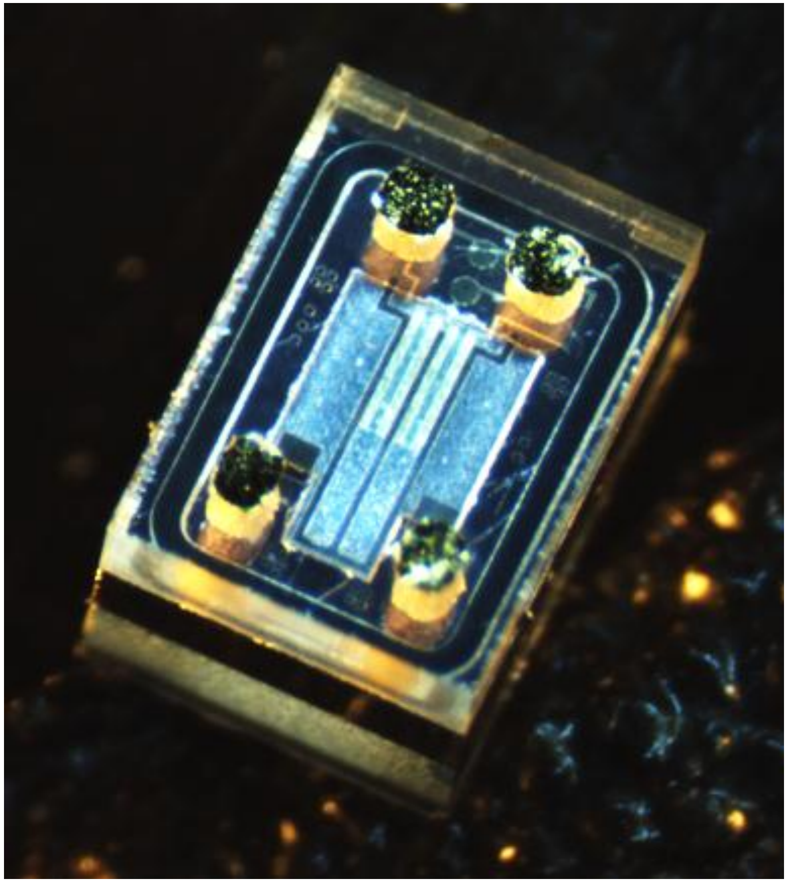
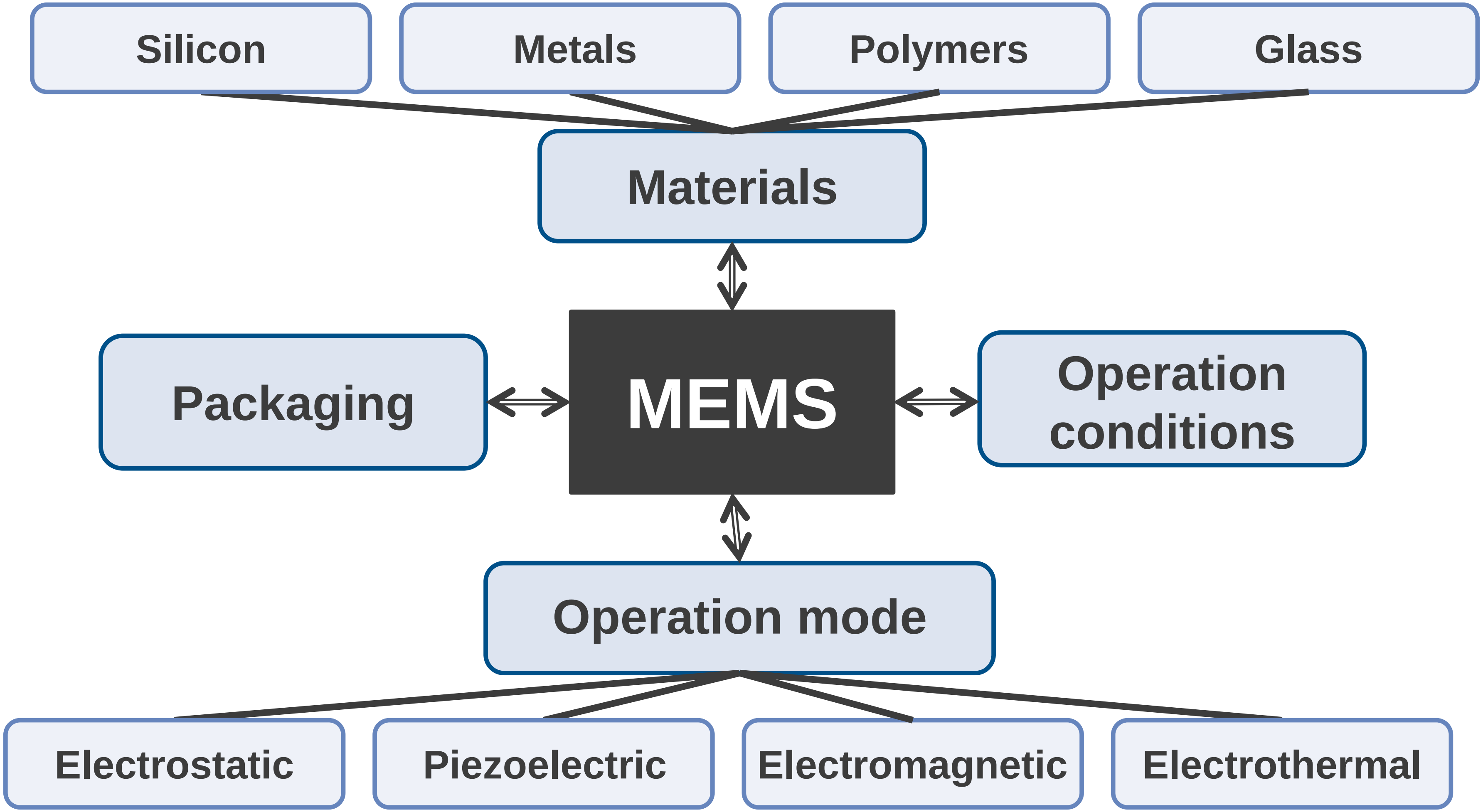
Outline

- Radiation tolerance of MEMS
- PiezorPress resonator design
- Electrical characterization
- Pressure sensitivity
- ^{60}Co irradiation tolerance



Radiation tolerance of MEMS



Silicon

Metals

Polymers

Glass

Materials

Packaging

MEMS

Operation conditions

Operation mode

Electrostatic

Piezoelectric

Electromagnetic

Electrothermal

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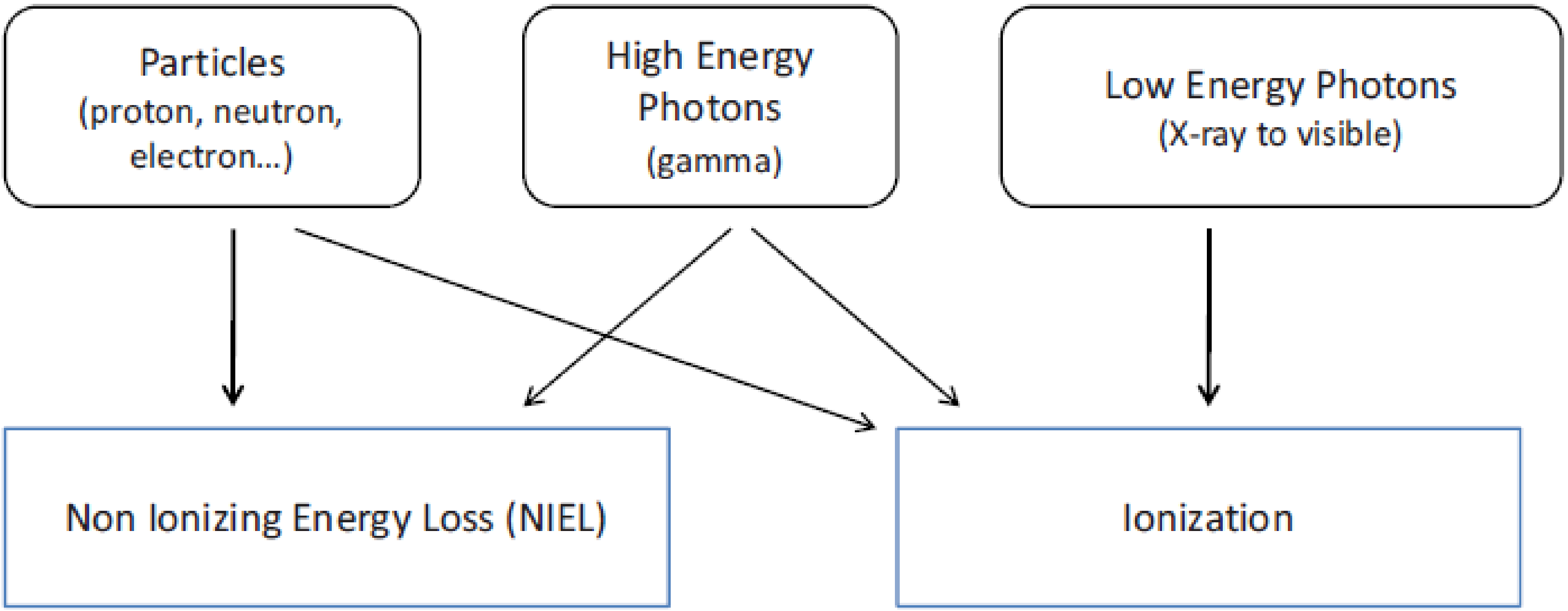
Radiation damage



Particles
(proton, neutron, electron…)

High Energy Photons
(gamma)

Low Energy Photons
(X-ray to visible)

Non Ionizing Energy Loss (NIEL)

Ionization

- Increased defect concentration
- Decreased carrier mobility, lifetime and concentration

- Charge accumulation
- Charge transport
- Bonding changes
- Decomposition

Adapted from :
European Space Agency Procedures Standards and Specifications, document ESA PSS-01-609 (May 1993) Radiation Design Handbook, available at: https://escies.org/ReadArticle?docId=263

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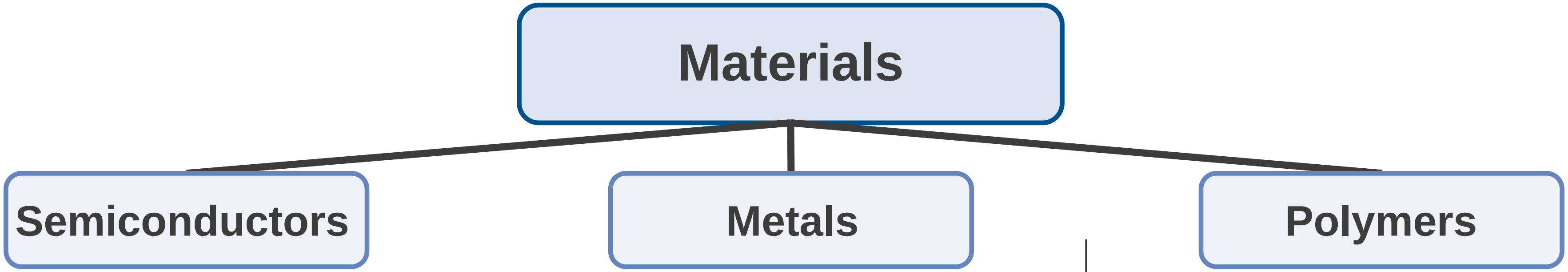
Effect of radiation on materials



Materials

Semiconductors

Metals

Polymers

Mechanical properties can be considered to be unaffected by radiation

Elasticity of SCSi changes by less than 0.1% up to 100 Mrad doses (1)

DD: Changes in carrier lifetime, mobility and concentration

Changes in mechanical properties

Outgassing

Decomposition

See H.R. Shea, *J. Micro/Nanolith. MEMS MOEMS* **8** (2009) 031303
(1) J. Gomes and H.R. Shea, *Proc. of SPIE* **7928** (2011) 79280G-1

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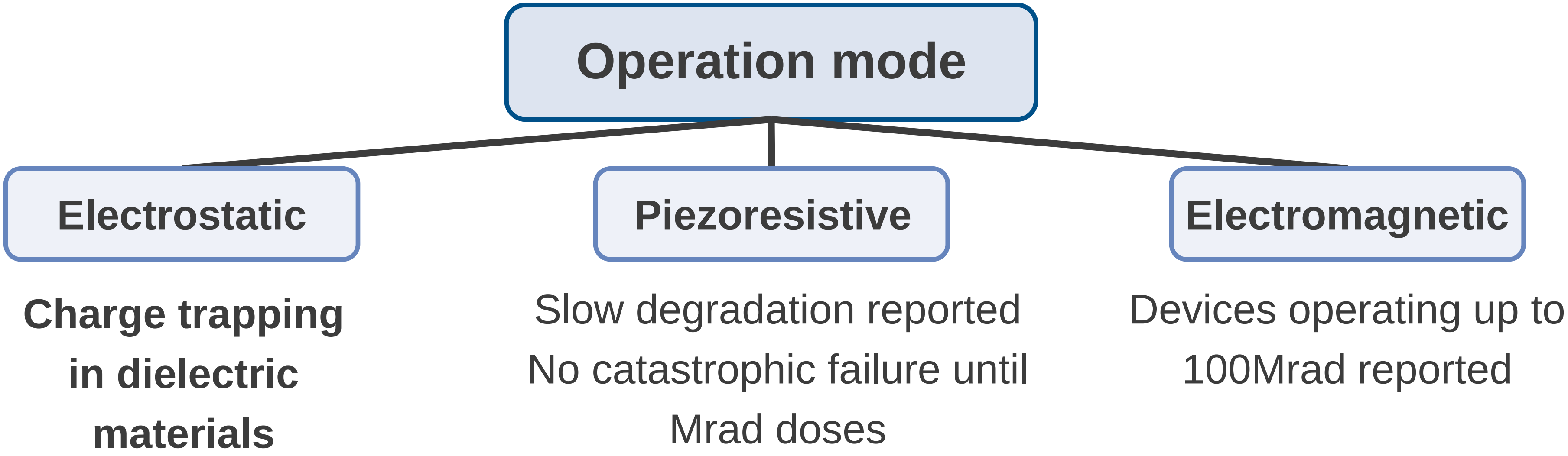
Radiation-induced failures in MEMS



Operation mode

Electrostatic

Charge trapping in dielectric materials

Piezoresistive

Slow degradation reported
No catastrophic failure until Mrad doses

Electromagnetic

Devices operating up to 100Mrad reported

See H.R. Shea, *J. Micro/Nanolith. MEMS MOEMS* **8** (2009) 031303

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Minimizing radiation damage in MEMS

- **Ensuring that all conductors be at well-defined potentials** and not be allowed to float to avoid undesired electrostatic forces (due to charging of conductors).
- Change of **dielectric material to one with lower trap density**.
- Adding a **charge dissipation layer on the dielectric**.
- A geometry change to **eliminate the dielectric from between moving surfaces**, and from under moving surfaces.
- A geometry change to **minimize the exposed area of dielectric**, or replacing the dielectric films with arrays of dielectric posts.
- A geometry change to **reduce the sensitivity to trapped charge**, e.g., stiffer restoring springs.
- **Electrical shielding**, by covering exposed dielectric with a conductor as at well-defined potential

Charge trapping in dielectric material

From: H.R. Shea, *J. Micro/Nanolith. MEMS MOEMS* 8 (2009) 031303
A.L. Hartzell, M.G. Da Silva, H.R. Shea, *MEMS Reliability,* Springer (2011)

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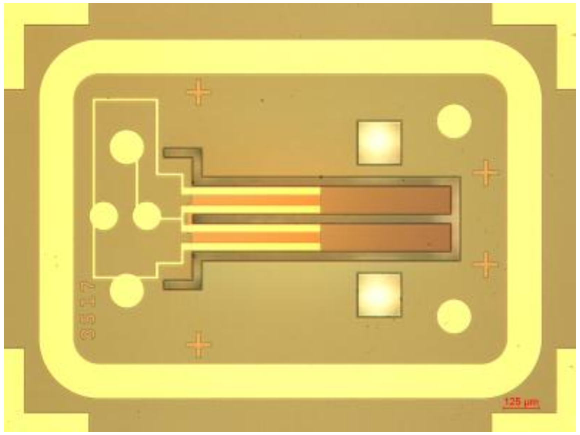
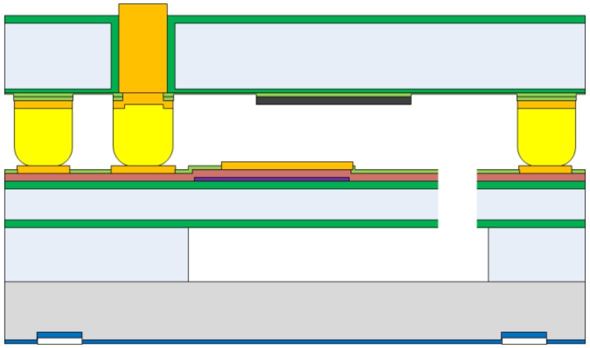
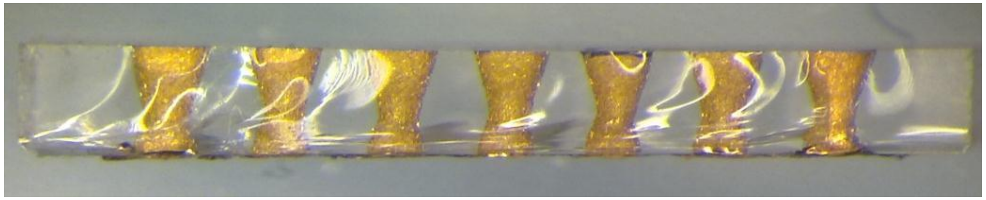
BAW resonator - Technological challenges

Resonator fabricated within ESA-TRP project

- Resonator for pressure sensing in small cavities (nl)
- TGV for electrical contact
- Eutectic bonding technology
- Bonding stress analysis
- Hermeticity testing







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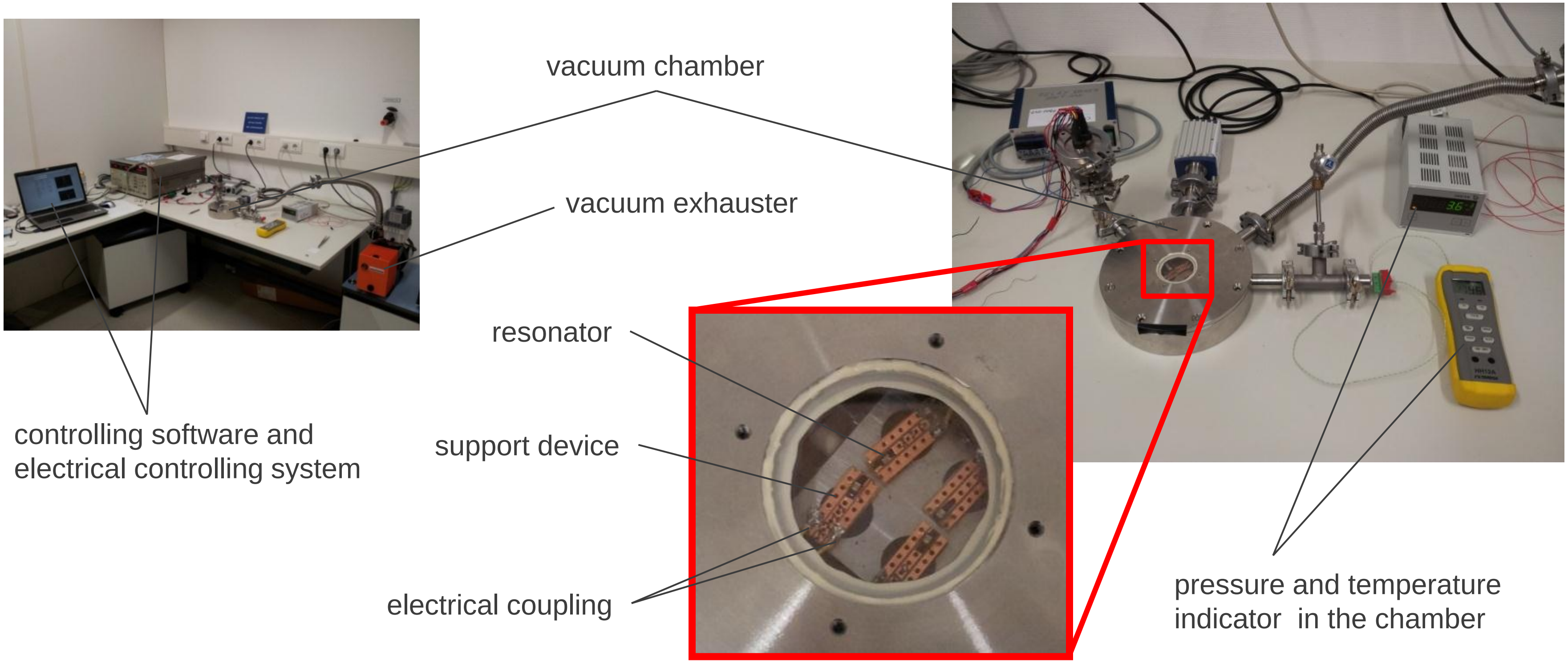
Experimental specifications:

- Test procedure:
  - Fixation of the resonators on a support device, wire-bonding and electrical testing.
  - Characterization of 4 resonators at a time using the depicted equipment.



vacuum chamber

vacuum exhauster

resonator

support device

electrical coupling

controlling software and
electrical controlling system

pressure and temperature
indicator in the chamber

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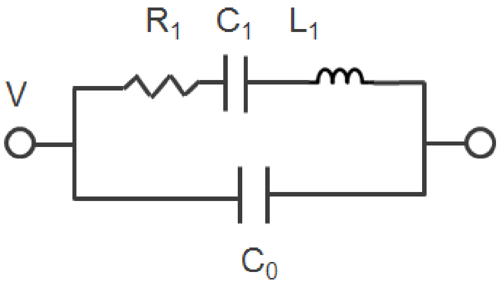
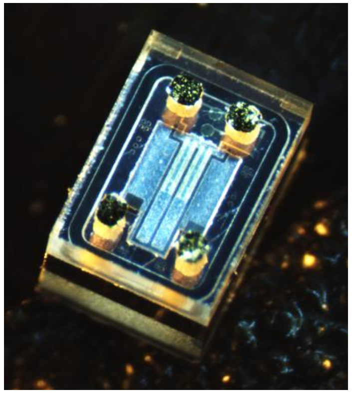
Electrical characterization of Piezo-resonators

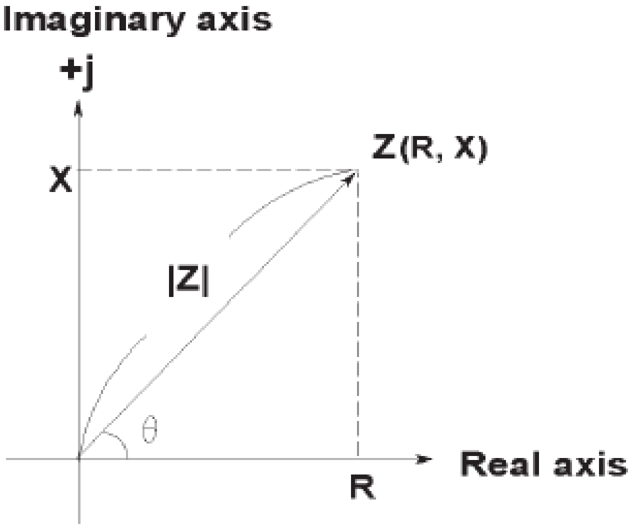
Butterworth-van-Dyke equivalent circuit





$$f_{serial} = \frac{1}{2\pi\sqrt{L_1 C_1}}$$

$$Q_{serial} = \frac{\omega_1 L_1}{R_1}$$



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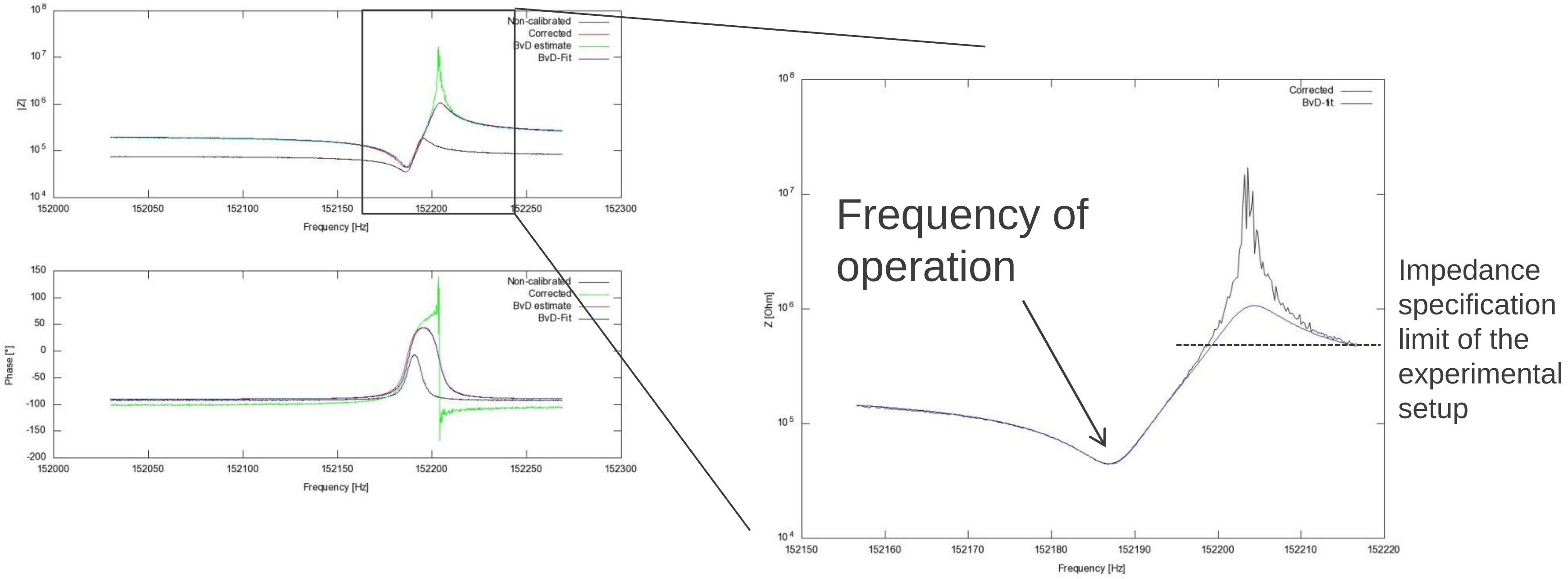
Improvement of BvD parameter extraction

- 4-parameter nonlinear fitting algorithm
- Temperature correction

Parameter	Standard deviation
f_{res_serial}	9.4ppm
Q-factor	370



Frequency of operation

Impedance specification limit of the experimental setup

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Influences on the resonator performance

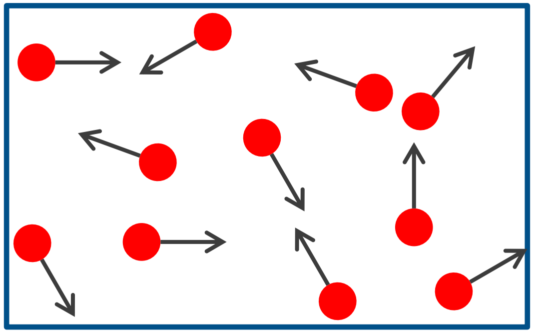
- Pressure
- Strain

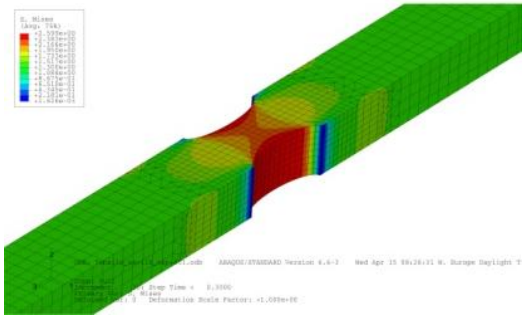
  → Influence of bonding on the strain in the device
- Ageing

  → Radiation

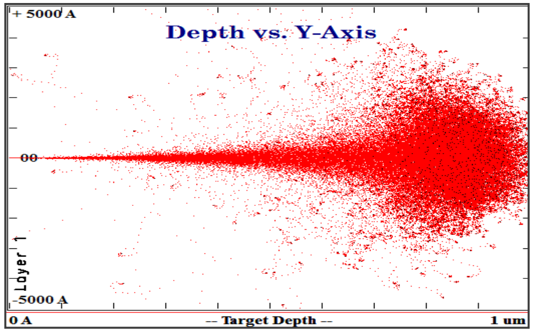
  → Mechanical loads

  → Environmental hazards





http://www.spacex.com



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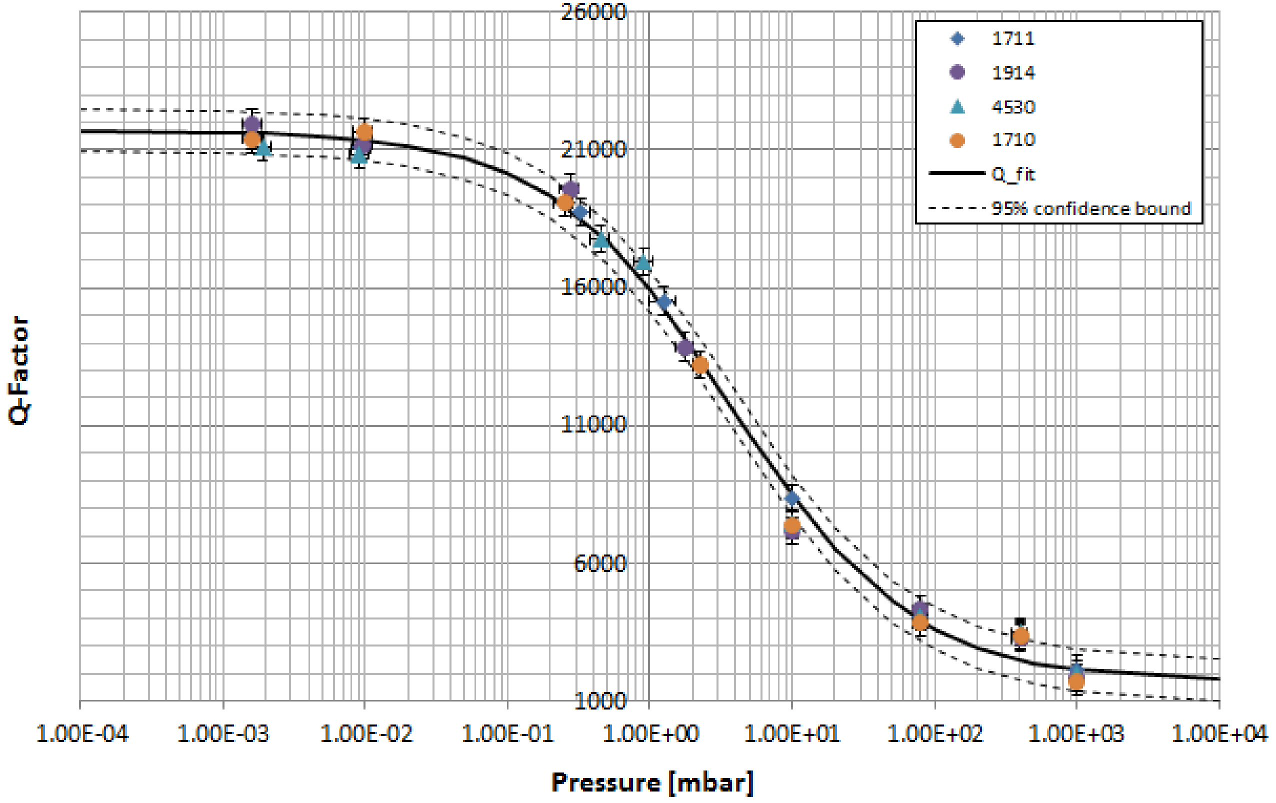
Resonator electrical testing



Pressure sensitivity maximum in the desired pressure regime

Good reproducibility of the Q-factor ↔ Pressure curves

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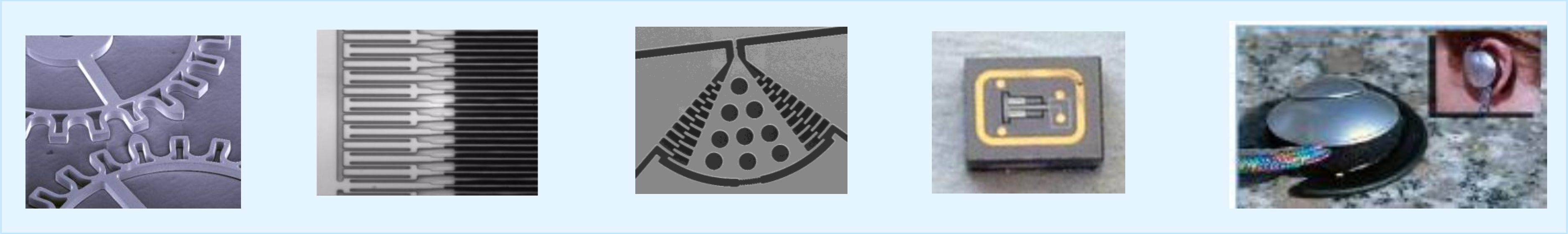
High Resolution X-ray Diffraction (HRXRD) in MEMS reliability:



Design:
- components
- device
- 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

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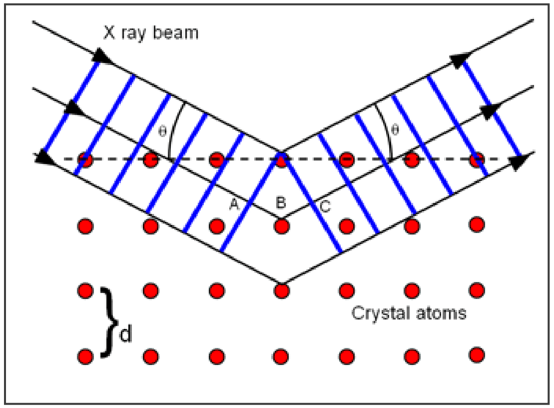
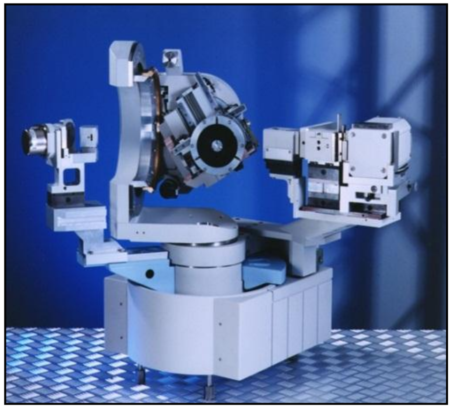
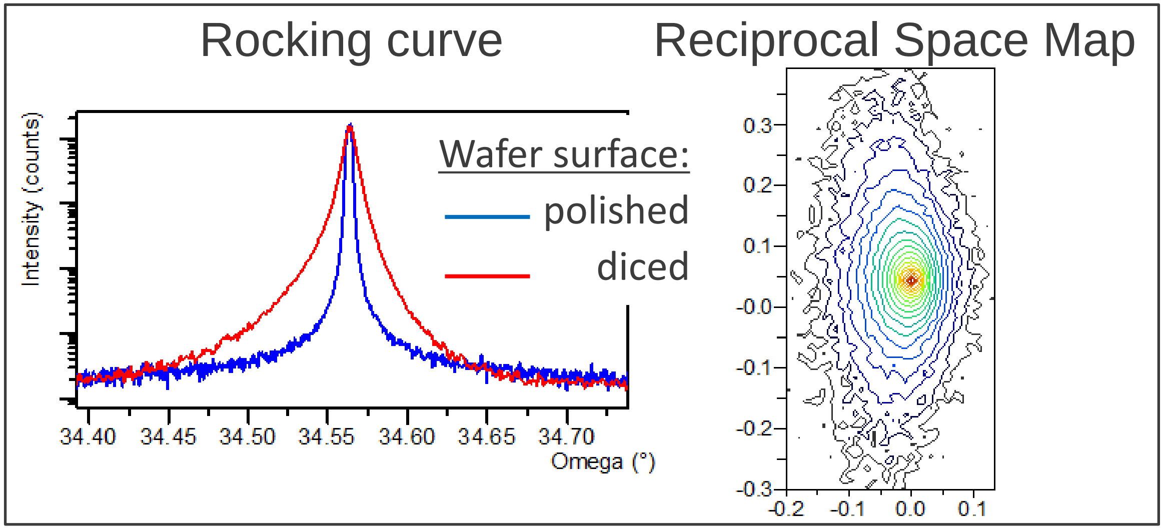
High-resolution X-ray Diffraction



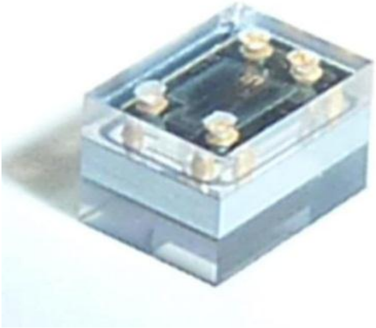
$$n\lambda = 2d\sin(\alpha)$$

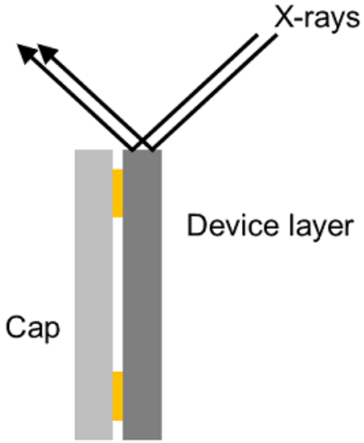


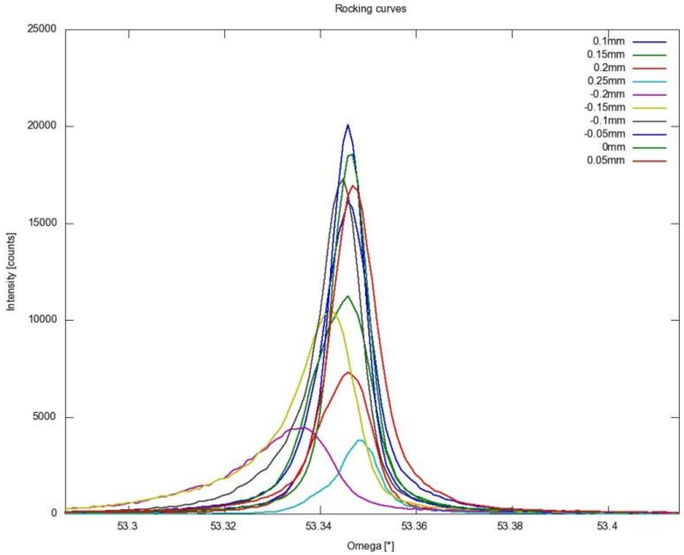


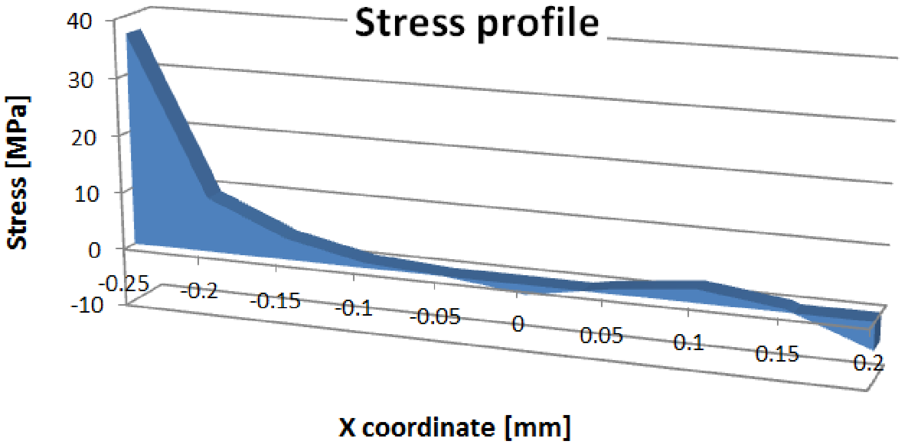
1. Strain
2. Curvature
3. Defects from diffuse scattering

Bonding stress analysis









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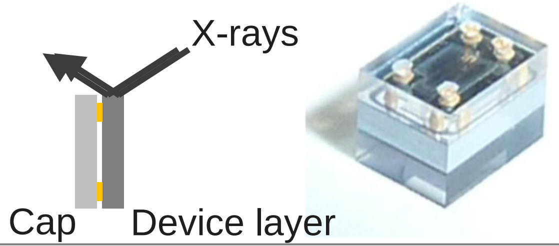
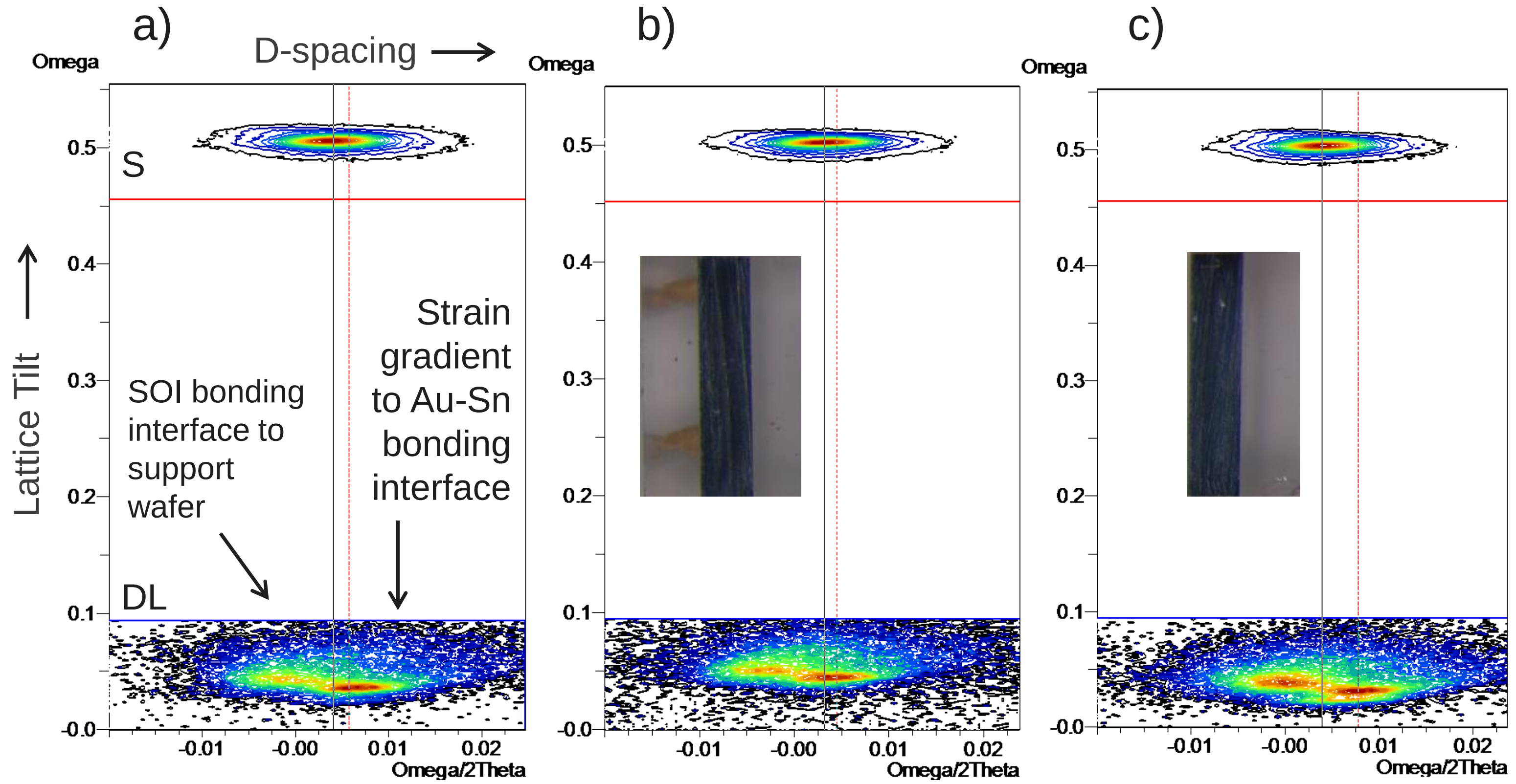
HRXRD investigation of bonding stress





Stress measurement prior to packaging (c) and WLP bonded devices (a and b). Only small changes have been observed → Au-Sn eutectic bonding is a suitable packaging approach which will influence the operation of the device in a negligible way.

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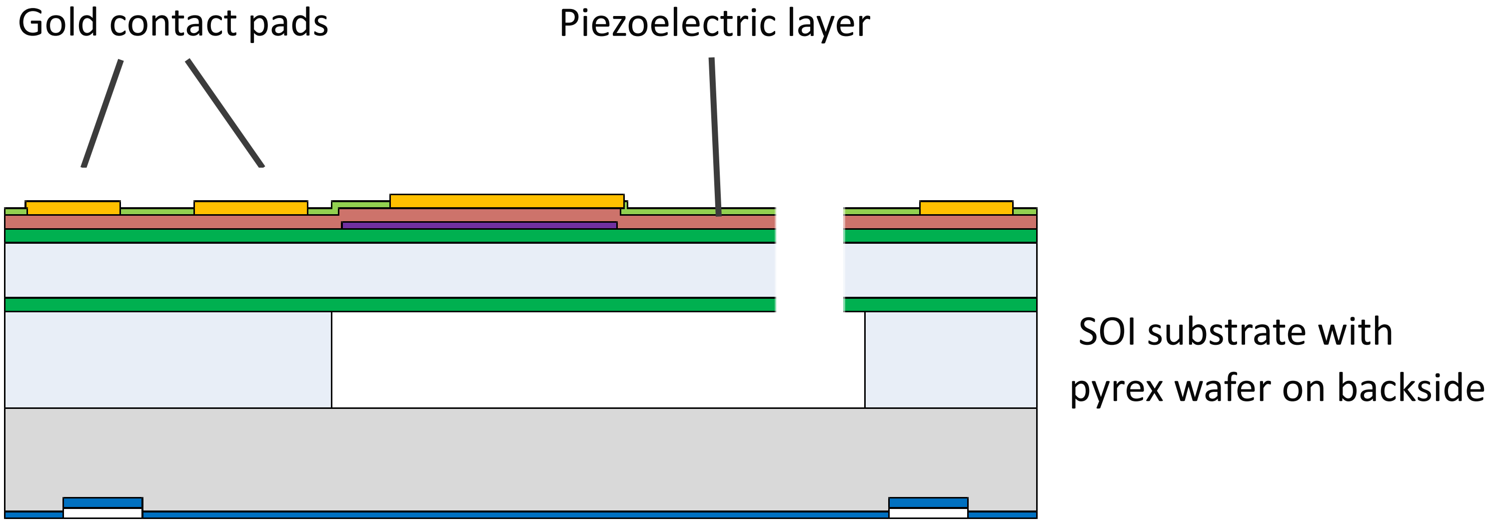
Possible degradation effects



- Mechanical properties dominated by SCSi (rad hard)
- Possibility of charge trapping in piezoelectric layer or SiO_n (bias or change in piezoelectricity of the piezoelectric material)

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Gamma – Irradiation

Test location:

- ESA Co-60 facility @ ESTEC

Test conditions:

- Dose rate: 90rad(Si)/min
  (Standard Dose rate window: 3.6krad/h to 36krad/h)
- Spot size ~25x25cm
- Functional tests on-site
- Annealing at RT at equal biasing conditions with functional tests after 1 week and 4 weeks.

ESCIES Dose Rate to Distance & Area Calculator

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Biasing conditions

- Biasing conditions heavily influence the radiation tolerance (especially charge yield)
- Increased radiation damage in floating devices has been reported.
- Devices with fixed potential showed less charge trapping.

L.P. Schanwald et al, *IEEE Trans. On Nucl. Sci.* **45** (1998)

Design rules aim at (i.a.): «Ensuring that all conductors be at well-defined potentials and not be allowed to float to avoid undesired electrostatic forces (due to charging of conductors)»

A.L. Hartzell, M.G. Da Silva, H.R. Shea, *MEMS Reliability,* Springer (2011)

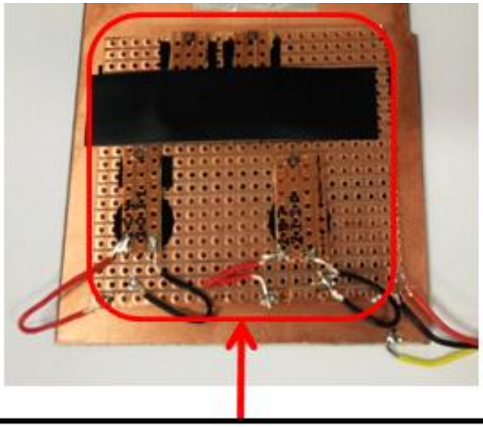
Biasing conditions during irradiation:

- ½ devices: Floating
- ½ devices: 50mV DC-Bias (operation at 50mV AC-voltage)

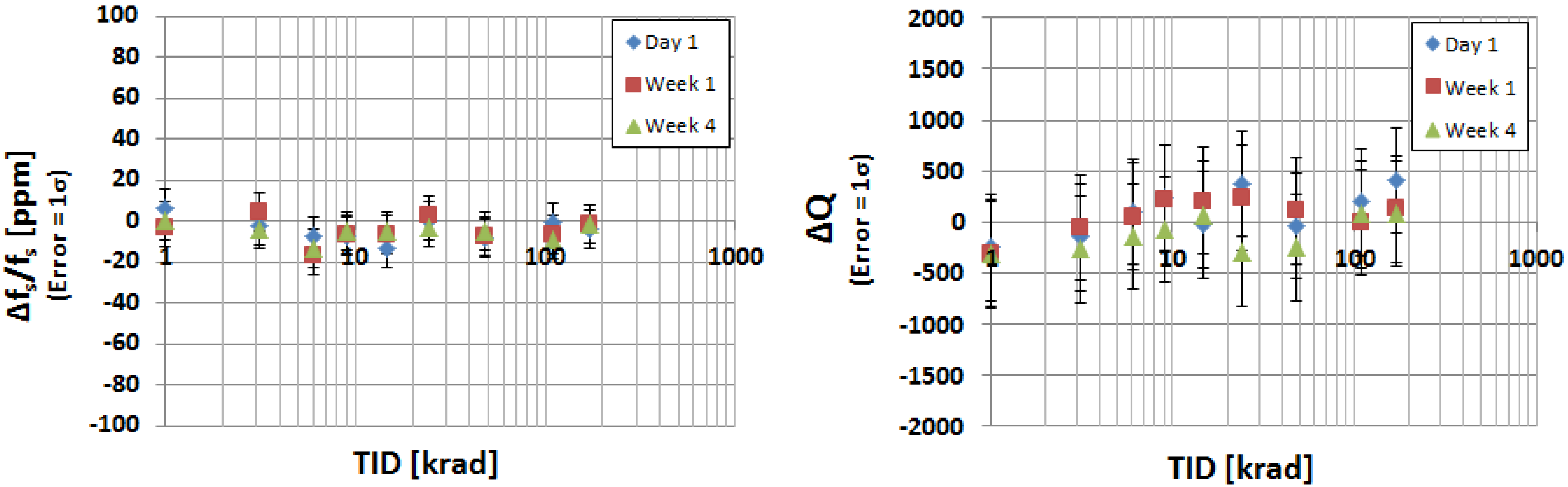
^{60}Co irradiation of MEMS resonators

Totally 31 irradiated devices

Dose [krad(Si)]	# Samples
3	4
6	4
9	4
15	4
24	4
48	4
110	4
170	3
Control	3


WALES MEMS components

Irradiation results



No statistically significant change in the resonance frequency and the Q- factor

No difference observed between biased (potential defined) and floating (undefined potential) devices

→ The gamma-irradiation does not lead to a statistically significant deterioration of the device performance

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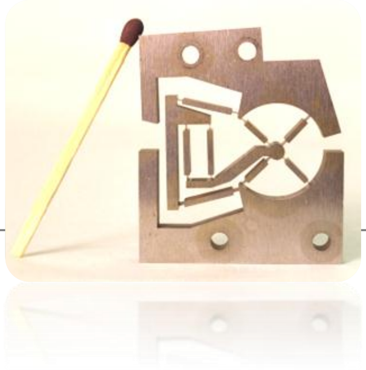
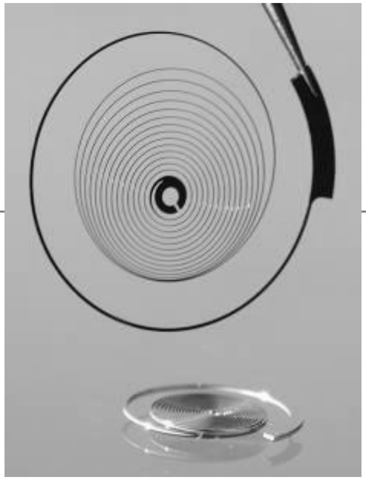
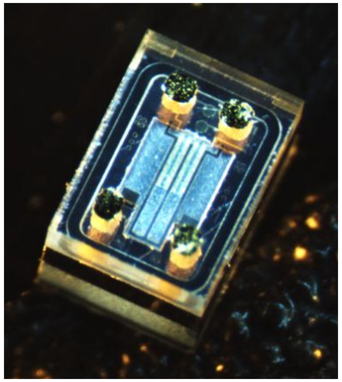
Conclusions





→ SCSi structures with a very small size.

Packaging stresses and environmental hazards during operation introduce defects during the life time of SCSi structures.



→ Increase of failure risk.

→ Reliability studies are needed to identify failure sources for better design and long term functioning.

- Tuning fork resonator MEMS used for pressure monitoring in small cavities
- Tools for MEMS quality control and non-destructive testing by HRXRD
- No deterioration of the device performance by TID observed

→ Steps towards more radiation-tolerant and reliable MEMS devices

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Thank you for your attention !

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