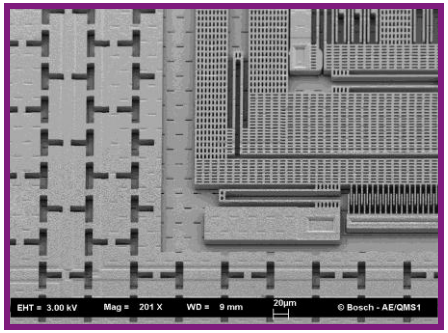
8th esa round table on micro and nano technologies
15 - 18 october 2012
European Space Agency

MEMS Sensors for Application in Space



V. Rochus, M. Akif Erismis, R. Jansen, M. Farghaly, M. Al-Moghazy, A. Ray Chaudhuri, P. Helin, S. Severi, S. Ranvier, H. Lamy, P. Rochus, A. Witvrouw, H. A. C. Tilmans and X. Rottenberg

presented by **Harrie Tilmans**

ESA-ESTEC, 17 October 2012

OUTLINE

- Intro MEMS for space

- SiGe-based MEMS technology platform

- SiGe-MEMS MicroSensors@imec.be
  - Inertial sensors
  - Pressure sensors
  - Magnetometer
  - Other

- Conclusions

MEMS for SPACE

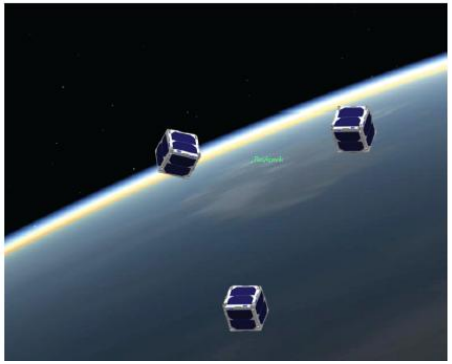
(spacecrafts, micro/picosatellites, ….)

Applications/potential use:

- GNC: "Guidance, Navigation and Control" (descent and landing operations, de-spin, attitude control, ….); Calculation of orientation and altitude of orbiting satellites
- Measuring satellite-generated magnetic fields (stemming from spacecraft electrical currents and residual magnetization) and measuring sheet of field-aligned currents (through measuring magnetic field $\vec{\nabla} \times \vec{H} = \vec{J}$)

Driving factors:

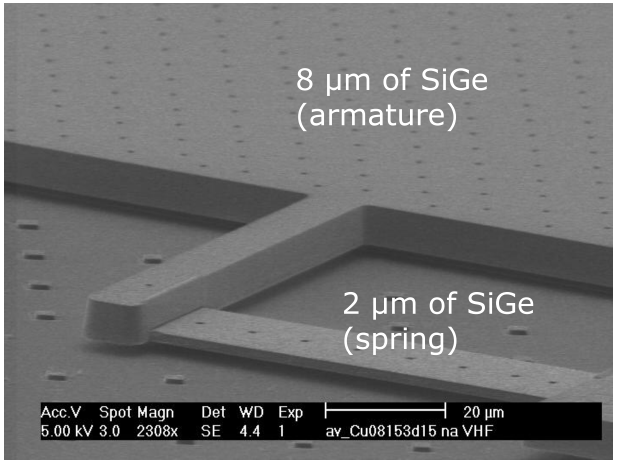
- Low mass,
- Small size/volume, high level of integration
- Low power consumption,
- Robust&Reliable (radiation tolerant)



Multiple sensor functions:

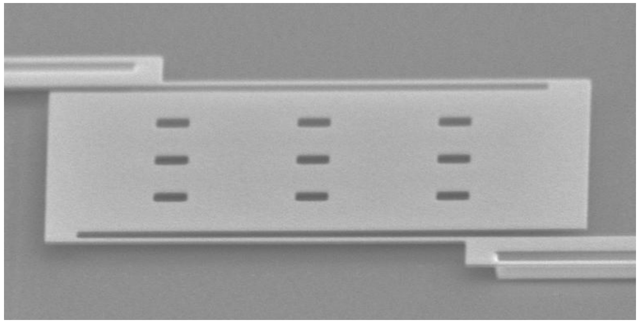
- Acceleration sensor (accelerometer)
- Angular rate/velocity sensor (gyroscope)
- Magnetic field sensor (magnetometer)
- Pressure sensor
- Sun sensor, bolometer, ….

→ MEMS provides a way to go!!



Imec’s SiGe-MEMS platform

“our working horse technology for building MEMS”



Imec's SiGe MEMS – PLATFORM

Generic poly-SiGe technology for MEMS:
- "stand-alone" MEMS, or,
- "MEMS above IC" (CMOS-MEMS)

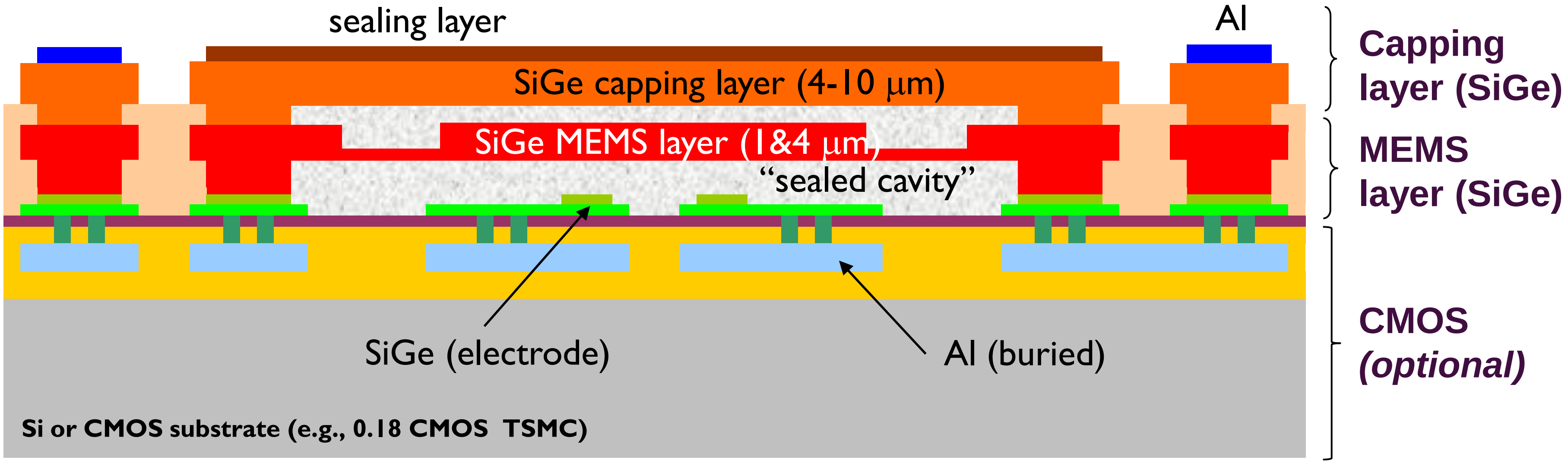
Two structural SiGe layers:
- **MEMS** structural layer (4µm standard)
- Thin film **capping/packaging** layer (4µm up to 10µm thick)

Gap SiGe structural layer of 0.5µm (optional: 0.2µm)

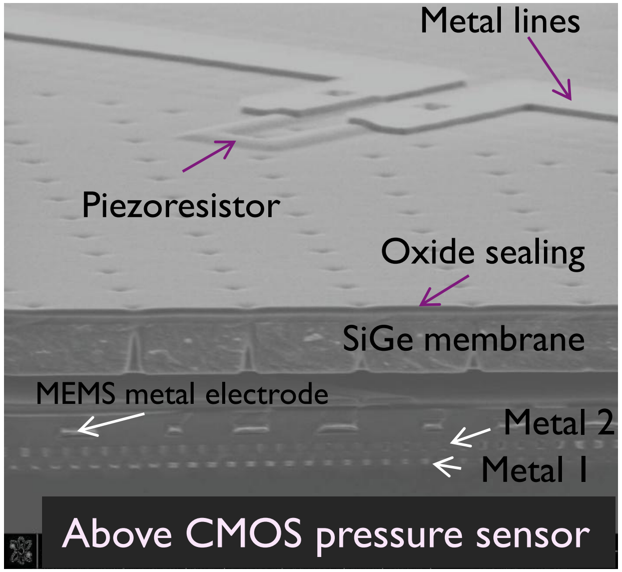
Low-T processing (< 460°C)

Hermetic package seal (1-100 Pa)

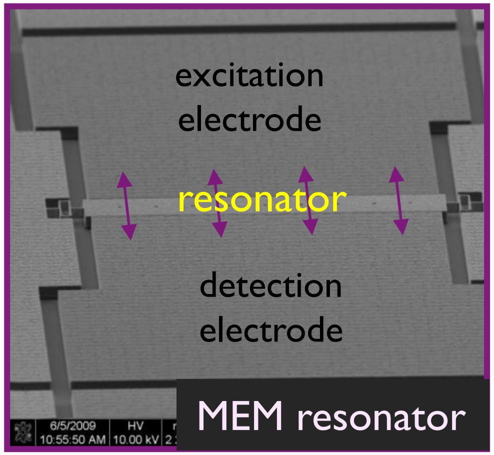
Optional modules:
- Optical (reflective)
- Electrical (metal trace)
- Piezo-resistive layer



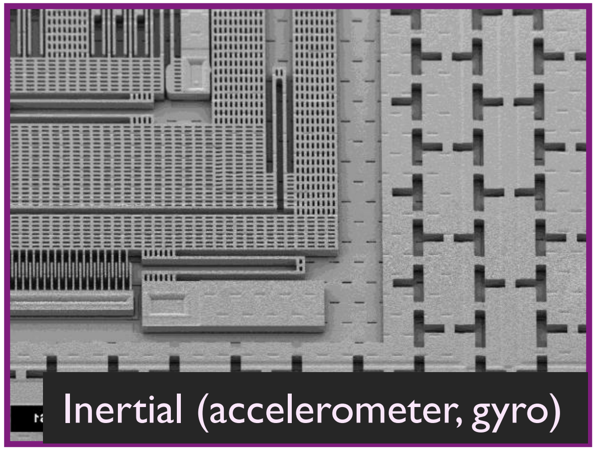
IMEC's SiGe MEMS PLATFORM: EXAMPLES



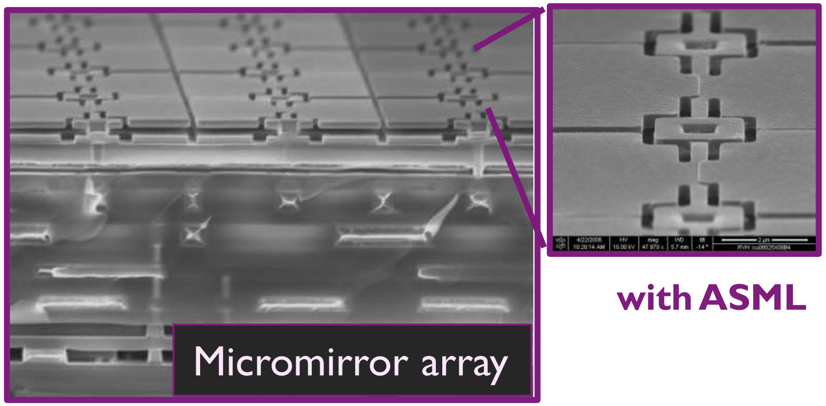
Above CMOS pressure sensor



MEM resonator

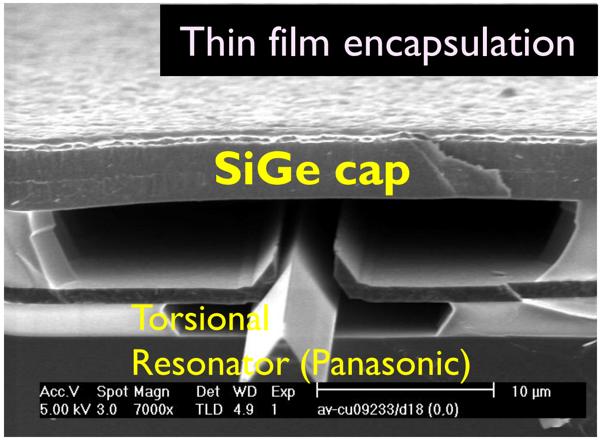


Inertial (accelerometer, gyro)



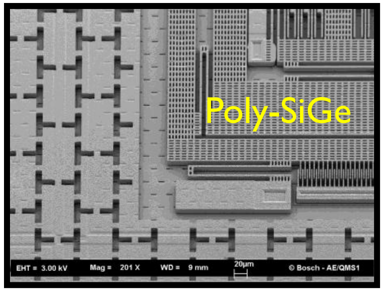
Micromirror array

with ASML



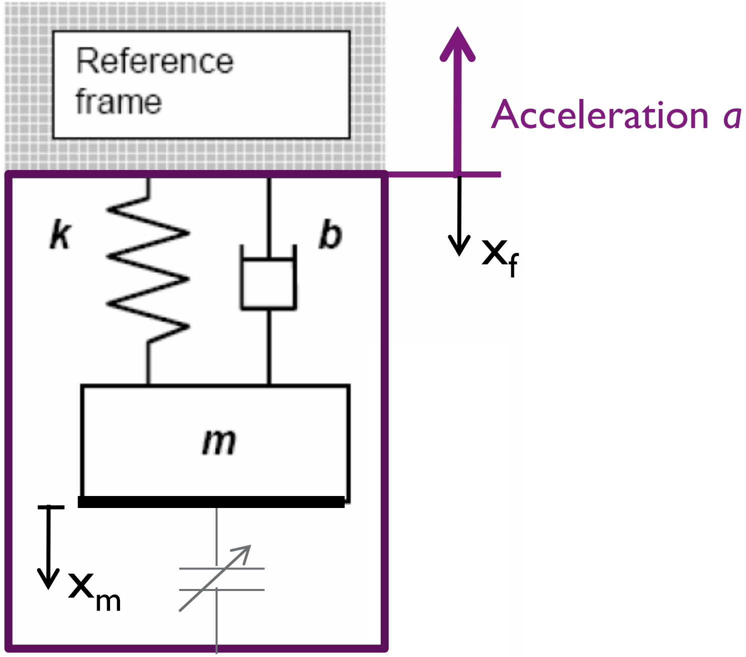
Thin film encapsulation

with Panasonic



SiGe-MEMS
INERTIAL SENSORS (IMU):

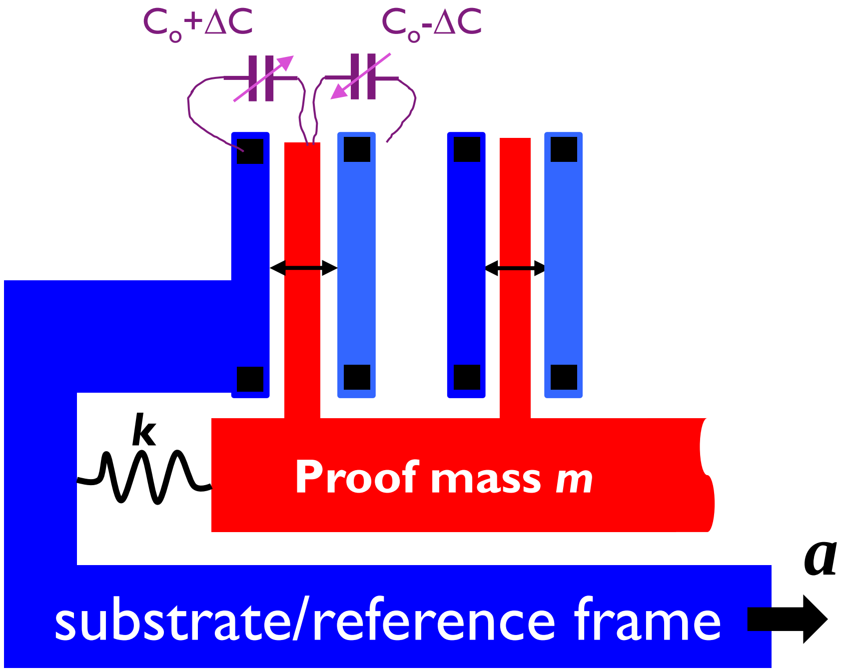
- ACCELEROMETERS
- GYROSCOPES

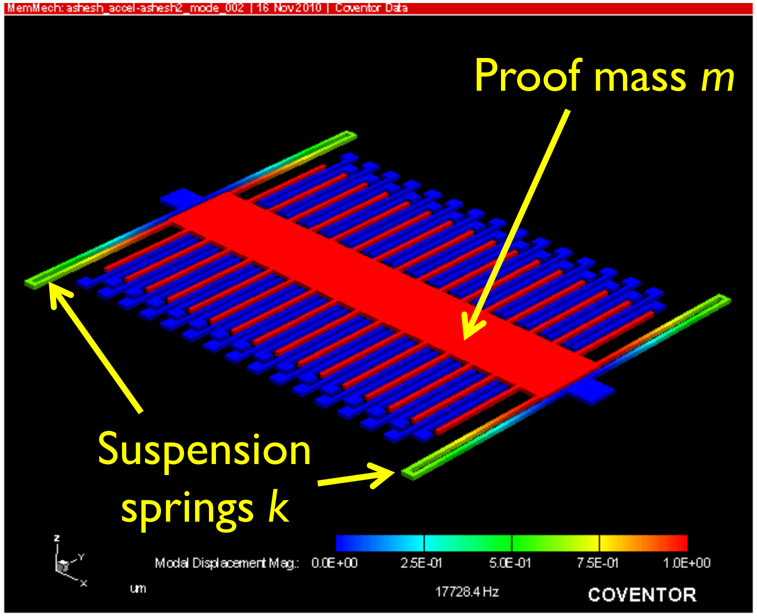


Measure displacement $x_m - x_f = f(a)$

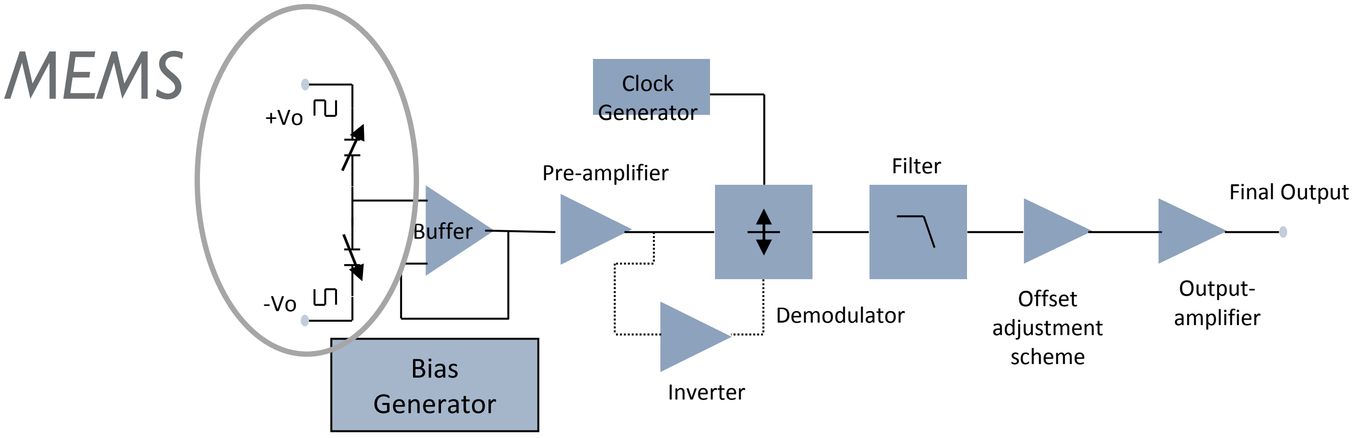
Feature:
ρ_{SiGe} (4500kg/m^3) > ρ_{Si} (2332kg/m^3)

IN-PLANE DIFFERENTIAL CAPACITANCE ACCELEROMETER:
PRINCIPLE of OPERATION

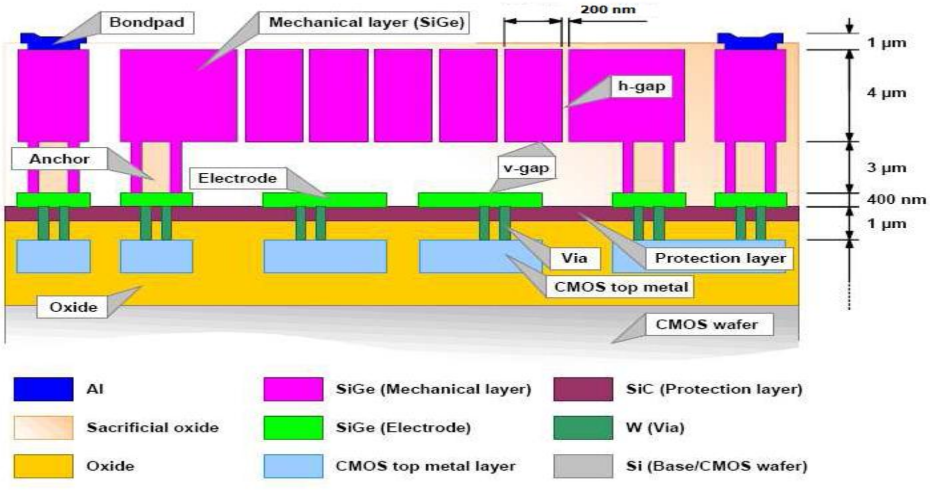




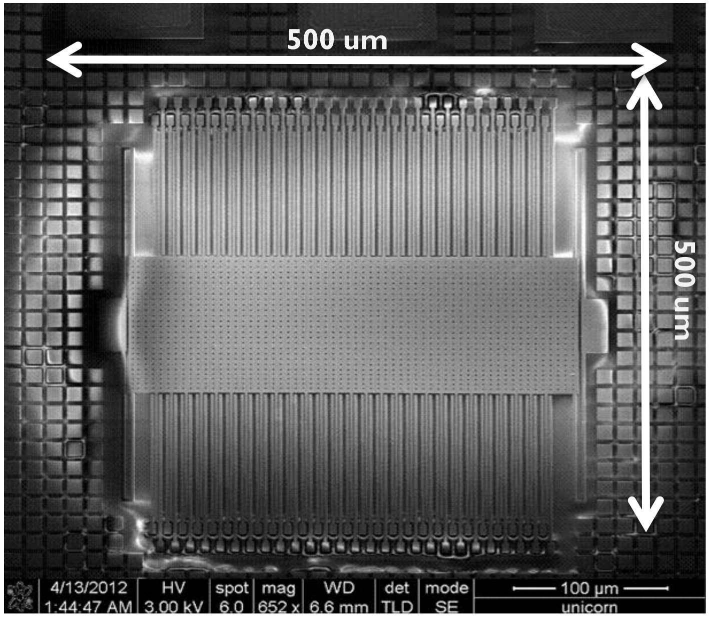
acceleration ***a*** → relative motion of proof mass → capacitance change ΔC → read-out



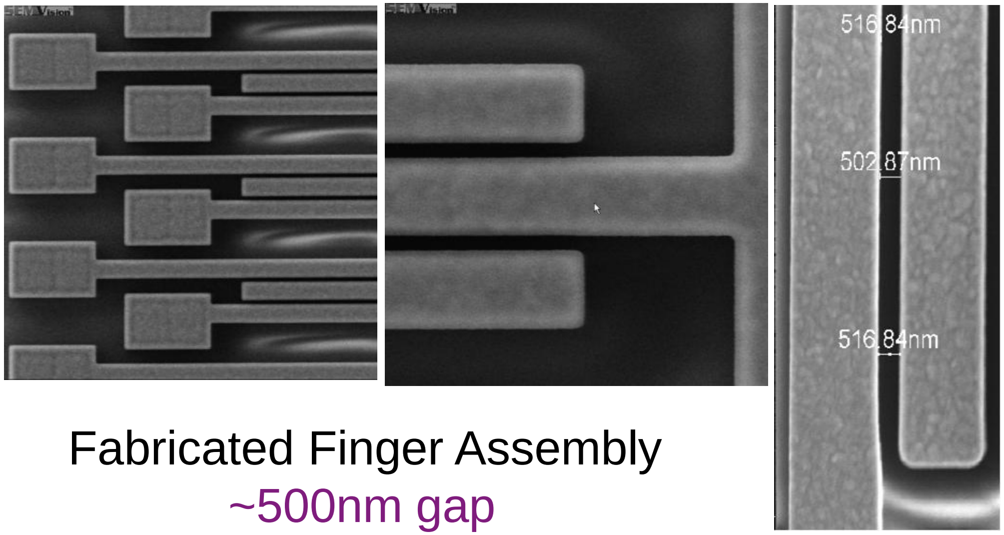
FABRICATION



Above-CMOS compatible SiGe MEMS Process

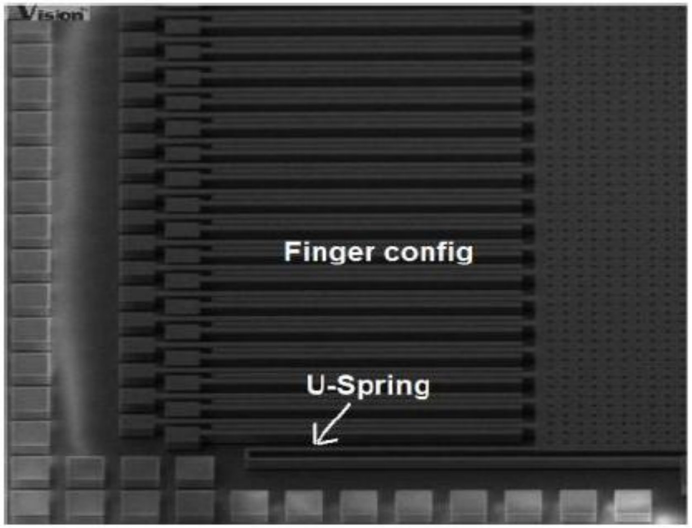


Fabricated Accelerometer



Fabricated Finger Assembly

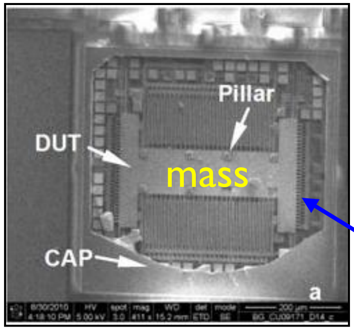
~500nm gap

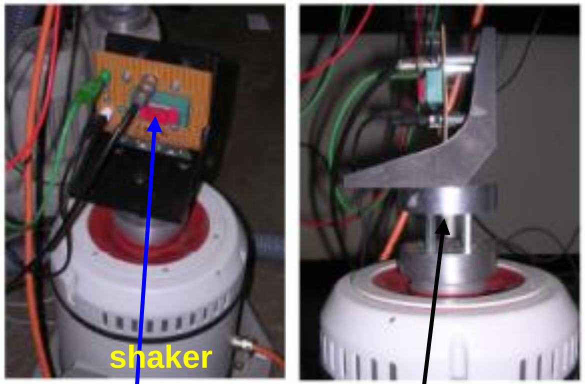


The Fabricated Accelerometer

POLY-SiGe MEMS ACCELEROMETERS: PERFORMANCE

Thin film packaged device

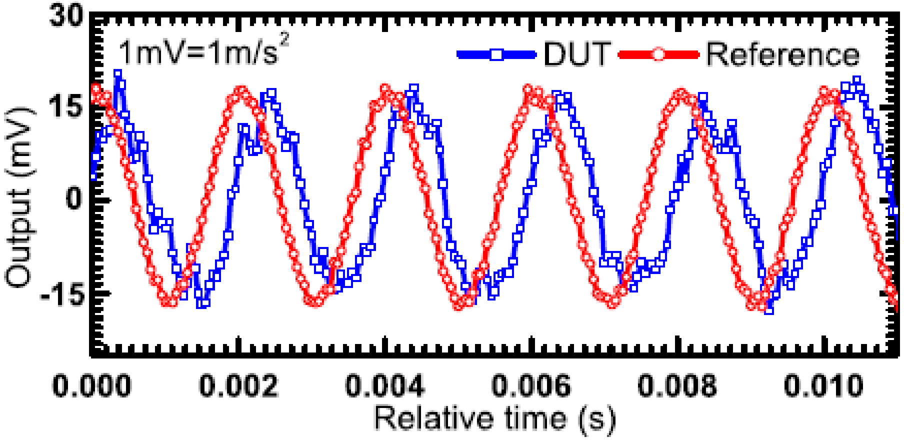


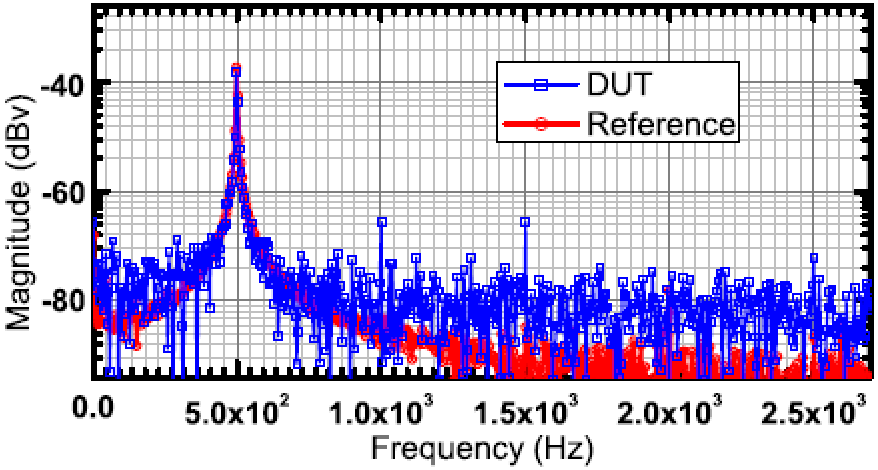


DUT

Reference
Brüel & Kjær 4383
(piezoelectric charge
accelerometer)

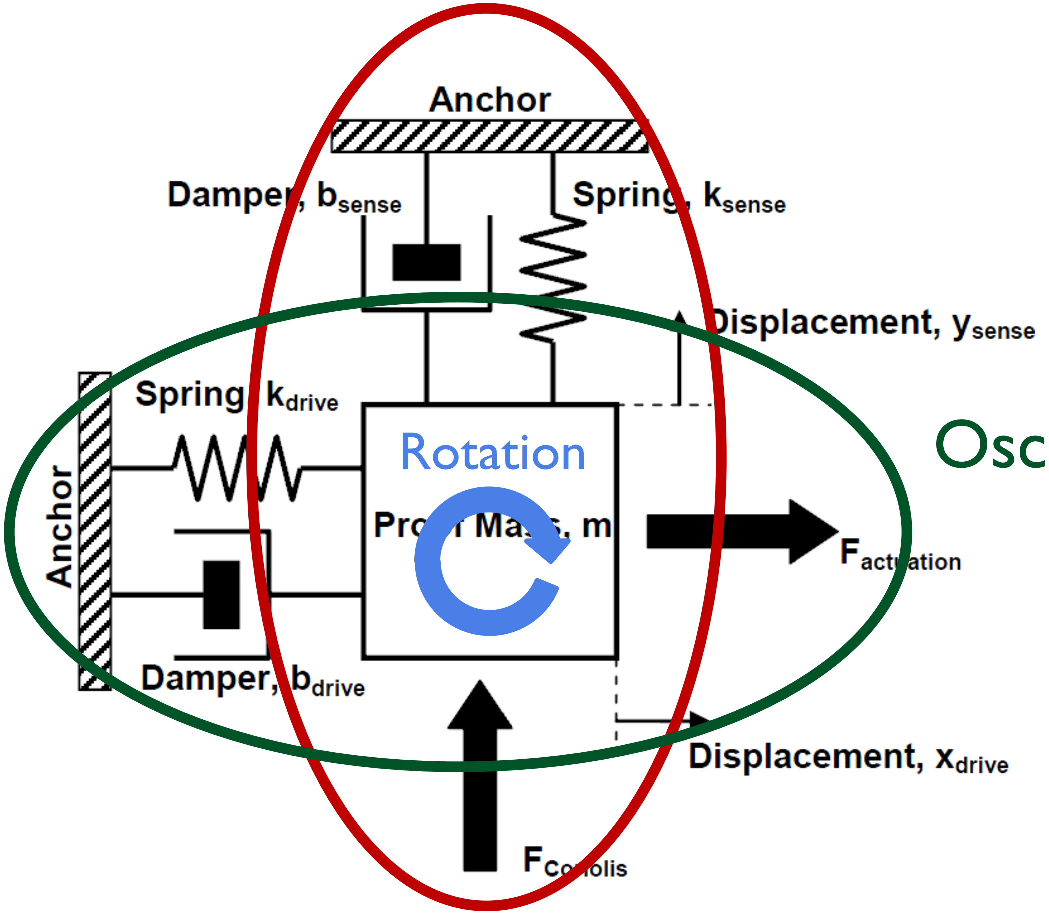
Accelerometer	SiGe MEMS @imec (typical specs)
range	few g
sensitivity/resolution	0.1-1 mg (~0.02 mg/√Hz)
bandwidth	50-1000 Hz
supply voltage	3.3 or 5V or “higher”
shock resistance	few thousand g
radiation hardness	50-100 krad TID
lifetime	“many” years
chip size (1 axis)	~ 1x1 mm^2



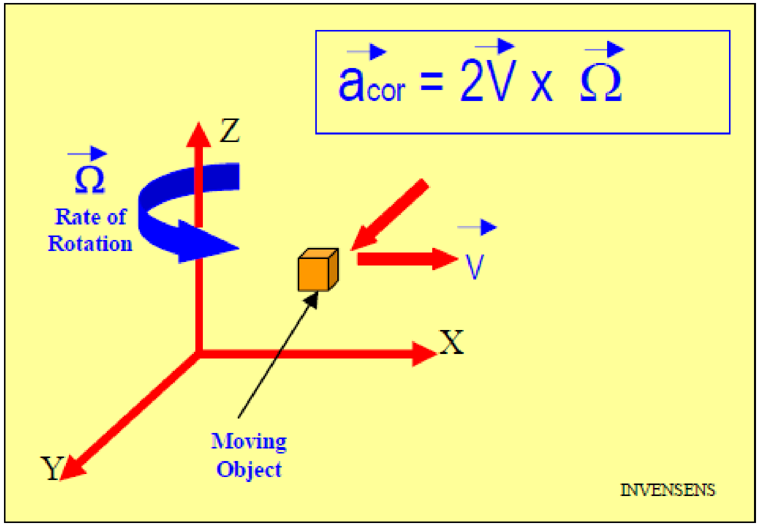


IN-PLANE VIBRATORY GYROSCOPE: PRINCIPLE of OPERATION

Accelerometer = Sense



Oscillator = Drive



Vibratory elements (proof mass) are used to sense rotation

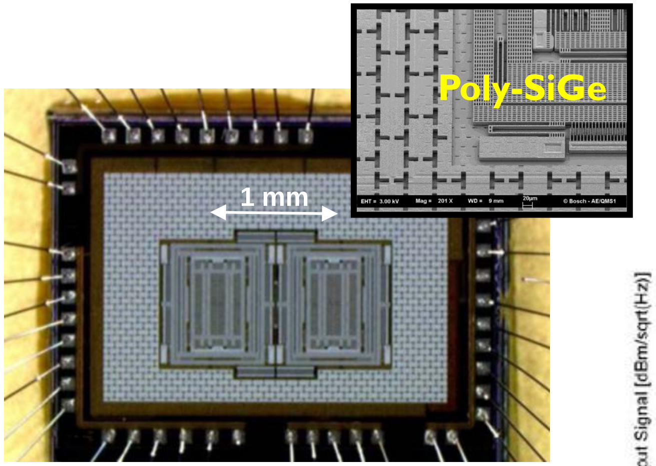
No rotating parts → no bearings → allows micromachining

Poly-SiGe MEMS GYROSCOPE: FABRICATION and PERFORMANCE

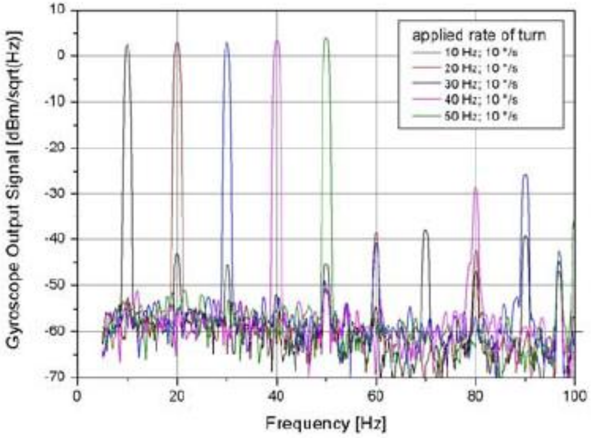
Above-CMOS demonstrator:

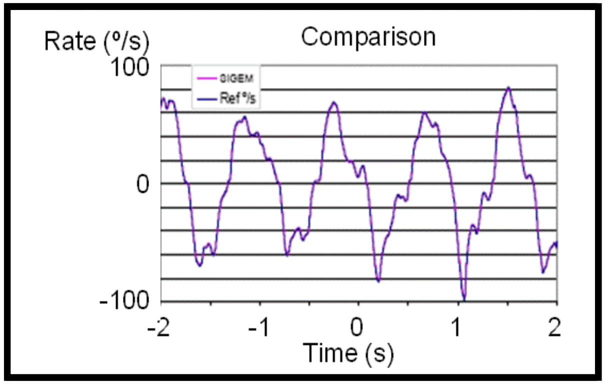
- 10 µm thick poly-SiGe MEMS gyroscope on top of 200mm HV 0.35µm CMOS (NXP)
  - VCO, PLL, amplifiers, etc.
  - Only 3 additional masks (not packaged)
- Movement detected by charge sensing (moving cap. combs)

Gyroscope	SiGe MEMS @imec (typical specs)
range	20-200 °/s
sensitivity/resolution	0.001 °/s/√Hz (0.01°/s @ 50Hz)
bandwidth	20-100 Hz
supply voltage	3.3 or 5V or “higher”
shock resistance	~ thousand g
radiation hardness	50-100 krad TID
lifetime	“many” years
chip size (1 axis)	~ 2x2 mm^2



Joint project with Bosch, NXP, IMSE-CNM, ASM

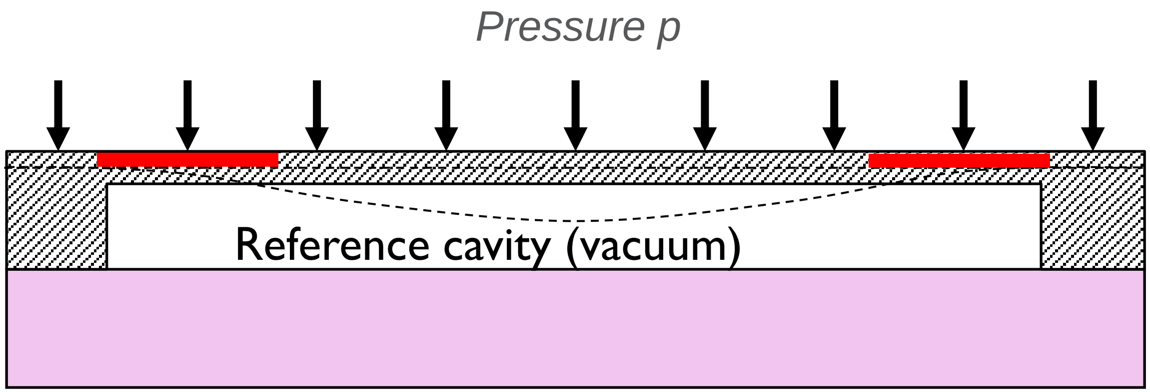




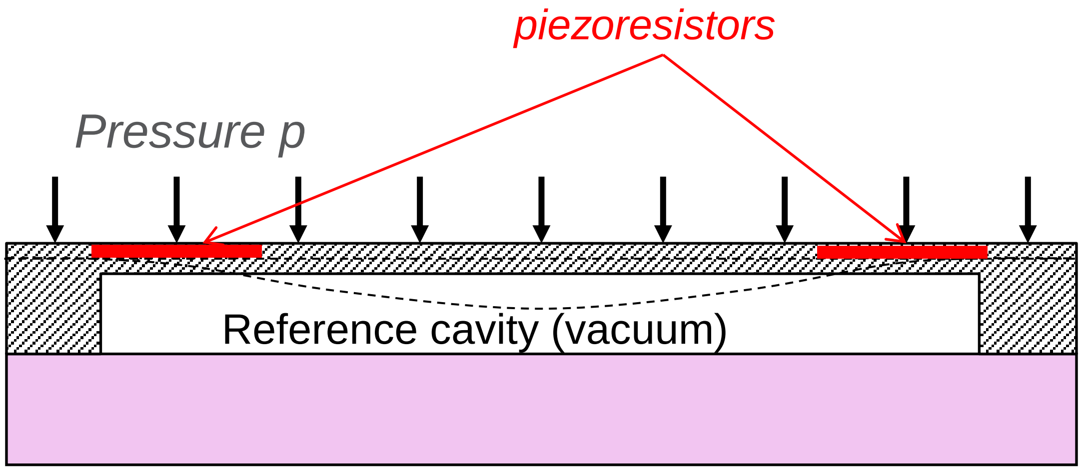
A. Scheurle et al., MEMS2007, pp. 39-42

PRESSURE SENSORS:

- *piezoresistive*
- *capacitive*

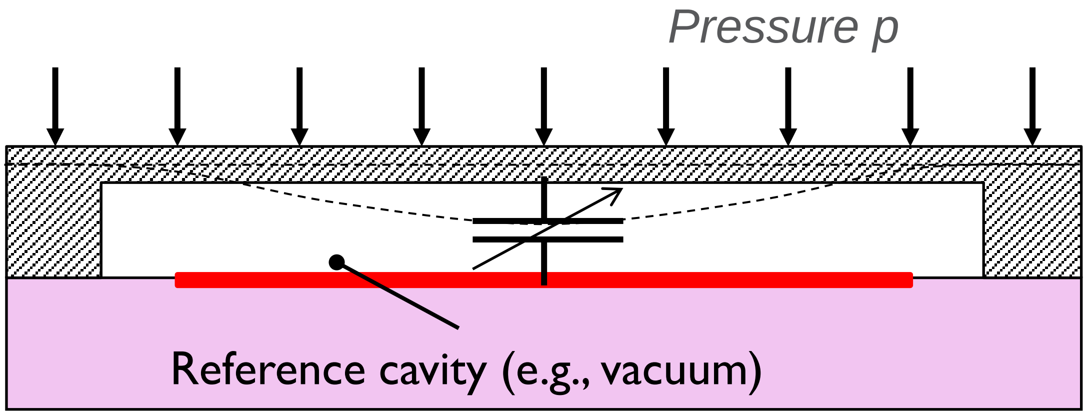


MEMBRANE TYPE PRESSURE SENSORS: PRINCIPLE of OPERATION



Piezoresistive

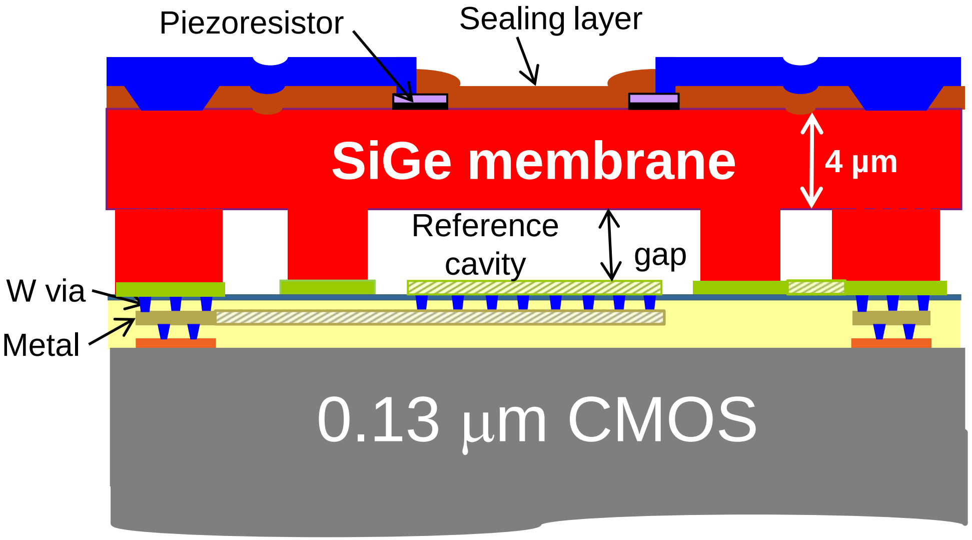
$p \rightarrow$ strain $\rightarrow \Delta R(p)$
$\rightarrow V_{out}(p)$

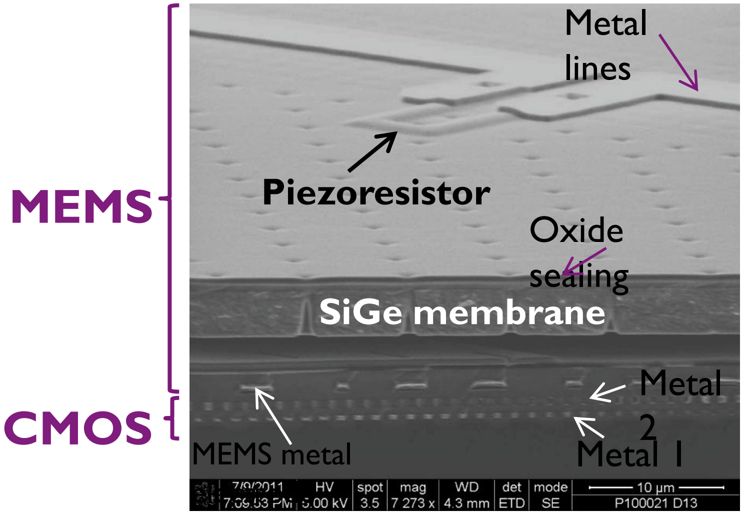


Capacitive

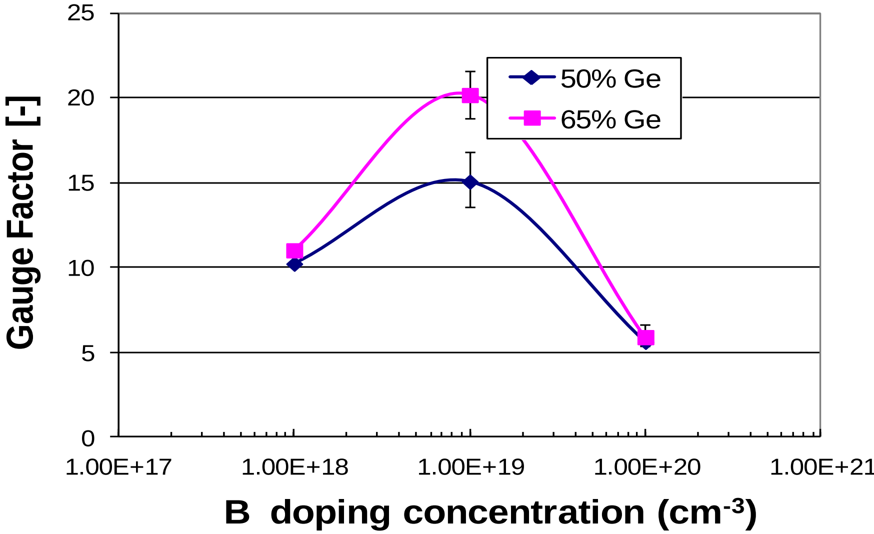
$p \rightarrow$ deflection $\rightarrow \Delta C(p)$
$\rightarrow V_{out}(p)$

PIEZORESISTIVE PRESSURE SENSOR: FABRICATION

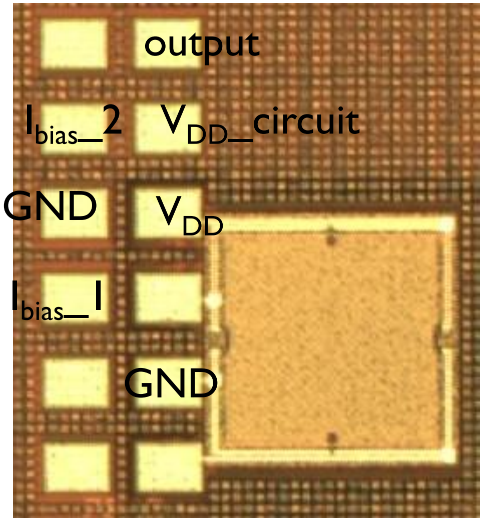




- 2-metal (Cu) 0.13µm CMOS
- W via to connect CMOS to MEMS
- SiGe structure thickness: 4µm (scalable)
- Gap: 3 or 1 µm in this work (can be scaled down to 0.5µm)
- Oxide (vacuum) sealed cavity
- B-doped piezoresistive SiGe layer (G≈20)
- Capacitive sensor combined

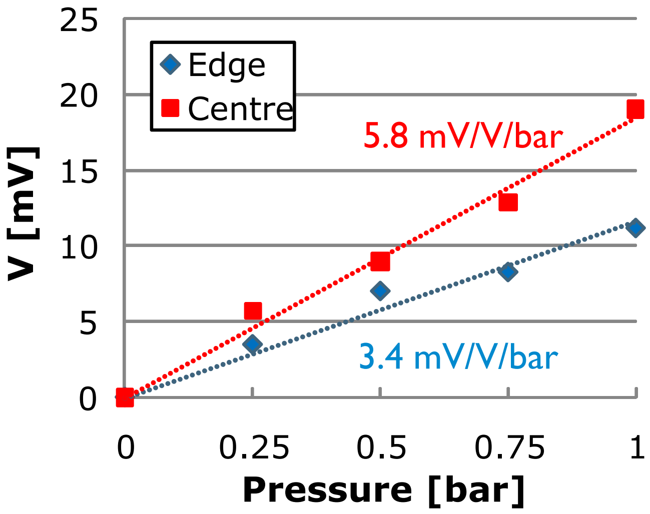


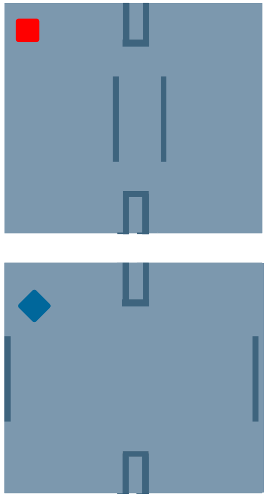
PIEZORESISTIVE PRESSURE SENSOR: PERFORMANCE

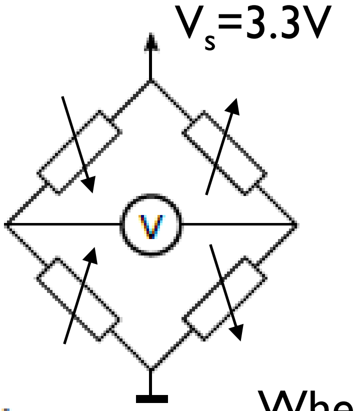


- SiGe membrane: 200x200 μm^2, 4µm thick
- "n-shape" piezoresistors

Piezoresistive pressure sensor	SiGe MEMS @imec (typical specs)
range	0.01-1 MPa
sensitivity	10-1000 mV/V/MPa
resolution	~ 10 Pa
supply voltage V_s	3.3 or 5V or "higher"
shock resistance	thousands of g
radiation hardness	50-100 krad TID
lifetime	"many" years
chip size	~ 0.5x0.5 mm^2

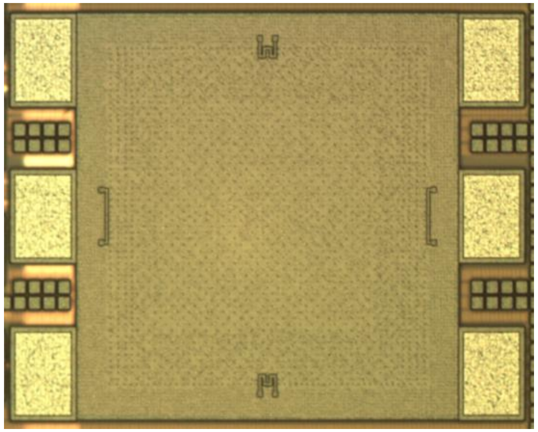






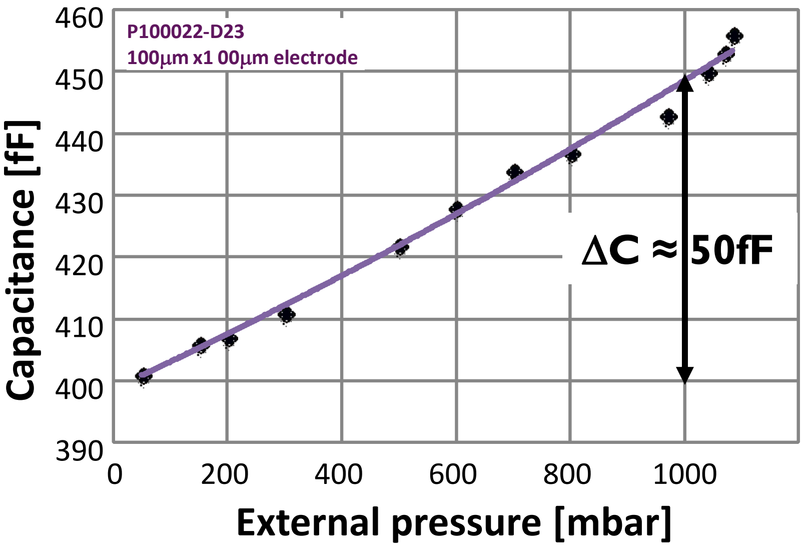
Wheatstone bridge

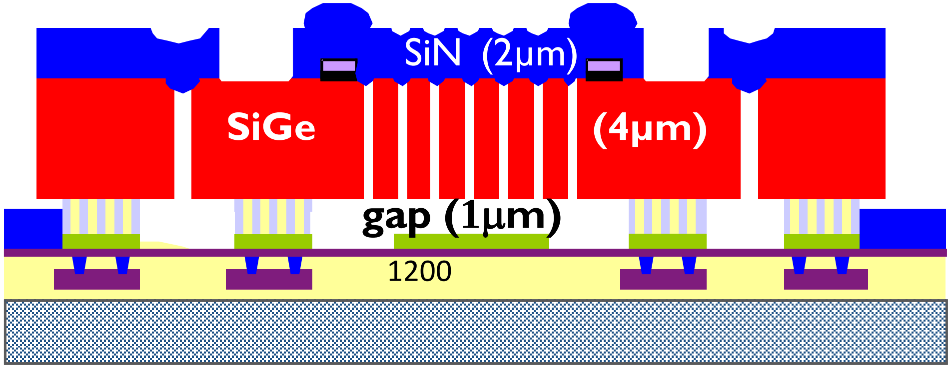
CAPACITIVE PRESSURE SENSOR: PERFORMANCE



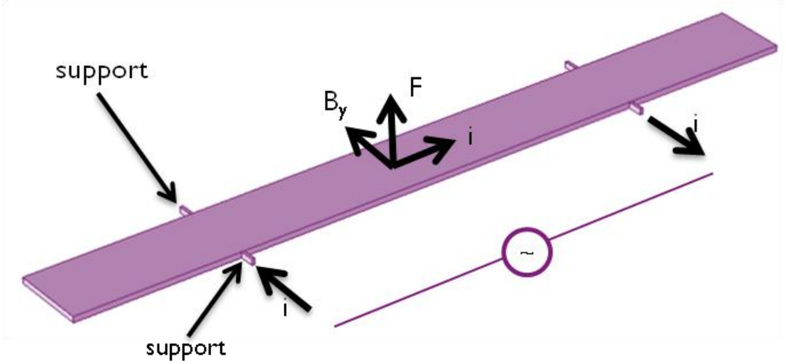
- SiGe membrane: 300x300 µm^2, 4µm thick SiGe + 2µm SiNy
- gap=1µm

Capacitive pressure sensor	SiGe MEMS @imec (typical specs)
range	0.005-0.5 MPa
sensitivity	~ 0.01 fF/Pa/mm^2
resolution	~ 1 Pa
supply voltage V_s	3.3 or 5V or “higher”
shock resistance	thousands of g
radiation hardness	50-100 krad TID
lifetime	“many” years
chip size	~ 0.5x0.5 mm^2



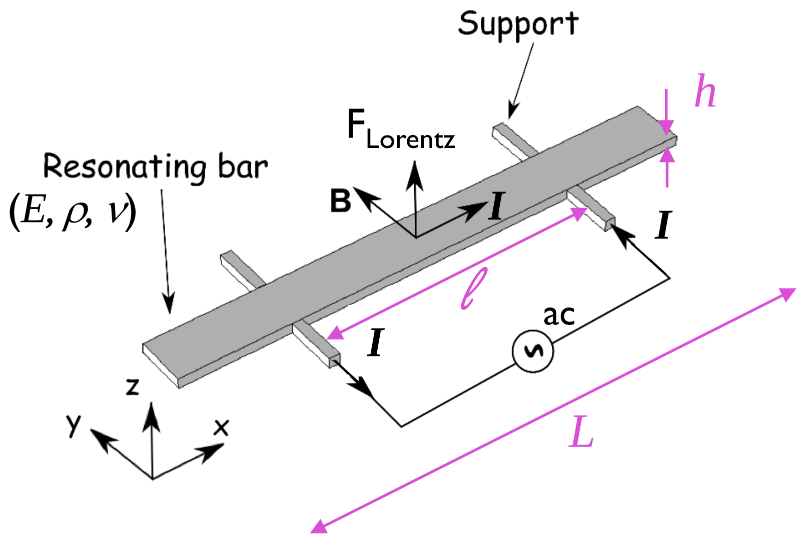


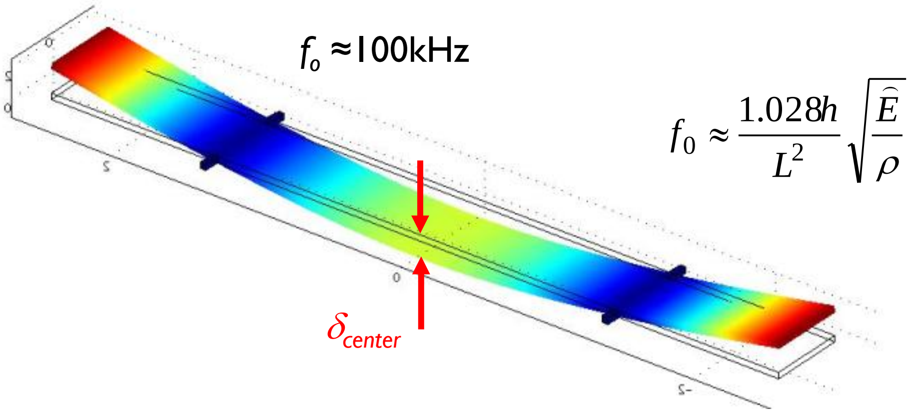
MAGNETIC FIELD SENSOR



RESONANT XYLOPHONE BAR MAGNETOMETER (XBM): PRINCIPLE of OPERATION

XBM: Free-Free beam supported at nodal points of fundamental resonance mode





$$f_0 \approx \frac{1.028h}{L^2}\sqrt{\frac{\hat{E}}{\rho}}$$

Alternating current I in magnetic field B → Lorentz force $F_L = \ell.I\times B$

→ Vibration of beam → at resonance amplitude is amplified by **Q**:

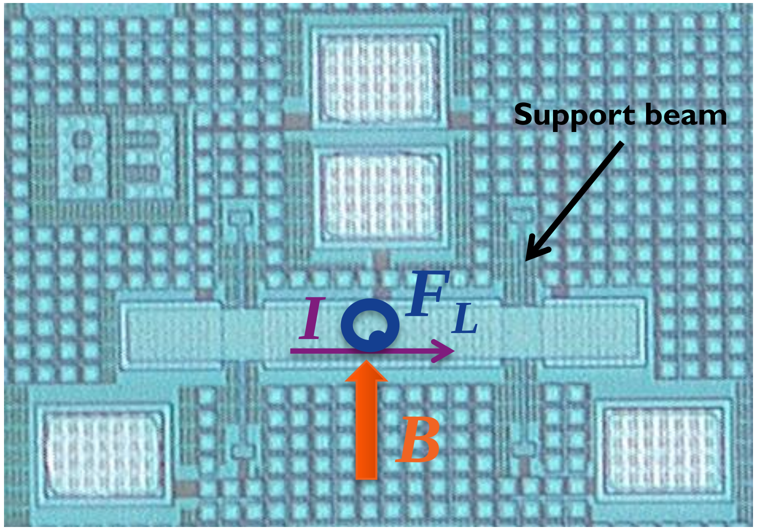
$$\boxed{\delta_{center} \propto B_y IQ}$$

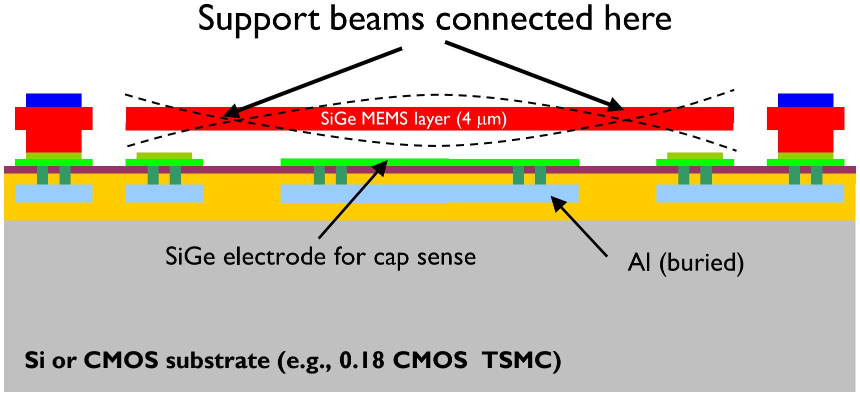
linear!!

→ Deflection can be measured capacitively or optically and is a measure for applied field B.

RESONANT XYLOPHONE BAR MAGNETOMETER (XBM): FABRICATION (in SiGe)

In-plane magnetometer



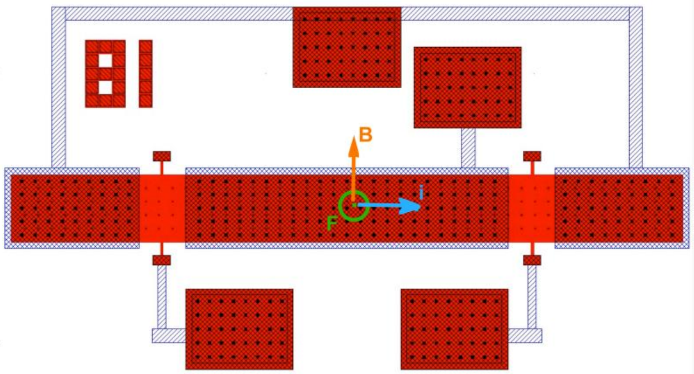

Support beams connected here

SiGe MEMS layer (4 µm)

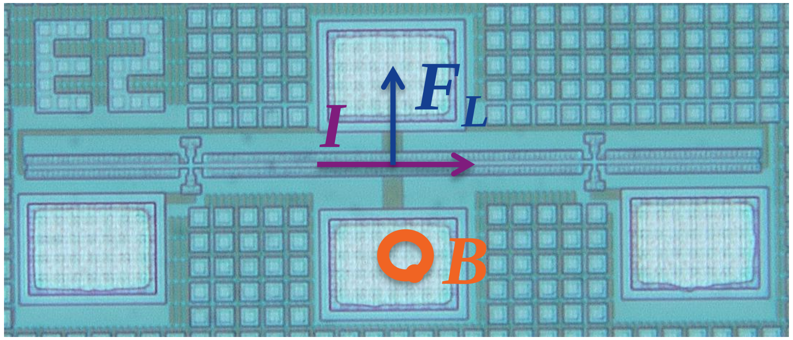
SiGe electrode for cap sense

Al (buried)

Si or CMOS substrate (e.g., 0.18 CMOS TSMC)



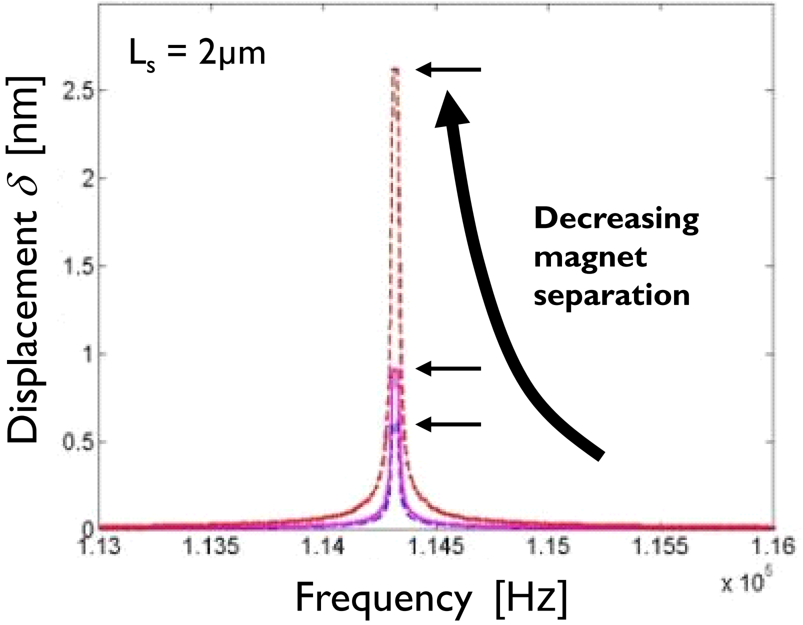
Out-of-plane magnetometer

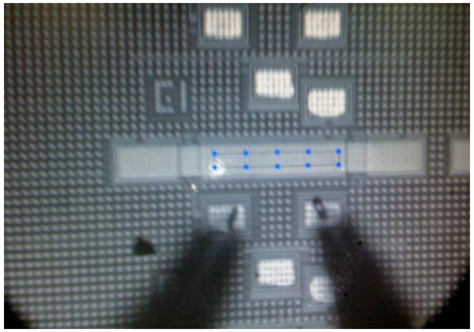


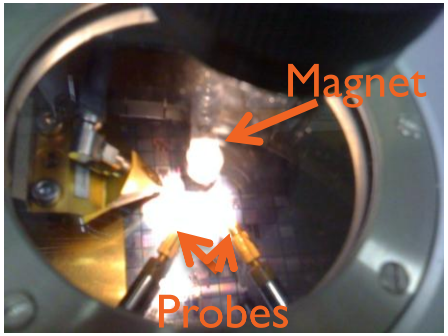
RESONANT XYLOPHONE BAR MAGNETOMETER: PERFORMANCE

- Preliminary measurements using reference magnets
- Optical detection using laser Doppler vibrometer

Magnetometer (XBM)	SiGe MEMS @imec (expected)
range	nT's to T's
sensitivity/resolution	tens of nT (perhaps nT's)
supply voltage	3.3 or 5V or "higher"
shock resistance	few thousand g
radiation hardness	50-100 krad TID
lifetime	"many" years
chip size (1 axis)	~ 1x1 mm^2

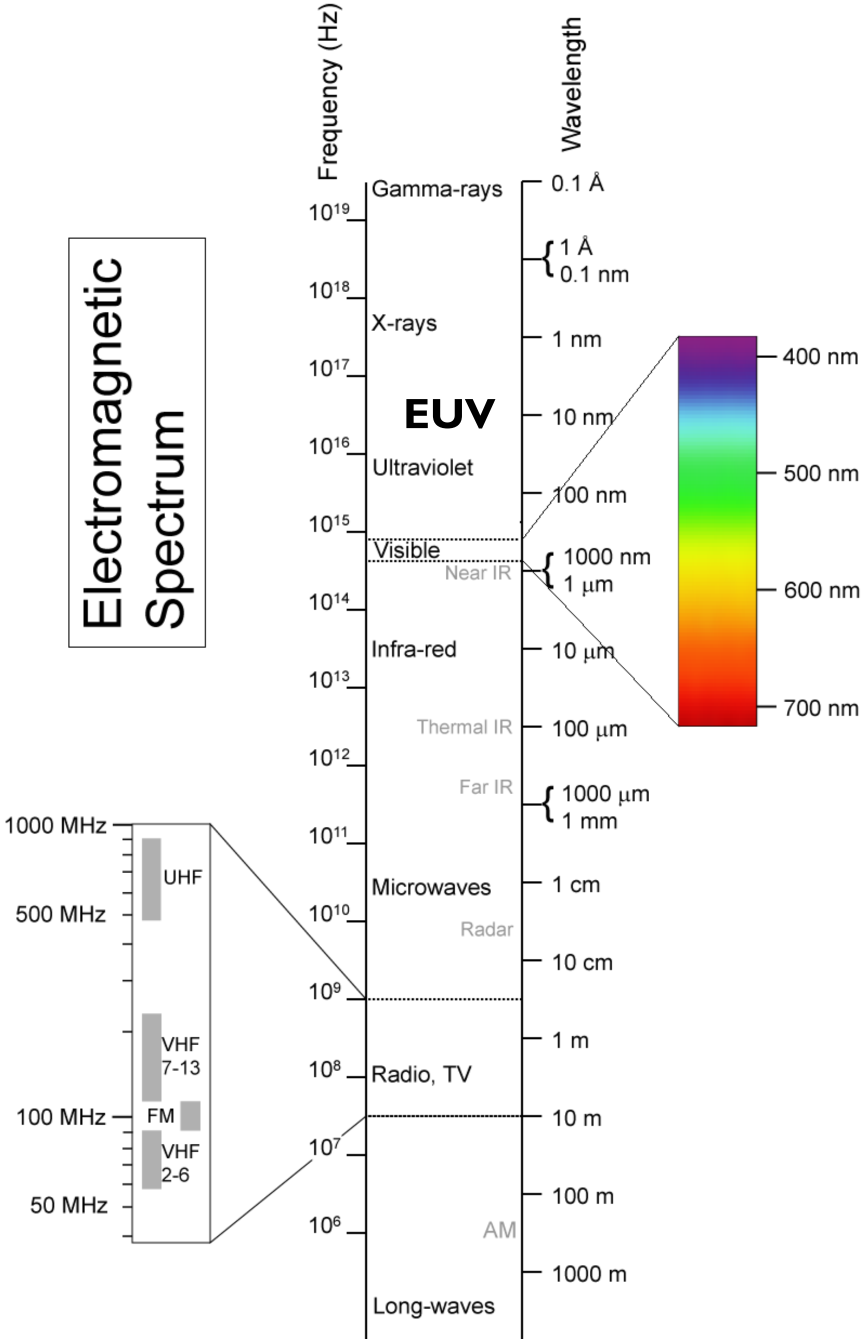




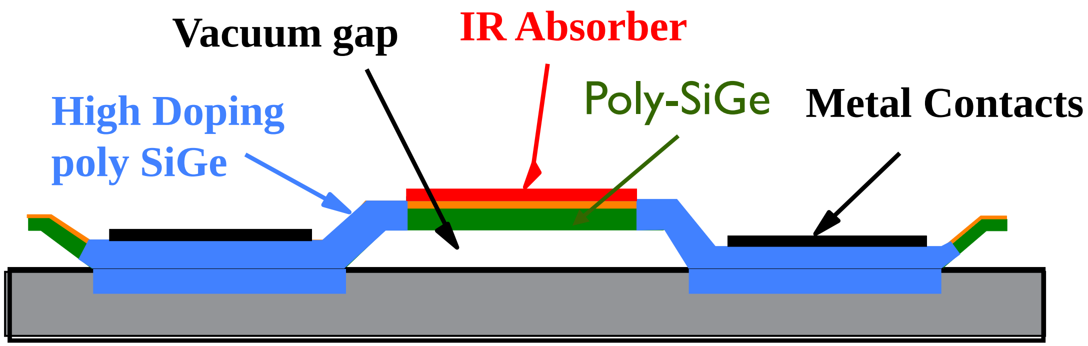


ELECTROMAGNETIC RADIATION SENSORS:

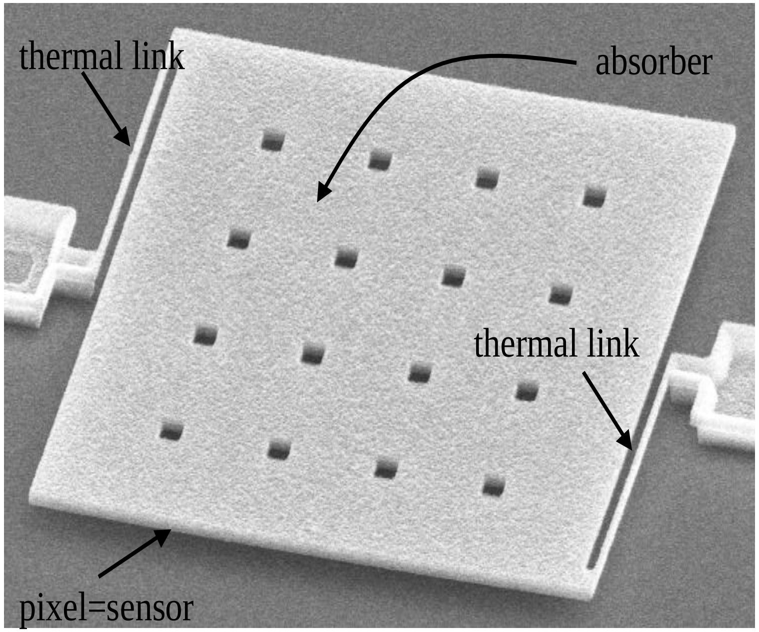
- Optical (light) sensors
- EUV sensor
- Image sensor
- Hyperspectral image sensor
- Infrared sensor (bolometer)
- ....

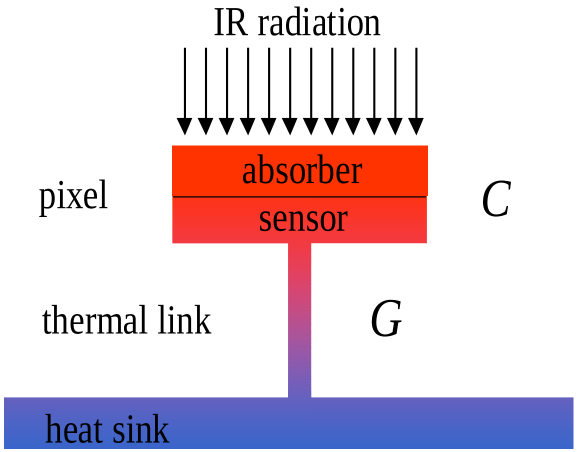


Poly-SiGe MICROBOLOMETER: PRINCIPLE OF OPERATION AND FABRICATION



Low thermal conductivity of poly-SiGe, 0.03 W/cm K



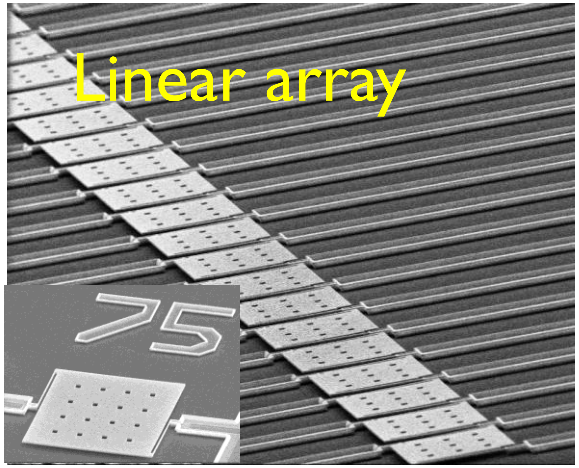


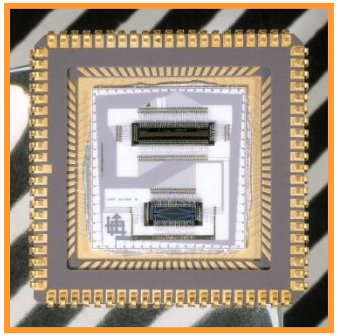
$$\Delta T = \frac{P_{IR}}{G} e^{-\frac{t}{\tau}}$$

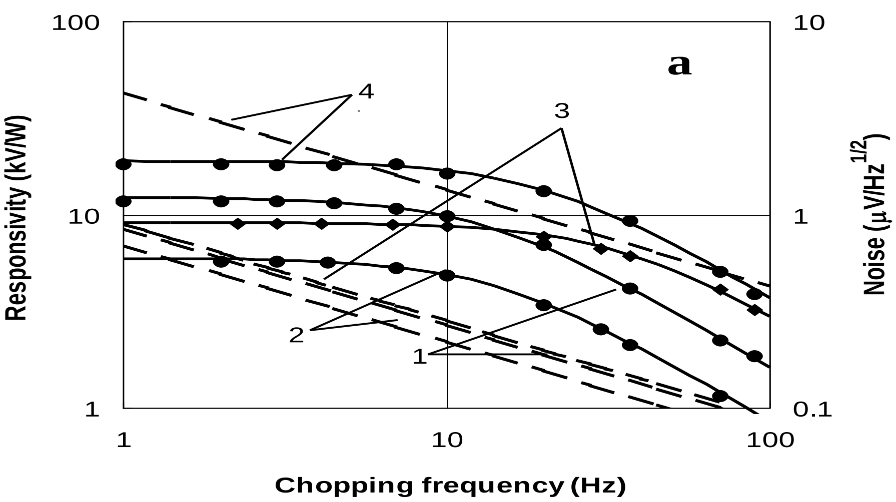
$$\tau = {}^{C}\!/_{G}$$

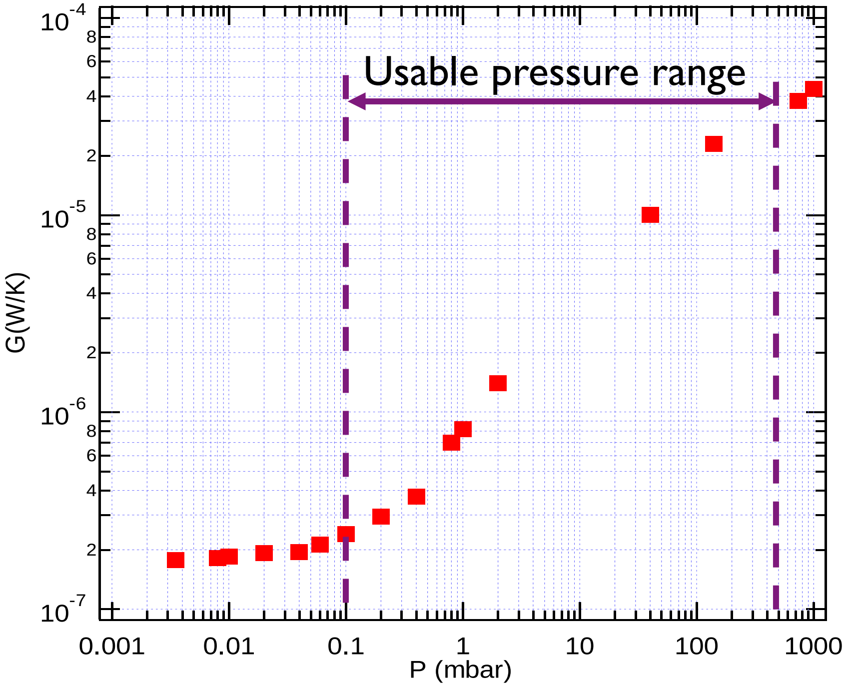
$$\Delta V \approx \Delta R \approx \alpha \Delta T$$

Poly-SiGe BOLOMETER STRUCTURE:
IR DETECTOR and PRESSURE SENSOR (PIRANI)

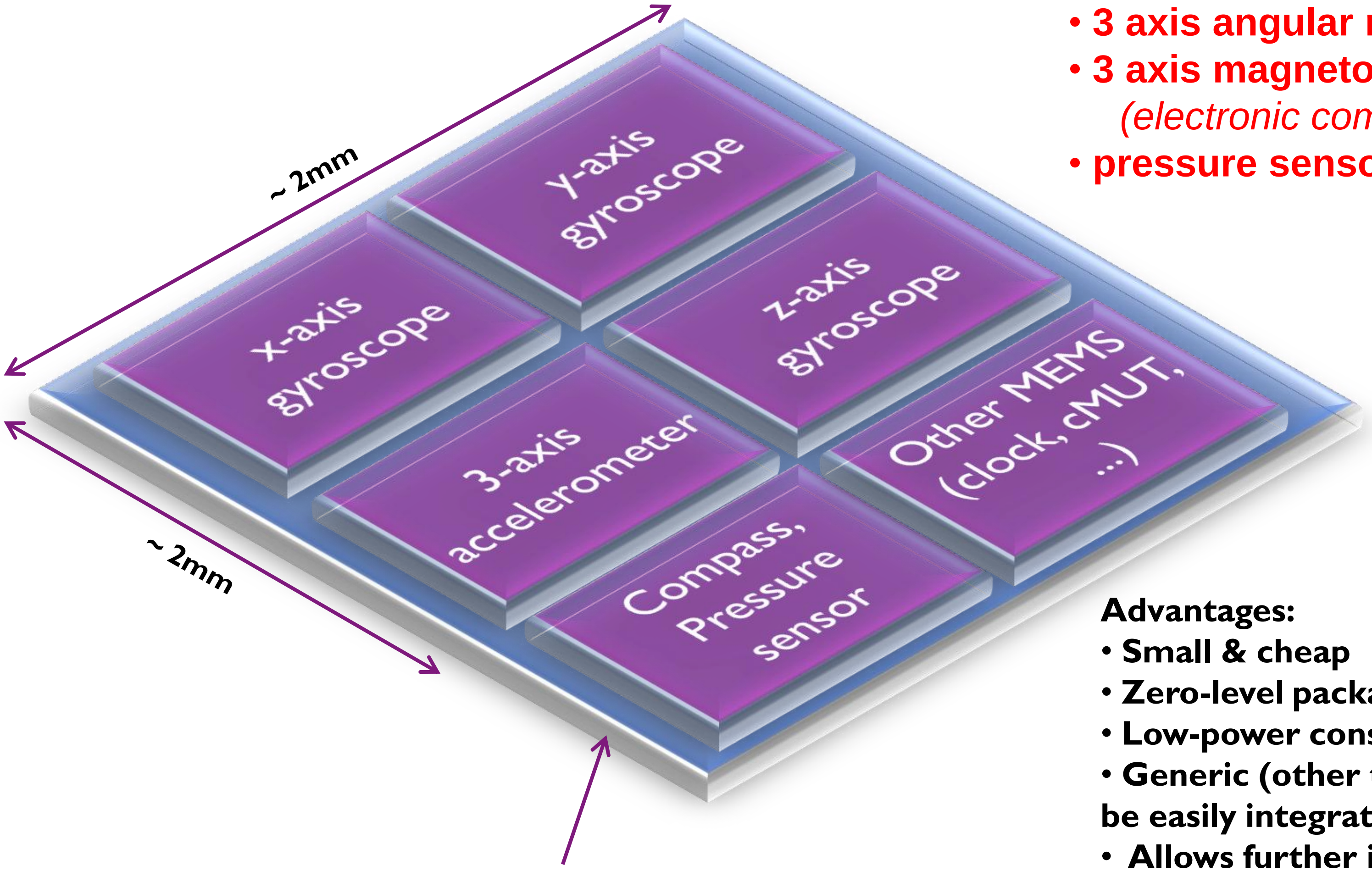








OPPORTUNITY IN IMEC'S POLY SIGE PLATFORM TECHNOLOGY: IMU++ (+)



Ultra Low Power CMOS Readout Circuit

10 axis motion tracking:

- **3 axis acceleration sensor**
- **3 axis angular rate sensor**
- **3 axis magnetometer** *(electronic compass)*
- **pressure sensor**

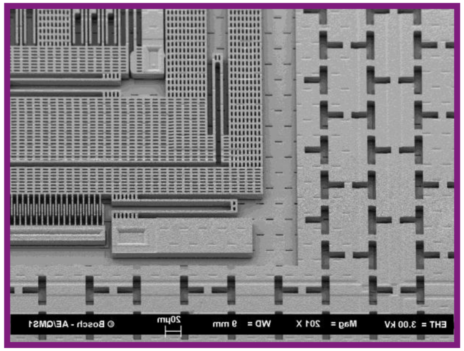
Advantages:

- **Small & cheap**
- **Zero-level packaged**
- **Low-power consumption**
- **Generic (other transducers can be easily integrated)**
- **Allows further integration (thinning, stacking, …)**

CONCLUSIONS

SiGe-MEMS

- Provides a versatile platform for a range of applications/devices including space&picosatellites.
- Poly-SiGe is the MEMS material of choice:
  - Low T deposition → above CMOS
  - Good mechanical properties (stress&stress gradient can be controlled)
  - Robust &Excellent mechanical reliability
  - High specific mass (>Si) → good for inertial sensors



- SiGe-MEMS baseline process (incl. thin film capping) is in place

Functionality of a range of MEMS sensors (accelerometer, gyroscope, pressure sensor, magnetometer) has been demonstrated, but further development is needed to demonstrate real application in space/picosatellites.

The weight (and volume) of the multi-sensor module is expected to be a fraction (<1‰) of the weight of a picosatellite.