Advanced MEMS and Microsystems

Dr. Danick Briand & Prof. Guillermo Villanueva

Course content and schedule

Dates	Topics	Lecturers
18.02	Introduction Transducers review: pre-recorded lectures	D. Briand / G. Villanueva
25.02	Sensors part I Exercices	D. Briand
04.03	Sensors part II Industrial seminar #1	D. Briand
11.03	Students presentations	D. Briand / G. Villanueva
18.03	Actuators and Optical MEMS Industrial seminar #2	D. Briand
25.03	Acoustic and Ultrasonic MEMS Industrial seminar #3	G. Villanueva
01.04	RF-MEMS	G. Villanueva
08.04	NEMS	G. Villanueva
15.04	Interactive session	D. Briand / G. Villanueva
29.04	Thermal and gas sensors Industrial seminar #4	D. Briand
06.05	Packaging	D. Briand
13.05	Packaging Industrial seminar #5	D. Briand
20.05	PowerMEMS Industrial seminar #6	D. Briand
27.05	Quiz + oral exam instructions Evaluation of the course	All

Announcements

TODAY MARCH 4

- **Lecture Sensors Part II: Capacitive accelerometers and gyroscopes**
- **Seminar 1 – Safran Sensing Technologies at 12h15**
  List of questions to answer available on moodle

NEXT WEEK MARCH 11

- **Hand-In Answers to Questions on Industrial Seminar 1 – Safran**
  Answers form available on moodle
- **YOUR Presentation (!Graded - Requires some homework!)**
- **SIGN UP: Link**

Announcements

TODAY March 4

- **Seminar 1 – Safran Sensing Solutions**

- **Questions related to industrial seminars**
- **Course requirement: written answers to be handed in (e.g. via the form)**

https://docs.google.com/forms/d/1D-PPqQGDI9h0Q2hgHyj4xwoY5fkz7jsyR_bP3FzBCWQ/edit

- **8 questions to be answered for each seminar (online on moodle)**
- **Individual assessement (not a group work)**
- **Deadline: 1 week after the seminar at the latest. If not handed in: Grade = 1.0**
- **Graded**

Evaluation:

- 10% on your answers to the questions for the 6 seminars
- 10% for your presentation on a MEMS device on the 11th of March
- 80% Individual oral examination to happen in June-July 2025

- **Questions?**

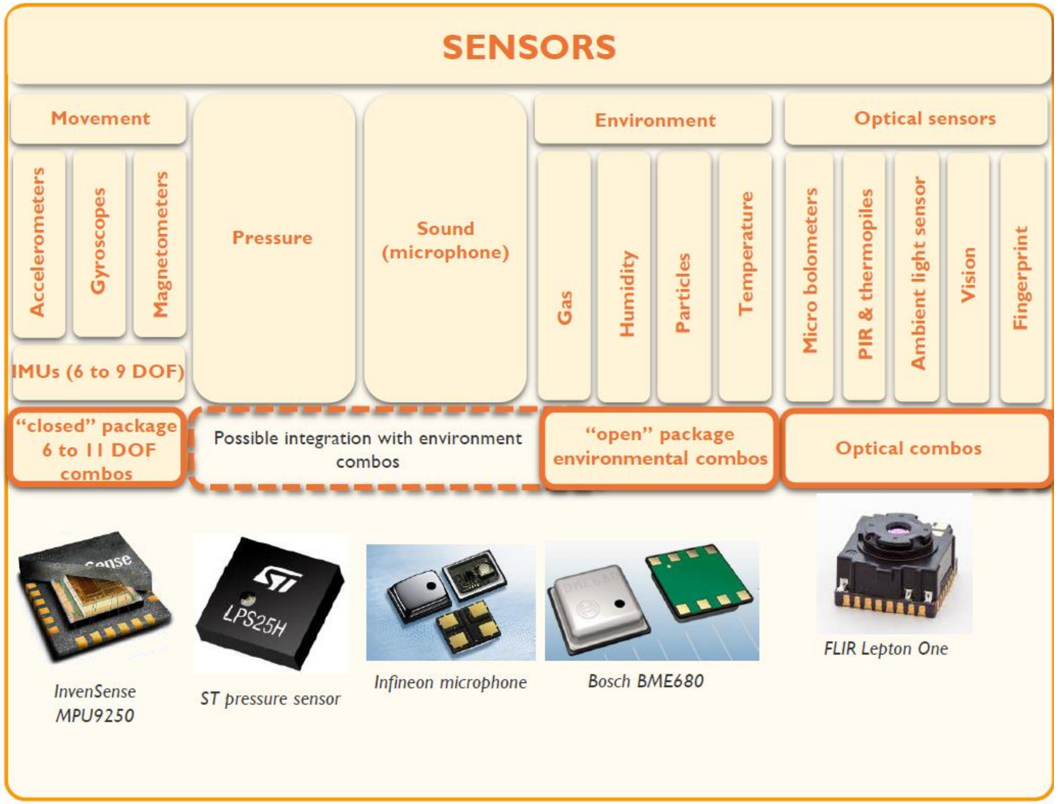
Presentations March 11 – Schedule & Topics

Timing	Team	Topic
10h15	Luciano Calcoen + Tristán Fonquerne Torres	MEMS oscillator for clocks
10h30	Alizée Anna André + Benoit Vignon	MEMS duplexers
10h45	Nicolas Robson + Alexandre Kiss	Thermoelectric energy harvesters
11h15	Adrien Cadet + Paul Krassiakov	Piezoelectric energy harvesters
11h30	Mathieu Dubois	Silicon photonic MEMS switches
11h45	Kilian Pouderoux	Shutter array
12h15	Cyprien Lacassagne	RF Switches
12h30	Maxime Nourry	Surface stress bio-sensors
12h45	Florent Gaspoz	Flow sensor
13h15	Grace Eunhyeong Kim	Pressure sensor
13h30	Alexandre Dao	Metal-oxide gas sensor

7 students are alone and can look at forming teams

3 students have not registered yet

Last week: Lecture Sensors Part 1



Lecture Sensors Part 1: Piezoresistive

➢ **Questions?**

Sensors Part II: Lecture content

- **Capacitive Sensing**
  - **Capacitive MEMS Sensors**
  - **Commercial Motion Sensors**
  - **Capacitive MEMS Accelerometers**
  - **Capacitive MEMS Gyroscopes**
  - **Capacitive MEMS Microphones in Week 6**
- **Comparison transduction principles**
- **Sensor Fusion**
- **Summary Questions**

LECTURE 2

Sensors – Part 2

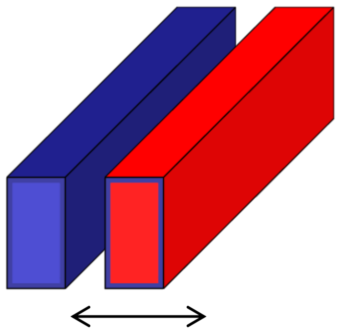
Danick Briand
Maître d'Enseignement et de Recherche (MER)
MEMS & Printed Microsystems group
EPFL-STI-LMTS

CAPACITIVE SENSING

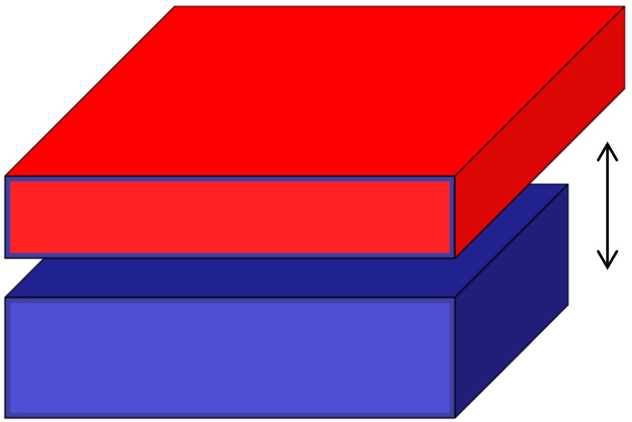
Motion sensing by changing capacity

Capacitors are …

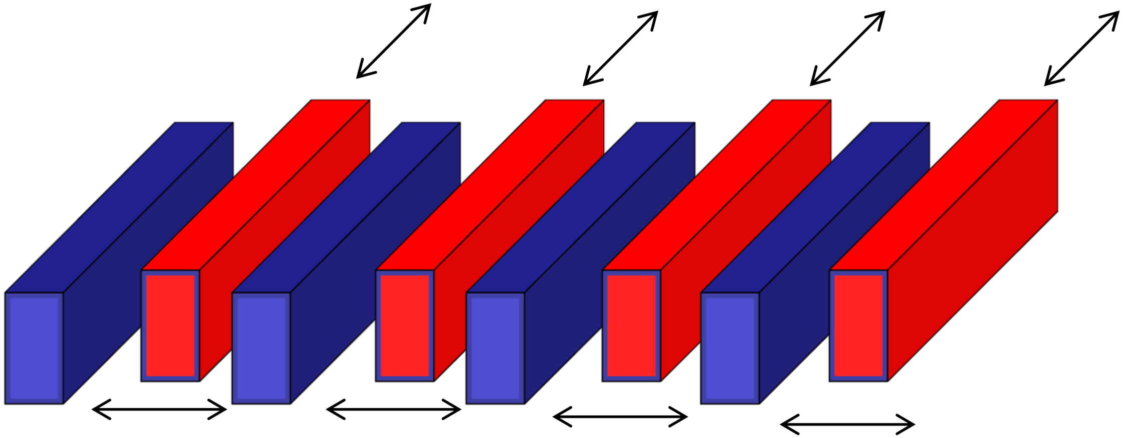
Vertical parallel plates



Horizontal parallel plates



Interdigitated fingers = combs



- **Also: Tilting configuration**
- **Movement Depends on Suspension (Degree of Freedom)**

Motion Sensing in MEMS ...

> **Single capacitors**
> - **Capacitance is function of gap or area**
> - **Can be nonlinear**

> **Differential capacitors**
> - **One capacitor increases while the other decreases**

$$C = \frac{\varepsilon A}{g}$$

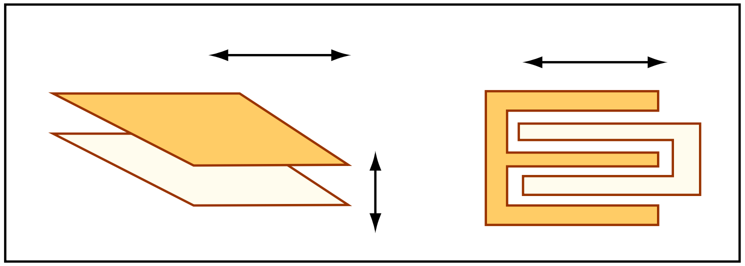
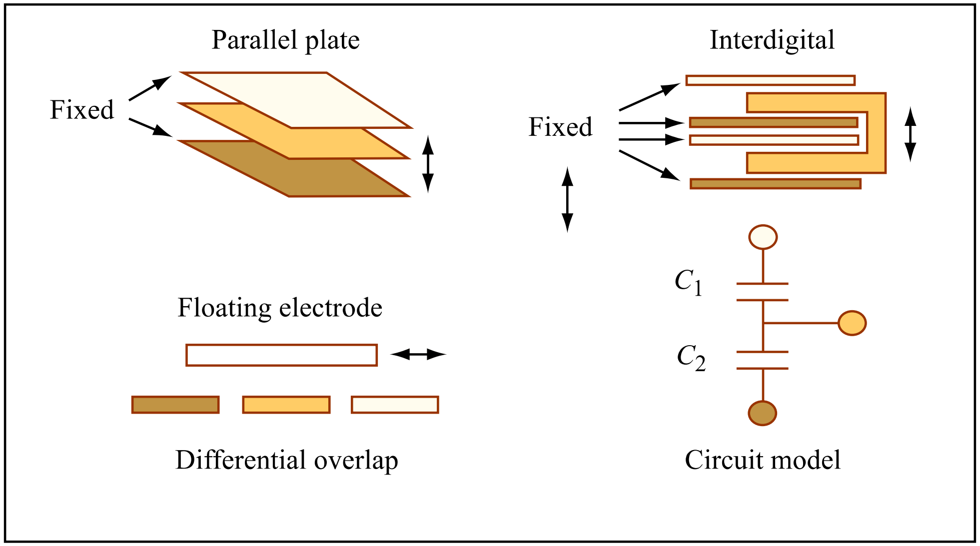


Image by MIT OpenCourseWare.
Adapted from Figure 19.3 in Senturia, Stephen D. *Microsystem Design*. Boston, MA: Kluwer Academic Publishers, 2001, p. 501. ISBN: 9780792372462.



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Adapted from Figure 19.4 in Senturia, Stephen D. *Microsystem Design*. Boston MA: Kluwer Academic Publishers, 2001, p. 501. ISBN: 9780792372462.

Differential Capacitors

- Differential drive creates sense signal proportional to capacitance difference
- Gives zero output for zero change
- Output linear with gap

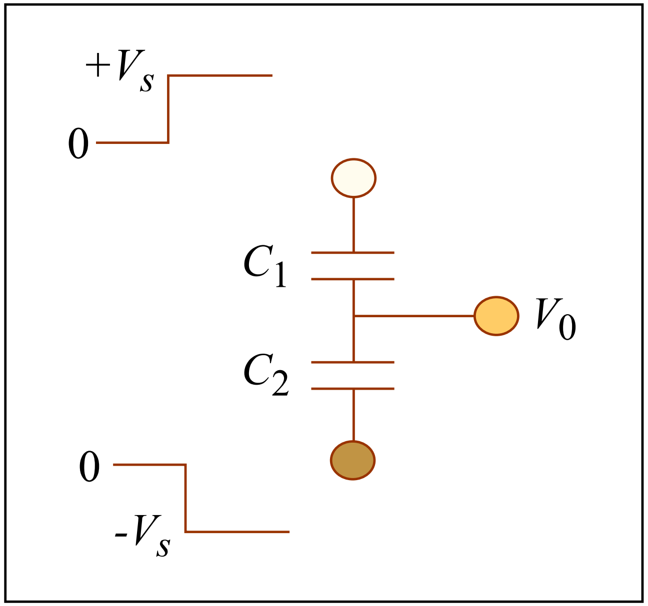


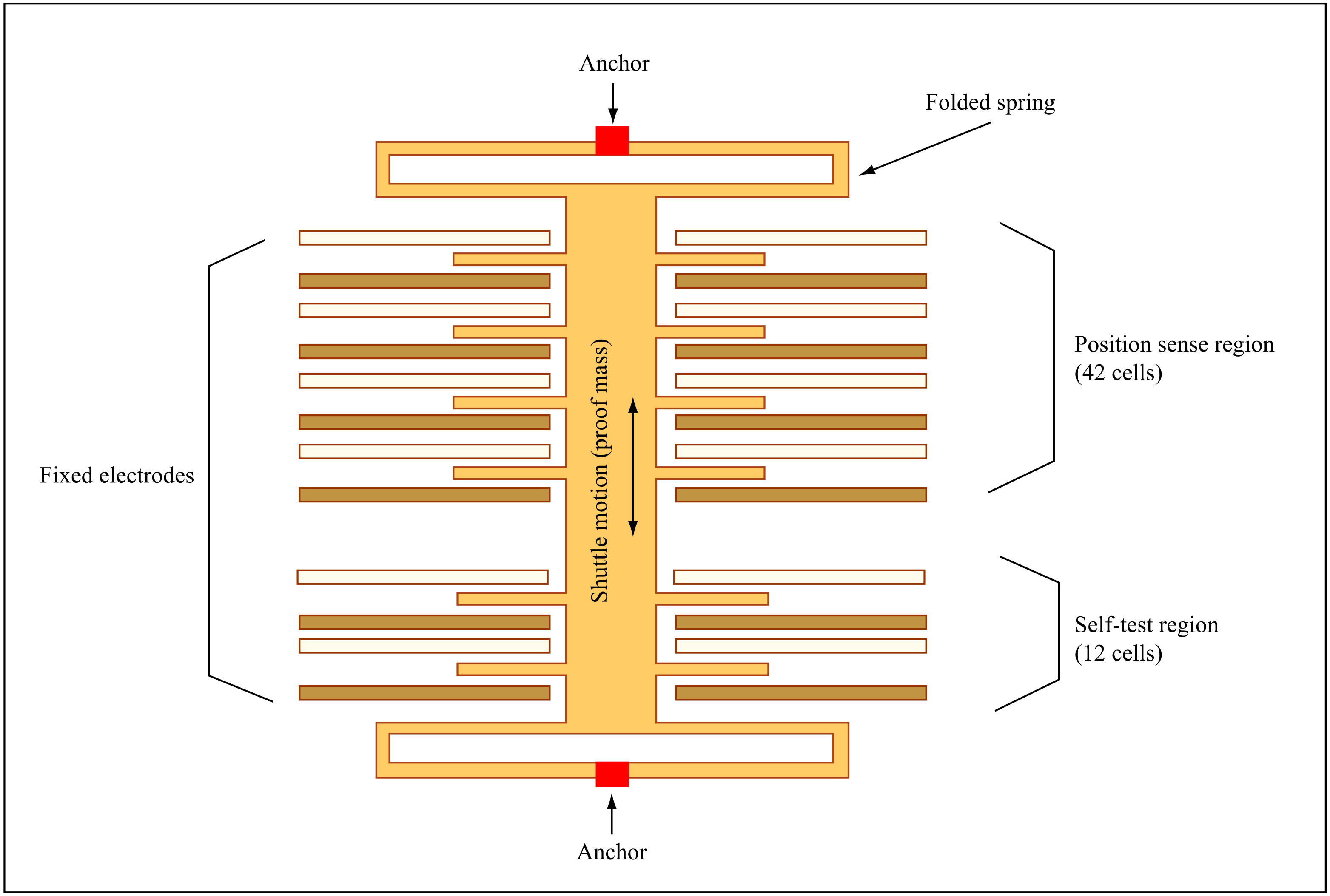
Image by MIT OpenCourseWare.
Adapted from Figure 19.5 in Senturia, Stephen D. *Microsystem Design*.
Boston, MA: Kluwer Academic Publishers, 2001, p. 502. ISBN: 9780792372462.

$$V_0 = -V_S + \frac{C_1}{C_1 + C_2}\left(2V_S\right) = \frac{C_1 - C_2}{C_1 + C_2} V_S$$

for parallel-plate capacitors where only g changes, this becomes

$$V_0 = \frac{g_2 - g_1}{g_1 + g_2} V_S$$

Differential Capacitors (Combs)



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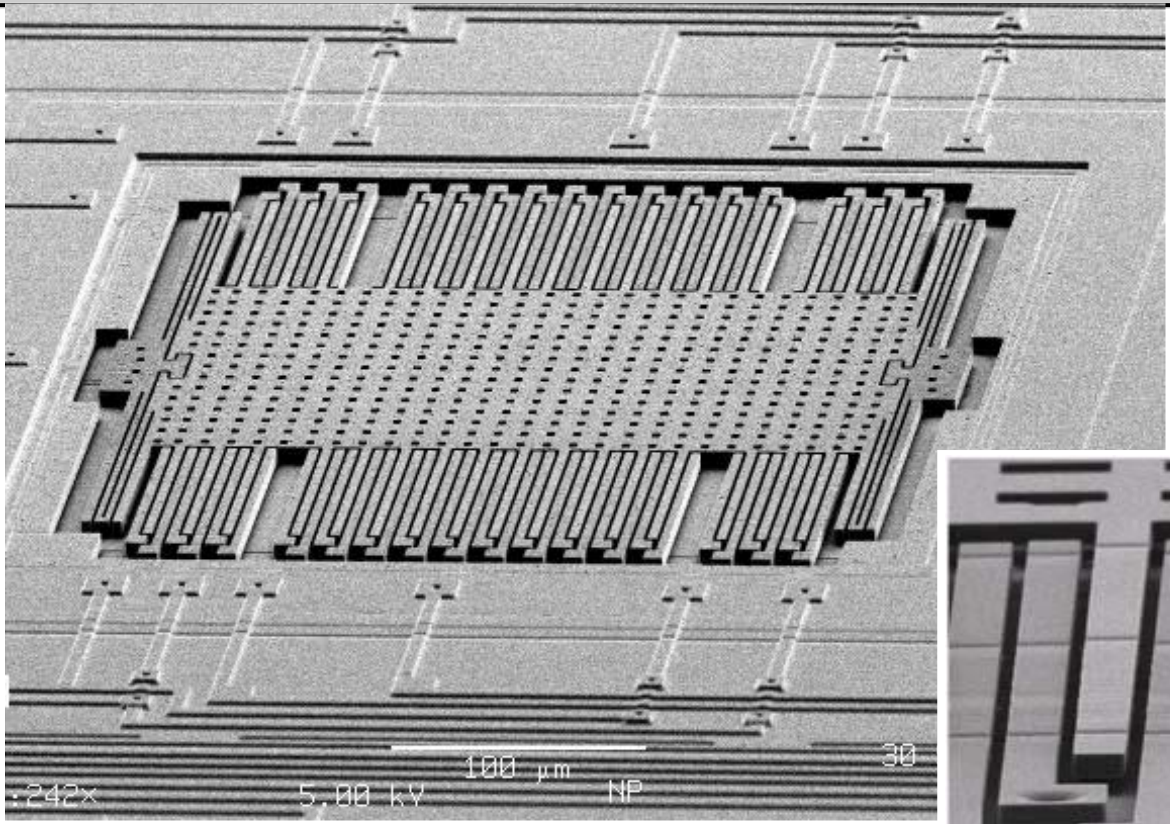
Adapted from Figure 19.17 in Senturia, Stephen D. *Microsystem Design*. Boston, MA: Kluwer Academic Publishers, 2001, p. 514. ISBN: 9780792372462.

Analog Devices Accelerometer – Differential Capacitors



$$F = ma = kx$$

$$x = \frac{m}{k}a$$

$$w = \sqrt{\frac{k}{m}}$$

$$x = \frac{a}{{w_0}^2}$$

$$C_1 = \frac{A}{d - x} \qquad C_2 = \frac{A}{d + x}$$

$$\Delta C = \frac{Ax}{d}$$

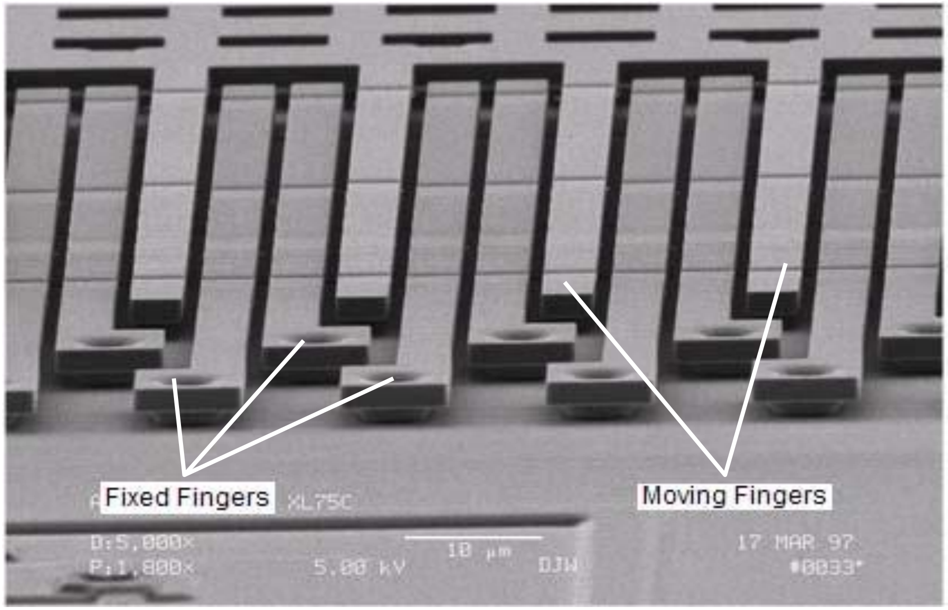


Figure 2. Poly-Silicon beam released after removing sacrificial oxide

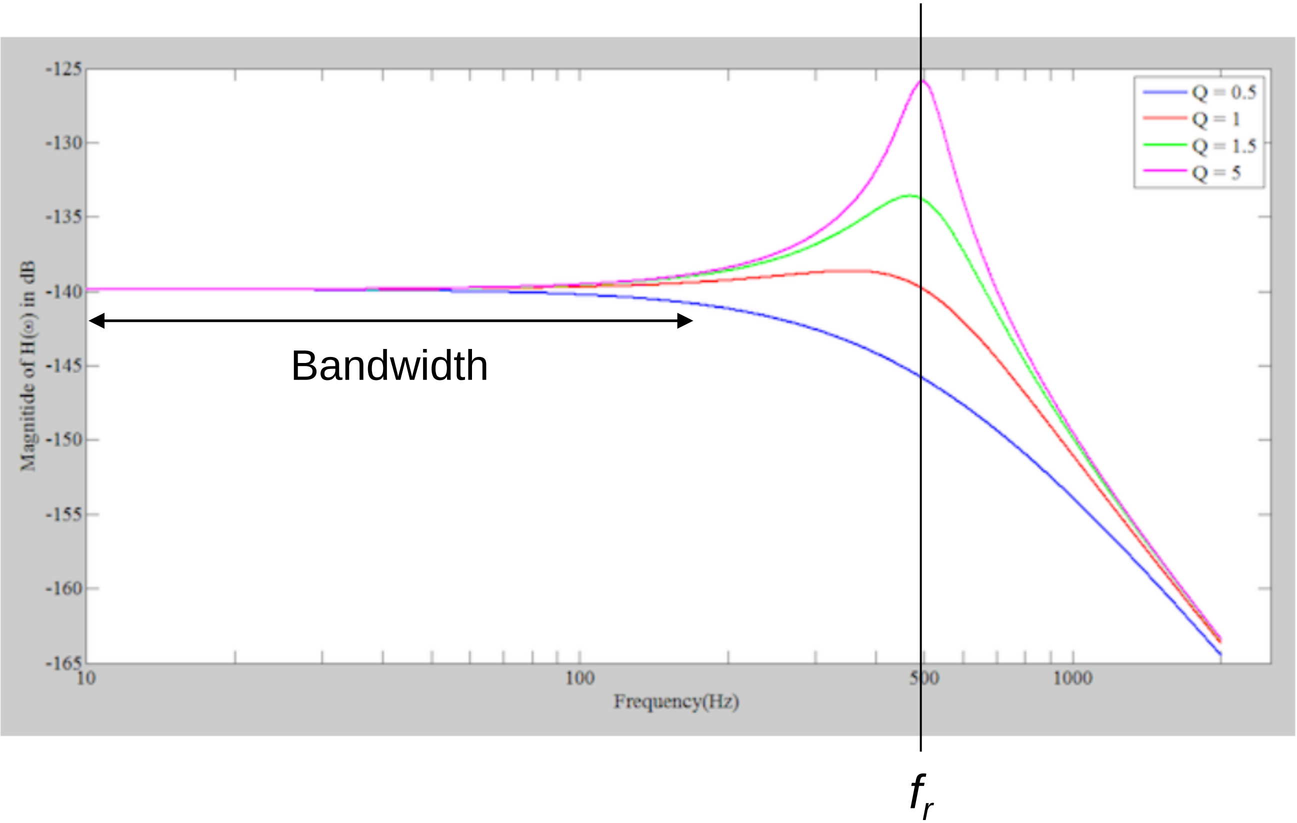
Sources: 1) John A. Yasaitis et al., Vol. 4979, 2003 SPIE, 2) "Comparing process flow of monolithic CMOS-MEMS intergration on SOI wafers with monolithic BiMOS-MEMS integration on Silicon wafer"; Solanki, A et al, 2010 53rd IEEE International Midwest Symposium on Circuits and Systems, p 1189-92, 2010

Bandwidth

- Bandwidth, frequency range of operation, is related to the Quality factor *Q*, and therefore function of resonance frequency and damping factor (*b*)

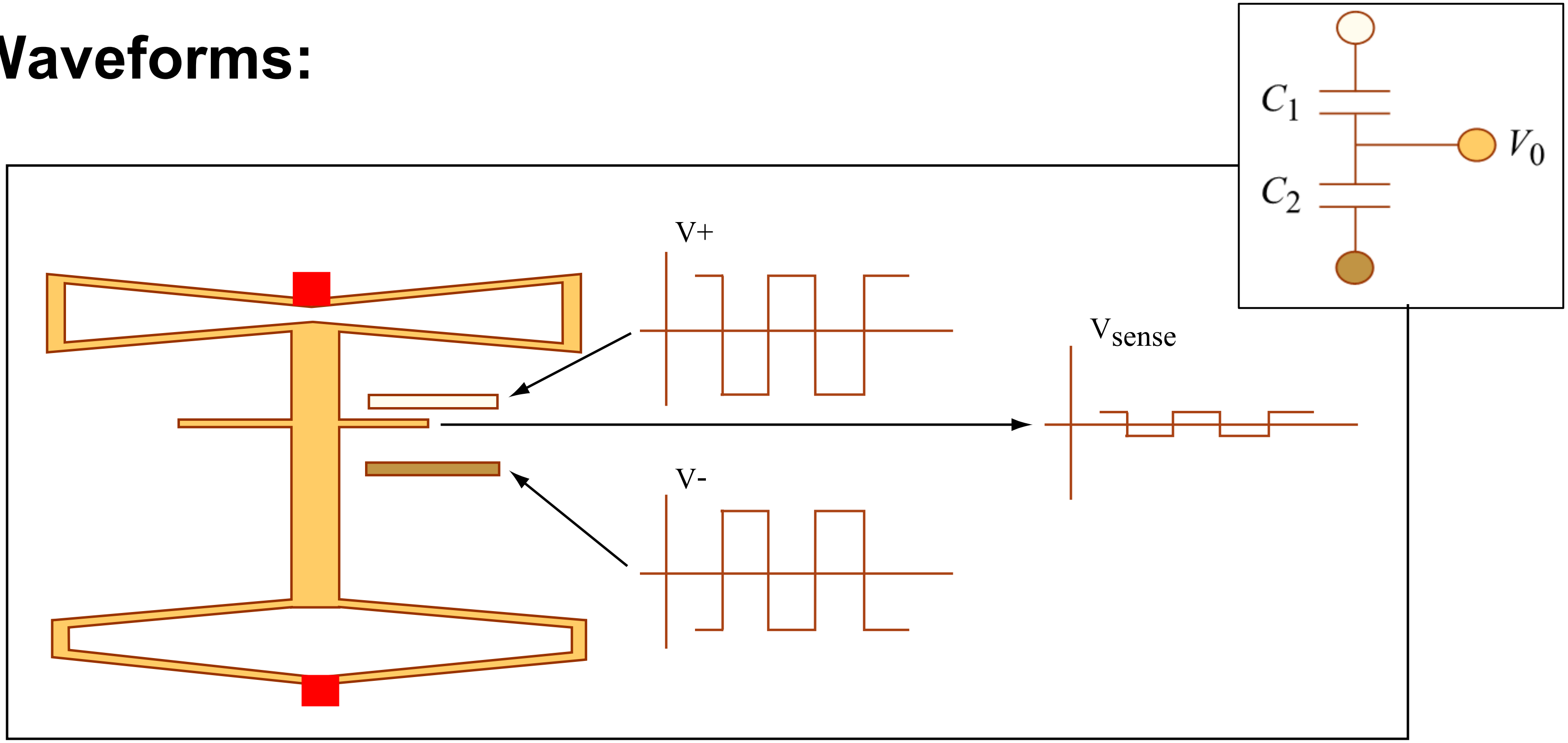
$$\omega_n = \sqrt{\frac{k}{m}}$$

$$Q = \frac{m\omega_n}{b}$$



from allaboutcircuits.com

- Oscillator provides AC waveform for sensing
- Waveforms:



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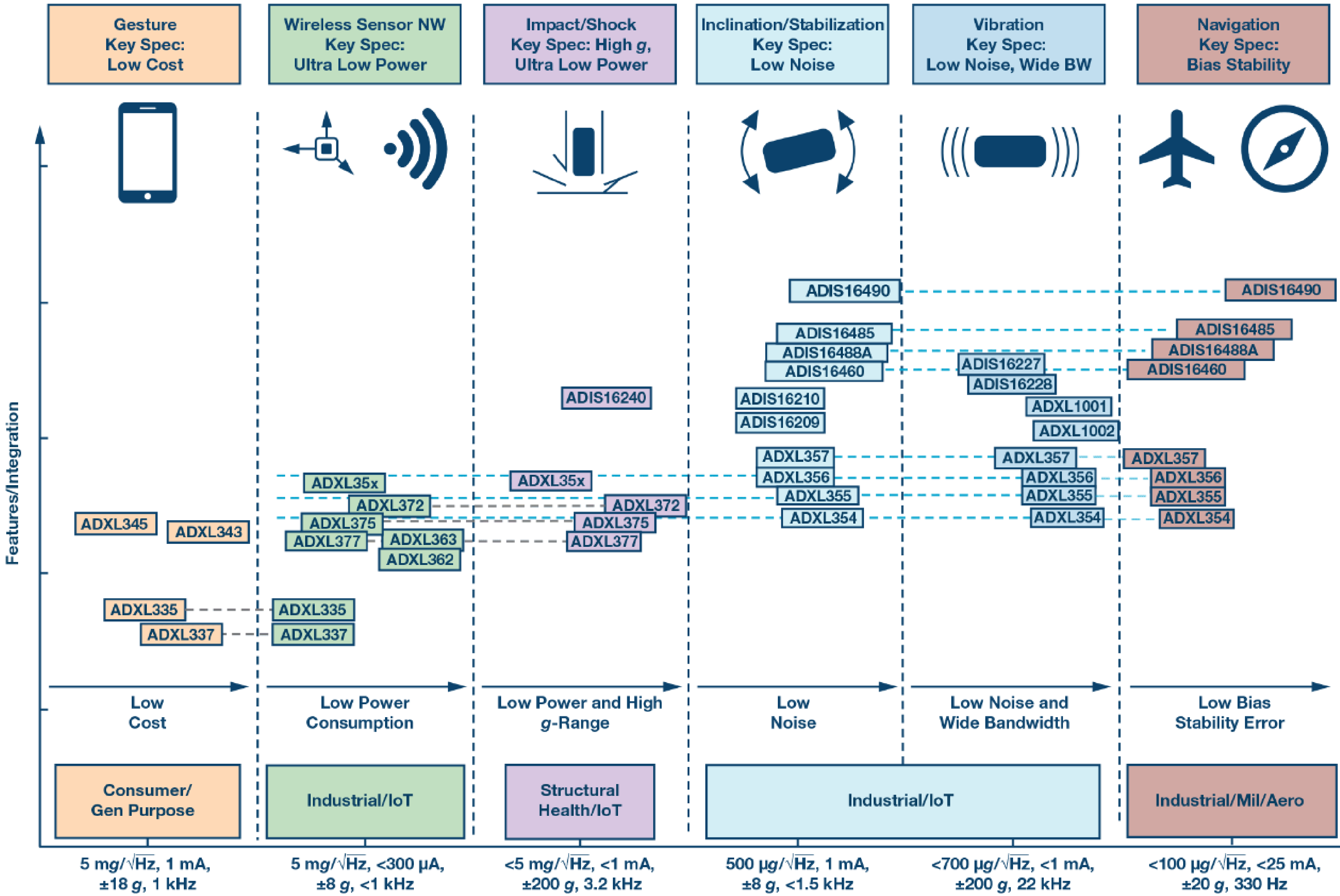
Adapted from Figure 19.21 in Senturia, Stephen D. *Microsystem Design*. Boston, MA: Kluwer Academic Publishers, 2001, p. 516. ISBN: 9780792372462.

Accelerometer requirements per application



from Analog Devices

Accelerometer specifications per application

Table 1. Accelerometer Grade and Typical Application Area

Accelerometer Grade	Main Application	Bandwidth	*g*-Range
Consumer	Motion, static acceleration	0 Hz	1 *g*
Automotive	Crash/stability	100 Hz	<200 *g*/2 *g*
Industrial	Platform stability/tilt	5 Hz to 500 Hz	25 *g*
Tactical	Weapons/craft navigation	<1 kHz	8 *g*
Navigation	Submarine/craft navigation	>300 Hz	15 *g*

from Analog Devices

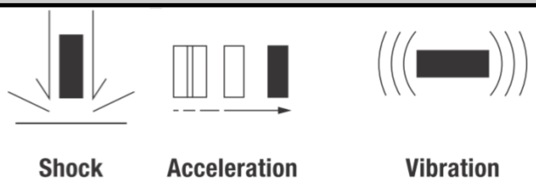
Sensing Applications

COMMERCIAL MOTION SENSORS

Motion sensors for what ?

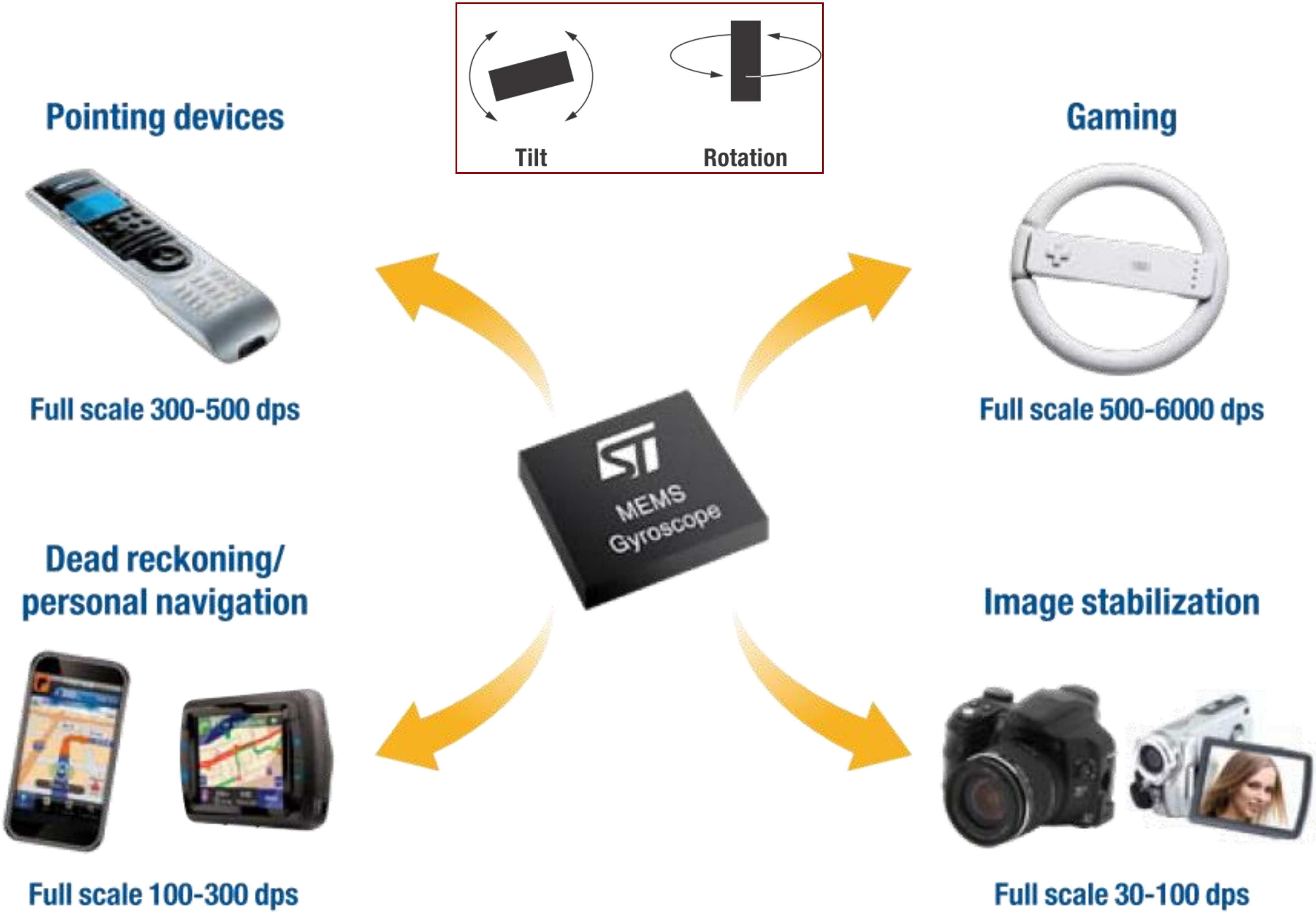
source: http://www.findmems.com

Accelerometers … Where and What



sources: http://www.findmems.com, http://www.st.com/mems

Gyroscopes … Where and What



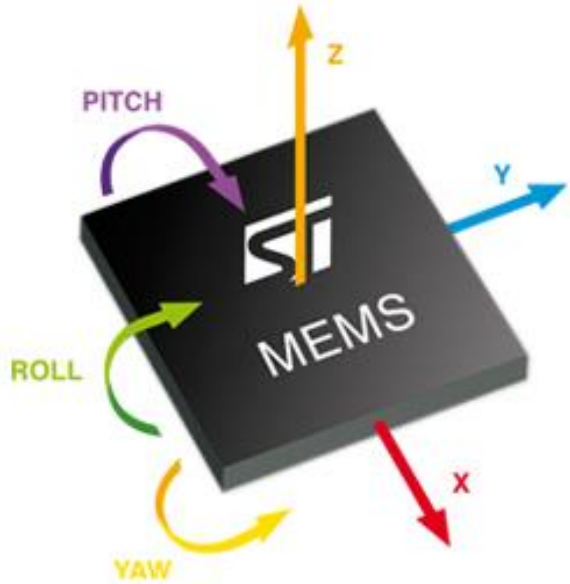
sources: http://www.findmems.com, http://www.st.com/mems

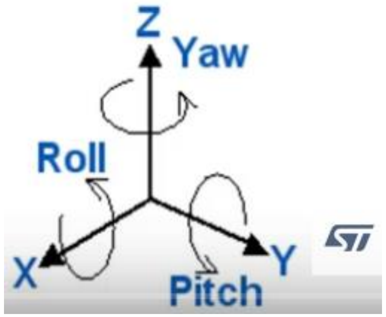
Accelerometers

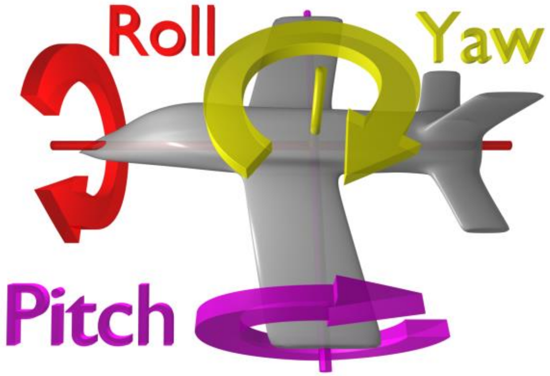
- Linear acceleration
- "z" is parallel to the gravity vector

Gyroscopes

- *Angular* rate
- "Pitch", "roll" and "yaw" are defined by the direction of the motion and by the vertical gravity vector







sources: www.st.com

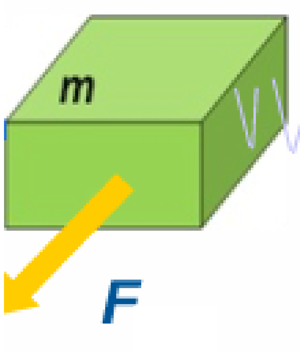
CAPACITIVE MEMS ACCELEROMETERS

Measurement of Acceleration – References in ‘g’

Newton’s 2nd law of motion

$$\vec{F}_N = m\,\vec{a}$$

Force is in same direction as acceleration



Transduction Chain:

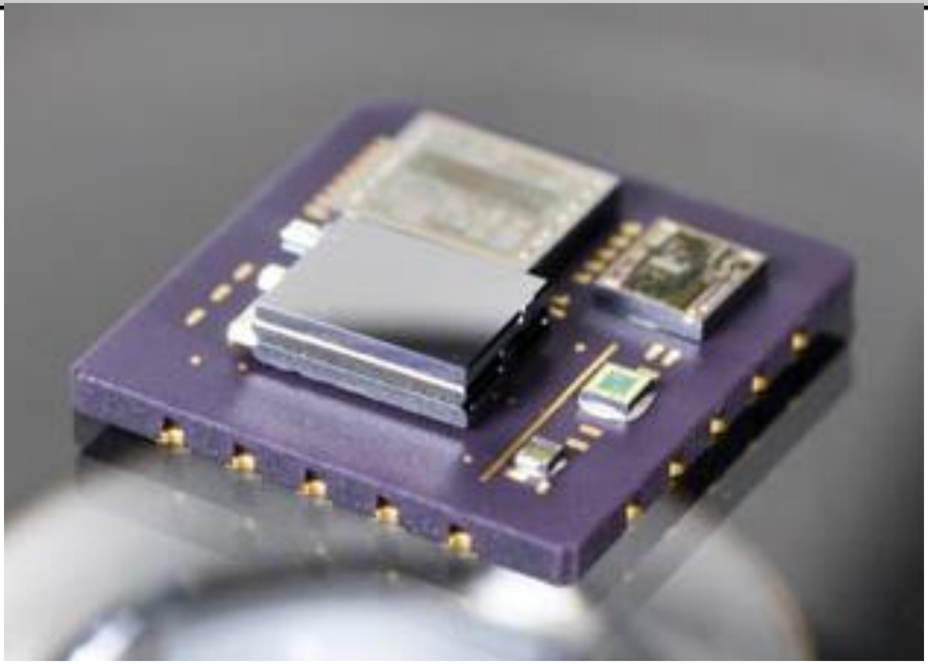
- Acceleration
- Force on Mass
- Mass Movement
- Capacitor Gap
- Capacity
- Voltage

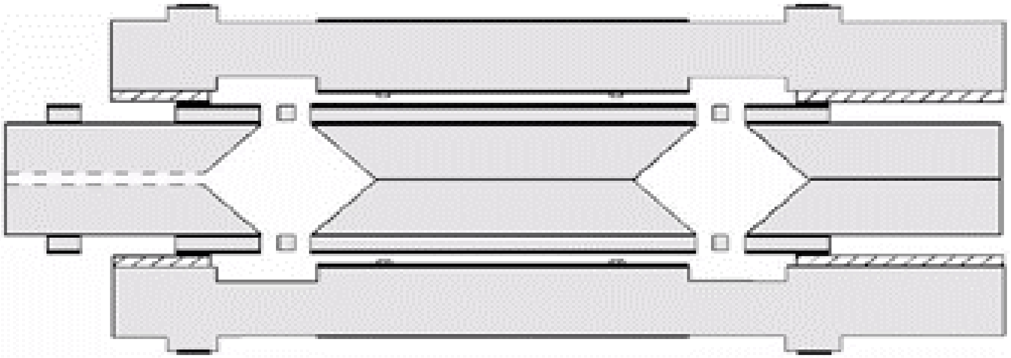
$$C = \frac{\varepsilon A}{g}$$

Passenger car acceleration	0.2 / 0.3g
Earth’s gravity	1g (by definition)
Emergency braking (Formula 1)	1g
Running	<5g (shock at low back level)
Bobsleigh rider in corner	5g
Human unconsciousness	7g
Walking down/up stairs	7.4/8g (shock at ankle level)
Running	8/12g (shock at ankle level)
Car Frontal choc @15Km/h	10/15g
Car Frontal choc high speed	35g (shock at head level, with Airbag)
Car Frontal choc high speed	40g (for the vehicle)
Car Frontal choc high speed	65g (shock at head level, without Airbag)
Tennis ball	500/700g

Colibrys Accelerometer (Parallel Plate Capacitor)

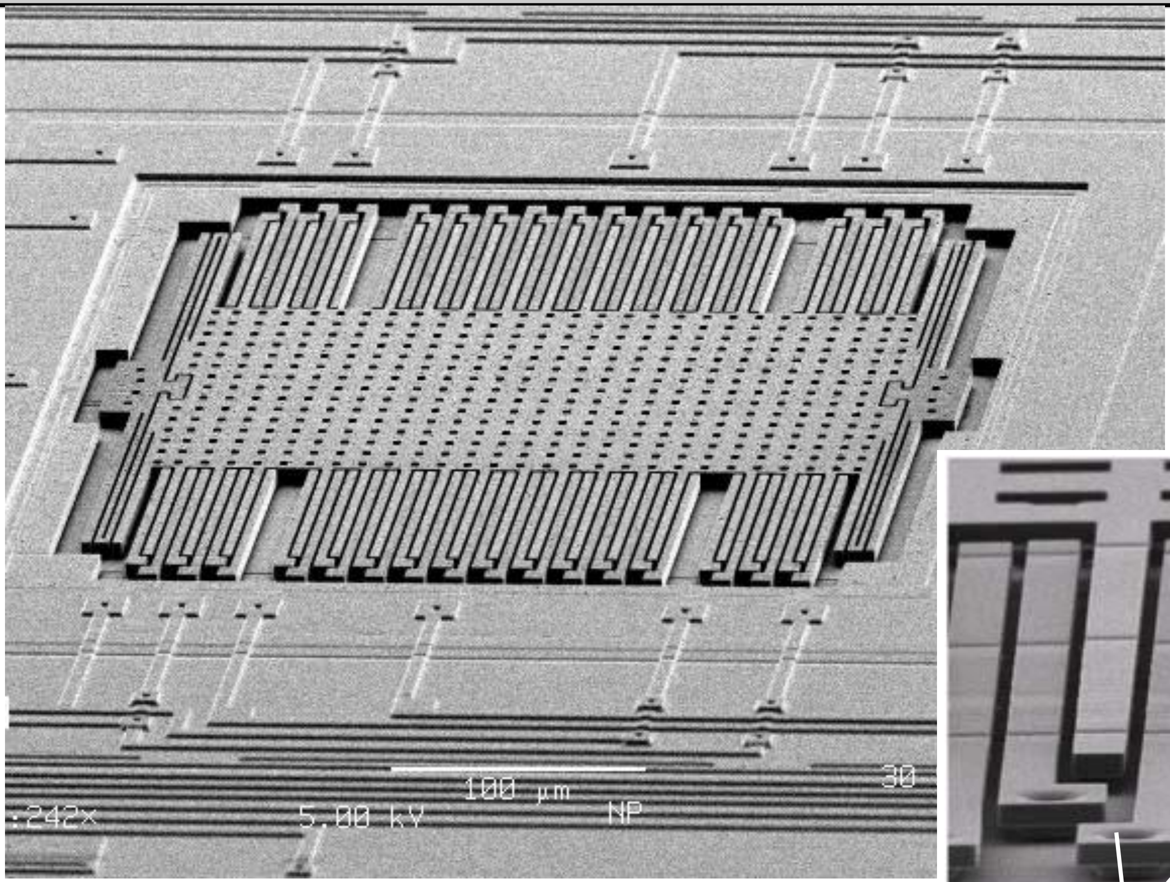
- Seismic mass is a bulk silicon piece
- Displacement sensor
- No actuator
- Several levels of micromachining
- KOH etched bulk micromachining
- Fusion bonding at high temperature
- Stoppers to limit shock impact
- Assembly in package with highly sensitive electronics
- Highly temperature independent





Accelerometers from Colibrys, Switzerland

Analog Devices – Differential Capacitors



Polysilicon surface micromachining

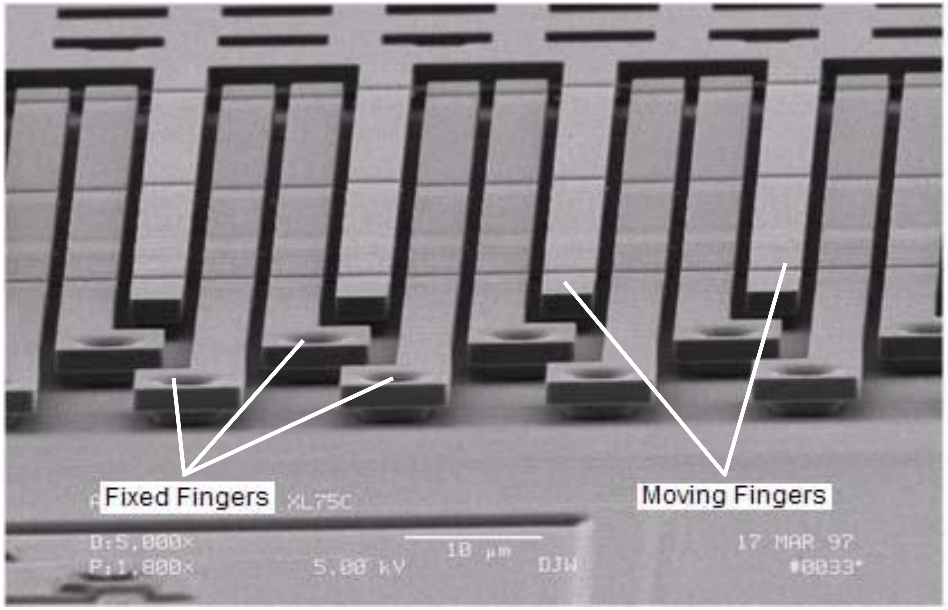
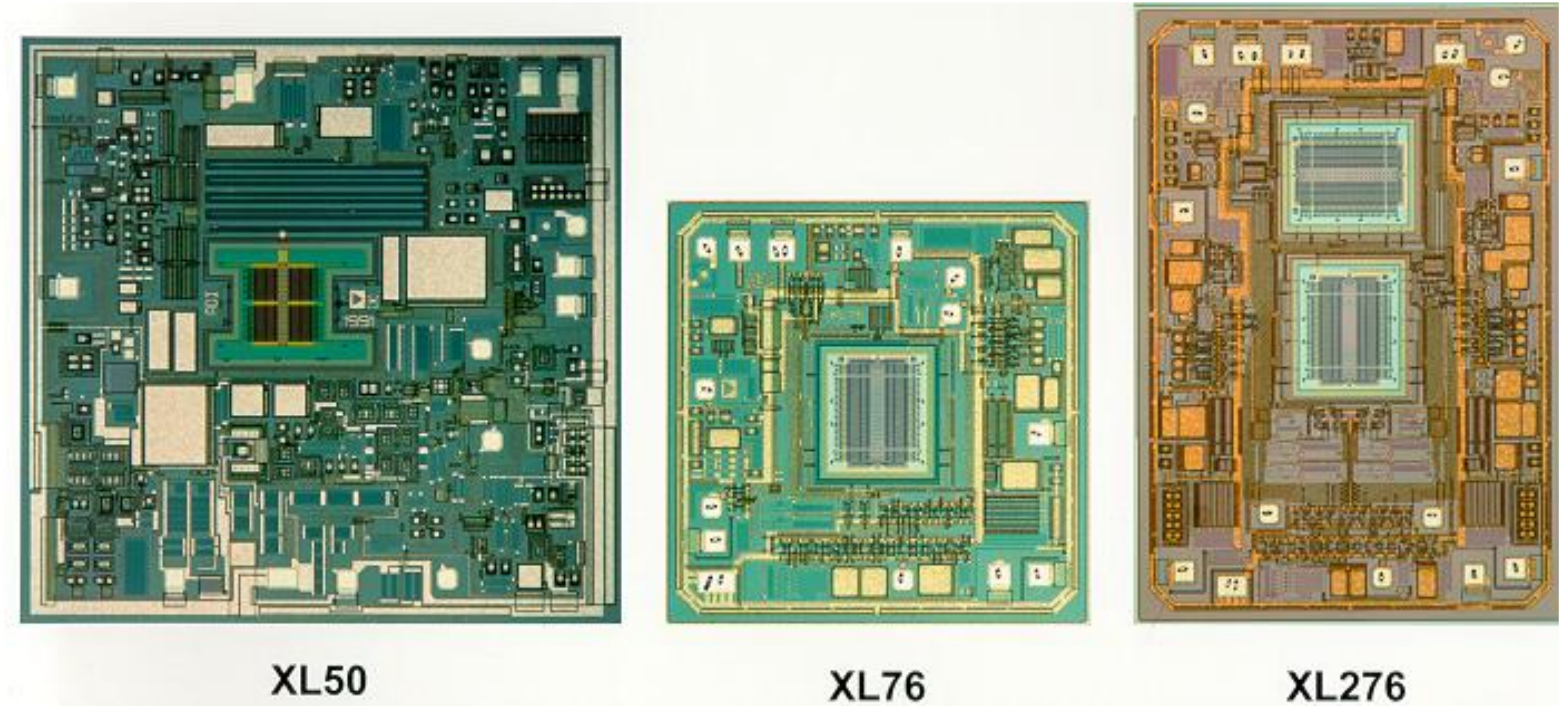


Figure 2. Poly-Silicon beam released after removing sacrificial oxide

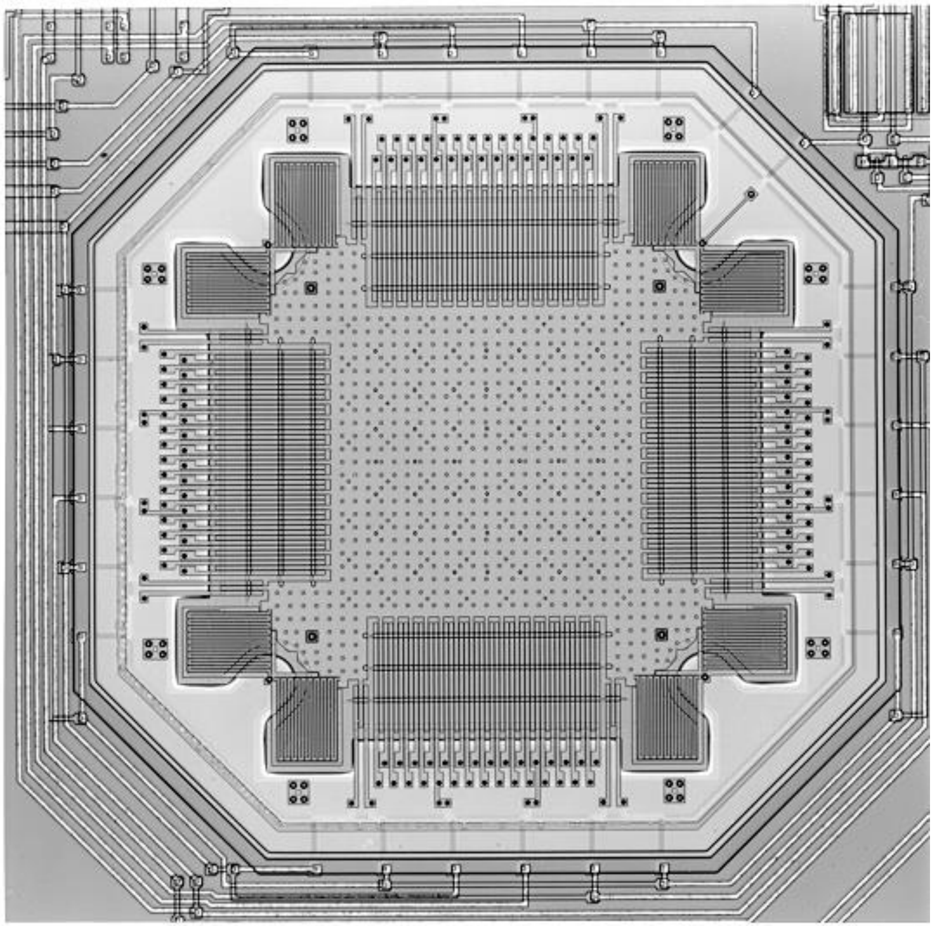
Sources: 1) John A. Yasaitis et al., Vol. 4979, 2003 SPIE, 2) “Comparing process flow of monolithic CMOS-MEMS intergration on SOI wafers with monolithic BiMOS-MEMS integration on Silicon wafer”; Solanki, A et al, 2010 53rd IEEE International Midwest Symposium on Circuits and Systems, p 1189-92, 2010



Monolithic Integration on CMOS. 1 MEMS for Each Axis

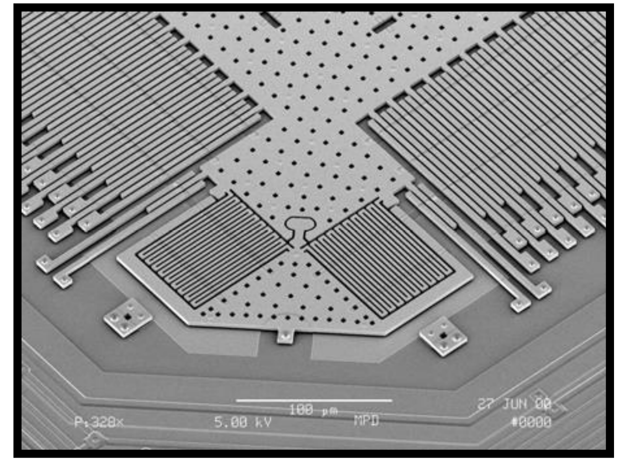
Analog Devices Chips

> **Then moved from two 1-axis sensors to one 2-axis**



ADXL202 Sensor Structure

Courtesy of Analog Devices, Inc. Used with permission.



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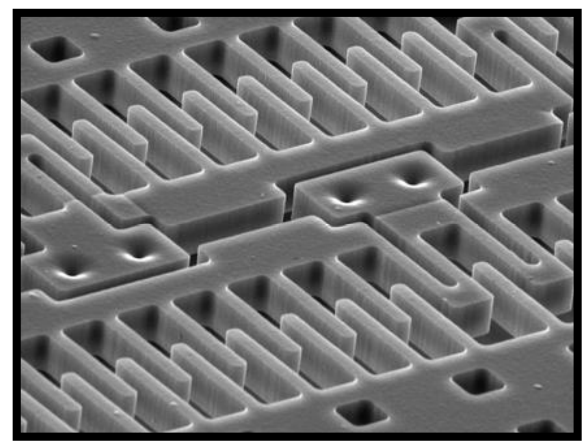

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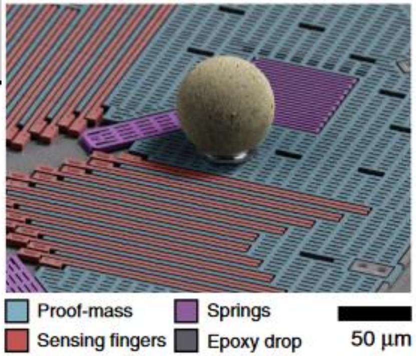
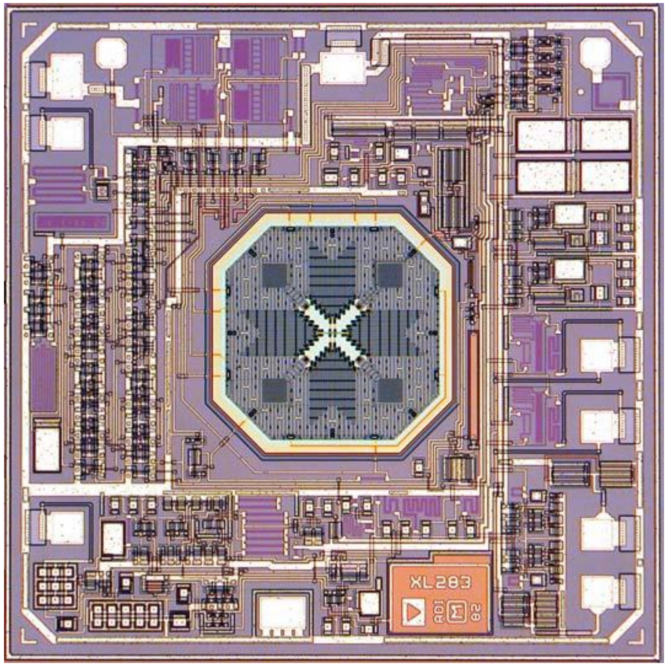
Analog Devices Chips



- > **ADXL203 two-axis accelerometer**
- > **Supports are in center of die to cancel 1st-order stresses due to packaging**



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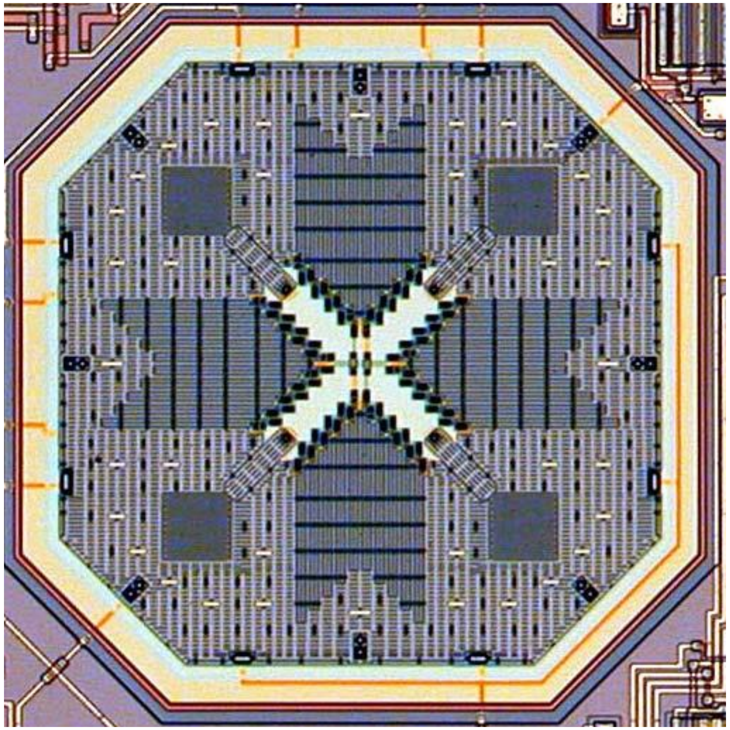

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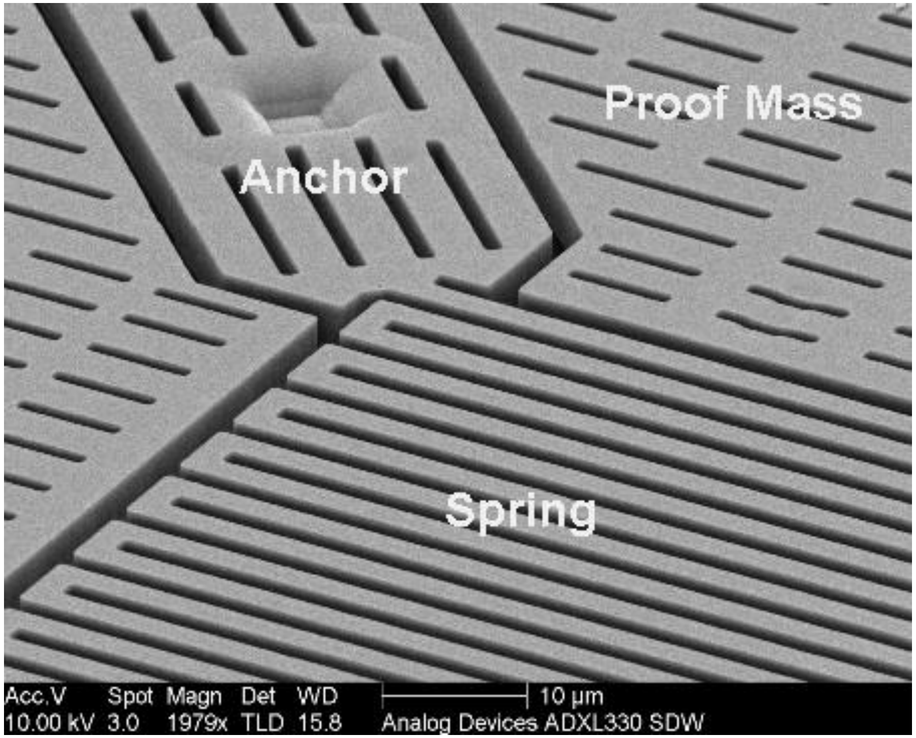
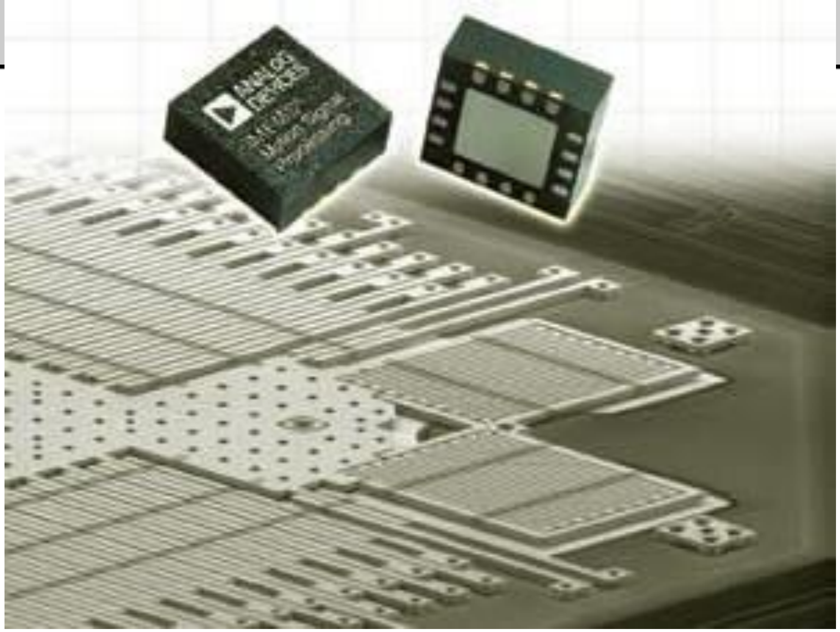
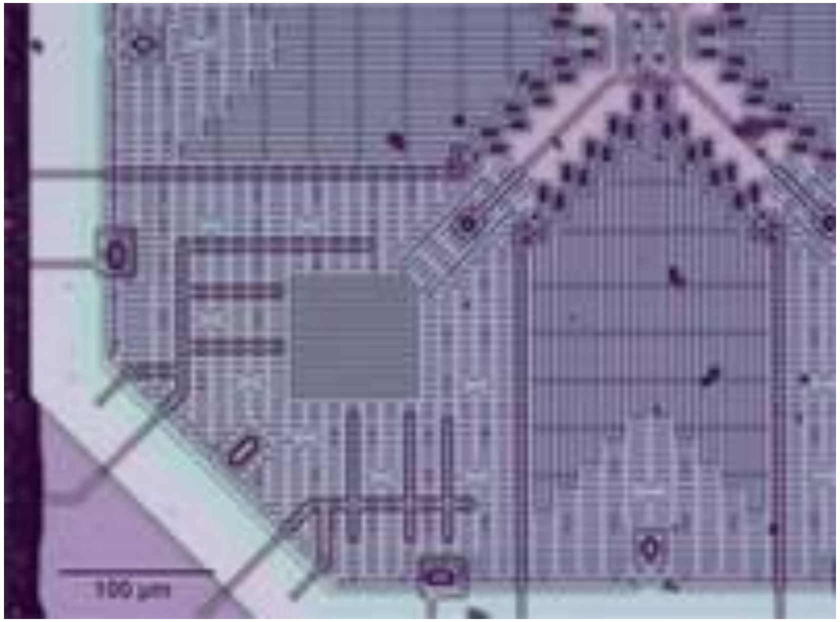
Analog Devices Chips

Accelerometers



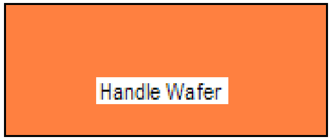




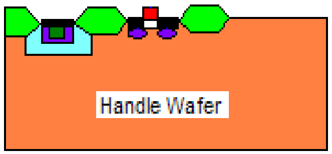
photos: *Analog Devices*

Analog Devices – Process Comparison

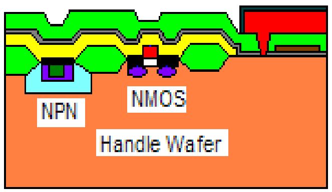
BiMOS



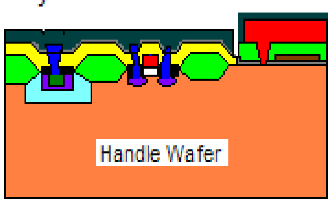
(a) Starting Substrate: Silicon wafer



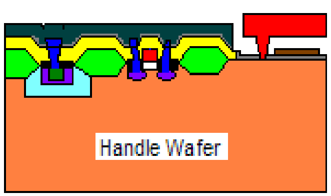
(b) 3um Bi-MOS Circuit Formation



(c) Polysilicon Sensor Formation

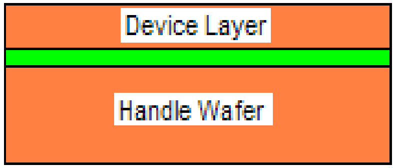


(d) Bi-MOS Circuit Completion

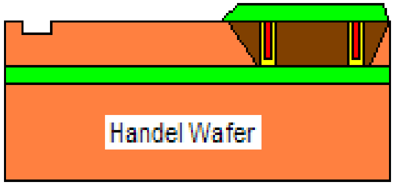


(e) Sensor patterned and released

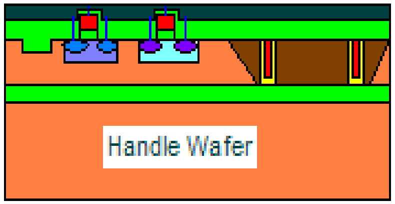
SOI MEMS



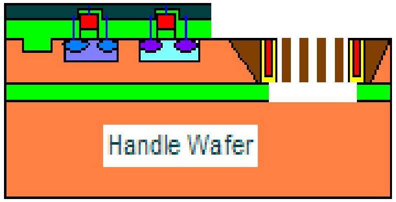
(a) Starting Substrate: 6" bonded SOI wafer



(b) Wafers shipped to CMOS Fab for Circuit Processing



(c) Wafer after 0.6um CMOS Circuitry



(d) Mask open, Beams are patterned and released

BiMOS

- Easier on-chip signal routing
- Lower parasitic capacity than SOI MEMS

SOI MEMS

- Thicker device layer
  → thicker beams & higher electrodes
  → larger signal!

Source: "Comparing process flow of monolithic CMOS-MEMS intergration on SOI wafers with monolithic BiMOS-MEMS integration on Silicon wafer"; Solanki, A; Prasad, K.; Nunan, K.; Oreilly, R. Source: 2010 53rd IEEE International Midwest Symposium on Circuits and Systems, p 1189-92, 2010

- **3 main ways to integrate z- axis acceleration sensor**

Vertical asymmetrical electrodes

- Electrodes with difference in height provides sensitivity along the z-axis:
- Cross sensitivity from other axis to compensate $$\Delta C_z = (C_A + C_B) - (C_C + C_D) = 2\varepsilon l\left(\frac{1}{d_1} + \frac{1}{d_2}\right)\Delta z$$

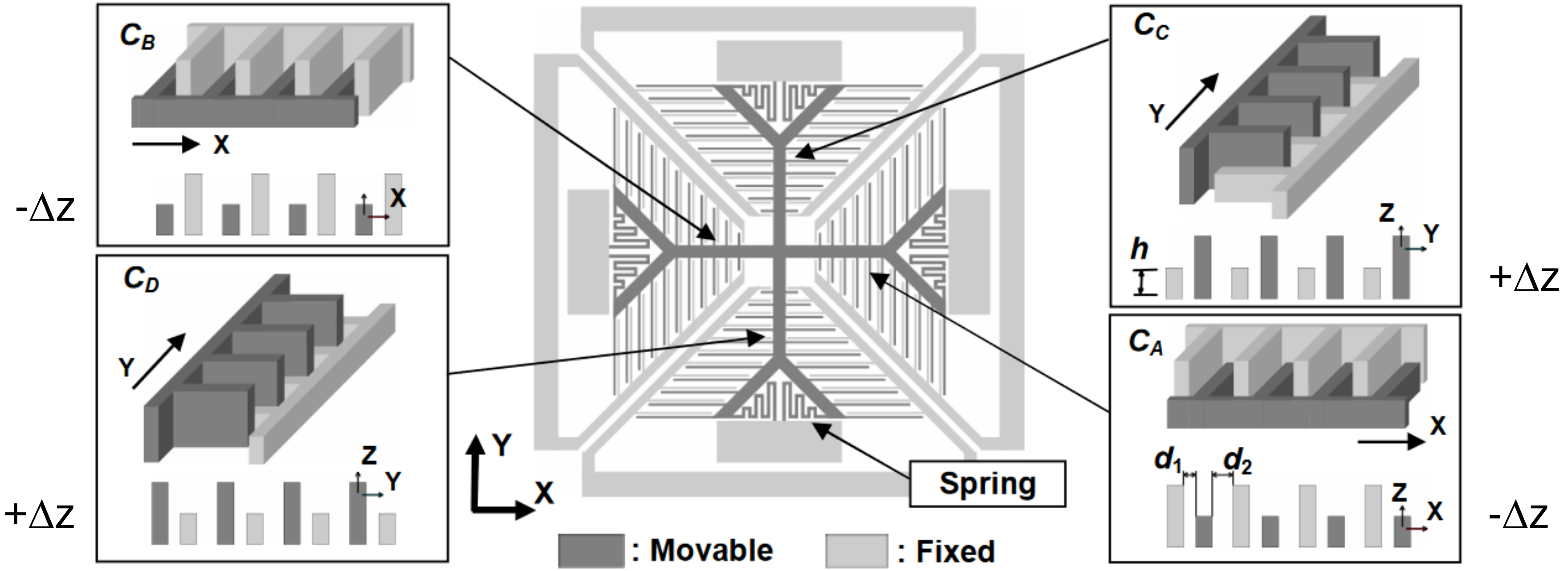
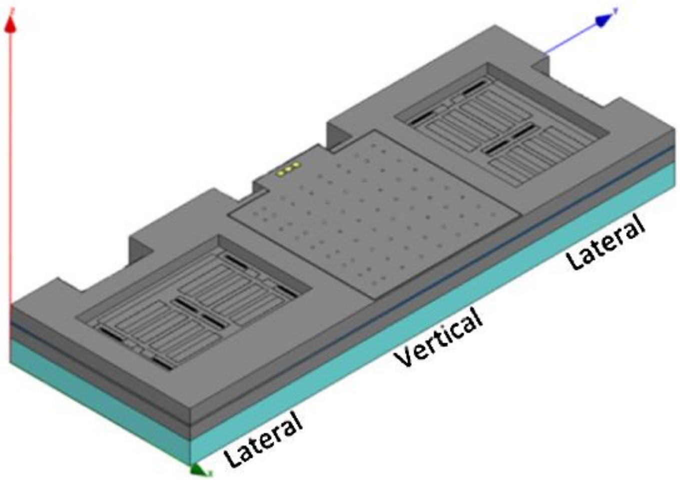


Figure 2 Schematics view of the device and four capacitors: (center) entire schematic view, (upper left) C_B, (lower left) C_D, (upper right) C_C, (lower right) C_A.

A differential capacitive three-axis accelerometer using vertical comb electrodes, Transducers 2007

- **3 main ways to integrate z- axis acceleration sensor**

Horizontal parallel plate capacitor



- Proof mass moving between 2 fixed electrodes
- Differential measurement
- Surface micromachining process on a Silicon On Insulator (SOI) wafer bonded to a glass substrate

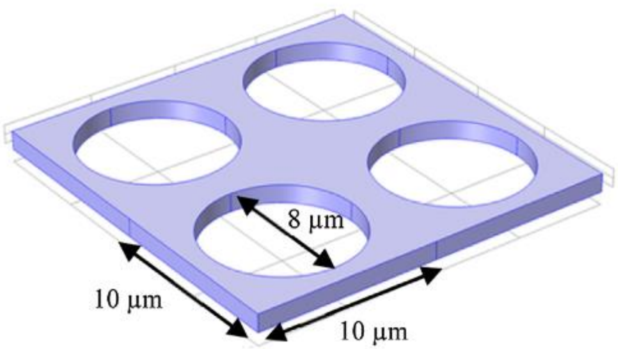
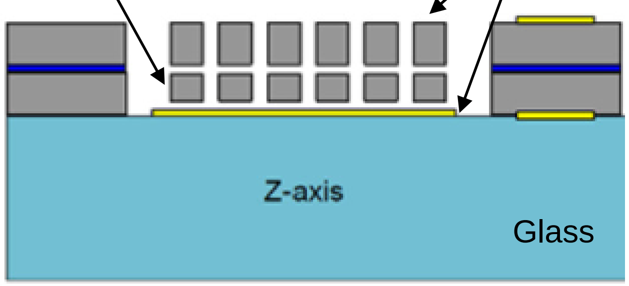


Fig. 3. Proof mass and top electrode structure of the vertical axis accelerometer which is composed of 10 × 10 µm^2 unit cells with a 4 µm damping hole radius.

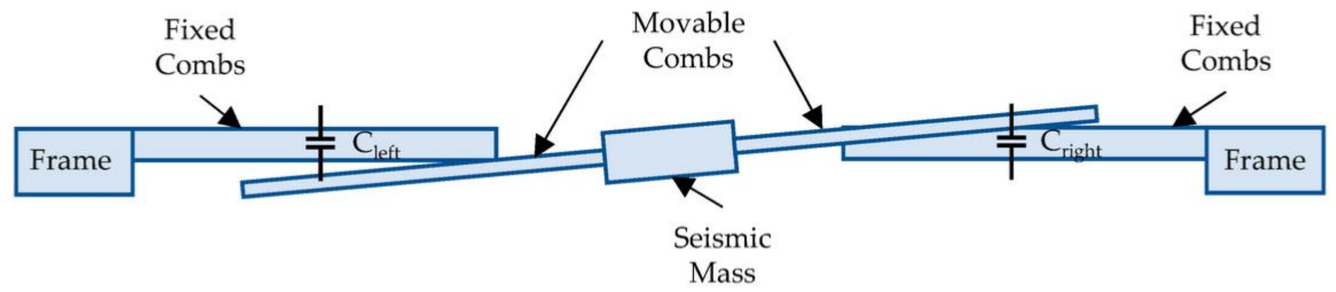


Sensors and Actuators A 244 (2016) 324–333

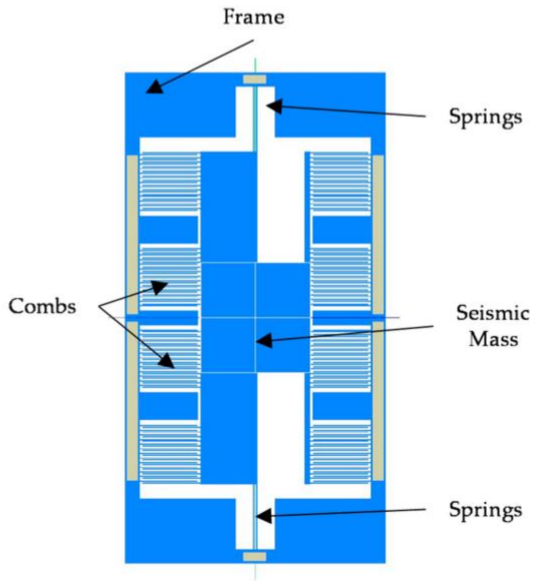
3 axis accelerometers

- **3 main ways to integrate z- axis acceleration sensor**

Asymmetric torsional proof mass



Top view



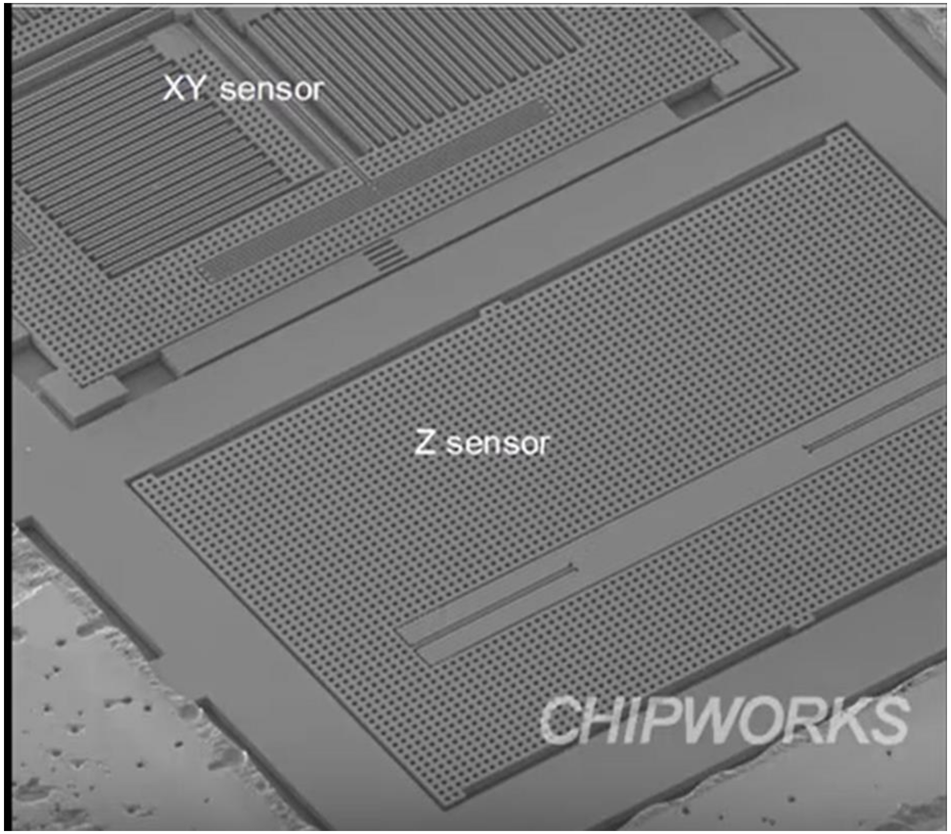
- Asymmetrical proof mass linked to a torsional bar with unbalanced moments under acceleration
- Comb electrodes for differential capacitance measurement
- Holes in proof mass plate for damping adjustment and surface micromachining process (i.e. etching of sacrificial layer)

Sensors 2021, *21*(10), 3564; https://doi.org/10.3390/s21103564

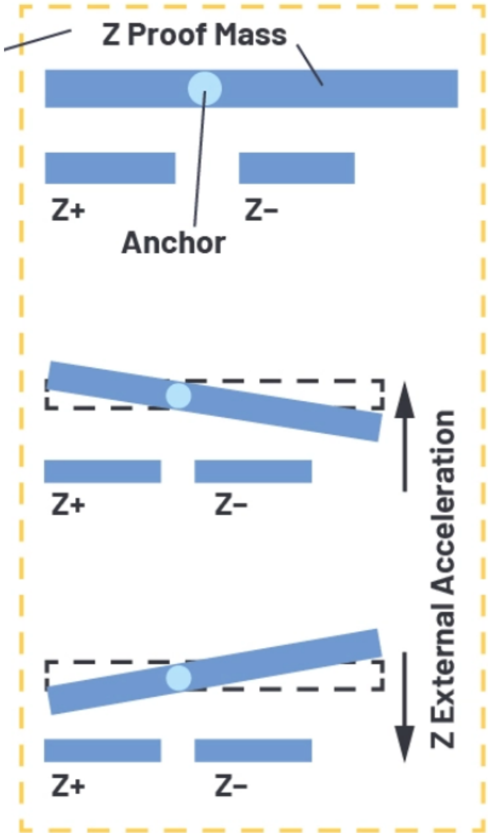
3 axis accelerometers

- 3 main ways to integrate z- axis acceleration sensor

Asymmetric torsional proof mass



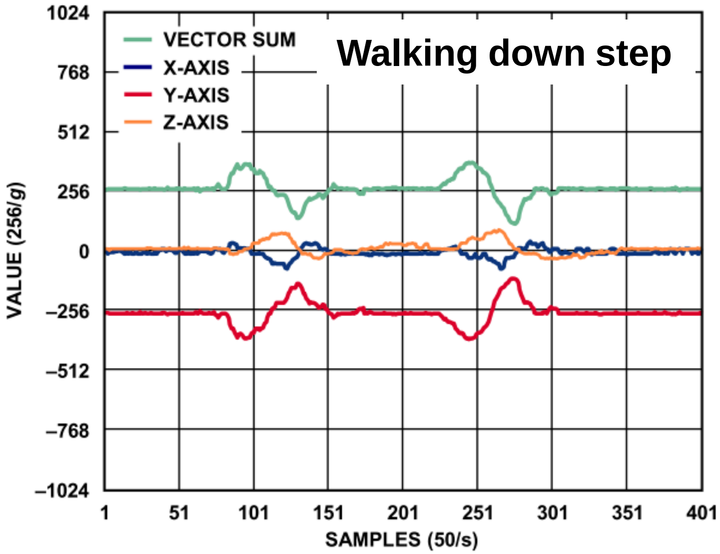
ST Microelectronics 3-axis accelerometer

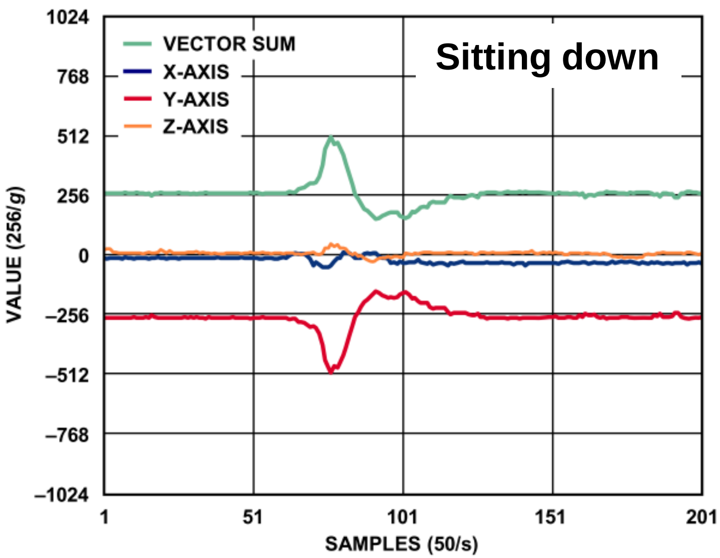


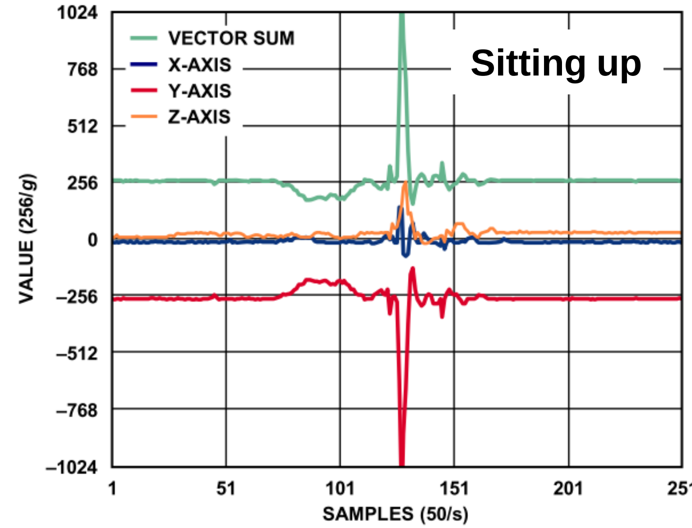
Z Sensor, Side View

Hard Disk Protection

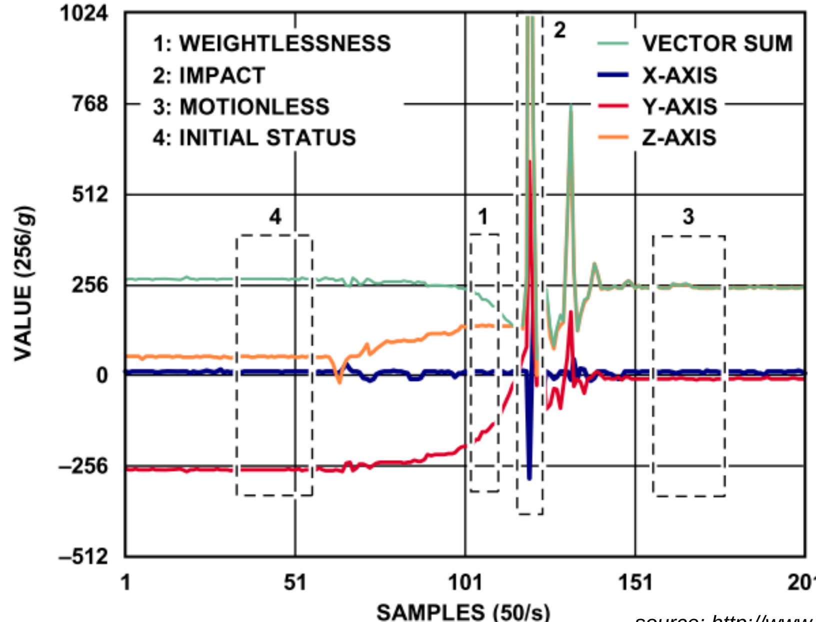
Distinguishing events and common motions







Drop down



source: http://www.analog.com

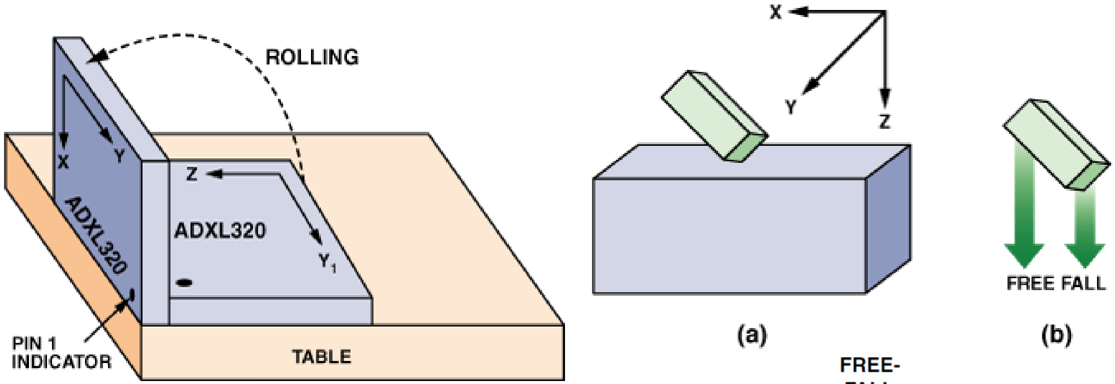
Hard Disk Protection

source: http://www.analog.com/library/analogdialogue/archives/39-11/hdd.html

- **Preventing impact shock on HDD**
- **"Early" detection required**

→ Change of acceleration!

→ Sum of at least two axes



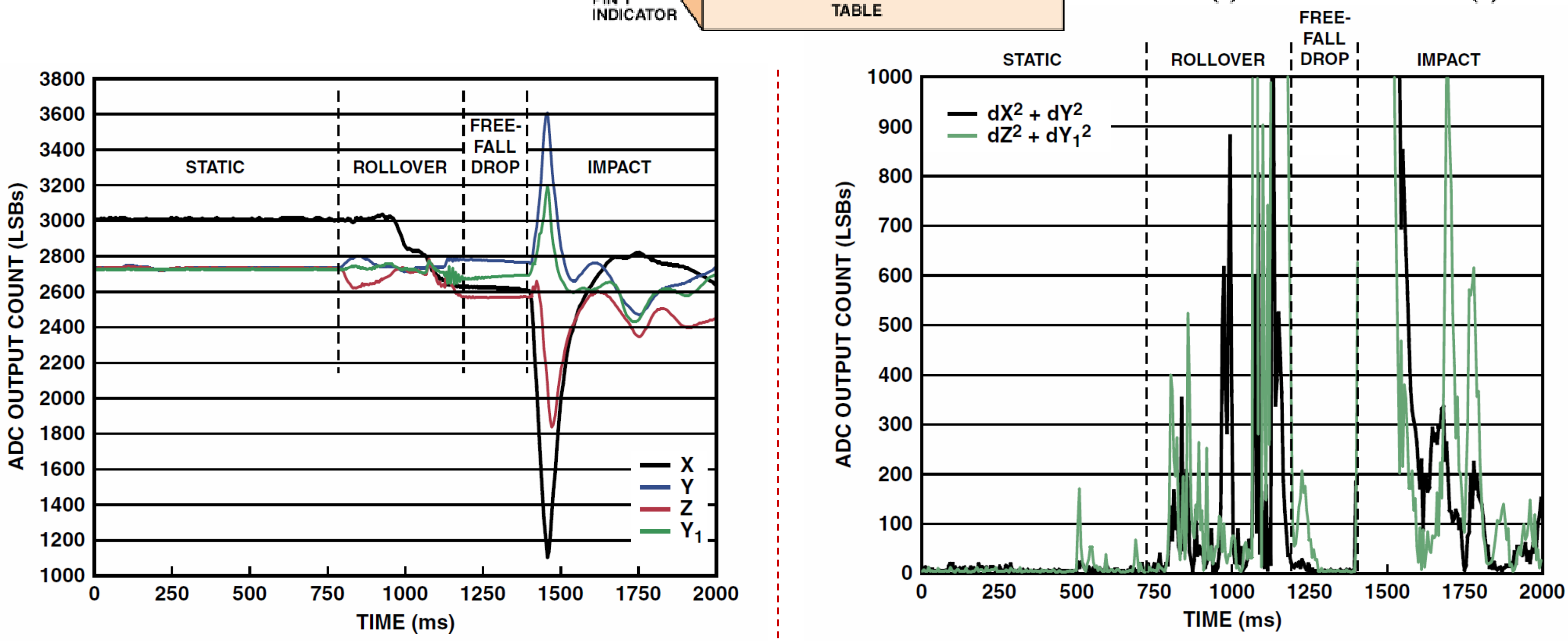


Figure 5. Traditional protection algorithm—sequence of responses sensed by the accelerometers.

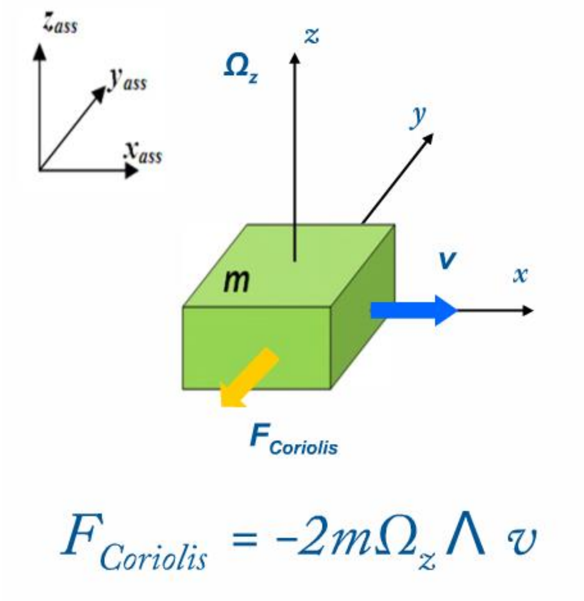
Figure 6. Differential acceleration algorithm-time-derivative plots for $(dX/dt)^2 + (dY/dt)^2$ and $(dZ/dt)^2 + (dY_1/dt)^2$.

CAPACITIVE MEMS GYROSCOPES

Coriolis

Force is *perpendicular* to
linear velocity *v* and angular velocity *Ω*

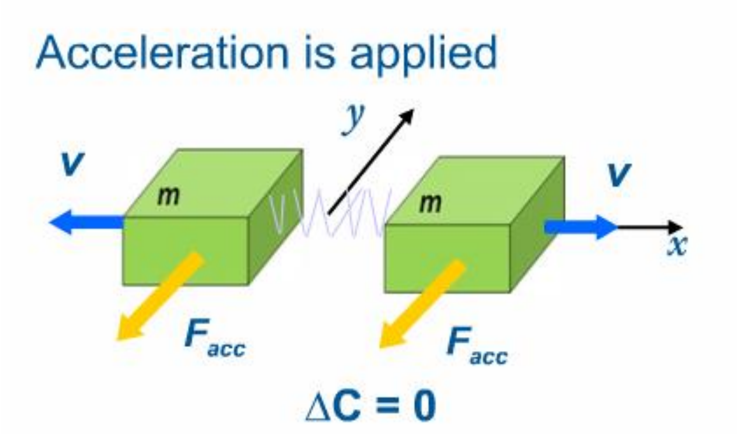
$$\vec{F}_C = 2\,m\,(\vec{v}\times\vec{\Omega}) = -2\,m\,(\vec{\Omega}\times\vec{v})$$



Newton

Force is in same direction as acceleration

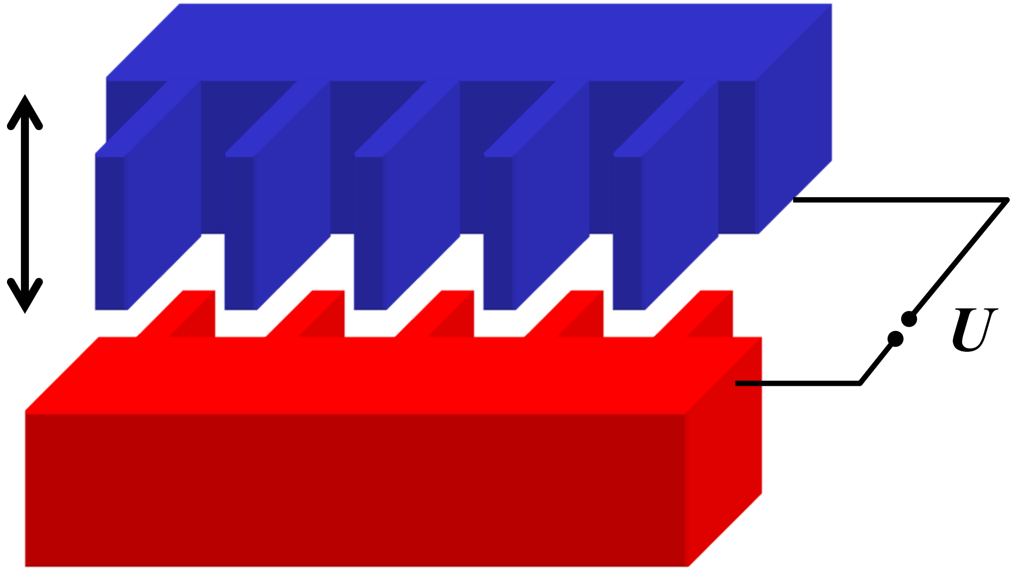
$$\vec{F}_N = m\,\vec{a}$$

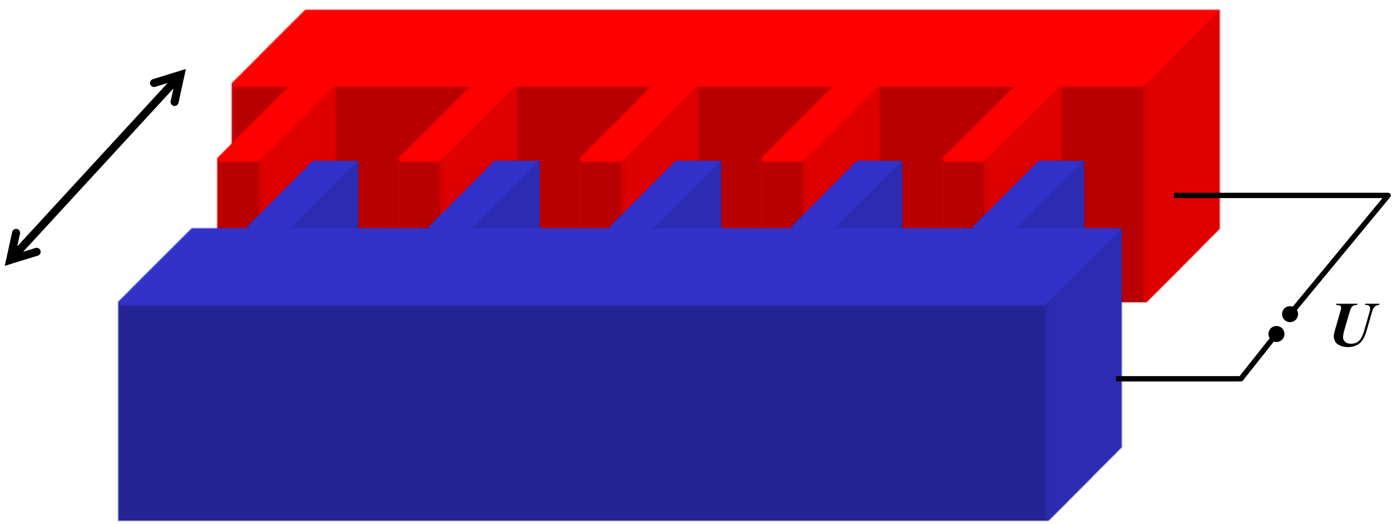


Interesting e-Learning Tutorial:
http://www.st.com/internet/com/MULTIMEDIA_RESOURCES/VIDEO/DEMO_VIDEO/epres_mems_gyroscope.swf

Electrostatic Comb-Drive Actuators for the Oscillating Masses

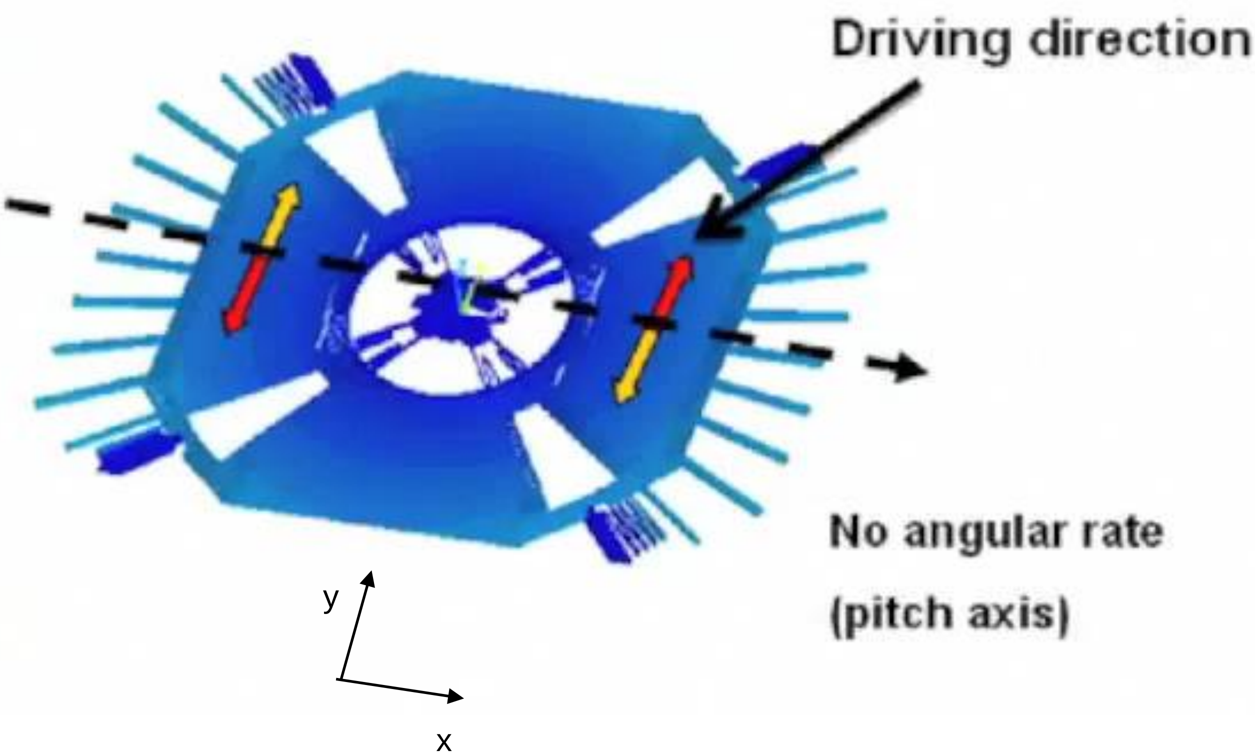
- **Low power**
- **Lateral actuation**
  - **In-plane motion**
- **Vertical actuation**
  - **Out-of-plane**
- **Movement depends on degree of freedom**
- **Vary accurate movement**

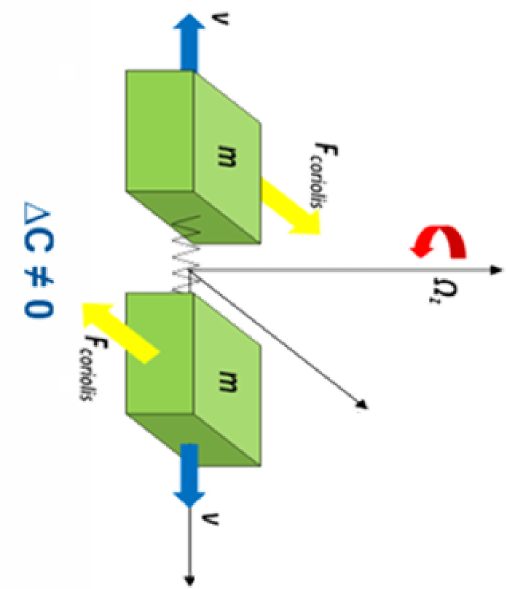




- **Moving disk in plane**
- **Vibrating, oscillation**
- **Coriolis force causes out-of-plane displacement**
- **Differential capacities are measured**

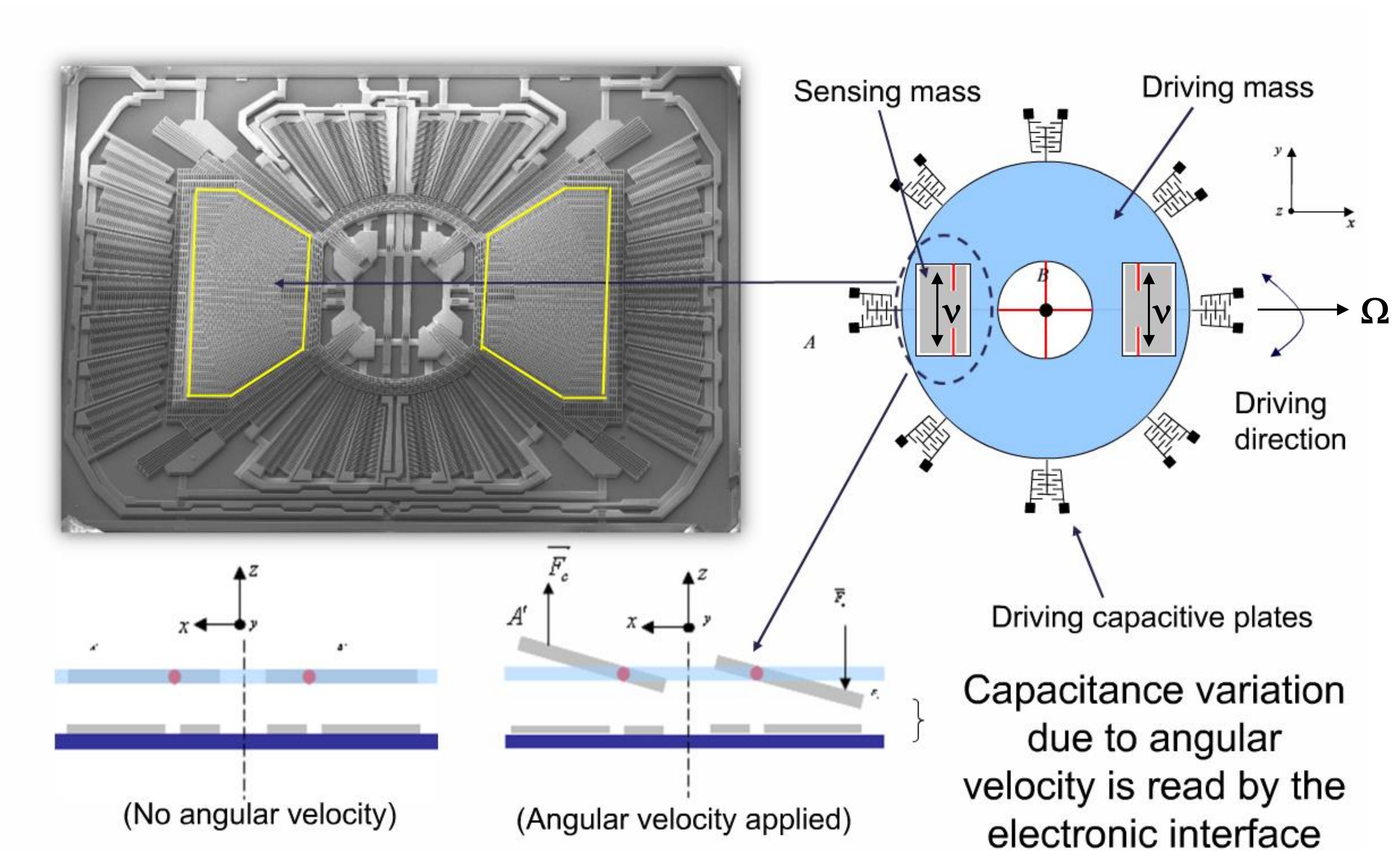
$$\vec{F}_C = 2\,m\,(\vec{v} \times \vec{\Omega}) = -2\,m\,(\vec{\Omega} \times \vec{v})$$





Interesting e-Learning Tutorial:
https://www.youtube.com/watch?v=I75IiNVRdfg

Gyroscope working principle

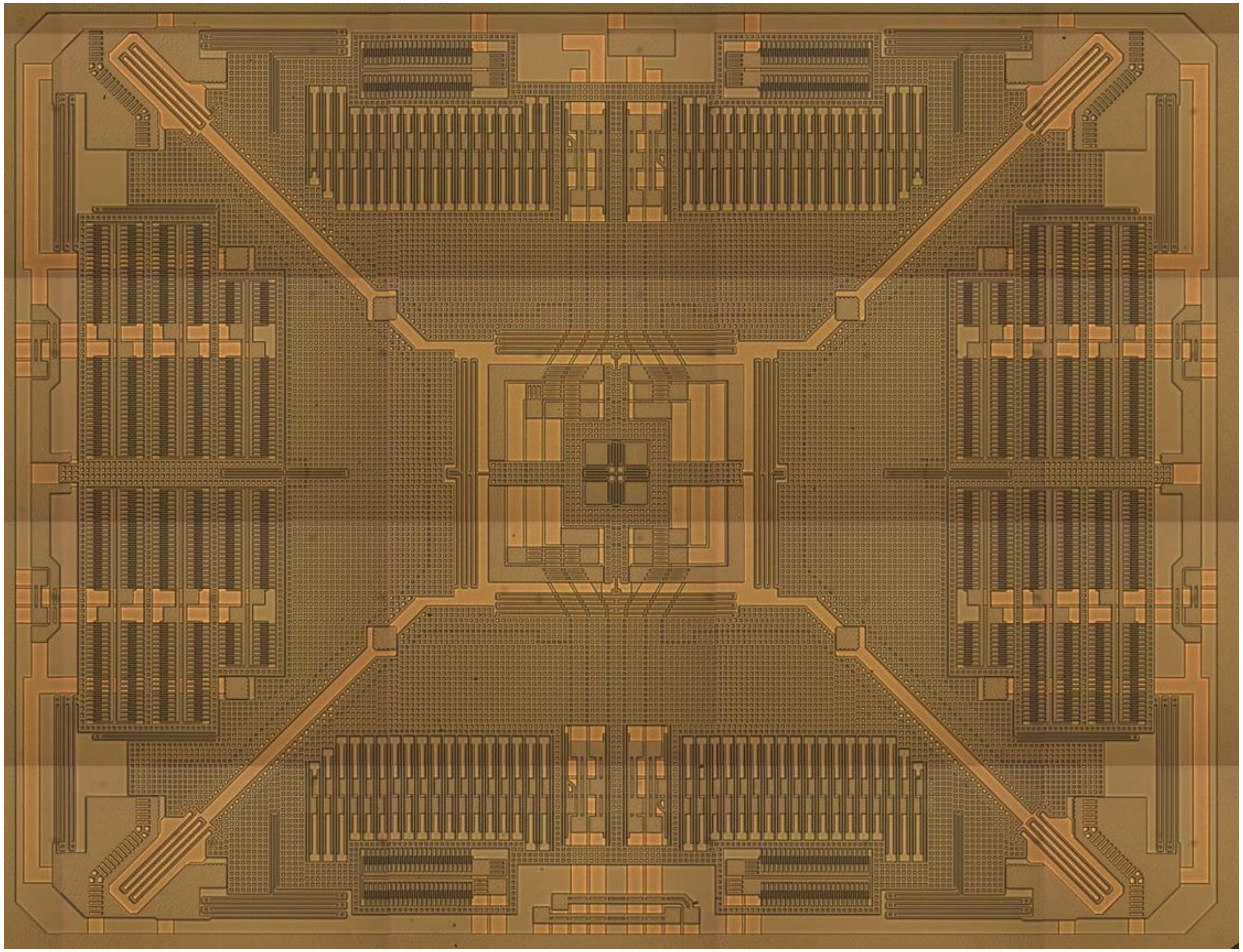


Capacitance variation due to angular velocity is read by the electronic interface

Source:: http://www.st.com

Apple – iPhone 4 Gyroscope From ST

- Comb-drive for in plane mass vibrations perpendicular to angular rate vector
- Parallel plate capacitor variations for roll and pitch measurements
- Large wings displaced in-plane for the yaw direction



Source: www.ifixit.com

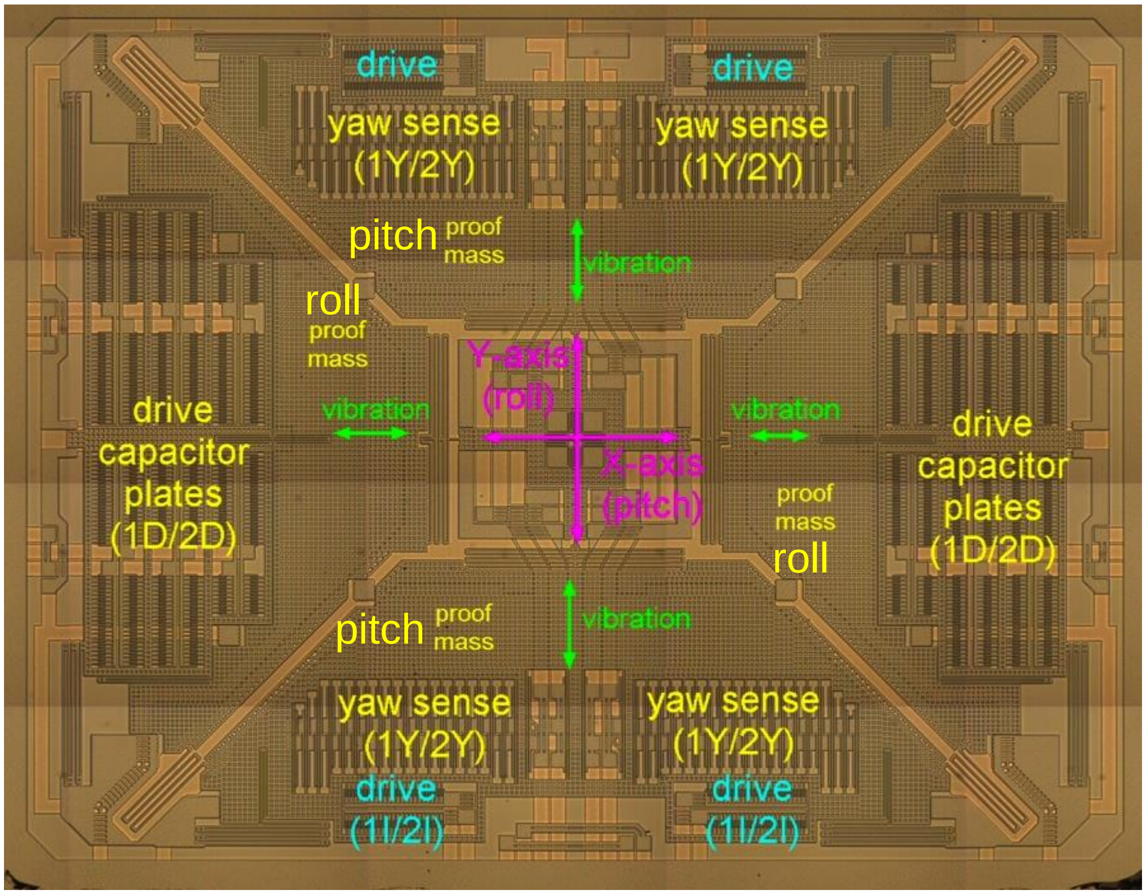
3-Axes Gyroscope with single mass

Coriolis forces out of plane for the roll and pitch angular rates

y

x

Ω roll



Ω pitch

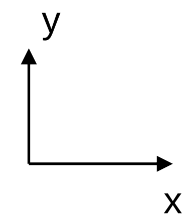
Explanations: https://www.youtube.com/watch?v=5BWerr7rJmU   x-y axis inverted !

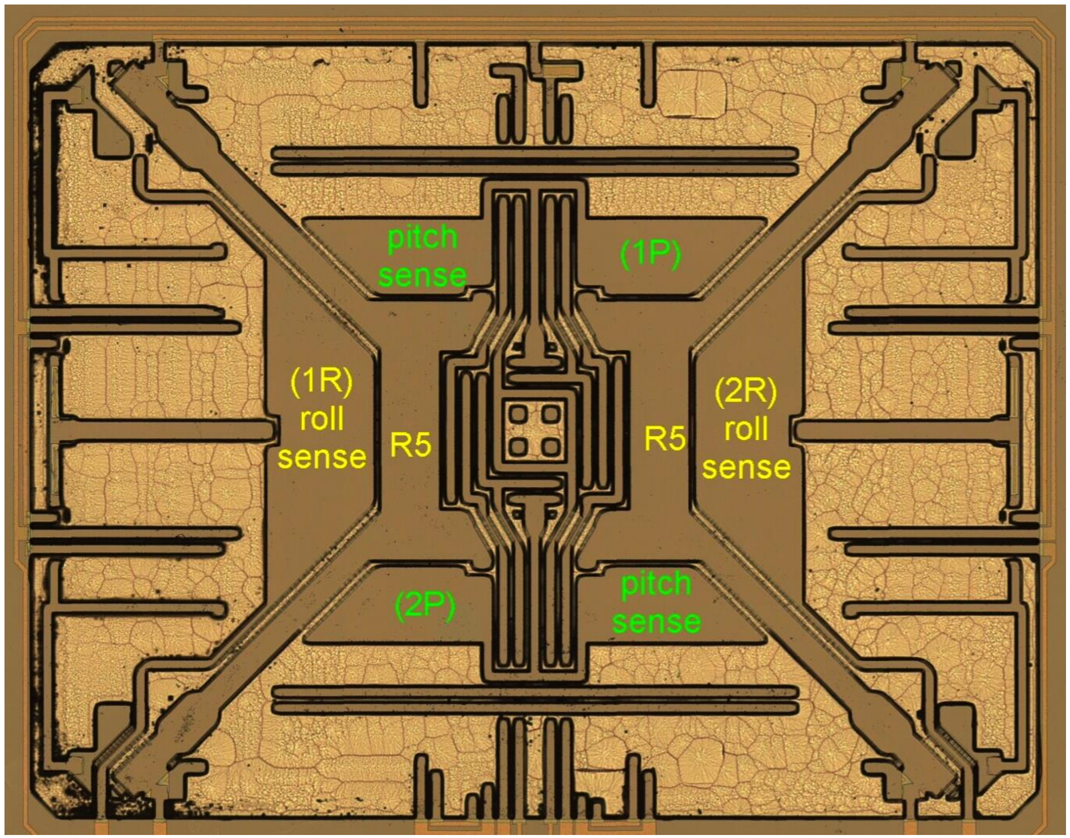
CHIPWORKS

Source: www.ifixit.com

Apple – iPhone 4 Gyroscope

Bottom electrodes for roll and pitch capacitive sensing





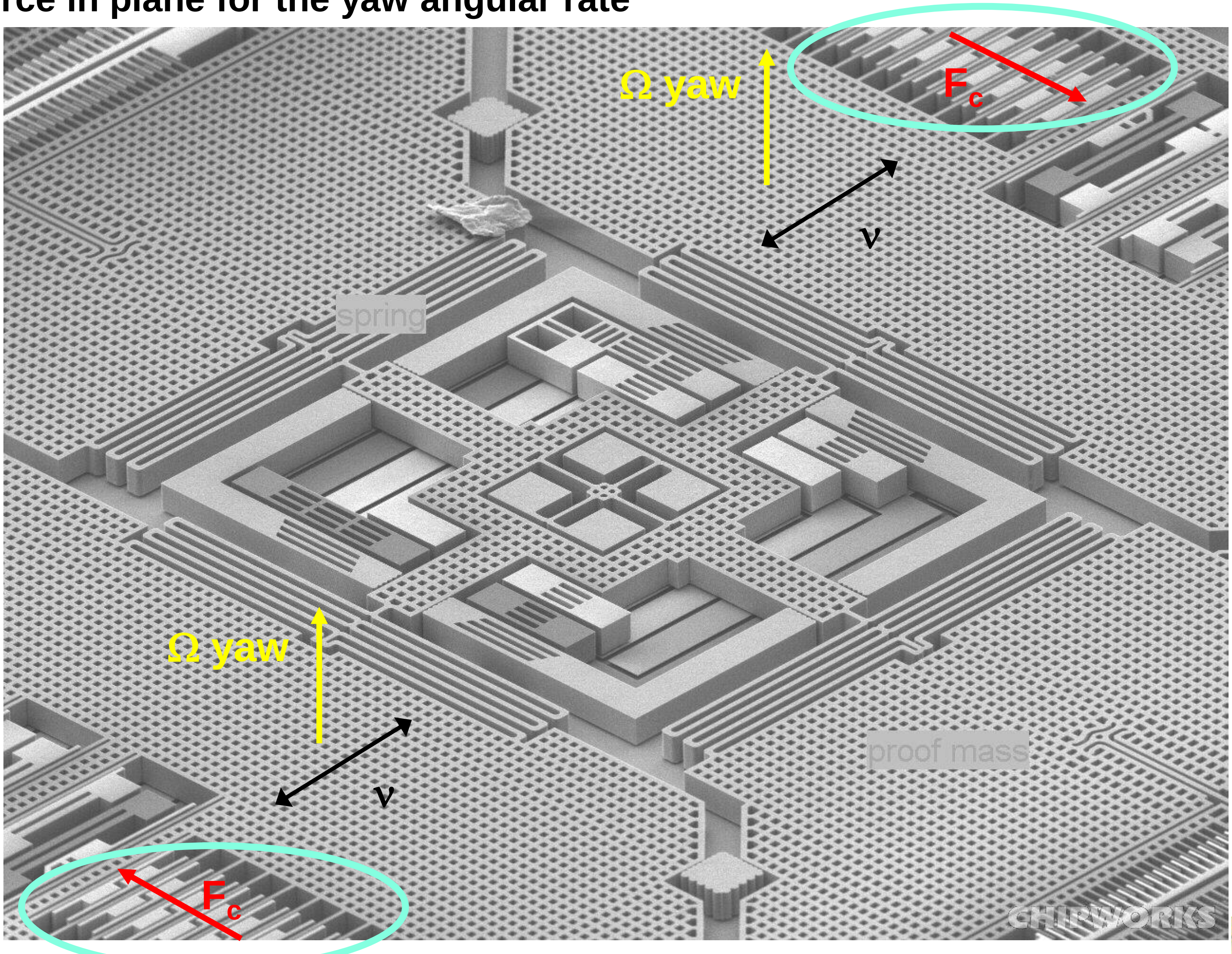
*** In video: this picture is rotated 90° because of x-y axis rotation**

Source: www.ifixit.com

Apple – iPhone 4 Gyroscope

Coriolis force in plane for the yaw angular rate

Vertical electrodes for yaw sensing



Vertical electrodes for yaw sensing

Source: www.ifixit.com

Capacitive and Piezoresistive Sensing

SUMMARY

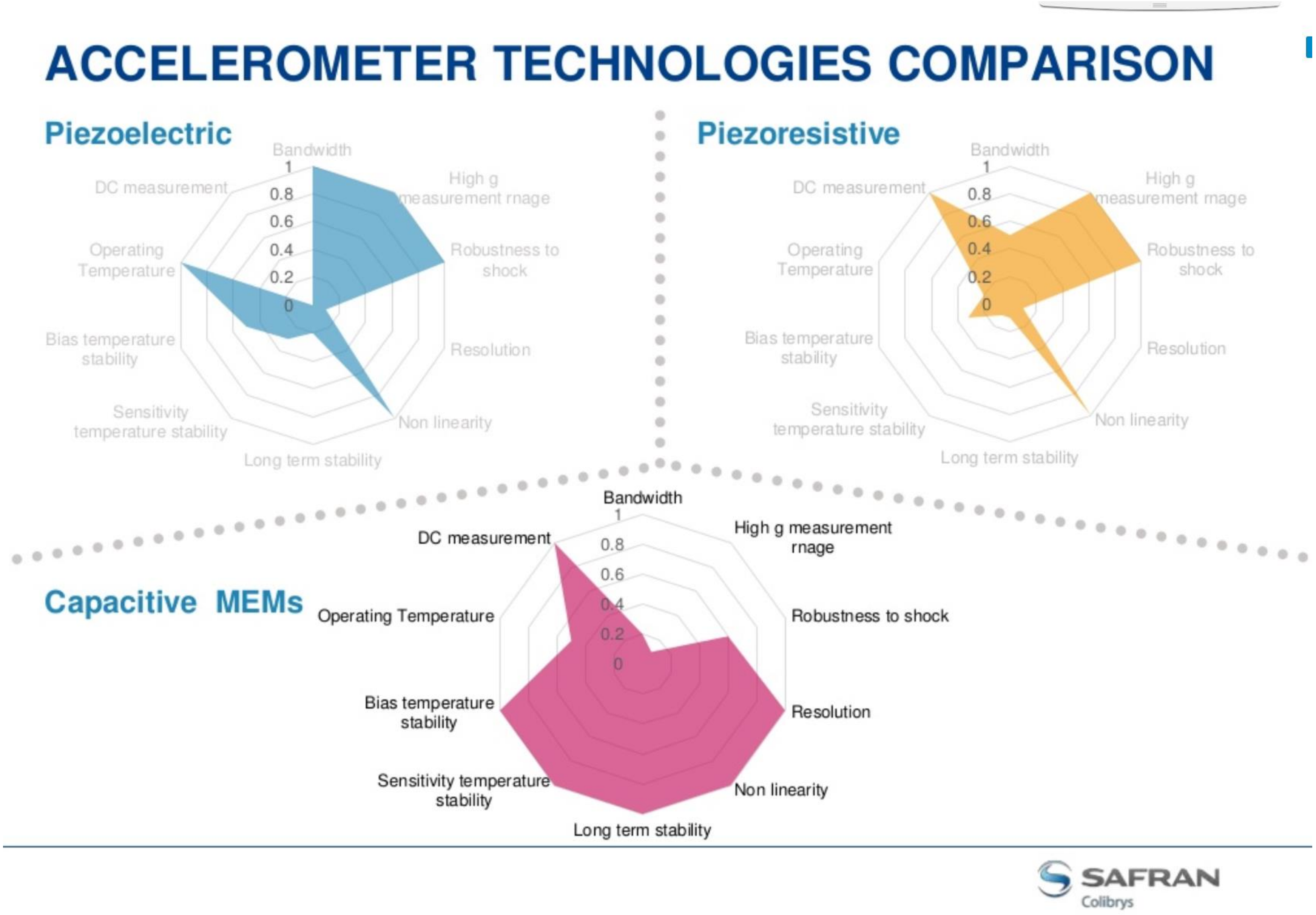
Piezoresistive Vs Capacitive sensing

Capacitive sensing is perhaps the most dominant position-sensing technique for microfabricated sensors. However, there are a number of limitations imposed on capacitive sensors:

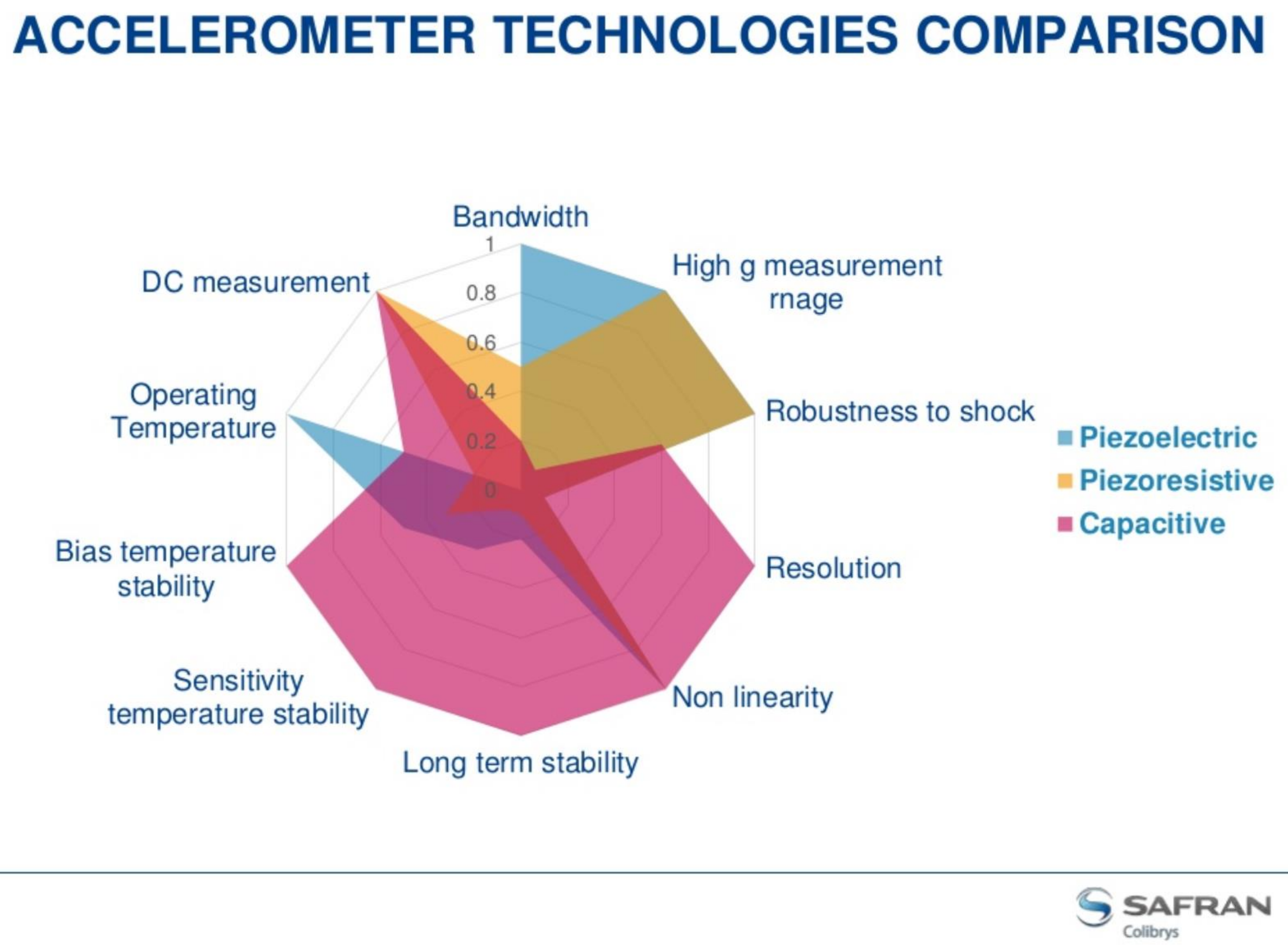
- **The detection of position is constrained to small vertical movement (parallel plate) and horizontal movement (transverse or lateral comb drives).**
- **The area of overlapped electrodes must be reasonably large (as a rule of thumb, tens of μm^2). If the overlap area is small and the vertical displacement is large, capacitive sensors are not suitable.**
- **Parasitic capacitances requiring specific electronics circuitry**

Ref: Chang Liu; MASS UIUC

Accelerometer Technologies Comparison (Colibrys)



Accelerometer Technologies Comparison (Colibrys)



“Merging data from multiple sensors — a process called sensor fusion— to create the most precise representation of the environment”

Current Developments and Trends

SENSOR FUSION

What’s going on?

Motion Sensors

Inertial

Linear & Gravity

- Accelerometer
- → Position i.r.t. gravity
- → Change of speed
- → Vibration & shock

Rotational

- Gyroscope
- → Angular rate
- → Rotation direction

Magnetic

- Magnetometer
- →Direction
- →Heading

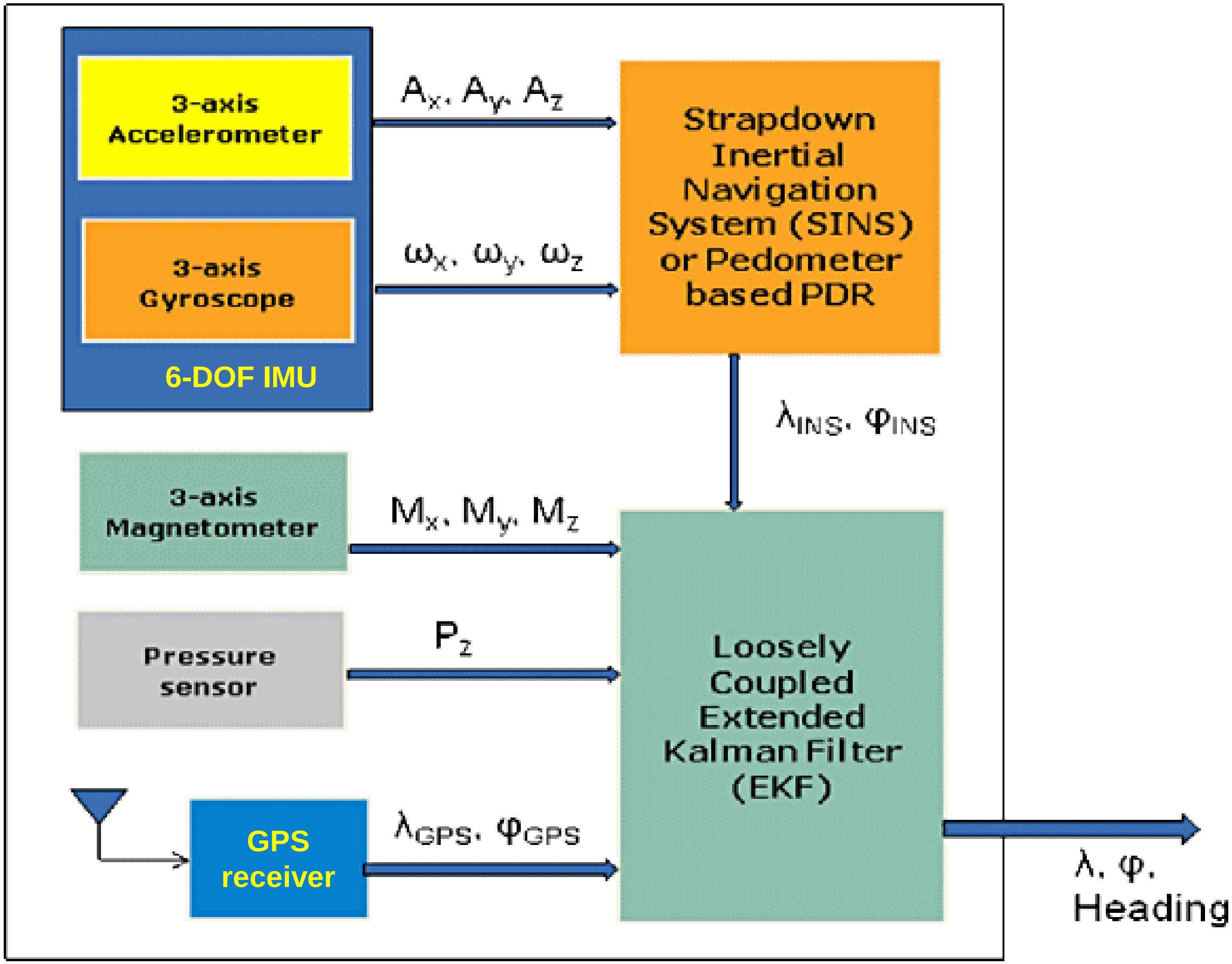
Pressure

- Pressure sensor
- → Altitude

Position

- GPS
- → Coordinates
- → Static
- → Dynamic

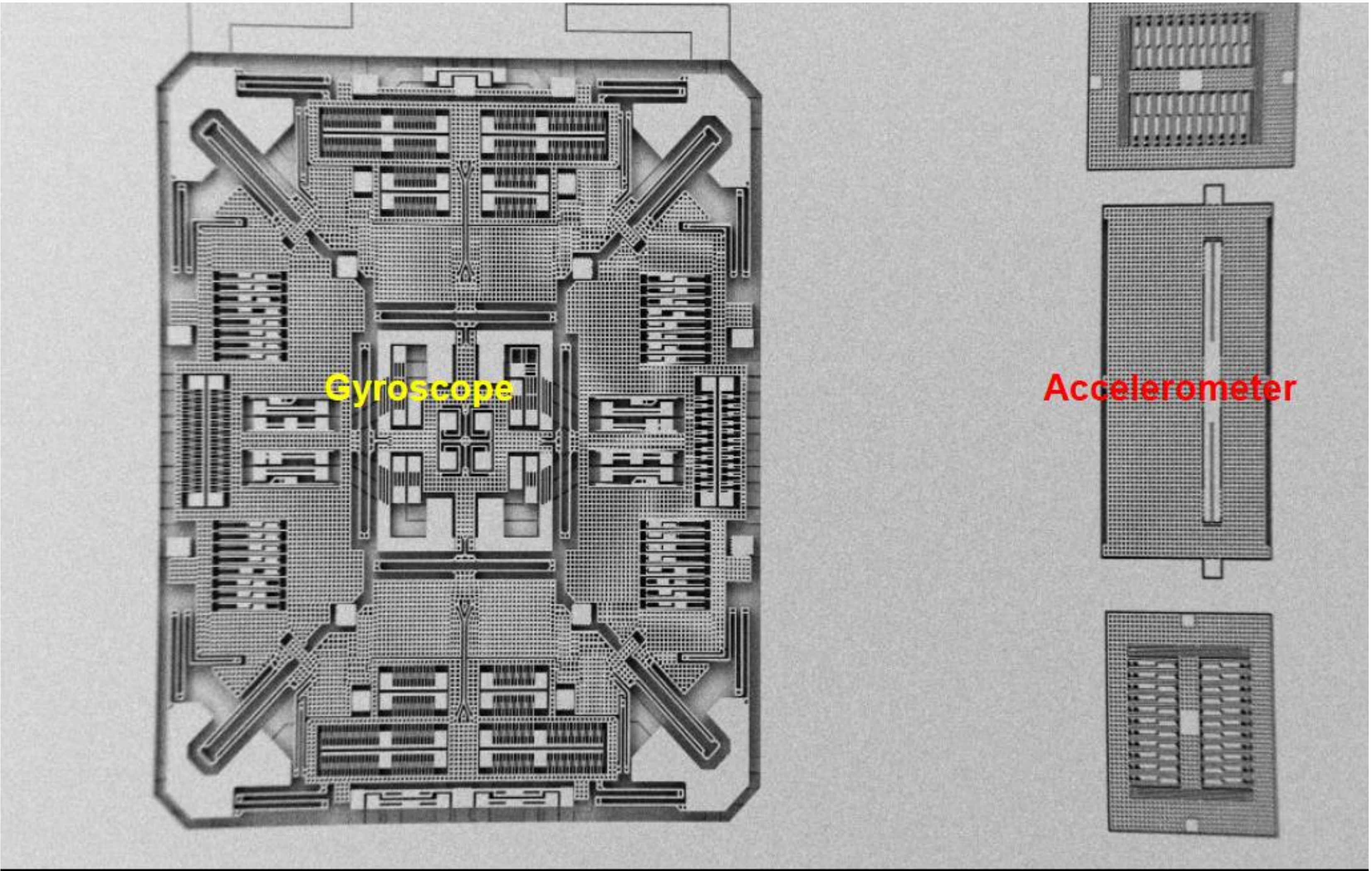
Sensor Fusion
→ Combining Sensors to get the «full picture»



http://www.findmems.com

Example for “Fusion” – iPhone 4

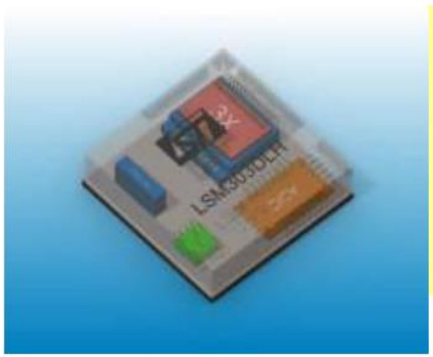
http://iphonegeartalk.com/tag/gyroscope-technology



High performance Accelerometer and Gyro on the same chip

LSM303DLH: 6-Axis Module overview

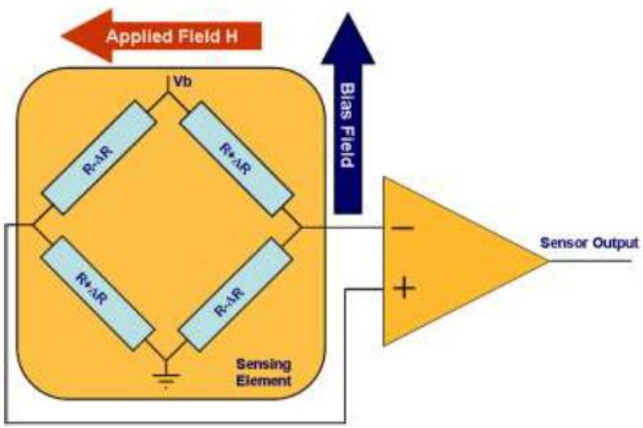
6D module: 3-Axis Accelerometer & 3-Axis Magnetometer

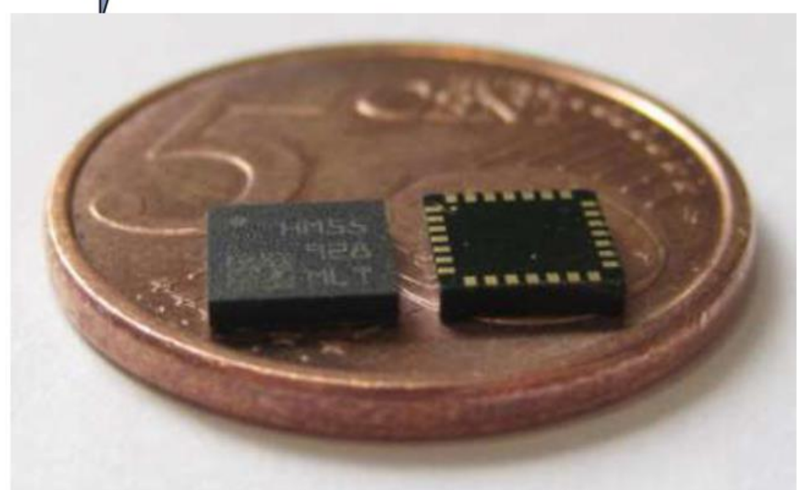


- 3A & 3M Module
- 1.0mA current consumption
- ±1.3 to 8.1 gauss MAG full scale
- ±2g/±4g/±8g Acc. full scale
- 1mg resolution (12 bit)
- Built-in Strap drive circuits
- Self test (Accel & Mag)
- I2C serial interface
- Power down mode
- LGA 28 – 5x5x1

Earth's magnetic field roughly 0.6 gauss

LSM303DLH cover all measurement range

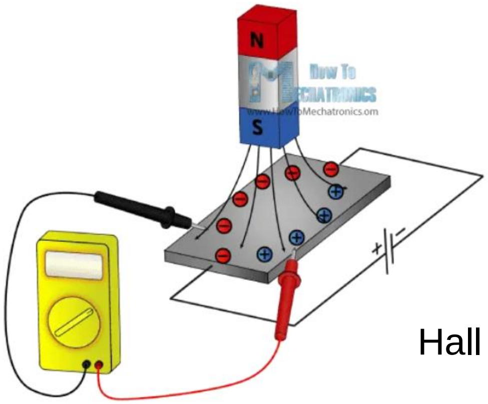




Magnetometer technology

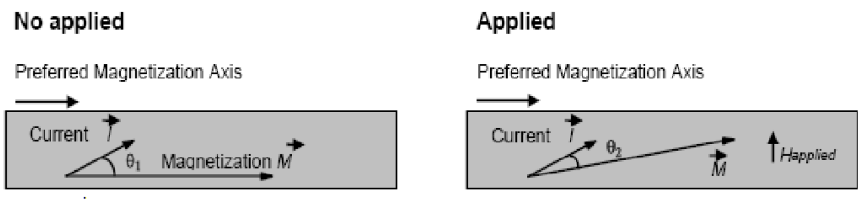
It measures the earth magnetic field by using Hall Effect or Magneto Resistive Effect.

Actually almost 90% of the sensors on the market use the Hall Effect.



Hall effect sensor

- AMR Sensor - Permalloy thin film material (NiFe alloy)



- Magneto-resistance is the property of a material to change the value of its electrical resistance when an external magnetic field is applied
- In AMR sensors, the sensing element is composed by material where a dependence of electrical resistance on the angle between the direction of electrical current and orientation of magnetic field is observed
- In Wheatstone Bridges AMR, the sensing element detects resistance change effects due to magnetic field change, that is translated into a digital word by the electronic section embedded into LSM303DLH

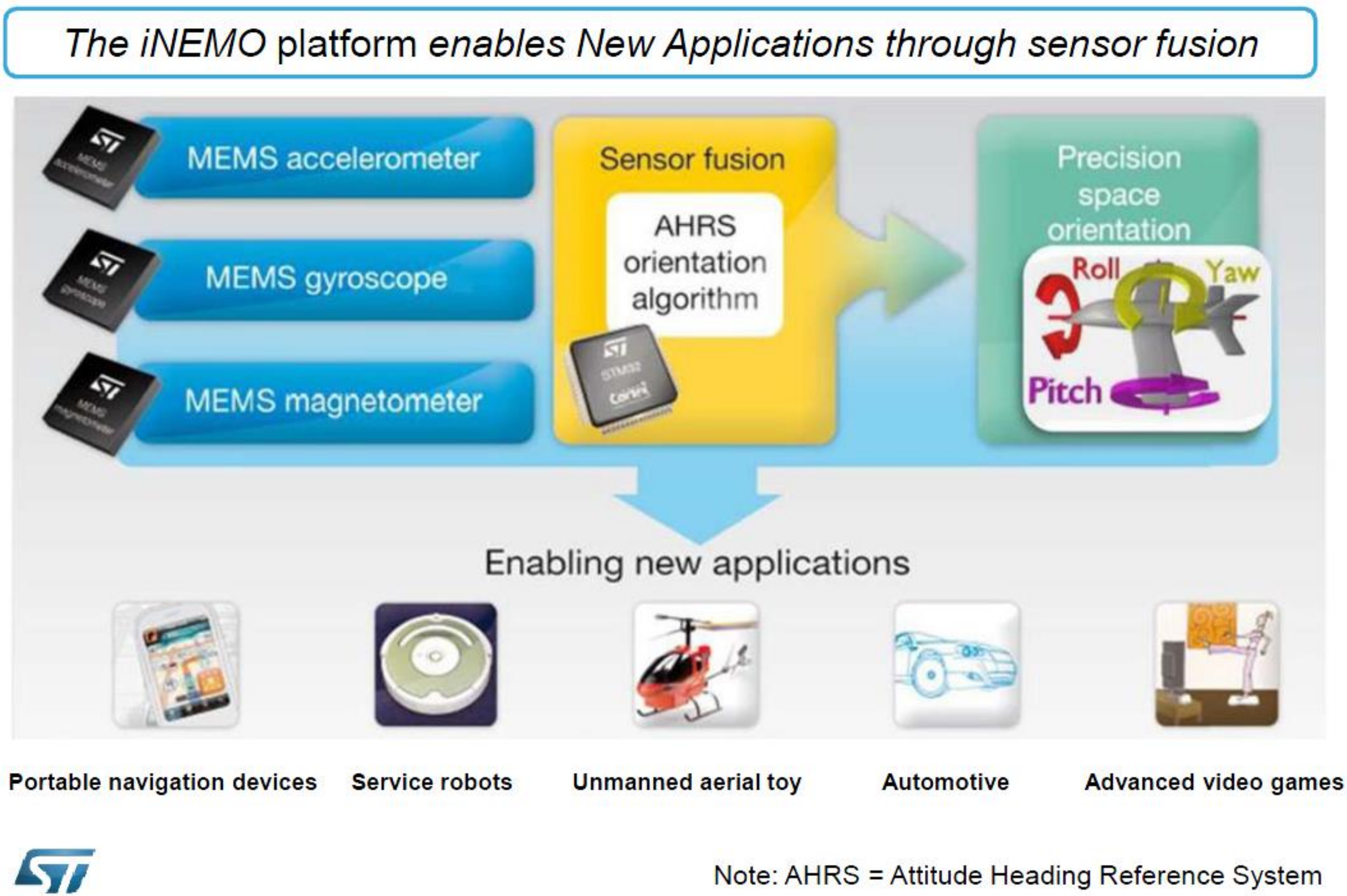
STMicroelectronics

STEVAL-MKI062V2 – iNEMO – 10-DOF

- **10-DegreesOfFreedom platform:**
  - 3-Axis Accelerometer
  - 3-Axis Gyroscopes
  - 3-Axis Magnetometer
  - 1 Dimension of pressure information

- STLM75: temperature sensor with –55 to +125°C range and I^2C
- MCU - STM32F103RE

MEMS Challenge – Smart Chips and Sensors

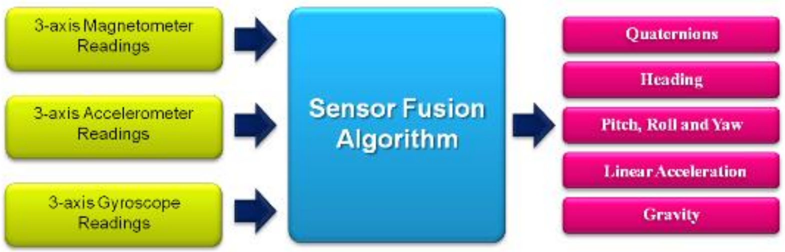


MEMS Challenge – Smart Chips and Sensors

iNEMO® Engine: the Software

ST solution fully deployed in Android and Windows platforms

28



- Sensor fusion combines the signal from multiple sensor and compensates the non idealities of standalone sensors
- The SW provides also advanced features such as:
  - Dynamic signal distortion (hand jitter) from inertial components
  - Magnetic distortions correction
  - Full calibration support

life.augmented

COMPANY CONFIDENTIAL

Inertial Sensors – Costs and Main Suppliers

Sensor Type	Cost Range	Suppliers
MEMS gyro (2 or 3 axis)	< $0.70 per axis	ST Micro InvenSense Epson
MEMS accelerometer (3 axis)	< $0.20 per axis	ST Micro VTI ADI Freescale
Magnetometer (3 Axis)	< $0.70 per axis	Honeywell AKM
MEMS pressure sensor	< $1.50	Bosch

Source: http://www.memsinvestorjournal.com/2011/09/mems-motion-sensors-market-overview-and-a-system-integrators-perspective.html

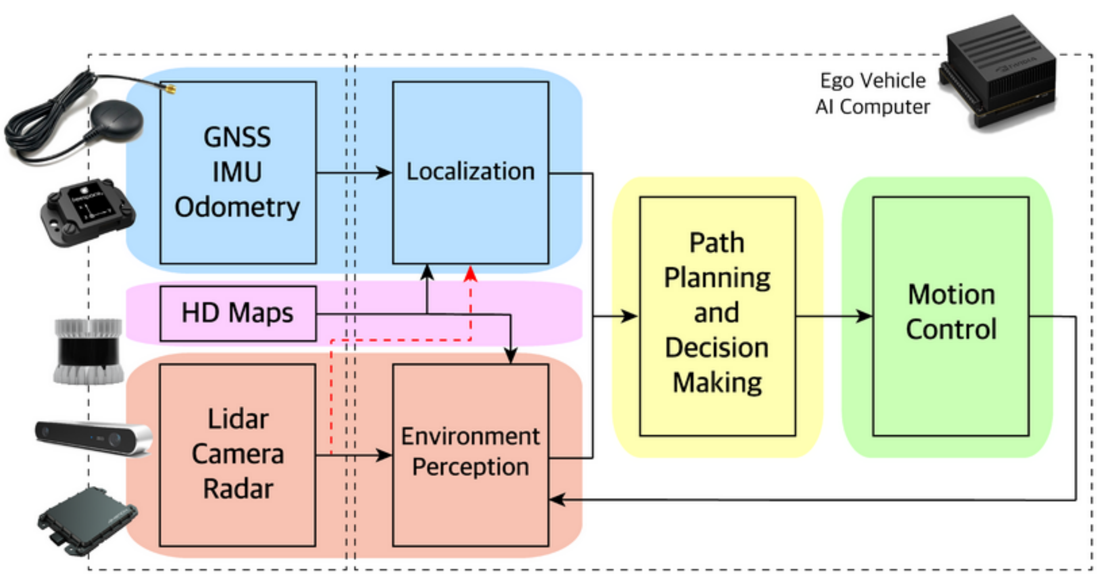
Motion Sensor Fusion

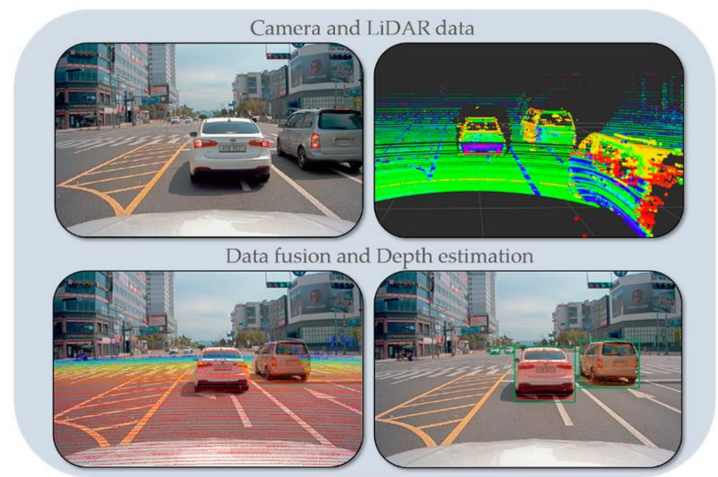
	Pros	Cons
GPS Receiver	▪ can provide initial position before entering buildings ▪ can retrieve the earth's declination angle to compensate the magnetometer heading to the appropriate geographic heading ▪ can calibrate pedometer step length when the device has a clear view to the sky outdoors ▪ can provide bounded accurate position (longitude and latitude) outputs and pseudo-range raw measurement outputs for loosely or tightly coupled Kalman filtering with INS	▪ cannot tell heading when the pedestrian is not moving ▪ cannot distinguish small variations in height (altitude)
Accelerometer	▪ can be used for a tilt-compensated digital compass when the smart phone is static or moving slowly ▪ can be used for pedometer step-counter detection ▪ can be used to detect if the pedestrian is in motion or at rest	▪ cannot differentiate the true linear acceleration from the earth gravity components when the smart phone is rotating ▪ is sensitive to shaking and vibration
Gyroscope	▪ can continuously provide the rotation matrix to INS ▪ can aid the digital compass in calculating heading when the magnetometer is disturbed	▪ bias drift over time leads to unlimited INS positioning error
Magnetometer	▪ can calculate absolute heading with respect to earth's magnetic north ▪ can be used to calibrate gyroscope sensitivity	▪ is sensitive to environmental magnetic interference fields
Pressure sensor	▪ can distinguish between floors for indoor navigation ▪ can aid GPS for altitude calculation and positioning accuracy when the GPS signal is degraded	▪ is sensitive to wind flow and weather conditions

source: http://www.findmems.com

Autonomous driving and vehicules

- Higher autonomy levels demand higher levels of accuracy and precision in object detection, classification and tracking and environmental modeling
- Sensor fusion combines raw data from all available sensors on the vehicle and provides rich data to accurately detect and classify an object





***Sensors* 2019, *19*(20), 4357**

***Symmetry* 2020, *12*(2), 324**

Summary Questions

- How does capacitive sensing work? Why to use MEMS?
- Why is differential capacitive readout benefitial?
- For a capacitive MEMS sensor, what material or geometric properties can be used for sensing? If a higher sensitivity is required, what parameters can an engineer consider in the sensor design?
- Describe the design and operation of MEMS Accelerometers and Gyroscopes
- What applications use MEMS Accelerometers and Gyroscopes and why?
- What is the self-test function in a capacitive MEMS Accelerometer?
- What are advantages of piezoresistive sensing compared to capacitive sensing and vice-versa?
- What is Sensor Fusion and what it is good for?

Capacitive Readout vs. Piezoresistive Readout 2020

	capacitive	piezoresistive
properties	- Measure capacitance $C = \frac{\varepsilon A}{g}$ - Distance change - Parallel Plate - Change in Common Surface - Comb Drive - « etched into silicon »	- Strain->stress->resistor change - Doping / thin film deposition - $\frac{\mathrm{d}R}{R} = G\varepsilon$
advantages	- Differential Readout - linearize - 'integrated in microsystems technology' - More easily manufactured - -	- Create an integrated readout - 'integrated' in microsytem technolgy - Linear (within the material limits) - 'can tolerate large displacment - -
drawbacks	- - Parallel plate - nonlinear - Higher sensitivity requires larger capacitors - Requires more space - Pull-in instability - Fabriaction tolerances in geometry - -	- Fabrication tolerances due to doping (can actually be well controlled) - temperature sensitivity (wheat stone bridge can solve it) - power consumption! - Thermal noise - Self-heating

Capacitive Readout vs. Piezoresistive Readout 2019

	capacitive	piezoresistive
properties	- change in capacitiance - C=eps*A/d - combs / interdigitated - parallel plate - differential readout - $C = \frac{\varepsilon A}{g}$	$\frac{dR}{R} = G\varepsilon$ - Change in resistor due to stress/strain - Sensor by ion implantion / diffusion doping
advantages	- differential readout - linearize - good sensitivity in uSystems - low power consumption - no heat-up upon readout - integrate well with MST -	- integrate well with MST - compact - larger displacements (no pull-in) - - -
drawbacks	- complex structure? - nonlinear / readout -> linearize? - combs might stick - pull-in instability - frequency measurement - less compact (surface requirement) - sensitive to humidity (package)	- power consumption (high) - self-heating - thermal noise - - -

Capacitive Readout vs. Piezoresistive Readout 2018

	capacitive	piezoresistive
properties	- Capactivie change due to movement or change in ε - small movements - large areas - parallel plates or comb drives - … $C = \frac{\varepsilon A}{g}$	- change in resistor due to stress/strain - sensor element by ion implantation or by diffusion implant $\frac{dR}{R} = G\varepsilon$
advantages	- stability - low power - good repeatability - can be integrated using MEMS technology - …	- can support large movements - small footprint - integration with electronics/process - …
drawbacks	- nonlinear response - linearization / more complex readout required - can be sensitive to discharges - sensitivity to humidity - …	- thermal noise - power dissipation - drift - …