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Design and Analysis of MEMS Accelerometers

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Qualtré
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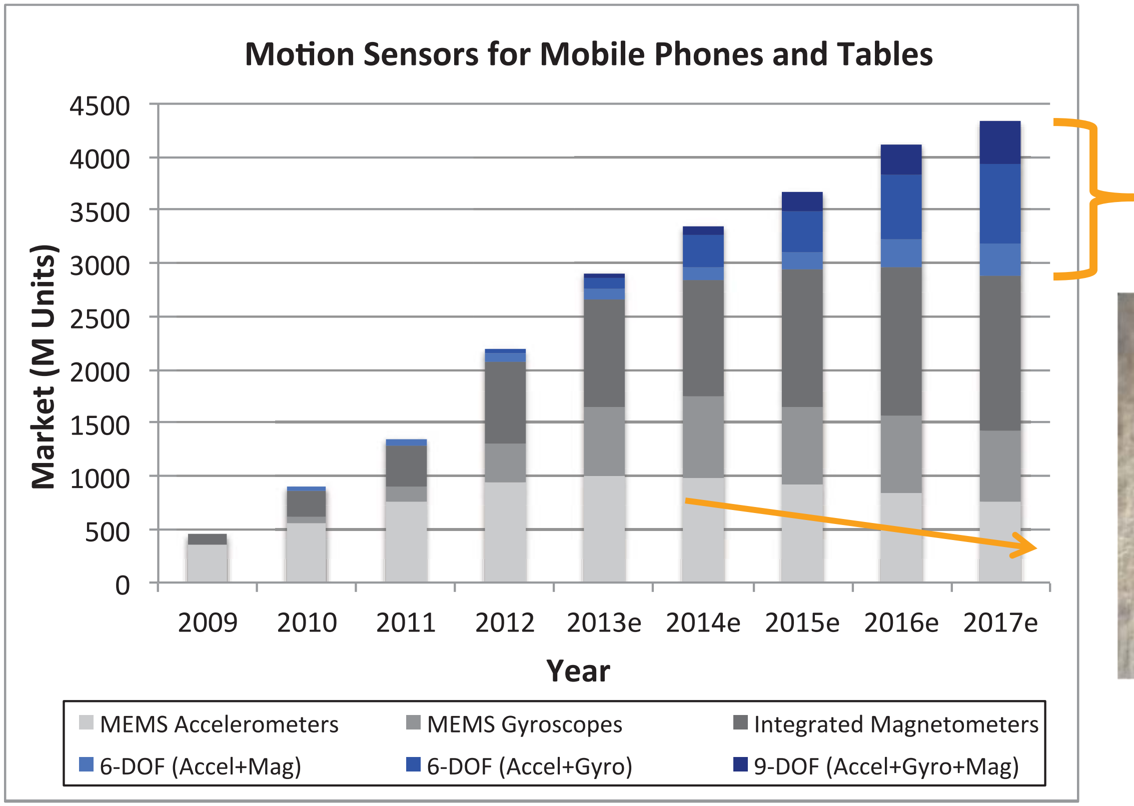
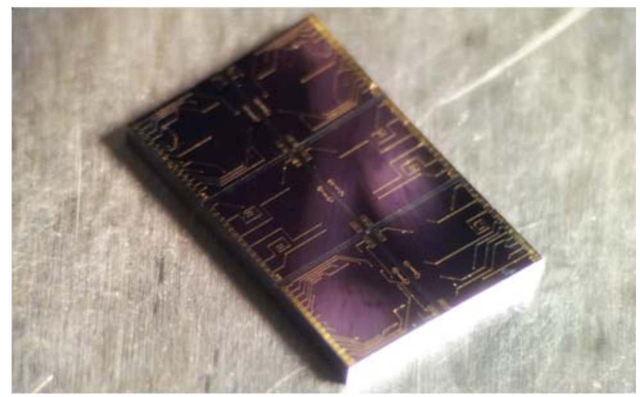
The Future of MEMS Accelerometers

- Are MEMS Accelerometers still relevant?



Source: Yole Développement, "Inertial Sensors in Mobile Products", 2012



Monolithic 6-DOF TIMU Die
(Qualtré/Georgia Tech)

- Shift in paradigm → Design for integration

Applications of MEMS Accelerometers

Industrial
- Platform stabilization
- Oil drilling orientation
- Robotic telepresence

Automotive
- Airbag deployment
- Rollover, anti-skid control

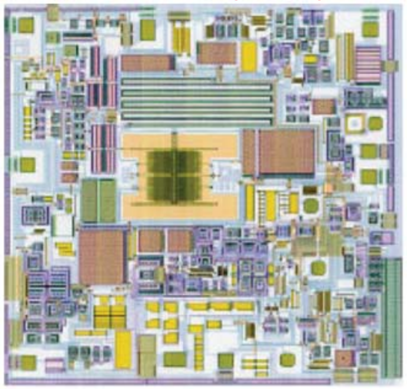
Consumer
- Interactive gaming
- Free-fall detection
- Camera stabilization
- Indoor navigation

Military
- Aircraft flight control
- Dead-reckoning

Evolution of MEMS Accelerometers

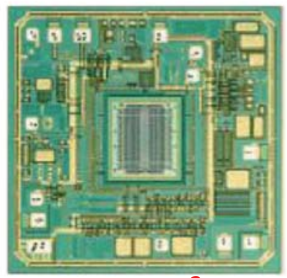
- Analog Devices Accelerometer (Automotive)

ADXL50 (1994)



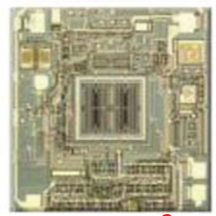
10.8 mm^2

ADXL76 (1996)



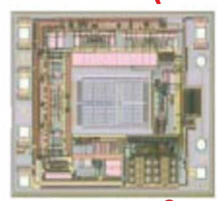
5.4 mm^2

ADXL78 (2001)



2.7 mm^2

ADXL180 (2006)

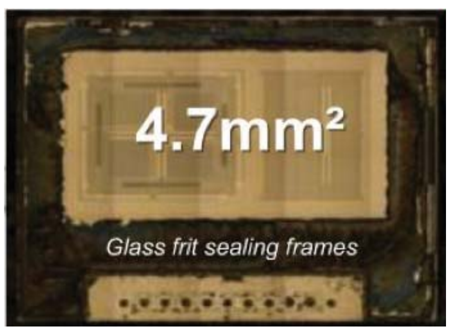


2.5 mm^2

M. Judy, Proc. Solid-State Sensors, Actuators, and Microsystems Workshop, Hilton Head Island, SC, Jun. 2004

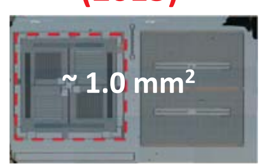
- STMicroelectronics Accelerometer (Consumer)

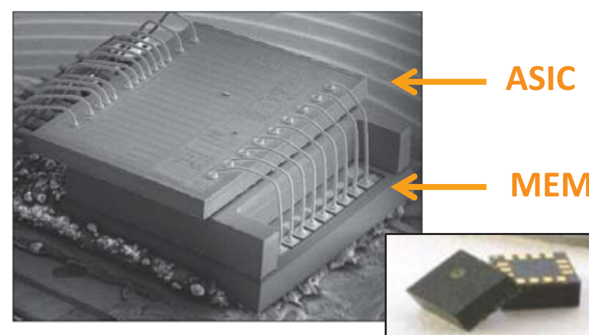
(2008)



(2010)

(2013)





ASIC

MEMS

LIS2DH

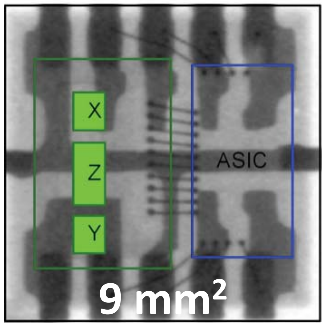
2x2x0.9 mm^3

Source: Yole Développement, "MEMS Packaging sample report", 2012

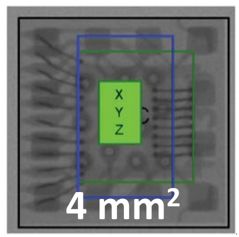
Sensor Scaling and Integration

- Bosch Sensortec (Consumer)

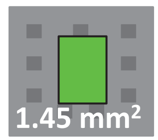
(2007)



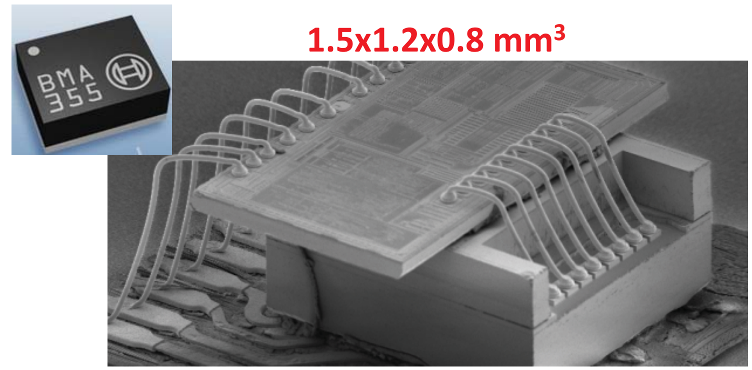
(2011)



(2013)



1.5x1.2x0.8 mm^3

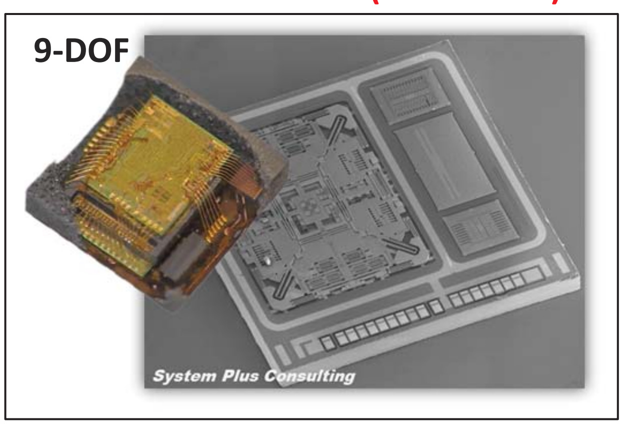


The Evolution of Compact Three Axis Accelerometers, St.J. Dixon-Warren, Chipworks Inc.

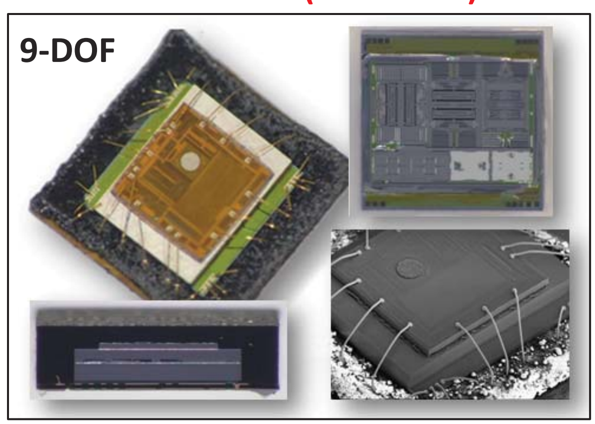
Source: www.bosch-sensortec.com

- Accelerometers in Multi-DOF Combos

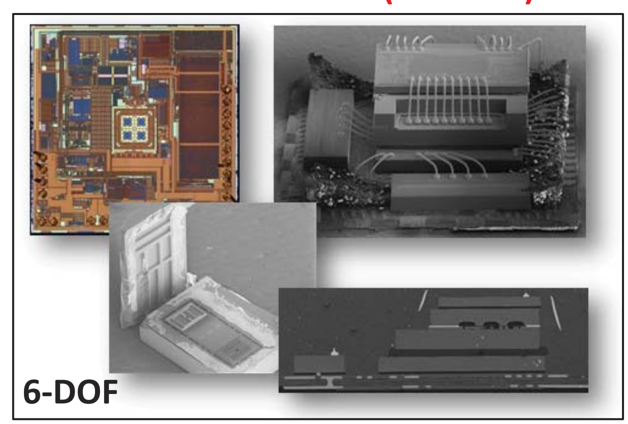
STMicroelectronics (LSMD333D)



Invensense (MPU9150)



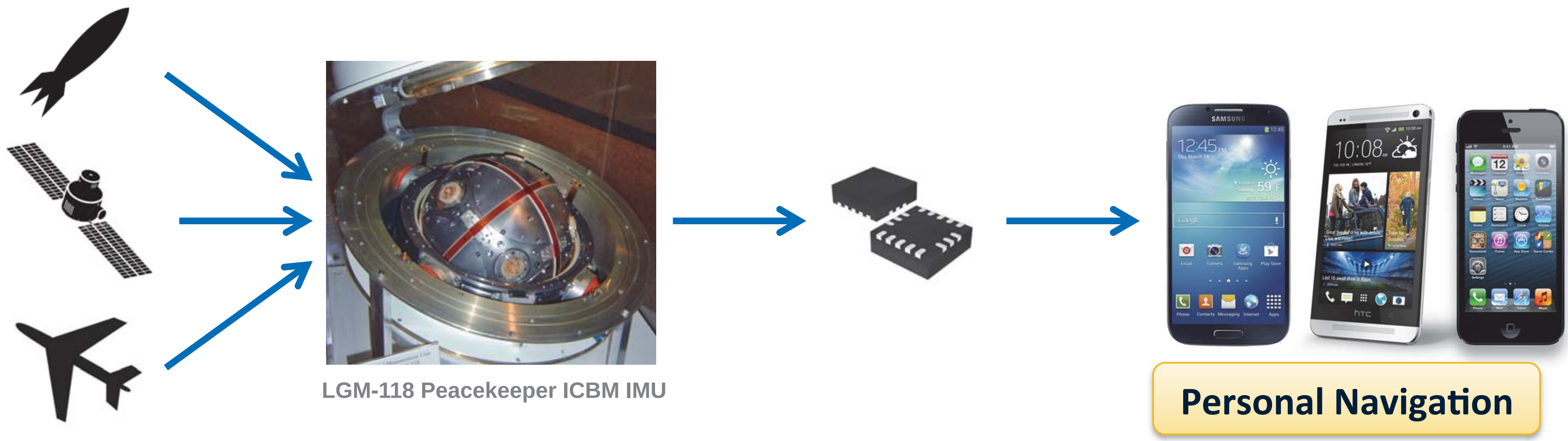
Bosch Sensortech (BMC050)



Source: System Plus Consulting – Reverse costing sample reports

Accelerometers in Personal Navigation

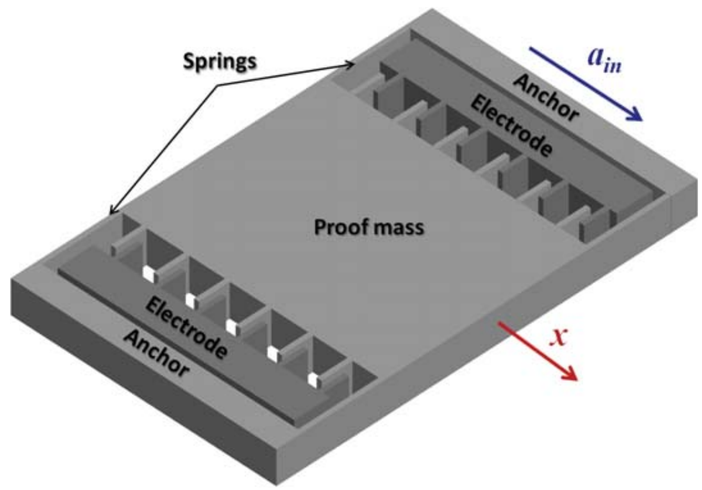
- Bringing navigation-grade performance into hand-held devices



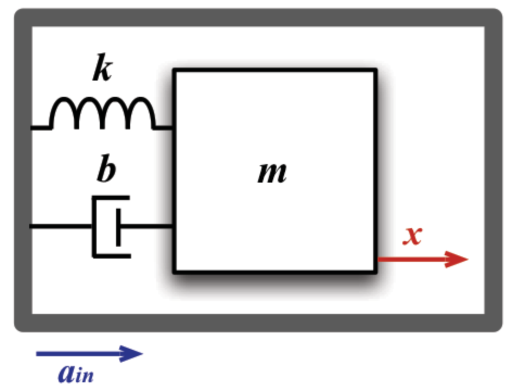
- High-performance micromachined accelerometers
  - Same fabrication platform as gyroscopes → size & cost advantage
  - Large dynamic range & BW → multi-purpose sensors
  - Robust and reliable → immune to shock and vibration

MEMS Capacitive Accelerometers

- Conventional MEMS accelerometer architecture



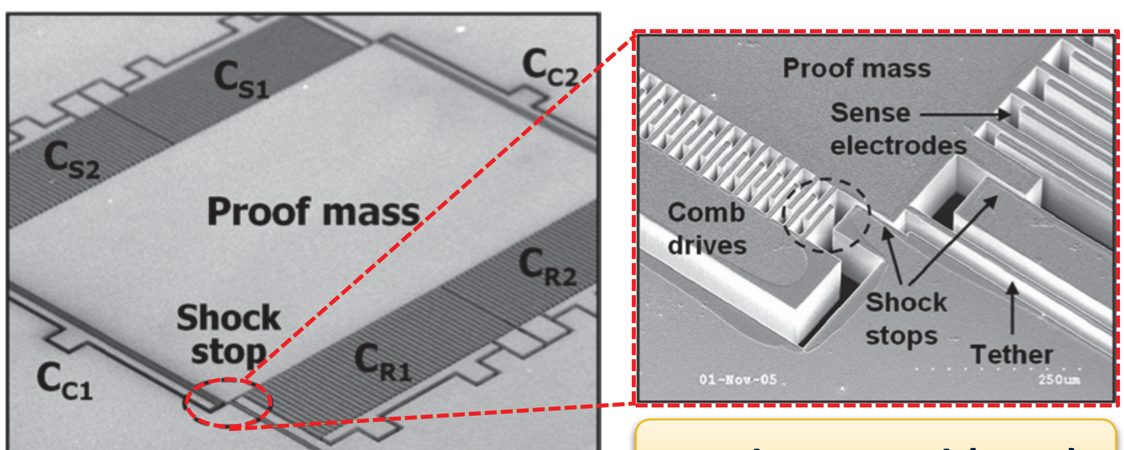
Lumped-Element Model



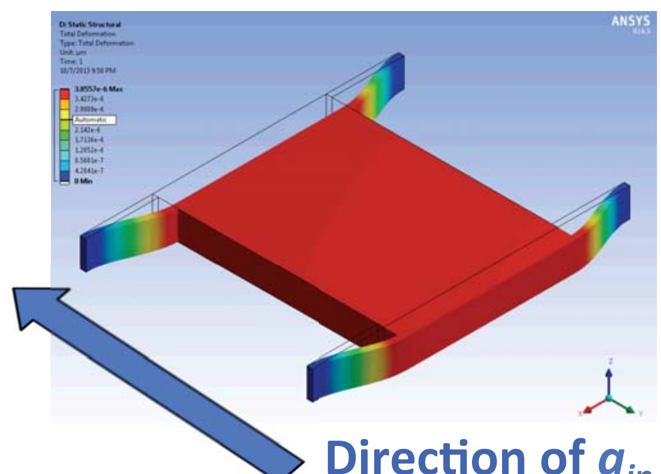
Steady state response:

$$m\,a_{in} = -k\,x$$

$$\frac{x}{a_{in}} = -\frac{m}{k}$$



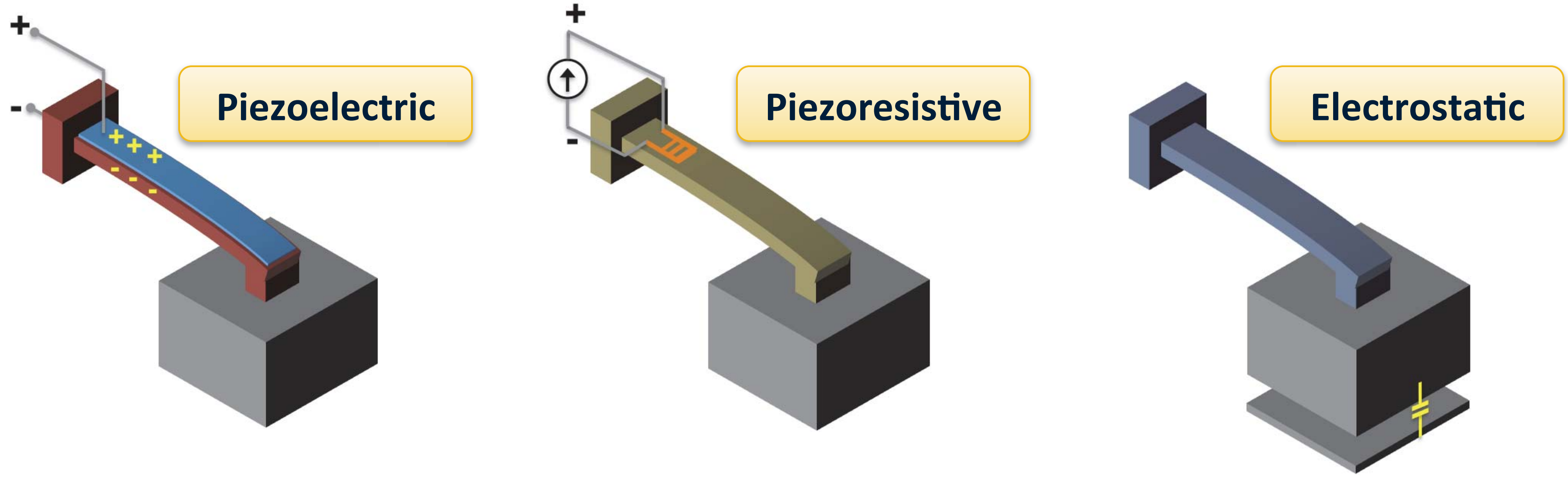
In-plane Accel (SEM)



Direction of a_{in}

Electromechanical Transduction

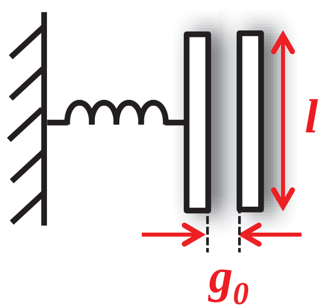
- Displacement has to be converted into electrical signal
- Most common sensing mechanisms:



- Most popular: electrostatic (capacitive) sensing

Parallel Plate

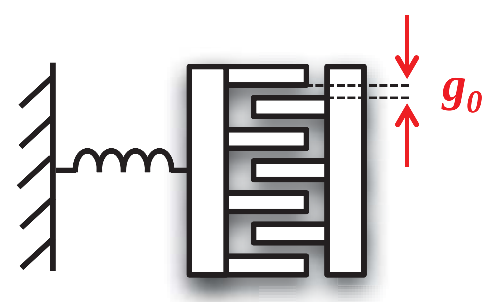
$$\frac{dC}{dx} = \frac{\varepsilon \cdot w \cdot t}{(g_0 - x)^2}$$



Comb Structure

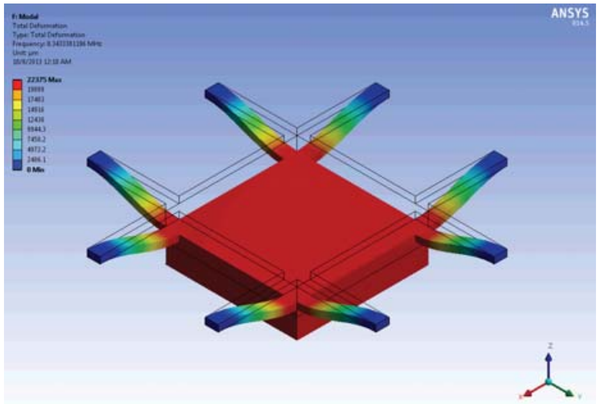
$$\frac{dC}{dx} = \frac{\varepsilon \cdot 2n \cdot t}{g_0}$$

t: thickness, n: # of fingers

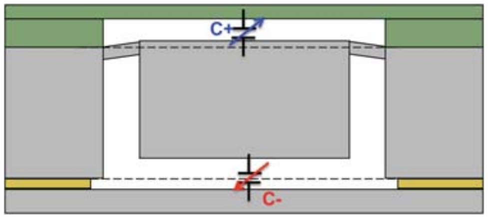


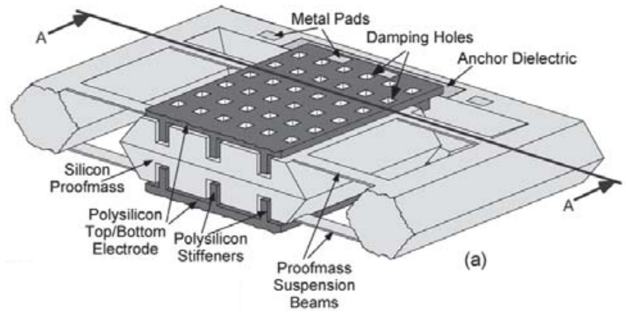
Out-of-Plane Detection: Translation

- In plane electrostatic sensing → capacitors defined by trenches
- Z-axis displacement requires out-of-plane (OOP) sense gaps



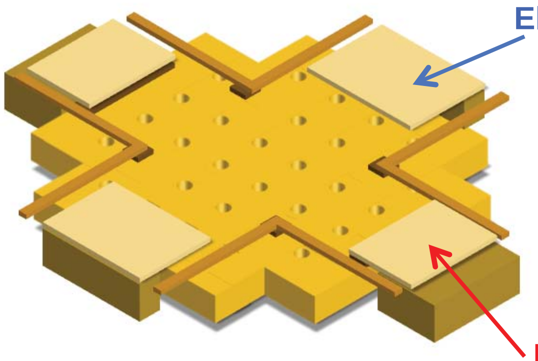
Translation Detection

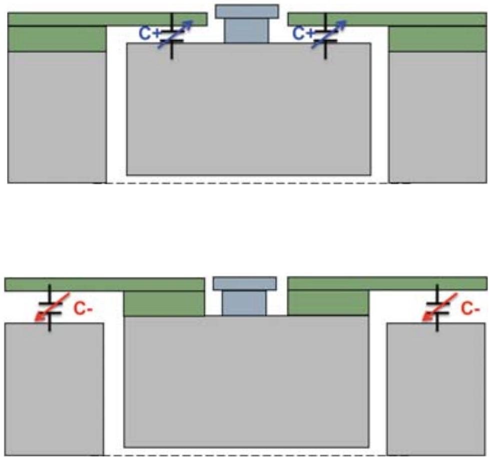


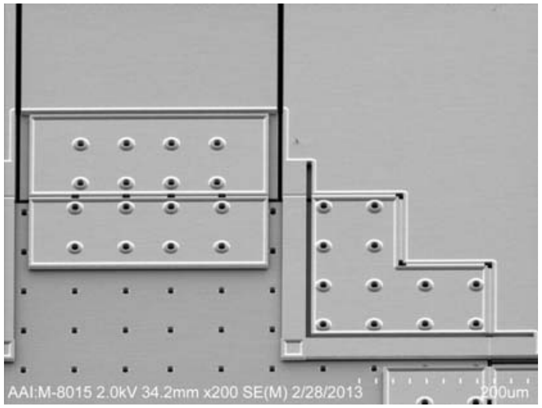


J. Chae, et. al., Journal of Microelectromechanical Systems, Vol. 14, No 2, Apr. 2005

- Differential sensing also achieved with moving electrodes

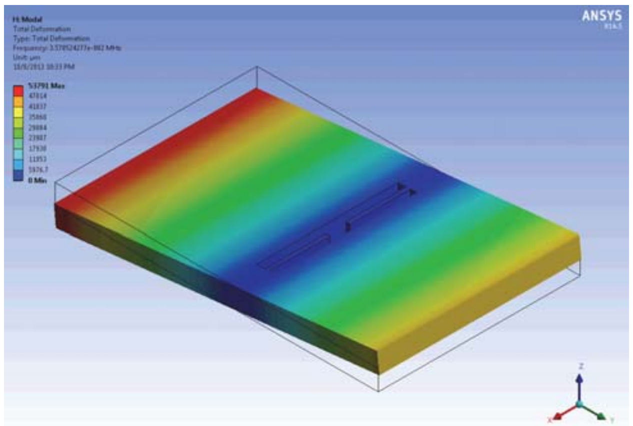




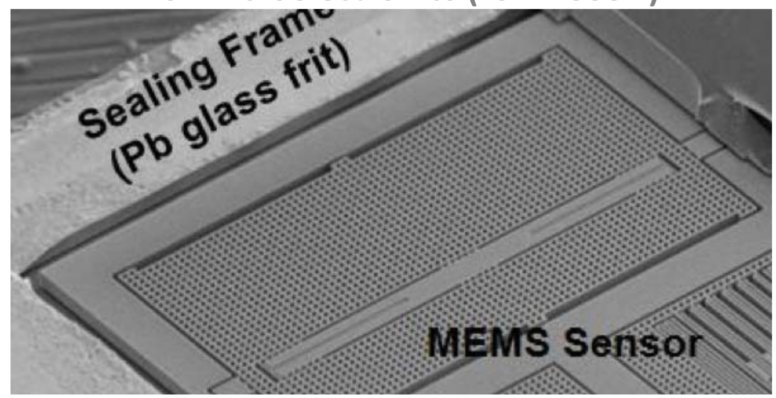


Out-of-Plane Detection: Rotation

- Many processes do not enable top capacitors → Teeter-totter

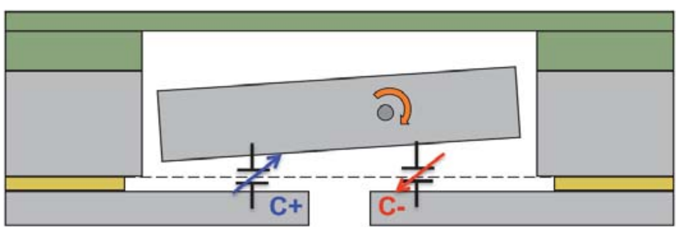


STMicroelectronics (LSMD333D)



- Center of mass offset from center of geometry

Torsion Detection



- In presence of z-axis acceleration, device tilts
- Electrodes strategically placed measure differential capacitance change

Metrics in Capacitive Accelerometers

- What to look for when designing parallel-plate capacitive accels

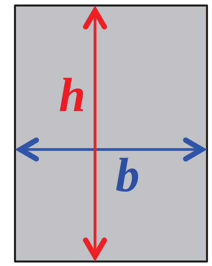
$$\Delta C_x \approx S_x \cdot a_x + S_{x2} \cdot a_x^2 + S_y \cdot a_y + S_z \cdot a_z + C_0$$

Scale Factor Non-linearity Cross-Axis Sensitivity Offset

Parameter	Units	Expression	Description
Resonance Frequency	Hz	$\omega_0 = \sqrt{\frac{k}{m}}$	Free-vibration frequency of accelerometer
Scale Factor	F/(m/s²)	$SF \approx \frac{1}{\omega_0^2} \frac{\varepsilon \cdot A_{elec}}{g_0^2}$	Linear term of the acceleration to capacitance change sensitivity
Quadratic non-linearity	F/(m/s²)²	$SF_2 \approx \frac{1}{\omega_0^4} \frac{\varepsilon \cdot A_{elec}}{g_0^3}$	Quadratic term of the acceleration to capacitance change sensitivity
Brownian Noise	(m/s²)/√Hz	$MNEA = \sqrt{\frac{4k_B \cdot T \cdot \omega_0}{Q \cdot m}}$	Mechanical noise equivalent acceleration
Pull-in Voltage	V	$V_{pi} = \sqrt{\frac{8\omega_0^2 \cdot m \cdot g_0^3}{27\varepsilon \cdot A_{elec}}}$	Voltage required to snap-down moving device to parallel
Bandwidth	Hz	$\omega_{3dB} \approx Q \cdot \omega_0$	Approximate 3 dB Bandwidth in over-damped second-order system

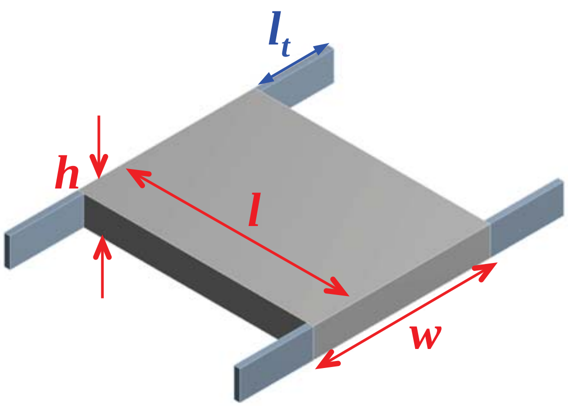
Designing for Scale Factor

- Mass: $m = \rho \cdot V = \rho \cdot (h \cdot w \cdot l)$
- Stiffness: $k = C_n \cdot \frac{E \cdot I}{l_t^3}$ Rectangular cross-section → $I = \frac{1}{12} b^3 \cdot h$

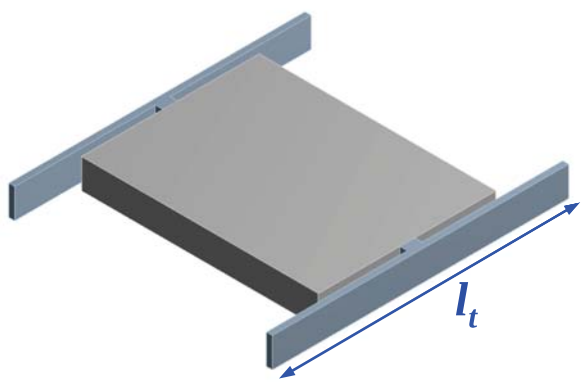


- ρ → Density E → Young's Modulus I → Second moment of area
- C_n depends on boundary conditions, loads and number of springs

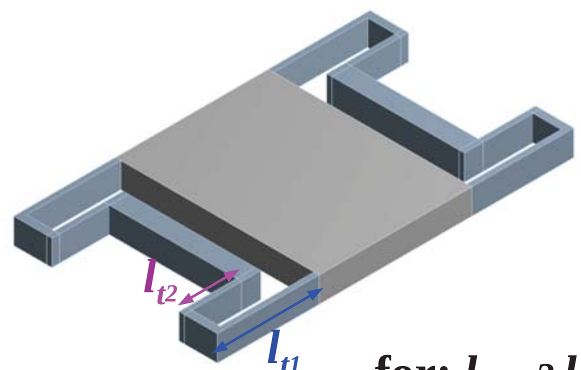
$C_n \approx 48$



$C_n \approx 384$



$C_n \approx 36$



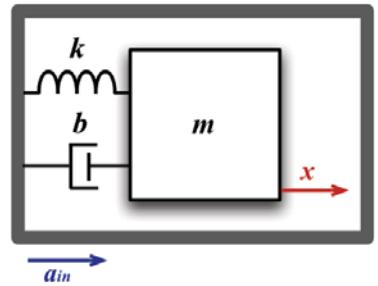
for: $l_{t1} = 2\, l_{t2}$

Dynamics of MEMS Accelerometers

- Second-order system approximation

$$m\frac{d^2x}{dt^2}+b\frac{dx}{dt}+kx=ma_{in}$$

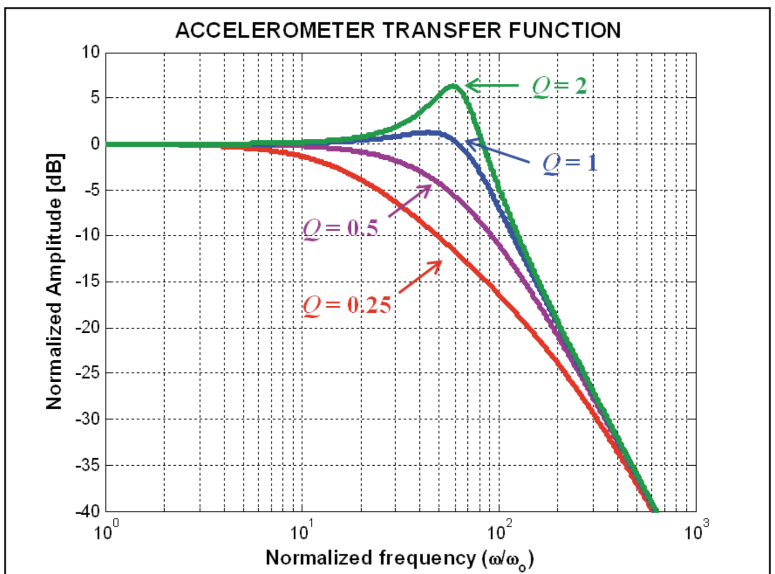
$$\omega_0=\sqrt{\frac{k}{m}} \qquad Q=\frac{\sqrt{km}}{b}$$

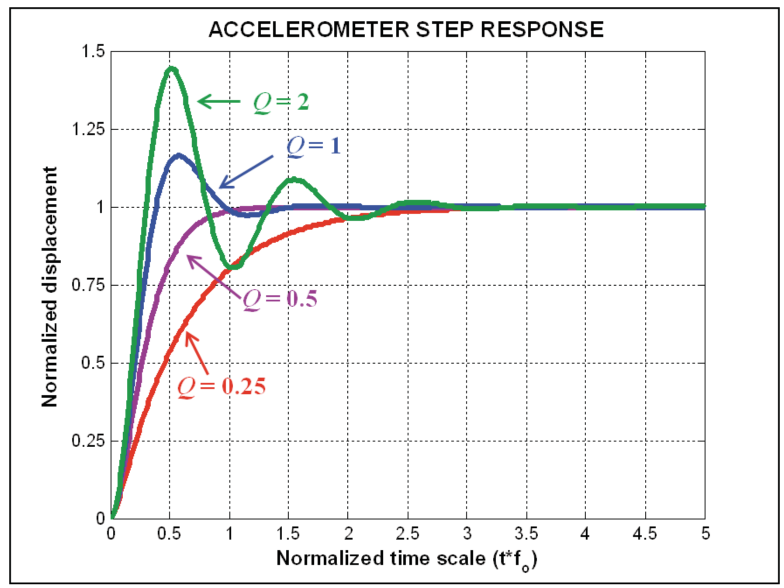


$$\frac{X(s)}{A_{in}(s)}=\frac{1}{s^2+\frac{\omega_0}{Q}s+\omega_0^2}$$

$\omega << \omega_0$ ⇒

$$\left|\frac{X(j\omega)}{A_{in}(j\omega)}\right|\approx\frac{1}{\omega_0^2}=\frac{m}{k}$$

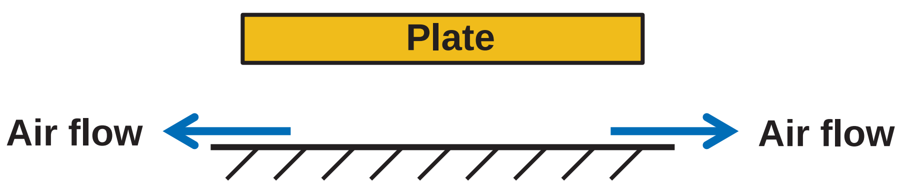


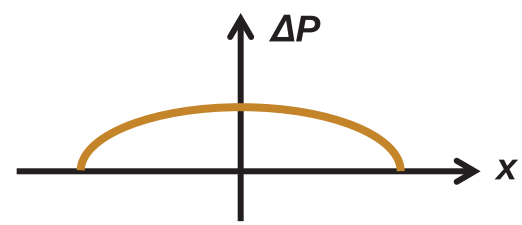


Quality Factor in Accelerometers

- Q in accelerometers dominated by squeeze-film damping (SFD)

$$\frac{1}{Q} = \frac{1}{Q_{\mathrm{SFD}}} + \frac{1}{Q_{\mathrm{TED}}} + \frac{1}{Q_{\mathrm{anchor}}} + \frac{1}{Q_{\mathrm{material}}} \longrightarrow \frac{1}{Q} \approx \frac{1}{Q_{\mathrm{SFD}}}$$





- In plates with narrow gaps, SFD is described by Reynold's equation
- For small changes in gap and pressure:

$$\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} = \frac{12\mu_{eff}}{h^3}\frac{dh}{dt}$$

h: Gap size

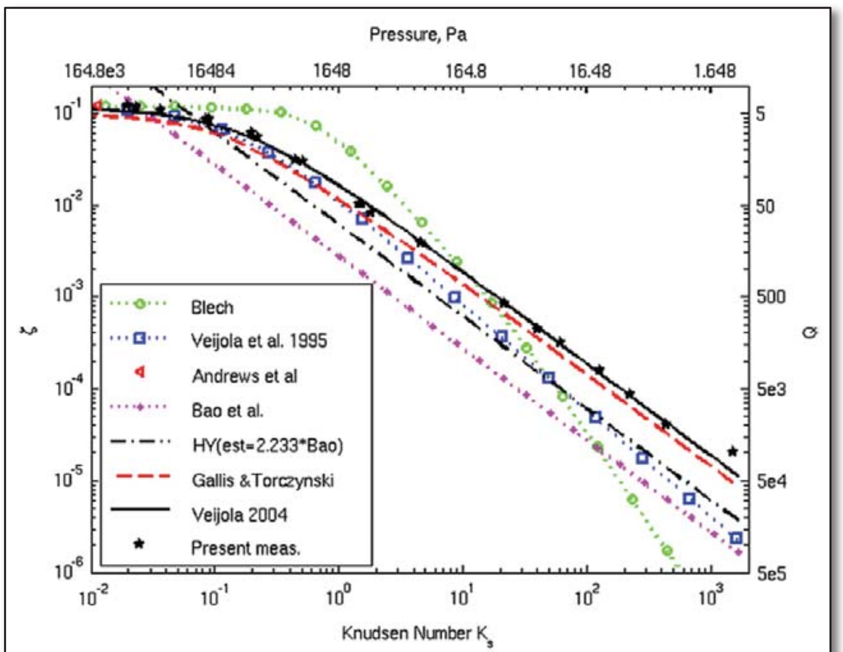
P: Pressure

μ: Coefficient of viscosity

Squeeze Film Damping

- Boundary conditions and approximations depend on pressure level
- Simplified damping coefficient:

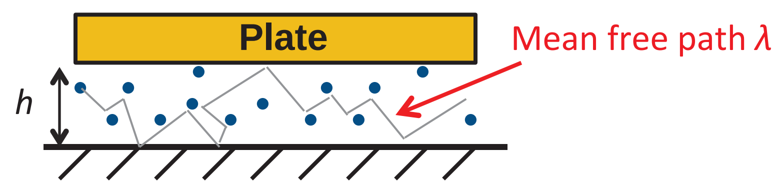
$$b \approx \frac{\mu_{eff} \cdot l \cdot t^3}{h^3} \longrightarrow Q \propto h^3$$



H. Sumali, J. Micromech. Microeng., Vol. 17 pp. 2231–2240 , 2007

Mean free path: $\lambda = \frac{\mu}{P}\sqrt{\frac{2k_B T}{m}}$

Knudsen Number: $K_s \approx \frac{\lambda}{h}$



- Second order effects:
  - Slip fluid-wall correction (Ks > 0.1)

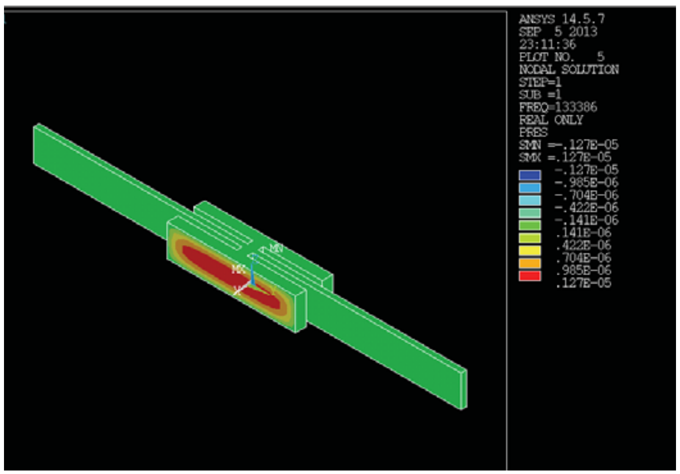
$$\mu_{eff} \approx \frac{\mu_0}{1 + 9.638 K_s^{1.159}}$$

  - Non-trivial boundary conditions (Ks > 1)

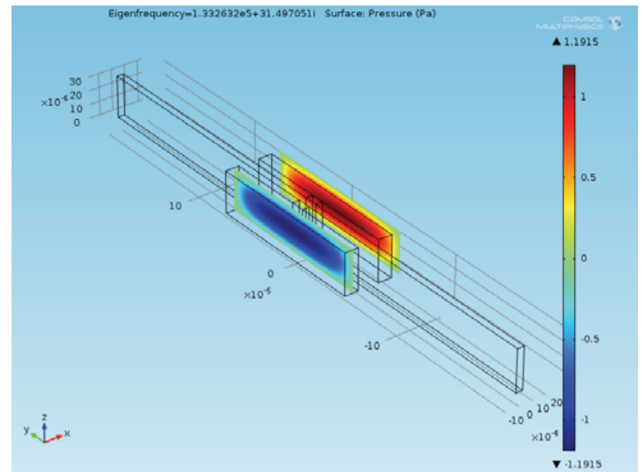
FEA modeling of SFD

- For complex geometries → SFD through finite element analysis (FEA)
- FEA elements incorporate second-order effects (slip correction, non-trivial boundaries)

ANSYS

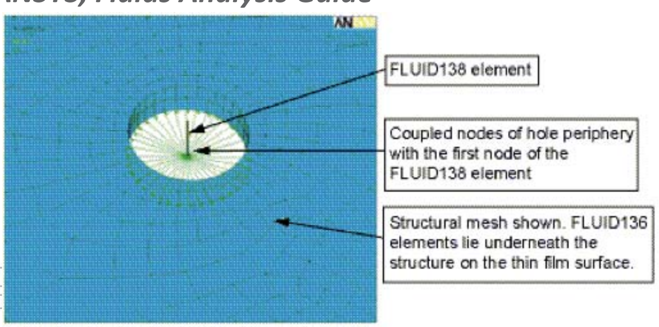


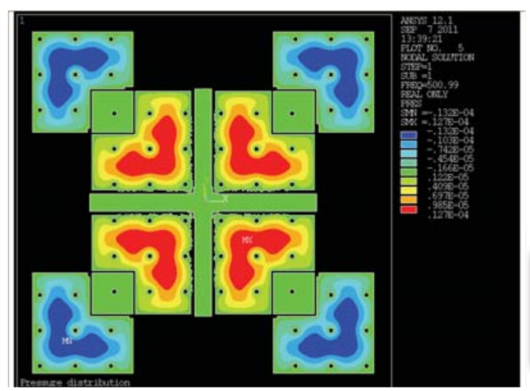
COMSOL



- Modeling release-holes

ANSYS, Fluids Analysis Guide

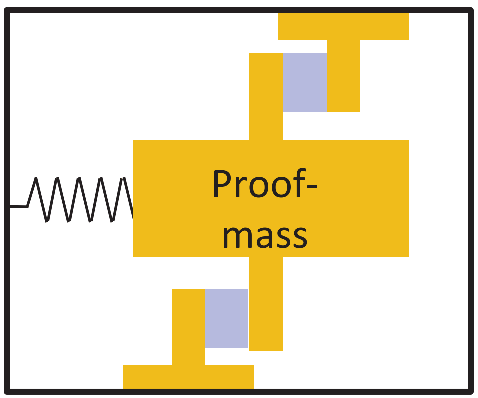




Pressure distribution in tri-axial accelerometer

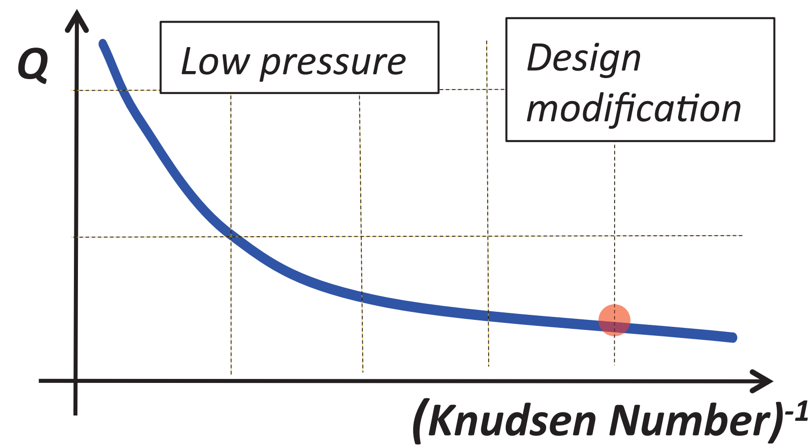
Static Accelerometers at Low Pressure

- Vacuum environment → Essential for resonators (i.e. gyroscopes)
- Monolithic integration → Accelerometers packaged at same pressure



Quality factor

$$Q = \frac{\sqrt{k\,m}}{b}$$

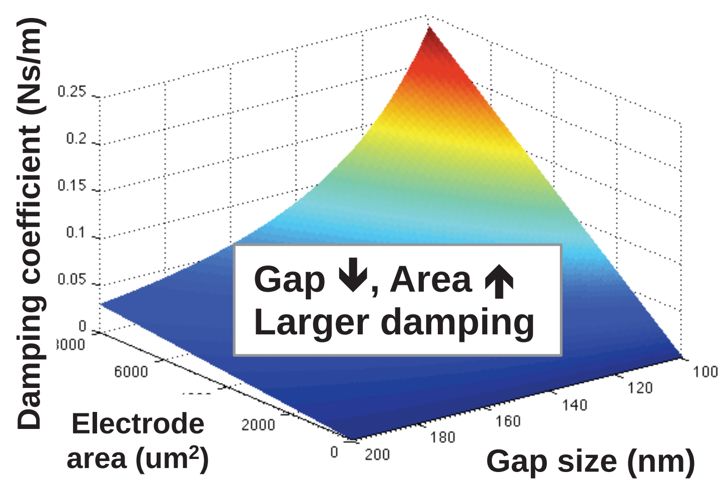


Damping in Parallel Plate

$$b \approx \frac{n_{elec} \cdot \mu_{eff} \cdot l \cdot t^3}{h^3}$$

n_{elec}: # of electrodes
μ_{eff}: Viscosity
l: Electrode length
t: Electrode height
h: Gap size

1. Narrow Gap
2. Large Electrode Area



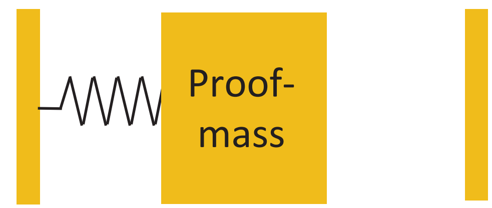
Narrow Gaps in Accelerometers

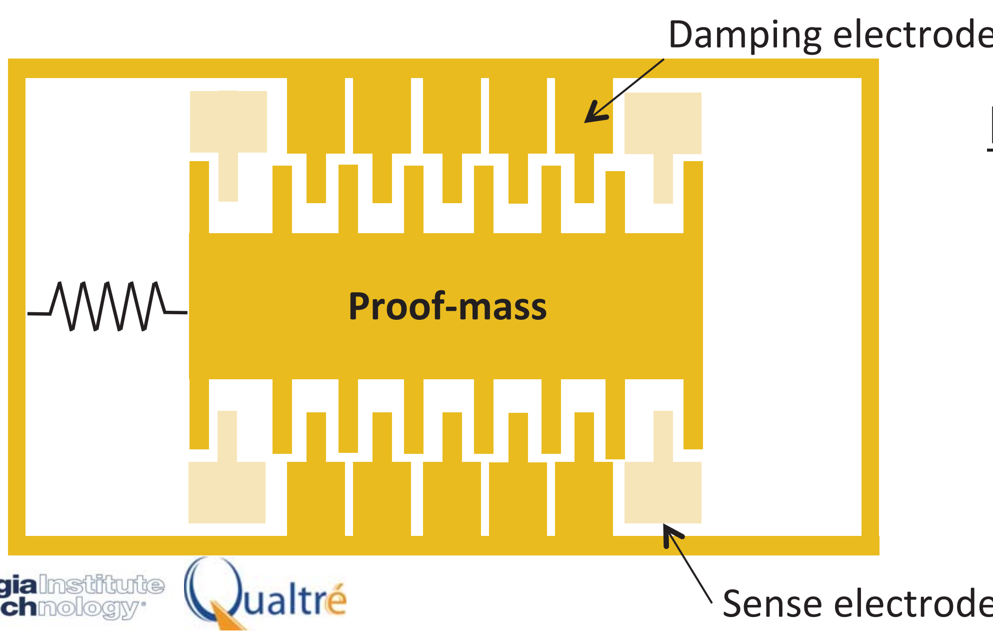
- Increased damping → lower Q
- Increased Scale factor
- Facilitates designing for higher BW
- Draw-back: lower pull-in voltage

$$SF = \frac{\Delta C}{a_{in}} \approx \frac{1}{\omega_0^2} \frac{\varepsilon \cdot A_{elec}}{g_0^2}$$

$$BW_{3dB} \approx Q \cdot \omega_0 \quad \text{(overdamped)}$$

$$F_{elec} \approx \frac{1}{2} \frac{\varepsilon \cdot A_{elec}}{g_0^2} V^2 \qquad V_{pull-in} \approx \sqrt{\frac{8}{27} \frac{k \cdot g_0^3}{\varepsilon \cdot n_{sens} \cdot A_{elec}}}$$





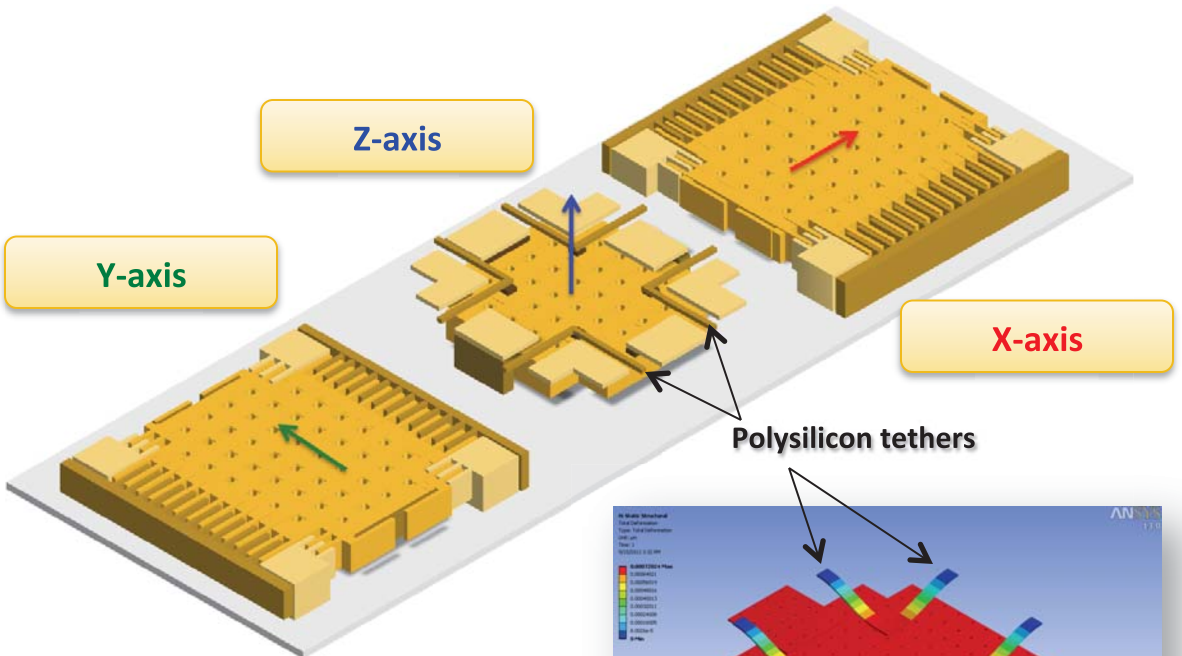
Independent damping electrodes

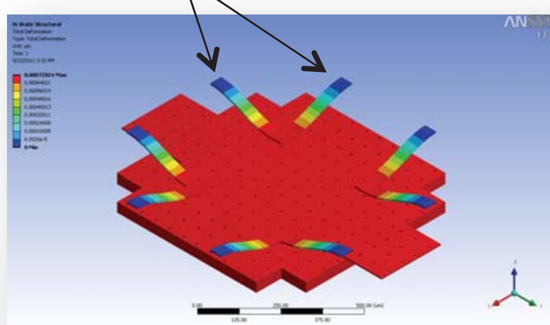
$$b = \mu_{eff} \cdot l \cdot \left(\frac{t}{g_0^3}\right)^3 \cdot \left(n_{sens} + n_{damp}\right)$$

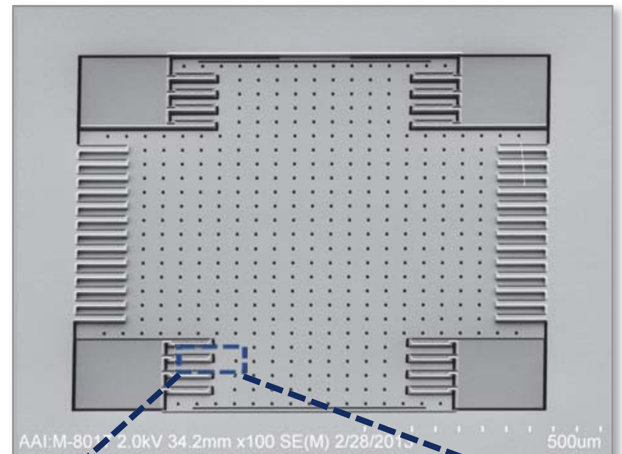
Only n_{sens} contributes to pull-in

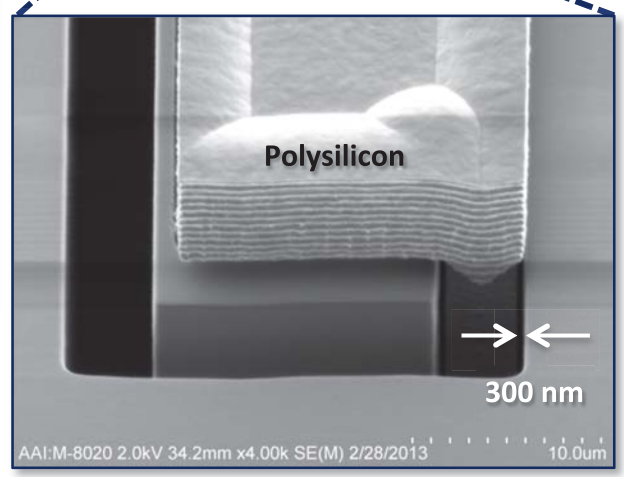
Low-Pressure Tri-axial Accelerometers

- Three individual proof-masses → x-, y-, z-axis detection

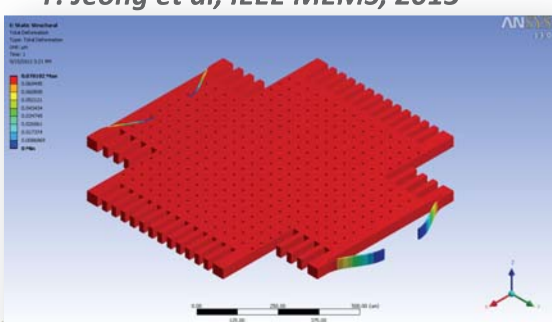






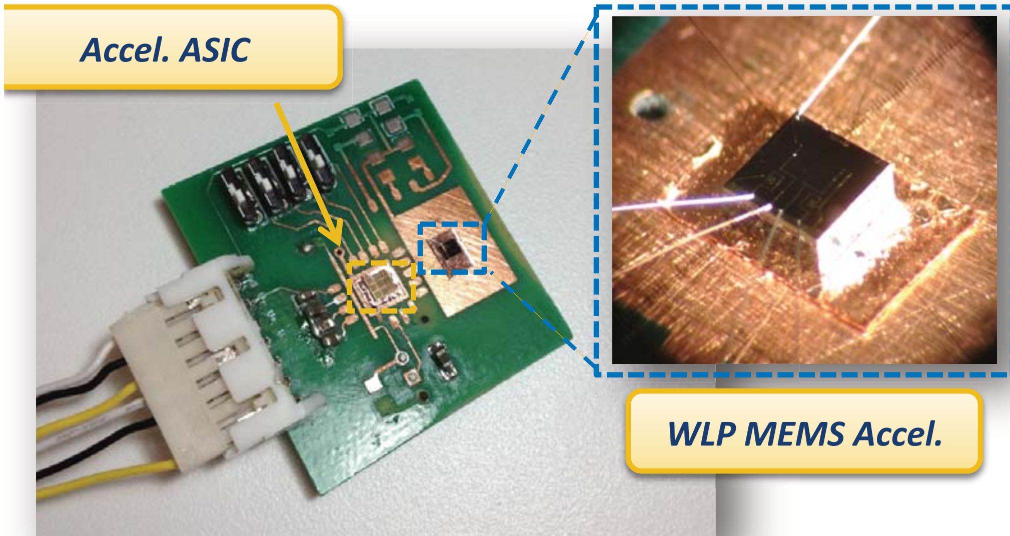


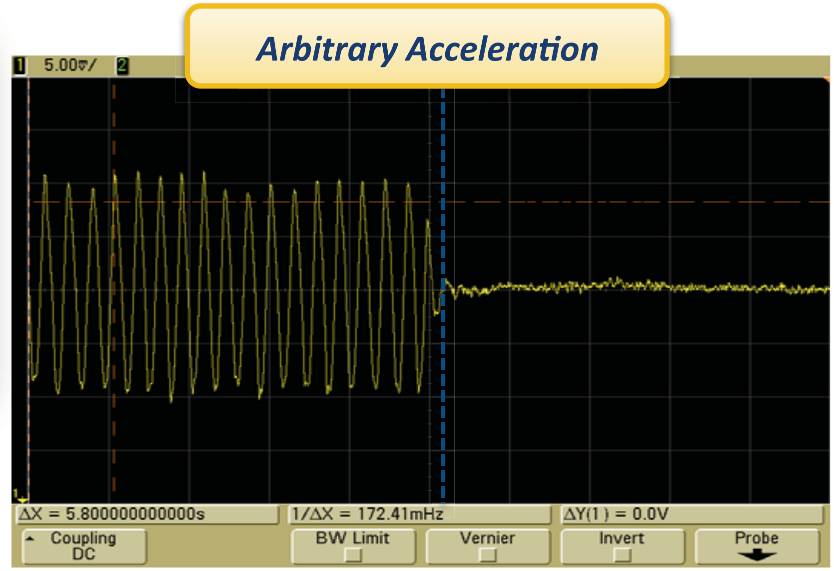
Y. Jeong et al, IEEE MEMS, 2013

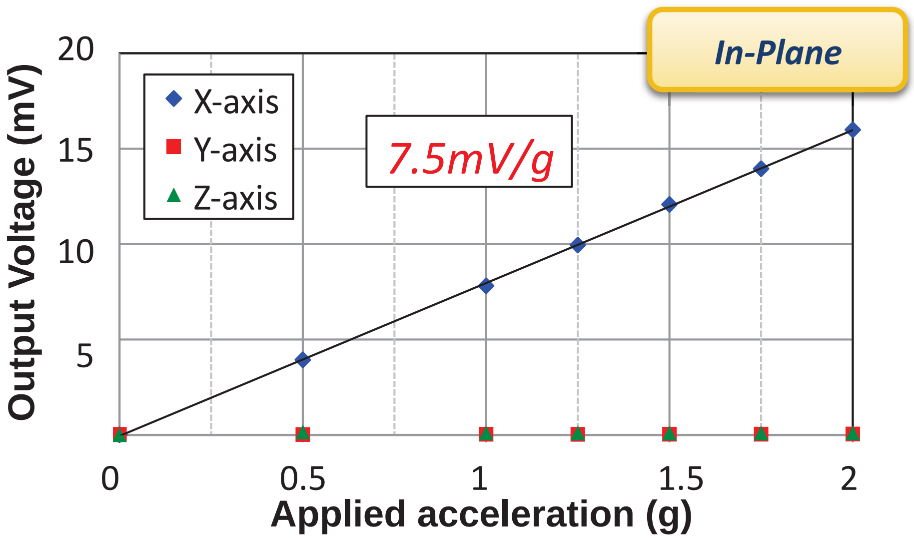


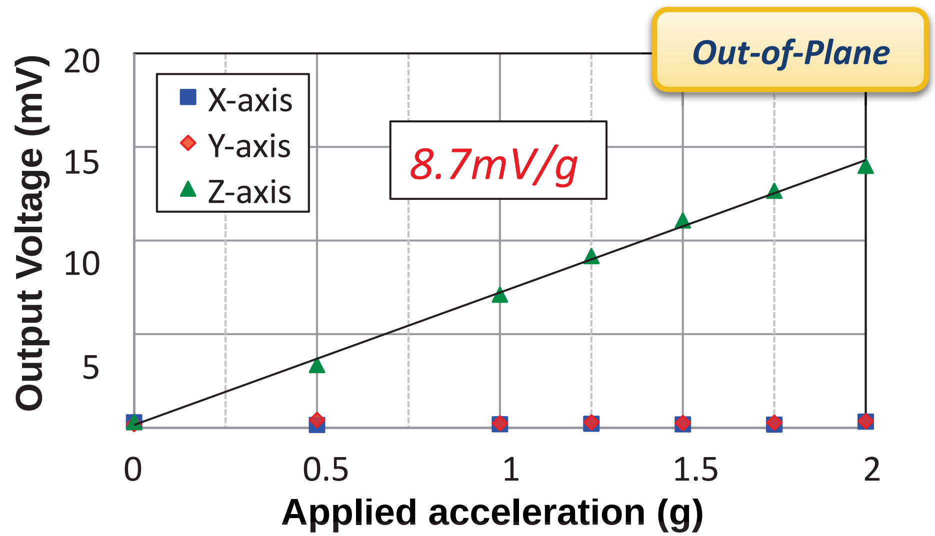
Response to Linear Acceleration

Low-Pressure Accelerometers Response



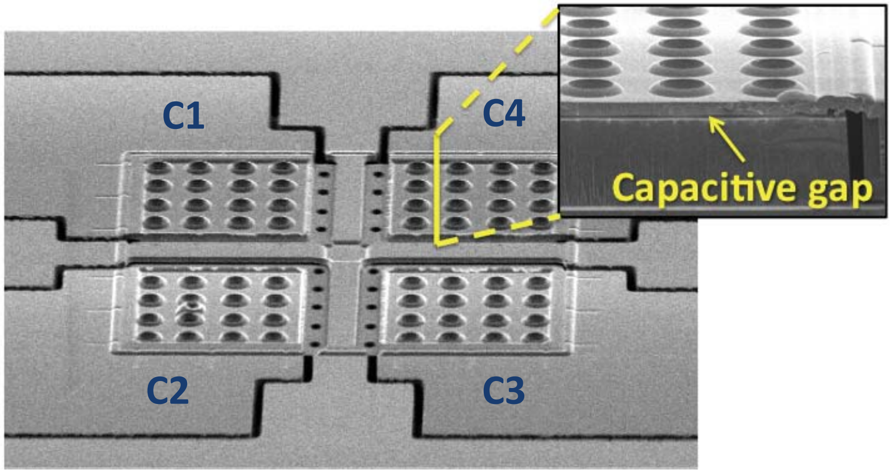




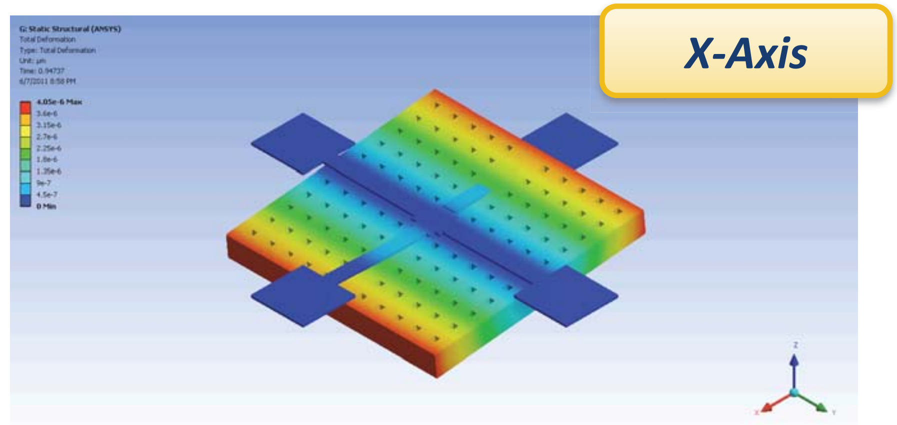


Single Proof Mass 3-axis Accelerometers

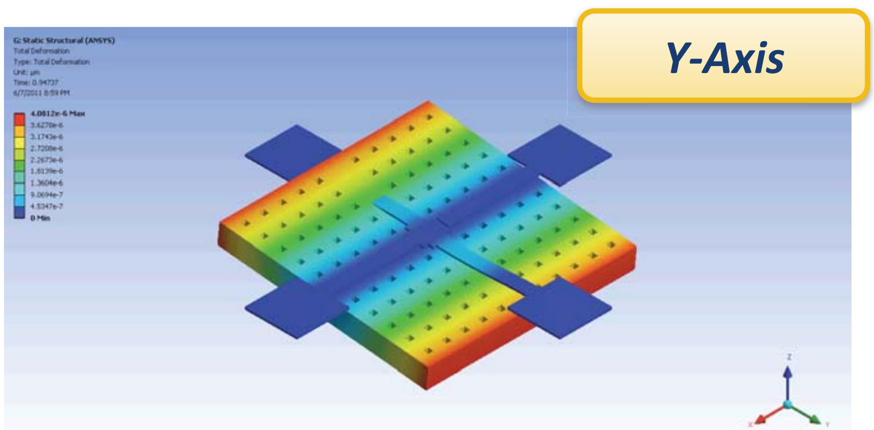
- Pendulum-like sensor with 4 top electrodes



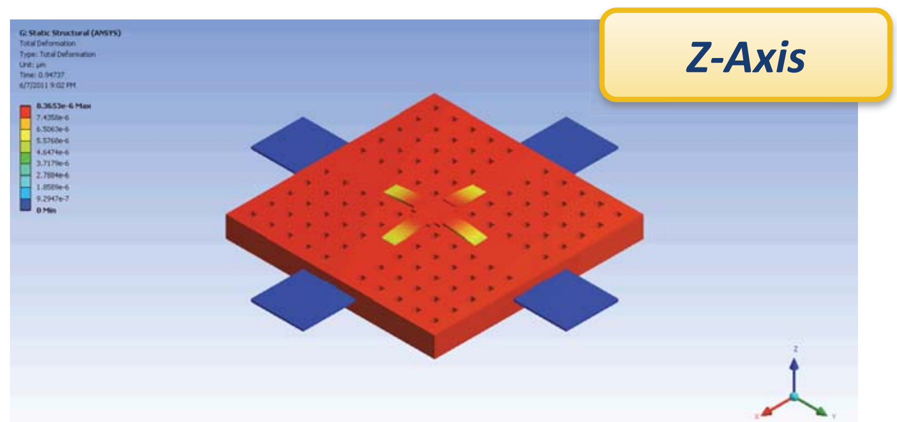
D. E. Serrano et al, to appear at IEEE MEMS, 2014



$\Delta C_{TOT} = (C1+C2) - (C3+C4)$



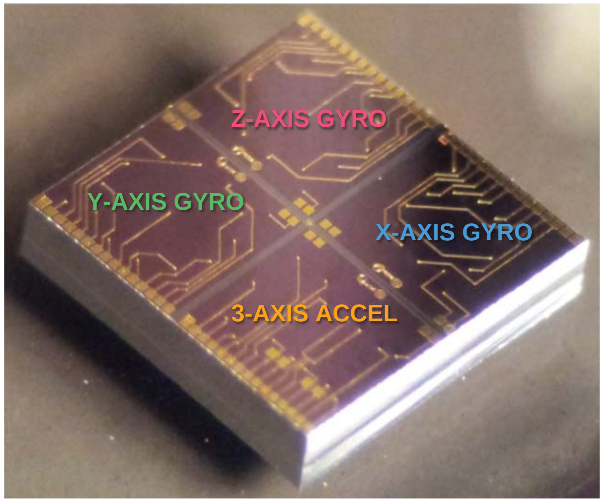
$\Delta C_{TOT} = (C1+C4) - (C2+C3)$

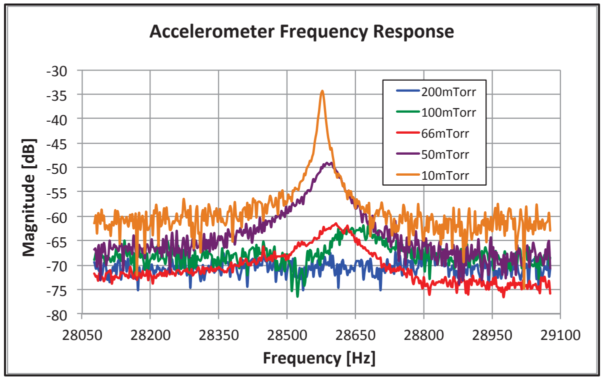


$\Delta C_{TOT} = (C1+C2+C3+C4) - 4C_{rest}$

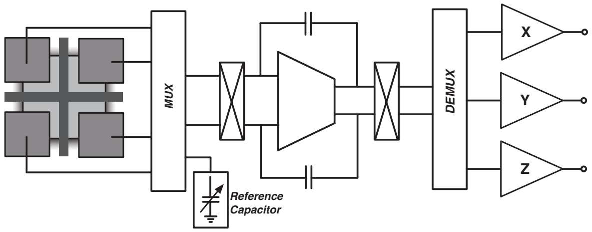
Pendulum Accelerometer Response

- Response of vacuum-packaged single proof mass design

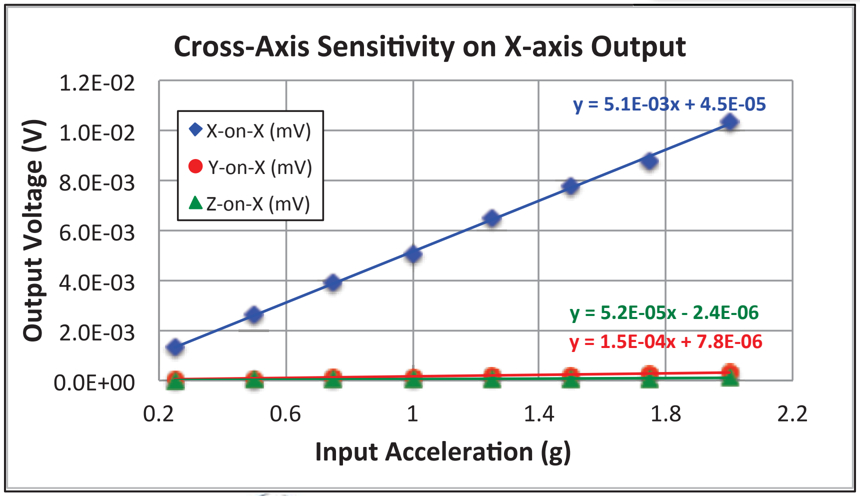


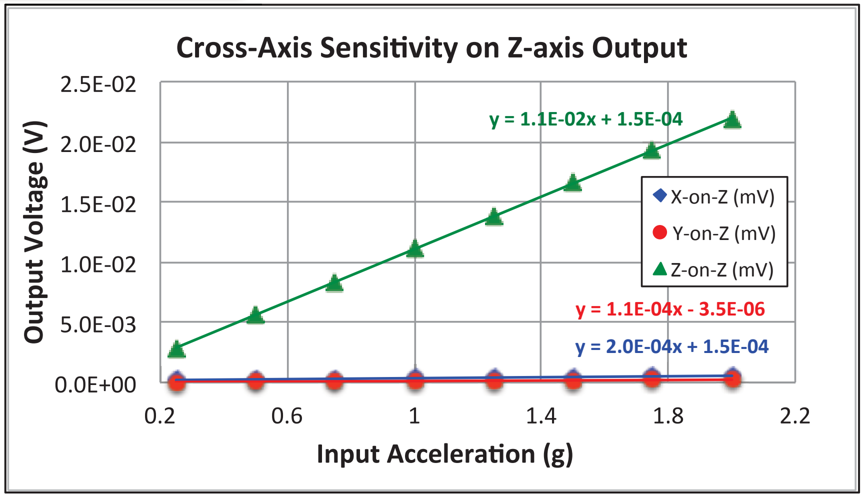


Interface IC



Scale Factor & Cross-Axis

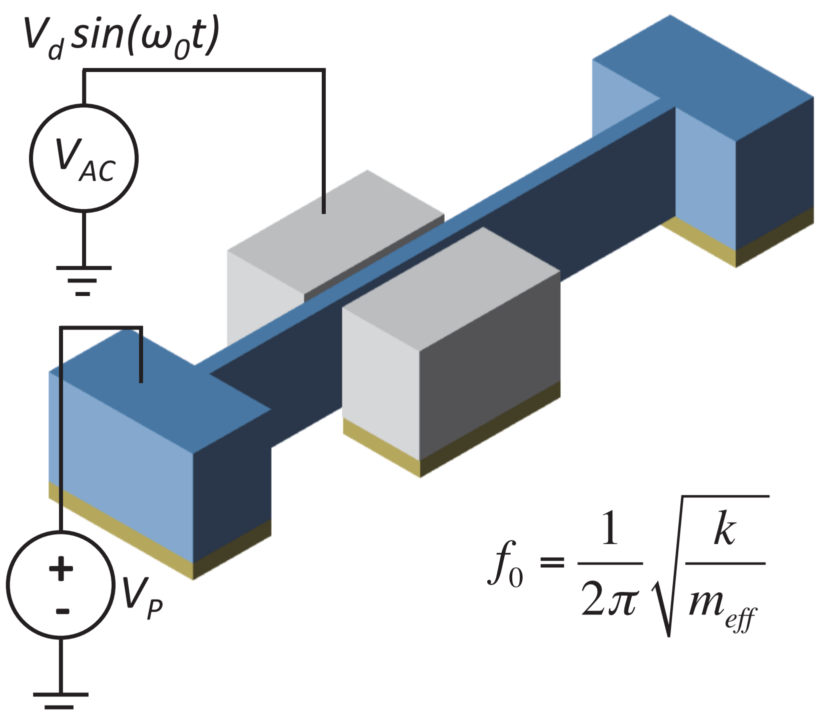




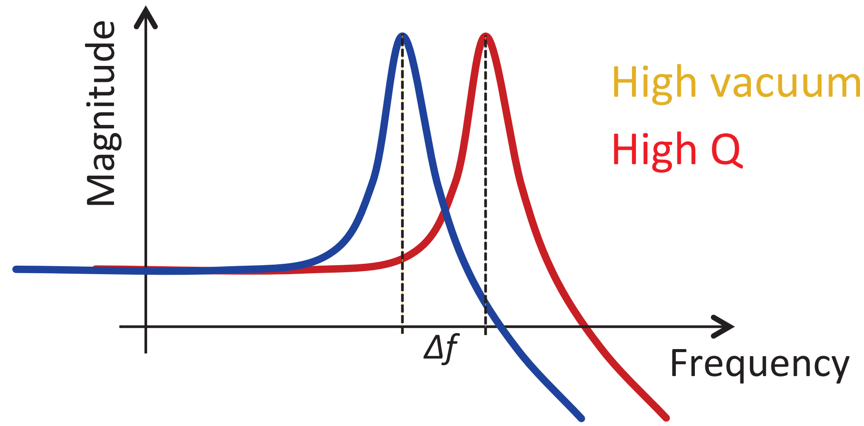
Resonant Accelerometers

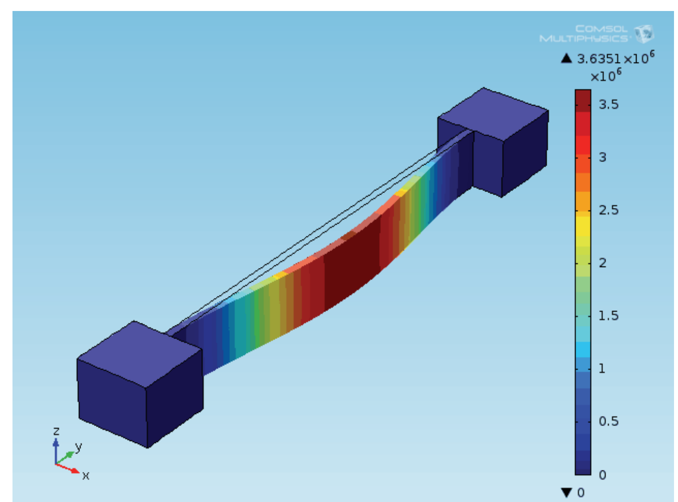
- At very low pressures (mTorr range), Q_{SFD} difficult to stabilize
- Different sensing technique → Change in resonance frequency

MEMS Resonator



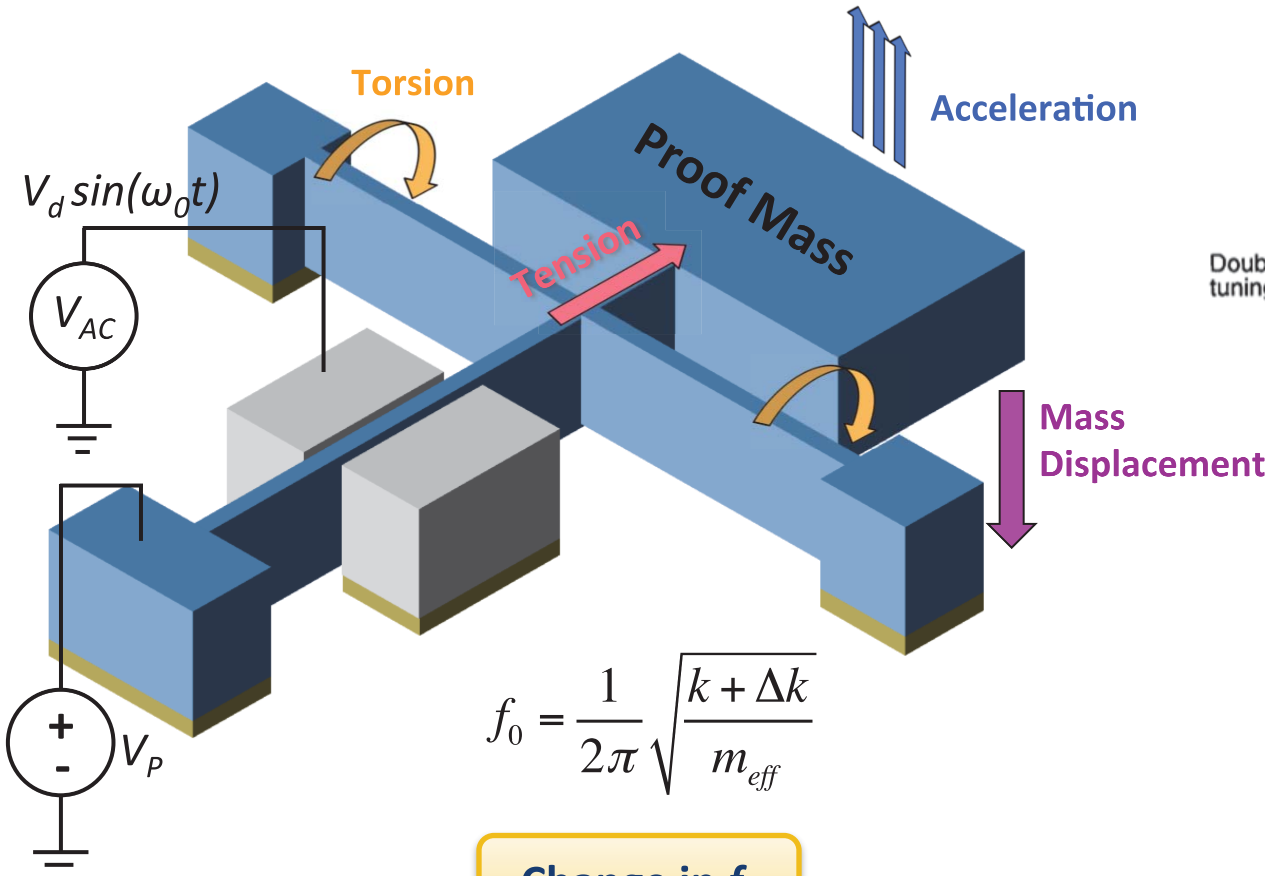
$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m_{eff}}}$$





Mass-Loaded Resonator

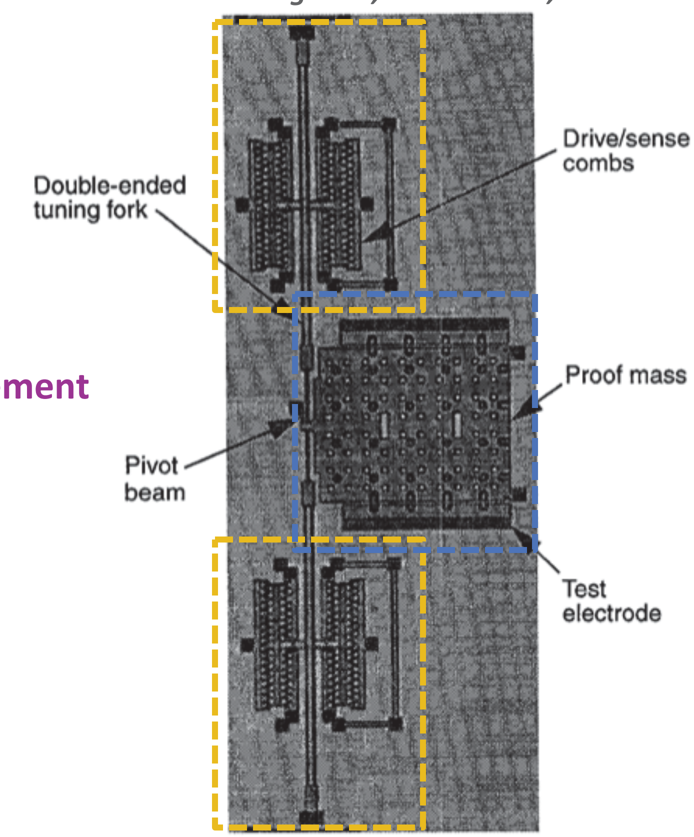
- At very low pressures (mTorr range), Q_{SFD} difficult to stabilize
- Different sensing technique required → Change in frequency



$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k+\Delta k}{m_{eff}}}$$

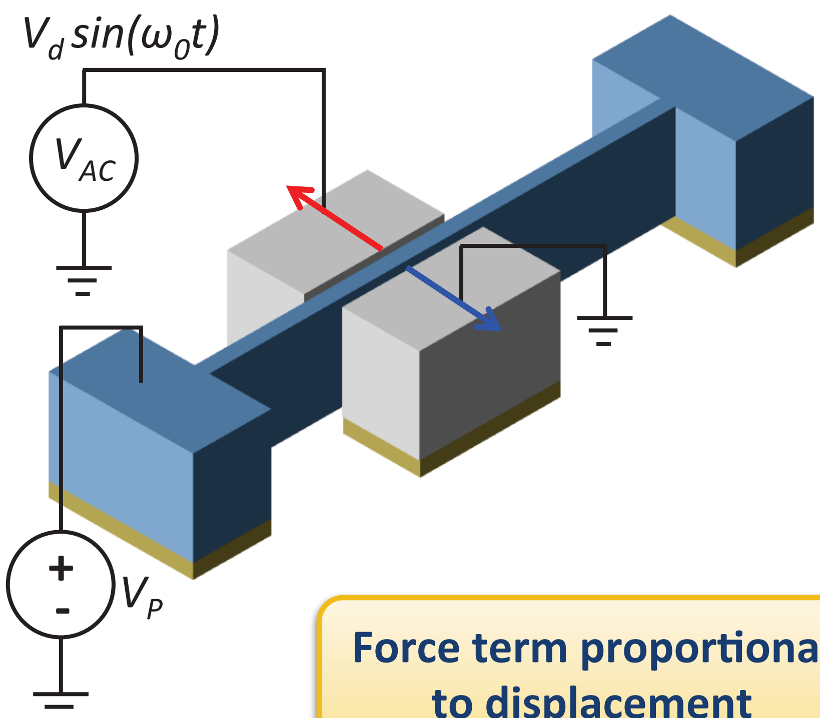
Change in f_0

T.A Roessing et al, Transducers, 1997



Electrostatic Spring Softening

- Mechanical loading of stiffness is not very effective
- Also, highly prone to fabrication imperfections and built-in stress
- Alternative: Electrostatic spring softening



Force term proportional to displacement

$$F_{elec} = \frac{1}{2}\frac{\partial C}{\partial x}V^2 = \frac{1}{2}\frac{\varepsilon A}{(g_0 \mp x)^2}V^2$$

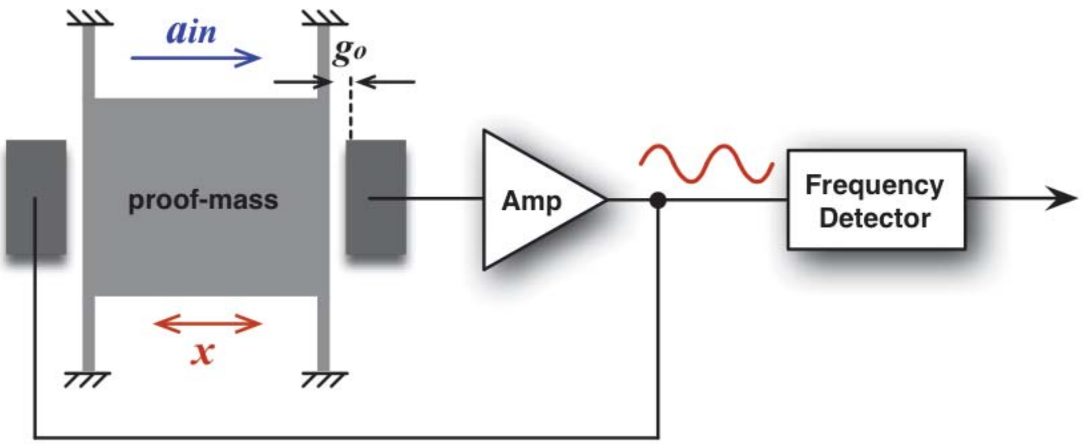
$$F_{elec} \approx \frac{1}{2}\frac{\varepsilon A}{g_0}V^2 \cdot \left(\frac{1}{g_0} \pm \frac{2}{g_0^2}x + \frac{3}{g_0^3}x^2 \pm \ldots\right)$$

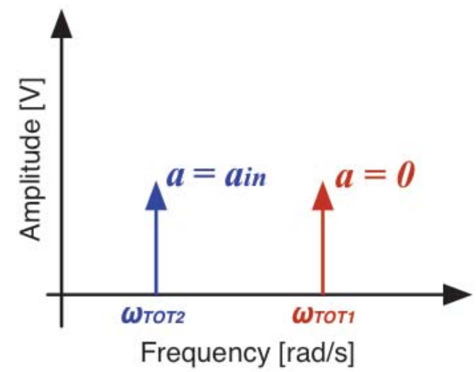
$$F_{elecTOT} = F_{elec1} - F_{elec2}$$

$$F_{elecTOT} \approx \frac{\varepsilon A}{g_0} \cdot \left(V_{AC} \cdot V_P + \frac{2 \cdot V_P^2}{g_0^2}x\right)$$

Accelerometer as a Resonator

- Replacing beam resonator with an accelerometer





$$m\frac{d^2x}{dt^2}+b\frac{dx}{dt}+kx=m\,a_{in}+F_{elecTOT}$$

Mechanical Transfer Function — Input Acceleration — Electrostatic Force

$$m\frac{d^2x}{dt^2}+b\frac{dx}{dt}+\left(k-\frac{2\varepsilon A}{g^3}V_P^2\right)x=m\,a_{in}+\frac{\varepsilon A}{g^2}V_{ac}V_P$$

$$\omega_{TOT}=\sqrt{\frac{k-2\frac{\varepsilon A}{g^3}V_P^2}{m}}$$

Gap g_0 changes with a_{in}

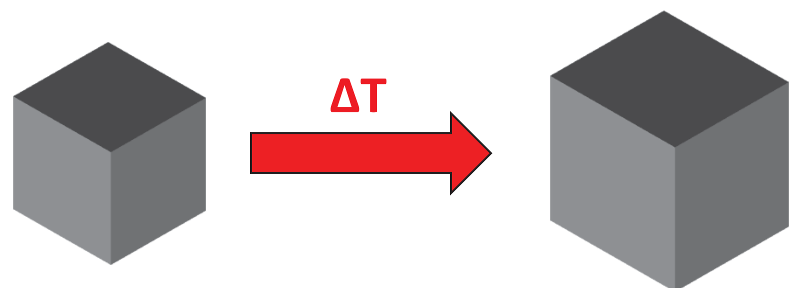
$$\frac{\partial\omega_{TOT}}{\partial a_{in}}\approx-\frac{3}{2}\frac{\varepsilon A}{k\,\omega_0\,g^4}V_{DC}^2$$

Challenges in Resonant Accelerometers

- Temperature coefficient of frequency (TCF)
  - Dimensional change → CTE or α (~ 2.6 ppm/ºC in silicon)
  - Material properties → TCE (~ -32 ppm/ºC in silicon)

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m_{eff}}} \propto \frac{w}{\sqrt{\rho}\cdot l^2} \qquad w = w_0\left(1+\alpha\cdot\Delta T\right) \qquad l = l_0\left(1+\alpha\cdot\Delta T\right) \qquad \rho = \rho_0\left(1-3\alpha\cdot\Delta T\right)$$

$$TCF_\alpha = \frac{1}{f_0}\frac{df}{dT} \approx \frac{\alpha}{2}$$

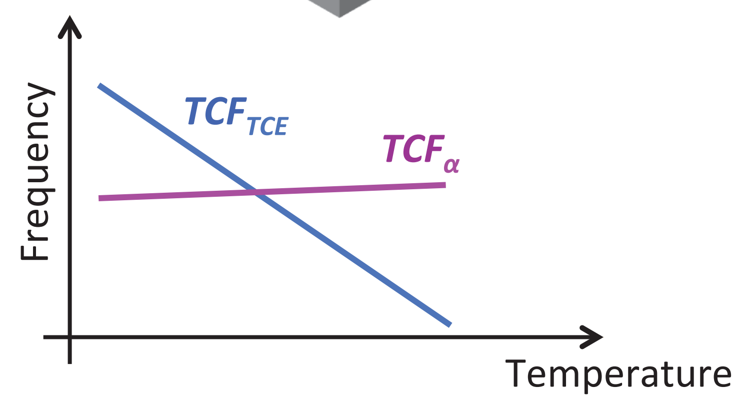


$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m_{eff}}} \propto \sqrt{E} \qquad E = E_0\left(1+TCE\cdot\Delta T\right)$$

$$TCF_{TCE} = \frac{1}{f_0}\frac{df}{dT} \approx \frac{TCE}{2}$$

TCF ≈ -30 ppm/ºC

SF ≈ 500-1500 ppm/g

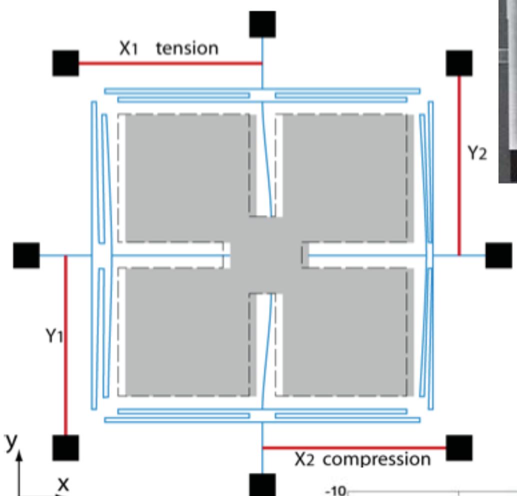


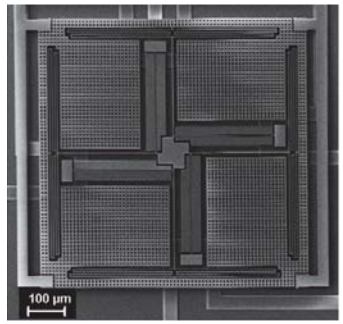
- Error in silicon resonant accelerometers: 20 – 60 mg/ºC

Dual-Resonator Approach

- Use two separate resonators operating differentially

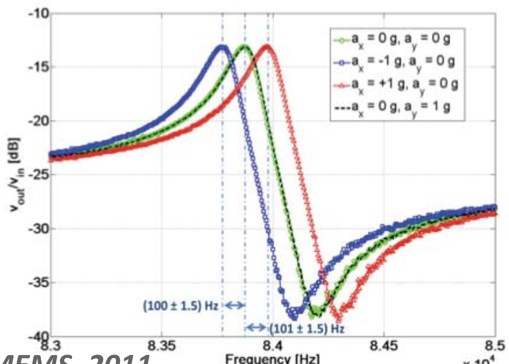
Example 1





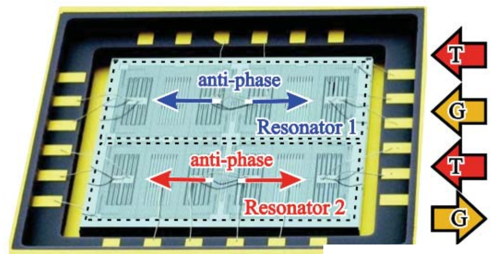
$$f = f_0\sqrt{1+\frac{NL^2}{EI}}$$

SF ≈ 200 Hz/g
@ 83 KHz

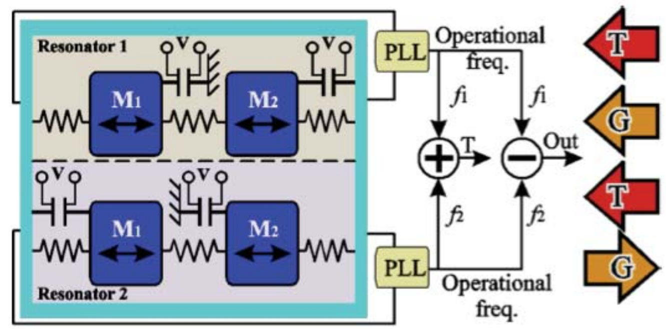


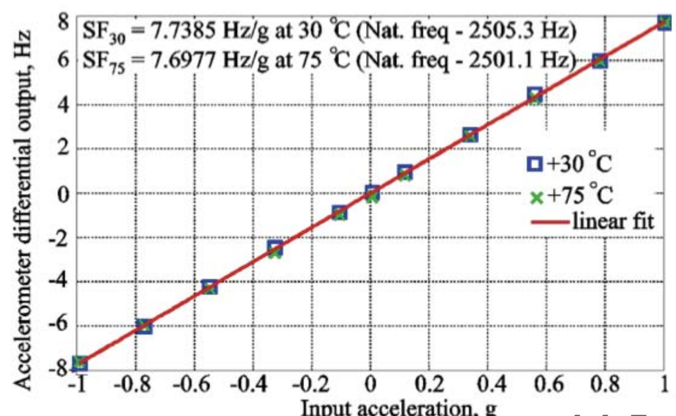
C. Comi, et al, IEEE MEMS, 2011

Example 2



Differential FM Accelerometer



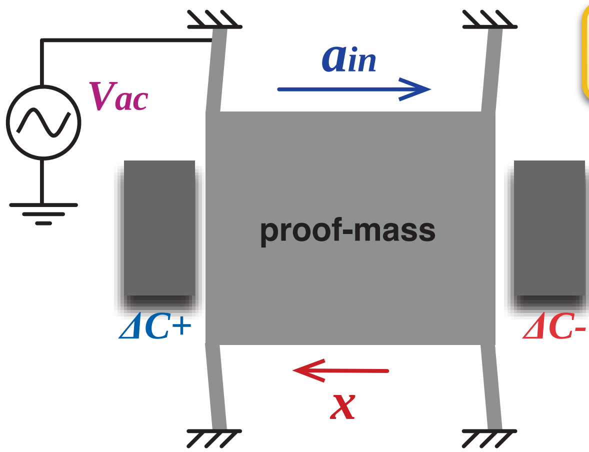


SF ≈ 7.7 Hz/g
@ 2.6 KHz

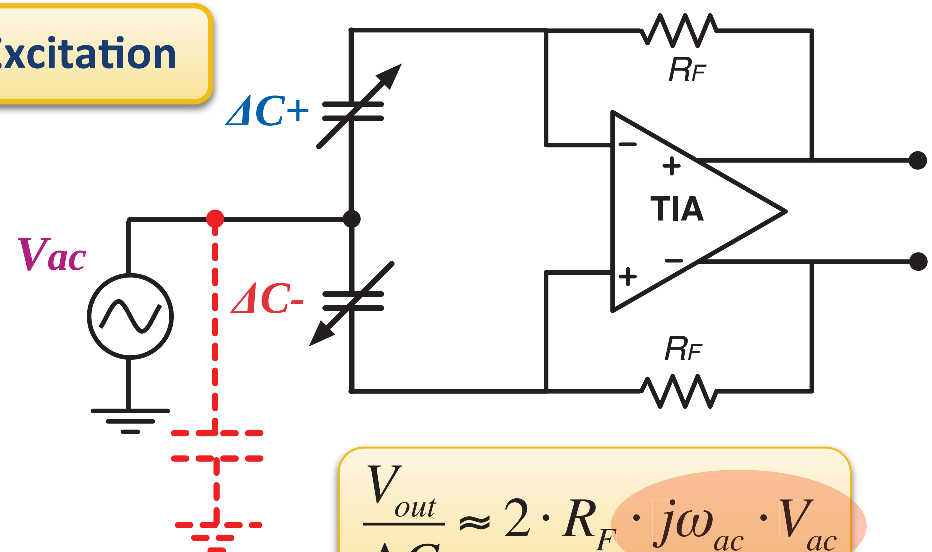
A.A. Trusov, et al, IEEE MEMS, 2013

Interfacing Capacitive Accelerometers

- Detection of capacitance change

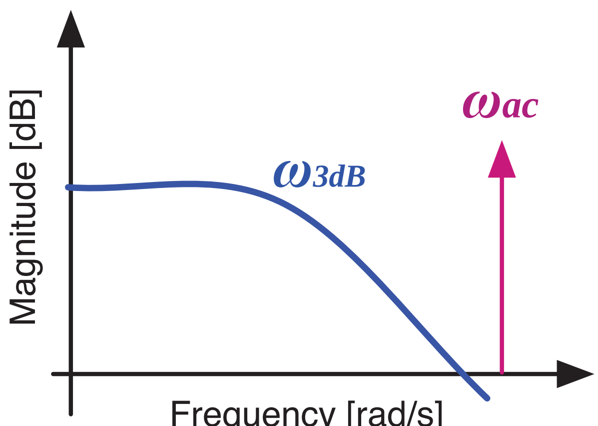


Sinusoidal Excitation



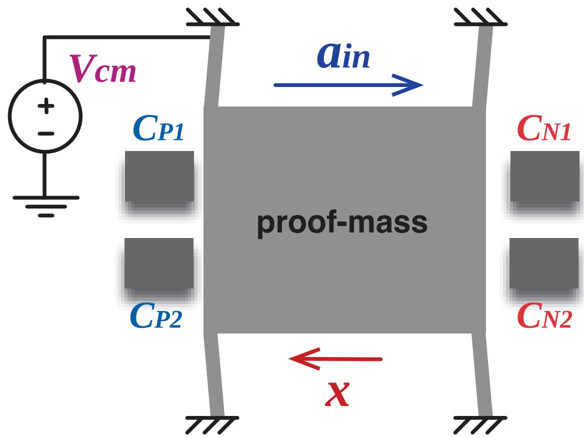
$$\frac{V_{out}}{\Delta C} \approx 2 \cdot R_F \cdot j\omega_{ac} \cdot V_{ac}$$

$$\omega_{3dB} \approx Q \cdot \omega_0 \quad \text{for} \quad Q < 1$$

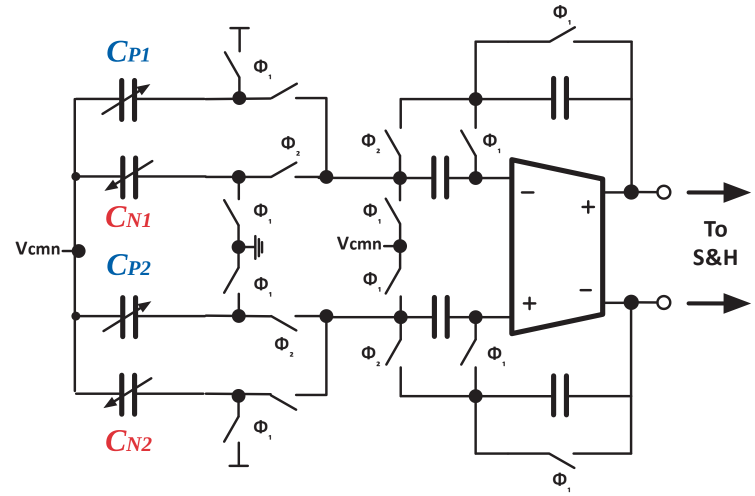


- To avoid electrostatic excitation: $\omega_{ac} >> \omega_{3dB}$
- <u>Challenges:</u>
  - Generating stable V_{ac}, ω_{ac}
  - Driving the “proof-mass node” (power)

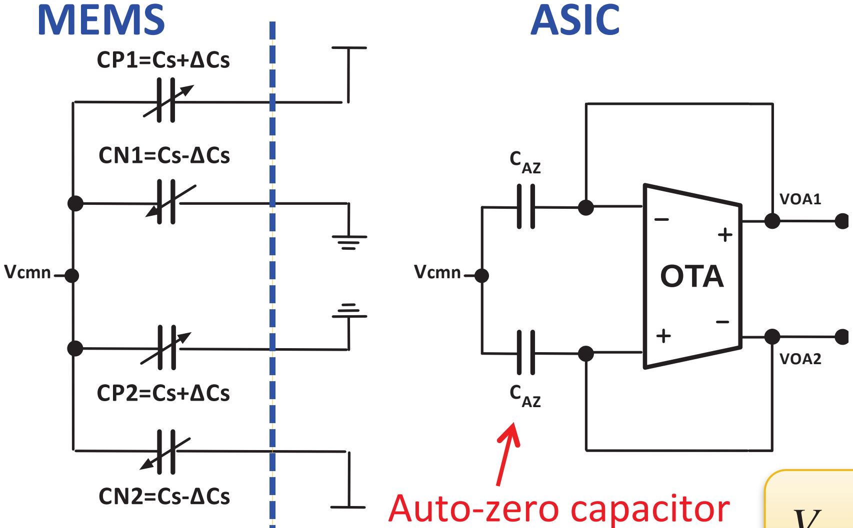
Switched-Capacitor Interfaces



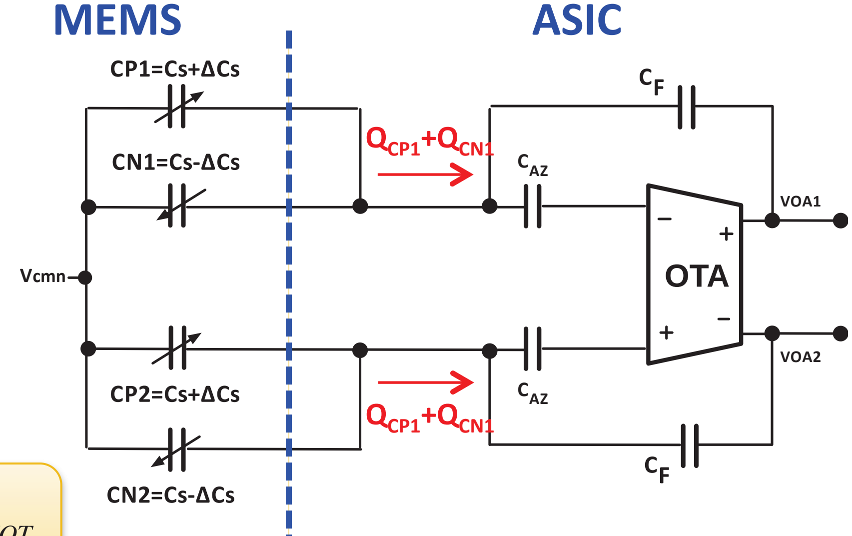
- Small IC area
- Low power
- Low noise (AZ, CDS)
- Multiplexing ability
- Digital output



Sampling Phase



Amplifying Phase

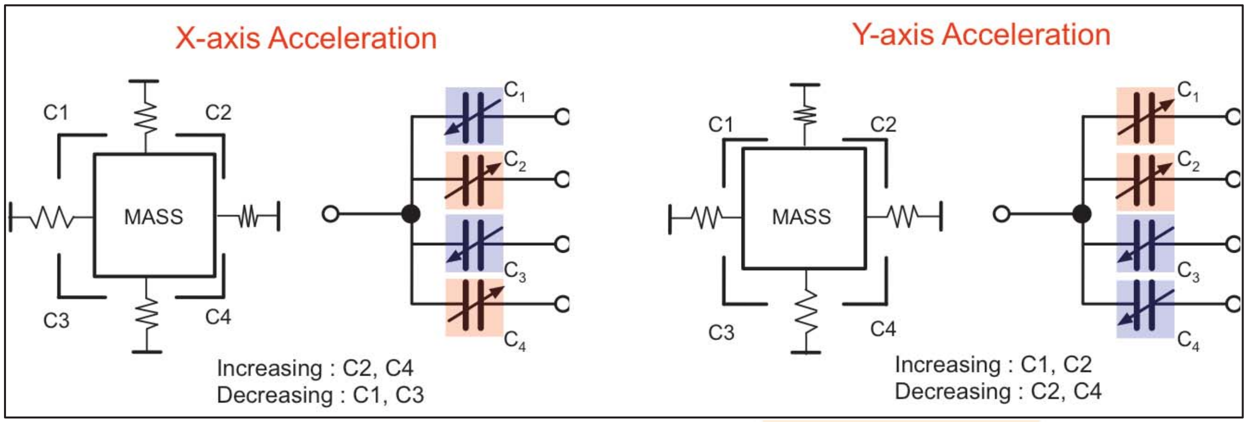


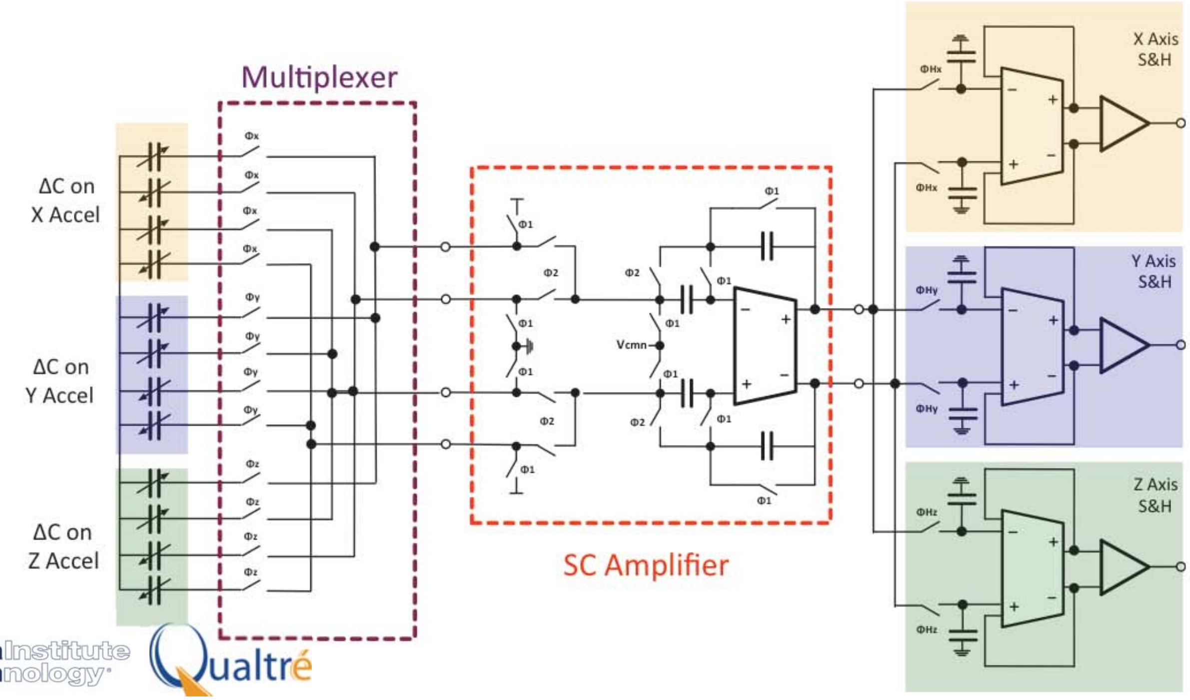
$$V_{out} = \frac{1}{2}\frac{V_{DD}}{C_F}C_{TOT}$$

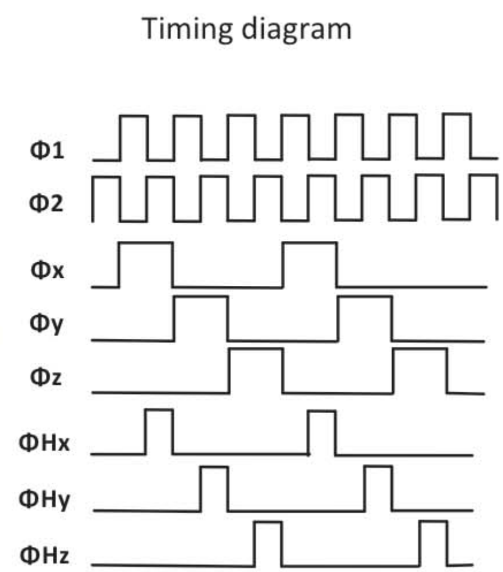
$$(C_{TOT} = C_{P1} - C_{N1} + C_{P2} - C_{N2})$$

Multi-Axis Sensing

- Multiplexing used to sense different axes with same interface



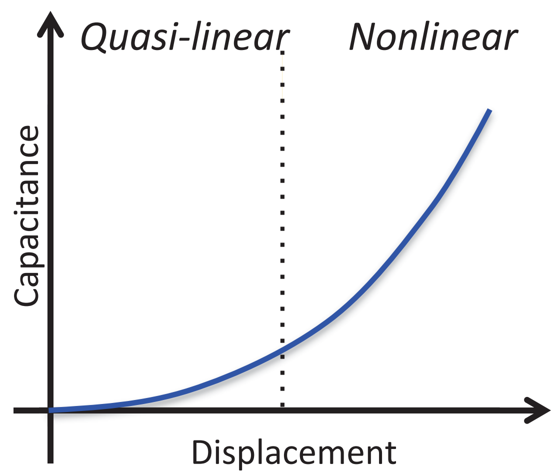




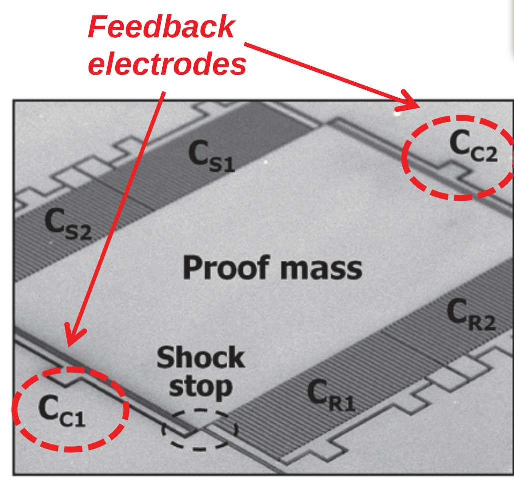
Closed-Loop Interfaces

- MEMS Sensitivity (parallel plate) → Strong function of gap (non-linear)

$$\frac{dC}{dx} = \frac{\varepsilon \cdot A}{(g_0 - x)^2}$$



- ✓ Linearizes output using FB
- ✓ Increases operational BW
- ✗ Degrades noise
- ✗ Increases complexity

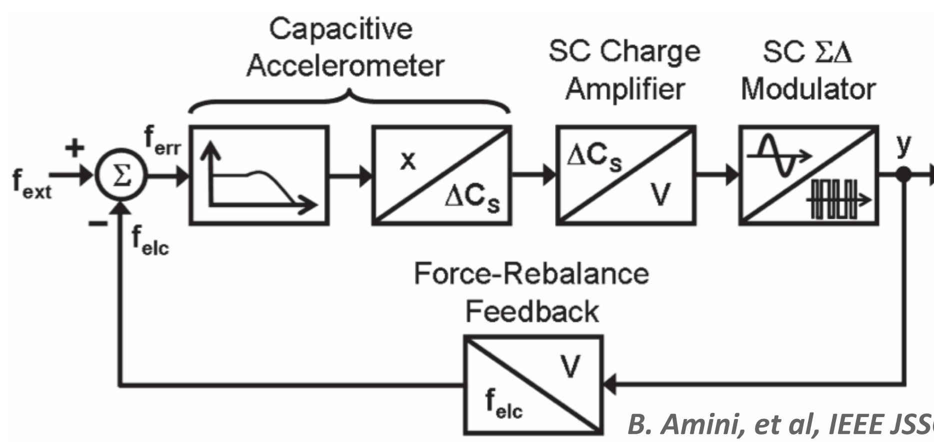


Force-to-Rebalance

$$F_{err} \propto x \approx 0$$

$$y = \frac{F_{elec}}{FB} \approx \frac{F_{ext}}{FB} = \frac{m \cdot a_{in}}{FB}$$

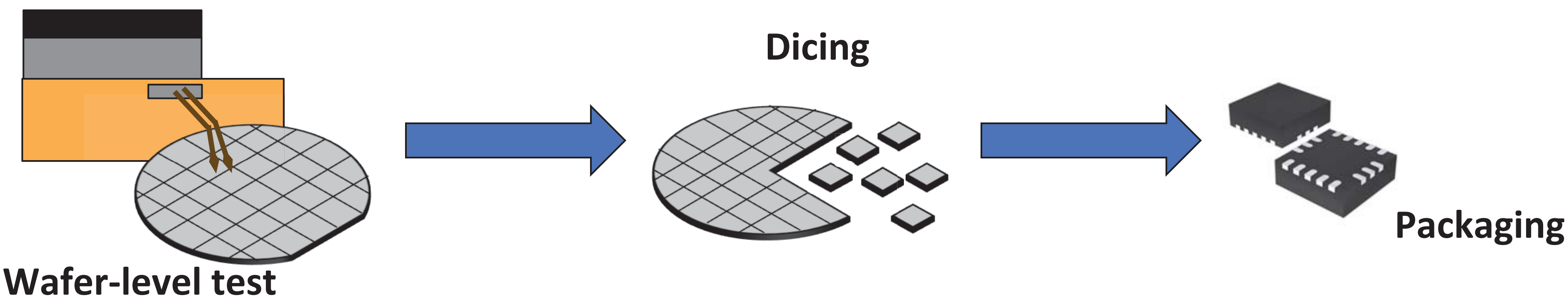
- F_{elec} proportional to input



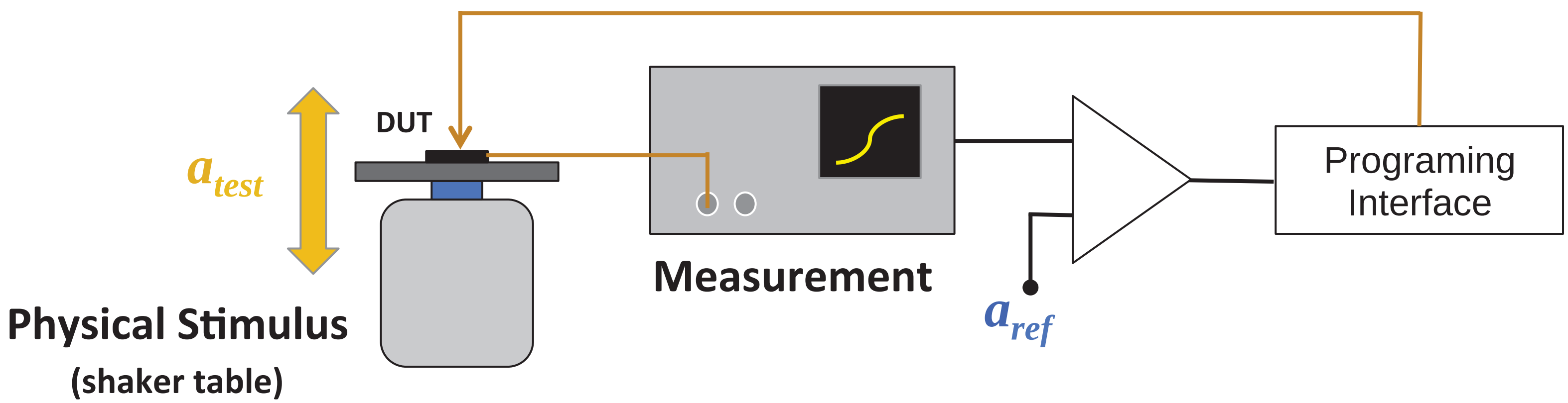
B. Amini, et al, IEEE JSSC, 2006

Calibration in MEMS Accelerometers

- Required to compensate for process variations
- Contributes significantly to overall cost of product

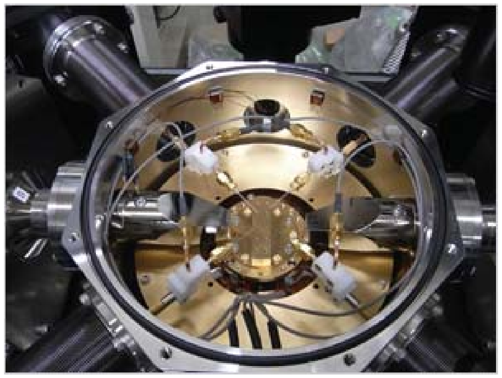


Calibration Procedure (Factory Trim)



Testing & Calibration

- Inertial MEMS require "unconventional" test methods
  - Vacuum prober, SEM, rate-table, shaker-table, temperature chamber

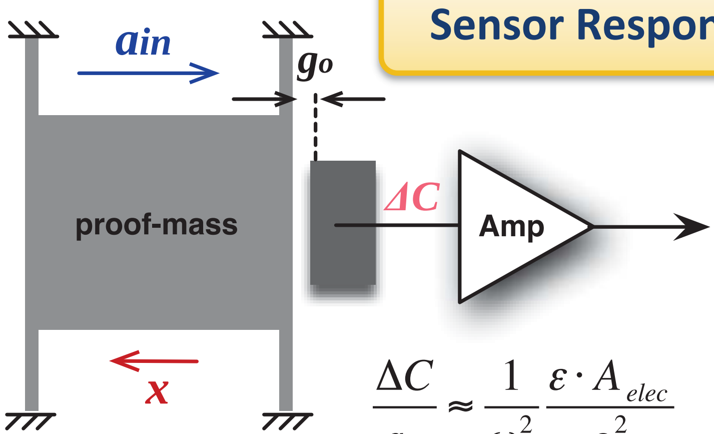


- Expensive equipment
- Sensor parameters dependent on fabrication tolerances
- Extended test time → temperature, pressure, physical stimuli

No Physical Stimulus Calibration

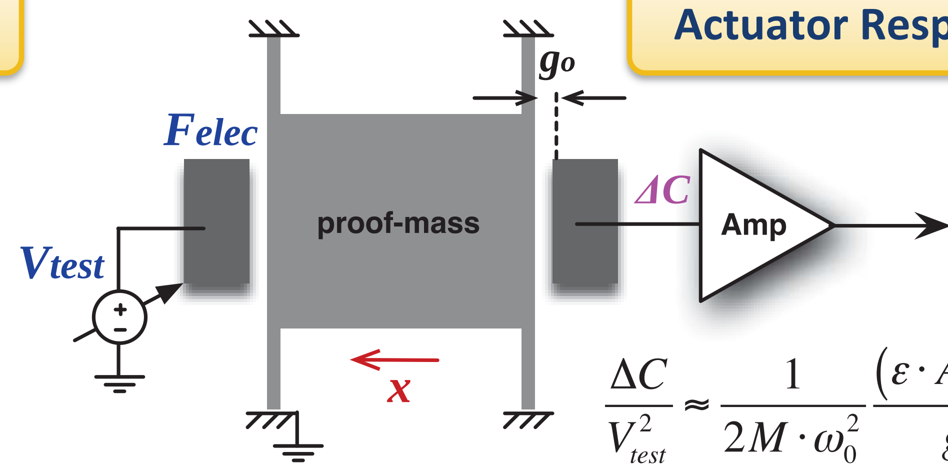
- Avoid time-consuming/expensive test
- In accelerometers: Turn the sensor into an actuator

Sensor Response

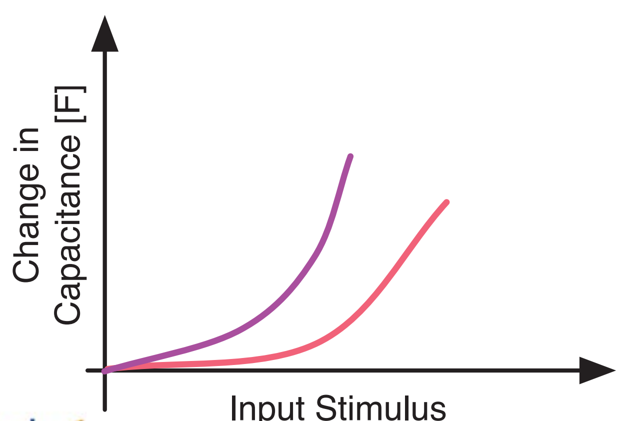


$$\frac{\Delta C}{a_{in}} \approx \frac{1}{\omega_0^2} \frac{\varepsilon \cdot A_{elec}}{g_0^2}$$

Actuator Response



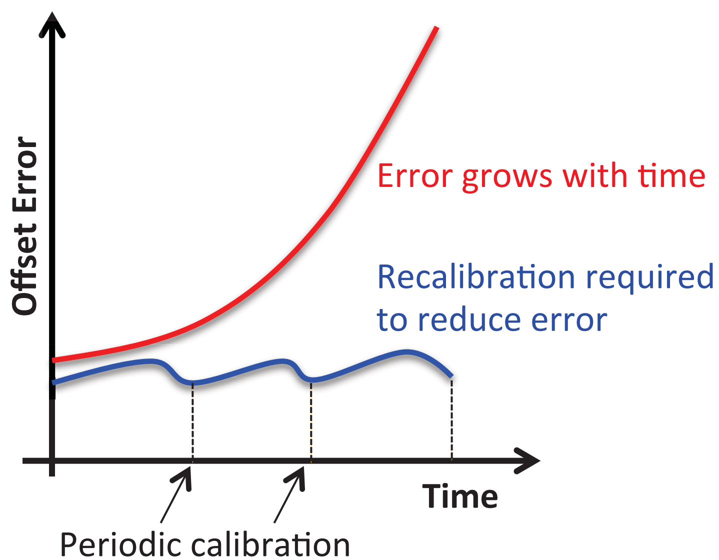
$$\frac{\Delta C}{V_{test}^2} \approx \frac{1}{2M \cdot \omega_0^2} \frac{(\varepsilon \cdot A_{elec})^2}{g_0^4}$$

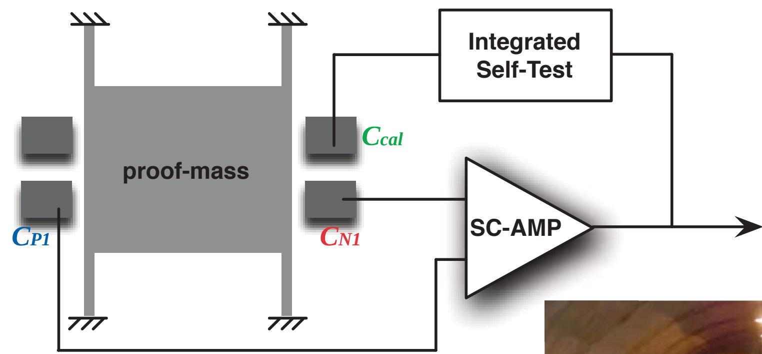


- Use V_{test} to emulate a_{in}
- No physical excitation needed

Built-In Self Test (BIST)

- Sensor parameters drifts over time
- Periodic re-calibration required for high-end applications



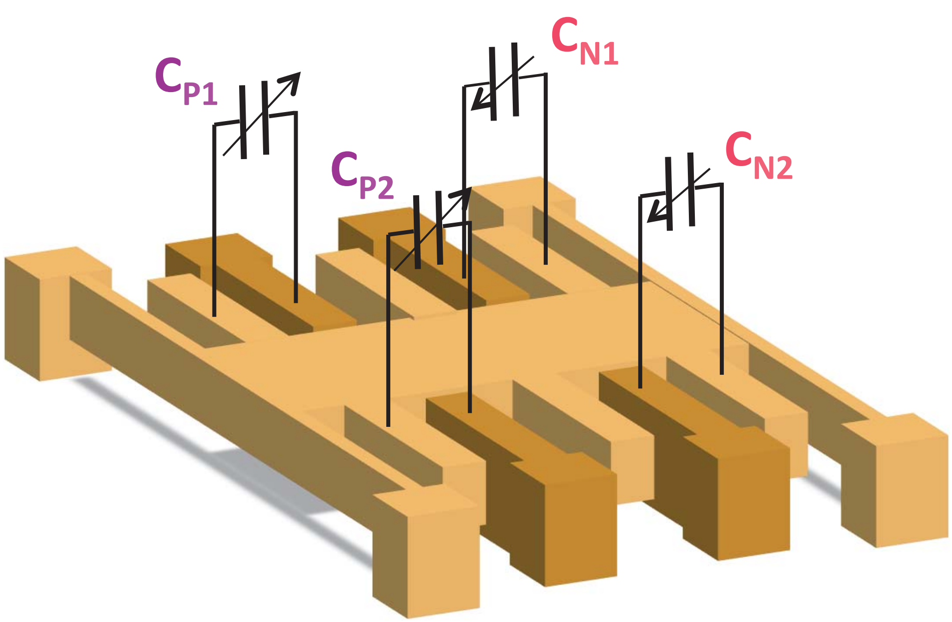


Self-Calibrate Stored Equipment

- <u>Issue:</u> Online calibration → How to test during operation?
- Calibration should be common mode to acceleration signal

Offset in Capacitive Accelerometers

- Offset in capacitive MEMS → Highly dependent on mismatch
  - Typical scale-factor (consumer) → ~ 10 - 100 fF/g & 250 mV/g (@ V_{DD} = 2.5)
  - It takes only 100 fF of mismatch to rail the output



$C_{s.P1} \neq C_{s.N1} \neq C_{s.P2} \neq C_{s.N2}$

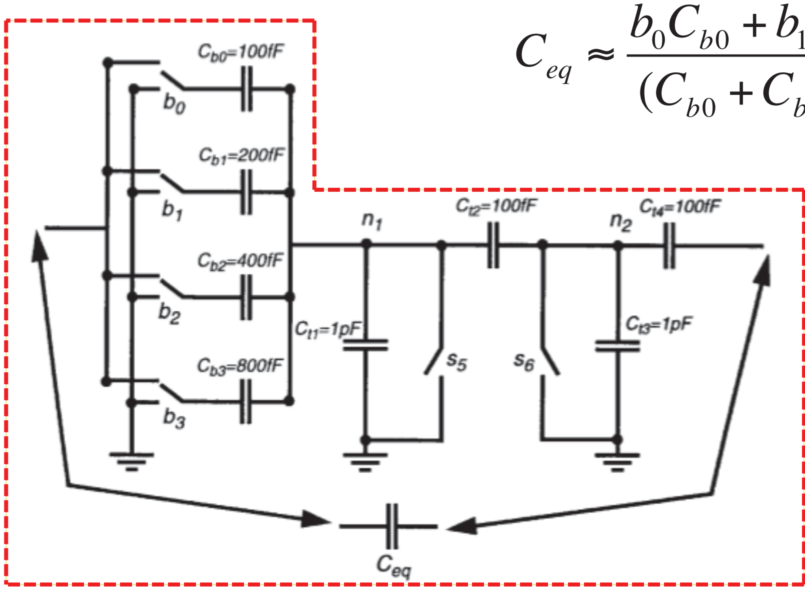
$$V_{out} = \frac{1}{2}\frac{V_{DD}}{C_F}(C_{P1} - C_{N1} + C_{P2} - C_{N2})$$

$$= \underbrace{\frac{2V_{DD}}{C_F}}_{\text{Sensitivity}}\Delta C + \underbrace{\frac{V_{DD}}{2C_F}(C_{S.P1} - C_{S.N1} + C_{S.P2} - C_{S.N2})}_{\text{Output Offset}}$$

- ΔC → change due to acceleration
- Cs → static capacitance, changes:
  - Process tolerances
  - Wafer bonding
  - Temperature

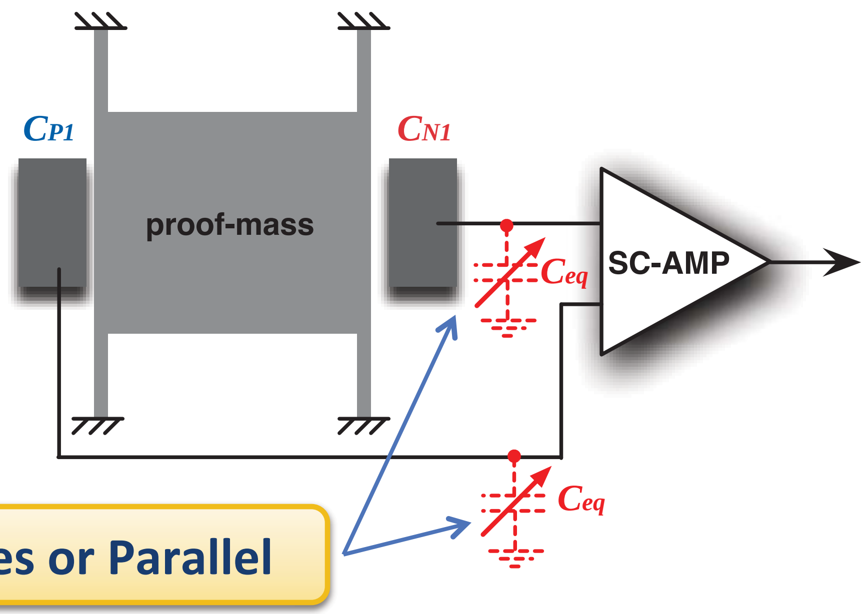
Offset Calibration – Discrete Steps

- Capacitor bank → add programmable capacitors in front-end
- Series/parallel combination allows bring offset down
- Limitation → Resolution



M. Lemkin, et al, IEEE JSSC, 1999

$$C_{eq} \approx \frac{b_0 C_{b0} + b_1 C_{b1} + b_2 C_{b2} + b_3 C_{b3}}{(C_{b0} + C_{b1} + C_{b2} + C_{b3}) + C_{t1}} \left(\frac{C_{t2}}{C_{t2} + C_{t3}} \right) C_{t4}$$

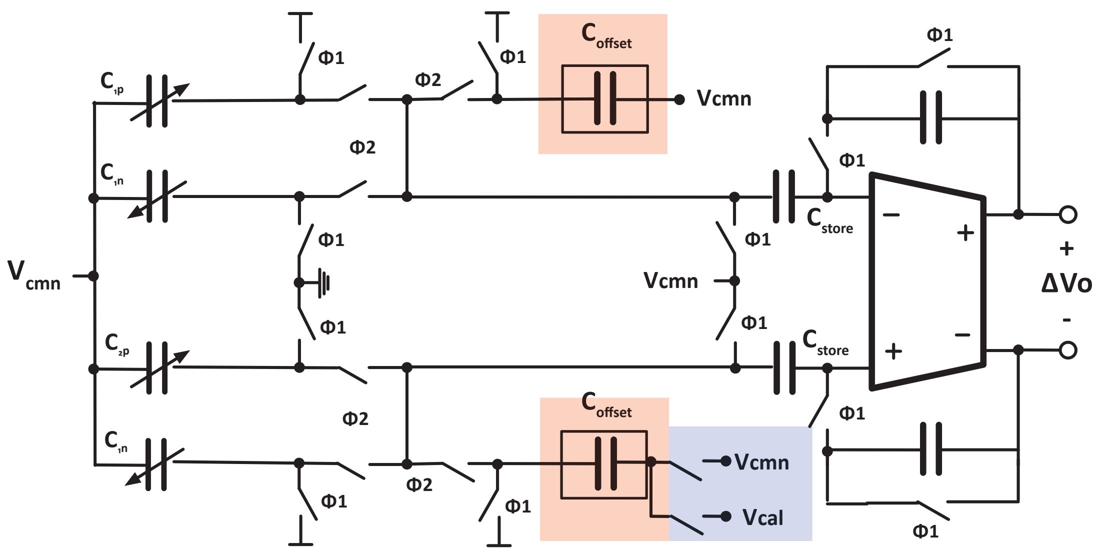


Offset Calibration – Fine Tuning

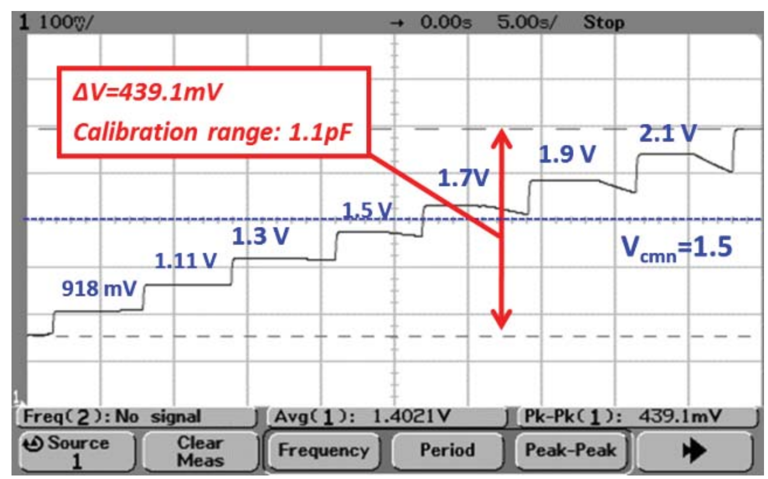
- In addition to capacitor bank (C_{offset}), add analog tuning voltage
- Allocate mux time-slot for calibration

$$V_{out} = \frac{2V_{DD}}{C_F}\Delta C + \frac{V_{DD}}{2C_F}C_{mismatch} + \frac{0.5V_{DD} - V_{cal}}{C_F}C_{offset}$$

Sensitivity **Offset** **Offset Calibration**

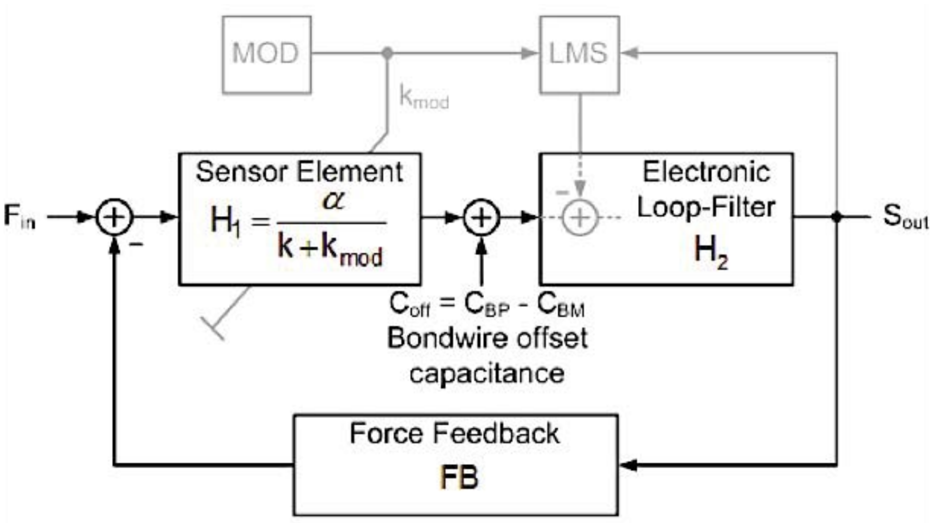


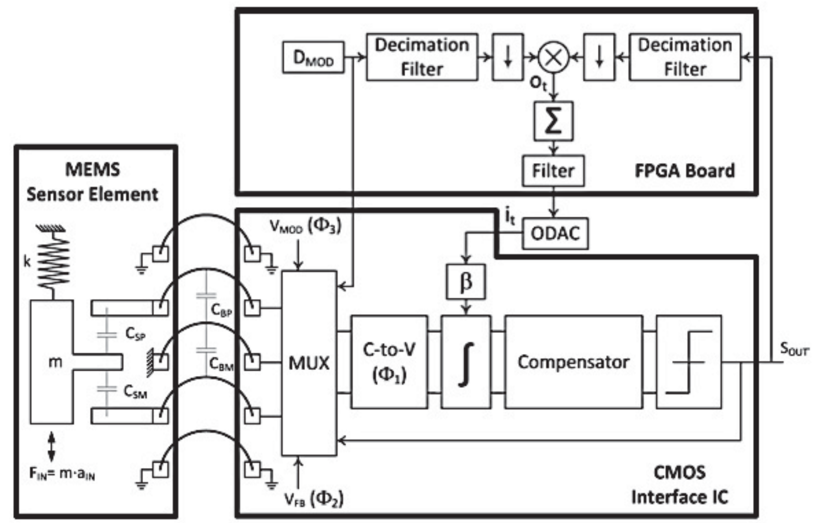
Offset vs. V_{cal}



Offset Calibration – Bond-wire Drift

- Thermal and Mechanical stress changes C between bond-wires
- Parametric modulation used to up-convert bond-wire C change





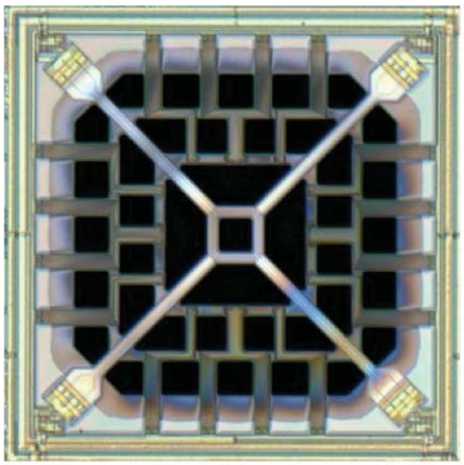
P. Lajevardi, et al, IEEE JSSC, 2013

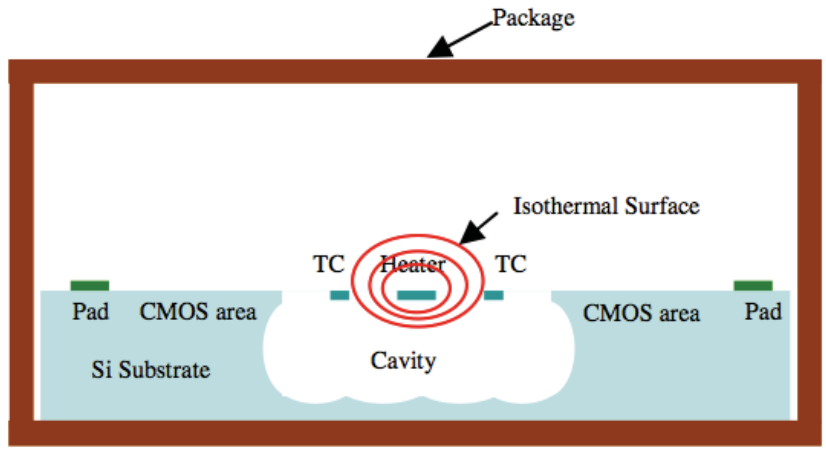
- Different transfer-function from:
  - a_{in} to S_{out}
  - C_{off} to S_{out} (dependent on k)

$$S_{OUT} \approx \underbrace{F_{IN}\frac{1}{FB}}_{\text{Sensitivity}} + \underbrace{C_{OFF}\frac{k}{\alpha \cdot FB}}_{\text{Offset}} + \underbrace{C_{OFF}\frac{k_{\mathrm{mod}}}{\alpha \cdot FB}}_{\text{Offset Calibration}}$$

Other Types of Micro-accelerometers

Thermal Convection





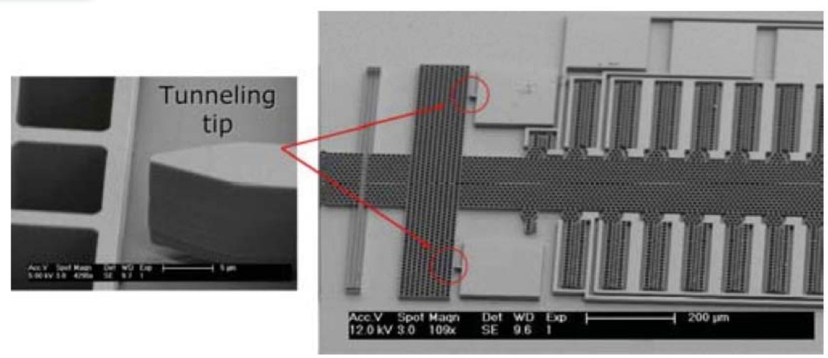
- ✓ High reliability & low-cost
- ✗ Degraded noise performance

Y. Cai, et al, solid-state sensors, actuators and microsystems workshop, Hilton-Head 2008

Tunneling Sensing

- ✓ High sensitivity (resolution)
- ✗ Large temperature dependency

L.A Oropeza-Ramos, et al, solid-state sensors, actuators and microsystems workshop, Hilton-Head 2008



Summary

- Accelerometer design is experiencing a shift in paradigm
- Integration with other (resonant) structures → e.g. gyroscopes
- Accelerometers in low-pressure are the "next big challenge"
- Reducing size without comprise in performance
  - Single-Proof mass designs?
- Online calibration extremely important in high-performance apps

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