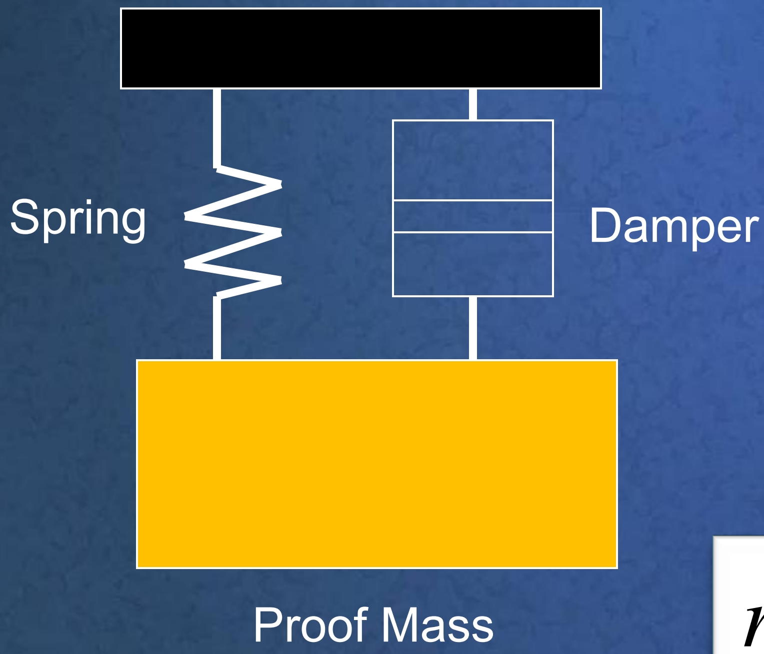
Accelerometers on Flexible Substrates

İsmail Erkin Gönenli

Advisor:
Zeynep Çelik-Butler

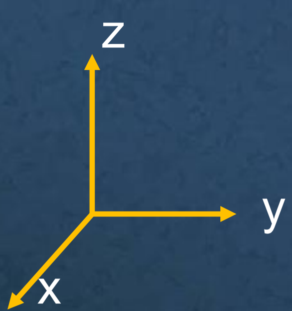
Department of Electrical Engineering
The University of Texas, Arlington

Physical Structure of an Accelerometer



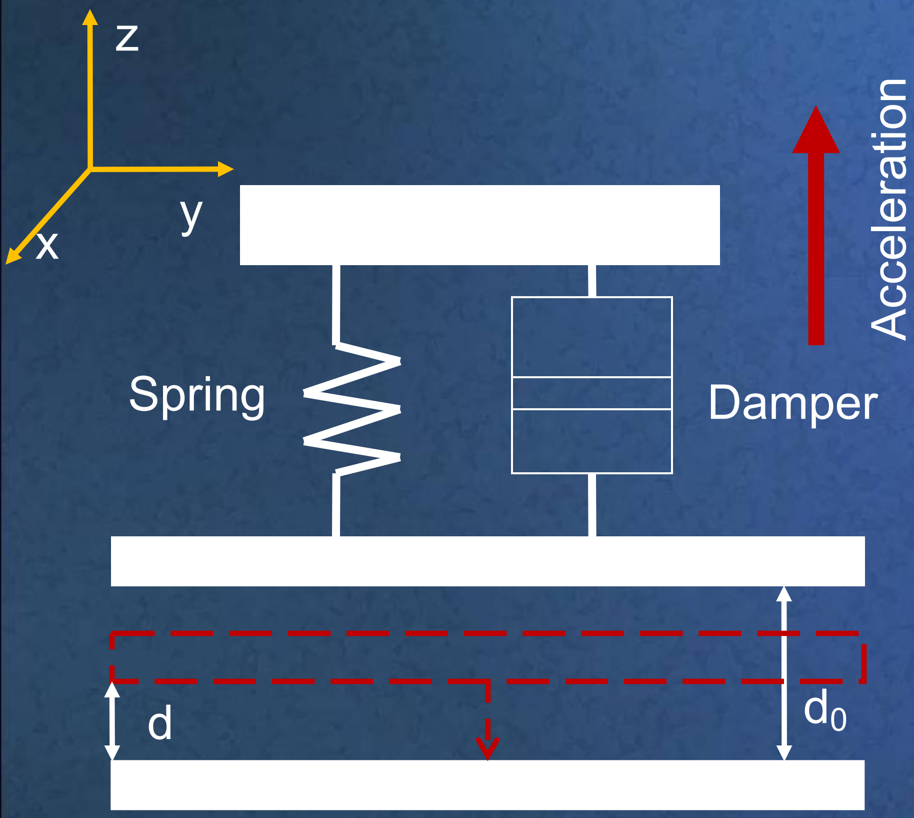
The structure of an accelerometer is formed by proof mass, damper and a spring. Whenever there is an acceleration, the proof mass moves which is opposed by the spring and the damper.

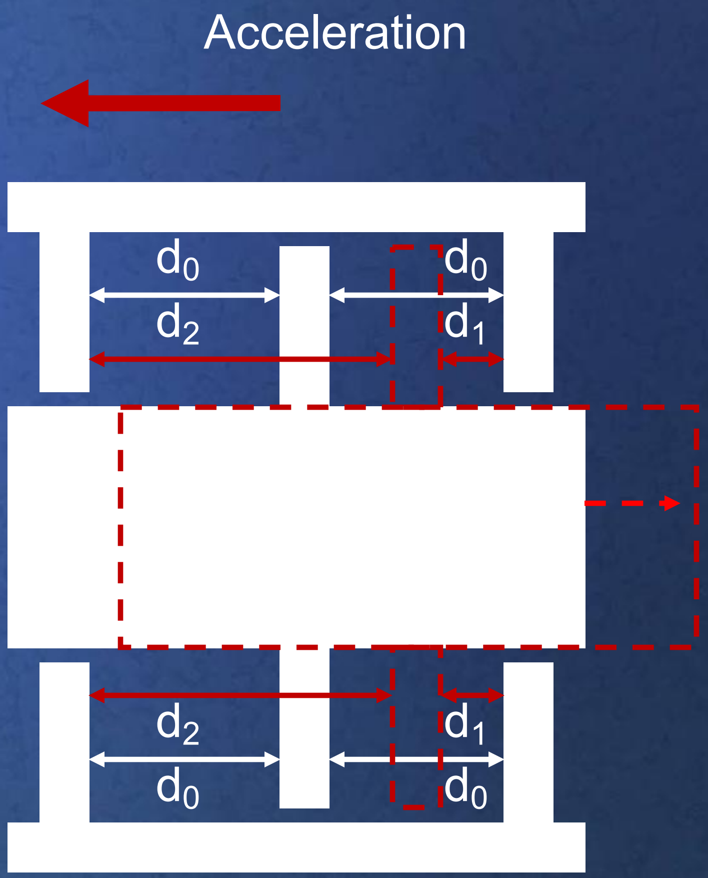
$$m\ddot{x} + b_m \dot{x} + k_m x = F_x(t)$$



•J. W. Gardner, V. K. Varadan and O. O. Awadelkarim, “Microsensors, MEMS and Smart Devices” , *John Wiley and Sons*, 2005

Basic Principle of Capacitive Accelerometer



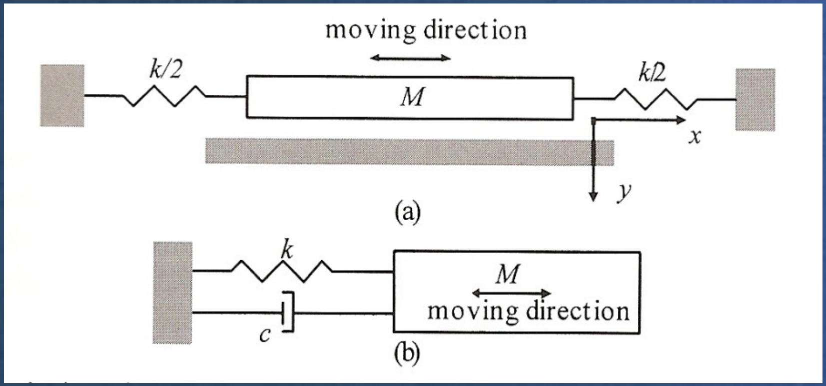


Accelerometer is based on parallel plate capacitance between a fixed plate and a movable plate connected to a spring. Acceleration is determined by the change in capacitance.

Damping Force

Damping: Dissipative forces such as friction, viscosity which take energy from the system and restrict its movement,

Slide Film Air Damping



$$\delta = \sqrt{2\mu / \rho\omega}$$

Effective decay distance

Low ω, δ>>d (Couette Flow)

δ comparable to d (Stokes Flow)

Navier-Stokes Equation

$$\rho\left[\frac{\partial \vec{v}}{\partial t} + (\vec{v}\cdot\nabla)\vec{v}\right] = \vec{F} - \nabla p + \mu\nabla^2\vec{v}$$

$$\vec{v} = u\vec{i} + v\vec{j} + w\vec{k}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = \frac{\mu}{\rho}\frac{\partial^2 u}{\partial z^2}$$

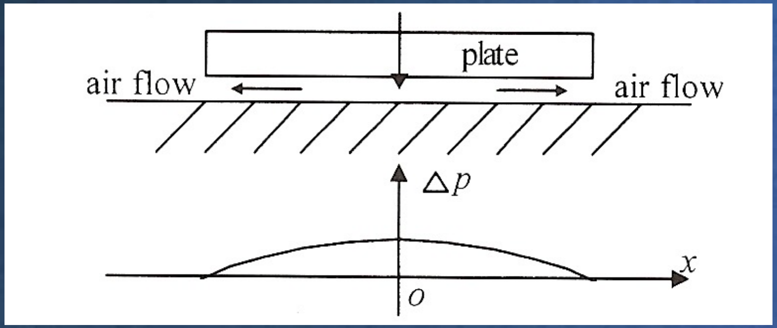
Movement in x-direction only

$$u(t) = a_0\omega\cos\omega t = u_0\cos\omega t$$

M. Bao, “Analysis and Design Principles of MEMS Devices”, *Elsevier*, 2005

Damping Force

Squeeze Film Air Damping



$$\omega_0 = \sqrt{\frac{k}{m}}$$

Free vibration frequency

$$\omega_c = \frac{\pi^2 h_0^2 p_a}{12 \mu w^2}$$

Cutoff frequency (elastic force equals damping force)

When $\omega_0 << \omega_c$

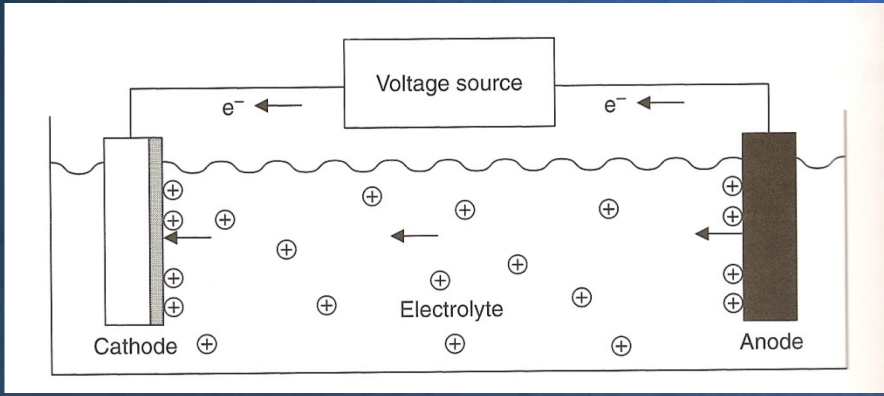
$$\xi = c_{d0} / 2m\omega_0$$

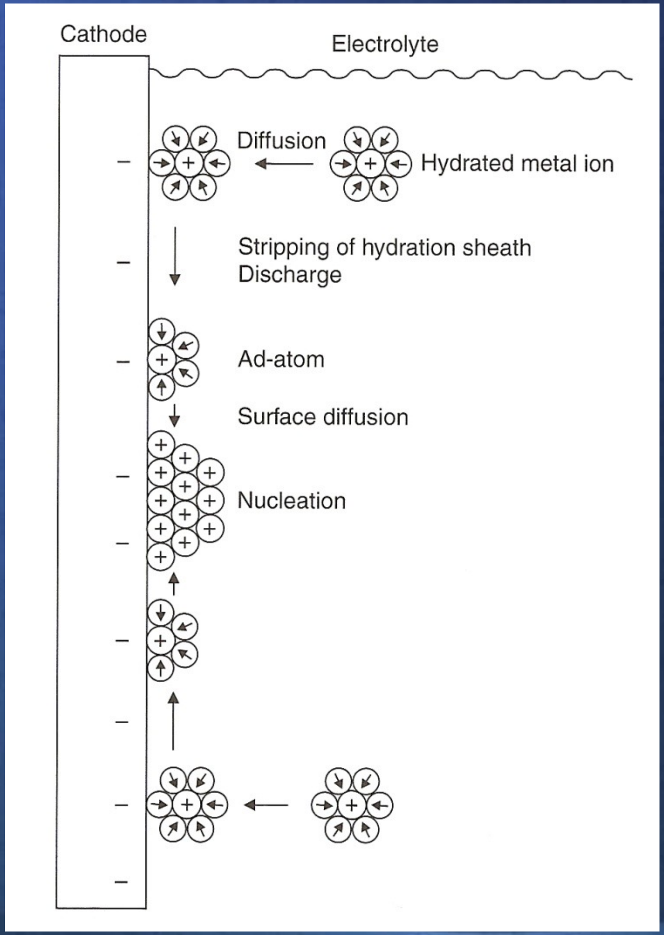
- Gas film is assumed to be incompressible.
- Coefficient of damping force is assumed constant.
- Squeeze action is slow and there is time for gas to leak.

$\xi<1 \rightarrow$ under damped (continues to oscillate at natural frequency)
$\xi=1 \rightarrow$ critically damped (comes to rest instantaneously)
$\xi>1 \rightarrow$ over damped (takes longer to come to rest)

- M. Bao, “Analysis and Design Principles of MEMS Devices”, *Elsevier*, 2005
- M. Bao and H. Yang, “Squeeze Film Air Damping in MEMS”, *Sensors and Actuators A*, vol. 136, pp. 3-27, 2007

Electroplating





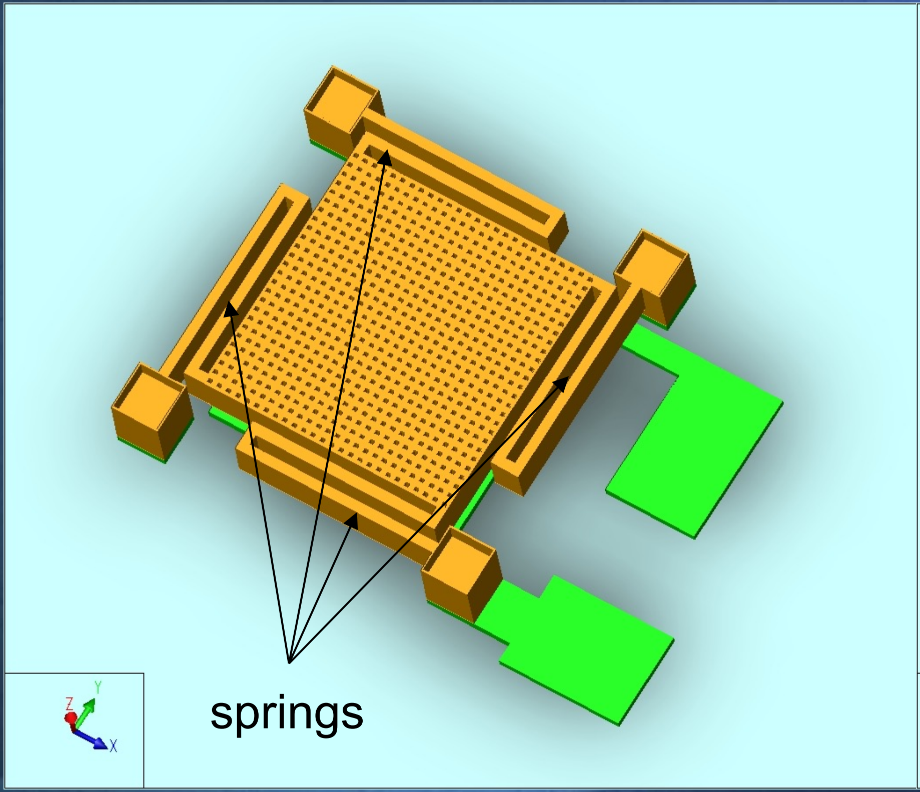
- Diffusion to cathode
- Metal ion discharge at cathode
- Nucleation through surface diffusion
- Fusion of nuclei to form a continuous film

• N. Kanani, “Electroplating”, *Elsevier*, 2004

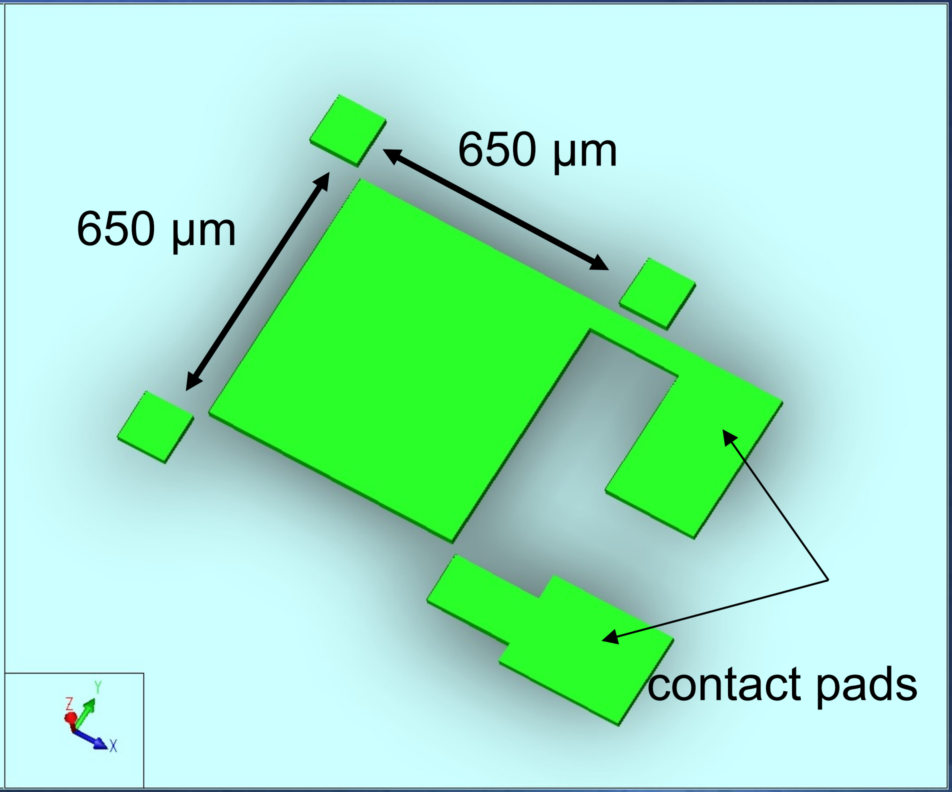
Accelerometer Design

Device 1

WHOLE STRUCTURE



BOTTOM ELECTRODES



Accelerometer Design

		Z-AXIS
Spring Constant (N/m)		10.118 (7.998)*
Damping Ratio	-40 ºF	0.550
	60 ºF	0.658
	160 ºF	0.753
Frequency (kHz)		25.297
Rest capacitance (pF)		1.894
ΔC (fF/g)		18.08
Mass (kg)		$1.581\ 10^{-8}$

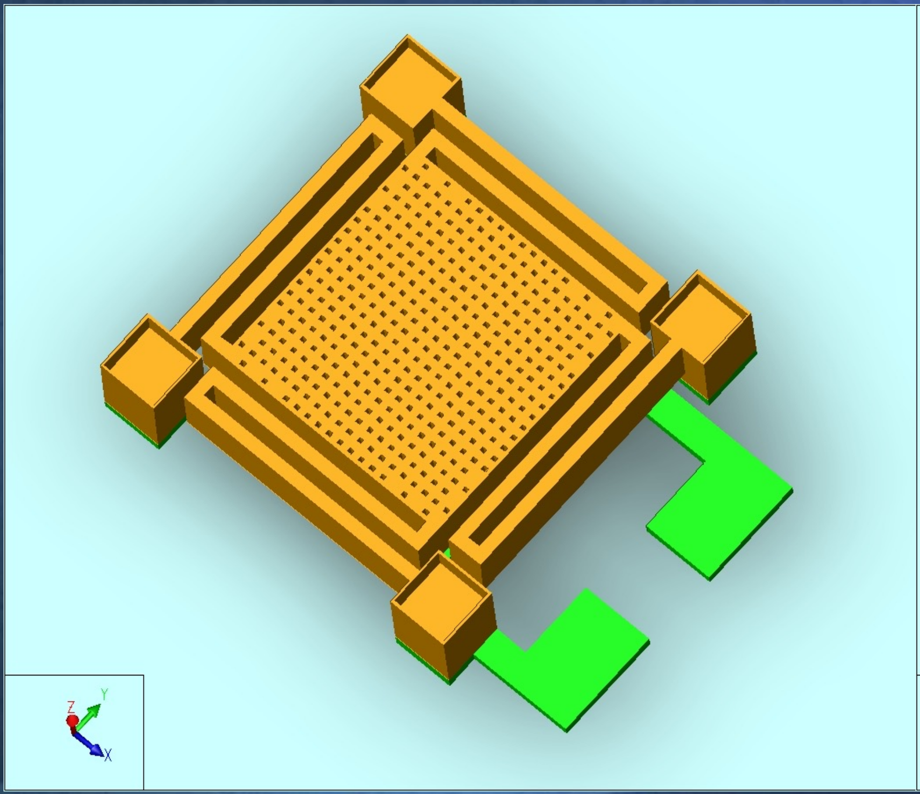
Device 1 Results

* Calculated from displacement

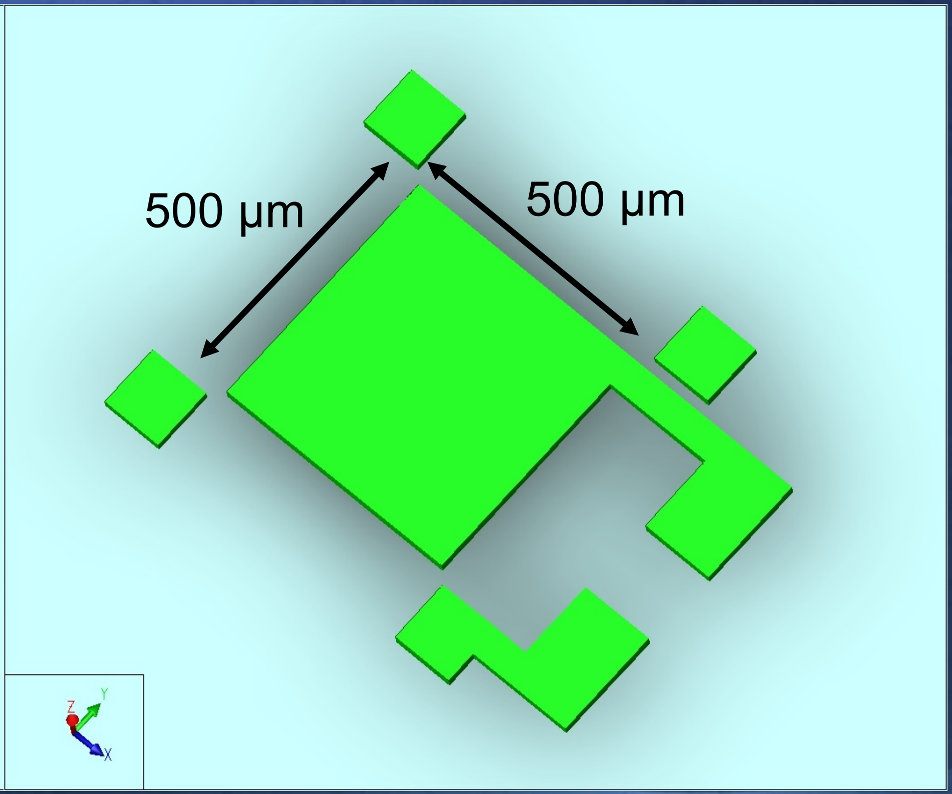
Accelerometer Design

Device 2

WHOLE STRUCTURE



BOTTOM ELECTRODES



Accelerometer Design

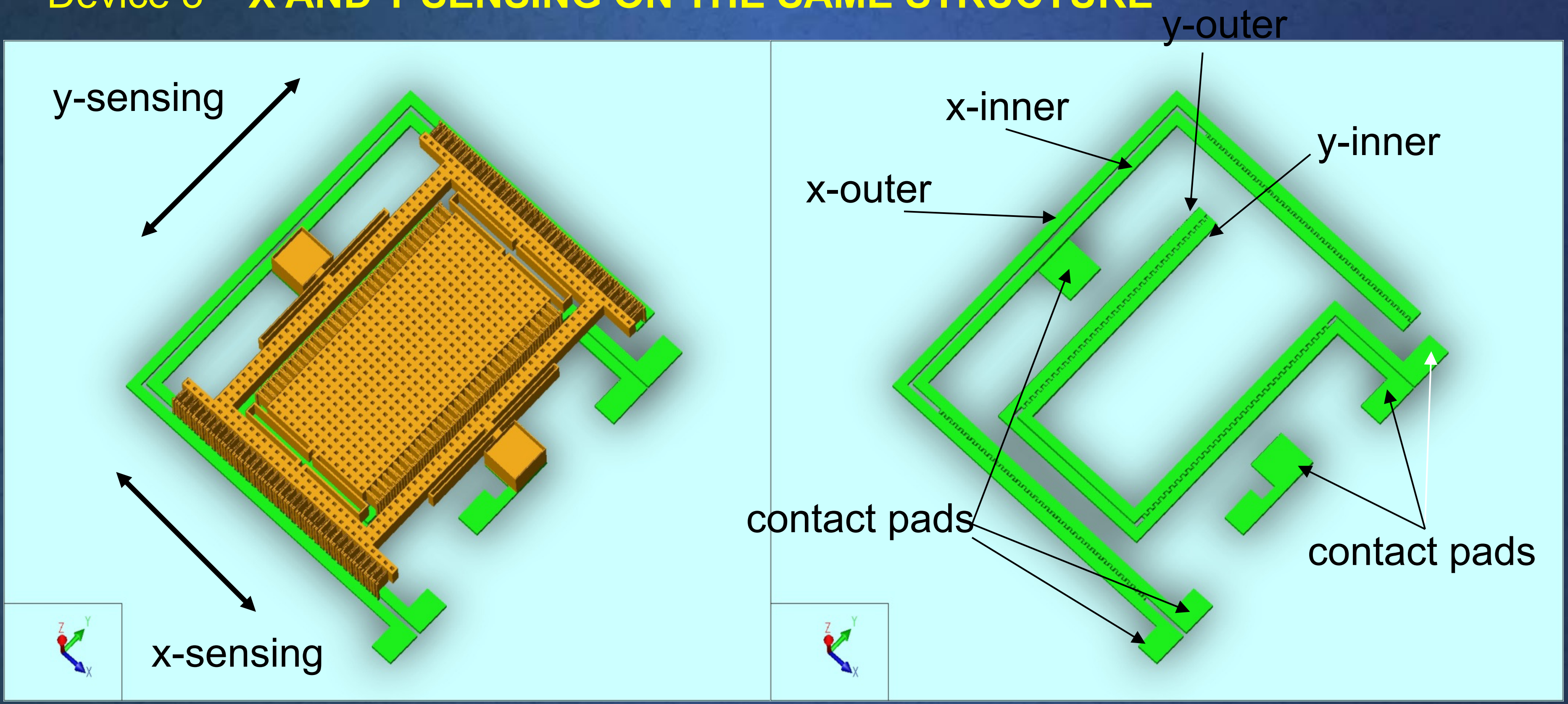
		Z-AXIS
Spring Constant (N/m)		10.118 (7.488)*
Damping Ratio	-40 ºF	0.553
	60 ºF	0.661
	160 ºF	0.756
Frequency (kHz)		32.188
Rest capacitance (pF)		1.125
ΔC (fF/g)		6.648
Mass (kg)		$9.766 \; 10^{-9}$

* Calculated from displacement

Device 2 Results

Accelerometer Design

Device 3 X AND Y SENSING ON THE SAME STRUCTURE



Dimensions: 1605 μm x 1281 μm for x-axis and 1550 μm x 910 μm for y-axis (INCLUDING COMB LENGTHS)

Number of movable combs: 72 for x-axis and 68 for y-axis

Effective comb length: 71 μm for x-axis and 75 μm for y-axis

Accelerometer Design

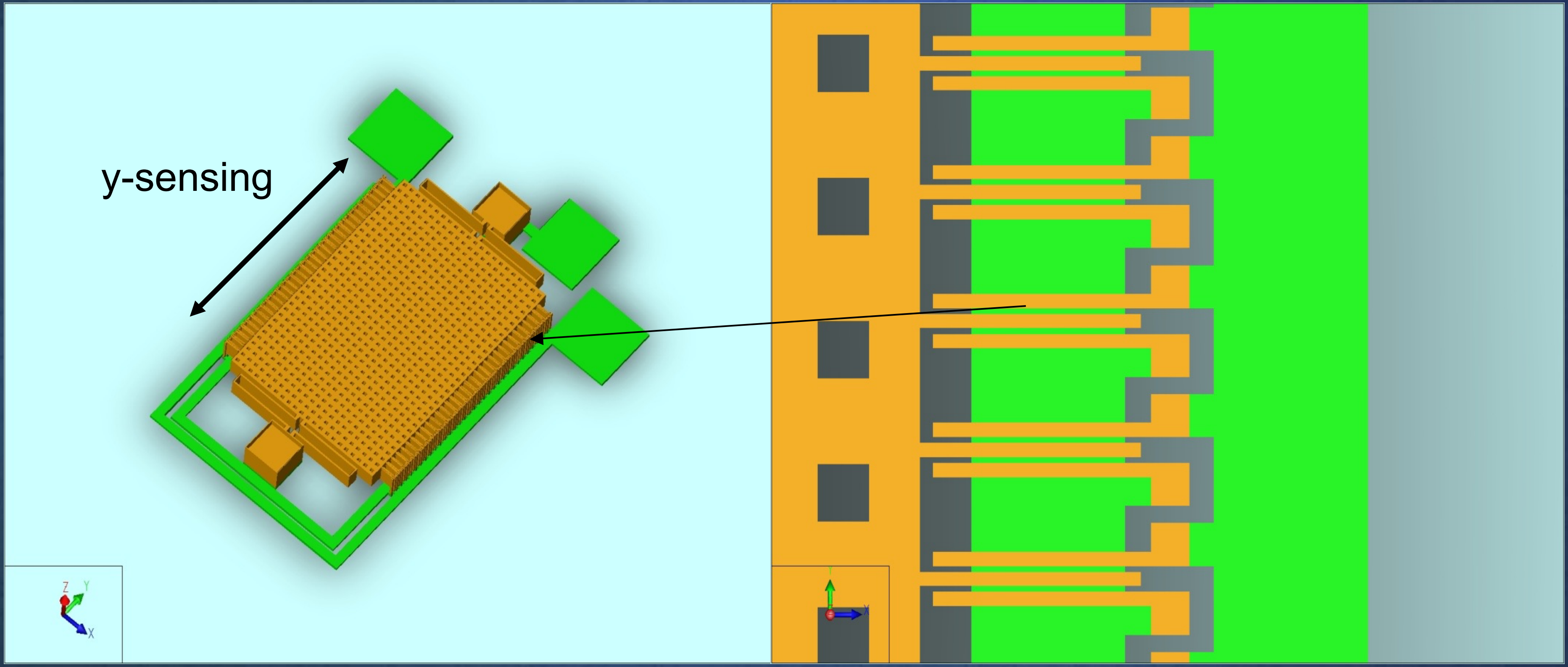
		X AXIS	Y AXIS
Spring Constant (N/m)		12.351*	24.794*
Damping Ratio	-40 ºF	0.553	0.545
	60 ºF	0.661	0.651
	160 ºF	0.756	0.745
Frequency (kHz)		13.086	23.549
Rest capacitance (pF)	inner	0.332	0.532
	outer	0.199	0.732
ΔC (fF/g)	inner	3.808	0.975
	outer	3.635	1.160
Mass (kg)		$7.213\ 10^{-8}$	$4.471\ 10^{-8}$

Device 3 Results

* Calculated from displacement

Accelerometer Design

Device 4 **SAME TWO STRUCTURES ORTHAGONAL WITH RESPECT TO EACH OTHER TO SENSE BOTH X AND Y AXIS**



Dimensions: 1605 µm x 1281 µm (INCLUDING COMB LENGTHS)
Number of movable combs: 66
Effective comb length: 81 µm

Accelerometer Design

		X AND Y-AXIS
Spring Constant (N/m)		24.063 (24.223)*
Damping Ratio	-40 ºF	0.548
	60 ºF	0.655
	160 ºF	0.749
Frequency (kHz)		18.799
Rest capacitance (pF)	inner	0.386
	outer	0.230
ΔC (fF/g)	inner	2.05
	outer	2.045
Mass (kg)		$6.809\ 10^{-8}$

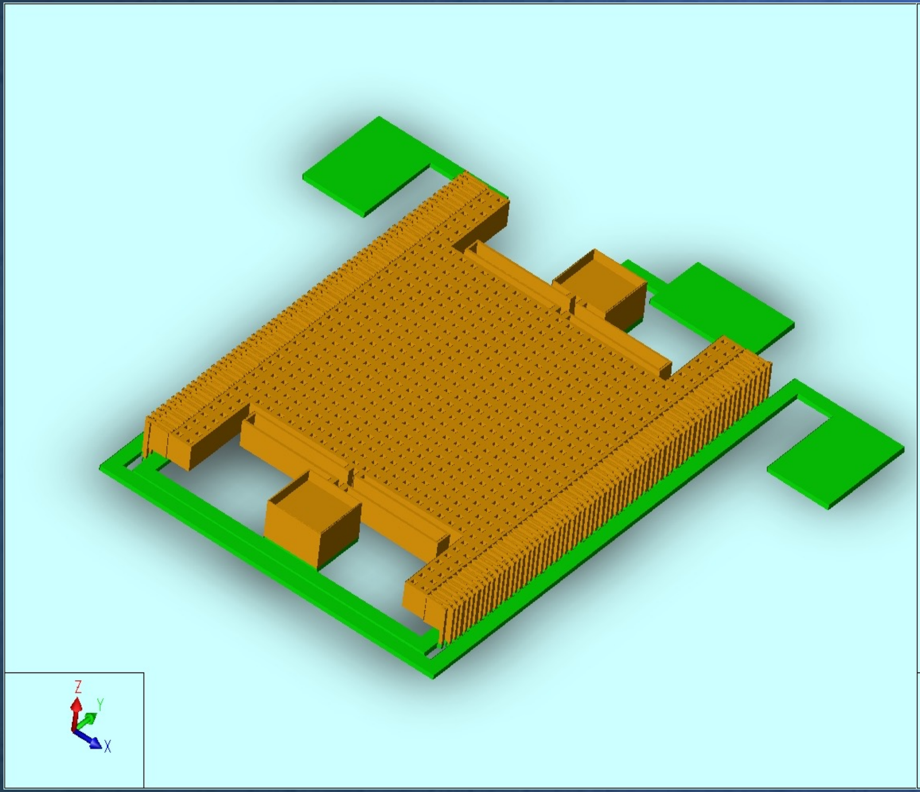
Device 4 Results

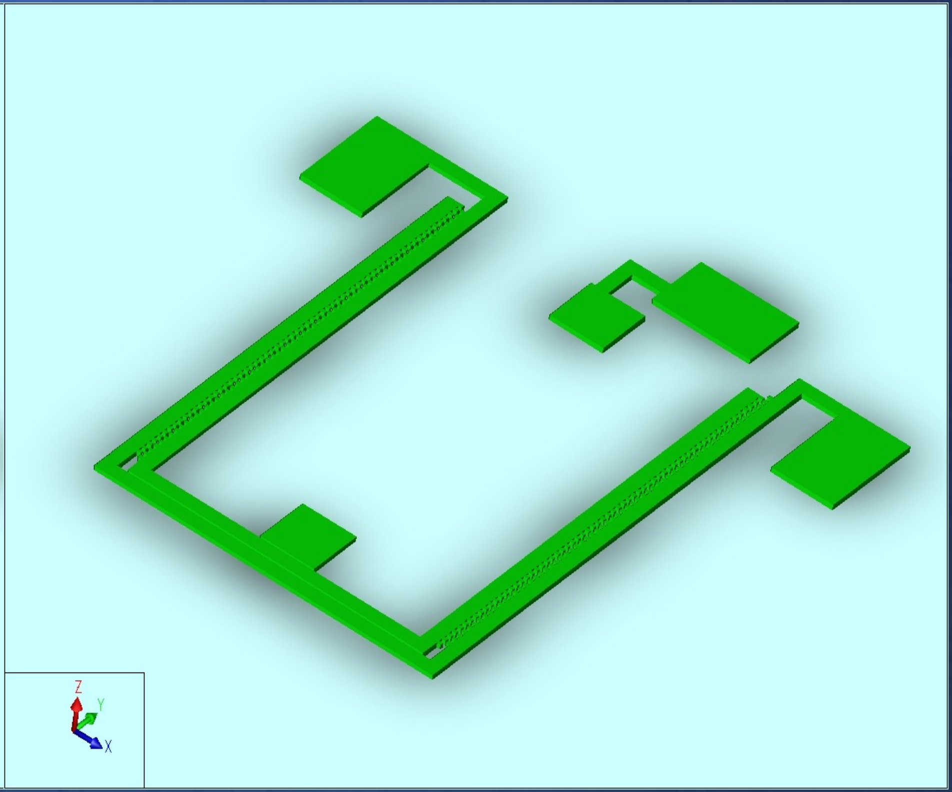
* Calculated from displacement

Accelerometer Design

Device 5

SAME TWO STRUCTURES ORTHAGONAL WITH RESPECT TO EACH OTHER TO SENSE BOTH X AND Y AXIS





Dimensions: 1900 µm x 1338 µm (INCLUDING COMB LENGTHS)
Number of movable combs: 128
Effective comb length: 64 µm

Accelerometer Design

		X AND Y-AXIS
Spring Constant (N/m)		24.063 (24.230)*
Damping Ratio	-40 ºF	0.559
	60 ºF	0.668
	160 ºF	0.764
Frequency (kHz)		19.846
Rest capacitance (pF)	inner	0.5573
	outer	0.3184
ΔC (fF/g)	inner	2.7
	outer	2.6
Mass (kg)		$6.109\ 10^{-8}$

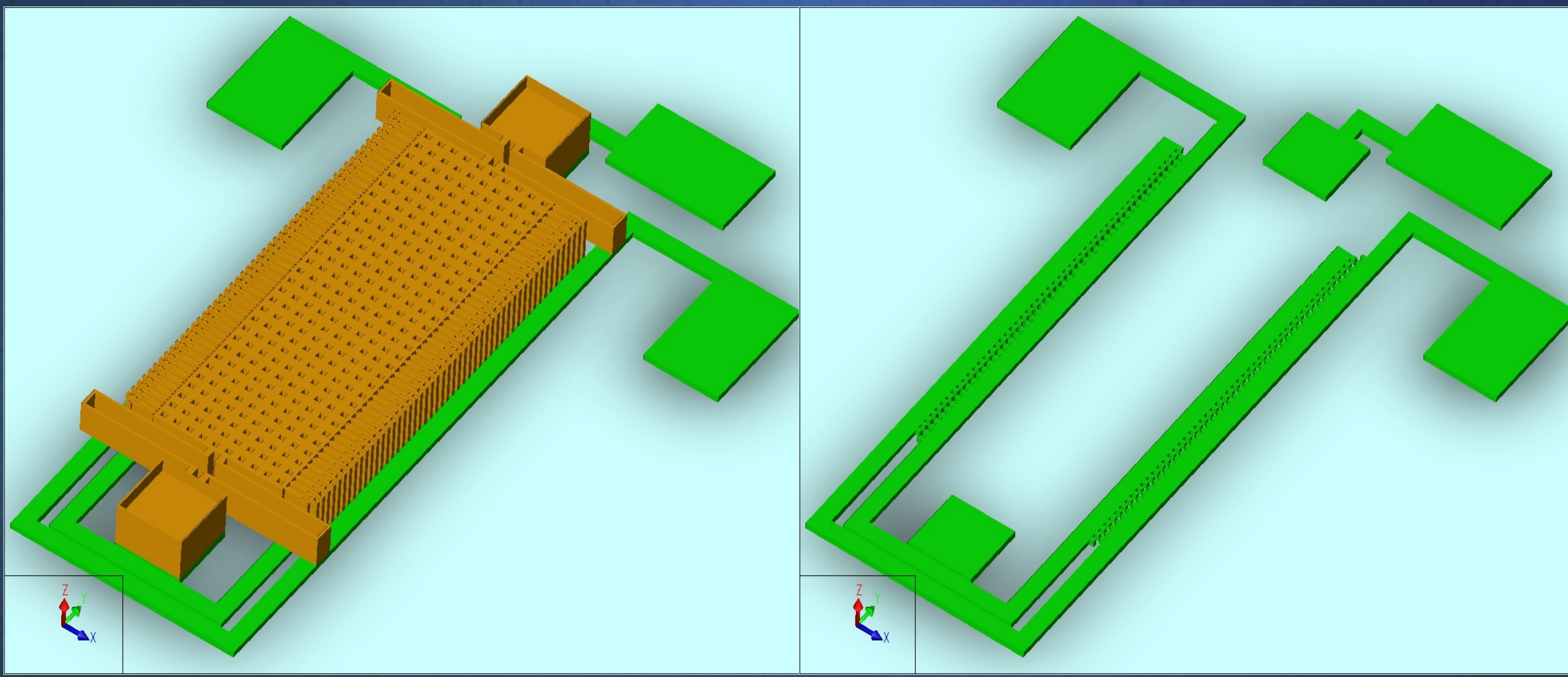
Device 5 Results

* Calculated from displacement

Accelerometer Design

Device 6

SAME TWO STRUCTURES ORTHAGONAL WITH RESPECT TO EACH OTHER TO SENSE BOTH X AND Y AXIS



Dimensions: 1500 µm x 632 µm (INCLUDING COMB LENGTHS)
Number of movable combs: 100
Effective comb length: 61 µm

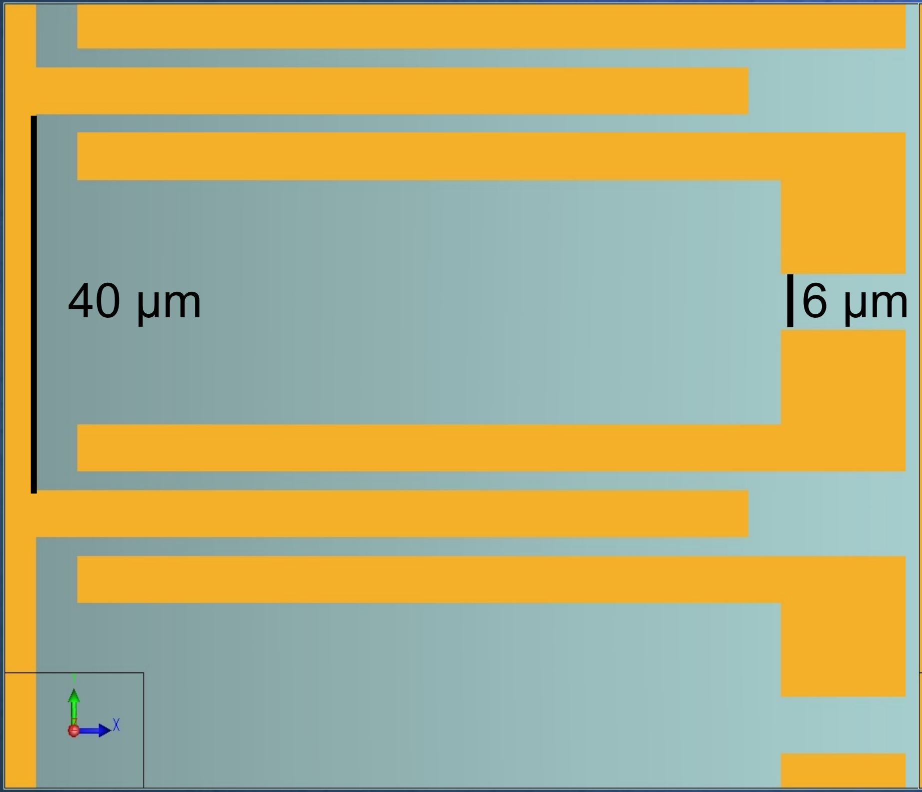
Accelerometer Design

		X AND Y-AXIS
Spring Constant (N/m)		24.063 (23.723)*
Damping Ratio	-40 ºF	0.543
	60 ºF	0.649
	160 ºF	0.742
Frequency (kHz)		28.541
Rest capacitance (pF)	inner	0.447
	outer	0.276
ΔC (fF/g)	inner	1.016
	outer	1.011
Mass (kg)		2.954 10^{-8}

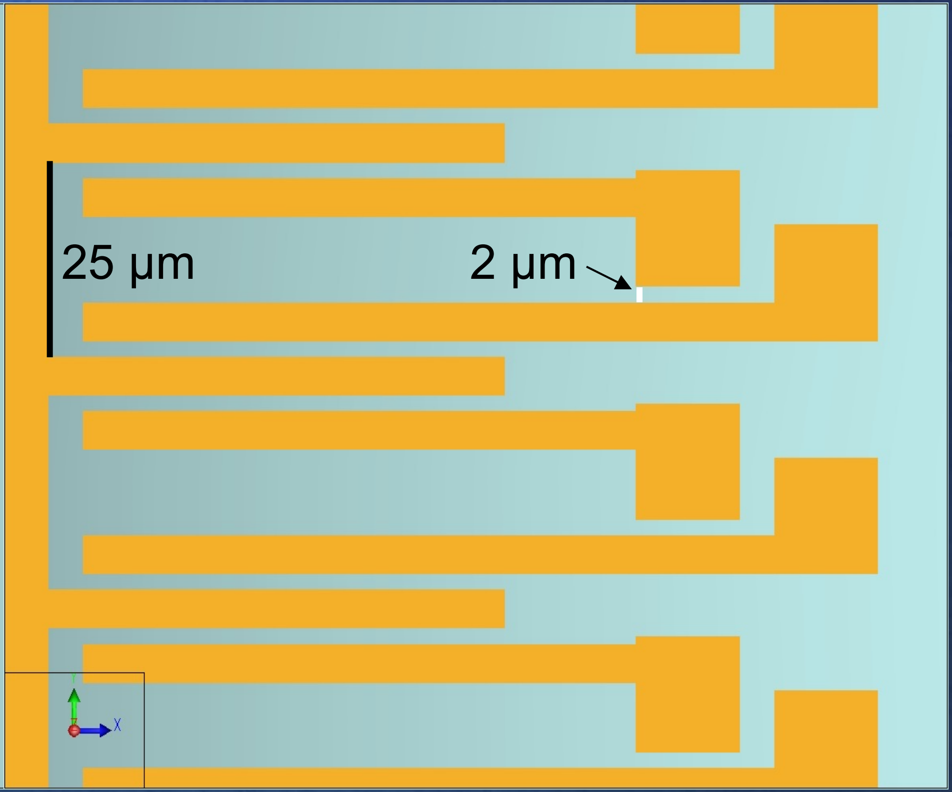
Device 6 Results

* Calculated from displacement

Accelerometer Design



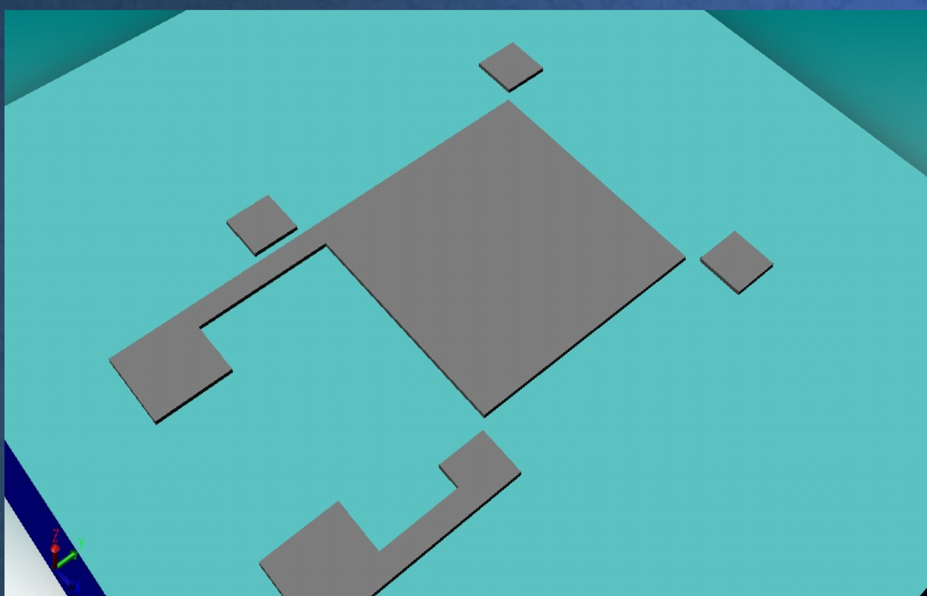
Devices 3 and 4

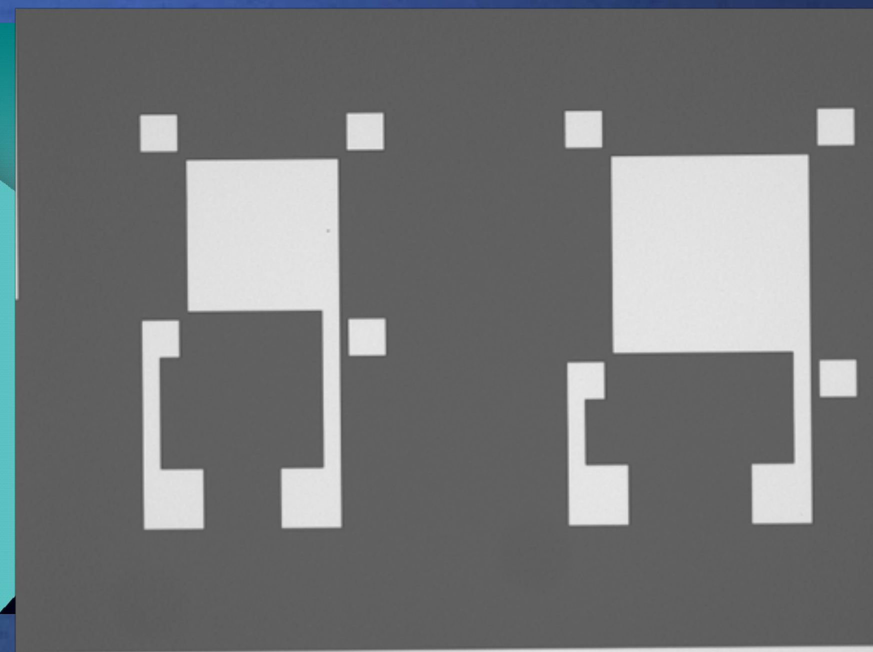


Devices 5 and 6

Accelerometer Fabrication

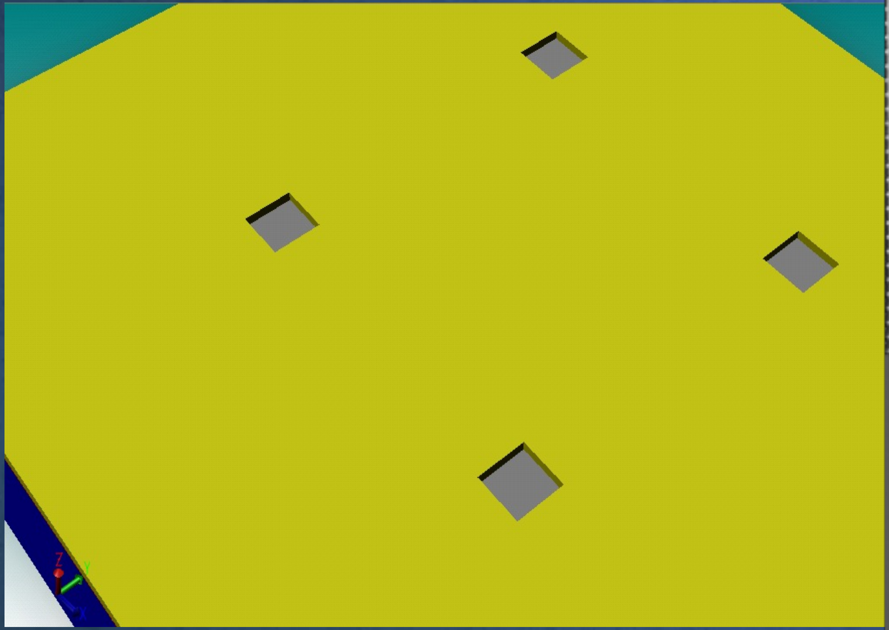
- Si/ Si_3N_4/ PI 5878G/ Si_3N_4/ Al.
- Metallization layer fabrication.

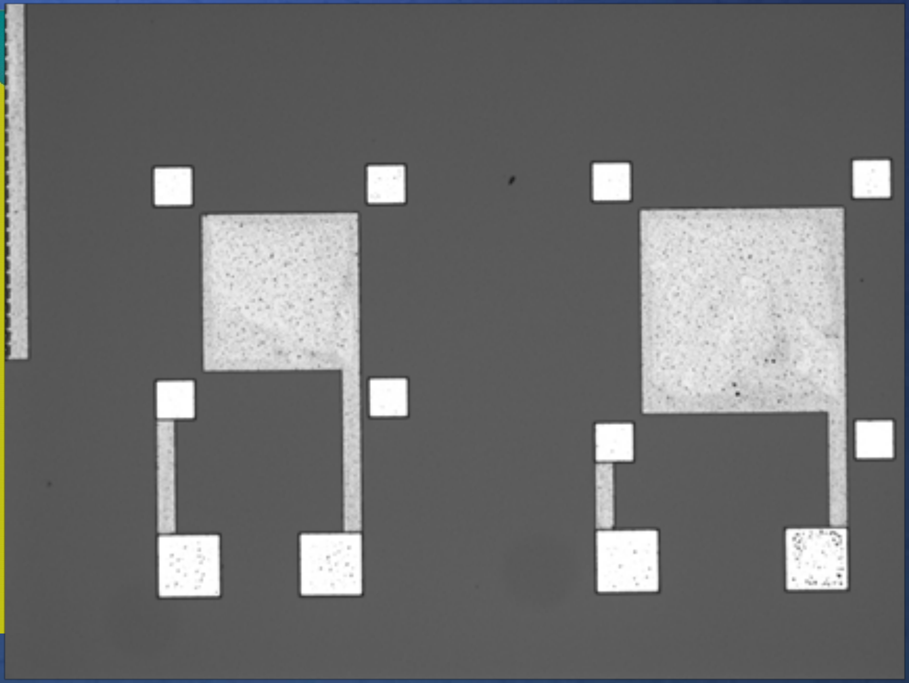




Accelerometer Fabrication

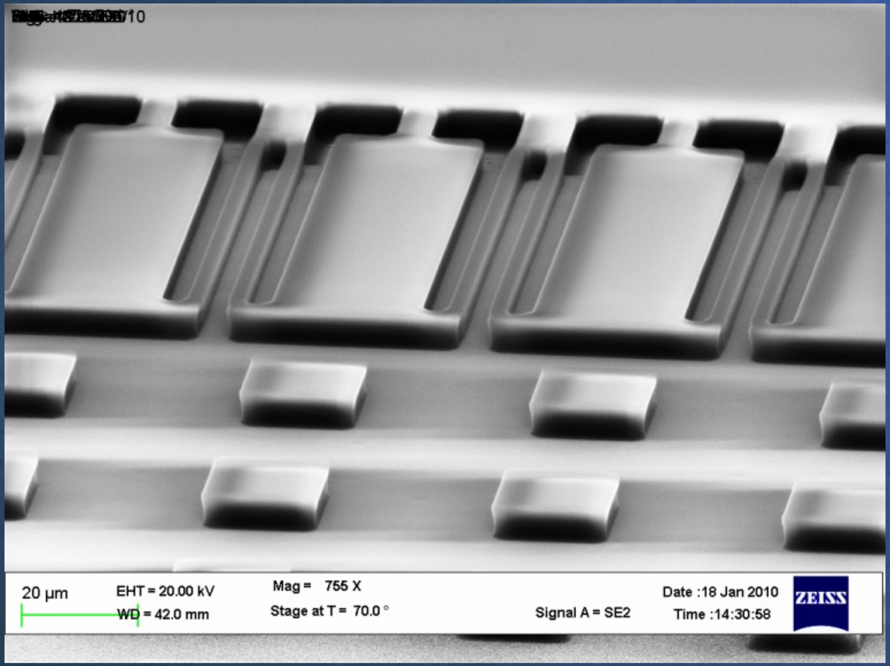
- Polyimide as sacrificial layer and patterning.
- Curing to obtain thickness of ~2.0 μm

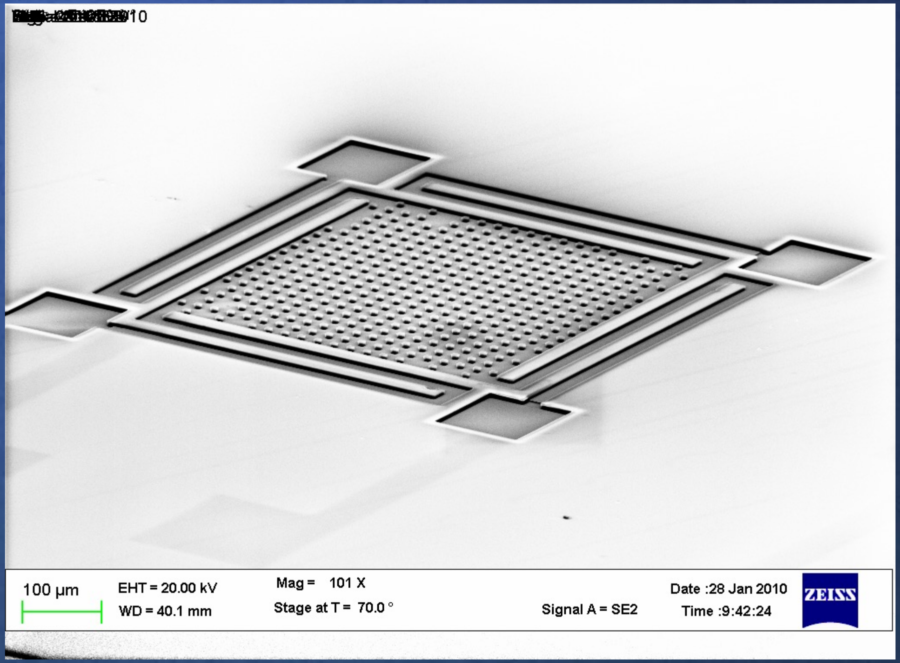




Accelerometer Fabrication

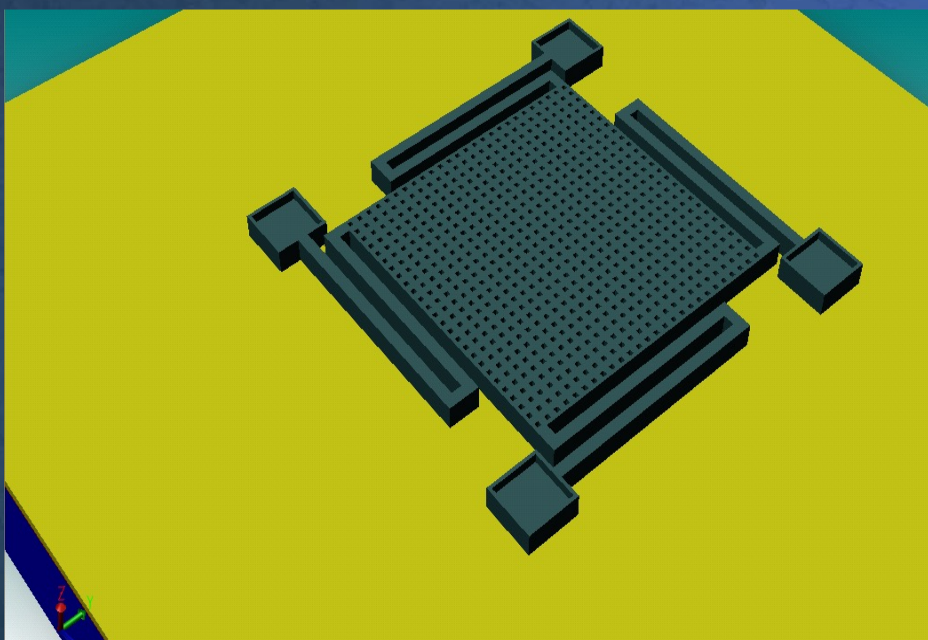
- Gold seed layer for electroplating (~0.1 µm).
- Mold photoresist (~6.0 µm)

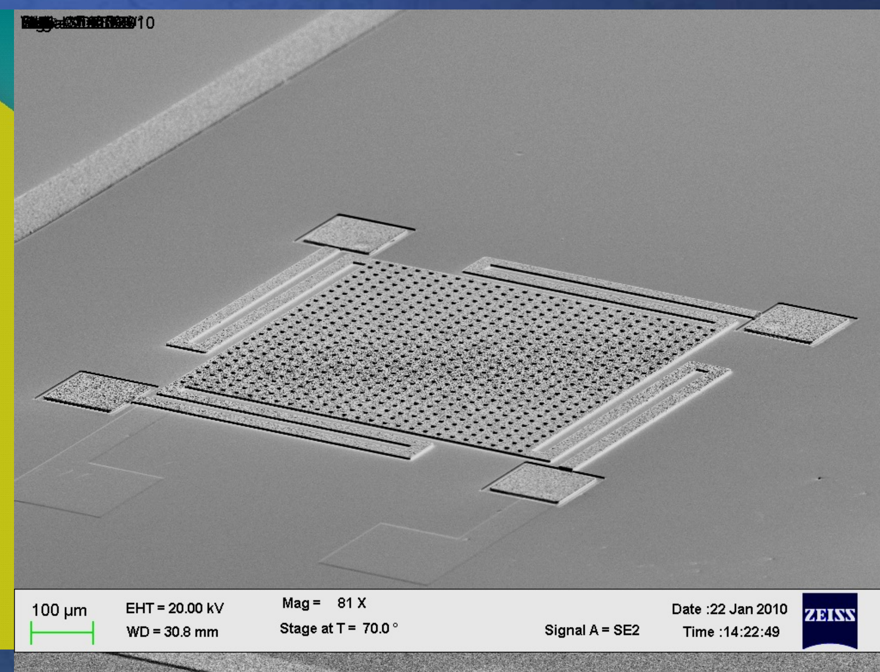




Accelerometer Fabrication

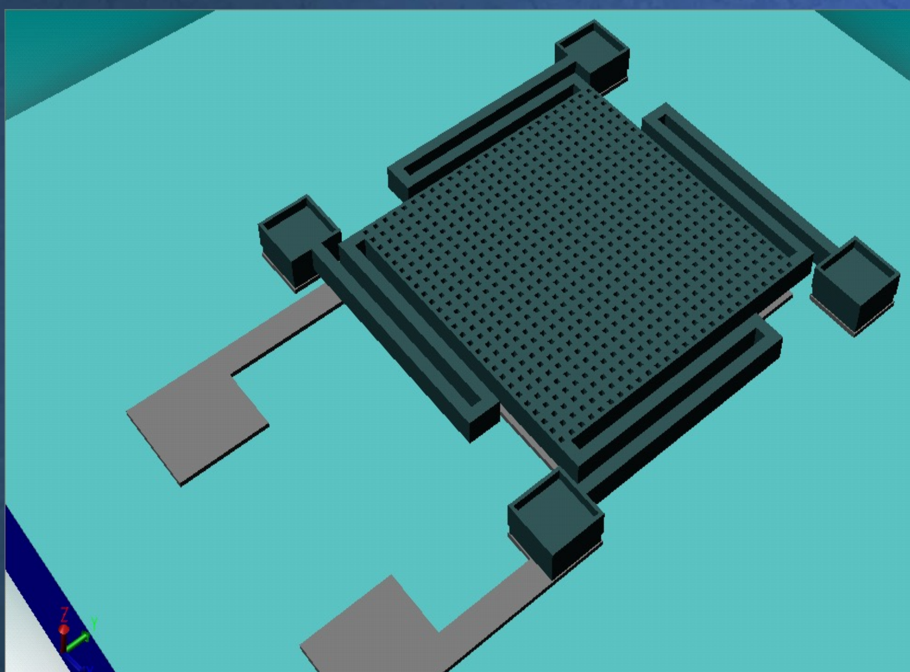
- UV-LIGA process to fabricate accelerometers.
- Ni electroplating to form the proof mass (~5.0 µm).
- Resist removal and etching off of the gold seed layer.

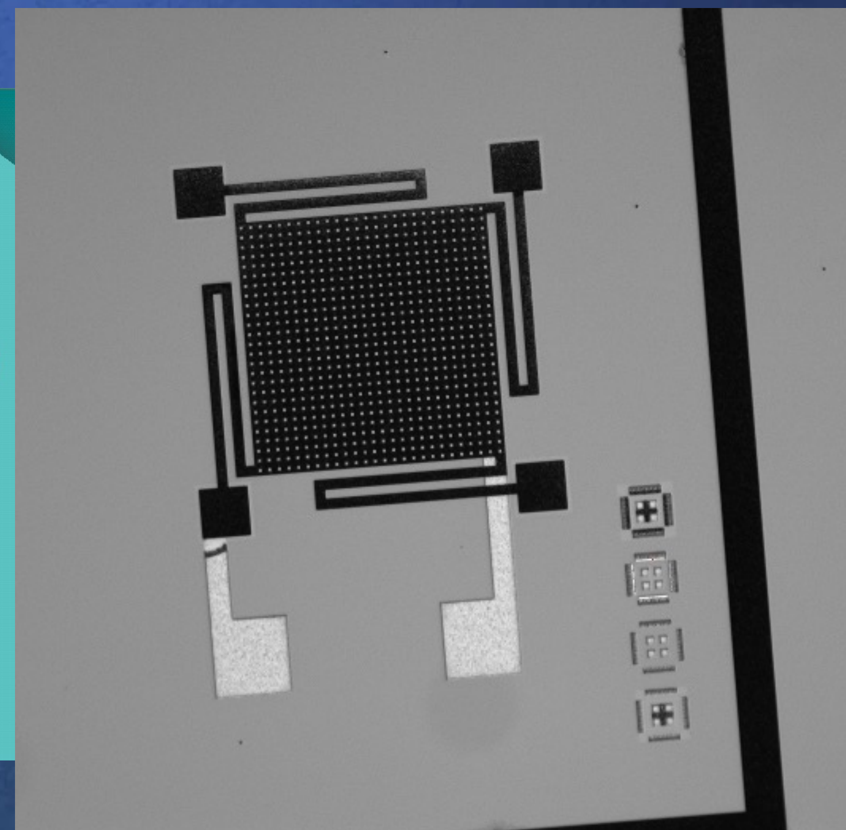




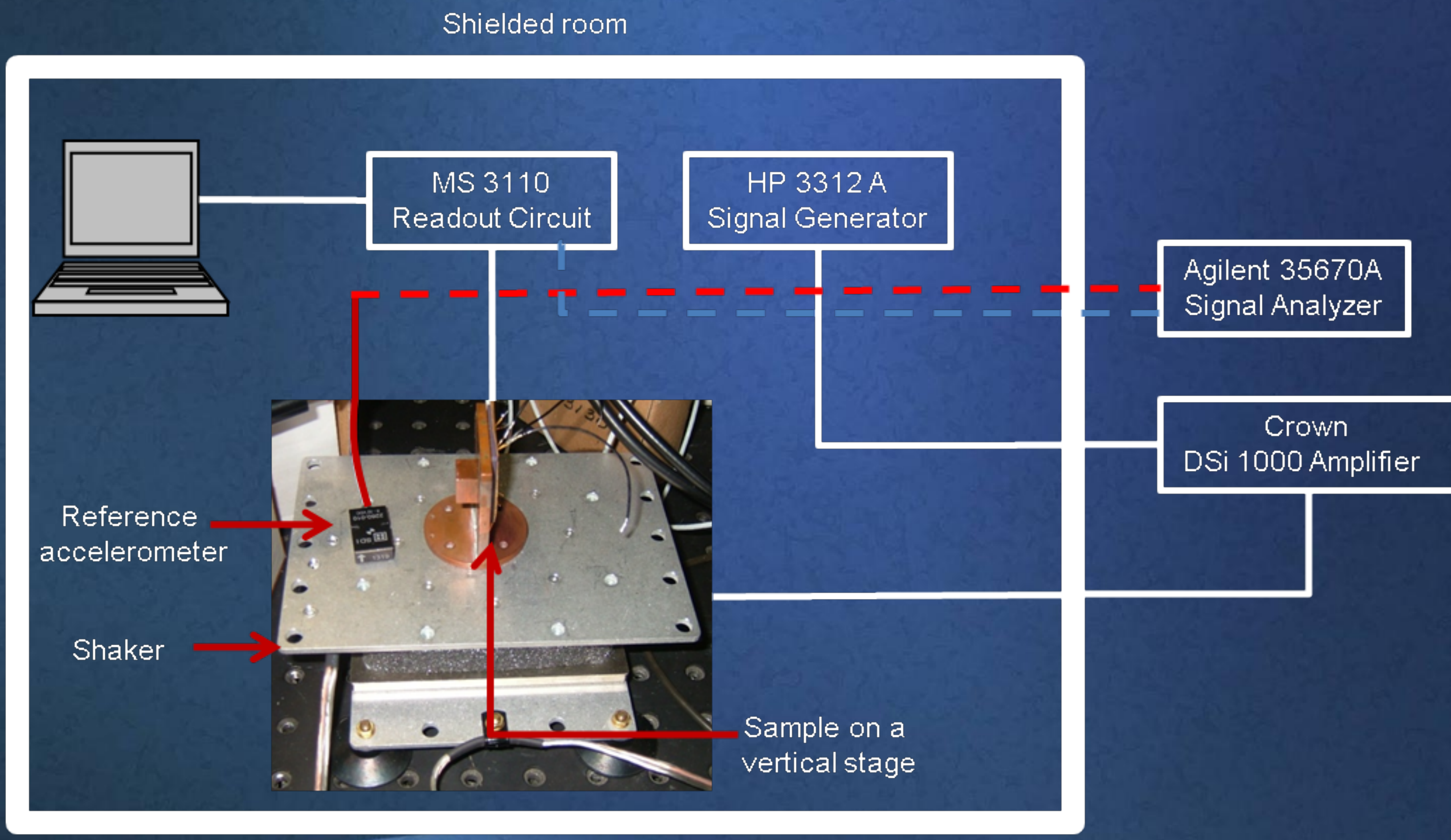
Accelerometer Fabrication

- Oxygen plasma ashing of the polyimide sacrificial layer to suspend the structure.





Setup for Characterization

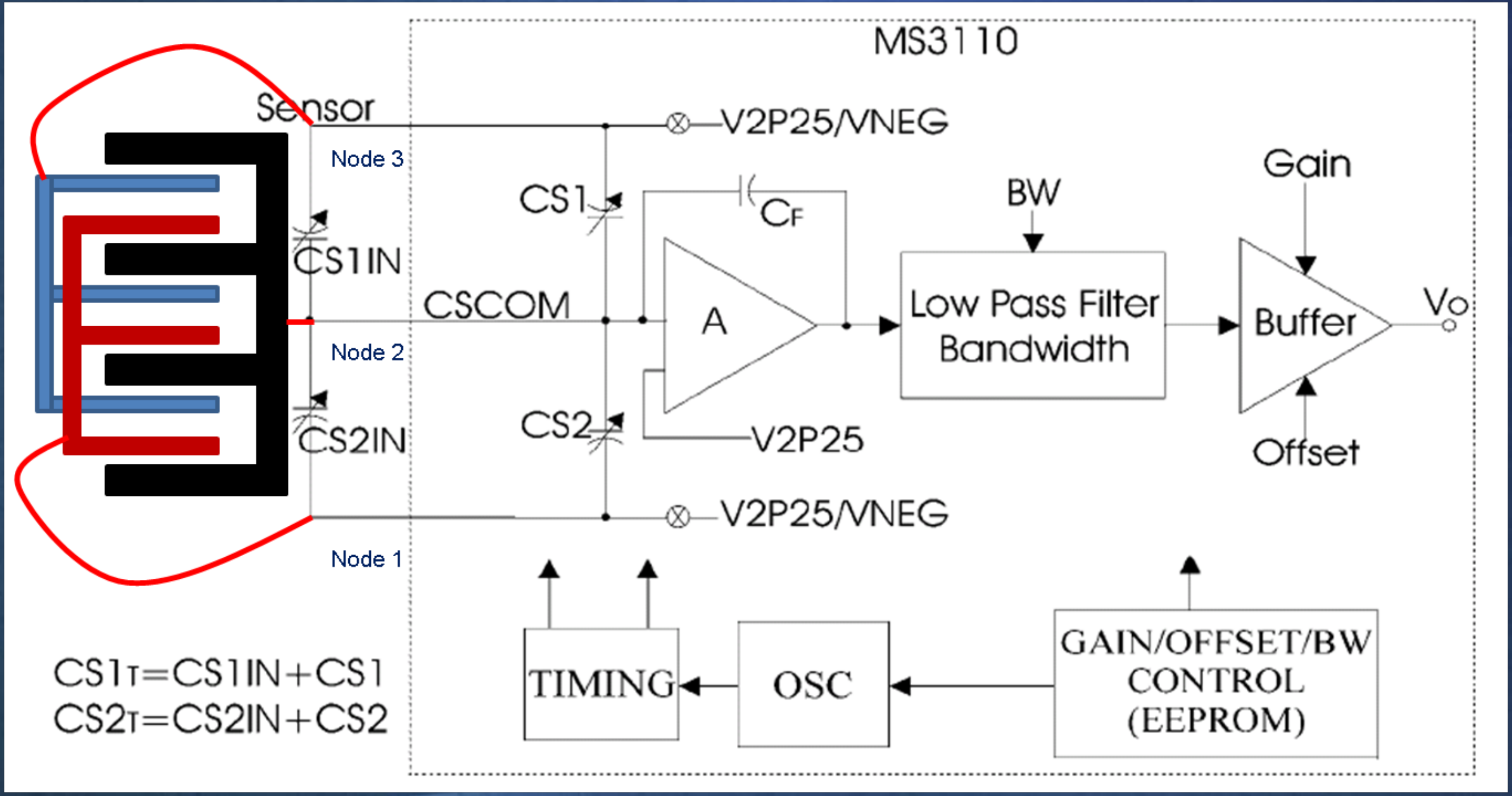


Setup for Characterization

CF (Trim capacitor)=5.130 pF
CS1 and CS2=Variable capacitors
Gain= 2 V/V
V_{ref} = 0.5 V

CS1IN and CS2IN: Device capacitances

$$V_{out} = 1.14 * V2P25 * Gain * \frac{CS2_T - CS1_T}{CF} + V_{ref}$$



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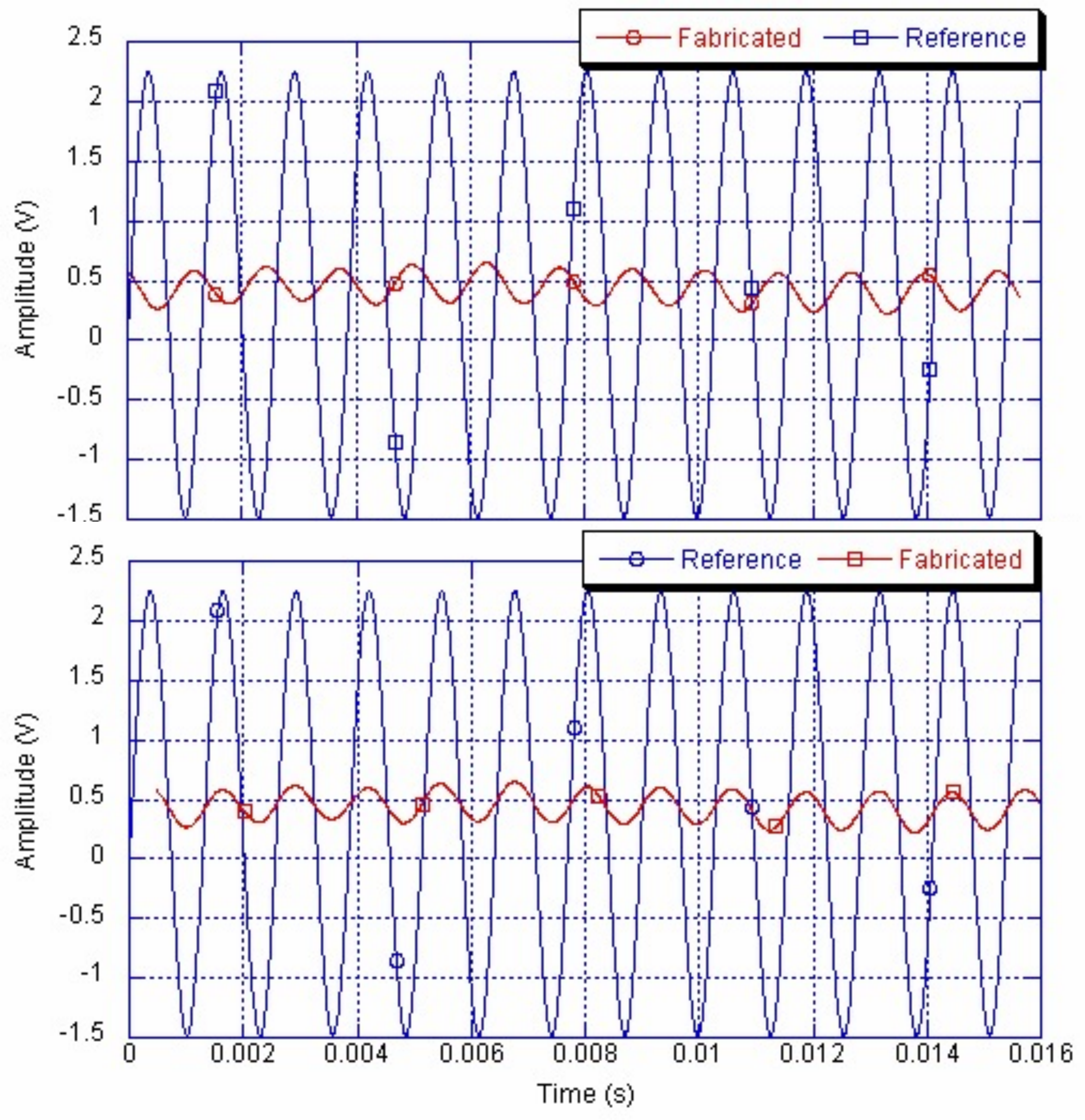
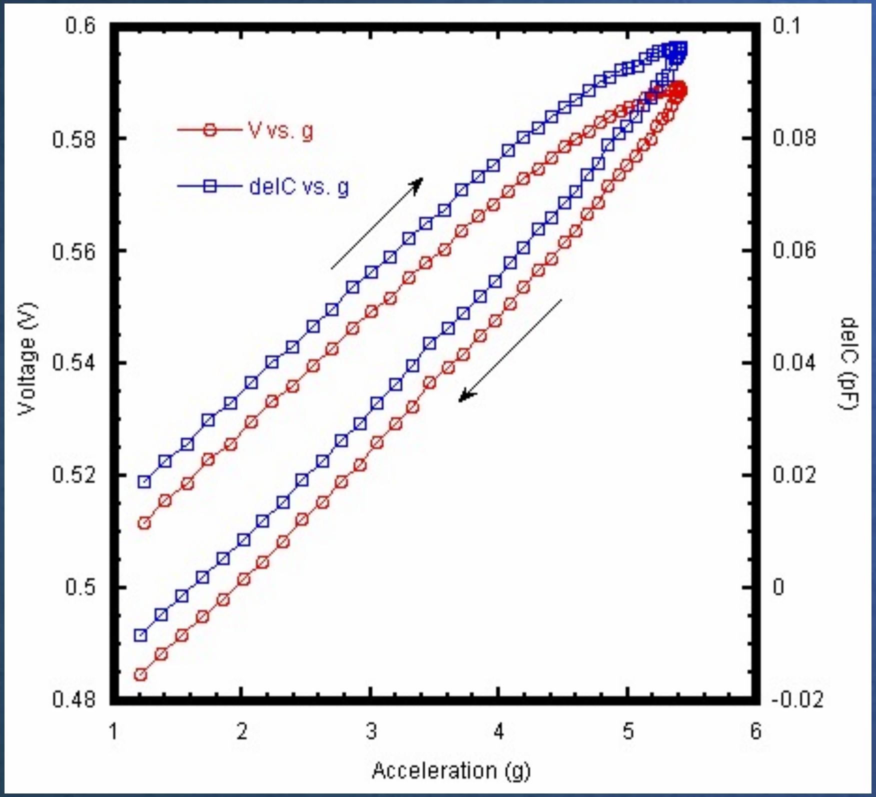
Measurement Results

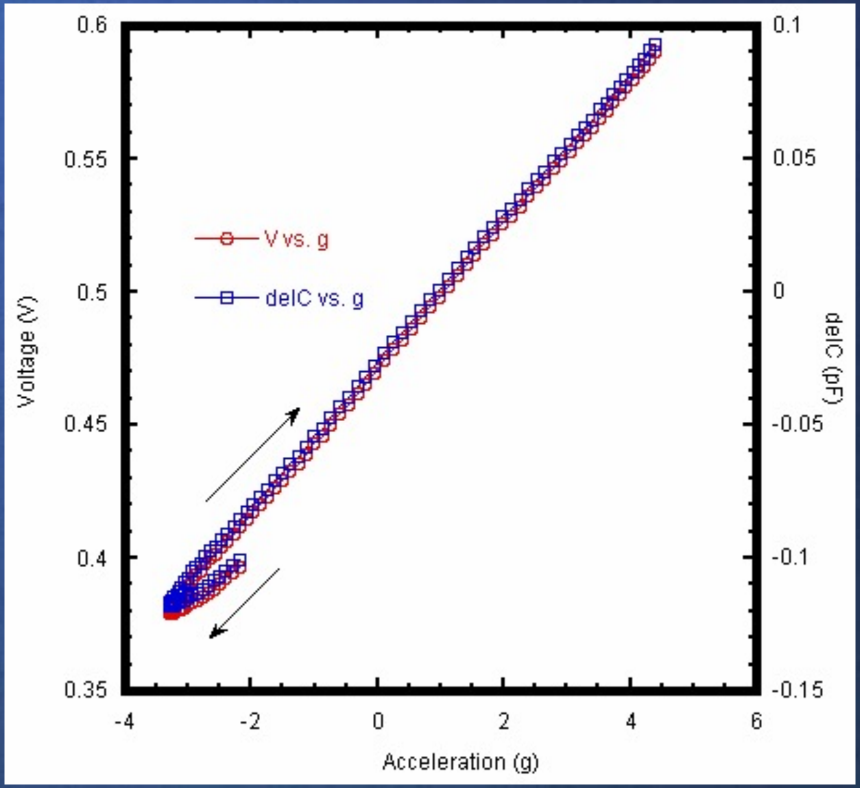


Measurement Results

- Voltage response and change in capacitance with respect to acceleration for z-axis accelerometers on Si and flexible substrate. Both samples are Device 2



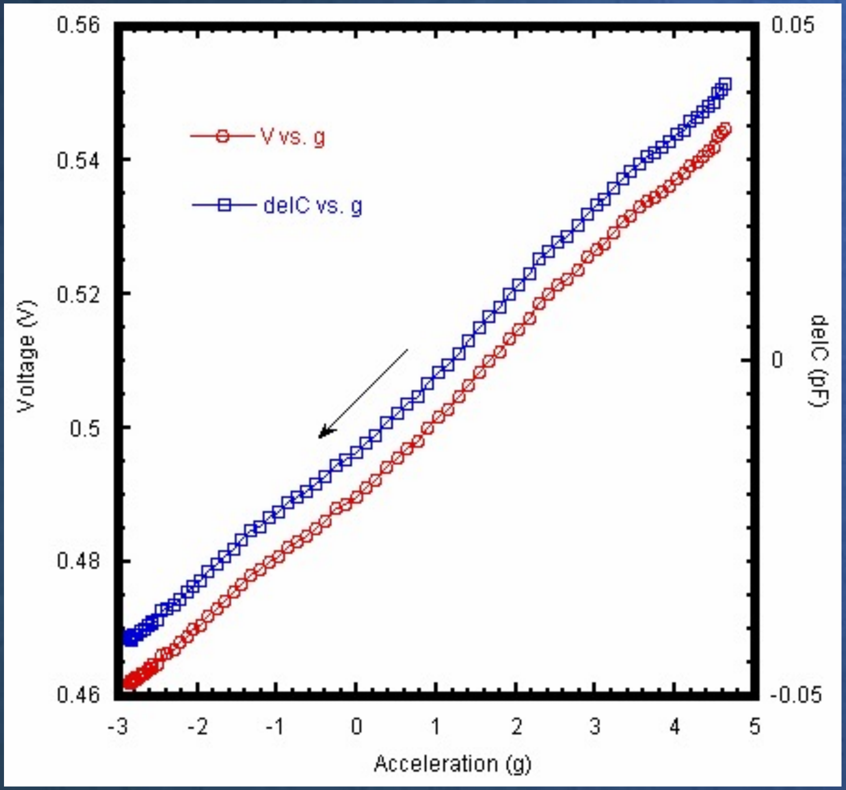
Si substrate, ΔC=21.9 fF/g



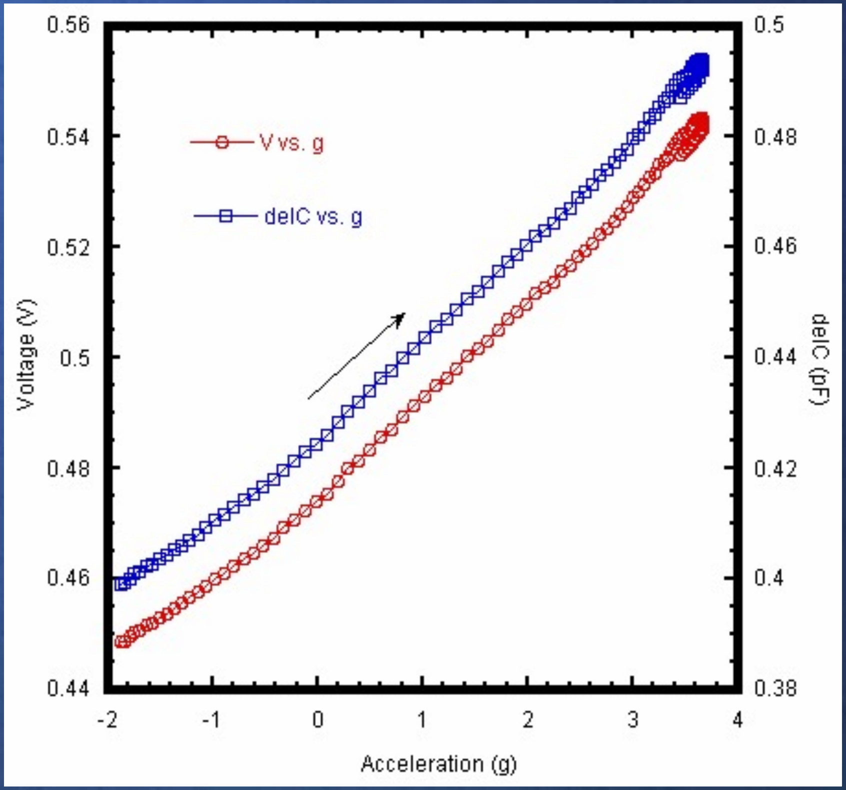
Flexible substrate, ΔC=27.7 fF/g

Measurement Results

- Voltage response and change in capacitance with respect to acceleration for z-axis accelerometers on Si and flexible substrate. Both samples are Device 4b



Si substrate, ΔC=11 fF/g



Flexible substrate, ΔC=17.5 fF/g