# MEMS Applications
# in
# Seismology

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**Seismic Instrumentation Technology Symposium**

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# Outline

- Overview of MEMS Technology
- MEMS Accelerometers
- Seismic Requirements
- Commercial Availability
- Noise & Detection Theory
- Current R & D Efforts
- Outlook

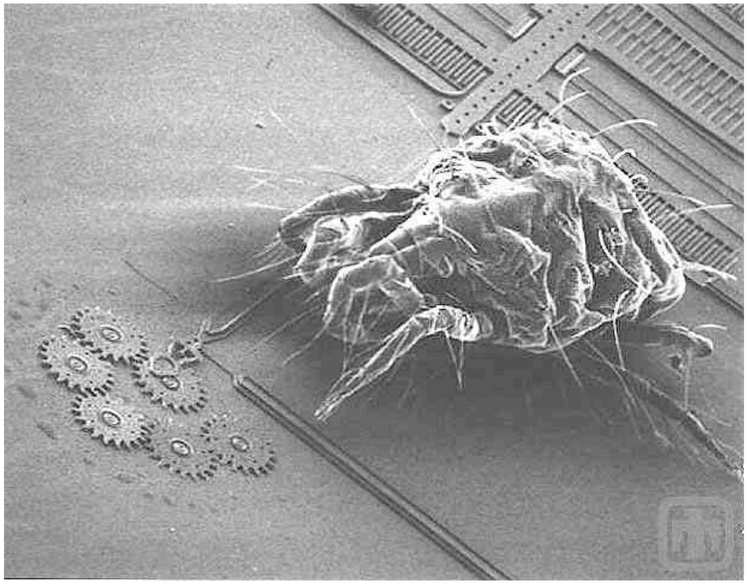
# What are MEMS?

Micro-Electro-Mechanical Systems (MEMS)

Features range from 1 to 100 microns.

Similar fabrication techniques as Integrated Circuits (IC). However, MEMS fabrication is a trickier process due to the incorporation of mechanical features

Distinguished from traditional mechanical systems more by their materials and methods of fabrication than by feature size.



Courtesy of Sandia National Laboratories,
SUMMiTTM Technologies, www.mems.sandia.gov

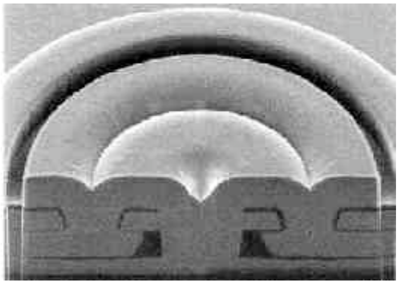
# What are MEMS?

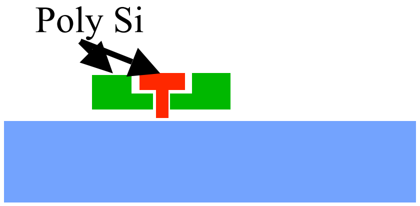
| Materials | Fabrication | Applications |
|---|---|---|
| **Silicon**<br>Single-crystal silicon makes a nearly perfect spring with very stable material properties.<br>**Polymers**<br>**Metals**<br>gold, nickel, chromium, titanium, tungsten, platinum, silver. | **Deposition**<br>Electroplating<br>Evaporation<br>Sputtering<br>**Lithography**<br>Photo, Electronic, Ion, X-ray<br>**Etching**<br>Wet Etching: Bathed in a chemical solvent<br>Dry Etching: Vapor/Plasma | Automotive air bags<br>Inkjet printers<br>DLP projectors<br>Consumer Electronics (Cell phone, Game Controllers, etc)<br>Sensors (pressure, motion, RF, magnetic, etc) |

# Three Dominant MEMS Microfabrication Technologies

## Surface Micromachining

Structures formed by deposition and etching of sacrificial and structural thin films



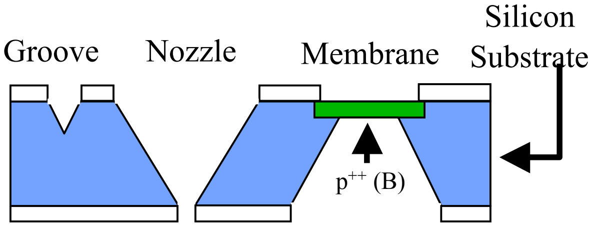


Silicon Substrate

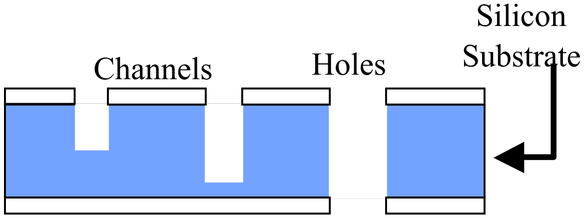
Courtesy of SNL MEMS Technology short course

## Bulk Micromachining

Structures formed by wet and/or dry etching of silicon substrate



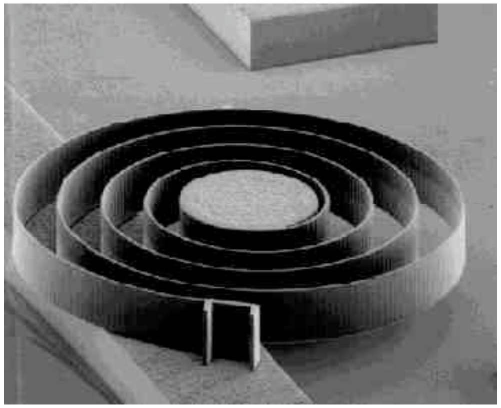
Wet Etch Patterns

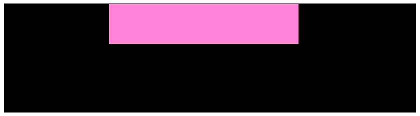


Dry Etch Patterns

## LIGA

Structures formed by mold fabrication, followed by injection molding

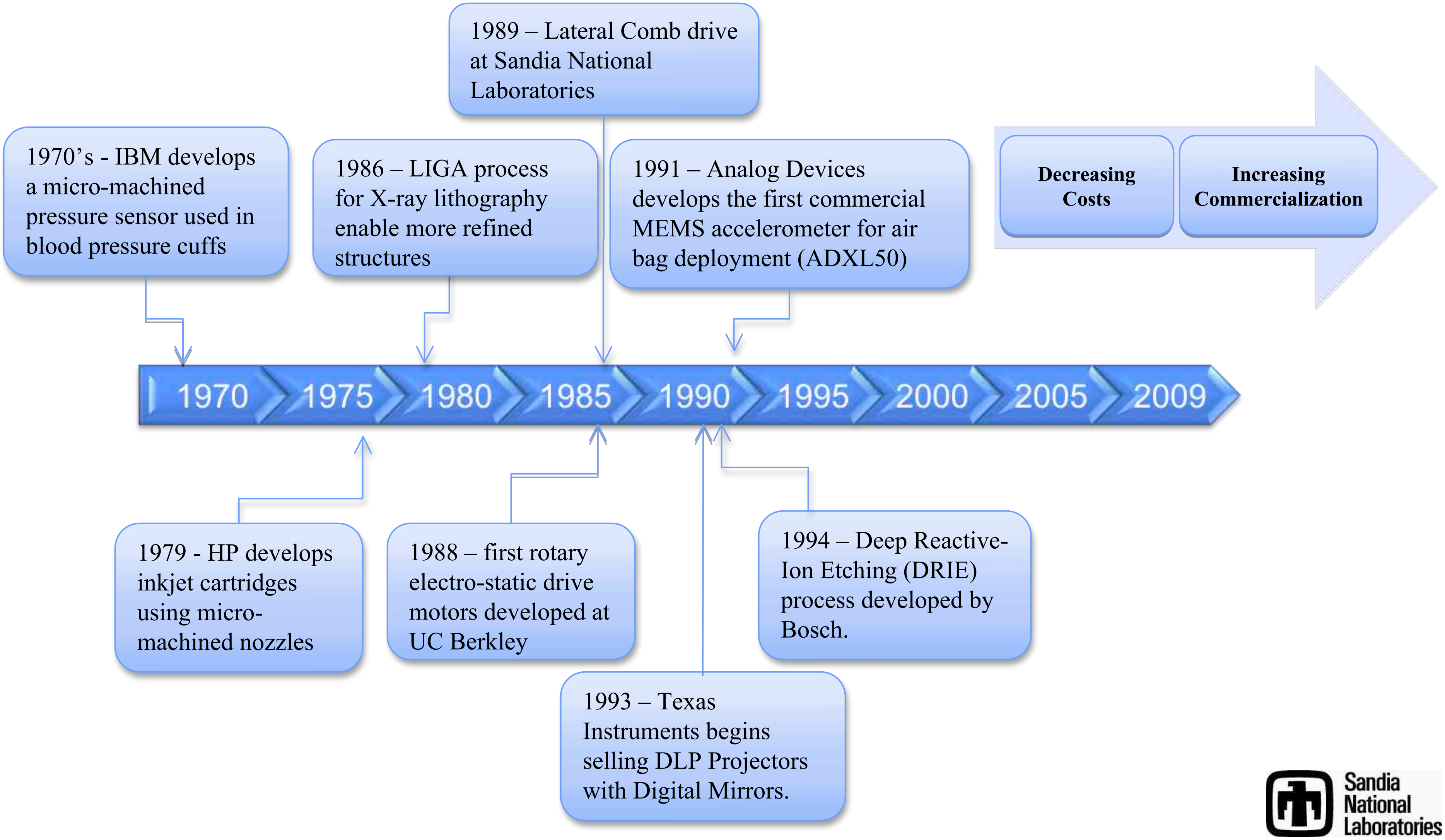




Metal Mold

Sandia National Laboratories

# MEMS History



1970’s - IBM develops a micro-machined pressure sensor used in blood pressure cuffs

1986 – LIGA process for X-ray lithography enable more refined structures

1989 – Lateral Comb drive at Sandia National Laboratories

1991 – Analog Devices develops the first commercial MEMS accelerometer for air bag deployment (ADXL50)

**Decreasing Costs**

**Increasing Commercialization**

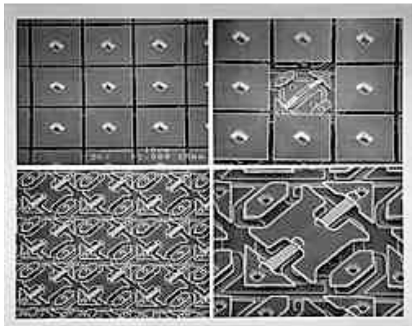
1979 - HP develops inkjet cartridges using micro-machined nozzles

1988 – first rotary electro-static drive motors developed at UC Berkley

1993 – Texas Instruments begins selling DLP Projectors with Digital Mirrors.

1994 – Deep Reactive-Ion Etching (DRIE) process developed by Bosch.

# MEMS Commercial Applications

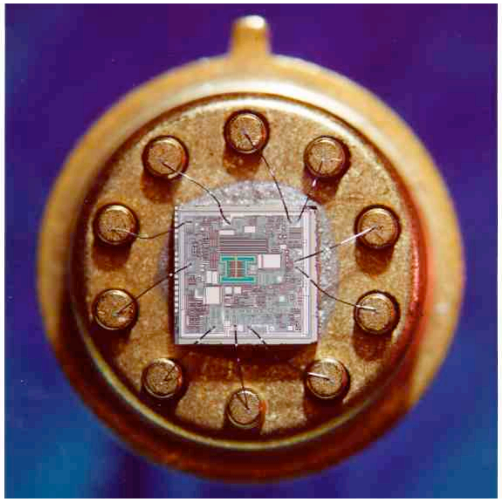


Digital Mirror Device

Texas Instruments

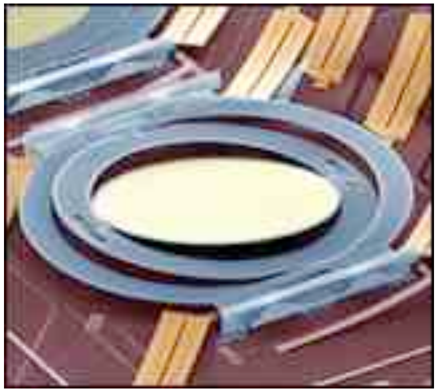
Ink Jet Cartridge

Hewlett Packard



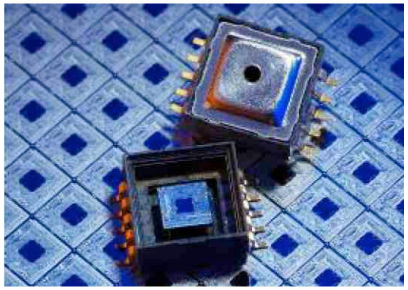
Accelerometer

Analog Devices



Micromirror switch

Lucent Technologies

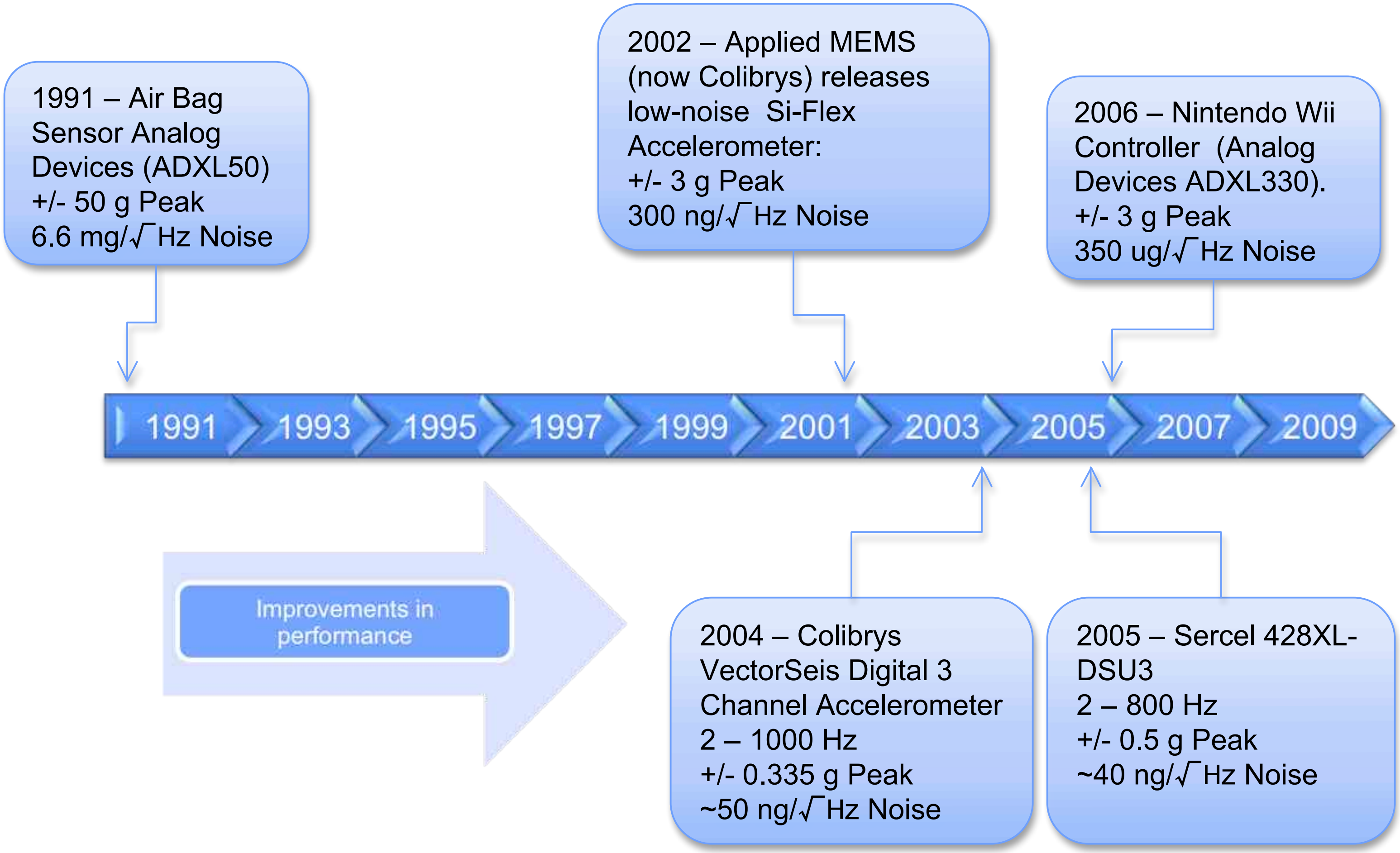


Pressure Sensor

Bosch MEMS

Courtesy of SNL MEMS Technology short course

# MEMS Accelerometer History



1991 – Air Bag Sensor Analog Devices (ADXL50)
+/- 50 g Peak
6.6 mg/$\sqrt{\text{Hz}}$ Noise

2002 – Applied MEMS (now Colibrys) releases low-noise Si-Flex Accelerometer:
+/- 3 g Peak
300 ng/$\sqrt{\text{Hz}}$ Noise

2006 – Nintendo Wii Controller (Analog Devices ADXL330).
+/- 3 g Peak
350 ug/$\sqrt{\text{Hz}}$ Noise

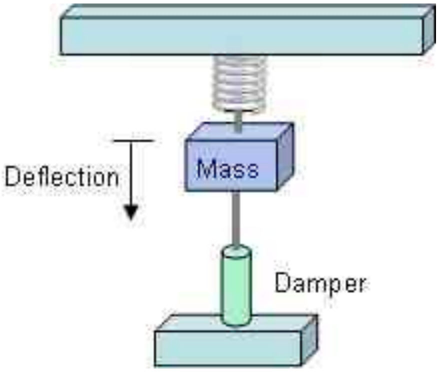
2004 – Colibrys VectorSeis Digital 3 Channel Accelerometer
2 – 1000 Hz
+/- 0.335 g Peak
~50 ng/$\sqrt{\text{Hz}}$ Noise

2005 – Sercel 428XL-DSU3
2 – 800 Hz
+/- 0.5 g Peak
~40 ng/$\sqrt{\text{Hz}}$ Noise

# What makes a MEMS Seismometer

**A MEMS Accelerometer with:**

- **Low noise floor (ng's/√Hz)**
- **~1 g upper range**
- **High sensitivity**



**Modeled as a spring-mass system**

**Proof mass measured in milli-grams**

**Bandwidth below the springs resonant mode (noise and response flat to acceleration)**

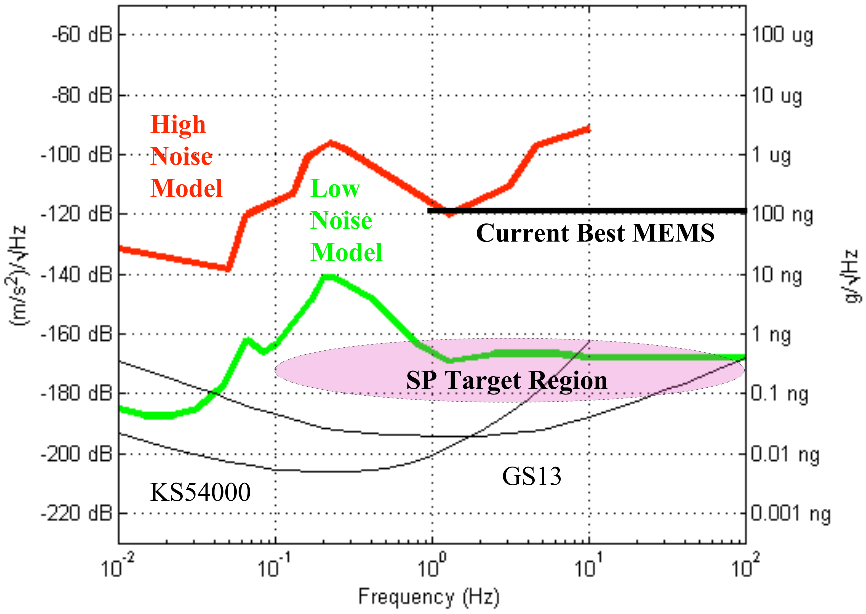
# Seismology Requirements

- **Noise floor**

  (relative to the LNM)
- **Peak acceleration**

  (Strong vs weak motion)
- **Sensitivity**
- **Linear dynamic range**
- **Bandwidth**

  (short-period, long-period, broadband)



**Requirements are ultimately application dependent**

# Strong Motion Requirements

**Many of the strong motion requirements may be met by today's MEMS Acclerometers:**

| | |
|---|---|
| **Noise** | **< 1 ug/$\sqrt{\text{Hz}}$** |
| Bandwidth | > 1-2 Hz |
| Peak Acceleration | 1-2 g's |
| Dynamic Range | ~100 dB |

# Weak Motion Requirements

**Weak motion requirements are more demanding:**

| **Noise** | **< 1 ng/√Hz** |
|---|---|
| Bandwidth | SP: 0.1 Hz to 10’s Hz<br>LP: < 0.01 Hz to 1’s Hz<br>BB: 0.01 Hz to 10’s Hz |
| Peak Acceleration | < 0.25 g |
| Dynamic Range | >120 dB |

**There are no MEMS accelerometers available today that meet the weak motion requirements.**

# Commercially Availability

There are many manufacturer’s of MEMS Accelerometers.

Most are targeted towards consumer, automotive, and industrial applications.

Only a few approach the noise levels necessary for strong-motion seismic applications

**Manufacturers**
Analog Devices
Bosch-Sensortec
*Colibrys
*Endevco
Freescale
*GeoSIG
*Kinemetrics
Kionix
MEMSIC
*PCB
*Reftek
Silicon Designs
STMicroelectronics
Summit Instruments
*Sercel
*Wilcoxon

*Noise Floor < 1 ug/$\sqrt{\text{Hz}}$

# Colibrys

Formerly Applied MEMS, I/O.
Oil & Gas Exploration

Produces VectorSeis which is sold through ION
(www.iongeo.com)

| Manufacturer | Colibrys | Colibrys | Colibrys | Colibrys |
|---|---|---|---|---|
| Model | SF 1500 | SF 2005 | SF3000 | Digital-3* |
| Technology | Capacitive | Capacitive | Capacitive | Capacitive Force Feedback |
| Output | Analog | Analog | Analog | Digital |
| Format | Chip | Chip | Module | Module |
| Axis | 1 | 1 | 3 | 3 |
| Power | 100 mW | 140 mW | 200 mW | 780 mW |
| Acceleration Range | +/- 3 g | +/- 4 g | +/- 3 g | +/- 0.2 g |
| Frequency Response | 0 – 1500 Hz | 0 – 1000 Hz | 0 – 1000 Hz | 0 – 1000 Hz |
| Sensitivity | 1.2 V/g | 500 mV/g | 1.2 V/g | 58 ng/bit |
| Self Noise | 300 – 500 ng/√Hz | 800 ng/√Hz | 300 - 500 ng/√Hz | 100 ng/√Hz |
| Weight | Not Specified | Not Specified | Not Specified | Not Specified |
| Size | 24.4 x 24.4 x 16.6 mm | 24.4 x 24.4 x 15 mm | 80 x 80 x 57 mm | 40 x 40 x 127 mm |
| Shock Range | 1500 g | 1500 g | 1000 g | 1500 g |
| Temperature | -40 to 125 °C | -40 to 85 °C | -40 to 85 °C | -40 to 85 °C |

*discontinued

# Endevco, PCB, Wilcoxon

Not strictly MEMS, but they are small and relatively low-noise.

All three companies make fairly similar Piezoelectric accelerometers

Industrial and Structural applications

| Manufacturer | Endevco | Endevco |
|---|---|---|
| Model | Model 86 | Model 87 |
| Technology | Piezoelectric | Piezoelectric |
| Output | Analog | Analog |
| Format | Module | Module |
| Axis | 1 | 1 |
| Power | 200 mW | 200 mW |
| Acceleration Range | +/- 0.5 g | +/- 0.5 g |
| Frequency Response | 0.003 – 200 Hz | 0.05 – 380 Hz |
| Sensitivity | 10 V/g | 10 V/g |
| Self Noise | 39 ng/√Hz @ 2 Hz<br>11 ng/√Hz @ 10 Hz<br>4 ng/√Hz @ 100 Hz | 90 ng/√Hz @ 2 Hz<br>25 ng/√Hz @ 10 Hz<br>10 ng/√Hz @ 100 Hz |
| Weight | 771 grams | 170 grams |
| Size | 62 x 62 x 53 mm | 29.8 x 29.8 x 56.4 mm |
| Shock Range | 250 g | 400 g |
| Temperature | -10 to 100 °C | -20 to 100 °C |

# Kinemetrics

Strong motion, seismic measurement

Force Balance Accelerometer

Available in single and three axis configurations

| Manufacturer | Kinemetrics | Kinemetrics |
|---|---|---|
| Model | EpiSensor ES-T | EpiSensor ES-U2 |
| Technology | Capacitive MEMS | Capacitive MEMS |
| Output | Analog | Analog |
| Format | Module | Module |
| Axis | 3 | 1 |
| Power | 144 mW | 100 mW |
| Acceleration Range | +/- 0.25 g | +/- 0.25 g |
| Frequency Response | 0 – 200 Hz | 0 – 200 Hz |
| Sensitivity | 10 V/g | 10 V/g |
| Self Noise | 60 ng/√Hz | 60 ng/√Hz |
| Weight | Not Specified | 350 grams |
| Size | 133 x 133 x 62 mm | 55 x 65 x 97mm |
| Shock Range | Not Specified | Not Specified |
| Temperature | -20 to 70 °C | -20 to 70 °C |

# Reftek

Strong motion measurement for seismic, structural, industrial monitoring

Available in single, three axis, and borehole configurations

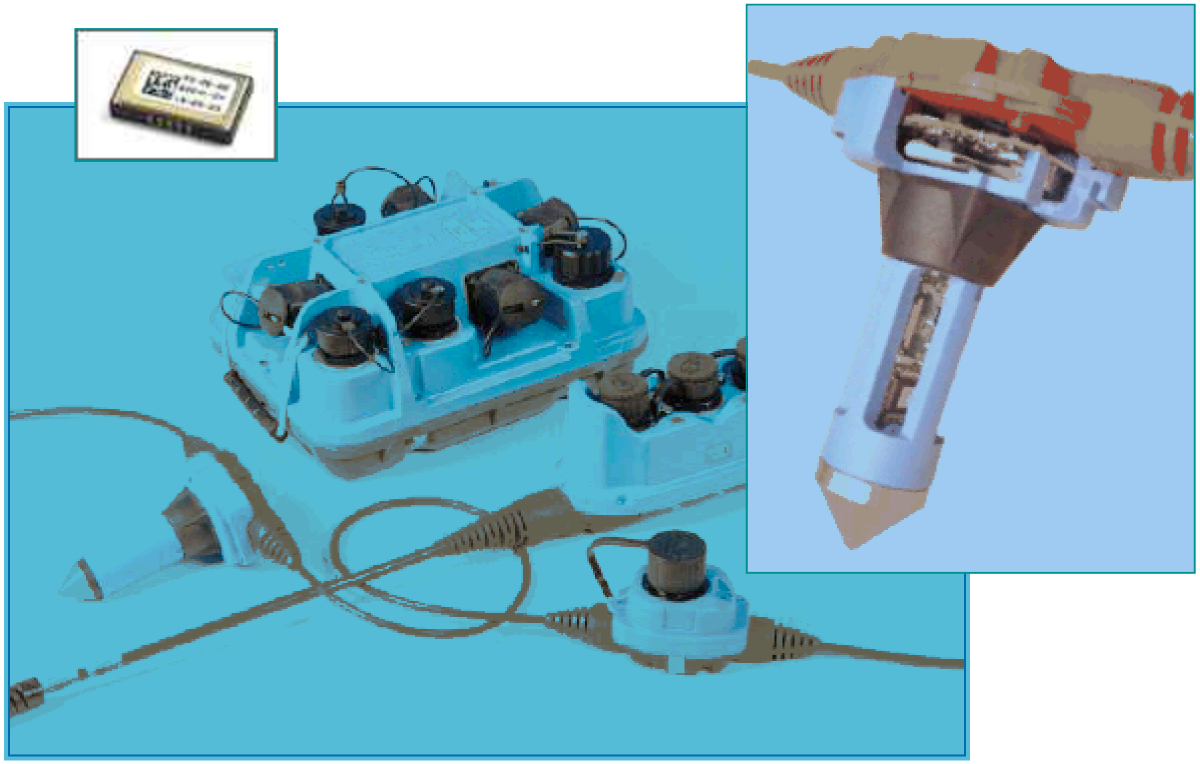
| | |
|---|---|
| Manufacturer | Reftek |
| Model | 131A* |
| Technology | Capacitive MEMS |
| Output | Analog |
| Format | Module |
| Axis | 3 |
| Power | 600 mW |
| Acceleration Range | +/- 3.5 g |
| Frequency Response | 0 – 400 Hz |
| Sensitivity | 2 V/g |
| Self Noise | 200 ng/√Hz |
| Weight | 1000 grams |
| Size | 104 x 101 x 101 mm |
| Shock Tolerance | 500 g |
| Temperature | -20 to 60 ˚C |

* uses Colibrys Accelerometers

# Sercel

Used in tomography studies for Oil & Gas Exploration

Sold as complete turn-key systems and not available for individual sales



| Manufacturer | Sercel |
|---|---|
| Model | DSU3-428 |
| Technology | Capacitive MEMS |
| Output | Digital |
| Format | Module |
| Axis | 3 |
| Power | 265 mW |
| Acceleration Range | +/- 0.5 g |
| Frequency Response | 0 – 800 Hz |
| Sensitivity | Not Specified |
| Self Noise | 40 ng/√Hz |
| Weight | 430 grams |
| Size | 159.2 x 70 x 194 mm |
| Shock Range | Not Specified |
| Temperature | -40 to 70 °C |

# MEMS accelerometers

## Advantages

- Small
- Can be low power, for less sensitive sensors.
- High frequency bandwidth (~ 1 kHz)

## Disadvantages

- Active device, requires power
- Poor noise and response at low frequencies (< 1 Hz), largely due to small mass, 1/f noise, or feedback control corner.
- Noise floor flat to acceleration, exacerbates noise issues at low frequency (< 1 Hz)

# Theoretical Noise

**Two main sources of noise:**

- **Thermo-mechanical**
  - Brownian motion
  - Spring imperfections
- **Electronic**
  - Electronics
  - Detection of mass position
  - Noise characteristics unique to detection technique

Thermo-mechanical noise for a cantilevered spring

$$a_n = \sqrt{\frac{4k_b T\omega_0}{Q\cdot m}}\,\frac{1}{\sqrt{Hz}}$$

| | |
|---|---|
| Boltzman's Constant | $k_B$=1.38x$10^{-23}$ J/K |
| Temperature | $T$ = 300 K |
| Resonant Frequency | $w_o$=314.16 rad/s (50Hz) |
| Quality Factor | $Q$ = 1000 |
| Proof Mass | $m$ = 1 gram ($10^{-3}$ kg) |

$a_n$ = 2.3 x 10^-9 m / $s^2$ / √*Hz*
= 0.2 *ng* / √*Hz*

| Traditional Seismometer | MEMS Accelerometer |
|---|---|
| Large mass (100's of grams) | Small mass (milligrams) |
| Thermo-mechanical noise is small | **Thermo-mechanical noise dominates** |
| **Electronic noise dominates** | Same electronic noise issue as traditional |

# Detection of mass position

Variety of ways to determine mass-position

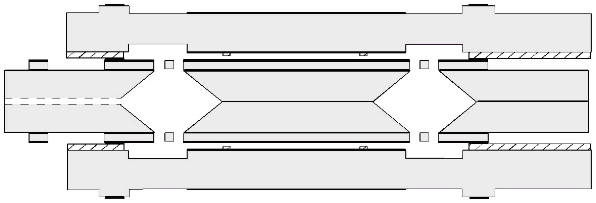
- Piezoelectric / Piezoresistive
- Capacitive
- Inductive
- Magnetic
- Fluidic
- Optical (diffraction, fabry-perot, michelson)

# Capacitive Detection

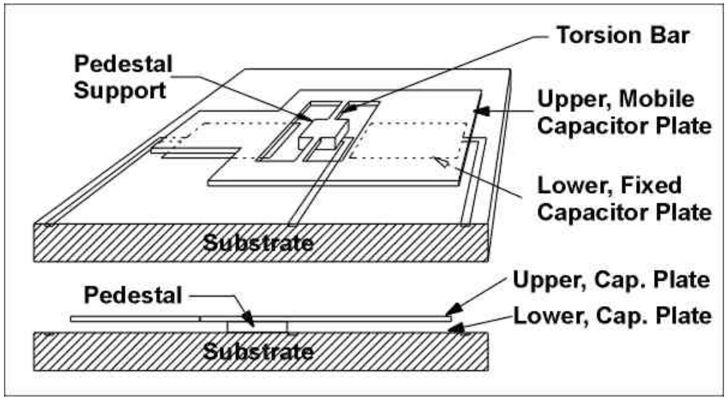
The most common method of mass position detection for current MEMS accelerometers is capacitive.

Capacitance is a weak sensing mechanism and force (for feedback contrl) which necessitates small masses (milligrams) and small distances (microns).

Feedback control employed for quietest solutions. Differential sampling for noise cancelation.



Colibrys bulk-micromachined proof mass sandwiched between differential capacitive plates



Silicon Designs capacitive plate with a pedestal and torsion bar.

# R&D Challenges

- Large proof mass and weak springs required.  This makes for a delicate instrument.
- Capacitance less useful as a detection and feedback mechanism for larger masses.
- Feedback control required to achieve desired dynamic range and sensitivity.
- R&D requires access to expensive MEMS fabrication facility
- 1/f electronic noise could limit low-frequency

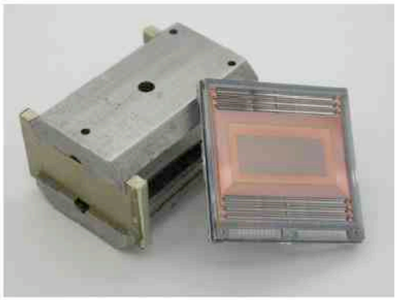
# DOE Funded R&D Projects

- Several posters on display
- Additional details and proceedings available at http://www.monitoringresearchreview.com/

- Characteristics:
  - Significantly larger proof mass (0.25 – 2 grams)
  - Non-capacitive mass position sensing (inductive, optical, fluidic)
  - Feedback control

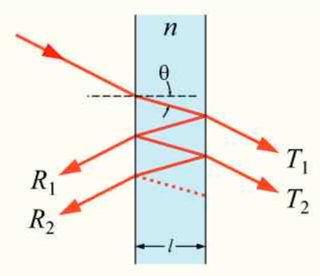
# DOE Funded R&D Projects

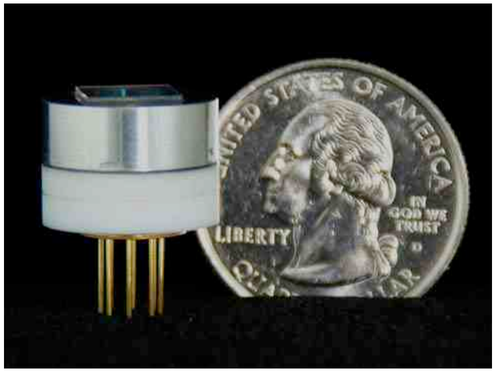
## Kinemetrics / Imperial College



- Inductive coil with force feedback
- Proof mass of 0.245 grams
- 0.1 - 40 Hz bandwidth, resonant mode at 11.5 Hz
- Demonstrated noise performance of 2-3 ng/$\sqrt{Hz}$ over 0.04 – 0.1 Hz, higher noise at frequencies > 0.1 Hz

## Symphony Acoustics



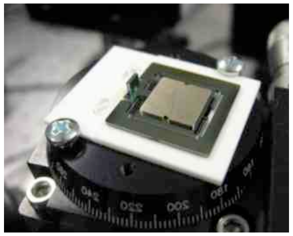


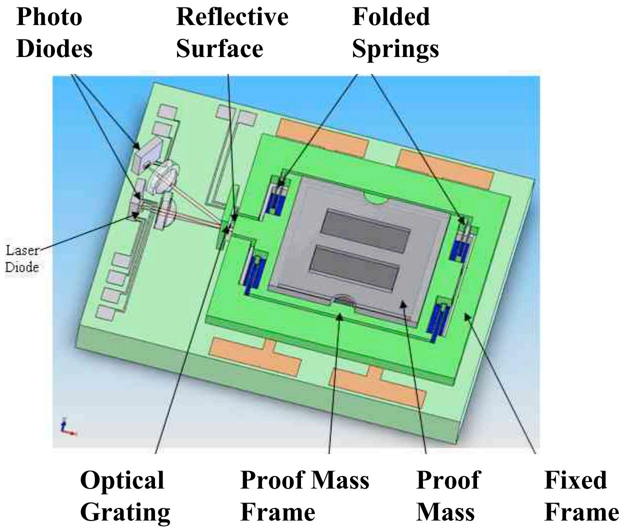
- Fabry-Perot optical cavity
- Proof mass of 1 gram
- 0.1 - 100Hz bandwidth
- Demonstrated noise performance of 10 ng/$\sqrt{Hz}$
- Theoretical noise performance of 0.5 ng/$\sqrt{Hz}$

# DOE Funded R&D Projects

## Sandia National Laboratories

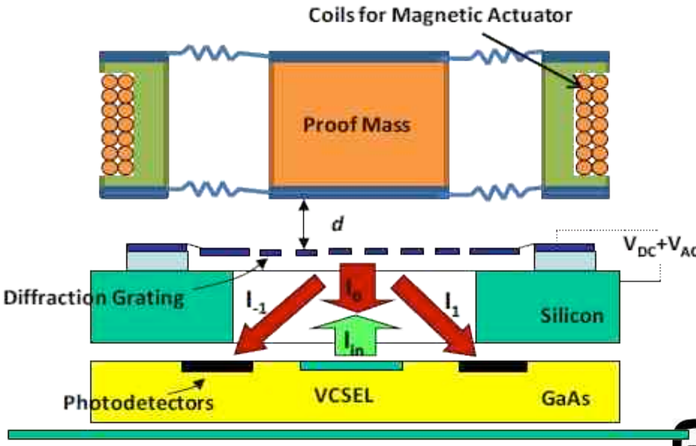
- Large proof mass (1 gram, tungsten)
- Meso-scale proof mass with MEMS diffraction grating and springs.
- Optical diffraction grating
- Theoretical thermo-mechanical noise 0.2 ng/$\sqrt{Hz}$ over 0.1 to 40 Hz



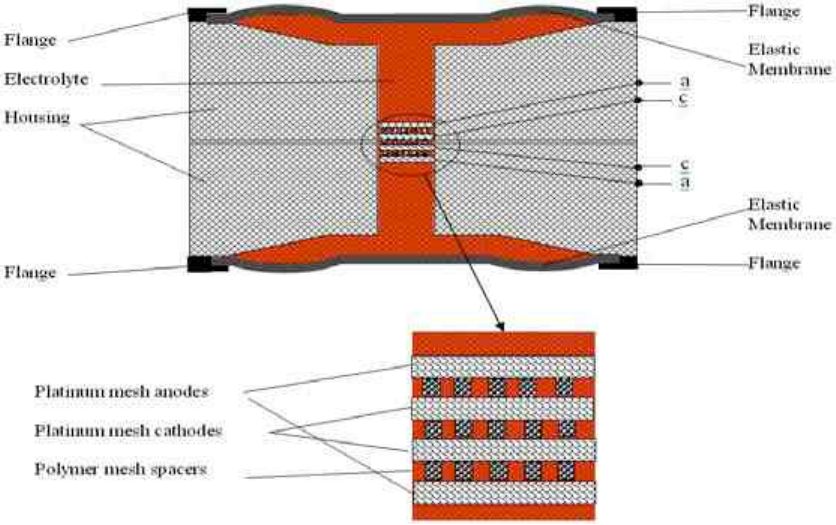


## Silicon Audio

- Large proof mass (2 gram)
- Meso-scale construction with MEMS diffraction grating
- Optical diffraction grating
- 0.1 to 100 Hz target bandwidth
- Theoretical thermo-mechanical noise 0.5 ng/$\sqrt{Hz}$ over 1 to 100 Hz

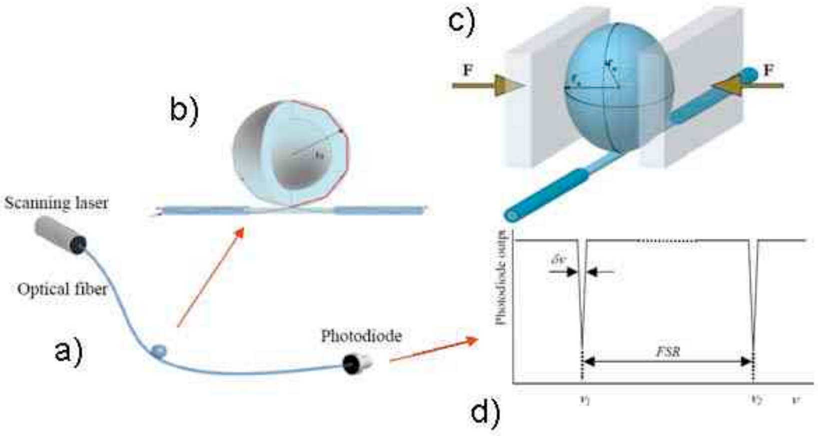


# DOE Funded R&D Projects



## PMD Scientific, Inc.

- Electrochemical fluid passing through a membrane
- Theoretical noise 0.5 ng/$\sqrt{Hz}$ over 0.02 to 16 Hz



## Michigan Aerospace Corp.

- Whispering Gallery Seismometer
- Optical coupling between a strained dielectric microsphere and an optical fiber
- Theoretical noise of 10 ng/$\sqrt{Hz}$

Sandia National Laboratories

# 5 year outlook

- **Over the next 5 years, there is a strong potential for at least one of the DOE R&D MEMS Seismometer projects to reach the point of commercialization.**
- **This would mean a MEMS Accelerometer with:**
  - a noise floor under the < LNM (~ 0.4 $ng/\sqrt{Hz}$)
  - Bandwidth between 0.1 and 100 Hz,
  - > 120 dB of dynamic range
  - small ( < 1 inch^3).
  - Low power (10’s mW)

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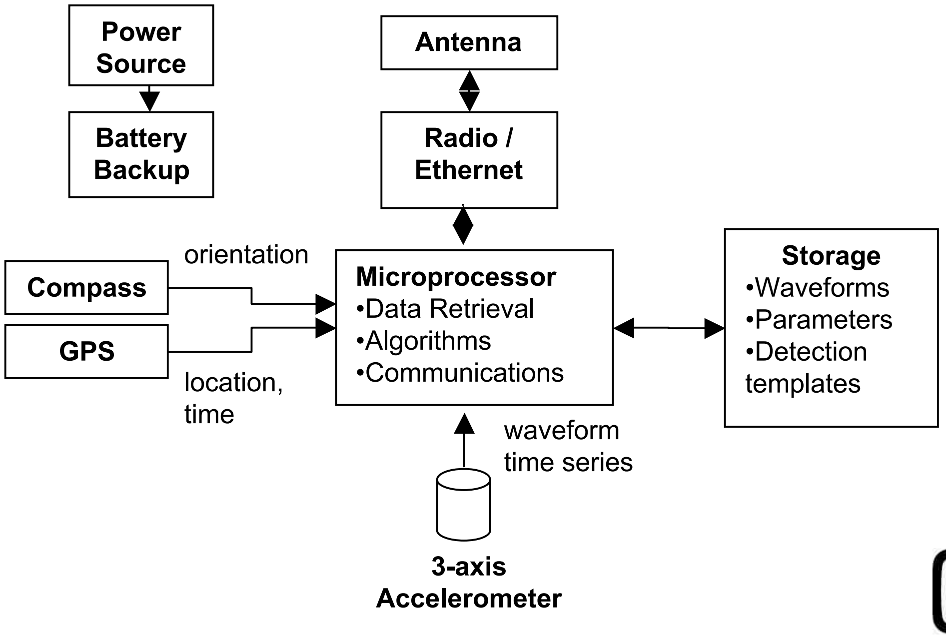
# Enabling Applications

- **Flexible R&D deployments**
- **Why simply connect a miniaturized transducer onto a traditional seismic system?**
- **Will require highly integrated packages:**
  - Digitizer
  - Microcontroller
  - GPS
  - Flash storage
  - Communications
  - Battery



# 10 year outlook

- MEMS Accelerometers have only been commercially available for ~18 years.
- Where were things 10 years ago?

- Further expansion into long period (~ 0.01 Hz)
- Small, highly integrated seismic systems

# Questions?

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