A Practical Guide to MEMS Inertial Sensors

Stanford PNT Symposium

Alissa M. Fitzgerald, Ph.D. | 14 November 2013

AMFITZGERALD
& ASSOCIATES

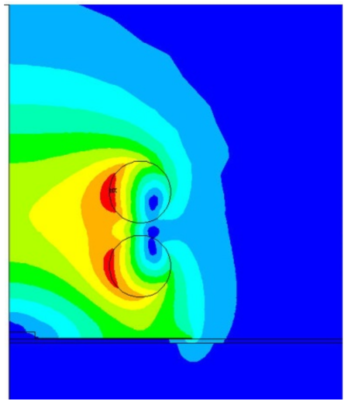
10th anniversary
2003 2013

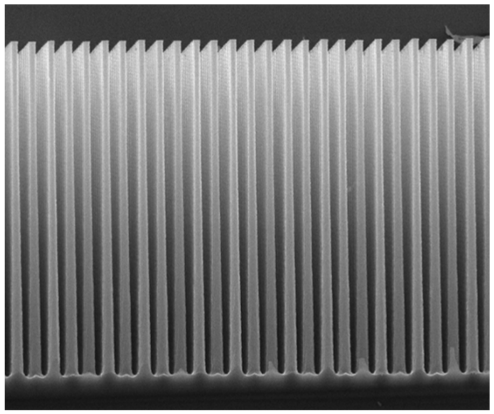
Overview

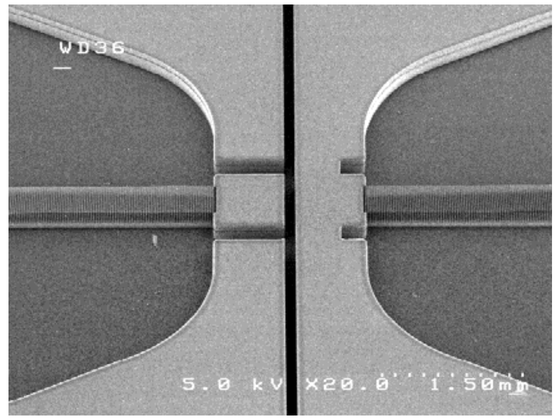
- **About AMFitzgerald**
- **How MEMS* are made**
- **MEMS inertial sensor overview**
- **Packaging**
- **6 DOF and more**
- **Appendix: Specifications for a selection of sensors**

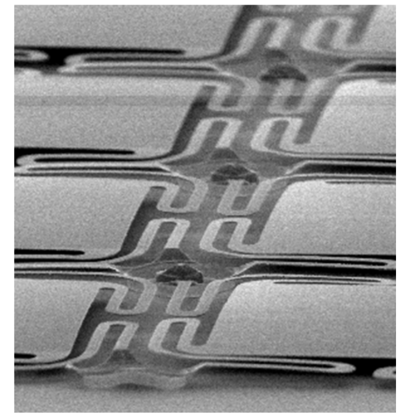
MEMS = Micro Electro Mechanical Systems

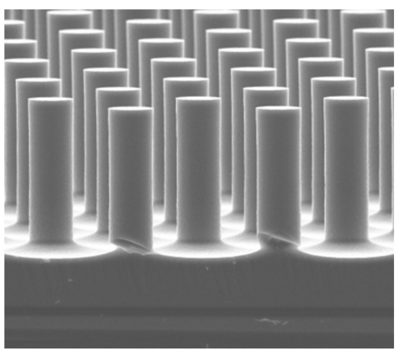
AMFitzgerald: Your Partner in MEMS Product Development

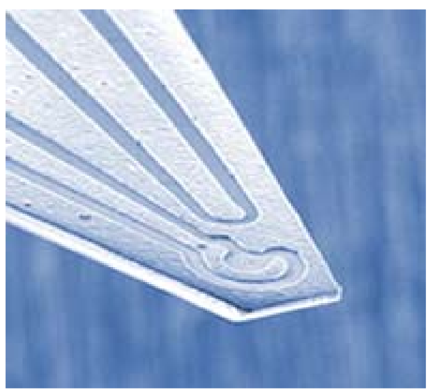


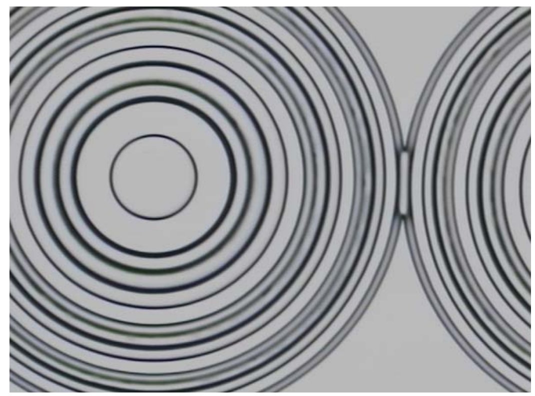


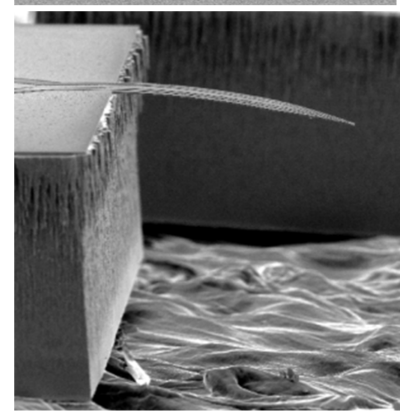


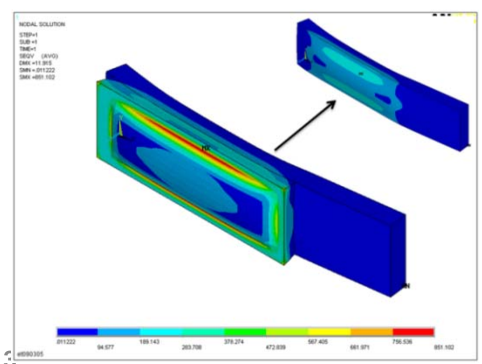


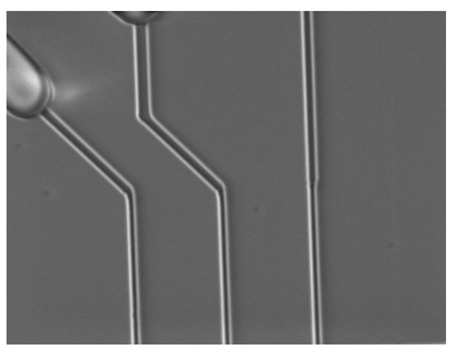


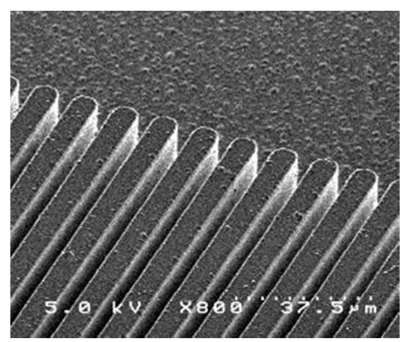










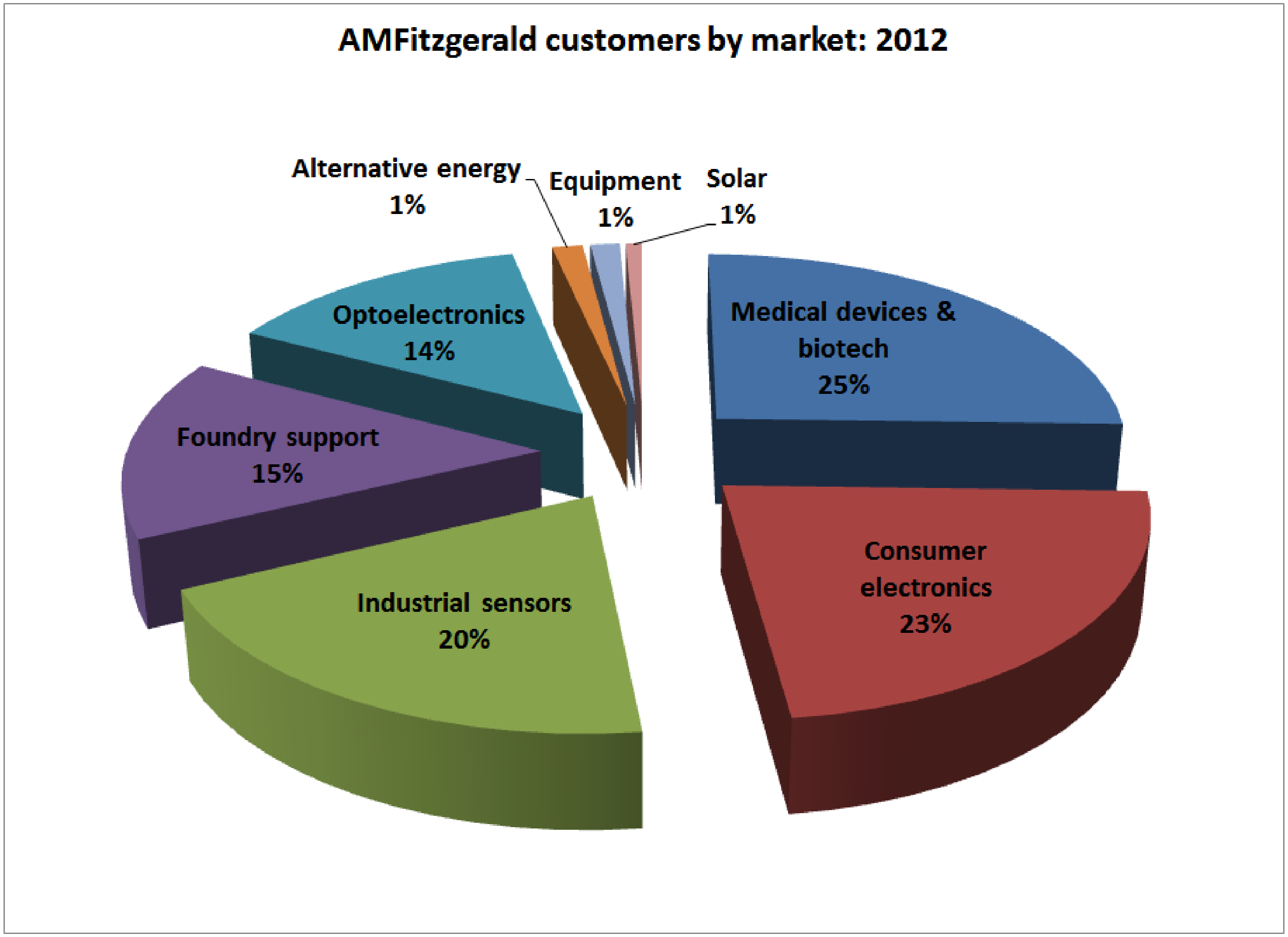


AMFitzgerald: MEMS solutions, from concept to production

Technology Strategy | Design Simulation | Prototyping & Process Integration | Low Volume Production | Package & Test | Foundry Production

← AMFitzgerald in-house → ← Strategic partners →

Our customer base is as diverse as MEMS itself



Types of MEMS developed in 2012:

- Optical switch
- Microfluidics
- Microphone
- Timing
- Microtexture
- Inkjet
- Radiation
- Motion
- Pressure
- Micro-mirror
- Cantilever
- IR imager
- Fuel cell
- Display
- Chemical

Birth of MEMS

- **Evolved from semiconductor processes**
- **1970's: using silicon processing to make mechanical devices, not transistors**
  - **Accelerometers**
  - **Pressure sensors**
  - **Inkjet nozzles**
- **1982: Petersen's "Silicon as a Mechanical Material"**

The coming age of

micromachines

Tiny mechanisms—valves, accelerometers, pressure sensors—can be etched in batches on silicon wafers then sliced into separate chips. These devices, ideally sized for linkup with microelectronic circuits, can monitor pollution, aid medical research, give robots a sense of touch, and more.

By JEANNE McDERMOTT
Drawings by Ed Lipinski

FREMONT, CALIF.

Jim Knutti, president and co-founder of Transensory Devices, Inc., held up a gray silicon device no bigger than a teardrop. It had two tiny terraces—pressure-sensing diaphragms—barely visible to the naked eye. I was looking at a miniscule "smart" pressure sensor, one of the incredible new breed of micromachines.

TDI's sensor, I discovered, is made much like millions of other microelectronic chips ["Superchips," PS,

Continued

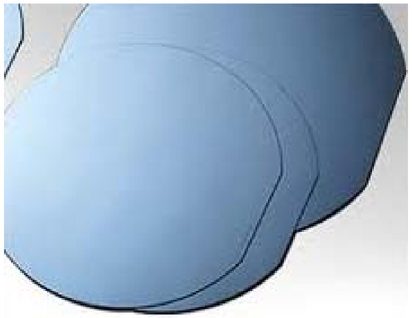
Three-in. silicon wafer (above) is etched with key elements of a gas chromatographer, a device that identifies the components of a gas mixture. In a chromatograph, gases are forced through a column of material that absorbs and then releases each component. The time it takes a particular gas to pass through the column and reach a sensor identifies it. On the wafer, made by MTI, the etched snake-like channels are sealed with a glass cover. Gases are admitted into or exhausted from these channels by solenoid-actuated valves and small squares etched through the wafer. Initially the gas sample is compressed into the thick wafer channel; then it's released into both the narrower delay channel and a gas-separation channel outside the wafer. The separation channel, packed with porous polymer particles, is the U-shape metal tube on the right side of MTI's chromatographic module (right). Then, at different times, the separated gases and still-mixed (reference) gases from the delay channel are passed over a sensor that generates voltage peaks. An oscilloscope, pen plotter, or liquid-crystal panel can display a chromatographer's output as "spikes" for various gases or as numbers. Such miniaturization could lead to walkie-talkie-size instruments, says MTI. Its latest chromatographer is housed, with a microcomputer and five wafer modules, in a 14-by-seven-by-20-in. case.

Popular Science, June 1984

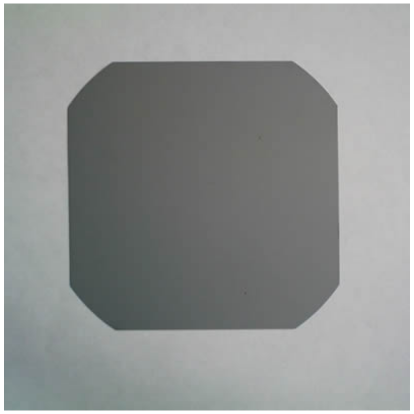
Silicon – the purest material refined by humans

Start

Finish

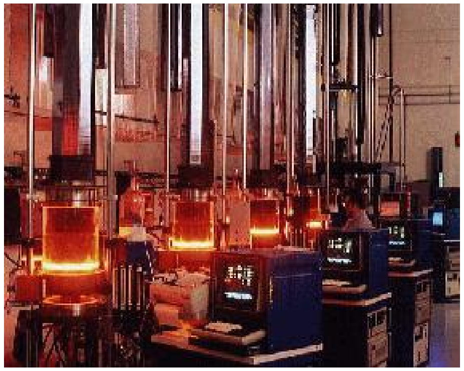


Semiconductor wafer



Solar cell wafer

Silicon dioxide

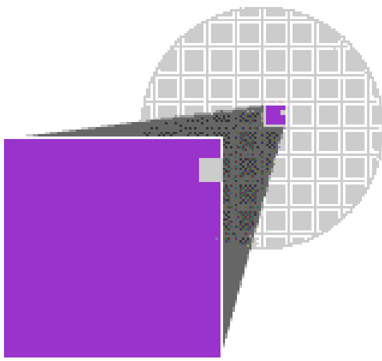


"Pulling" crystals

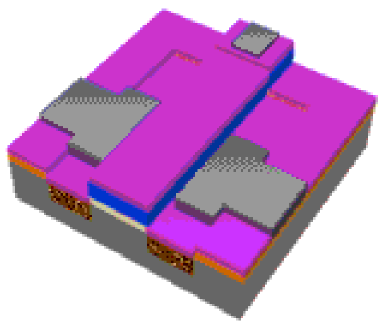
Ingot

Silicon process technology

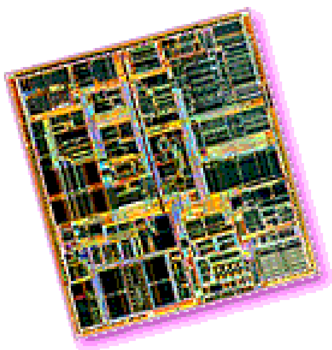
- **Developed to make transistors and integrated circuits**



Silicon wafer



Material deposition
Lithographic patterning
Material etch back
Repeat for multiple layers

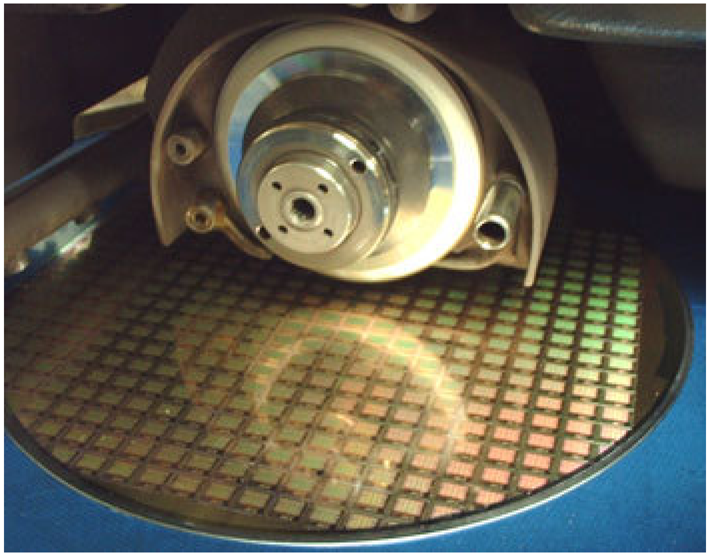


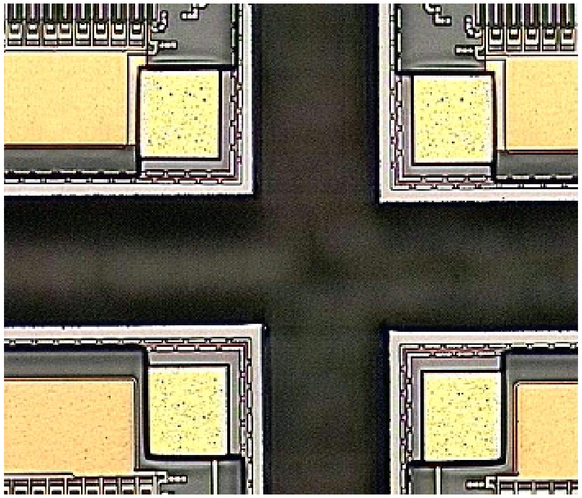
Microprocessor

Images from: http://www.intel.com/education/chips/index.htm

Wafer dicing

- **Similar to cutting tile**





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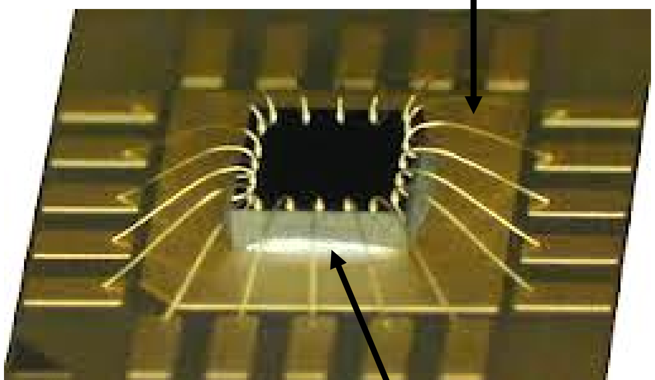
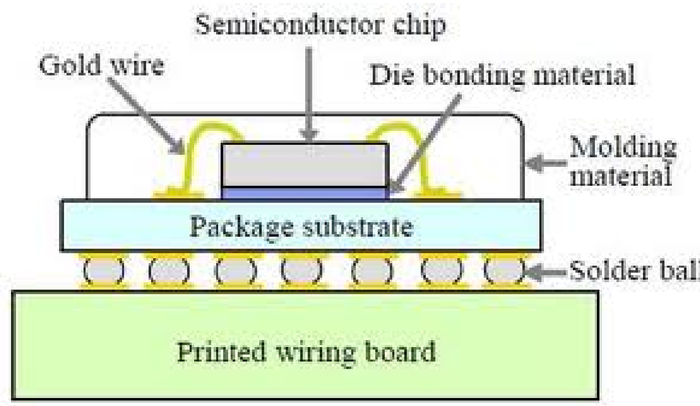
Die attach and wire-bonding

25 micron (1 mil) gold wire



Die attach epoxy



MEMS accelerometer schematic

- Displacement transduction method:
  - Capacitive
  - Piezoresistive
  - Thermal (MEMSIC)
  - Piezoelectric

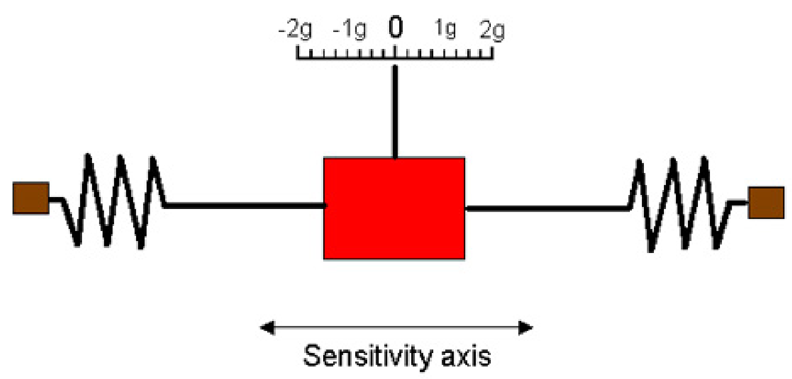
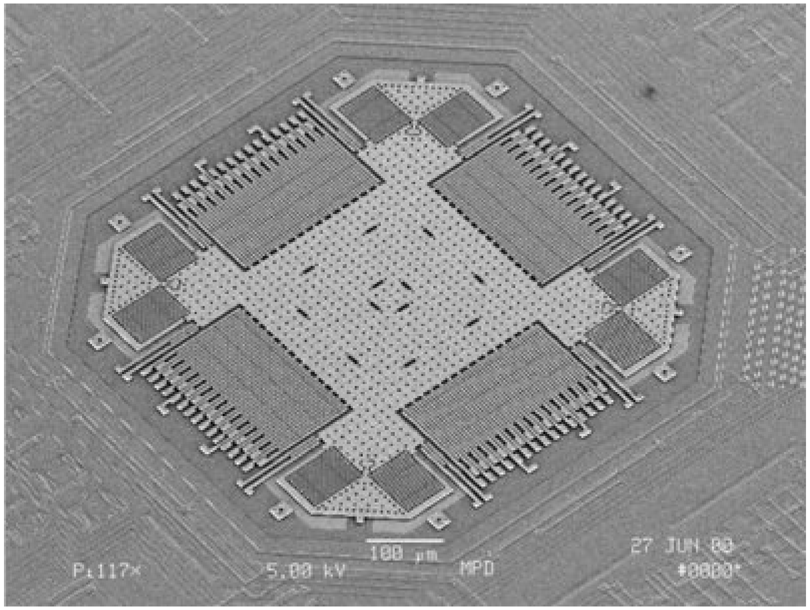


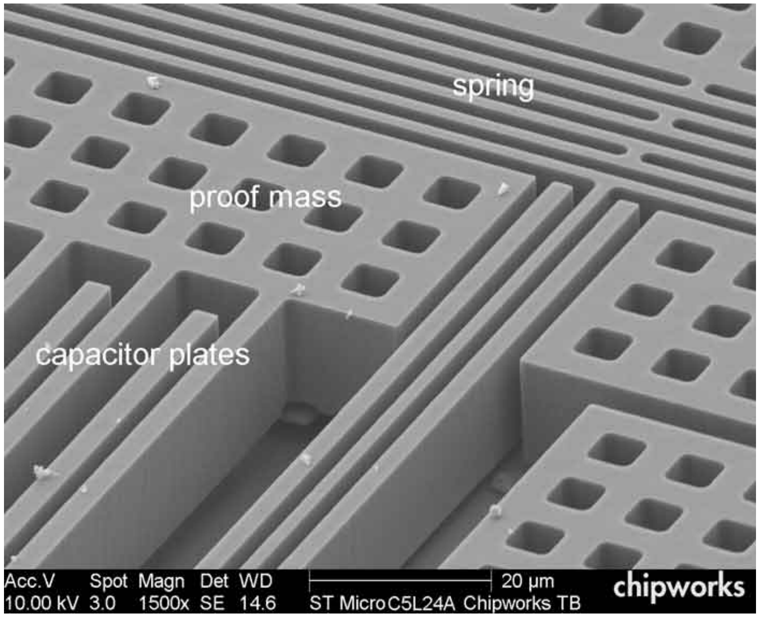
Fig. 1. Schematic structure of an accelerometer

In practice: diversity of architectures

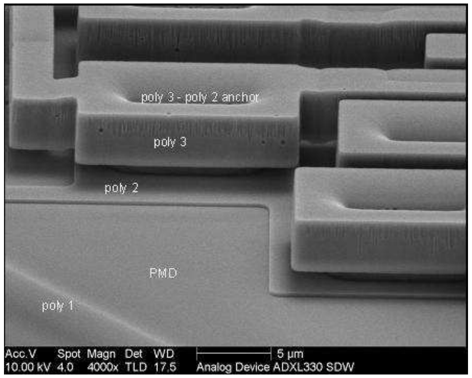
Accelerometers



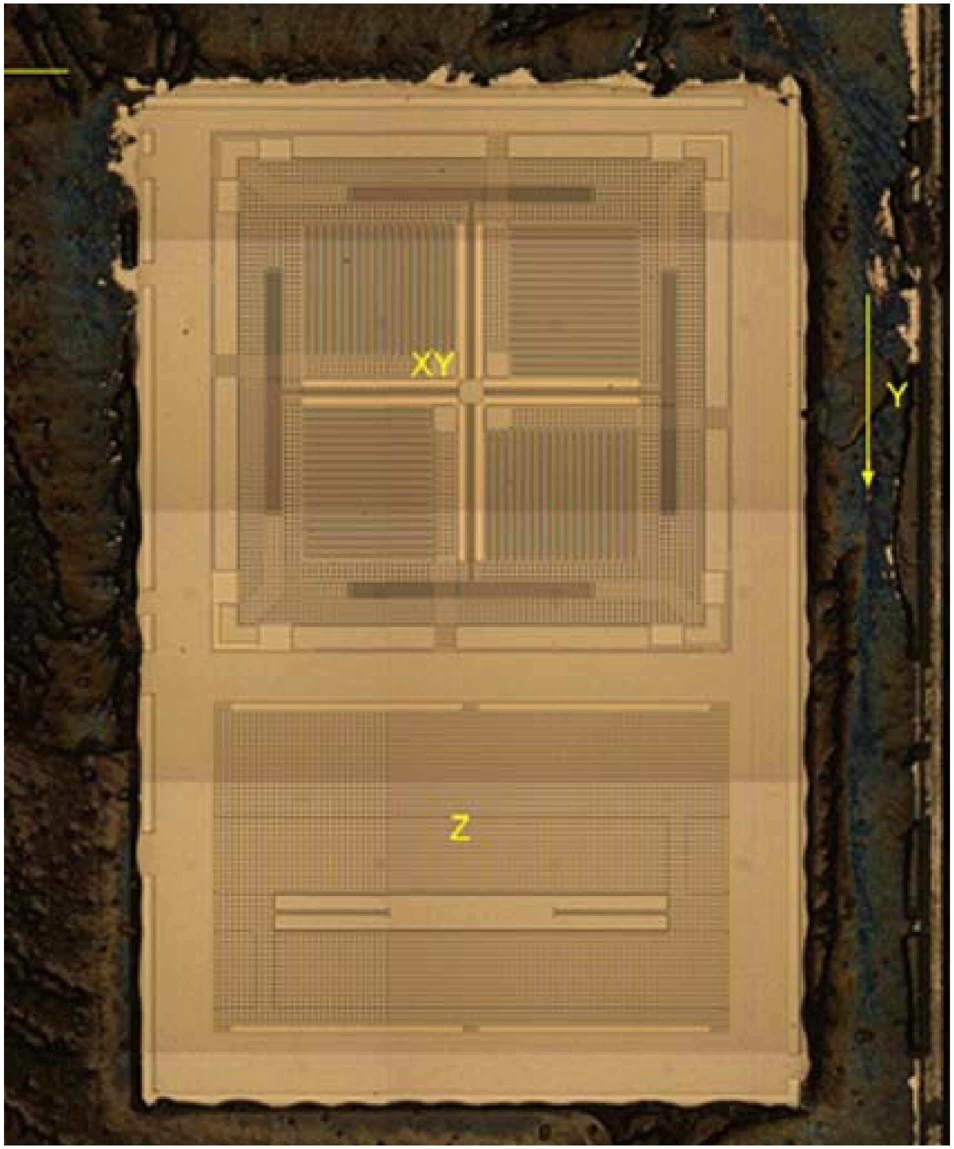
ADI ADXL50



ST C5L24A



3-Axis accelerometer

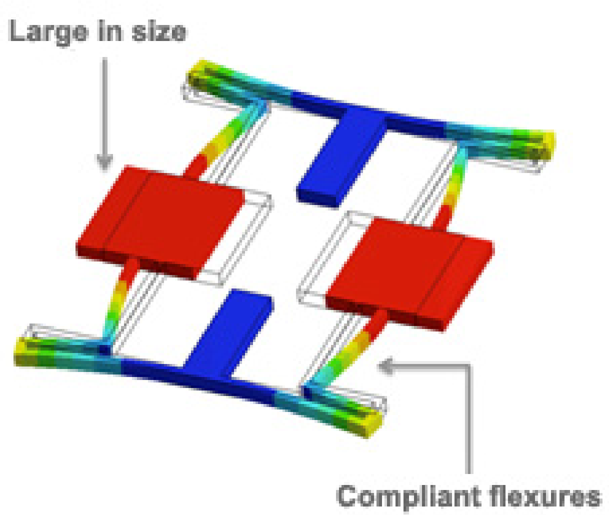


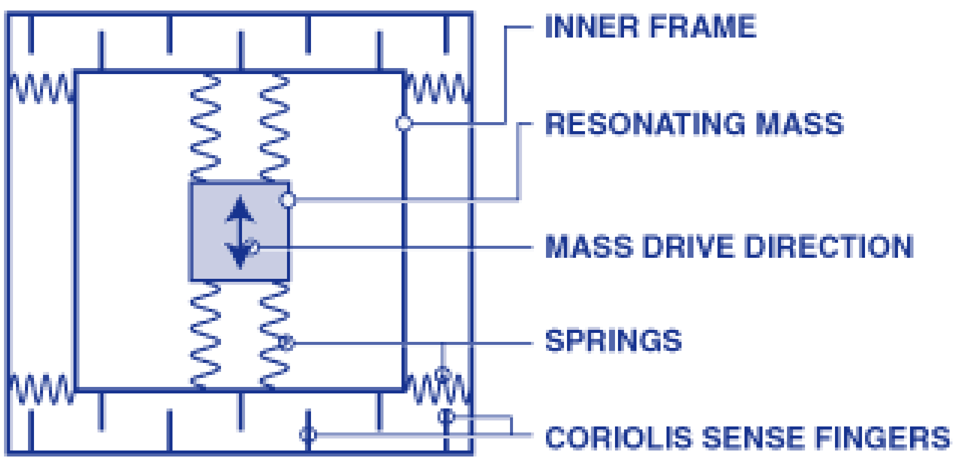
Source: ST, Chipworks
iPhone 4 Teardown

MEMS gyroscopes schematic

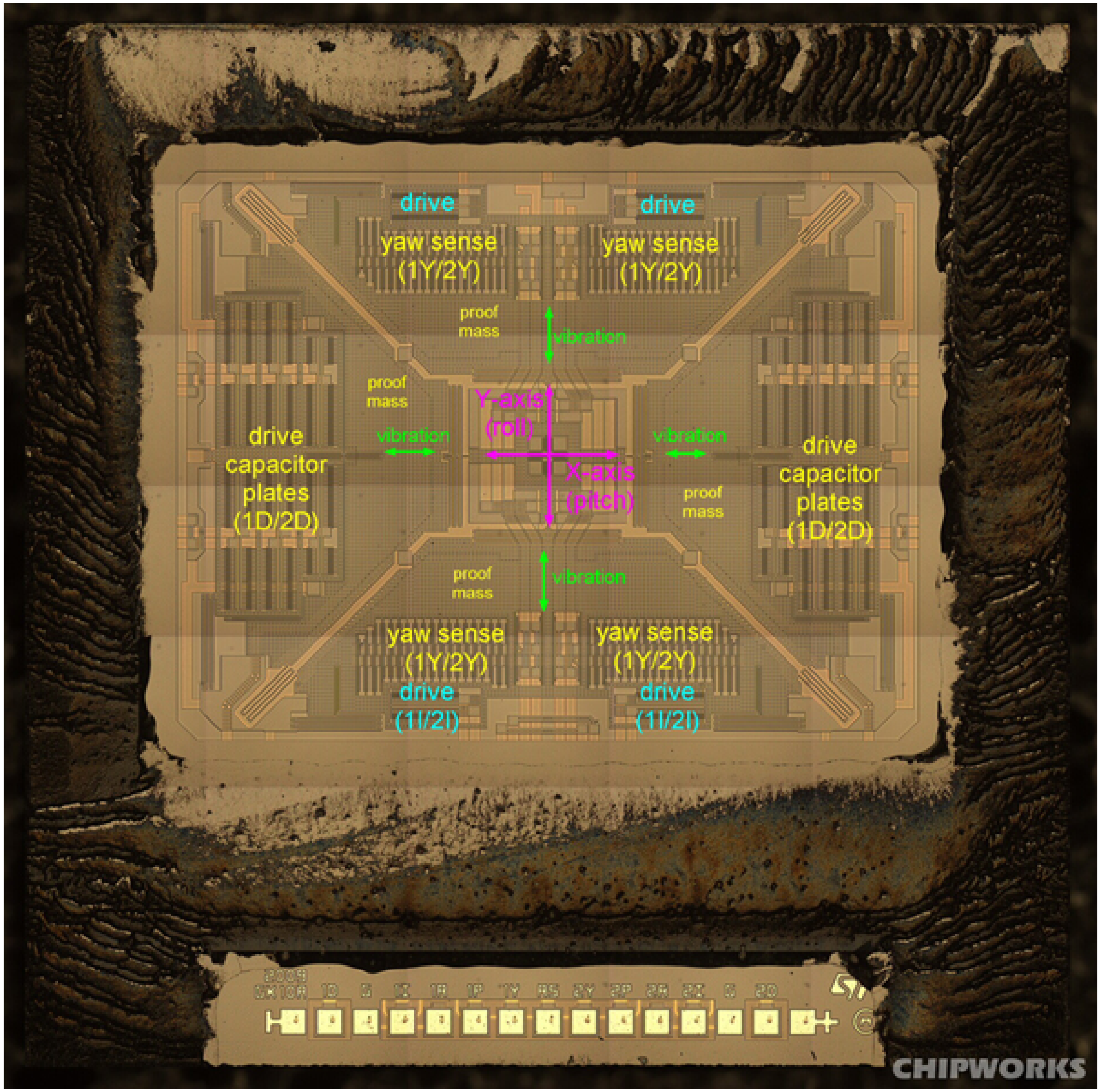
- Rotation of component exerts perpendicular coriolis force on resonating proof mass
- Displacement is measured capacitively

Conventional Tuning-Fork Gyros





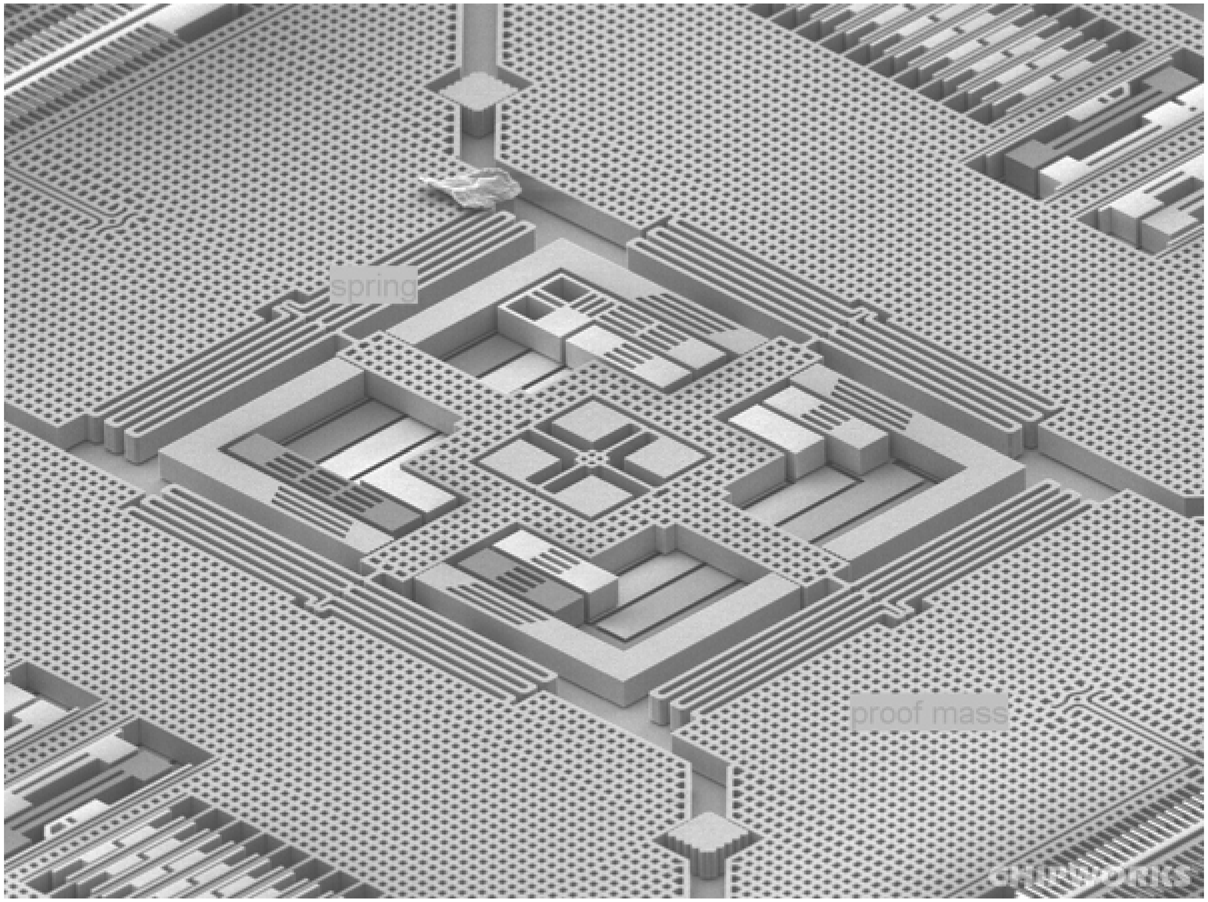
2-axis gyroscope



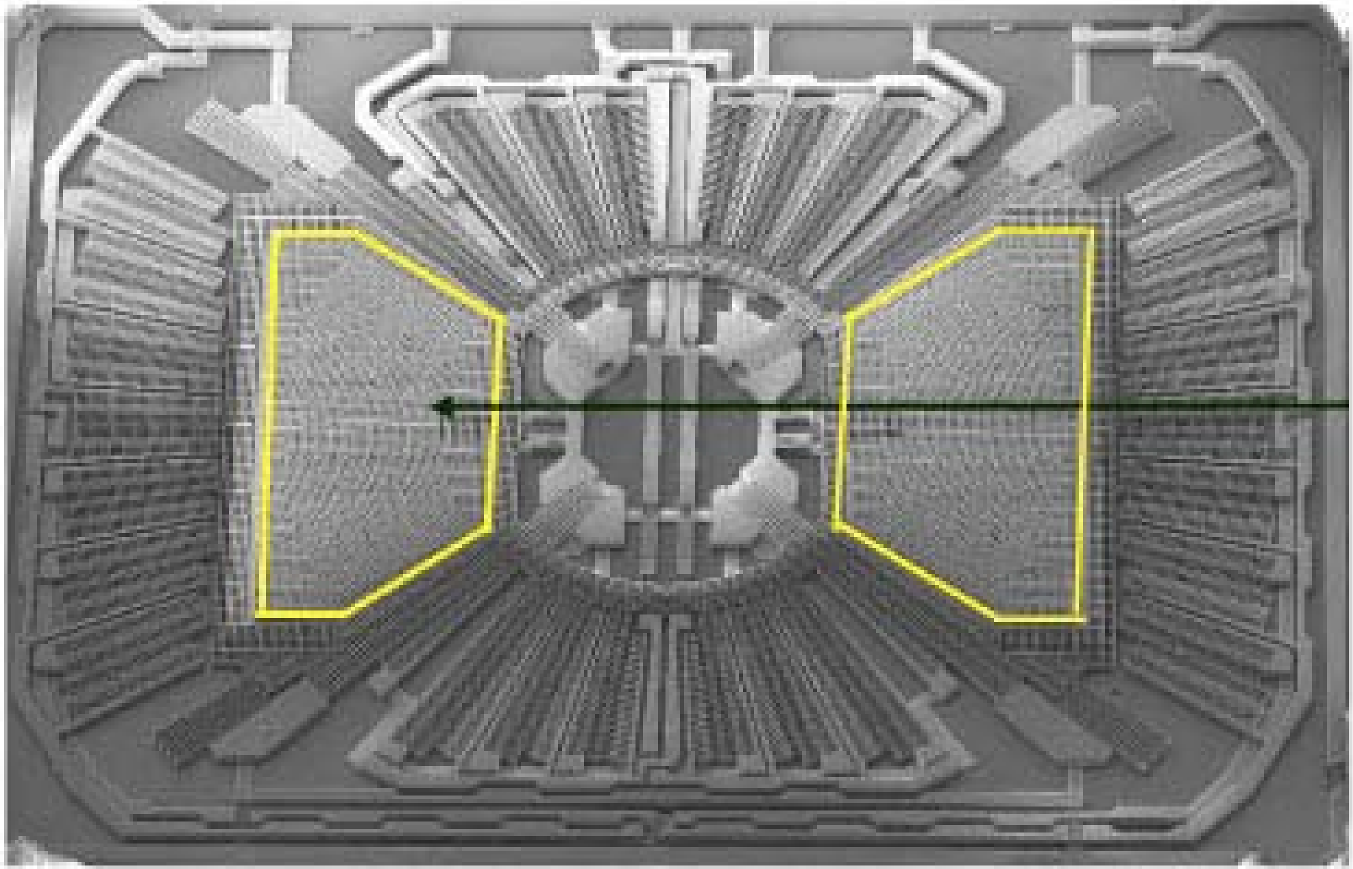
Source: ST, Chipworks
iPhone 4 Teardown

2-axis gyroscope

Source: ST, Chipworks
iPhone 4 Teardown



3-axis gyroscope: introduced 2009

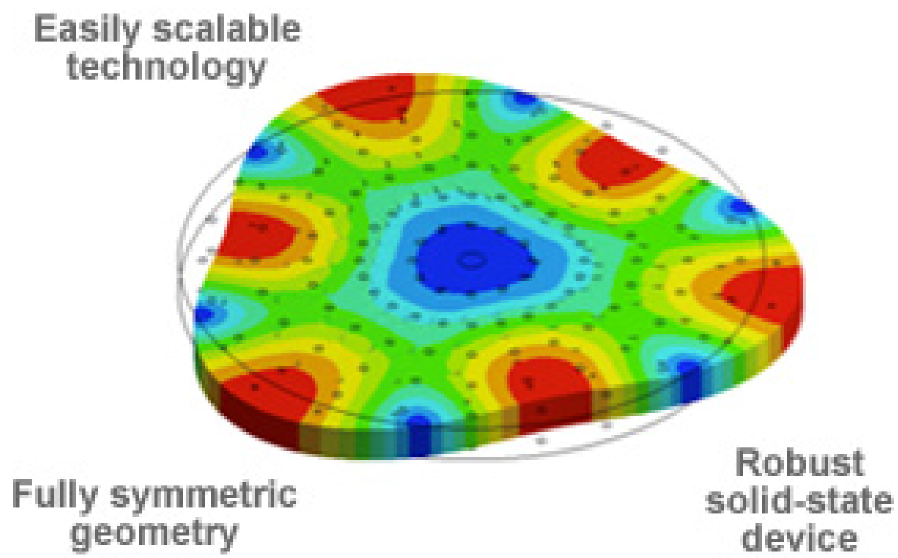


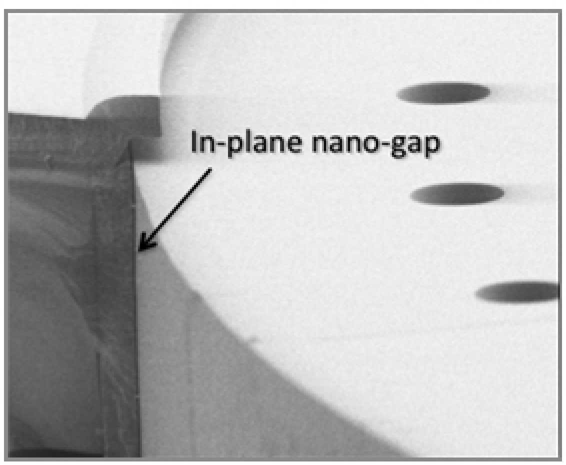
Package size: 4.4 x 7.5 x 1.1 mm

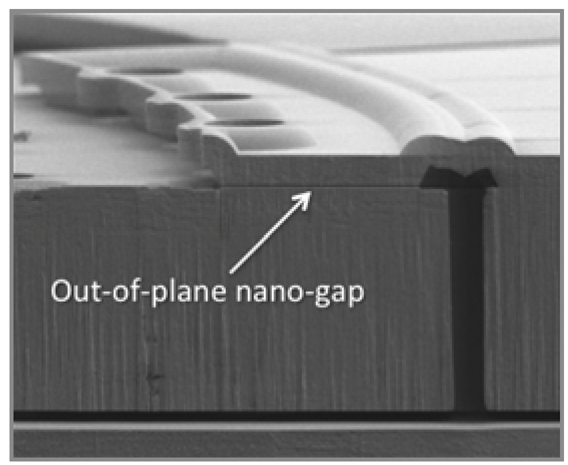
Source: ST, Chipworks

Bulk acoustic wave gyro – similar in concept to HRG

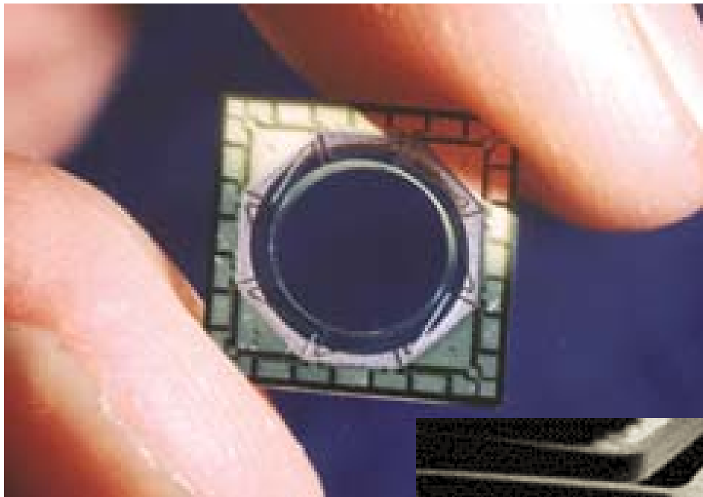
Qualtré's BAW Gyroscope

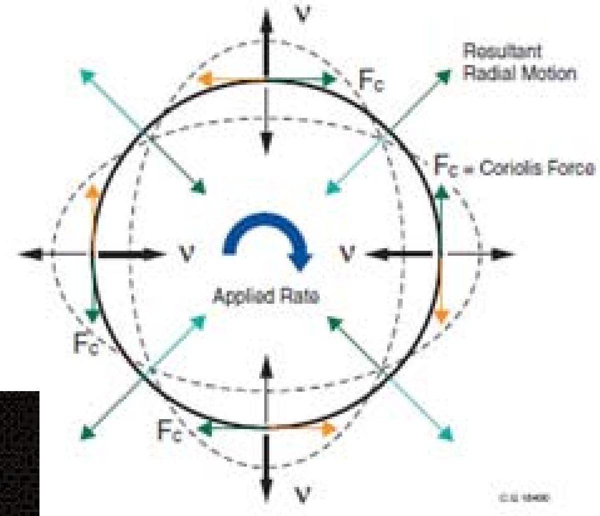


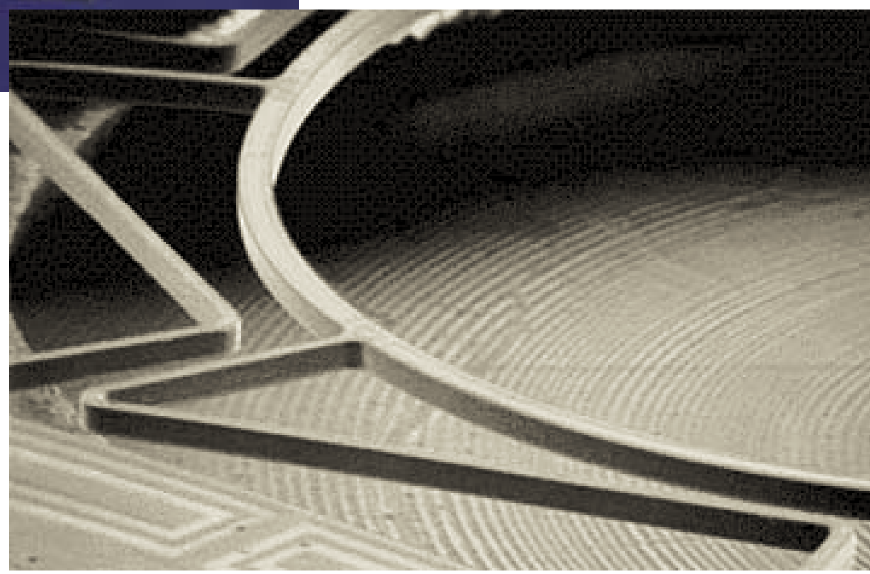




Precision single-axis with inductive drive/sense



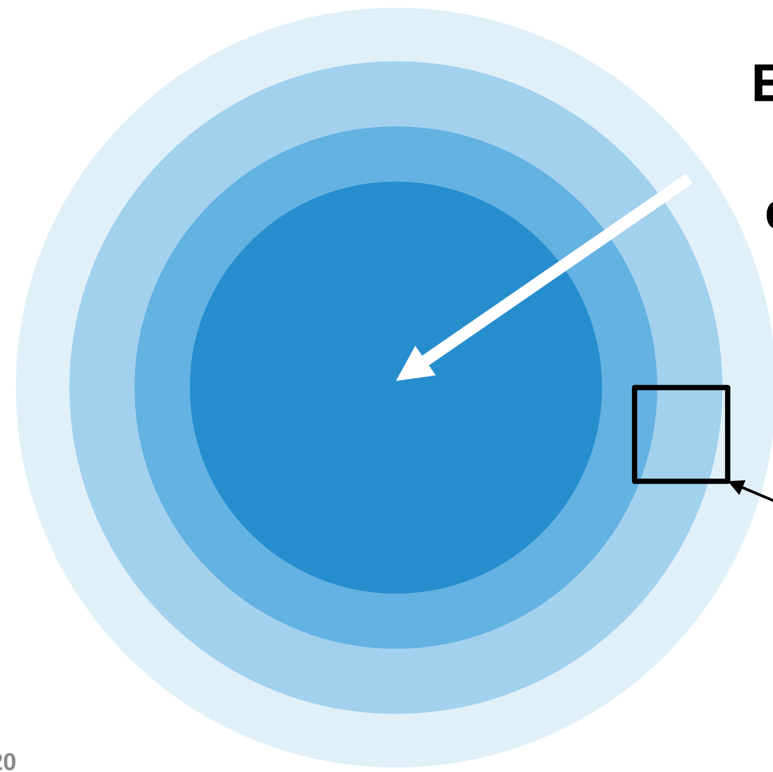




Source: Silicon Sensing Systems

Performance challenges with MEMS inertial sensors

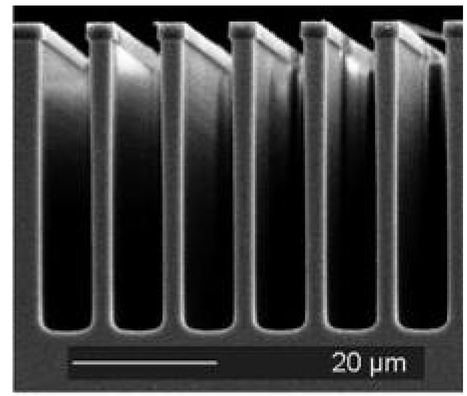
- **Silicon etch uniformity affects all devices**
  - Yield
  - Calibration
  - Performance binning



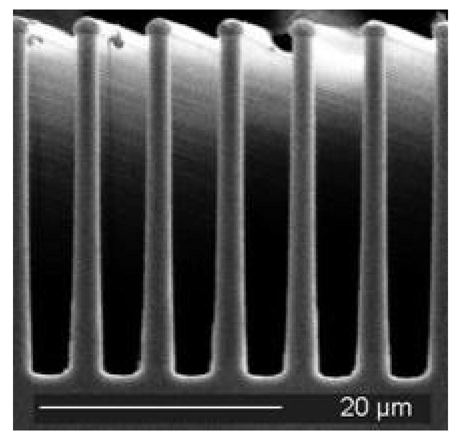
Edge of wafer etches faster

Bigger chips can span etch zones

Top heavy



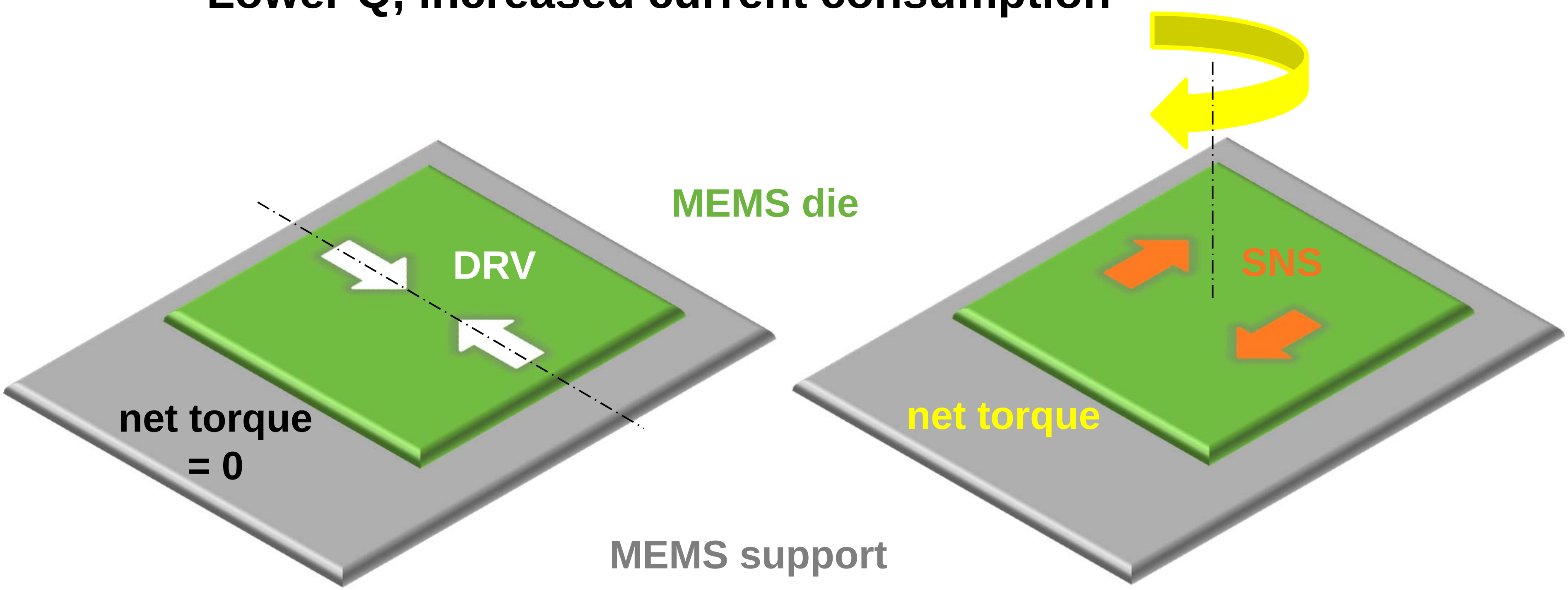
Bottom heavy



Source: Intellisense

Performance challenges with MEMS inertial sensors

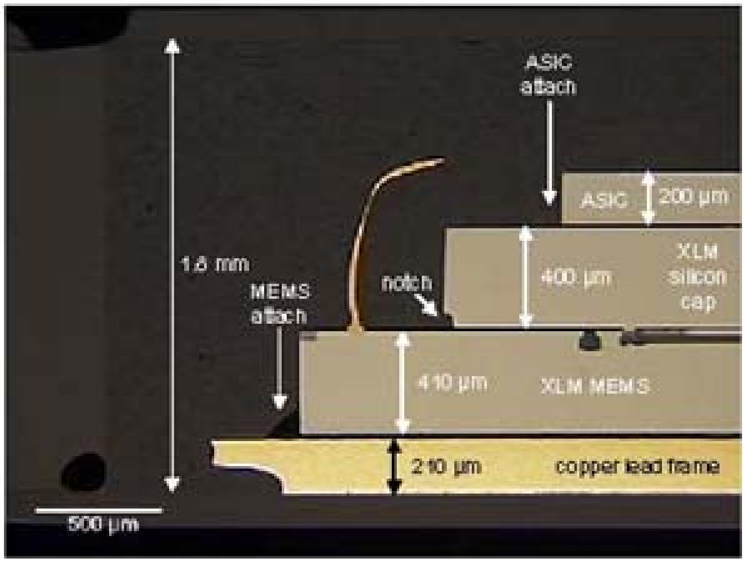
- **Temperature sensitivity from CTE mismatch**
- **Energy dissipation through structure and package**
  - **Anchor design critical**
  - **Die attach materials**
  - **Lower Q, increased current consumption**



Used with permission from Tronics

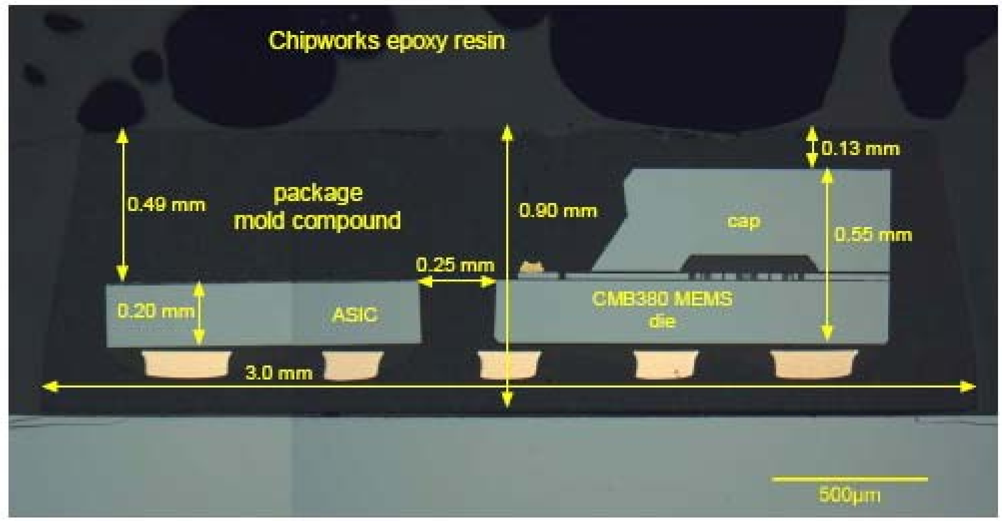
By the way, these sensors need ASICs*!

Stacked



Source: Chipworks photo of Kionix KXM52

Side-by-side



Source: Chipworks photo of Bosch SMB380

***Application-Specific Integrated Circuits**

6 DOF "Combo" Sensors and more…

- **Combo = accel, gyro, magnetometer, altimeter, etc.**

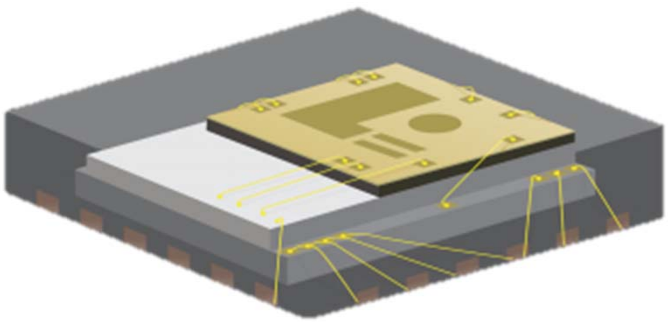
- **The Dream: Monolithic integration**
  - **Fabricate all sensors and control circuitry on same piece of silicon**
  - **Small form factor, lower parasitics**

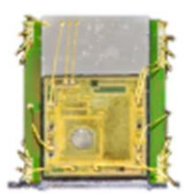
- **Reality today: Most are Multi-Chip Modules**
  - **Gyros need vacuum, accels need partial atmosphere**
  - **Best strategy to fight yield problems**
    - **ASICs yield at 98+%**
    - **Accels yield at 60+%**
    - **Gyros yield at 25+%**
  - **Easier to swap out sensors and ASIC chips mid-product cycle**

InvenSense **vs. Competition**

Patented **Single Cavity Multi-Axis Motion Sensor Technology**
enables **Higher Integration and Smaller Size**

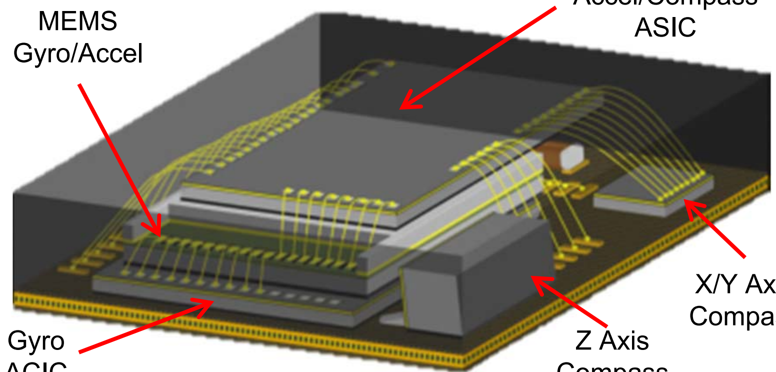
InvenSense 9-Axis

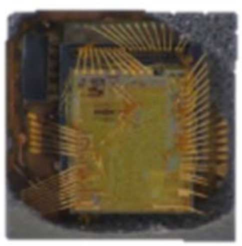


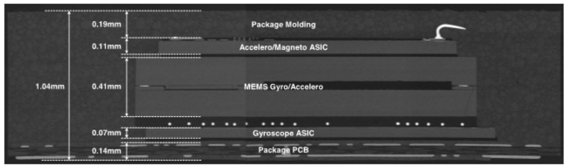


3x3x1 mm³
3 Die
<30 Wire bonds

Competition 9-Axis







4x4x1 mm^3
5 Die, including 1 vertical (Z-axis Magnet)
>55 Wire bonds

Used with permission

Application grade and bias stability

Application grade	Bias stability	Relative accuracy (*)	Main application
CONSUMER AND AUTOMOTIVE GYRO			
Consumer	10 °/s	3%	Motion interface
Automotive	1 °/s	0.3%	ESP
HIGH PERFORMANCE GYRO			
Low-end Tactical also called Industrial	10°/h (Earth rate)	10 ppm	Amunitions & rockets guidance
Tactical	1°/h	1 ppm	Platform stabilization
Short-term Navigation	0.1°/h	100 ppb	Missile navigation
Navigation	0.01°/h	10 ppb	Aeronautics navigation
Strategic	0.001°/h	1 ppb	Submarine navigation

Range of current MEMS gyros

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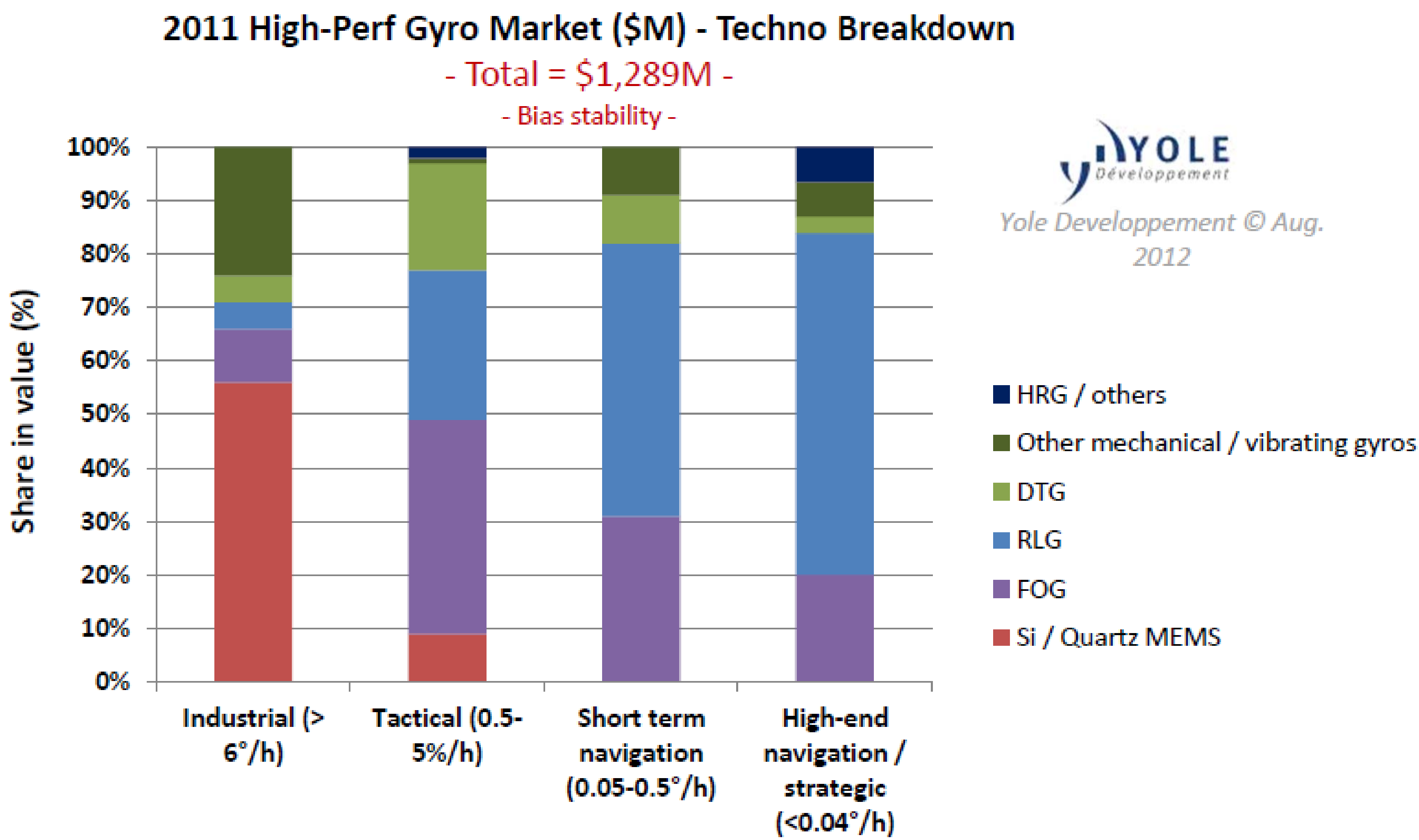
MEMS is only starting to compete on tactical grade performance



Summary

- **MEMS fabrication technology enabled low-cost, small form-factor inertial sensors**
  - **Wide variety of device architectures and specifications**
  - **Broad adoption in consumer-grade applications in just 6 years due to low cost**
- **Current sensor performance limited by current architecture and manufacturing methods**
  - **Not likely to reach beyond Tactical Grade without technology shift**

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Specifications

Silicon Sensing Systems – Single Axis High Performance

		Supply Voltage (Vdd)	Dynamic Range	Bias Variation with Temp	Bias Instability	In-Band Quiescent Noise	Bandwidth (Gain -3dB)	Operating Temp	Current Consumption	Dimensions (mm)	Mounting Options	Interface		Price	
	PinPoint™	3.3V	±75°/s to ±2700°/s	±3°/s	24°/hr to 40°/hr	<0.18°/s (100Hz)	5 -160 Hz (User Selectable)	-40°C to +85°C	4mA	5.7 x 4.8 x 1.2 to 6.3 x 2.7 x 5.5	SMD , flat, orthogonal	Analogue, Digital SPI®	Read More	Under $55	Download Brochure
	CRG20	5V	±75°/s to ±300°/s	±2.5°/s	5°/hr	0.33°/sec to 0.8°/sec	40Hz to 75Hz	-40°C to +105°C	60 mA	9 x 9.5 x 3.44	SMD	Analogue, Digital SPI®	Read More	Under $200	Download Brochure
	CRS03	5V	±80°/s to ±573°/s	< ±3°/s to < ±30°/s	10°/hr	0.04°/sec to 0.29°/sec	>10Hz to >55Hz	-40°C to +85°C	35mA	27 x 27 x 9 to 29 x 29 x 18.4	Case Unsealed, PCB Unpackaged	Analogue	Read More	Under $300	Download Brochure
	CRS07	5V	±100°/s to ±573°/s	±3°/s to ±30°/s	10°/hr	0.5°/sec to 0.29°/sec	>10Hz to >55Hz	-40°C to +85°C	< 35 mA	21 x 22 x 11.55 to 24.2 x 24.5 18.3	Case unsealed, PCB unpackaged	Analogue	Read More	Under $300	Download Brochure
	CRS09	5V	±100°/s to ±200°/s	< ±1°/s to < ±3°/s	3°/hr	0.03°/sec	55Hz	−20°C to +85°C	100mA	63 x 63 x 19	Case unsealed	Analogue	Read More	Under $1250	Download Brochure
	CRS39	5V	±25°/s	±0.14°/s	0.2°/hr	0.015°/sec	25Hz	−10°C to +110°C	80mA	75 x 24.5 x 21.5 to 98 x 42.5 x 23	Case unsealed, PCB unpackaged	Analogue	Read More	Enquire	Download Brochure
	CRH01	5V	25°/s to 400°/s	±0.2°/s to ±0.50°/s	0.4°/hr	0.02°/sec	90Hz	-40°C to +85°C	60mA	35 x 35 x 25 to 38 x 35 x 25	Case unsealed	Analogue	Read More	Enquire	Download Brochure
	SIRRS01	5V	±50°/s to ±1,500°/s	< ±3°/s	3°/hr	0.30°/sec to 0.55°/sec	>50Hz to >60Hz	-40°C to +75°C	< 50 mA	31.8 x 31.8 x 17.3	Case sealed	Analogue	Read More	Enquire	Download Brochure

Supply Voltage (Vdd) Dynamic Range Bias Variation with Temp Bias Instability In-Band Quiescent Noise Bandwidth (Gain -3dB) Operating Temp Current Consumption Dimensions (mm) Mounting Options Interface

ST MEMS Gyroscopes

Part #	Description	Fullscale	Main Features
L3GD20H	3-axis gyroscope in 3x3 LGA package. One single gyro for many applications: • Navigation • Location based services • Geo-fancing, • Gaming, • Pointing devices, etc.	• ±245dps • ±500dps • 2000dps	• Very Low noise (0.011 dps/√Hz) • Ultra Low Power Consumption • Embedded Power down • Embedded Sleep Mode • 16-bit Resolution • I²C/SPI interfaces • Embedded FIFO • Embedded Temp. Sensor • Wide V. Range: 2.2V to 3.6V • Low voltage compatible IOs, 1.8 V
L2G3IS	2-axis OIS gyroscope in 3x3.5x1 LGA Package Applications: • optical image stabilization • Applications requiring very high sensitivity and ultra low noise.	• ±65dps • ±130 dps	• Ultra Low noise (0.006 dps/√Hz) • Low Power Consumption • Power-down and Sleep Mode for smart power Saving • SPI digital interface • Embedded temp. sensor • Integrated low and high-pass filters with user-selectable bandwidth • Wide V. range: 2.4 V to 3.6 V • Low voltage-compatible IOs (1.8V)

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ST MEMS Inertial Modules

Part #	Description	Fullscales	Main Features
LSM6DS0	iNEMO inertial module in 3x3: • 3-axis accelerometer • 3-axis gyroscope	Accel: ±2/±4/±8 g Gyro: ±245/±500/±2000 dps	• Embedded Power-down • Embedded Sleep modes • SPI/I2C serial interface • Embedded Temp. Sensor • Embedded FIFOs • V. Range: 1.71 V to 3.6 V • Independent IOs supply (1.8 V) • Embedded Selftest
LSM9DS0	iNEMO inertial module in 4x4 LGA Package: • 3-axis accelerometer • 3-axis gyroscope • 3-axis magnetometer	Accel: ±2/±4/±6/±8/±16 g Mag: ±2/±4/±8/±12 Gyro: ±245/±500/±2000 dps	• SPI / I2C serial interfaces • V. Range 2.4 V to 3.6 V • 16-bit data output • Power-down / low-power mode • Programmable interrupt generators • Embedded self-test • Embedded temperature sensor • Embedded FIFO • Position and motion detection • Click/double-click recognition • Intelligent power saving for handheld devices

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ST Compass Modules

Part #	Description	Fullscales	Main Features
LSM303C/ LSM303E	E-compass in 2x2 LGA Package • 3-axis accelerometer • 3-aixs magnetometer Applications: • Tilt-compensated compasses • Motion-activated functions	Accel: ±2/±4/±8 g Mag: ±16 Gauss	• Ultra-compact • High-performance • SPI / I2C serial interfaces • 16-bit data output • Analog supply voltage 1.9 V to 3.6 V • Power-down mode / low-power mode • Programmable interrupt generators • Embedded temp. sensor • Embedded FIFO

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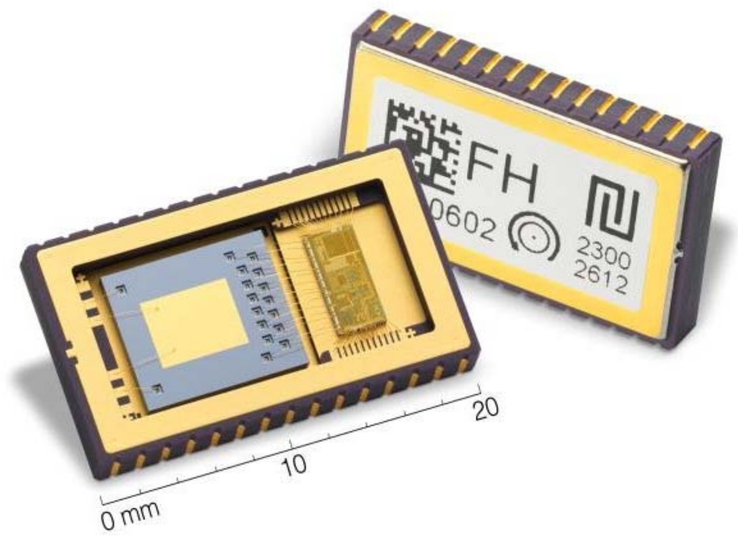
Example of a high performance MEMS Gyro



GYPRO2300 released at Electronica, Nov 2012

- Z-axis Angular Rate Sensor
- 300°/s input range, 100 Hz BandWidth
- 24-bit output (SPI)
- Bias Instability (Allan variance): 1°/h
- Bias variation over temp (-40/+85°C): +/- 0.05 °/s
- Noise density: 10°/h/√Hz
- Power consumption: 25mA under 5V
- 19.6 x 11.5 x 2.9 mm
- 2 grams

tronics