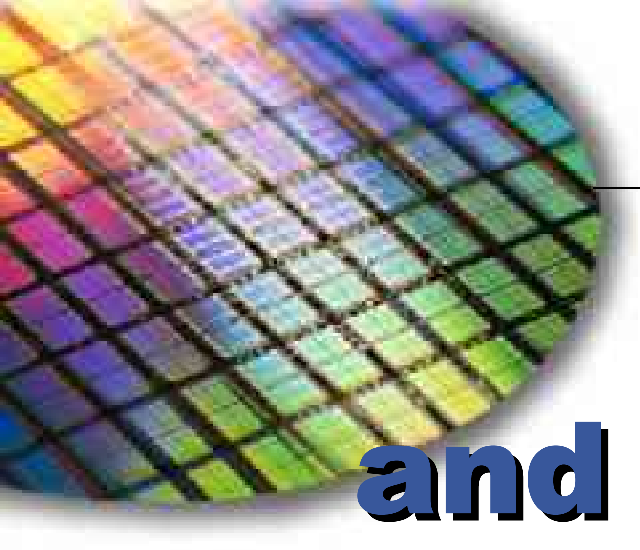

Design and Development of Accelerometers and Gyros

Tutorial 2B

Bob Sulouff
Analog Devices Inc.
Cambridge, MA. 02139

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ANALOG DEVICES

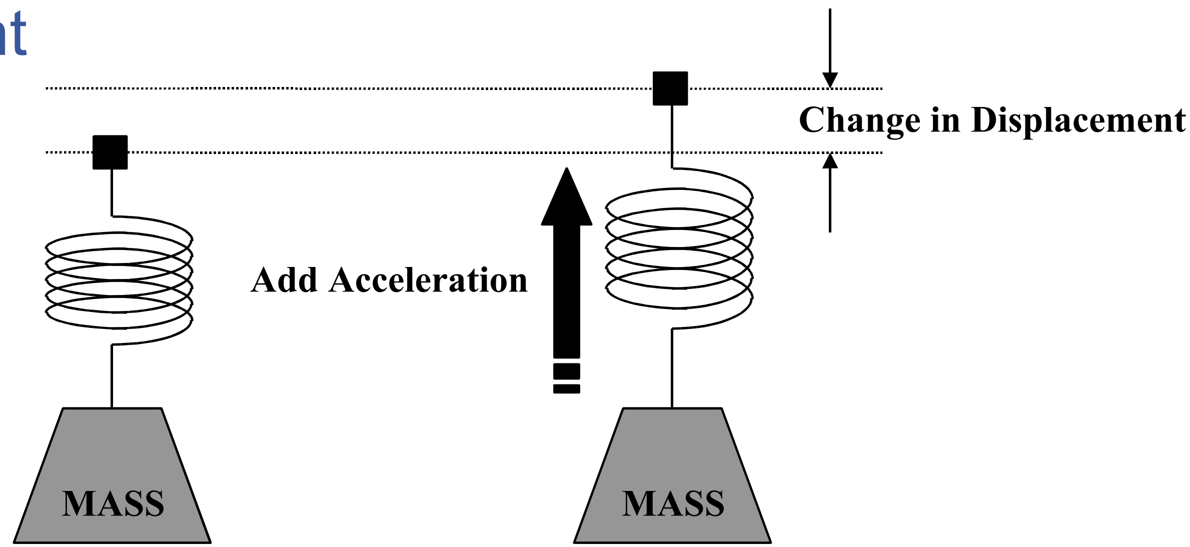
Presentation Outline

- Inertial Sensor Design Approach
- Product Improvements
- Applications
- Gyroscope Design & Applications
- Conclusions

*i*MEMS® Technology

F=MA

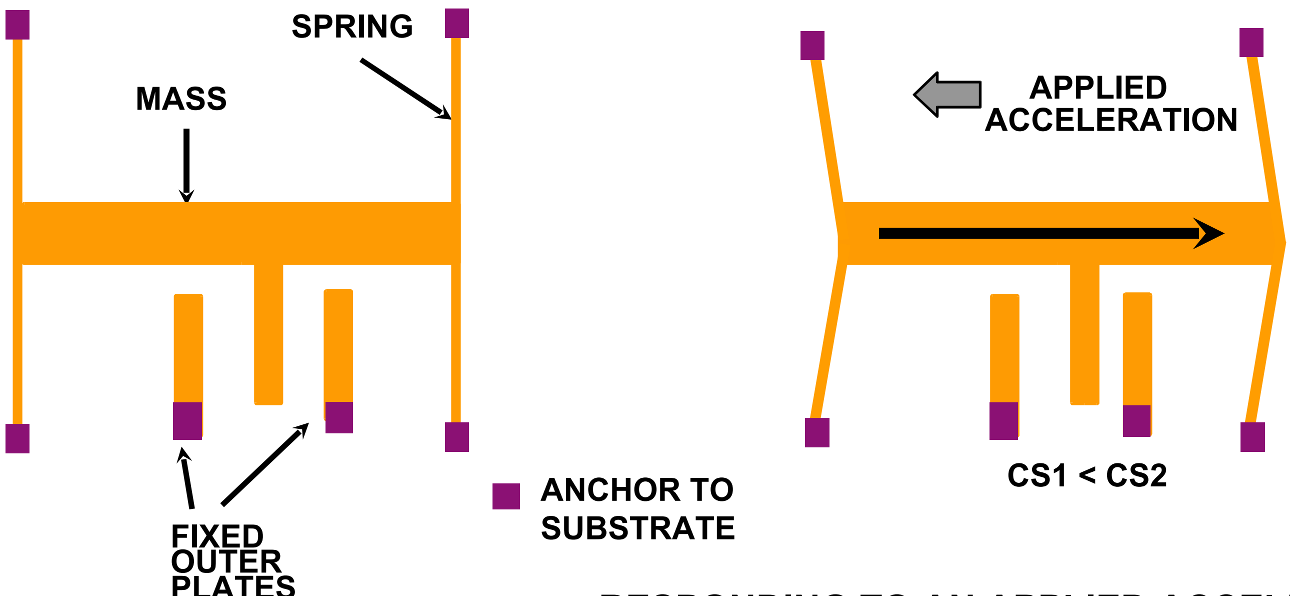
- Acceleration can be measured using a simple mass/spring system.
  - Force = Mass * Acceleration
  - Force = Displacement * Spring Constant
  - So   Displacement = Mass * Acceleration / Spring Constant



*i*MEMS® Technology

Sensor Principle: Differential Capacitive Sensing

- **Use Silicon to make the spring and mass, and add fingers to make a variable differential capacitor**
- **Measure change in displacement by measuring change in differential capacitance**

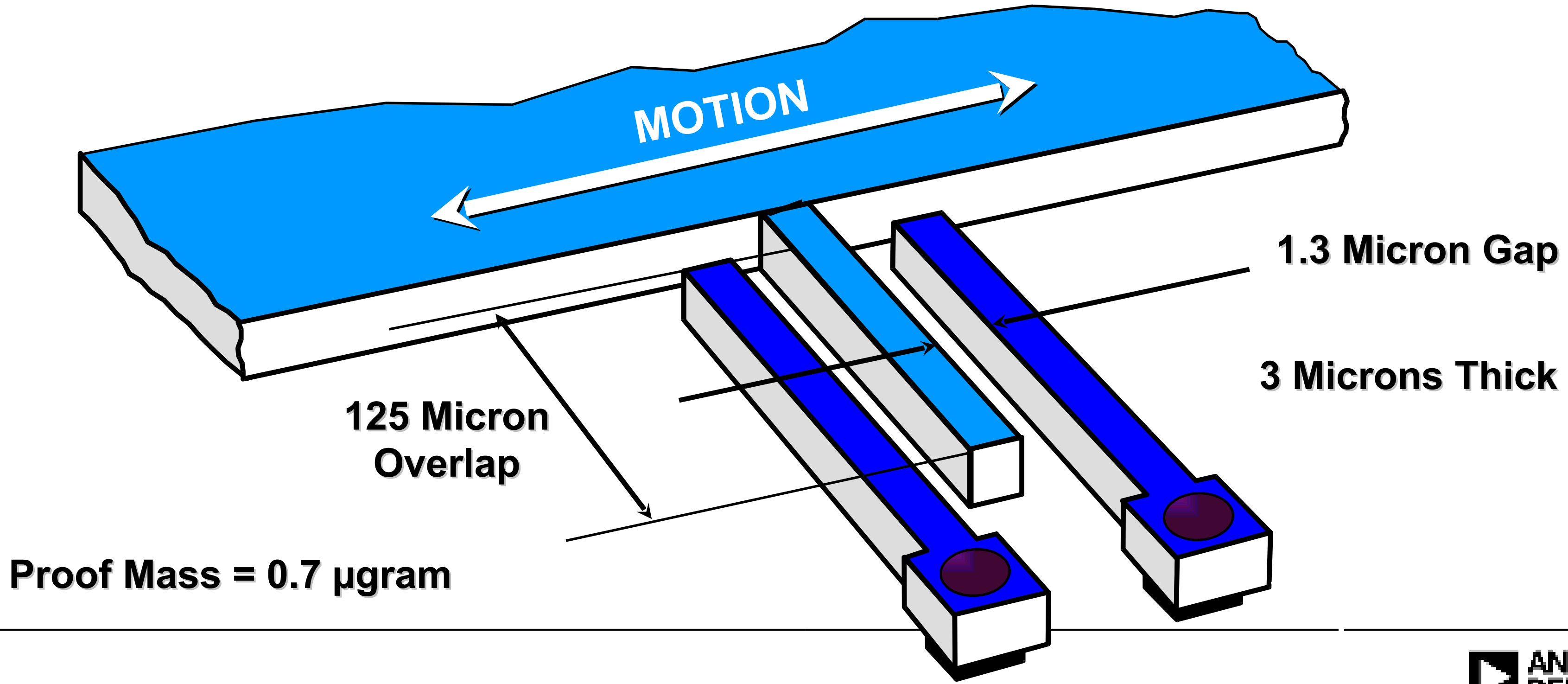


SENSOR AT REST

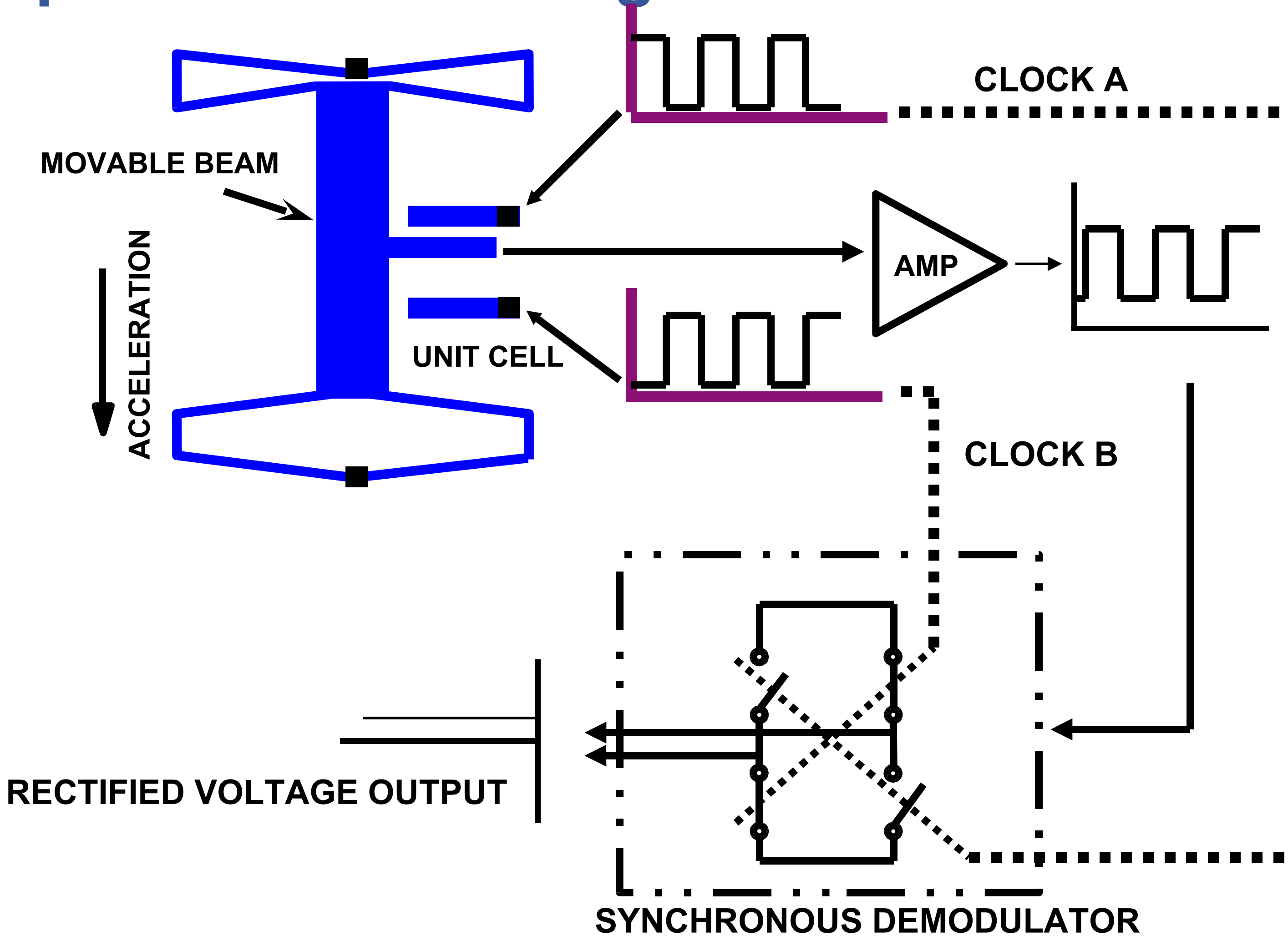
RESPONDING TO AN APPLIED ACCELERATION (MOVEMENT SHOWN IS GREATLY EXAGGERATED)

ADI Accelerometers: Key Dimensions Interesting Facts

- 0.1 pF per side for the differential capacitor
- 20 zF (10-21 F) smallest detectable capacitance change
- 2.5 pm minimum detectable beam deflection (one tenth of an atomic diameter)

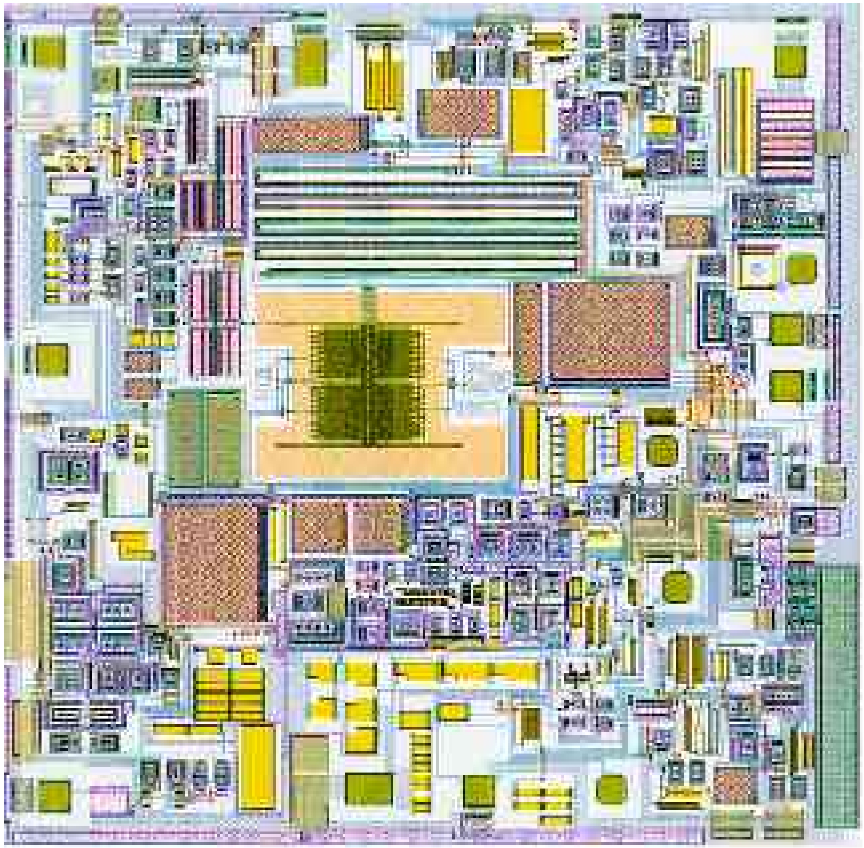


*i*MEMS® Technology
Capacitance to Voltage Conversion



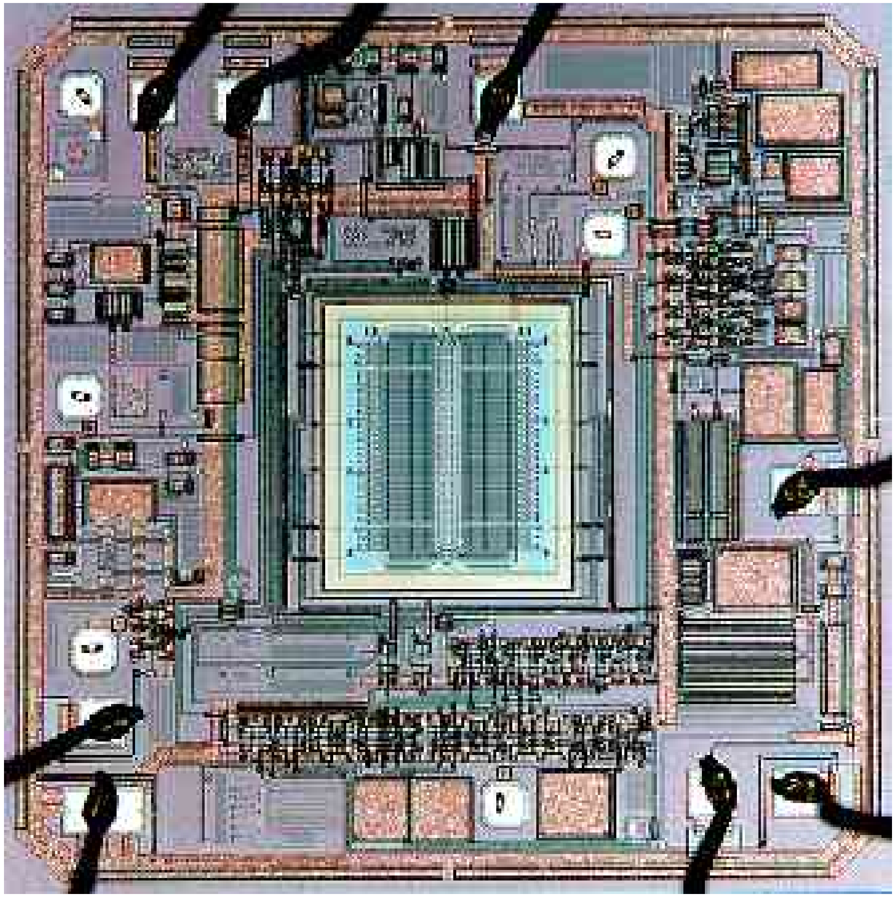
Design Evolution ADXL50 (1993)

- **Circuit architecture**
  - Closed loop
    - Concerns about polysilicon lead to force feedback design
  - 0.6 V p-p complimentary modulation of differential capacitors
  - Resistive biasing/FB (3 MΩ)
- **MEMS design**
  - Dielectric under structure
  - Anchors at periphery
  - Beam not centered or symmetric



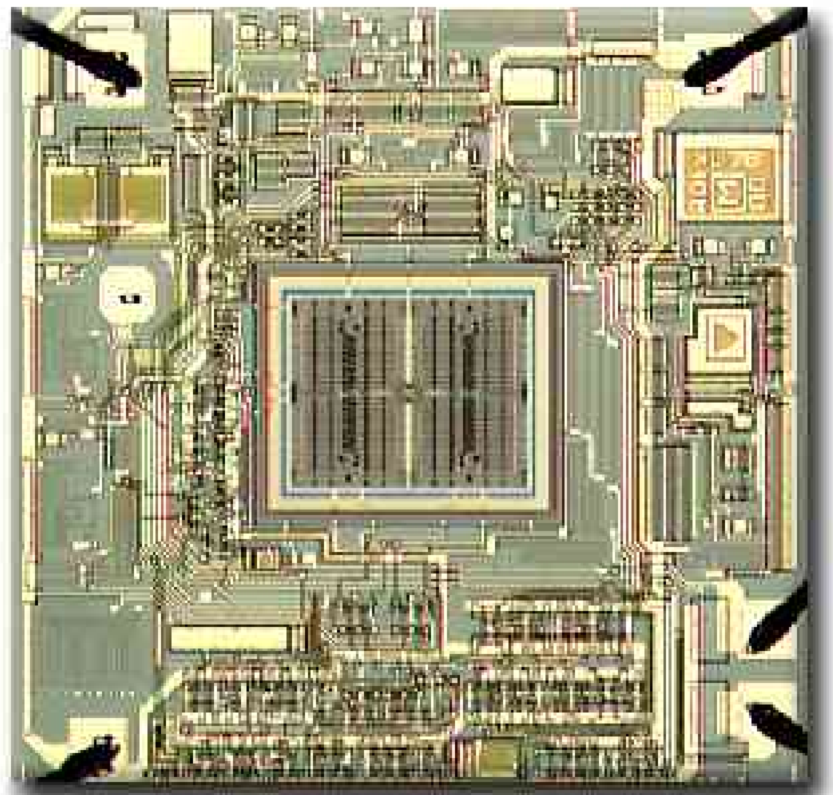
Design Evolution ADXL76 (1996)

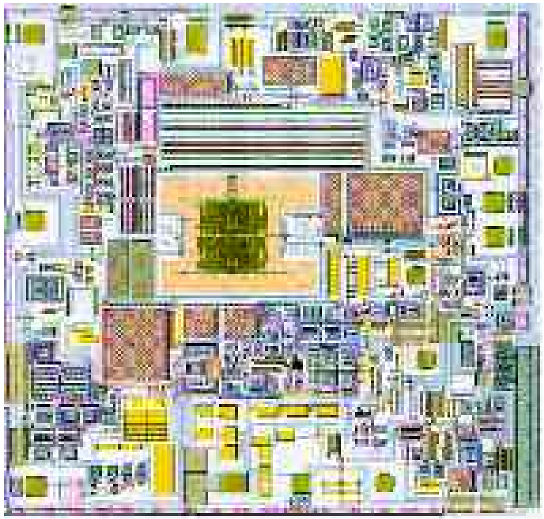
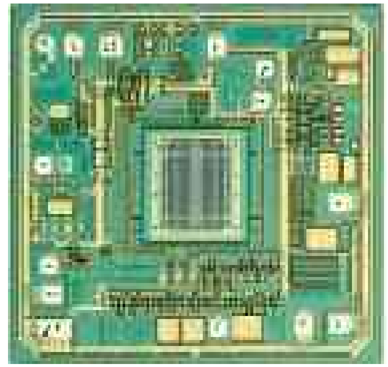
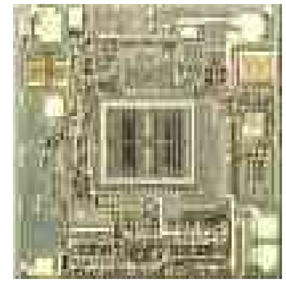
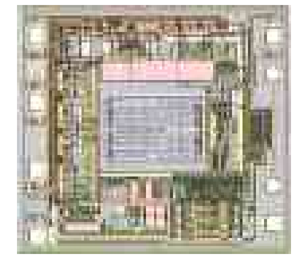
- Circuit architecture
  - Open loop
    - Polysilicon robustness now confirmed
    - Full supply complimentary clocks
    - Reduced die size
    - Ratiometric
  - Switched cap filter
  - Switch biasing
- MEMS Design
  - Conductor under structure
  - Anchors on axis
  - Beam centered & symmetric
    - Better offsets & tempco's



Design Evolution
ADXL78 (2002)

- **Circuit architecture**
  - **Closed loop**
    - Overload performance pushed design back to feedback
    - Servo complimentary clock amplitude
    - Differential architecture
      - Ratiometric & EMI resistant
- **MEMS Design**
  - **Two structures**
  - **Conductor under structure**
  - **Two springs/structure**
    - Robust to process variations
  - **Beam centered & symmetric**
- **Layout**
  - **Compact!**

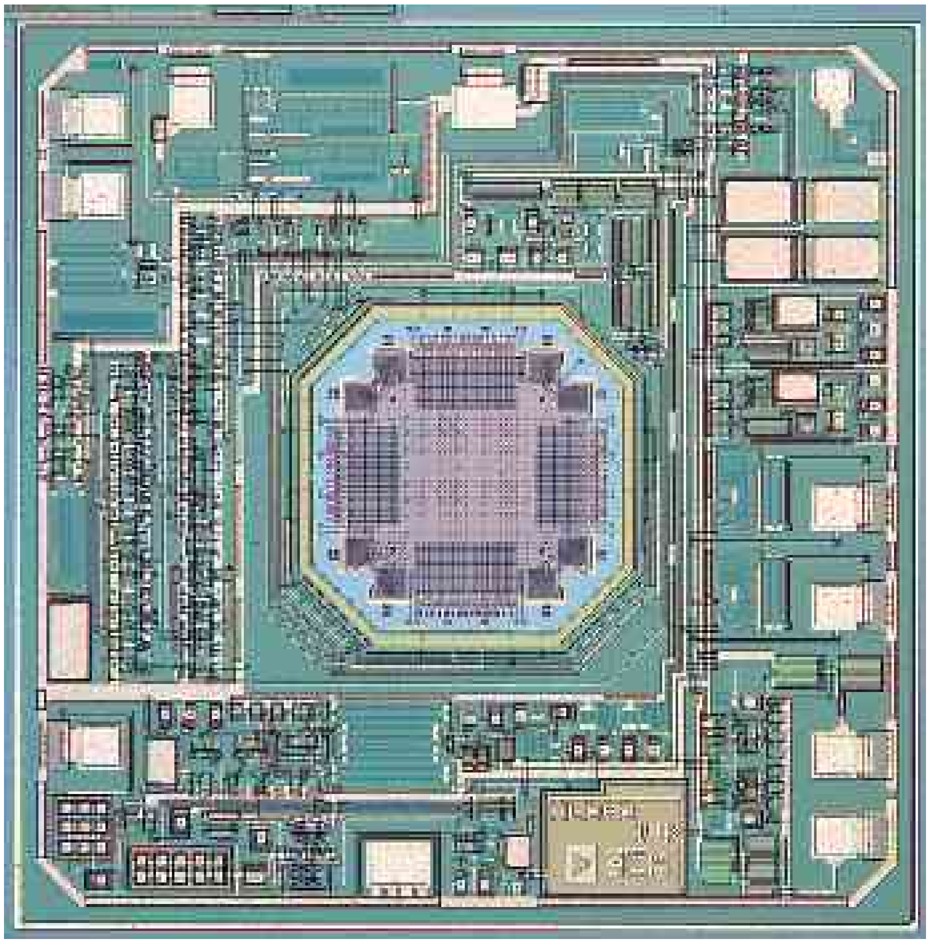


	ADXL50 (1993)	ADXL76 (1996)	ADXL78 (2002)	ADXL40 (2004)	
Die Area	10.8	5.4	2.7	2.5	mm^2
MEMS Area	0.43	0.38	0.27	0.22	mm^2
% MEMS	4.0%	7.0%	10%	8.8%	
C_s	100	100	40	160	fF
f_o	25.0	24.5	24.5	12.5	kHz
Noise	4.0	1.0	1.0	1.0	mgee/ rt.hz
Offset	3.0	1.0	0.5	0.5	gee

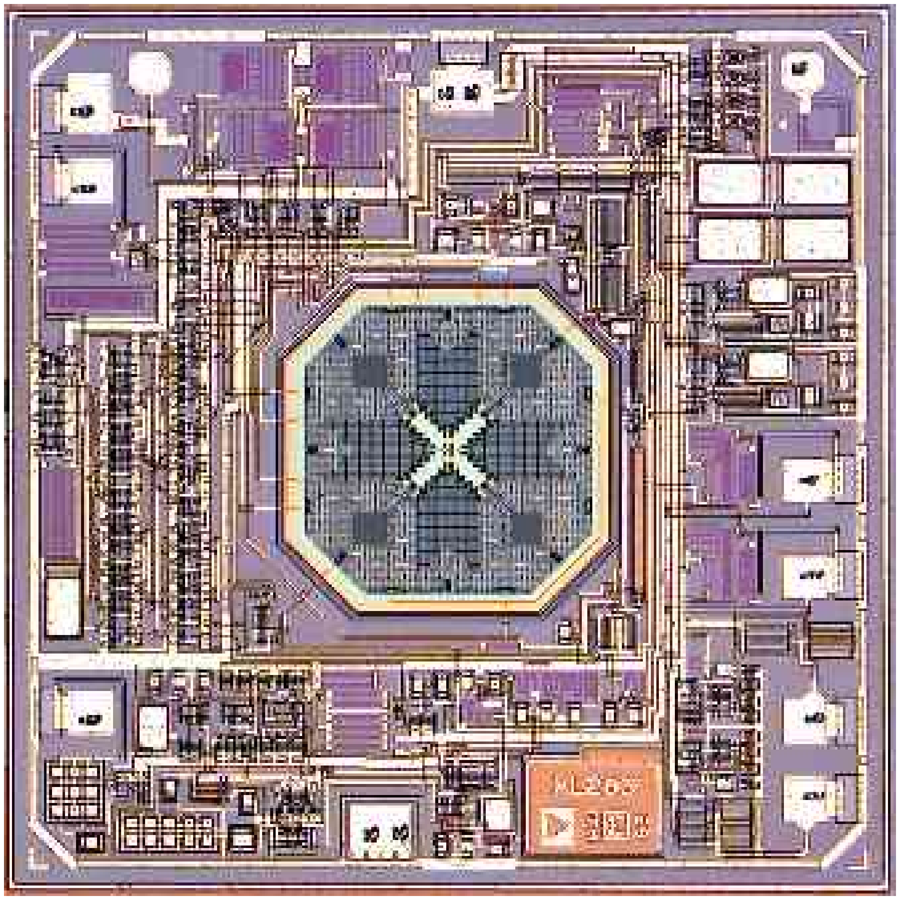
ANALOG DEVICES

Design Example:
ADXL203 50 mg accurate, +/- 1.7 g, 2 axis XL



- **Problem:**
  - **How do we get a 10x improvement in null accuracy with minimal investment?**
- **Solution:**
  - **Start with ADXL202 platform and make minimal changes**
    - Structure
    - Electronics

Design Example:
ADXL203 50 mg accurate, +/- 1.7 g, 2 axis XL



- **Problem:**
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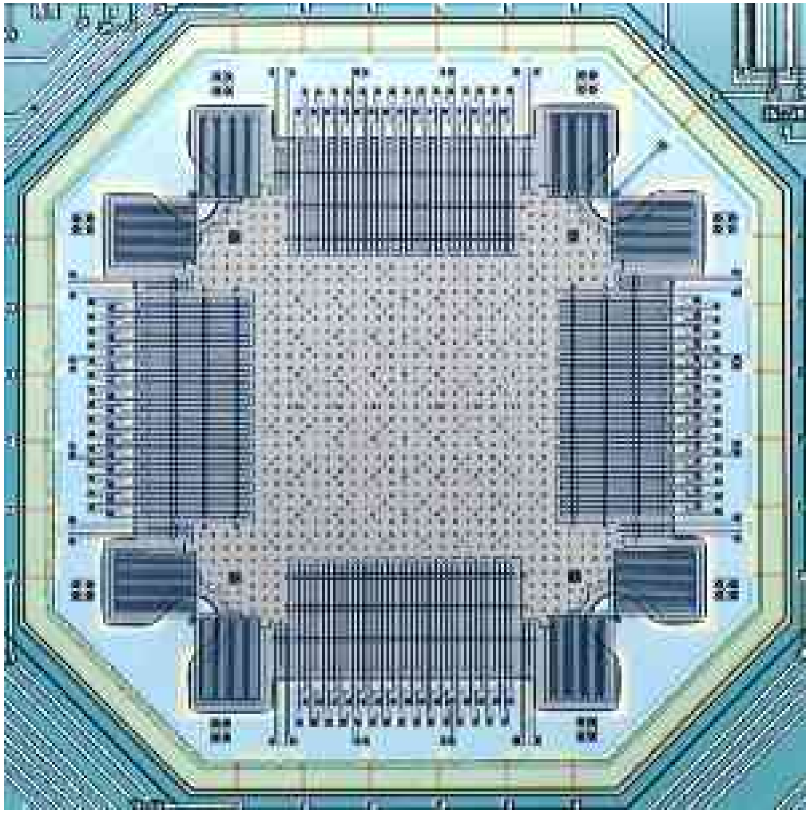
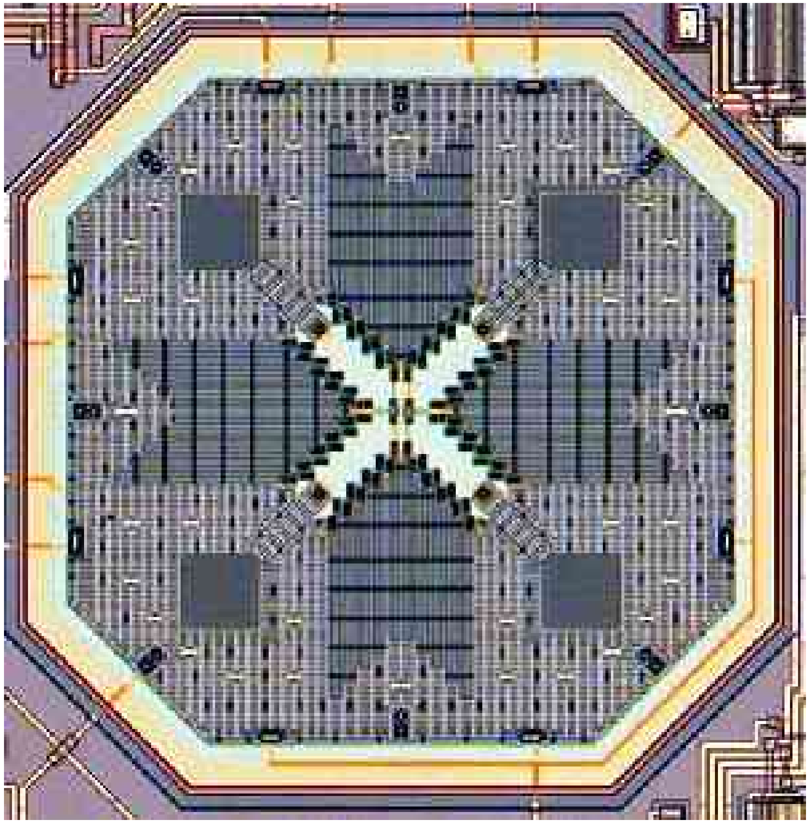




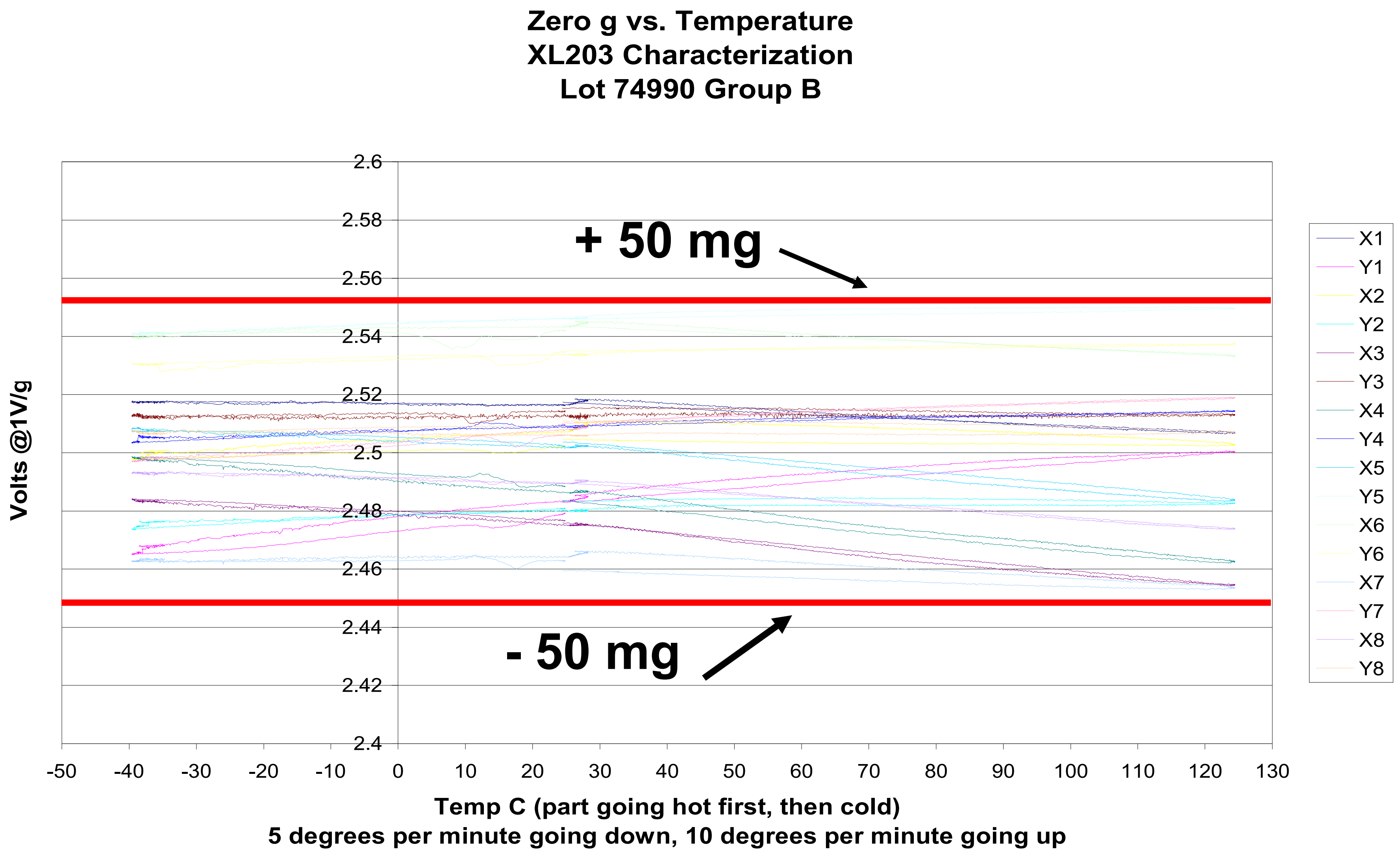
- Move anchors towards center of die
  - Modeling & experiment verification
- Lower resonant frequency (10 kHz -> 5.5 kHz)
- Use 4 µm polysilicon

ADXL203 Highlights

- **Culmination of 15 years of learning**
  - Process, structure design, electronics, and packaging
- **Typical 50 mg absolute accuracy over temperature, -40 to 125C**
  - Measure absolute tilt to 3 degrees over temp
  - Resolve tilt changes to 0.01 degrees (1 mm over 100 m)
- **Minimalist circuitry**
  - For small size, thus low cost
  - Low noise (110 µg/rt Hz.)
  - Low drift
- **Small 5 x 5 x 2 mm LCC package enabled by integration**

- **Details:**
  - Sensitivity
    - 8.2nm/g
  - Resolution
    - 1Hz BW -> 800fm (Gyro 16 fm)
    - 100 fF -> 50zF (Gyro 12 zF)
  - Offset
    - 0.05 g -> 4 Å (250 ppm)

ADXL203 0 g Data Over Temperature

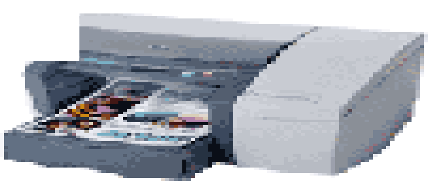


Interesting Applications

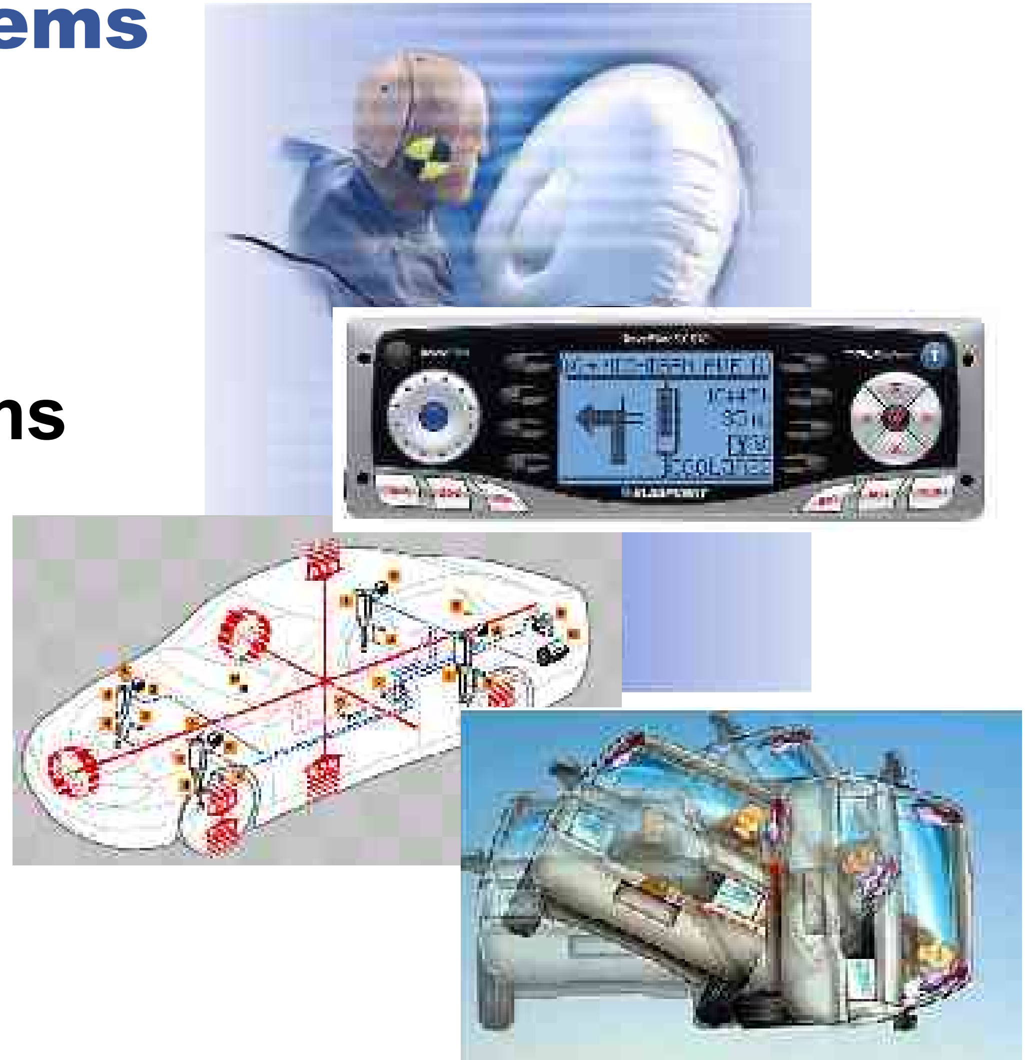
- Air Bags
- Gesture Recognition
- Security
- Tilt Correction
- GPS Inertial Ref
- Toys – Sports
- Vibration Sense
- Projector Keystone

"There are 1.6 MEMS devices per person in use today in the U.S. and the number is expected to grow to nearly 5 devices per person by 2004.

—MEMS Industry Group



ADI's *i*MEMS® Inertial Sensors in Automotive Systems



- Air Bag Systems
- Navigation Systems
- Car Alarms
- Vehicle Dynamic Control Systems
- Rollover Safety Systems

ANALOG DEVICES

ADI Sensors Used in Consumer and Industrial Products and Applications

Sports Aids

Health Products
(Blood Pressure Monitors)

Sports Products (Pedometers)

Performance Meters

LCD Projectors

PC Security

ANALOG DEVICES

Blood Pressure Monitor

- Company: OMRON
- Product: Portable Blood Pressure Monitoring Device
- ADI Inside: ADXL311JE
- Function: Tilt Sensing
  - Measures forearm angle to ensure correct positioning of the wrist (at heart level)
  - Results in higher blood pressure measurement accuracy

Developing Applications
Motion Sensing in Smart Handhelds

- Tilt-sensing and motion recognition for handheld devices
- Intuitive spatial browsing on small screen devices
- Orientation and location detection for mobile phones

*i*MEMS® Technology For Handhelds

Application Ideas

- **Situational Awareness**
  - **Enables optimization of phone features and functions based on the detection of environmental context, e.g.:**
    - Turns off display when phone is held at ear level
    - Turns off vibrating mode when phone is not carried or held (not moving)
    - Automatically activates pedometer function when walking motion is recognized
    - Automatically selects portrait or landscape display orientation for picture taking or gaming
    - Manages incoming calls based on user's activity level

*i*MEMS® Technology For Handhelds

- **Large Document Panning and Zooming**
  - Enables intuitive display control of large documents (e.g. maps) through tilt or inertial sensing
- **Single-Handed Operation**
  - Enables one hand operation of simple functions
- **Data Entry/Selection**
  - Enables menu and cursor control through tilt sensing and motion detection
- **Intuitive Gaming**
  - Enhances gaming experience by providing intuitive, button-less control of gaming action
- **Electronic Compass Tilt-Compensation**

ANALOG DEVICES

Cellular Phone/Pedometer

- **Company:** FUJITSU
- **Product:** DoCoMo Cellular Phone for Japanese Market
- **ADI Inside:** ADXL311JE
- **Function:** Motion Sensing for Pedometer Function

  - Displays number of steps walked
  - Displays distance walked based on stride input
  - Displays calories expanded based on user weight input

ANALOG DEVICES

Pedometers

Pedometer model SDM [Tailwind and SDM Triax 100
Company: Nike, Inc.
ADI Inside: iMEMS® ADXL78 and ADXL278 accelerometers

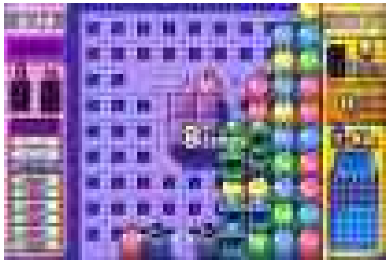
Function: Shock, tilt and inertial sensing for foot motion measurements resulting in accurate speed and distance information

Laptop Security

Anti-Theft™ PCMCIA Card for Laptop Computers
Company: Caveo Technology
ADI Inside: iMEMS® ADXL202E accelerometer

Function: Inertial and tilt measurement for security perimeter and motion password setting

Gaming

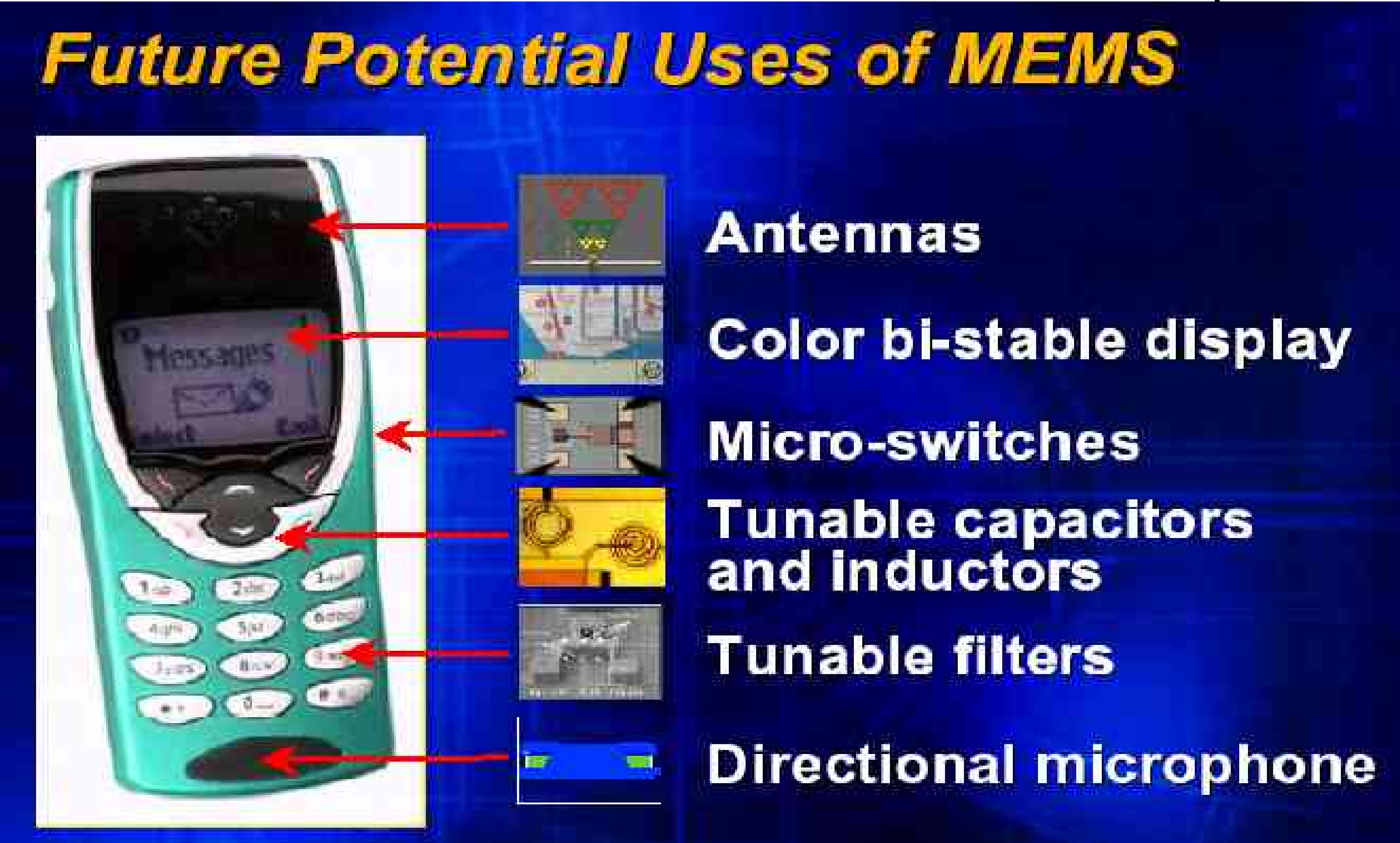


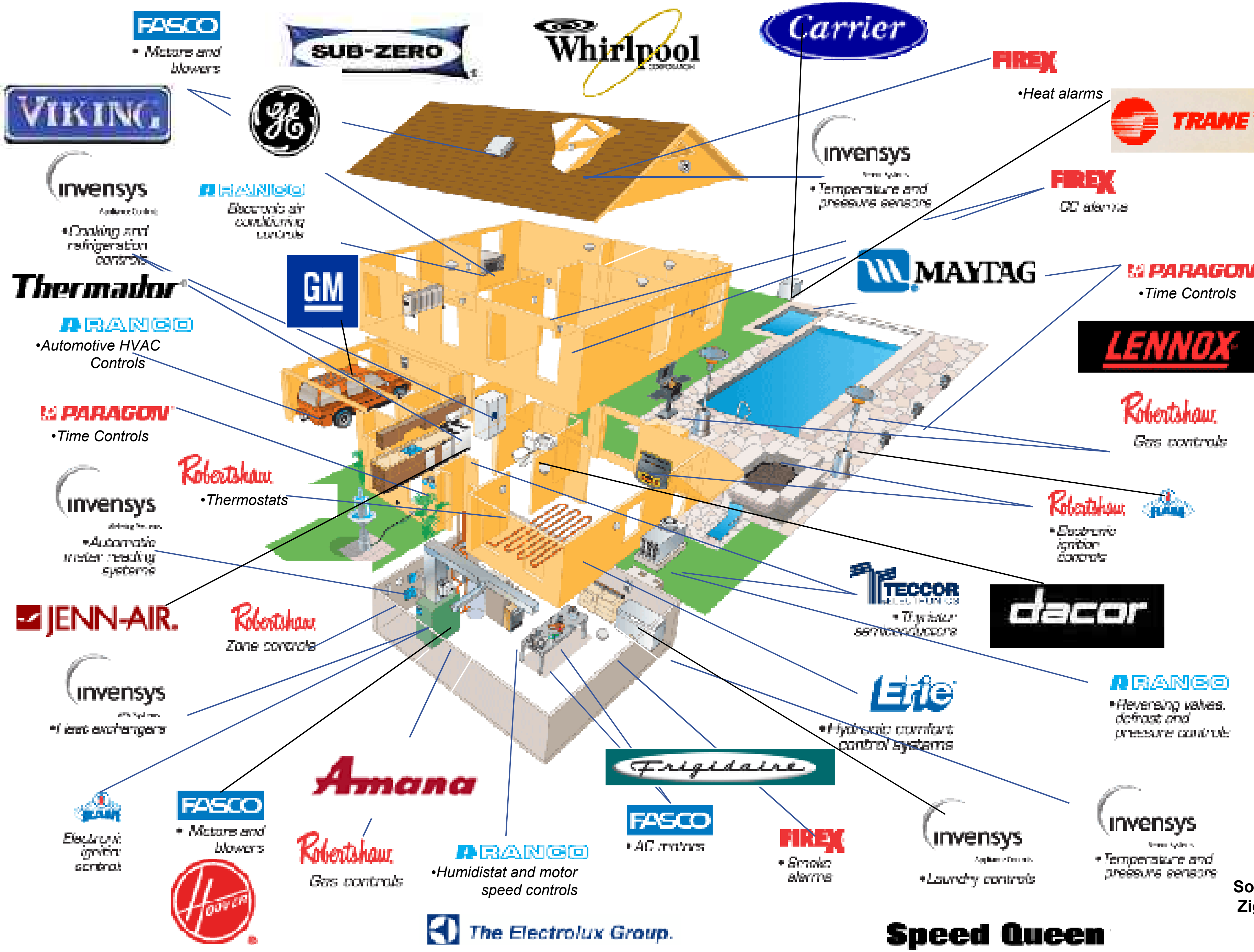
Game Boy® Advance with Kirby Tilt-n-Tumble™ and Happy Panechu™
Company: Nintendo
ADI Inside: iMEMS® ADXL202 and ADXL202E accelerometers

Function: Tilt measurement resulting in intuitive game feature control

MEMS in Personal Communications

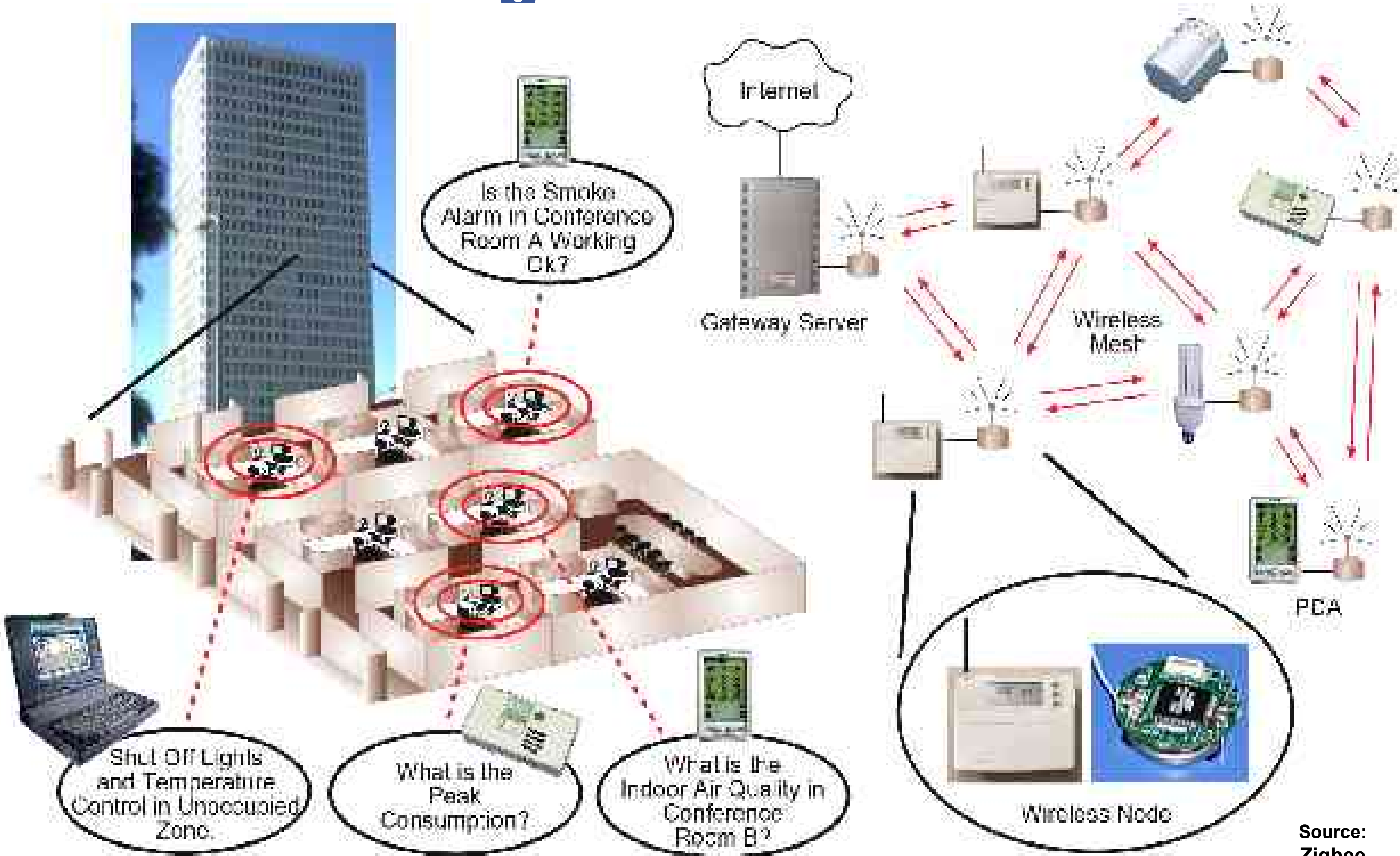
Intel Developers Conf.





Source: Zigbee

Wireless Buildings



Source: Zigbee

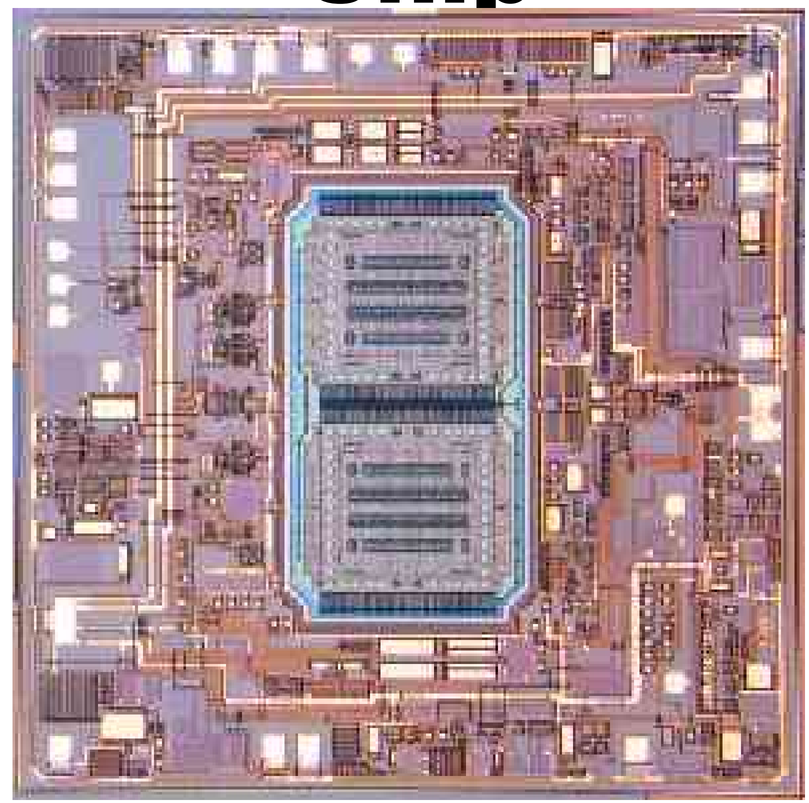
Key to success: reduced installation costs

Integrated Micromachined Gyro

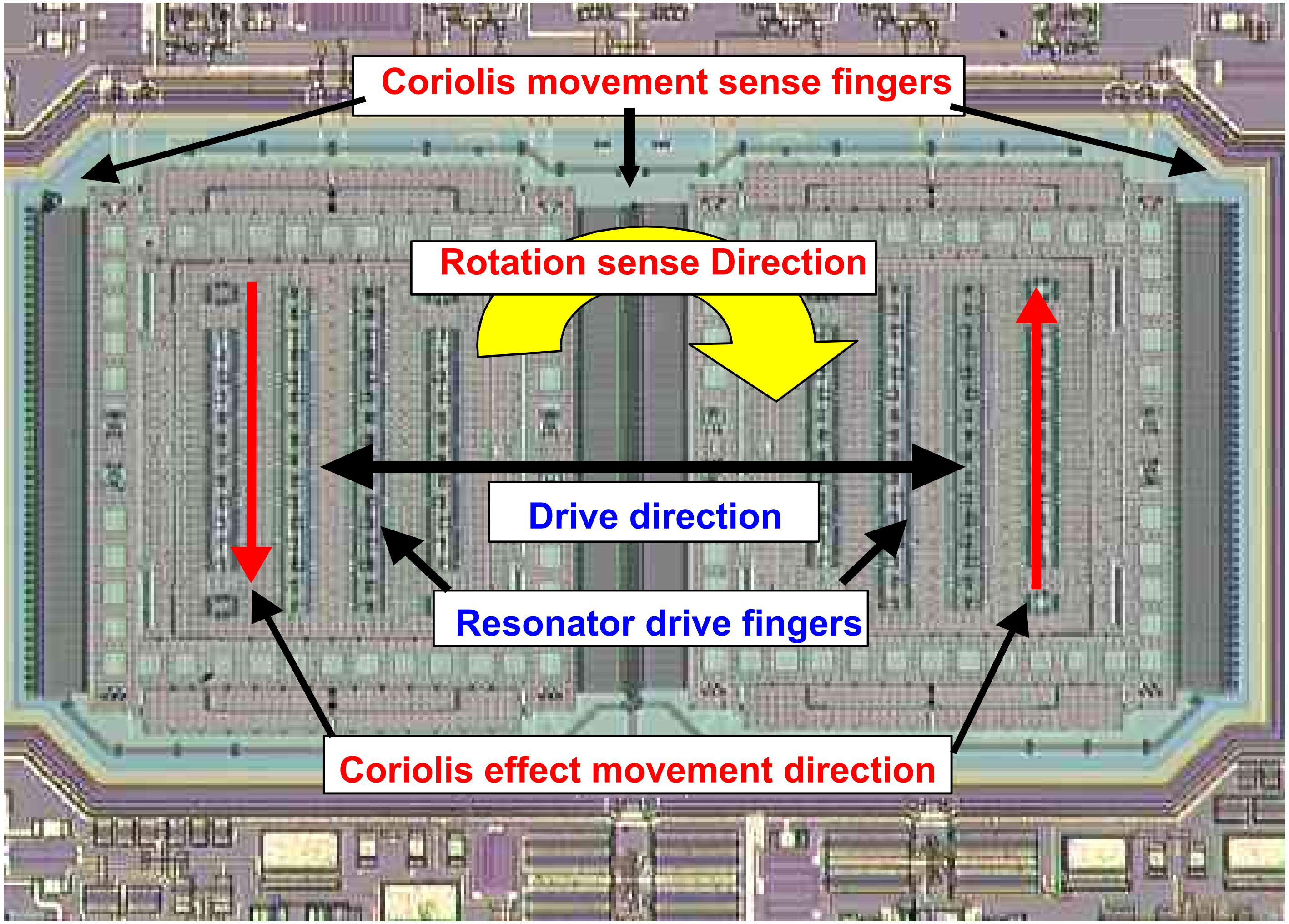
Single Chip Rate Sensor
5V Operation
Std Atmosphere
150 deg per second
Self-Test
0.03 deg/sec/sqrt hz
Compensated 5%

Lessons Learned In Accelerometer Development of Meso Structures Detecting Nano dimensions now applied to sub pico-dimensions

Single Chip



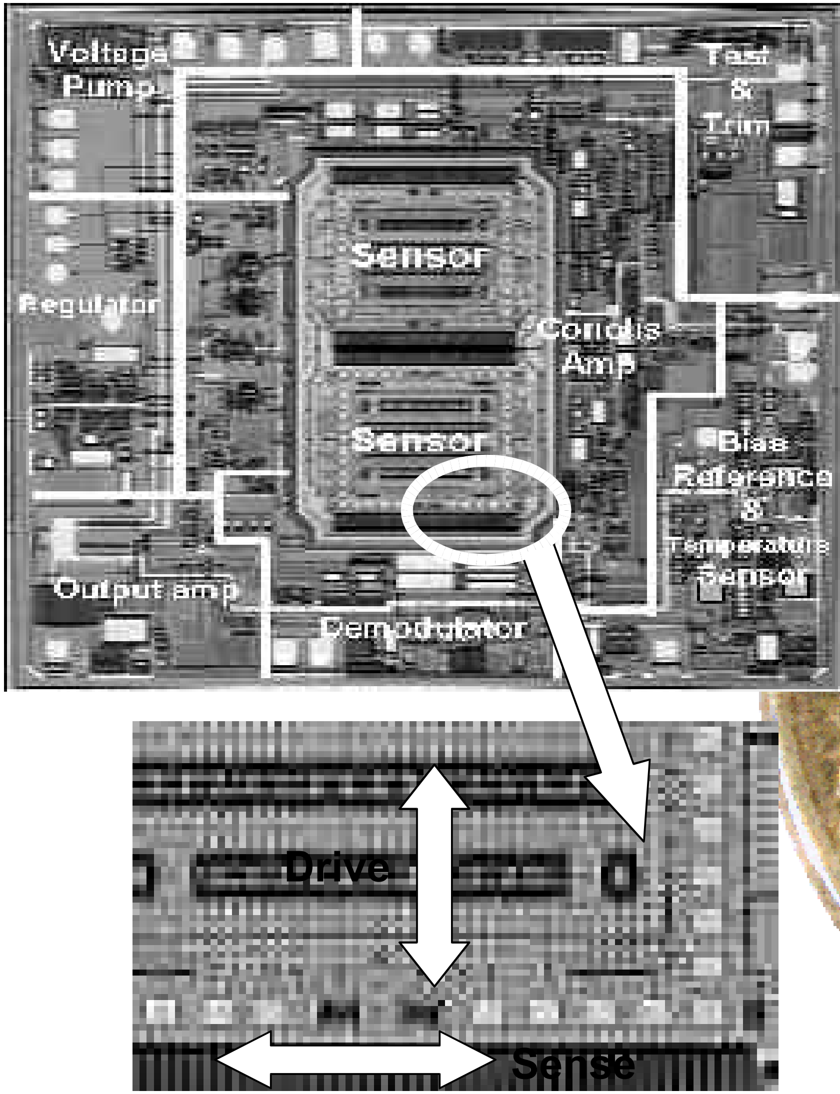
iMEMS Gyro Sensor

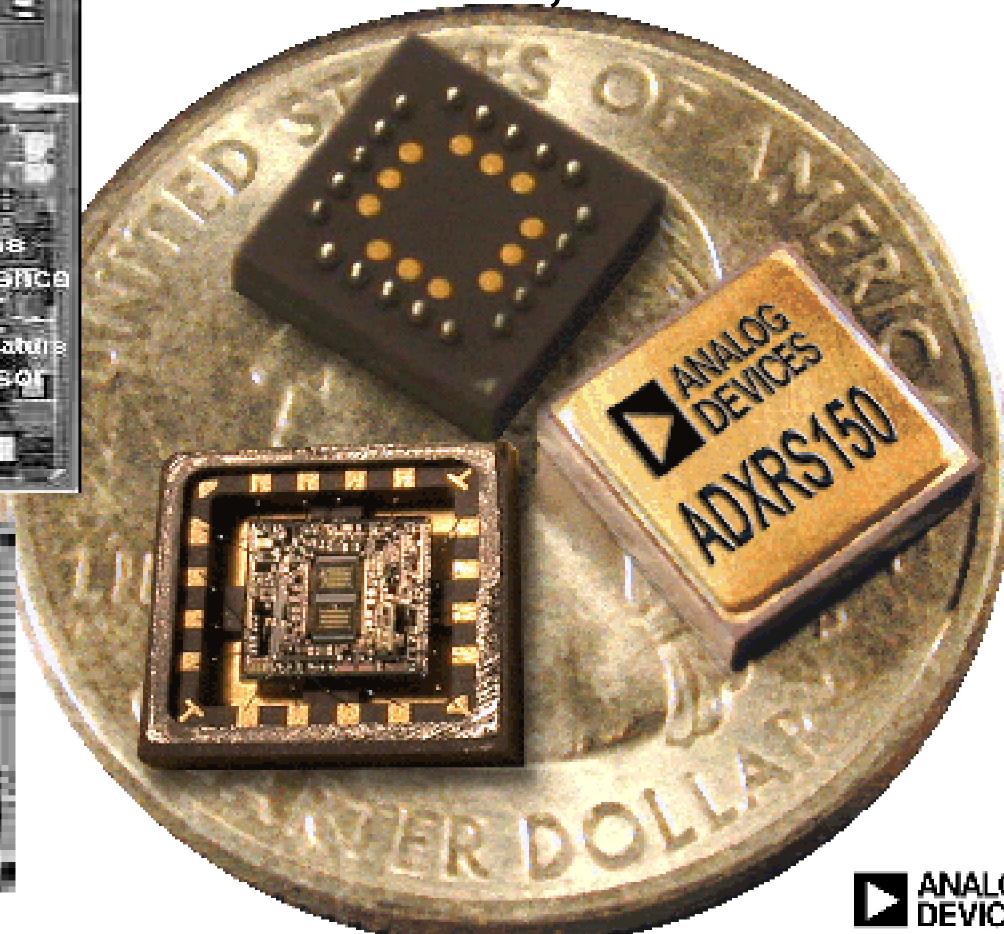


ANALOG DEVICES

Coriolis Accel Full Scale Deflection 0.3 Nanometers
Quadrature Rejection 1 ppm

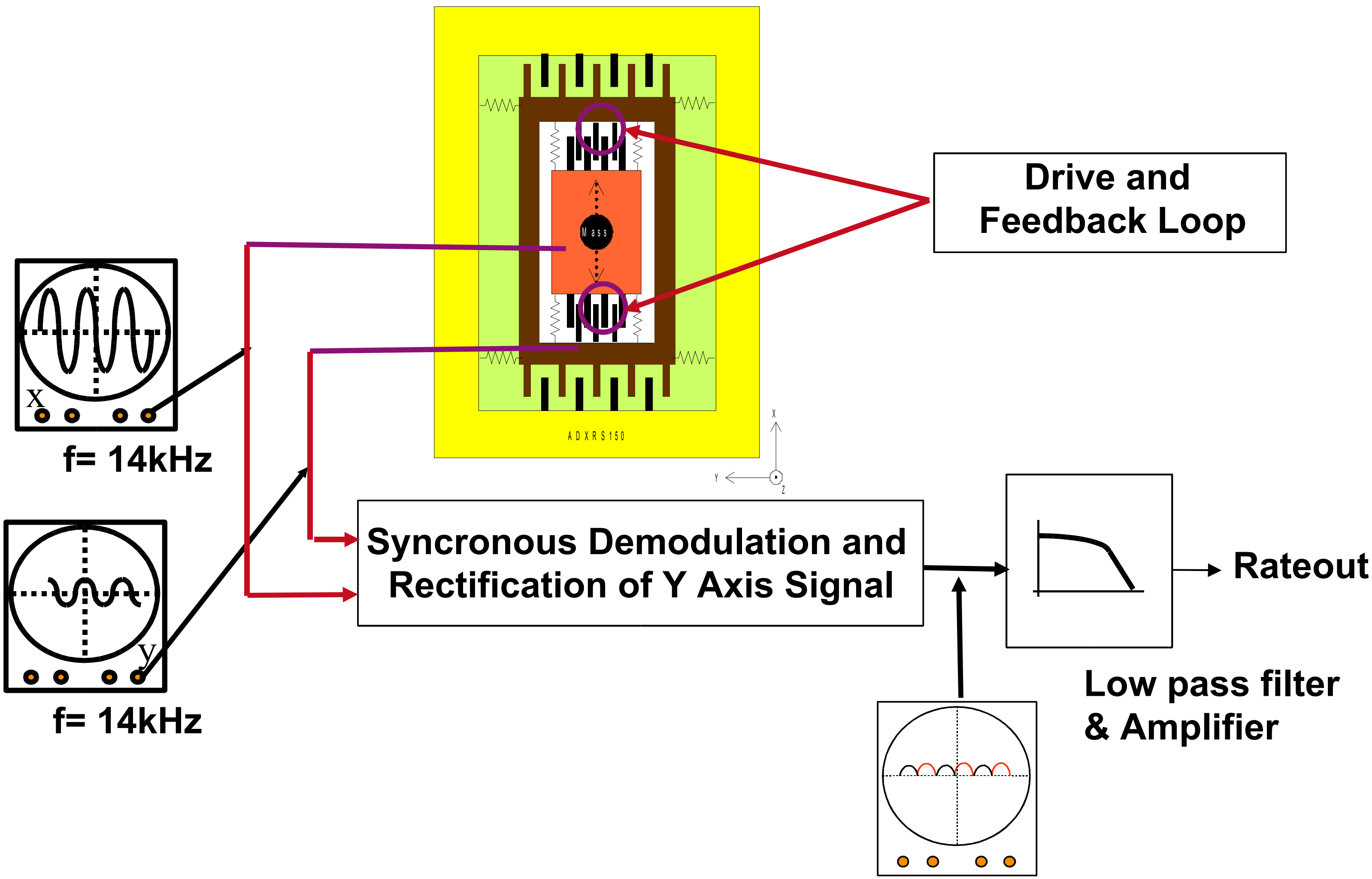
Design Issues:
Aerodynamics, Shock, Vibration, Thermal



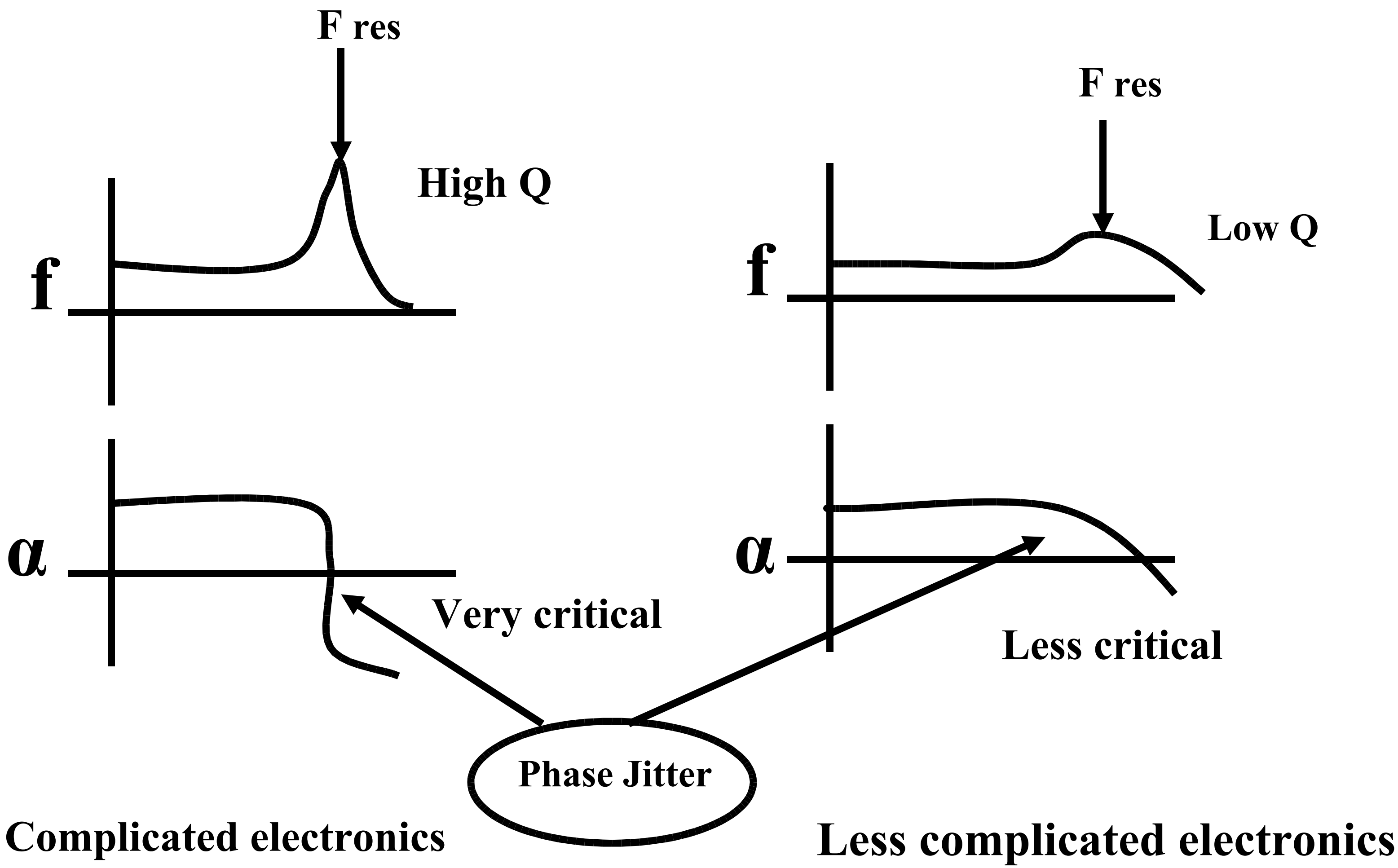


ANALOG DEVICES

Simplified Gyro Blockdiagram

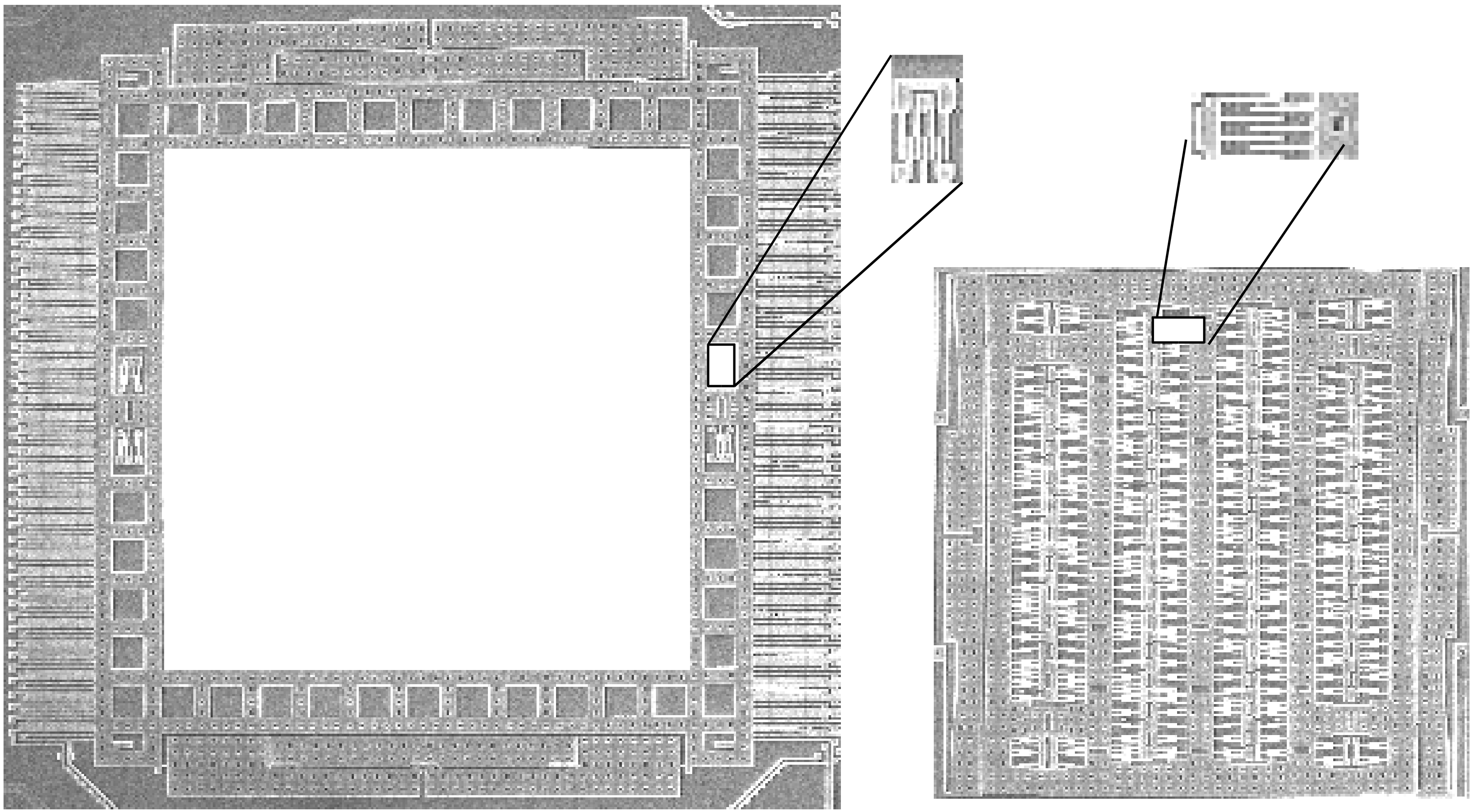


Gyro Packaging: in Vacuum or Air ?

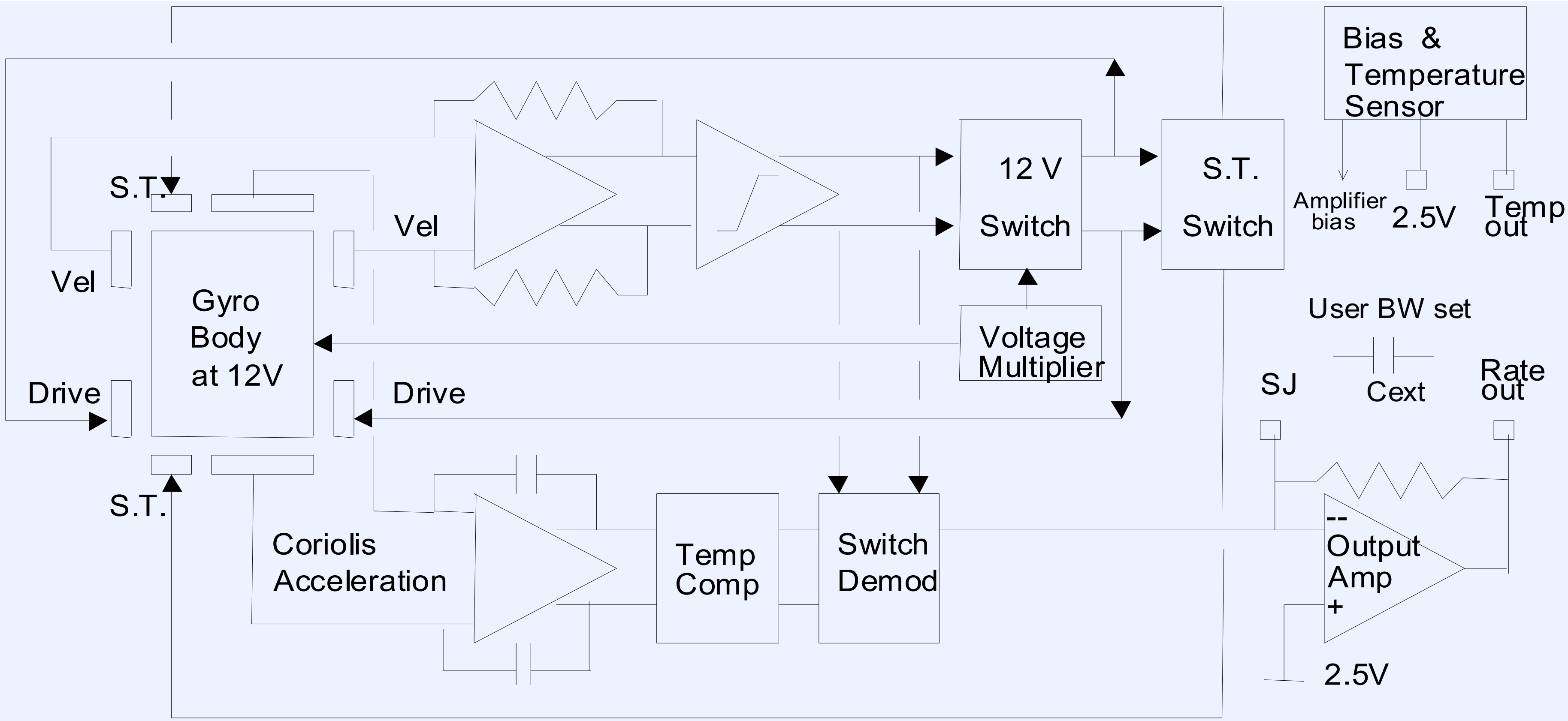


Gyro Structure

- Separated Accelerometer and Resonator



Electronic Design and Mechanical Design Interdependent



Functional Block Diagram

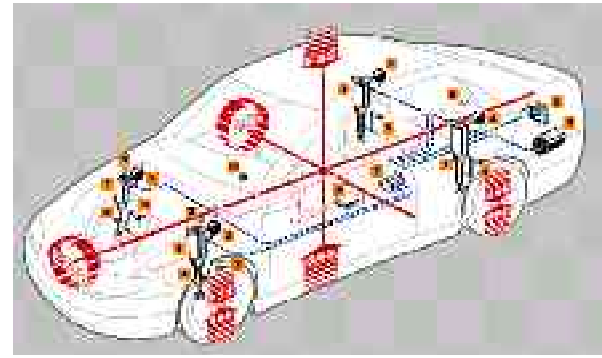
Gyro - Root Allan Variance

Seconds

$$\sigma(\tau) = \sqrt{\frac{1}{2\cdot(m-1)}\cdot\sum_{i=1}^{m-1}(y(i+1)-y(i))^2}$$ for m successive y(i) averaged

Automotive Gyroscope Markets

- Vehicle Dynamic Control
  - **Interaction between anti-lock brake, electronic brakeforce distribution, traction control, and active yaw control systems to achieve dynamic stability**
- Rollover
  - **Extension of airbag safety systems for SUVs, vans, pickup trucks, and high-end vehicles**
- Navigation
  - **Provide additional real-time location input and directions when GPS satellites are not available.**

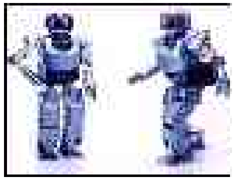


ANALOG DEVICES

Applications for Gyroscopes

- Flight Controls/Training Systems
  - Unmanned aircrafts
  - Supplement to flight dynamic co
  - Supplement to GPS Guidance
- Robotics
  - Industrial robots
  - Toy Robots
- Weapon Systems
  - Smart Artillery Shells
  - Missile Guidance
- Platform stabilization
  - Camera
  - Machinery
  - Wheelchair stabilization
- Computer/Consum
  - Input devices
  - Handheld GPS






Conclusions

- Inertial Sensor Designs are Mechanical Structures of Mass Supported by Springs
- Inertial Forces on the Mass Result in Displacement that is Sensed Capacitively
- New Trends in Applications for Motion Detection are Occuring in Hand-held Devices and Portable Devices
- Gyroscopes Vibrate an Accelerometer and Measure Coriolis Acceleration that Indicates Angular Rate

Questions Please