Smart, Low-Power MEMS Help Usher in the Wearable Era

Fari Assaderaghi

Vice President

Advanced Technology Development

InvenSense®

Sensing Everything

Outline

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- Although a lot of hype on IOT and wearables, they are becoming real
  - Much more than just smart watches and fitness bands
- Microstructure transducers are key enables of these systems
  - Plethora of sensors and actuators, many more being developed
- Low power consumption crucial
  - The need for Always On
  - Avoid charging every 24 hours
  - Innovate at every level: MEMS, circuit, system architecture, algorithm
- Dramatic advancement in low power design, device performance and size necessary to unleash full potential of wearables

IOT and Wearables, Hype or Reality?

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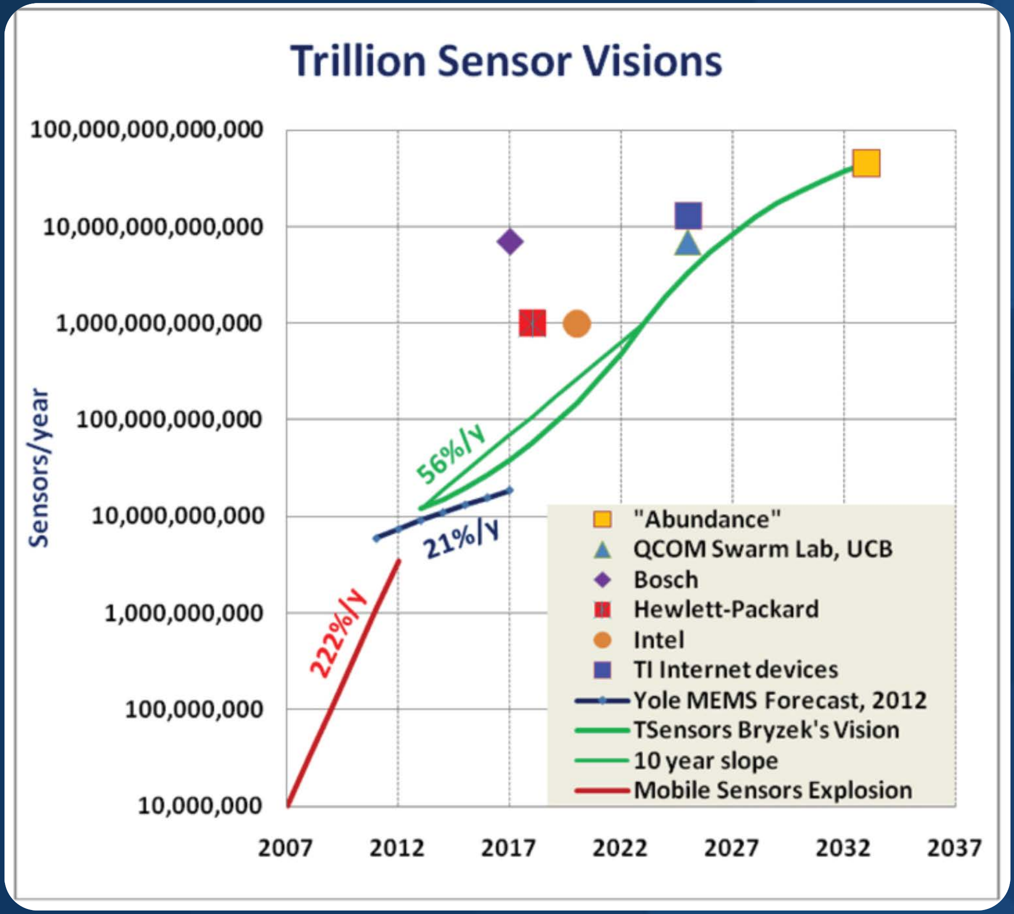

TSensors Summit, Oct. 2013

IoT and Wearables, Hype or Reality?

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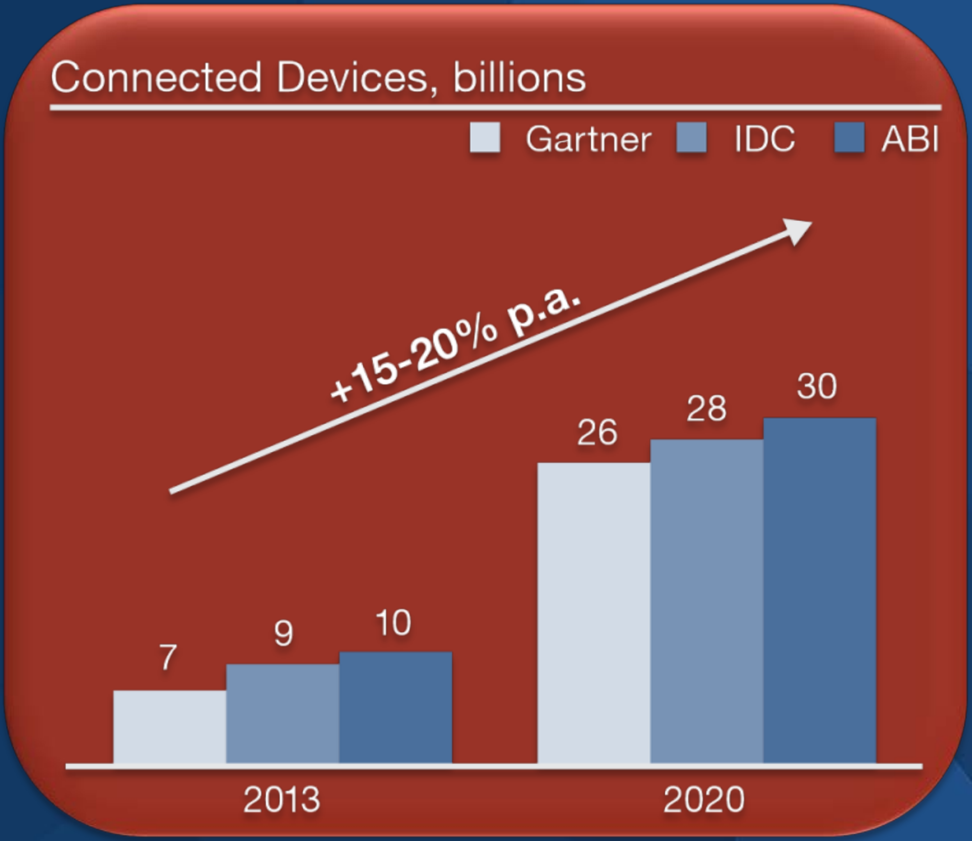
- Semiconductor Growth Drivers
  - 2000-2007 – personal computing, internet
  - 2007-2014 – wireless communication
  - **2014-2020 – IoT**
- The number of connected IoT devices is to reach 20 –30 billion by 2020
- Wearables are arguably the hottest and the most hyped sector



Wearables: The Internet of Us

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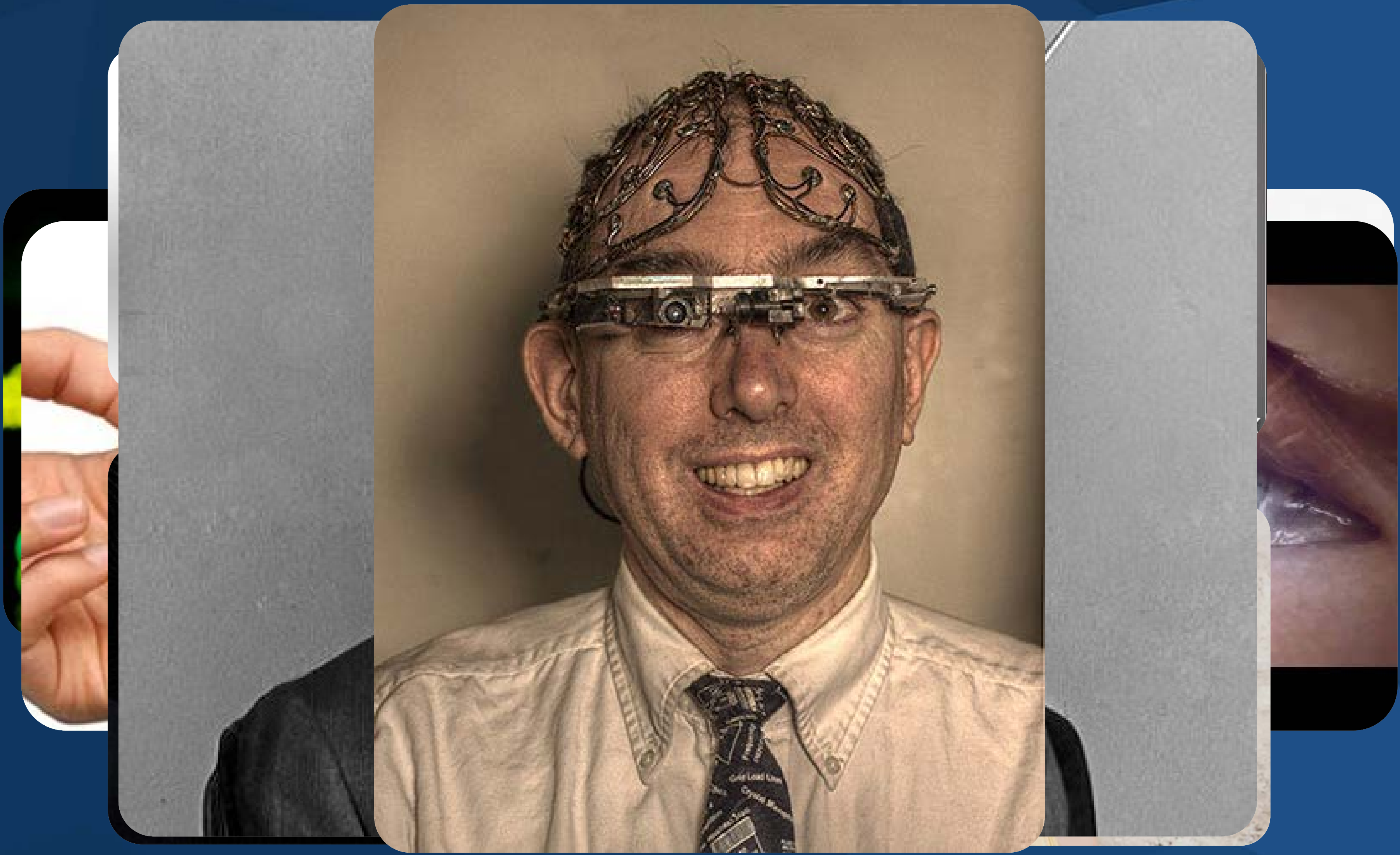

Proliferation of Wearables

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Augmented Reality

Wearable Computing

Activity Tracker

Virtual Reality

Fitness Watch

Earbud and Fitness Tracking

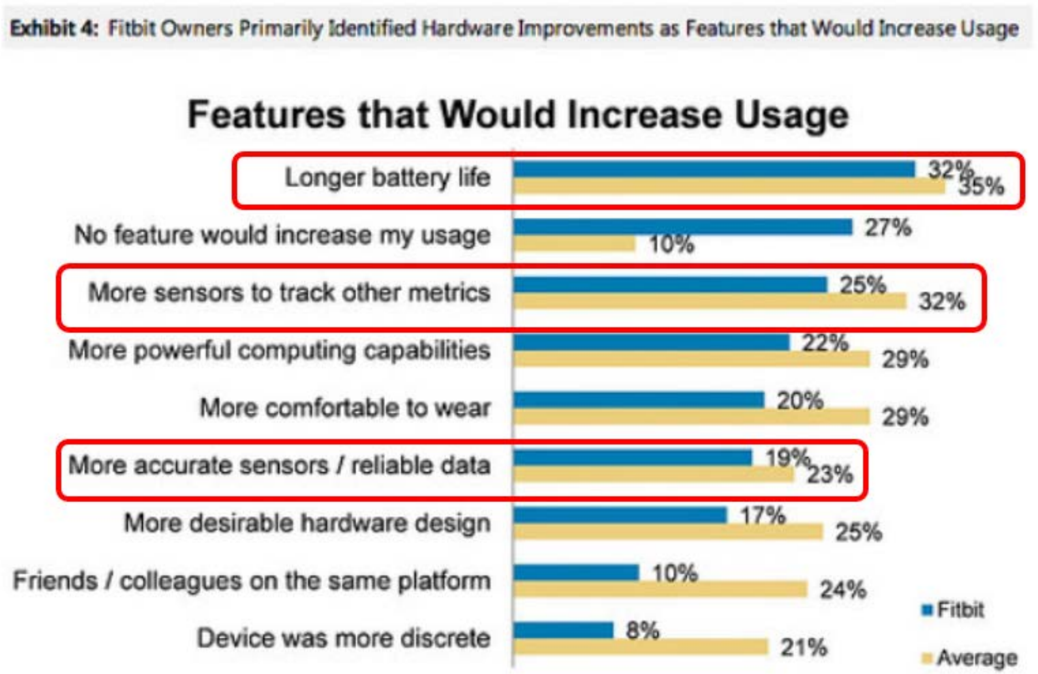
Head-Mount Display

Extreme Sports Cam

Gesture Control

Smart Low-Power Transducers

Key Enablers of Always-On Context-Aware Wearables



Morgan Stanley Research, September 2015

Step Count Isn't Enough

Activity/Context
Steps, Activity, Stairs, Sleep

Vital Signs Monitoring
PPG Motion Artifact Correction
HRV
Heart Rate Tracking
Blood Pressure

Running: Speed/Distance/Route
Biking: Speed/Distance/Route

Health Services

+

GPS

Transducers Relevant to Wearables

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Activity recognition and classification, calorie count, GNSS assist, vital signs assist, gesture recognition and UI assist

- Accelerometer
- Gyroscope
- Barometric pressure sensor
- Magnetometer

User Interface

- Microphone
- Haptic
- Force sensor
- Proximity and Ambient light sensor (ALS)

Vital signs monitoring

- Photoplethysmography (PPG)
- Blood pressure monitor
- Oximeter

Environment monitoring

- UV sensor
- Temperature and humidity (RH&T) sensor
- Gas sensor

Transduction Mechanisms

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- Electrostatic (Capacitive)
  - Used in majority of MEMS interfaces today
  - Converts the stimulus to microstructure displacement
  - We will cover it in some detail
- Piezoresistive
  - Transduces strain to resistance change
- Piezoelectric
  - Transduces force to (charge displacement) to voltage
- Thermal sensors
  - Transduce temperature (IR energy) to resistance change
- Chemiresistors
  - Transduce gas presence to resistance change
- Optical transducers
  - (HRM, PPG based, ALS)

Piezoelectric Transduction Examples

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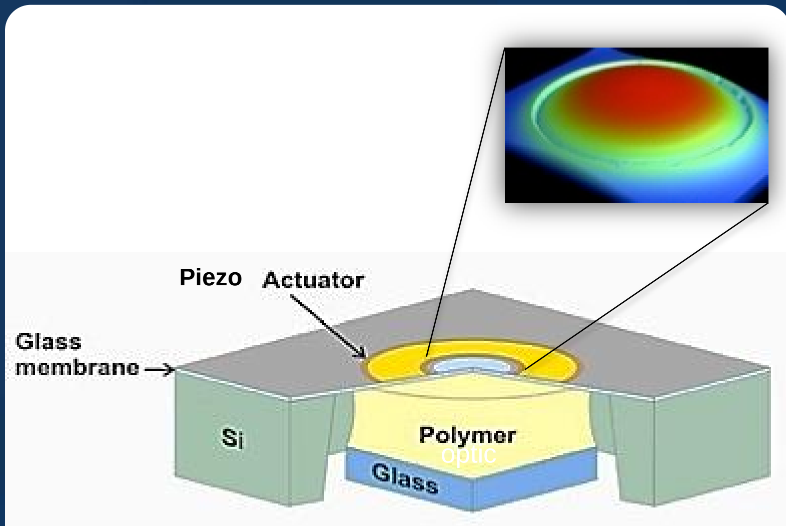
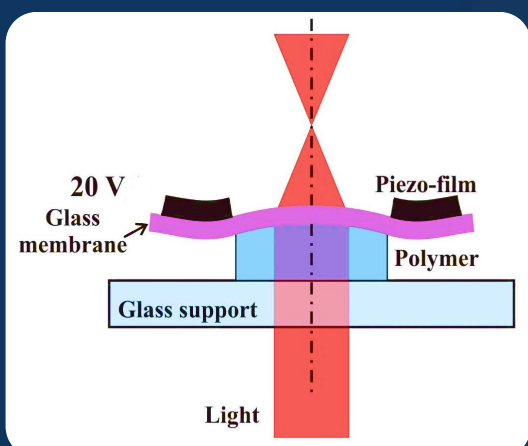
Piezo-Actuator for Autofocus

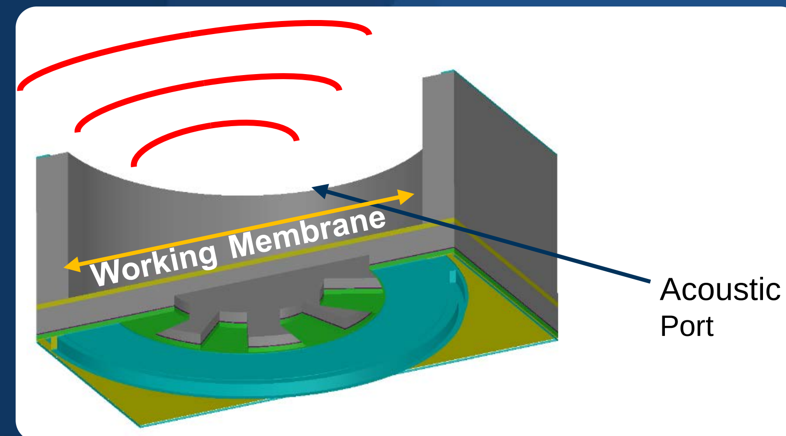


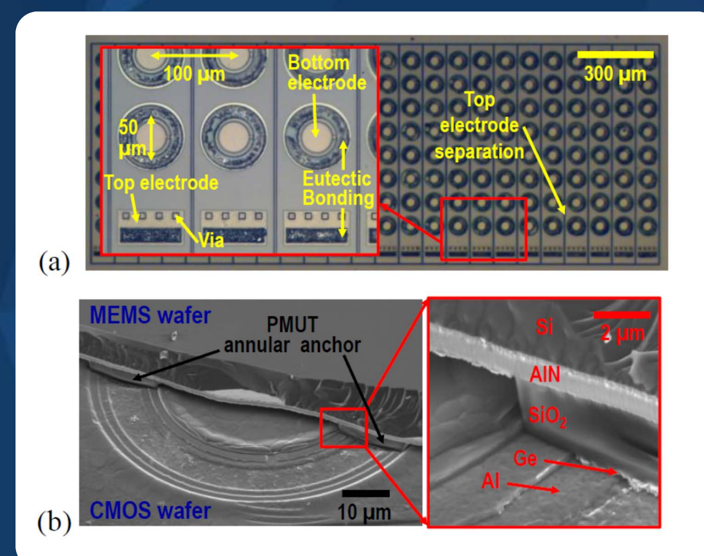
Tunable lens: TLens®



poLight Corporation

PMUT (Piezoelectric Micromachined Ultrasonic Transducer) Array for fingerprint and gesture





UC Berkeley, UC Davis, InvenSense

Apple Watch and the Taptic Engine

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The taptic engine is what sets the Apple Watch apart. Without the taptic engine, the Apple Watch is just a beautiful digital trinket. With it, however, the device becomes much more.

Instead of vibrating furiously like other smartwatches, the Apple Watch does something that feels like a genteel nudge. It's far classier and less distracting.

Film Based Actuators Using Piezoelectric Polymers

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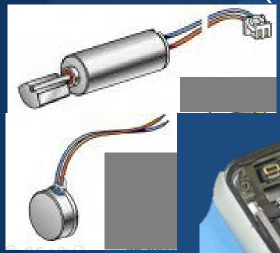
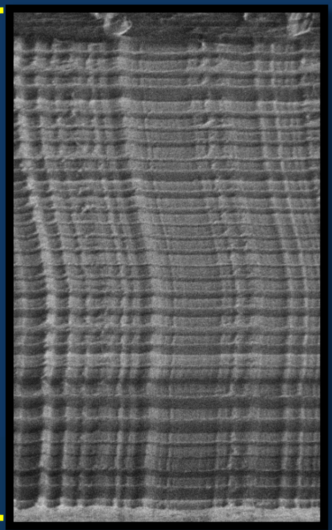
Eccentric Rotating Mass (ERM), and Linear Resonant Actuator (LRA)

Mechanical actuators



Rigid & bulky

150um



SEM Actuator cross-section

Thin, flexible and conformable

Film actuators

Novasentis Corp.

Chemiresistors

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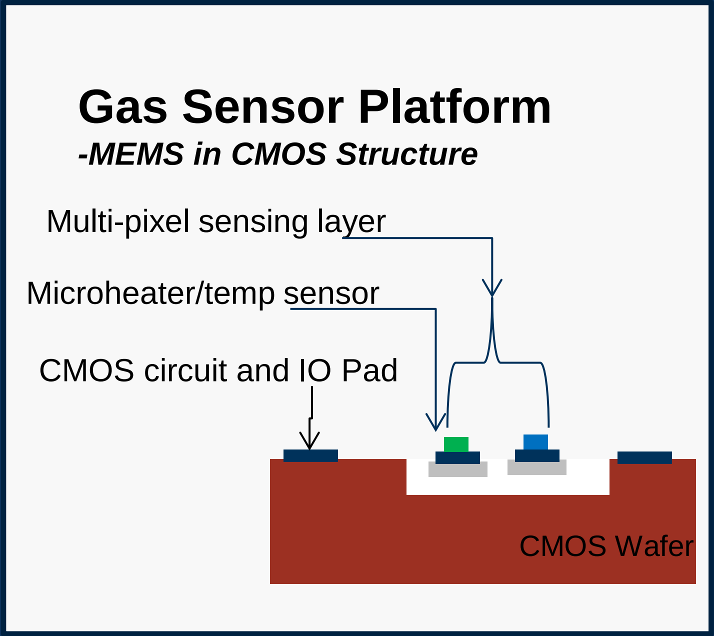
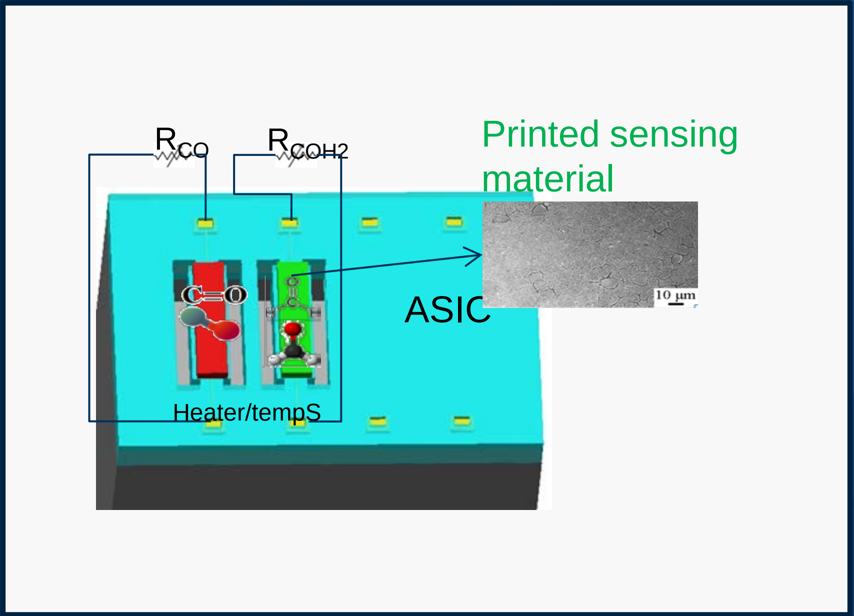
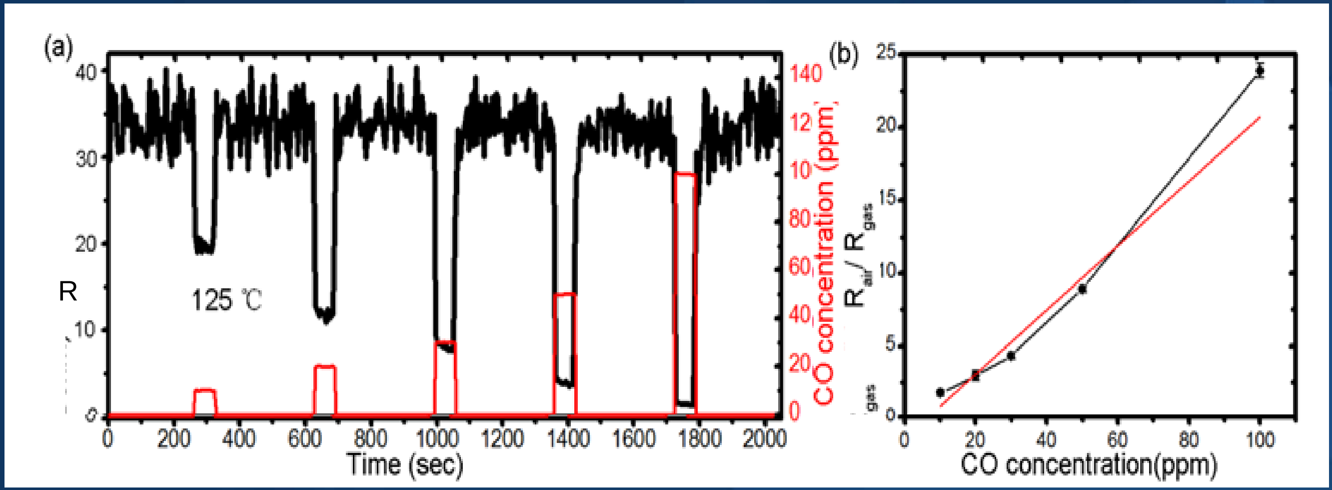
Convert presence of certain gas to change of resistance





Carbon Monoxide Detection



Electrostatic (Capacitive) Transduction

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- The most dominant mechanism used in MEMS
- Gyroscopes, accelerometers, microphones, altimeters, magnetic Lorentz Force sensors, timing devices
- Key characteristics
  - Typically no need for special materials
  - Can move in-plane and out-of-plane (multi-axes sensing)
  - Needs bias voltage, sometimes large
  - Output signals can be extremely small

Canonical Electro-Mechanical Mass-Spring System

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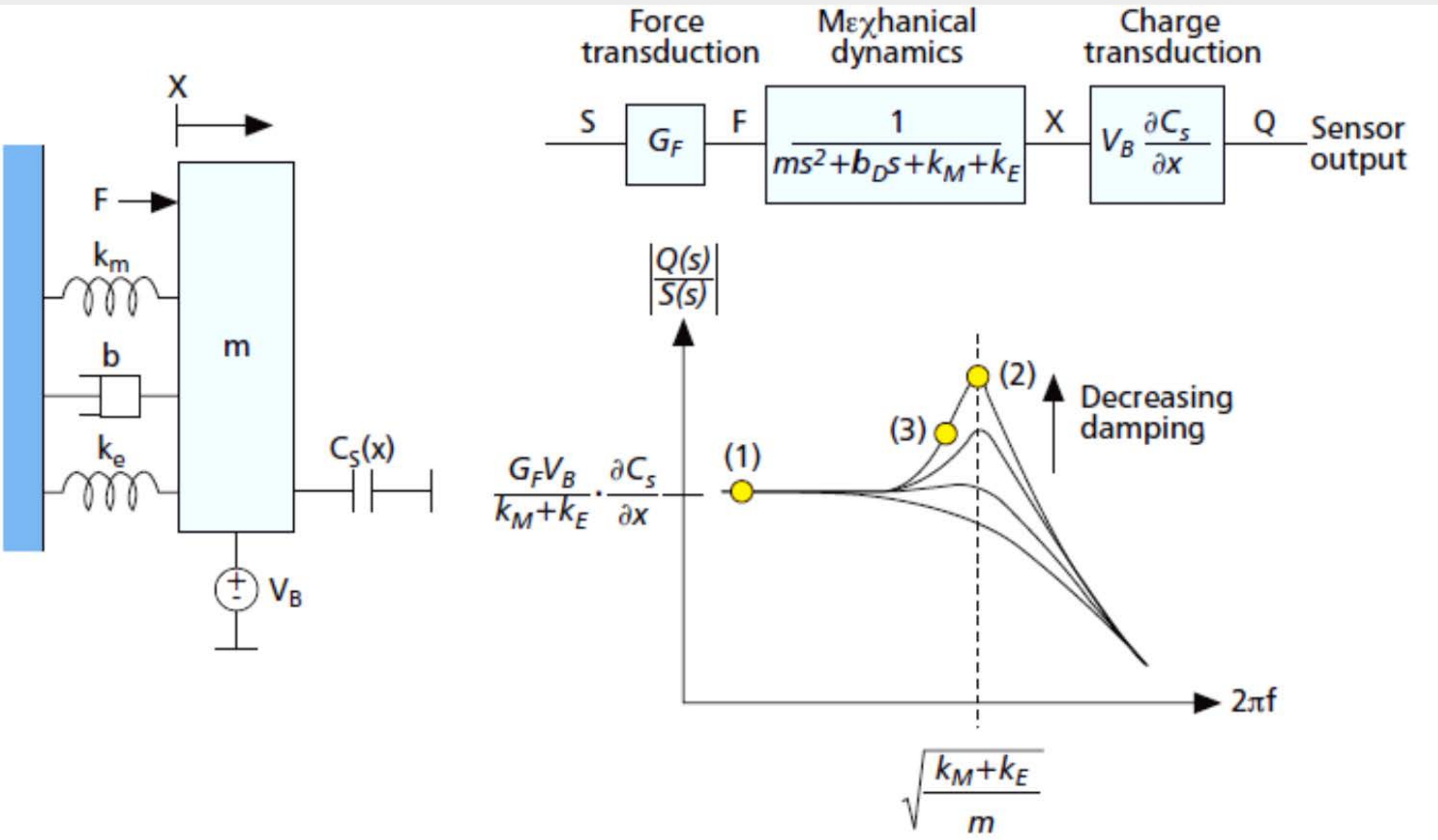

D. Shaeffer, IEEE Comms Magazine, April 2013

Capacitive Sense

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For capacitive sensing, we need to think about charge

$$i = \frac{dQ}{dt}$$

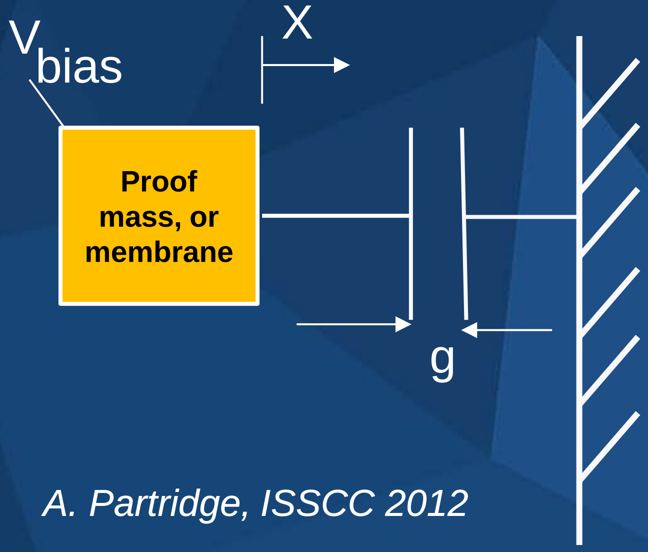
This not always leads to

$$i = C\frac{dV}{dt}$$

But could be $i = V_{bias}\frac{dC}{dt}$

$$\Delta Q(\Delta x) = V_{bias}\frac{\partial C_s(x)}{\partial x}\Delta x$$

Bias voltage can be a few volts to 10’s of volts



A. Partridge, ISSCC 2012

Example: MEMS Microphone

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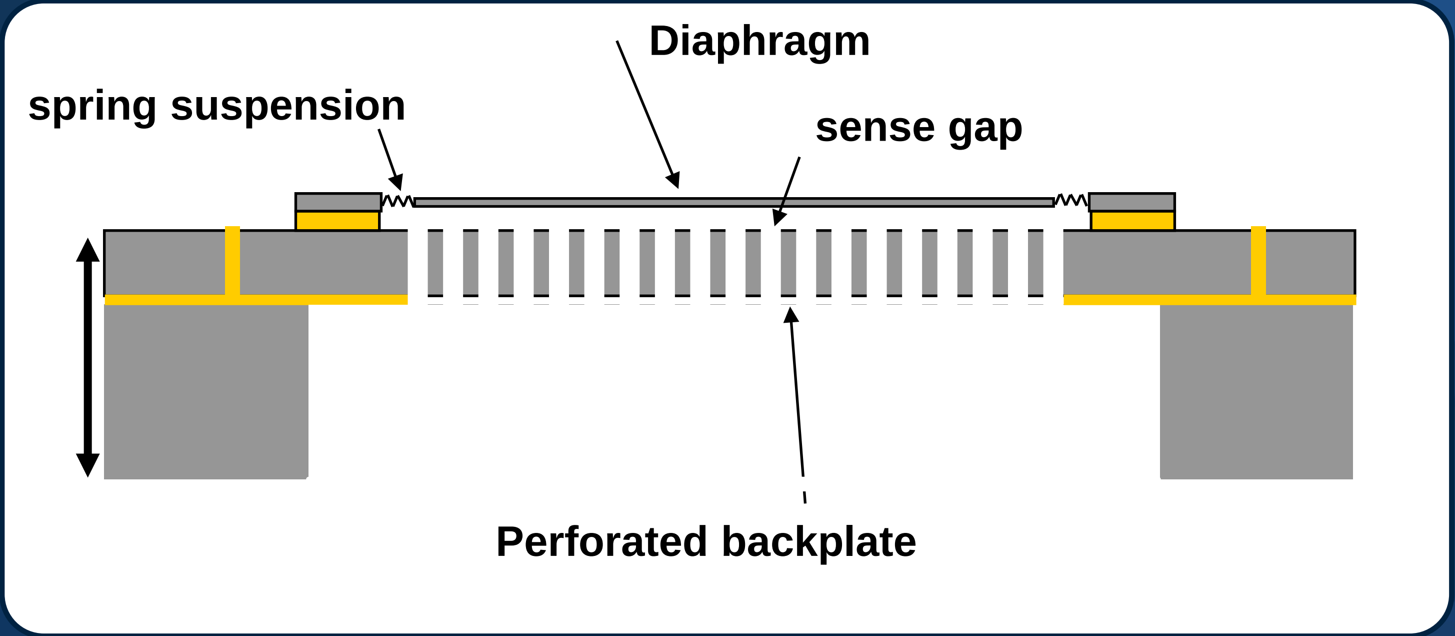
Sound = Air Pressure Fluctuation



- Diaphragm and backplate electrodes form a capacitor
- Sound pressure causes the diaphragm to vibrate and change the capacitance
- Very large dynamic range
  - Reference level: (94dB SPL): 1Pa
  - Normal conversation (60 dB SPL): 20 mPa
  - Can cover from 134dB (100Pa) (near jet engine) to <28dB (0.5mPa) (quiet library)

MEMS Microphone

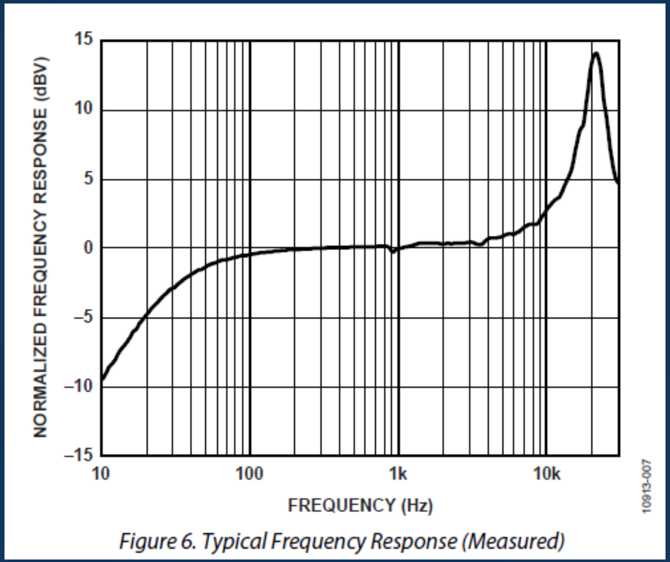
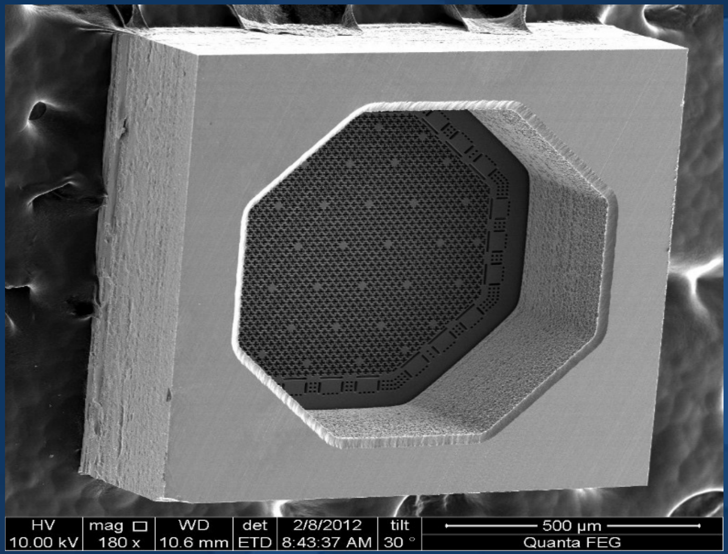
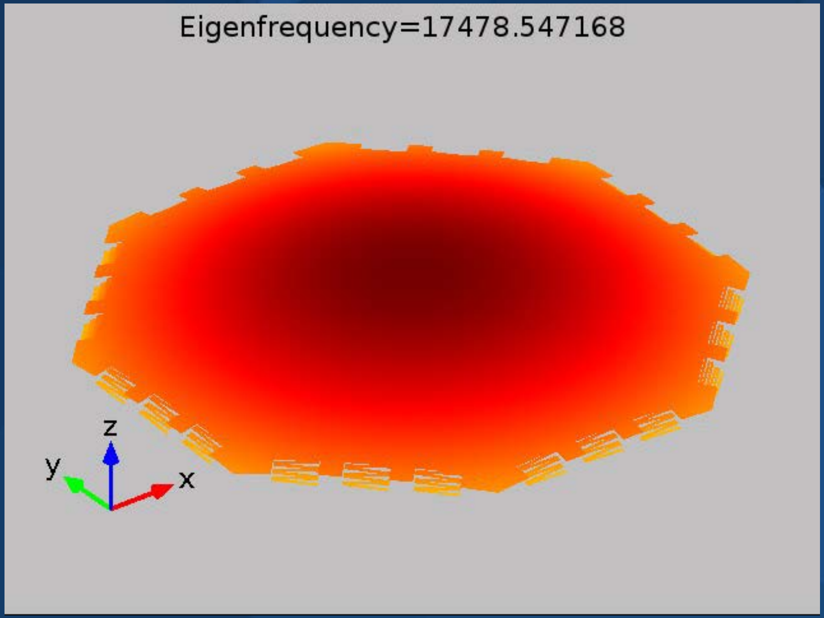


Figure 6. Typical Frequency Response (Measured)





- The membrane movement is from <<Å level at the lowest SPL to µm level at the highest SPL
- Need to be able to sense aF of capacitance change

Capacitive Drive

- Force transduction is important for sensors that require the proof mass to be driven to a known motion
- Electrostatic force for parallel plate

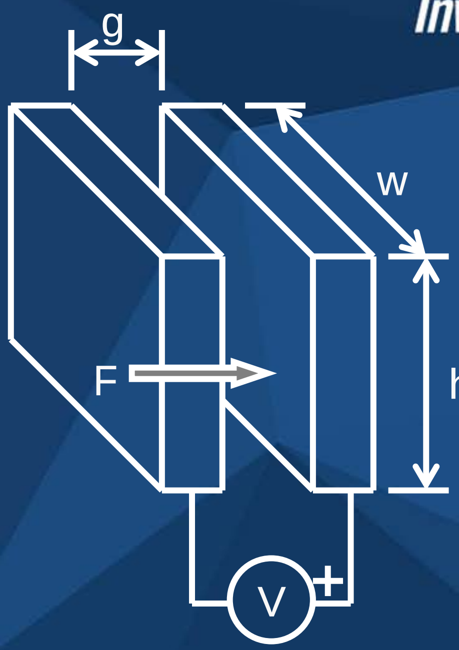
$$F = \frac{\epsilon_c wh}{2g^2} V^2$$

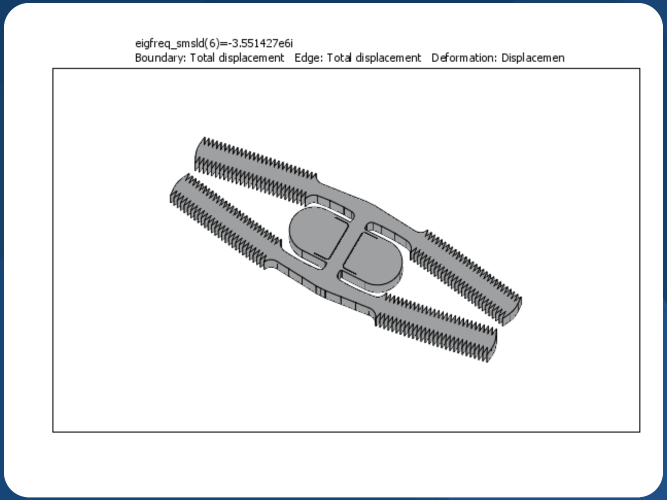
- We can use DC bias and AC drive

$$F = \frac{\epsilon_c wh}{2g^2} (V_{bias} + V_{drive})^2$$

- Set $V_{bias} >> V_{drive}$ and we get a bipolar offset drive

$$F_{offset} \approx \frac{\epsilon_c wh}{2g^2} V_{bias} V_{drive}$$





SiTime Resonator for Real Time Clock
524KHz / 2^{19} = 1Hz → 1sec

Basic Equations for Accelerometer and Gyroscope

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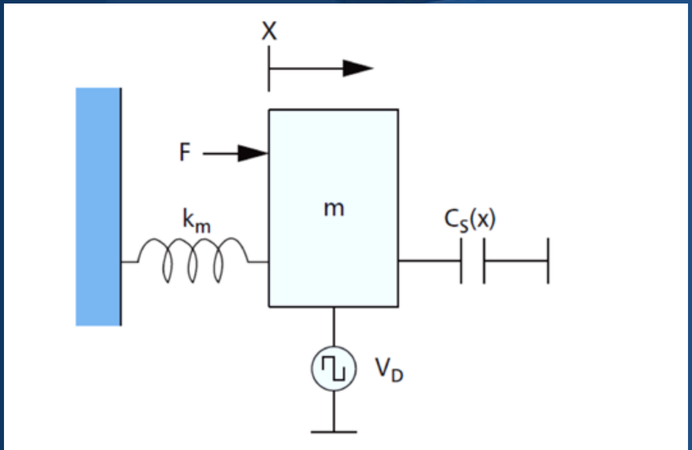
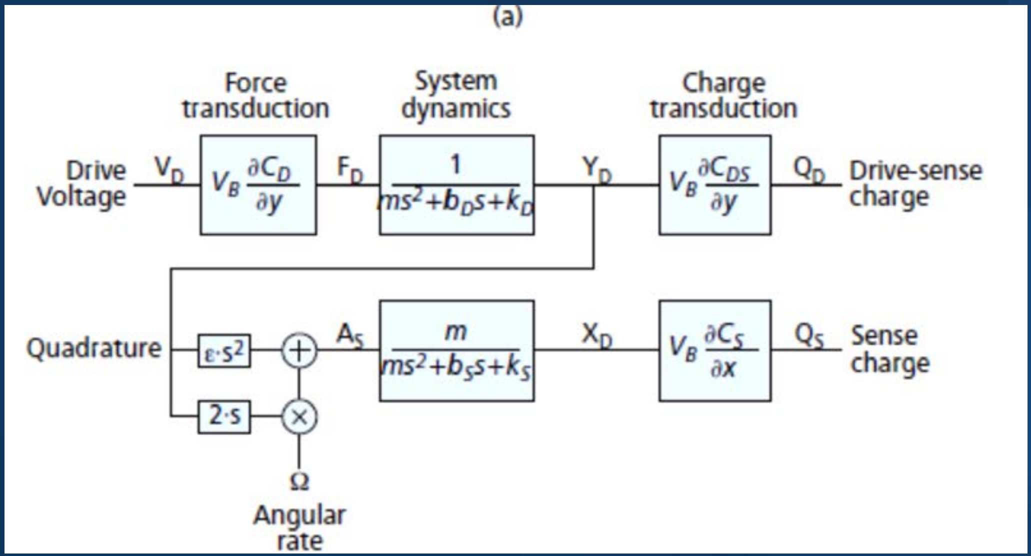
Accelerometer

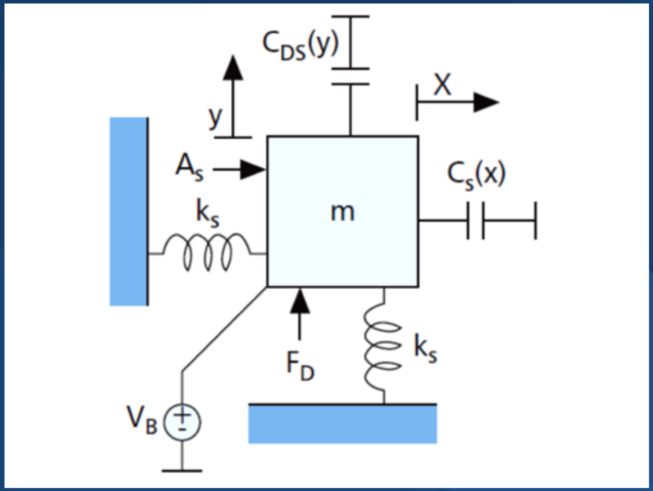
- Input force, Newton's Second Law: $\vec{F} = m\vec{a}$
- Output displacement, Hooke's Law, F = *k*x



Rate Gyroscope

- Input force, Coriolis Effect, $\vec{F} = -2m(\vec{\Omega}X\vec{V})$
- Output displacement, Hooke's Law, F = *k*x, x = F/*k*





D. Shaeffer, IEEE Comms, Apr 2013

Capacitive Sensing Schemes

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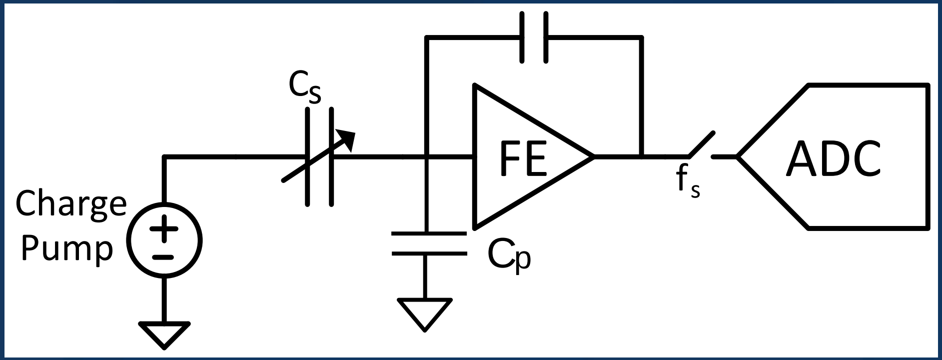
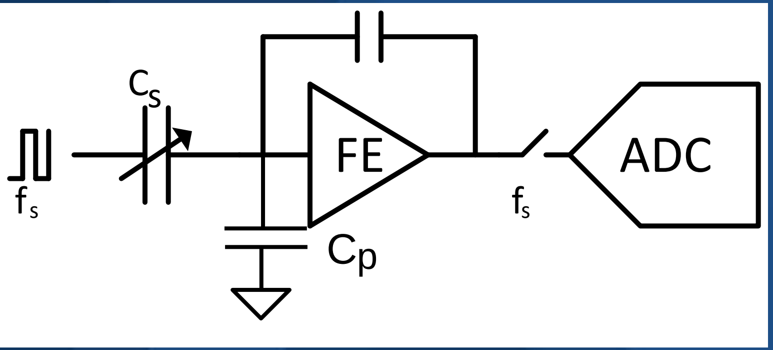
Continuous Time Interface



- Charge-pump multiplies transducer output
- Common for Microphones, Gyros, Resonators

Discrete Time Interface



- Electrical modulation at the front-end
- Common in “DC” sensors
  - Accelerometers, Pressure sensors

Sensor Figure of Merit: SNR/(Energy per Conversion)

$$\frac{SNR}{E_C} \propto \frac{1}{4kT}\frac{\Delta x^2}{g^2}\frac{{V_B}^2}{{V_{DD}}^2}\left(\frac{C_s}{C_s+C_p}\right)$$

For a given SNR requirement, reduce power by

- Maximizing mechanical full-scale swing
- Maximizing bias or drive voltage
- Minimizing parasitic capacitance

Exploit all Tools of Power-conscious Low-noise Design

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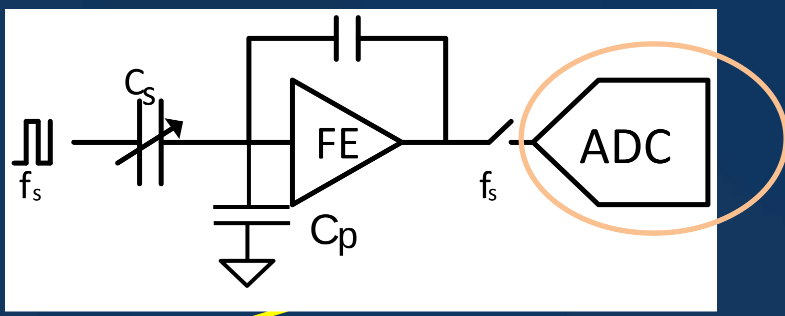
Accelerometer

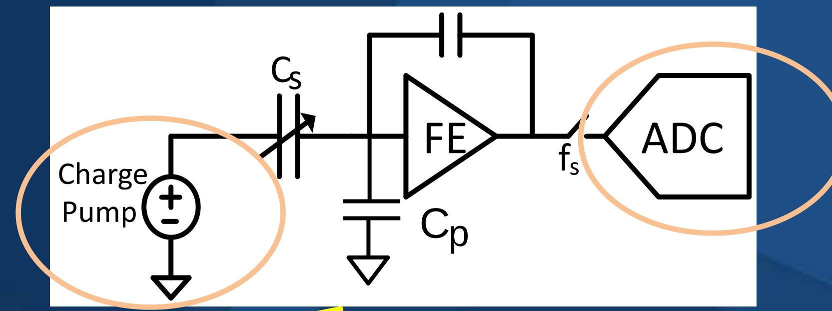
Duty cycled operation → Low latency

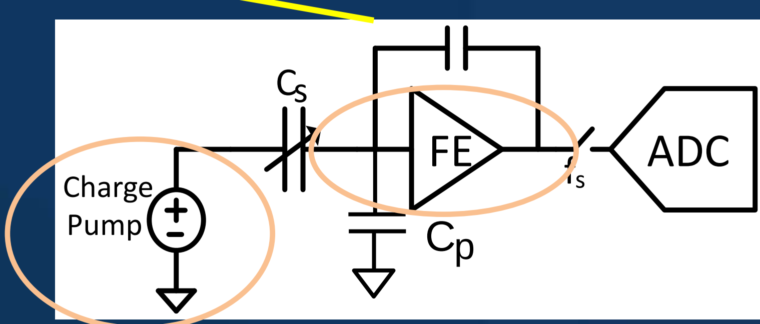


Microphone

Transducer gain & front-end

High dynamic-range and bandwidth ADC





Gyroscope

Transducer gain

Weak signal & Quadrature → Front-end

Power Savings by Duty-Cycled Operation

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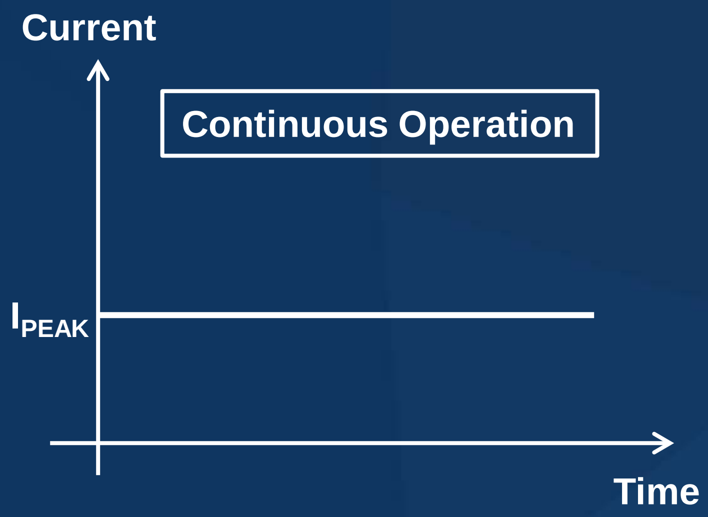
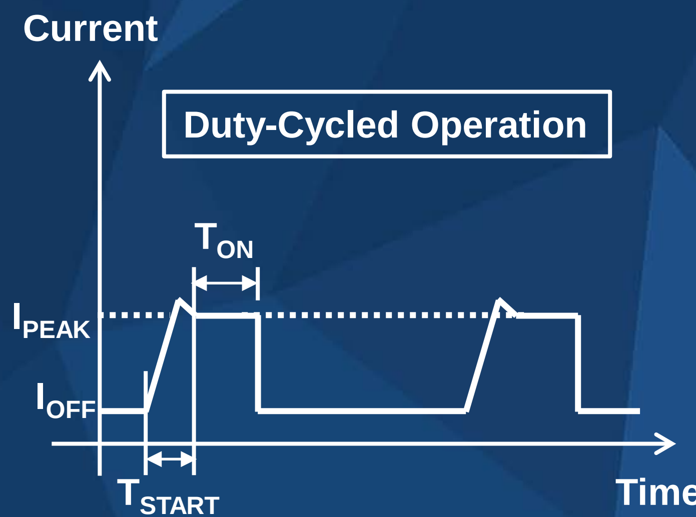
Efficiently reduces power for applications with low update rates

Challenges:

- **I_{OFF}**: Current from circuit blocks that cannot be duty-cycled, and leakage current
- **T_{START}**: Finite circuit start-up time → Want $T_{START} \ll T_{ON}$
- **$T_{ON, MIN}$**: Limited by the max operating bandwidth, which is normally related to MEMS resonant frequency





Low Power Gyro Quadrature Cancellation

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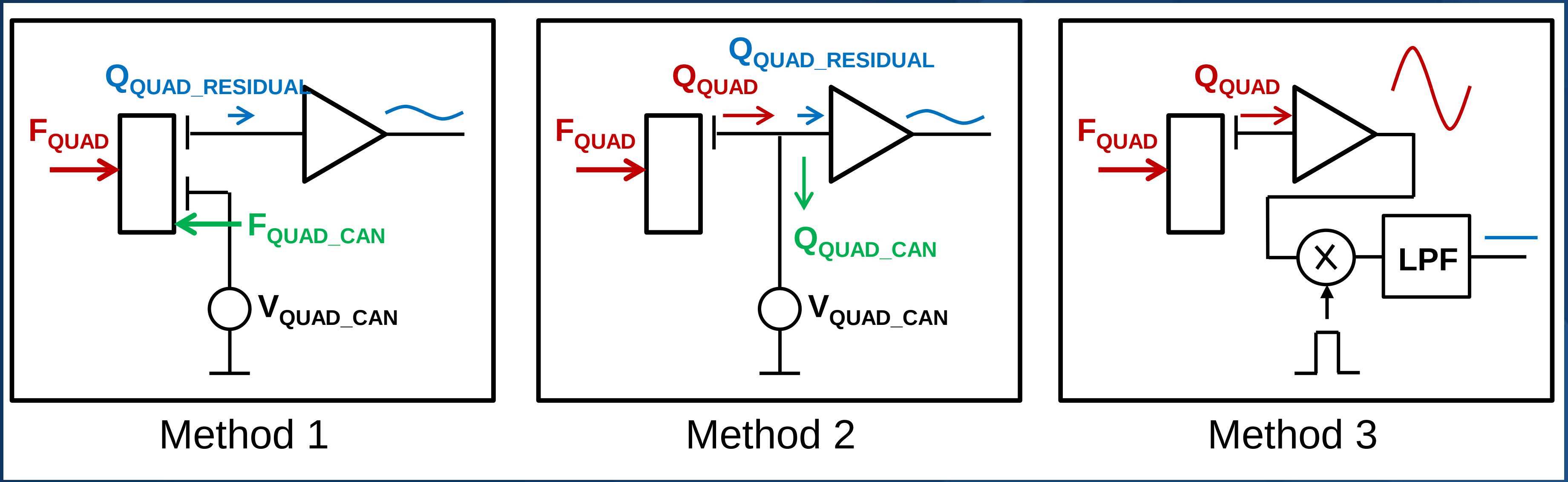
- Quadrature can be removed several ways
  1. At MEMS in force domain
  2. At sense amplifier in charge domain
  3. At demodulator in phase domain
- Compared to Method 3, Method 1 and 2 relieve the headroom requirement at analog front-end, allowing larger gain and suppression of ADC noise, achieving lower power
- Quadrature cancellation in force domain (Method 1) increases circuit complexity and power
- Method 2 is optimal for power consumption



Charge Pump Design Considerations

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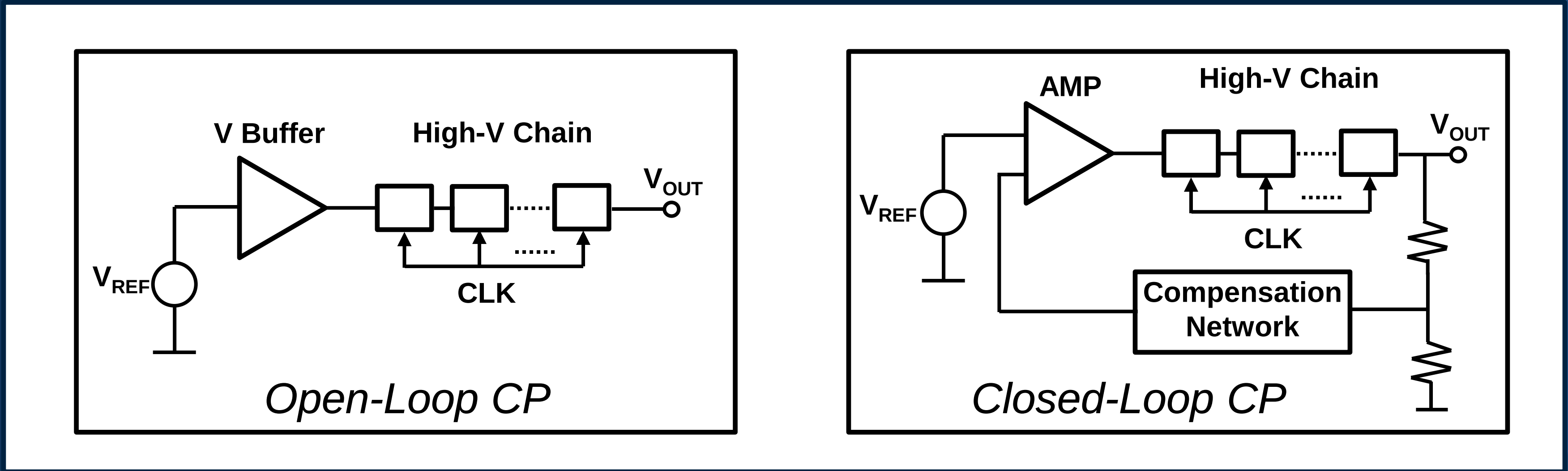

- Open-Loop Charge Pump
  - ✓ Simpler implementation
  - ✓ No stability concern
  - ✓ No resistive load at output
  - ✓ Lower power consumption
  - × Output voltage variation over temperature on the order of 2%
- Closed-Loop Charge Pump
  - × More complex
  - × Stability needs to be checked
  - × Resistive feedback increasing load current
  - × Higher power consumption
  - ✓ Output voltage variation over temperature on the order of 0.1%

- Charge pump architecture should be decided based on the sensor accuracy requirements

Key Considerations

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- Accel and gyro: The larger the proof mass, the larger the sensing signal
  - To keep area small, need high aspect ratio silicon to achieve large mass
- Displacement can be <Å, ΔC < aF → Minimize parasitic C
- High density interconnect for multiple electrodes, shielding of sensitive connections
- Design of high dynamic range, high performance and low power ADC's, critical
- For sensors with mechanical oscillation (Gyro, MEMS timing), need low cavity pressure for high-Q
- Large bias voltages lead to higher transducer gain → Charge pump design

Example – InvenSense Process Platform

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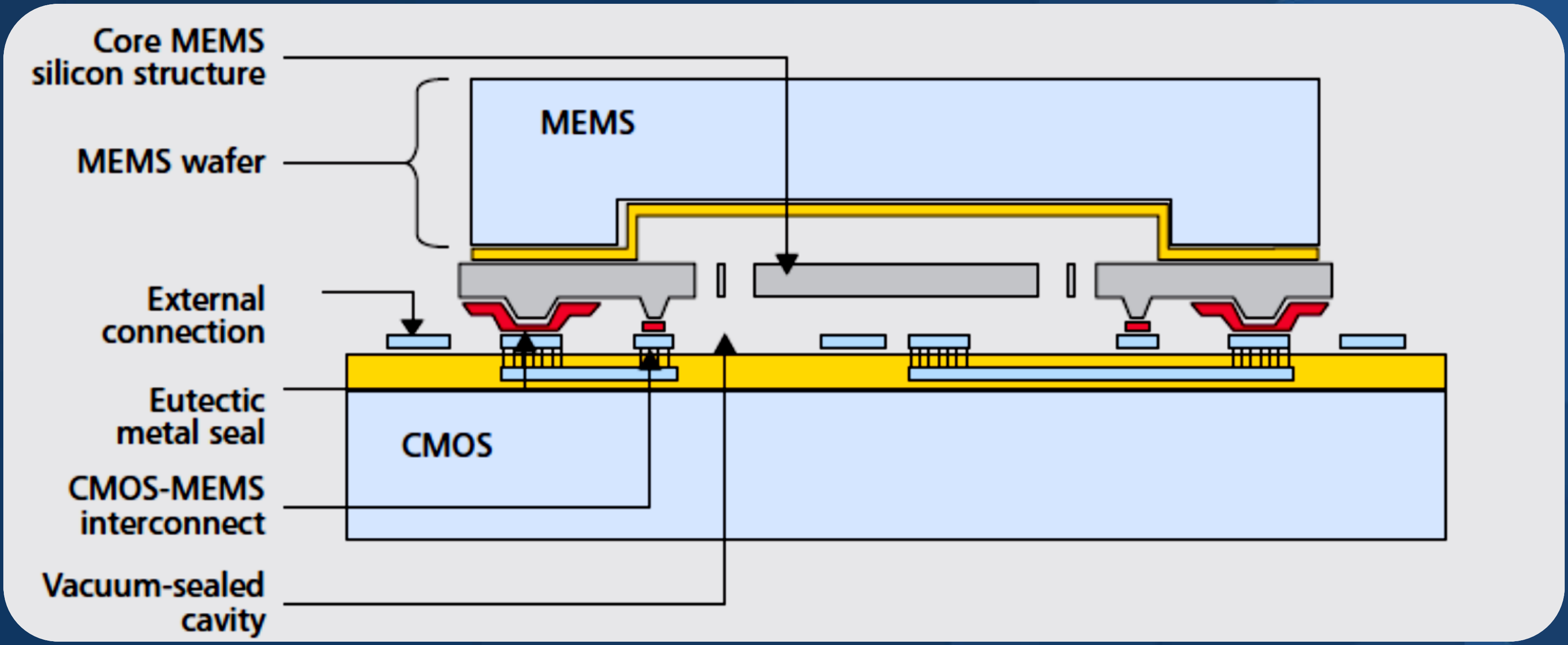
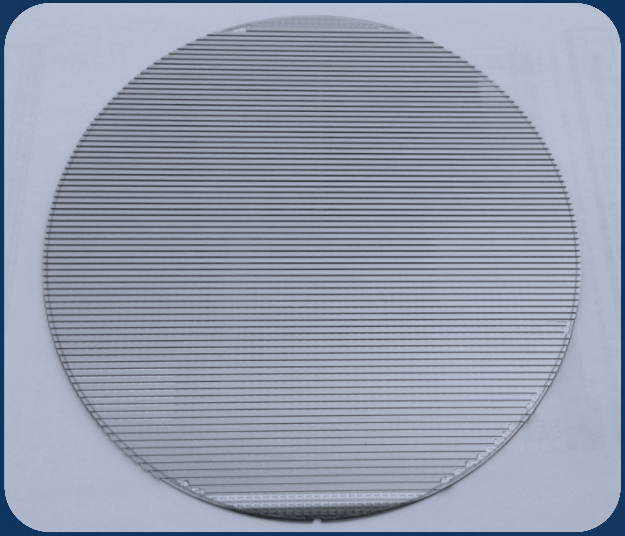
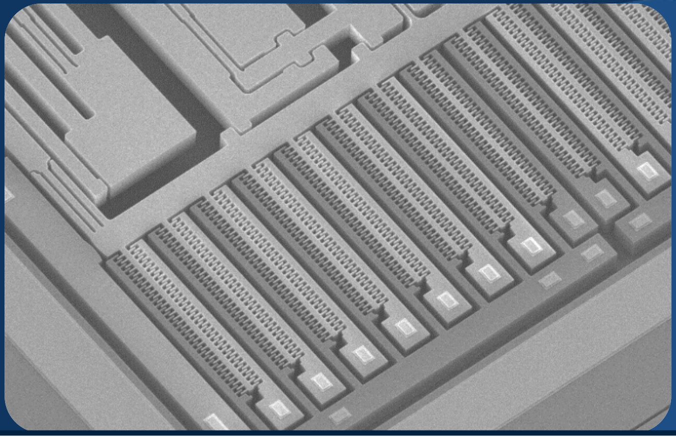
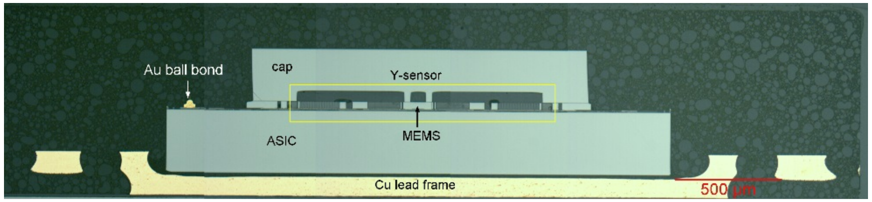


- Single crystalline silicon structure with high aspect ratio
- Wafer scale integration of MEMS and CMOS for small form factor
- Vacuum sealed structure
- Low parasitic capacitance
- High density interconnect for multiple electrodes and easy shielding
- Integration of multiple sensors

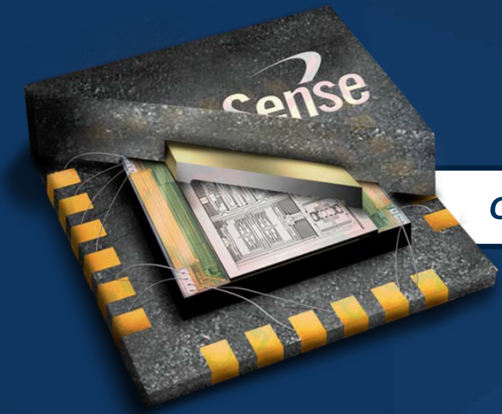
InvenSense Accel and Gyro Examples



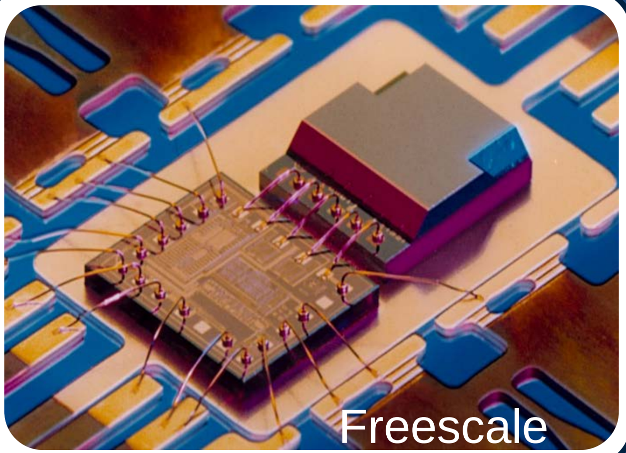




From Chipworks



Compare with



Example: SiTime's MEMS TCXO

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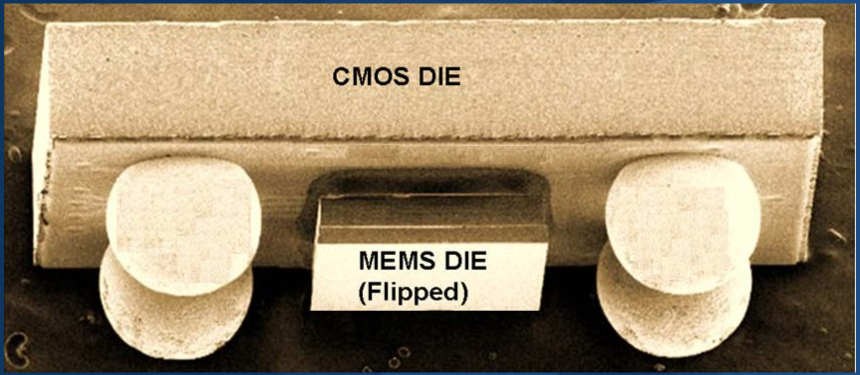
Comparison Table (TCXO)

Parameter	This work	Maxim DS32kHz	Epson TG-3530
Supply Voltage (V)	1.5 to 4.5	2.7 to 3.5	2.2 to 5.5
Temperature Range (°C)	-40 to 85	-40 to 85	-20 to 70
Frequency Stability vs. Temp (ppm)	± 3	± 7.5	± 5
Supply Sensitivity (ppm/V)	± 0.25	2.5	± 1
Start up time (s)	0.2	1	3
Current (μA) Clock enabled, no load	1 typ 1.5 max	1.85 typ 4 max	1.7 typ 4 max
Package Size (mmxmm)	1.55x0.85	18.5x6.35	5x10.1

12.9: A 1.55x0.85mm² 3ppm 1.0μA 32.768kHz MEMS-based Oscillator
34 of 35



Useful for wearables

- Very accurate real time clock
- Watch-dog timer
- BLE's Sleep Clock Timing
- Significant role in power consumption of cyclic sleep scenario

Applied Circuit Techniques

- Sub-threshold design
- Duty-cycling TDC
- Open Loop regulators
- Digital regulator to track P & T
- Low swing driver

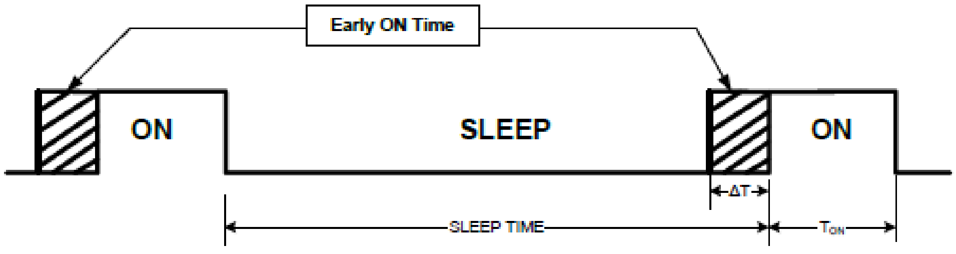


Figure 7: Connection event profile due to sleep clock inaccuracies

Smart Sensors and Algorithms for System-Level Power Saving

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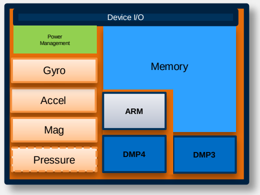
Platform Solution:
Software/System Integration

- *MotionApps*
- Sensor based Navigation Assist
- Ui/Ux
- Sensor based PPG Assit

Content:
Algorithms

- *SensorFusion*
- Runtime Calibration
- Classification
- Gestures

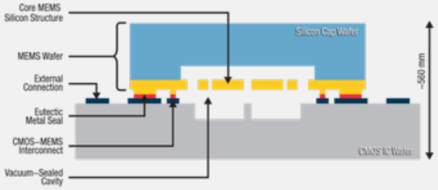
Content:
SoC Integration

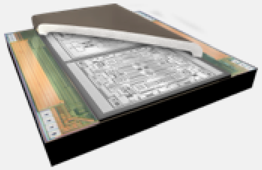


- 6/7/9 Axis Inertial Sensors
- 4^{th} Gen Digital Motion Processor
- FIFO/Memory

Product:
Sensor Integration

Foundation:
Process Technology





MEMS Technology to *Full Context* Solution

Concept of Sensor Fusion

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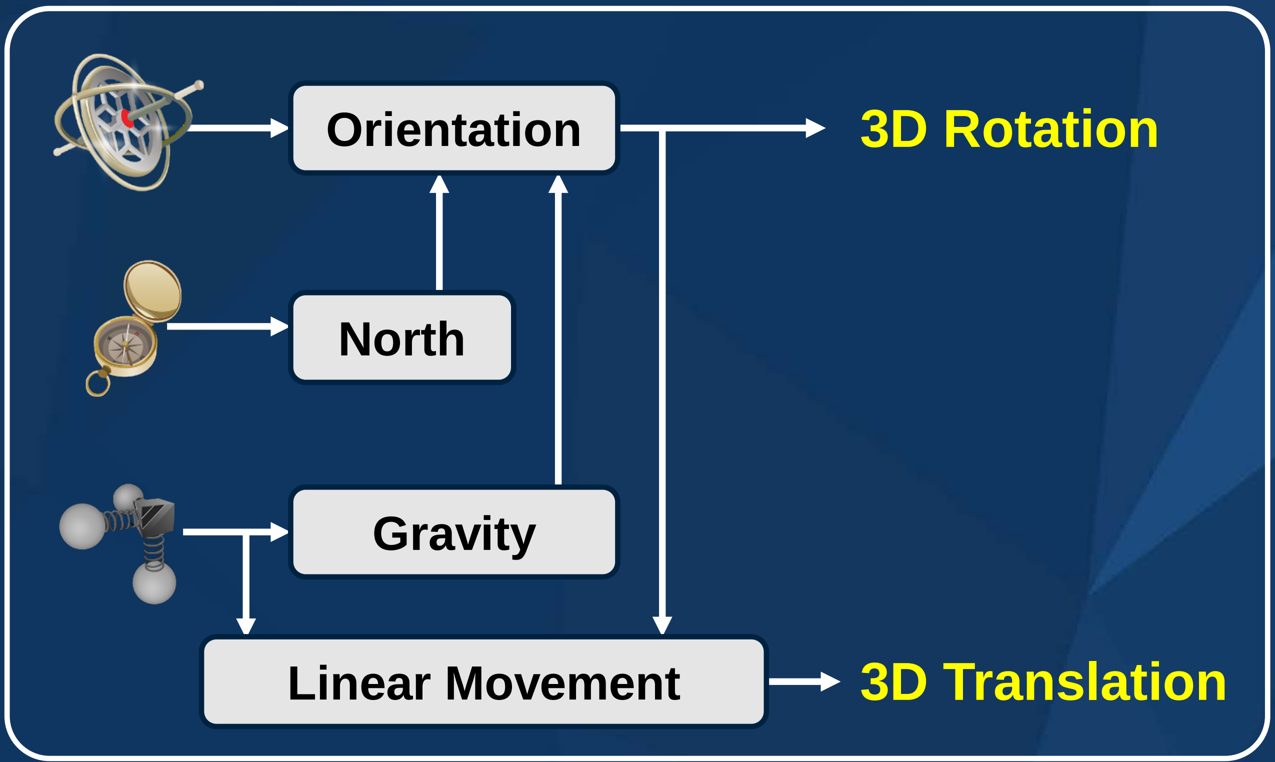


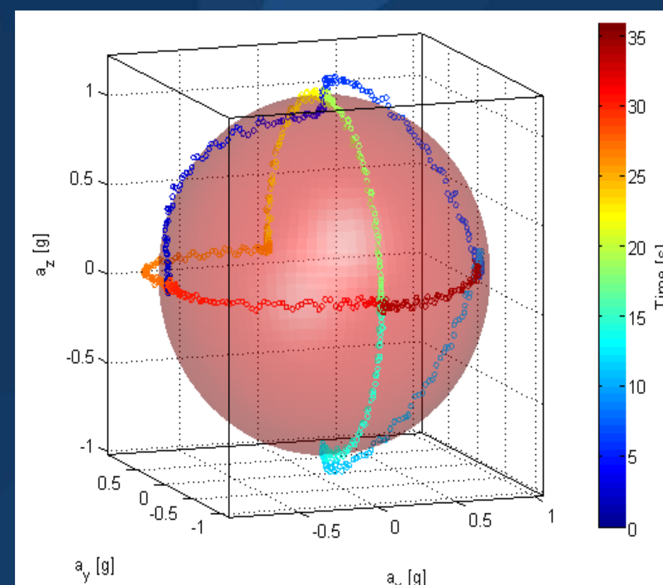
- Orientation
  - Euler angles
  - Rotation matrices
  - Quaternion
  - Angle change
- Linear acceleration

Digital Motion Processing (DMP) Engine

- 6 degree-of-freedom (DOF) motion
- Activity Detection
- Continuous Calibration
  - DMP enabled accel, gyro, mag offset calibration

DMP – Accel offset calibration

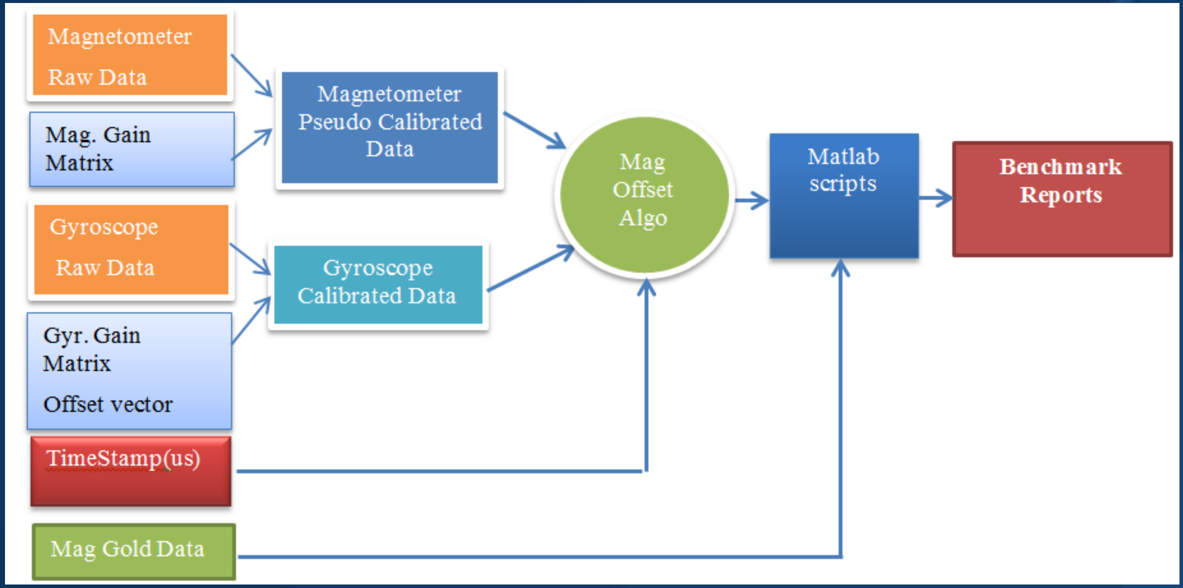
- Accelerometer data monitored for motion around 3 axes
- Data fit to sphere and offset updated
- Better than 10mg can be achieved

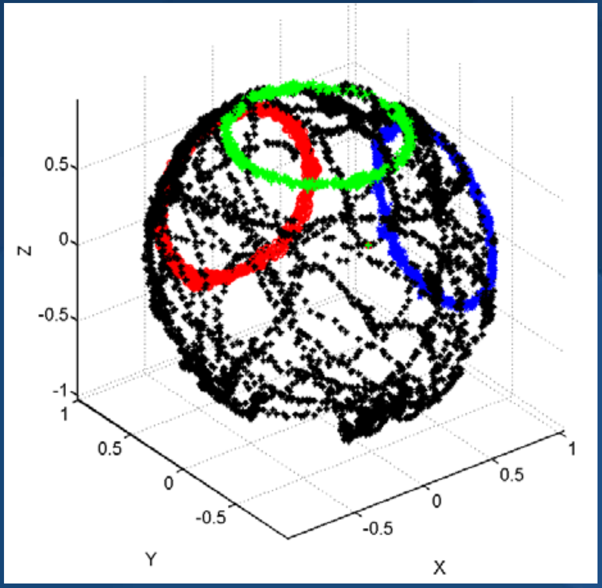


Best motion for accel calibration

DMP – Magnetometer Correction

- Mag data monitored for motion around 3 axis
- Data fit to sphere and offset updated
  - Similar to accelerometer
- With gyro data convergence improves (“smaller” gesture needed), robustness improves
- Anomaly detection prevents updates under interference





Basic Activity Classification (BAC) Benchmark

InvenSense

OEM-1 confusion matrix (%)						
		Algorithm Output				
		Still	Walk	Run	Bike	Car
Gold	Still	57.4	40.4	0.0	0.9	1.3
	Walk	8.7	83.3	1.0	6.1	0.9
	Run	1.2	4.3	94.5	0.0	0.0
	Bike	0.0	4.5	0.0	90.5	5.0
	Car	44.7	0.0	0.0	2.7	52.5

OEM-2 confusion matrix (%)						
		Algorithm Output				
		Still	Walk	Run	Bike	Car
Gold	Still	42.7	29.1	2.1	5.2	20.9
	Walk	5.5	80.9	0.4	0.8	12.4
	Run	5.3	3.8	88.5	0.0	2.4
	Bike	4.9	8.4	36.7	49.3	0.7
	Car	7.2	0.0	0.2	15.4	77.0

InvenSense AAR confusion matrix (%)						
		Algorithm Output				
		Still	Walk	Run	Bike	Car
Gold	Still	**83.2**	2.8	0.0	11.1	2.9
	Walk	5.6	**85.3**	1.4	6.3	1.3
	Run	0.7	4.2	**95.2**	0.0	0.0
	Bike	5.5	0.0	0.0	**94.5**	0.0
	Car	3.9	0.0	0.0	0.0	**96.0**

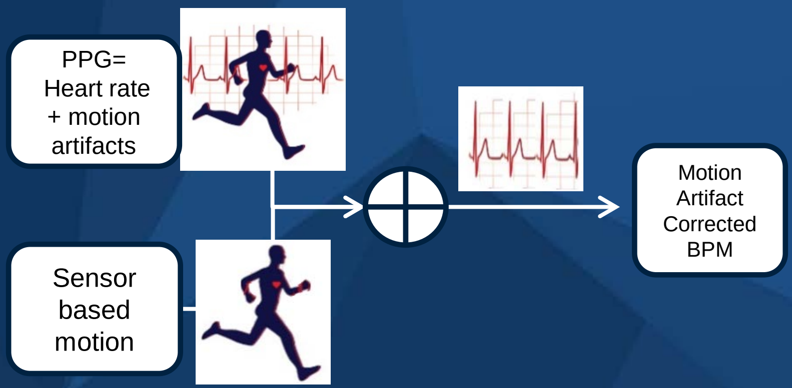
Algorithm	**DMP Current (uA)**
Basic Activity Classification / Pedometer	120uA
9 axis fusion	15
6 axis fusion	9
Accel offset cal	18
Gyro offset cal	12
Mag offset cal	22

Addressing Heart rate (PPG based) Accuracy and Power Problems

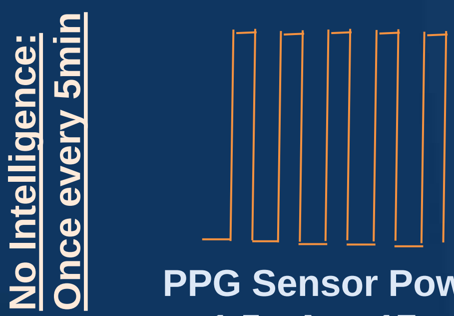
InvenSense

Problem: Heart rate measurement is not reliable when body is in motion

Solution: Remove motion from the PPG light signal

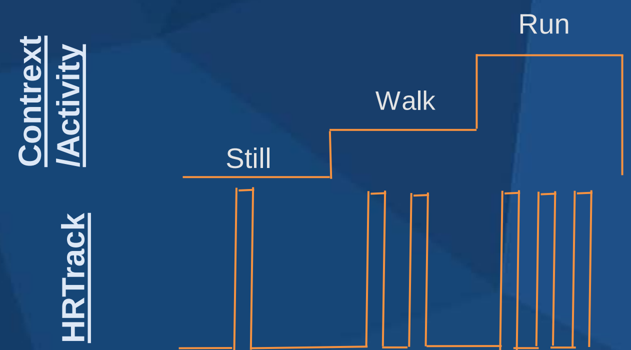


Problem: HRM Kills Battery when turned on too often



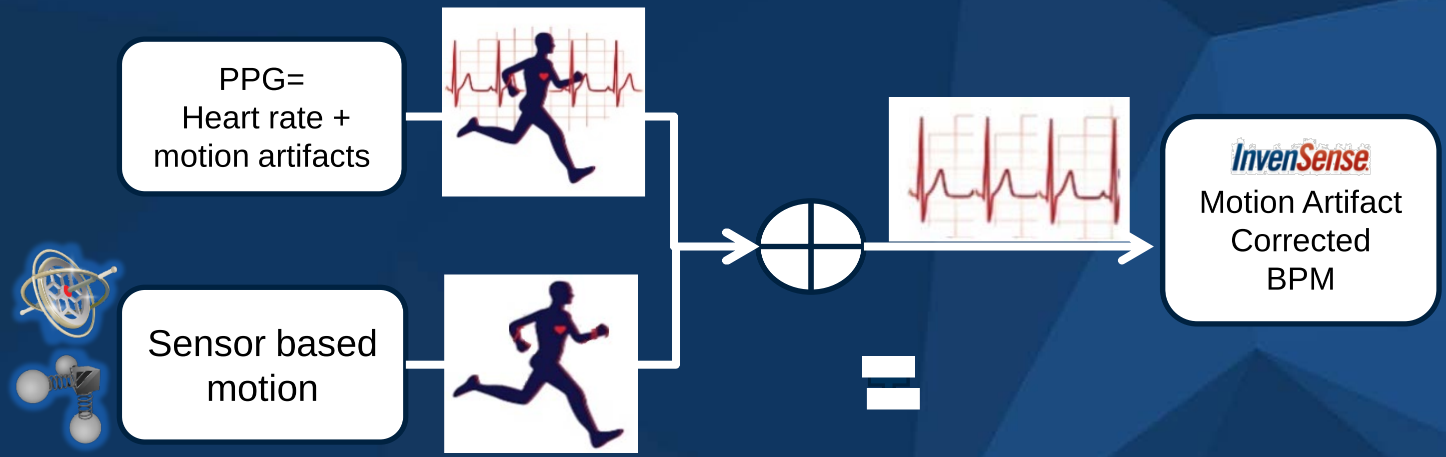
PPG Sensor Power:
1.5mA to 17mA

Solution: Turn on HRM only when necessary (combine with context)

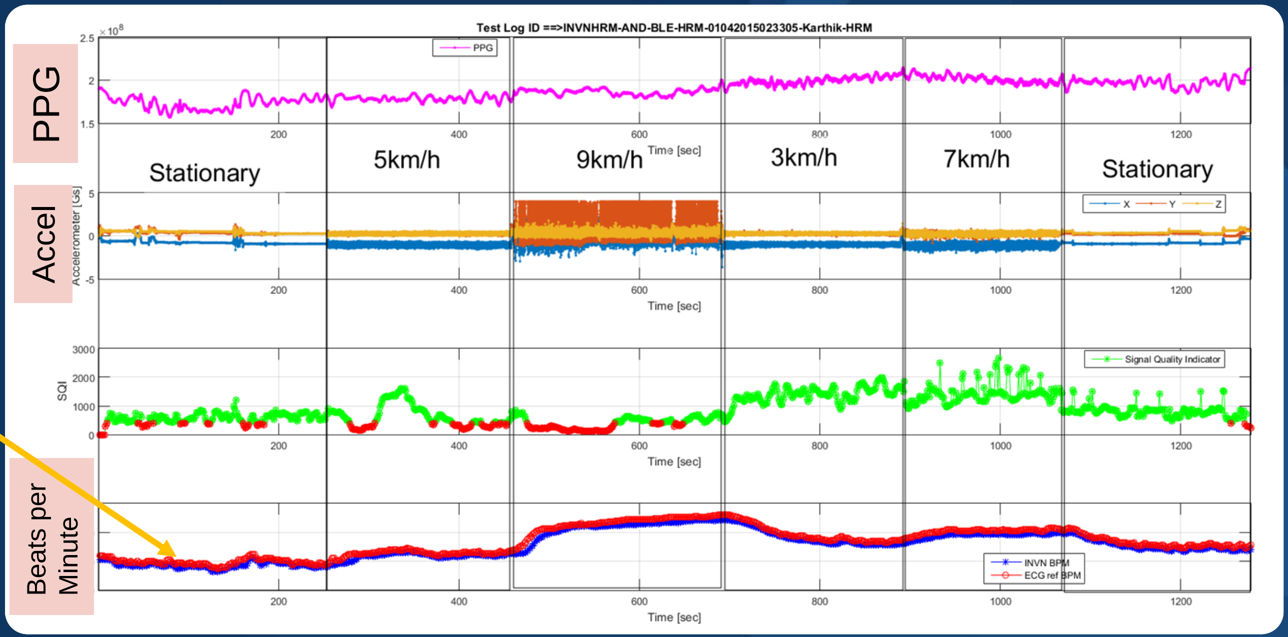


In-Activity HRM Accuracy Improvement

InvenSense



Matches Reference BPM Well



Sensor-Assisted GNSS

GPS is a battery killer

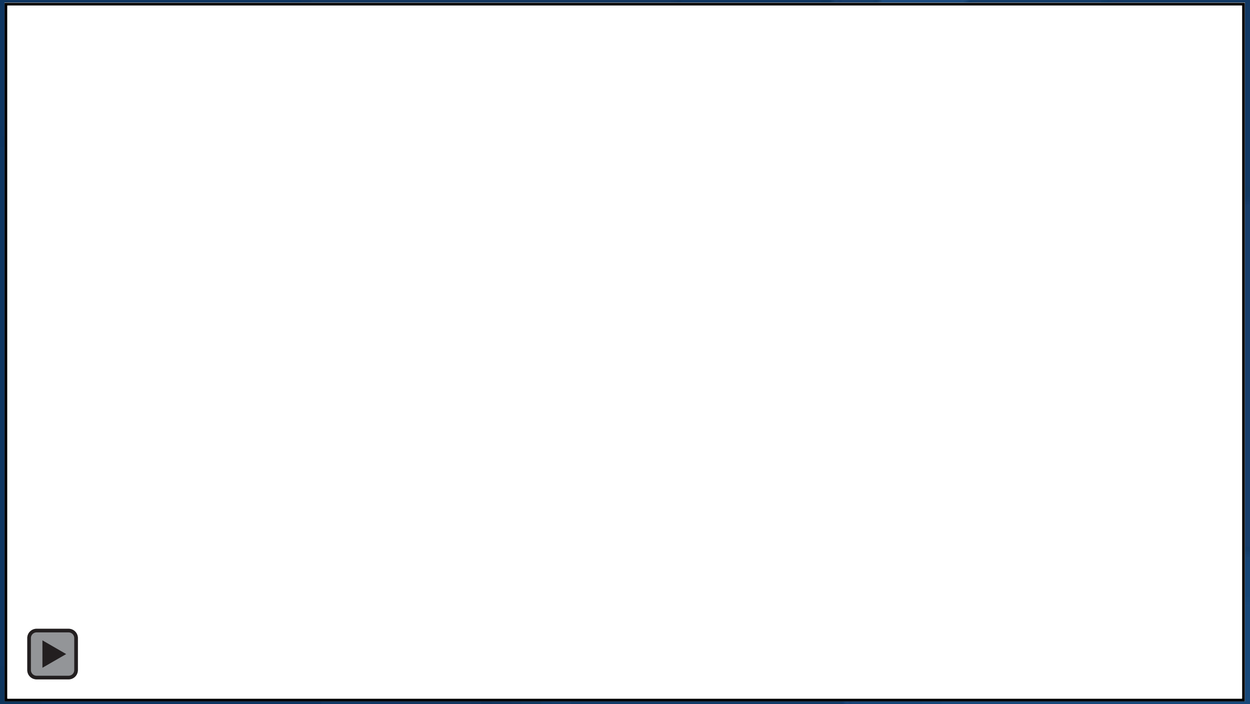
Fitbit Surge:
- 7 day Battery life
- 5hr GPS Battery life

TomTom GPS Watch:
- 17 day Battery life
- 10hr GPS Battery life

Strava Fitness Apps
- 4-6hr Battery Life w/ GPS

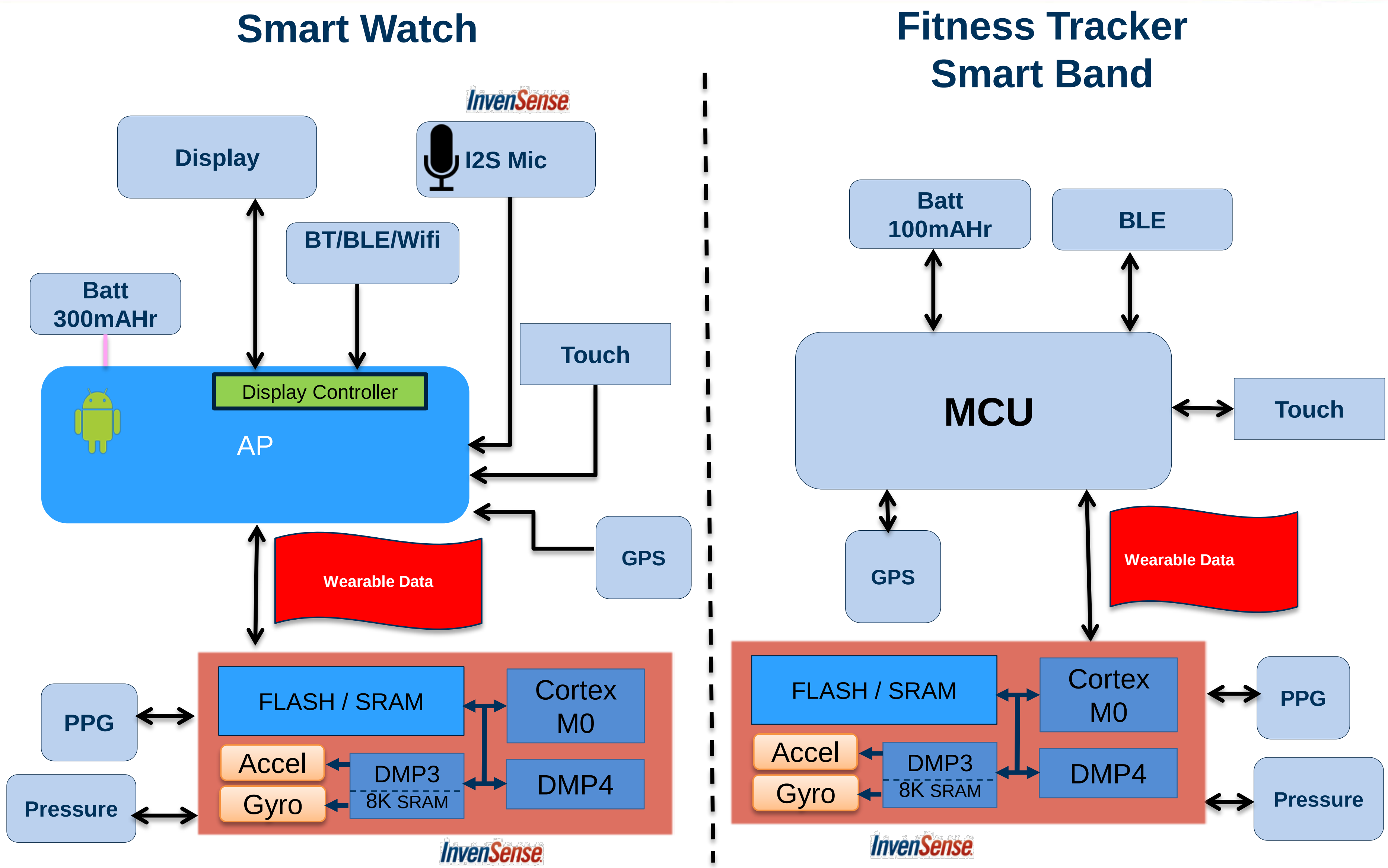
GNSS duty cycling using sensor data and algorithms

Keep accuracy of Run/Bike Speed/Dist/Route. Up to 60% power reduction



Complete Sensor Solution in 3x3mm

InvenSense



Conclusion

InvenSense

- The era of wearables has begun
- New microstructure sensors and actuators are key enablers
- Still dramatic advancement in power consumption, device performance, and size necessary to unleash full potential of wearables
- Innovations in IC design critical to meeting future needs
  - Efficient MEMS/Circuit fabrication and packaging
  - Extreme low power circuits with required SNR and range
    - Analog design techniques
  - Digital techniques to reduce analog deficiencies
    - Low power DSP, sensor fusion, and context aware algorithms