Microsensors, Microsystems and MEMS

CERN
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Outline

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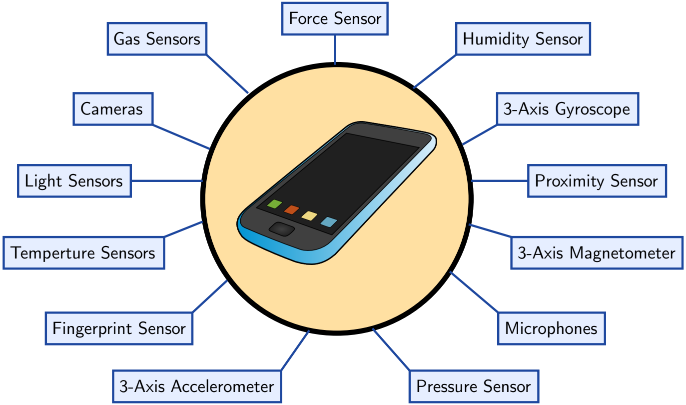
Introduction — Definitions

- Microsensor → Sensor realized with micro-fabrication technologies
- Microactuator → Actuator realized with micro-fabrication technologies
- Microsystem → Complete system realized with micro-fabrication technologies
- MEMS → Micro-electro-mechanical system (formally subset of microsystems, often used as a synonym of microsystem and/or microsensor)
- The introduction of micro-fabrication technologies enabled the widespread diffusion of sensors in almost any application field
    - Mobile devices/IoT
    - Automotive
    - Domotics
    - Entertainment

Introduction — Sensors for IoT/Mobile Devices (Consumer Market)



Force Sensor

Gas Sensors

Humidity Sensor

Cameras

3-Axis Gyroscope

Light Sensors

Proximity Sensor

Temperture Sensors

3-Axis Magnetometer

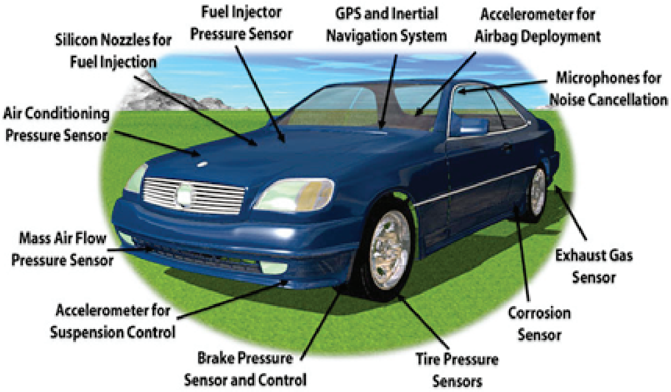
Fingerprint Sensor

Microphones

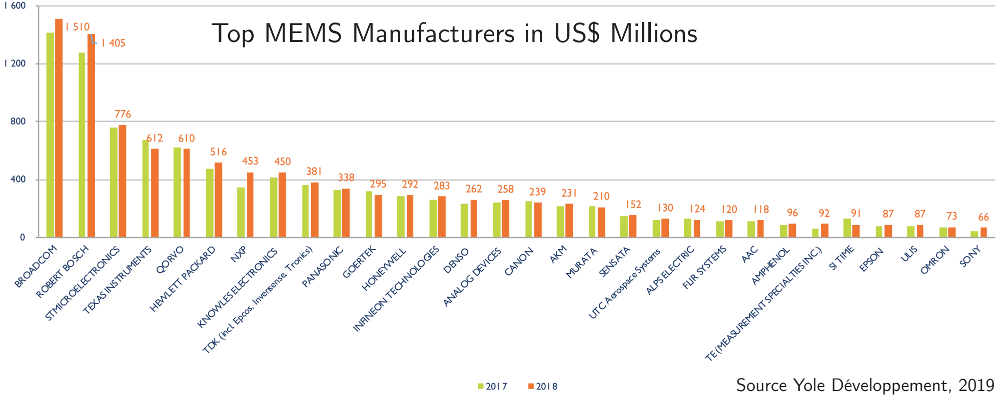
3-Axis Accelerometer

Pressure Sensor

Introduction — Sensors and Actuators for Cars (Automotive Market)

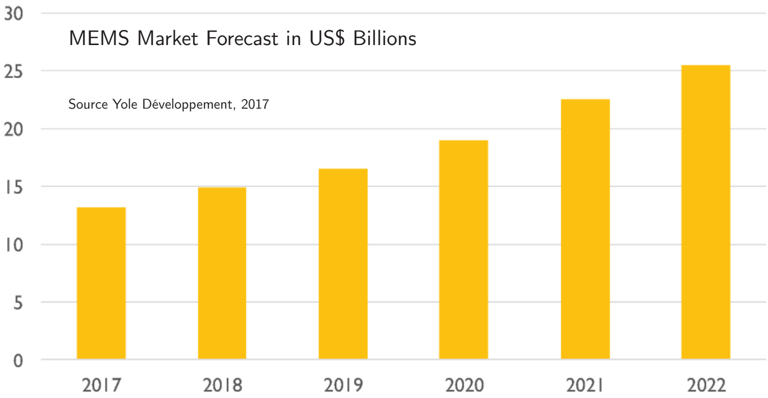


Introduction — Sensor and MEMS Market


Top MEMS Manufacturers in US$ Millions

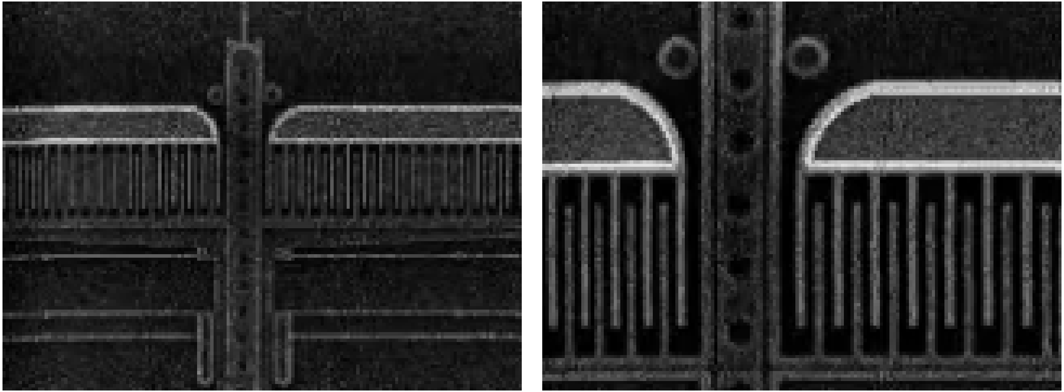
Source Yole Développement, 2019

Introduction — Sensor and MEMS Market

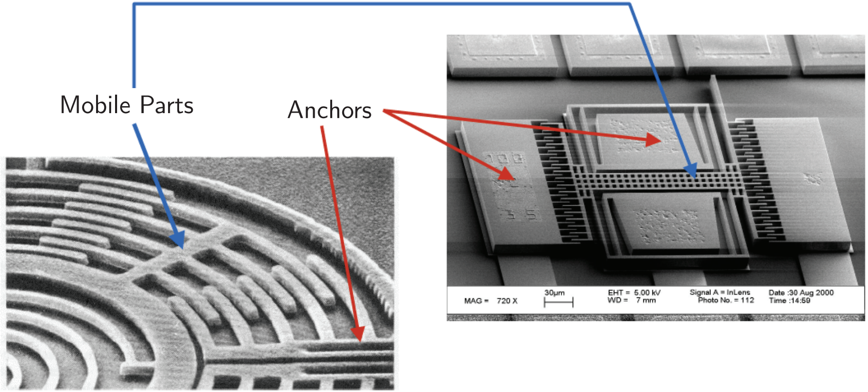


Outline

Microsensors and MEMS — What Are We Talking About?

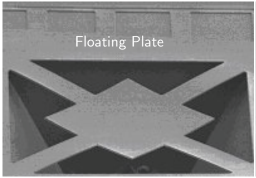


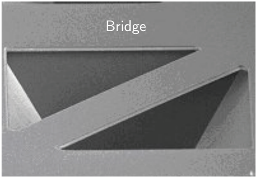
Microsensors and MEMS — What Are We Talking About?

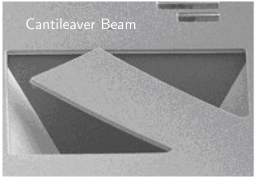

Mobile Parts

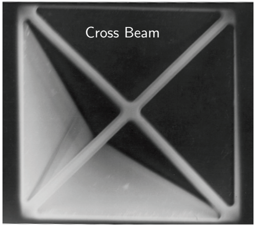
Anchors

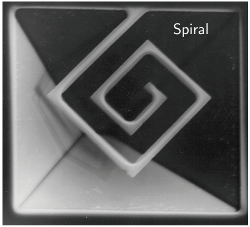
Microsensors and MEMS — What Are We Talking About?

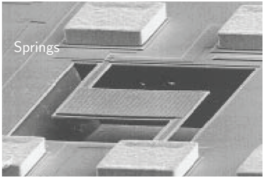












Microsensors and MEMS — Available Materials

Standard materials

- Mono-crystalline silicon (Si) → Anisotropic semiconductor crystal
- Poly-crystalline silicon (Polysilicon) → Mostly isotropic semiconductor material
- Silicon dioxide (SiO_2) → Excellent thermal and electrical insulator
- Silicon nitride (Si_3N_4) → Excellent electrical insulator
- Aluminum (Al) → Good electrical conductor

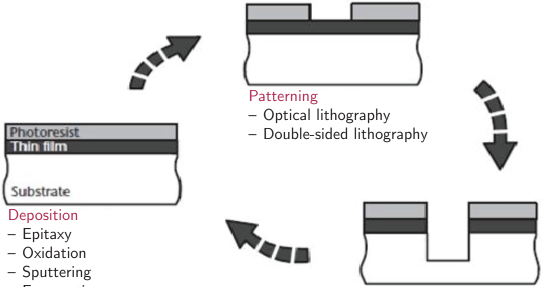
Specific materials

- Copper (Cu) → Excellent electrical conductor
- Gold (Au) and Platinum (Pt) → Excellent electrical conductors, mostly inert
- Various polymer, ceramic and composite materials

Microsensors and MEMS — Fabrication Process

- Micro-fabrication technology for MEMS → Micromachining
- Processing steps
  - Deposition
  - Patterning (photolithography)
  - Etching
- Substrate → Silicon wafer
  - Standard wafer
  - Silicon on Insulator (SOI) wafer
- Surface micromachining → The process does not involve the silicon substrate
- Bulk micromachining → The process involves the silicon substrate

Microsensors and MEMS — Fabrication Process

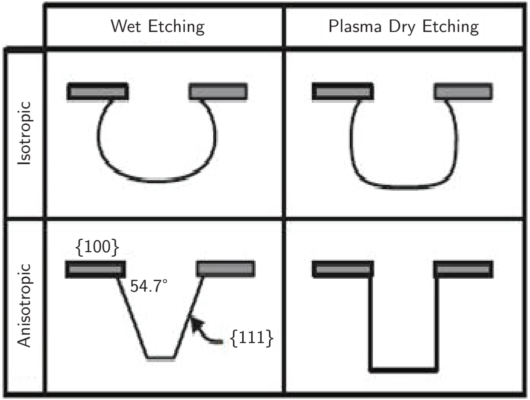


Deposition
- Epitaxy
- Oxidation
- Sputtering
- Evaporation
- CVD/LPCVD/PECVD
- Spin-on method
- Sol-gel
- Anodic bonding
- Silicon fusion bonding

Patterning
- Optical lithography
- Double-sided lithography

Etching
- Wet isotropic
- Wet anisotropic
- Plasma
- RIE
- DRIE

Microsensors and MEMS — Etching of Silicon

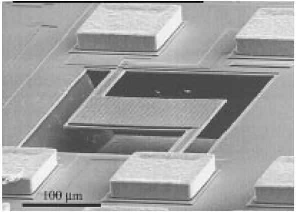


Microsensors and MEMS — Etching of Silicon

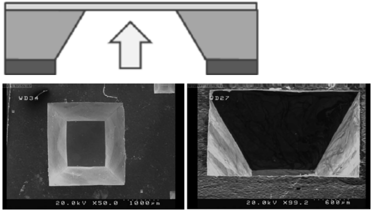
Anisotropic Etching of Silicon

- KOH (Potassium Hydroxide)
- EDP (Ethylene Diamine and Pyrocatechol)
- TMAH (Tetramethylammonium Hydroxide)

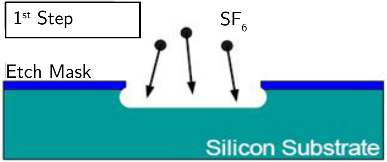
Front-Side Etching (Grooves)



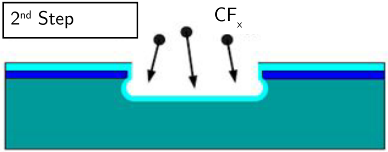
Back-Side Etching (Membranes)



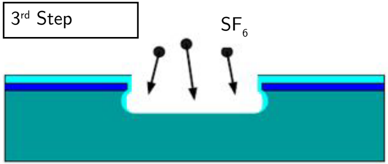
Microsensors and MEMS — Deep Reactive Ion Etching (DRIE)



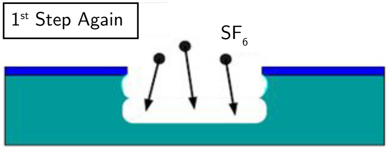
Silicon Etched



Polymer Layer Deposition

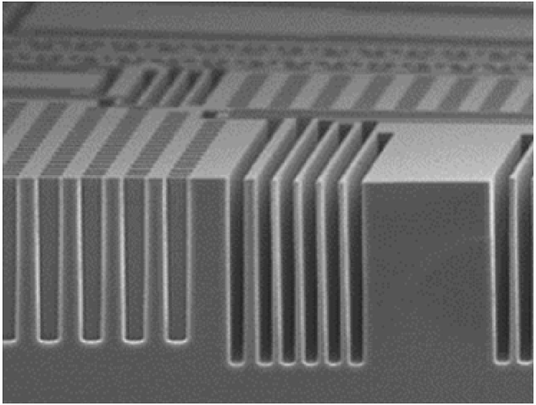


Bottom Polymer Layer Etched

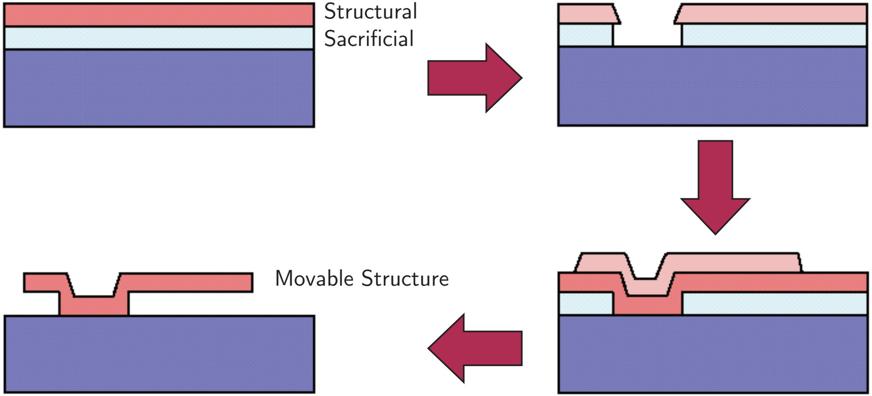


Polymer Layer and Silicon Etched

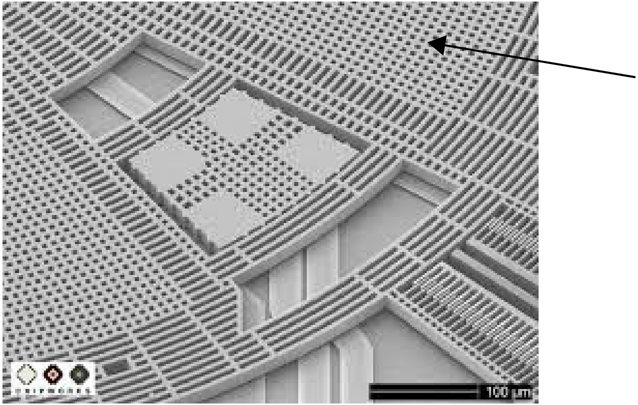
Microsensors and MEMS — Deep Reactive Ion Etching (DRIE)



Microsensors and MEMS — Sacrificial Layer

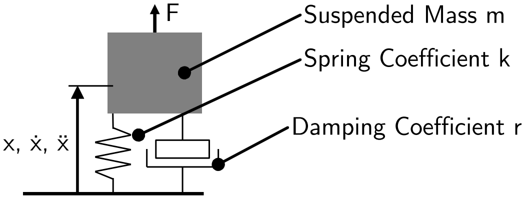


Microsensors and MEMS — Sacrificial Layer



Holes for Sacrificial Layer Etching

Microsensors and MEMS — Movable MEMS Structures

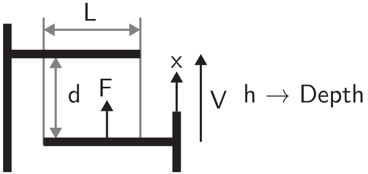


- $m\ddot{x}(t) + r\dot{x}(t) + kx(t) = F(t) \rightarrow G(s) = \frac{X(s)}{F(s)} = -\frac{\frac{1}{k}}{1 + \frac{1}{\omega_0 Q}s + \frac{1}{\omega_0^2}s^2}$
- $\omega_0 = \sqrt{\frac{k}{m}}$ → Resonance frequency
- $Q = \frac{\sqrt{km}}{r}$ → Quality factor

Microsensors and MEMS — Sensing and Actuation

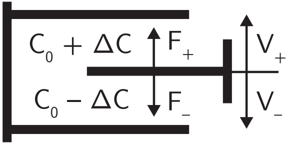
- How to actuate movable structures (apply F) and sense the movement (detect x)?
- Actuation
  - Thermal → Thermal expansion (bi-layer structures)
  - Piezoelectric → Charge ⟶ Force
  - Capacitive → Electrostatic force
- Sensing
  - Piezoresistive → Stress ⟶ Resistance variation
  - Piezoelectric → Force ⟶ Charge
  - Capacitive → Capacitance variation
- Capacitive sensing/actuation
  - Parallel-plate structures
  - Comb-finger structures

Microsensors and MEMS — Parallel-Plates



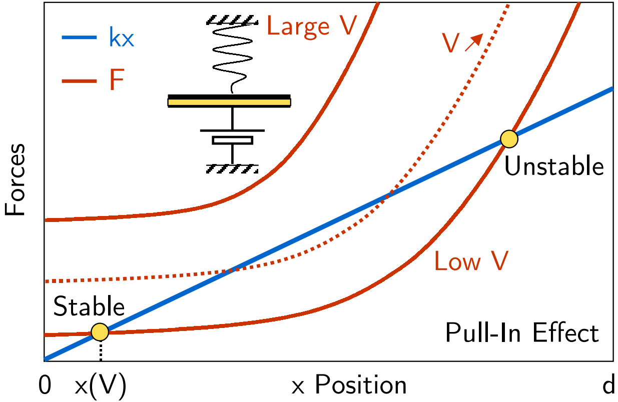
- $C = \dfrac{\varepsilon_0 L h}{d} \rightarrow d \to d_0 - x \rightarrow C = \dfrac{\varepsilon_0 L h}{d_0 - x}$
- Sensing $\rightarrow \Delta C = C(x) - C(0) = \dfrac{\varepsilon_0 L h x}{d_0^2 - d_0 x} \xrightarrow[x \ll d_0]{} \Delta C \approx \dfrac{\varepsilon_0 L h x}{d_0^2}$
- Actuation $\rightarrow E = \dfrac{1}{2} C V^2 \rightarrow |F| = \left|\dfrac{dE}{dx}\right| = \dfrac{V^2 \varepsilon_0 L h}{2\,(d_0 + x)^2} \xrightarrow[x \ll d_0]{} |F| \approx \dfrac{V^2 \varepsilon_0 L h}{2 d_0^2}\left(1 - \dfrac{2x}{d_0}\right)$

Microsensors and MEMS — Parallel-Plates

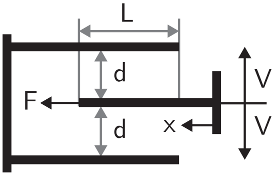


- Interaction between sensing and actuation
  - Measure x → Read C → Apply V → Generate F → Change x
  - Solution → Use differential structures (with $V_+ = V_-$, $F_+ = F_-$ for $x = 0$)
- Non-linear function F(x) → Spring softening effect and pull-in effect
  - $m\ddot{x}(t) + r\dot{x}(t) + kx(t) = -F(t) = -\frac{V^2\varepsilon_0 Lh}{2d_0^2} + \frac{V^2\varepsilon_0 Lhx(t)}{d_0^3}$ → $k \to k - \frac{V^2\varepsilon_0 Lh}{d_0^3}$
  - The spring coefficient k is lowered by applying V → The resonance frequency ω_0 decreases

Microsensors and MEMS — Parallel-Plates



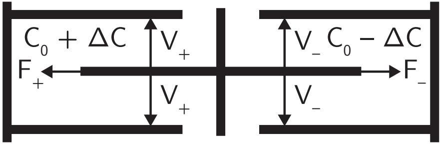
Microsensors and MEMS — Comb-Fingers



$h \rightarrow$ Depth

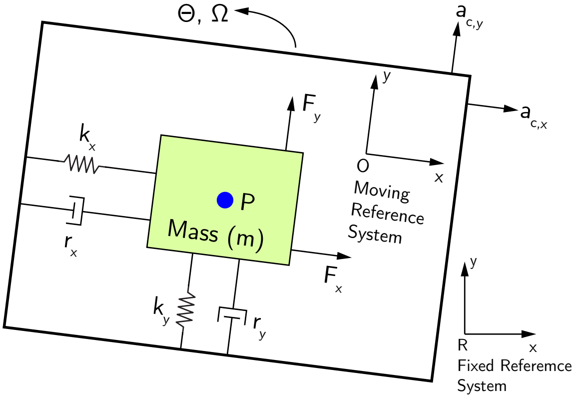
- $C = \dfrac{2\varepsilon_0 L h}{d}$ ➔ $L \rightarrow L_0 + x$ ➔ $C = \dfrac{2\varepsilon_0 h\left(L_0 + x\right)}{d}$
- Sensing ➔ $\Delta C = C(x) - C(0) = \dfrac{2\varepsilon_0 h x}{d}$
- Actuation ➔ $E = \dfrac{1}{2} C V^2$ ➔ $|F| = \left|\dfrac{dE}{dx}\right| = \dfrac{V^2 \varepsilon_0 h}{d}$

Microsensors and MEMS — Comb-Fingers



- Interaction between sensing and actuation
  - Measure x → Read C → Apply V → Generate F → Change x
  - Solution → Use differential structures (with $V_+ = V_-$, $F_+ = F_-$ for $x = 0$)
- Linear function F(x) → No spring softening effect
  - $m\ddot{x}(t) + r\dot{x}(t) + kx(t) = -F(t) = -\dfrac{V^2 \varepsilon_0 h}{d}$
  - The spring coefficient k is independent of V → The resonance frequency ω_0 remains constant

Microsensors and MEMS — Inertial Sensors



Microsensors and MEMS — Inertial Sensors

- Absolute acceleration of the mass in the moving reference system $(\vec{i}, \vec{j}, \vec{k})$

$$\vec{a} = \left(\ddot{x}\vec{i} + \ddot{y}\vec{j}\right) + \Omega\vec{k} \times \left[\Omega\vec{k} \times \left(x\vec{i} + y\vec{j}\right)\right] + \dot{\Omega}\vec{k} \times \left(x\vec{i} + y\vec{j}\right) +$$

$$+ 2\Omega\vec{k} \times \left(\dot{x}\vec{i} + \dot{y}\vec{j}\right) + \left(a_{c,x}\vec{i} + a_{c,y}\vec{j}\right)$$

- Differential equations along x and y

$$-k_x x - r_x \dot{x} + F_x = m\left(\ddot{x} - \dot{\Omega}y - 2\Omega\dot{y} - \Omega^2 x + a_{c,x}\right)$$

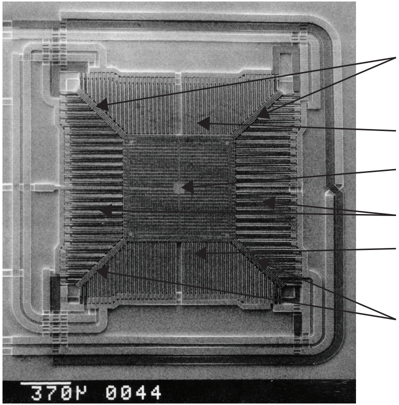
$$-k_y y - r_y \dot{y} + F_y = m\left(\ddot{y} + \dot{\Omega}x + 2\Omega\dot{x} - \Omega^2 y + a_{c,y}\right)$$

- $a_{c,x}$ and $a_{c,y}$ → Linear accelerations
- $\Omega\dot{y}$ and $\Omega\dot{x}$ → Coriolis acceleration
- $\Omega^2 x$, $\Omega^2 y$ → Negligible, being $\Omega \ll \sqrt{k_{x,y}/m}$

Microsensors and MEMS — Accelerometer

- Accelerometer → $F_x = 0,\ F_y = 0,\ \Omega = 0$
- $m\ddot{x} + r_x\dot{x} + k_x x + m a_{c,x} = 0$
- $m\ddot{y} + r_y\dot{y} + k_y y + m a_{c,y} = 0$
- Sensitivity $\frac{x}{a_{c,x}}$ → $\mu_x = -\frac{m}{k_x}$
- $\omega_{0,x} = \sqrt{\frac{k_x}{m}},\ Q_x = \frac{\sqrt{k_x m}}{r_x}$
- Sensitivity $\frac{y}{a_{c,x}}$ → $\mu_y = -\frac{m}{k_y}$
- $\omega_{0,y} = \sqrt{\frac{k_y}{m}},\ Q_y = \frac{\sqrt{k_y m}}{r_y}$

Microsensors and MEMS — Two-Axis Accelerometer



Springs

Comb-Fingers y

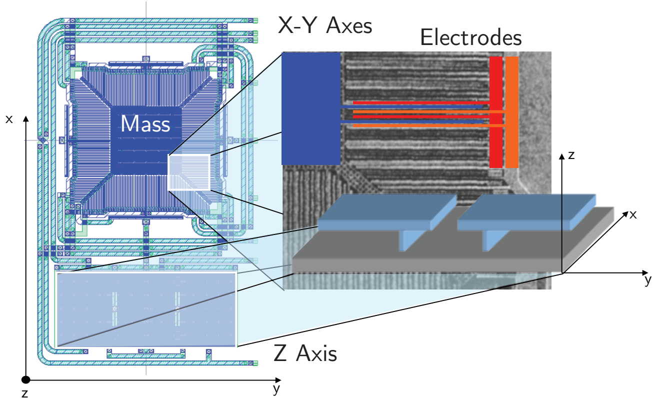
Mass

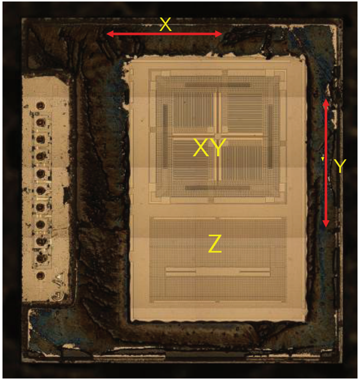
Comb-Fingers x

Comb-Fingers y

Springs

Microsensors and MEMS — Three-Axis Accelerometer

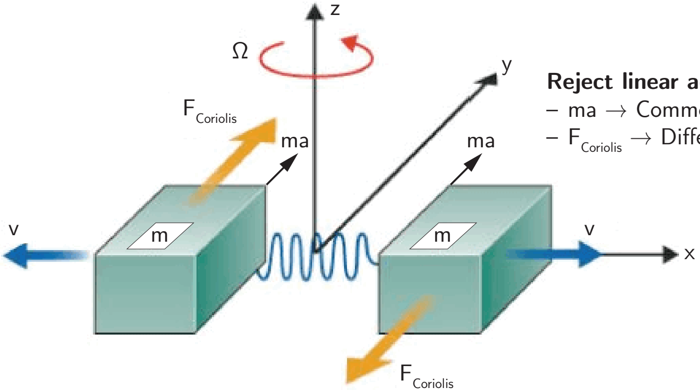




Microsensors and MEMS — Gyroscope

- Gyroscope → $a_{c,x} = 0,\ a_{c,y} = 0,\ \Omega$ constant $(\dot{\Omega} = 0),\ F_x = F_0 \sin(\omega t),\ F_y = 0,\ y \ll x$
- $m\ddot{x} + r_x\dot{x} + k_x x = F_x$ → Driving → $X(\omega) = \dfrac{\frac{F_0}{\omega_{0,x}^2 m}}{\sqrt{\left(1 - \frac{\omega^2}{\omega_{0,x}^2}\right)^2 + \left(\frac{\omega}{\omega_{0,x} Q_x}\right)^2}}$
- $m\ddot{y} + r_y\dot{y} + k_y y = -2m\Omega\dot{x}$ → Sensing → $Y(\omega) = \dfrac{\frac{2m\omega\Omega X}{k_y}}{\sqrt{\left(1 - \frac{\omega^2}{\omega_{0,y}^2}\right)^2 + \left(\frac{\omega}{\omega_{0,y} Q_y}\right)^2}}$
- Maximum sensitivity y/Ω → $\omega_{0,x} = \omega_{0,y} = \omega$
  - $\mu_{max} = \dfrac{2m\omega F_0 Q_x Q_y}{k_x k_y}$
  - Spring softening effect → Tuning of $\omega_{0,y}$ to match $\omega_{0,x}$

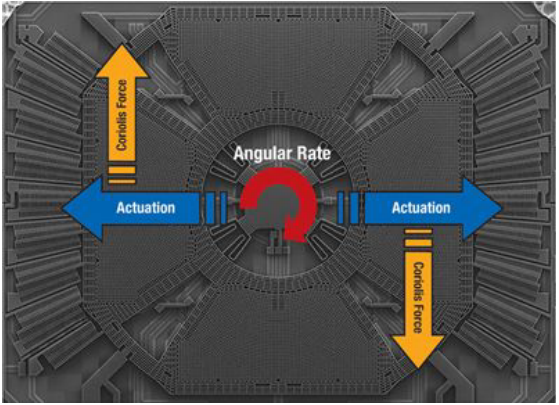
Microsensors and MEMS — Two-Mass Gyroscope



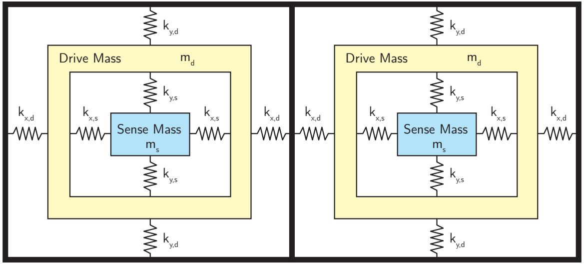
Reject linear accelerations

- ma → Common-mode signal
- $F_{Coriolis}$ → Differential signal

Microsensors and MEMS — Two-Mass Gyroscope

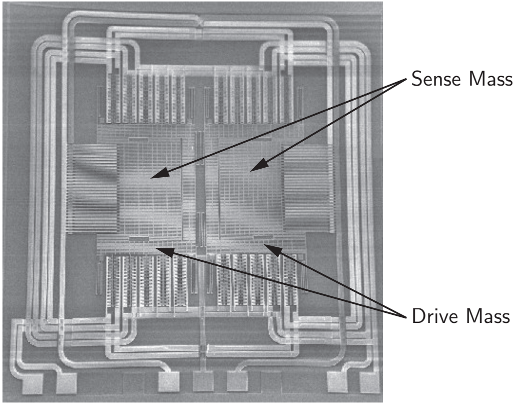


Microsensors and MEMS — Four-Mass Gyroscope

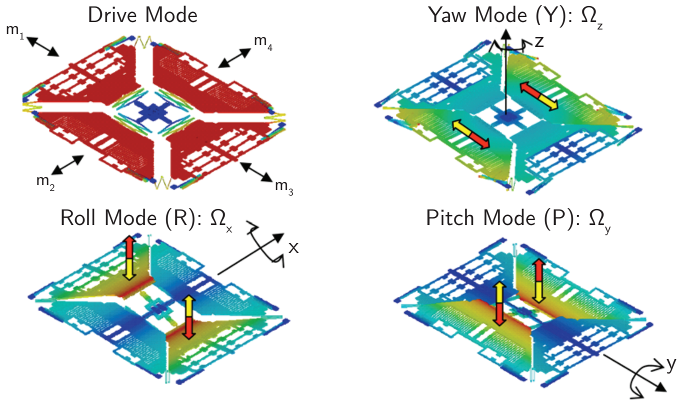


- Optimal driving → $k_x \gg k_y$
- Optimal sensing → $k_y \gg k_x$
- Optimal sensitivity → $\omega_{0,x} \approx \omega_{0,y}$ → $k_x \approx k_y$
- Four-mass gyroscope → Decouple sensing and driving $\omega_{0,x}$, $\omega_{0,y}$, k_x, k_y

Microsensors and MEMS — Four-Mass Gyroscope



Microsensors and MEMS — Three-Axis Gyroscope



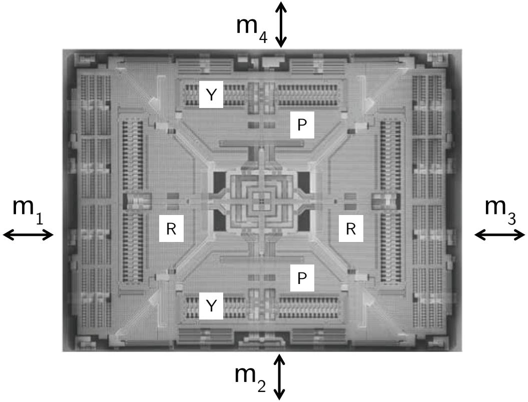
Drive Mode

Yaw Mode (Y): Ω_z

Roll Mode (R): Ω_x

Pitch Mode (P): Ω_y

Microsensors and MEMS — Three-Axis Gyroscope



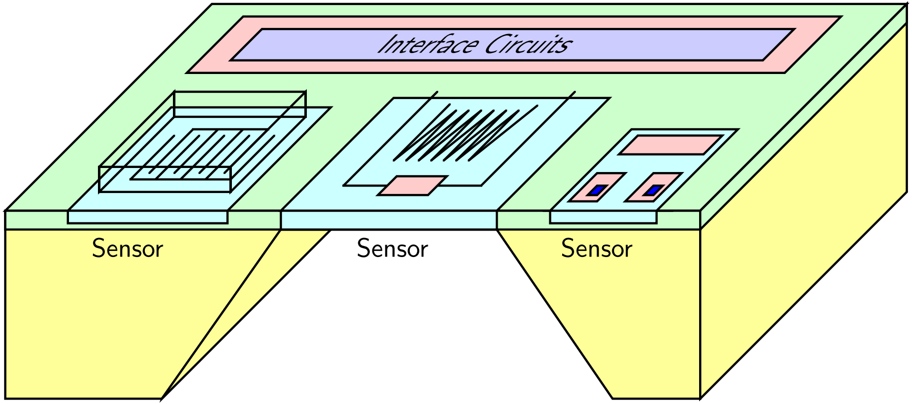
Outline

1. Introduction
2. Microsensors and MEMS
   - Available Materials
   - Fabrication Process
   - Sensing and Actuation
   - Inertial Sensors
3. Integrated Microsystems
   - Architecture
   - Analog Front-End Circuits
   - A/D Converters
4. Conclusions

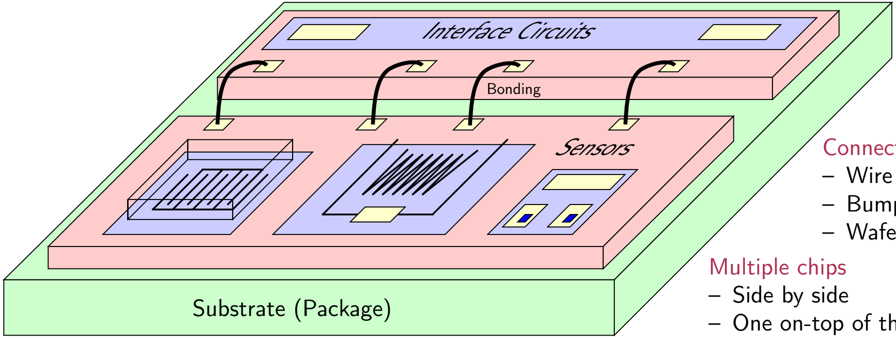
Integrated Microsystems

- Integrated microsystem → MEMS device + interface circuits + package
- MEMS device, interface circuits and package must be designed and optimized together from the very beginning
  - Optimal MEMS device + Optimal interface circuit + Optimal package → Not necessarily optimal microsystem
  - The specifications and performances of the different blocks must be balanced
  - Loading effects and interactions among blocks must be considered
- Architectural choices
  - Single chip or multiple chips?
  - Analog or digital signal processing?
- Key parameters (assuming that the required performances are obtained)
  - Cost
  - Size
  - Power consumption

Integrated Microsystems — Single Chip



Integrated Microsystems — Multiple Chips



Connection
- Wire bonding
- Bump bonding
- Wafer-wafer bonding

Multiple chips
- Side by side
- One on-top of the other

Integrated Microsystems — Single Chip vs Multiple Chips

Single chip

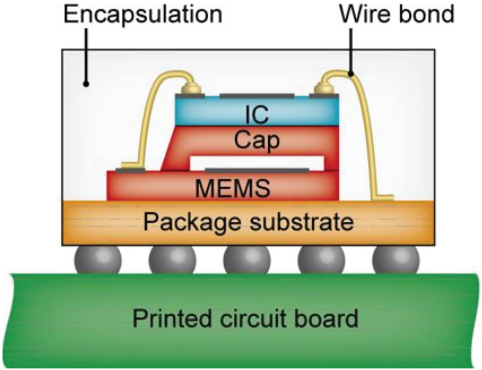
- ☺ Reliability (no bonding)
- ☺ Minimal parasitics
- ☺ Simple assembling
- ☹ Yield (different failure mechanisms)
- ☹ Optimal process only for circuits
- ☹ Reduced flexibility
- ☹ Technology scaling

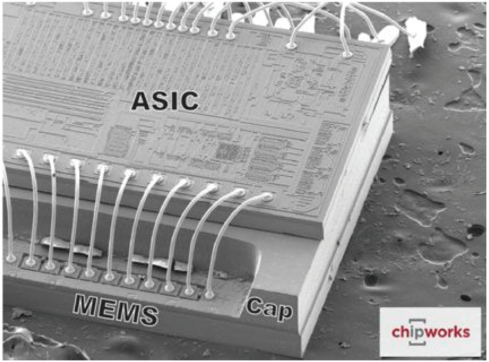
Multiple chips

- ☺ Yield (different processes)
- ☺ Optimal process for sensors and circuits
- ☺ Maximal flexibility
- ☺ Technology scaling
- ☹ Reliability (bonding wires)
- ☹ Additional interconnection parasitics
- ☹ Complex assembling

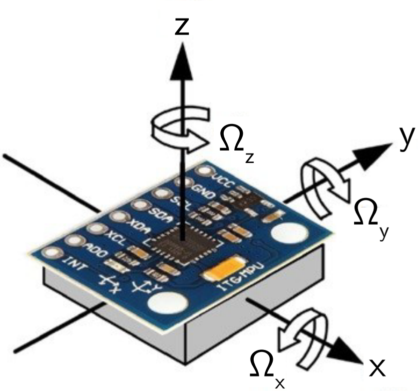
The two-chip approach turned out to be the winning solution for MEMS

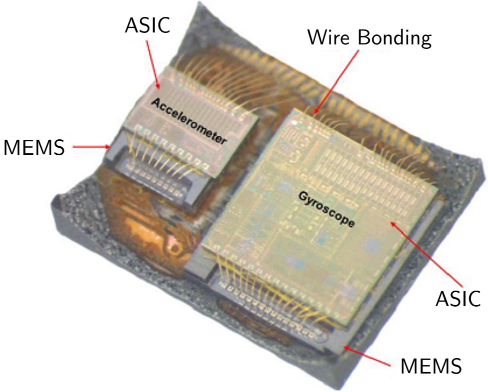
Integrated Microsystems — Assembling



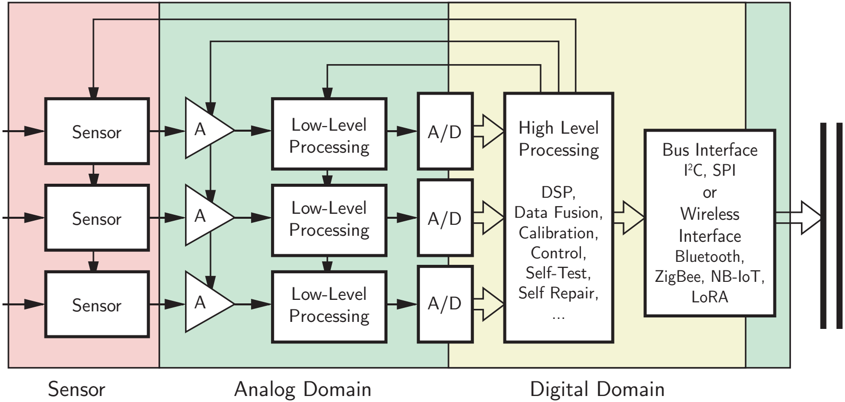


Integrated Microsystems — Six-Axis Inertial Sensor





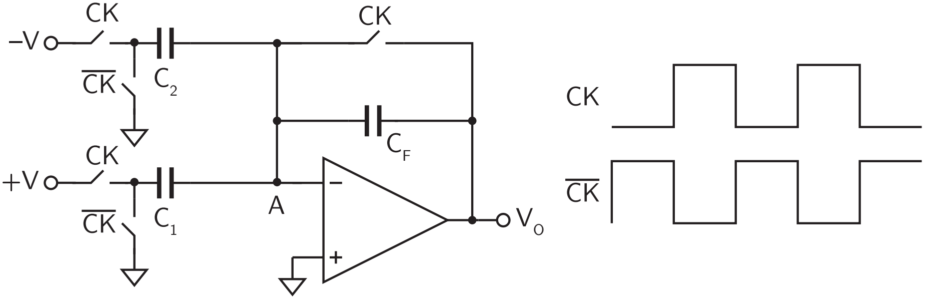
Integrated Microsystems — Architecture



Integrated Microsystems — Analog Front-End Circuits

- Sensor readout → Depends on the sensor output quantity
  - Voltage → Voltage amplifier
  - Current → Transimpedance amplifier
  - Charge → Charge amplifier
  - Resistance variation → Bridge + voltage amplifier
  - Capacitance variation → Capcitance-to-voltage converter
- Key design issues
  - Offset and noise → Chopper stabilization or correlated-double sampling are often used
  - Parasitics and parasitic effects → Try to compensate for them as early as possible in the processing chain (eventually using feedback)
- Capcitance-to-voltage converter
  - Tiny capacitance variations → ΔC in the aF range
  - Large capacitances → $C(0)$ in the pF range

Integrated Microsystems — Capacitance-to-Voltage Converter

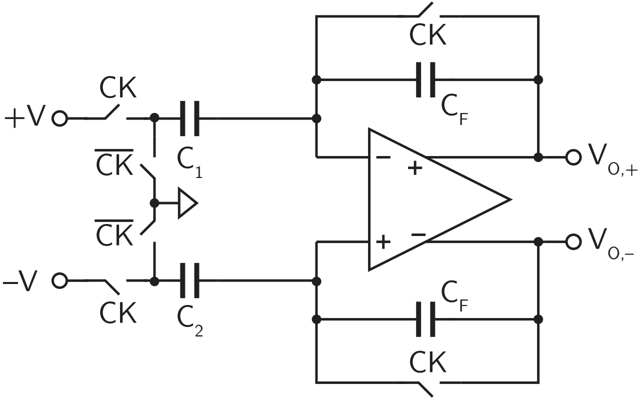


- Single-ended structure → $C_1 = C_0 + \Delta C$ and $C_2 = C_0$
- Differential structure → $C_1 = C_0 + \Delta C$ and $C_2 = C_0 - \Delta C$

Integrated Microsystems — Capacitance-to-Voltage Converter

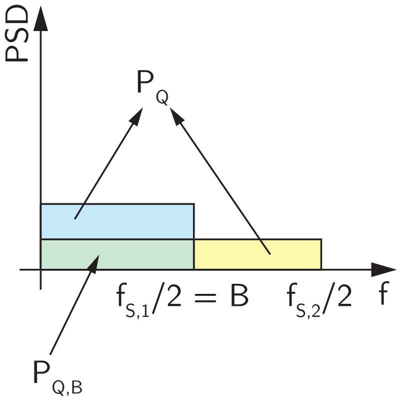
- $CK = 1,\ \overline{CK} = 0$
  - $Q_{1,CK} = C_1V,\ Q_{2,CK} = -C_2V,\ Q_{F,CK} = 0$
  - $V_O = 0$
- $\overline{CK} = 1,\ CK = 0$
  - $Q_{1,\overline{CK}} = 0,\ Q_{2,\overline{CK}} = 0,\ Q_{F,\overline{CK}} = C_FV_O$
  - Node A is isolated → $Q_{1,\overline{CK}} + Q_{2,\overline{CK}} + Q_{F,\overline{CK}} = Q_{1,CK} + Q_{2,CK} + Q_{F,CK}$ → $C_1V - C_2V = C_FV_O$
  - $V_O = \dfrac{C_1V - C_2V}{C_F}$
- Single-ended structure → $V_O = \dfrac{C_0 + \Delta C - C_0}{C_F}V = \dfrac{\Delta C}{C_F}V$
- Differential structure → $V_O = \dfrac{C_0 + \Delta C - C_0 + \Delta C}{C_F}V = \dfrac{2\Delta C}{C_F}V$
- Typically implemented with fully-differential structure

Integrated Microsystems — Capacitance-to-Voltage Converter

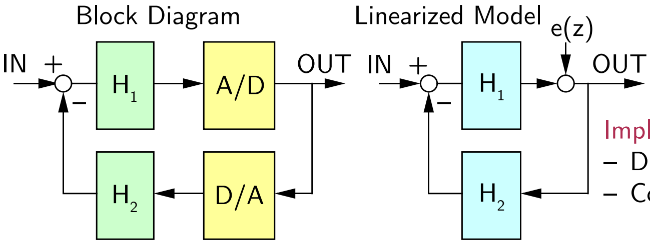


Integrated Microsystems — A/D Converters

- A/D converter for sensor applications
  - Small bandwidth (maximum tens of kHz)
  - High resolution and accuracy (up to 20 bits)
- Oversampled A/D converters
  - Sigma-delta modulators
  - Incremental A/D converters
- Total quantization noise power → $P_Q = \frac{\Delta^2}{12}$
- Oversampling ratio → $M = \frac{f_S}{2B}$
- In-band quantization noise power → $P_{Q,B} = \frac{\Delta^2}{12M}$



Integrated Microsystems — Sigma-Delta Modulators (ΣΔMs)

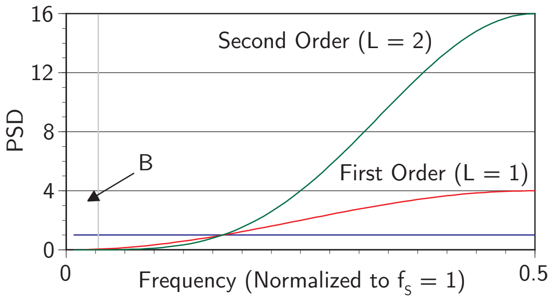


Implementation:

- Discrete-time (DT) → $H_1(z)$, $H_2(Z)$
- Continuous-time (CT) → $H_1(s)$, $H_2(s)$

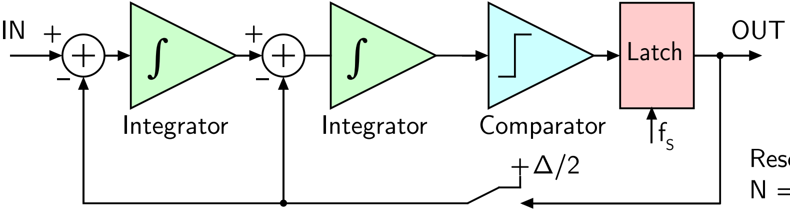
- Signal transfer function → $\mathrm{STF} = \dfrac{H_1(z)}{1 + H_1(z)H_2(z)}$ → $\mathrm{STF} = 1$
- Quantization noise transfer function → $\mathrm{NTF} = \dfrac{1}{1 + H_1(z)H_2(z)}$ → $\mathrm{NTF} = \left(1 - z^{-1}\right)^{L}$

Integrated Microsystems — Sigma-Delta Modulators (ΣΔMs)



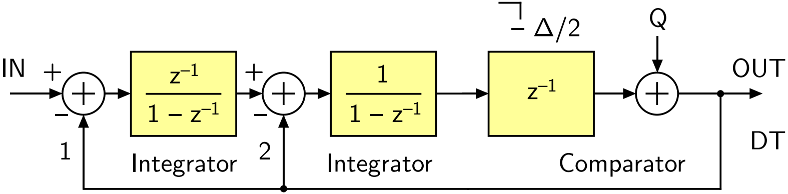
- Noise shaping → Quantization noise pushed at high frequency
- In-band quantization noise power → $P_{Q,B} = \dfrac{\Delta^2 \pi^{2L}}{12\,(2L+1)\,M^{2L+1}}$

Integrated Microsystems — Second-Order ΣΔM



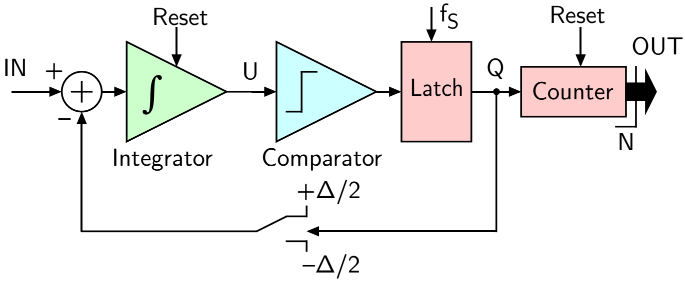
Resolution

$N = 15 \log_2 M - 11.1$



DT Implementation

Integrated Microsystems — Incremental A/D Converter

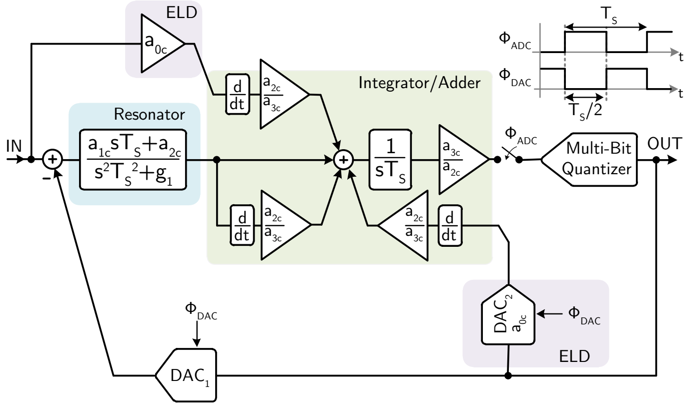


- Reset at the beginning of each conversione cycle → $U(0) = 0$
- N-bit resolution → 2^N clock periods → $U(k+1) = U(k) + \left[IN - (-1)^{Q(k)+1}\,\Delta/2\right]$
- $OUT = 2^{N+1} IN/\Delta$

Integrated Microsystems — CT ΣΔM

- CT ΣΔM
  - ☺ Relaxed operational amplifier bandwidth requirements → Low power consumption
  - ☺ Sampling at the input of the quantizer → Inherent antialiasing filtering
- Example → Third-order, single-loop, multi-bit CT ΣΔM [3, 4, 5]
- Designed for minimizing power consumption (P) and maximizing dynamic range (DR)
  - ☺ Feedforward architecture → Reduced integrator voltage swing
  - ☺ Multi-bit quantizer (15 levels) → Reduced jitter sensitivity and quantization noise
  - ☺ DAC with three-level current-steering elements → Reduced noise at low input signal levels
  - ☺ Third-order loop filter with only two operational amplifiers → Reduced power consumption
- Target → $\mathrm{DR} > 100\,\mathrm{dB}$ and $\mathrm{P} < 0.5\,\mathrm{mW}$
- Among best-in-class A/D converters for MEMS applications

Integrated Microsystems — CT ΣΔM



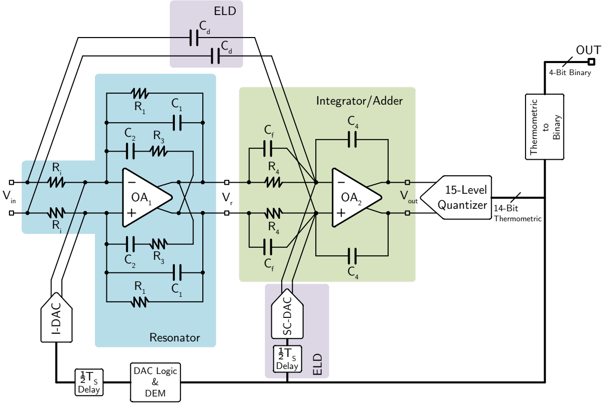
$$a_{0c} = a_1\tau_d + a_2\frac{\tau_d^2}{2} + a_2\frac{\tau_d^6}{6}$$

$$a_{1c} = a_1 + a_2\tau_d + a_2\frac{\tau_d^2}{2}$$

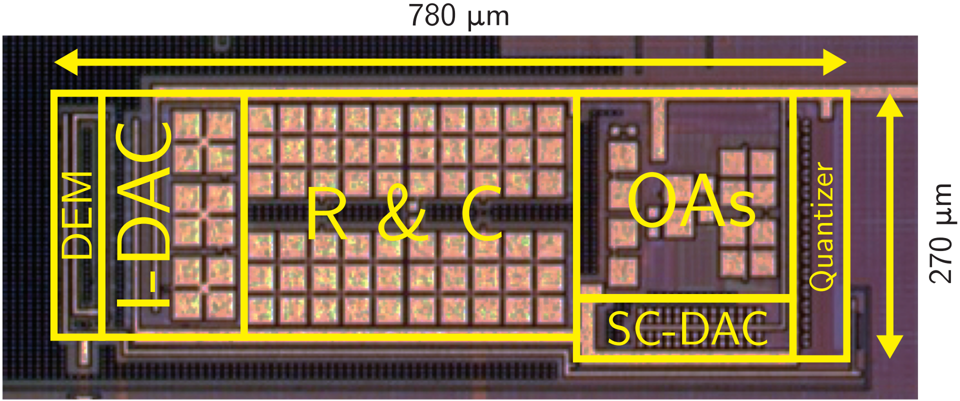
$$a_{2c} = a_2 + a_3\tau_d$$

$$a_{3c} = a_3 - a_1 g_1$$

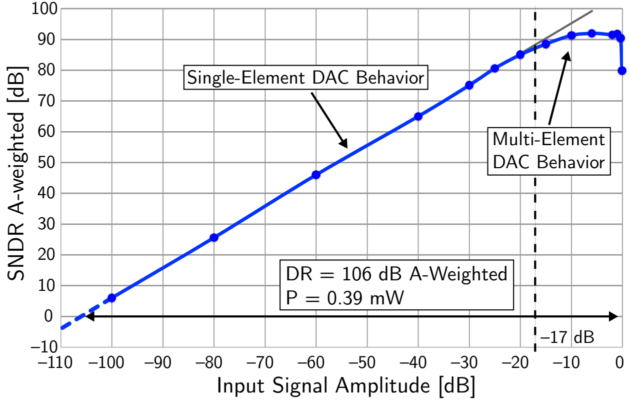
Integrated Microsystems — CT ΣΔM



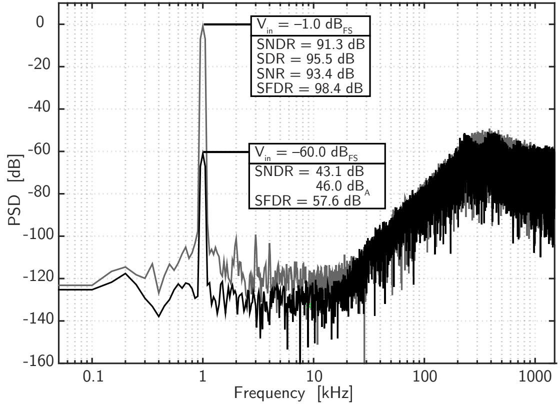
Integrated Microsystems — CT ΣΔM



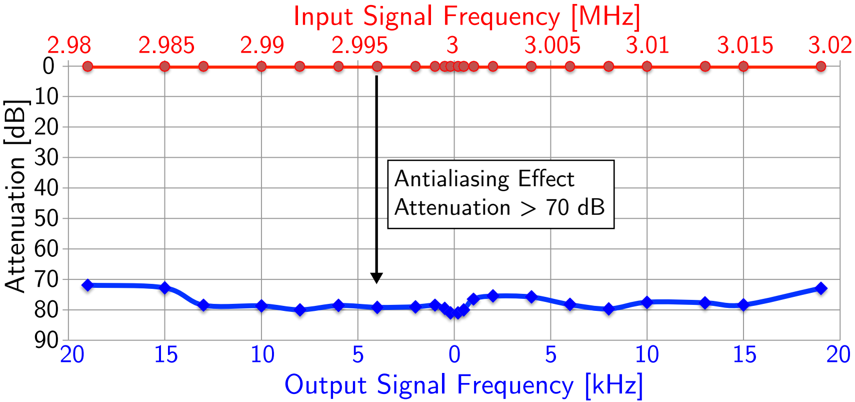
Integrated Microsystems — CT ΣΔM



Integrated Microsystems — CT ΣΔM



Integrated Microsystems — CT ΣΔM



Antialiasing Effect
Attenuation > 70 dB

Outline

Conclusions

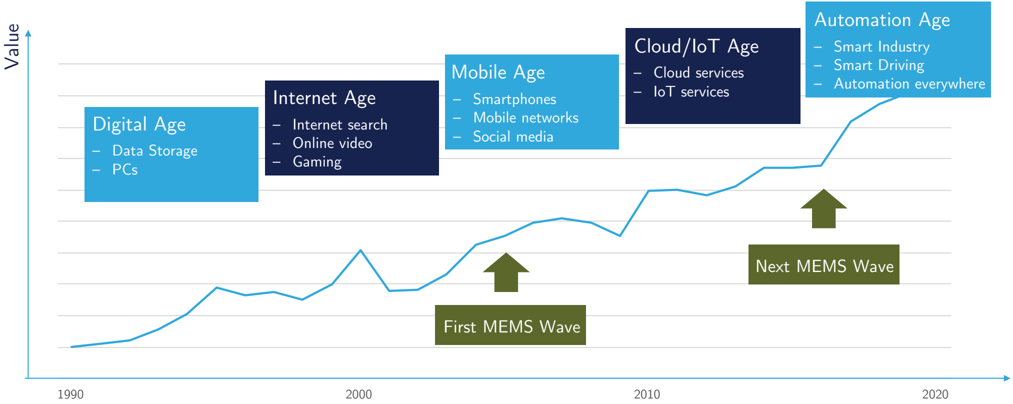
Crucial aspects in microsystem design

- Concurrent design of MEMS device, front-end circuits and package
- Choice of microsystem partitioning → Number of chips, analog/digital boundary

Open issues and trends in microsystem design

- Testing and calibration involving physical quantities → Contributes significantly to the microsystem cost
- Increased accuracy → Can enable many new applications
- Multiple sensors and data fusion → Neural networks and deep learning

Conclusions



Digital Age
- Data Storage
- PCs

Internet Age
- Internet search
- Online video
- Gaming

Mobile Age
- Smartphones
- Mobile networks
- Social media

Cloud/IoT Age
- Cloud services
- IoT services

Automation Age
- Smart Industry
- Smart Driving
- Automation everywhere

First MEMS Wave

Next MEMS Wave