ME 141B: The MEMS Class
Introduction to MEMS and MEMS Design

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MEMS Case Study: A Capacitive Accelerometer

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Outline

• Accelerometer Fundamentals
• Analog Devices Accelerometer
  ➢ History
  ➢ Structure
  ➢ Design and Modeling
  ➢ Fabrication and packaging
  ➢ Noise and Accuracy
Why Accelerometer?

• Measurement of acceleration
  ➢ Central element of inertial guidance systems
  ➢ Crash detection for air-bag deployment
  ➢ Vibrational analysis
  ➢ Steady images in video recorder
Two approaches to measuring acceleration

- Open loop: Measure change due to acceleration
  - In absence of force feedback
- Closed loop: A disturbance in a position control system
  - Disturbance = measurand
  - Controller output (counters disturbances) = system output

Most accelerometers are open-loop

In any case, a proof-mass is held by elastic support to rigid frame

Acceleration of frame causes mass to move relative to frame, bending or stretching support

Detection of accelerations by direct observation, or by detection of deformation of support (piezo)
Accelerometer Types

• Open vs. Closed loop sensing
  ➢ Open loop: measure change due to acceleration
  ➢ Closed loop: a disturbance in a position control system

• Quasi-Static vs. resonant sensing
  ➢ Quasi-static sensing: motion of mass follows time-evolution of applied inertial force without significant retardation or attenuation
    • Mechanical resonant frequency > frequency of acceleration
    • Measure displacement due to acceleration
      ➢ Optical, capacitive, piezo, tunneling
  ➢ Resonant sensing
    • Measure change in resonant frequency
      ➢ Due to position-dependant nonlinear spring

• Today: quasi-static capacitive accelerometer
Accelerometer Fundamentals

- Displacement and acceleration are coupled together by a fundamental scaling law
  - A higher resonant frequency implies less displacement
    - High frequency and low sensitivity
  - Measuring small accelerations requires floppier structures
    - High sensitivity and low frequency

\[
x = \frac{F}{k} = \frac{ma}{k}
\]

\[
x = \frac{a}{\omega_0^2}
\]
Accelerometer Fundamentals

• Displacement and acceleration are coupled together by a fundamental scaling law
  ➢ Scale factor depends only on resonant frequency and not affected by choice of large mass and stiff spring or small mass and compliant spring
  ➢ Only ratio is important
  ➢ If one needs to make an accelerometer that responds quickly (high resonant frequency), the amplitude of the position signal to be sensed will be small
    • I.e. 50 g Analog Devices accelerometer has resonant frequency of 24.7kHz, maximum displacement is 20 nm, but if f is 1kHz, max displacement is 1.2 um
Accelometer fundamentals

- Noise due to damping = Brownian motion noise
- Turns into an equivalent acceleration
  - I.e. 24.7 kHz resonant frequency, and mass of $2.2 \times 10^{-10}$ kg, and Q of 5, rms acceleration noise = $4.83 \times 10^{-3}$ m/sec^2/sqrt(Hz)
  - Thus can get huge SNR with microaccelerometers

$$a_{n,rms} = \sqrt{\frac{4k_B T \omega_0}{mQ}}$$
Initial application arena was Automotive crash sensor

Navigation sensors have Tighter specs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Automotive</th>
<th>Navigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>±50g (airbag) ±2g (vehicle stability system)</td>
<td>±1g</td>
</tr>
<tr>
<td>Frequency Range</td>
<td>DC- 400Hz</td>
<td>DC-100Hz</td>
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<tr>
<td>Resolution</td>
<td>&lt;100mg (airbag) &lt;10mg (vehicle stability system)</td>
<td>&lt;4μg</td>
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<tr>
<td>Off-axis Sensitivity</td>
<td>&lt;5%</td>
<td>&lt;0.1%</td>
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<tr>
<td>Nonlinearity</td>
<td>&lt;2%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Max. Shock in 1msec</td>
<td>&gt;2000g</td>
<td>&gt;10g</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>-40°C to 85°C</td>
<td>-40°C to 80°C</td>
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<tr>
<td>TC of Offset</td>
<td>&lt;60mg/°C</td>
<td>&lt;50 μg/°C</td>
</tr>
<tr>
<td>TC of Sensitivity</td>
<td>&lt; 900ppm/°C</td>
<td>±50ppm/°C</td>
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</table>
Piezoresistive accelerometers

- Use piezoresistors to convert stress in suspension beam → change in resistance → change in voltage
- First MEMS accelerometer used piezoresistors
  - Bulk micromachined
  - Glass capping wafer to damp and stop motion
- Simple electronics
- Piezoresistors generally less sensitive than capacitive detection
Capacitors for position measurement

- **Single capacitors**
  - Capacitance is a function of gap or area
  - Can be nonlinear

- **Differential capacitors**
  - One capacitor increases while the other decreases
  - Have virtue of cancelling many effects to first order, providing signal that is zero at base state
Using a differential capacitor

• Differential drive creates sense signal proportional to capacitance difference
• Gives zero output for zero change
• Output linear with gap

\[ V_0 = -V_s + \frac{C_1}{C_1 + C_2} (2V_s) = \frac{C_1 - C_2}{C_1 + C_2} V_s \]

for parallel-plate capacitors where only \( g \) changes, this becomes

\[ V_0 = \frac{g_2 - g_1}{g_1 + g_2} V_s \]

5/25/09
• Fabrication not reported, but here is my best guess (using nested-mask process)
Thermal accelerometer

- Thermal convection accelerometer
- Gas is proof mass
- Movement of gas under acceleration changed thermal profile
Transimpedance circuits

- The simplest type of circuit measures the displacement current in a capacitor using transimpedance amplifier
  - Transimpedance converts current to voltage
  - Nulls out parasitic capacitance

- If source is DC, measure velocity of motion $\Rightarrow V_0 \sim dx/dt$

- But velocity is not really what we want... we want position

\[ Q = C(x,t)V_c \]
\[ v_- \approx v_+ = 0 \Rightarrow V_c = V_s \]
\[ i_c = \frac{dQ}{dt} = C(x,t)\frac{dV_s}{dt} + V_s \left. \frac{\partial C}{\partial x} \right|_{v_s} \frac{dx}{dt} \]
\[ i_c = V_s \left. \frac{\partial C}{\partial x} \right|_{v_s} \frac{dx}{dt} = -\frac{V_0}{R_F} \]

\[ V_0 = -R_F V_s \left. \frac{\partial C}{\partial x} \right|_{v_s} \frac{dx}{dt} \]

constant
If source is AC, we can determine capacitance directly
First, must use frequency high enough such that velocity term is negligible
Second, operate above corner frequency of LP filter

\[ i_c = \frac{dQ}{dt} = C(x,t) \frac{dV_c}{dt} + V_c \frac{\partial C}{\partial x} \bigg|_{V_c} \frac{dx}{dt} \]

\[ V_s = V_{s0} \cos(\omega t) = \text{Re}\left\{V_{s0} e^{j\omega t}\right\} \]

\[ i_c = \left[ C(x,t) j\omega + \frac{\partial C}{\partial x} \bigg|_{V_c} \frac{dx}{dt} \right] V_s \]

\[ i_c \approx C(x,t) j\omega V_s \]

\[ V_0 = -i_c \left( C_F // R_F \right) = -i_c \frac{R_F}{1 + j\omega C_F R_F} \]

\[ V_0 \approx -i_c \frac{R_F}{j\omega C_F R_F} = -i_c \frac{C(x,t) j\omega V_s}{j\omega C_F} \]

\[ V_0 \approx -\frac{C(x,t)}{C_F} V_s \]
Non-inverting op-am circuits

- Requires close matching of input capacitances to ground
- Now there is no virtual ground and parasitic capacitance appears in output
- Most suitable for applications in which transistors are integrated with the capacitive position sensing element

\[ V_0 = V_x = \frac{C_1 - C_2}{C_1 + C_2 + C_p} V_s \]
AC Methods Require Demodulation

- For AC methods, output signal is a high frequency sinusoid (carrier) multiplied by a low frequency signal
- This is an amplitude-modulated (AM) signal
- We want to retrieve the low frequency component
  - Peak detector
  - Synchronous demodulator
Synchronous Demodulation

- Use a nonlinear circuit to multiply $V_0$ by an in-phase sinusoid
- This modulates to baseband
- Relative phase is important
Signal-to-noise issues

- To get a big signal, use a big voltage
- BUT-
- Voltage creates a force that can modify the state of the mechanical system (analogous to the self-heating problem in resistance measurement)
- Noise floor minimum often set by LPF bandwidth
- But amplifier noise will often dominate

\[ V_0 \approx -\frac{C(x,t)}{C_F} V_s(t) \]
Analog Devices
Accelerometer

- Genesis: an ADI engineer heard about forming mechanical sensors on silicon
- Market pull was airbag accelerometers (50g)
  - Current product was $50
  - Auto manufacturers wanted $5 price point
- Team was formed in 1986, first product in 1993
  - Fabrication process was under development since early 80’s at Berkeley
ADI accelerometers

- Initially partitioned systems to *integrate* electronics on-chip
  - This ensured that they could achieve good SNR
- BUT
  - Entailed large infrastructure costs that essentially hemmed future opportunities
- This is an example where up-front partitioning has *multi-decade* consequences
• How to integrate MEMS + circuits?
• Several different approaches
  ➢ MEMS first
  ➢ Circuits first
  ➢ MEMS in the middle
• ADI chose MEMS-in-the-middle
  ➢ Mostly developed at Berkeley
  ➢ 6” fab line
  ➢ ~1 million sensors/week (as of 2005)
Differential Capacitor structure
• Surface micromachined in polysilicon
• Shuttle forms proof mass
• Suspended on folded springs that are attached to substrate only on anchor points
• Cantilivered electrodes attached to the shuttle
• Each cantilever is positioned between two fixed electrodes
• 42 repeat units on device
• Self-test region → electrodes connected to drive circuit that can apply electrostatic force on shuttle
• 24 masks, 11 mechanical, 13 electronics
Fabrication sequence
Fabrication sequence

- **Electronics first**
  - Lightly p-doped wafer
  - MOS/PMOS transistors, interconnects between circuit and sensor region, n+ runners and ground plane
  - LPCVD nitride and BPSG oxide (borophosphosilicate glass)
  - Moat clearing

- **Sensor next**
  - Overcoat of LPCVD nitride for etch stop
  - Sacrificial oxide layer (1.6 um thick!)
  - Contact opening for n+ interconnect
  - Sensor – amorphous polysilicon, doped phosphorus, 150 Ohms/square, 0.3-0.5 um grain size, 40-75Mpa stress

- **Put it all together**
  - Thin oxide, nitride deposited, sacrificial oxide removed
Packaging

• When to do die saw, before or after release?
• ADI decided to do die separation after release and invented a wafer-handling method to protect the released region during sawing
  - One tape layer with holes corresponding to mechanical region
  - A second tape layer covering the entire chip
  - Saw from the back (must have pre-positioned alignment marks on wafer back to do this)
Packaging

• Processing issues
  ➢ Stiction at- and post-release
    • Solved at-release stiction with bumps under poly structures
    • Post-release stiction avoided with proprietary coating
    • Thermally evaporated silicone coating
    • Has to withstand packaging temps

• Laser Trimming
  ➢ Set offsets, slopes, etc..
  ➢ At wafer scale
  ➢ Before packaging
System Diagram

- Oscillator provides AC waveform for sensing
- Waveforms:
• Inertial acceleration or electrostatic force from self-test electrodes $\rightarrow$ displacement
  - Unbalances differential capacitor
    - Output is amplified, demodulated, and low pass filtered to give output signal
    - Magnitude of sensor output depends on mechanical displacement due to acceleration, and amplitude of square waves
Stiffness of Springs

- Can use parallel-plate approximation to sense capacitance (off by 50%)
- Beam bending model gives good estimate of stiffness

\[
C_{\text{sense}} \approx 42 \frac{\varepsilon_0 H L_0}{g_0 \pm y} \approx 60 \text{fF} \left[ 1 \pm \frac{y}{g_0} \right]
\]

\[
k = 2 \frac{\pi^4}{6} \left[ \frac{E W H^3}{(2L_1)^3 + (2L_2)^3} \right] \approx 5.6 \text{ N/m}
\]

\[
\omega_0 = 24.7 \text{ kHz}
\]
Design and Modeling

- Q of mechanical resonance is 5
  - Extremely hard to model accurately
  - Squeezed film damping between fingers
  - Couette drag beneath proof mass
  - Complex actual geometry
  - Rough model gives Q = 34, a poor estimate
• First accelerometer used feedback control to keep plates fixed
• Let’s use PD (proportional derivative) control to see what it affects
  \[ K(s) = K_0 (1 + \gamma s) \]
• Input is disturbance \( D(s) \) – acceleration
• Output is force from controller \( F(s) \)
• \( H(s) \) is accelerometer: SMD (surface mounted device)

\[
\frac{F(s)}{D(s)} = -\frac{HK}{1 + HK} = \frac{-\frac{K_0}{m} (1 + \gamma s)}{s^2 + \left(\frac{b}{m} + \gamma \frac{K_0}{m}\right)s + \frac{k + K_0}{m}}
\]
• Use feedback to get both
  - Critical damping (when ON)
  - Insensitivity to material properties
• Choose $K_0 \gg k$
  - ADI chose 10x
• Critical damping is when $b^2 = 4ac$ ($Q_{\text{closed-loop}} = 1/2$)
  - Can pick $K_0$ and gamma to meet both requirements
• Sensor response will be insensitive to change

$$
\begin{align*}
  F(s) &= -\frac{K_0}{m}(1 + \gamma s) \\
  D(s) &= s^2 + \left(\frac{b}{m} + \gamma \frac{K_0}{m}\right)s + \frac{k + K_0}{m}
\end{align*}
$$

$$
\begin{align*}
  \left(\frac{b}{m} + \gamma \frac{K_0}{m}\right)^2 &= 4\left(\frac{k + K_0}{m}\right) \\
  \frac{b}{m} + \gamma \frac{K_0}{m} &\approx 2\sqrt{\frac{K_0}{m}} \\
  \frac{\omega_0}{Q_{\text{o.i.}}} + \gamma \frac{K_0}{m} &\approx 2\sqrt{\frac{K_0}{m}} \\
  \gamma \frac{K_0}{m} &\approx 2\sqrt{\frac{K_0}{m}} - \frac{1}{Q_{\text{o.i.}}} \sqrt{\frac{k}{m}} \approx 2\sqrt{\frac{K_0}{m}} \\
  \gamma &\approx 2\sqrt{\frac{m}{K_0}}
\end{align*}
$$
In the next generation, ADI abandoned feedback

Why?
- After years of testing, ADI found that PolySi was structurally stable for intended markets
- Feedback required extra electronics → bigger chip → $$
- Needed external capacitor to set LPF
  - Extra cost, extra complexity
- Closed-loop design was not ratiometric to power supply
  - Customer needed to measure supply voltage
- DC bias at fingers for force feedback caused charges to move and thus devices to drift

Therefore, the removed feedback
Next generation specifications

• Test study is of ADXL150 (XL76)
• Text lists 22 specifications, covering sensitivity, range, temperature range, supply voltage, nonlinearity, cross-axis response, bandwidth, clock noise, drop test, shock survival, etc..etc..
• Also, response is ratiometric, proportional to supply voltage

5/25/09
Noise and Accuracy

• Noise is specified as 1mg/Hz\(^{1/2}\) in a bandwidth from 10Hz to 1000 Hz
• Corresponding Brownian noise estimate is half that value, corresponding to a rms position noise of 0.013nm
• Offset errors
  ➢ If a device is not perfectly balanced at zero g, turning on voltage aggravates the offset
  ➢ Accurate etching required special “dummy” features to ensure that all cuts had the same profile (we have seen similar effects when we looked at DRIE)
• Cross-axis sensitivity is low because of squeeze-film damping and differential capacitor measurement
ADXL202 2-axis accelerometer

- Then moved from two 1-axis sensors to one 2-axis
Newer designs

- ADXL203 two-axis accelerometer
- Supports are in center of die to cancel 1st-order stresses due to packaging
The latest design: ADXL40

- The newest designs use an SOI-MEMS process
  - Also developed at Berkeley
- Enables several circuit features
  - 0.6um CMOS allows 10x more transistors in same size
  - Allows poly fuse trims to be set on-chip
    - Can trip AFTER packaging
The latest design: ADXL40

- **MEMS**
  - Higher-aspect ratio structures lead to more squeezed-film damping $\Rightarrow Q=1$
  - Trench isolation allows self-test to be electrically isolated from sensing fingers
    - Allows 2x voltage applied $\Rightarrow 4x$ force
Summary

- Accelerometers are MEMS success story!
- Early system partitioning decisions have had profound downstream effects
  - Eases sensor design and sensing
  - Requires large internal infrastructure