CASE STUDY:

A Capacitive Accelerometer

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Thanks to SDS and Tim Dennison (ADI)

Outline

> **Accelerometer fundamentals**

> **Analog Devices accelerometer**

- **History**
- **Structure**
- **Design and modeling**
- **Fabrication and packaging**
- **Noise and accuracy**

Measurement choices

> **Two approaches to measuring acceleration**

- **Open loop: Measure change due to acceleration**
- **Closed loop: A disturbance in a position control system**

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
    - Mechanical resonant frequency > Frequency of acceleration
    - Measure displacement due to acceleration

      Optical, Capacitive, Piezoresistive, Tunneling
  - Resonant sensing
    - Measure change in resonant frequency

      Due to position-dependent nonlinear spring
- Today's example involves a quasi-static accelerometer

Accelerometer fundamentals

> **Displacement and acceleration are coupled together by a fundamental scaling law**

- **A higher resonant frequency implies less displacement**
  - » **high *f* & low sensitivity**
- **Measuring small accelerations requires floppier structures**
  - » **high sensitivity and low *f***

$$x = \frac{F}{k} = \frac{ma}{k}$$

$$\boxed{x = \frac{a}{\omega_0^2}}$$

> **Johnson noise in the damping mechanism gives rise to a fundamental noise floor for acceleration measurement**

$$a_{n,rms} = \sqrt{\frac{4k_B T \omega_0}{mQ}}$$

Accelerometer specifications

- **Initial application arena was automotive crash sensor**
- **Navigation sensors have tighter specs**

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

Table 1 on p. 1642 in Yazdi, N., F. Ayazi, and K. Najafi. "Micromachined Inertial Sensors." *Proceedings of the IEEE* 86, no. 8 (August 1998): 1640-1659. © 1998 IEEE.

Piezoresistive accelerometers

- Use piezoresistors to convert stress in suspension beam → change in resistance → change in voltage
- First MEMS accelerometer used piezoresistors
  - Roylance and Angell, IEEE-TED ED26:1911, 1979
  - Bulk micromachined
  - Glass capping wafers to damp and stop motion
- Simple electronics
- Piezoresistors generally less sensitive than capacitive detection

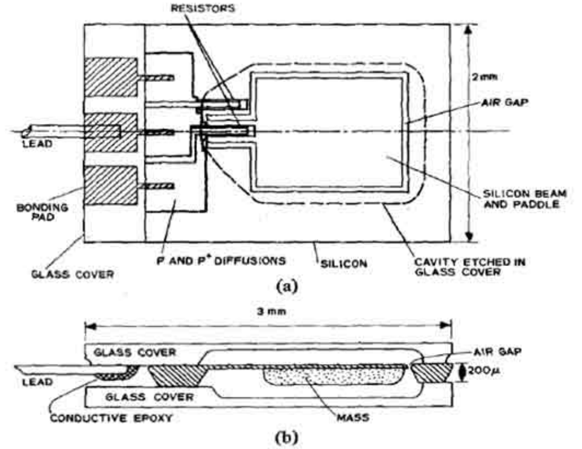


Fig. 1. Top and cross-section views of the accelerometer. (a) Top view. (b) Centerline cross section.

Figure 1 on p. 1911 in Roylance, L. M., and J. B. Angell. "A Batch-fabricated Silicon Accelerometer." *IEEE Transactions on Electron Devices* 26, no. 12 (December 1979): 1911-1917. © 1979 IEEE.

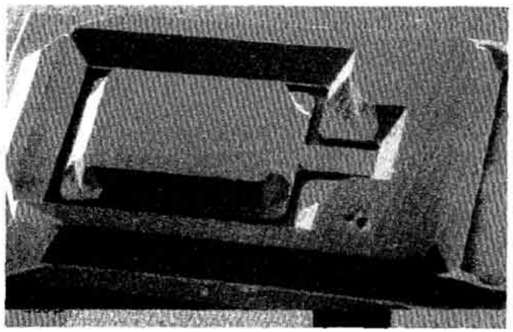
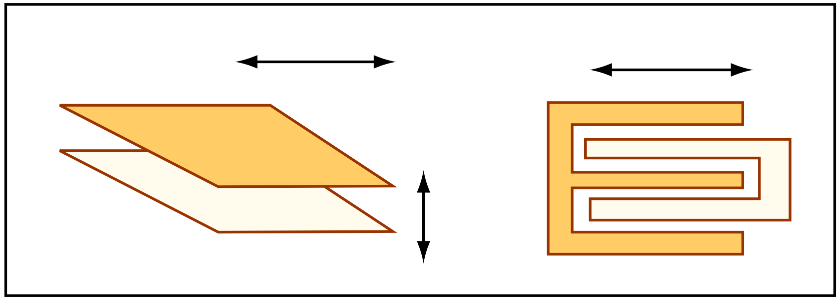


Fig. 2. SEM of backside of the accelerometer with a silicon mass after KOH etch.

Figure 2 on p. 1911 in Roylance, L. M., and J. B. Angell. "A Batch-fabricated Silicon Accelerometer." *IEEE Transactions on Electron Devices* 26, no. 12 (December 1979): 1911-1917. © 1979 IEEE.

Capacitors for position measurement

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



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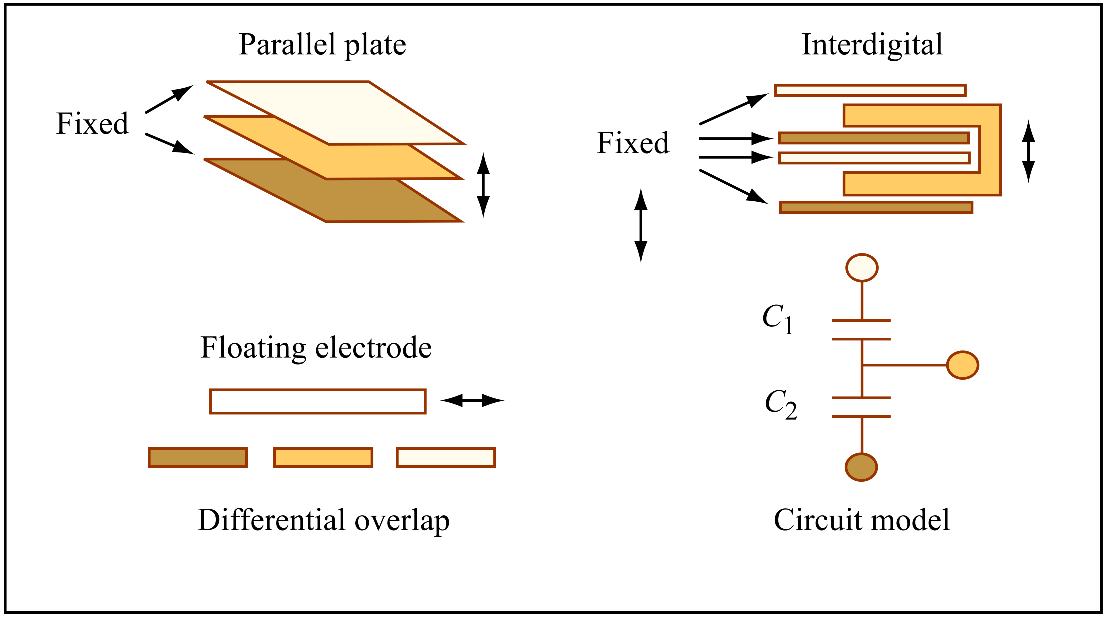
Adapted from Figure 19.3 in Senturia, Stephen D. *Microsystem Design*. Boston, MA: Kluwer Academic Publishers, 2001, p. 501. ISBN: 9780792372462.

> **Differential capacitors**
- **One capacitor increases while the other decreases**



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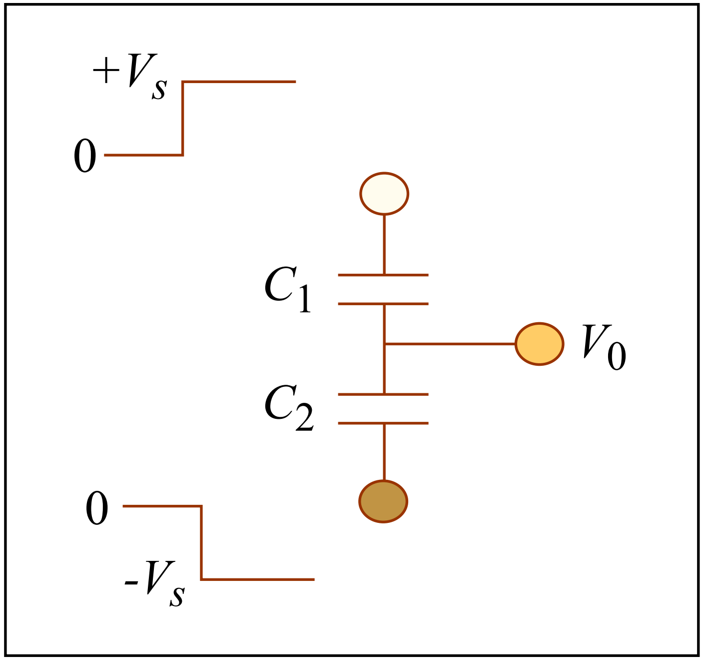
Adapted from Figure 19.4 in Senturia, Stephen D. *Microsystem Design*. Boston, MA: Kluwer Academic Publishers, 2001, p. 501. ISBN: 9780792372462.

Using a differential capacitor

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



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Boston, MA: Kluwer Academic Publishers, 2001, p. 502. ISBN: 9780792372462.

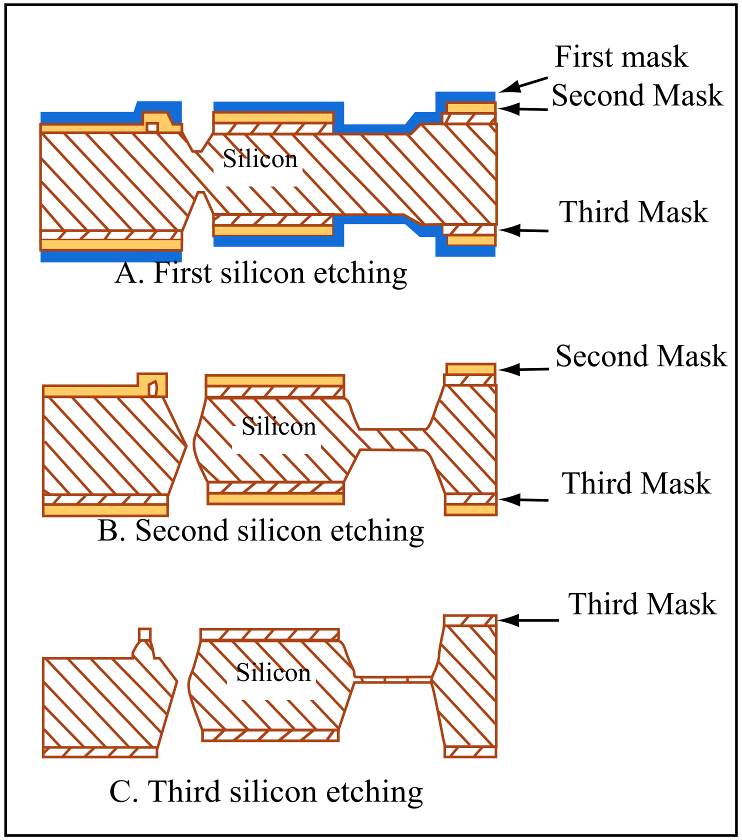
$$V_0 = -V_S + \frac{C_1}{C_1 + C_2}\left(2V_S\right) = \frac{C_1 - C_2}{C_1 + C_2} V_S$$

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

$$V_0 = \frac{g_2 - g_1}{g_1 + g_2} V_S$$

Bulk-micromachined capacitive accelerometer

- Fabrication not reported, but likely uses nested-mask process



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Adapted from Figure 3 on p. 688 in Sasayama, T., S. Suzuki, S. Tsuchitaii, A. Koide, M. Suzuki, T. Nakazawa, and N. Ichikawa. "Highly Reliable Silicon Micro-machined Physical Sensors In Mass Production." *The 8th International Conference on Solid-State Sensors and Actuators and Eurosensors IX: digest of technical papers. June 25-29, 1995*, Stockholm, Sweden. Stockholm, Sweden: Foundation for Sensor and Actuator Technology, 1995, pp. 687-690. ISBN: 9789163034732.
Figure originally from Koide, A., K. Sato, S. Suzuki, and M. Miki. *Technical Digest of the 11th Sensor Symposium: June 4-5, 1992, Arcadia Ichigaya, Tokyo*. Tokyo, Japan: Institute of Electrical Engineers of Japan, 1992, pp. 23-26.

Thermal accelerometer

- MEMSIC thermal convection accelerometer
- Gas is proof mass
- Movement of gas under acceleration changes thermal profile

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Transimpedance circuits

> The simplest type of circuit measures the displacement current in a capacitor using a transimpedance amplifier

- Transimpedance converts current to voltage
- Nulls out parasitic capacitance

> If source is DC, measure velocity of motion

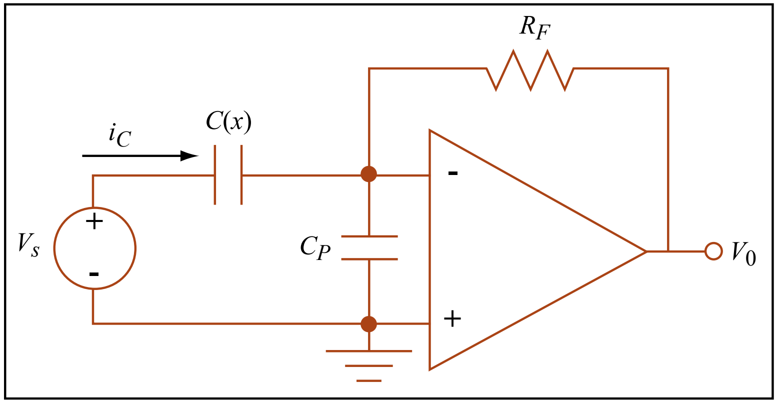
> Velocity is not really what we want…

$$Q = C(x,t)V_c$$

$$v_- \approx v_+ = 0 \Rightarrow V_c = V_s$$

$$i_C = \frac{dQ}{dt} = C(x,t)\cancel{\frac{dV_S}{dt}} + V_S \left.\frac{\partial C}{\partial x}\right|_{V_S} \frac{dx}{dt}$$

$$i_C = V_S \left.\frac{\partial C}{\partial x}\right|_{V_S} \frac{dx}{dt} = -\frac{V_0}{R_F}$$



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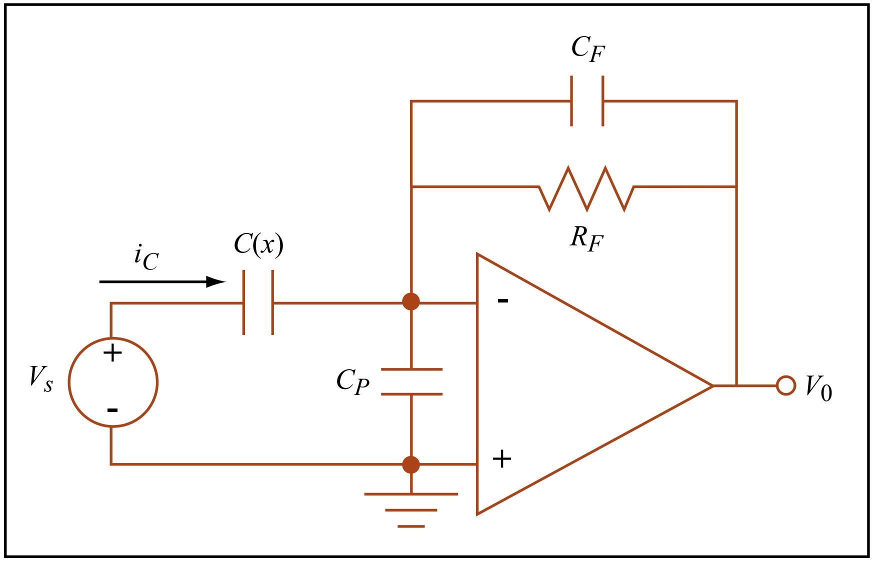
Adapted from Figure 19.6 in Senturia, Stephen D. *Microsystem Design*.
Boston, MA: Kluwer Academic Publishers, 2001, p. 503. ISBN: 9780792372462.

$$V_0 = \underbrace{-R_F V_S \left.\frac{\partial C}{\partial x}\right|_{V_S}}_{\text{constant}} \frac{dx}{dt}$$

Transimpedance circuits

- If source is AC, can measure position
- First, must use frequency high enough such that velocity term is negligible
- Second, operate above corner frequency of LP filter



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Adapted from Figure 19.7 in Senturia, Stephen D. *Microsystem Design*. Boston, MA: Kluwer Academic Publishers, 2001, p. 504. ISBN: 9780792372462.

$$i_C = \frac{dQ}{dt} = C(x,t)\frac{dV_c}{dt} + V_c \left.\frac{\partial C}{\partial x}\right|_{V_c} \frac{dx}{dt}$$

$$V_S = V_{S0}\cos(\omega t) = \mathrm{Re}\left\{V_{S0}e^{j\omega t}\right\}$$

$$i_C = \left[C(x,t)\,j\omega + \cancel{\left.\frac{\partial C}{\partial x}\right|_{V_c}\frac{dx}{dt}}\right]V_S$$

$$i_C \approx C(x,t)\,j\omega V_s$$

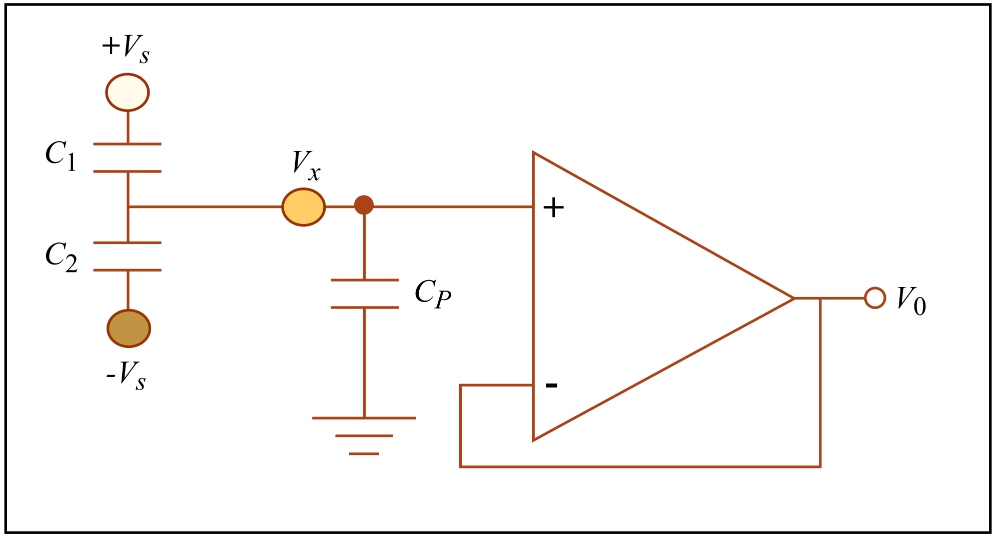
$$V_0 = -i_c\left(C_F\,//\,R_F\right) = -i_c\frac{R_F}{1 + j\omega C_F R_F}$$

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

$$\boxed{V_0 \approx -\frac{C(x,t)}{C_F}V_S}$$

Non-inverting op-amp circuits

> **Now there is no virtual ground and parasitic capacitance appears in output**



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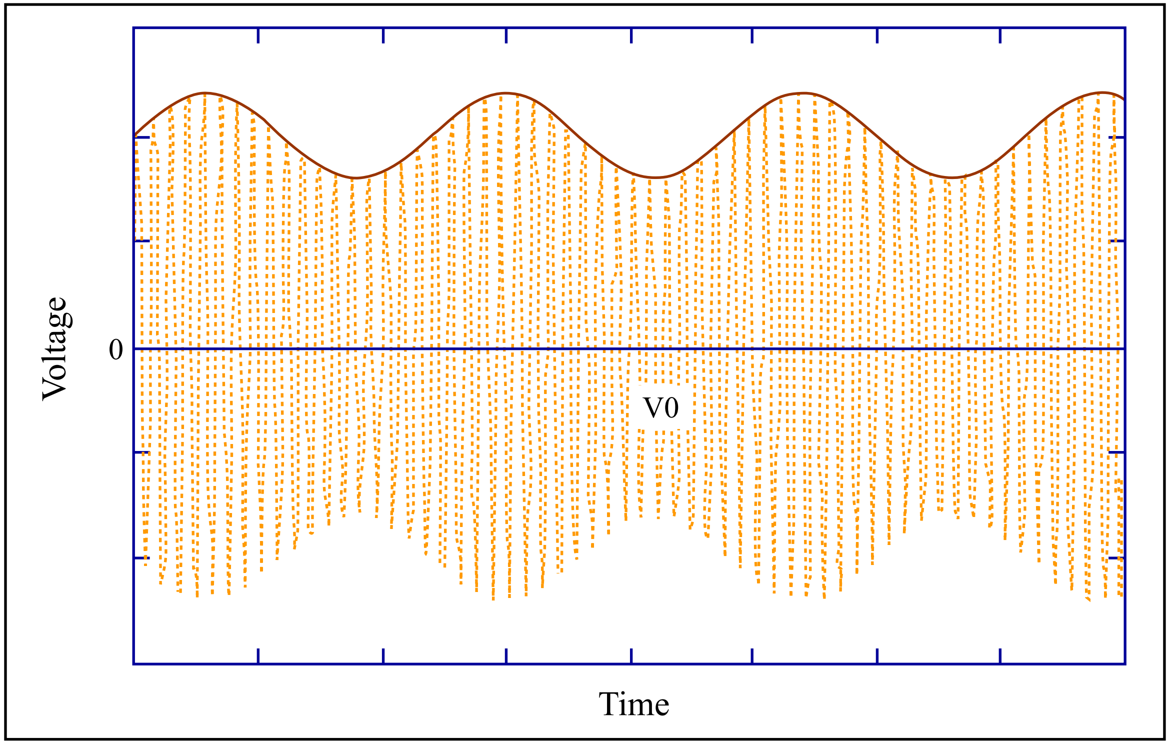
Adapted from Figure 19.9 in Senturia, Stephen D. *Microsystem Design*. Boston, MA: Kluwer Academic Publishers, 2001, p. 506. ISBN: 9780792372462.

$$V_0 = V_x = \frac{C_1 - C_2}{C_1 + C_2 + C_P} V_S$$

AC Methods Require Demodulation

- For AC methods, output signal is a HF sinusoid (carrier) multiplied by a LF signal
- This is an amplitude-modulated (AM) signal
- We want to retrieve the low-frequency component

$$V_0 \approx -\frac{C(x,t)}{C_F} V_S(t)$$



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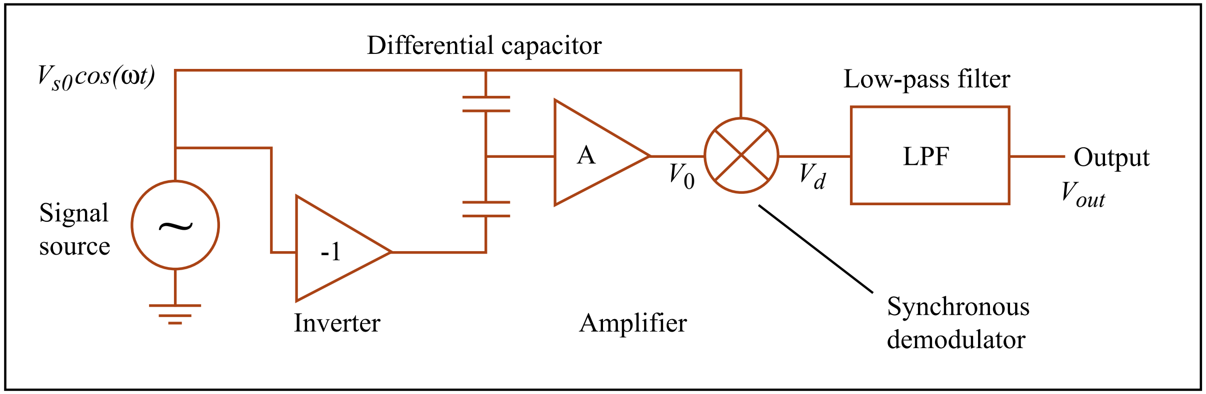
Adapted from Figure 19.11 in Senturia, Stephen D. *Microsystem Design*. Boston, MA: Kluwer Academic Publishers, 2001, p. 508. ISBN: 9780792372462.

Synchronous Demodulation

- Use a nonlinear circuit to multiply V_0 by an in-phase sinusoid
- This demodulates to baseband
- Relative phase is important



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Adapted from Figure 19.13 in Senturia, Stephen D. *Microsystem Design*. Boston, MA: Kluwer Academic Publishers, 2001, p. 509. ISBN: 9780792372462.

$$V_0 \approx -\frac{C(x,t)}{C_F}V_S$$

$$V_0 \approx -\frac{C(x,t)}{C_F}V_{S0}\cos(\omega t)$$

$$V_d = V_0 \cdot V_s = V_0 \cdot V_{s0}\cos(\omega t + \theta)$$

Allow phase shift

$$V_d = -\frac{C(x,t)}{2C_F}V_{s0}^2\left[\cos(\theta) + \cos(2\omega t + \theta)\right]$$

$$V_{out} = -\frac{C(x,t)}{2C_F}V_{s0}^2\cos(\theta)$$

Signal-to-noise Issues

> **To get a big signal, use a big voltage**

$$V_0 \approx -\frac{C(x,t)}{C_F} V_S(t)$$

— 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**

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**

Analog Devices accelerometer

> **Initially partitioned system 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 system partitioning has *multi-decade* consequences**

ADI system partitioning

> How to integrate MEMS + circuits?

> Circuits typically are run on continually changing (and improving) fabrication lines

> MEMS typically cannot economically support such high throughputs

> Foundries will not accept non-pristine wafers

> Thus, must combine both in-house in a dedicated foundry
  - This usually sets circuit technology
  - For ADI, foundry is in Cambridge and Limerick

ADI system partitioning

> How to integrate MEMS + circuits?

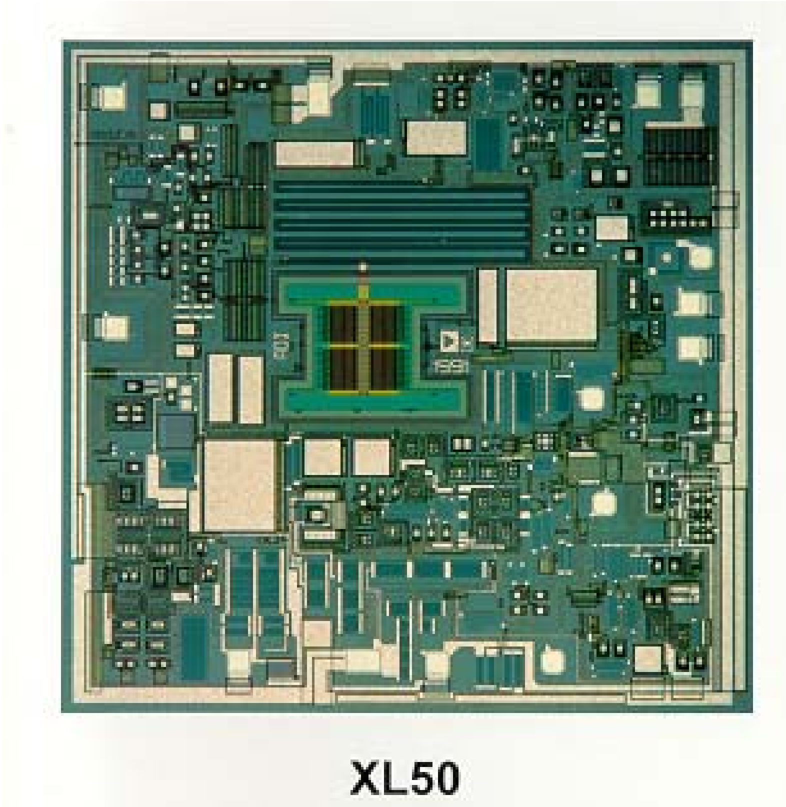
> Several different approaches

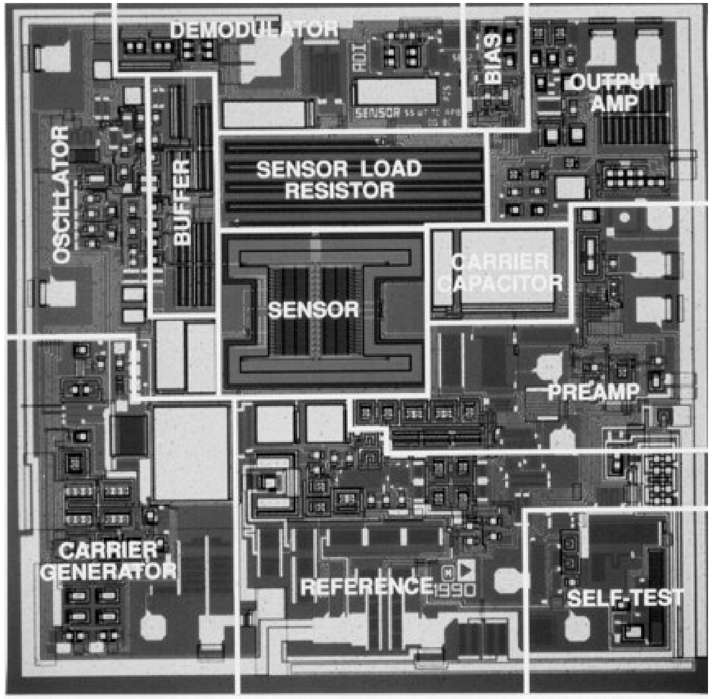
- MEMS first
- Circuits first
- MEMS in the middle

> ADI chose MEMS-in-the-middle

- Mostly developed at Berkeley
- 6” fab line
- ~1 million sensors/week (as of 2005)

Analog Devices ADXL50





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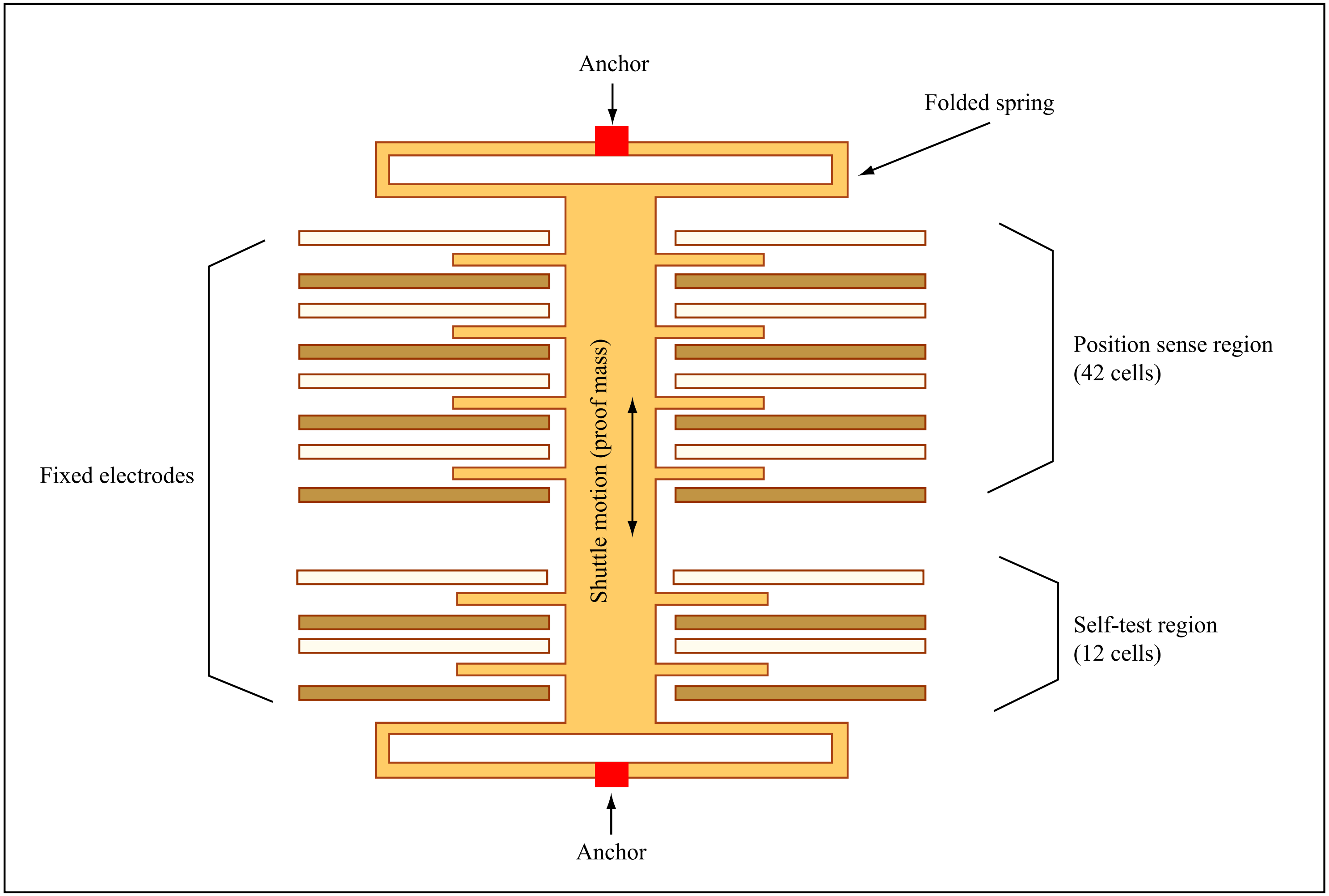
Differential capacitor structure



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Closer views

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Even closer

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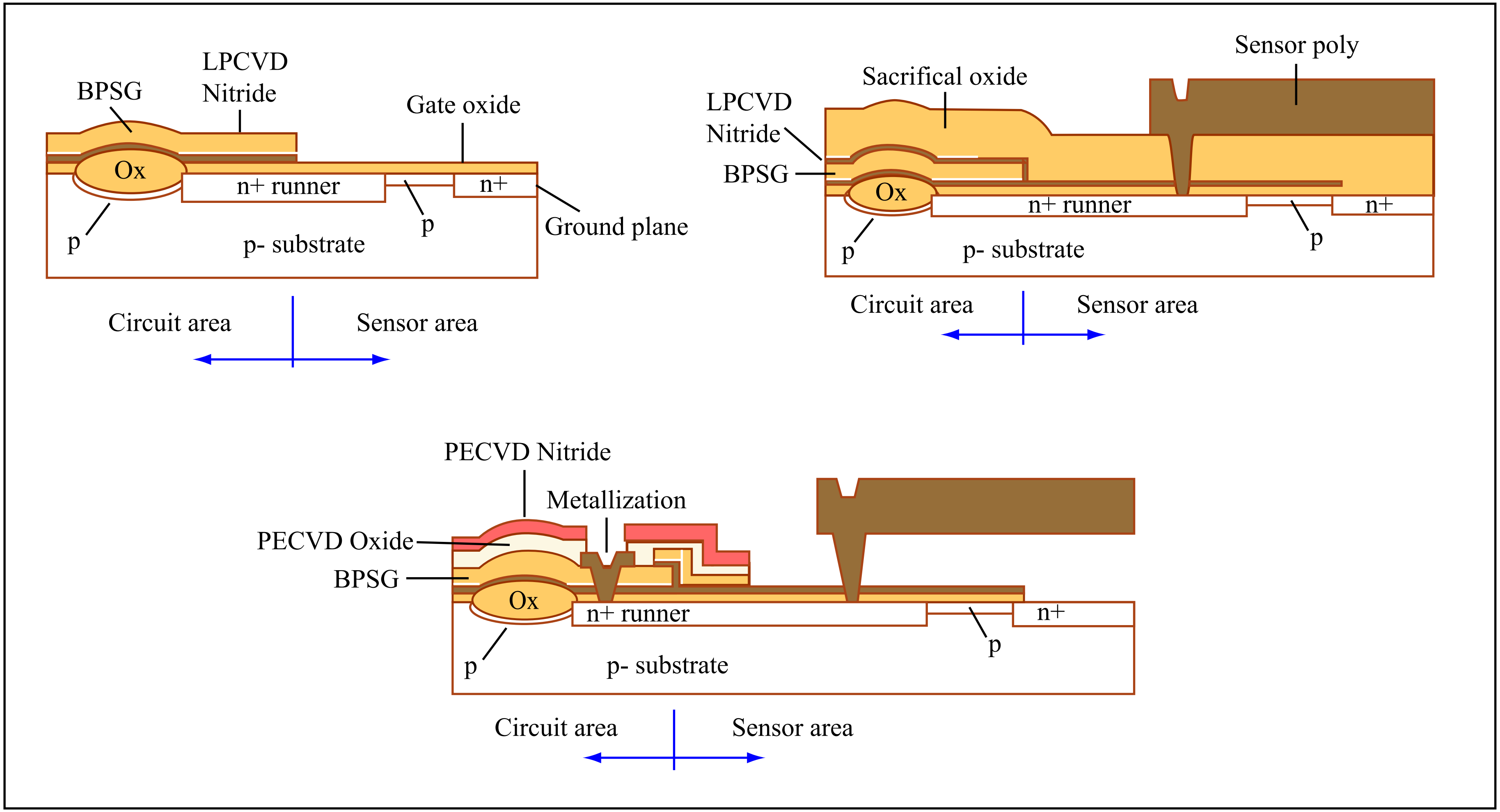
Fabrication sequence



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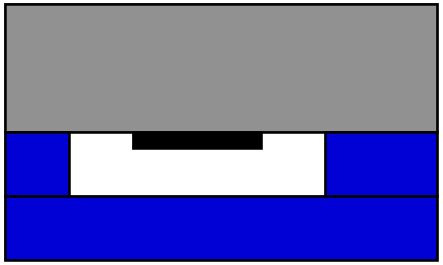
Packaging

> 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)



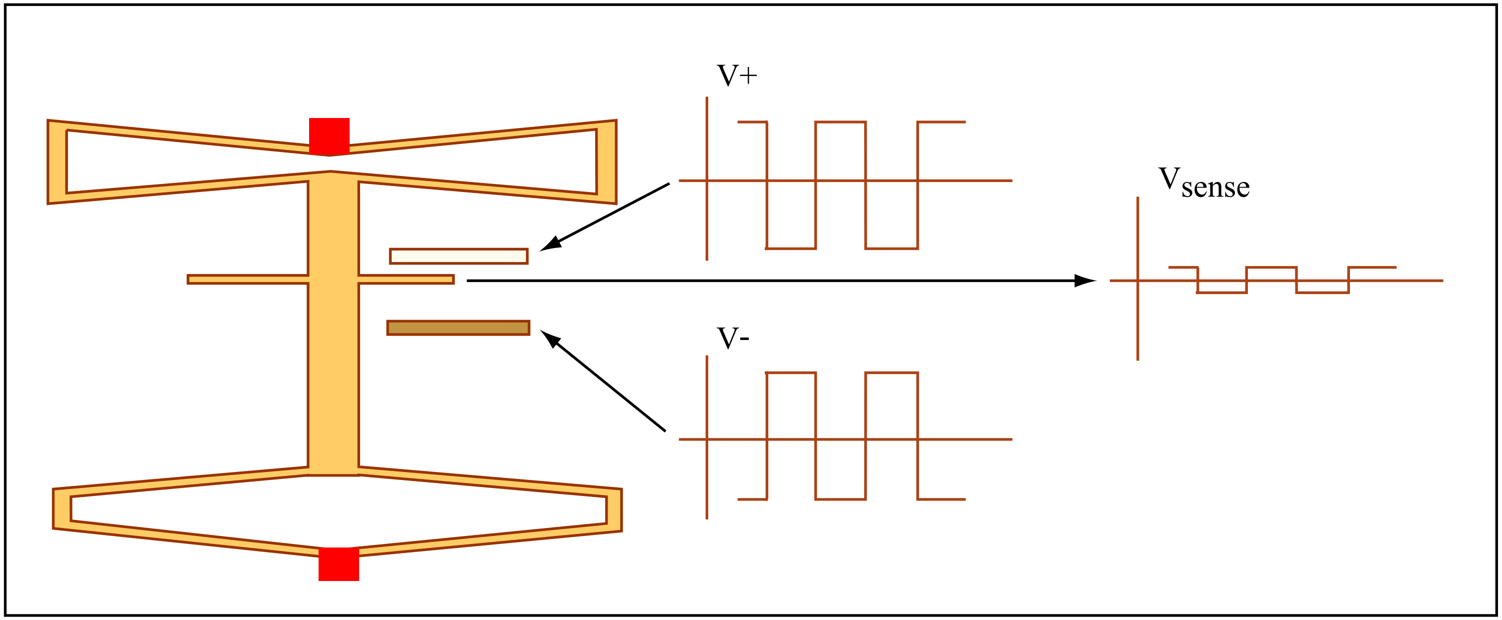
Packaging

- 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:**



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Adapted from Figure 19.21 in Senturia, Stephen D. *Microsystem Design*. Boston, MA: Kluwer Academic Publishers, 2001, p. 516. ISBN: 9780792372462.

Stiffness of springs

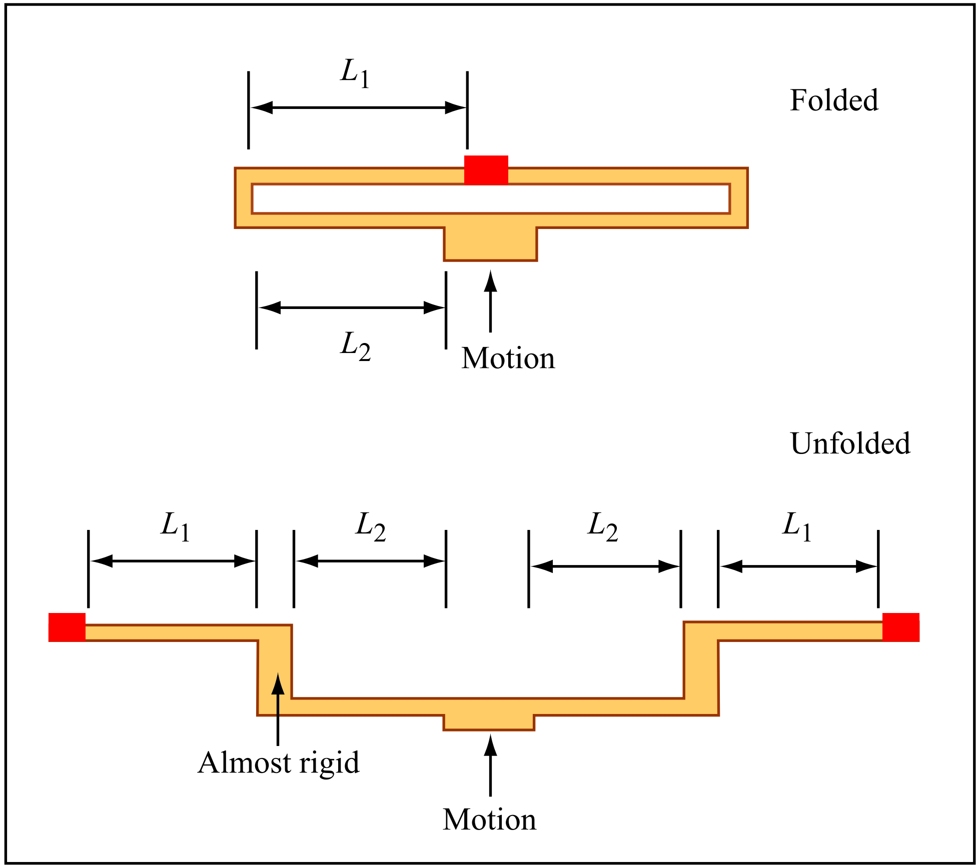
$$C_{sense} \approx 42\frac{\varepsilon_0 H L_0}{g_0 \pm y} \approx 60\text{fF}\left[1 \pm \frac{y}{g_0}\right]$$

- Parallel-plate approximation to sense capacitance is off by about 50%

- Beam bending model gives good estimate of stiffness

$$k \cong 2\frac{\pi^4}{6}\left[\frac{EWH^3}{(2L_1)^3 + (2L_2)^3}\right] \cong 5.6 \text{ N/m}$$

$$\omega_0 = 24.7 \text{ kHz}$$



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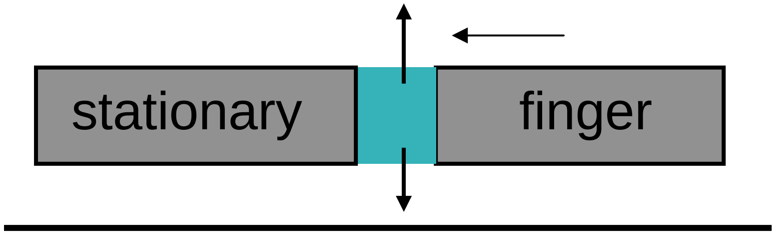
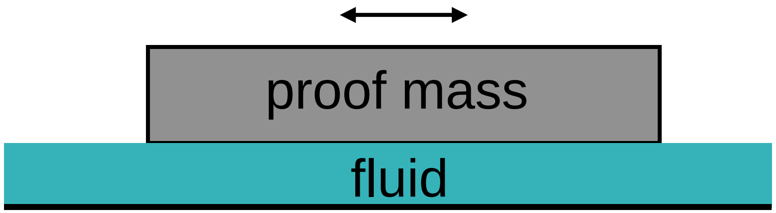
Design and modeling

> **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**





ADXL50

- **First accelerometer used feedback control to keep plates fixed**
- **Let's use PD 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**

$$\frac{F(s)}{D(s)} = -\frac{HK}{1+HK} = \frac{-\frac{K_0}{m}(1+\gamma s)}{s^2 + \left(\frac{b}{m} + \gamma\frac{K_0}{m}\right)s + \frac{k+K_0}{m}}$$

ADXL50

- Use feedback to get both
  - Critical damping (when ON)
  - Insensitivity to material properties
- Choose $K_0 >> k$
  - ADI chose 10x
- Critical damping is when $b^2=4ac$ ($Q_{closed\text{-}loop}=1/2$)
  - Can pick K_0 and γ to meet both requirements
- Sensor response will be insensitive to changes in *k*

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

$$\left(\frac{b}{m} + \gamma\frac{K_0}{m}\right)^2 = 4\left(\frac{k+K_0}{m}\right)$$

$$\left(\frac{b}{m} + \gamma\frac{K_0}{m}\right) \approx 2\sqrt{\frac{K_0}{m}}$$

$$\left(\frac{\omega_0}{Q_{o.l.}} + \gamma\frac{K_0}{m}\right) \approx 2\sqrt{\frac{K_0}{m}}$$

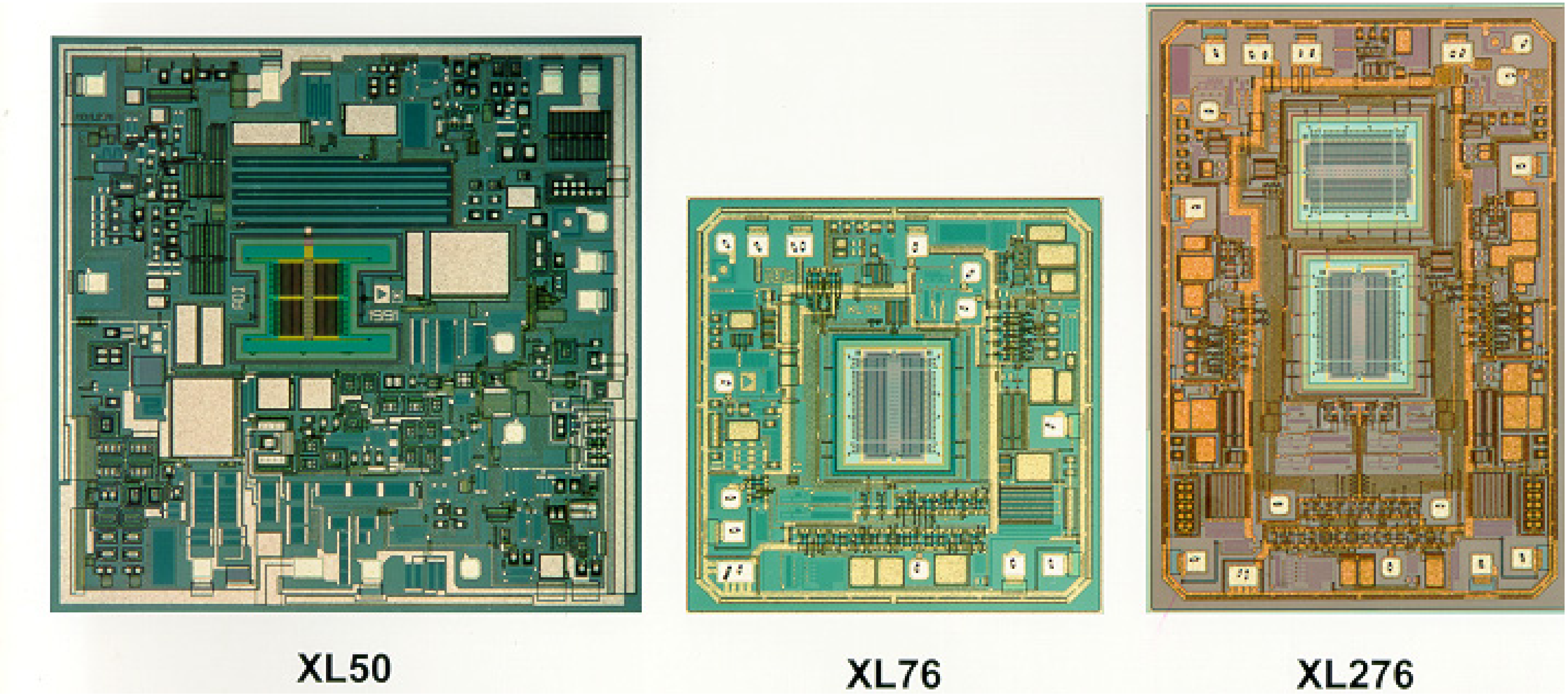
$$\gamma\frac{K_0}{m} \approx 2\sqrt{\frac{K_0}{m}} - \frac{1}{Q_{o.l.}}\sqrt{\frac{k}{m}} \approx 2\sqrt{\frac{K_0}{m}}$$

$$\gamma \approx 2\sqrt{\frac{m}{K_0}}$$

The next generations

- **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**
    - **Customers needed to measure supply voltage**
  - **DC bias at fingers for force feedback caused charges to move and thus devices to drift**
- **Therefore, they removed feedback**

Analog Devices Dies shots



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Next generation specifications

- Text 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 the supply voltage
- **Sensitivity is** βV_s = 38 mV/g

$$V_{out} = \frac{V_S}{2} \pm \underbrace{\alpha}_{\text{offset}} + a\beta V_S$$

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Noise and accuracy

> **Noise is specified as 1 mg/Hz$^{1/2}$ in a bandwidth from 10 Hz to 1000 Hz**

> **Corresponding Brownian noise estimate is half that value, corresponding to a rms position noise of 0.013 nm**

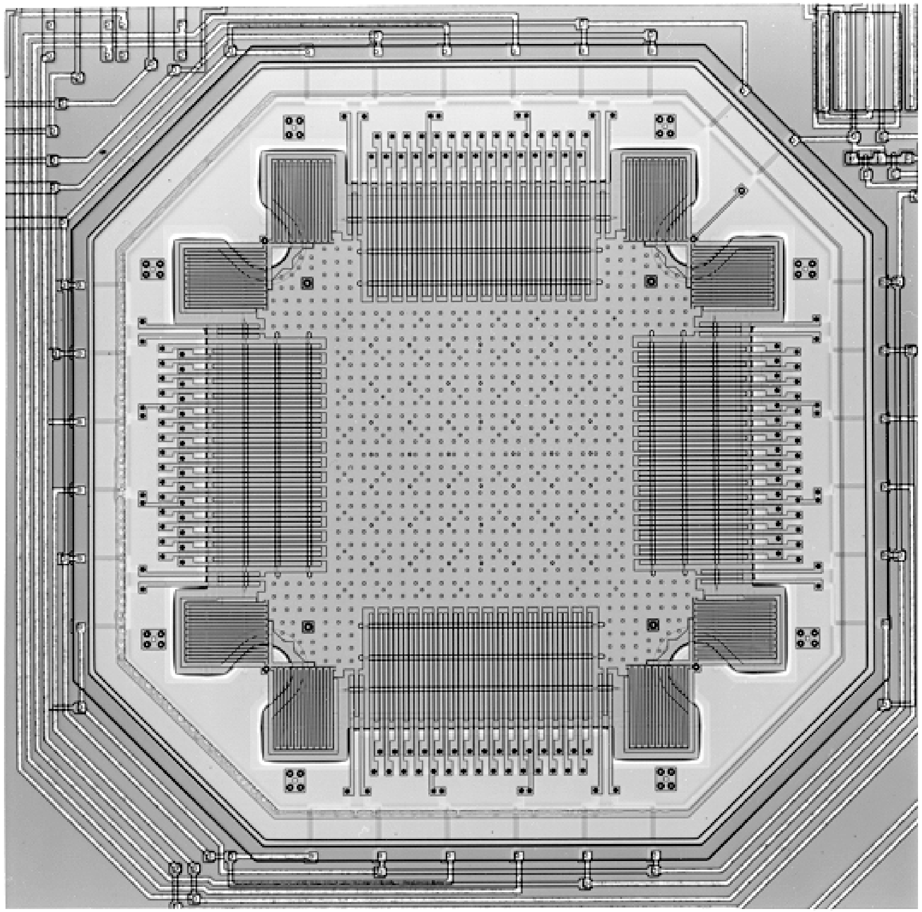
> **Offset errors**

- **If 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



ADXL202 Sensor Structure

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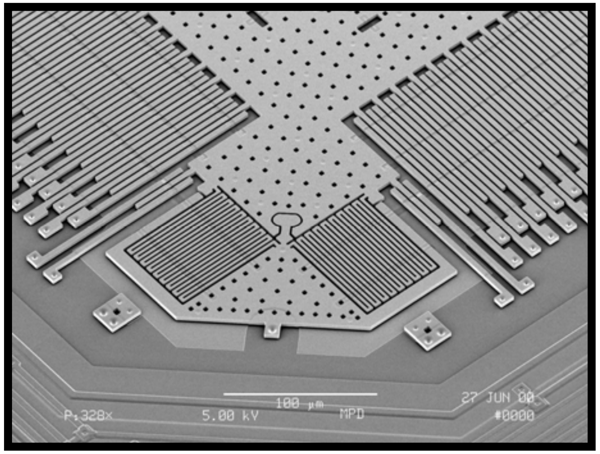

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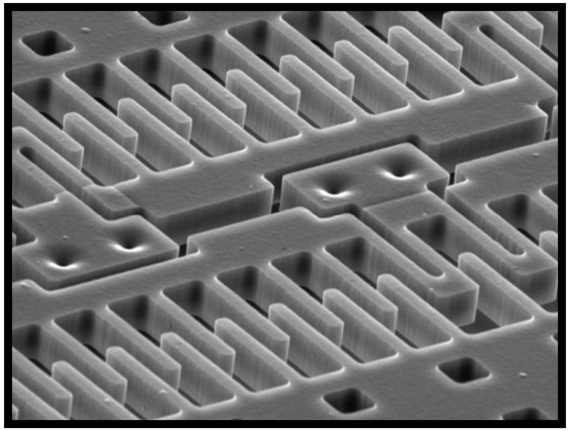

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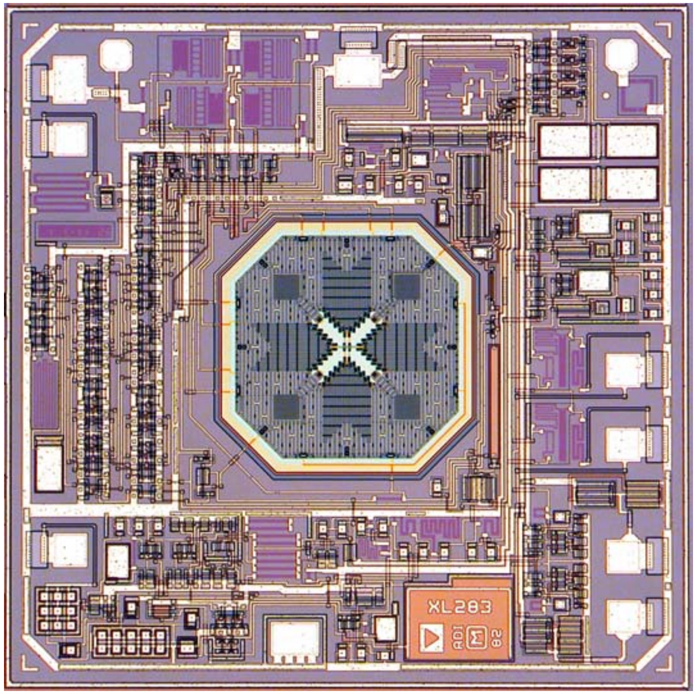
Newer designs

- ADXL203 two-axis accelerometer
- Supports are in center of die to cancel 1st-order stresses due to packaging



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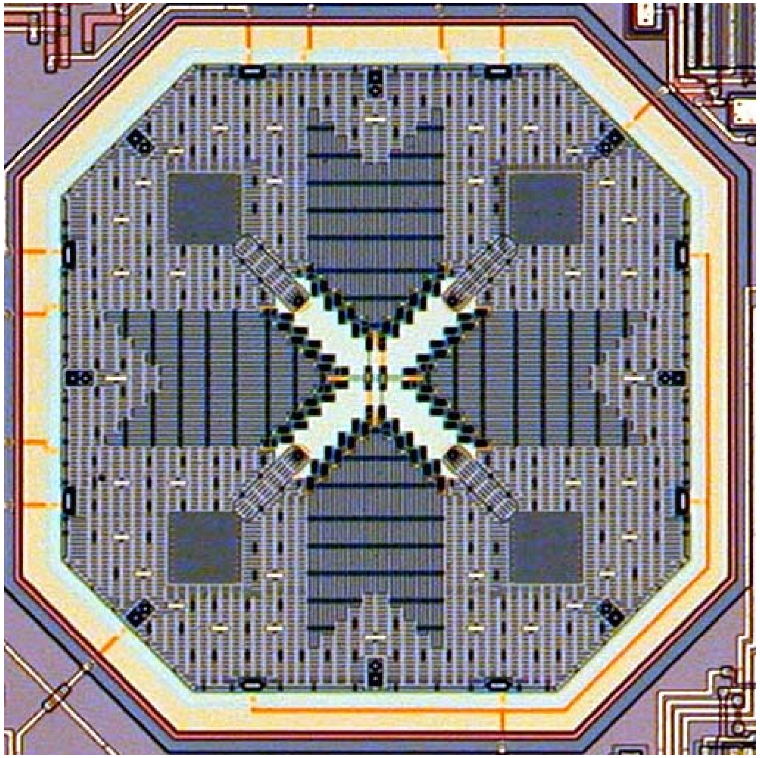


Courtesy of Analog Devices, Inc. Used with permission.

The latest design: ADXL40

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

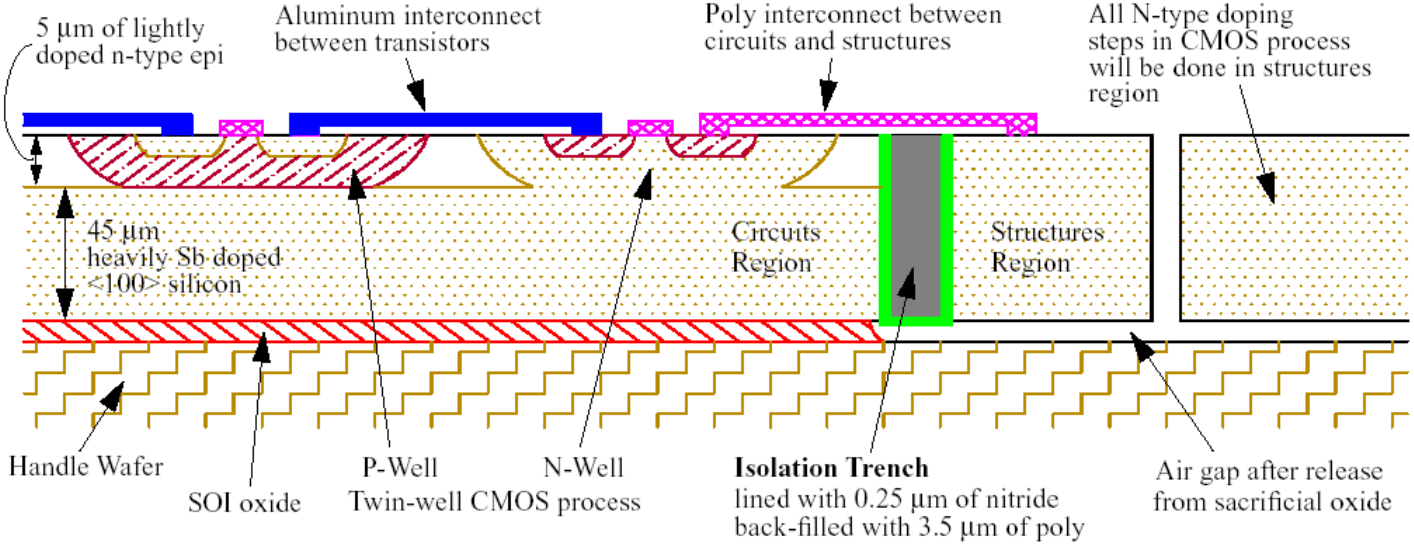
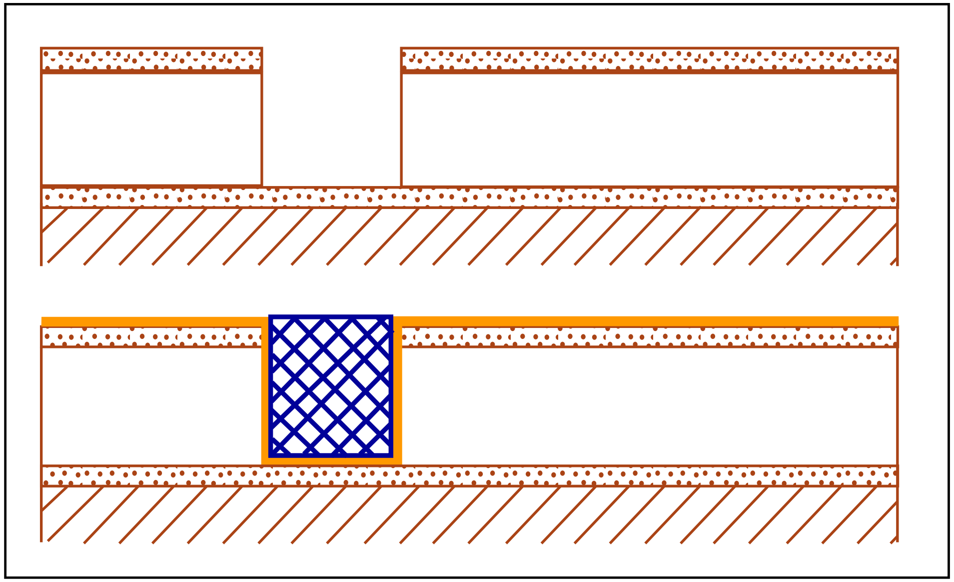


Figure 1 on p. 637 in Brosnihan, T. J., J. M. Bustillo, A. P. Pisano, and R. T. Howe. "Embedded Interconnect and Electrical Isolation for High-aspect-ratio, SOI Inertial Instruments." In *Transducers '97 Chicago: 1997 International Conference on Solid State Sensors and Actuators: digest of technical papers, June 16-19, 1997*. Vol. 1. Piscataway, NJ: IEEE, 1997, pp. 637-640. ISBN: 9780780338296. © 1997 IEEE.

The latest design: ADXL40

> MEMS

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



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ADXL40

> Die shots

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New accelerometer markets

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Summary

> **Accelerometers are a MEMS success story**

> **Early system partitioning decisions have had profound downstream effects**

- **Eases sensor design and sensing**
- **Requires large internal infrastructure**
  - » **And can never go to TSMC…**