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

Measurement Choices

- 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

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

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

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 amplitde of the position signal to be sensed will be small
    - Ie. 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

Accelerometer fundamentals

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

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

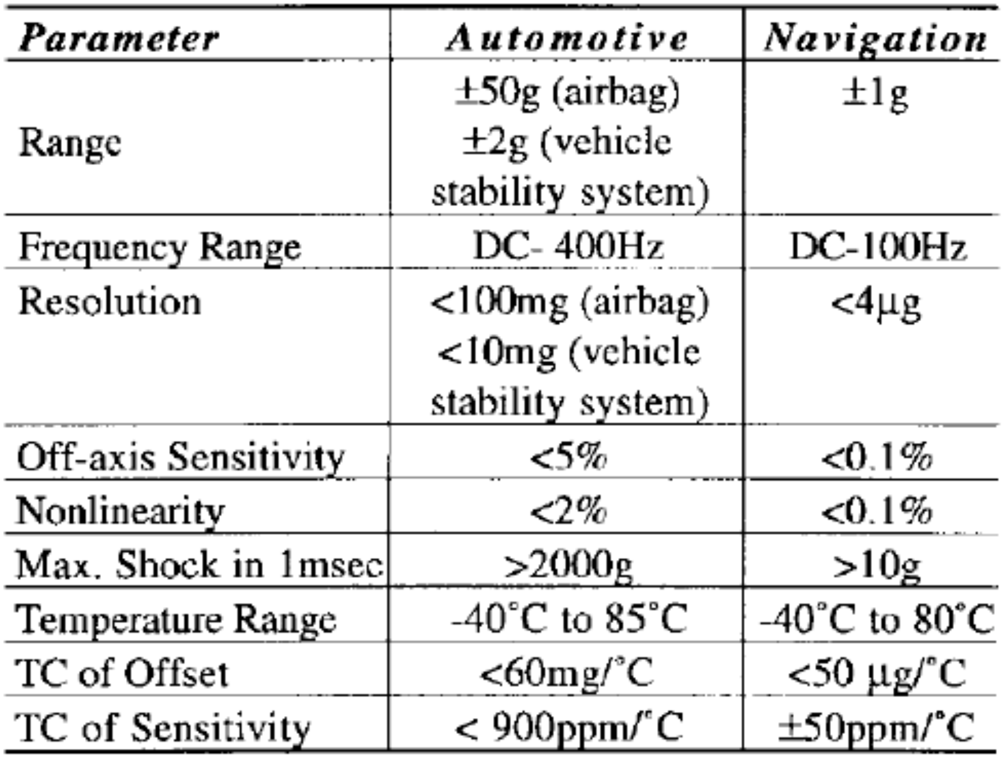
Accelerometer Specifications

Initial application arena was

Automotive crash sensor

Navigation sensors have

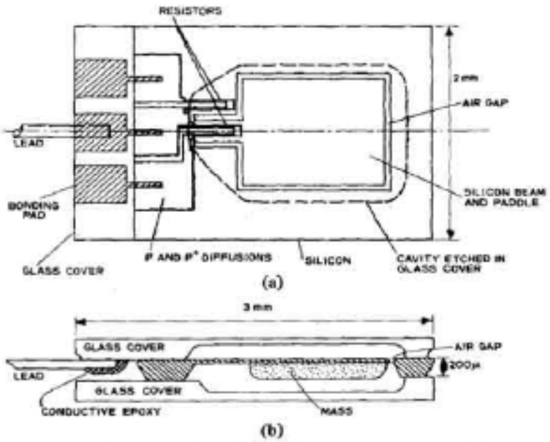
Tighter specs



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

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
- Piezoresistos generally less sensitive than capacitive detection



(a)

(b)

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

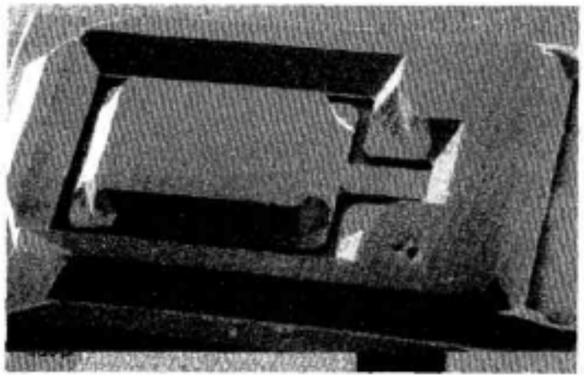
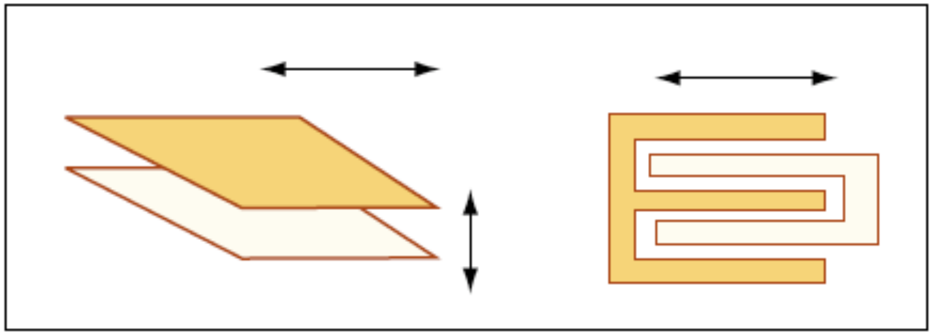
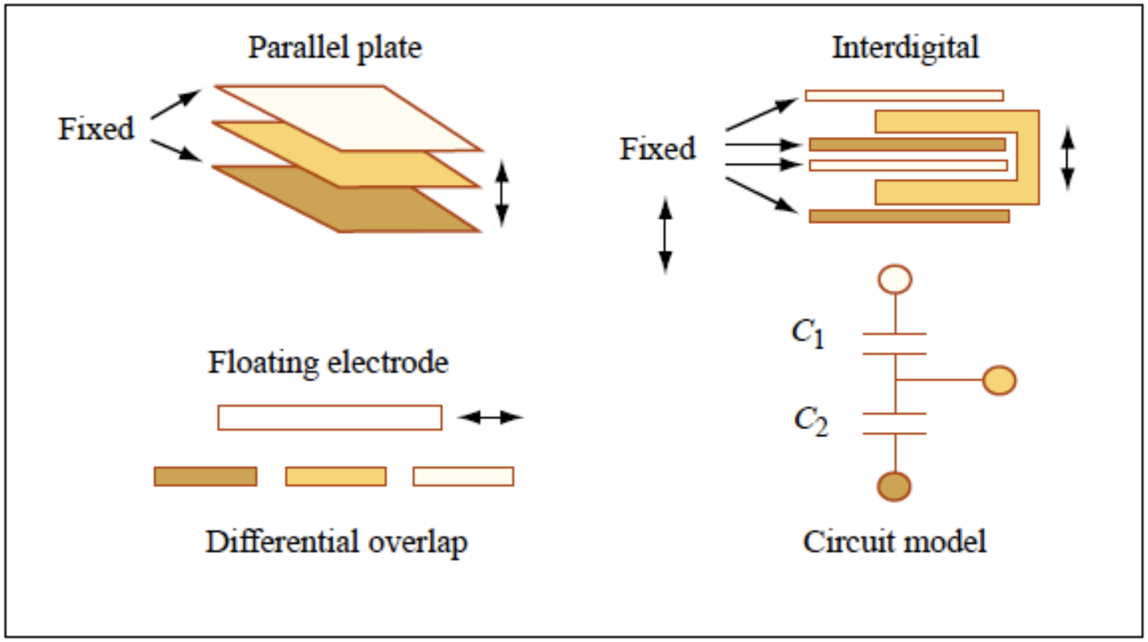


Fig. 2. SEM of backside of the accelerometer with a silicon mass after KOH etch.

Capacitors for position measurement

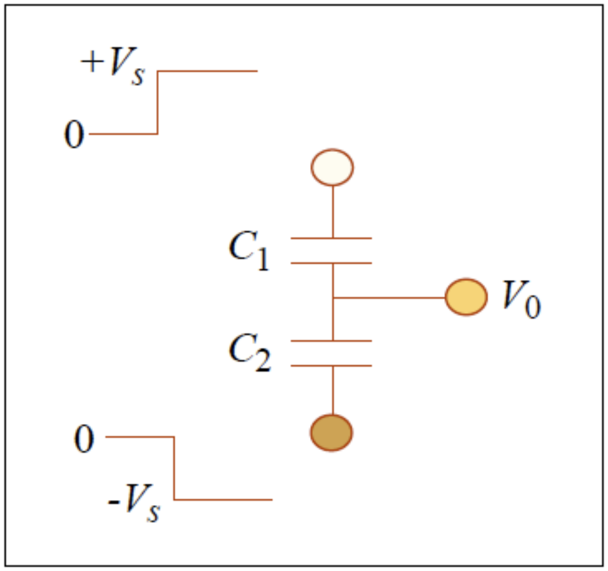
- Single capacitors
  - Capacitance is a function of gap or area
  - Can be nonlinear
- Differential capacitors
  - One capacitor increases while the other decreases
  - Have virtue of cancelling many effects to first order, providing signal that is zero at base state





Using a differential capacitor

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



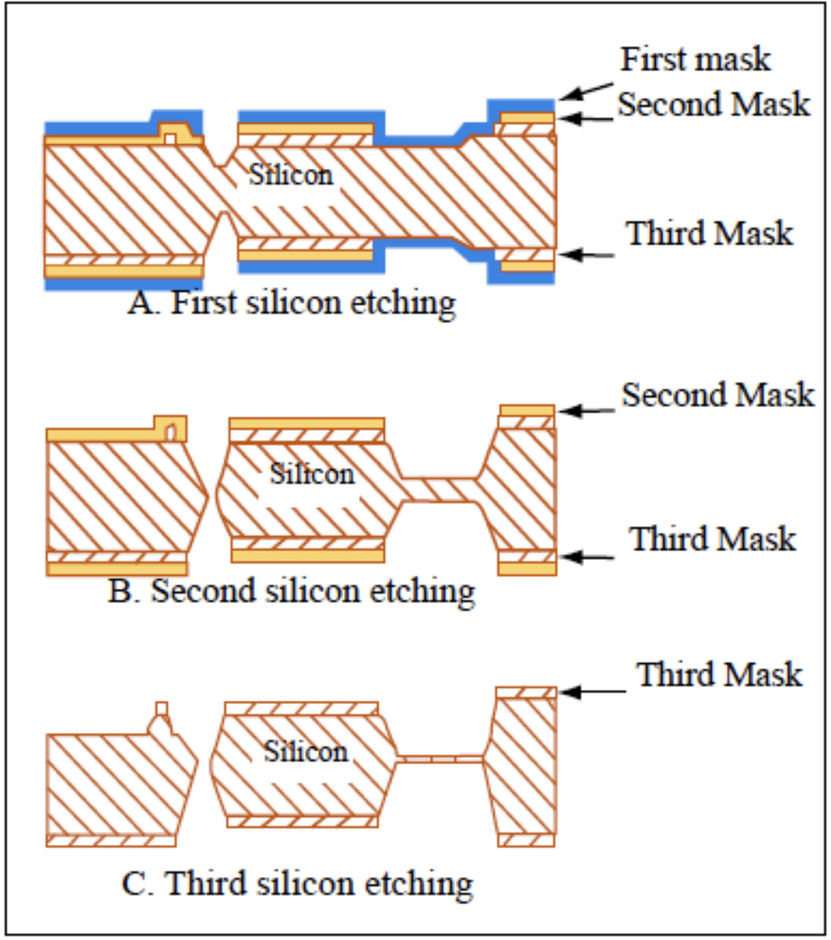
$$V_0 = -V_S + \frac{C_1}{C_1 + C_2}(2V_S) = \frac{C_1 - C_2}{C_1 + C_2} V_S$$

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

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

Bulk micromachined capacitive accelerometer

- Fabrication not reported, but here is my best guess (using nested-mask process)



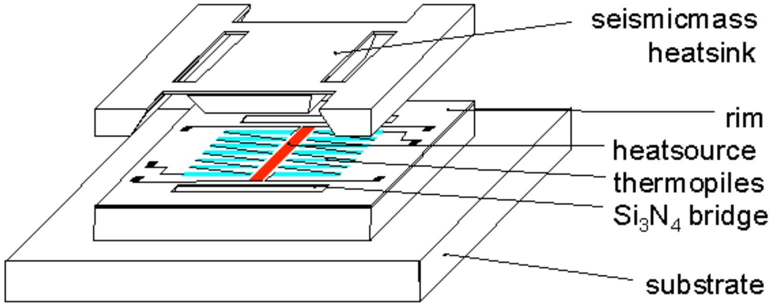
A. First silicon etching

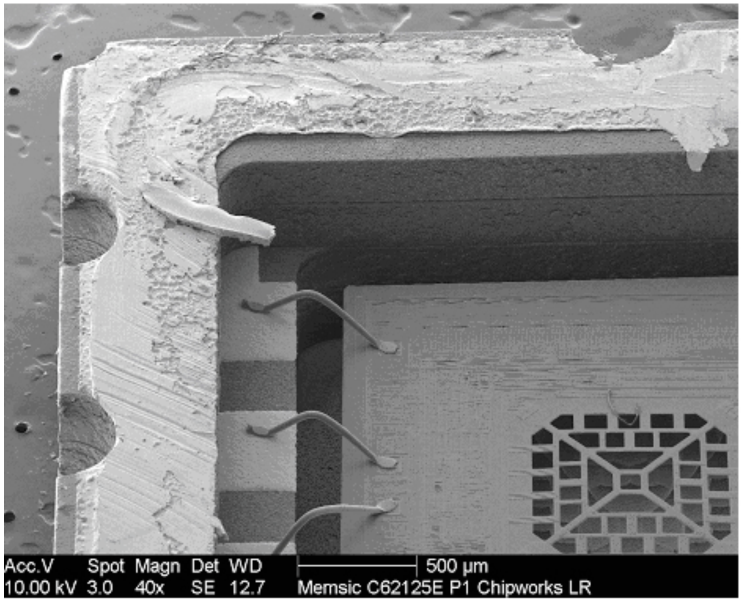
B. Second silicon etching

C. Third silicon etching

Thermal accelerometer

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





Transimpedance circuits

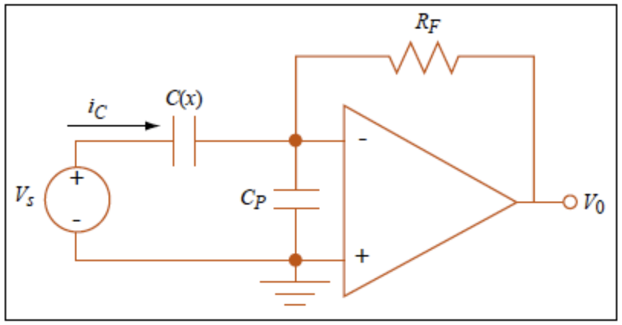
- The simplest type of circuit measures the displacement current in a capacitor using transimpedance amplifier
  - ➢ Transimpedance converts current to voltage
  - ➢ Nulls out parasitic capacitance
- If source is DC, measure velocity of motion → $V_0 \sim dx/dt$
- But velocity is not really what we want…we want position

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

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

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

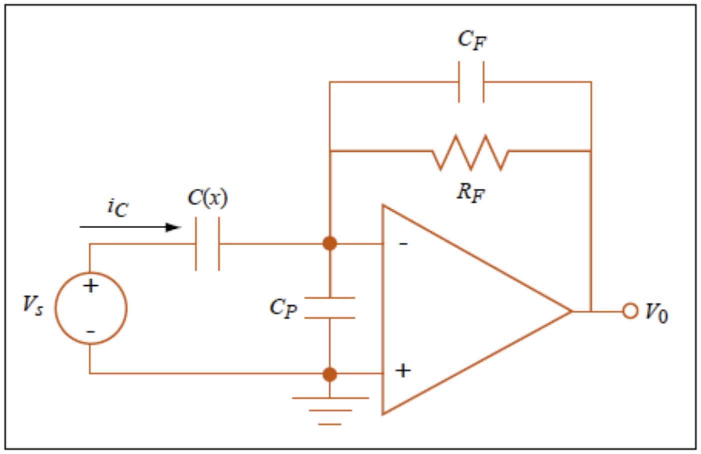
$$i_C = V_S \left.\frac{\partial C}{\partial x}\right|_{V_S} \frac{dx}{dt} = -\frac{V_0}{R_F}$$



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

Transimpedance Circuits

- 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



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

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

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

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

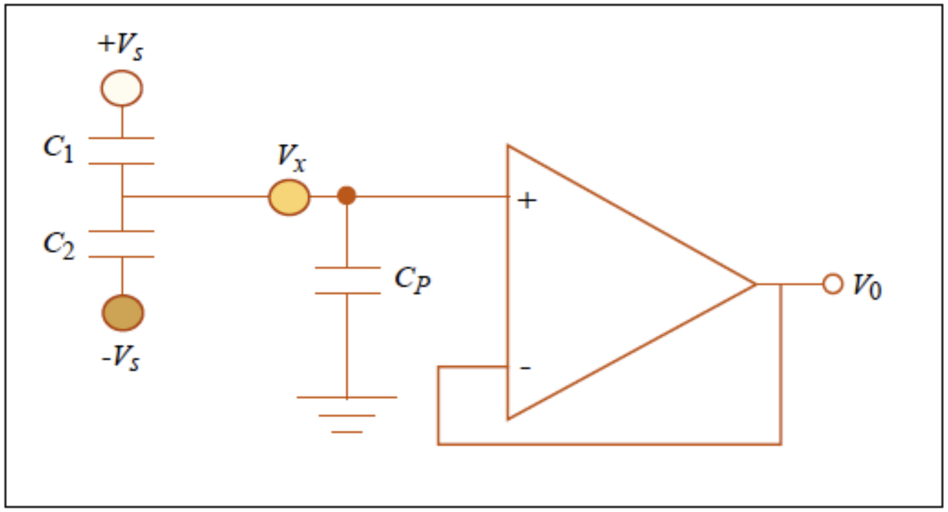
$$V_0 = -i_c\left(C_F // R_F\right) = -i_c\frac{R_F}{1 + j\omega C_F R_F}$$

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

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

Non-inverting op-am circuits

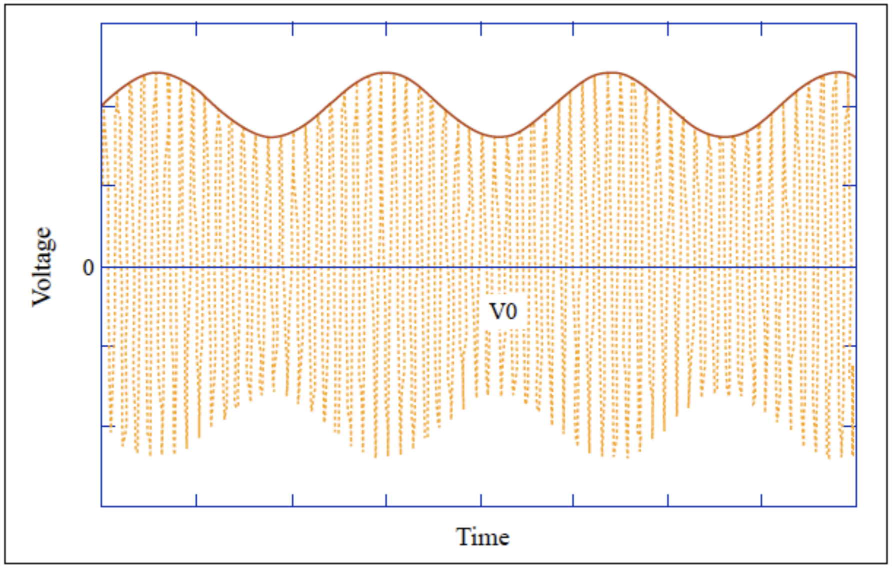
- Requires close matching of input capacitances to ground
- Now there is no virtual ground and parasitic capacitance appears in output
- Most suitable for applications in which transistors are integrated with the capacitive position sensing element



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

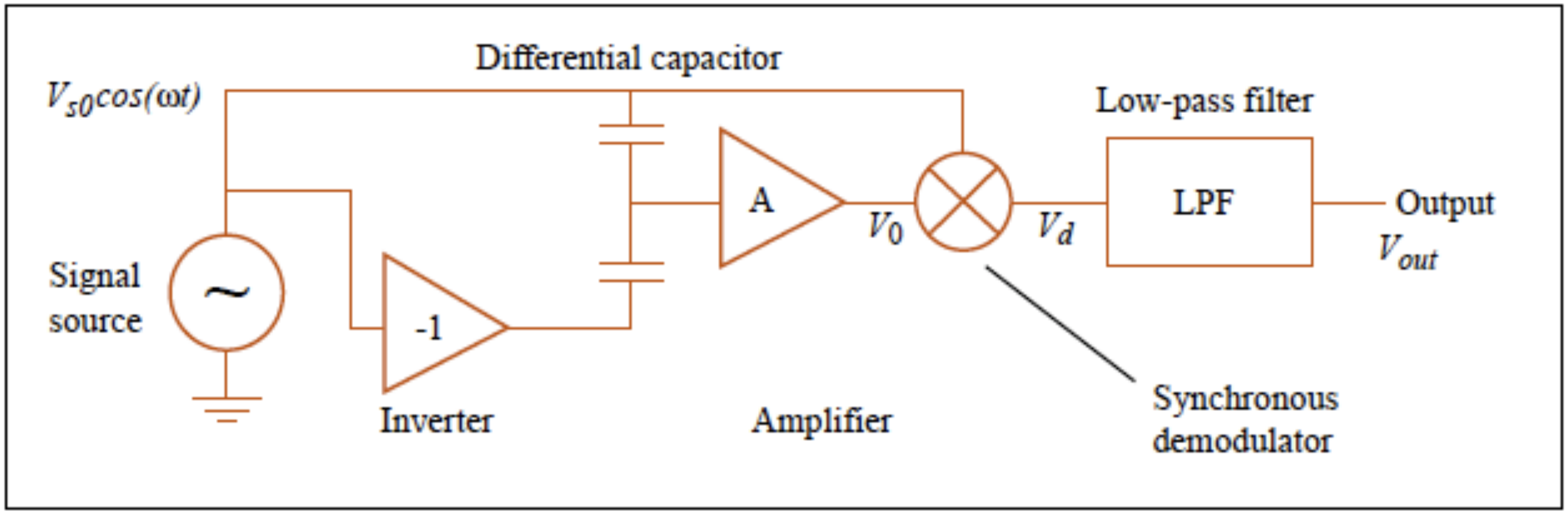
AC Methods Require Demodulation

- 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

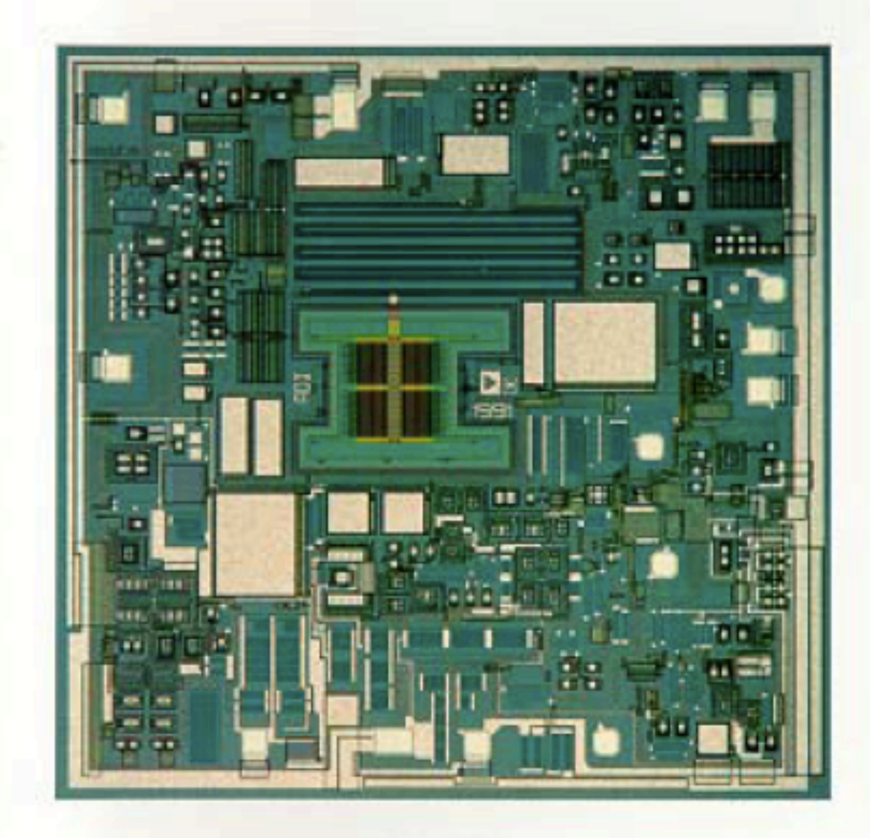
ADI accelerometers

- 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

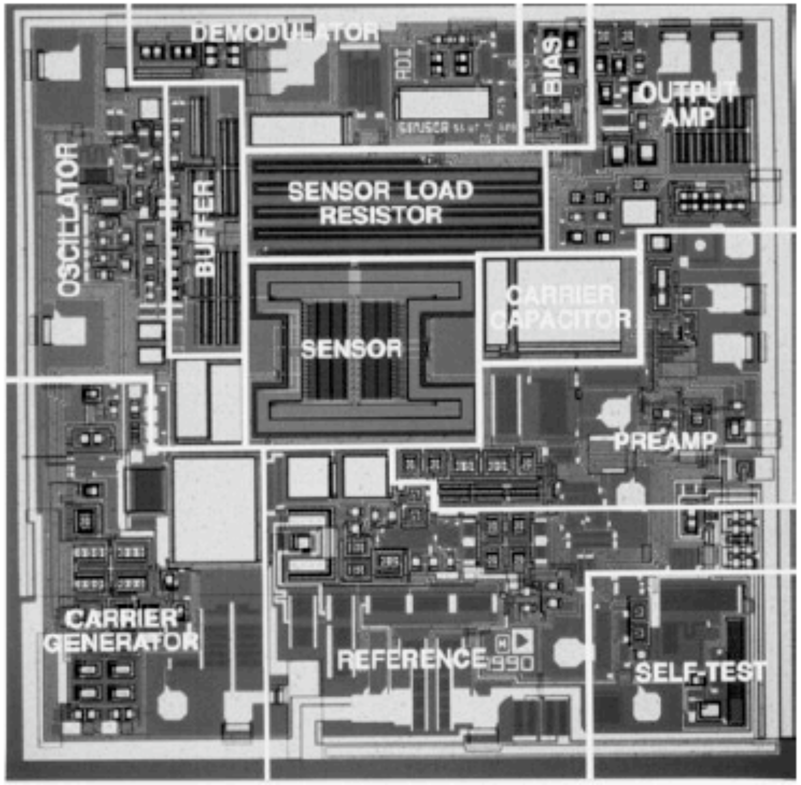
ADI system partitioning

- How to integrate MEMS + circuits?
- Several different approaches
  - MEMS first
  - Circuits first
  - MEMS in the middle
- ADI chose MEMS-in-the-middle
  - Mostl developed at Berkeley
  - 6” fab line
  - ~1 million sensors/week (as of 2005)

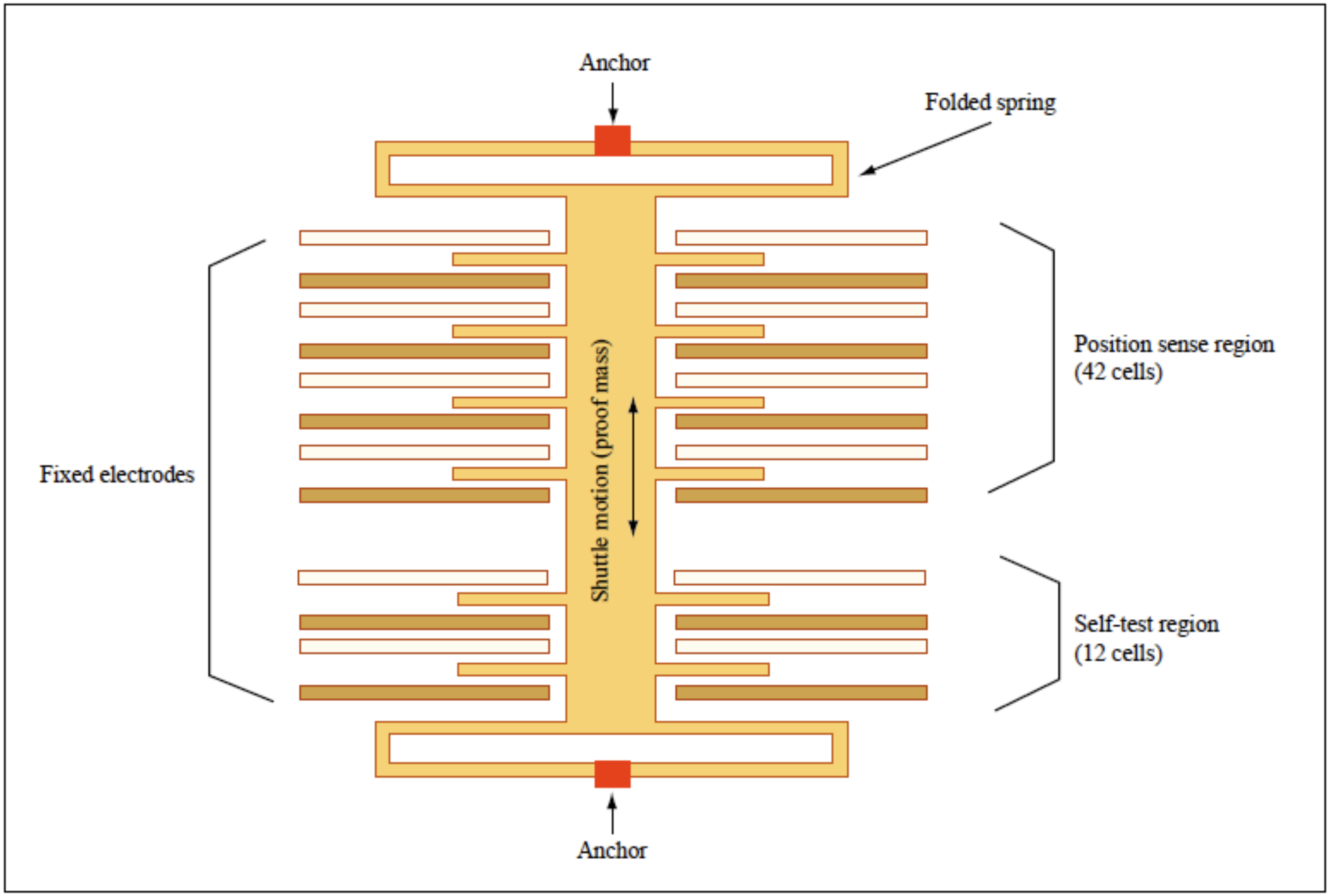
Analog Devices ADXL50



XL50



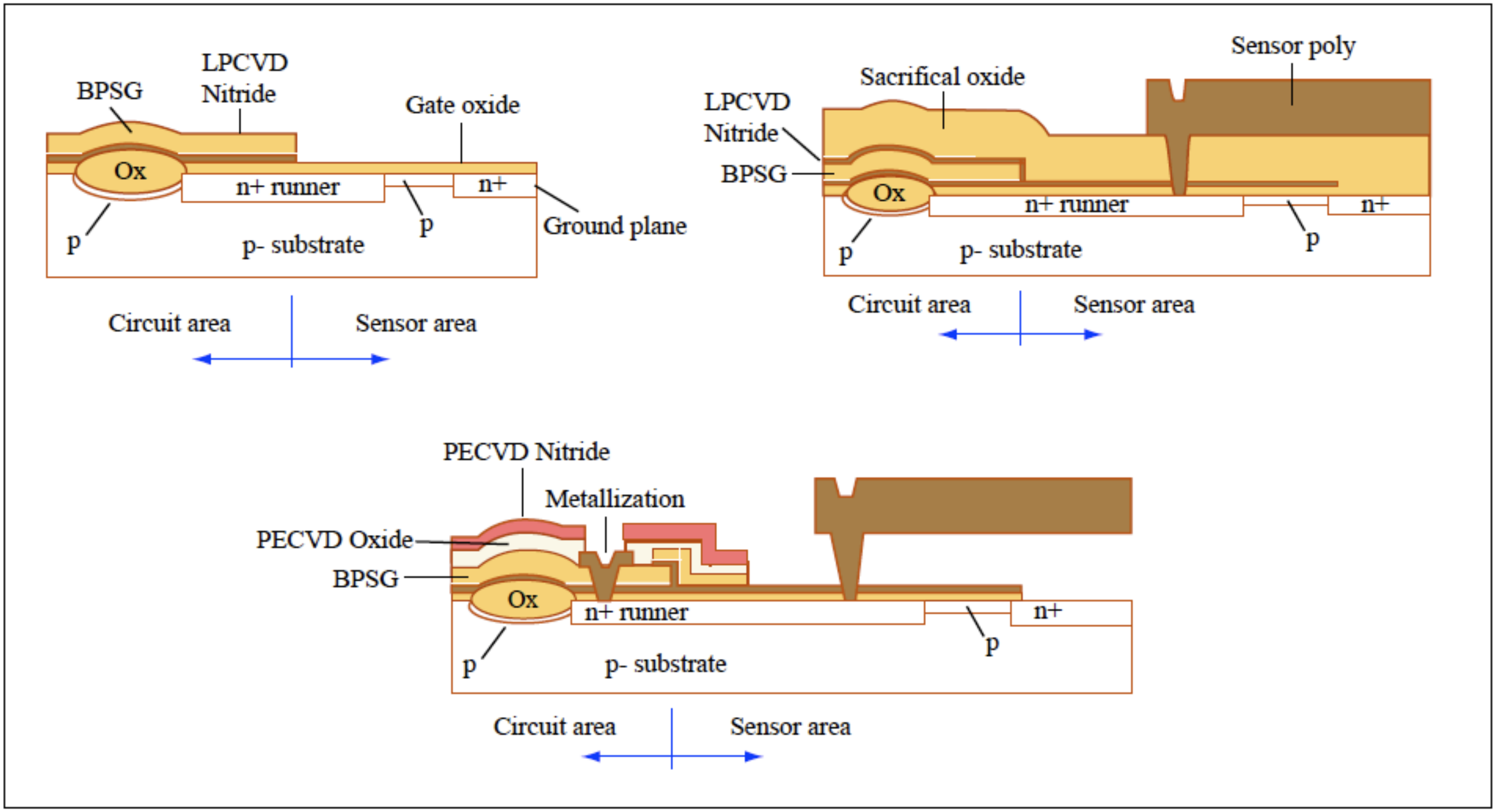
Differential Capacitor structure



ADI accelerometer

- 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

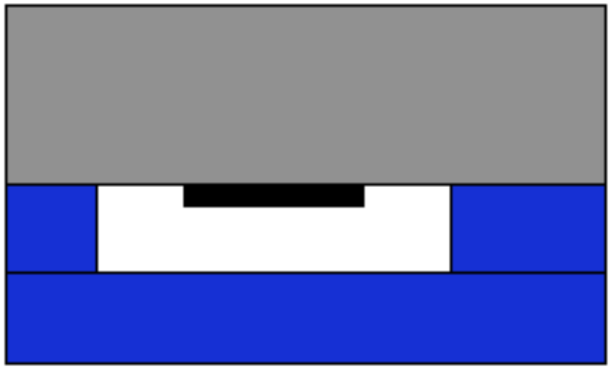


Fabrication sequence

- Electronics first
  - Lightly p-doped wafer
  - MOS/PMOS transitors, 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 – amorphouse 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 of 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)

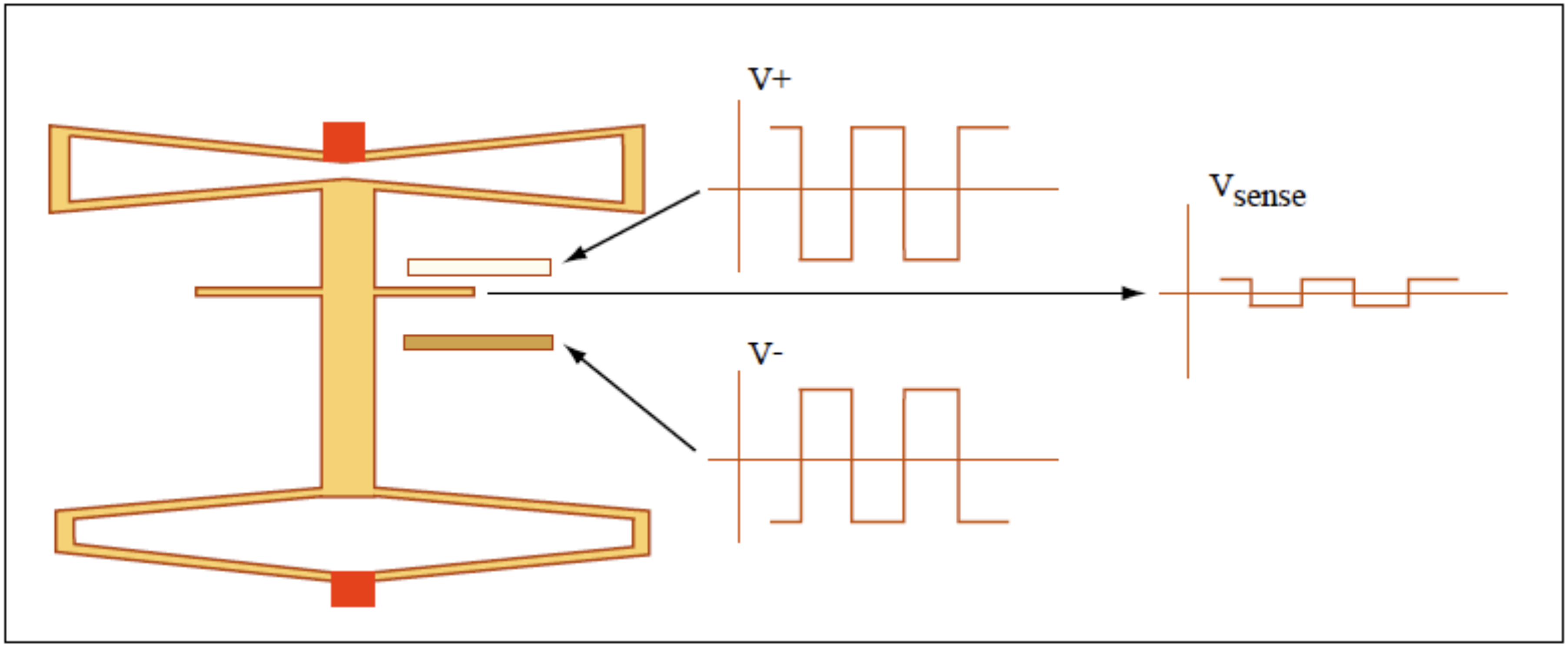


Packaging

- 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

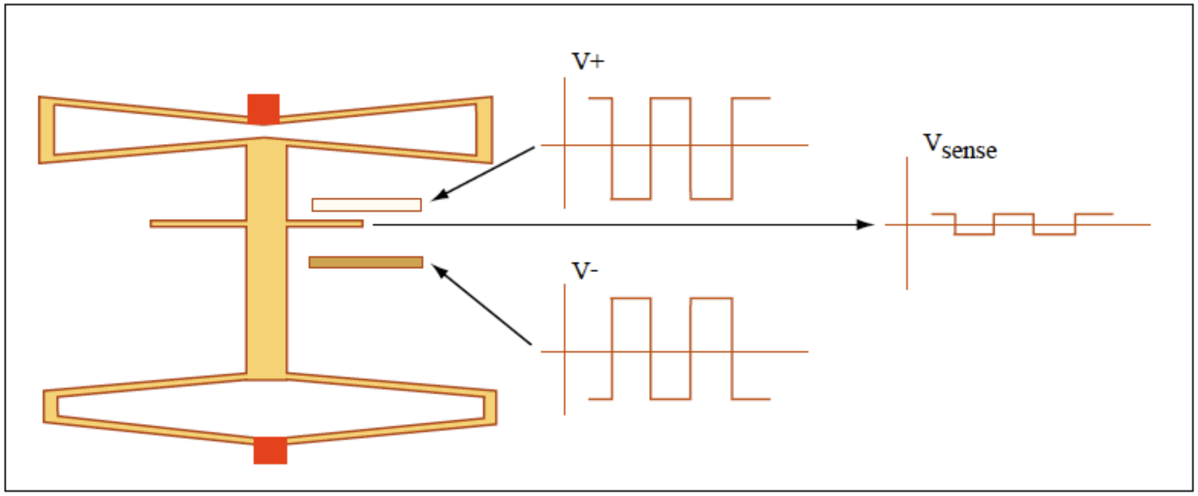
System Diagram

- Oscillator provides AC waveform for sensing
- Waveforms:



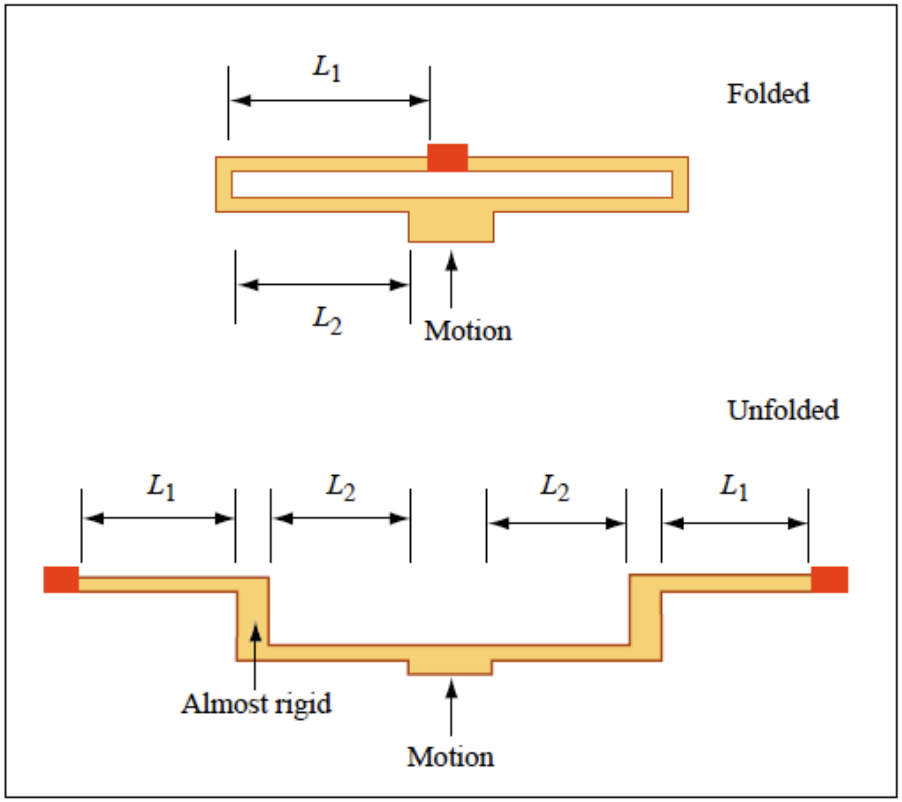
System Diagram

- Inertial acceleration or electrostatic force from self-test electrodes → 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



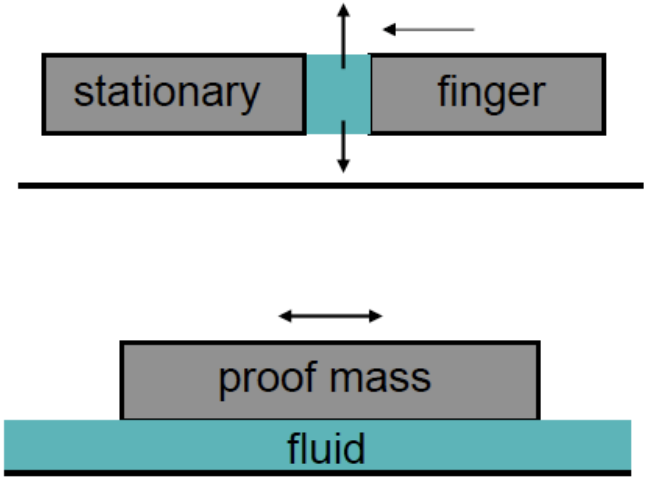
$$C_{sense} \approx 42\frac{\varepsilon_0 H L_0}{g_0 \pm y} \approx 60\text{fF}\left[1 \pm \frac{y}{g_0}\right]$$

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

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

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 (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)

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

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 gamma to meet both requirements
- Sensor response will be insensitive to change

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

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

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

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

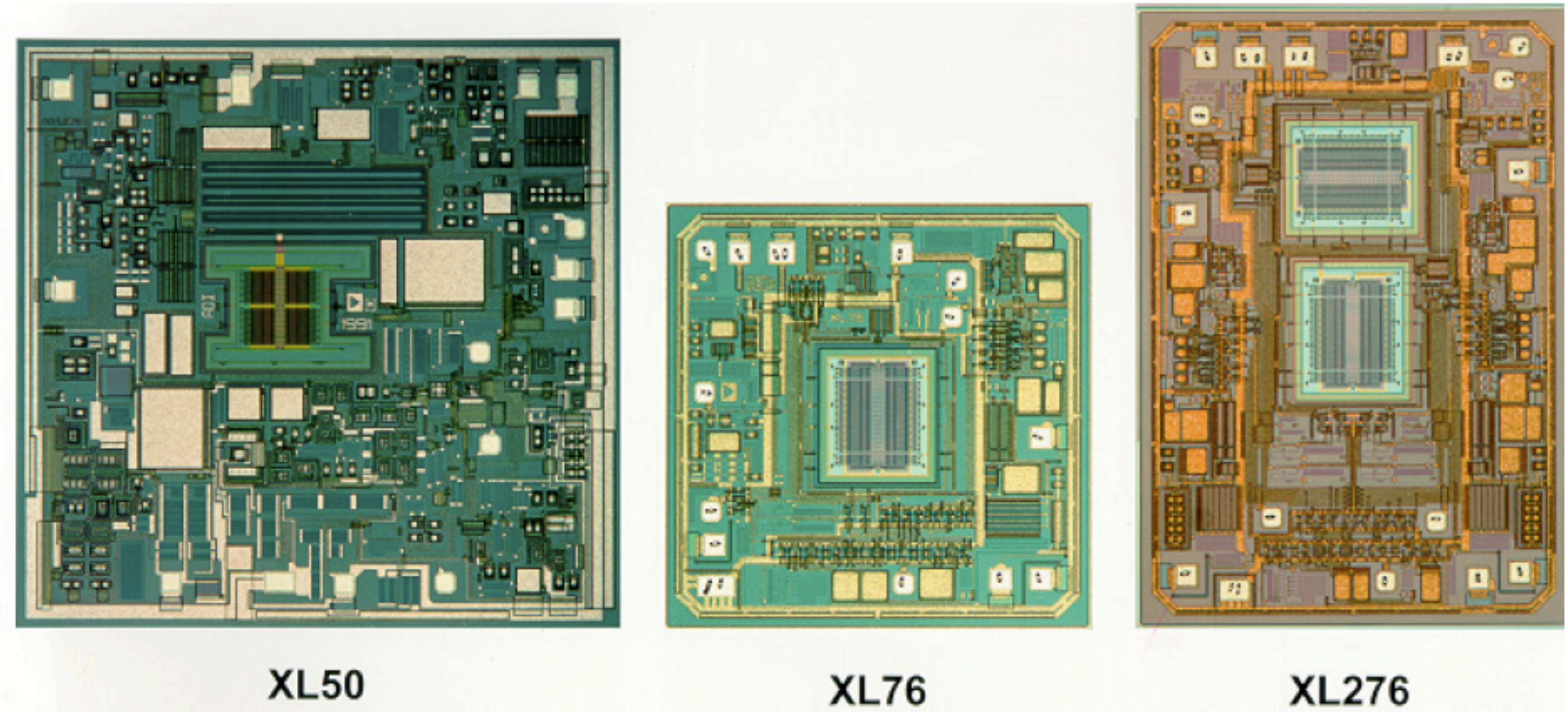
$$\gamma\frac{K_0}{m} \approx 2\sqrt{\frac{K_0}{m}} - \frac{1}{Q_{o.l.}}\sqrt{\frac{k}{m}} \approx 2\sqrt{\frac{K_0}{m}}$$

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

The next generations

- In the next generation, ADI abandoned feedback
- Why?
  - ➢ After years of testing, ADI found that PolySi was structually 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

Analog Devices Dies



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Next generation specifications

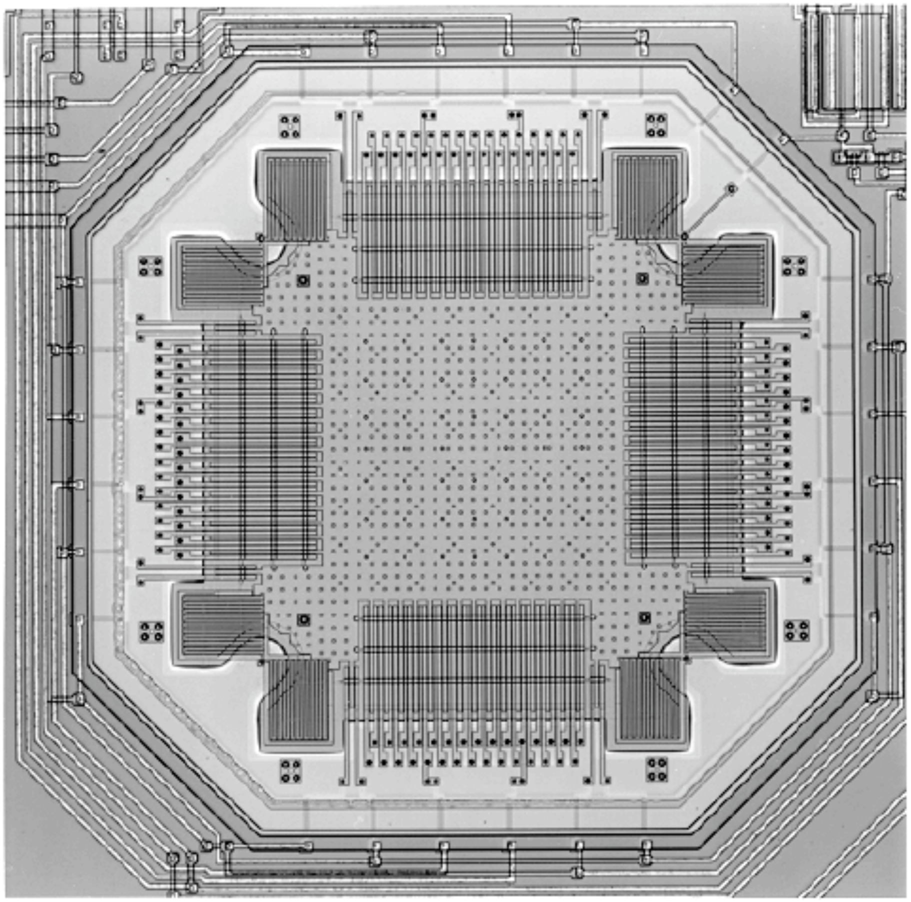
- Test study is of ADXL150 (XL76)
- Text lists 22 specifications, covering sensitivity, range, temperature range, supply voltage, nonlinearity, cross-axis response, bandwidth, clock noise, drop test, shock survival, etc..etc..
- Also, response is ratiometric, proportional to supply voltage

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



ADXL202 Sensor Structure

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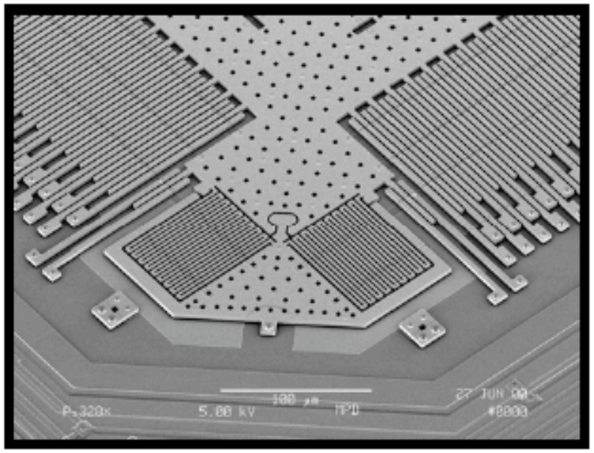

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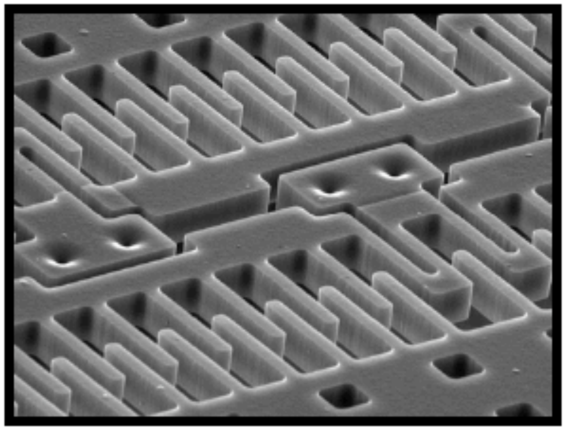

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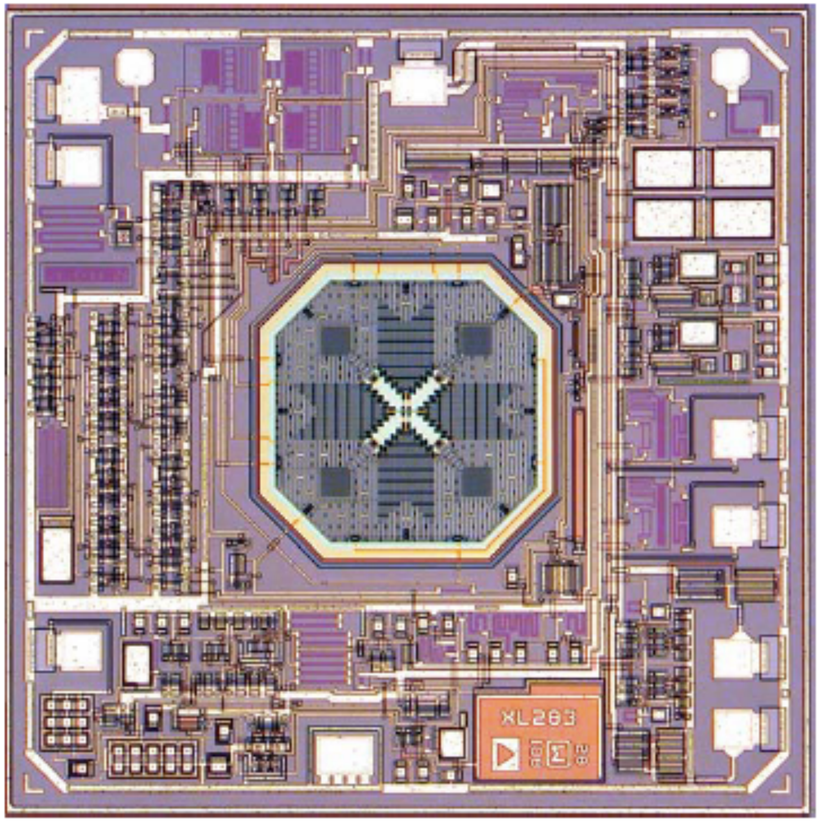
Newer designs

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



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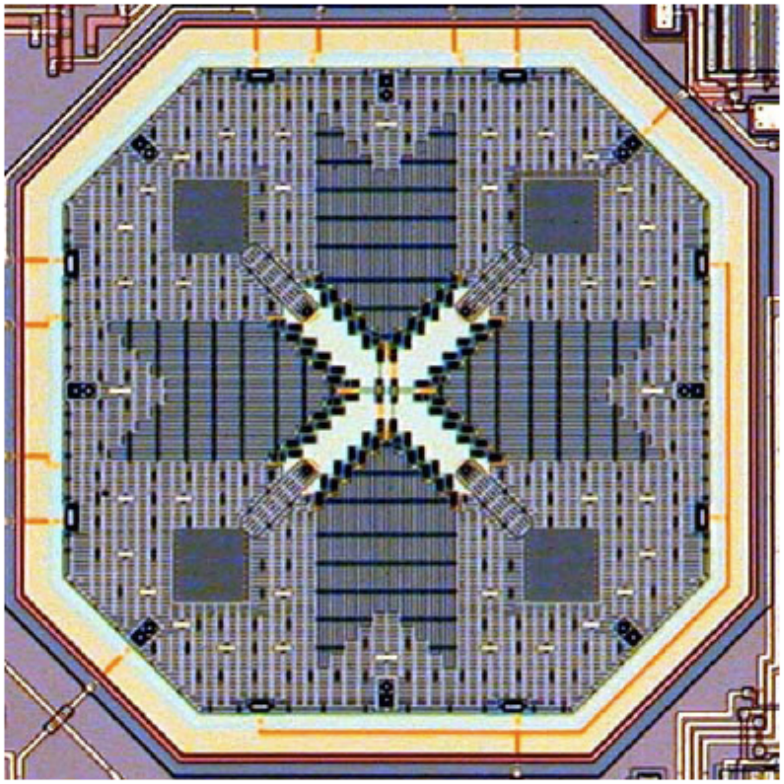

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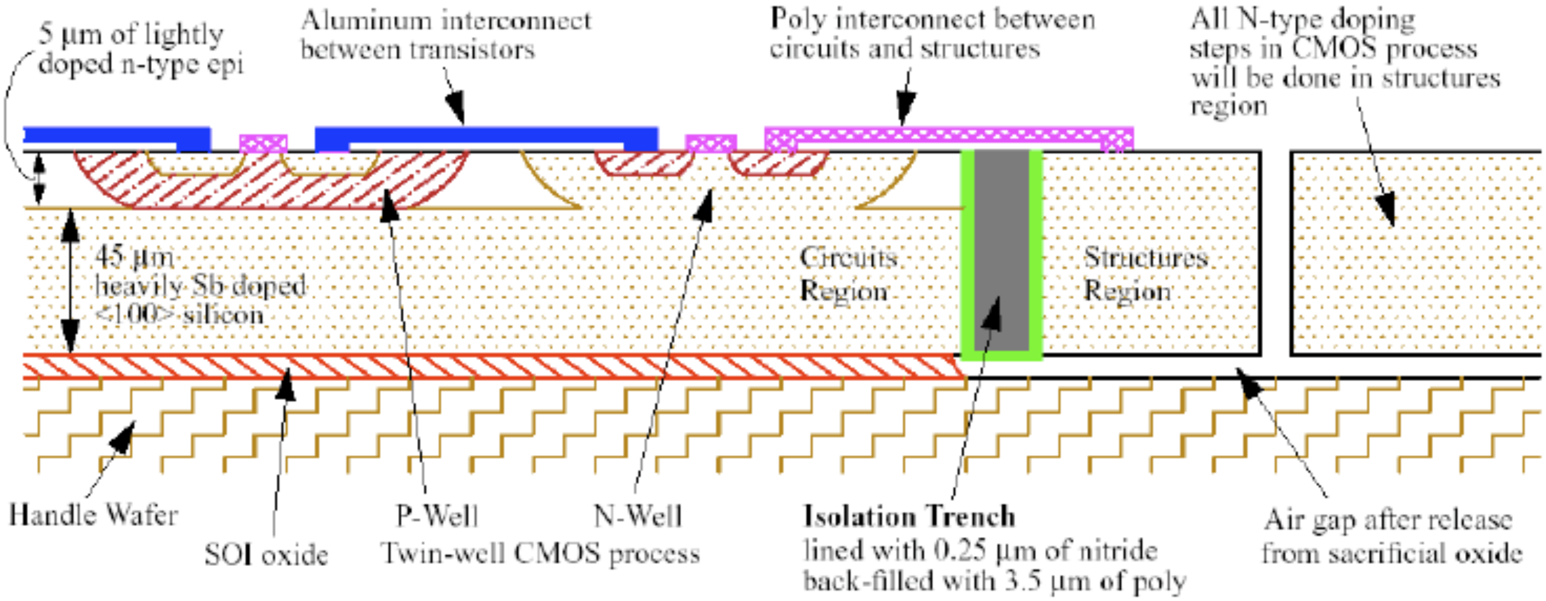
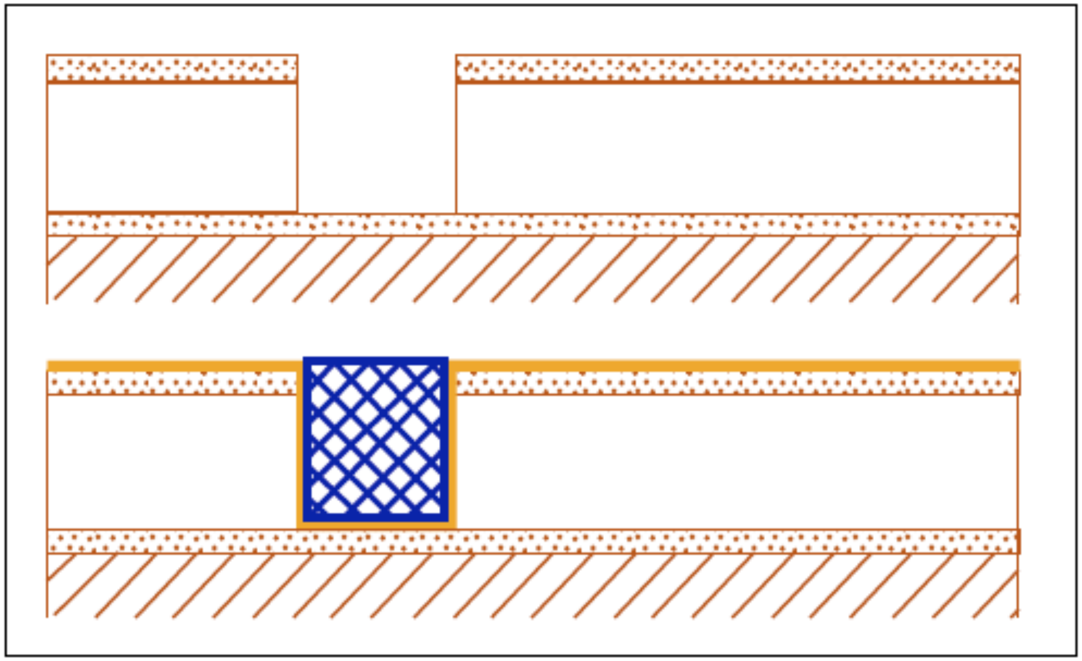
The latest design: ADXL40

- 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 → Q=1
  - ➢ Trench isolation allows self-test to be electrically isolated from sensing fingers
    - Allows 2x voltage applied → 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