3-Axis Accelerometer with Differential Sense Electronics

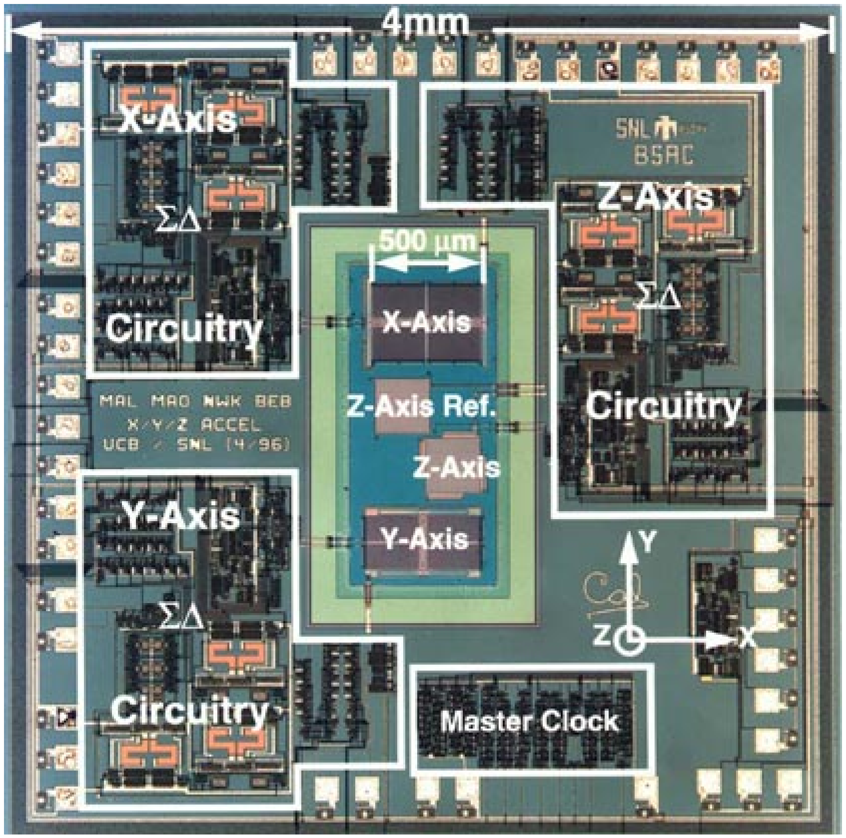
Bernhard E. Boser

Berkeley Sensor & Actuator Center

Dept. of Electrical Engineering and Computer Sciences

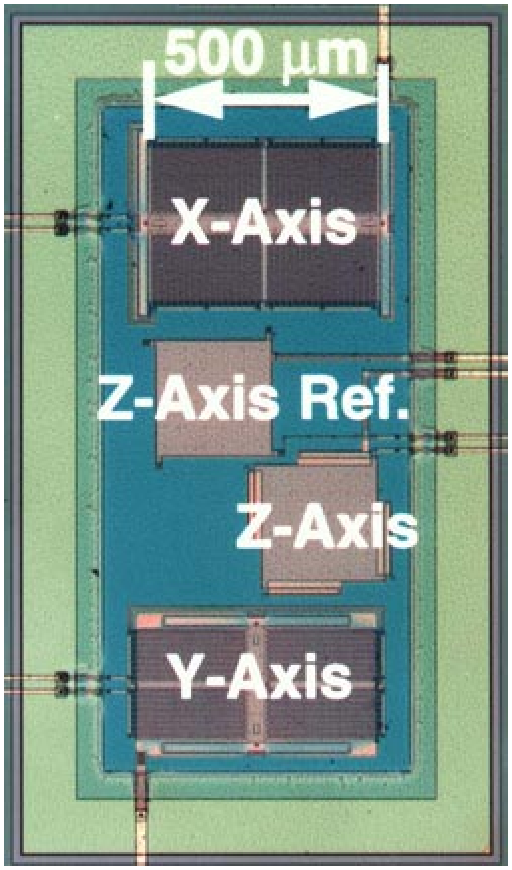
University of California, Berkeley

3-Axis Accelerometer



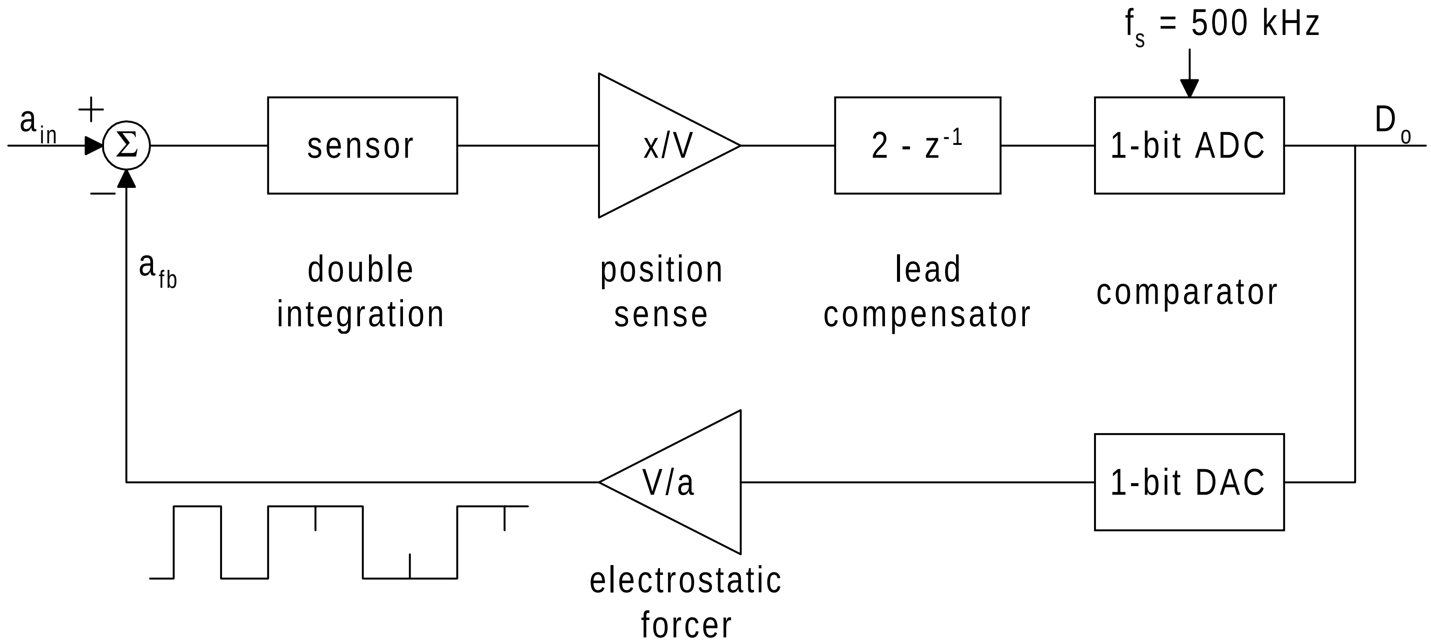
- 3 independent sensors for x/y/z-axis acceleration
- digital output (ΣΔ force-feedback)
- 500 kHz sampling rate
- 2 µm CMOS (DPSM)
- 4 x 4 mm^2 die
- 5V / 9mA per axis

Sense Elements



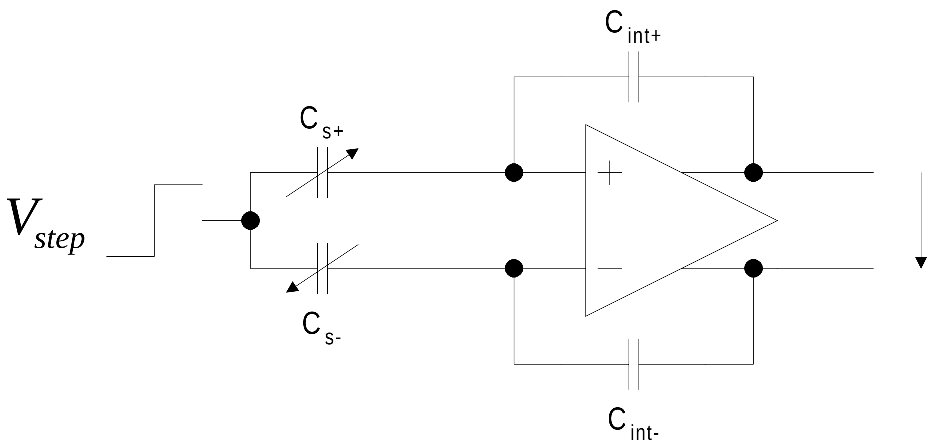
Ref.: M. Lemkin et al., “A 3-axis surface micromachined ΣΔ accelerometer,” in digest ISSCC, pp. 202-203, February 1997.

Digital Force Feedback



- 3 identical loops (1 per axis)
- shared clocks and bias

Position Sense Principle



$$\Delta V \propto V_{step} \times \frac{\Delta C}{C_{int}}$$

- pseudo-differential: reduces switch charge injection errors
- drive proof-mass: extensible to multi-axis sensing
- C_s tied to virtual ground: no driven shield

ISSUES:

- set DC level at amplifier input
- demodulate output (i.e. compute ΔV)

Sensitivity (x-axis)

resonant frequency	$f_r = 3.2$ kHz
sense capacitor	$C_s = 100$ fF
sense voltage	$V_{step} = 2V$
input signal	$a = 1$ mG

proof-mass displacement

$$\Delta x = \frac{a}{(2\pi f_r)^2} = 24 \times 10^{-12} m$$

capacitance change ($x_0 = 2\mu m$)

$$\Delta C \approx C_s \frac{\Delta x}{x_0} = 1.2 \times 10^{-18} F$$

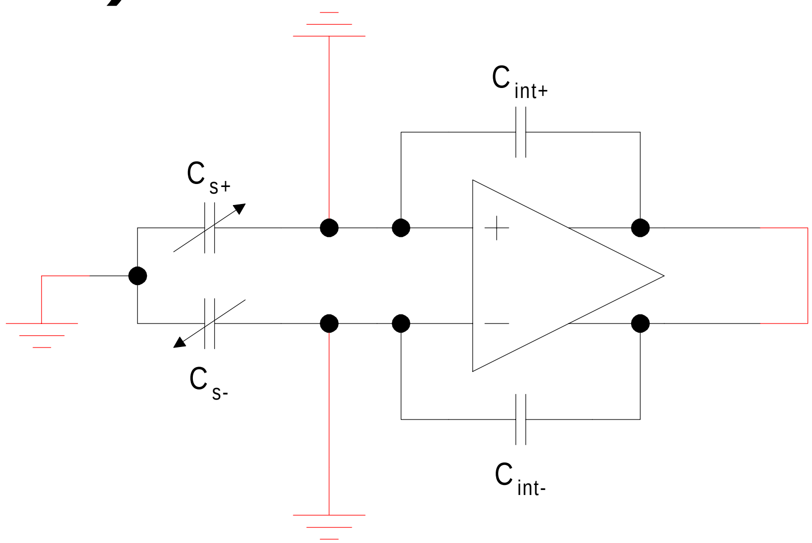
output voltage ($C_{int} = C_s$)

$$\Delta V \approx V_{step} \frac{\Delta C}{C_{int}} = 24 \mu V$$

Multi-Phase Operation

1) Set DC-Level
2) Cancel Offset & 1/f noise
3) Sense ΔC
4) Compare (for 1-Bit feedback)
5) Force-feedback

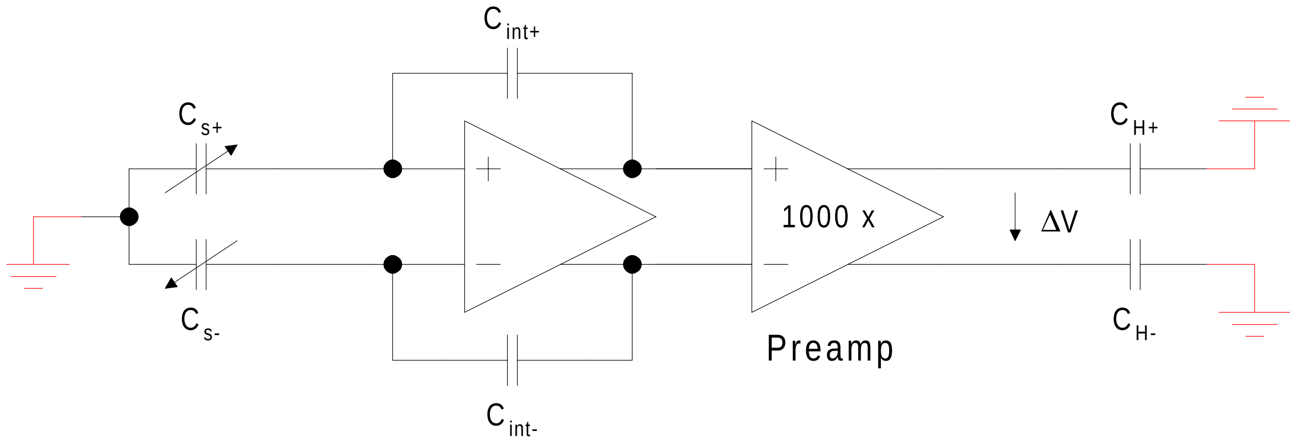
1) Set DC-Level



- Zero charge on C_s, C_{int}
- kT/C noise:

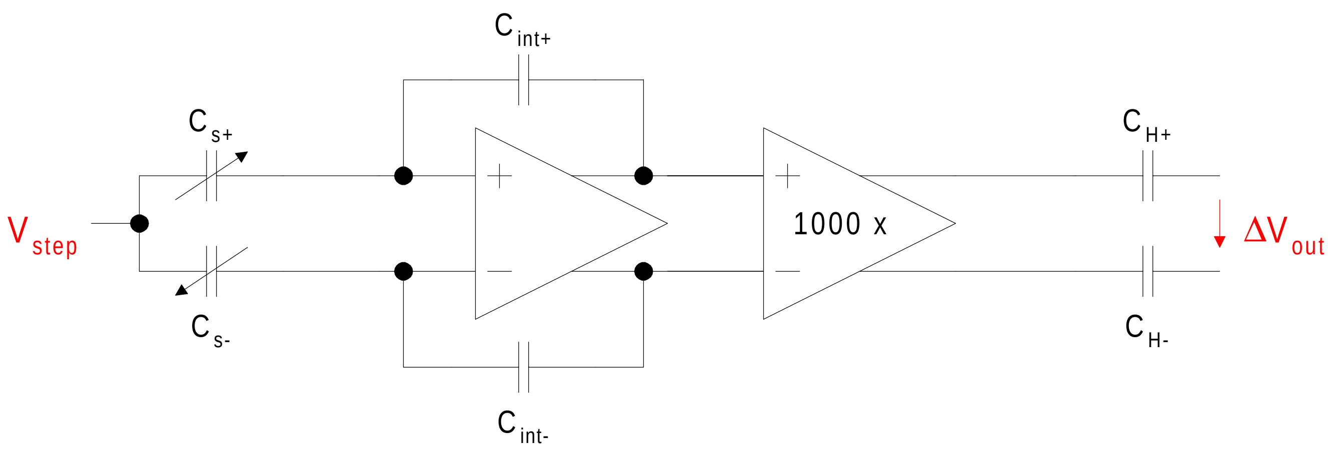
$$\sqrt{\frac{k_B T}{C_s}} \approx 200\mu V \qquad \textit{for } C_s = 100\, fF \ \ \textit{(room temperature)}$$

2) Cancel Offset and 1/f Noise



- Ideally, $\Delta V = 0$. Corrupted by
  - kT/C noise sampled onto C_s & C_{int}
  - offset & 1/f noise from integrator & preamplifier
- Error stored on C_H: first-order cancellation
- Residual error: kT/C_H --> $C_H >> C_s$
- Preamplifier boosts signal level & SNR

3) Sense ΔC_s

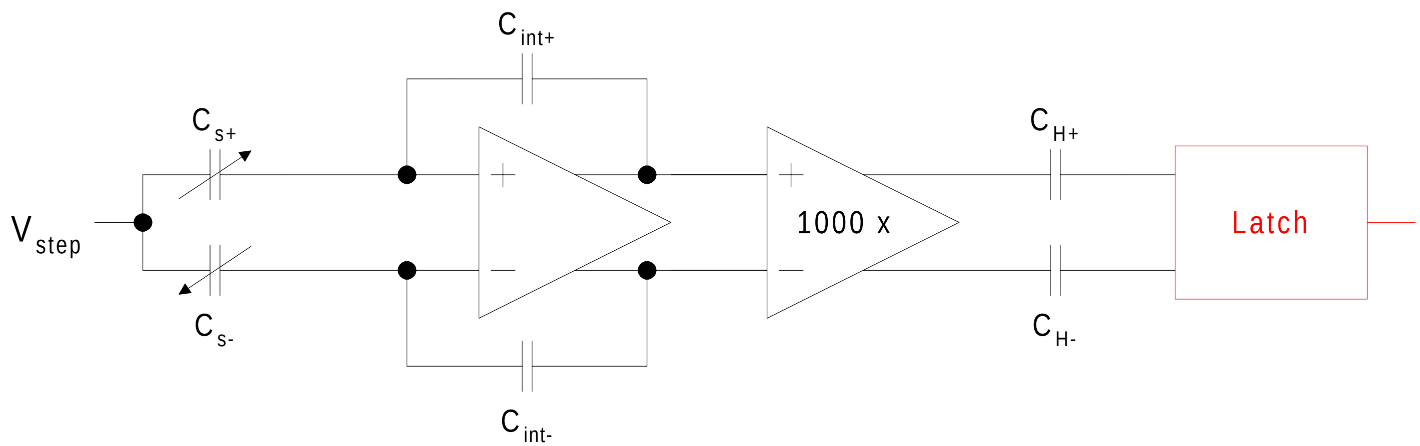


signal $$\Delta V_{out} \approx 1000 \times V_{step} \times \frac{\Delta C_s}{C_{\text{int}}}$$

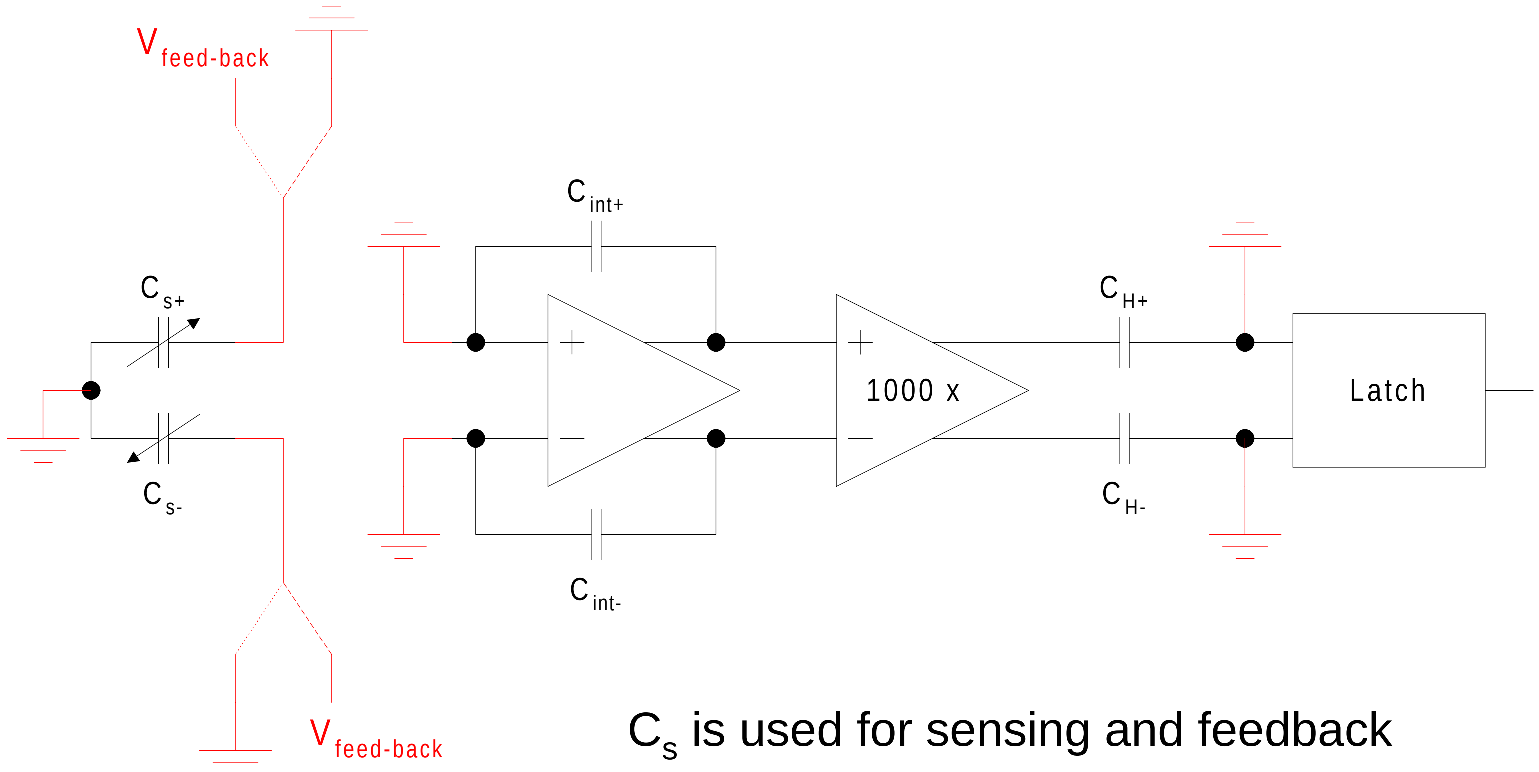
noise $$\overline{\left(\Delta V_{out,noise}\right)^2} \approx \frac{k_B T}{C_H}$$

(ignoring excess amplifier noise)

4) Compare



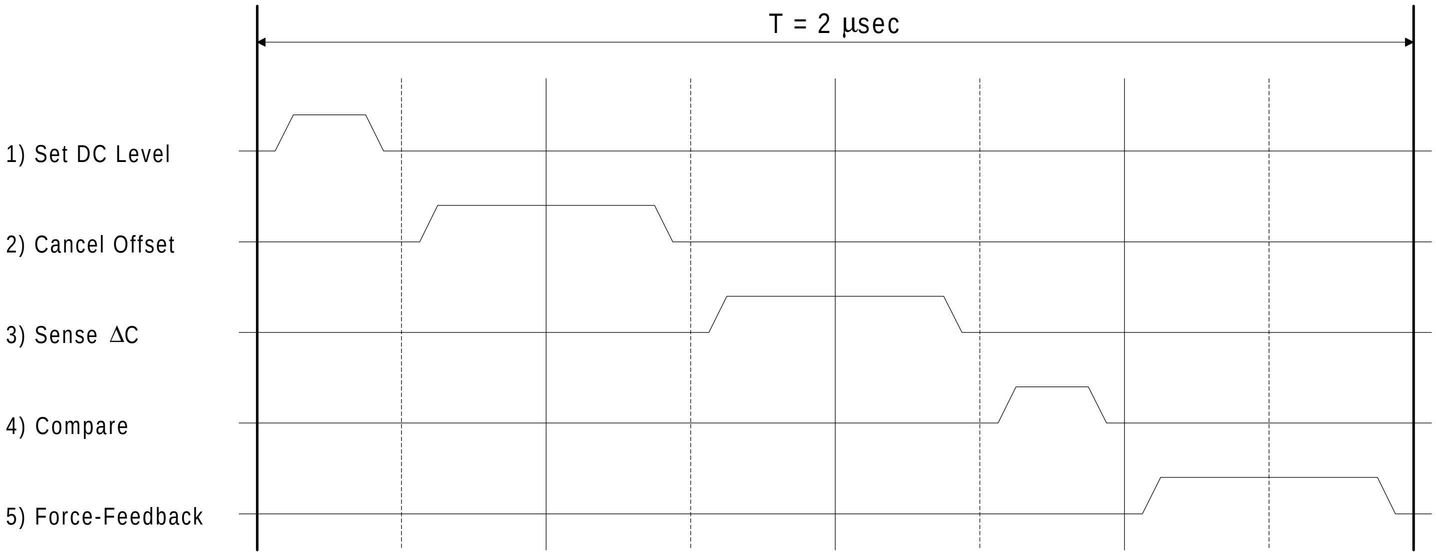
5) Force-Feedback



C_s is used for sensing and feedback

- maximizes available capacitance
- minimizes noise
- maximizes F_{fb} (accelerometer input range)

Four-Phase Clock



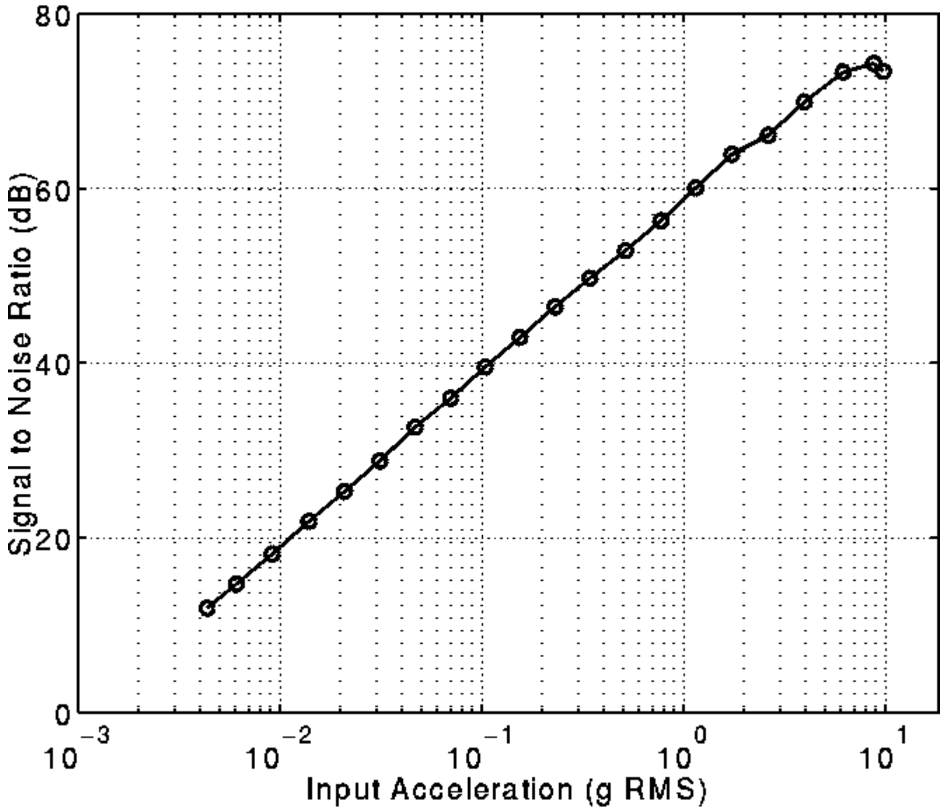
Second-Order Issues

- Common-Mode Feedback (CMFB)
- Frequency Compensation
- Parasitic Electrostatic Feedback
- Preamp Offset Cancellation

Performance Summary

	mass	**resonant frequency**	**noise floor**	**input range**	C_s	dC_s/dx
x-axis	0.38 µg	3.2 kHz	110 µG/rt-Hz	± 10 G	100 fF	44 fF/µm
y-axis	0.26 µg	4.2 kHz	160 µG/rt-Hz	± 10 G	75 fF	34 fF/µm
z-axis	0.39 µg	8.3 kHz	990 µG/rt-Hz	± 15 G	300 fF	150 fF/µm

Measured SNR versus Input

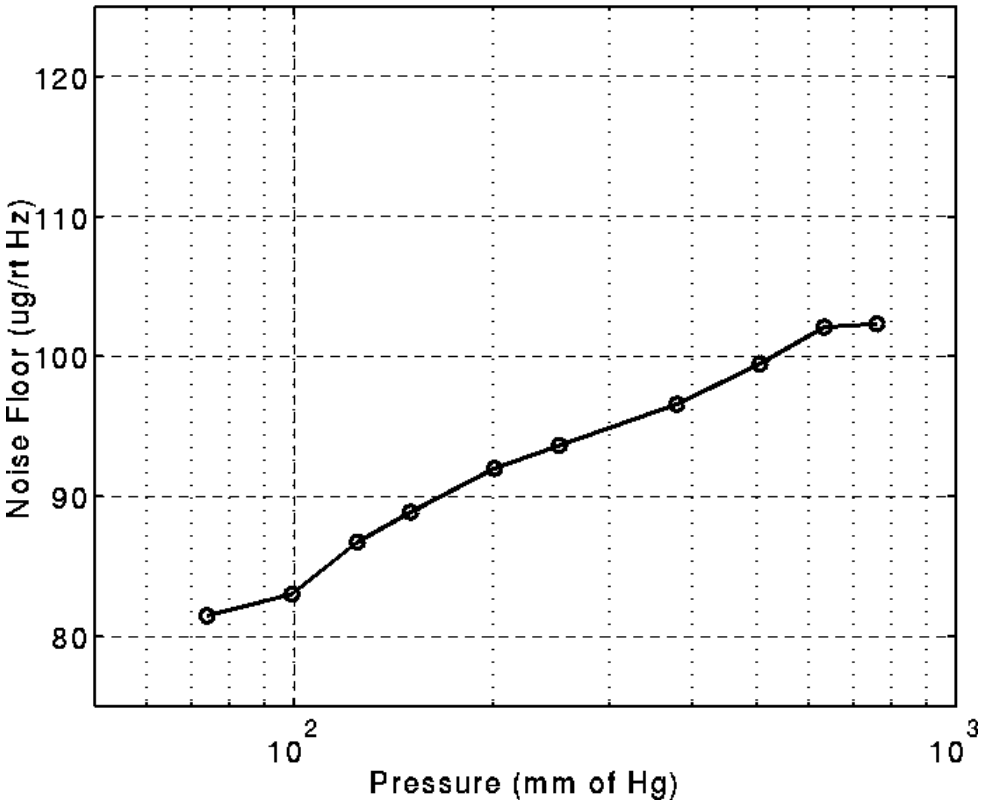


Input: 400 Hz sinusoid

Measurement Bandwidth: 100 Hz

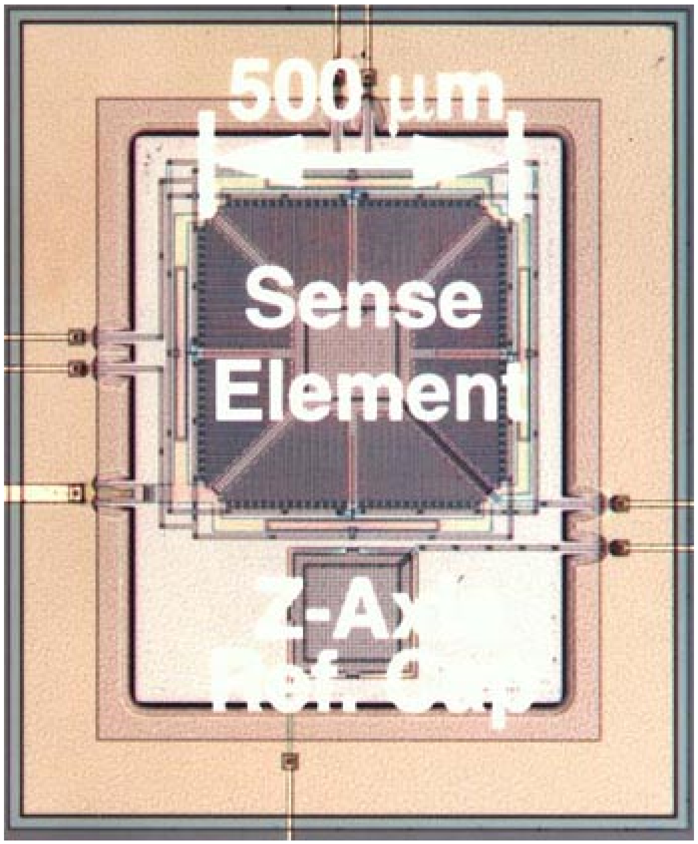
(x-axis sensor)

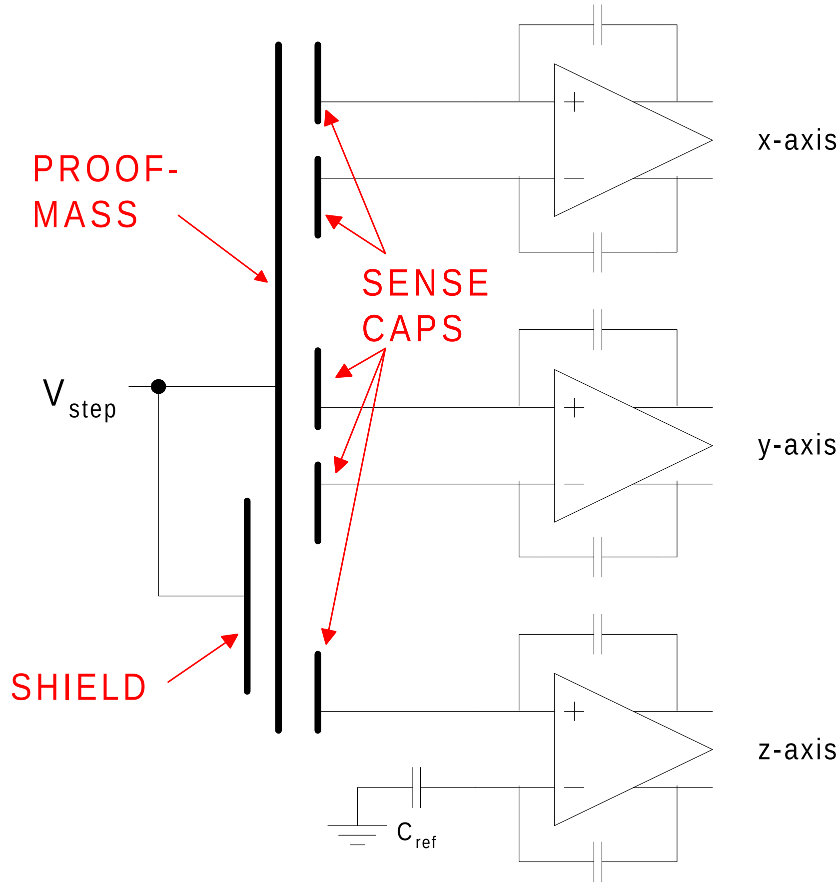
Noise Floor versus Pressure



(x-axis sensor)

Multi-Axis Sensing





Single Proof-Mass 3-Axis Accelerometer