EE C245 – ME C218 Introduction to MEMS Design Fall 2007

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Lecture 21: Gyros & Capacitive Transducers

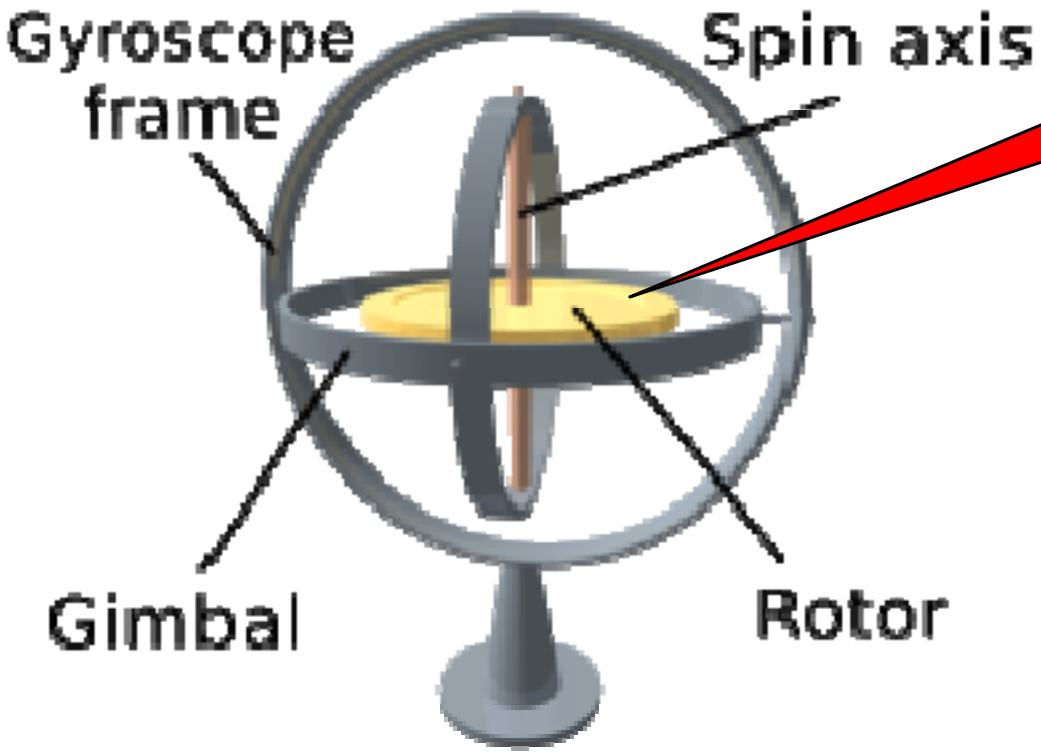
Lecture Outline

- Reading: Senturia, Chpt. 5, Chpt. 6, Chpt. 21
- Lecture Topics:
  - Project: Gyroscopes
  - Deep Reactive-Ion Etching (revisited)
  - Energy Conserving Transducers
    - Charge Control
    - Voltage Control
  - Parallel-Plate Capacitive Transducers
    - Linearizing Capacitive Actuators
    - Electrical Stiffness
  - Electrostatic Comb-Drive
    - 1st Order Analysis
    - 2nd Order Analysis

Gyroscopes

Classic Spinning Gyroscope

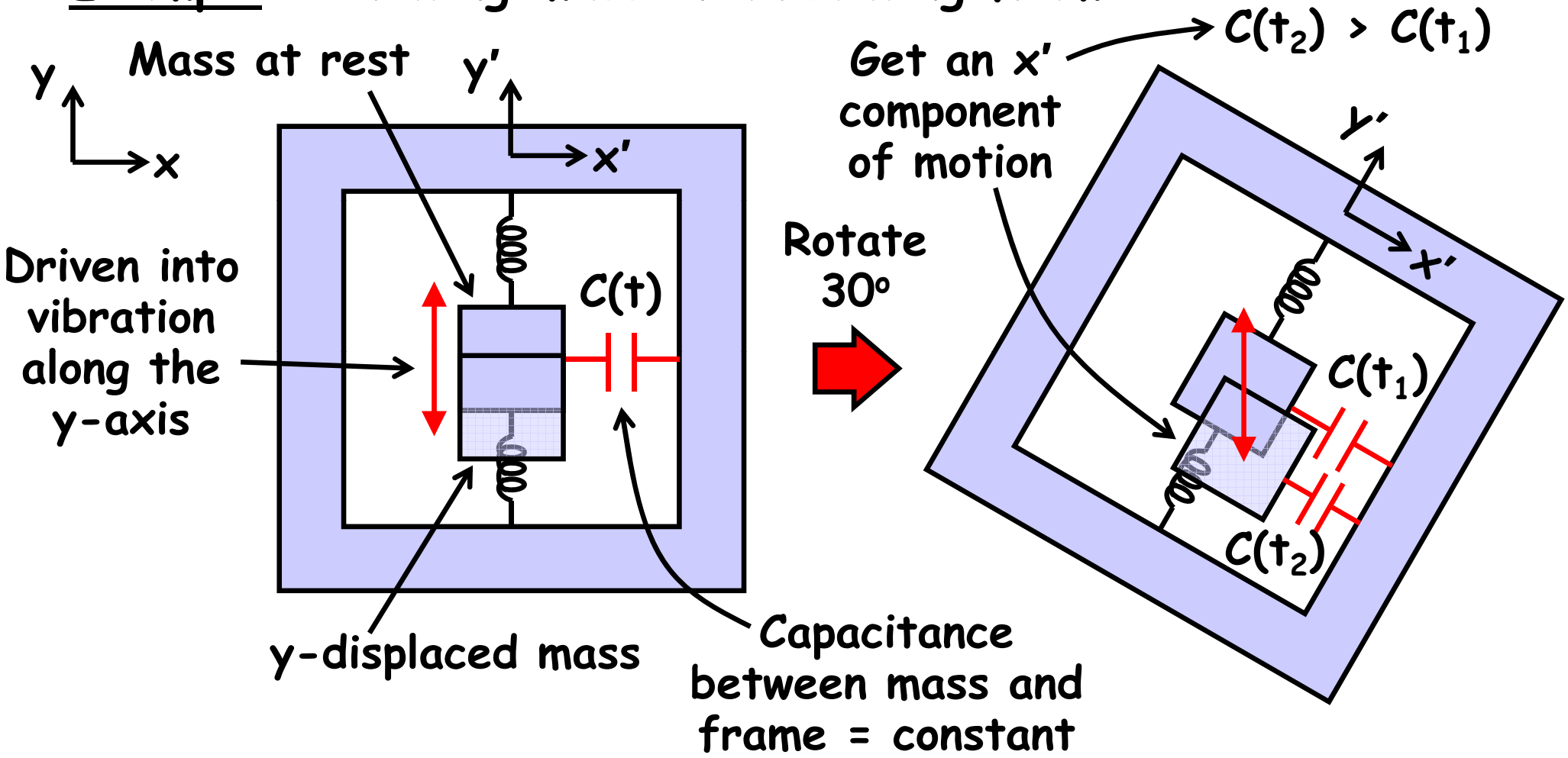
- A gyroscope measures rotation rate, which then gives orientation → very important, of course, for navigation
- Principle of operation based on conservation of momentum
- <u>Example</u>: classic spinning gyroscope



Rotor will preserve its angular momentum (i.e., will maintain its axis of spin) despite rotation of its gimbled chassis

Vibratory Gyroscopes

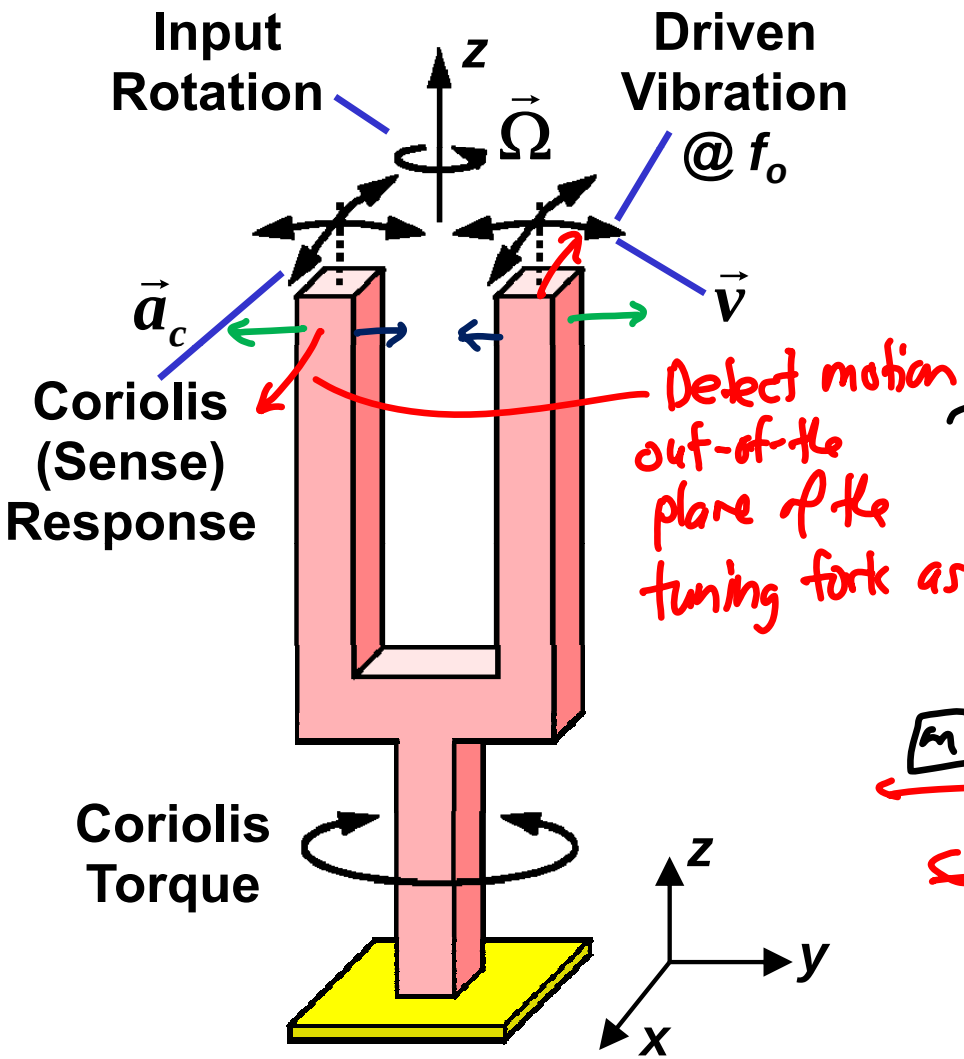
- Generate momentum by vibrating structures
- Again, conservation of momentum leads to mechanisms for measuring rotation rate and orientation
- <u>Example</u>: vibrating mass in a rotating frame



Basic Vibratory Gyroscope Operation

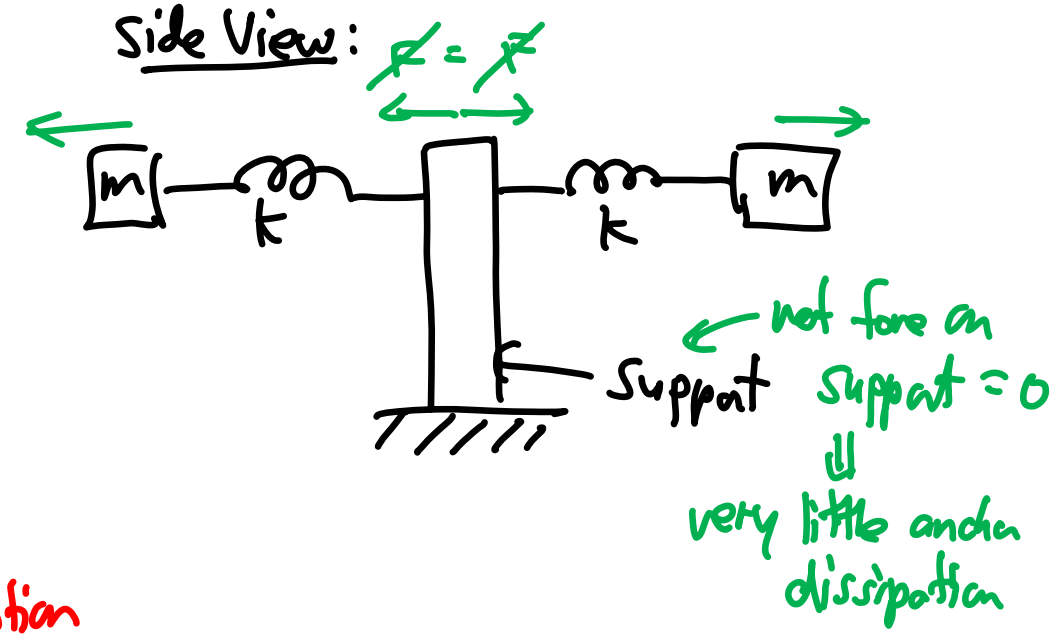
Principle of Operation

- Tuning Fork Gyroscope:

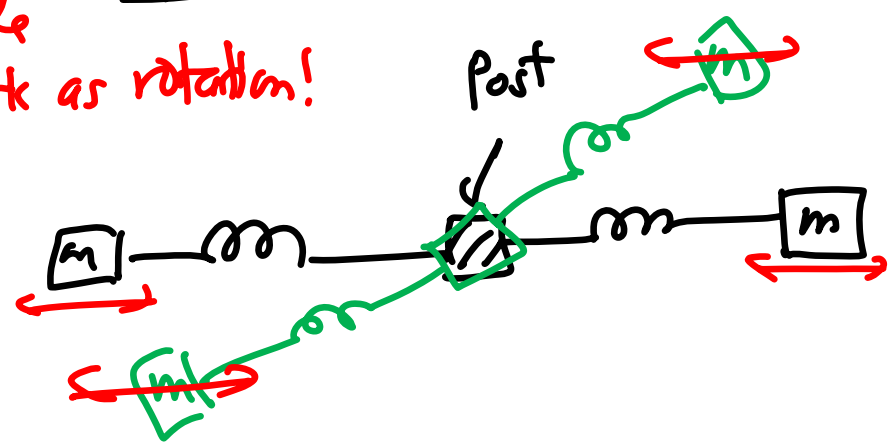


Detect motion out-of-the plane of the tuning fork as rotation!

Side View:



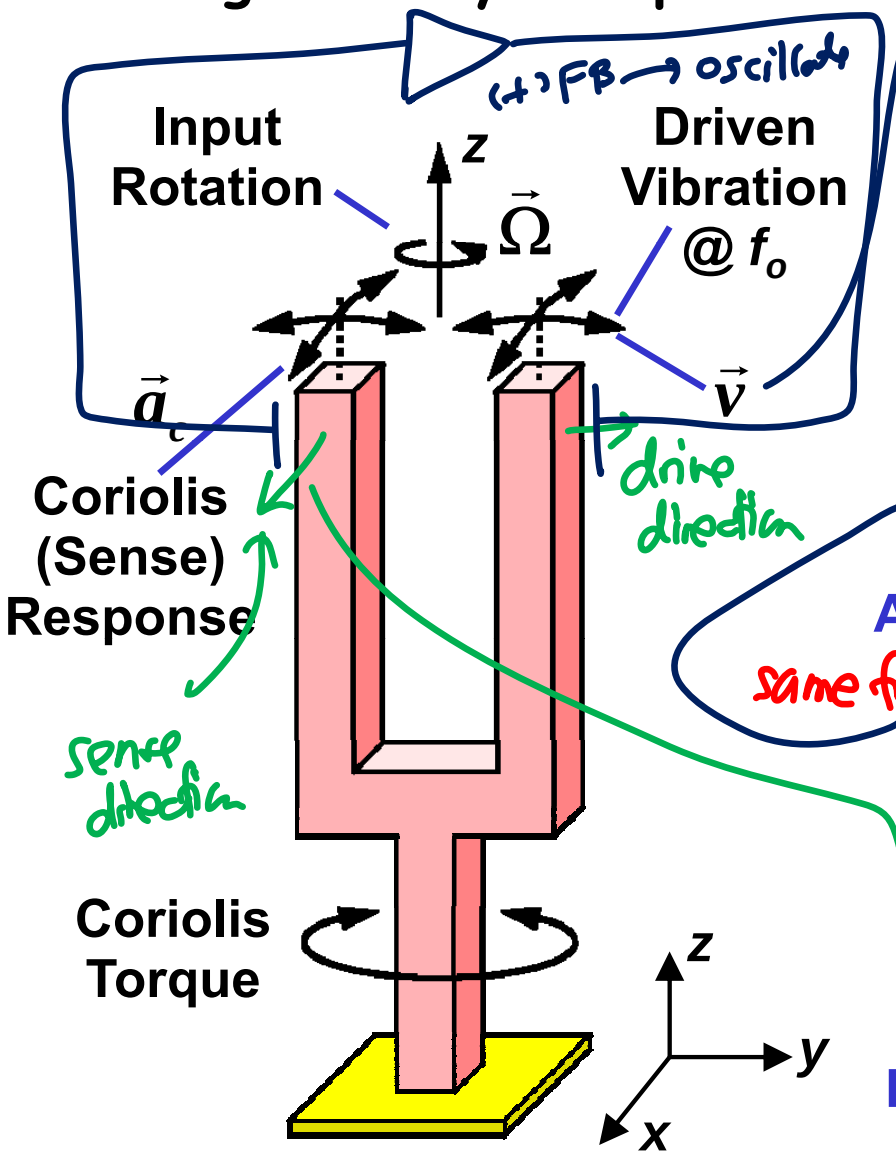
Top View:



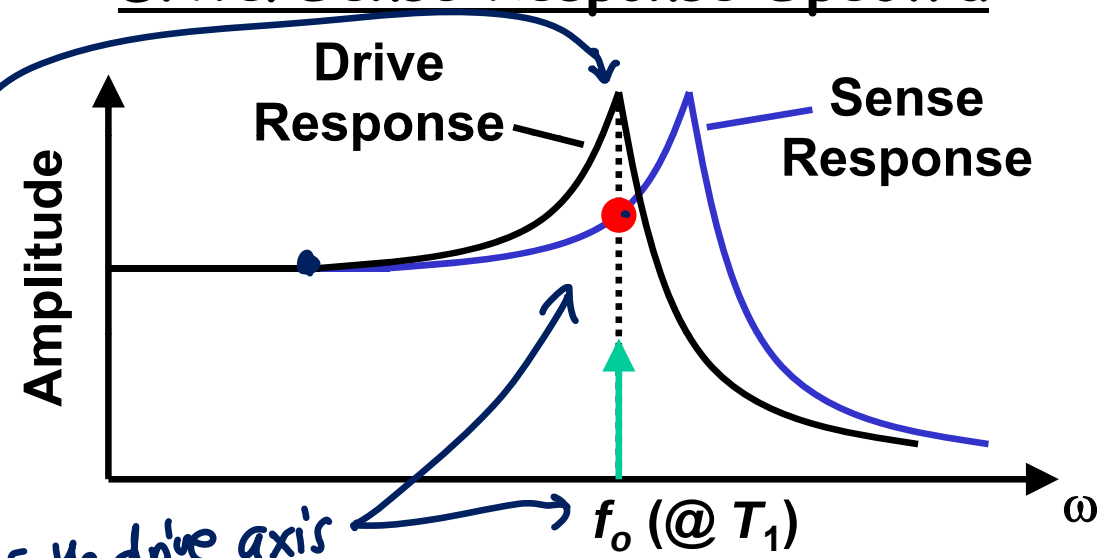
Basic Vibratory Gyroscope Operation

Principle of Operation

- Tuning Fork Gyroscope:



Drive/Sense Response Spectra:



of the drive axis

Coriolis Acceleration — Driven Velocity — Rotation Rate

same frequency

$$\vec{a}_c = 2\vec{v} \times \vec{\Omega}$$

Coriolis Force — Beam Mass

$$\vec{x} = \frac{\vec{F}_c}{k} = \frac{m\vec{a}_c}{k} = \frac{\vec{a}_c}{\omega_r^2}$$

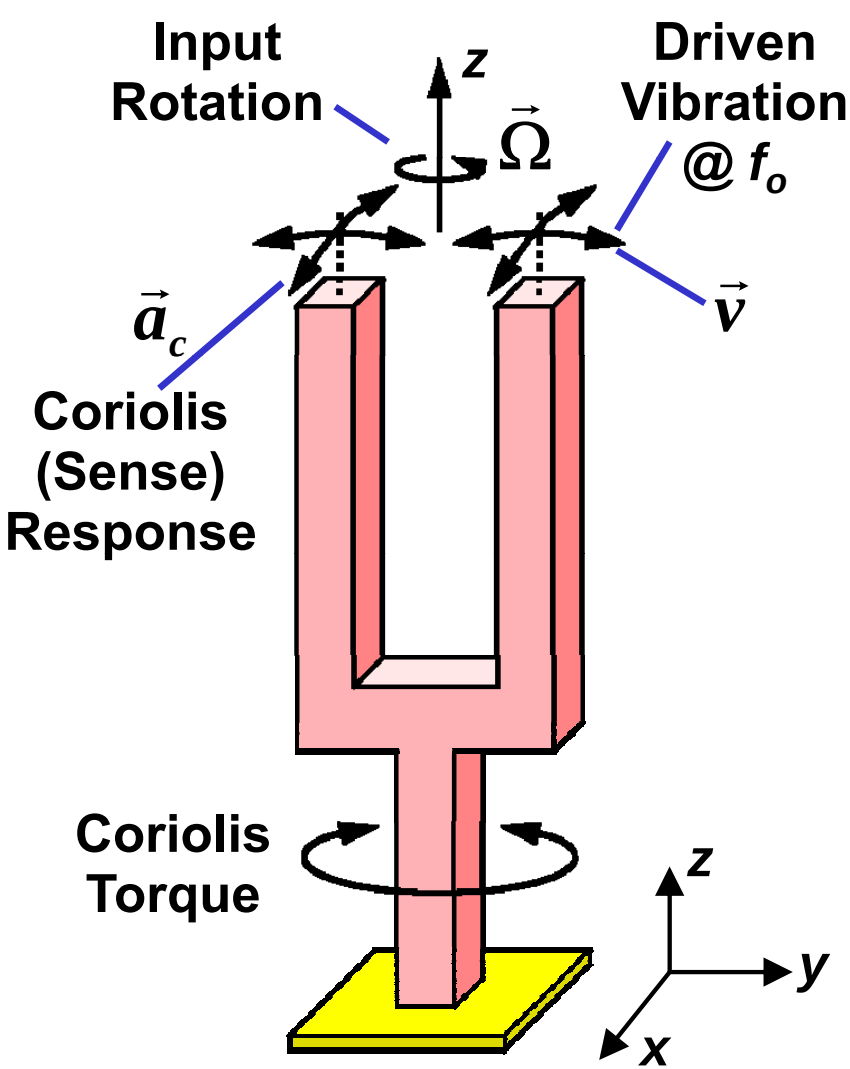
for below resonance

Coriolis Displacement — Beam Stiffness (in sense direction) — Sense Frequency

Vibratory Gyroscope Performance

Principle of Operation

- Tuning Fork Gyroscope:

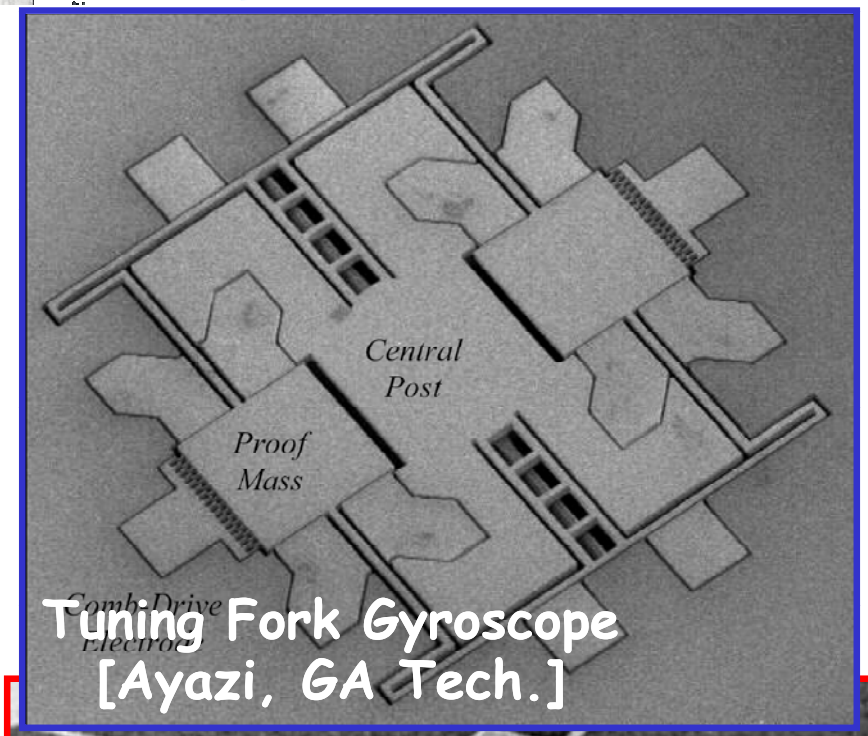


$$\vec{x} = \frac{\vec{F}_c}{k} = \frac{m\vec{a}_c}{k} = \frac{\vec{a}_c}{\omega_r^2} \qquad \vec{a}_c = 2\vec{v} \times \vec{\Omega}$$

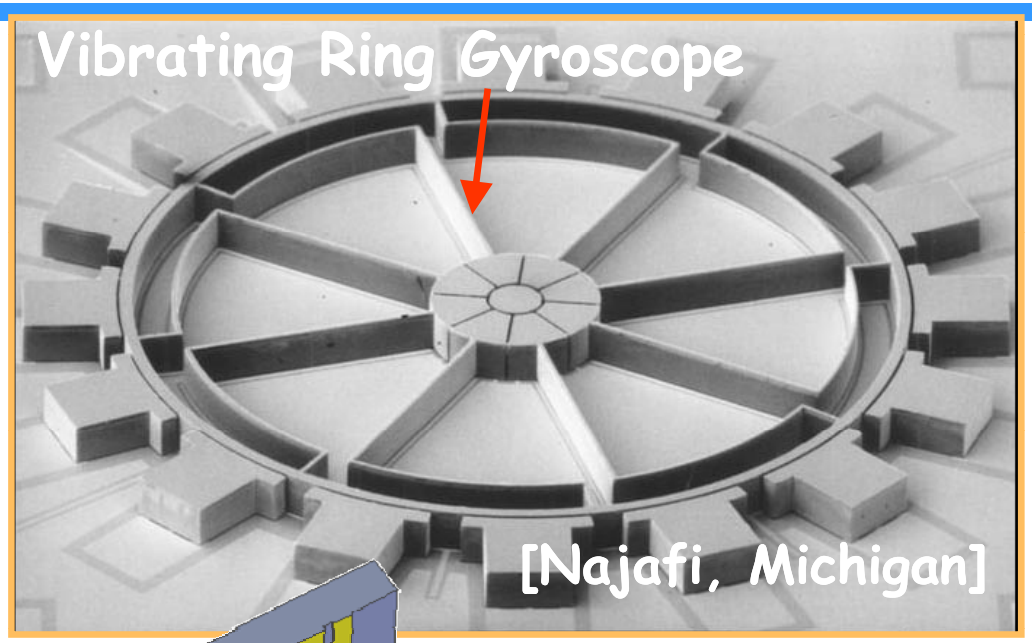
Beam Mass — Beam Stiffness — Sense Frequency — Driven Velocity

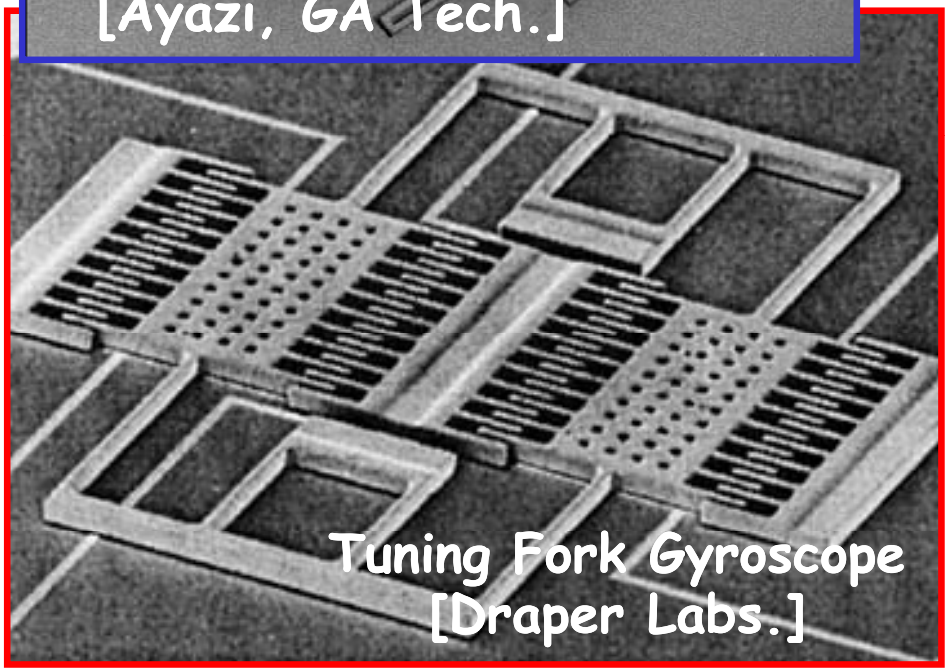
- To maximize the output signal x, need:
  - Large sense-axis mass
  - Small sense-axis stiffness
  - (Above together mean low resonance frequency)
  - Large drive amplitude for large driven velocity (so use comb-drive) → $v = \omega_o X$, want X = large!
  - If can match drive freq. to sense freq., then can amplify output by Q times ← $x = \frac{QF_c}{k}$

MEMS-Based Gyroscopes

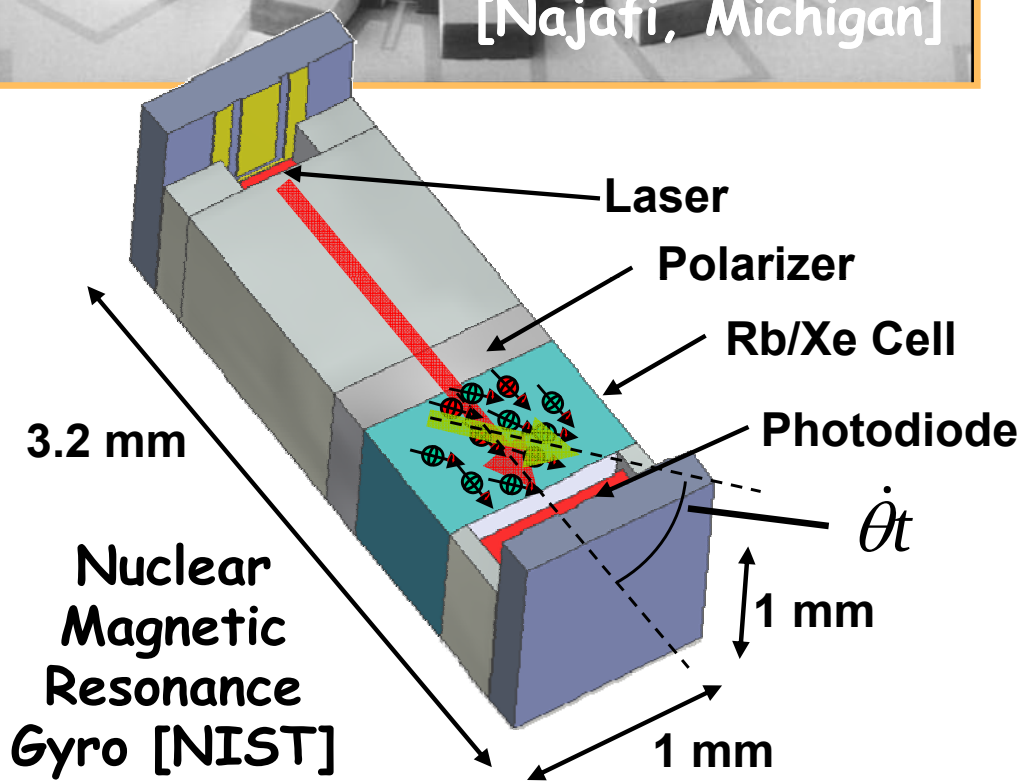


Tuning Fork Gyroscope
[Ayazi, GA Tech.]



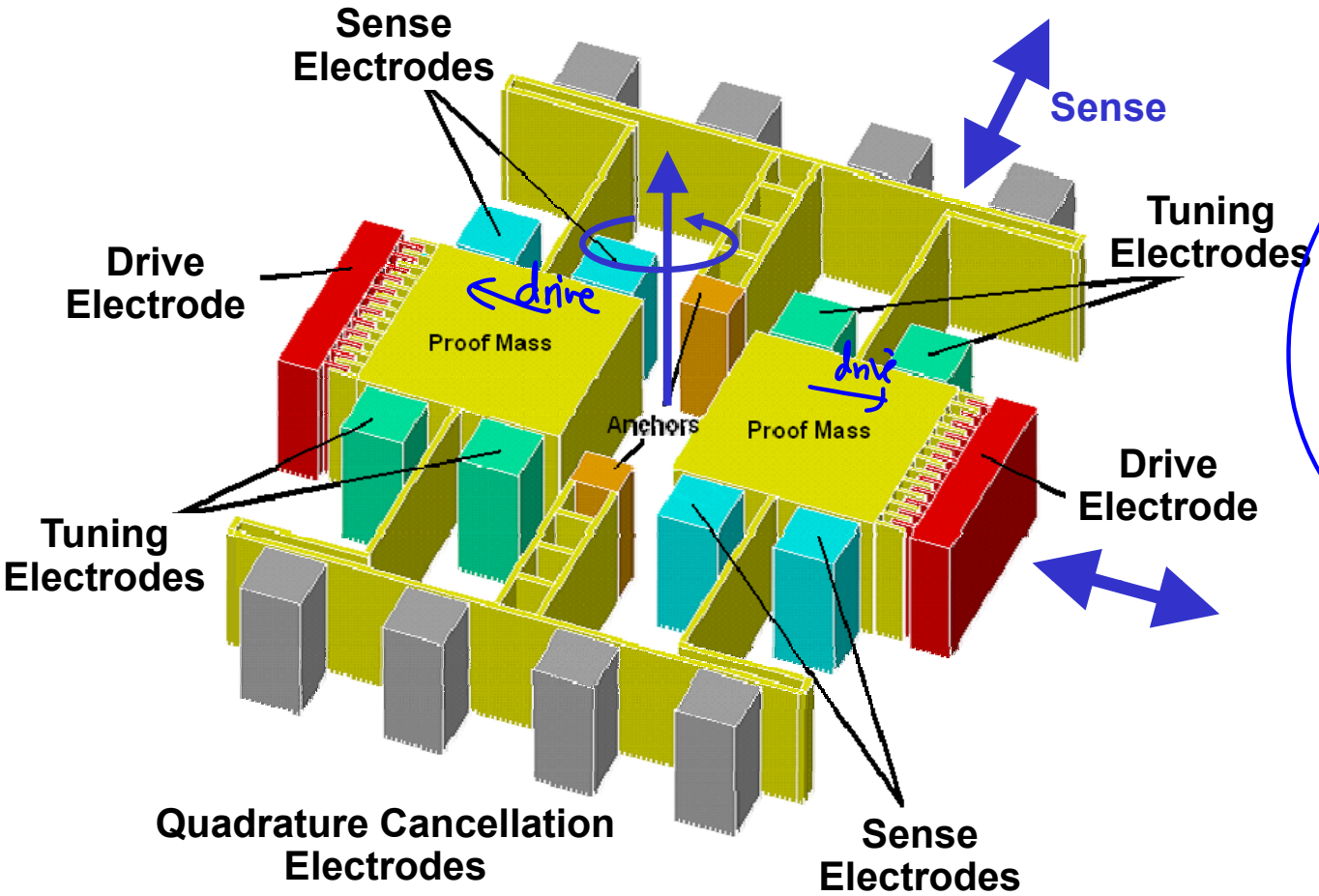


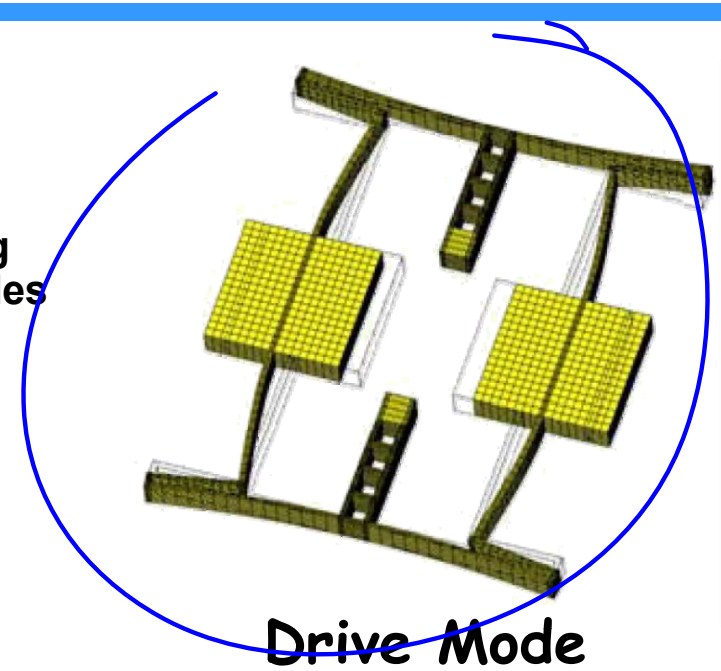
Tuning Fork Gyroscope
[Draper Labs.]

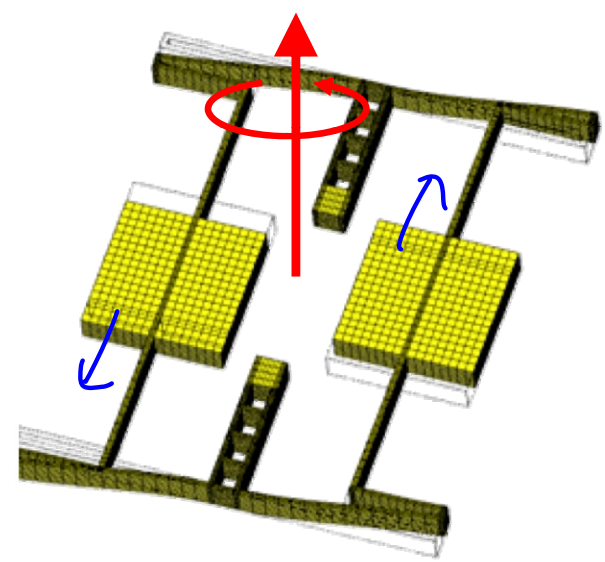


Nuclear Magnetic Resonance Gyro [NIST]

MEMS-Based Tuning Fork Gyroscope

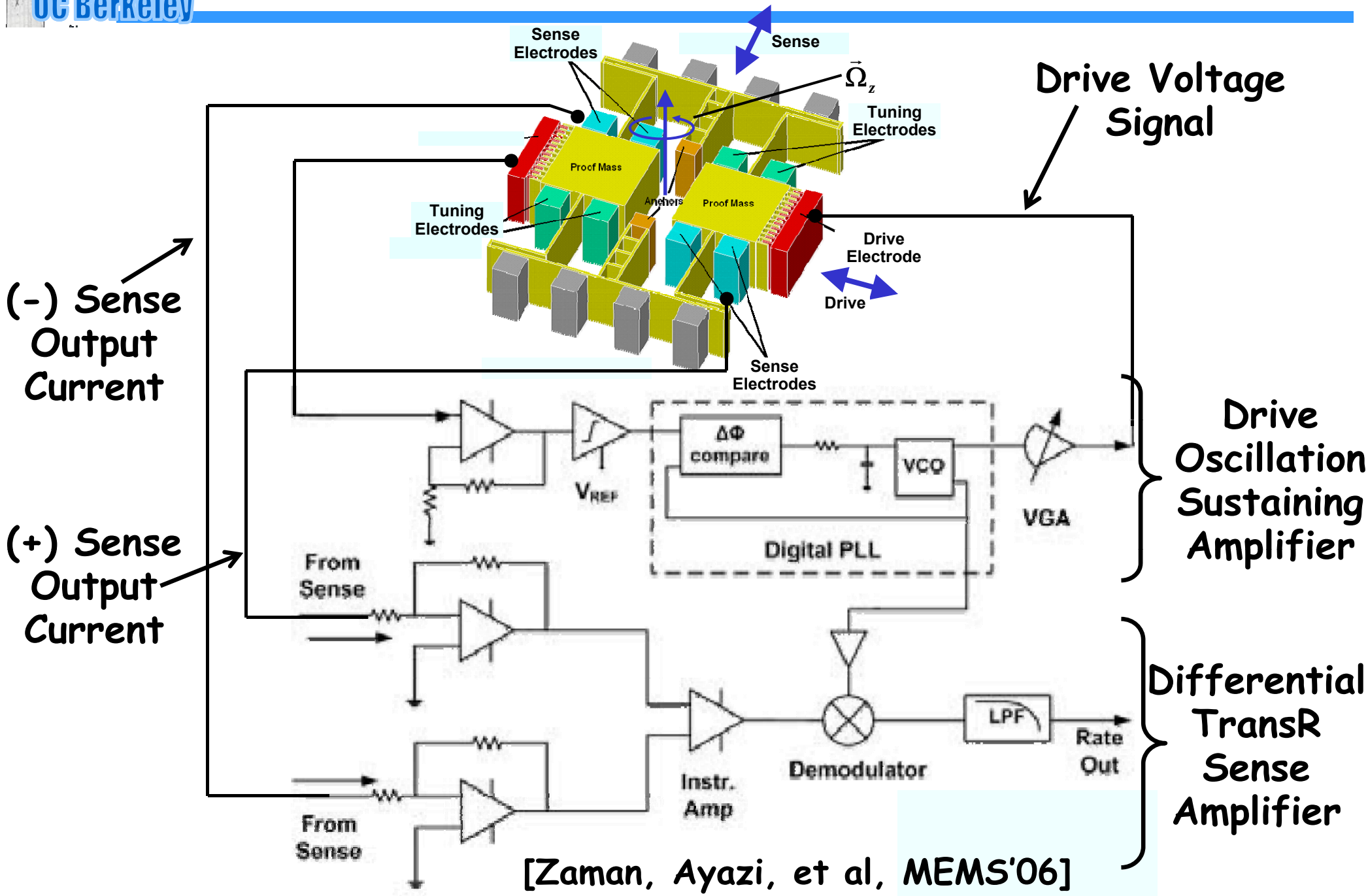






- In-plane drive and sense modes pick up z-axis rotations
- Mode-matching for maximum output sensitivity
- From [Zaman, Ayazi, et al, MEMS'06]

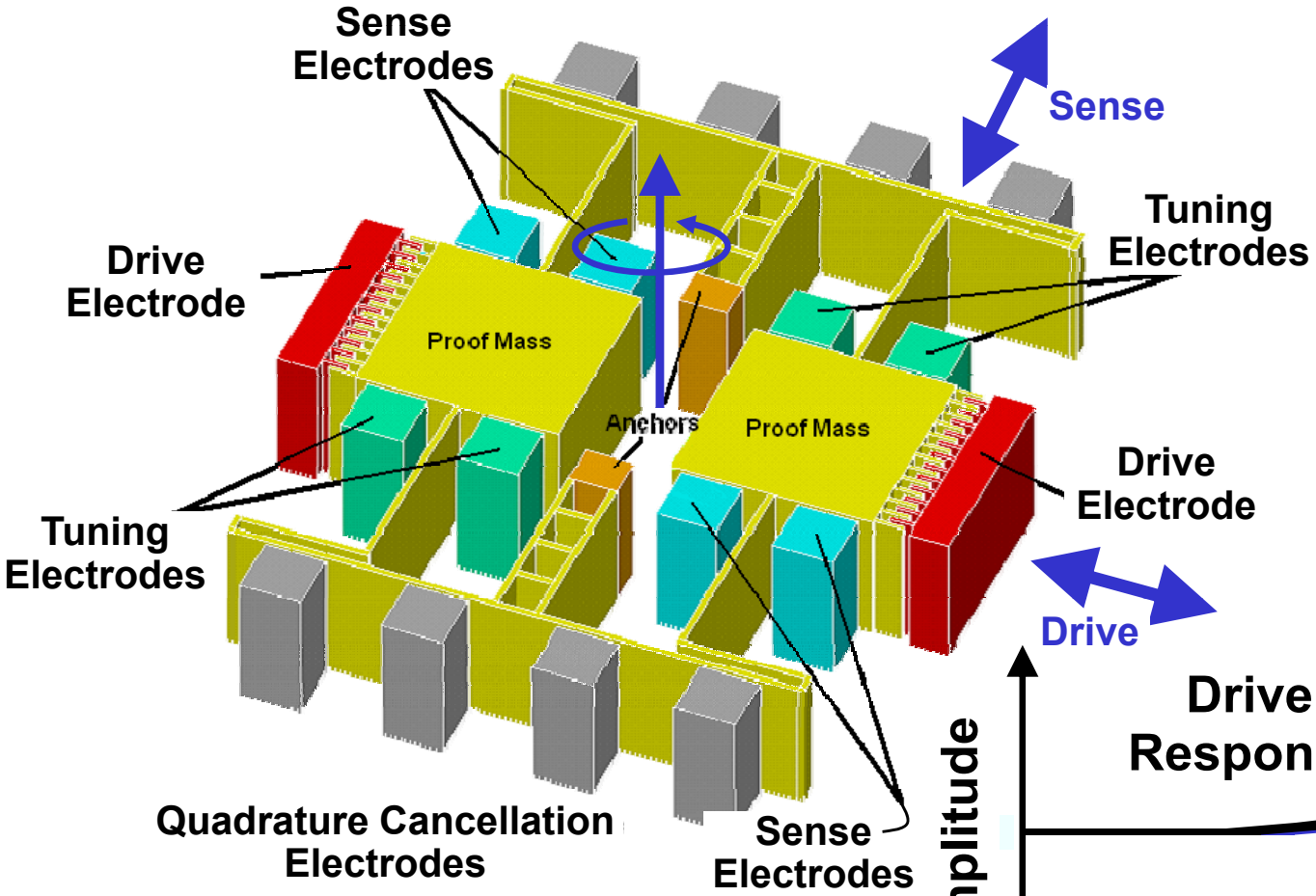
MEMS-Based Tuning Fork Gyroscope



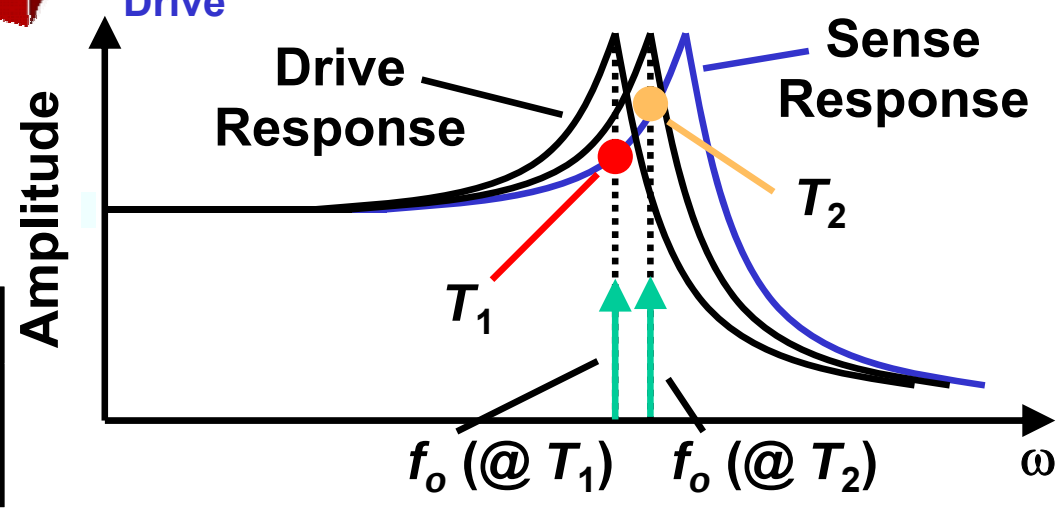
[Zaman, Ayazi, et al, MEMS'06]

MEMS-Based Tuning Fork Gyroscope

- Drive and sense axes must be stable or at least track one another to avoid output drift



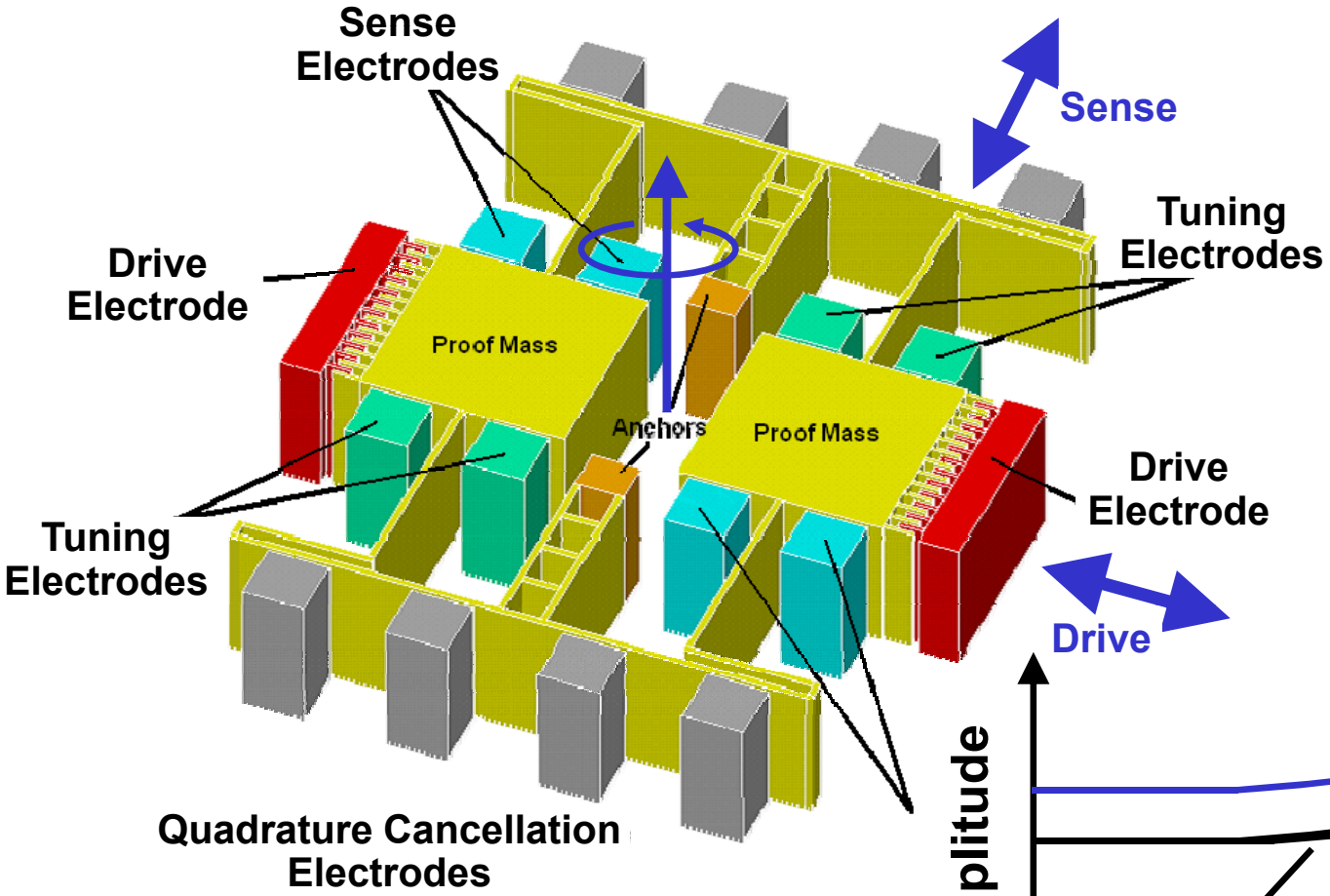
Problem: if drive frequency changes relative to sense frequency, output changes ⇨ bias drift



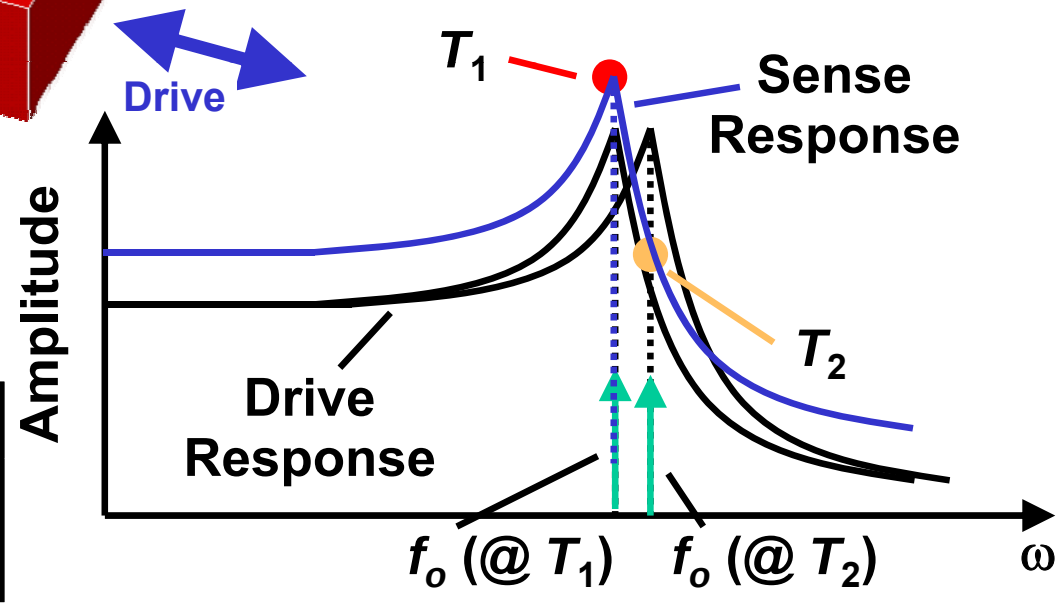
Need: small or matched drive and sense axis temperature coefficients to suppress drift

Mode Matching for Higher Resolution

- For higher resolution, can try to match drive and sense axis resonance frequencies and benefit from Q amplification



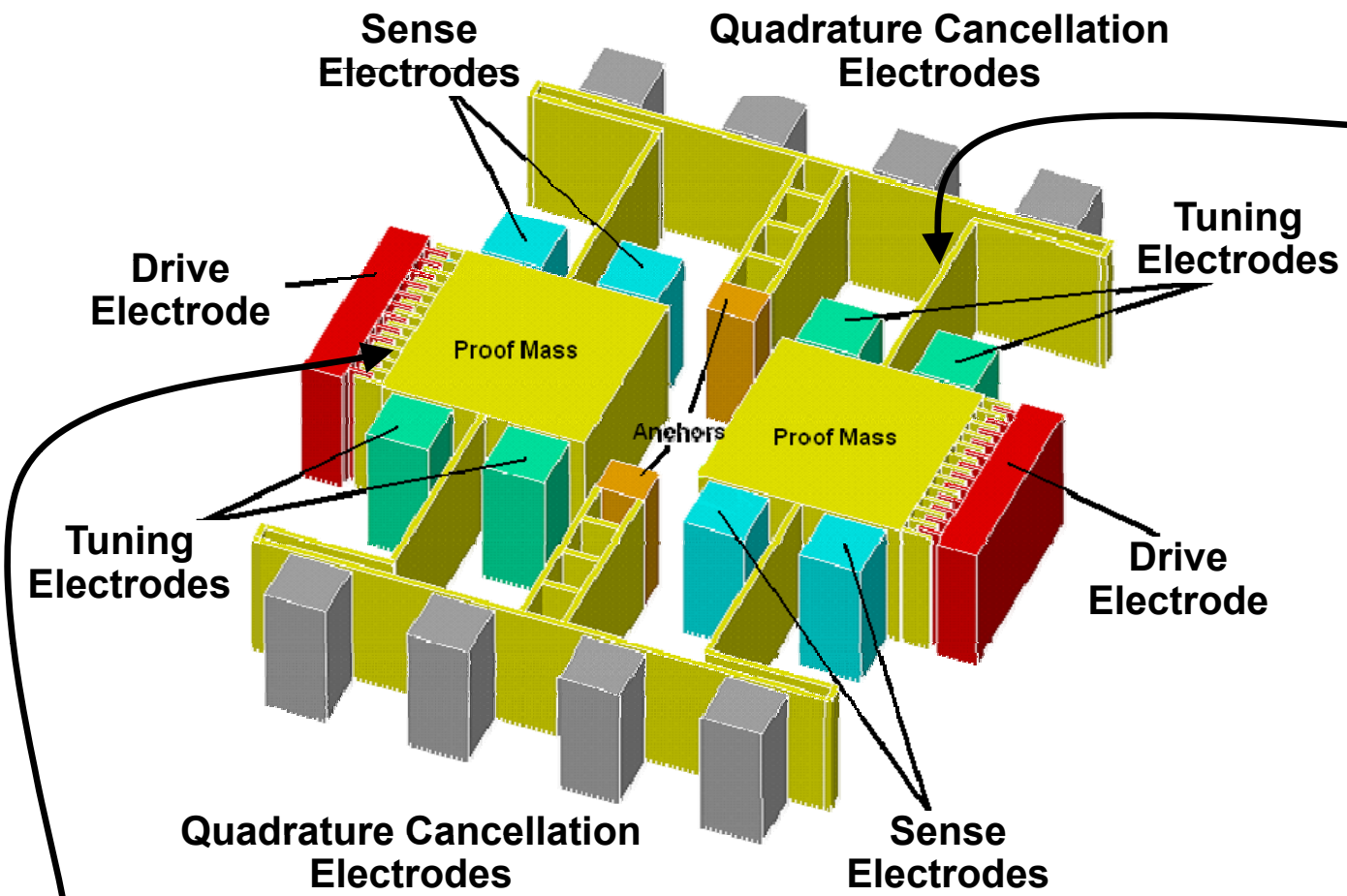
Problem: mismatch between drive and sense frequencies ⇨ even larger drift!

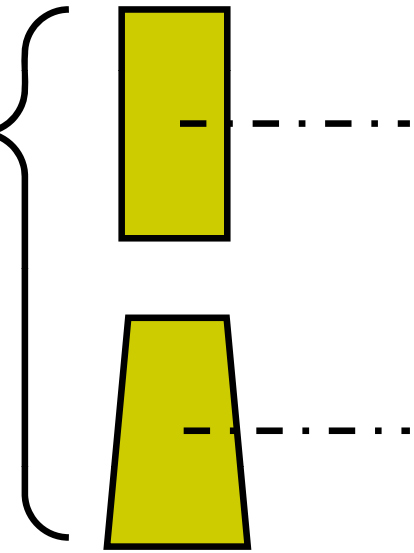


Need: small or matched drive and sense axis temperature coefficients to make this work

Issue: Zero Rate Bias Error

- Imbalances in the system can lead to zero rate bias error





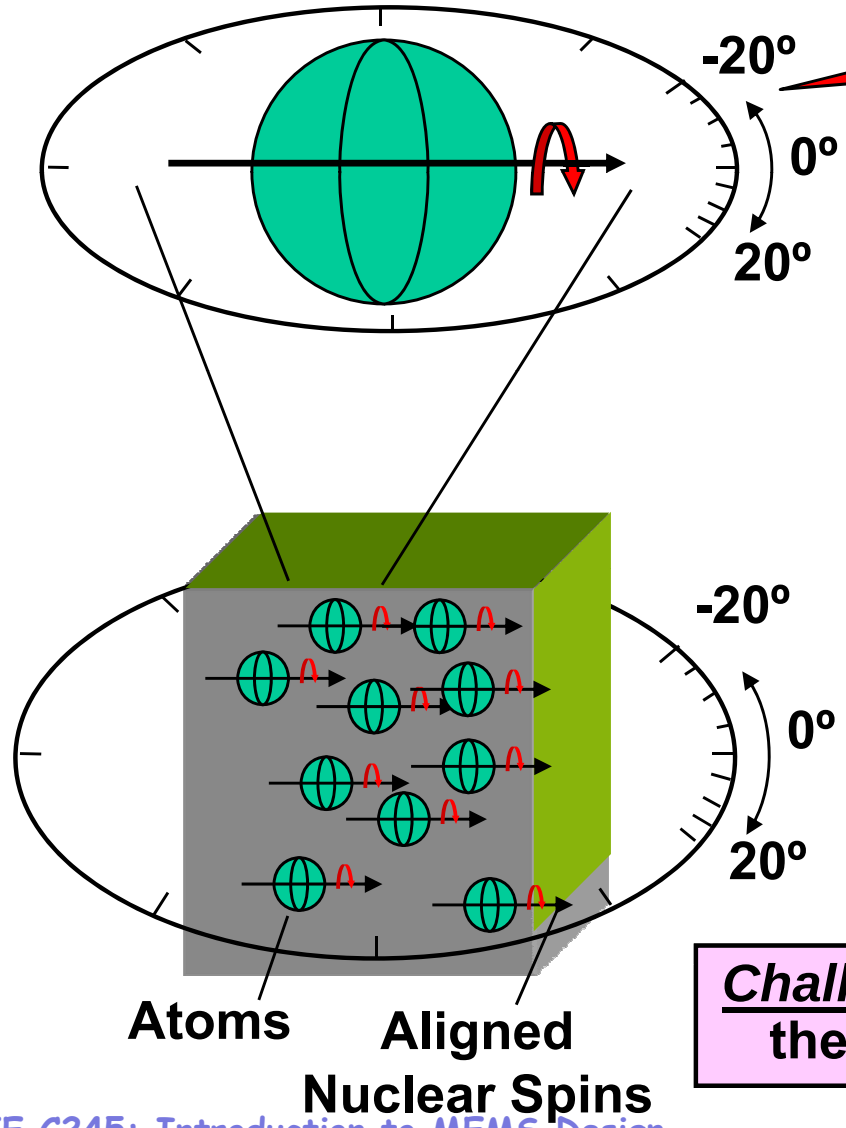
Mass imbalance ⇨ off-axis motion of the proof mass

Quadrature output signal that can be confused with the Coriolis acceleration

Drive imbalance ⇨ off-axis motion of the proof mass → **Output signal in phase with the Coriolis acceleration**

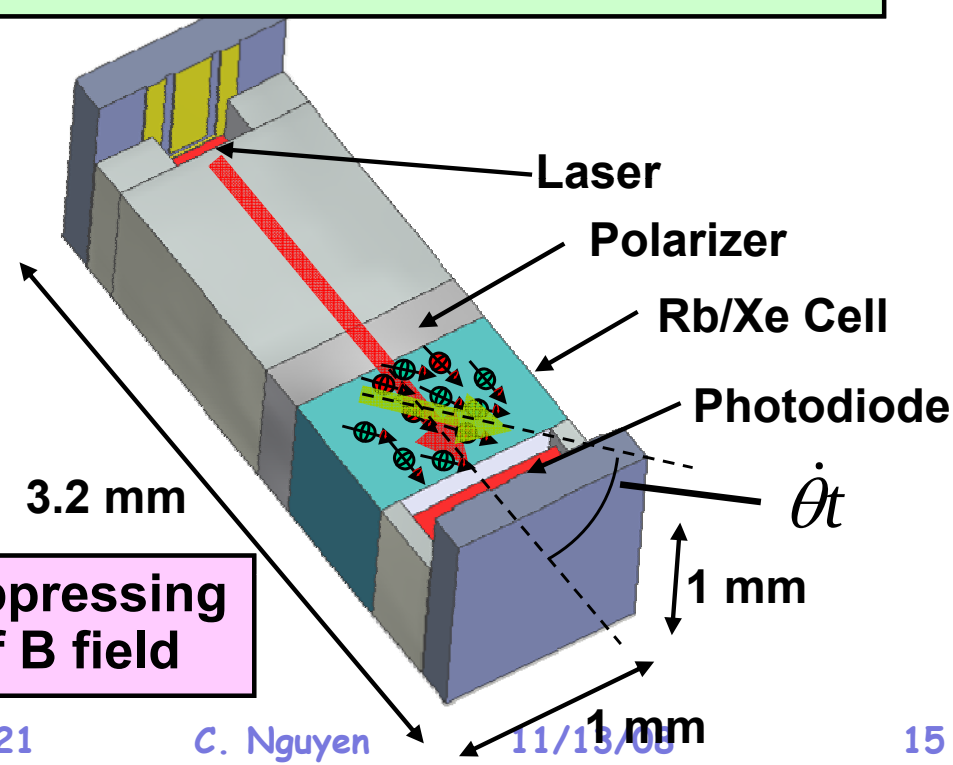
Nuclear Magnetic Res. Gyroscope

- The ultimate in miniaturized spinning gyroscopes?
  - ↳ from CSAC, we may now have the technology to do this



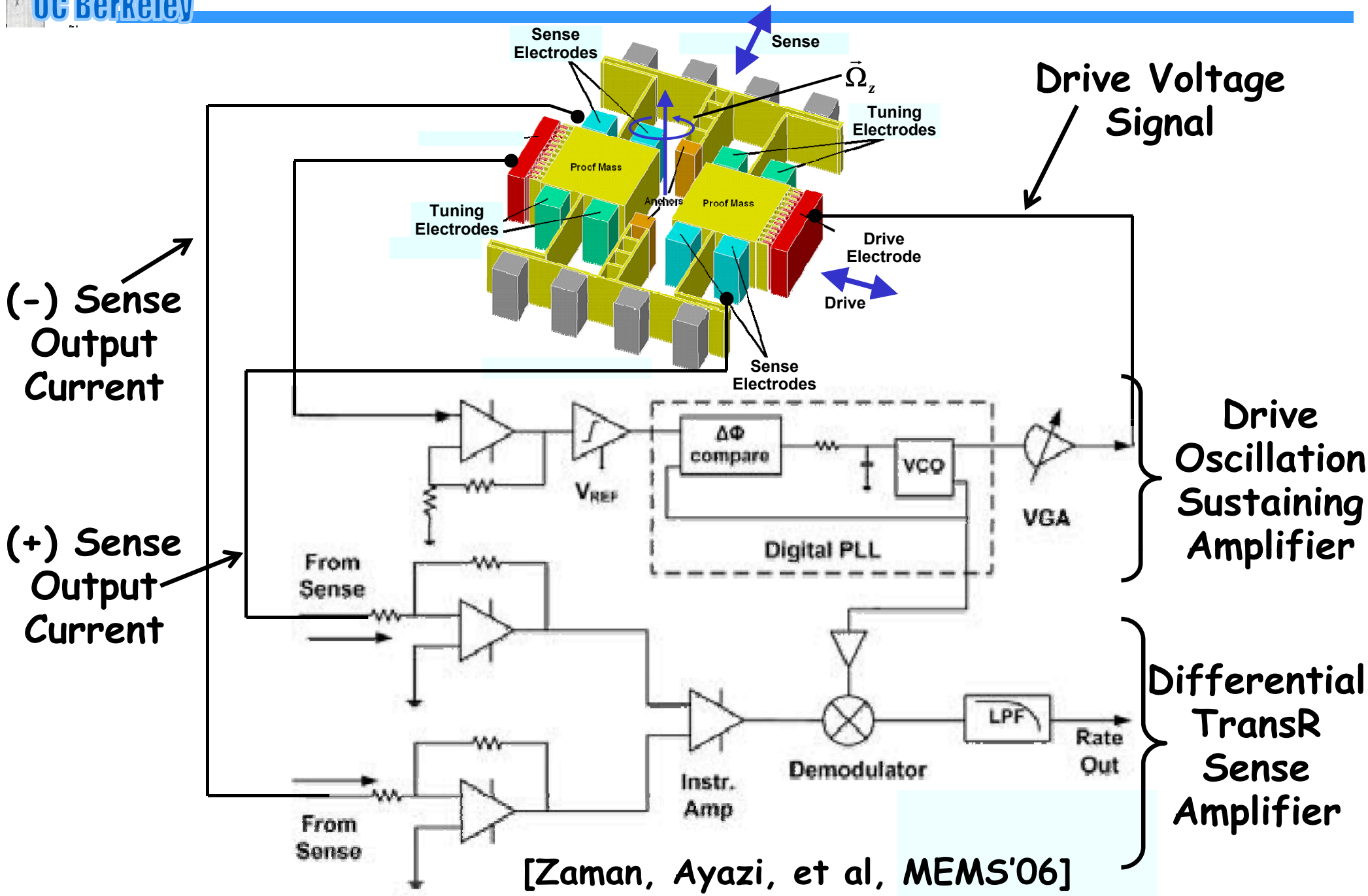
Better if this is a noble gas nucleus (rather than e-), since nuclei are heavier ⇨ less susceptible to B field

Soln: Spin polarize Xe^{129} nuclei by first polarizing e- of Rb^{87} (a la CSAC), then allowing spin exchange



Challenge: suppressing the effects of B field

MEMS-Based Tuning Fork Gyroscope



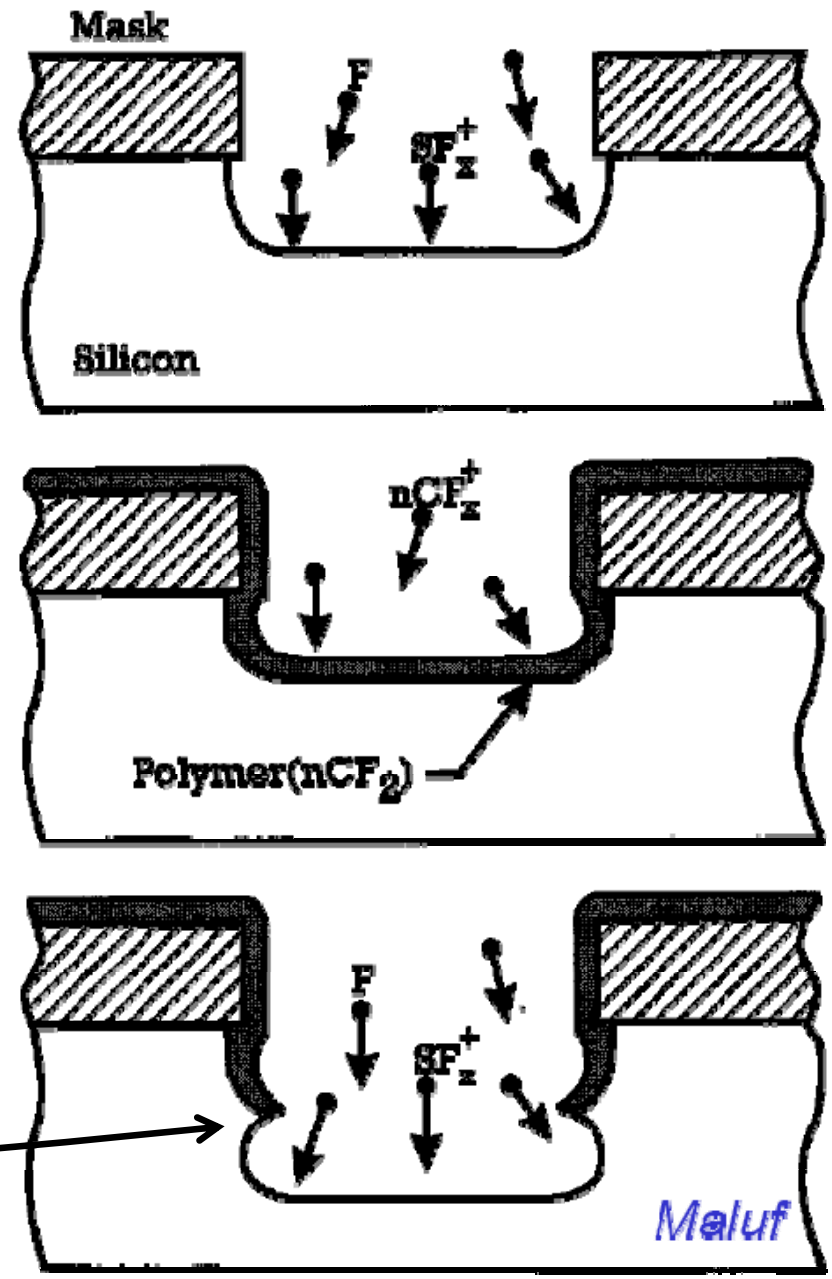
[Zaman, Ayazi, et al, MEMS'06]

Deep Reactive-Ion Etching

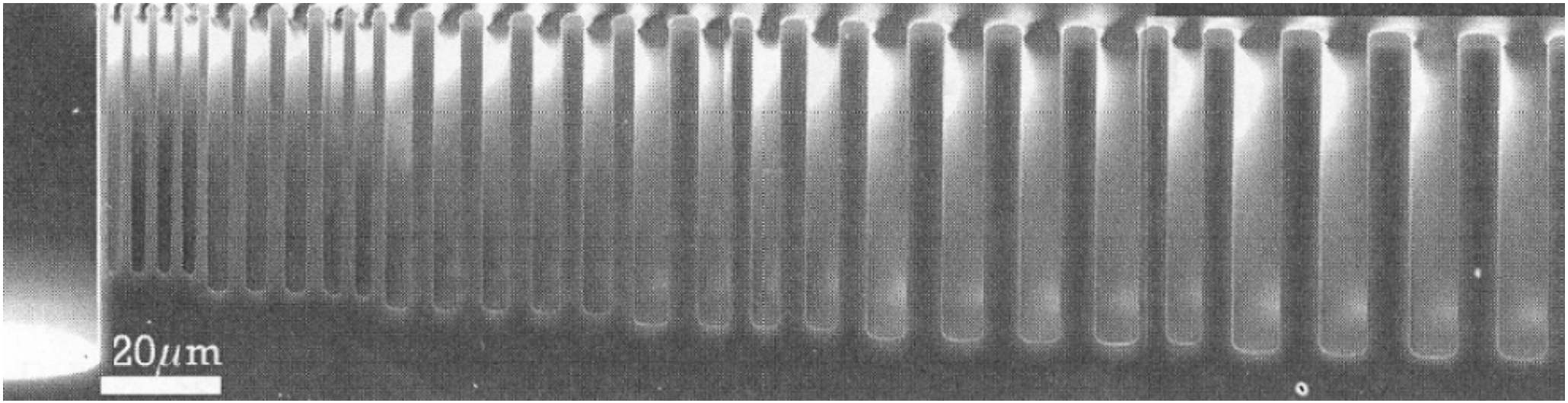
Deep Reactive-Ion Etching (DRIE)

The Bosch process:

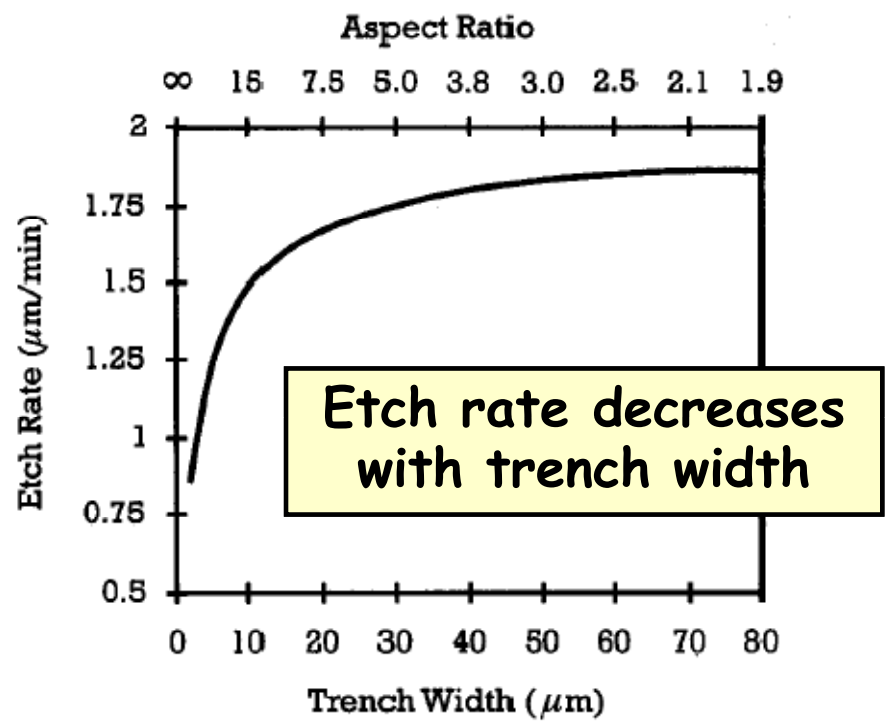
- Inductively-coupled plasma
- Etch Rate: 1.5-4 μm/min
- Two main cycles in the etch:
  - Etch cycle (5-15 s): SF_6 (SF_x^+) etches Si
  - Deposition cycle: (5-15 s): C_4F_8 deposits fluorocarbon protective polymer $(CF_2^-)_n$
- Etch mask selectivity:
  - SiO_2 ~ 200:1
  - Photoresist ~ 100:1
- Issue: finite sidewall roughness
  - scalloping < 50 nm
- Sidewall angle: 90° ± 2°



DRIE Issues: Etch Rate Variance



- Etch rate is diffusion-limited and drops for narrow trenches
  - Adjust mask layout to eliminate large disparities
  - Adjust process parameters (slow down the etch rate to that governed by the slowest feature)



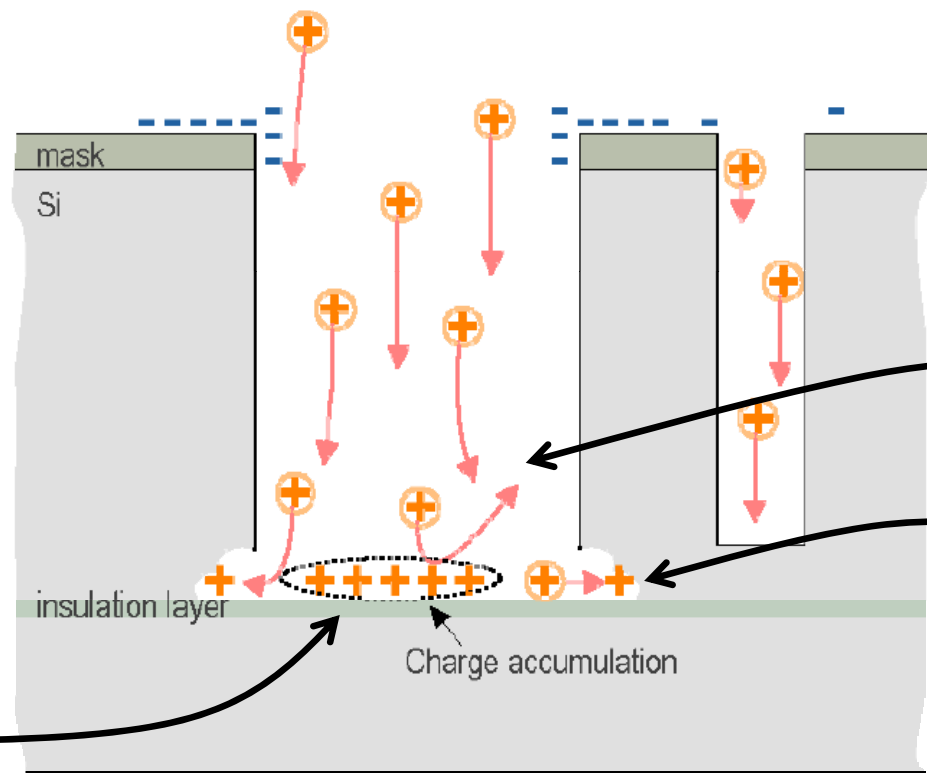
DRIE Issues: "Footing"

- Etch depth precision
  - Etch stop: buried layer of SiO_2
  - Due to 200:1 selectivity, the (vertical) etch practically just stops when it reaches SiO_2
- Problem: Lateral undercut at Si/SiO_2 interface → "footing"
  - Caused by charge accumulation at the insulator

Poor charge relaxation and lack of neutralization of e^-'s at insulator

↓

Ion flux into substrate builds up (+) potential



Charging-induced potential perturbs the E-field

↓

Distorts the ion trajectory

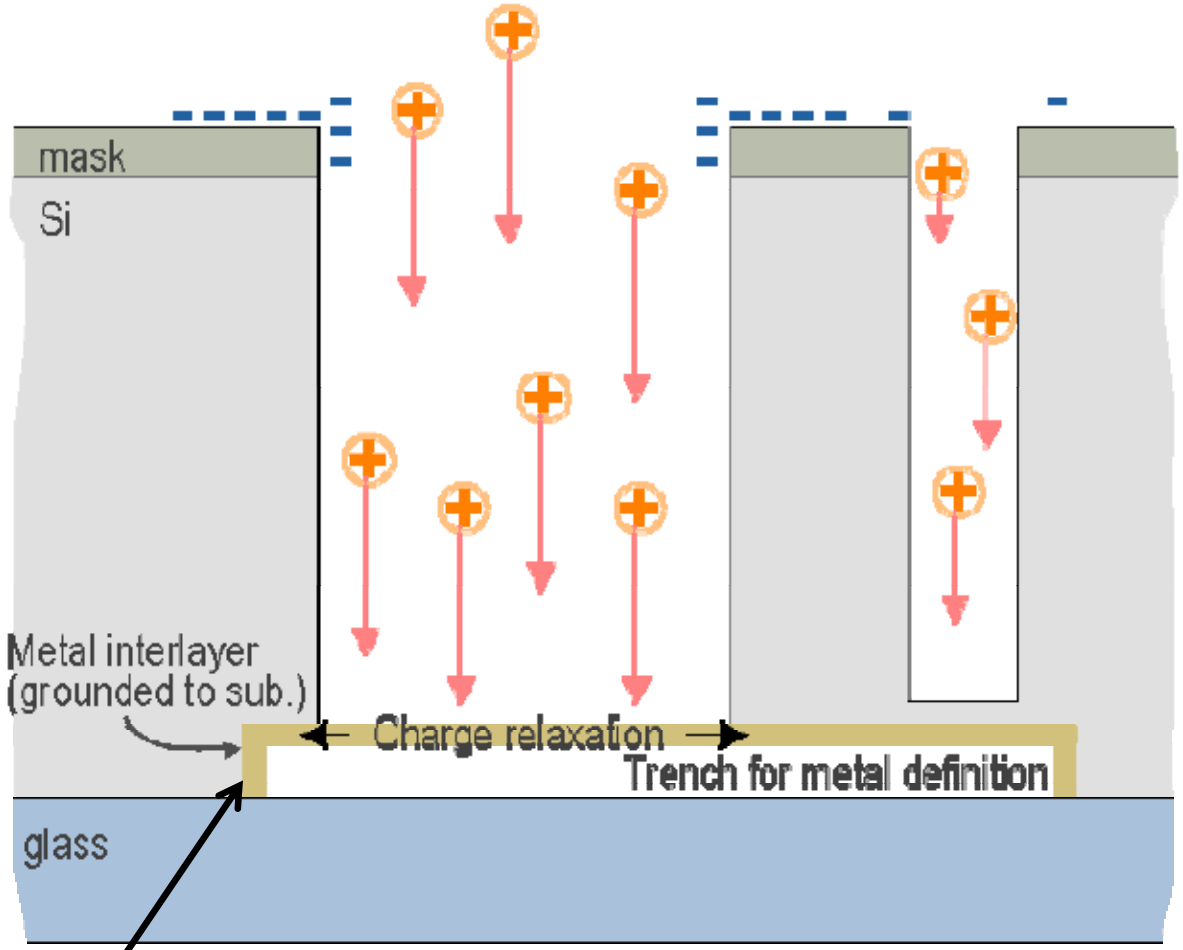
↓

Result: strong and localized damage to the structure at $Si-SiO_2$ interface → "footing"

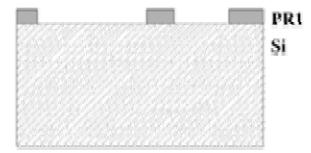
Recipe-Based Suppression of "Footing"

- Use higher process pressure to reduce ion charging [Nozawa]
  - High operating pressure → concentration of (-) ions increases and can neutralize (+) surface charge
  - Issue: must introduce as a separate recipe when the etch reaches the Si-insulator interface, so must be able to very accurately predict the time needed for etching
- Adjust etch recipe to reduce overetching [Schmidt]
  - Change C_4F_8 flow rate, pressure, etc., to enhance passivation and reduce overetching
  - Issue: Difficult to simultaneously control footing in a narrow trench and prevent grass in wide trenches
- Use lower frequency plasma to avoid surface charging [Morioka]
  - Low frequency → more ions with low directionality and kinetic energy → neutralizes (-) potential barrier at trench entrance
  - Allows e^-'s to reach the trench base and neutralize (+) charge → maintain charge balance inside the trench

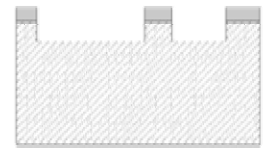
Metal Interlayer to Prevent "Footing"



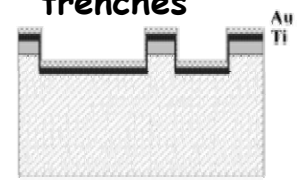
Pre-defined metal interlayer grounded to substrate supplies e's to neutralize (+) charge and prevent charge accumulation at the Si-insulator interface



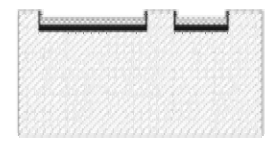
(a) Photolithography 1 (sacrificial)



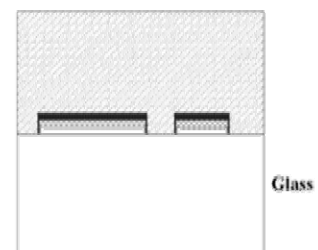
(b) Preparatory trenches



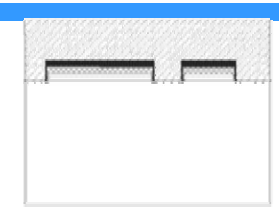
(c) Metal interlayer deposition



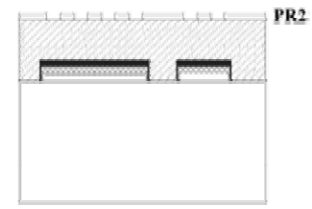
(d) Lift-off (remove PR)



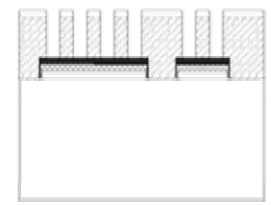
(e) Anodic Bonding



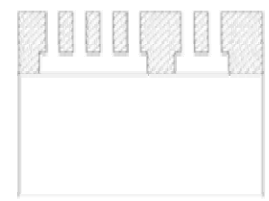
(f) Silicon Thinning



(g) Photolithography 2



(h) DRIE



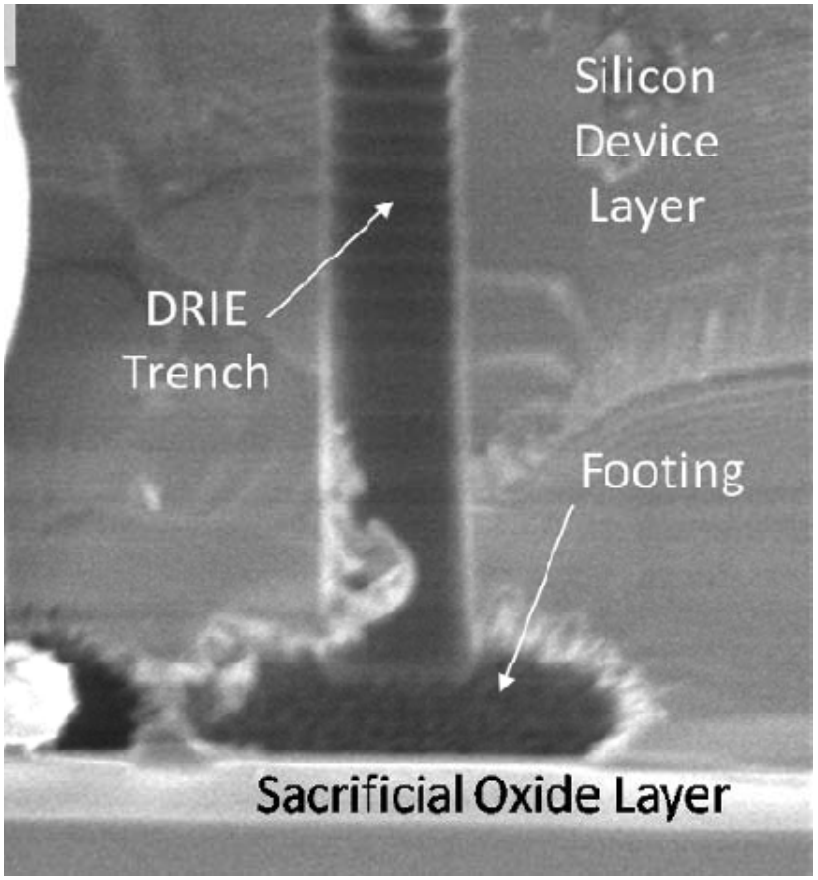
(i) Remove metal interlayer

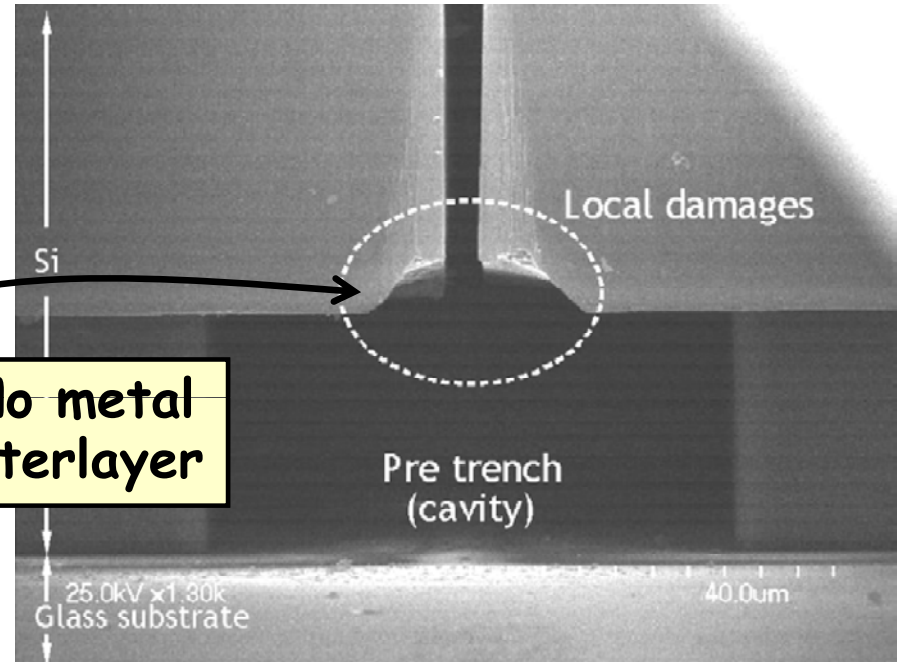
(i) Metallize

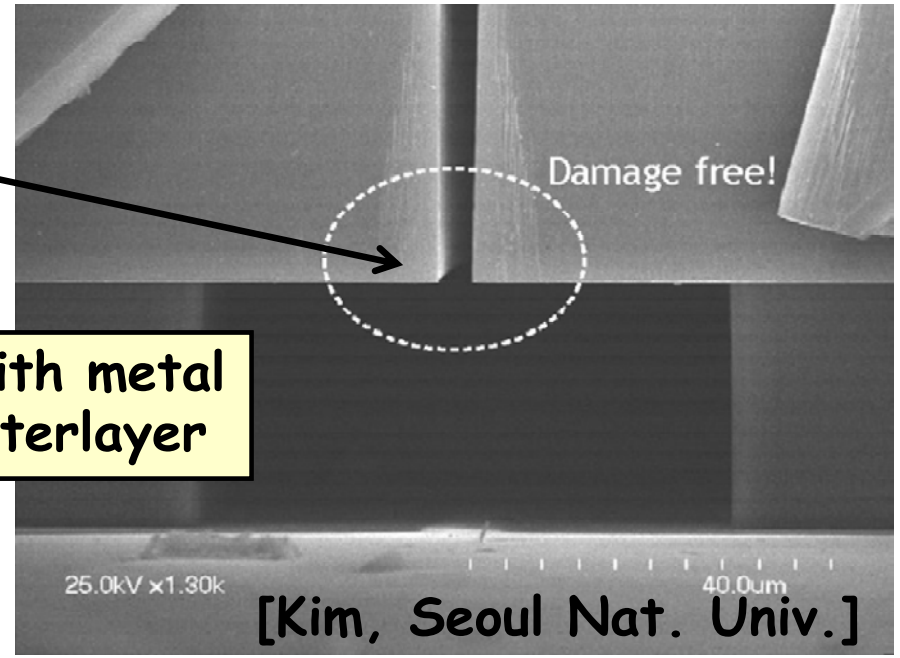
Footing Prevention (cont.)

- Below: DRIE footing over an oxide stop layer
- Right: efficacy of the metal interlayer footing prevention approach

[Kim, Stanford]

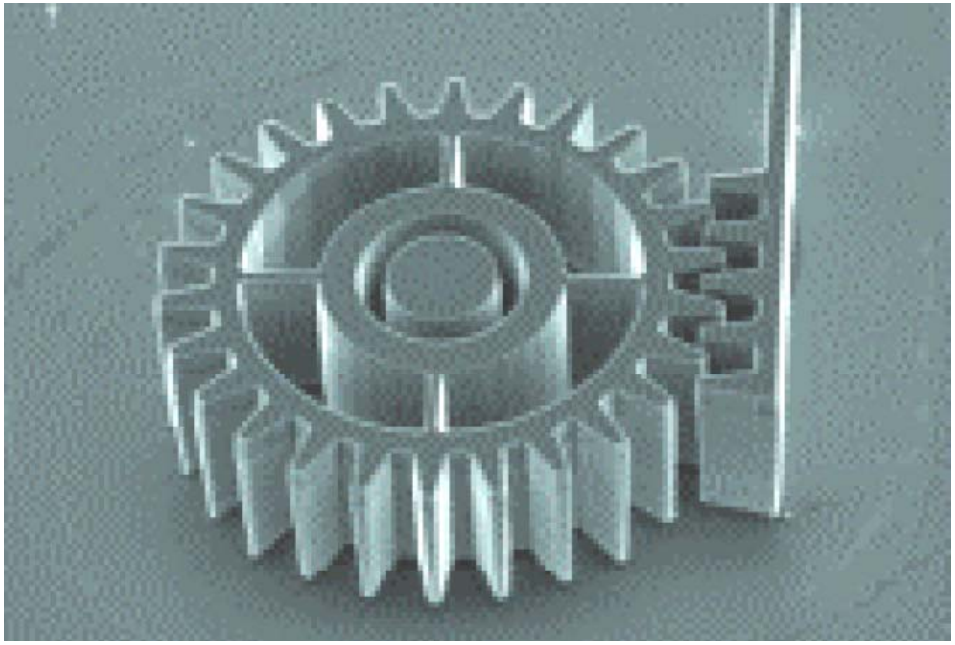






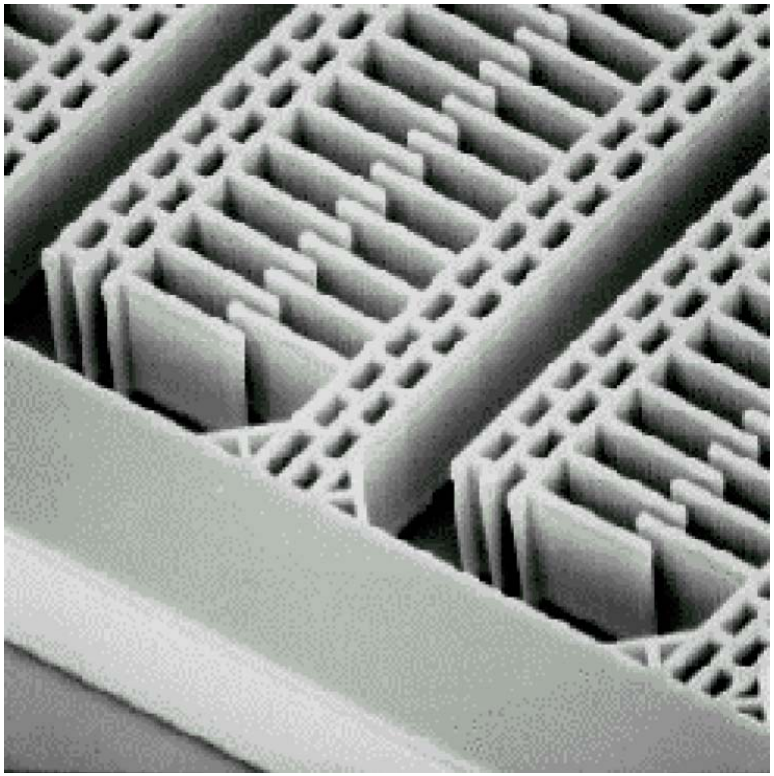
[Kim, Seoul Nat. Univ.]

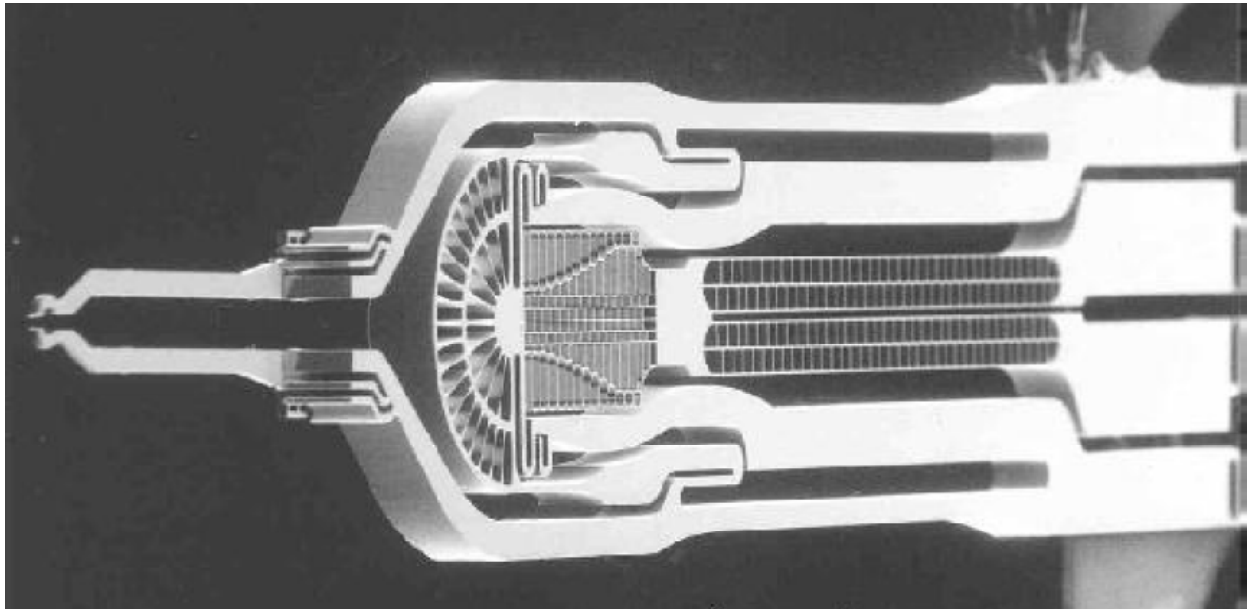
DRIE Examples



High aspect-ratio gear

Tunable Capacitor [Yao, Rockwell]

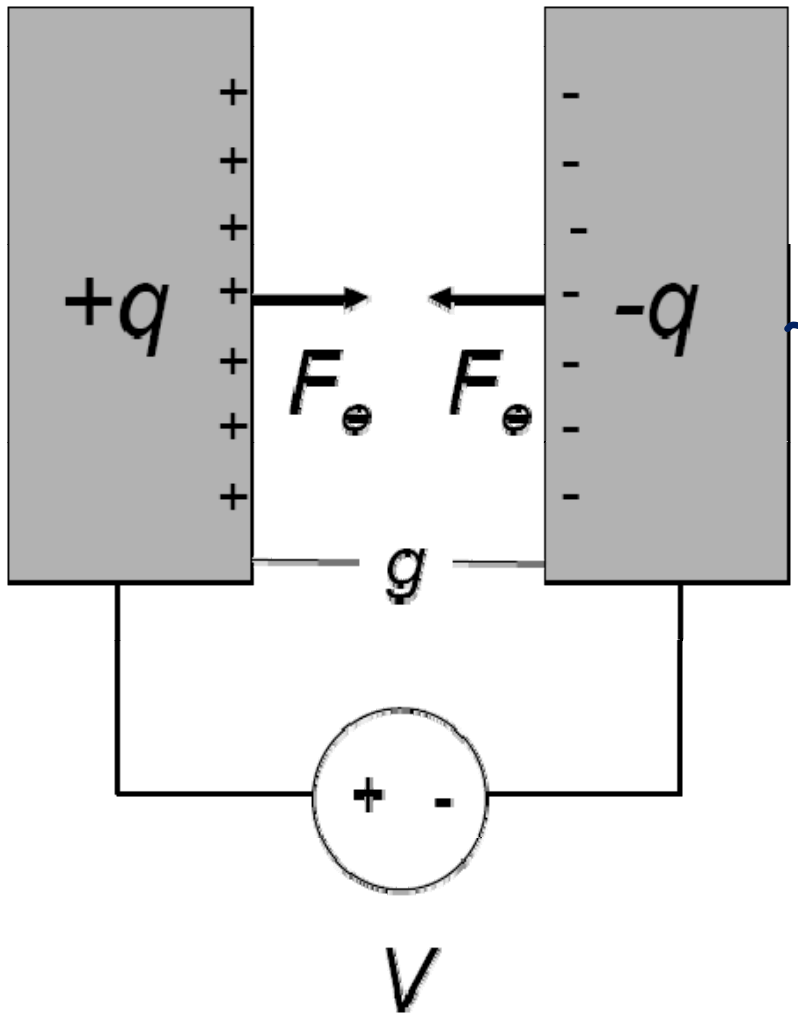




Microgripper [Keller, MEMS Precision Instruments]

Energy Conserving Transducers

Basic Physics of Electrostatic Actuation



- <u>Goal</u>: Determine gap spacing g as a function of input variables
- First, need to determine the energy of the system
- Two ways to change the energy:
  - Change the charge q
  - Change the separation g

$$\Delta W(q,g) = V\Delta q + F_e\Delta g$$

$$dW = Vdq + F_e dg$$

- <u>Note</u>: We assume that the plates are supported elastically, so they don't collapse

Stored Energy

- Here, the stored energy is the work done in increasing the gap after charging capacitor at zero gap

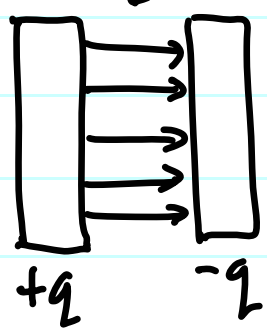
$$\mathcal{W} = 0 + \int_0^g F_e \, dg'$$

No change in charge: $dq = 0$

Electric Field

$$\mathcal{E} = \frac{q}{\epsilon A}$$

cross-sectional area



$$F_e = \left(\frac{q}{2}\right)\mathcal{E} = \frac{1}{2}\frac{q^2}{\epsilon A}$$

(independent of gap)

$$\therefore \mathcal{W} = \int_0^g F_e \, dg' = F_e g' \Big|_0^g = F_e g$$

$$\therefore \boxed{\mathcal{W}(g) = \frac{1}{2}\frac{q^2}{\epsilon A} g}$$