EE C245 – ME C218 Introduction to MEMS Design Fall 2007

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Lecture 21: Gyros & Capacitive Transducers

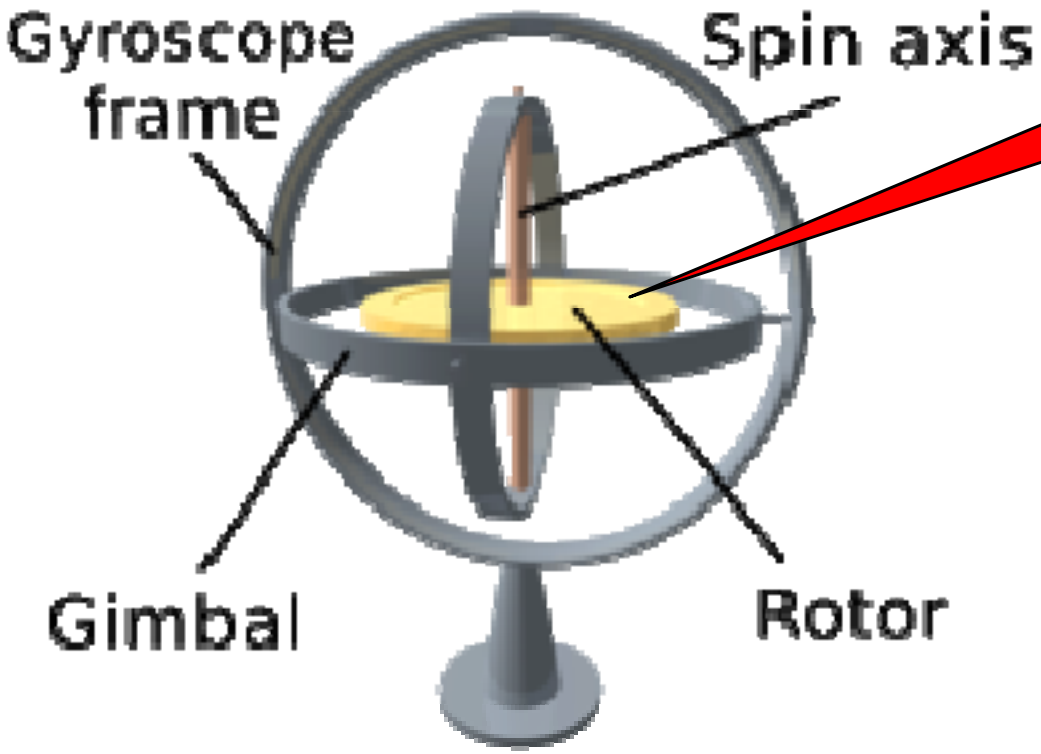
Lecture Outline

- 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

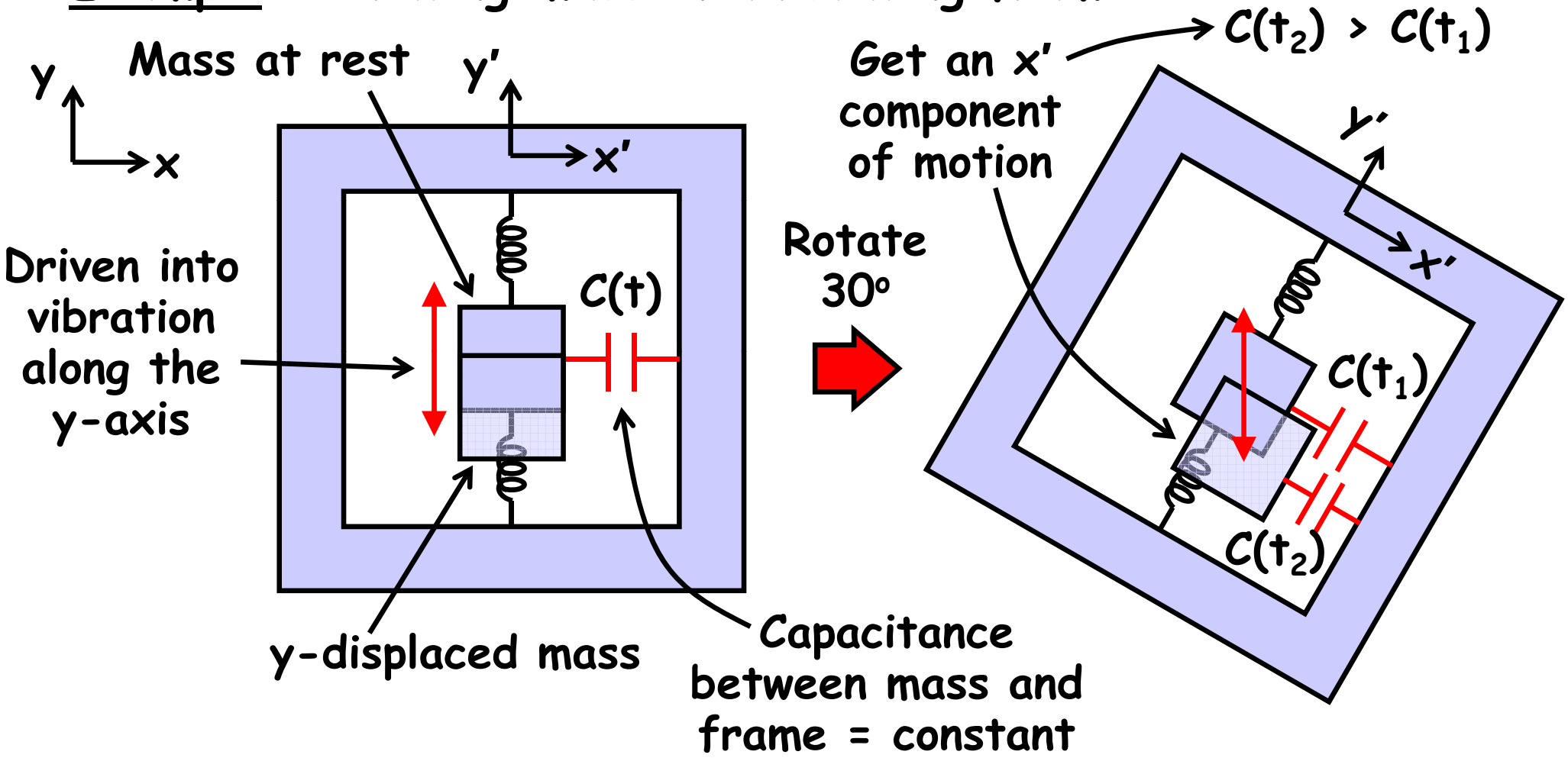
- A gyroscope measures rotation rate, which then gives orientation → very important, of course, for navigation
- Principle of operation based on conservation of momentum
- <u>Example</u>: classic spinning gyroscope



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

Vibratory Gyroscopes

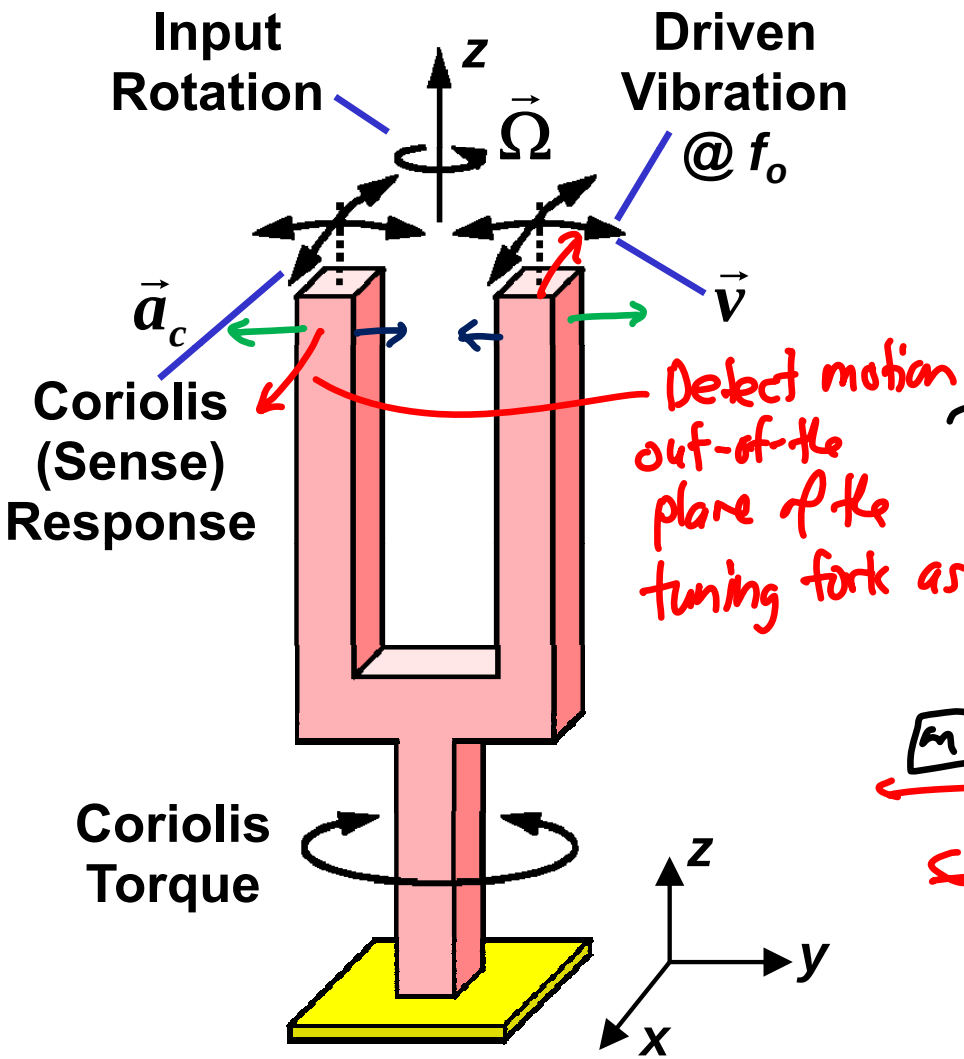
- Generate momentum by vibrating structures
- Again, conservation of momentum leads to mechanisms for measuring rotation rate and orientation
- <u>Example</u>: vibrating mass in a rotating frame



Basic Vibratory Gyroscope Operation

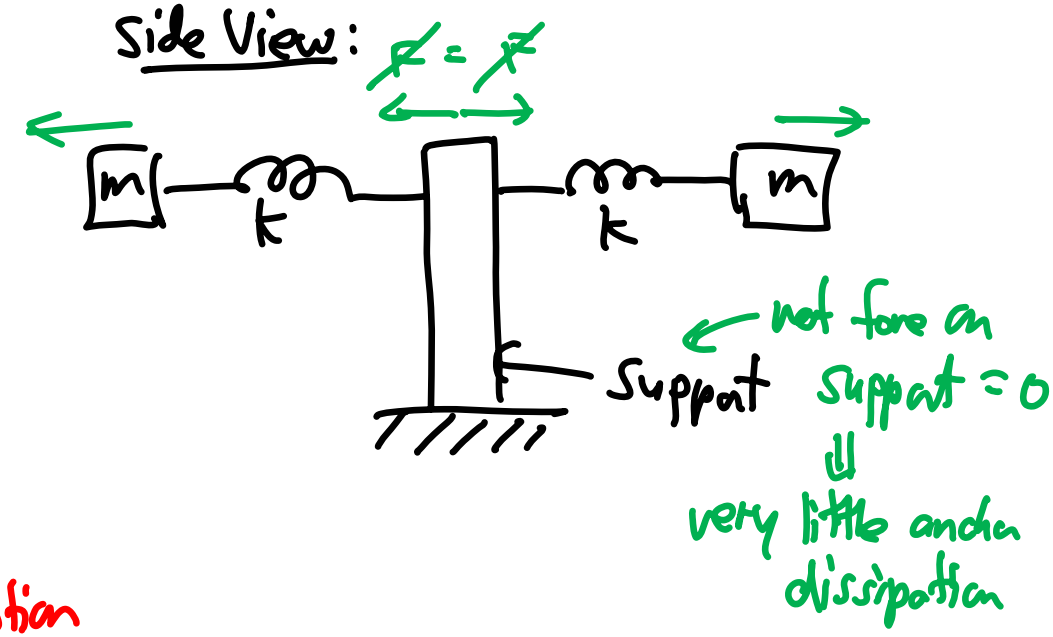
Principle of Operation

- Tuning Fork Gyroscope:

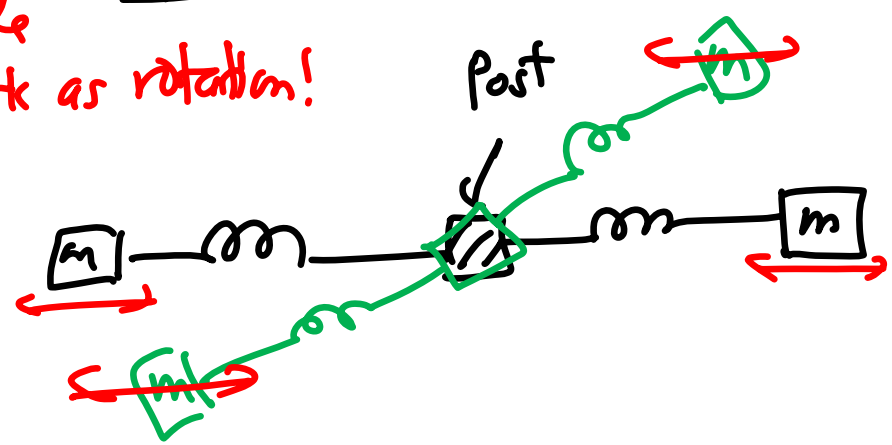


Detect motion out-of-the plane of the tuning fork as rotation!

Side View:



Top View:

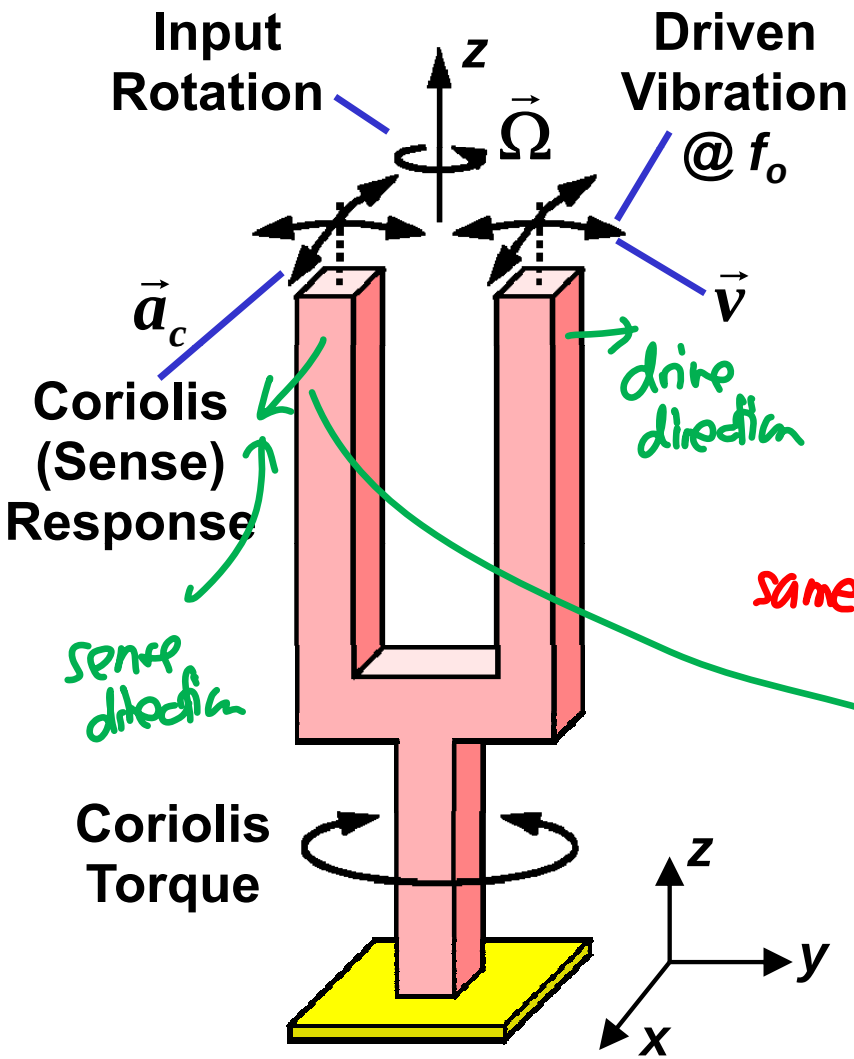


Basic Vibratory Gyroscope Operation

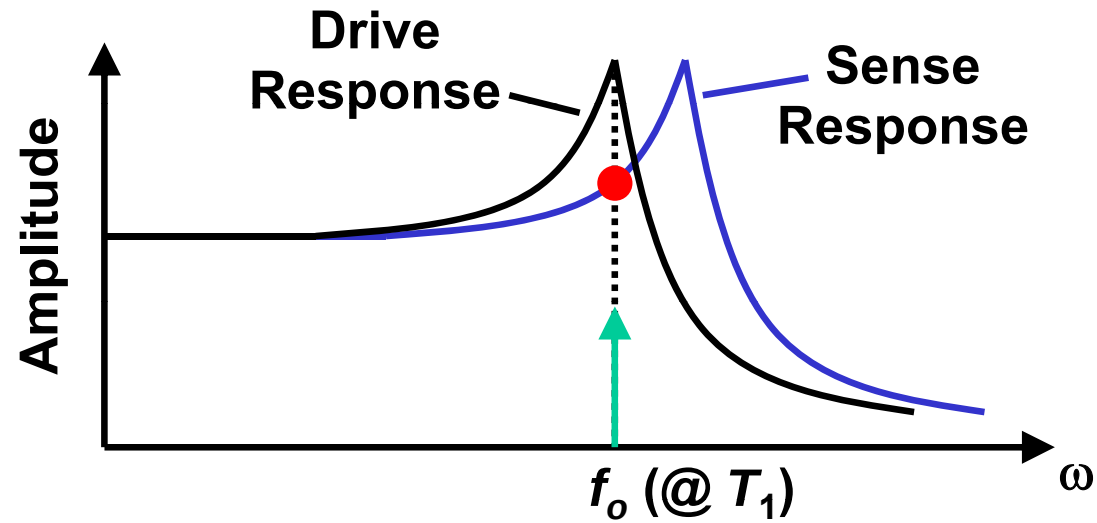
UC Berkeley

Principle of Operation

- Tuning Fork Gyroscope:



Drive/Sense Response Spectra:



Coriolis Acceleration — Driven Velocity — Rotation Rate

same frequency

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

Coriolis Force — Beam Mass

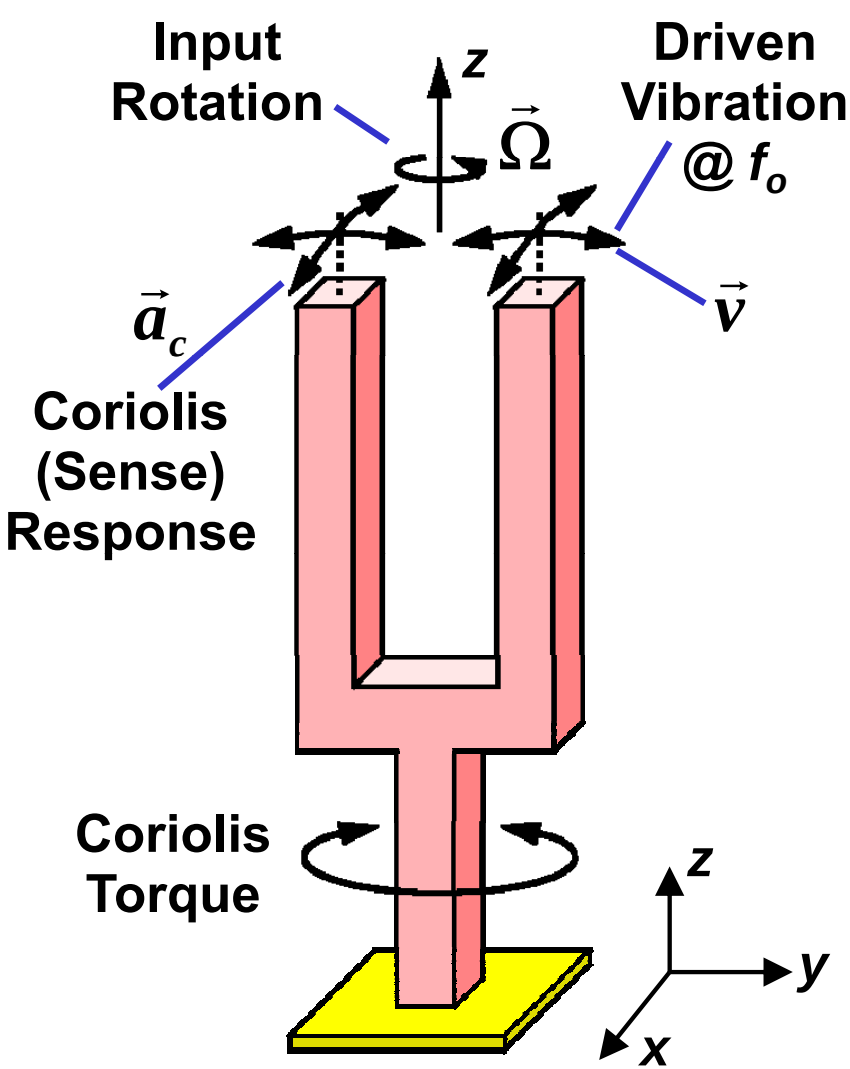
$$\vec{x} = \frac{\vec{F}_c}{k} = \frac{m\vec{a}_c}{k} = \frac{\vec{a}_c}{\omega_r^2}$$

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

Vibratory Gyroscope Performance

Principle of Operation

- Tuning Fork Gyroscope:

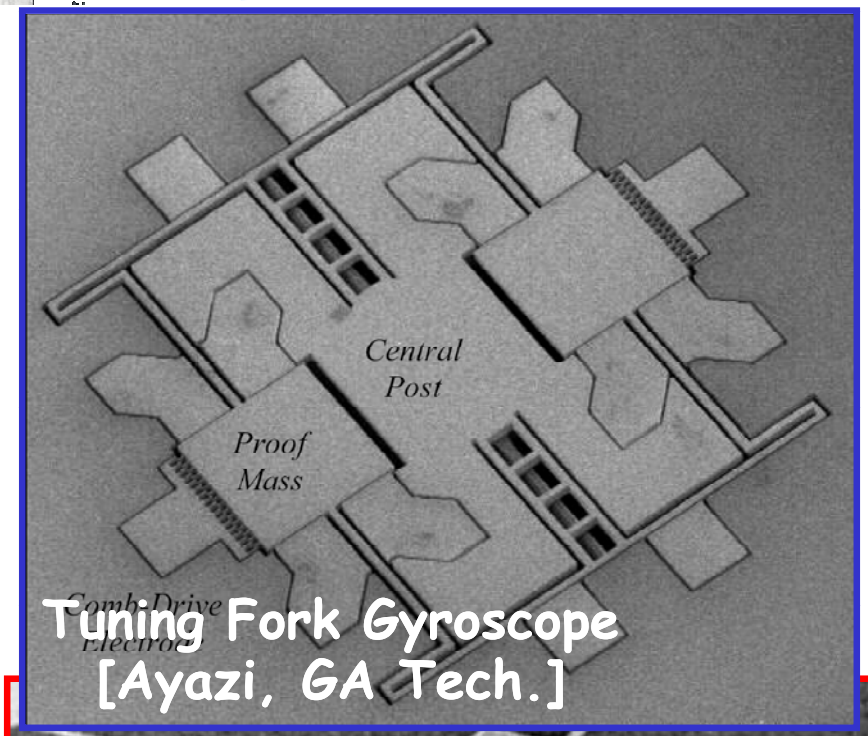


$$\vec{x} = \frac{\vec{F}_c}{k} = \frac{m\vec{a}_c}{k} = \frac{\vec{a}_c}{\omega_r^2} \qquad \vec{a}_c = 2\vec{v} \times \vec{\Omega}$$

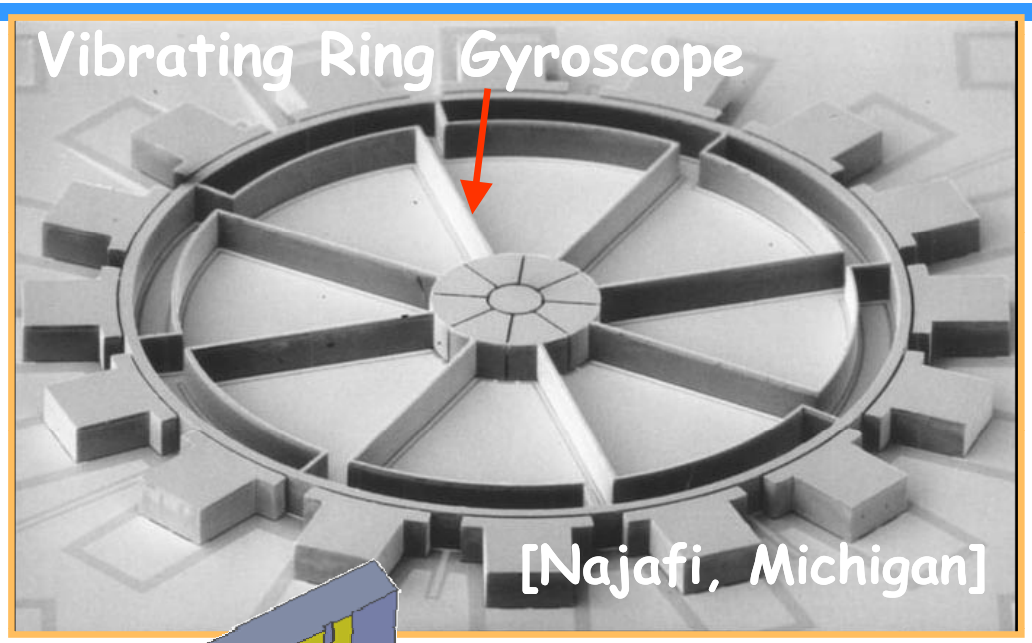
Beam Mass — Beam Stiffness — Sense Frequency — Driven Velocity

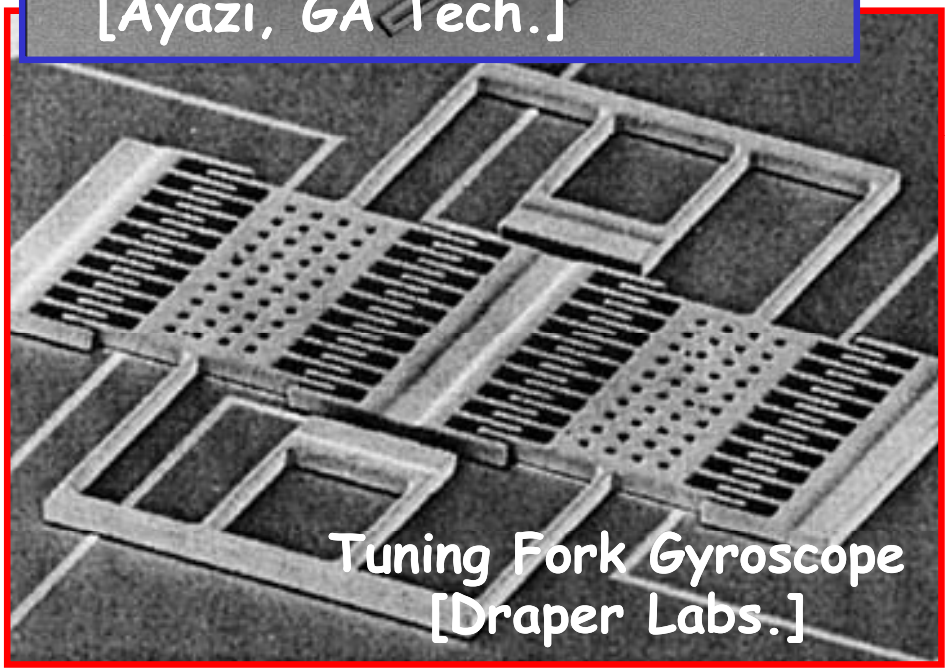
- To maximize the output signal x, need:
  - Large sense-axis mass
  - Small sense-axis stiffness
  - (Above together mean low resonance frequency)
  - Large drive amplitude for large driven velocity (so use comb-drive) → $v = \omega_o X$, want X = large!
  - If can match drive freq. to sense freq.,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

MEMS-Based Gyroscopes

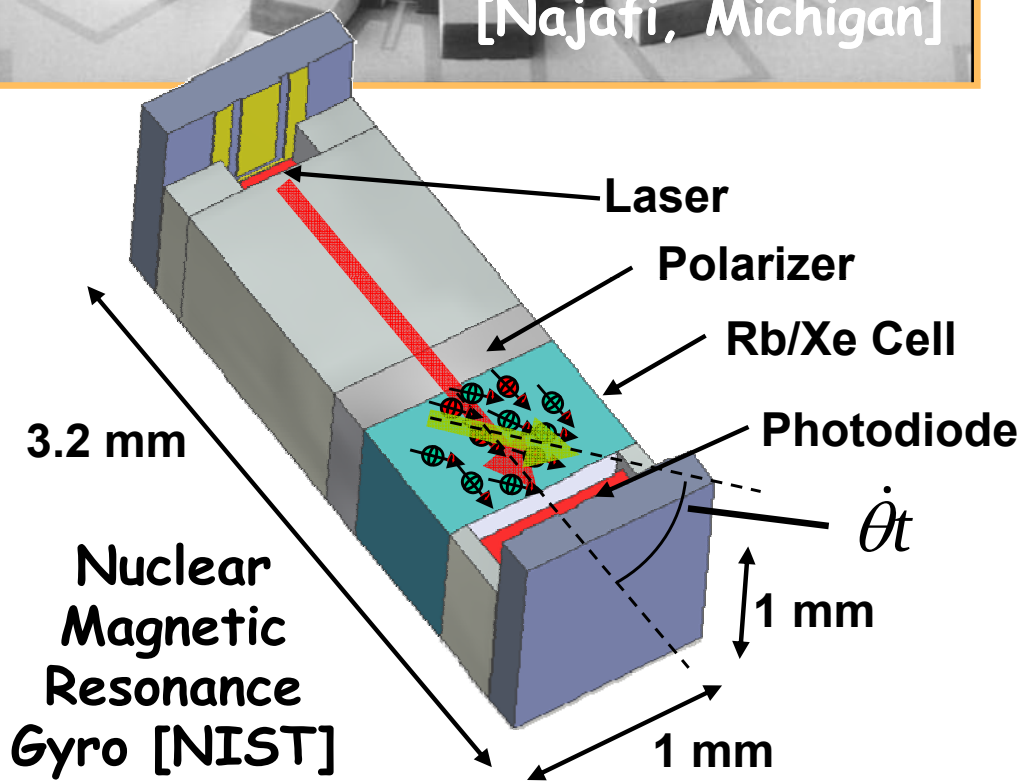


Tuning Fork Gyroscope
[Ayazi, GA Tech.]



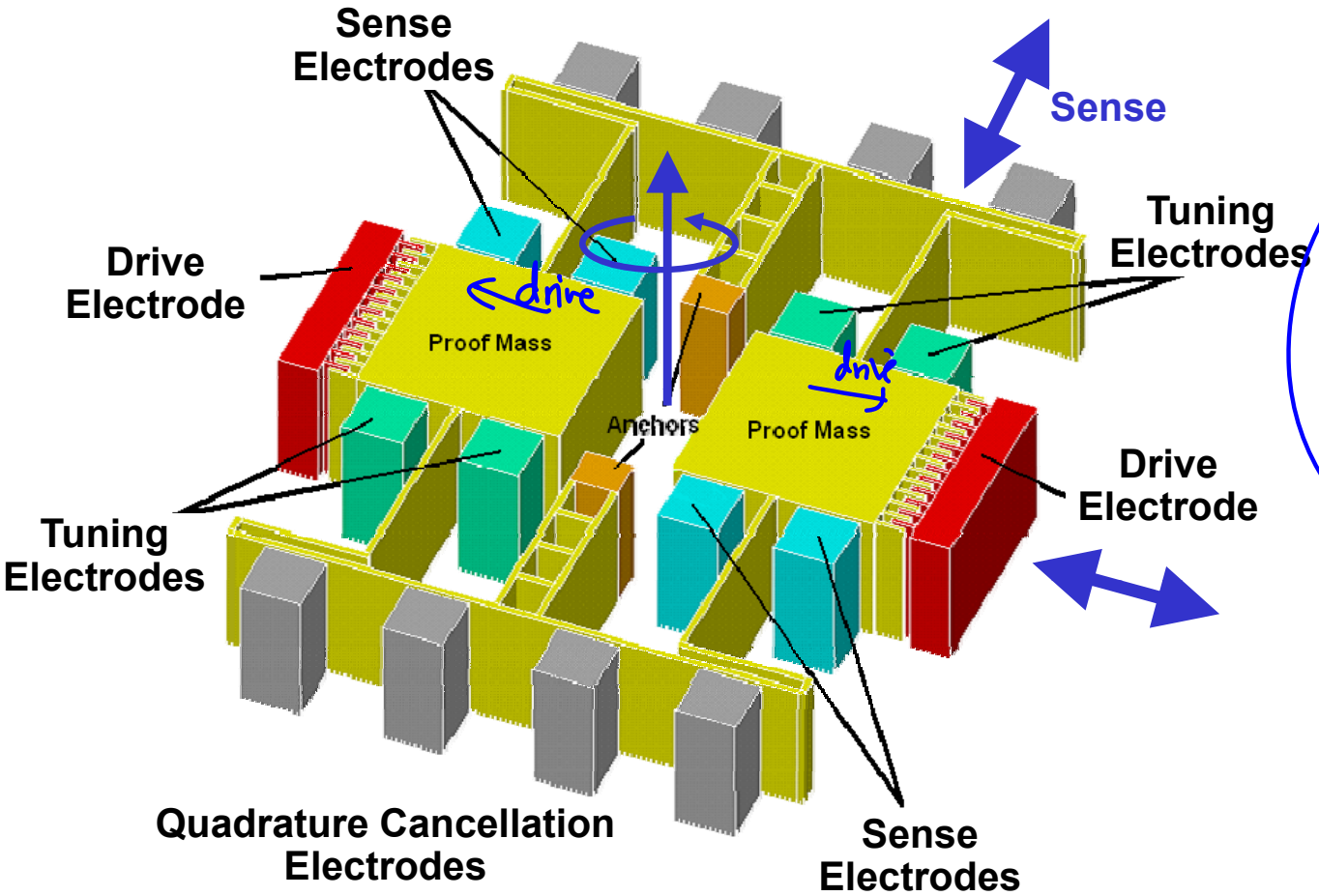


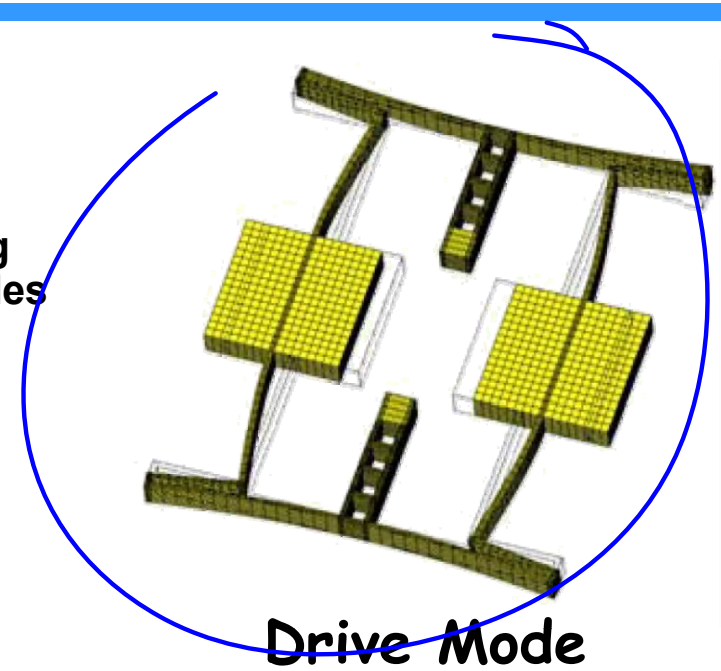
Tuning Fork Gyroscope
[Draper Labs.]

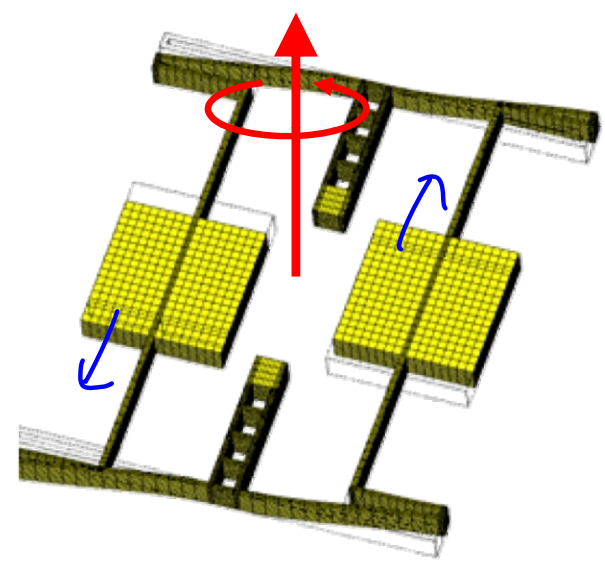


Nuclear Magnetic Resonance Gyro [NIST]

MEMS-Based Tuning Fork Gyroscope

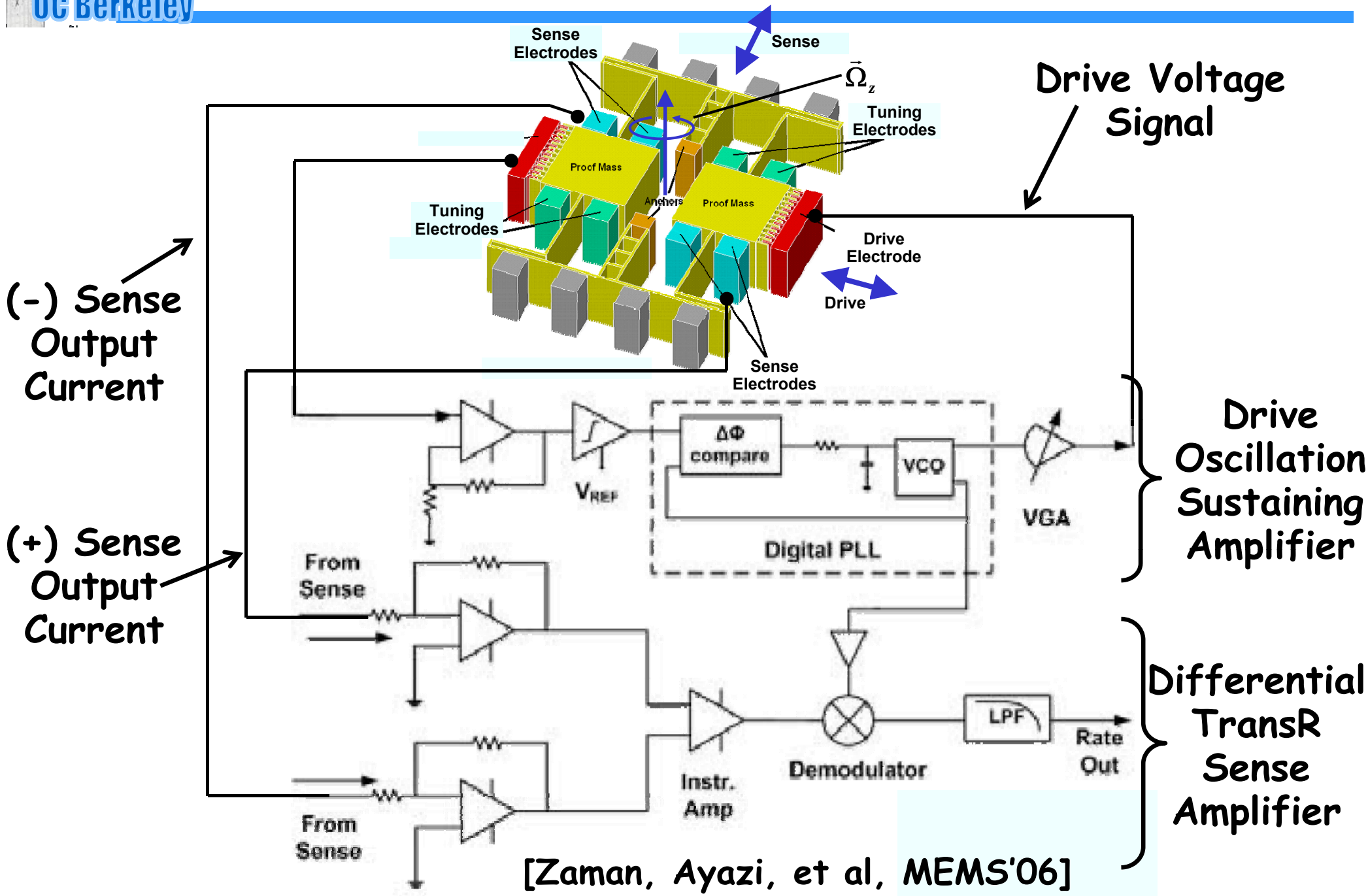






- In-plane drive and sense modes pick up z-axis rotations
- Mode-matching for maximum output sensitivity
- From [Zaman, Ayazi, et al, MEMS'06]

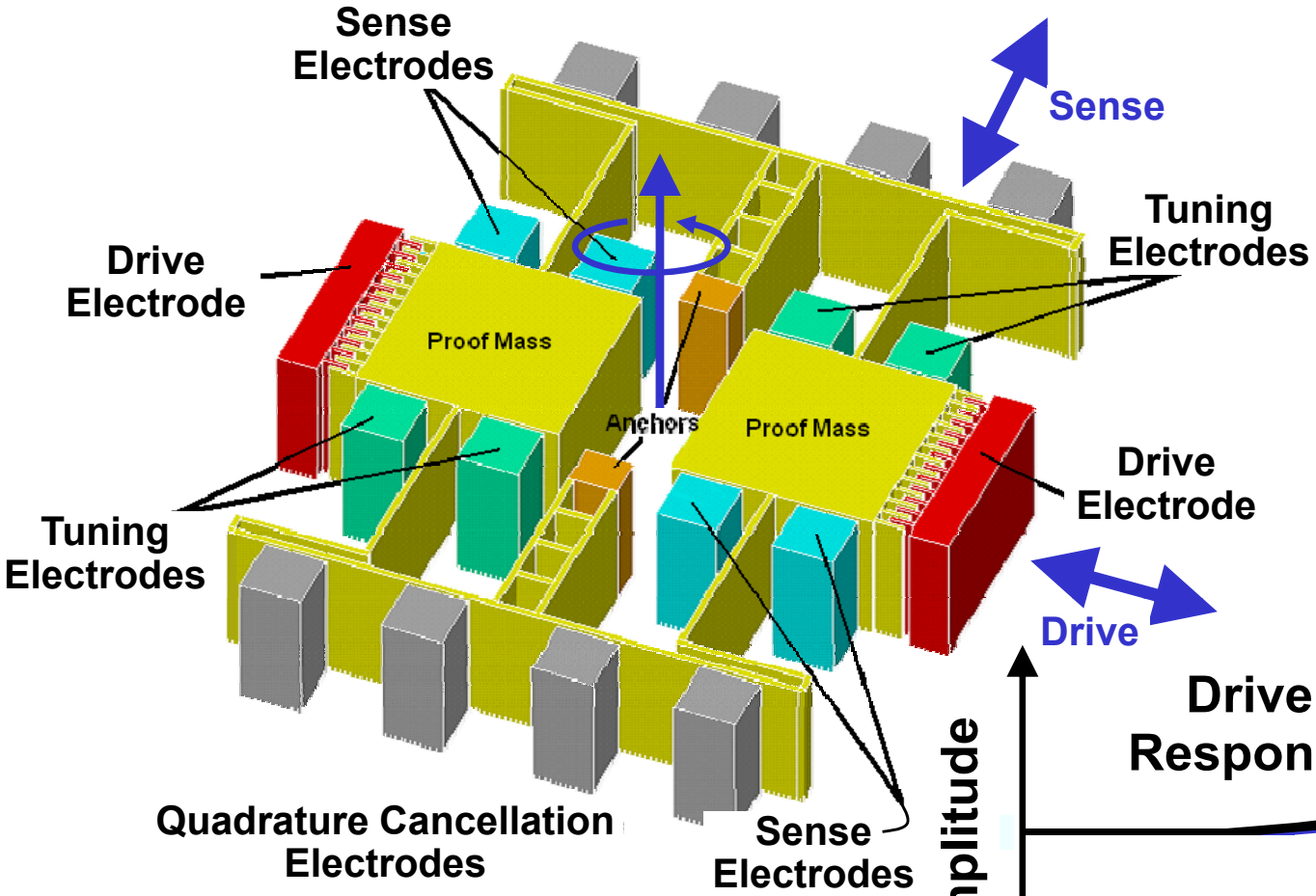
MEMS-Based Tuning Fork Gyroscope



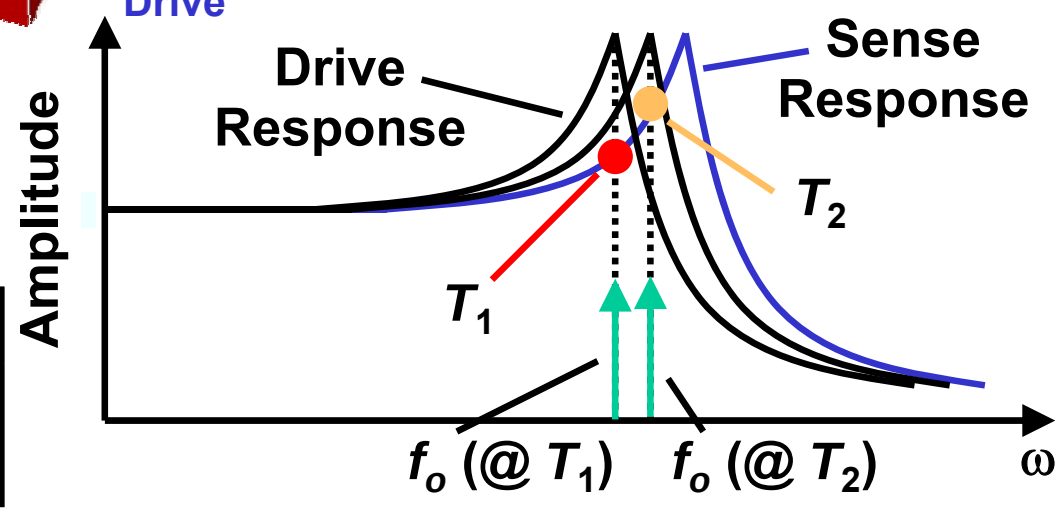
[Zaman, Ayazi, et al, MEMS'06]

MEMS-Based Tuning Fork Gyroscope

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



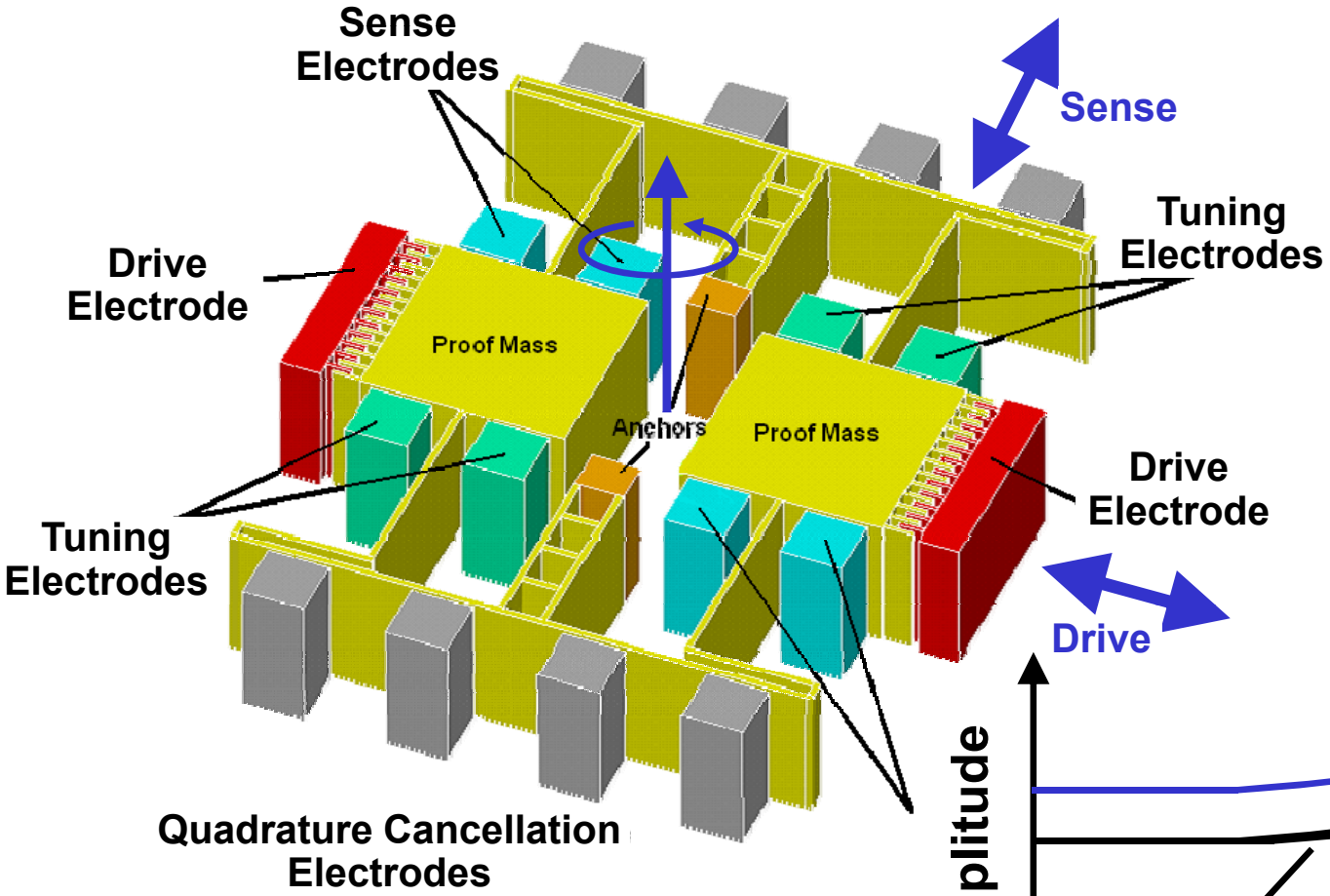
Problem: if drive frequency changes relative to sense frequency, output changes ⇨ bias drift



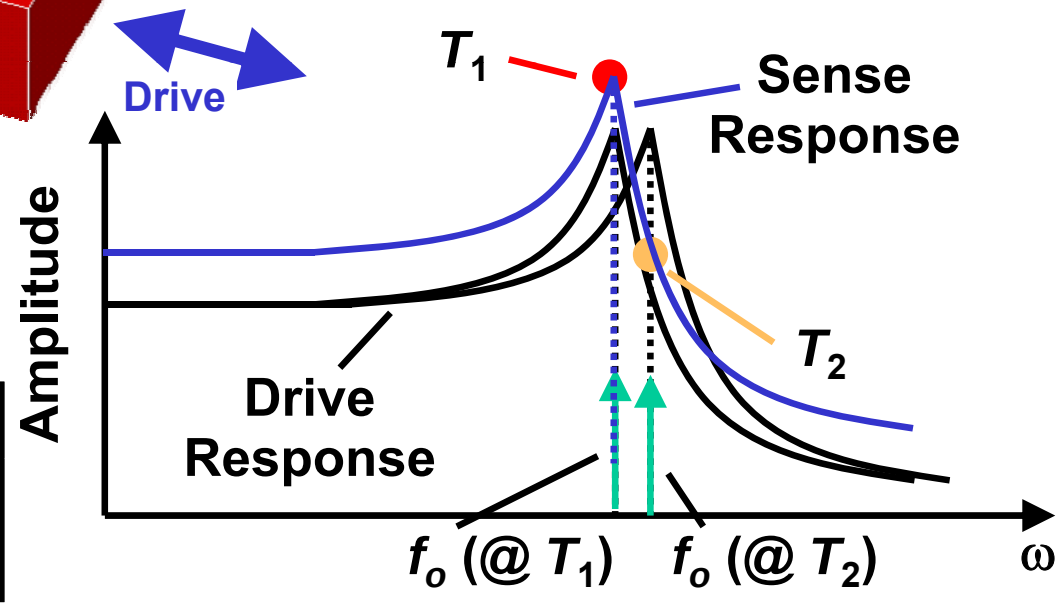
Need: small or matched drive and sense axis temperature coefficients to suppress drift

Mode Matching for Higher Resolution

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



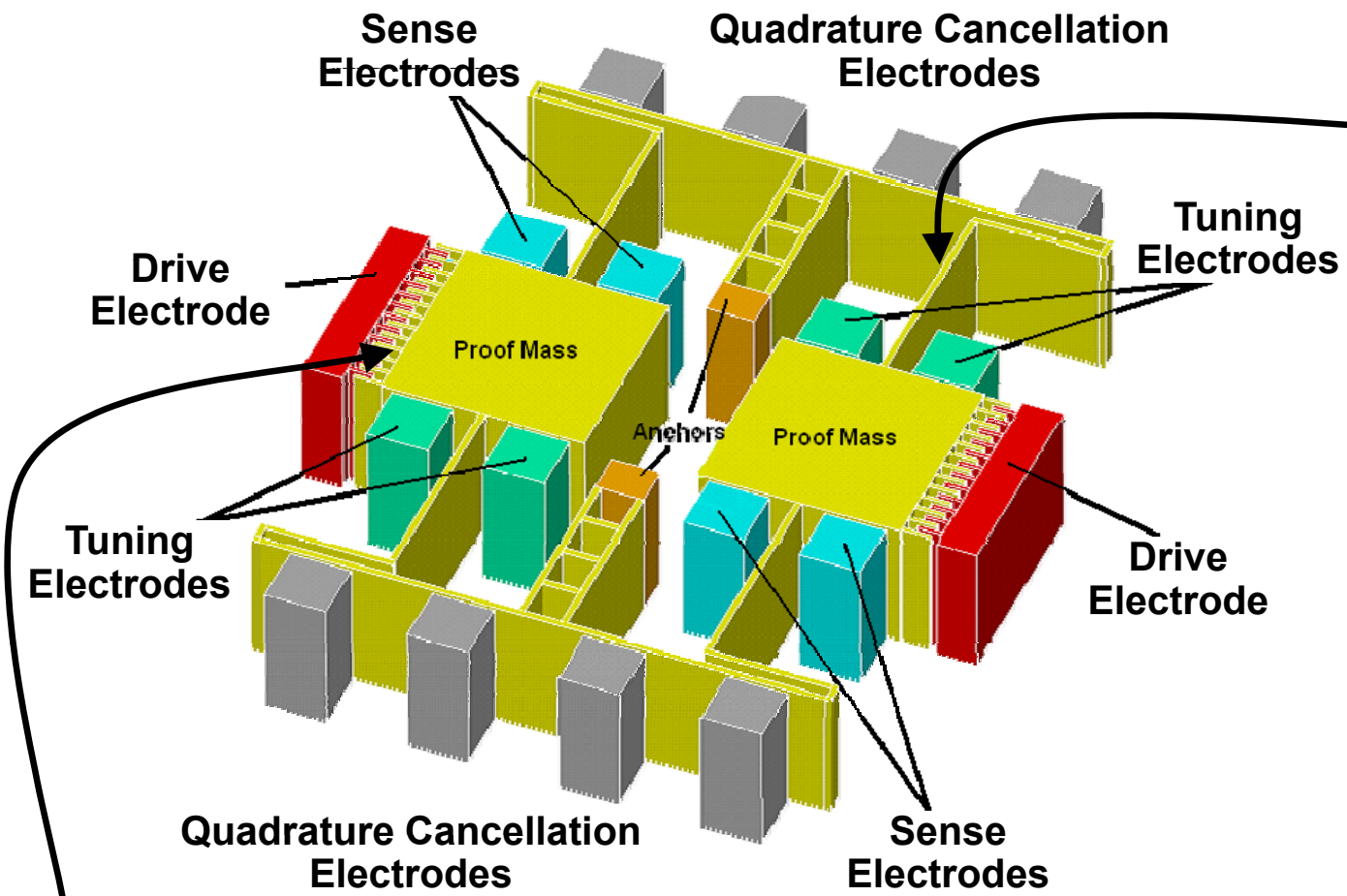
Problem: mismatch between drive and sense frequencies ⇨ even larger drift!

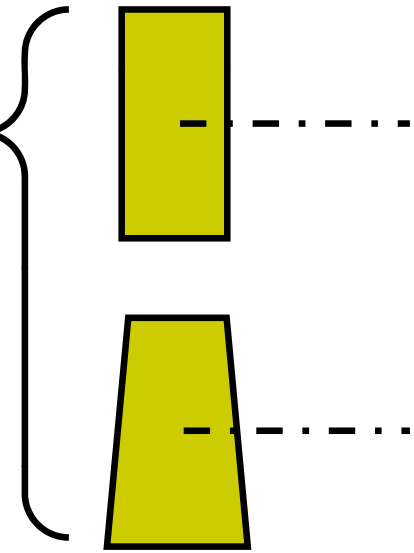


Need: small or matched drive and sense axis temperature coefficients to make this work

Issue: Zero Rate Bias Error

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





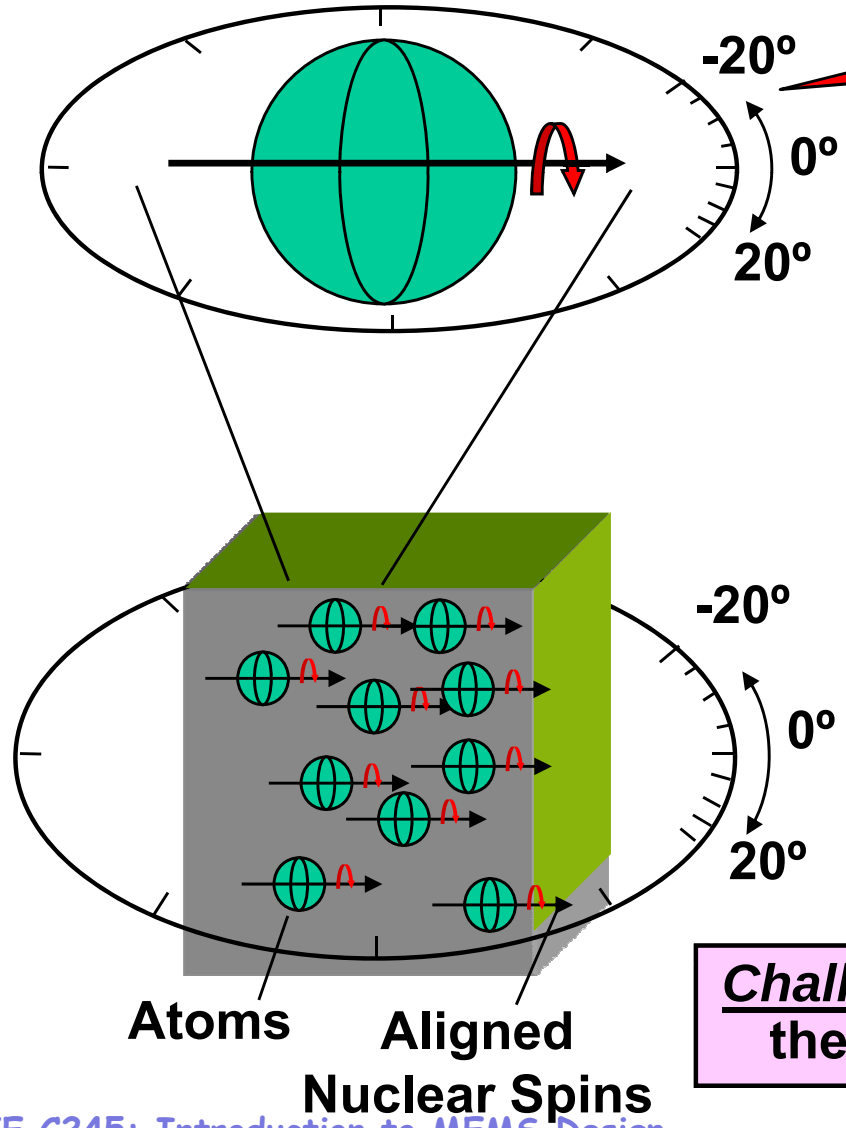
Mass imbalance ⇨ off-axis motion of the proof mass

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**

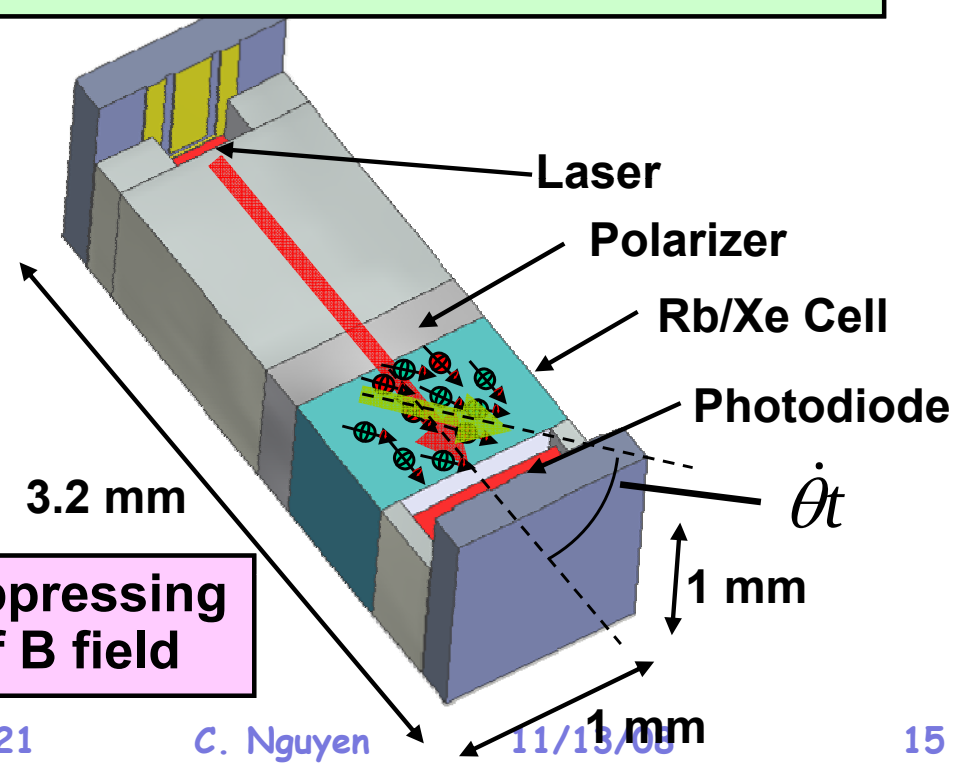
Nuclear Magnetic Res. Gyroscope

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



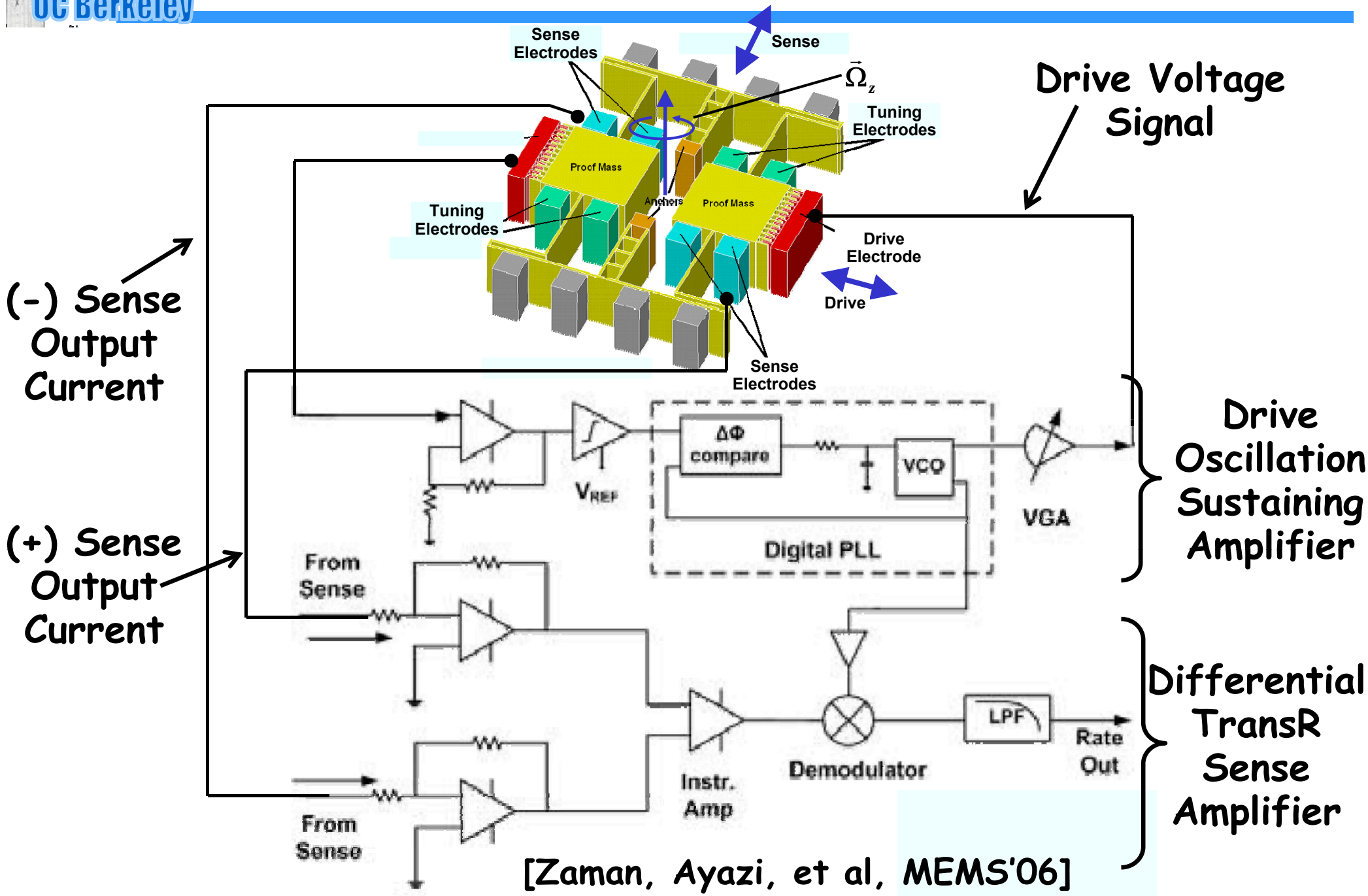
Better if this is a noble gas nucleus (rather than e-), since nuclei are heavier ⇨ less susceptible to B field

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



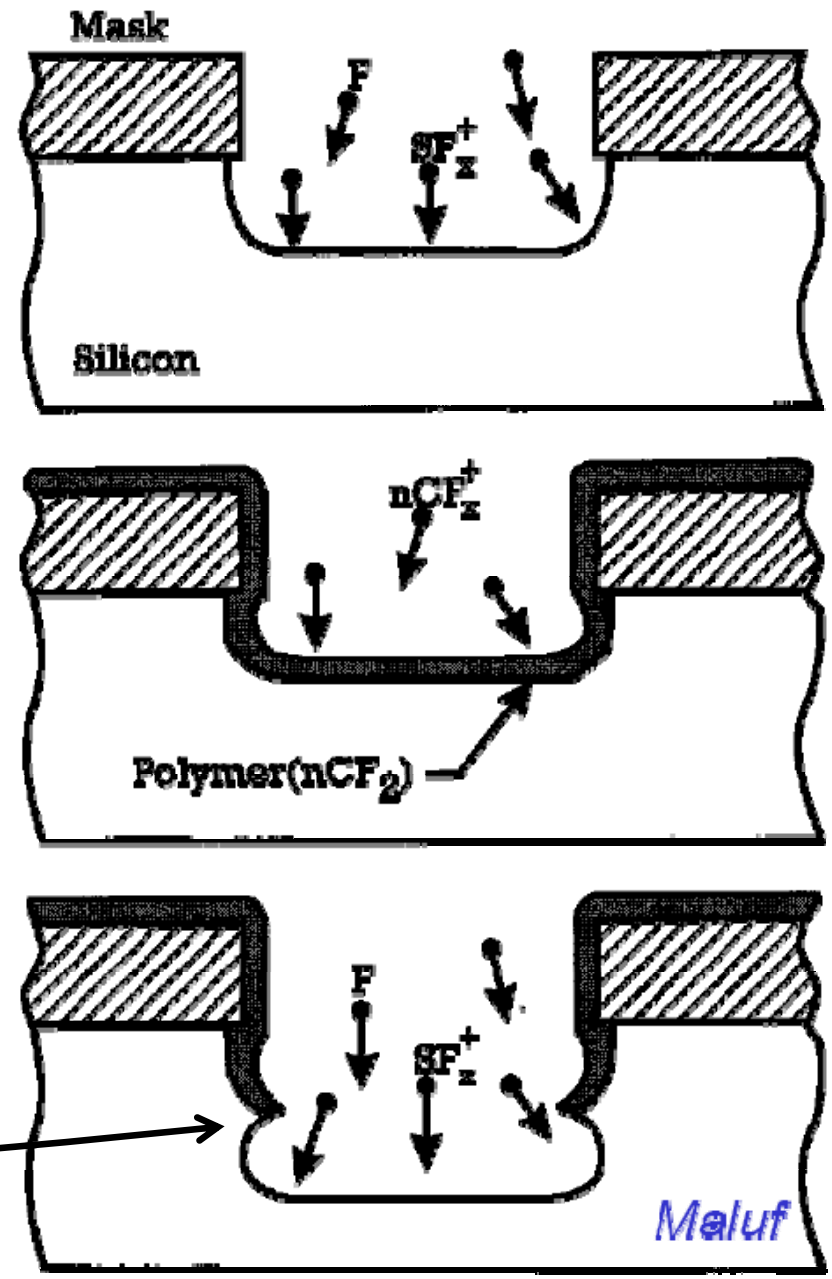
[Zaman, Ayazi, et al, MEMS'06]

Deep Reactive-Ion Etching

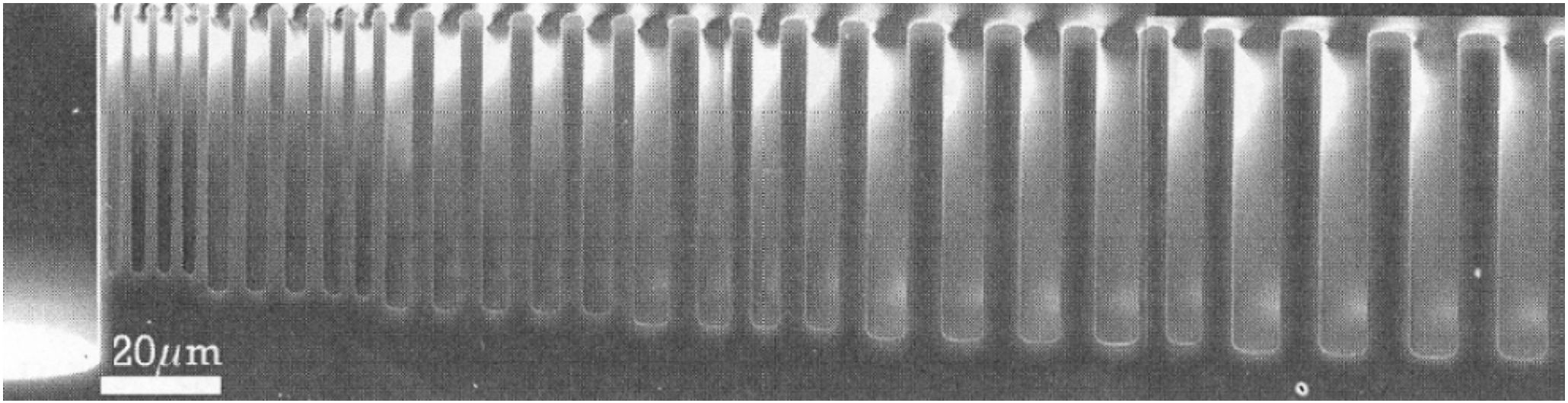
Deep Reactive-Ion Etching (DRIE)

The Bosch process:

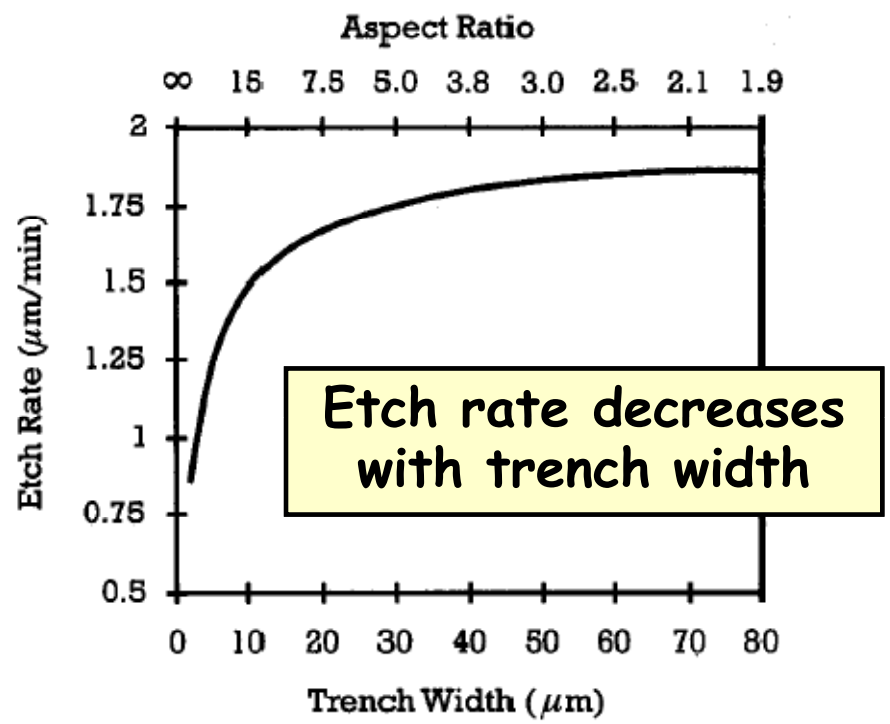
- Inductively-coupled plasma
- Etch Rate: 1.5-4 μm/min
- Two main cycles in the etch:
  - Etch cycle (5-15 s): SF_6 (SF_x^+) etches Si
  - Deposition cycle: (5-15 s): C_4F_8 deposits fluorocarbon protective polymer $(CF_2^-)_n$
- Etch mask selectivity:
  - SiO_2 ~ 200:1
  - Photoresist ~ 100:1
- Issue: 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)



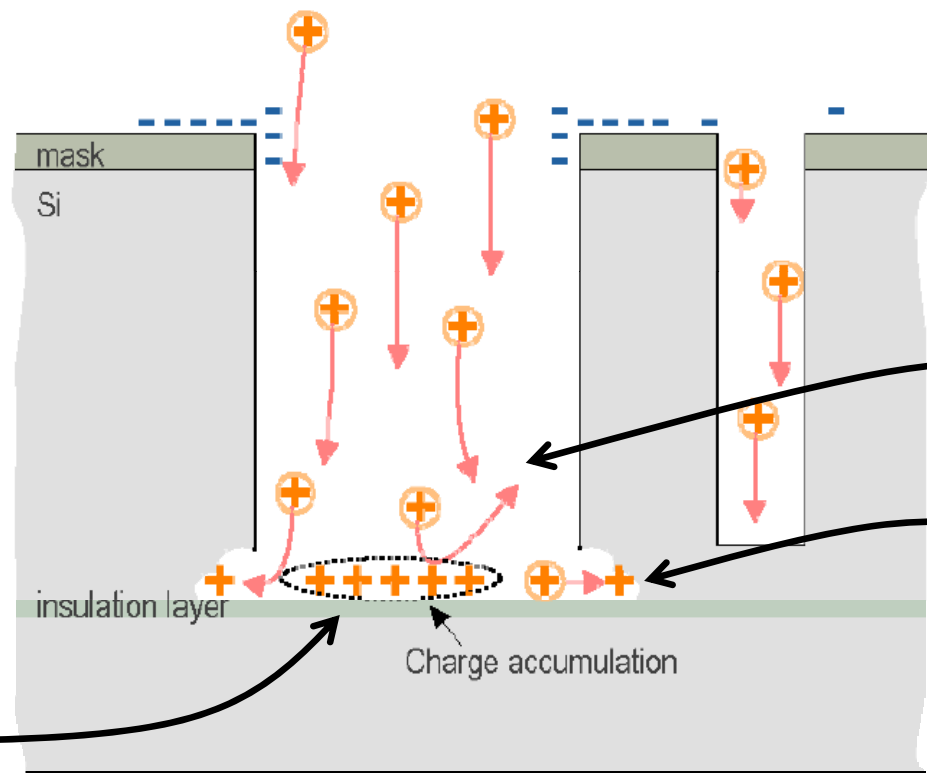
DRIE Issues: "Footing"

- 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

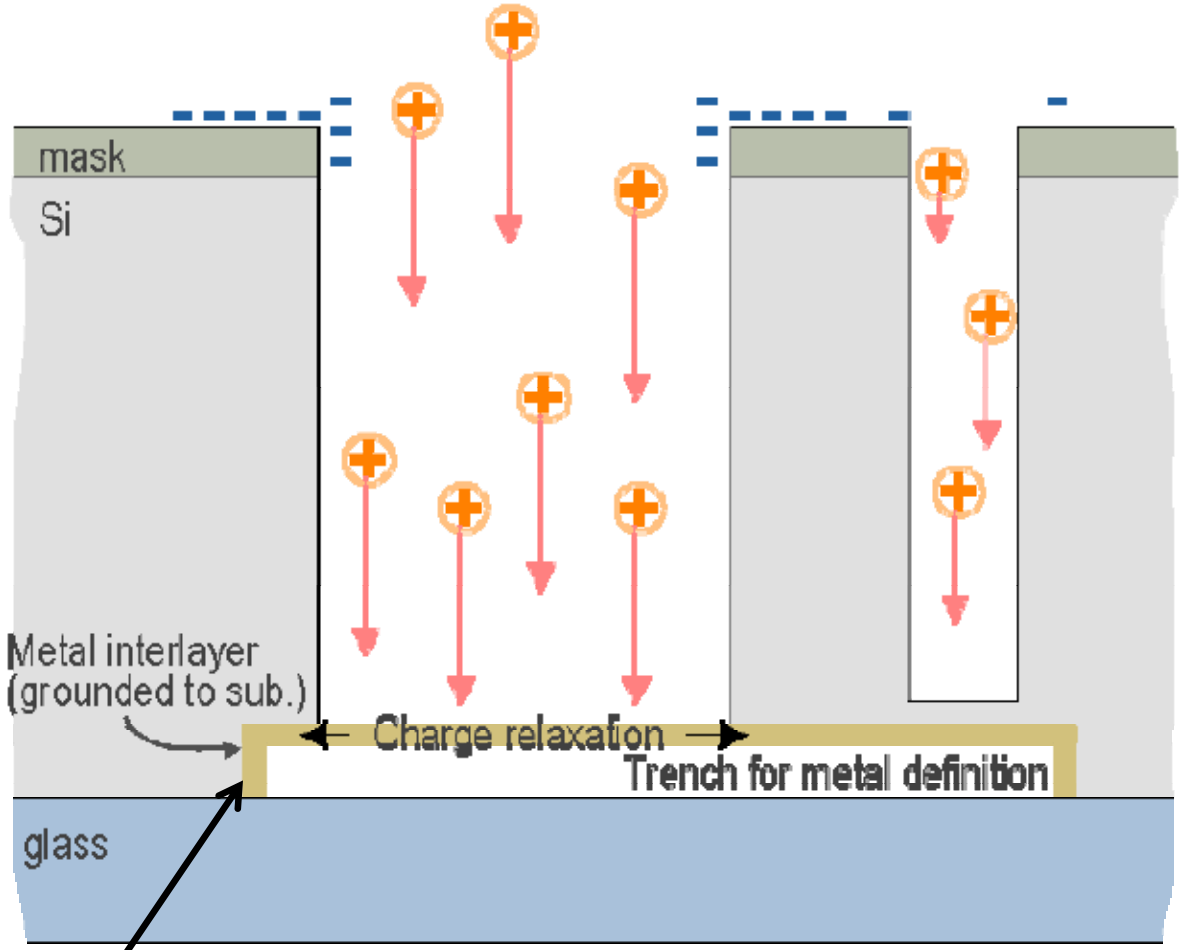
↓

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

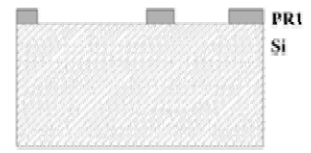
Recipe-Based Suppression of "Footing"

- 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

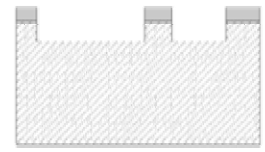
Metal Interlayer to Prevent "Footing"



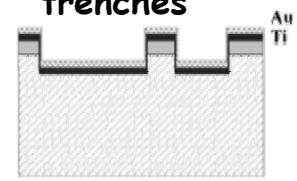
Pre-defined metal interlayer grounded to substrate supplies e's to neutralize (+) charge and prevent charge accumulation at the Si-insulator interface



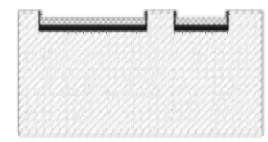
(a) Photolithography 1 (sacrificial)



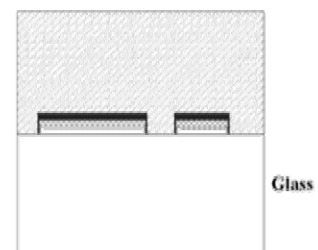
(b) Preparatory trenches



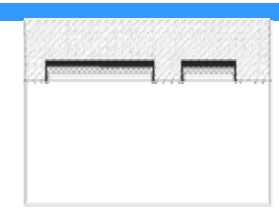
(c) Metal interlayer deposition



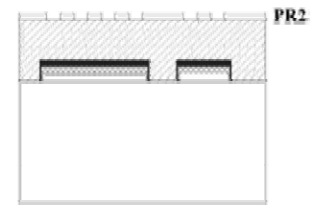
(d) Lift-off (remove PR)



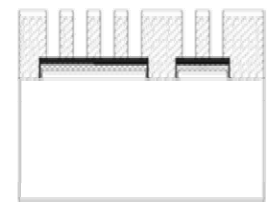
(e) Anodic Bonding



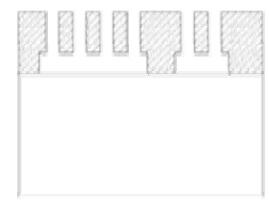
(f) Silicon Thinning



(g) Photolithography 2



(h) DRIE



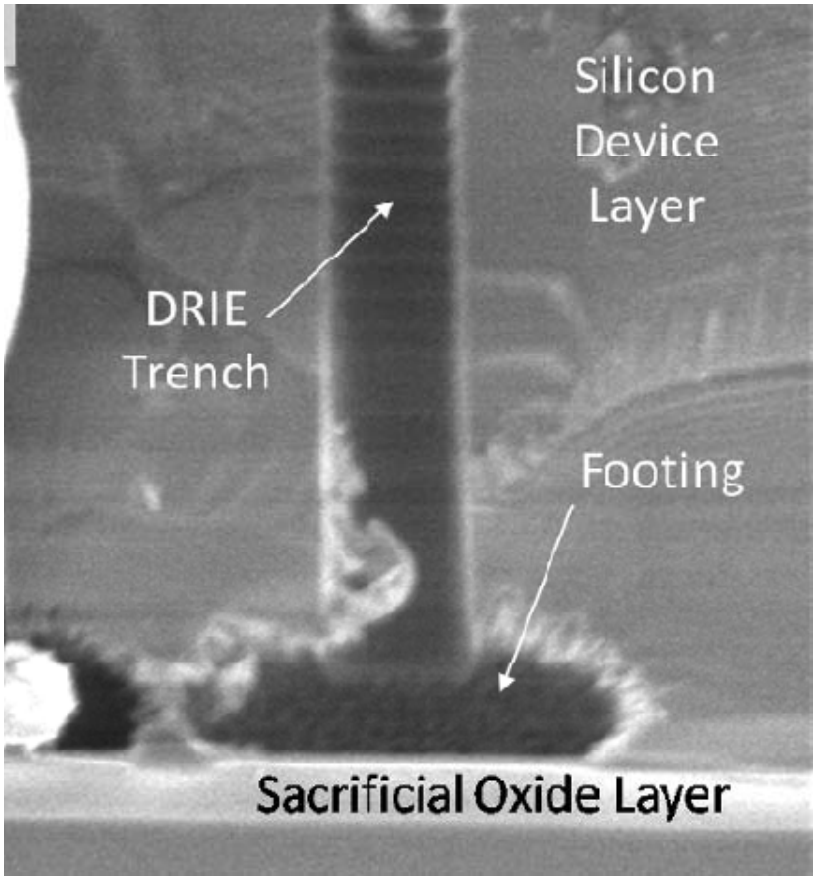
(i) Remove metal interlayer

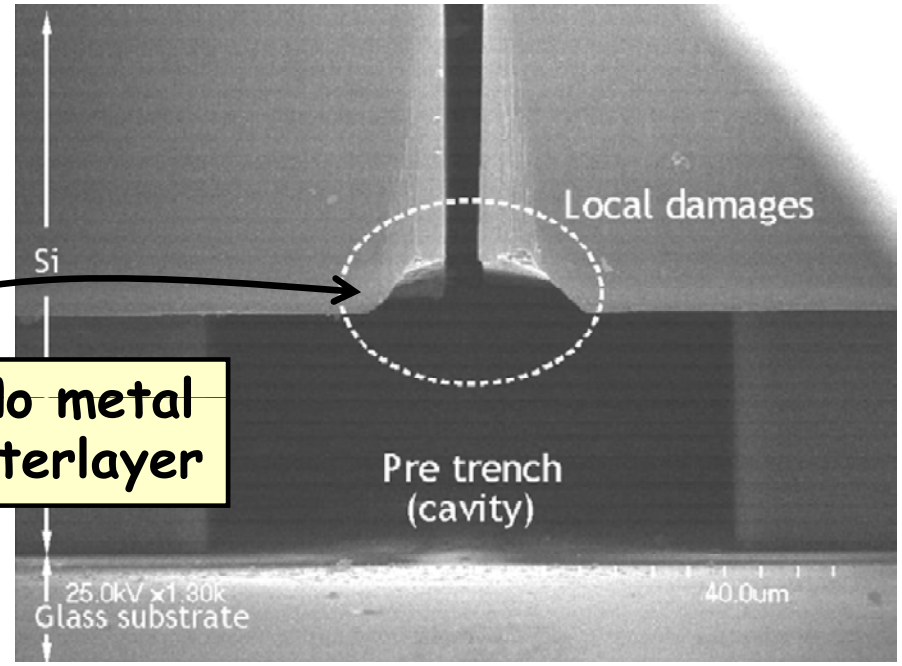
(i) Metallize

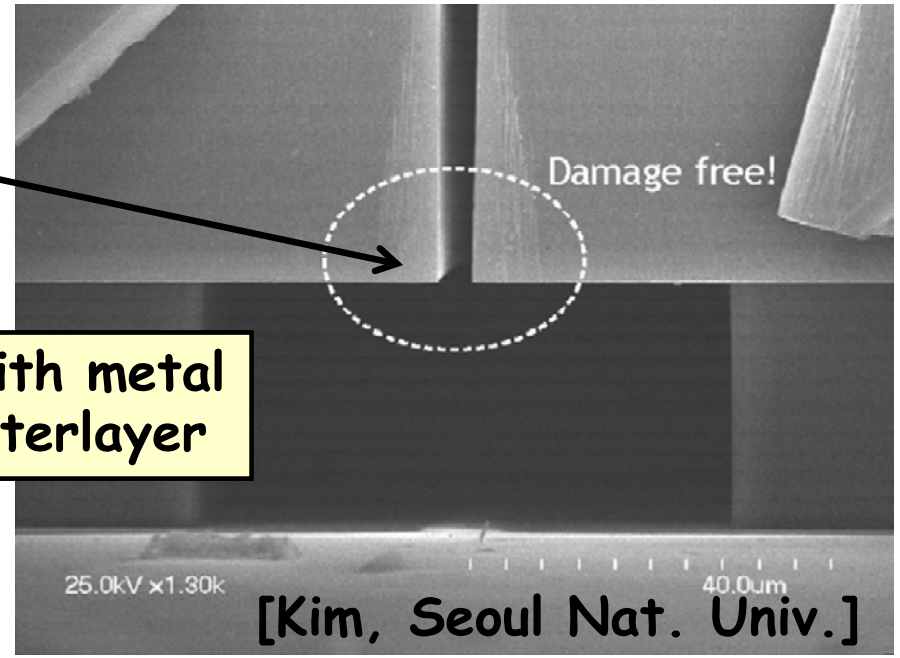
Footing Prevention (cont.)

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

[Kim, Stanford]

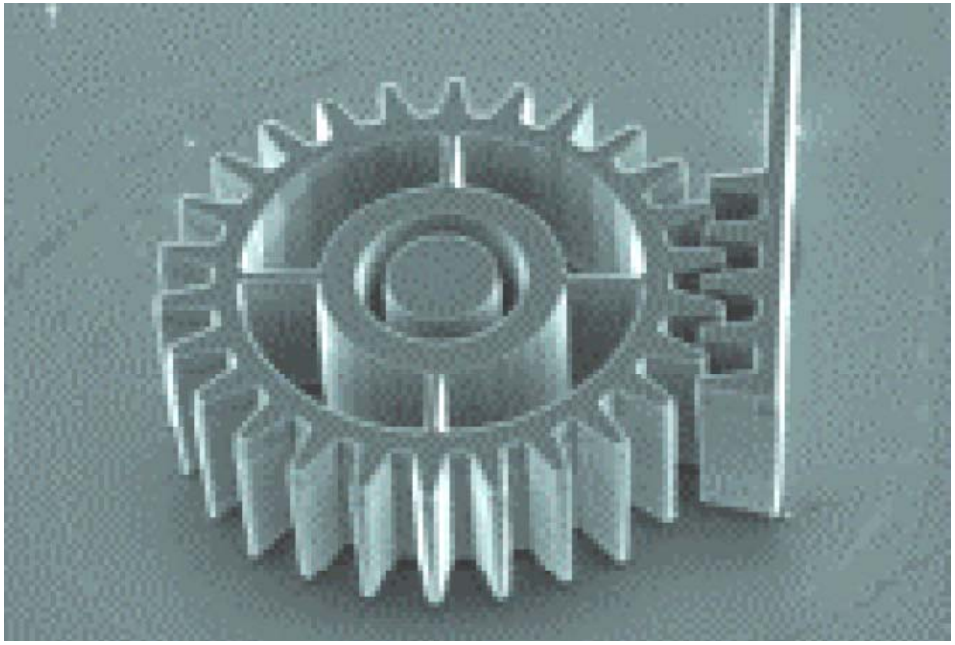






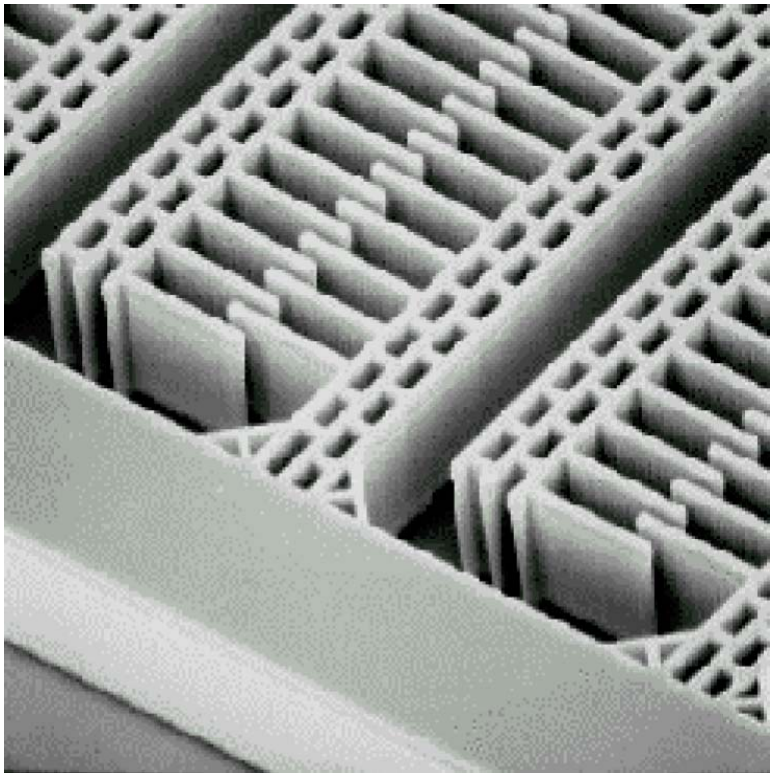
[Kim, Seoul Nat. Univ.]

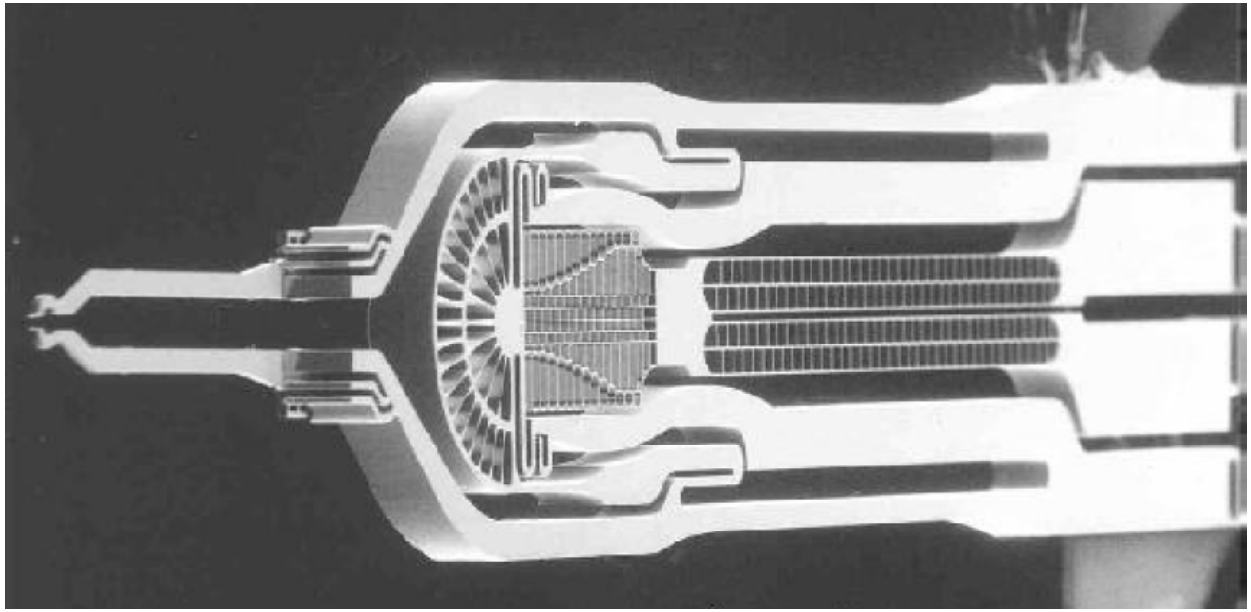
DRIE Examples



High aspect-ratio gear

Tunable Capacitor [Yao, Rockwell]

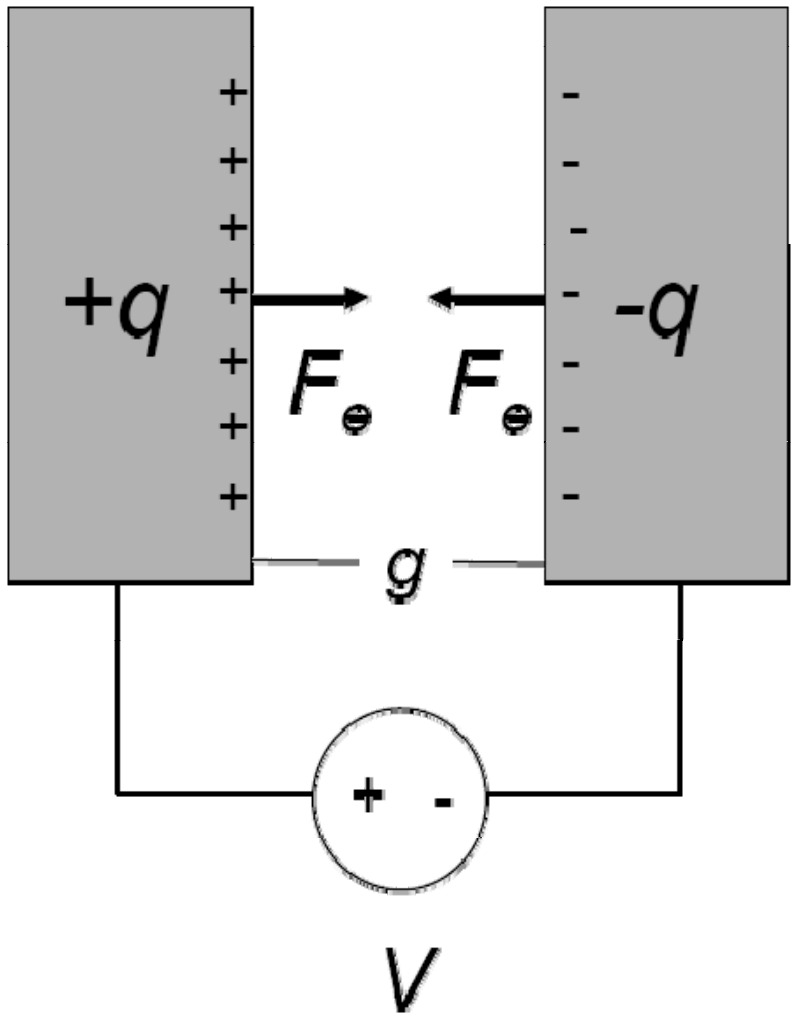




Microgripper [Keller, MEMS Precision Instruments]

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

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

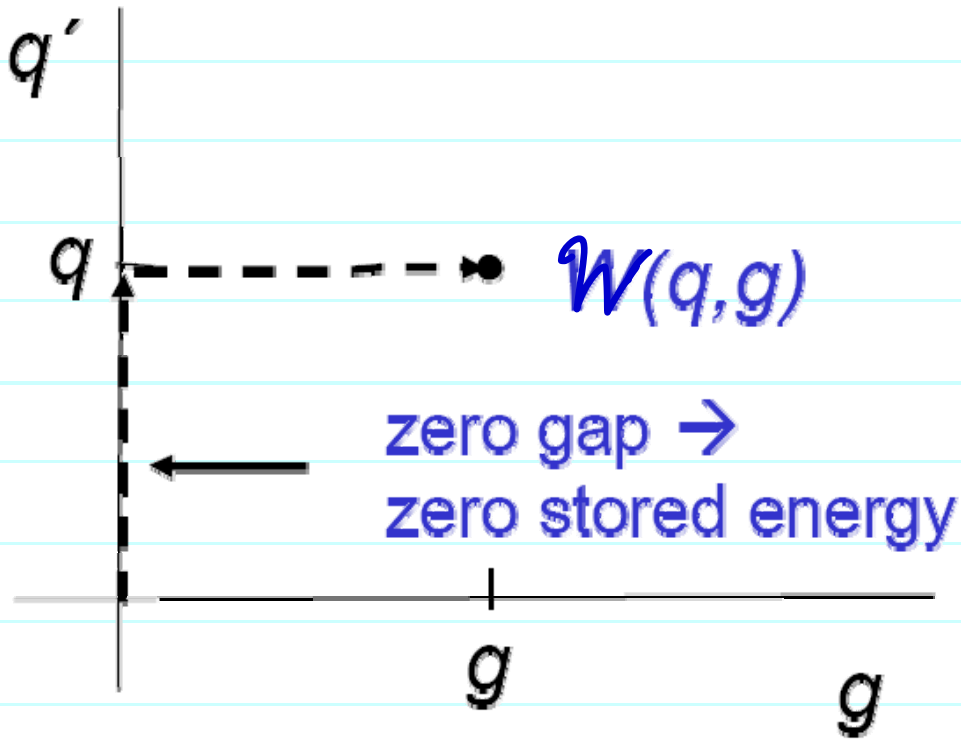
$$dW = Vdq + F_e dg$$

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

Stored Energy

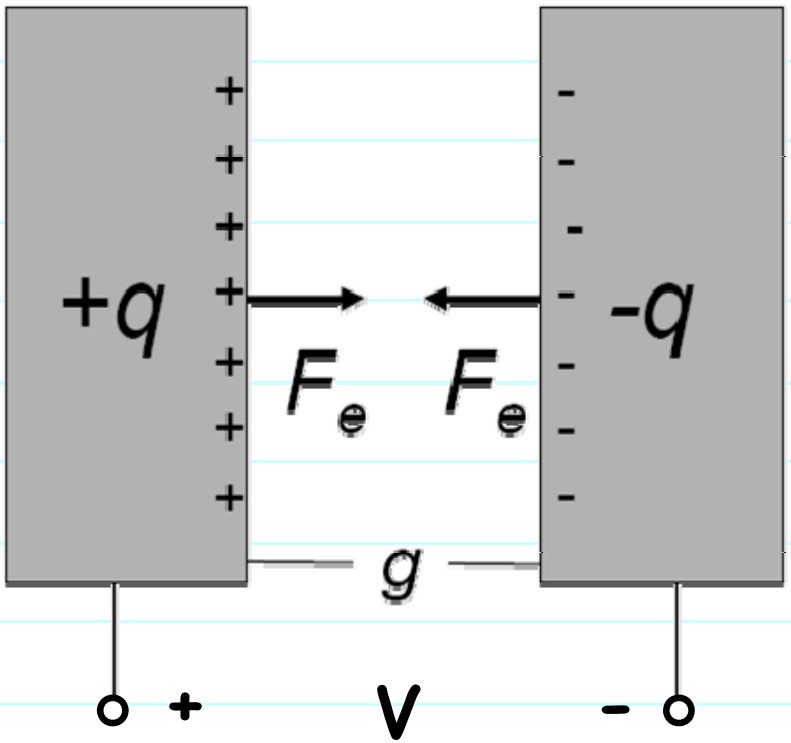
- Here, the stored energy is the work done in increasing the gap after charging capacitor at zero gap

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



Charge-Control Case

- Having found stored energy, we can now find the force acting on the plates and the voltage across them:



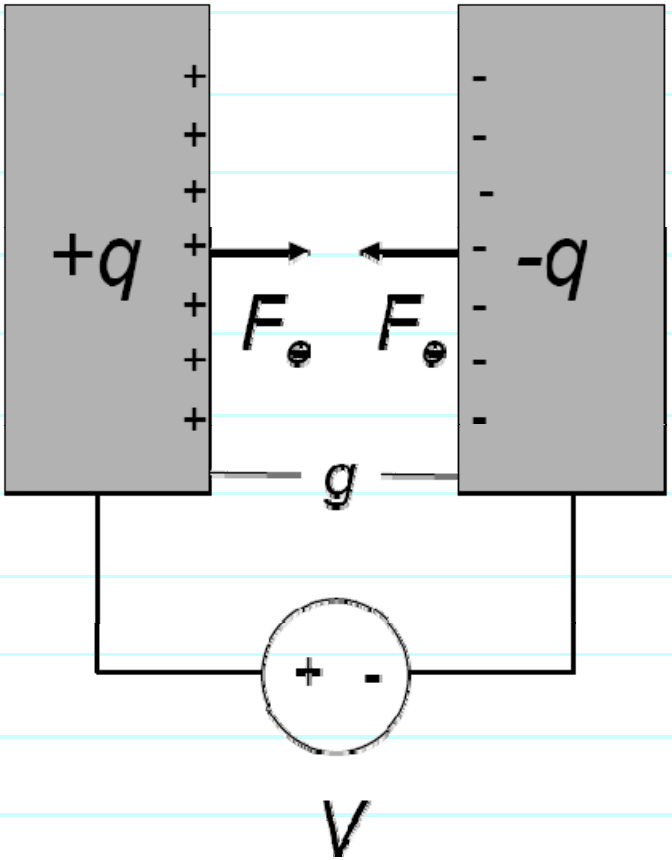
Voltage-Control Case

- Practical situation: We control V
  - Charge control on the typical sub-pF MEMS actuation capacitor is difficult
  - Need to find F_e as a partial derivative of the stored energy $\mathcal{W} = \mathcal{W}(V,g)$ with respect to g with V held constant? But can't do this with present $\mathcal{W}(q,g)$ formula
  - <u>Solution</u>: Apply Legendre transformation and define the co-energy $\mathcal{W}'(V,g)$

Co-Energy Formulation

- For our present problem (i.e., movable capacitive plates), the co-energy formulation becomes

$$\mathcal{W}'(V,g) = qV - \mathcal{W}$$



Electrostatic Force (Voltage Control)

- Find co-energy in terms of voltage

$$W' = \int_0^V q(g,V')dV' = \int_0^V \left(\varepsilon \frac{A}{g}\right) V' dV' = \frac{1}{2}\left(\frac{\varepsilon A}{g}\right) V^2 = \frac{1}{2}CV^2$$

(as expected)

- Variation of co-energy with respect to gap yields electrostatic force:

$$F_e = -\left.\frac{\partial W'(V,g)}{\partial g}\right|_V = -\frac{1}{2}\underbrace{\left(-\frac{\varepsilon A}{g^2}\right)}V^2 = \frac{1}{2}\frac{C}{g}V^2$$

strong function of gap!

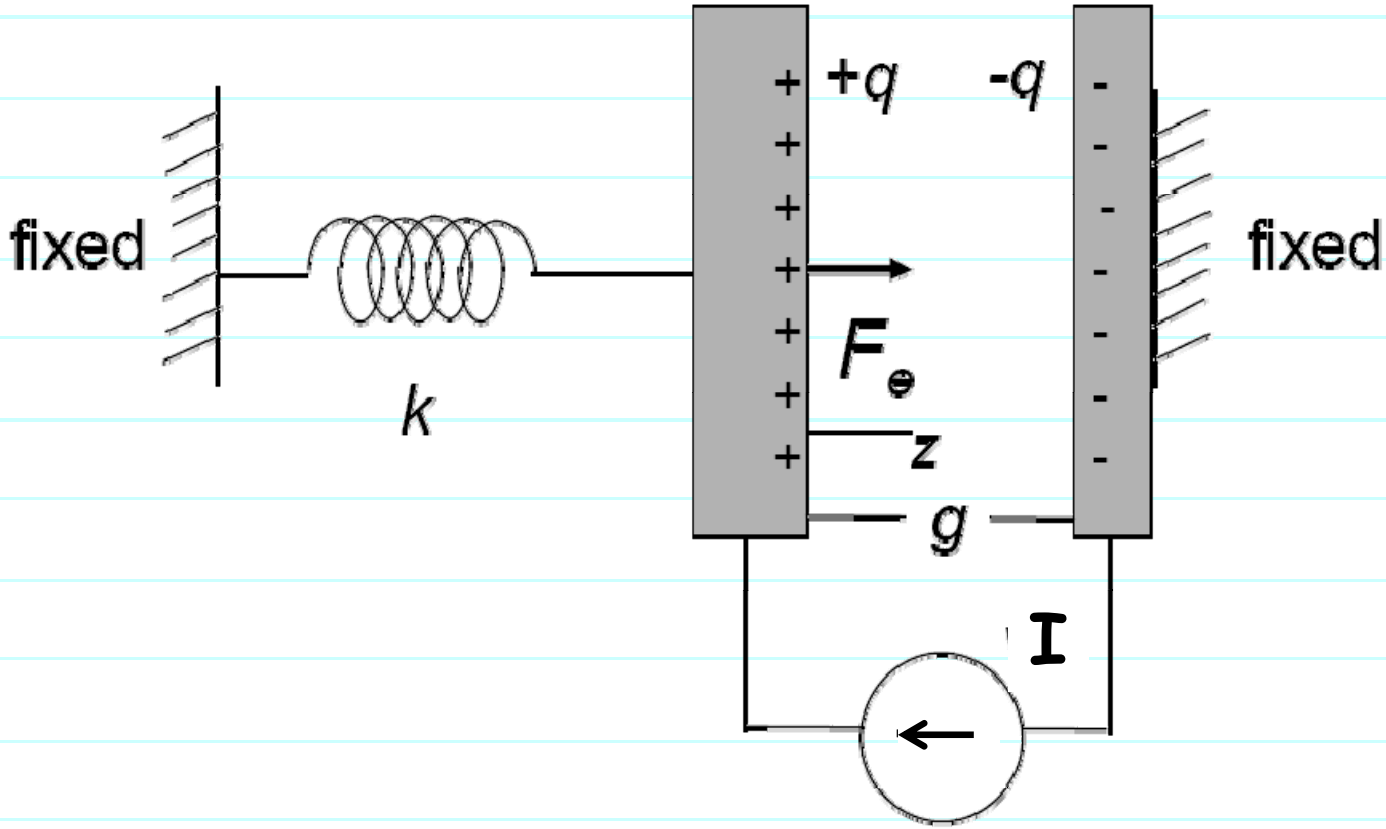
- Variation of co-energy with respect to voltage yields charge:

$$q = \left.\frac{\partial W'(V,g)}{\partial V}\right|_g = \left(\frac{\varepsilon A}{g}\right)V = CV$$

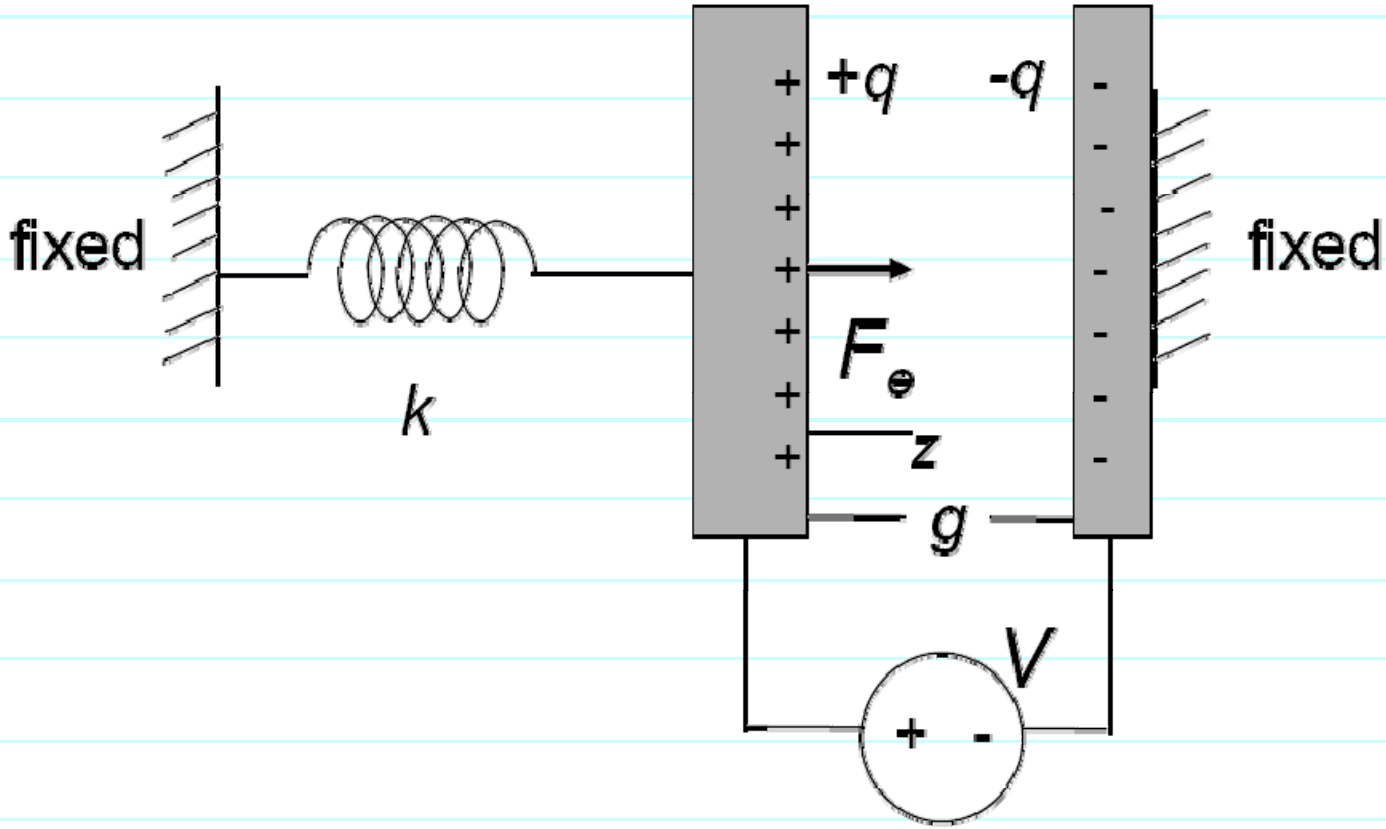
as expected

Spring-Suspended Capacitive Plate

Charge Control of a Spring-Suspended C

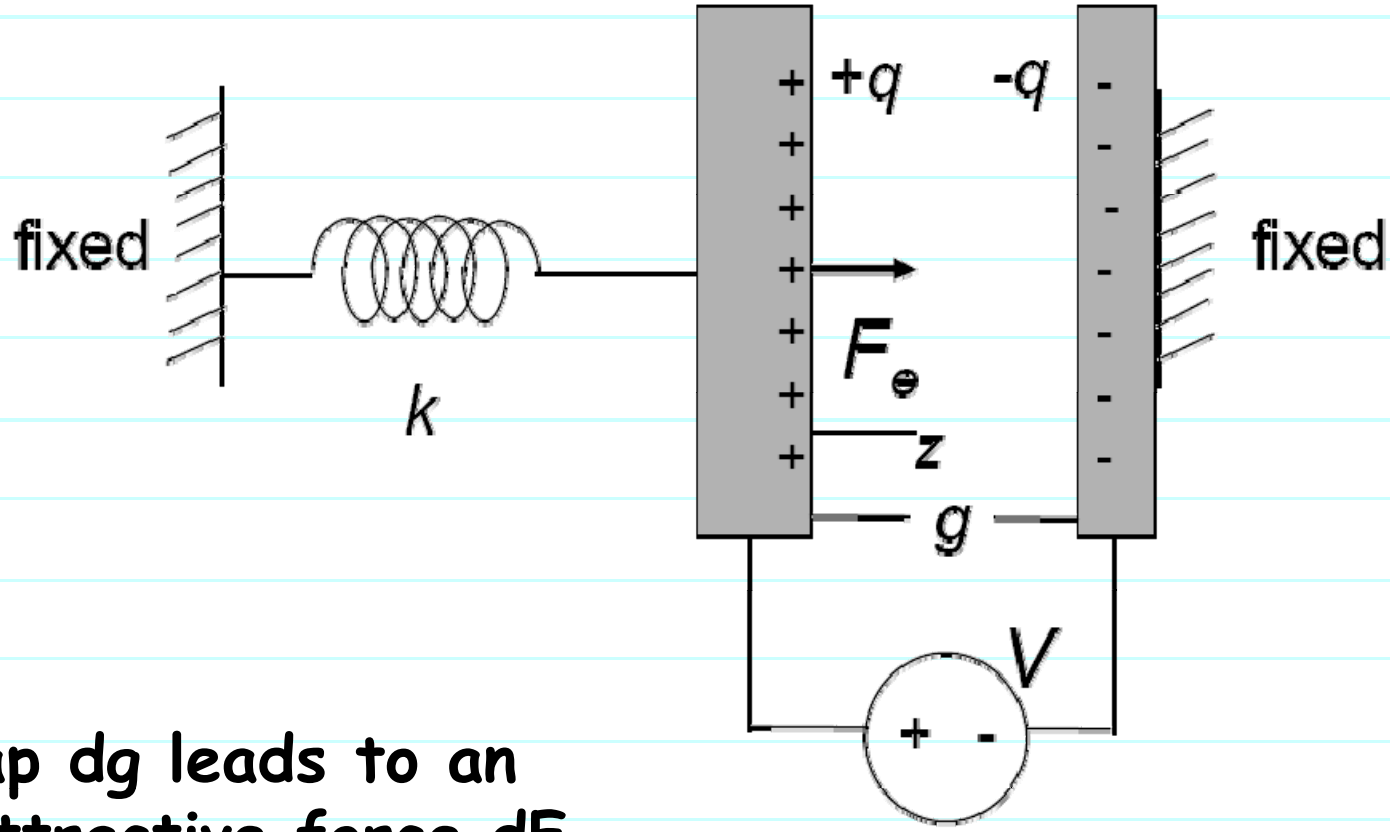


Voltage Control of a Spring-Suspended C



Stability Analysis

- Net attractive force on the plate:



- An increment in gap dg leads to an increment in net attractive force dF_{net}

Pull-In Voltage V_{PI}

- V_{PI} = voltage at which the plates collapse
- The plate goes unstable when

$$k = \frac{\varepsilon A V_{PI}^{2}}{g_{PI}^{3}} \quad (1) \qquad \text{and} \qquad F_{net} = 0 = \frac{\varepsilon A V_{PI}^{2}}{2 g_{PI}^{2}} - k(g_o - g_{PI}) \quad (2)$$

pull-in gap

- Substituting (1) into (2):

$$0 = \frac{\cancel{\varepsilon A V_{PI}^2}}{2 g_{PI}^{\cancel{2}}} - \frac{\cancel{\varepsilon A V_{PI}^2}}{g_{PI}^{\cancel{3}}}(g_o - g_{PI})$$

$$\frac{g_o - g_{PI}}{g_{PI}} = \frac{1}{2} \rightarrow g_o = \frac{3}{2} g_{PI}$$

$$\therefore \boxed{g_{PI} = \frac{2}{3} g_o}$$

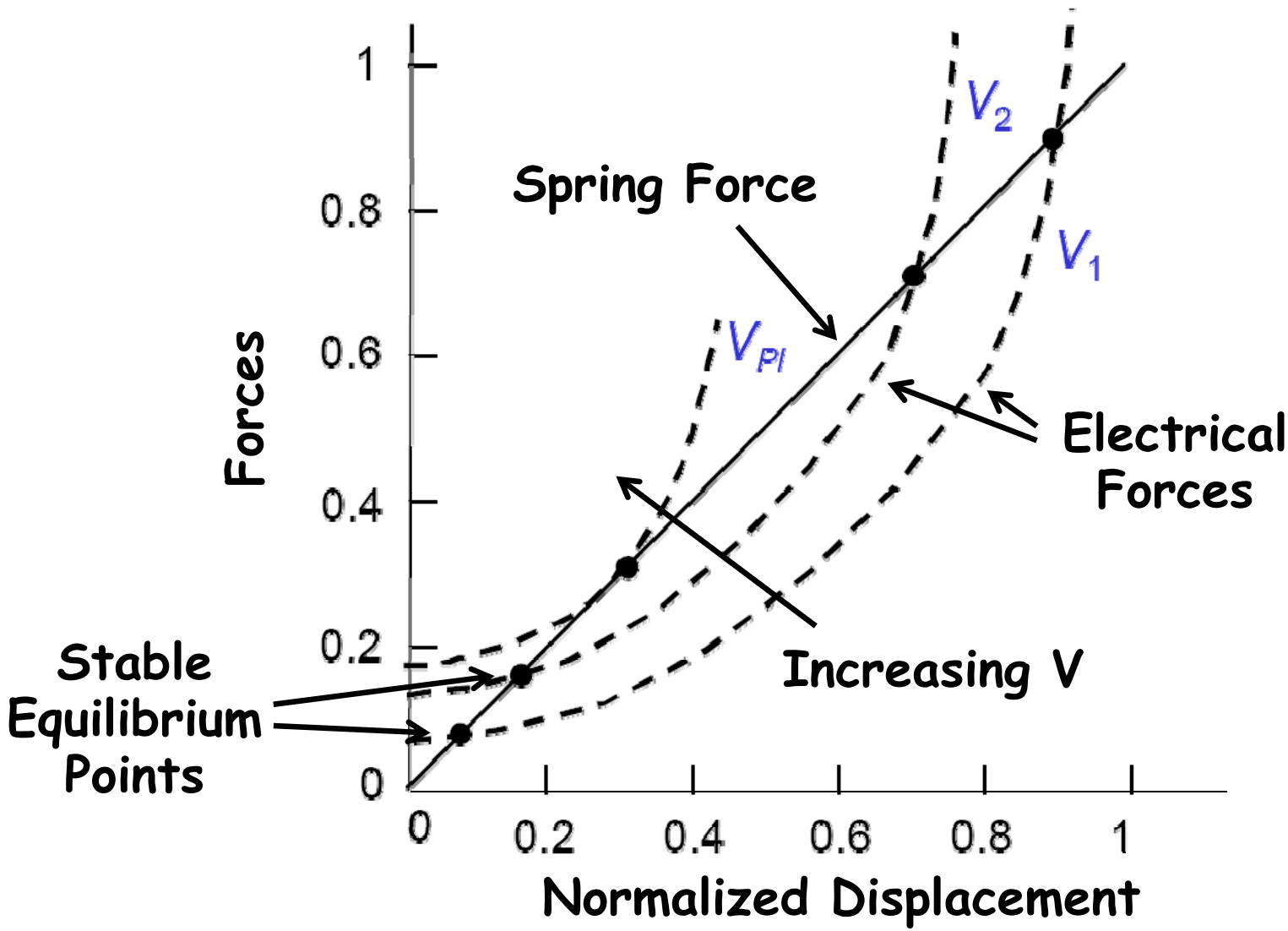
$$V_{PI} = \sqrt{\frac{k g_{PI}^3}{\epsilon A}}$$

$$\therefore \boxed{V_{PI} = \sqrt{\frac{8}{27} \frac{k g_o^3}{\epsilon A}}}$$

When a gap is driven by a voltage to (2/3) its original spacing, collapse will occur!

Voltage-Controlled Plate Stability Graph

- <u>Below</u>: Plot of normalized electrostatic and spring forces vs. normalized displacement $1-(g/g_o)$



Advantages of Electrostatic Actuators

- Easy to manufacture in micromachining processes, since conductors and air gaps are all that's needed → low cost!
- Energy conserving → only parasitic energy loss through I^2R losses in conductors and interconnects
- Variety of geometries available that allow tailoring of the relationships between voltage, force, and displacement
- Electrostatic forces can become very large when dimensions shrink → electrostatics scales well!
- Same capacitive structures can be used for both drive and sense of velocity or displacement
- Simplicity of transducer greatly reduces mechanical energy losses, allowing the highest Q's for resonant structures

Problems With Electrostatic Actuators

- Nonlinear voltage-to-force transfer function
- Relatively weak compared with other transducers (e.g., piezoelectric), but things get better as dimensions scale