EE C247B – ME C218
Introduction to MEMS Design
Spring 2020

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Lecture Module 12: Capacitive Transducers

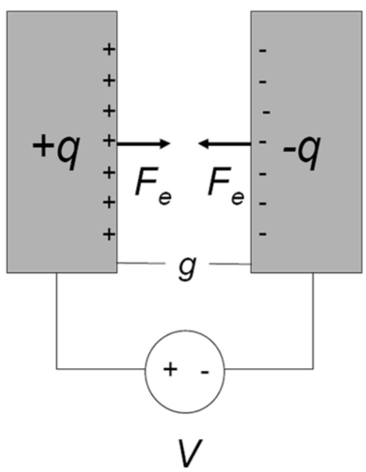
1

Lecture Outline

- Reading: Senturia, Chpt. 5, Chpt. 6
- Lecture Topics:
  - 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

2

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

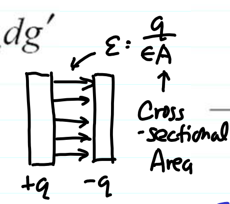
3

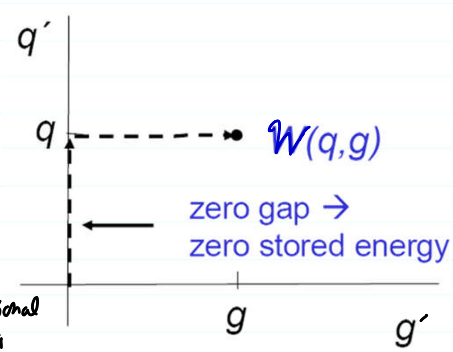
Stored Energy

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

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

No change in charge: $dq=0$





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

(independent of g)

$\therefore W = \int_0^g F_e dg' = F_e g'\Big|_0^g = F_e g$

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

same answer when { Work done to charge C to q at fixed gap

For a capacitor C:

$q = CV \rightarrow V = \frac{q}{C}$

$\therefore W(q) = \int_0^q V dq = \int_0^q \left(\frac{q}{C}\right) dq$

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

4

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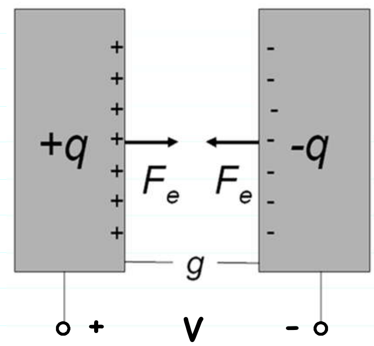
Charge-Control Case

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



From $dW = Vdq + F_e dg$:

⇒ Force is given by:

$$F_e = \left.\frac{\partial W(q,g)}{\partial g}\right|_{q=const.} = \frac{\partial}{\partial g}\left(\frac{1}{2}\frac{q^2}{\epsilon A}g\right)$$

∴ $\boxed{F_e = \frac{1}{2}\frac{q^2}{\epsilon A}}$ ⇒ independent of gap spacing!

⇒ Voltage is given by:

$$V = \left.\frac{\partial W(q,g)}{\partial q}\right|_{g=const.} = \frac{\partial}{\partial q}\left(\frac{1}{2}\frac{q^2}{\epsilon A}g\right) = \frac{qg}{\epsilon A} \quad \therefore \boxed{V = \frac{q}{C}}$$

⇒ consistent w/ what we already know ✓

5

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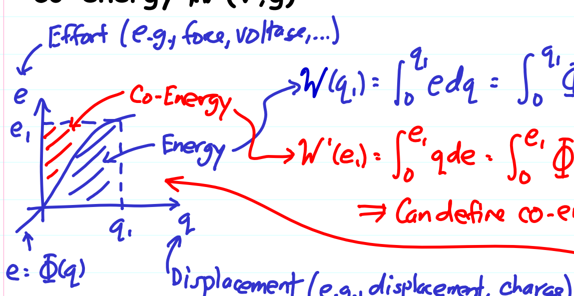
Voltage-Control Case

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



$$W(q_1) = \int_0^{q_1} e\,dq = \int_0^{q_1} \Phi(q)\,dq$$
$$W'(e_1) = \int_0^{e_1} q\,de = \int_0^{e_1} \Phi^{-1}(e)\,de$$

For a linear system, these will be equal.

⇒ Can define co-energy as: $W'(e) = eq - W(q)$ (from this plot)

6

Co-Energy Formulation

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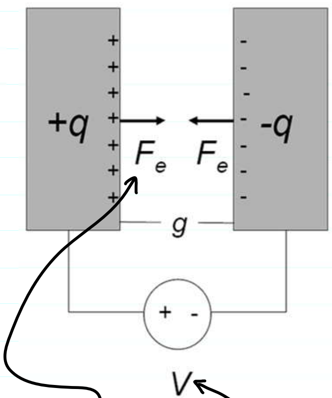
- For our present problem (i.e., movable capacitive plates), the co-energy formulation becomes

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



Differentially, this becomes:

$$d\mathcal{W}'(V,g) = (q\,dV + V\,dq) - d\mathcal{W}(q,g)$$

But $\left[d\mathcal{W}(q,g) = F_e\,dg + V\,dq\right]$

$$\boxed{d\mathcal{W}'(V,g) = q\,dV - F_e\,dg}$$ Working Co-Energy Expression

From which:

Charge, $Q = \left.\dfrac{\partial \mathcal{W}'(V,g)}{\partial V}\right|_{g=\text{const.}}$

Force, $F_e = -\left.\dfrac{\partial \mathcal{W}'(V,g)}{\partial g}\right|_{V=\text{const.}}$ ⇒ this gives force as a function of applied voltage

7

Electrostatic Force (Voltage Control)

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- Find co-energy in terms of voltage (w/ gap held constant)

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

(as expected)

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

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

strong function of gap!

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

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

8

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Spring-Suspended Capacitive Plate

9

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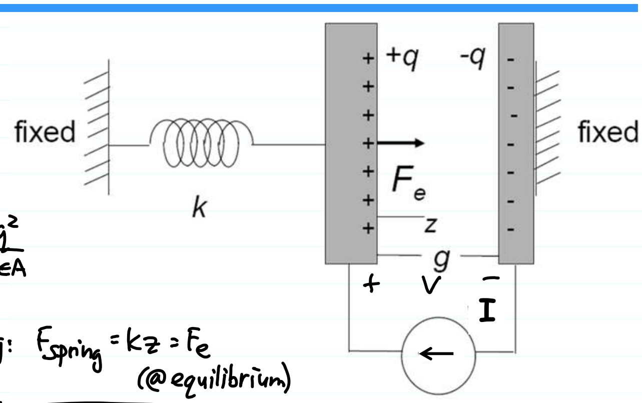
Charge Control of a Spring-Suspended C



Force generated by charge q supplied by current I:

$$F_e = \frac{\partial W(q,g)}{\partial g}\bigg|_q = \frac{q^2}{2\epsilon A}$$

Restoring force of spring: $F_{spring} = kz = F_e$ (@ equilibrium)

And the gap:

$$g = g_o - z = g_o - \frac{F_e}{k} = \boxed{g_o - \frac{1}{2}\frac{q^2}{\epsilon A}\frac{1}{k} = g}$$

initial gap

⇒ can increase q and drive $g \to 0$

$$V = \frac{q}{C} = \frac{q}{\epsilon A} g = \boxed{\frac{q}{\epsilon A}\left(g_o - \frac{1}{2}\frac{q^2}{\epsilon A}\frac{1}{k}\right) = V}$$

⇒ V↓ as g↓

10

Voltage Control of a Spring-Suspended C

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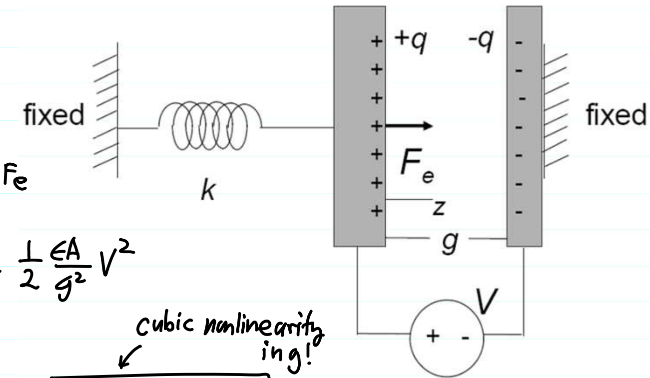

Again, $F_{spring} = kz = F_e$
But now:

$$F_e = \frac{\partial W'(V,g)}{\partial g}\bigg|_V = \frac{1}{2}\frac{\epsilon A}{g^2}V^2$$

cubic nonlinearity ing!

And the gap:

$$g = g_0 - z = g_0 - \frac{F_e}{k} = \boxed{g_0 - \frac{1}{2}\frac{\epsilon A V^2}{g^2 k} = g}$$

$\Rightarrow$ g shows up on both sides!
If $V\uparrow \rightarrow g\downarrow \rightarrow F_e\uparrow$
Feedback!
If loop gain >1, then this will go unstable!

Charge: (for a stable gap)

$$q = \frac{\partial W'(V,g)}{\partial V}\bigg|_g = CV = \boxed{\frac{\epsilon A}{g}V = q}$$

11

Stability Analysis

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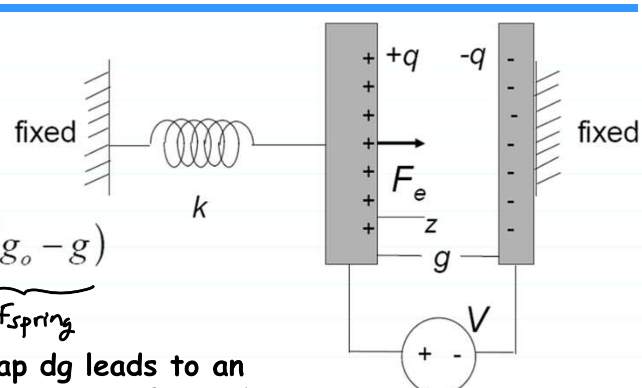
- Net attractive force on the plate:



$$F_{net} = \underbrace{\frac{\varepsilon A V^2}{2g^2}}_{F_e} - \underbrace{k(g_o - g)}_{F_{spring}}$$

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

$$dF_{net} = \frac{\partial F_{net}}{\partial g}dg = \left[-\frac{\epsilon A V^2}{g^3} + k\right]dg$$

Thus, need this = (+) $\Rightarrow$ $\boxed{k > \frac{\epsilon A V^2}{g^3}}$
(for a stable uncollapsed state)

$F_{net}\downarrow \rightarrow dF_{net} = (-)$

If $g\downarrow \rightarrow dg = (-)$, then for stability need $\rightarrow$ otherwise, plate collapses

12

Pull-In Voltage V_{PI}

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

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

$2g_{PI}$ ← 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!

13

Voltage-Controlled Plate Stability Graph

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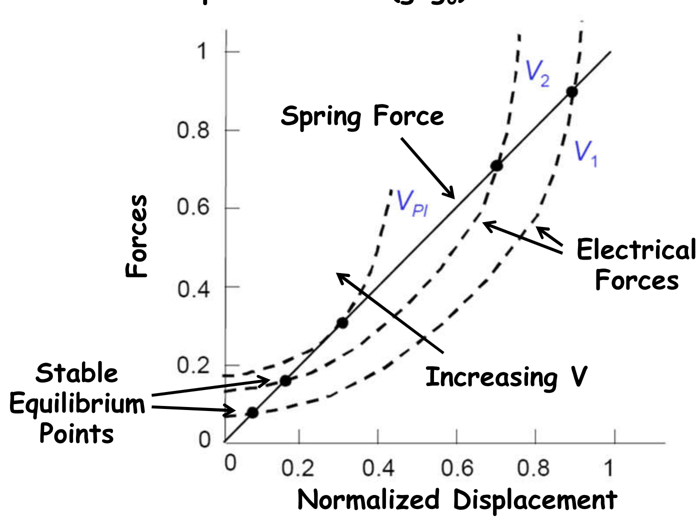
- Below: Plot of normalized electrostatic and spring forces vs. normalized displacement $1-(g/g_o)$



14

Advantages of Electrostatic Actuators

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- 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

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15

Problems With Electrostatic Actuators

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

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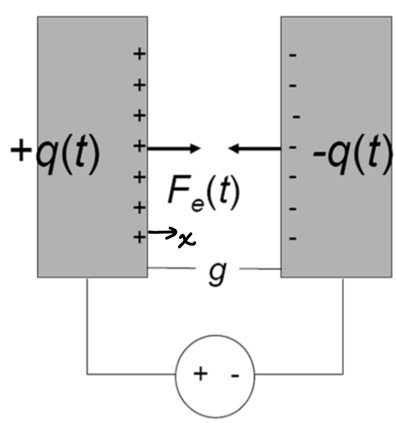
16

Linearizing the Voltage-to-Force Transfer Function

17

Linearizing the Voltage-to-Force T.F.

- Apply a DC bias (or polarization) voltage V_P together with the intended input (or drive) voltage $v_i(t)$, where $V_P >> v_i(t)$



$v(t) = V_P + v_i(t)$

$$F_e(t) = \frac{\partial W}{\partial x} = \frac{\partial}{\partial x}\left(\frac{1}{2}C[v(t)]^2\right)$$

$$= \frac{1}{2}\frac{\partial C}{\partial x}[v(t)]^2 = \frac{1}{2}(V_P + v_i(t))^2\frac{\partial C}{\partial x}$$

$$= \frac{1}{2}\left[V_P^2 + 2V_P v_i(t) + [v_i(t)]^2\right]\frac{\partial C}{\partial x}$$

$$[V_P >> v_i(t)] \Rightarrow F_e(t) = \underbrace{\frac{1}{2}V_P^2\frac{\partial C}{\partial x}}_{\text{DC Offset}} + \underbrace{V_P\frac{\partial C}{\partial x}v_i(t)}_{\text{AC drive signal}}$$

$$C(x) = \frac{\epsilon A}{g_o - x} = C_o\left(1 - \frac{x}{g_o}\right)^{-1} \underset{[x \ll g_o]}{\approx} C_o\left(1 + \frac{x}{g_o}\right)$$

$$\therefore \frac{\partial C}{\partial x} \approx \frac{C_o}{g_o} \Rightarrow \boxed{F_e(t) = \frac{1}{2}\frac{C_o}{g_o}V_P^2 + V_P\underbrace{\frac{C_o}{g_o}}_{\sim\text{const.}}v_i(t)}$$

~const. ∴ linear

18

Differential Capacitive Transducer

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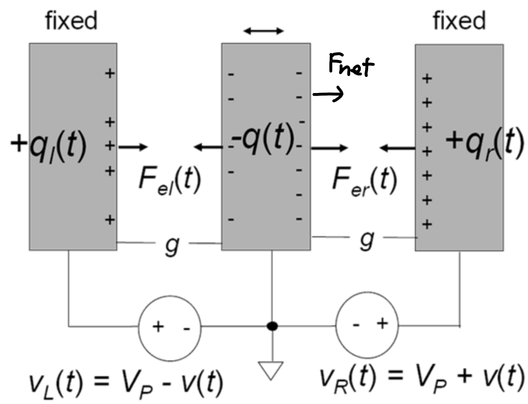
- The net force on the suspended center electrode is

$$F_{net} = F_{er}(t) - F_{el}(t)$$



Do the math.

Assume matched gaps.

$$F_{net}(t) = \frac{1}{2}\frac{\partial C}{\partial x}\left\{[v_R(t)]^2 - [v_L(t)]^2\right\}$$

$$= \frac{1}{2}\frac{\partial C}{\partial x}\left\{\left(\cancel{V_P^2} + 2V_P v(t) + \cancel{[v(t)]^2}\right) - \left(\cancel{V_P^2} - 2V_P v(t) + \cancel{[v(t)]^2}\right)\right\}$$

$$\therefore \boxed{F_{net}(t) = 2V_P\frac{\partial C}{\partial x}v(t) = 2V_P\frac{C_o}{g_o}v(t)}$$

⇒ Linear w/ $v(t)$! (gap match limited)

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19

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Remaining Nonlinearity (Electrical Stiffness)

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20

Parallel-Plate Capacitive Nonlinearity

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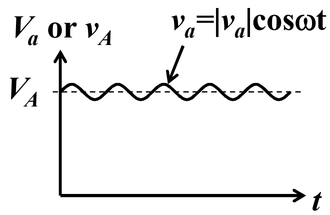
- **Example**: clamped-clamped laterally driven beam with balanced electrodes
- Nomenclature:

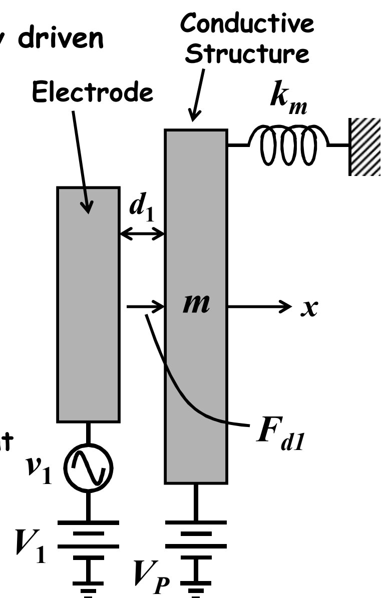


V_a or $v_A = V_A + v_a$

Total Value

DC Component (upper case variable; upper case subscript)

AC or Signal Component (lower case variable; lower case subscript)



Parallel-Plate Capacitive Nonlinearity

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- **Example**: clamped-clamped laterally driven beam with balanced electrodes
- Expression for $\partial C/\partial x$:

$$C_1(x) = \frac{\epsilon A}{d_1 + x} = C_{o1}\left(1 + \frac{x}{d_1}\right)^{-1} \rightarrow \frac{\partial C_1}{\partial x} = -\frac{C_{o1}}{d_1}\left(1 + \frac{x}{d_1}\right)^{-2}$$

[Expand the Taylor series further]

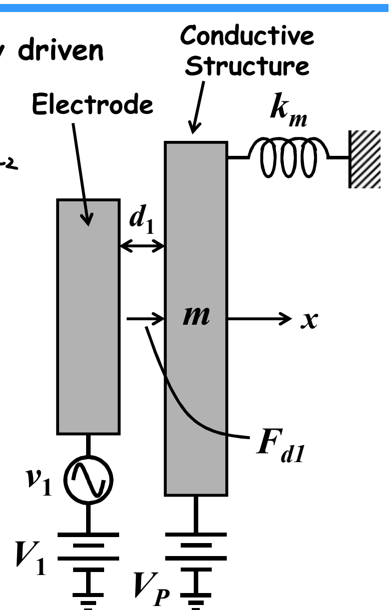
$$\frac{\partial C_1}{\partial x} = -\frac{C_{o1}}{d_1}\left(1 + A_1 x + A_2 x^2 + A_3 x^3 + \cdots\right)$$

where $A_1 = -\frac{2}{d_1}$

$A_2 = \frac{3}{d_1^2}$

$A_3 = -\frac{4}{d_1^3}$

$\vdots$



Parallel-Plate Capacitive Nonlinearity

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- Thus, the expression for force from the left side becomes:

$$F_{d1} = \frac{1}{2}\frac{\partial C}{\partial x}(V_P - V_1 - v_1)^2 = \frac{1}{2}\frac{\partial C}{\partial x}(V_{P1} - v_1)^2$$

{small displacements: $x \ll d_1$}

$$F_{d1} = \frac{1}{2}\left(-\frac{C_{o1}}{d_1}\right)(1 + A_1 x)(V_{P1}^2 - 2V_{P1}v_1 + v_1^2)$$

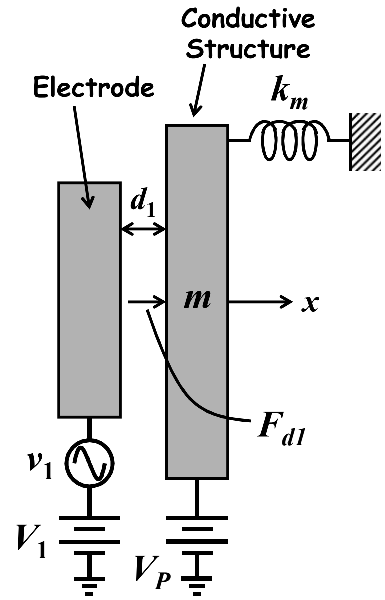
$$= \frac{1}{2}\left(-\frac{C_{o1}}{d_1}\right)\left\{V_{P1}^2 - 2V_{P1}v_1 + v_1^2 + A_1V_{P1}^2 x - 2A_1V_{P1}xv_1 + A_1 x v_1^2\right\}$$

@resonance: $x = \frac{QF_{d1}}{jk} \approx \frac{Q}{jk}\frac{\partial C}{\partial x}V_{P1}v_1$

Thus:

$v_1 = |v_1|\cos\omega_o t \rightarrow x = |x|\sin\omega_o t$

x 90° phase-shifted from v_1



23

Parallel-Plate Capacitive Nonlinearity

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- Retaining only terms at the drive frequency:

$$F_{d1}\big|_{\omega_o} = \underbrace{V_{P1}\frac{C_{o1}}{d_1}|v_1|\cos\omega_o t}_{\text{Drive force arising from the input excitation voltage at the frequency of this voltage}} + V_{P1}^2\frac{C_{o1}}{d_1^2}|x|\sin\omega_o t$$

Proportional to displacement

90° phase-shifted from drive, so in phase with displacement

- These two together mean that this force acts against the spring restoring force!
  - A negative spring constant
  - Since it derives from V_P, we call it the electrical stiffness, given by:

$$\boxed{k_e = V_{P1}^2\frac{C_{o1}}{d_1^2} = V_{P1}^2\frac{\varepsilon A}{d_1^3}}$$

24

Electrical Stiffness, k_e

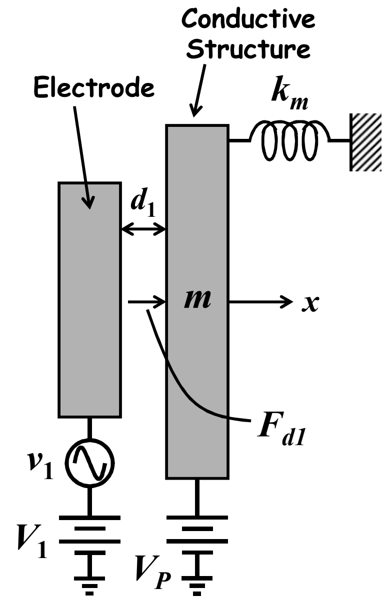
- The electrical stiffness k_e behaves like any other stiffness
- It affects resonance frequency:

$$\omega_o' = \sqrt{\frac{k}{m}} = \sqrt{\frac{k_m - k_e}{m}}$$

$$= \sqrt{\frac{k_m}{m}}\left(1 - \frac{k_e}{k_m}\right)^{1/2}$$

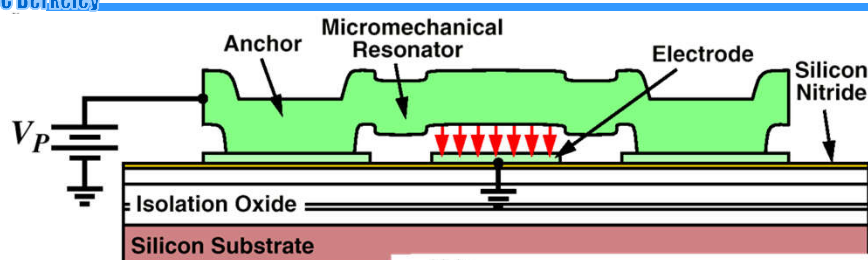
$$\boxed{\omega_o' = \omega_o\left(1 - \frac{V_{P1}^2}{k_m}\frac{\varepsilon A}{d_1^3}\right)^{1/2}}$$

Frequency is now a function of dc-bias V_{P1}



25

Voltage-Controllable Center Frequency



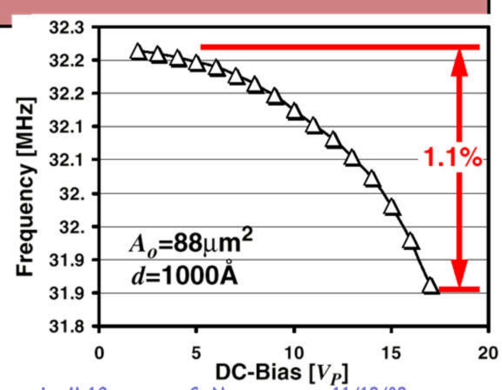
- Quadrature force ➠ voltage-controllable electrical stiffness:

$$k_e = \frac{\varepsilon_o A_o}{d^3} V_P^2$$

Electrode Overlap Area

Gap

$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_m - k_e}{m_r}}$$



26

Microresonator Thermal Stability

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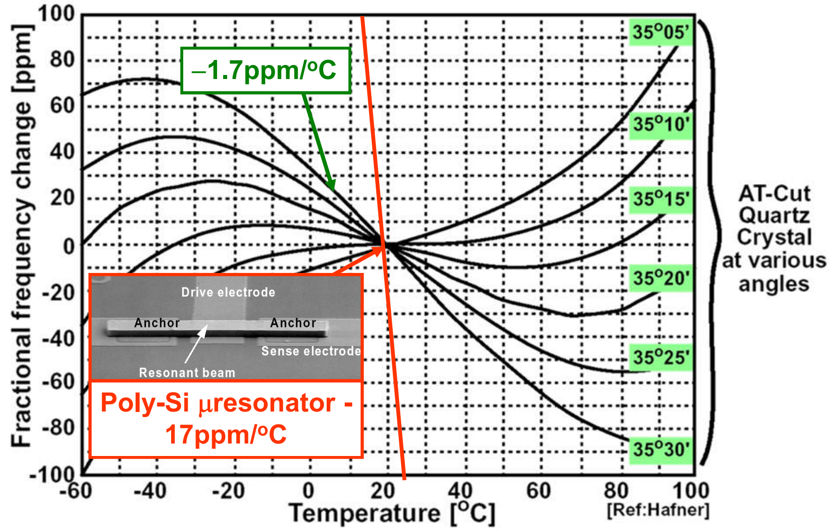

- Thermal stability of poly-Si micromechanical resonator is 10X worse than the worst case of AT-cut quartz crystal

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27

Geometric-Stress Compensation

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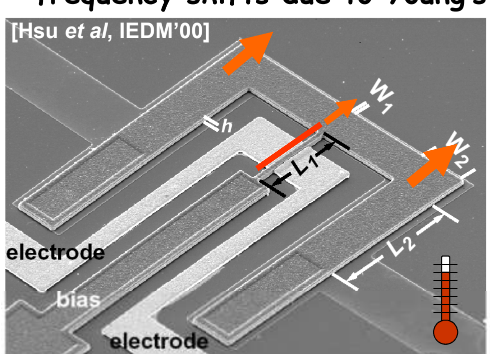
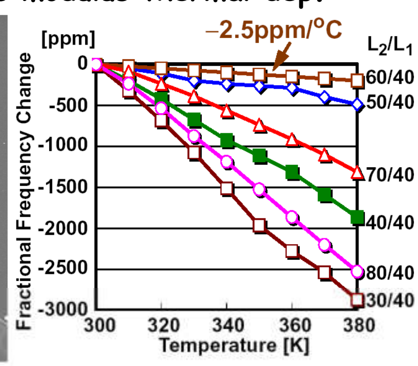
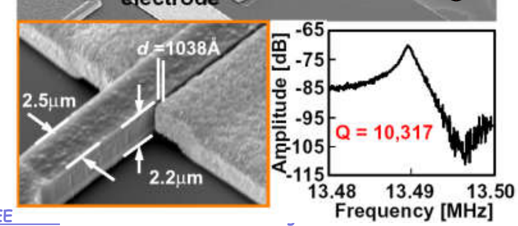
- Use a temperature dependent mechanical stiffness to null frequency shifts due to Young's modulus thermal dep.







- ***Problems***:
  - stress relaxation
  - compromised design flexibility

[Hsu *et al* IEDM 2000]

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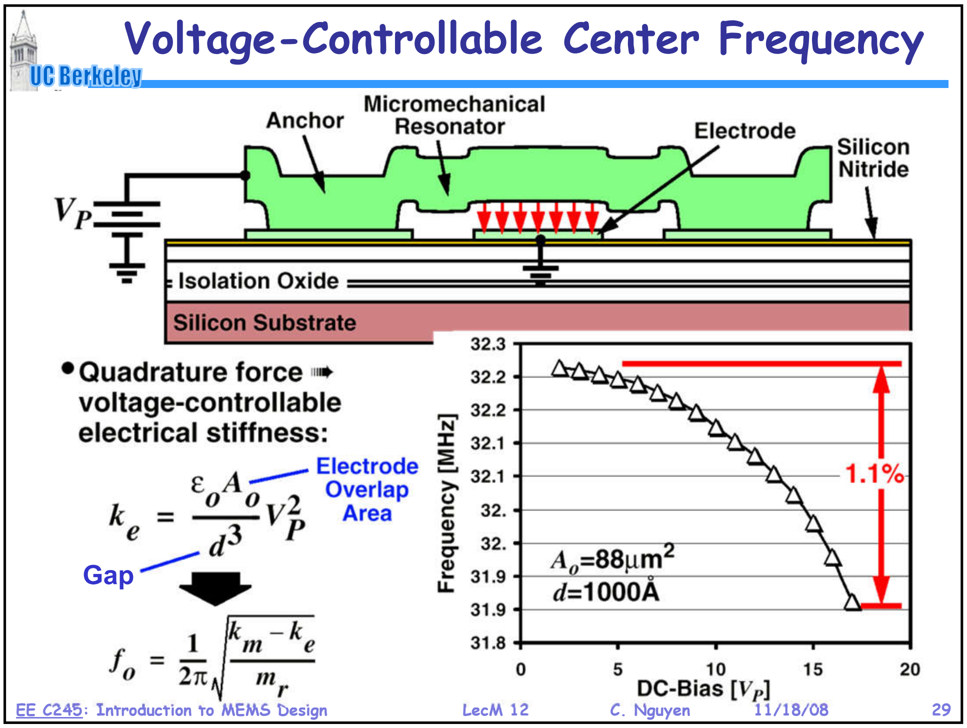
28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Voltage-Controllable Center Frequency
Anchor
Micromechanical Resonator
Electrode
Silicon Nitride
V_P
Isolation Oxide
Silicon Substrate
• Quadrature force ➠ voltage-controllable electrical stiffness:
$k_e = \frac{\varepsilon_o A_o}{d^3} V_P^2$
Electrode Overlap Area
Gap
$f_o = \frac{1}{2\pi}\sqrt{\frac{k_m - k_e}{m_r}}$
Frequency [MHz]
32.3
32.2
32.2
32.1
32.1
32.
32.
31.9
31.9
31.8
0
5
10
15
20
DC-Bias [V_P]
1.1%
A_o=88μm^2
d=1000Å
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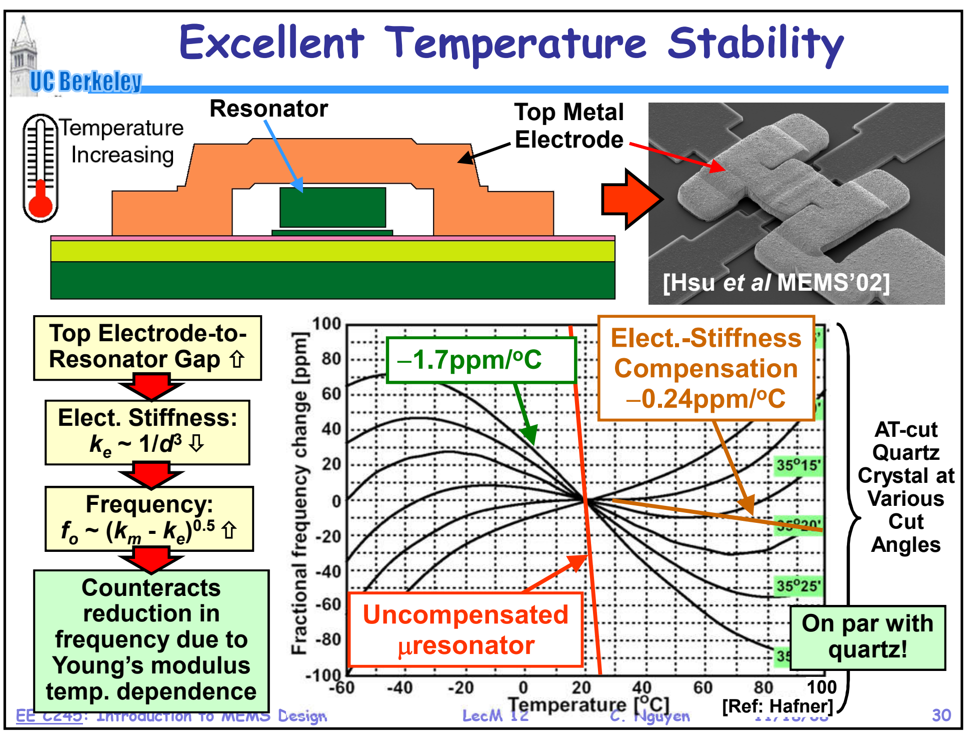
29

29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Excellent Temperature Stability
Temperature Increasing
Resonator
Top Metal Electrode
[Hsu et al MEMS'02]
Top Electrode-to-Resonator Gap ⇧
Elect. Stiffness: $k_e \sim 1/d^3$ ⇩
Frequency: $f_o \sim (k_m - k_e)^{0.5}$ ⇧
Counteracts reduction in frequency due to Young's modulus temp. dependence
Fractional frequency change [ppm]
–1.7ppm/°C
Elect.-Stiffness Compensation –0.24ppm/°C
35°15'
35°20'
35°25'
Uncompensated μresonator
On par with quartz!
AT-cut Quartz Crystal at Various Cut Angles
100
80
60
40
20
0
-20
-40
-60
-80
-100
-60
-40
-20
0
20
40
60
80
100
Temperature [°C]
[Ref: Hafner]
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LecM 12
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30

30

Measured $\Delta f/f$ vs. T for k_e-Compensated μResonators

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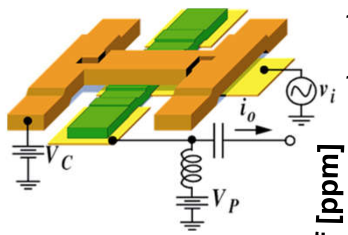
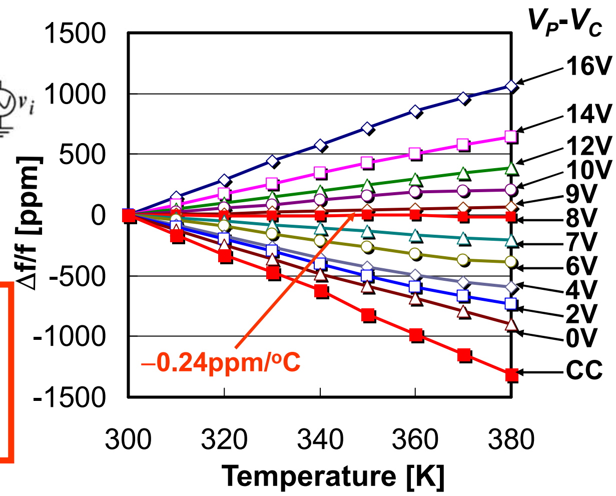


Design/Performance:
f_o =10MHz, Q=4,000
V_P=8V, h_e=4μm
d_o=1000Å, h=2μm
W_r=8μm, L_r=40μm

[Hsu *et al* MEMS'02]



- Slits help to release the stress generated by lateral thermal expansion ▯ linear TC_f curves ▯ –0.24ppm/°C!!!

31

Can One Cancel k_e w/ Two Electrodes?

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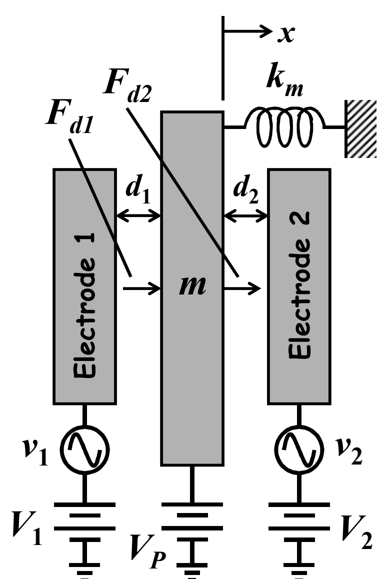
- What if we don't like the dependence of frequency on V_P?
- Can we cancel k_e via a differential input electrode configuration?
- If we do a similar analysis for F_{d2} at Electrode 2:

$$F_{d2}\Big|_{\omega_o} = \overbrace{-V_{P2}\frac{C_{o2}}{d_2}|v_2|\cos\omega_o t}^{\text{Subtracts from the } F_{d1} \text{ term, as expected}} \underbrace{+V_{P2}^2\frac{C_{o2}}{d_2^2}|x|\sin\omega_o t}_{\text{Adds to the quadrature term} \rightarrow k_e\text{'s add, no matter the electrode configuration!}}$$



32

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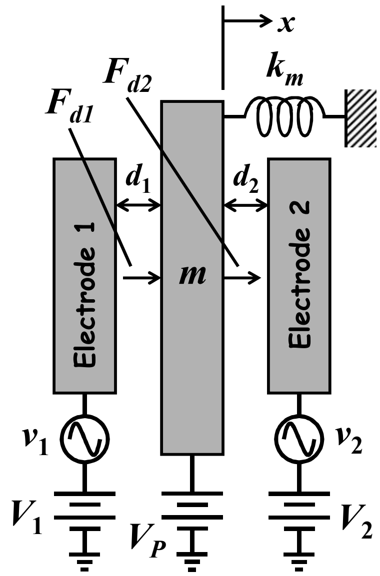
Problems With Parallel-Plate C Drive

- Nonlinear voltage-to-force transfer function
  - Resonance frequency becomes dependent on parameters (e.g., bias voltage V_P)
  - Output current will also take on nonlinear characteristics as amplitude grows (i.e., as x approaches d_o)
  - Noise can alias due to nonlinearity
- Range of motion is small
  - For larger motion, need larger gap … but larger gap weakens the electrostatic force
  - Large motion is often needed (e.g., by gyroscopes, vibromotors, optical MEMS)



33

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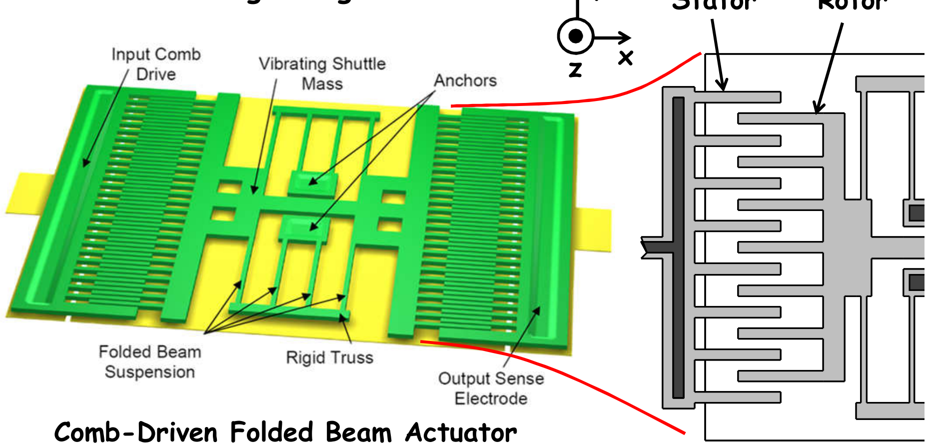
Electrostatic Comb Drive

34

Electrostatic Comb Drive

- Use of comb-capacitive tranducers brings many benefits
  - Linearizes voltage-generated input forces
  - (Ideally) eliminates dependence of frequency on dc-bias
  - Allows a large range of motion



Comb-Driven Folded Beam Actuator

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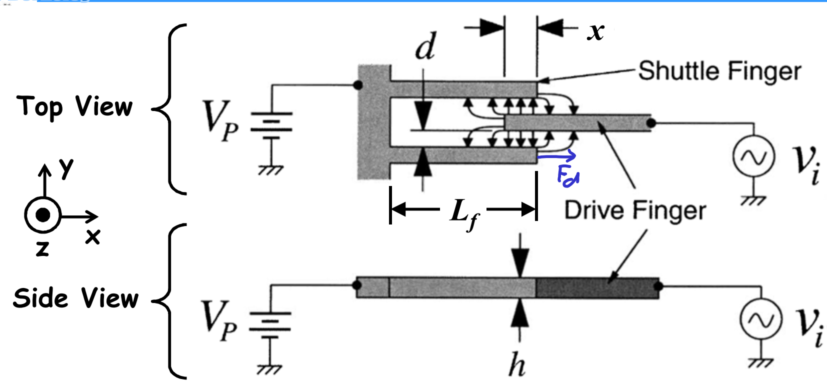
35

Comb-Drive Force Equation (1st Pass)



$$C(x) = \frac{2\epsilon_o x h}{d} \rightarrow \left[\frac{\partial C}{\partial x} = \frac{2\epsilon_o h}{d}\right]$$

When $v_i = (+) \rightarrow F_d = (-)$ ✓

$$F_d = \frac{\partial W'}{\partial x} = \frac{1}{2}\frac{\partial C}{\partial x}(V_P - v_i)^2 = \frac{2}{2}\frac{\epsilon_o h}{d}(V_P^2 - 2V_P v_i + v_i^2) \approx \boxed{-2V_P\frac{\epsilon_o h}{d}v_i = F_d}$$

But wait! This ignores other practical effects!

(No dependence on x! LINEAR!)

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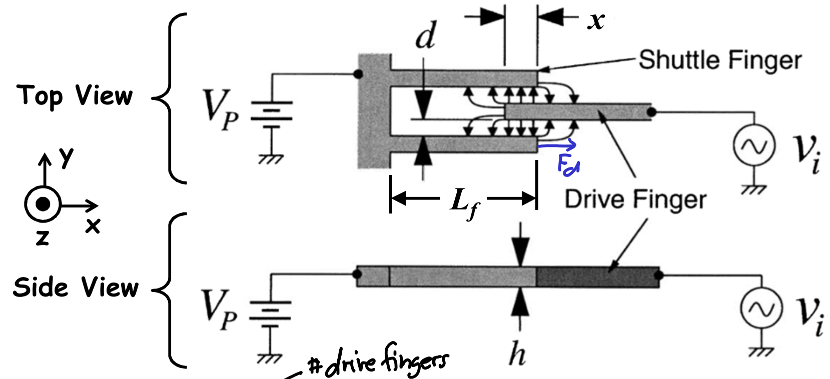
36

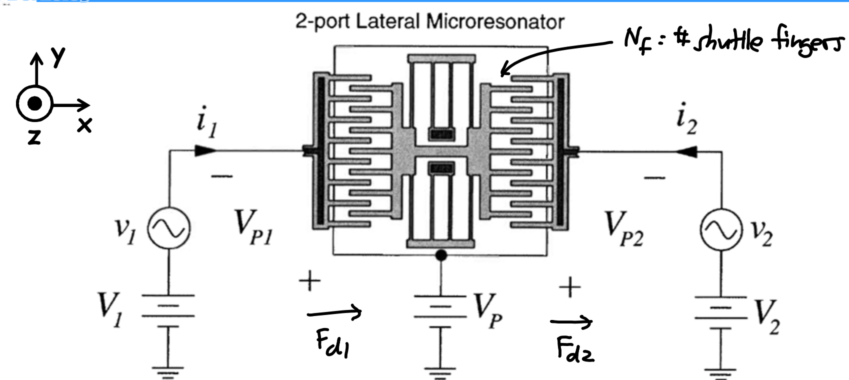
Lateral Comb-Drive Electrical Stiffness



- Again: $C(x) = \frac{2N\varepsilon h x}{d} \rightarrow \frac{\partial C}{\partial x} = \frac{2N\varepsilon h}{d}$
- No ($\partial C/\partial x$) x-dependence → no electrical stiffness: k_e = 0!
- Frequency immune to changes in V_P or gap spacing!

37

Typical Drive & Sense Configuration



Simple Analysis:

$$F_{d1} = \frac{1}{2}\frac{\partial C_1}{\partial x}(v_1 - V_{P1})^2 = \frac{1}{2}\left(-\frac{\epsilon_o h}{d_1}\right)(v_1^2 - 2V_{P1}v_1 + V_{P1}^2)(2N_f)$$

$$F_{d2} = \frac{1}{2}\frac{\partial C_2}{\partial x}(v_2 - V_{P2})^2 = \frac{1}{2}\left(\frac{\epsilon_o h}{d_2}\right)(v_2^2 - 2V_{P2}v_2 + V_{P2}^2)(2N_f)$$

$$\therefore F_{net} = F_{d1} + F_{d2} = \frac{1}{2}\left(\frac{\epsilon_o h}{d}\right)\left(v_2^2 - v_1^2 - 2(V_{P2}v_2 - V_{P1}v_1) + V_{P2}^2 - V_{P1}^2\right)(2N_f)$$

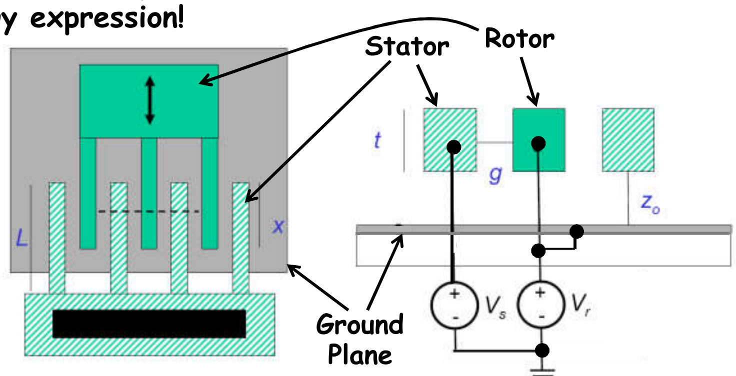
For $V_1 = V_2$, $v_1 = -v_2$

$$\boxed{F_{net} = 2(2N_f)\left(\frac{\epsilon_o h}{d}\right)V_{P1}v_1}$$

38

Comb-Drive Force Equation (2nd Pass)

- In our 1st pass, we accounted for
  - Parallel-plate capacitance between stator and rotor
- … but neglected:
  - Fringing fields
  - Capacitance to the substrate
- All of these capacitors must be included when evaluating the energy expression!

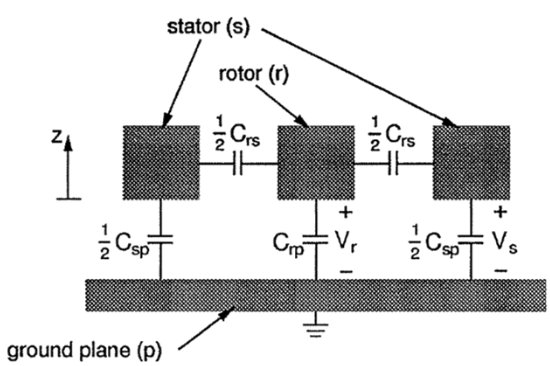


39

Comb-Drive Force With Ground Plane Correction

- Finger displacement changes not only the capacitance between stator and rotor, but also between these structures and the ground plane → modifies the capacitive energy

$$F_{e,x} = \frac{\partial W'}{\partial x} = \frac{1}{2}\frac{dC_{sp}}{dx}V_s^2 + \frac{1}{2}\frac{dC_{rp}}{dx}V_r^2 + \frac{1}{2}\frac{dC_{rs}}{dx}\left(V_s - V_r\right)^2$$



[Gary Fedder, Ph.D., UC Berkeley, 1994]

40

Capacitance Expressions

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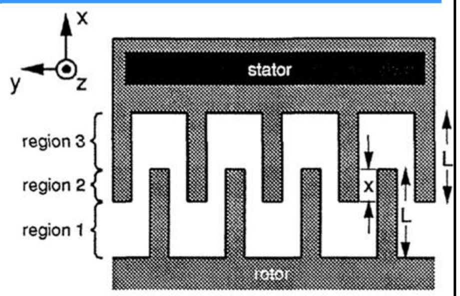
- Case: $V_r = V_P = 0V$
- C_{sp} depends on whether or not fingers are engaged

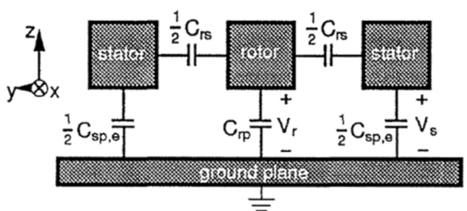


$$C_{sp} = N[C'_{sp,e}x + C'_{sp,u}(L-x)]$$

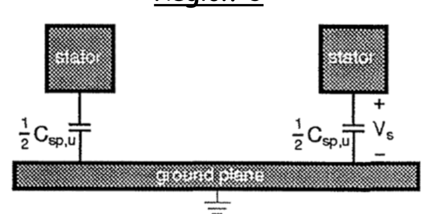
$$C_{rs} = NC'_{rs}x$$

Capacitance per unit length

Region 2



Region 3



[Gary Fedder, Ph.D., UC Berkeley, 1994]

41

Comb-Drive Force With Ground Plane Correction

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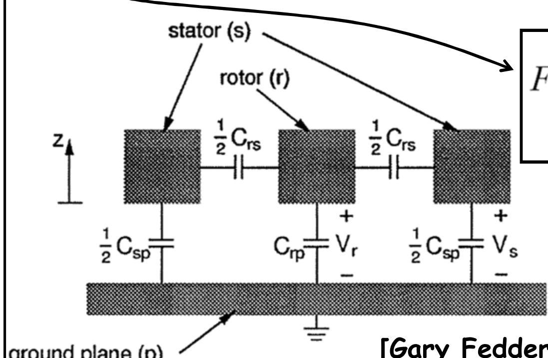
- Finger displacement changes not only the capacitance between stator and rotor, but also between these structures and the ground plane → modifies the capacitive energy

$$F_{e,x} = \frac{\partial W'}{\partial x} = \frac{1}{2}\frac{dC_{sp}}{dx}V_s^2 + \frac{1}{2}\frac{dC_{rp}}{dx}V_r^2 + \frac{1}{2}\frac{dC_{rs}}{dx}(V_s - V_r)^2$$



$$\boxed{F_{e,x} = \frac{N}{2}(C'_{rs} + C'_{sp,e} - C'_{sp,u})V_s^2}$$

(for $V_r = V_p = 0$)

[Gary Fedder, Ph.D., UC Berkeley, 1994]

42

Simulate to Get Capacitors → Force

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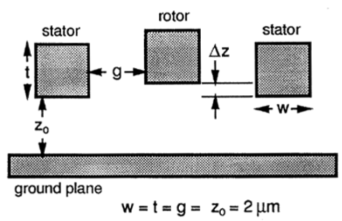
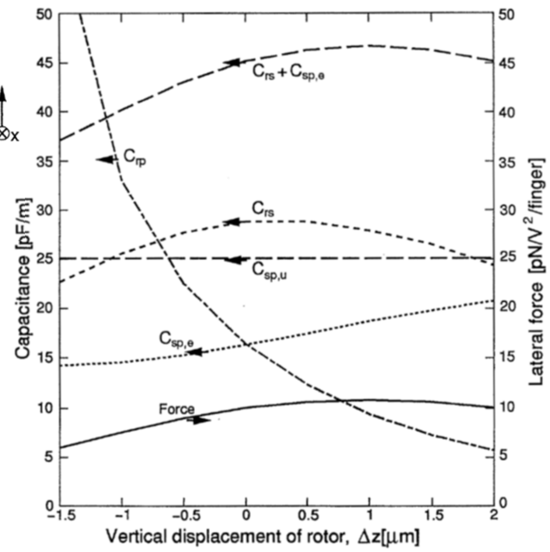
- **Below**: 2D finite element simulation



$$F_{e,x} = \frac{N}{2}(\underbrace{C'_{rs} + C'_{sp,e} - C'_{sp,u}}) V_s^2$$

20-40% reduction of $F_{e,x}$



43

Vertical Force (Levitation)

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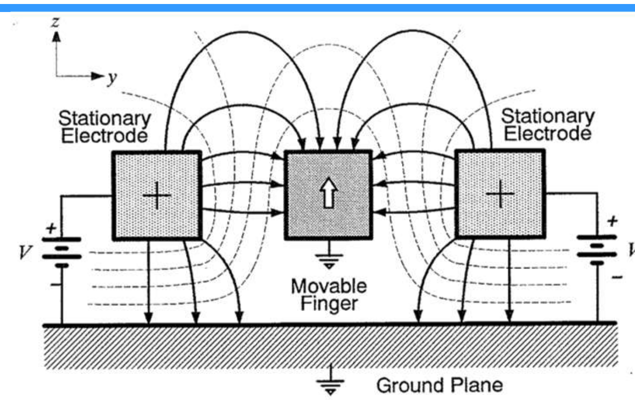


$$F_{e,z} = \frac{\partial W'}{\partial z} = \frac{1}{2}\frac{dC_{sp}}{dz}V_s^2 + \frac{1}{2}\frac{dC_{rp}}{dz}V_r^2 + \frac{1}{2}\frac{dC_{rs}}{dz}(V_s - V_r)^2$$

- **For V_r = 0V (as shown):** $F_{e,z} = \frac{1}{2} Nx \left[\frac{d\left(C'_{sp,e} + C'_{rs}\right)}{dz}\right] V_s^2$

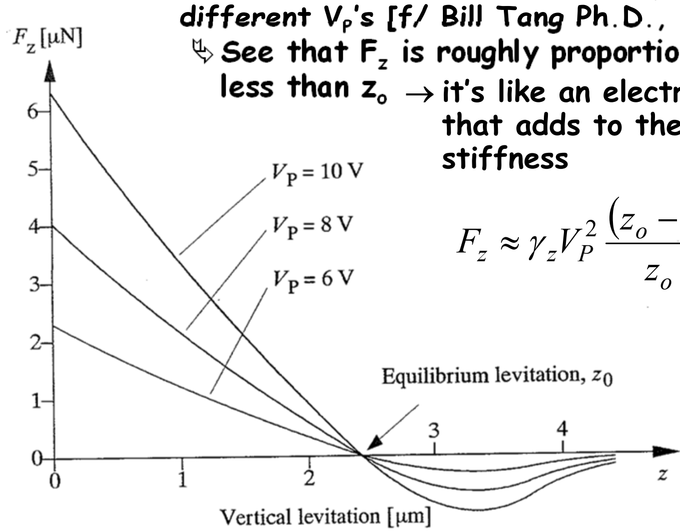
44

Simulated Levitation Force

- Below: simulated vertical force F_z vs. z at different V_P's [f/ Bill Tang Ph.D., UCB, 1990]
  - See that F_z is roughly proportional to –z for z less than z_o → it's like an electrical stiffness that adds to the mechanical stiffness

$$F_z \approx \gamma_z V_P^2 \frac{(z_o - z)}{z_o} = k_e(z_o - z)$$

Electrical Stiffness



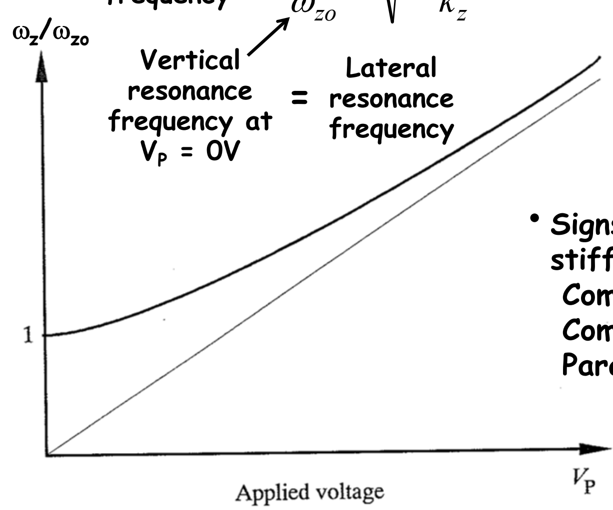
45

Vertical Resonance Frequency

Vertical resonance frequency →

$$\frac{\omega_z}{\omega_{zo}} = \sqrt{\frac{k_z + k_e}{k_z}} \quad \text{where} \quad k_e = \left(\frac{\gamma_z}{z_o}\right)V^2$$

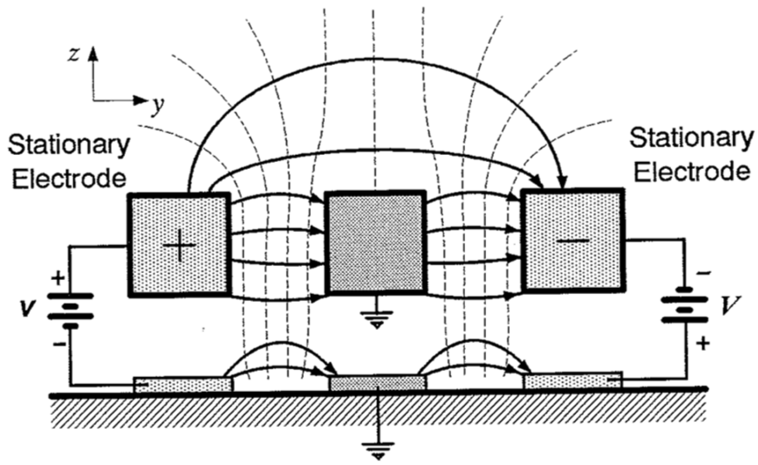
Vertical resonance frequency at V_P = 0V = Lateral resonance frequency



- Signs of electrical stiffnesses in MEMS:
  - Comb (x-axis) → k_e = 0
  - Comb (z-axis) → k_e > 0
  - Parallel Plate → k_e < 0

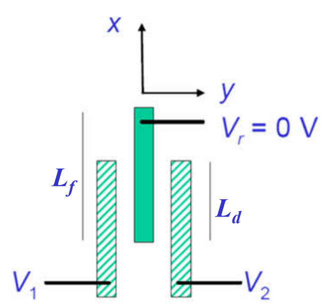
46

Suppressing Levitation



- Pattern ground plane polysilicon into differentially excited electrodes to minimize field lines terminating on top of comb
- Penalty: x-axis force is reduced

Force of Comb-Drive vs. Parallel-Plate



Gap = d_o = 1 μm
Thickness = h = 2 μm
Finger Length = L_f = 100 μm
Finger Overlap = L_d = 75 μm

- Comb drive (x-direction)
  - $V_1 = V_2 = V_S = 1V$

$$F_{e,x} = \frac{1}{2}\frac{\varepsilon_o h}{d_o} V_s^2$$

- Differential Parallel-Plate (y-direction)
  - $V_1 = 0V,\ V_2 = 1V$

$$F_{e,y} = \frac{1}{2}\frac{\varepsilon_o h L_d}{d_o^2} V_2^2$$

$$\frac{F_{e,y}}{F_{e,x}} = \frac{\frac{1}{2}\frac{\varepsilon_o h L_d}{d_o^2} V_2^2}{\frac{1}{2}\frac{\varepsilon_o h}{d_o} V_s^2} = \frac{L_d}{d_o}$$

Parallel-plate generates a much larger force; but at the cost of linearity