Voltage-Controllable Center Frequency

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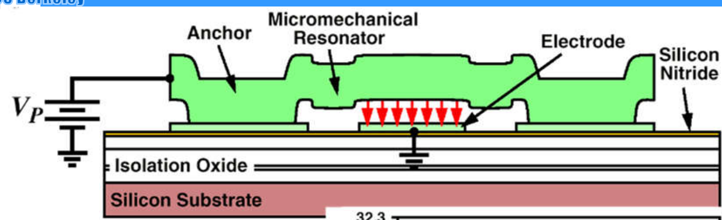


- Quadrature force ➠ voltage-controllable electrical stiffness:

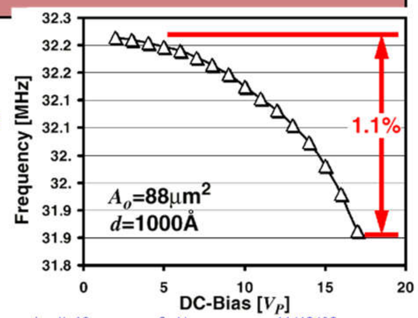
$$k_e = \frac{\varepsilon_o A_o}{d^3} V_P^2$$

Electrode Overlap Area

Gap

⬇

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



Microresonator Thermal Stability

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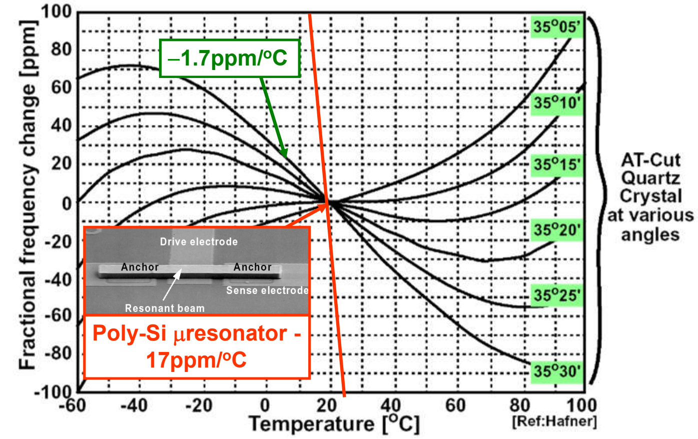

- Thermal stability of poly-Si micromechanical resonator is 10X worse than the worst case of AT-cut quartz crystal

Geometric-Stress Compensation

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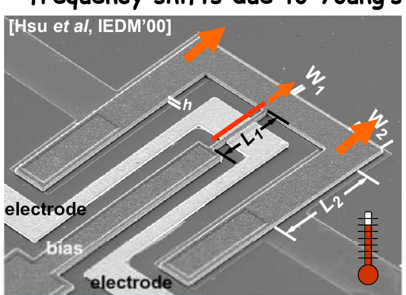
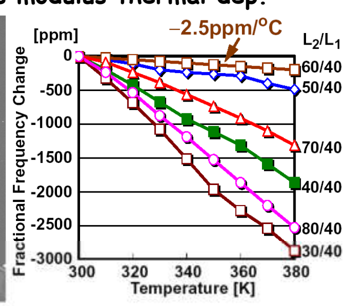
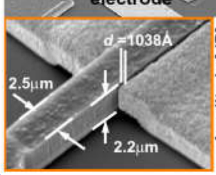
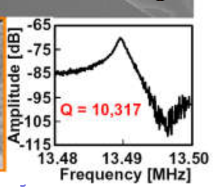
- Use a temperature dependent mechanical stiffness to null frequency shifts due to Young's modulus thermal dep.









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

[Hsu *et al* IEDM 2000]

Voltage-Controllable Center Frequency

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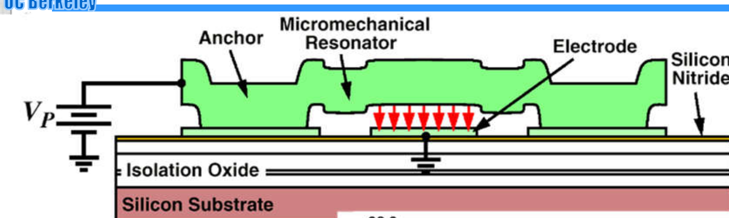

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Gap

⬇

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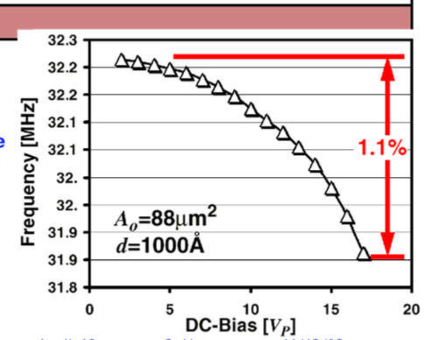

Excellent Temperature Stability

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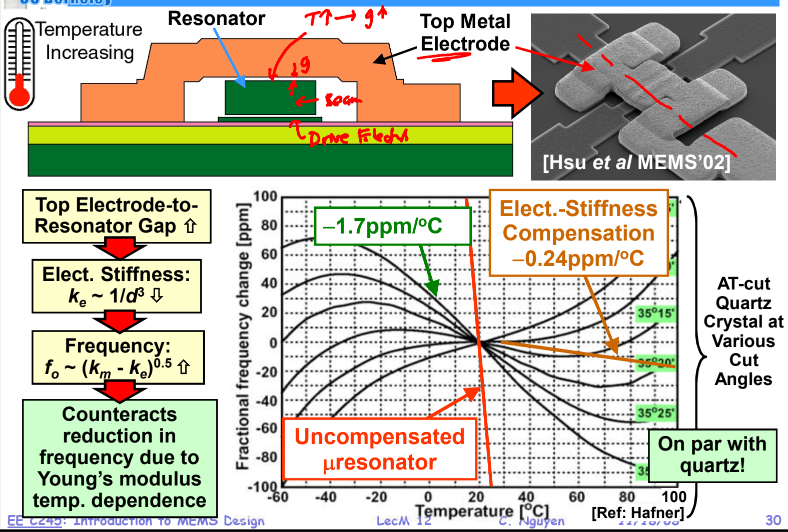

Measured $\Delta f/f$ vs. T for k_e-Compensated μResonators

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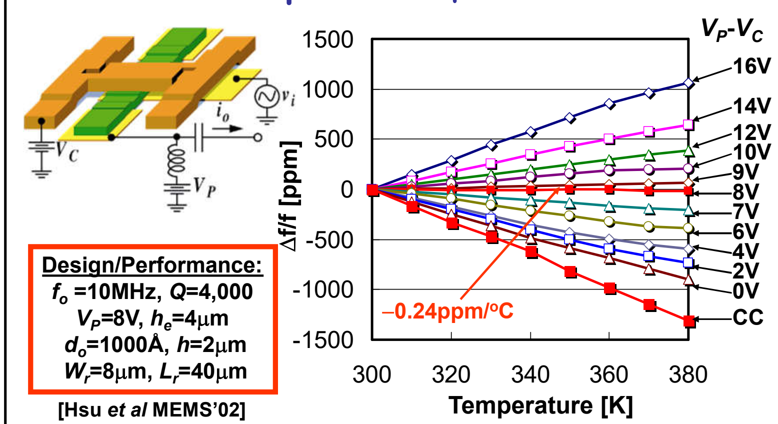

- Slits help to release the stress generated by lateral thermal expansion ⍰ linear TC_f curves ⍰ -0.24ppm/°C!!!

Can One Cancel k_e w/ Two Electrodes?

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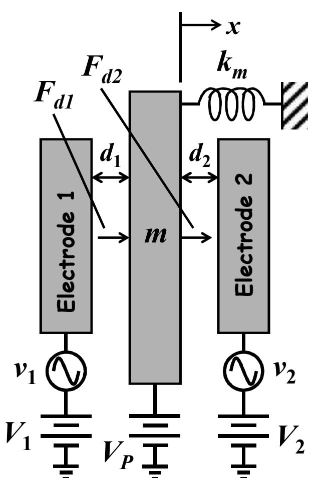
- What if we don't like the dependence of frequency on V_P?
- Can we cancel k_e via a differential input electrode configuration?
- If we do a similar analysis for F_{d2} at Electrode 2:

Subtracts from the F_{d1} term, as expected

$$F_{d2}\big|_{\omega_o} = -V_{P2}\frac{C_{o2}}{d_2}|v_2|\cos\omega_o t + V_{P2}^2\frac{C_{o2}}{d_2^2}|x|\sin\omega_o t$$

Adds to the quadrature term → k_e's add, no matter the electrode configuration!



Problems With Parallel-Plate C Drive

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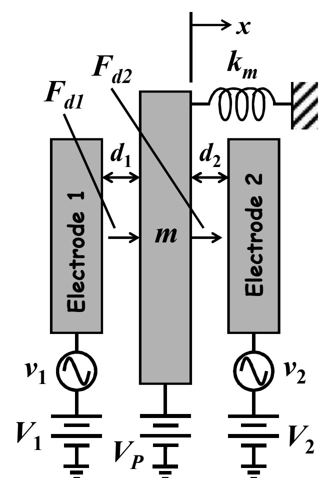
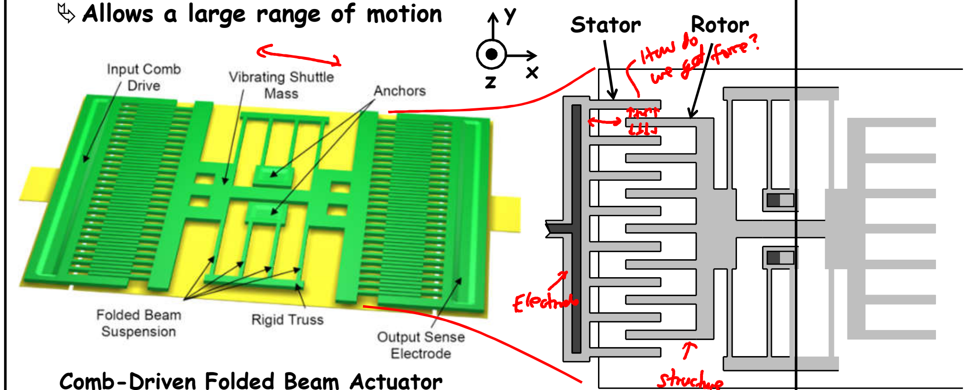
- Nonlinear voltage-to-force transfer function
  - Resonance frequency becomes dependent on parameters (e.g., bias voltage V_P)
  - Output current will also take on nonlinear characteristics as amplitude grows (i.e., as x approaches d_o)
  - Noise can alias due to nonlinearity
- Range of motion is small
  - 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)



Electrostatic Comb Drive

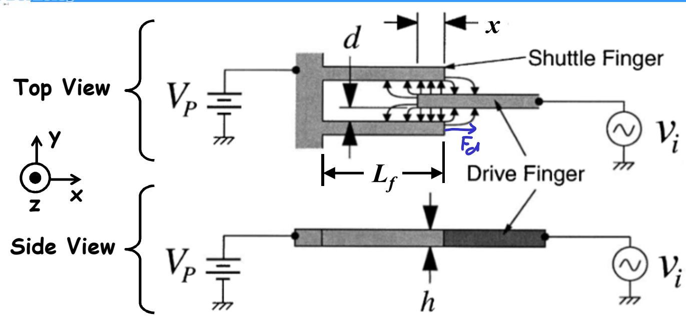
Electrostatic Comb Drive

- 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

Comb-Drive Force Equation (1st Pass)



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

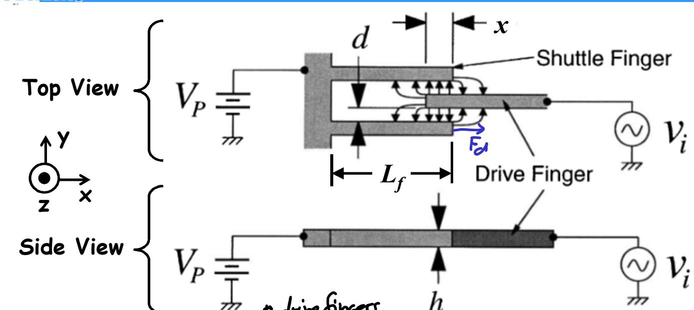
$F_d = \frac{\partial W'}{\partial x} = \frac{1}{2}\frac{\partial C}{\partial x}(V_P - v_i)^2 = \frac{2}{2}\frac{\epsilon_o h}{d}(V_P^2 - 2V_P v_i + v_i^2) \approx \boxed{-2V_P \frac{\epsilon_o h}{d} v_i = F_d}$

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

→ But wait! This ignores other practical effects!

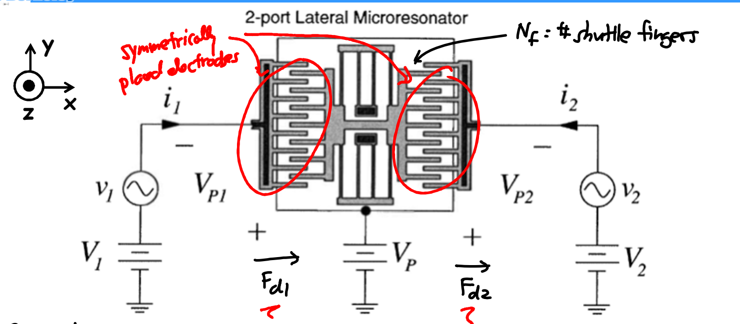
(No dependence on x! LINEAR!)

Lateral Comb-Drive Electrical Stiffness



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

Typical Drive & Sense Configuration



Simple Analysis:

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

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

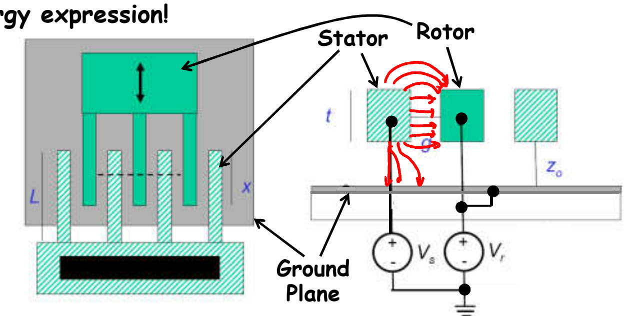
$$\therefore F_{net} = F_{d1} + F_{d2} = \frac{1}{2}\left(\frac{\epsilon_o h}{d}\right)(v_2^2 - v_1^2 - 2(V_{P2}v_2 - V_{P1}v_1) + V_{P2}^2 - V_{P1}^2)(2N_f)$$

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

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

Comb-Drive Force Equation (2nd Pass)

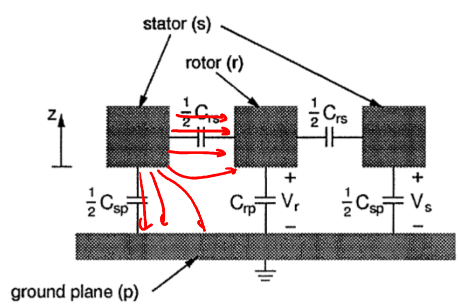
- In our 1st pass, we accounted for
  - Parallel-plate capacitance between stator and rotor
- … but neglected:
  - Fringing fields
  - Capacitance to the substrate
- All of these capacitors must be included when evaluating the energy expression!



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

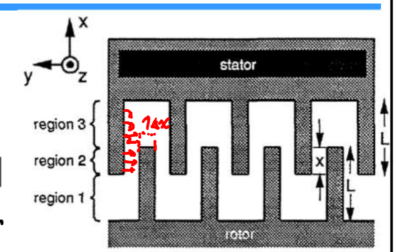
$$F_{e,x} = \frac{\partial W'}{\partial x} = \frac{1}{2}\frac{dC_{sp}}{dx}V_s^2 + \frac{1}{2}\frac{dC_{rp}}{dx}V_r^2 + \frac{1}{2}\frac{dC_{rs}}{dx}(V_s - V_r)^2$$



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

Capacitance Expressions

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

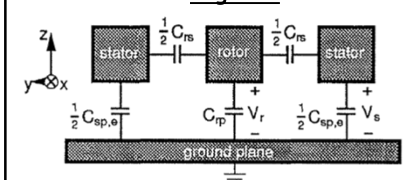


$$C_{sp} = N[C'_{sp,e}x + C'_{sp,u}(L - x)]$$

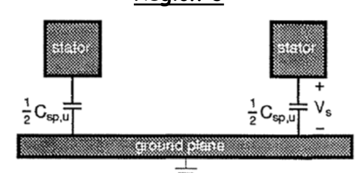
$$C_{rs} = NC'_{rs}x$$

Capacitance per unit length

Region 2



Region 3



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

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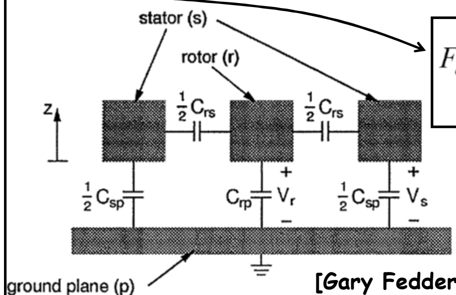


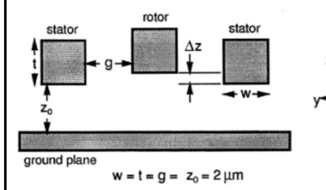
$$F_{e,x} = \frac{N}{2}(C'_{rs} + C'_{sp,e} - C'_{sp,u})V_s^2$$

(for $V_r = V_p = 0$)

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

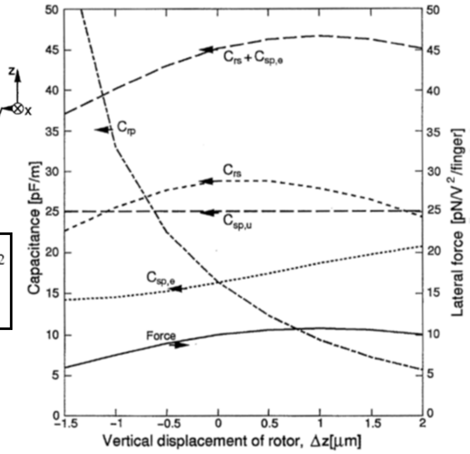
Simulate to Get Capacitors → Force

- Below: 2D finite element simulation

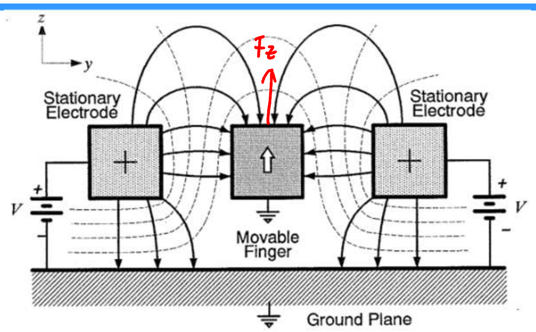


$$F_{e,x} = \frac{N}{2}(C'_{rs} + C'_{sp,e} - C'_{sp,u})V_s^2$$

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



Vertical Force (Levitation)

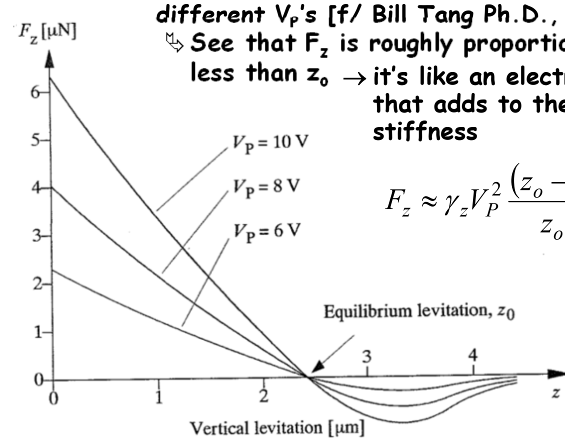


$$F_{e,z} = \frac{\partial W'}{\partial z} = \frac{1}{2}\frac{dC_{sp}}{dz}V_s^2 + \frac{1}{2}\frac{dC_{rp}}{dz}V_r^2 + \frac{1}{2}\frac{dC_{rs}}{dz}(V_s - V_r)^2$$

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

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

Vertical Resonance Frequency

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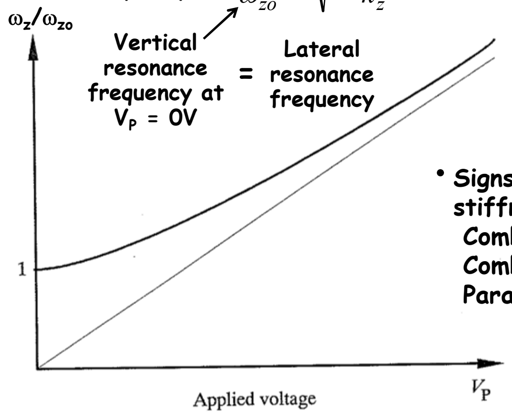
Vertical resonance frequency → $\frac{\omega_z}{\omega_{zo}} = \sqrt{\frac{k_z + k_e}{k_z}}$ where $k_e = \left(\frac{\gamma_z}{z_o}\right)V^2$



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

Suppressing Levitation

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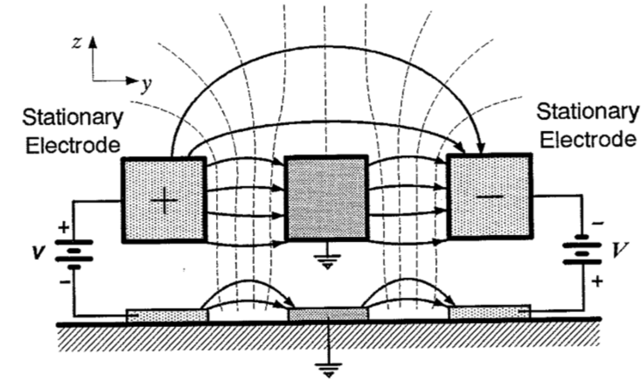

- Pattern ground plane polysilicon into differentially excited electrodes to minimize field lines terminating on top of comb
- Penalty: x-axis force is reduced

Force of Comb-Drive vs. Parallel-Plate

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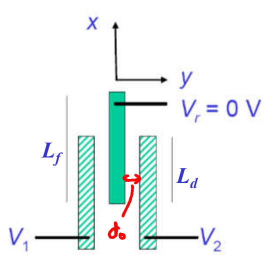

Gap = d_o = 1 μm
Thickness = h = 2 μm
Finger Length = L_f = 100 μm
Finger Overlap = L_d = 75 μm

- 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