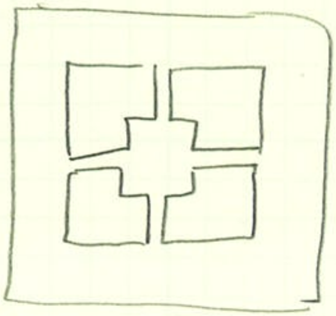
2. Implementing PPA's – fairly straightforward to implement for vertical motion

SOI process:

Design



Si: $E = 168\ GPA$, $\delta = 2.35\ g/cm^3$

proof mass: 250μm x 250μm wide
10μm thick

springs: 250μm long, 5μm wide, 10μm thick

$N_{Leg} = 4$, $N_{Zig} = 1$

Device layer: 10μm

Box layer: 5μm

Handle: 500μm

Using Formulas previously given:

$K = 215.04\ N/m$

$m = 2.9375 \times 10^{-11}\ Kg$

$w_n = 2.7 \times 10^{6}\ rad/s$

$f_n = 430.6\ KHz$

} high due to small proof mass

C at rest = 0.1107 pF

C at PI = 0.166 pF

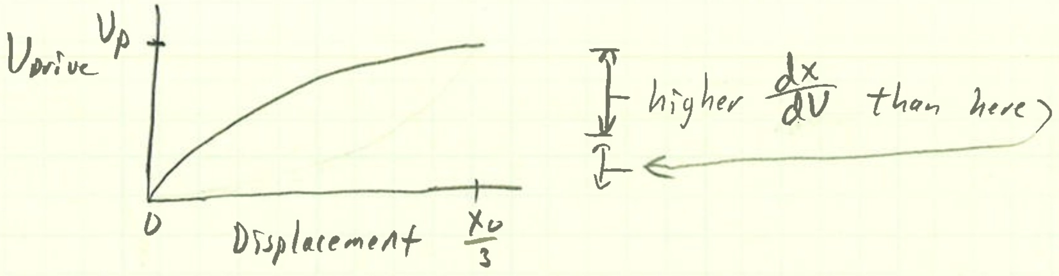
$V_{PI} = 120\ V$

Force at PI = 358.4 μN

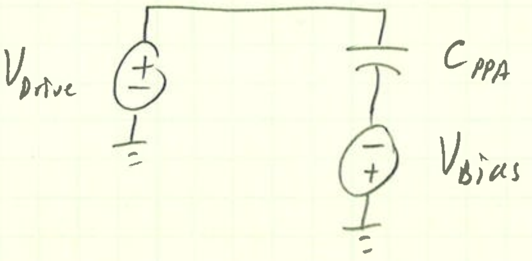
Note, the Frame and the Handle also forms a capacitor which is in series with the C_{PPA} → a problem for the Series Cap Method

→ Often a DC bias V is applied so that a smaller drive voltage is needed to achieve a bigger range of motion:

Ex :



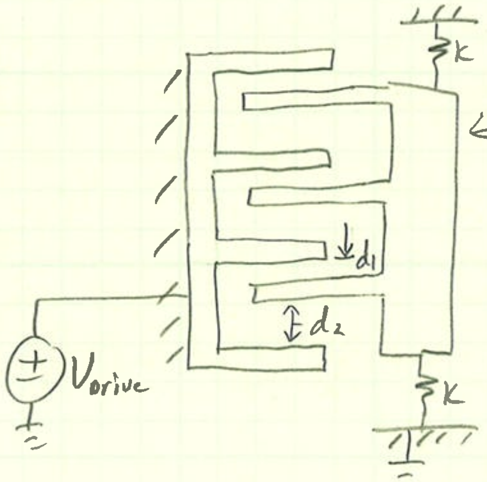
$\therefore$ Sometimes this is done to lower V_{Drive}



$\Leftarrow$ negative bias voltage applied to other electrode

This may limit motion range to $\frac{2}{30}X_0 \leq x \leq \frac{9}{30}X_0$, but V_{Drive} might drop from 100V to 25V, with a −75V bias

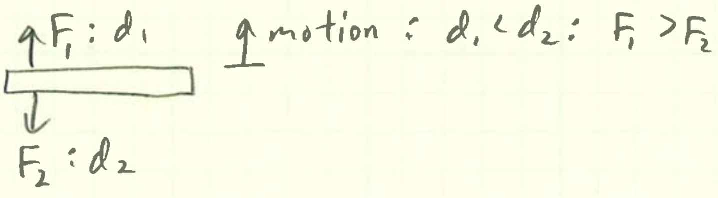
3. It can be difficult to realize latteral moving PPAs due to small surface area for C_{PPA}. However, consider this



← n PPAs arranged for latteral movement

← fringing is now a significant part of the total capacitance. $\beta \equiv$ fringing effect correction factor

each tooth :



motion : $d_1 < d_2$: $F_1 > F_2$

1) GCA's Continued

$$F_{EL} = \frac{n\varepsilon_0\varepsilon_r A\beta}{2}\left[\frac{1}{(d_1-x)^2} - \frac{1}{(d_2+x)^2}\right]V^2$$

This electrostatic actuator is called a Gap-Closing Actuator (GCA) and is often used as a binary actuator by applying $V_{Drive} = 0V$ (no motion) or $V_{Drive} > V_p$ (full motion)

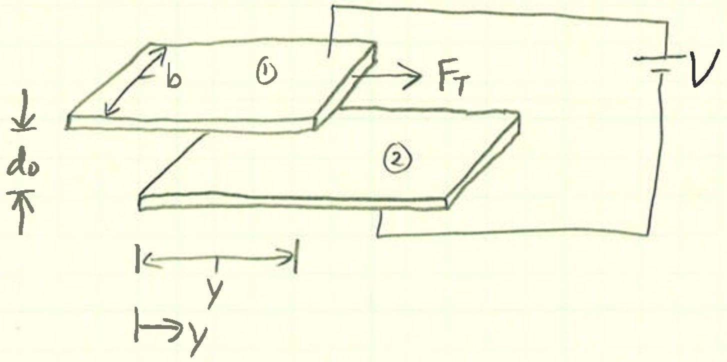
→ Mechanical stops are usually used to prevent the electrodes from making contact for $V_{Drive} > V_p$ {with minimal surface area to prevent stiction problems}

The larger $d_2 : d_1$ ratio → the more the GCA acts like a PPA.

As $d_2 \rightarrow d_1$, the stable range of motion decreases from $\frac{x_o}{3}$ toward 0 and V_p increases as $d_2 \rightarrow d_1$

At $d_2 = d_1$: $F_2 = F_1$ → no lateral motion (for an "ideal" device)

2) Tangential Electrostatic Actuation



Electrode ② is fixed in space

Electrode ① can move along y only

$C = \frac{\varepsilon_0 \varepsilon_r b y}{d_0}$ { ignoring fringing }

→ Electrostatic force seeks to increase C

Energy balance equation : $F_T \Delta y + \frac{dE_c}{dy} \Delta y + \frac{dE_B}{dy} \Delta y = 0$

$$\frac{dE_c}{dy} = \frac{1}{2} \frac{\partial C(y)}{\partial y} V^2 = \frac{\varepsilon_0 \varepsilon_r b V^2}{2 d_0}$$

$$\frac{dE_B}{dy} = -\frac{\partial Q(y)}{\partial y} V \qquad \{ Q = CV \}$$

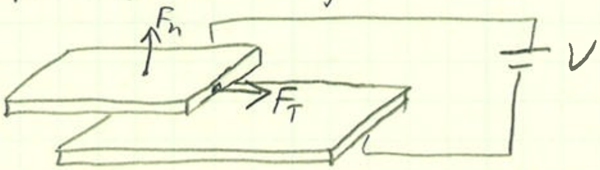
$$= -\frac{\partial C(y) V^2}{\partial y}$$

$$= -\frac{\varepsilon_0 \varepsilon_r b V^2}{d_0}$$

$$F_T = -\frac{dE_c}{dy} - \frac{dE_B}{dy} = -\frac{\varepsilon_0 \varepsilon_r b V^2}{2 d_0} + \frac{\varepsilon_0 \varepsilon_r b V^2}{d_0} = \frac{\varepsilon_0 \varepsilon_r b V^2}{2 d_0}$$

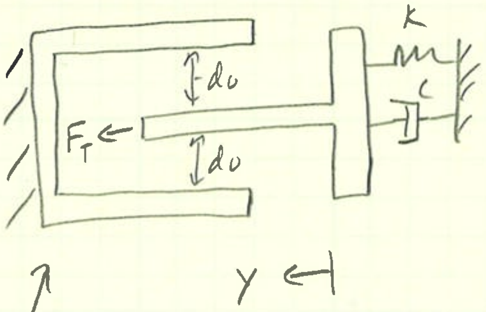
↑ observe that force is independent of displacement

a. <u>Expanding the design</u>



although $F_T = \frac{\varepsilon_0 \varepsilon_r b V^2}{2 d_0}$, a normal force also exists between the electrodes : $F_n = -\frac{\varepsilon_0 \varepsilon_r b y V^2}{2 (d_0)^2}$

Consider this design:



↑ ignors capacitance between tip end and the other electrode

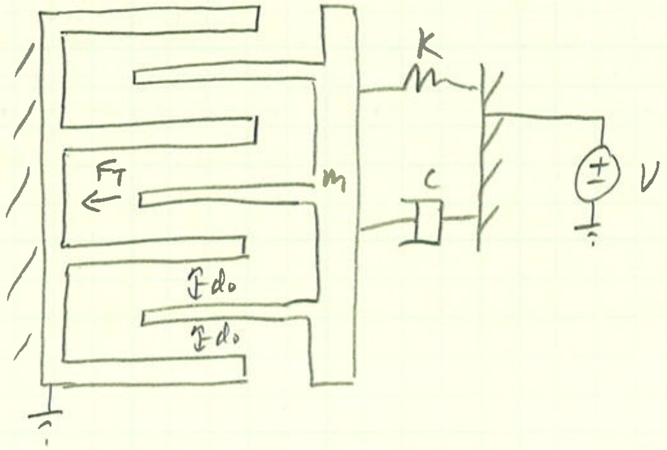
$$F_T \simeq 2 \left(\frac{\varepsilon_0 \varepsilon_r b V^2}{2 d_0} \right) = \frac{\varepsilon_0 \varepsilon_r b V^2}{d_0}$$

Fringing can be a sizable amount of the total capacitance

∴ use β to account for this : $\beta > 1$

$$\therefore F_T = \frac{\varepsilon_0 \varepsilon_r b \beta V^2}{d_0}$$

Gang multiple elements together



← n tangential electode pairs

$$F_T = \frac{n \varepsilon_0 \varepsilon_r b \beta V^2}{d_o}$$

→ easily implemented in Device Layer of an SOI wafer for lateral motion → called a "Combdrive Actuator" → "CDA"

Design issues:

① design fingers wide enough to be considered as "rigid"

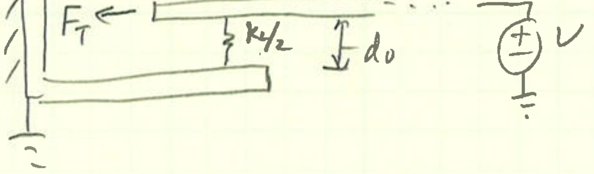
② design enough initial electrode overlap

③ design enough clearance between finger end and back wall at full displacement range

④ design sufficient suspension system

⑤ Lateral Instability

→ a real suspension system will usually allow some motion perpendicular to F_T



K_L → latteral suspension spring constant

As the movable electrode is displaced, the suspension system may let the movable comb displace away from its centered position

→ at this point, this off-centered position results in an imbalance in forces normal to F_T

→ $C_0 = \frac{2 \varepsilon_0 \varepsilon_r b y}{d_0}$ {when balanced}

→ as V ↑, a latteral instability will eventually be reached, equivalent to the GCA pull-in voltage

→ this occurs for $V > \sqrt{\frac{K_x d_0^2}{C_0}}$

∴ design K sufficiently stiff and limit V to maintain lateral stability