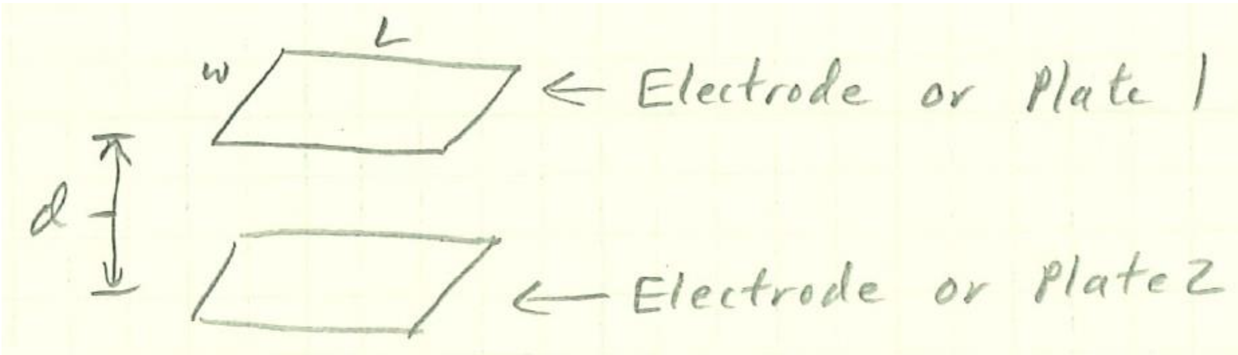
Lecture 9/19/22

Capacitive Sensing

1. Simple Parallel Plate Capacitor



d is the electrode separation distance.

For A >> d^2: fringing effects can be ignored and $C = \frac{\varepsilon_o \varepsilon_r A}{d}$

where: ε_o = permittivity of free space = 8.854 pF/m

ε_r = relative permittivity of the dielectric material between the electrodes
For a vacuum $\varepsilon_r = 1$, and for most gases: $\varepsilon_r \approx 1$

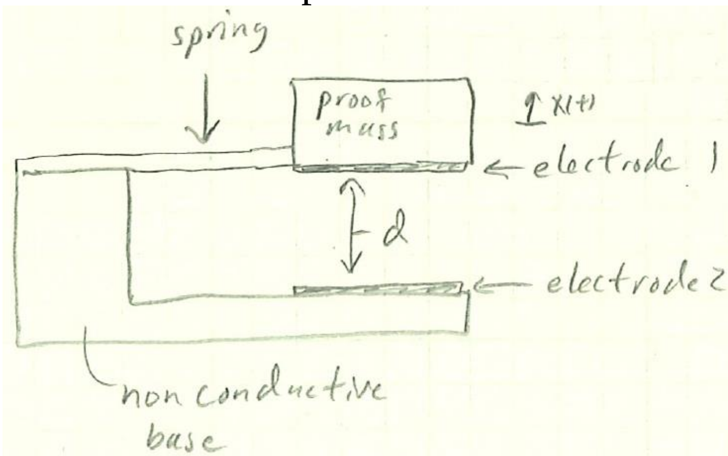
A = electrode overlapping surface area = wL here

Ways to detect with a capacitive sensor (non-fringing sensor):

1) Change the dielectric material, i.e. change ε_r → this can be difficult to do.

2) Change the electrode separation distance → easy to do.

Consider this simple MEMS accelerometer:

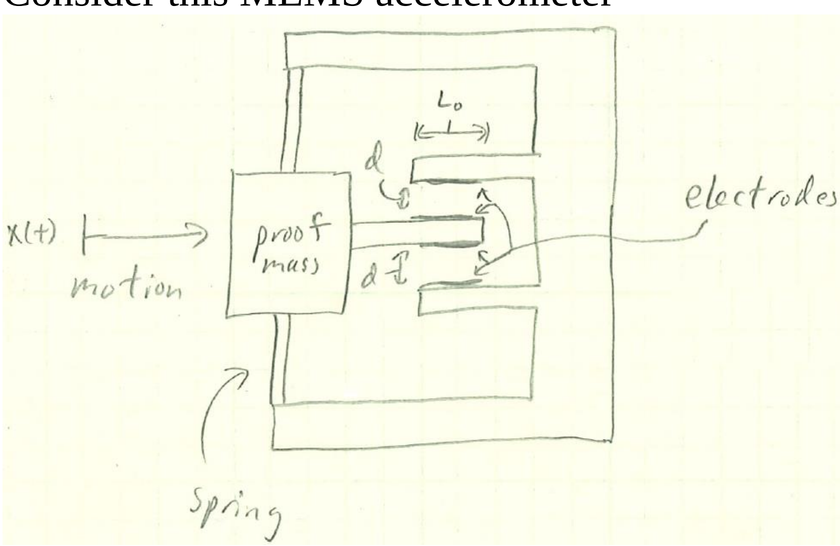


$$C = \frac{\varepsilon_o \varepsilon_r A}{d_o + x(t)}$$

where d_o is d when x(t) = 0 (“at rest” condition)

3) Change the electrode overlap area → easy to do.

Consider this MEMS accelerometer



d, w, and ε_r are constants here.

$$L(t) = L_o + x(t)$$

$$\therefore C(t) = \frac{\varepsilon_o \varepsilon_r w L(t)}{d} = \frac{\varepsilon_o \varepsilon_r w}{d}(L_o + x(t))$$

2. Typical Capacitor Sizes in MEMS

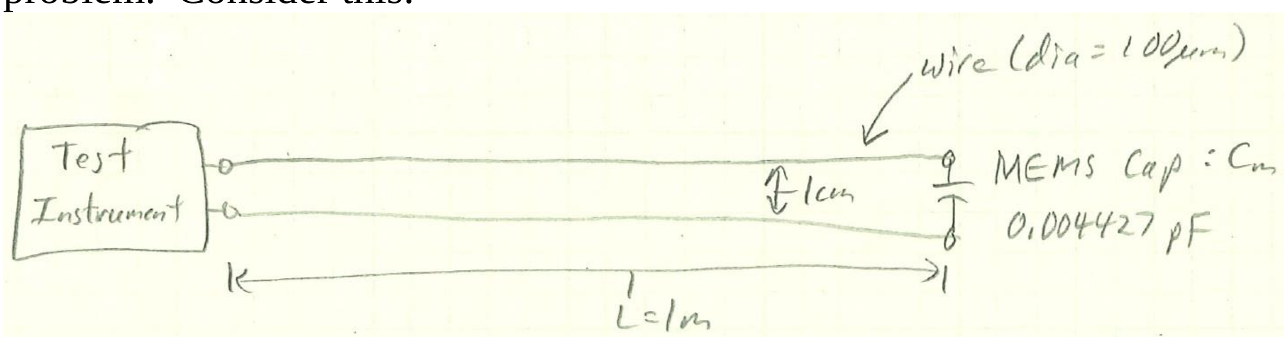
For a parallel plate capacitor: let w = 50 µm, L = 100 µm, d = 10 µm, and $\varepsilon_r = 1$

$$\therefore C = \frac{(8.854)(50x10^{-6})(100x10^{-6})}{10x10^{-6}} = 0.004427\, pF = 4.427\, fF$$

1 fF = $1x10^{-15}$ F ! → a <u>very</u> small capacitance!

Consider that a 10% change is C is only 0.4427 fF!

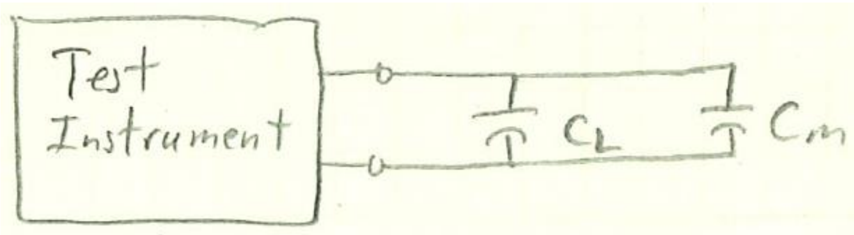
With sensor capacitances this small, stray capacitance can be a big problem. Consider this:



For the cable: $C_L \approx \frac{(8.854)(100x10^{-6})(1)}{0.01} = 0.08854pF$

Observe that: $\frac{C_L}{C_m} = 20 \rightarrow C_L = 20C_m$! or $C_L = 200\Delta C_m|_{10\%\Delta}$!

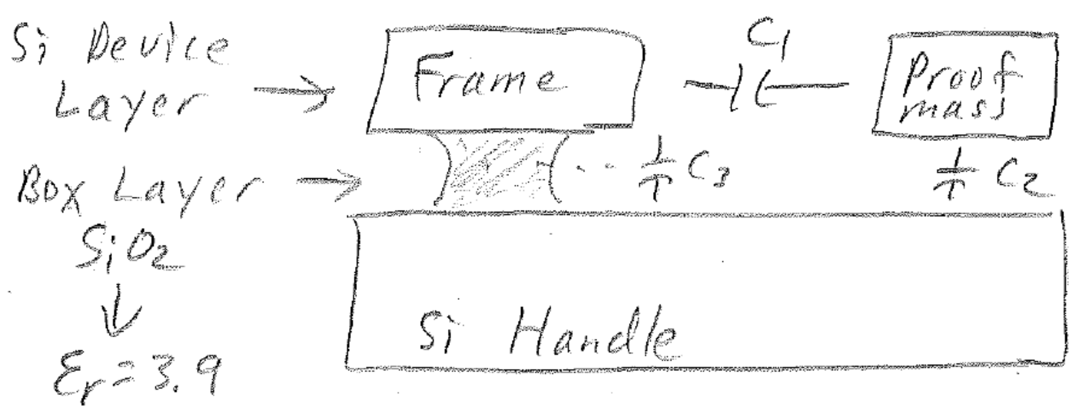
Instrumentation model:



C_m adds with C_L. Therefore, you need to locate the interface circuitry as close to the MEMS capacitor as possible, such as on the same chip.

Note: stray capacitance can also be an issue on the MEMS chip between different microstructures.

Example: A cross-section of an SOI MEMS device:



C_1 → desired capacitance between two microstructures

C_2 → stray capacitance in air ($\varepsilon_r \sim 1$)

C_3 → stray capacitance in SiO_2 ($\varepsilon_r = 3.9$)

So, C_2 and C_3 may not be able to be ignored, depending on the design, particularly with a typical Box Layer thickness of 0.5 µm to 1µm.

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3. Capacitor Interface Circuity: Oscillator

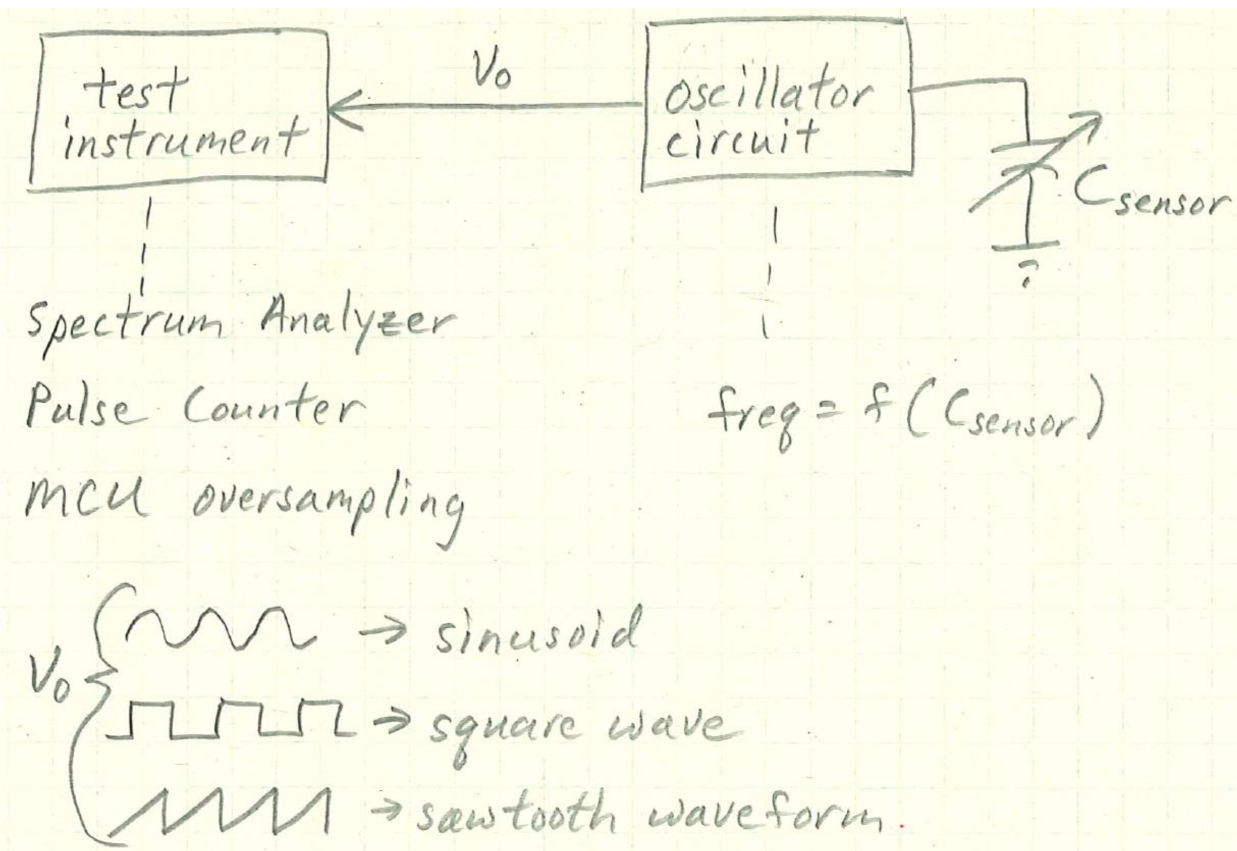
Consider C: $q = CV$ and $\dot{q} = \dot{C}V + \dot{V}C = i(t)$

In most EE application: $\dot{C} = 0 \rightarrow i(t) = C\frac{dV}{dt}$

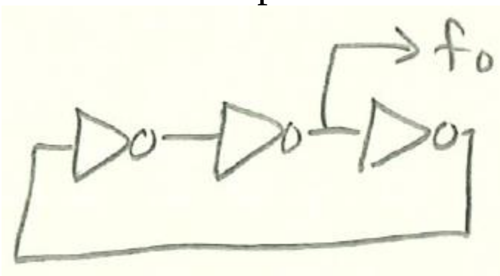
However, with capacitive sensors, $\dot{C} \neq 0$ usually

So, how then do you measure C(t)???

One technique is to place C(t) in an oscillator circuit where freq = f(C):



Consider a simple CMOS ring oscillator:



It is a closed chain of an odd number of inverter stages → unstable

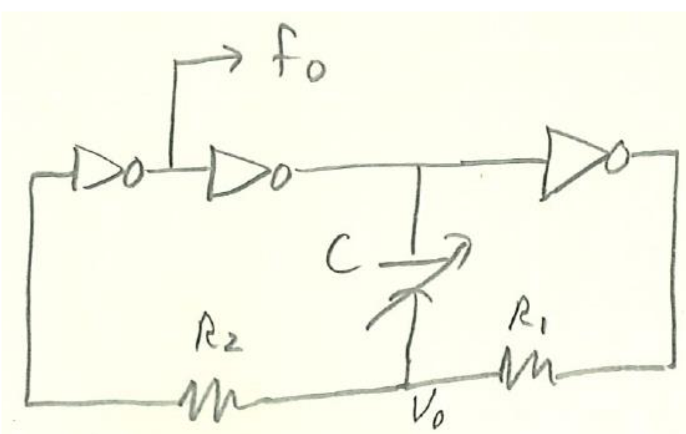
Let τ_d = propagation delay per inverter

N = number of inverters

It take two complete cycles for two state changes (1 period)

Therefore: $f = \frac{1}{2\tau_d N}$

Although this oscillator circuit is not useful for a capacitive sensor interface circuit, consider this related circuit:



This oscillator circuit is called a relaxation oscillator, and it is based on an RC time constant that controls when a state change occurs in the unstable chain of CMOS inverters.

Circuit analysis:

Assume: (1) $R_1 = R_2 = R$

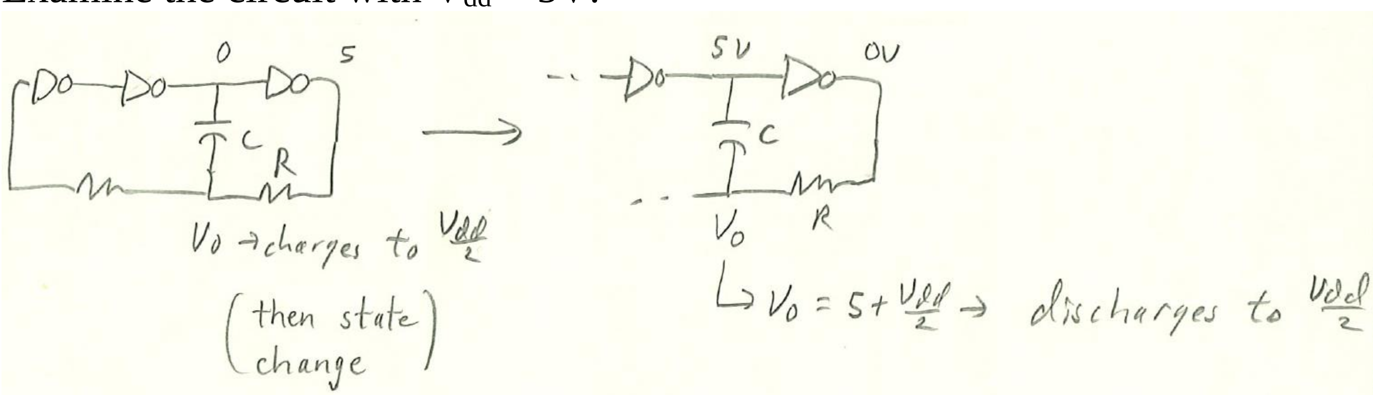
(2) C >> input capacitance on an inverter

(3) The inverter trip voltage: $V_{tr} = \frac{V_{dd}}{2}$

Therefore, when V_o crosses V_{tr}, the system changes state.

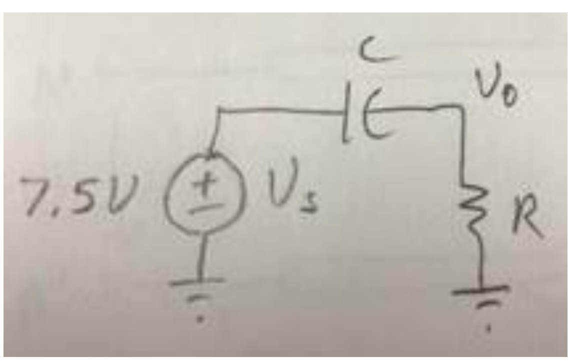
The RC time constant determines the output frequency, f_o, let's see how:

Examine the circuit with V_{dd} = 5V:



With V_{dd} = 5V: V_{tr} = 2.5V

At switching time, we have this circuit model:



With this model, C is fully discharged initially and v_o = 7.5V. We want to find t for v_o = 2.5V.

$$\frac{V_o}{V_s} = \frac{R}{R + \frac{1}{sC}} = \frac{s}{s + \frac{1}{RC}}$$

$$V_s(s) = \frac{7.5}{s}$$

$$V_o(s) = V_s(s)\left(\frac{s}{s + \frac{1}{RC}}\right) = \frac{7.5}{s + \frac{1}{RC}}$$

$$v_o(t) = 7.5e^{-\frac{t}{RC}}$$

We want to evaluate t when $v_o(t)$ = 2.5 V

$$2.5 = 7.5e^{-\frac{t}{RC}}$$

Solving for t: $t = -RCln\left(\frac{2.5}{7.5}\right) = 1.0986RC$

For the square wave output: T = 2t and f = 1/T, and $f = \frac{0.455}{RC}$

For an actual circuit, the equation for f will be slightly different due to the analysis assumptions. But for low frequency square waves (less than about 1 MHz), it should be close. This also works for fixed C: R-sensor.

For the case where $C = \frac{\varepsilon_o \varepsilon_r A}{d} = \frac{\varepsilon_o \varepsilon_r A}{x(t)}$ → plate separation C sensor,

$f = \frac{0.455}{RC} = \frac{0.455x(t)}{R\varepsilon_o \varepsilon_r A}$ → therefore $f \propto x(t)$