University of California at Berkeley
College of Engineering

EECS C245 – ME C218 Midterm Exam

Fall 2003 | Prof. Roger T. Howe, Dr. Thara Srinivasan | October 15, 2003

Your name: *SOLUTIONS*
Circle your course: EE C245 ME C218

Your student ID: ________________________

Guidelines

Closed book and notes; two 8.5” x 11” pages (both sides) of *your own notes* are allowed.
You may use a calculator.
Do not unstaple the exam.
Show all your work and reasoning on the exam in order to receive full or partial credit.

Score

Problem	Points Possible	Score
1	8	8
2	12	12
3	12	12
4	12	12
5	12	12
Total	56	*56!*

1. Microfabrication and Miniaturization [8 pts.]

   Answer the following questions:

   a. [2 pts.] Of the following etching methods, circle the one which could be used to create deep trenches with vertical sidewalls on a Si {100} wafer:

      KOH   DRIE (circled)   sputtering XeF_2

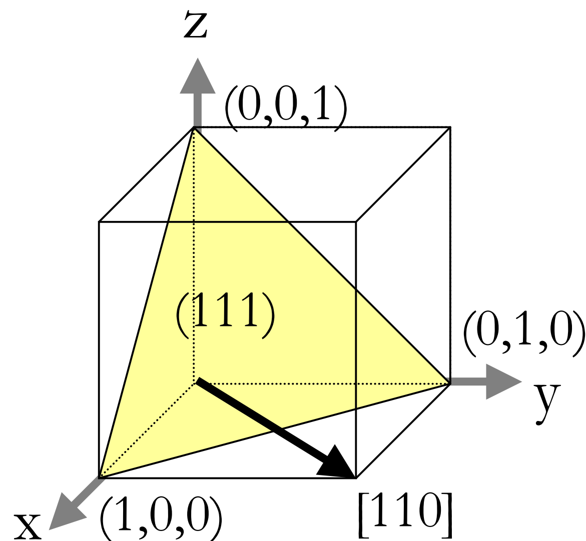
   b. [2 pts.] For each the following materials, list one method which can be used to deposit or apply a thin film onto a Si wafer:

polysilicon	aluminum	photoresist	PSG
LPCVD	sputtering, evaporation	spin casting	LPCVD

   c. [2 pts.] When doing the layout of a spring suspension for a MEMS accelerometer, you want to compare how much the beams will sag under their own weight for different dimensions. You begin by looking at how the gravitational force scales as the system is miniaturized, and find that gravitational force scales as [s^x], where s is the length scale and x =

      1   2   3 (circled)   4

   d. [2 pts.] Draw the (111) plane and the [110] direction on the axes below.



2. Bulk Etching [12 pts.]

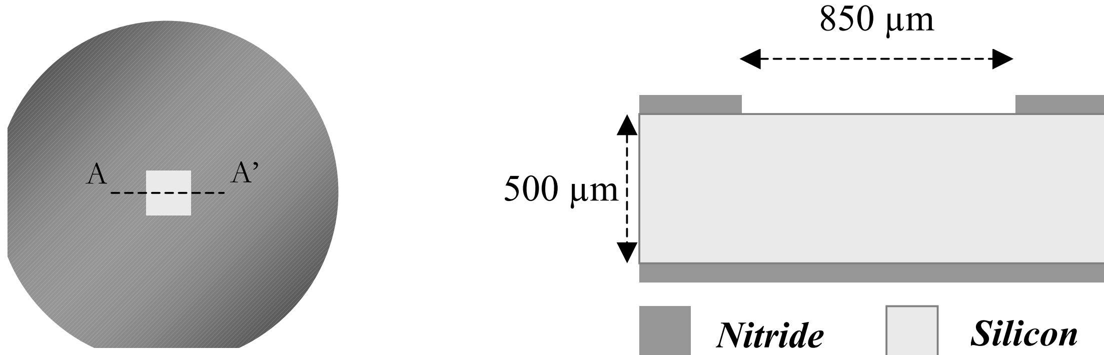
The Si {100} wafer shown below has a patterned silicon nitride mask on its top surface, and an unpatterned nitride layer on the bottom surface. With TMAH, the etch selectivity between the {100} and {111} planes is 35:1, and the {100} etch rate is 1 µm/min.

Assuming that the nitride layer and all other Si crystal planes are not etched, sketch the wafer cross section *after 400 minutes of etching* on the drawing at the bottom of the page. Also enter the following dimensions after etching:

a. Si etch depth [2 pts.] 400 µm

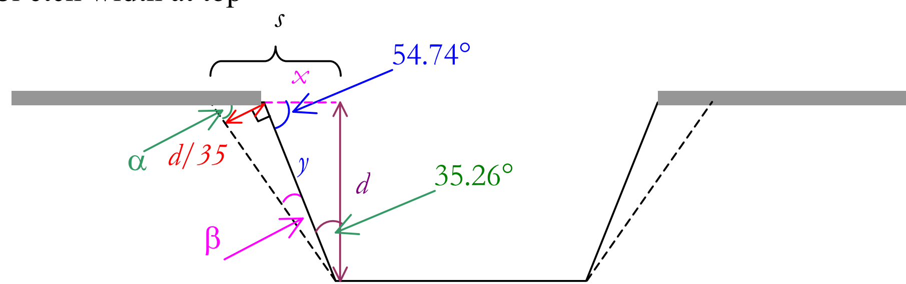
b. Si etch width at top [3 pts.] 878.4 µm

c. Si etch width at bottom [3 pts.] 284.4 µm



a. Si etch depth = etch time × {100} etch rate = (400 min.)(1 µm/min) = 400 µm

b. Si etch width at top



First calculate y using right triangle and 54.74°:

Sin 54.74 = d/y; y = 1.225d

Next calculate β using right triangle:

Tan β = (d/35)/(1.225d) β = 1.336°

Then using (β + 35.26) calculate s

$\tan(\beta+35.26) = s/d$ $\qquad$ $s = 0.7426d$

If d = 400 μm, s = 297.0 μm.

Using 35.26°, calculate x:

$\tan(35.26) = x/d$ $\qquad$ $x = 0.7070d = 282.8$ μm

Lateral undercut = (s-x) = 14.20 μm

Si etch width at top = 850 +2(14.20) = **878.4 μm**

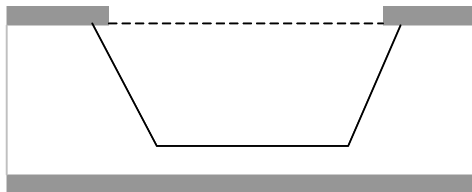
Partial credit was given for a correct drawing, correct β, and also if the 1/35 etch rate for {111} vs {100} was used on a direction not perpendicular to the (111) plane.

c. Si etch width at bottom = 850 – 2x = 850 – 2(282.8) = **284.4 μm**

Partial credit was also given for an answer of 0 if the rest of the dimensions were listed correctly, since silicon etching does not actually reach the very bottom of wafer.

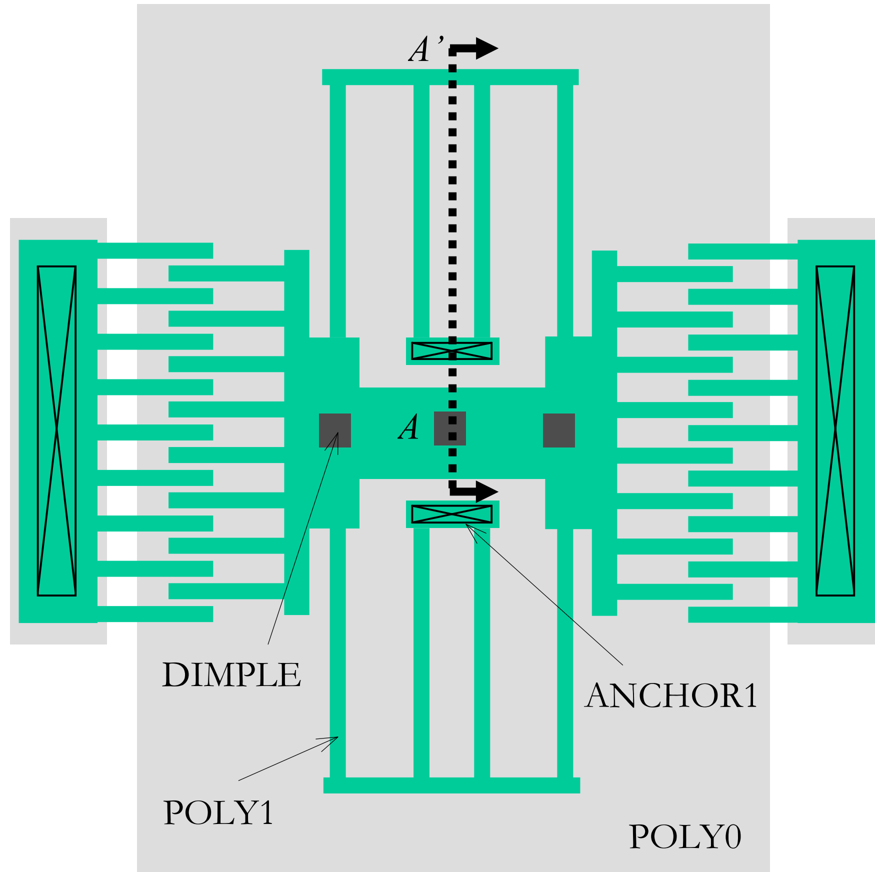
d. [4 pts.] Sketch the cross section after 400 minutes of etching.

Drawing should include lateral undercut, sidewalls which make roughly 54.7° angles to the horizontal (100) plane, and a flat bottom.



3. Surface Micromachining [12 pts]

The layout of the lateral resonator shown below is sent to the MUMPS foundry to be fabricated.



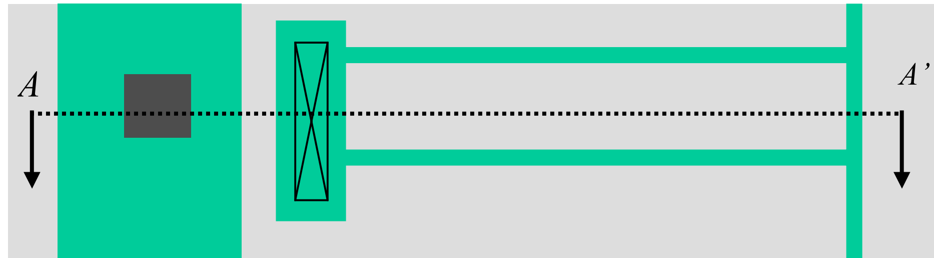
The MUMPS film thicknesses are:

Silicon nitride	0.6 μm
POLY0	0.5 μm
DIMPLE depth	0.75 μm
Oxide1	2 μm
POLY1	2 μm

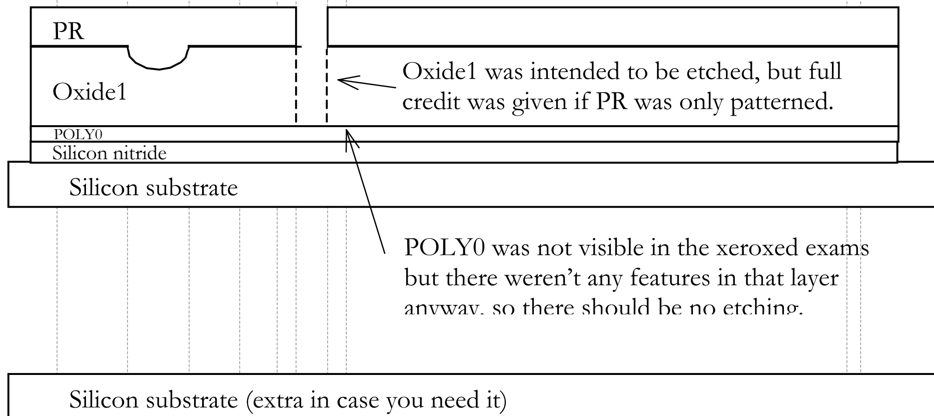
The order in which the masks are used is as follows:

POLY0
DIMPLE
Oxide1
POLY1

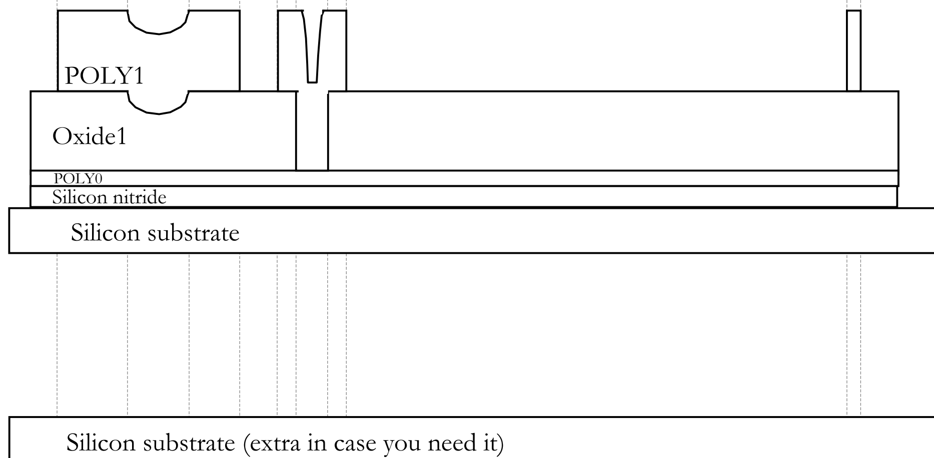
Draw the following cross sections (*A-A'*) on the substrates given below using the provided guide lines:



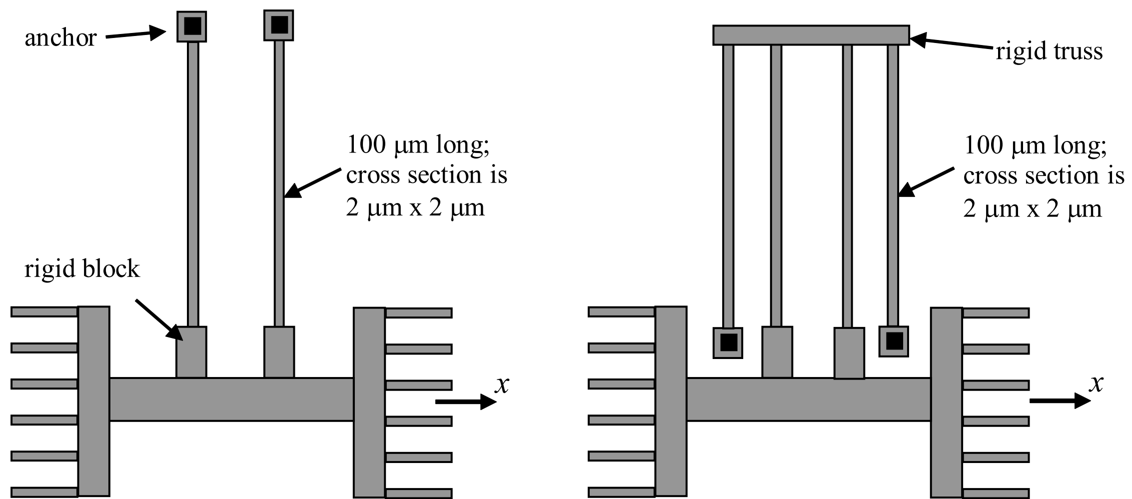
a) [6 pts.] After the process has reached the Oxide1 etching for ANCHOR1 but before photoresist removal:



b) [6 pts.] Before release:



4. MEMS suspension analysis [12 points]



(a) [3 pts.] What is the numerical value of the spring constant k_x (units: N/m) of the simple one-sided suspension on the left? *Given*: polysilicon structural material with E = 160 GPa. In case it's not on one of your formula sheets, the spring constant of a cantilever of length L_c, width W, and bending thickness h is given by $k_x = \frac{EWh^3}{4L_c^3}$.

③ a) For a cantilever of length $L_c = 50\mu m$

$$k_{x,\,cant} = k_0 = \frac{EWh^3}{4L_c^3} = \frac{160\times10^9 Pa\,(2\times10^{-6})^4 m^4}{4\,(50\times10^{-6})^3 m^3}$$

$$k_0 = 5.12\ N/m$$

Each leg has two cantilevers in series $\Rightarrow k_{leg}^{-1} = k_0^{-1} + k_0^{-1}$

$$k_{leg} = k_0/2$$

$$k_x = 2k_{leg} = 2[k_0/2] = \boxed{5.12\ N/m}$$

(b) [3 pts.] What is the numerical value of the spring constant k_x (units: N/m) of the folded one-sided suspension on the right?

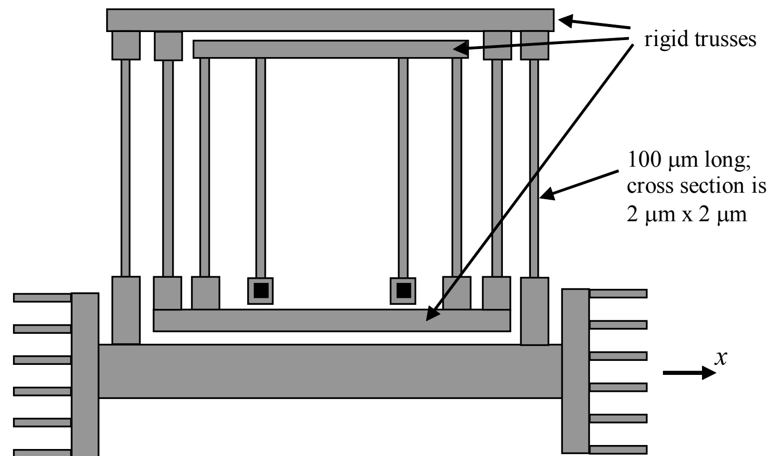
b) Folded suspension : each leg is two cantilevers in series.
and the legs are in series

half of total

$$k_x'^{-1} = k_{leg}^{-1} + k_{leg}^{-1} \Rightarrow k_x' = k_{leg}/2$$

$$k_x = \underbrace{2k_x'}_{in\ \parallel} = 2(k_{leg}/2) = k_{leg} = k_0/2 = \boxed{2.56\ N/m}$$

(c) [3 pts.] You're unsatisfied with these designs, so you turn to a double-folded, one-sided suspension. What is the numerical spring constant k_x (units: N/m) of this suspension?



c) Double-folded suspension: four legs are in series; half of total

$$k_x'^{-1} = k_{leg}^{-1} + k_{leg}^{-1} + k_{leg}^{-1} + k_{leg}^{-1} \Rightarrow k_x' = k_{leg}/4$$

$$k_x = 2\,k_x' = 2(k_{leg}/4) = (k_0/2)/2 = k_0/4 = \boxed{1.28\,N/m}$$

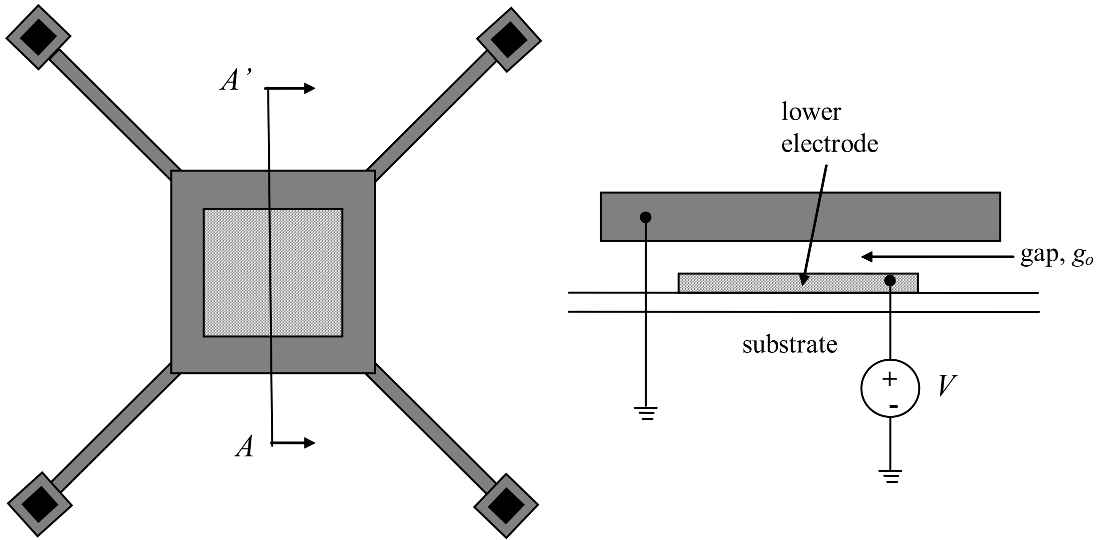
(d) [3 pts.] What is the resonant frequency in kHz of the lateral resonator with the simple one-sided suspension from part (a)? *Given*: the density of polysilicon is 2330 kg/m^3 and the area of the shuttle and comb fingers is 700 μm^2; you can neglect the effective mass of the suspension beams.

d) mass is just mass of shuttle and comb fingers:

$$m = \rho \cdot A \cdot t = (2.33\times10^{3}\,kg\,m^{-3})(700\times10^{-12}\,m^2)(2\times10^{-6}\,m)$$
$$= 3.26\times10^{-12}\,kg$$

$$f_1 = \frac{1}{2\pi}\omega_1 = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{1}{2\pi}\sqrt{\frac{5.12\,N/m}{3.26\times10^{-12}\,kg}} = \boxed{199.4\,kHz}$$

5. Electrostatic Actuators [12 points]



(a) [4 pts.] The lower electrode is connected to a voltage supply of value $V = 2$ V, while the suspended plate is grounded. The gap between the lower electrode and the plate is $g_o = 1$ μm. Find the area A of the lower electrode in μm^2 such that the electrostatic force on the plate is 100 nN.

(4) a)

$$F_e = \frac{1}{2}V^2 \frac{dC}{dz}\bigg|_{z=0} = -\frac{1}{2}V^2\frac{C_o}{g_o} = -\frac{1}{2}V^2\frac{\epsilon_o A}{g_o^2} = -100\,nN$$

$$A = \frac{2|F_e|g_o^2}{\epsilon_o V^2} = \frac{2(100\times10^{-9})(10^{-6})^2}{(8.85\times10^{-12})(2)^2} = \boxed{5650\,\mu m^2}$$

(b) [4 pts.] What is the electrical spring constant k_e in μN/μm for the applied voltage and lower electrode area you found in part (a)? If you were unable to solve part (a), you can use $A = 4000$ μm^2 for this part.

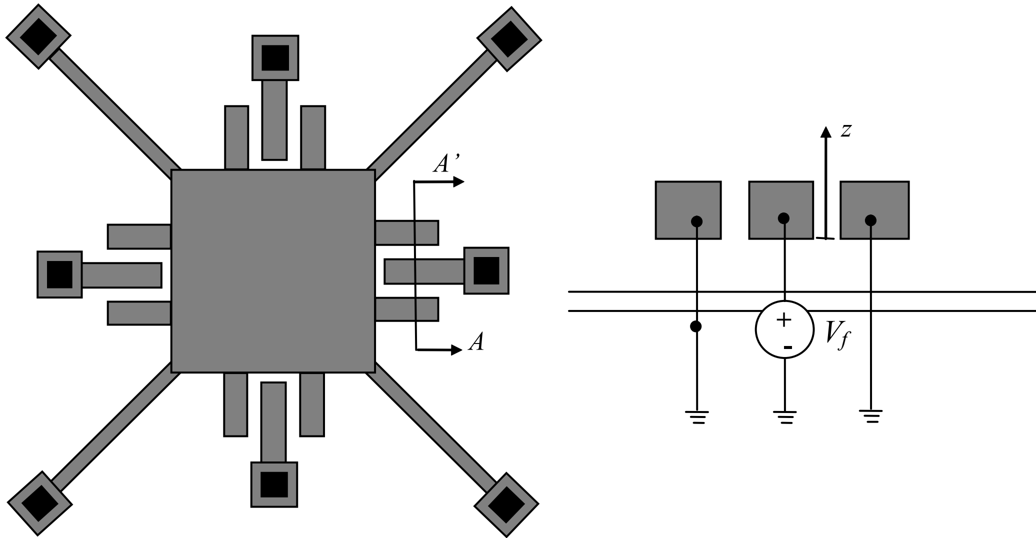
b)

$$F_e = -\frac{1}{2}V^2 \frac{\epsilon_o A}{(g_o+z)^2}$$

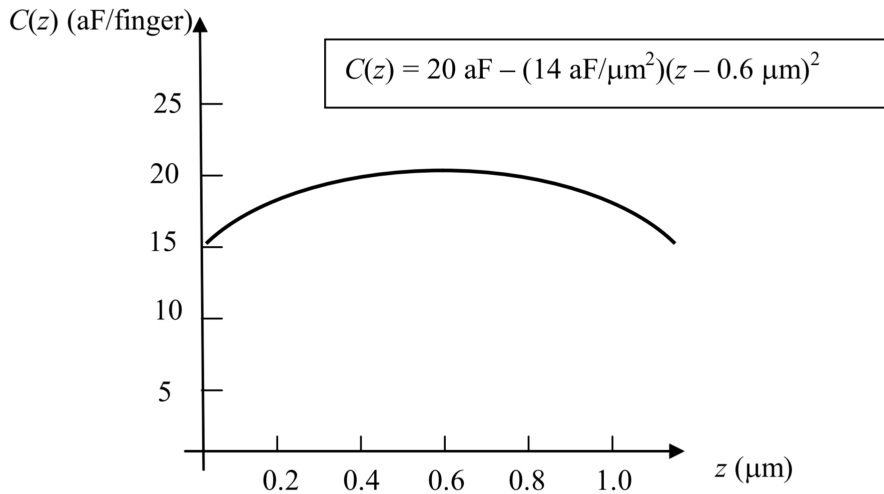
$$= \underbrace{-\frac{1}{2}V^2\frac{\epsilon_o A}{g_o^2}}_{100nN}\frac{1}{(1+z/g_o)^2} \cong -100nN\left(1-\frac{2z}{g_o}\right)$$

$$= -100nN + \underbrace{\left(\frac{200nN}{g_o}\right)}_{-k_e} z$$

$$k_e = -\frac{0.2\mu N}{1\mu m} = \boxed{-0.2\,\mu N/\mu m}$$



In a different structure, we would like to use levitation electrodes around the perimeter of the suspended plate to apply vertical force in the z direction to the plate. The capacitance variation for one electrode (shown in cross section above) is found by finite-element analysis and plotted on the graph below.



(c) [4 pts.] For a voltage $V_f = 5$ V, find the levitation force in nN, given that the vertical position of the plate is $z = 0$.

c)

$$F_{e,z} = 4\left[\frac{1}{2}V^2\frac{dC}{dz}\right]\Bigg|_{z=0} = 2(5V)^2\left[-2\left(14\frac{aF}{\mu m^2}\right)(-0.6\mu m)\right]$$

$$= 4 \cdot 25 \cdot 28 (0.6) \qquad \frac{V^2 aF}{\mu m} = \frac{10^{-18}}{10^{-6}}\frac{N\text{-}m}{m} = 10^{-12} N$$

840

$$\boxed{F_{e,z} = .840\,nN}$$