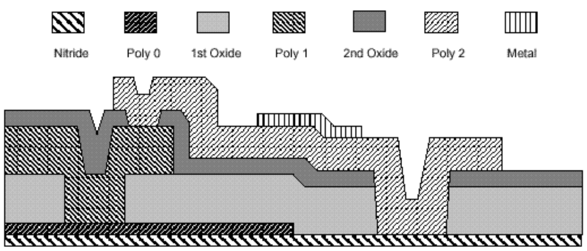
Spring 2002 EE M250B Prof. Ming C. Wu

Midterm Exam

Material	ρ_m kg/m^3	E GPa	ν	α_T μstrain/K	σ_o MPa	Comment
Silicon	2331	page 193		2.8		Cubic
α-Quartz	2648	page 573		7.4, 13.6		Hexagonal
Quartz (fused)	2196	72	.16	0.5		Amorphous
Polysilicon	2331	160	~0.2	2.8	Varies	Random grains
Silicon dioxide	2200	69	.17	0.7	-300	Thermal
Silicon nitride	3170	270	.27	2.3	+1100	Stoichiometric
	3000	270	.27	2.3	-50 – +800	Silicon rich
Aluminum	2697	70	~.3	23.1	varies	Polycrystalline

ε_0	Free-space permeativity	8.854×10^{-12}	F/m
μ_0	Free-space permeability	$4\pi \times 10^{-7}$	Henry/m

- Use the following design rules for problems that use MUMPs process:

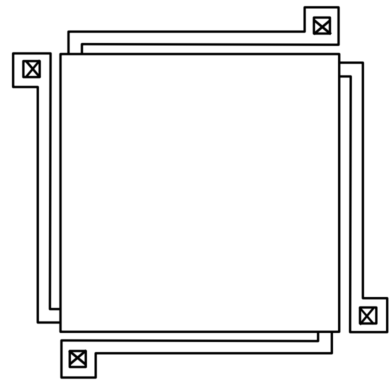


Material Layer	Thickness (μm)	Lithography Level Name
Nitride	0.6	--
Poly 0	0.5	POLY0 (HOLE0)
First Oxide	2.0	DIMPLE
		ANCHOR1
Poly 1	2.0	POLY1 (HOLE1)
Second Oxide	0.75	POLY1_POLY2_VIA
		ANCHOR2
Poly 2	1.5	POLY2 (HOLE2)
Metal	0.5	METAL (HOLEM)

Level 1	Level 2	Minimum Feature	Minimum Spacing	Enclose	Spacing	Cut-In	Cut-Out
POLY0	-	2	2				
	ANCHOR1			4/B/2.5	4/A/2.5		
	POLY1			4/C/2.6			
	ANCHOR2			5/E/2.8	5/F/2.8		
	POLY2			5/D/2.7			
POLY1	-	2	2				
	POLY0						
	ANCHOR1			4/G/2.6			
	ANCHOR2				3/K/2.11		
	POLY2			4/O/2.14			
	DIMPLE			4/N/2.13			
	POLY1_POLY2_VIA			4/H/2.9			
POLY2	-	2	2				
	POLY0						
	POLY1				3/I/2.10	5/P/2.14	4/Q/2.14
	VIA			4/L/2.9			
	ANCHOR2			5/J/2.7			
	METAL			3/M/2.12			
HOLEM	HOLE2			2/U/2.16			
HOLE2	HOLE1			2/T/2.16			

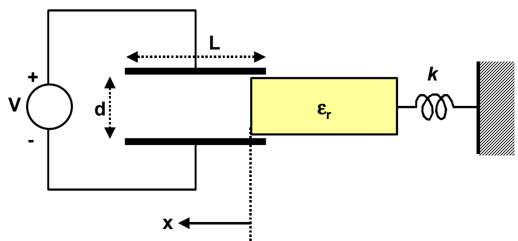
Polysilicon	Young's modulus	160 Gpa
	Poisson's ratio	0.28
	Density	2.33 g/cm^3

(15 pts) 1) Consider the gap-closing actuator shown on the right (top view) fabricated by the MUMPs process: A square polysilicon plate is suspended by four flexure beams. The plate moves downward when a voltage bias is applied between the plate and the Poly0 electrode. The area of the plate is 100 μm x 100 μm, and the flexure beams are 100 μm long. The width of the flexure beam is the minimum width allowed by the design rule.

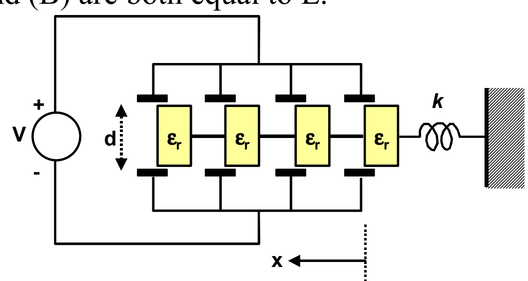


a) Which layer of polysilicon shall we use for the plate if we want to achieve maximum displacement? What is the maximum displacement before pull-in?
b) What is the spring constant for the actuator? Use the polysilicon layer that requires minimum voltage for the flexure spring.
c) What is the pull-in voltage for the actuator using the design in (a) and (b)?

(25 pts) 2) In HW#1, we solve the electrostatic actuator with movable dielectric (Figure (A)). Here, we consider a slightly different actuator (Figure (B)). Both the dielectric and the parallel plate capacitors are equally divided into N segments. The parallel plates are connected electrically and fixed mechanically. The dielectric segments are mechanically linked together. The total length of the capacitor plates and dielectric in (A) and (B) are both equal to L.



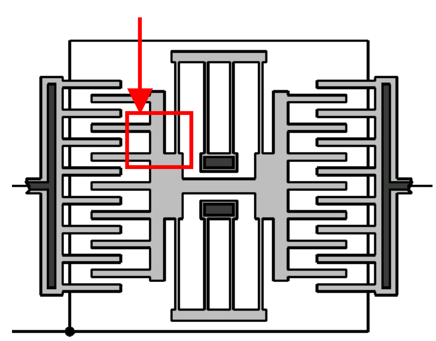
(A)



(B)

a) Find the force of the new actuator. Is the force the same as that in actuator (A)?
b) The actuator (A) can be used as tunable capacitor. The tuning range of such capacitor is defined as the ratio of maximum capacitance to minimum capacitance. What is the tuning ratio for the tunable capacitor in (A)?
c) What is the tuning ratio for the tunable capacitor (B)?
d) If we fix the operating voltage (i.e., same voltage for maximum capacitance), what is the ratio of resonant frequency achievable in structure (A) and (B)? What is the ratio of the capacitance tuning ratio?

(35 pts) 3) Design the following comb drive electrostatic actuators using the MUMPs design rules. To maximize the electrostatic force, stacked POLY1-POLY2 layers are used for comb fingers. The spring constant of the folded flexure spring is $k = 0.1$ N/m.



a) To achieve a displacement of 1 μm at 10 V bias, what is the minimum number of fingers needed?
b) Assume minimum beam width, compare the lengths of the flexure beams when they are realized by (i) POLY1 only,

(ii) POLY2 only, and (iii) stacked POLY1-POLY2.

c) If the mass of the spring is considered, the resonant frequency of the comb drive actuator is

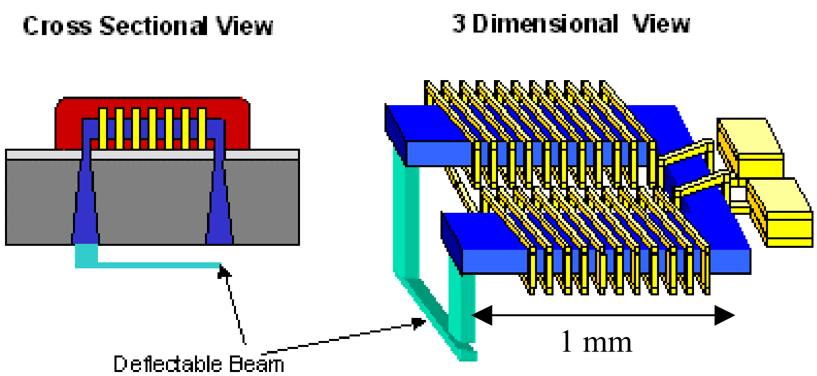
$$f_r = \frac{1}{2\pi}\sqrt{\frac{k}{M_p + 0.3714M}}$$

where M_p and M are the masses of the comb plates and spring, respectively. Find the resonant frequency of the comb drive for the three different spring structures in (b). Which structure has the highest resonant frequency? Assume comb fingers are 20 µm long. Use minimum width and space allowed by the design rule.

d) One of the high-order resonances is out-of-plane (i.e., up-and-down) oscillation. For the three spring structures in (b), which one has the largest ratio of resonant frequencies between the high-order oscillation and the fundamental oscillation?

e) Draw the layout of the square area marked on the figure (where combs and fingers are connected) for the 3 spring structures in (b). Mark all dimensions using the design rule.

(25 pts) 4) Consider the following magnetic relay:



It consists of a permalloy core with permeability μ_{core} = 1000 and a N-turn coil. The permalloy has an "U" shape, and each side is 1 mm long. The cross sectional area of the permalloy core is 30 µm (width) x 10 µm (thickness). A permalloy cantilever beam is connected to the U structure, as shown in the Figure. The permalloy cantilever is 10 µm thick, 30 µm wide, and 500 µm long. The area of the exposed permalloy in the air gap at the tip of the cantilever is A_{gap} = 30 µm x 30 µm. The air gap spacing is 10 µm. Ignore the vertical structure connecting the U to the cantilever and the gap. The Young's modulus of the permalloy is 100 GPa.

a) Find the expression for magnetic force of the actuator.

b) For N = 100, find the current required to bend the permalloy cantilever to contact.

c) How does the force scale with the area of the air gap?