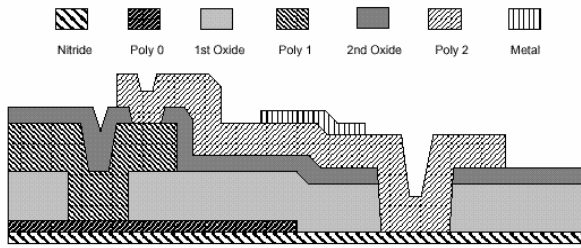


Material	ρ_m kg/m ³	E GPa	ν	α_T $\mu\text{strain/K}$	σ_o MPa	Comment
Silicon	2331	page 193		2.8		Cubic
α -Quartz	2648	page 573		7.4, 13.6		Hexagonal
Quartz (fused)	2196	72	.16	0.5		Amorphous
Polysilicon	2331	160	~ 0.2	2.8	Varies	Random grains
Silicon dioxide	2200	69	.17	0.7	-300	Thermal
Silicon nitride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

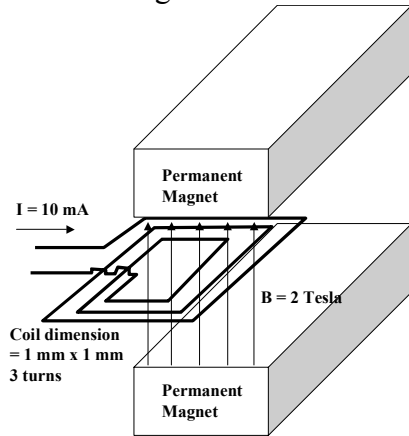


Material Layer	Thickness (μm)	Lithography Level Name
Nitride	0.6	--
Poly 0	0.5	POLY0 (HOLE0)
First Oxide	2.0	DIMPLE
		ANCHOR1
Poly 1	2.0	POLY1 (HOLE1)
Second Oxide	0.75	POLY1_POLY2_VIA
		ANCHOR2
Poly 2	1.5	POLY2 (HOLE2)
Metal	0.5	METAL (HOLEM)

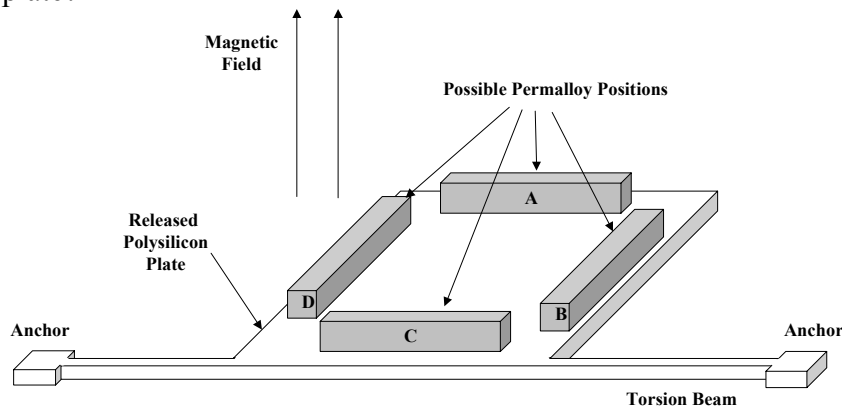
Level 1	Level 2	Minimum Feature	Minimum Spacing	Enclose	Spacing	Cut-In	Cut-Out
POLY0	-	2	2				
	ANCHOR1			4/B/2.5	4/A/2.5		
	POLY1			4/C/2.6			
	ANCHOR2			5/E/2.8	5/F/2.8		
	POLY2			5/D/2.7			
POLY1	-	2	2				
	POLY0						
	ANCHOR1			4/G/2.6			
	ANCHOR2				3/K/2.11		
	POLY2			4/O/2.14			
	DIMPLE			4/N/2.13			
	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

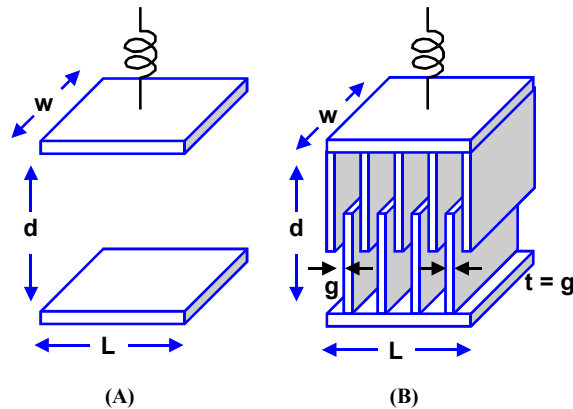
- (20 pts) 1) Answer the following questions. Please be direct and brief.
- Does Si have piezoelectric effect? Why?
 - Can piezoresistors be used as actuators? Why?
 - Find the magnitude and direction of the magnetic force for the following actuator:



- Under a constant external magnetic field as shown in the following figure, which of the following permalloy (A, B, C, or D) will produce the largest torque to lift up the torsion plate?



- (30 pts) 2) Consider the following two electrostatic actuators:



Structure (A) is parallel plate actuator, and structure (B) is vertical comb drive actuators. For structure (B), the number of combs is the maximum that can fit under the plate with the same

length as the parallel plate actuator, L . The drawing is only an illustration, and not an indication of the actual number of fingers.

- What is the force density of the parallel plate actuator (A), i.e., the force per unit area of the plate?
- What is the force density of the vertical comb actuator (B)? Please note you should normalize the force to the area perpendicular to the direction of motion.
- Using SUMMiT-V process, $d = 11 \mu\text{m}$, $g = 1 \mu\text{m}$, $t = 1 \mu\text{m}$. Which actuator has larger force density? What is their ratio (vertical comb drive to parallel plate actuator)?

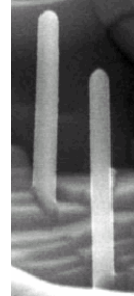
- (20 pts) 3) Find the resonant frequency of single-wall carbon nanotubes (CNT) with the following dimension:

Diameter $d = 50 \text{ nm}$

Length = 1000 nm

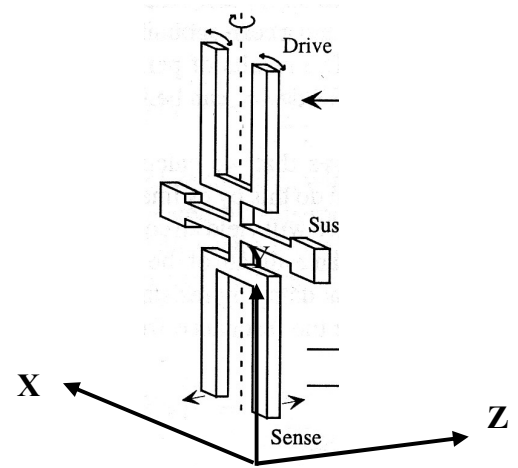
Assume the Young's modulus is 1000 GPa. For simplicity, assume the carbon nanotubes can be considered as solid circular cantilevers with effective volume density equal to the weight of CNT divided by the volume of CNT.

Calculate the density of the nanotube by assuming the length of carbon-to-carbon bond to be 0.4 nm and two-dimensional hexagonal lattice for the carbon sheet. The atomic weight of carbon is 12 (i.e., 1 mole of carbon atoms (6×10^{23}) weigh 12 gram).

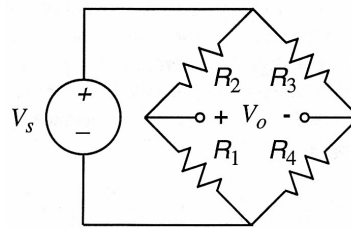


- (40 pts) 4) Consider a Quartz gyroscope as shown on the right.
- If the vibration direction is along X direction, draw the position and shape of the drive electrodes on the gyroscope.
 - If the gyro is designed to sense rotation around the Y axis, draw the sensing electrodes on the structural diagram. Please note the sensing tine is at the bottom.
 - If the crystal orientation of the Quartz substrate is mistaken during the fabrication stage such that the crystal x axis is aligned to y in the figure, and crystal y is aligned to $-x$ in the figure, z is still aligned. Would the gyro work under the electrode configuration of (a) and (b)? Back up your answer with calculation.
 - Continue with part (c), if we mistakenly use a x-cut Quartz substrate such that the crystal x is aligned with z in the figure, crystal y is aligned with x in the figure, and crystal z is aligned with y in the figure, would the gyro work under the electrode configuration of (a) and (b)? Back up your answer with calculation.

<<Continue to next page>>



- (40 pts) 5) Most of the piezoresistive sensors fabricated to date use p type silicon due to constraint in fabrication process. Advances in deep reactive ion etching and epitaxial growth have relieved many of those constraints. N-type silicon actually has higher maximum piezoresistive coefficient.
- What is the maximum piezoresistive coefficient for n-type Si? Which is the crystal direction for that?
 - Consider an n-type cantilever force sensor. The cantilever beam has a length of L , a width of W , and a thickness of t . Assume the dimensions of the piezoresistor are equal to $\frac{1}{4}$ of the cantilever beam. The force will be applied at the tip of the cantilever. Find the sensitivity of the cantilever force sensor (in units of Volt / Newton). Using the following circuit for measuring the force:



where R_1 and R_3 are piezoresistors placed at maximum stress point, and R_2 and R_4 are reference resistors whose resistance values are equal to that of piezoresistors at zero stress.

- The resolution of the force sensor is limited by thermal noise. Thermal noise (or Johnson noise) can be expressed as $S_J = 4k_B T R$, where k_B is Boltzmann constant, T is the temperature in Kelvin, and R is the resistance. S_J is the spectral density function of the voltage noise (unit: V^2/Hz). The resolution of the force sensor is $\frac{\text{Noise}}{\text{Sensitivity}}$. Find the force resolution of the cantilever beam in (b). The unit of force resolution is Newton per square root of Hz.
- How does the force resolution scale with the length and thickness of the cantilever beam?
- What dimensions is needed to achieve a resolution of $fN / \sqrt{\text{Hz}}$ (femto-Newton per square root of Hz)?