EEE 5354L Lecture 11: MEMS: Thermal Actuator Design

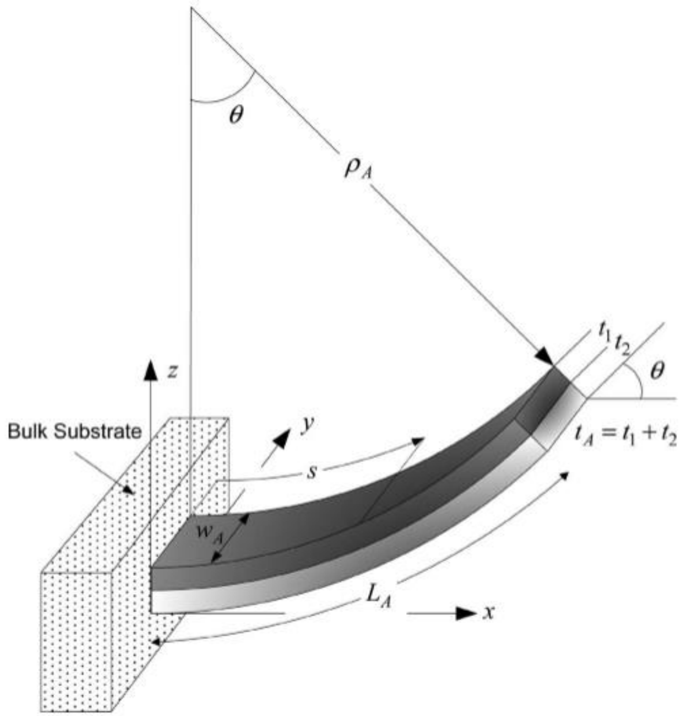
Dingkang Wang

Department of Electrical and Computer Engineering

Topics

- Introduction to Electrothermal Bimorph Actuation
- Process Flow
- Layout and Mask Design Task
- MEMS Characterization

Electrothermal Bimorph Actuation



BI·MORPH

Two, layers

Strain due to temperature change in each layer:

$$\begin{cases} \varepsilon_{T1} = \alpha_1 \Delta T \\ \varepsilon_{T2} = \alpha_2 \Delta T \end{cases}$$

Corresponding stress:

$$\begin{cases} \sigma_{T1} = E_1 \varepsilon_{T1} = E_1 \alpha_1 \Delta T \\ \sigma_{T2} = E_2 \varepsilon_{T2} = E_2 \alpha_2 \Delta T \end{cases}$$

ΔT: temperature change.

$\alpha_{1,2}$: temperature coefficient of expansion of first and second layer

$E_{1,2}$: Young's modulus of first and second layer

Electrothermal Bimorph Actuation

- The **curvature** ρ_A due to temperature change:

$$r_T = \frac{1}{\rho_A} = \frac{4t_1^2 + 4t_2^2 + 6t_1 t_2 + \frac{E_1 t_1^3}{E_2 t_2} + \frac{E_2 t_2^3}{E_1 t_1}}{6(t_1 + t_2)\Delta\alpha_T \Delta T}$$

$$\rho_A = \beta_r \Delta\alpha_T \Delta T$$

- **$\boldsymbol{\beta_r}$ is bimorph curvature coefficient**

$$\beta_r = \frac{6(t_1 + t_2)}{4t_1^2 + 4t_2^2 + 6t_1 t_2 + \frac{E_1 t_1^3}{E_2 t_2} + \frac{E_2 t_2^3}{E_1 t_1}}$$

$t_{1,2}$ are the thickness of each layer

Electrothermal Bimorph Actuation

- Tangential angle at the beam end is given by

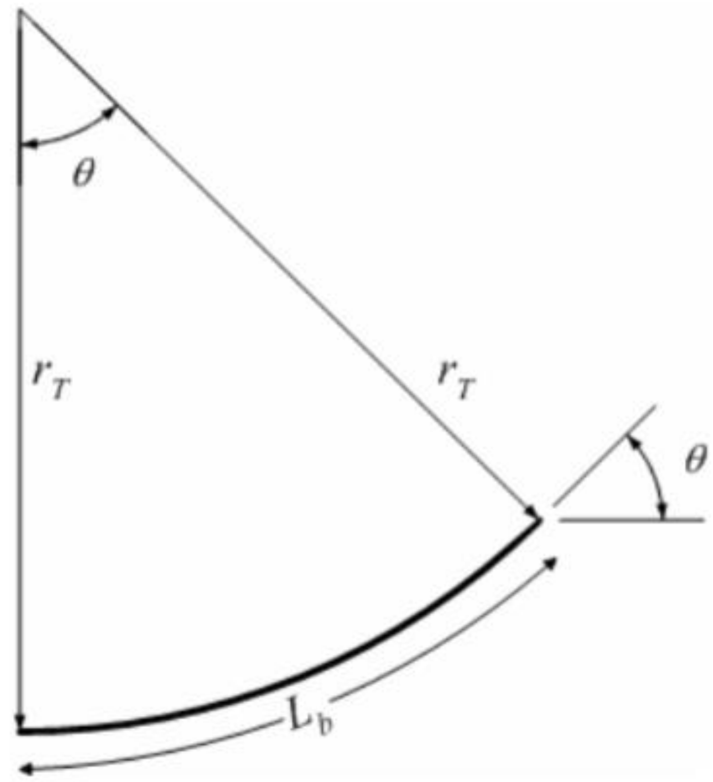
$$\theta = \frac{L_b}{r_T}$$

- Substituting the expression for

$$\theta(\Delta T) = \beta_r L_b \Delta\alpha_T \Delta T$$

We can define bimorph actuation **responsivity γ**

$$\gamma = \frac{\theta}{\Delta T} = \beta_r L_b \Delta\alpha_T$$



Electrothermal Bimorph Actuation

$$\gamma = \frac{\theta}{\Delta T} = \beta_r L_b \Delta\alpha_T$$

Responsivity can be increased by selecting bimorph combination of large $\Delta\alpha_T$ thermal expansion coefficients (CTEs).

SiO_2 with Al has a large $\Delta\alpha_T$ of 23.2 e-6/K

Materials	CTE (10^{-6}/K)	Thermal Conductivity (W/mK)	Young's Modulus (GPa)	Poisson Ratio
Si	3.0	150.0	179	0.27
Poly-Si	1.6	-	160	0.22
SiO_2	0.4	1.4	70	0.17
Si_3N_4	3.3	30.0	310	0.24
SiC	3.5	86.5	457	0.14
Al	23.6	237.0	70	0.35
Au	14.5	318.0	78	0.44
Cu	16.9	401.0	120	0.34
Pt	8.9	71.6	168	0.38
Pb	28.7	35	160	0.42
Cr	5.0	93.9	279	0.21
Ti	8.6	21.9	116	0.32
Ni	12.8	90.9	200	0.31

- But we will choose SiO_2 with Ti for teaching lab because Ti has larger **resistance** and greater **Young's modulus**

	Resistivity(nΩm)	**Young's modulus**
Al	28.2	70GPa
Ti	420	116GPa

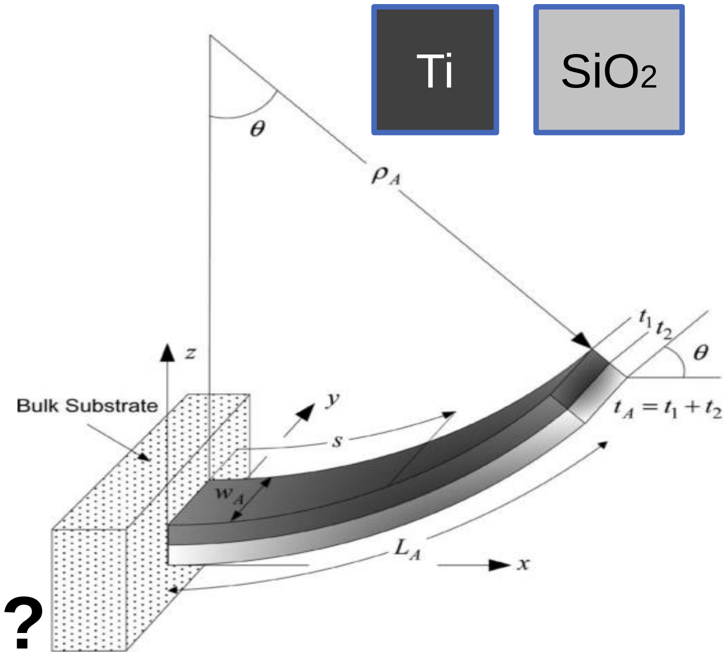
- Larger resistance means less current is needed to actuate Ti/Ox bimorph

$$P = I^2 R$$

Design Task of Bimorph Actuation

Given:

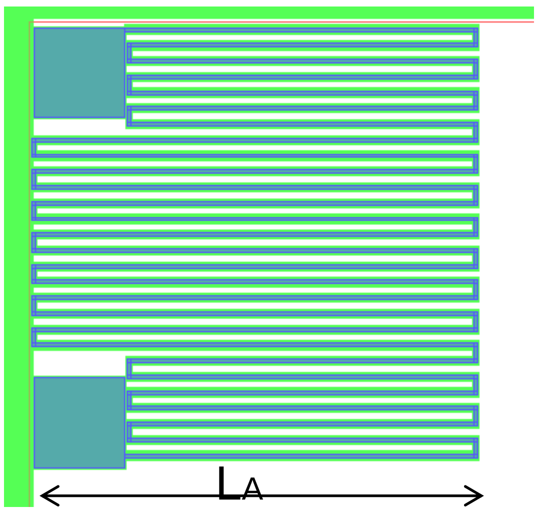
- ✓ 0.4 um SiO_2 + 0.3um Ti
- ✓ Ti as the heater.
- ✓ Mask Area of 3mm × 3mm,
- ✓ Maximum Temperature is 300℃

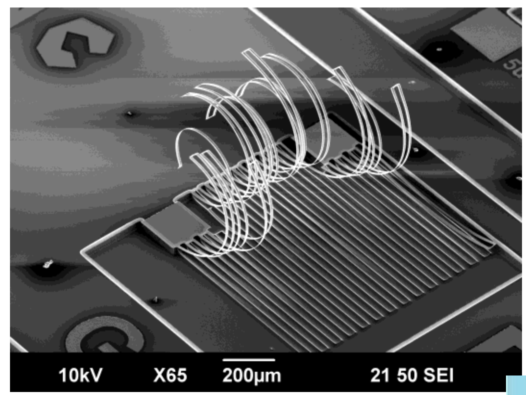


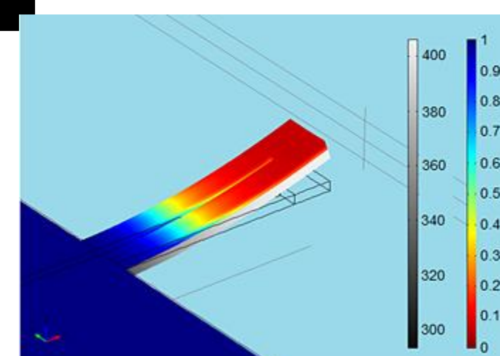
How would you achieve the maximum elevation *h* at the tip?

Design Task

- Draw your layout for *L_A*, calculate your θ and *h*.
- Or performed finite element simulation for θ and *h* with tool like COMSOL
- Layout due on 03/12, show your draft on the next lecture and discuses.







Layer Definition

Layer Name	No	Type
Ti	1	Darkfield
Ox	2	Clearfield
Outline	3	Line

PECVD (400 nm)

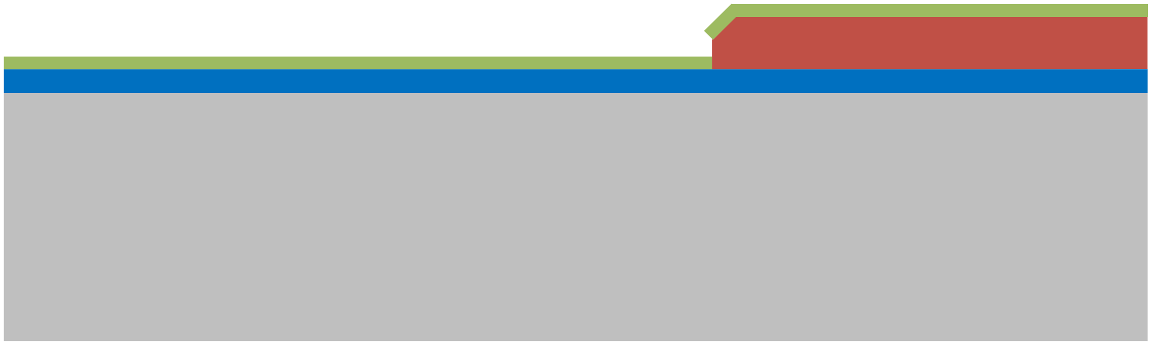
- PECVD 400 nm SiO_2

Photolithography (Mask 1) – Metal Lift-off

- Bake the wafer at 100˚ C for 5 minutes
- Coat the wafer with 2um of AZ-1512 PR
- Bake the wafer at 100˚ C for 2 minutes
- Expose the PR with Karl Suss mask aligner
- Develop the PR in AZ-300 developer

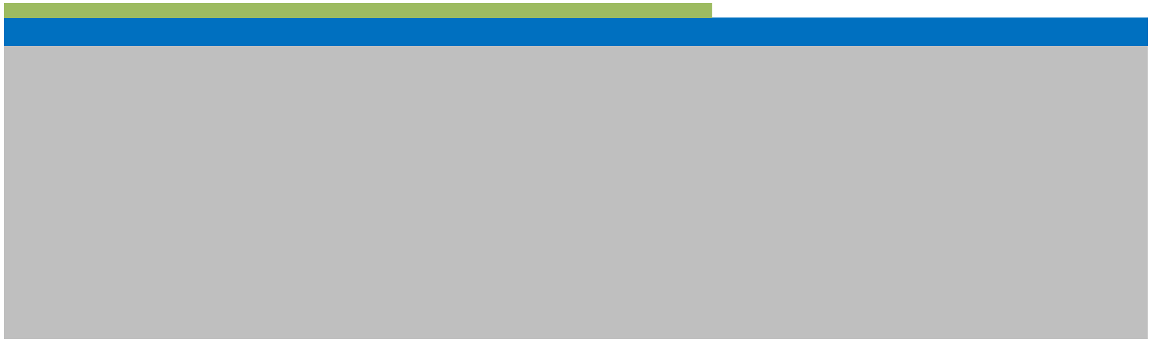
Sputtering Metal (Ti/Ni)

- Sputter a 300 nm layer of Ti, 100 nm Nickel using KJL CMS-18 MULTI-SOURCE sputter system
- Using Ni as the passivation lay to cover Ti for DRIE etch



Lift-off Ti/Ni

- Put the wafer in lift-off bath for 40 minutes at 70° C
- Rinse them in the dump rinser
- Put the wafer in acetone beaker and put it in ultrasonic cleaner for 2 minutes
- Put the wafer in IPA beaker for 2 minutes



Photolithography (Mask 2) – SiO_2

- Bake the wafer at 100° C for 5 minutes
- Coat the oxidized wafer with 2um of AZ-1512
- Bake the wafer at 100° C for 2 minutes
- Expose the wafer in Karl Suss
- Develop it in AZ-300 developer
- Hard Bake at 100 ° C for 5 minutes

Buffered Oxide Etchant (BOE) Etch

- Wet etching the oxide in BOE to get access to silicon

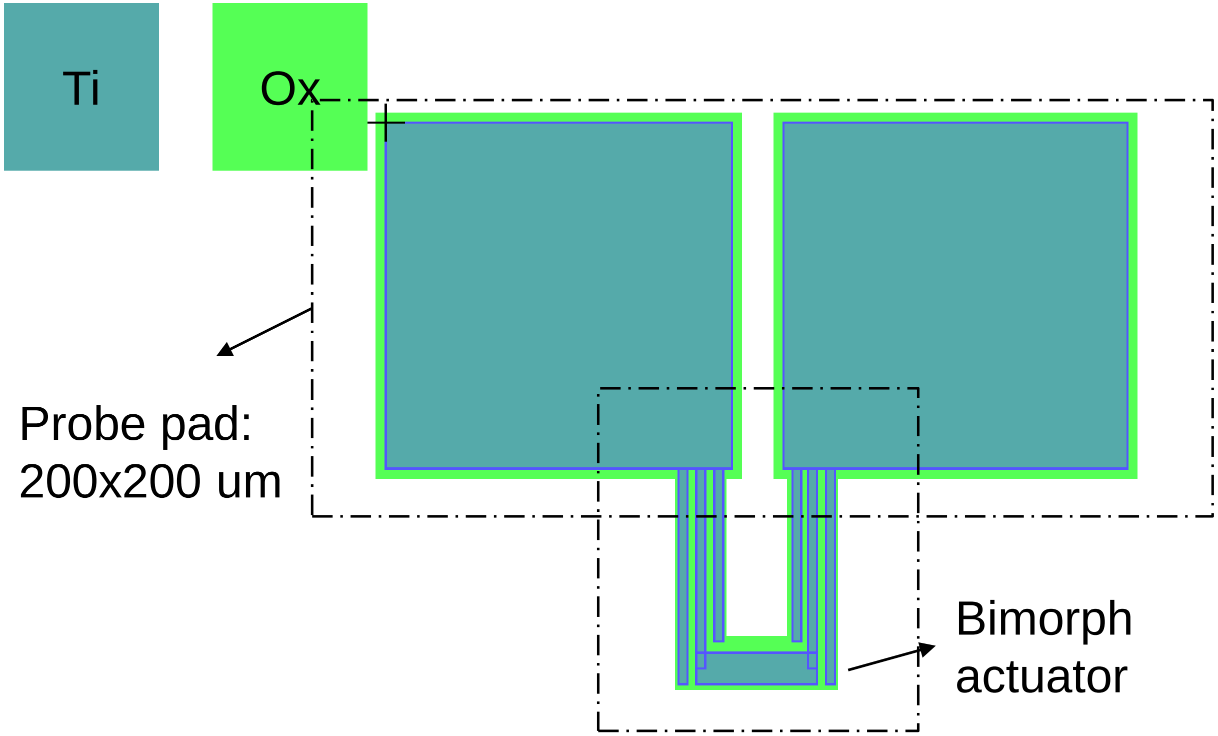
Strip off PR

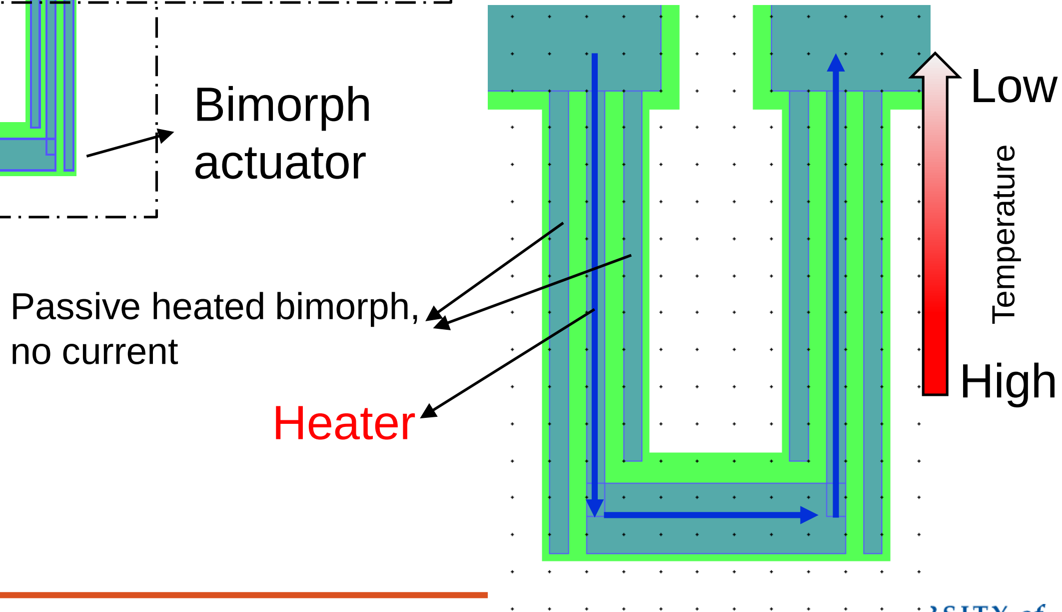
- Using Acetone, IPA and DI water to strip off PR.

DRIE Etch

- Anisotropic etch 15 um
- Isotropic etch to release structure

Basic Designs

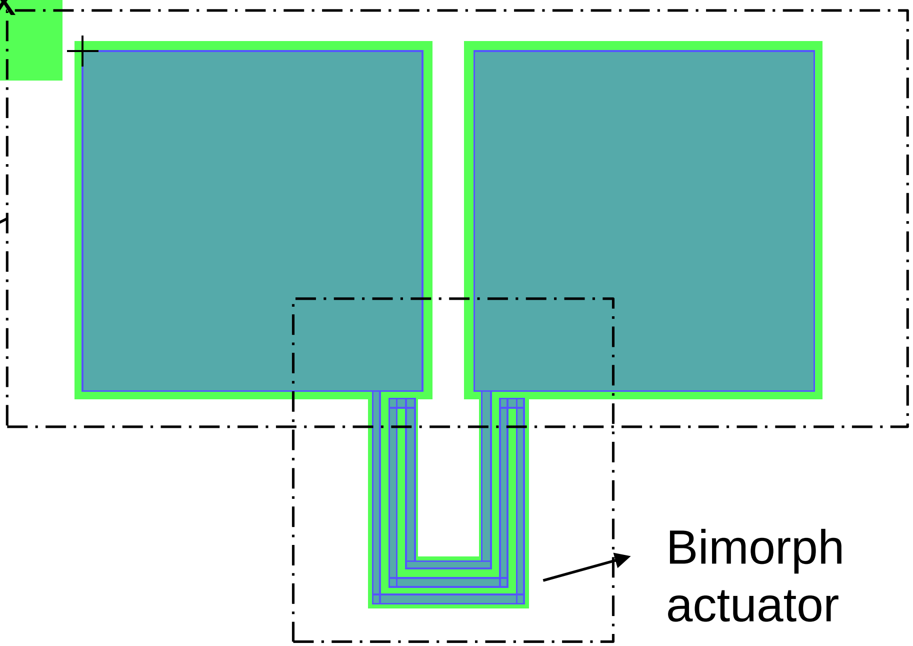




Basic Designs

Ti

Ox

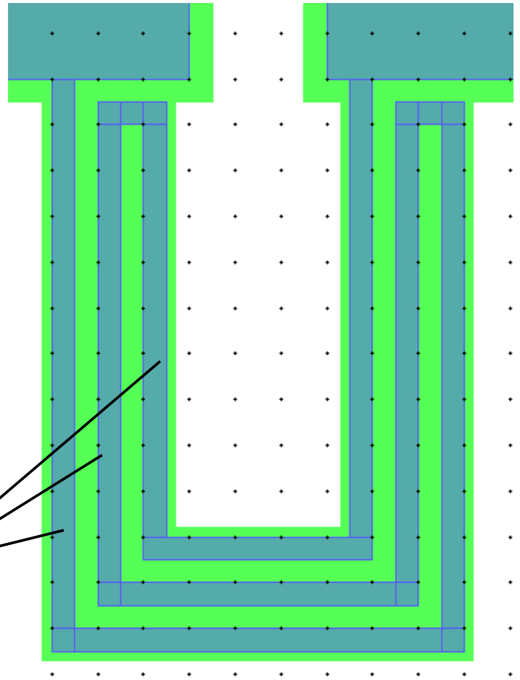


Probe pad:
200x200 um

Bimorph
actuator

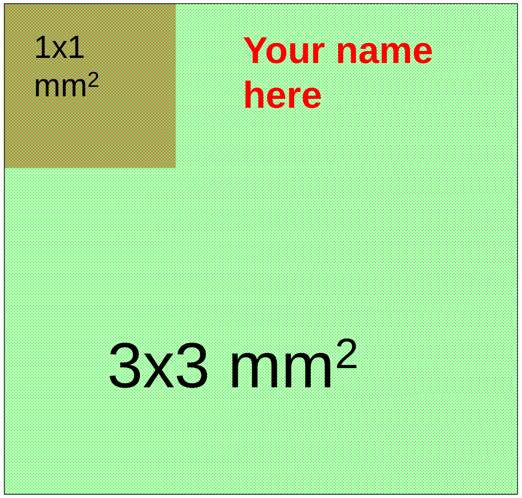
Longer path, larger resistance,
needs higher voltage

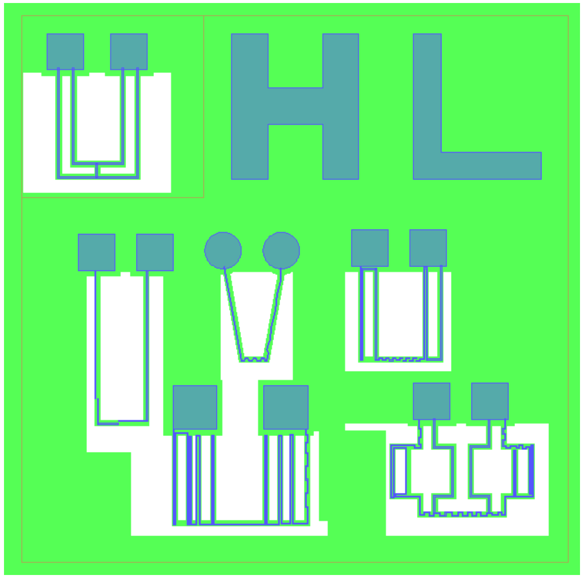
Heater



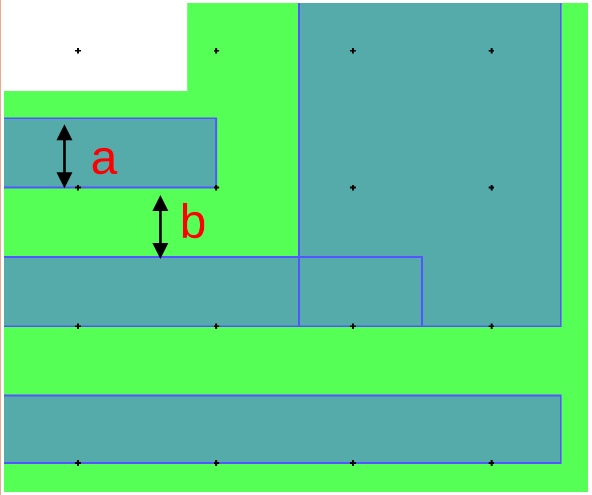
Layout Design Requirements

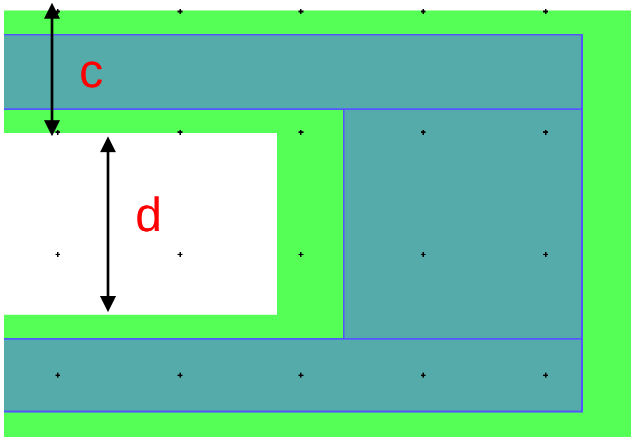
1. Each student is given a 3mm × 3mm area
2. All your drawings should be within 3 × 3 mm^2
3. Draw your name on the top right corner
4. On the top left corner, the 1mm x 1mm area is allocated for MEMS Design Contest.
5. Make several thermal actuator designs in the rest of the areas.



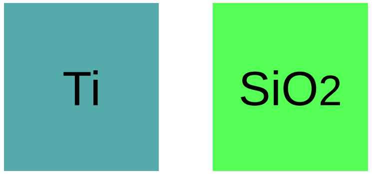


Design Rules



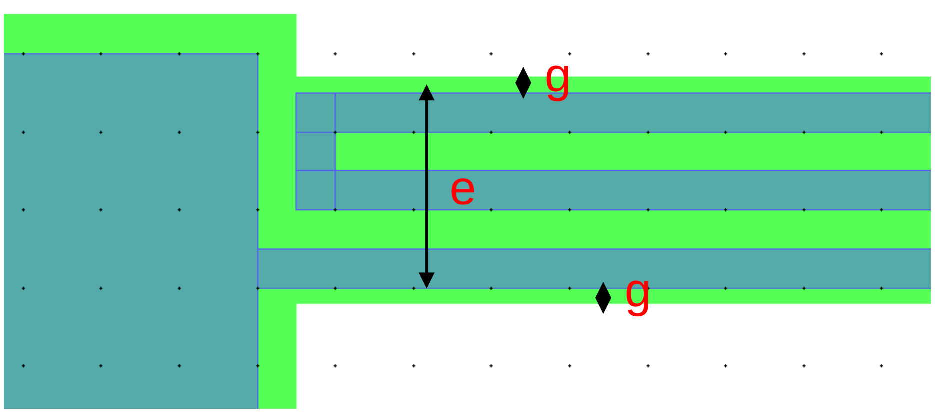


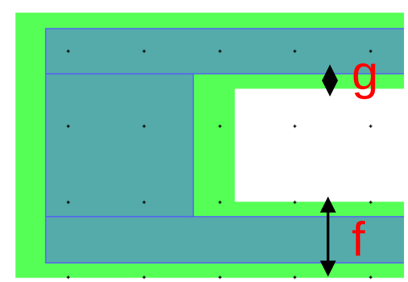
1. Minimal width of Ti: 5um (a)
2. Minimal gap between Al: 5um (b), recommend>15um for non-critical feature.
3. Minimal width of Ox: 10um (c)
4. Minimal gap of Ox: 15um (d)

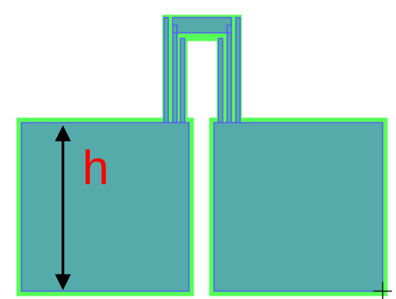


Design Rules

6. For bimorph actuator, maximum width of Ox 30um(e)
7. For bimorph actuator, maximum width of Ti is 10um(f)
8. Minimal enclosure boundary of Ox to Ti: 2um(g), make it larger if possible
9. For probe pads in Ti, minimal size is 200 x 200 um^2(h), or circles with d = 200um minimal gap is 15 um
10. In Ti layer, make sure current can flow from one pad to another pad through actuator without short or open circuit.
11. Two letters on Ti with minimal width: 15um

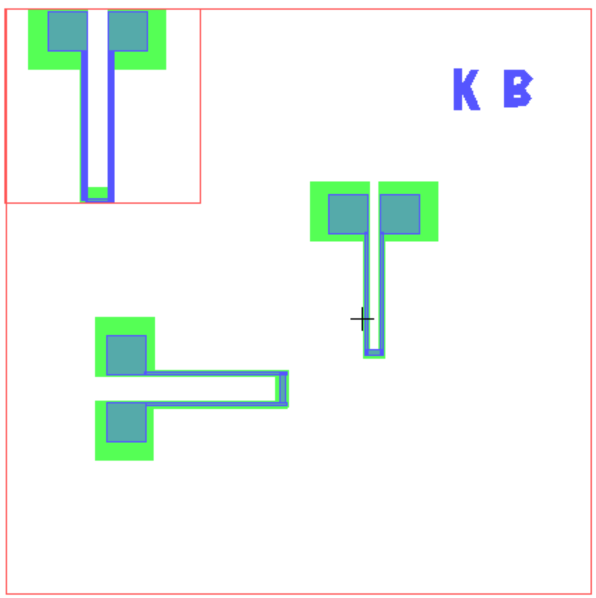




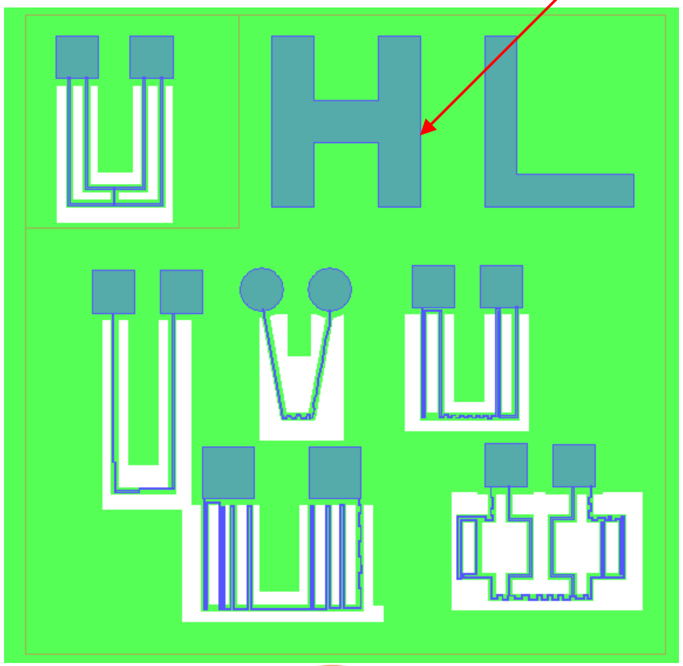


Design Rules

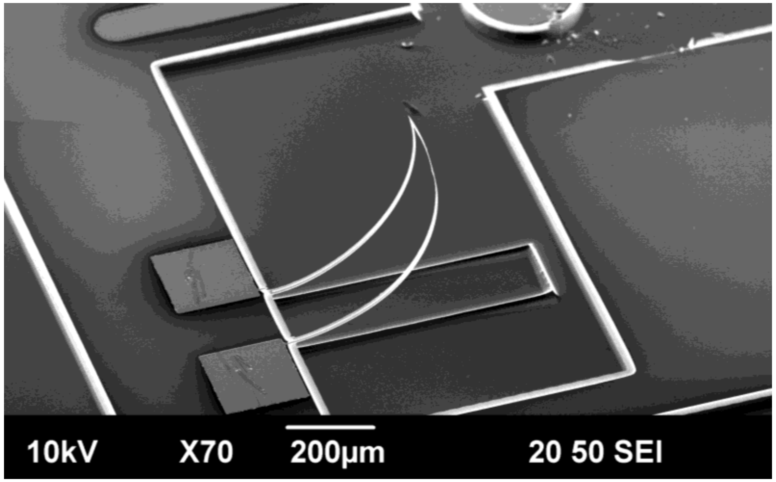
12. Make sure you make good use of the whole design area!
13. Use Ox lay to cover the blank space.
14. Write your name on Ti layer, and cover with Ox(Don’t make it too large)

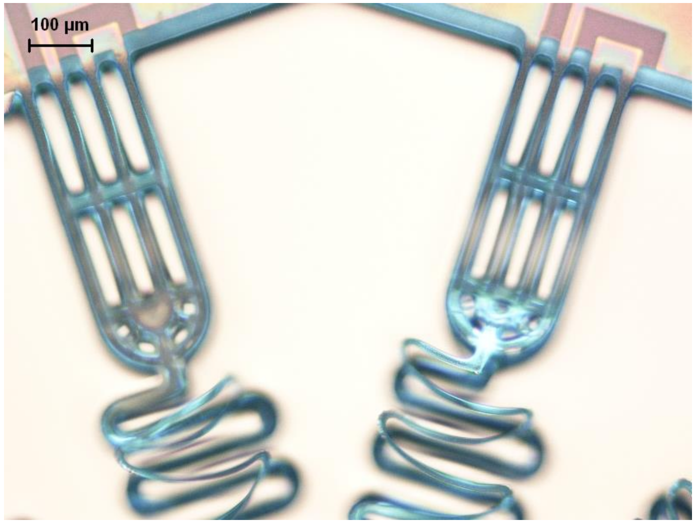


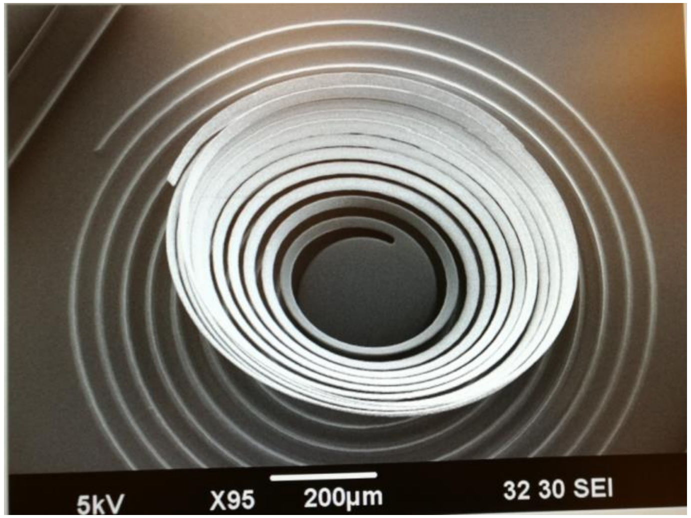
Name is too large

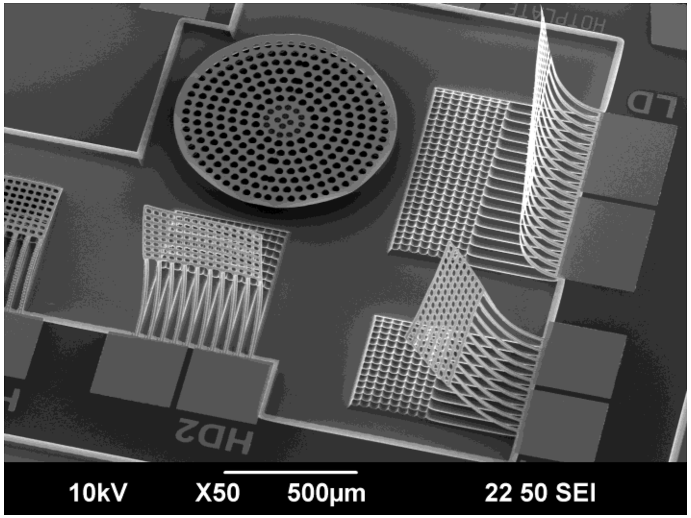


Previous Design

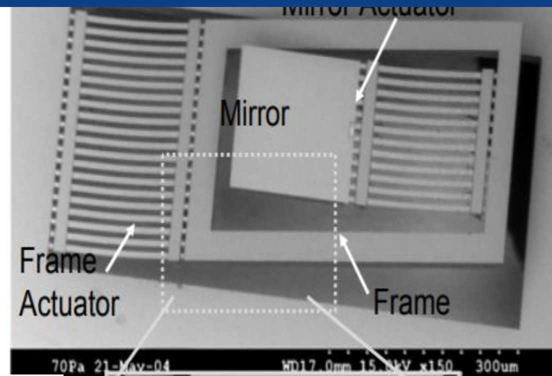


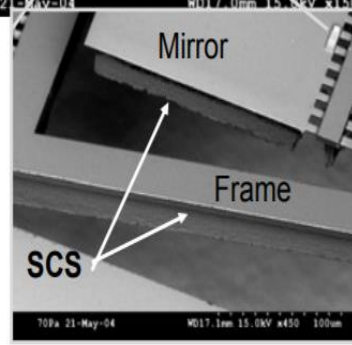


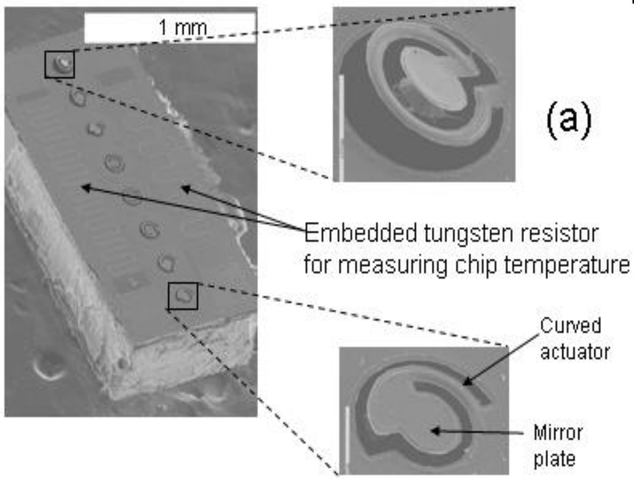


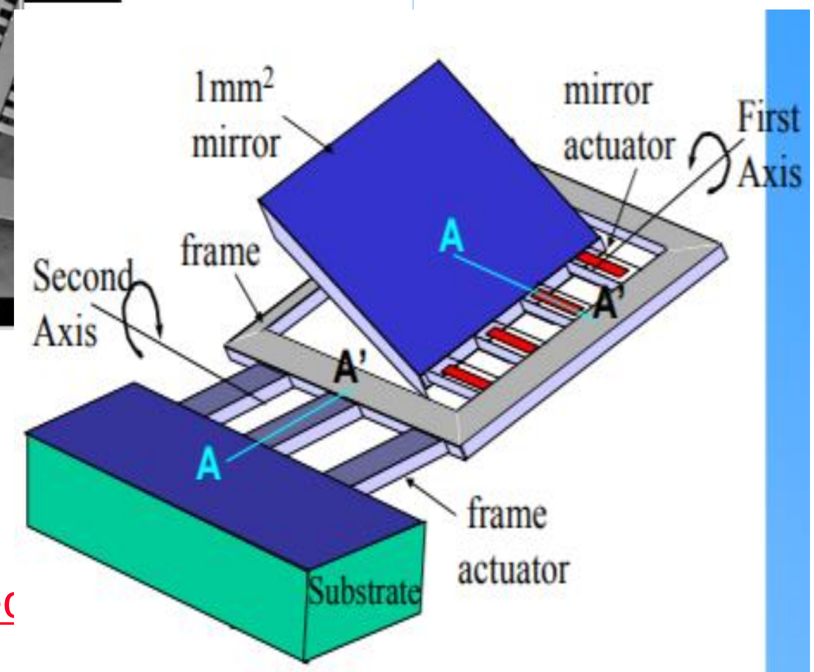


Design Example: MEMS Mirrors







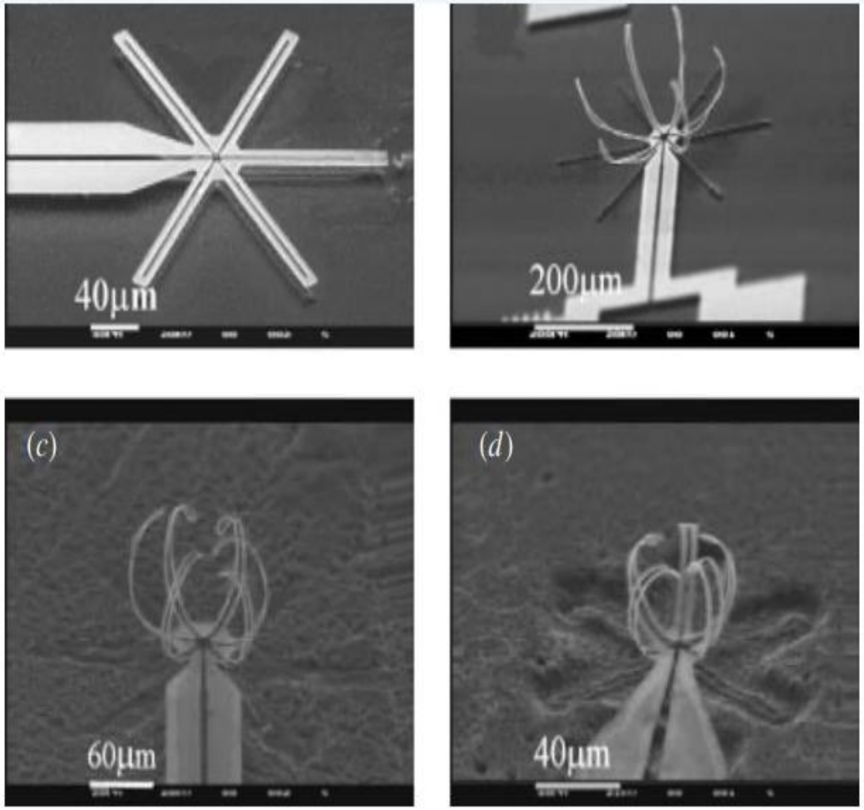


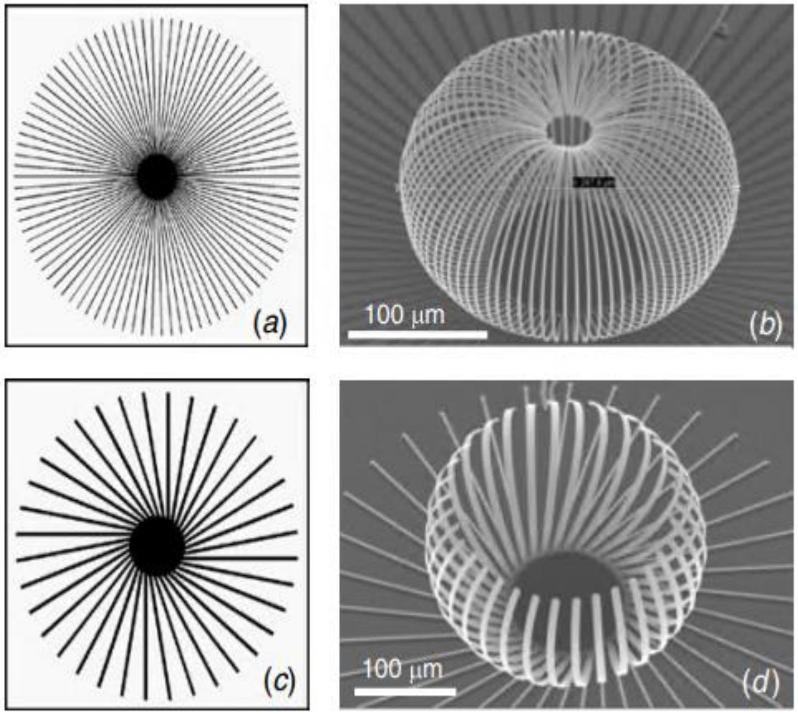
Jain et al, Optical MEMS 2003

Videos:
http://www.mems.ece.ufl.edu/bml/BML_vide(

More MEMS Mirror Design on:
http://www.mems.ece.ufl.edu/bml/

Design Example: Some Arts?





Luo, J. K., et al. "Fabrication and characterization of diamond-like carbon/Ni bimorph normally closed microcages." *Journal of Micromechanics and Microengineering* 15.8 (2005): 1406.

Moiseeva, E., et al. "Single-mask microfabrication of three-dimensional objects from strained bimorphs." *Journal of Micromechanics and Microengineering* 17.9 (2007): N63.

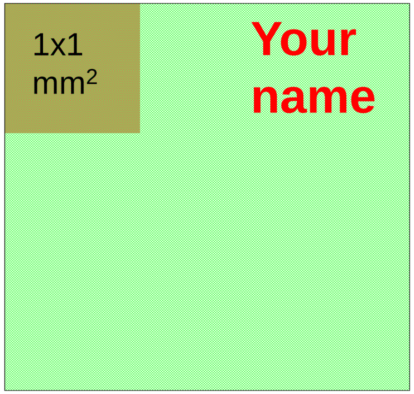
MEMS Actuator Design Contest

Goal: To maximize the tip displacement

Rules:

1. The design must be drawn in the allocated 1mm x 1mm area
2. You may choose any topology,
3. Follow the design rules

Prizes: Gold, Silver, Bronze



Characterization of Bimorph Actuators

- Measure the resistance of your bimorph Al and make sure it is not shorted or open circuit.
- Apply a DC voltage to actuate the bimorph and measure the maximum elevation *h* at the tip.
- Apply an AC voltage to observe the vibration of the bimorph and measure the resonant frequency.
- Place your MEMS on a hotplate that is heated at 200 deg. C, and measure the maximum elevation *h* at the tip under a high magnitude microscope.