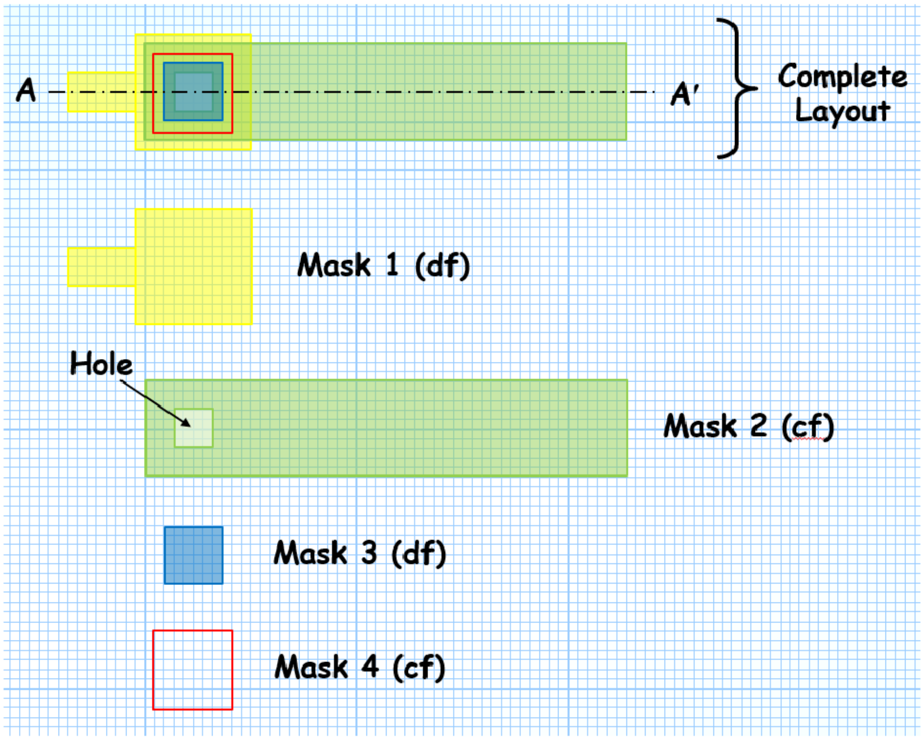
Problem 1. **Total 30 points**

You are given the layout below along with the process traveler to follow. In the layout, each box corresponds to 1 μm^2. In the mask legend, cf = "clear field" and df = "dark field". In the process traveler, assume that all lithography steps use positive photoresist, except when otherwise indicated, and that all etch steps are 100% selective to the intended film. Also, assume that RIE etches are anisotropic, but any other type of etch has some degree of isotropy. Follow the instructions after the process traveler.



Process Traveler:

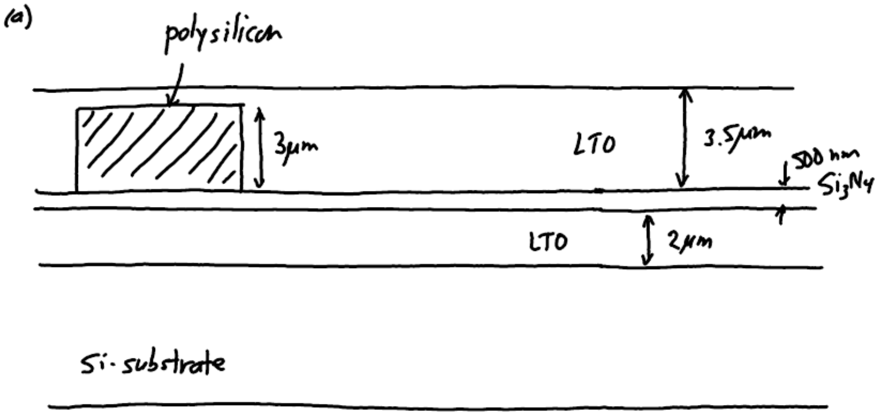
i) Deposit 2 μm of low-temperature oxide (LTO) via LPCVD.
ii) Deposit 500 nm of silicon rich nitride via LPCVD.
iii) Deposit 3 μm of LTO via LPCVD.
iv) Lithography via Mask 1.
v) Etch oxide via RIE and stop on silicon nitride.
vi) Remove photoresist.
vii) Deposit 4 μm of *in situ*-phosphorous-doped polycrystalline silicon via LPCVD at 610°C.
viii) Chemical Mechanical Polish (CMP) using a slurry that softens silicon, but not oxide. Stop on oxide.
ix) Deposit 500 nm of LTO via LPCVD.
x) Deposit 2 μm of *in situ*-phosphorous-doped polycrystalline silicon via LPCVD at 610°C.
xi) Deposit 2 μm of LTO via LPCVD.
xii) Lithography via Mask 2.
xiii) Etch oxide via RIE and stop on polysilicon.
xiv) Etch polysilicon via RIE and stop on oxide.
xv) Remove photoresist.
xvi) Lithography via Mask 3.
xvii) Etch oxide via RIE and stop when the etch reaches polysilicon or nitride on the substrate.
xviii) Remove photoresist.
xix) Deposit 100 nm of *in situ*-phosphorous-doped polycrystalline silicon via LPCVD at 610°C.
xx) Lithography via Mask 4.
xxi) Etch polysilicon via wet etching.
xxii) Dip in HF until structures are fully released.

Instructions:

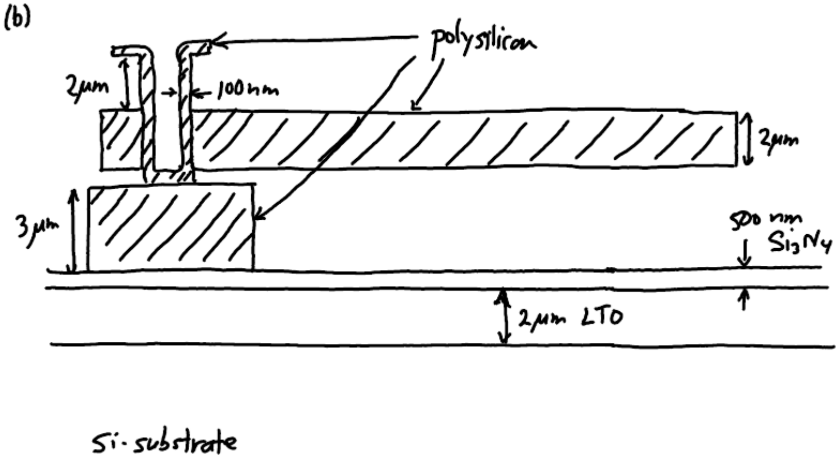
(a) Draw the cross-section through step (ix) along the A-A′ axis.

(b) Draw the final cross-section along the A-A′ axis.

(a)

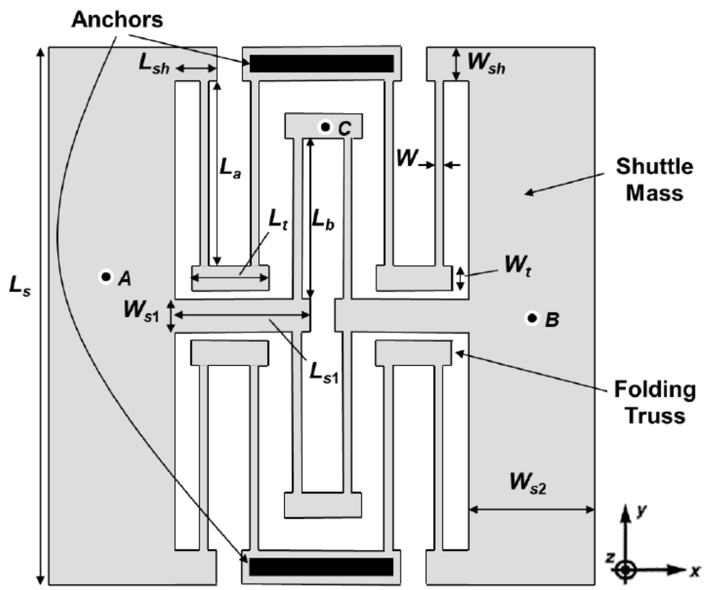


(b)



Problem 2. **Total 90 points**

The figure below presents the top view of a small micromechanical filter constructed in a 2μm-thick structural layer. Here, everything is suspended 2 μm above the substrate except for the anchoring locations indicated as the darkly shaded regions. Data on the structural material used in this problem is given in the box below the figure. Also, assume that all folding trusses and shuttles are rigid in all directions, including the vertical (i.e., z) direction. All suspension and coupling beam widths are 2 μm.



Geometric Dimensions: (all beams have width W)
L_a = 100μm; L_b = 90μm; L_s = 250μm; L_{s1} = 40μm; L_{sh} = 10μm; L_t = 50μm;
W = 2μm; W_{s1} = 8μm; W_{s2} = 50μm; W_{sh} = 10μm; W_t = 5μm; Thickness, h = 2μm;
Shuttle Area = 26,040 μm^2

Structural Material Properties:
Young's Modulus, E = 150 GPa; Density, ρ = 2,300 kg/m^3
Poisson ratio, ν = 0.226, Quality Factor, Q = 50,000
Thermal Expansion Coeff., $\alpha_{Tb} = 5\times10^{-6}$, Resistivity = 10 μΩ-m,
Specific Heat, c_p = 0.7 J/(g K), Thermal Conductivity, k = 90 W/(m K)

Substrate Properties:
Thermal Expansion Coeff., $\alpha_{Ts} = 2.8\times10^{-6}$

Please answer the following questions regarding this structure.

(a) Provide an expression and numerical value with units for the spring constant at location A.

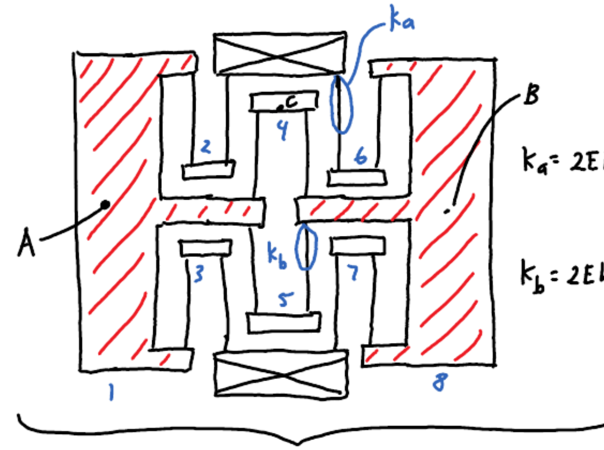
(b) If an x-directed (i.e., towards the right) force of 10 μN is applied at location A, how much does location B displace? Give an expression and provide a numerical value with units.

(c) Suppose you directed a laser at point B on the structure while it sits in vacuum with its substrate at 20°C. If the absorbed laser power is 5 mW, what is the temperature at point B? Provide an expression and numerical value.

(d) If the structure were released in an isotropic wet etchant then rinsed in a special liquid solution with a liquid-air interface surface tension of 5×10^{-3} N/m and a contact angle of 89°, would it be stuck after drying?

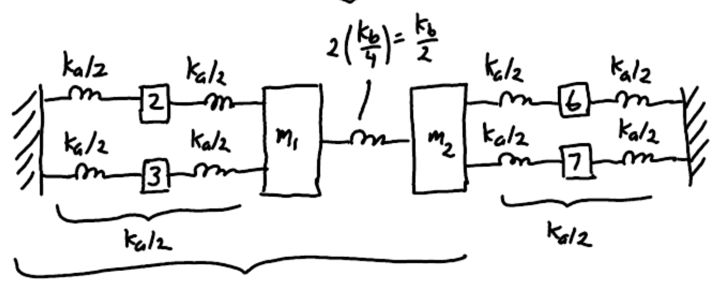
(e) For this part, assume that the release etch at the end of the fabrication process was sufficient to release everything *except* the shuttles. Also, assume that anything released does not stick to the substrate. Suppose that after release, the suspension beams bend so that point C ends up 4 μm above the substrate at 20°C. After careful inspection, you discover that there is a 10 nm film of a mystery material atop the structural material (everywhere) and suspect that this film deposited at the end of the structural material deposition step. If the deposition temperature for both the structural material and this mysterious thin film was 500°C, and assuming the film has the same elastic modulus as the structural material, what is the thermal expansion coefficient of the mysterious thin film?

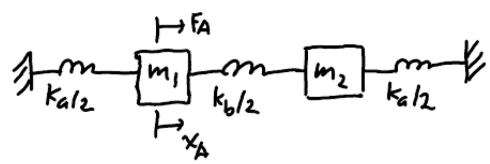
(a)



$$k_a = 2Eh\left(\frac{W}{L_a}\right)^3 = 2(150G)(2\mu)\left(\frac{2\mu}{100\mu}\right)^3$$
$$= \underline{4.8\ N/m}$$

$$k_b = 2Eh\left(\frac{W}{L_b}\right)^3 = 2(150G)(2\mu)\left(\frac{2\mu}{90\mu}\right)^3$$
$$= \underline{6.58\ N/m}$$



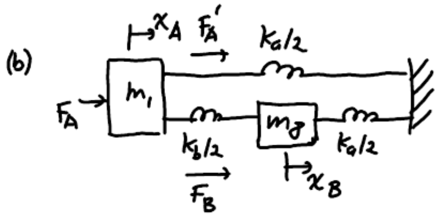


$$F_A = k_A x_A$$

$$k_A = \frac{k_a}{2} + \left(\frac{k_a}{2} \,\Big\|\, \frac{k_b}{2}\right)$$

Plug in numbers: $k_A = \frac{4.8}{2} + \left(\frac{4.8}{2} \,\Big\|\, \frac{6.58}{2}\right) = 3.78\ N/m$

(b)



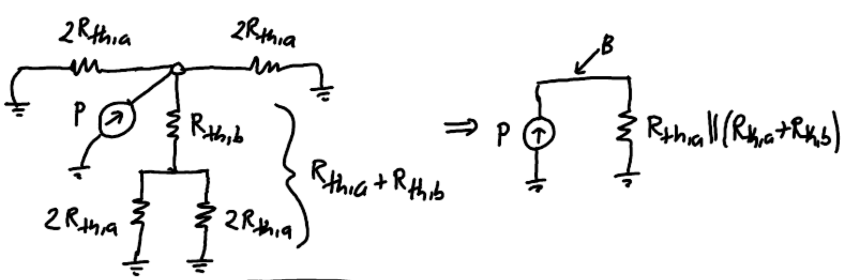
$F_A = F_A' + F_B$

$F_B = \left(\frac{k_a}{2} \| \frac{k_b}{2}\right) x_A$

$$x_B = \frac{F_B}{k_a/2} = \left[\frac{\left(\frac{k_a}{2}\|\frac{k_b}{2}\right)}{\frac{k_a}{2}}\right] x_A = \frac{k_b}{k_a+k_b}\,\frac{F_A}{\left(\frac{k_a}{2}+\frac{k_a}{2}\|\frac{k_b}{2}\right)} = x_B$$

Plug in numbers: $x_B = \left(\frac{6.58}{48+6.58}\right)\left(\frac{10\mu}{3.78}\right) = 1.53\,N/m$

(c)



$T_B = T_o + P\left[R_{th,a}\|(R_{th,a}+R_{th,b})\right] = 20 + (5m)\left[(277.78k)\|(277.78k+250k)\right]$

$\Rightarrow T_B = 935\,°C$

$\left[R_{th,a} = \frac{L_a}{k_{th}Wh} = \frac{100\mu}{(90)(2\mu)(2\mu)} = 277{,}778\,K/W,\; R_{th,b} = \frac{L_b}{k_{th}Wh} = \frac{90\mu}{(90)(2\mu)(2\mu)} = 250{,}000\,K/W\right]$

(d) The shuttle masses dominate the area. (Ignore other area contributions)

The stiffness against stiction comes from springs attached to anchors. $\rightarrow k_a$

$F_{stiction} = \frac{2A_p\gamma_{la}\cos\theta_c}{(g-z)} = k_a z = F_{spring}$

$A_p \triangleq$ underside area of shuttle

$\Rightarrow$ quadratic solution: $z = \frac{g}{2} \pm \sqrt{\frac{g^2}{4} - \frac{8A_p\gamma_{la}\cos\theta}{4k_a}}$

$\gamma_{la} \triangleq$ liquid-air surface tension

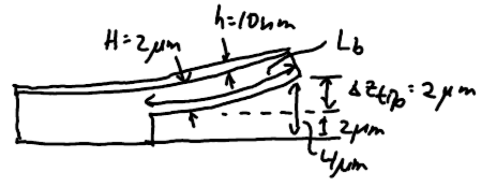
Plug in numbers: $g = 2\mu$, $\gamma_{la} = 5m$, $\theta_c = 89°$, $A_p = 26040\mu^2$

$\theta_c \triangleq$ contact angle

$\therefore z = 1\mu \pm \sqrt{\frac{(2\mu)^2}{4} - \frac{8(26040\mu^2)(5m)\cos(89°)}{4(48)}} = 0.76\mu m$ or $1.23\mu m$

Both $< 2\mu m$ $\therefore$ no sticking!

(e)



To bend upwards, the stress must be tensile.

$\left[I_x = \frac{1}{12}WH^3\right]$

The internal bending moment: $M_x = \frac{1}{2}\sigma_0 WHh$

$\therefore$ the strain gradient is: $\Gamma = \frac{1}{R} = -\frac{M_x}{EI_x} = -\frac{1}{2}\frac{\sigma_0 Wh}{E'I_x} = 6\frac{\sigma_0}{E}\frac{h}{H^2}$

and $\Delta z_{tip} = \frac{1}{2}\Gamma L_b^2 = \frac{1}{2}(6)\frac{\sigma_0}{E'}\frac{h}{H^2}L_b^2 \Rightarrow \Delta z_{tip} = 3\frac{\sigma_0}{E'}h\left(\frac{L_b}{H}\right)^2$

$\sigma_0 = \frac{1}{3}\Delta z_{tip}E'\frac{1}{h}\left(\frac{H}{L_b}\right)^2$

Want this $\qquad T_d - T_r$

$\sigma_0 = \sigma_{f,mismatch} = E'\epsilon_{f,mismatch} = E'(\alpha_{Tf} - \alpha_{Tb})\Delta T$

(+) or tensile for $\Delta z_{tip} = (+)$ $\qquad$ film $\qquad$ beam

$\therefore \alpha_{Tf} = \alpha_{Tb} + \frac{1}{3}\frac{\Delta z_{tip}}{\Delta T}\frac{1}{h}\left(\frac{H}{L_b}\right)^2 = 3\mu + \frac{1}{3}\frac{1}{(500}\frac{2\mu}{-20)}\frac{1}{(10n)}\left(\frac{2\mu}{90\mu}\right)^2$

$\Rightarrow \alpha_{Tf} = 73.6\times10^{-6}$

Midterm Statistics	
Top Score	117
Average	91
Median	98
Std. Dev.	20