# PROBLEM SET #4

*Issued: Thursday, Oct. 7, 2010,*

*Due (at 7 p.m.): Thursday, Oct. 14, 2010*, in the EE C245 HW box in 240 Cory.

**1.** One method to estimate the compressive stress in a thin film is to fabricate fixed-fixed beams of varying lengths, as shown in Figure 1(a). Here, the length of the smallest beam that buckles gives a lower limit on the compressive stress in the film. For this problem, assume the structure has the dimensions shown in Figure 1 (b).

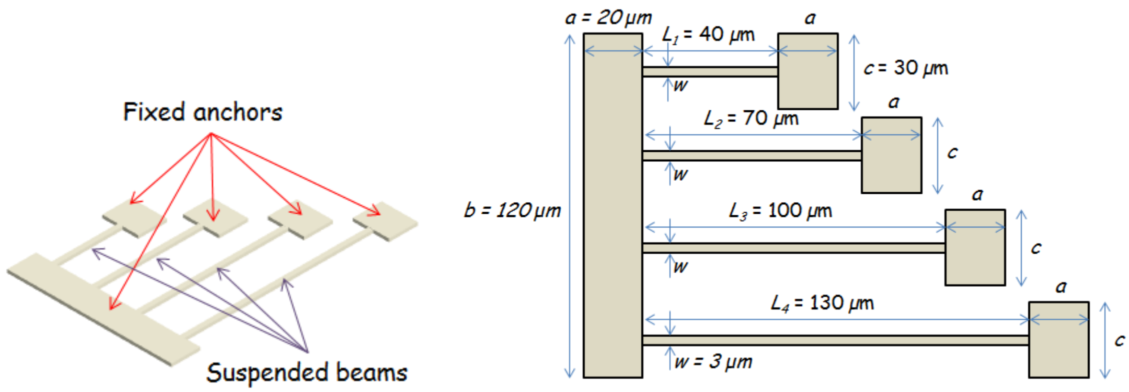


**Figure 1 (a) and (b). Fixed-fixed beam array for problem 1.**

The structure illustrated in Figure 1 can be fabricated on a (100) Si wafer using the following one mask fabrication process:

- Thermally grow 2.0 μm of $SiO_2$.
- Deposit 1.4 μm of polysilicon using LPCVD
- Spin positive PR, expose using the pattern shown in Figure 1 (b), then develop
- Etch polysilicon using reactive ion etching (anisotropic)
- Etch $SiO_2$ using a timed HF etch (isotropic)

**(a)** Assume an oxidation furnace costs \$36/hour to operate. Calculate how much more expensive it is to grow a 4.0 μm film of $SiO_2$ than a 2.0 μm film of $SiO_2$.

**(b)** Explain whether one should use a clear-field mask or a dark-field mask during the exposure step of this process.

**(c)** Assume that 49 wt. % hydrofluoric acid (which is the concentration straight out of an HF bottle) etches $SiO_2$ isotropically at 3.0 μm per min with infinite selectivity to polysilicon. Answer the following, rounding all answers to the nearest second.

(i) Calculate the etch time needed to free the beams from $SiO_2$, i.e., at the instant there is a nonzero gap between the beam and the $SiO_2$ below.

(ii) Calculate the etch time needed to remove all of the $SiO_2$ below the beams.

(iii) Calculate the etch time needed to completely release the entire structure, including the anchors.

**(d)** Suppose that after etching the $SiO_2$ long enough to fully release the beams but not the anchors, the structure is inspected with a microscope and it is observed that only the 130 μm long beam is buckled. Give upper and lower bounds on the magnitude of the compressive residual stress that was present in the polysilicon film. Assume that the anchors are infinitely stiff. Round to the nearest ten MPa. Use a Young's modulus of $E$ = 150 GPa for polysilicon.

**(e)** Suppose now that the anchors are not infinitely stiff and move a very tiny amount ($\Delta x$ < 10 nm) when x-directed forces are applied by the compressed beam as shown in Figure 2. Considering the nonzero compliance of the anchors, explain why the estimated range of compressive stress you found in part (d) is either an overestimate or an underestimate of the true compressive stress.

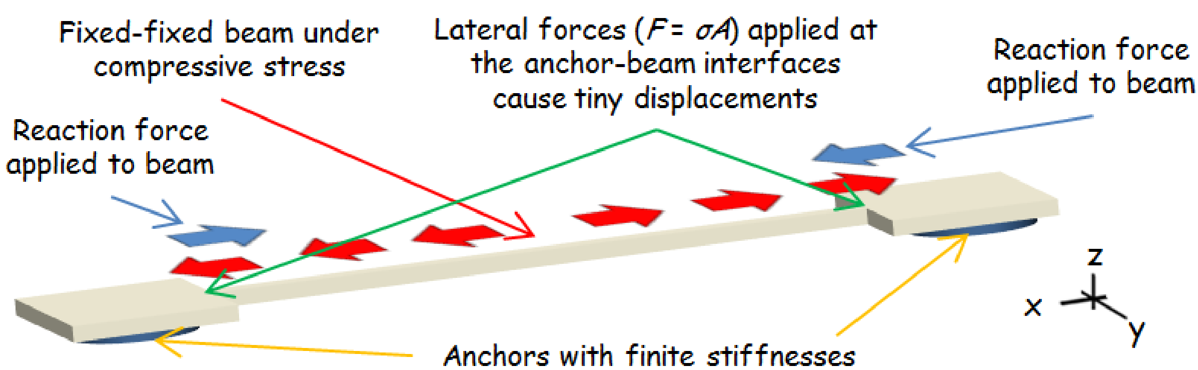


**Figure 2. Illustration of a fixed-fixed beam under compressive stress.**

**2.** Suppose that chemical vapor deposition of a material with properties summarized in the table at the bottom of the page yields a film with non-uniform grain sizes with the cross-sectional structure shown below (which is not quite to scale). Here, the deposition starts with small symmetric grains, but as time passes in the chamber the earlier grains cluster and deform, while newly deposited grains remain smaller.

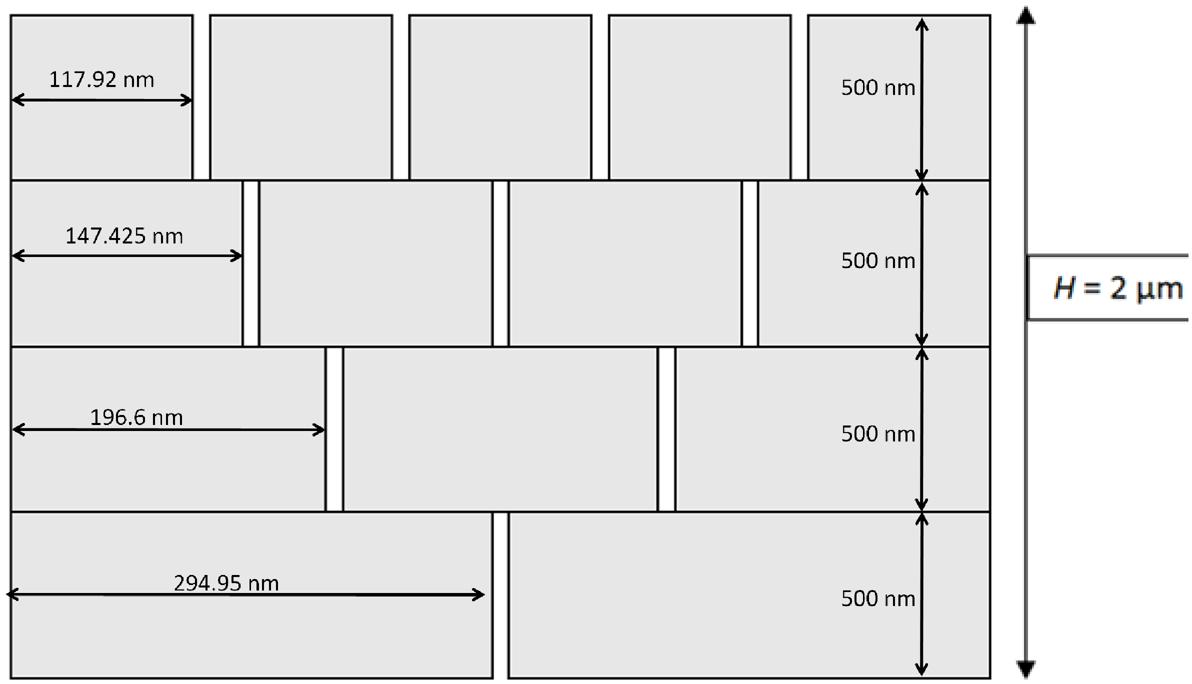


**Figure 3. Cross section of a CVD film with non-uniform grains.**

**(a)** If all gaps between grains are of uniform separation $g = 0.1\ nm$, and we cool this film from a stress-free state at $T_i = 650\ °C$ to room temperature (where the gaps fully close), what are the final stress and strain gradients? Provide formulas and sketch plots with appropriate marked values. Assume a continuous linear gradient.

**(b)** Assume this film is now shaped into a cantilever beam with length $L = 100\ \mu m$ and width $W = 5\ \mu m$. As the beam relieves its internal stress gradient, it will begin to warp. What is the deflection at the tip of the beam? Which direction does it deflect?

**(c)** You attempt to negate this deflection by depositing a very thin stressed film on top of the beam, with properties at room temperature in the table below. Should the film itself be under tensile or compressive stress? How thick does it need to be?

**Table1. Material properties for problem 2.**

| | **Film Properties (part a, b, c)** | **Thin Stressed Film (part c)** |
|---|---|---|
| Young's Modulus ($E$) | 150 GPa | 180 GPa |
| Linear Thermal Coefficient ($\alpha_T$) | 1.3 µstrain/K | 2.7 µstrain/K |
| Density ($\rho$) | 2700 kg/m$^3$ | 2600 kg/m$^3$ |
| Poisson's Ratio ($\nu$) | 0.3 | 0.3 |
| Initial Uniform Stress ($\sigma_0$) | 0 MPa | 400 MPa |

**3.** This problem concerns the mechanical robustness of a microneedle with a square cross section $W(x) = H(x)$ summarized in Figures 4 and 5. Assume the small channel in the middle of the microneedle has negligible effects on its mechanical properties, which is a fair approximation if the dimensions of the channel are much smaller than those of the microneedle.

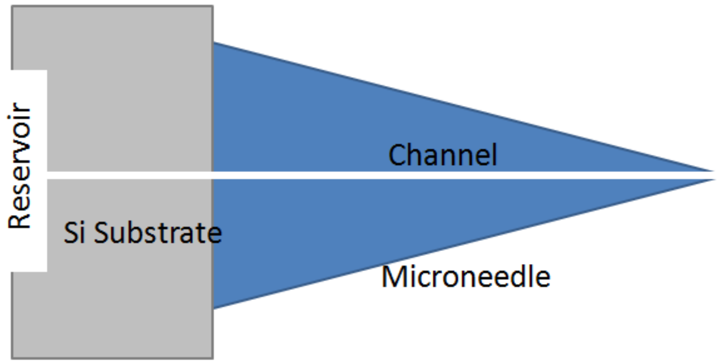


**Figure 4. Cross section of a microneedle.**

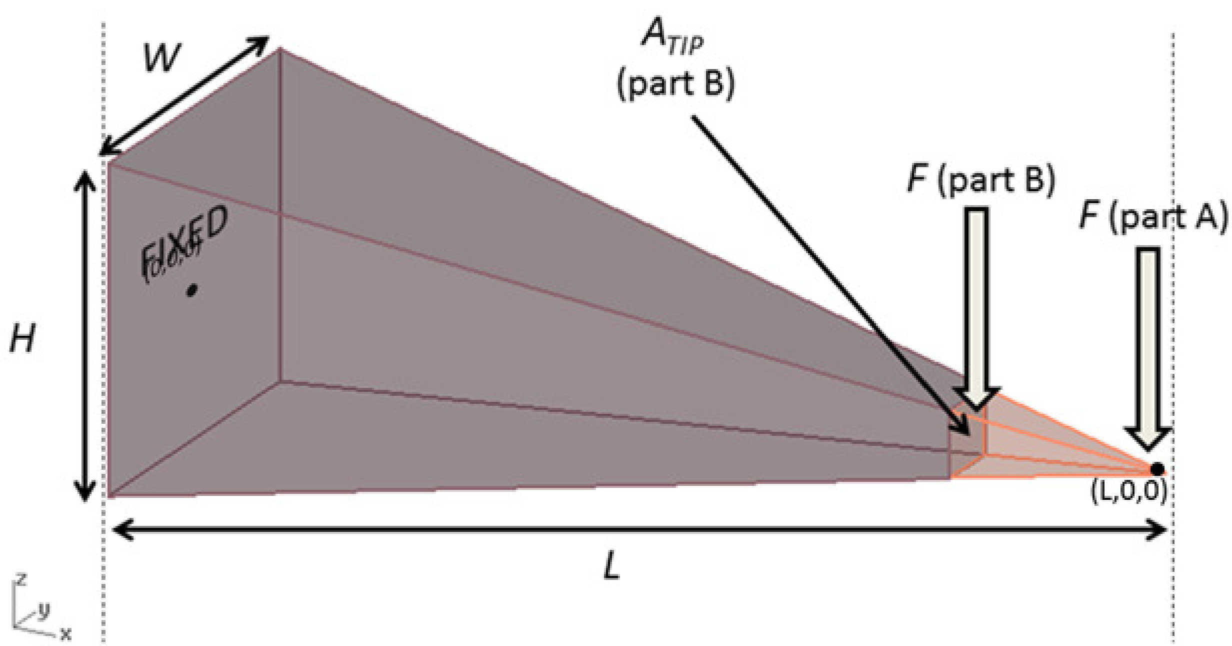


**Figure 5. Microneedle dimensions for parts (a) and (b). Here, the channel is not displayed for simplicity.**

**(a)** Derive the stiffness of the structure with respect to a vertical z-directed force $F(part\ A)$ applied at the tip as shown in Figure 4.

**(b)** The maximum yield stress of a material (denoted $\sigma_{ys}$) is defined as the stress where the material begins to irreversibly deform. In the case of a microneedle, if the lateral force $F$ induces a stress exceeding $\sigma_{ys}$ the tip will be permanently bent (rendering the device useless). Suppose we define the sharpness of a tip as $S = 1/A_{TIP}$. What is the maximum sharpness of a microneedle under the lateral force $F(part\ B)$ shown in Figure 5? [Hint: At what distance does the stress in the microneedle exceed the yield stress?]