Etchant	Composition	Etching Temp.	Etch Rate (μm/min)	(100)/(111) Etch Rate Ratio	Etch Mask
HF: HNO_3: water (or CH_3COOH) (HNA)	10 mL: 30 mL: 80 mL	22°C	0.7–3.0	1/1	Si_3N_4, SiO_2 (300 Å/min)
Ethylene diamine: pyrocatechol: water (EPW)	750 mL: 120 g: 240 mL	115°C	1.25	35/1	SiO_2, Si_3N_4, Ag, Ag, Cr, Cu, Ta
KOH: water	44 g: 100 mL	85°C	1.4	400/1	Si_3N_4, SiO_2 (14 Å/min)
TMAH	25 wt% TMAH	95°C	0.6	30/1	SiO_2, Si_3N_4, Ag, Ag, Cr, Cu, Ta

Source: Adapted from [2].

TABLE 2.2 Wet Etchants for Silicon

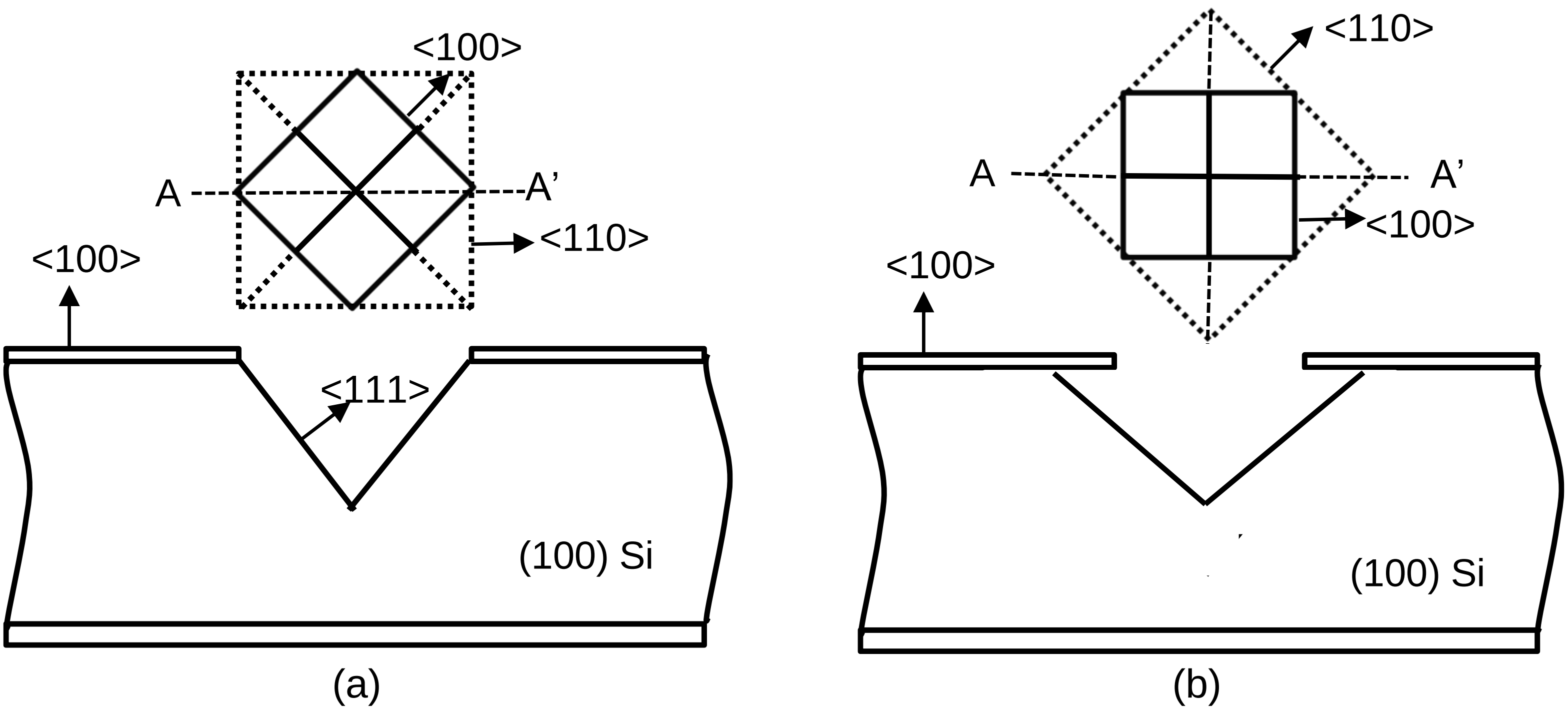


Figure 2.8

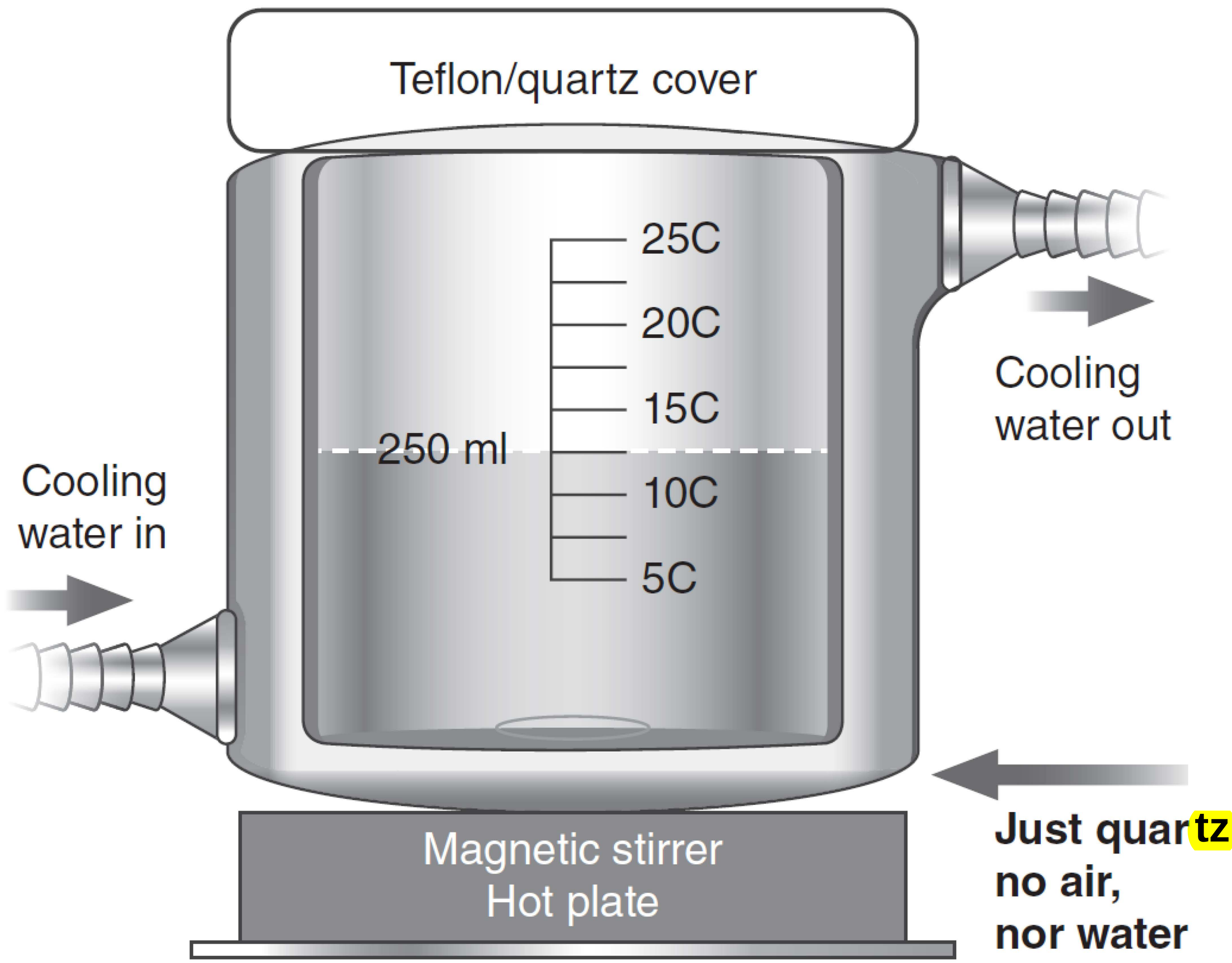

Teflon/quartz cover
25C
20C
15C
250 ml
10C
5C
Cooling water in
Cooling water out
Magnetic stirrer Hot plate
Just quartz no air, nor water

Figure 2.23

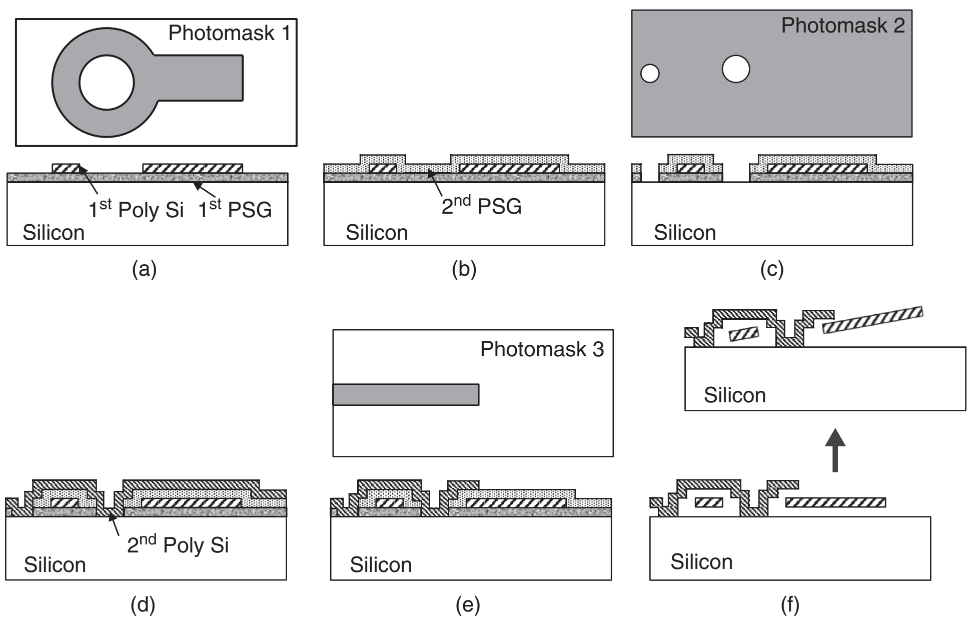
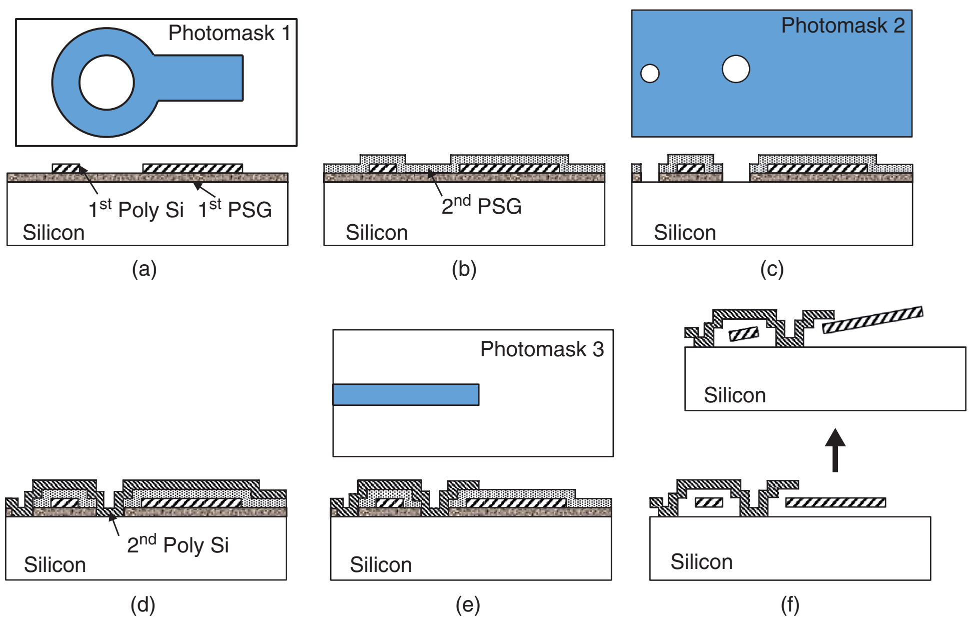

Photomask 1
1st Poly Si
1st PSG
Silicon
(a)
2nd PSG
Silicon
(b)
Photomask 2
Silicon
(c)
2nd Poly Si
Silicon
(d)
Photomask 3
Silicon
(e)
Silicon
Silicon
(f)

Figure 2.29

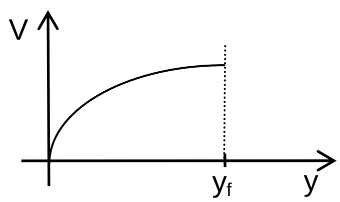


Photomask 1
1st Poly Si
1st PSG
Silicon
(a)
2nd PSG
Silicon
(b)
Photomask 2
Silicon
(c)
2nd Poly Si
Silicon
(d)
Photomask 3
Silicon
(e)
Silicon
Silicon
(f)

Figure 2.29

Question: For the vertical comb drive shown in Fig. 3.2, *sketch* applied voltage V as a function of the vertical distance y (for y between 0 and y_f). [Hint: The spring force of the movable polysilicon beam is equal to ky where k and y are the spring constant and the distance in vertical direction as indicated in Fig. 3.2, respectively. The electrostatic force (acting vertically on the movable beam) is equal to $e_o V^2 l/g$, where l and g are the beam length and the air gap, respectively, as indicated in Fig. 3.2.]

Answer: $ky = e_o V^2 l/g$ ➔ $V = \sqrt{\frac{gky}{\varepsilon_o l}}$



Question and answer on p. 93

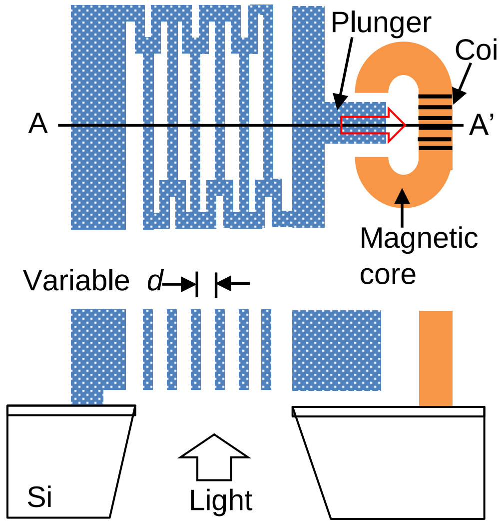
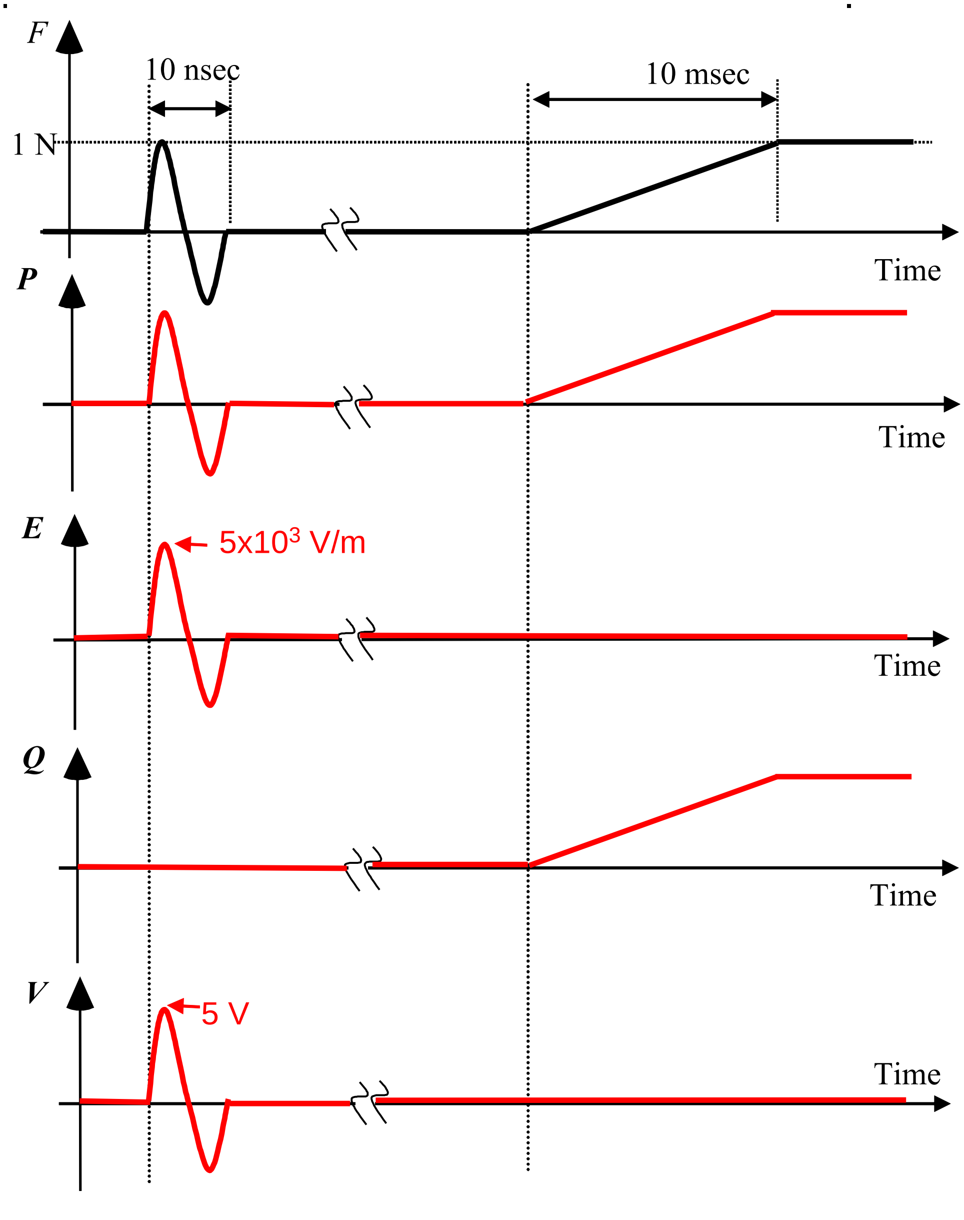


Fig. 3.11



$2\pi\cdot\tau = 2\pi\cdot\rho\varepsilon = 2\pi\cdot 10^7 x 10^{-12} = 62.8$ μsec, which is much less than10 msec, but much greater than 10 nsec. Thus, all the charge transfer happens during 10 msec, but not during 10 nsec.

Polarization field follows the strain exactly.

Electric field is zero for 10 msec ramp, since charge transfer through ZnO happens fast enough to cancel out any E-field.

Stress $T = 1N/(1x10x10^{-6})$

$= 10^5$ N/m^2

$E = d_{31}T/\varepsilon$

$= -5x10^{-12}x10^5/10^{-10}$

$= -5x10^3$ V/m

10 nsec is too short for charge transfer through ZnO, and no charge shows up at the electrodes due to the 10 nsec sinusoidal force.

$|V| = |Eh|$ (note: it is E, not Q)

$= 5x10^3x10^{-3}$

$= 5$ V

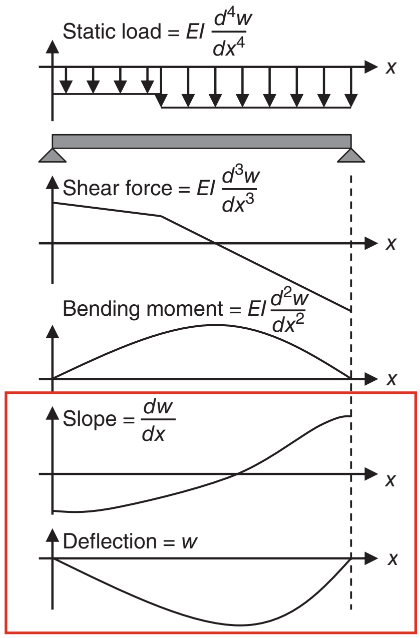
Answer to the Question on p. 113 (the 3rd question after Fig. 3.18)

Structure	Governing Equations	Equivalent Spring Constant *k' (N/m³)*	Buckling Stress σ_c *(N/m²)*
Cantilever	$EI\frac{d^4w}{dx^4} = Pb - \frac{\varepsilon_o bV^2}{2g^2}$	$\frac{2Et^3}{3l^4}$	NA
Bridge (Two Edges Clamped)	$EI\frac{d^4w}{dx^4} + 1(-\nu)bt\frac{d^2w}{dx^2} = Pb - \frac{\varepsilon_o bV^2}{2g^2}$	$\frac{32Et^3}{3l^4} + \frac{8\sigma(1-\nu)t}{l^2}$	$\frac{4Et^2}{3l^2(1-\nu)}$
Clamped Circular Plate	$D\nabla^4 w + \sigma t\nabla^2 w = P - \frac{\varepsilon_o V^2}{2g^2}$	$\frac{16Et^3}{3\rho^4(1-\nu^2)} + \frac{4\sigma t}{\rho^2}$	$\frac{4Et^2}{3\rho^2(1-\nu^2)}$

TABLE 6.1

6.2.3 Vibrations of Beams

The figure below shows the relationships among *static* load, shear force, bending moment, deflection-curve slope, and deflection curve for a beam with its two edges simply supported. Those are all related to each other through spatial differentiation or integration, stemming from the governing equation, static load = $EI\frac{d^4w}{dx^4}$, which is solved according to the boundary conditions. Both the bending moment and the displacement are *zero* at the two edges because they are simply supported.



Now, if the beam is naturally vibrating (without any forced input, i.e., zero static load), there is an alternating inertia load due to the acceleration/deceleration of the beam going through vibration, and the governing equation is $EI\frac{\partial^4 w}{\partial x^4} = -\rho_1\frac{\partial^2 w}{\partial t^2}$, where ρ_1 is the beam mass per unit length. Assuming a sustained free vibration ($w(x, t) = w(x)\sin\omega t$ or $w(x)e^{j\omega t}$), the governing equation becomes $\rho_1\omega^2 w = EI\frac{\partial^4 w}{\partial x^4}$.

General solution is $w(x) = C_1e^{ax} + C_2e^{-ax} + C_3\sin ax + C_4\cos ax$, where $a = \sqrt[4]{\frac{\rho_1\omega^2}{EI}}$. From B.C.'s for simply supported ends, $w(0) = w(l) = 0$ and $w''(0) = w''(l) = 0$, we obtain $w(x) = C\sin ax$ and $al = l\sqrt[4]{\frac{\rho_1\omega^2}{EI}} = n\pi$, where $n = 1, 2, 3, \ldots$ Thus, $\omega_1 = \frac{\pi^2}{l^2}\sqrt{\frac{EI}{\rho_1}}$, $\omega_2 = \frac{4\pi^2}{l^2}\sqrt{\frac{EI}{\rho_1}}, \ldots, \omega_n = \frac{n^2\pi^2}{l^2}\sqrt{\frac{EI}{\rho_1}}$. So, we see that the solution of the differential equation along with the resonant frequencies can easily be obtained for simply supported edges. Other boundary conditions yield more complex solutions, which are tabulated in Table 6.4 that shows the resonant frequencies and mode shapes for the first, second, third, and

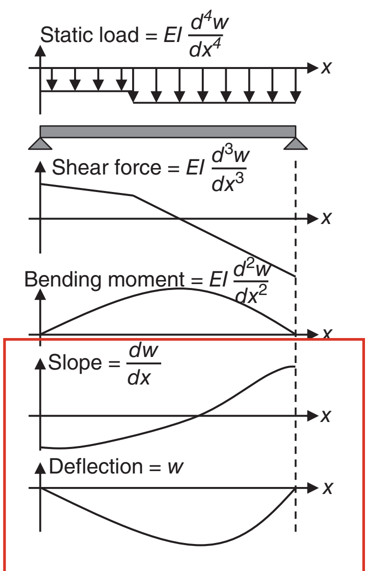
18. Z.Y. Guo, Z.C. Yang, Q.C. Zhao, L.T. Lin, H.T. Ding, X.S. Liu, J. Cui, H. Xie, and G.Z. Yan, "A lateral-axis micromachined tuning fork gyroscope with torsional Z-sensing and electrostatic force-balanced driving," Journal of Micromechanics and Microengineering, 20, 2010, 025007.
19. H. Qu, "CMOS MEMS fabrication technologies and devices," Micromachines, 2016, 7, 14; doi:10.3390/mi7010014.
20. J. Liewald, B. Kuhlmann, T. Balslink, M. Trachtler, M. Dienger, and Y. Manoli, "100 kHz MEMS vibratory gyroscope," Journal of Microelectromechanical Systems, 22(5), October 2013, pp. 1115–1125.
21. J. Seeger, M. Lim, and S. Nasiri, "Development of high-performance, high-volume consumer MEMS gyroscopes," Solid-State Sensors, Actuators, and Microsystems Workshop, Hilton Head, SC, 2010, pp. 61–64.

Questions and Problems

Question 6.1 Using Rayleigh's energy method, we can calculate the fundamental resonant frequency of an elastic body by assuming a deflection curve. What would you do to estimate the resonant frequency as accurately as possible?

Question 6.2 When a beam (with a moment of inertia equal to 10^{-20} m^4) goes through a pure bending by a bending moment, the stress at a point 1 μm away (in the thickness direction) from the beam axis is measured to be 1,000 Pa. What is the stress at a point 0.5 μm away (in the same thickness direction) from the beam axis?

Question 6.3 A simply supported beam goes through a pure bending by a distributed load and is analyzed to have the shear force, bending moment, slope, and deflection as shown at right. If the beam has *clamped* edges (rather than simply supported edges), how the curves will look like? Sketch the new curves on the same figure at right.



Question 6.4 On the graph at right, sketch the shear force, bending moment, slope, and deflection when the beam (with its two ends being simply supported) is under a uniform distributed load (i.e., a load that is *not* varying, or constant in magnitude, along the beam axis, *x*). Note that the load that is shown at right has a step variation at a point along the beam axis and is not the load for this problem.

Question 6.5 A thin polysilicon beam (100 μm long, 2 μm thick, and 6 μm wide) is *simply supported* at its two edges. What *compressive* residual stress will cause the beam to be buckled? Assume the polysilicon has Young's modulus of 140 GPa.

Example in Section 1.5.1.

[Example] For air (amu ≈ 29) at 300 K, $\lambda = \frac{0.05}{P}$ [mm] and $\Phi = 3.77 \times 10^{20} P$ [$cm^{-2}sec^{-1}$] with P in torr. At $P = 10^{-6}$ torr, $\Phi = 3.77 \times 10^{14}/cm^2sec$. ➔ If each striking molecule sticks on surface, it takes ≈ 2.7 seconds to form a monolayer on solid surface (since 1 monolayer of solid-surface atoms ≈ $10^{15}/cm^2$).

Question 1.1 Dichlorosilane (SiH_2Cl_2) is ~~liquid at room temperature, and~~ contained in a cylinder as liquid. However, we can still deliver a gaseous SiH_2Cl_2 to low-pressure CVD (LPCVD) system for silicon nitride deposition. Explain how this is possible.

Equation (6.3)

Thus, noting that the stress σ on any point of a cross section is $-\frac{z}{C}\sigma_{max}$, we obtain

$$\sigma = -\frac{Mz}{I} \qquad (6.3)$$

The Eq. (6.3) shows an important relationship between stress σ (on any point of the beam cross-section, directed toward the beam axis, i.e., x) and the bending moment M, when a beam goes through pure bending. The stress σ is dependent on M, z and I (moment of inertia), and we need to know M to obtain stress distribution.

Question: What is the moment of inertia for a cantilever with a rectangular cross-section with b and h being the width and height (or thickness) of the beam, respectively?

Answer: $I = \int_A z^2 dA = \int_{-b/2}^{b/2}\int_{-h/2}^{h/2} z^2 dz dy = \frac{bh^3}{12}$.

Question: If a beam (with a moment of inertia equal to 10^{-20} m^4) goes through a pure bending by a bending moment equal to 10^{-10} N·m, what is the stress at a point 1 μm away (in the thickness direction) from the beam axis?

Answer: $\sigma = \left|\frac{Mz}{I}\right| = \frac{(10^{-10}\,\mathrm{N\cdot m})x(10^{-6}\,\mathrm{m})}{10^{-20}\,\mathrm{m}^4} = 10^{-4}\,\mathrm{N/m}^2$

Equation (8.6)

$$P = -\gamma_{la}\left(\frac{\cos\theta_{top} + \cos\theta_{bottom}}{h} + \frac{\cos\theta_{left} + \cos\theta_{right}}{w}\right)$$

Problem 1.4 In LPCVD with SiH_4, if x_s is defined to be the fractional area that has adsorbed SiH_4, it is reasonable to take that the adsorption rate is equal to $An_o(1 - x_s)$ while the sum of the desorption rate and decomposition rate is equal to Bx_s, where A and B are constants, and n_o = silane input concentration. Based on this simple model, derive an equation for deposition rate $R_D \approx \frac{Cn_o}{An_o + B}$ with C being another constant.

Problem 3.1 Assume that the resistivity and the dielectric constant of ZnO are 10^7 Ωcm and 8×10^{-13} F/cm, respectively.

Problem 3.5 A piezoelectric ZnO crystal (with h = 1 mm, w = 5 mm and l = 10 mm) is covered with two electrodes as shown at right, and is applied with a sinusoidal force that is uniformly distributed over the top and bottom faces. Assume d_{33} = 10 pC/N, d_{31} = -5 pC/N, d_{15} = -14 pC/N, ρ (resistivity) = 10^7 Ω·cm, and ε (dielectric constant) = 10^{-12} F/cm for ZnO. For the open-circuit type, ignoring mechanical resonance effect, (a) *sketch* (on the figure below) the polarization field P within the ZnO, the electrical field E within the ZnO, the electrical charge Q developed on the top electrode, and the voltage V developed between the two electrodes as a function of time. (b) Calculate the *peak* electrical field and voltage, and indicate those on the E and V curves. Assume that the magnitude of the applied force is 1 N.

Problem 3.6 As shown below, a piezoelectric ZnO crystal (h = 1 mm, w = 5 mm and l = 10 mm) is covered with two electrodes, and is applied with a force that is uniformly distributed over the top and bottom faces. The electrodes are connected to a unity gain amp with 1 MΩ input resistance. Ignoring mechanical resonance effect, (a) *sketch* (on the figure below) the magnitudes of the polarization field P within the ZnO, the electrical field E within the ZnO, the electrical charge Q developed on the top electrode, and the voltage v_o after the unity gain amplifier, as a function of time; (b) calculate the *peak* electrical field and voltage, and indicate those on the E and V curves. Assume d_{33} = 10 pC/N, d_{31} = -5 pC/N, d_{15} = -14 pC/N, ρ (resistivity) = 10^7 Ω·cm, and ε (dielectric constant) = 10^{-12} F/cm for ZnO. Assume that the magnitude of the applied force is 1 N.

Figure 4.9 (a) An air-backed FBAR built on a SiN support layer with piezoelectric ZnO film. (b) A three-port (one-dimensional) model of the resonator with one electrical port (having electrical voltage and current) and two acoustic ports (each port having mechanical force and particle velocity) ~~if the electrodes are negligible~~.

Question 4.9 For a disk resonator with 0.3 µm air gap (Fig. 4.4); (a) will there be any measurable electromechanical resonance, if V_p is equal to 0 V and (b) what will happen if V_p is increased higher than 300 V?

Question 5.8 If the electrostatically-actuated optical reflective switch shown in Fig. 5.15 has the light reflectivity as shown in Fig. 5.16b for λ = 1,425nm, what are the thickness and refractive index of the SiN_X membrane?

Question 6.6 A thin polysilicon cantilever (100 μm long, 2 μm thick, 6 μm wide) with one edge clamped is deflected by a static point force (1 dyne) as shown below. ~~(a)~~ Ignoring the cantilever weight, sketch the shear force, bending moment and deflection as a function of the beam axis, x. Where is the maximum stress?

Equation (8.1)

$$-\gamma_{la} \cos(180° - \theta_Y) = \gamma_{la} \cos\theta_Y = \gamma_{sa} - \gamma_{sl} \qquad (8.1)$$

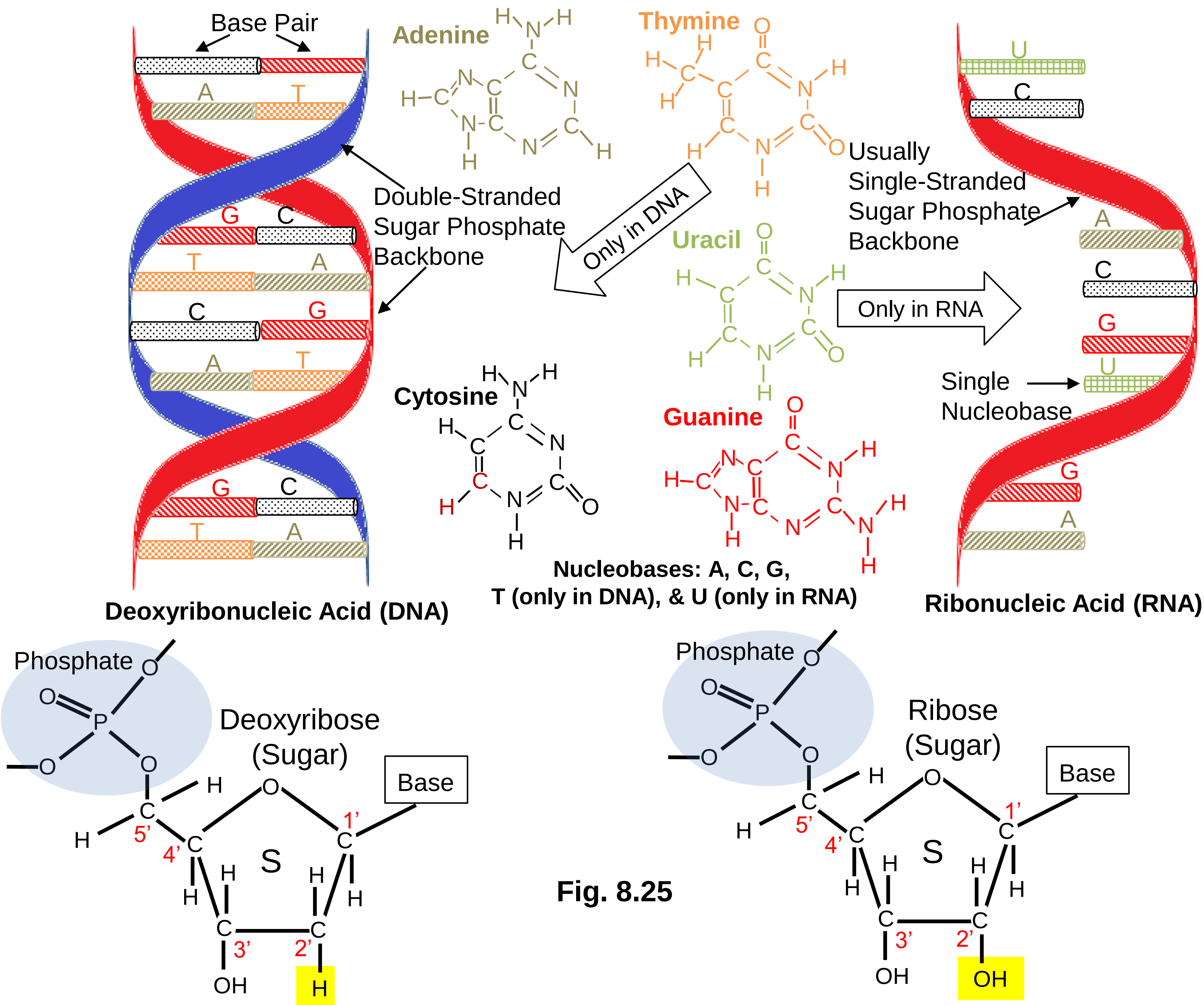


Fig. 8.25

Figure 8.25 Structures of deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). The sugars in DNA and RNA are *deoxy*ribose and ribose, respectively, which differ by one oxygen, as yellow-highlighted at the bottom. The lack of the hydroxyl group on the 2’ carbon makes DNA chemically more stable (or less reactive) than RNA.