ECE/ME 449 Spring 08, Prof. Feinerman, Test #4 solutions 5/6/08, **Closed** Book and **Closed** Notes

Undergraduates $\bar{x}$ = 48.5, σ =14.0, Graduates $\bar{x}$ = 78.5, σ = 13.4

Element	Molecular weight, grams	Atomic number	Density, gm/cc	Resistivity, $\mu\Omega$*cm
Hydrogen (H)	1.00794	1	Gas	Insulator
Carbon (C)	12.0107	6	1.8 (graphite)	1100$\mu\Omega$cm
Oxygen (O)	15.9994	8	Gas	Insulator
Silicon (Si)	28.0855	14	2.33	10^{11} or less
Argon	39.948	18	Gas	Insulator

Avogadro's Number, $N_{Av} = 6.022*10^{23}$ atoms/mole, Boltzmann's constant, $k_B = 1.3807*10^{-23}$ J/^{o}K

Ideal gas law, $P*V = N * k_B * T$, $Z = \frac{n*\bar{c}}{4}$, gas mean velocity $\bar{c} = \sqrt{\frac{8*k_B*T}{\pi*m}}$, $0^oC = 273.15^oK$

1 atmosphere = $1.013*10^5$ Pa = $1.013*10^5$ N/m^2 = 760.0 torr = 14.696 pounds/in^2.

1 foot = 12 inches, 1 inch = 2.54 cm, 1 cm = 10 mm = 10^4 μm = 10^7 nm

MEMS = **M**icro**E**lectro**M**echanical **S**ystems, NEMS = **N**ano**E**lectro**M**echanical **S**ystems

1) List one **advantage** and one **disadvantage** a microfluidics device has for society (that means you, your relatives, their friends, …)? $\bar{x}$ = 8.8, σ = 2.9

Too many answers to list.

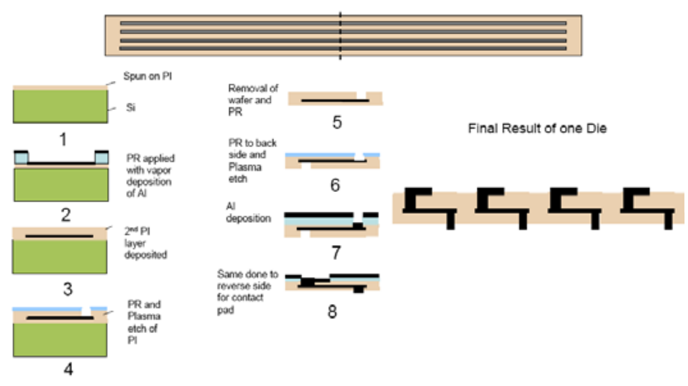
2) Explain how **"fluidic capacitance," and "fluidic inductance"** are like a capacitor or an inductor respectively. Give an example how you would demonstrate fluidic capacitance **and** fluidic inductance. $\bar{x}$ = 3.9, σ = 4.4

Microfluidic system shows "fluidic capacitance," when changing the pressure across the inlet to outlet changes the volume of fluid stored. This is similar to an electric circuit where changing the voltage across the circuit changes the amount of charge stored. This happens if the fluid is a gas, a liquid containing a gas (bubbles for example), or if the walls of the microfluidic system have some give to them (a section of the wall has a compliant diaphragm, or walls are elastic like latex). Liquids have a very small compressibility compared to gasses. Electrical capacitance measures how much energy is stored in voltage, and fluidic capacitance how much energy is stored in fluid's volume. $C_{fluidic} = \frac{\Delta Volume}{\Delta Pressure}$ and $C_{electrical} = \frac{\Delta Charge}{\Delta Voltage}$

Microfluidic system shows "fluidic inductance," when dropping the pressure across the inlet to outlet doesn't immediately change the flow through the system. This is similar to an electric circuit where changing the voltage across the circuit doesn't immediately change the amount of current going through it. This happens whenever there is stored kinetic energy in the microfluidic system. Electrical inductance measure how much energy is stored in electric current, and fluidic inductance measures how much energy is stored in fluid's kinetic energy. $H_{fluidic} = \frac{\Delta Pressure}{\dot{Q}}$

where $\dot{Q} = \frac{\partial Q}{\partial t}$, $H_{electrical} = \frac{\Delta Voltage}{\dot{I}}$ where $\dot{I} = \frac{\partial I}{\partial t}$

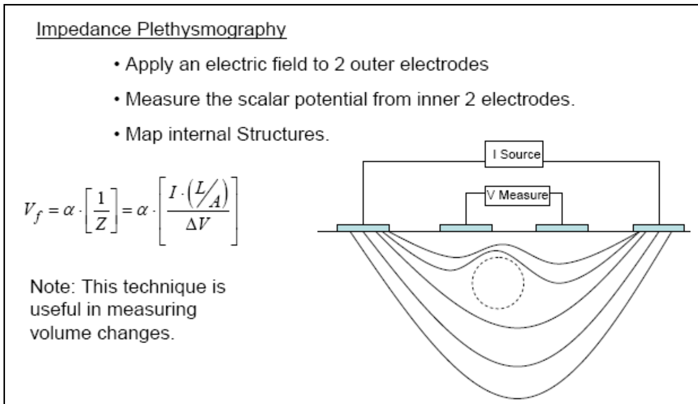
3) *Your classmate's project "volume measurement of a blood vessel" uses aluminum for the electrodes. Aluminum will probably corrode so gold would be a better choice for his device. List one advantage and one disadvantage for electroplating instead of using physical vapor deposition to create the gold film.* $\bar{x} = 7.5$, $\sigma = 2.6$



+ electroplating can use very simple equipment, and only puts Au where it is needed. PVD will deposit Au everywhere. Electroplating can make films that are several μm thick.

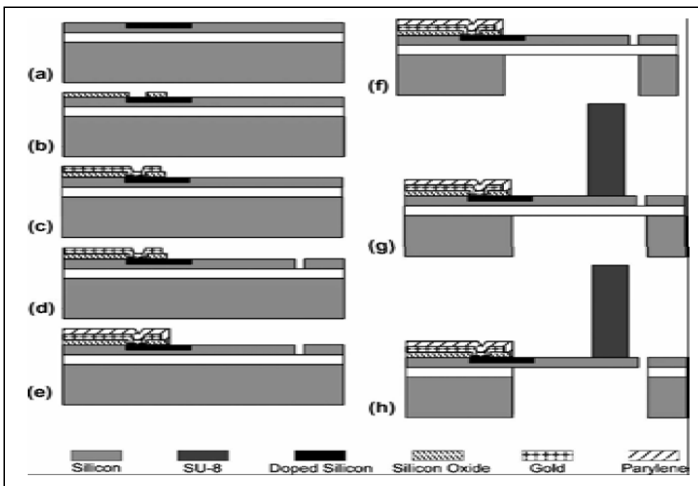
- electroplating can generate toxic waste, film is not as smooth as PVD, process more complex (need to deposit and then remove plating base). Electroplated films can have high stress levels.

4) *Your classmate's project is to perform a "volume measurement of a blood vessel." What electrical signal vs. time would you expect to see if this sensor was attached to your skin?* $\bar{x} = 2.8$, $\sigma = 3.6$



Every heartbeat should cause the vessel to expand and contract with the vessel filled with blood that has a different impedance than tissue.

5) *In which process step (a - h) is the Oxford DRIE* ***required*** *in the project "Artificial Hair Cell Flow Sensor"? How else might the same result be accomplished ?* $\bar{x} = 4.4$, $\sigma = 3.1$



DRIE is required in step f to etch through wafer. DRIE could be used to carry out step d, but an ordinary RIE is all that is necessary.

Alternatives for step f could be XeF_2, or a wet anisotropic etch that can be masked like EDP, KOH, TMAH, etc. An ordinary RIE or CF_4/O_2 plasma will not be able to etch through wafer.

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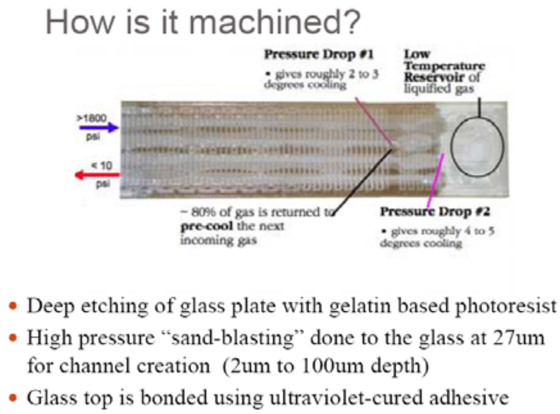
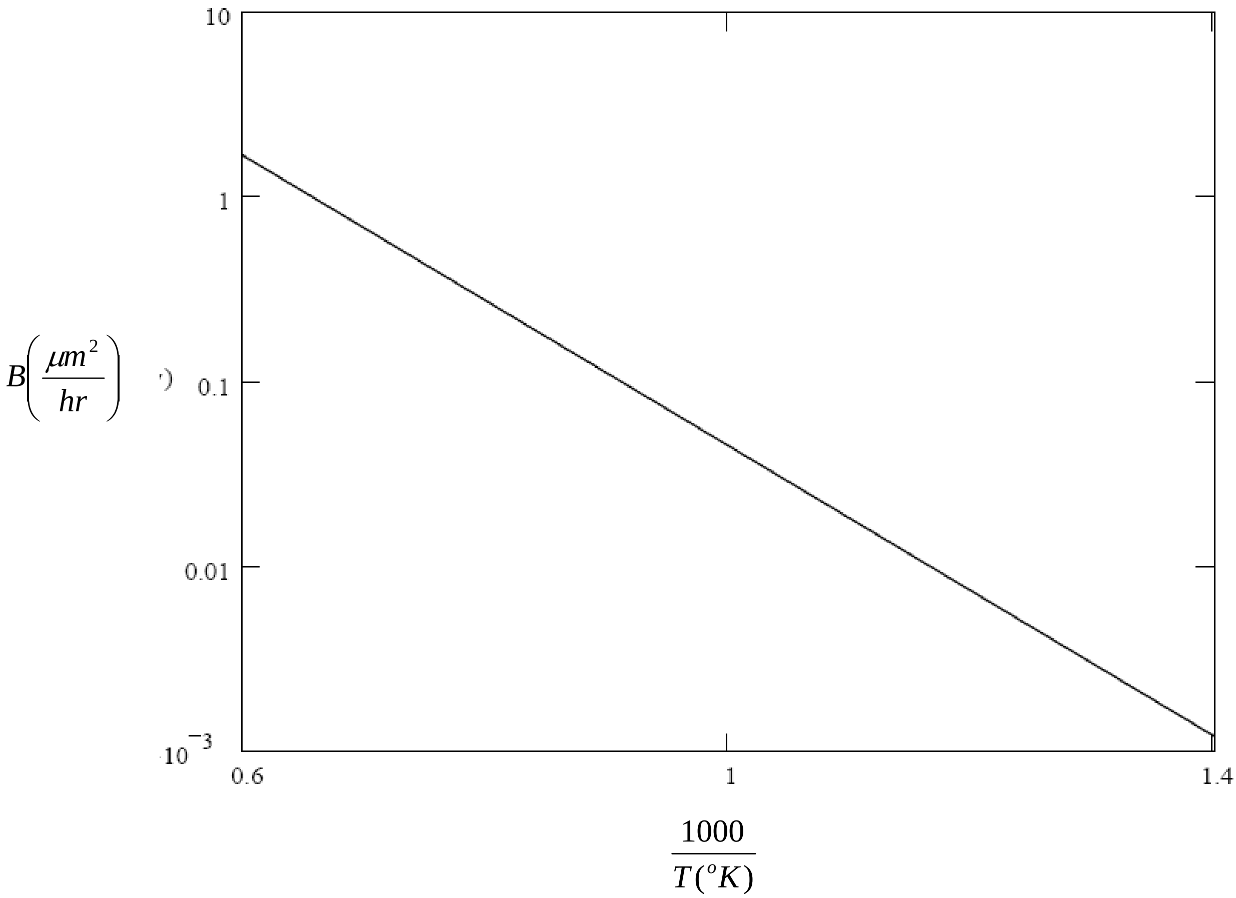
6) *List* ***one*** *advantage to the environment for how the channels are etched in the Joule- Thompson Refrigerator discussed last week. List* ***one*** *disadvantage of an alternative etch that could be used instead.* $\bar{x} = 7.8$, $\sigma = 3.6$



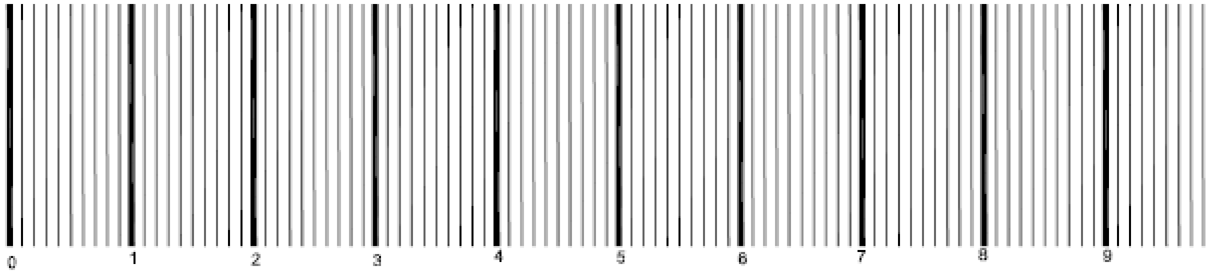
+ sand blasting is a fairly simple etch process, uses environmentally benign materials, and can create deep channels. Gelatin based photoresist may be slightly more environmentally benign than novolac resin based resist, depending on the solvents used which are often quite toxic.

- Alternative etches would be buffered HF but that produces toxic waste, and the etch is not anisotropic. A second alternative would be STS-AOE which can perform a deep etch of glass, but it's expensive equipment, and etches very slowly.

7) *What is the parabolic oxidation rate at 1000°C* **?** *The vertical axis is the parabolic oxidation rate, B, in μm^2/hour, and the horizontal axis is 1000/temperature in units of $^oK^{-1}$.* $\bar{x}$ = 15.2, σ = 8.3



Using the ruler provided, 2*S_X=80.0u, and 4*S_Y=60.5u, so S_X=40.0u, and S_Y=15.1u.



$1000^oC = 1273^oK$, and $\frac{1000}{1273^o K} = 0.786 = 0.6 + .186 = .6 + \frac{x}{S_x} * 0.4$, solving gives

$x = \frac{0.186}{0.4} * S_x = 18.6u$. Drawing a right angle to the x axis at this point, and then a line parallel to the x-axis allows us to find corresponding B. and it is 7.7u above the 0.1μm^2/hour point.

$B = 0.1\frac{\mu m^2}{hr} * 10^{7.7/S_Y} = 0.32\frac{\mu m^2}{hr}$. Grading was 5, 10, and 10 points for 1273^{o}K, x intercept, and y intercept respectively.

8) *When a can of soda is opened up bubbles of CO_2 are released from the surface of the can. You can assume the density of soda is ~1 gm/cc, and g=9.81*m/s^2=981*cm/s^2.* $\bar{x} = 6.7, \sigma = 8.4$

   a) *How many bubbles are released from the soda assuming the bubbles have a diameter, D=2mm, internal pressure ~1 atmosphere, and there are ~2.2 grams of CO_2 dissolved in a 500 cc soda can at 5^{o}C. What is the total volume in the bubbles released (while they are still at 5^{o}C)?*

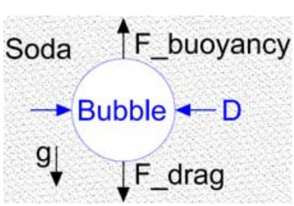
   b) *What is the fastest the bubbles can float up? You can assume the viscosity of soda, ν=0.01 poise, and F_{drag} = 3*π*ν*D*velocity. ($poise = \frac{gm}{cm * s}$)*

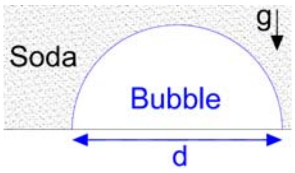
   c) *The CO_2 is dissolved in the soda at high pressure (~2 atmospheres) and the bubbles grow as the CO_2 comes out of solution. A crude model for when a bubble will detach is when the attachment force equals the buoyancy force. Assuming the bubbles have a hemispherical shape when they detach, and that the attachment force is from surface tension, γ=70 dynes/cm, then what is the diameter of bubbles that have just lifted off? $F_{attachment} = \pi * d * \gamma$ (dyne = gm*cm/s^2).*

$mCO_2 = \frac{12.0107gm + 2*15.9994gm}{mol} * \frac{mol}{6.02*10^{23}} = 7.31*10^{-23}gm$, $NCO_2 = \frac{2.2gm}{m\_CO_2} = 3.01*10^{22}$

$VCO_2 = \frac{NCO_2 * k_B * 278^o K}{atm} = 1.14*10^{-3}m^3 = 1140cc$, $V_{bubble} = \frac{\pi * D^3_{bubble}}{6} = 4.19*10^{-9}m^3 = 4.19\mu L$

\# bubbles = VCO_2/V_{bubble} = 272,000

	Maximum velocity achieved when drag force balances the buoyancy force, or $3*\pi*\nu*D_{bubble}*velocity = \frac{\rho*g*\pi*D^2_{bubble}}{6}$, and velocity = 218cm/s. Neglected gas density since << soda density. Reynold's # = 4360 >> 1. The actual drag is proportional to diameter^2 and the bubbles rise much more slowly.



Detachment when surface adhesion force = buoyancy force or

$\pi * d * \gamma = \frac{\rho * g * \pi * d^3}{12}$ or d =0.925cm. Once the hemisphere is detached

it becomes a sphere and $d' = \sqrt[1/3]{0.5} * d = \sqrt[1/3]{0.5} * \sqrt{\frac{12 * \gamma}{\rho * g}} = 0.734cm$

I believe companies abrade the inside of the can so the bubble attachment area is much smaller. This lets them control the bubble size, which can change the user's drinking experience. Grading was 7, 6, 6, and 6 points for $N_{bubbles}$, V_{total}, $velocity_{bubble}$, and d_{detach}, respectively.

9) *The heart pumps ~5 liters/minute, the viscosity of the blood is ~0.03 poise, and there are ~$2*10^{10}$ capillaries that are 8 μm in diameter. How long is the average capillary if the pumping pressure across each capillary is ~7000 Pa (52.5 mm Hg) and you assume Poiseulle flow* ***?*** *What is the Reynold's number for this flow if we assume the density of blood is 1.025 gm/cc* ***?*** *One estimate of the adult body is that it contains 10^{13} red blood cells (RBC), and each RBC can carry 10^9 oxygen molecules. If we assume that all of this oxygen is delivered every minute, through the network of capillaries, then what is the rate oxygen molecules leave the capillary* $\left(\frac{\#Oxygen\_molecules}{\mu m^2 * s}\right)$ ***?*** $\bar{x}$ *= 7.8,* σ *= 6.9*

Poiseulle flow $Q = \frac{\pi * D^4}{128 * \nu} * \frac{\Delta P}{L}$ *where* ν *is viscosity,* ΔP *is the pressure drop, and D and L are the diameter and length of the cylinder, respectively.* $Pa = \frac{N}{m^2} = \frac{10 * dyne}{cm^2}$*, liter = 10^3 cc*

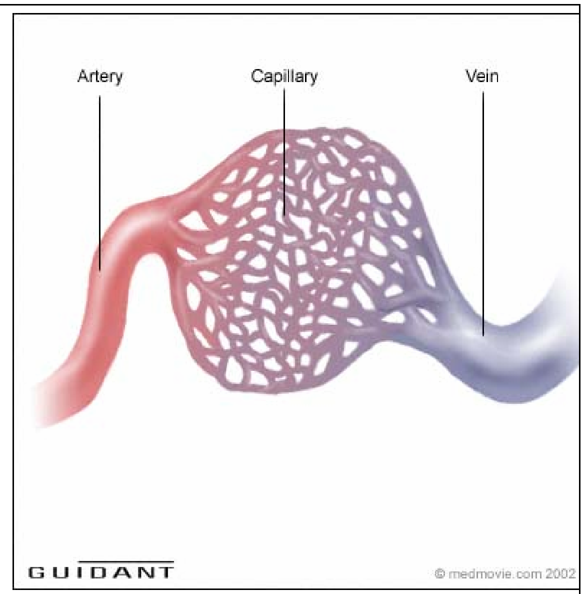
$\mathrm{Re} = \frac{D * \overline{v\_blood} * \rho}{\nu}$ *where* $\overline{v\_blood}$ *is the average blood velocity.*

$\frac{Q}{N_{cap.}} = \frac{\pi * D^4}{128 * \nu} * \frac{\Delta P}{L}$ so **L = 5.63cm** since $N_{cap.} = 2*10^{10}$.

capillaries are in parallel ! $\frac{Q}{N_{cap.}} = \frac{\pi * D^2}{4} * \overline{v\_blood}$

so $\overline{v\_blood} = 8.29 * 10^{-3} \frac{cm}{s}$.

$\mathrm{Re} = \frac{D * \overline{v\_blood} * \rho}{\nu} = 2.27 * 10^{-4} << 1$. $Q \neq \overline{v\_blood}$ In capillaries the viscosity of the blood drops because the cells line up single file to get through capillaries.



Density of whole blood ~1.06 gm/cc. $\frac{10^{13} * 10^{9} O_2}{N_{CAP.} * \pi * D * L * 60s} = 5.89 * 10^{3} \frac{O_2}{\mu m^2 * s}$ O_2 molecules are exchanged through capillary walls. As a suggestion, choose mks or cgs units, and stick with that system. Problems typically involve mixed units, and carelessness here means you solve the problem and still get the wrong answer! Grading was 7, 6, 6, and 6 points for $N_{bubbles}$, V_{total}, $velocity_{bubble}$, and d_{detach}, respectively.