ENGR 145 **Chemistry of Materials** **Fall 2023**

Sample Exam #3
December 1-2, 2022

Duration: 24 hours; 11:30am Nov. 30 – 11:30 am Dec. 1
Submit your answers via Canvas by 11:30 am EST on Dec. 1

Any resources (book, notes, web, etc.) are allowed, but you are not allowed to talk with anyone during the exam. With submission of your answers, you implicitly affirm that all work is your own, without consultation of peers or others.

1a. Silicon is a classic example of a semiconductor. Suppose a single crystal of Si contains $10^{-24}/m^3$ boron atoms, and all B atoms in the Si are ionized. Is this material p-type or n-type? Explain your answer through a description of the differences between n-type and p-type doping. (10)

P-type Si contains a small amount of a Group III dopant such as B which replaces a Si in the crystal. The Group III atom has an energy level just above the top of the valence band (VB) of the Si, and thermal energy promotes an electron from the VB to the boron atom, creating a hole in the VB. In n-type silicon, the material would contain a small amount of a Group V dopant such as As which replaces an Si in the crystal. The Group V atom has an energy level just below the bottom of the conduction band (CB) of the Si, and thermal energy promotes an electron from the As to the VB, creating an electron in the CB. For this problem, it is clear that the material will be p-type.

b. Calculate the lowest frequency of electromagnetic radiation that is able to create an electron-hole pair in intrinsic Si. Take the bandgap to be 1.14 eV. (5)

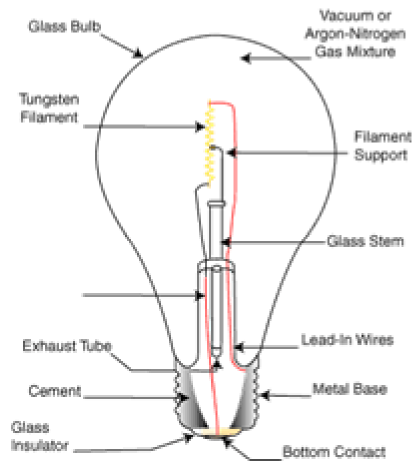
The fundamental equation is $E = h\nu$. Thus, the frequency $\nu = E/h$.

$\nu = 1.14 \text{ eV}/4.13\text{x}10^{-15} \text{ eV-s} = 2.76\text{x}10^{14} \text{ s}^{-1} = 2.76\text{x}10^{14}$ Hz.

c. In your own words, explain why little to no current passes across a p-n junction under 'reverse bias' conditions.

Under reverse bias conditions, electrons are removed from the n-type side and holes are removed from the p-type side. This dilutes the carrier concentration that can cross the so-called depletion zone, effectively prohibiting the passage of current.

2. Consider a common incandescent light bulb, the components of which are shown below.



a. Calculate the resistance of a tungsten wire having a length of 5 cm and a diameter of 1.5 mm. The electrical resistivity of tungsten is 5.6 x 10^{-8} Ω-m.

$$\rho = \frac{RA}{l}$$

Area A = π x (0.75x10^{-3} m)^2

R = (5.6 x 10^{-8} Ω-m x 5x$^{10\text{-}2}$m)/ π x (0.75x10^{-3} m)^2 x 5x10^{-2}m =1.58x10^{-3} Ω.

b. Briefly explain the choice of tungsten as the filament material. (5)

The filament in an incandescent bulb can reach a temperature of about 4500^{o}F, thus a metal with a very high melting point is needed. Tungsten has been a favored choice. Tungsten is a metal (delocalized electrons) but also is a covalently-bonded network. The latter is responsible for the high melting point of tungsten.

c. Briefly explain, based on your knowledge of electrical properties of materials, why the tungsten filament in a bulb is a coil rather than a straight wire. (5)

The filament must be resistive enough to cause sufficient heating for the filament to glow with while-yellow light. A coil is longer than a straight wire spanning a given distance. The longer wire has a higher resistance. Also, a coiled filament has a greater light output.

d. Why is glass, specifically soda-lime glass, a good choice for the bulb material, rather than say a plastic? (5)

Soda-lime glass is amorphous and thus transparent and will not deform by heat emanating from the hot coil.

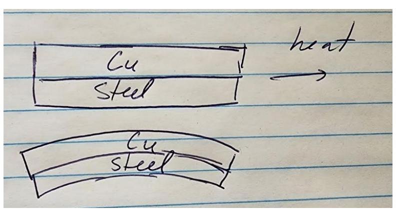
3a. Consider a steel rod having a linear coefficient of thermal expansion of 1.2×10^{-5} $(^oC)^{-1}$. Calculate the elongation of a 30 cm rod upon heating from 25^oC to $150\ ^oC$. (10)

$\alpha_l \Delta T = \Delta l / l_0$; $\Delta T = 125^oC$; $l_0 = 30$ cm

$\Delta l = 1.2 \times 10^{-5}\ (^oC)^{-1} \times 125^oC \times 30$ cm = 30.045 cm

b. Now consider a strip of the same steel, sandwiched to a strip of copper of similar thickness. Such a configuration is sometimes called a bimetal strip. Assume that the adhesion between the two strips is very good. The linear coefficient of thermal expansion of copper is 1.7×10^{-5} $(^oC)^{-1}$. The different thermal expansion coefficients will cause the bimetal strip to bend upon heating.

Sketch a cross-section of a flat bimetal strip, labeling which strip is steel and which is Cu, and predict the direction of bending upon heating based on the information given. Also: upon bending, one surface will be in tension and the other in compression. Which is which? (10)



The copper will expand more than the steel, given its greater linear coefficient of expansion, leading to bending as sketched above. The Cu strip will be in tension, with the steel strip in compression.

c. In your own words, briefly explain how a common thermostat containing a bimetal strip works. (5)

The bending of a bimetal strip on heating, for example, can close an electrical contact that in turn activates an air conditioning system to cool the area to a temperature set on the thermostat.

4. Biaxially-oriented polypropylene (BOPP) is a popular dielectric used in commercial capacitors.

a. Assume that you have a 10 μm-thick BOPP films in between two metal plates, each having an area of 5 cm^2. Calculate the capacitance at an applied voltage of 2,000 V. Assume a value of 2.2 for the dielectric constant of BOPP. (10)

$$C = \varepsilon \frac{A}{l}$$

C = capacitance, A is the electrode area, l is the distance between electrodes (hence it is the thickness of the dielectric, and ε is the dielectric permittivity. The dielectric constant or relative permittivity, ε_r, is

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$$

$\varepsilon = 2.2 \times 8.8\times10^{-12}$ F/m = 1.95×10^{-11} F/m; A = 5cm^2 = 5×10^{-4} m^2; l = 10×10^{-6} m

C = 1.95×10^{-11} F/m x 5 x 10^{-4} m^2/10×10^{-6} m = 9.73×10^{-10} F

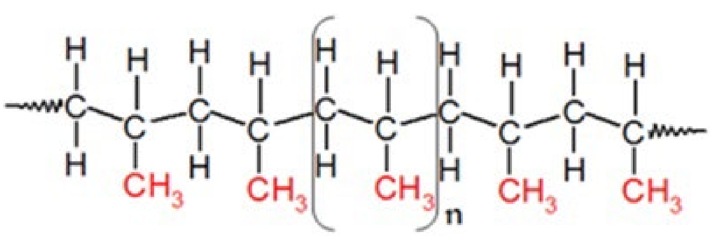
b. BOPP has a high dielectric breakdown strength, allowing very thin (a few microns) films to be used. Based on fundamentals of capacitance, why is a small thickness of a dielectric beneficial? (10)

Capacitance depends inversely on the thickness of a dielectric, l:

$$C = \varepsilon \frac{A}{l}$$

Thus, a small dielectric thickness is beneficial for a high capacitance.

c. What are the types of polarization that can be exhibited by polypropylene in the presence of an electric field? (5)



Polypropylene contains no ions and very small C-H dipoles. Hence, electronic polarization is the only contributor to the dielectric constant. The low dielectric constant of 2.2 is consistent with only electronic polarization.

Extra Credit (10)

Write a short essay, no more than about 300 words, comparing 'subtractive' manufacturing to the more recent push toward 'additive' manufacturing, emphasizing advantages and disadvantages of each. Why might additive manufacturing be appealing in the context of growing attention to sustainability? Be sure to cite any sources of information.

This is an example answer. Individual responses and citation can differ considerably.

Subtractive manufacturing, where material is removed to create a final part or structure has been used over many centuries. It is inherently wasteful as the material removed (called scrap) is frequently discarded or, more recently, steps are taken to recycle the scrap. Examples of subtractive manufacturing include drilling, milling, and laser cutting. In contrast, the newer methods of additive manufacturing have the advantage of manufacturing from a 'bottom-up' approach. Examples include stereolithography and fused deposition modeling, the latter being the most common process for 3-D printing of plastics. A good summary of contrasts between additive and subtractive manufacturing can be found at https://formlabs.com/blog/additive-manufacturing-vs-subtractive-manufacturing.

Additive manufacturing supports sustainability in several ways (https://24x7mag.com/market-trends/additive-manufacturing-sustainable-manufacturing):

- Lower energy consumption and hence lower energy costs
- Less waste, due to an additive build-up of structures rather than removal of material
- Streamlined waste processing and the ability to recycle material for a subsequent 'build'

Additive manufacturing will likely be an important element for the growing realization of a circular economy.