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

Exam #3
November 30-December 1, 2023

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. Germanium pre-dates silicon as the material used to construct the first transistor (Bell Labs, 1947). Ge has a bandgap of 0.67 eV. Calculate the frequency of light that is necessary to promote an electron from the valence to the conduction band. (10)

$E = h\nu$ $\quad h = 4.135667 \times 10^{-15}\ eV\text{-}s$

$\nu = \frac{E}{h}$

$$\nu = \frac{0.67\,eV}{4.135667 \times 10^{-15}\ eV \cdot s} = 1.62 \times 10^{14}\ Hz$$

b. One reason that germanium is not used for semiconductor devices is its lower bandgap vs. silicon, which can lead to more thermal generation of e-h pairs. Why might this be a problem? (5)

Uncontrolled generation of e-h pairs will throw off the carrier concentration in the semiconductor. The lower bandgap allows heat to impact the concentration, which is not easy to control by engineers. An increase in e-h pairs may also interfere with junction functions.

c. Suppose a single crystal of Ge contains $10^{-24}/m^3$ boron atoms, and all B atoms in the Ge 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)

B is a group III metal, while Ge is a group IV metal. This presents a charge difference in the material, where the B takes on an electron, becoming B^-. This B^- is fixed, leaving a nearby Ge^+ ion mobile in the material. This positive mobile charge is characteristic of p-type doping. N-type doping would be the result of a dopant with more valence e^- than Ge, like As. This extra e^- would be mobile in this case, which is characteristic of n-type doping. This difference explains why this Ge semiconductor is an example of p-type doping.

2a. A steel railroad track has a thermal expansion coefficient of 11.5×10^{-6} mm/mm°-C. Calculate the elongation of a section of track that is 10m long if the ambient temperature changes from 60°F to 85°F. (10)

$\frac{\Delta \ell}{\ell_0} = \alpha_\ell \Delta T$ $T_0 = \frac{5}{9}(60-32) = 15.56°C$ $T_f = \frac{5}{9}(85-32) = 29.44$

$\Delta T = 29.44 - 15.56 = 13.88°C$

$\alpha_\ell = 11.5 \times 10^{-6}\ C^{-1}$ $\ell_0 = 10m \times \frac{1000mm}{1m} = 10{,}000mm$

$\Delta T =$ must convert

$\frac{\ell_f - 10{,}000mm}{10{,}000mm} = 11.5\times10^{-6}\frac{1}{°C}(13.88°C)$

$\ell_0 = 10m$ $\ell_f = 10{,}001.60mm = 10.0016\ m$

The 10m strip elongates by 0.0016m to a length of 10.0016m, or 10,001.6mm

b. Continuously-welded rail (CWR) was laid for the first time in the U.S. in 1933, and gradually replaced short, jointed rails shown below. The length of these rails was usually standardized at 39 feet.

In your own words:

What considerations drove the transition to CWR? (5)

Although the CWR fails to intrinsicly address Thermal Expansion concerns, it is most likely used because of how it interacts with the train and its passengers. Having no gaps ensures a smoother ride, while also preventing derailments. Safety most likely drove this transition.

How do materials engineers deal with thermal expansion of CWR in an attempt to prevent buckling when the ambient temperature is hot?

The welding applied to the rail causes a temperature increase when laying down. This increase in temperature causes an expansion in the steel when cooled, the rails are held in place and cannot contract, so they are put in Tension. This prevents buckling in hot environments, as the preheated steel is ready for the thermal expansion.

3a. You are asked to build a capacitor using two plates of metal, for example aluminum. For the dielectric, you have several materials to choose from: (i) Nylon 11, ε = 6; (ii) poly(vinylidene fluoride) or PVDF, ε = 10; and (iii), biaxially-oriented polypropylene, ε = 2.2. Assume a constant thickness for each material. To obtain the largest capacitance at a fixed voltage, which of the three material sheets should you use? Back up your answer with basic equations. (10)

$C = \varepsilon \frac{A}{l}$, this equation relates dielectric permittivity to capacitance. Because A and l are both constant in this scenario, the largest capacitance will come from the material with the highest ε. In this case, PVDF should be used. There is a direct relationship.

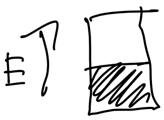
b. Now consider that you have access to different thicknesses of Nylon 11. How will the capacitance change as the polymer film thickness decreases? (10)

As seen by the equation $C = \varepsilon \frac{A}{l}$, capacitance is inversely proportional to thickness. The capacitance of Nylon 11 will increase when its dielectric thickness decreases.

c. Why might there be a practical lower limit to the thickness of the polymer dielectric? (5)

Obviously, once the dielectric becomes too thin, it will be nearly impossible or overly expensive to manufacture on a large scale. Resistance would also decrease with a low thickness according to $R = \frac{\rho l}{A}$. This may not be favorable. Workability is the main concern, involving manufacturing issues.

4a. Using an energy band model, explain why metals have both high electrical and thermal conductivity. (10)

For metals, the energy band model looks like: E  .
Here, the valence and conduction bands overlap, making electron movement very easy. These mobility allows electrons to transfer both heat and electricity with relative ease. No band gap needs to be crossed. So all energy goes into the excited electron.

b. Diamond is a rather odd material, in that it is an excellent electrical insulator and an excellent thermal conductor. In your own words, offer explanations for both. (10)

Diamond is an excellent electrical insulator because it has the highest bandgap out of most, if not all, materials. Diamond's Thermal conductivity comes from its C-C covalent bonds, which are very strong. These bonds and their strength allow rapid vibration between molecules, leading to thermal conductivity and heat transfer.

c. Suggest an application where high thermal conductivity along with high electrical resistance would be desirable. (5)

A desirable application of a material like this is in an electronic device or computer. Some connections may be fragile and it is not desireable to interfere with the circuit. At the same time, the device cannot get too hot. This may be of good use in electrical casings, as the wire or device should not overheat, but it should also not shock a user who is handling it.

Extra Credit (10)

Write a short essay, no more than about 300 words, on a commercial process for doping of highly-pure silicon with, for example, boron or arsenic.

Doping silicon would first require very pure silicon. This could be achieved by either submerging a patterned crystal in molten material and allowing the silicon to form in an ordered pattern, or by taking a silicon crystal and using a hot ring to push impurities out. After a pure sample has been gathered, the silicon must be sliced into thin wafers that can be used in electronic applications. A polymer called a photoresist should then be placed on the silicon wafer. When a desired region to be doped is mapped out, a mask should be placed over the regions that should stay protected. The photoresist, being sensitive to light radiation, should then be flashed with UV light, in a process called photolithography. This exposes the Silicon and allows the Silicon to be doped. The exposed silicon can then be bombarded with Boron or arsenic. This intentionally creates impurities in the desired regions, enhancing silicon's conductive abilities. This must be performed in a controlled environment to ensure that there are no unneeded impurities being added to the Silicon. Assuming the outlined steps above have been followed, a commercially repeatable doping process can now be performed.