Engineering 45

The Structure and Properties of Materials

Final Examination
May 20, 2000

Name: ____________________

Section: ____________________

Problem 1 _______
Problem 2 _______
Problem 3 _______
Problem 4 _______
Problem 5 _______
Problem 6 _______

Total _______

Problem 1: (15 points)

(a) Suppose you are given three materials, and are told that one is an insulator, one an intrinsic semiconductor, and one a metal. You send them out for x-ray diffraction, and find that one has the NaCl structure, one has the β−ZnS, and one has the fcc. Which is most likely to be the metal, which the semiconductor and which the insulator, and why?

(b) You look at them closely. One is transparent, two are not. Which is transparent, and why?

(c) One of the materials is noticeably colder to the touch. Which is it most likely to be, and why?

(d) You accidentally drop them on the floor. Two break, one does not. Which would you expect to survive, and why?

(e) You coat each with a strip of platinum and drop it in saltwater. After a few minutes, one shows visible corrosion, two do not. Which corrodes rapidly, and why?

Problem 3: (15 points)

(a) Consider a binary system that contains two components, A and B. Component A has an FCC structure in its pure state while component B is BCC. The simplest possible binary phase diagram for the system is a eutectic diagram. Why? Sketch the phase diagram and label the phase fields.

(b) Given a temperature and composition (T,x) of the phase diagram in (a) it is possible to extract three pieces of information from the phase diagram: the phases present at (T,x), the compositions of the phases, and the fractions of the phases. Describe how.

Problem 3: (20 points)

(a) Suppose a one-component system has only three equilibrium phases: gas (g), liquid (l), and crystalline solid (s). At atmospheric pressure these phases are assumed in the sequence s $\rightarrow$ l $\rightarrow$ g as the temperature is raised at low pressure. Explain this behavior in terms of the expected relative energies and entropies of the three phases (assume the pressure is low enough that the pv term in the Gibbs free energy can be neglected), and provide a simple illustrative sketch of the variation of free energy with temperature.

(b) The liquid phase can be cooled some distance below its melting point, T_m, before crystallizing to (s). Explain this behavior in terms of the nucleation-and-growth mechanism of a structural phase transformation. Why is there a thermodynamic barrier to the formation of a nucleus?

(c) A liquid phase will ordinarily solidify into a crystalline solid if cooled slowly, but may form a glass if cooled very rapidly. Explain this observation in terms of the relative kinetics of crystallization and glass formation (begin by showing that the crystalline solid <u>must</u> nucleate, while the glassy phase need not, but you must also explain why the glassy phase does not <u>always</u> form, since its kinetics are more favorable).

(d) If a typical crystalline semiconductor is melted and then quenched into a glassy state its conductivity increases significantly (it may even become metallic). However, if a typical crystalline metal is melted and quenched into a glassy state, its conductivity decreases significantly. Interpret this phenomenon.

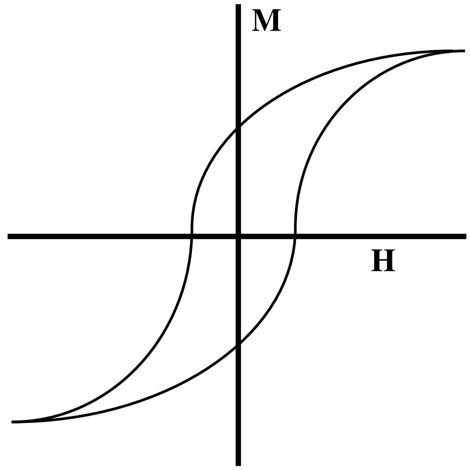
Problem 4: (15 points)

(a) Define the *Fermi energy,* E_F, of a material. Given its definition, show that a semiconductor behaves as an n-type extrinsic semiconductor if E_F is significantly greater than the energy at the midpoint of the band gap, and as a p-type extrinsic semiconductor if E_F is significantly below the mid-point of the band gap.

(b) Illustrate the behavior of the band structure at a junction between n-type and p-type semiconducting material and describe (briefly and qualitatively) how the band structure produces an asymmetry in the conduction characteristics of the junction.

(c) Some materials function as *photoconductors* in the sense that their normal conductivities are very low, but increase dramatically when they are illuminated with visible light. Explain how a semiconductor can behave as a photoconductor, and why a good photoconductor is opaque to visible light.

Problem 5: (15 points)



Simple ferromagnetic materials, like Fe, Ni and Co, are ferromagnetic at low temperature essentially because their atoms have net magnetic moments that align with one another.

(a) If a ferromagnetic material that has previously been magnetized is placed in a magnetic field, H, its magnetization, M, will trace out a "magnetic hysteresis loop" like that shown above as the field is cycled between large positive to large negative values. Explain the hysteresis in terms of the magnetic microstructure and its response to the magnetic field.

(b) How does the behavior of "hard" and "soft" magnetic materials differ? Identify a technological application for which one would want a "hard" magnet, and one for which one would want a "soft" magnet.

(c) How might you make a ferromagnetic material "harder"?

Problem 6: (20 points)

Alvin Underfoot, a random undergraduate, supported himself, in part, from the modest profits of a small consulting business in which he applied what he had learned in E45 to solve the problems of the world. Since virtually no one had ever heard of him, his list of potential clients was not large. On the other hand, he was admirably qualified to offer complete confidentiality to those who made use of his services. For precisely this reason, Alvin's services were retained by a famous and accomplished superheroine with an unfortunate personal problem. She is, she tearfully confessed, an incurable exhibitionist. Even when flying on her many missions of mercy, she cannot bear to conceal herself from her admiring public, but insists on piloting transparent glass aircraft. These have an unfortunate proclivity to disintegrate in mid-air, a circumstance that has made her into an unusually proficient parachutist, but at considerable cost in bruises and broken bones. Since she is not, by training, a material girl, she needs a dedicated materialist to help her make her aircraft more reliable.

Her immediate problem concerned her available aircraft, made of the finest high-temperature glass, which were needed for immediate missions. How might they be made more resistant to fracture? In response, Alvin first explained why glass is brittle and, after thinking for some time, suggested that her planes might be improved by washing their surfaces with a certain acid that would chemically attack sharp surface cracks and blunt them into furrows. While she was doing that, he would consider more long-term solutions.

(a) Qualitatively, why is silica glass brittle, and why might Alvin's suggestion be of some help?

Alvin's client was pleased with his initial work, which increased the average lifetime of her aircraft from one flight to almost three, and returned for his suggestions for long-term solutions.

Alvin's first effort was to replace silica glass with a tough, transparent polymeric plastic. The resulting aircraft worked fine until his client accelerated to supersonic speeds, as was her practice, at which point aerodynamic heating caused the wings to droop like Dali's clocks, and caused our superheroine to practice skydiving.

(b) What difference in the basic mechanism of deformation makes it possible for transparent plastic (polymeric) to be tougher than transparent silica glass? Why might a tough plastic soften at high temperature?

Alvin's second effort was to build the aircraft of a fiber-reinforced plastic, in which fibers of transparent glass were used to strengthen a matrix of tough plastic. With some effort, he achieved a composite with very respectable mechanical properties at moderately high temperature. Unfortunately, the stuff was opaque.

(c) Why would a mixture of transparent materials be opaque?

Alvin's third effort was to return to a high-temperature glass, but to heat-treat it during forming so that the region near its surface had a high residual compressive stress. The resulting glass exhibited a high resistance to fracture, but, unfortunately, its fracture resistance disappeared when it was exposed to high temperature.

(d) Why would a compressive stress near the surface increase toughness? Why would the toughness disappear when the material was annealed at high temperature?

With this failure, Alvin conceded defeat. In desperation, he suggested that she steal an idea from Alaska Airlines, build her aircraft of aluminum, and paint a picture of herself on the outside. Our superheroine was last seen parachuting into the Caribbean, surrounded by fragments of glass.