Engineering 45

The Structure and Properties of Materials

Final Examination
May 15, 2001

Problem 1: (20 points)

(a) Show how the β-ZnS and NaCl crystal structures are derived from the FCC by filling selected interstitial sites in the FCC unit cell.

(b) Let compound A have the β-ZnS structure, while B has the NaCl structure. One is a semiconductor, one an ionic insulator. Which and why?

(c) Both A and B are brittle. One cleaves on {111}, one on {100}. Which and why?

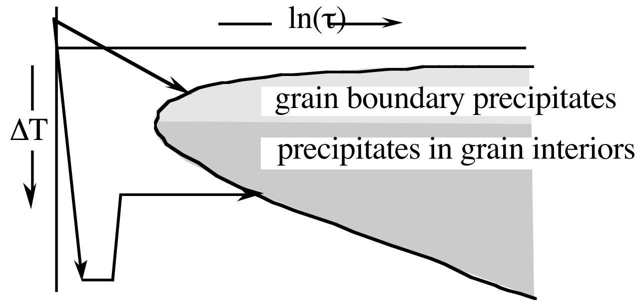
(d) One of the compounds has an unusually low value of Poisson's ratio. Which is the more likely choice and why?

Problem 2: (20 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.

(c) If a polygranular sample of the A-rich solution, □, is cooled into the two-phase, □+□, region the kinetics of precipitation of □ are described by the kinetic diagram given below, where □ is the time required to initiate the transformation and □T is the undercooling below the temperature at which □ precipitation becomes thermodynamically possible.



If the material is cooled as indicated by the upper arrow, the final microstructure contains nuclei of □ almost exclusively in the grain boundaries of the □ grains. Why might you expect this?

(d) If the material is cooled and then heated, as indicated by the lower path in the figure, the final microstructure consists of a dense distribution of □ precipitates in the interiors of the □ grains. Why?

Problem 3: (20 points)

To turn a piece of single crystal silicon into a functional semiconducting device, such as an n-p-n bipolar transistor, it is necessary to achieve a high purity silicon starting material, add chemically appropriate dopants in the proper places, and keep them there.

(a) The silicon crystal that is the starting material for an n-p-n junction that is to be used at room temperature has a band gap of moderate size (1.1 eV), and can be made so that it is chemically very pure. Why are these properties important?

(b) Suppose that the Si starting material has an unacceptably high level of impurities. A much purer Si can usually be made by re-melting the starting material and re-solidifying it under controlled conditions. Why and how does this method work?

(c) To make an n-p-n junction device, one must use at least two different solutes, one that acts as a donor and one as an acceptor. B and P are common choices. Which is the donor and which the acceptor? Both are substitutional solutes. Why is this important?

(d) Since boron is difficult to extract from Si, Si crystals often contain a moderate boron content as-received. Assuming this makes them p-type, how can P be used to change the dominant carrier type in the regions that are to be n-type?

(e) Give a rough schematic drawing of the band structure of an n-p-n device, indicating the position of the Fermi level in each of the three regions when no external voltage is imposed. Explain why the band structure has the shape you have drawn.

Problem 4: (15 points)

Visible light spans a range of wavelength between 0.4-0.7 μm, corresponding to a photon energy between ~ 2eV and ~ 4 eV.

(a) An old practical test says that if you can see through a piece of material, it is almost certainly a good insulator. Why?

(b) Why the modifier "almost"? How can a transparent material fail to be a good insulator? [Hint: you can see through NaCl if you squint, but it is not a very good insulator.]

(c) On the other hand, there are many good insulators that you cannot see through, including both opaque ceramics and brightly colored plastics. Describe at least one possible microstructure that creates an opaque insulator.

(d) Alvin Underfoot, a random undergraduate of great academic promise, accepted a summer job with Watergate Technologies. On arrival he was, naturally, assigned to the mail room. While inspecting incoming materials, he came across a package labeled "optical fibers". The fibers were metallic gray in color and totally opaque. Alvin sent them back as rejects. Shortly afterward, he was called in by his boss's boss, Priscilla Pureheart, PhD. Instead of commending him, she fired him. "Alvin," she said, "you are an imbecile. Instead of firing you, we should shoot you. The fibers you returned were super-high-tech fibers for use with our hot new semiconductor lasers, and were desperately needed. They are exceptionally clear and transparent." Alvin left, shaking his head in bewilderment. What was his mistake?

Problem 5: (15 points)

(a) An isotropic, linear elastic material has two independent elastic constants. These are normally chosen from the set E (Young's modulus), ν (Poisson's ratio), β (the bulk modulus), G (the shear modulus). Define each and describe how it could be measured.

(b) The yield strength of a ductile material tends to scale with its shear modulus, G. Why would you expect this?

(c) The shear modulus of Fe is about 3 times that of Al, and it is found that steels have about 3 times the yield strength of aluminum alloys with similar microstructures. Nonetheless, it is possible to make Al alloys that have yield strengths higher than those of many steels. Why might you expect this?

Problem 6: (15 points)

Joe Hardhat was an experienced crane operator working on a major repair of the Bay Bridge. His primary job was to lift, set and move heavy concrete rails that separated the work areas from the bridge traffic . During a mandated periodic inspection of his crane, a crack of appreciable size was found in one of the outriggers that support the crane against tip-over during a lift. Since the contractor (Joe’s boss) was anxious to keep the crane in service, and since the crack did not seem all that large, the inspector ruled that hey could continue to operate the crane if it successfully completed a safety test in which it lifted 50% more than its rated load. The crane had no apparent difficulty doing this.

Late the following day, after the crane had successfully completing a number of lifts, the cracked outrigger suddenly failed and toppled over. Joe Hardhat lost his life in the accident. His coworkers were amazed, since the load that caused the failure was (at least from its markings) no greater than several others he had lifted earlier in the day.

(a) Why is not surprising that a cracked outrigger might suddenly fail on lifting a load no greater than it had successfully lifted on many prior occasions?

Alvin Underfoot, a formerly random undergraduate now gainfully employed as a metallurgical consultant, was summoned to the scene. On reviewing the recent history of the crane, he pointed out that the official who had inspected the crane was an incompetent who should be re-educated or re-assigned. "He is the probable cause of the accident", announced Alvin.

(b) Alvin was at least superficially right. Why?

However, the story doesn't end there. As a Cal-educated engineer, Alvin was trained to do a thorough job. To verify his interpretation of the failure he had the outrigger sectioned and examined the fracture in a scanning electron microscope. What he saw disturbed him. After doing a series of calculations and a couple of fracture-toughness tests he announced that the investigation must be reopened. "This crack could not possibly have propagated to failure under the load it was supposed to have been carrying," he announced. "There is something very wrong here."

Sure enough, further investigation revealed that poor Joe had been viciously murdered for his insurance by his faithless wife and her secret lover (Joe's boss). When the concrete rail Joe was lifting at the time of the accident was retrieved from the bottom of the bay, it was found that it had been drilled out and filled with lead, more than doubling its weight.

(c) How did Alvin know?