Problems – Electrical Properties

1. When subjected to an applied voltage of 10 V, a current of 5 A flows through a metal wire which is 20 m long and 1 mm in diameter. What is the electrical resistivity of the metal.

2. The electrical conductivity of copper is 5.8x10^{7} (□-m)$^{-1}$. Determine the resistance of a copper wire which is 1 km long and 0.318 mm in diameter.

3. 12 gauge copper wire is typically used in household electrical wiring. The diameter of this wire is 0.0808 inches. Determine the room-temperature resistance associated with a 12 gauge copper wire 1000 feet long.

4. A pure aluminum interconnect with a semicircular cross-section runs between two transistors on an integrated circuit. The interconnect is 10 microns long and has a radius of 200 nm. Across its length is a voltage of 5 V. The room-temperature conductivity of pure Al is 3.4 x10^{7} (□ m)$^{-1}$.
(a) Determine the current density flowing through the interconnect.
(b) The operating temperature of the device is 60 ^{o}C. Would you expect the current density flowing through the interconnect to be higher, lower, or the same as that at room temperature? Briefly justify your answer.
(c) Suppose an Al - 5 wt% Cu alloy was used in place of pure aluminum. Would you expect the current density flowing through the interconnect to be higher, lower, or the same as that for a pure Al interconnect? Briefly justify your answer.

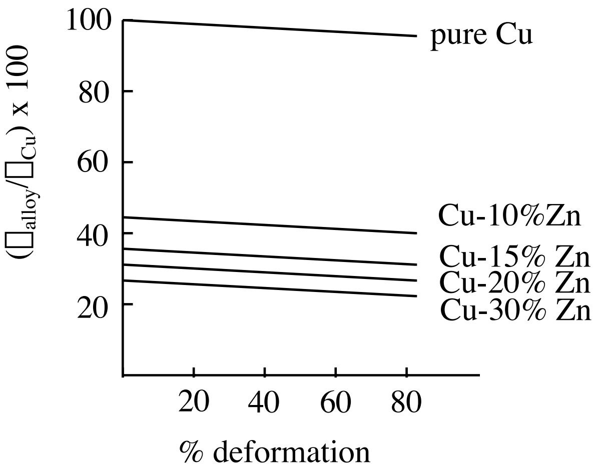
5. A resistive heating element is to be built from tungsten wire 0.05 mm in diameter. The element should dissipate 50 Watts of power. The resitivity of tungsten is 9 □□-cm.
(a) Estimate the length of the wire required for such a device operating at 110 V.
(b) Suppose the temperature dependence of the resistivity is included in the calculation. Would the design now call for a longer or shorter wire relative to when the T-dependence was ignored?
(c) What, if any, effect would a nick in the wire have on its performance?

6. One important application of metal conductors is for wire in resistance-heated furnace elements. Consider a 1 mm diameter chromel (a Ni-Cr alloy) to produce a 1 kW furnace coil in a furnace operated at 110 V.
(a) What length of wire would be required for this furnace design? The resistivity of chromel is 1.08x10^{-6} □-m at room temperature.

(b) When in use as a heating element the temperature of the wire increases, and the resistivity of the chromel changes. How would you expect this change to affect the length of the wire you specify? Briefly justify your answer.

(c) Suppose the wire is deformed prior to installation so it has a high concentration of defects such as dislocations and grain boundaries. How would this affect the calculation? Would the length need to be longer/shorter when using the high-defect wire.

7. The electrical conductivity of copper-zinc alloys (brasses) as a function of composition and degree of deformation is described in the adjacent figure. Rationalize the decrease in conductivity due to composition and deformation.



8. What typical metals and what general electrical properties (high, intermediate, low resistivity; temperature coefficient of resistivity) would you recommend for the following applications:

a. electrical furnace windings;
b. electrical power transmission lines;
c. electrical resistance standards.

9. Copper and aluminum cables compete for electrical wiring applications. Consider two wires, one of copper and the other of aluminum, having the same resistance. What is the ratio of weights of these wires if they have the same length? Is there a potential drawback to the use of aluminum wire regarding its safety?

10. Design the filament of a 60 Watt light bulb for 110 V. The light bulb operates at 1500 °C.

a) Briefly describe a commercial light bulb in order to recognize the design constraints.

b) Select the material, considering the high temperature needed.

c) Calculate the resistance needed for 60 Watt, then calculate the dimensions of the wire. You will need to make a decision concerning the length or the thickness of the wire. In doing so, be realistic. It will be necessary to visualize these dimensions in order to obtain a reasonable solution.

d) In commercial light bulbs, the filament has the shape of a double winding. Propose the dimensions of such an arrangement.

11. A 120 V source is placed directly across a tungsten filament 10 m in length and 50 microns in diameter.

(a) What current is passssed initially?

(b) What is the power in Watts?

(c) If the filament were perfectly insulated thermally and allowed to heat due to the resistance, aaproximately what temperature would be reached if the initial current flowed for 1 second? Assume the heat capacity of tungsten is 25 J/mole-K.

(d) What would the resistance be at this temperature?

12. Using well-labeled energy-band diagrams to describe why a metal is a good electrical conductor and an insulator like a ceramic or a polymer is a poor electrical conductor.

13. Consider a capacitor with a plate area of 1 mm x 1 mm and a plate separation of 100 μm. If the gap is filled with a titanate whose dielectric constant is 50, what is the maximum charge that can be stored at when for an applied voltage of 5 V. If the titanate is removed and replaced by air, what plate area will be required to store this same amount of charge?

14. Estimate the distance a light beam will travel between pulses at a clock frequency of 3 Ghz. Draw this distance on the edge of your solution set.

15. Suppose an insulating piece of pure SiO_2 (silicon dioxide) glass has a bandgap, E_g, of 6eV.

(a) Quantitatively show that this glass would be transparent to violet light with a wavelength of 300nm.

(b) Suppose the SiO_2 contains a small concentration of impurities which introduce a donor level in the gap 1.0 eV below the bottom of the conduction band. Will the glass still be transparent to the violet light? Justify your answer.

16. How many atoms are contained in 1 cubic centimeter of silicon? If silicon is doped with 10^{18} atoms/cm^3 of boron, how much boron has been added in terms of atomic percent?

17. A typical 64 Mbyte dynamic RAM chip can be carried on a piece of silicon approximately 1cm^2 in size. Estimate the lateral dimension associated with an individual transistor - storing a single data bit - on this chip.

18. Briefly describe why the electrical resistivity of pure copper increases as temperature increases, whereas the electrical resistivity of pure silicon decreases with increasing temperature.

19. At the melting point of pure silicon, how many electrons are excited from the valence band to the conduction band? What fraction of the total number of valence electrons (that are responsible for covalent bonding) does this correspond to?

20. Suppose you are asked to characterize a new semiconductor material. Its conductivity at 20°C is 250 $\Omega^{-1}m^{-1}$. At 100 °C the conductivity is 1100 $\Omega^{-1}m^{-1}$. What is the magnitude of its band gap. Would you expect at room temperature that this material would have a higher or lower electrical conductivity than pure Si? Why?

21. Consider a specimen of pure silicon with a gap energy of 1.12 eV.
  a) Sketch a well-labeled energy-band diagram for pure silicon.
  b) At a temperature of 0 K, would you expect the conductivity of this silicon to be more like that of: (i) SiO_2 at 300 K; (ii) Si at 300 K; or (iii) Cu at 300 K? Briefly explain your answer.
  c) Suppose the silicon at 0 K is illuminated by a beam of light whose wavelenth is 2 mm. Will the silicon absorb or transmit this light? Quantitatively justify your answer. Will the adsorbtion/transmission property change if the silicon is allowed to warm to room temperature? Briefly explain your answer.
  d) Suppose the silicon is doped with arsenic whose donor level lies 0.054 eV below the conduction band. Will this dopant affect the adsorbtion/transmission behavior of the silicon for 2 μm wavelength light? Briefly explain your answer.

22. The band gap for pure silicon is 1.12 eV. The acceptor level for Boron doped into silicon is 0.045 eV above the top of the valence band (figure 12-5 Ohring). At room temperature (300 K), compare the number of holes created in the valence band for silicon doped with 10^{17} Boron atoms/cm^3 to the number of electron-hole pairs in pure silicon at this same temperature. Which of these materials has the higher electrical conductivity? Why?

23. The band gap for pure silicon is 1.12 eV. The donor level for Sb doped into silicon is 0.039 eV below the bottom of the conduction band. At room temperature (300 K), compare the number of electrons excited into the conduction band for pure silicon and silicon doped with 10^{17} Sb atoms/cm^3. Which of these materials has the higher electrical conductivity? Why?

24. Using well-labeled energy-band diagrams to describe the differences between intrinsic silicon, p-type silicon, and n-type silicon.

25. Contrast the effect on the electrical conductivity of doping pure Si with 1 wt% Al to that of alloying pure Al with 1 wt% Si. What is the approximate increase or decrease in electrical conductivity in each case?

26. List the dominant (majority) charge carrier(s) in each of the following semiconductors:
a. intrinsic Si
b. intrinsic Ge
c. Si doped with P (at low temperature)
d. Ge doped with P (at low temperature)
e. GaAs doped with Zn (at low temperatures)

27. How would you expect increasing temperature to affect the operation of a p-n junction diode?

28. Outline a sequence of processing steps that could be used to create a pad of pure copper metal with lateral dimensions of 100 μm x100 μm and a thickness of 100 nm to be deposited on a 1 inch diameter silicon wafer so that the pad is electrically isolated from the silicon except for a single connecting lead which has lateral dimensions of 10 μm x 10 μm.

29. With one sentence each, describe the function of each of the following processing steps in the manufacture of a semiconductor device:
- a) evaporation
- b) oxidation
- c) ion implantation
- d) diffusion
- e) solidification processing
- f) lithography.

30. In a single, short, well-constructed paragraph define the acronym MEMS, describe how this field is related to the semiconductor industry, and cite at least one example of a MEMS device.

Multiple Choice Review Questions.

In the following, choose the single best answer that completes the phrase.

35. The electrical resistivity of a metal:
a) is much lower than that of a semiconductor like silicon;
b) is inversely proportional to conductivity;
c) increases with increasing temperature;
d) almost always increases when alloying elements are added to the metal;
e) all of the above.

36. The electrical resistivity of a metal increases with increasing temperature, because:
a) the conduction band is empty;
b) acceptor levels become filled and holes appear in the valence band;
c) the vibration amplitude of the metal atoms increase and the probability that a conduction electron will scatter from a metal atom increases;;
d) the metal becomes superconducting;
e) none of the above.

37. Polymers are poor electrical conductors, because:

a) carbon atoms have only six electrons;
b) the filled valence band and empty conduction band are separated by a large energy gap;
c) different polymer molecules are bonded to each by weak secondary bonds;
d) they exhibit thermoplastic behavior;
e) none of the above.

38. Single-crystal silicon is typically preferred over polycrystalline silicon in device applications, because:
a. single crystals are easy to grow;
b. single-crystal silicon has a lower gap energy than polycrystalline silicon;
c. single crystal silicon has a higher conductivity than polycrystalline silicon;
d. single crystal silicon is easier to oxidize than polycrystalline silicon;
e. all of the above.

39. Consider a parallel plate capacitor whose gap is filled with air that is fully charged by a voltage V across the gap. If a dielectric material such as silica is placed in the gap instead of air, the net charge on the plates would:
a. decrease;
b. increase;
c. stay the same;
d. go to zero;
e. none of the above.

40. A hole:
a) corresponds to a missing Si atom;
b) carries a net charge of –1;
c) corresponds to a missing electron from the valence band;
d) all of the above;
e) none of the above.

41. A pure semiconductor such as silicon:
a) has a filled valence band at zero Kelvin
b) is transparent to photons with an energy < the gap energy
c) has a gap energy less than a typical insulator like SiO_2
d) all of the above
e) only a and c.

42. Resistivity decreases with increasing temperature in an intrinsic semiconductor, because:
a. there is a higher vacancy concentration at high temperature;
b. more electron-hole pairs are created;
c. atomic vibration amplitudes are higher;
d. dopant atoms contribute fewer electron holes.

43. Suppose a particular intrinsic semiconductor has a bandgap energy of 1.75eV. Photon irradiation can create electron-hole pairs in this semiconductor if the photon wavelength is:
a. 100nm
b. 7nm
c. both a and b
d. neither a or b

44. Pure GaAs is a semiconductor with a bandgap of 1.47eV. It transmits infrared light (□ = 1500 nm), because:

a. light photons with this wavelength do not carry enough energy to excite electrons from the valance band to the conduction band;
b. the light photons are small enough to fit between the atoms in the crystal and pass right through;
c. dopants which would introduce additional energy levels on the band diagram and lead to photon absorbtion are absent;
d. at room temperature there are no available empty energy levels in the GaAs conduction band to accommodate any more electrons excited from the valance band;
e. the photons can follow dislocation lines as easy pathways through the GaAs.

45. Pure single-crystal Ge has a gap energy E_g of 0.67 eV. It is transparent to:

a. red light with a wavelength of 720 nm;
b. X-rays;
c. UV light with a wavelength of 0.101 nm;
d. all of the above;
e. none of the above.

46. Pure silicon can be converted into a p-type semiconductor by doping with small amounts of:

a) B;
b) Ga;
c) Al;
d) Cd;
e) all of the above.

47. n-type silicon:

a) has a higher electrical conductivity at room temperature than intrinsic (pure) silicon;
b) can be created by doping with a group III element;
c) is formed when dopants introduce electrons into the otherwise-empty conduction band;
d) can be created by alloying Si with Ge.
e) none of the above.

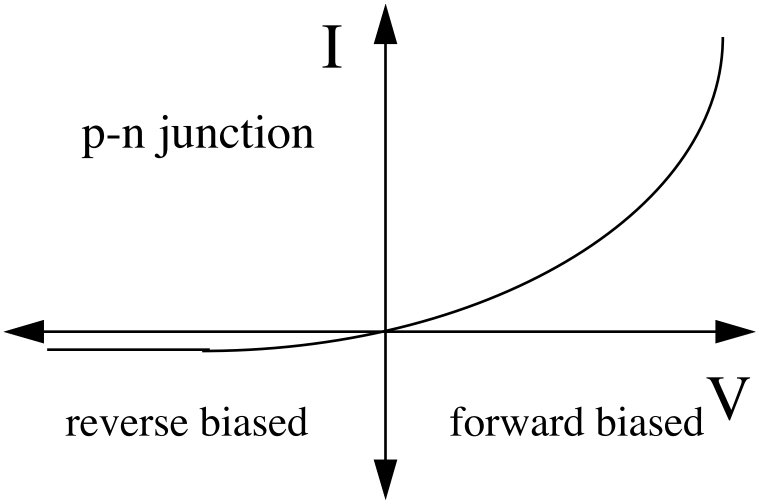
48. When added to silicon in small concentrations Antimony (Sb), a group V element, would:

a. increase the hole concentration in the valance band;
b. increase the electron concentration in the conduction band;
c. become the majority carrier;
d. react with silicon to form a compound.

49. If pure germanium (Ge) is doped with gallium (Ga), the electrical conductivity increases, because:
a. Ga is a metal;
b. Ga introduces electron-hole pairs into the Ge;
c. electrons are injected in the Ge conduction band;
d. holes are introduced into the valence band;
e. none of the above.

50. A p-n junction has a non-linear I-V curve, because:
a. mobile charge carriers can't cross the depletion region until some threshold voltage is applied;
b. it obeys Ohm's Law;
c. electron-hole pairs must be created;
d. none of the above.

51. The I-V curve associated with a typical p-n junction displays very non-linear behavior with a rapid increase in current with increasing voltage beyond some threshold in the forward-biased regime, because:
a. ion cores start to move in response to the applied V;
b. additional thermal energy is needed to create more electron-hole pairs;
c. a minimum applied potential is needed for significant numbers of electrons and holes to cross the depletion region and allow current to flow;
d. Ohm's law doesn't become valid in a p-n junction until a critical voltage is applied.
e. intrinsic electron-hole pairs must be created in the device.



52. Lithography is used in semiconductor device processing to:
a. create gate oxides;
b. pattern;
c. metallize;
d. grow single crystals;
e. none of the above.

53. Ion implantation is used in semiconductor device processing to:
a. create gate oxides;
b. pattern;
c. metallize;
d. grow single crystals;
e. none of the above.

54. Evaporation processes are used in the manufacture of semiconductor devices to:
a. deposit thin films;
b. clean surfaces;
c. grow oxide layers;
d. all of the above.

55. n-type doping increases the electrical conductivity of pure silicon by:
a. eliminating the band gap;
b. introducing electrons into the conduction band;
c. introducing holes in the valence band;
d. generating an excess of electron-hole pairs;
e. none of the above.

56. The manufacture of a silicon-based microelectronic device typically uses a large number of processing steps including:
a. solidification processing;
b. cold rolling;
c. dopant in-diffusion;
d. lithographic patterning;
e. X-ray diffraction.

57. One would use lithography during semiconductor device fabrication to:
a. introduce p-type dopants;
b. introduce n-type dopants;
c. measure dopant concentrations;
d. create features patterned in the wafer plane.