The University of Melbourne

Semester Two 2002

Department: **SCHOOL OF PHYSICS**
Subject Number: **640-381**
Subject Title: **PRINCIPLES AND APPLICATIONS OF SENSORS**

Exam Duration: 3 Hours

Reading Time: 15 Minutes

This paper has 7 pages

Authorised Materials:

Calculators are permitted in accordance with the rules of the Faculty of Science. They should not have been programmed nor should they store additional information.

Instructions to Invigilators:

This exam paper may be retained by the students.

Instructions to Students:

Attempt **ALL** questions. Total marks=100.

Useful formulae:

$P = \sigma T^4$, $\sigma = 5.67 \times 10^{-8}$ $WM^{-2}K^{-4}$
$F = 9.6 \times 10^4$ C/mol, $D_m = 1.3 \times 10^{-9}$ m^2/sec
$\alpha_m = 1.5 \times 10^6 mol/Pa$, $h = \frac{P}{\rho g}$
$g = 10ms^{-2}$, $\rho_{Hg} = 1.3595 \times 10^4$ kgm^{-3}
$P_{atm} = 101.325$ kPa

Question 1: (14 marks)

(a) The heating wires of a 2 kW electric heater are "red hot" at a temperature of 900 Celsius. Assuming 100 percent of the heat output is due to radiation and that the wires act as blackbody radiators, what is the effective area of the radiation surface?

(b) A man plans a ski streak down a mountainside. Initially he stands in still air at the top of the mountain with no clothes on. The outside temperature is 0 degrees Celsius. Assume his skin acts like a perfect blackbody.

(i) Calculate the energy absorbed by his skin over a 1 minute interval from the surrounding environment.

(ii) Calculate the energy radiated by his skin over this minute, assuming a surface temperature of 33 degrees C. (He has just taken his clothes off).

(iii) What is the net loss in energy from his skin?

(c) Why have most terrestrial creatures evolved electromagnetic sensors (eyes) in the visible part of the electromagnetic spectrum?

(3+3+2+2+4 = 14 marks)

Question 2: (20 marks)

(a) Briefly explain the operation of a catalytic sensor used for the purpose of detecting flammable gas in underground mines.

(b) An example of an amperometric chemical sensor is a Clark oxygen sensor. The operation principle of the electrode is based on the use of one electrolyte solution contained within the electrode assembly to transport oxygen from an oxygen-permeable membrane to the metal cathode. The cathode arises from a two step oxygen-reduction process that may be represented as:

$$O_2 + 2H_2O + 2e^- \rightarrow H_2O_2 + 2OH^-$$
$$H_2O_2 + 2e^- \rightarrow 2OH^-$$

The membrane electrolyte-electrode system is a one-dimensional diffusion system with partial pressure P_0. At steady-state the electrode current is given by:

$$I \approx \frac{4FA\alpha_m D_m P_0}{x_m}$$

where A is the electrode area, α_m is the solubility of oxygen in the membrane, F is the Faraday constant, D_m is the diffusion constant and x_m is the thickness of the membrane. The sensor sensitivity is defined as the ratio of the current to oxygen partial pressure:

$$S = \frac{I}{P_0}$$

Now given that $S \approx 7.5 \times 10^{-12} A/kPa$ is required and that the cathode area is $2.6 \times 10^{-6} m^2$

(i) What is the membrane thickness?

(ii) How do we increase the sensitivity?

(iii) What parameters can realistically be changed?

(5+5+5+5 = 20 marks)

Question 3: (16 marks)

(a) Explain the characteristics of:
An absolute pressure sensor, a gauge pressure sensor, a differential pressure sensor.

(b) The atmospheric pressure can fluctuate between 99 kPa and 102 kPa. If one used a U-tube barometer filled with mercury (Hg) to measure these pressures:

(i) What would be the height difference measured in mm of mercury at the maximum pressure?

(ii) What would be the height difference measured in mm of mercury at the minimum pressure?

(iii) Is this a good sensor for this kind of measurement? Please explain your answer.

(iv) What is the sensitivity of the U-tube barometer?

(v) How could the sensitivity of the sensor be improved?

(3+2+2+3+3+3 = 16 marks)

Useful formulae:

$k_B = 1.38 \times 10^{-23}$
$h = 6.63 \times 10^{-34}$
$E = hf - \phi$
$n_1 \sin\theta_1 = n_2 \sin\theta_2$
$c = \lambda f$
$\Delta x \Delta p_x \geq \hbar/2$
$e = 1.60 \times 10^{-19}C$
$1Å = 10^{-10}m$
$E_g = 3.53 k_B T_c$

Question 4: (21 marks)

(a) In order to maximise the number of electrons emitted from a surface via the photoelectric effect, the surface can be coated with material possessing a low work function. The minimum work function that can be achieved by such coatings is, in practice, about 1.5 eV.

(i) What is meant by the term 'work function' for a material?

(ii) What is the maximum wavelength of light that will result in photoemission from a surface with a workfunction of 1.5 eV ?

(iii) Can the photoelectric effect be used to detect photons used in optical fiber communications with a wavelength of 1.55 μm? If not, how can such photons be detected?

(2+2+2=6 marks)

(b) A micro-channel plate is often used for light detection. Describe how it works, including a diagram. How does it differ (in structure and application) from a conventional photomultiplier tube?

(4 marks)

(c) Describe the operation of a microbending optical fiber sensor. In your description, include the role of Snell's law and two possible applications of such a sensor. Include diagrams in your description.

(5 marks)

(d) X-ray emission is often used to identify the elements present in a sample. The electronic energy levels are given, in electron volts, by the Bohr theory as:

$$E_n = -13.6\frac{Z^2}{n^2}$$

where Z is the atomic number of the element.

(i) Sketch the x-ray emission spectrum detected when a beam of energetic electrons hits a target such as gold.

(ii) An X-ray tube emits X-rays whose minimum wavelength is 2×10^{-11} m. What is the operating voltage of the tube?

(iii) A suitcase is irradiated with X-rays to determine whether its owner is trying to smuggle gold in the handle. What is the wavelength of the x-ray emitted when an electron in gold makes a transition from the n=4 state to the n=1 state? (The atomic number of Gold is 79.)

(2+2+2=6 marks)

Question 5: (13 marks)

(a) A small object of mass 1 g is confined to move between two rigid walls separated by 1.00 cm.

(i) Calculate the minimum speed of the object.

(ii) Is this speed measurable?

(2+1=3 marks)

(b) Bragg diffraction involves the interference of two waves reflected from adjacent crystal planes.

(i) Sketch a figure of this situation. Indicate the spacing of the crystal planes (d), and the angle(θ) between the reflected wave and the crystal plane.

(ii) Use the figure to derive the Bragg law describing the angles at which maximum reflected intensity occurs:

$$2\text{d}\sin\theta = \text{n}\lambda$$

In this formula, what is the significance of 'n' ?

(2+2=4 marks)

(c) Describe how Bragg reflection can be used in optical fibers to make sensors of temperature and strain. Illustrate your answer with a diagram.

(4 marks)

(d) A 1 cm^3 cubic crystal of NaCl is illuminated with x-rays of wavelength 1.39 Å. The first order reflection of Bragg scattering of the x-rays is observed at an angle of 14.3°. Calculate the lattice spacing.

(2 marks)

Question 6: (16 marks)

(a) Discuss the similarities and differences between Scanning Tunnelling Microscopy (STM) and Atomic Force Microscopy (AFM). In your answer, draw schematic diagrams of each, and include a description of the different imaging modes. Include a discussion of the STM quantum mechanical tunnelling current.

(8 marks)

(b) Superconductors are used to make SQUIDS, which are able to detect very small magnetic fields.

(i) What does the acronym 'SQUID' stand for?

(ii) Sketch and label the phase diagram of magnetic field versus temperature for type I and type II superconductors. What are the differences between these types of superconductor?

(iii) The superconducting energy gap for lead (Pb) is 2.73×10^{-3} eV. Find the minimum frequency of a photon that can be absorbed by lead at T=0 Kelvin to break apart a Cooper Pair.

(iv) At what temperature would you expect Pb to become superconducting?

(1+3+2+2=8 marks)

END OF EXAM