THE UNIVERSITY OF MELBOURNE

SEMESTER TWO ASSESSMENT 2003

Department: SCHOOL OF PHYSICS
Subject Number 640-381
Subject Name: PRINCIPLES & APPLICATIONS OF SENSORS

Time allowed: 3 Hours
Reading time allowed: 15 minutes
This paper has 8 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:

The exam paper may be retained by the students.

Instructions to Students:

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

Some useful formulae and data follows:

Capacitance $C = \frac{A\varepsilon}{d}$,

Charge Q = C V,

Resistance R = ρ A/l

Charge from a Piezoelectric effect Q= d F

Charge from the Pyroelectric effect. $Q = P_Q A \Delta T$

Seebeck-Peltier effect: $\frac{dV}{dT} = \alpha \frac{dT}{dx}$

$\varepsilon_0 = 8.854\times10^{-12}$ F/m

$\mu_0 = 4\pi\times10^{-7}$ H/m

Stress = Force/Unit Area

Strain = Δl/l

Young's Modulus Y = Stress/Strain

(For $BaTiO_3$, $\varepsilon_r = 1700$, d = 78 pC/N, $P_Q = 4\times10^{-4}$ $C.m^{-2}K^{-1}$)

(For PVDF, $\varepsilon_r = 12$, d = -30 pC/N, $P_Q = 0.4\times10^{-4}$ $C.m^{-2}K^{-1}$)

(For Al $Y = 70\times10^9$ $N.M^{-2}$, resistivity $\rho = 2.75\times10^{-8}$ Ωm)

(For Cu resistivity $\rho = 1.69\times10^{-8}$ Ωm)

Assume g= 10 ms^{-2}

Density of Mercury 13.595×10^3 Kg m^3

P_{atm}= 101.325 kPa

Critical Magnetic field $Bc(T) = Bc(0K)\left[1 - \left(\frac{T}{T_c}\right)^2\right]$

Kinetic energy $E_{KE} = \frac{1}{2}mv^2$

Energy of spring system $E = \frac{1}{2}kA^2$

Vibrational energy $E_v = \left(v + \frac{1}{2}\right)\eta\omega$

Angular frequency $\omega = 2\pi f$

Speed of light $c = f\lambda$

Photon Energy $E = hf$

Reduced mass $\mu = \frac{m_1 m_2}{m_1 + m_2}$

Frequency of vibration $\omega^2 = \frac{k}{\mu}$

De Broglie wavelength $\lambda = \frac{h}{p}$

Linear momentum $p = mv$

Bragg reflection $2d \sin\theta = n\lambda$

Bragg wavelength $\lambda_b = 2nD$

The magnetic field at a distance r from a current carrying wire is $B = \frac{\mu_o I}{2\pi r}$, where μ_o $= 4\pi \times10^{-7}$ N/A^2

Boltzmann's constant $k_B = 1.381\times10^{-23}$ J/K

Planck's constant, $h = 6.63\times10^{-34}$ Js

Electron mass=9.109×10^{-31} kg

Electron charge = 1.602×10^{-19} C

1 atomic mass unit = 1.661×10^{-27} kg

Speed of light in vacuum 3×10^8 m/s

1Å = 1×10^{-10}m

$\hbar = \frac{h}{2\pi}$

1 H 1.0																	2 He 4.0
3 Li 6.9	4 Be 9.0											5 B 10.8	6 C 12.0	7 N 14.0	8 O 16.0	9 F 19.0	10 Ne 20.2
11 Na 23.0	12 Mg 24.3											13 Al 27.0	14 Si 28.1	15 P 31.0	16 S 32.1	17 Cl 35.5	18 Ar 40.0
19 K 39.1	20 Ca 40.1	21 Sc 45.0	22 Ti 47.9	23 V 50.9	24 Cr 52.0	25 Mn 54.9	26 Fe 55.9	27 Co 58.9	28 Ni 58.7	29 Cu 63.6	30 Zn 65.4	31 Ga 69.7	32 Ge 72.6	33 As 74.9	34 Se 79.0	35 Br 79.9	36 Kr 83.8
37 Rb 85.5	38 Sr 87.6	39 Y 88.9	40 Zr 91.2	41 Nb 92.9	42 Mo 95.9	43 Tc 98.9	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
55 Cs 132.9	56 Ba 137.3	57 La 138.9	72 Hf 178.5	73 Ta 181.0	74 W 183.9	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po 209	85 At 210	86 Rn 222
87 Fr 223	88 Ra 226	89 Ac 227	104 Rf 261	105 Ha 262.0													

Question 1: (14 Marks)

a. Explain how a Pyroelectric electric sensor differs from one that employs the Peltier effect. Include in you answer a description of the different Physical processes used in each sensor.

(6 marks)

b. Describe two other uses of the Peltier effect additional to being used as a temperature sensor.

(4 marks)

c. A steam furnace operates in the pressure range 10 –15 atm. An open-tube manometer is used to measure the pressure inside the furnace.

i. If the pressure in the furnace is 12.34 atm, a height difference of how many millimetres of mercury would be measured?

ii. Is this a good sensor for this application?

(2+2=4 marks)

Question 2 (10 Marks)

a. Briefly explain the physical processes that make a Piezoelectric sensor work.

(4 marks)

b. Derive a formula that relates the strength of an applied force F, to a Piezo-electric sensor of cross sectional area A and thickness d to the Voltage generated across it's surface.

(2 marks)

c. A 1 mm thick piezoelectric sensor with an area of 2 ×2 cm, develops a voltage of 3.2 kV. If the sensor is made of PVDF, what weight is being applied to the sensor?

(2 marks)

d. What voltage would it generate if the sensor were made of $BaTiO_3$.

(2 marks)

Question 3: (24 Marks.)

An 200 kg mass is hung from the end of a 50 cm long aluminium (Al) cylinder of radius 2cm. The diameter of the Al cylinder is monitored by a piezoresitive sensor, consisting of an insulated 0.1 mm radius copper wire wrapped once around the cylinder.

a. Derive a formula relating the diameter of the Al cylinder to the applied weight.

(6 marks)

b. Using your result from (a) derive a formulas relating the length and radius of the measuring wire to the weight of the mass.

(4 marks)

c. Using your results from (a) and (b) derive a formula relating the Resistance of the copper wire to the applied weight.

(4 marks)

d. What is resistance change in the Cu wire sensor due to the weight?

(4 marks)

e. What is the sensitivity of the sensitivity of the Cu sensor to weight's hung on the Al cylinder?

(3 marks)

f. What would be the sensitivity of a sensor consisting of 10 loops of copper wire to weights on the cylinder

(3 marks)

Question 4 (13 Marks)

(a) Atomic Spectroscopy

(i) Sketch the characteristic X-ray spectrum observed when a beam of energetic electrons hits a material such as Tungsten. Label the features of the spectrum.

(ii) Bohr Theory gives the energy levels within an atom as

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

A material is irradiated with X-rays. Peaks corresponding to the k_α (n=2→n=1) and k_β (n=3→n=1) transitions are observed at wavelengths of $1.664\text{x}10^{-10}$m and $1.404\text{x}10^{-10}$m respectively. What element is the target composed of?

(3+3=6 marks)

(b) The v=0 to v=1 vibrational transition of the NO molecule occurs at a frequency of 5.63×10^{13} Hz.

(i) Calculate the effective force constant for this molecule.

(ii) Calculate the classical amplitude of vibration in the v=0 vibrational state.

(iii) We wish to fabricate a photodetector to measure the associated vibrational transition of the molecule above. Select a material from those listed in table 1 below that would be suitable for this photodetector.

Table 1

Material	Bandgap (eV) At 300K
Si	1.11
Ge	0.66
HgCdTe	0.3
InSb	0.17

(2+3+2=7 marks)

Question 5 (12 Marks)

(a) Optical fibre Based sensors

(i) An optical fibre with an internal Bragg grating is illuminated using a broadband source. The spacing between the modified regions of the core at the Bragg grating is 200nm. The refractive index of the core is 1.5. Calculate the wavelength for which a minimum in transmission occurs.

(ii) Describe how a sensor based on such a fibre could be used to monitor changes in temperature.

(2+3=5 marks)

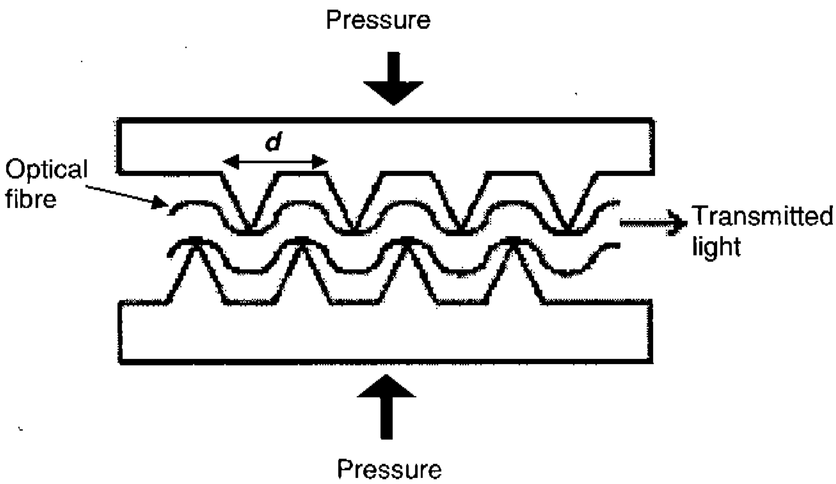

Figure 1

(b) Describe how variations in intensity of light transmitted through the sensor depicted in Figure 1 might be used to monitor changes in pressure. (Assume the period, ***d***, of the 'jaws' is of the same order as the wavelength of the transmitted light).

(3 marks)

(c) The resolution of an optical microscope is limited by the wavelength of the incident light. Describe an optical fibre based technique which can be used to obtain optical images with a significantly improved resolution compared with conventional optical microscopy.

(4 marks)

Question 6 (9 Marks)

(a) Sketch the characteristic critical magnetic field curve as a function of temperature for both type I and type II superconductors. Use these curves to outline the differences between type I and type II superconductors. Describe an application for each type of superconductor.

(5 marks)

(b) A Lead wire has a radius of 3.0mm and is maintained at a temperature of 4.2K. The critical magnetic field $B_c(0K)$ is 0.0803 Tesla and T_c is 7.193K

(i) Find the critical magnetic field in Lead at this temperature.
(ii) What is the maximum current that the wire can carry and still remain in the superconducting state at this temperature.

(2+2=4 marks)

Question 7 (16 Marks)

(a) Sensors of structure.

(i) A crystal of NaCl is illuminated with X-rays of wavelength 1.392Å. The first-order reflection of Bragg scattering of the X-rays is observed at an angle of 14.3°. Calculate the lattice spacing.
(ii) The above experiment is repeated using electrons instead of X-rays to obtain a diffraction pattern from NaCl. NaCl has a cubic structure. For low energy electrons incident normal to the crystal surface, the maxima in intensity are observed according to the expression

$$d \sin\theta = n\lambda$$

where d is the spacing between the atoms at the surface.What is the energy of the incident electrons if we observe the first maximum at the same angle as in part (i) above. Express your answer in eV.

(2+4=6 marks)

(b) Atomic scale microscopy can be undertaken using an atomic force microscope.

(i) What is the physical principle upon which the atomic force microscope is based?
(ii) What is the principle advantage of atomic force microscopy over scanning tunning microscopy?
(iii) The 2 main modes of operation of the atomic force microscope are referred to as 'contact' and 'non-contact'. Describe each of these 2 modes of operation.

(iv) For a cantilever with a small spring constant k, the minimum detectable force gradient is determined by the thermal vibration of the cantilever. If the energy of the vertical thermal vibration is given by $\frac{1}{2} k_B T$, what is the limit of resolution for a cantilever with k=1.5N/m operated at 300K in the contact mode?

(3+1+4+2=10 marks)

END OF EXAMINATION PAPER