ENGINEERING TRIPOS PART IIB

Monday 1 May 2006 2.30 to 4

Module 4B13

ELECTRONIC SENSORS AND INSTRUMENTATION

*Answer not more than **three** questions.*

All questions carry the same number of marks.

*The **approximate** percentage of marks allocated to each part of a question is indicated in the right margin.*

There are no attachments.

STATIONERY REQUIREMENTS
Single-sided script paper
Graph paper

SPECIAL REQUIREMENTS
Engineering Data Book
CUED approved calculator allowed

You may not start to read the questions printed on the subsequent pages of this question paper until instructed that you may do so by the Invigilator

1 (a) A semiconductor thermistor with the following properties is to be used in a temperature measurement circuit: R = 200 Ω at 20 °C with β' = 3200. The thermistor is connected into a simple potential divider circuit with a fixed resistor of value 200 Ω and powered from a supply voltage of +2 V , or alternatively, is powered by a 5 mA constant current source.

Derive the non-linearity of the output when measuring temperature over the range 20 – 40 °C, for each of the 2 cases and comment on the result. [30%]

(b) The housing of a laboratory oven, used for rapid temperature cycling of biological samples, has a small platinum resistance thermometer attached for measurement and control purposes. The device has the following properties:

nominal resistance:	100 Ω at 25 °C	mass:	0.1 g
temperature coefficient:	0.385 Ω K^{-1}	area:	20 mm^2
adhesive/backing thickness:	0.1 mm		
specific heat capacity:	1.1 J g^{-1} K^{-1}		
thermal conductivity:	0.3 W K^{-1} m^{-1}		

(i) Calculate the time-constant of the temperature measurement system and estimate the maximum temperature cycling frequency which the sensor could monitor reliably.

(ii) If the resistance thermometer is powered by a constant current circuit delivering 10 mA, estimate the temperature measurement error induced by power dissipation in the sensor, at a nominal 20 °C. [50%]

(c) A low cost pyrometer system assumes a fixed value of emissivity for surfaces equal to 0.95. In practice, however, it is not uncommon for metal surfaces to have an emissivity in the range 0.5 – 0.8 . What error can this introduce in the indicated temperature of a clothes iron, if the iron is actually at 160 °C ? [20%]

State all assumptions and approximations made.

2 (a) Briefly list and explain the main advantages of using a *group* of references when doing precision measurements. [20%]

(b) A sensor circuit, which is to have its temperature coefficient determined, normally gives a 2V DC output with a constant standard input. The differences between it's output V_0 and the outputs V_A to V_D of a group of four 2V DC references are shown below as the temperature is changed.

Difference voltage in mV

Temperature ($°C$)	*15.2*	*16.4*	*21.0*	*24.5*	*26.1*
V_0 - V_A	+0.7	+1.3	+2.5	+3.4	+3.9
V_0 - V_B	+2.2	+2.6	+4.6	+6.1	+6.8
V_0 - V_C	+2.5	+3.0	+5.3	+7.0	+7.8
V_0 - V_D	+1.4	+1.5	+3.2	+4.7	+5.1

Using *only* the results $V_0 - V_A$, *estimate* the temperature coefficient of the sensor in the units, $\% / °C$. Note that a 2 mV change is 0.1 % at the voltage levels used here.

Assuming that the *mean* voltage of the four references is unchanging and stays at *2V exactly* during the measurements, obtain an accurate value for the temperature coefficient of the sensor under test, using a graph as part of your method. Are there any differences that you can discern in the four references ? [50%]

(c) A 2 V DC reference voltage level can be obtained by connecting the output of a 10V DC standard to a 5 : 1 resistive potential divider.

Show the circuit of a *Hamon* 5 : 1 ratio divider circuit using 4 resistors only and explain fully its advantages compared to a normal voltage divider made of 5 equal series connected resistors. Illustrate your answer assuming that the four resistors chosen are indicated as having values of *2000, 2001, 2003 and 2005* Ω when tested with an accurate multimeter. [30%]

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3 (a) Describe briefly why silicon based micro-electro-mechanical systems (MEMS) have become important for mechanical sensors. In your answer explain with the aid of cross section diagrams what is meant by:

(i) bulk Si micromachining and,
(ii) surface micromachining

with particular reference to low cost MEMS manufacturing. Comment on the desirability and feasibility of integrated MEMS with readout electronics on the same silicon substrate. [50%]

(b) With reference to the secondary electron micrograph of a commercially available surface micromachined acceleration sensor in Figure 1-I and the higher magnification image in Figure 1-II, describe the construction of and main features of the capacitative read-out device. Explain what the features are near the labels U, V, W and X in Figure 1, and estimate the overall size of the mechanical device. Draw a cross section of the region near V labelling the various layers and their electrical functions. Identify the sensitive axis for measuring acceleration, and outline what is meant by:

(i) open loop operation and,
(ii) closed loop operation with electrostatic force feedback.

Taking the silicon proof mass thickness to be $3\ \mu m$, and making reasonable estimates of any unknown quantities, calculate the required spring constant of the mechanical system (in Newtons per metre) if the capacitance of one of the sets of electrodes is to change by $1\ \%$ when the acceleration is $5\ m\ s^{-2}$. [50%]

cont.

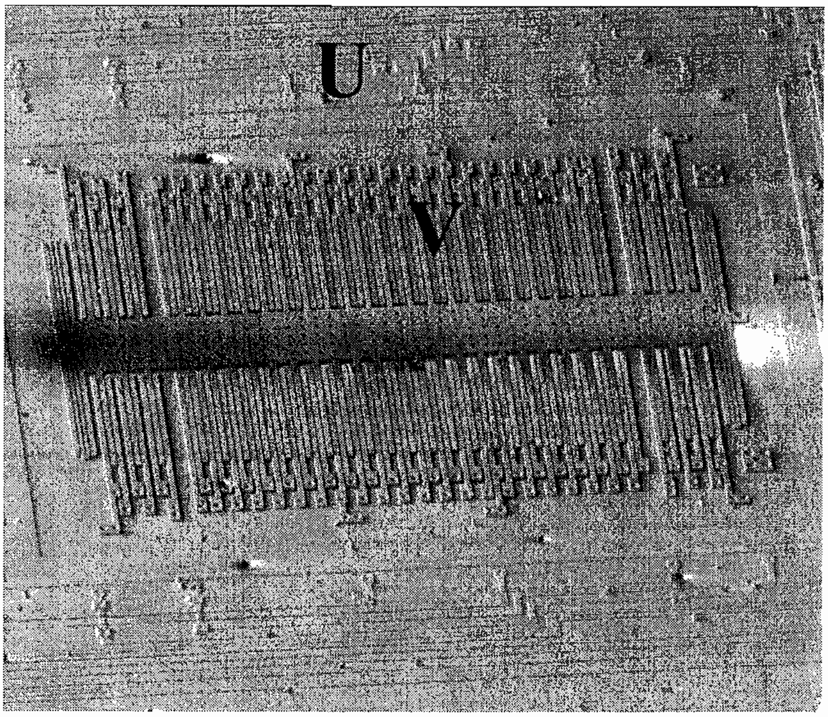

Figure 1- I

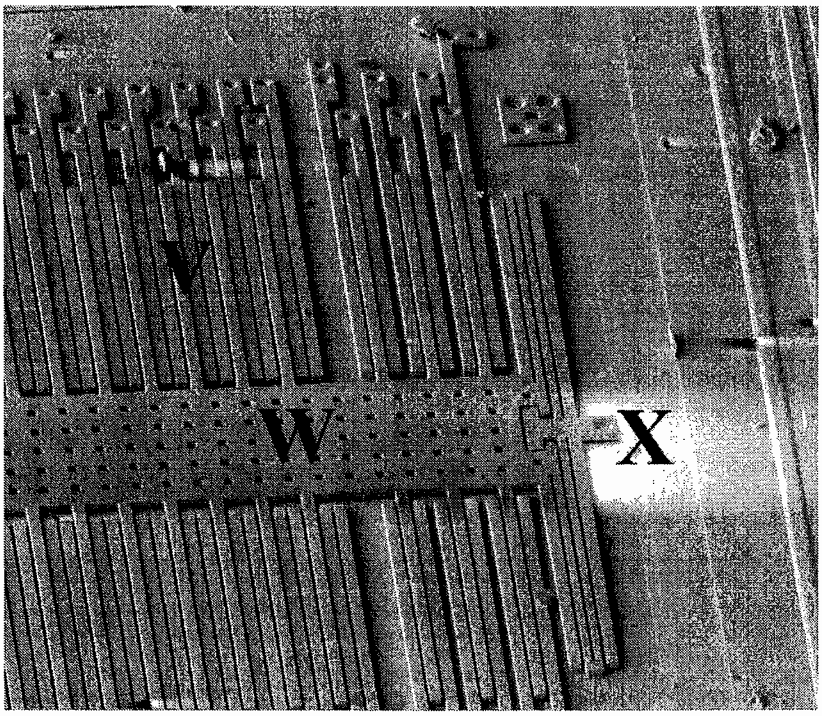

Figure 1- II

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4 An ultrasonic microscopy system can capture images of the inside of solid structures by monitoring reflections from a scanned, incident 20 MHz ultrasonic beam. It is intended to set up such a system to look at the integrity of soldered joints underneath IC packages on epoxy printed circuit boards (PCBs), which can not be inspected by the usual visual means. To achieve good ultrasonic coupling, the entire sample and transducers are immersed in water for the imaging process. This situation is illustrated schematically in Figure 2 and some relevant properties of materials are given in Table 1.

(a) Assuming that the system can resolve features with dimensions approaching a wavelength, what spatial resolution in mm does this correspond to and how much of the incident beam power is reflected back from a water-epoxy interface ? [15%]

(b) If the ultrasonic transducer is made from PZT, has a diameter of 20 mm and focuses to a small spot at a distance of 50 mm, estimate the received ultrasonic power back at the transducer when the beam is reflected from a smooth part and scattered from a rough part of the surface of a flat epoxy PCB, expressed as a fraction of the ultrasonic power initially launched into the water by the transducer. [45%]

(c) If the drive signal to the transducer is 10 V_{rms} and it has a conversion efficiency of 5 % with an electrical impedance of 50 Ω, calculate the change in open-circuit signal magnitude produced across the transducer when the beam is reflected from a water-epoxy-water interface and a water-epoxy-copper interface. All surfaces should be considered to be rough and the IC package may be considered to be thin enough to neglect attenuation and multiple reflections within it. [40%]

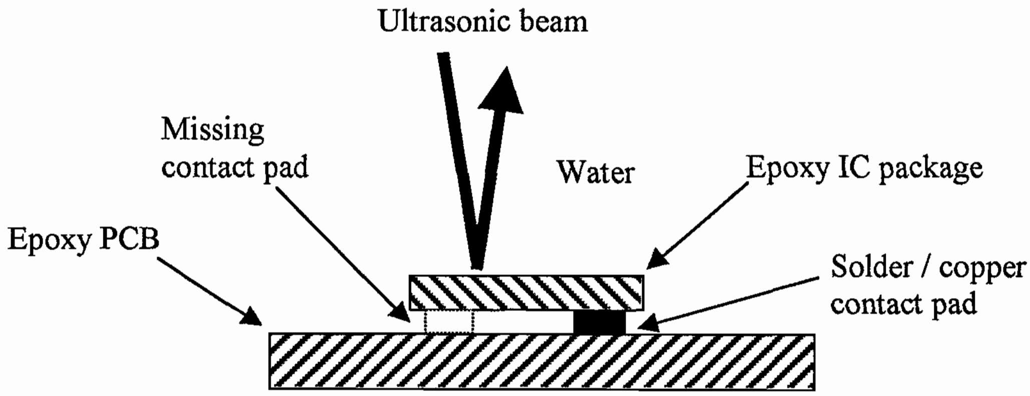

Figure 2

cont.

	Density ($kg\ m^{-3}$)	Speed of sound ($m\ s^{-1}$)	Attenuation @ 20 MHz ($dB\ m^{-1}$)
Water	1000	1500	35
Copper / solder	9200	3500	-
Epoxy	2100	2400	-
PZT	7500	4000	-

Table 1: Physical properties of materials

State all assumptions and approximations made.

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5 An electro-plating machine, used for the silver plating of large brass candlesticks, runs with a DC current up to 100 A. As part of the plating control system, the current is to be monitored with a Hall Effect sensor, placed in close proximity to the power cable.

The Hall sensor is based on an InSb (indium antimonide) square slice of dimensions 2 mm × 2 mm × 0.01 mm thick, patterned with appropriate electrodes and oriented with the magnetic field orthogonal to the plane of the slice. The carrier mobility in the InSb is 5×10^4 cm^2 V^{-1} s^{-1} and it has a carrier density of 10^{15} cm^{-3}.

(a) If the Hall sensor is placed 5 cm from the axis of the cable, what is the magnetic flux density seen by the sensor when the plating current is set to maximum ? [10%]

(b) Calculate the electrical resistance across the slice and the magnitude of the Hall voltage observed, if the sensor were exposed to a 1mT magnetic field when powered with a drive voltage of 5 V across the slice. [40%]

(c) Calculate the 10% - 90% rise-time at the output of the sensor, if the current were to increase instantaneously due to a short circuit in the machine. [30%]

(d) What is the expected intrinsic noise level of the current sensor system, expressed as an RMS noise current, considering only the thermal noise of the sensor over its intrinsic bandwidth ? [20%]

State all assumptions and approximations made.

END OF PAPER