IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2014

EEE/EIE PART III/IV: MEng, Beng and ACGI

Corrected Copy

BIOMEDICAL ELECTRONICS

Friday, 24 January 10:00 am

Time allowed: 3:00 hours

There are SIX questions on this paper.

Answer FOUR questions.

All questions carry equal marks.

Any special instructions for invigilators and information for candidates are on page 1.

Examiners responsible First Marker(s) : P. Georgiou
Second Marker(s) : T. Constandinou

1. This question relates to the design of an instrument for measuring bio-potentials from neurons in the brain.

   a) Explain why a potential of 70mV exists across the cell membrane of a neuron when it is at rest. [3]

   b) Figure 1.1 shows an AC coupled bio-potential amplifier for measuring neural activity from the brain. The electrodes used have a capacitance C_E=60μF and V_{sig} and V_{os} denote the measured bio-potential and common mode offset.

      i. Give one advantage and one disadvantage of using AC rather than DC coupled bio-potential amplifiers for this application. [2]
      ii. C_1 and R_1 are used to AC couple the input signal to the amplifier. C_1 is chosen to be 100pF. State why 100pF is a suitable value. [1]
      iii. Derive the input voltage to the amplifier V_{in}, and show that it is high pass function stating the equation of the cut off frequency stating any assumptions made. To aid you calculations you may use just one branch of the differential input for your analysis. [2]
      iv. Calculate a suitable value for R_1 to give you a high pass cut off at 10 Hz. [1]

   c) The Bio-potential amplifier in Figure 1.1 is used as part of a monitoring system to detect the action potential signal shown in Figure 1.2. The gain of the bio-potential amplifier is set to A=1000. The output of the Bio-potential amplifier is band-pass filtered between 0.3KHz and 5KHz with a 20dB/decade high-pass followed 40dB/decade low-pass filter. A final gain stage is added to maximize the dynamic range between +3V to -3V.

      i. Sketch the complete schematic of this monitoring system, calculating suitable resistor values for your filters. You may assume all capacitors are, C=100pF for your filters. [5]
      ii. Choose suitable gains and calculate resistor values to ensure that the action potential shown in Figure 1.1 utilises the maximum dynamic range of the measurement system. [4]

   d) The bio-potential amplifier shown in Figure 1.1 is to be modified to allow a fully integrated implementation in CMOS for recording from a micro-needle array. The requirements are the gain of the modified amplifier is set by a ratio of capacitors and the output and input common mode voltages at DC are the same. Sketch the schematic of the modified bio-potential amplifier. [2]

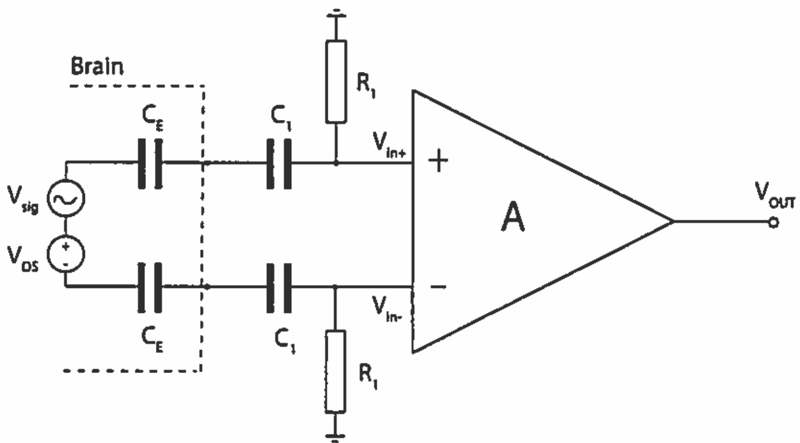
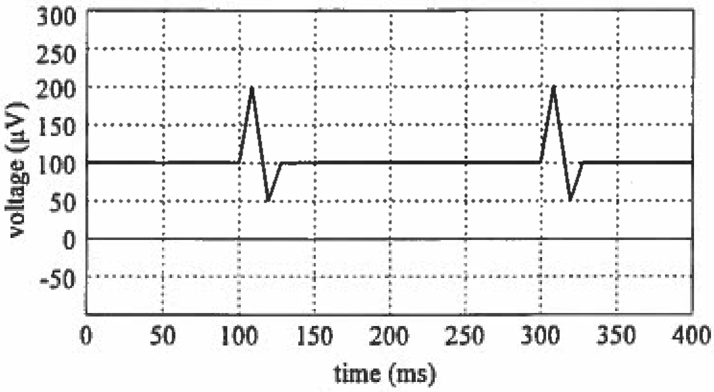


Figure 1.1


300
250
200
150
100
50
0
-50
voltage (μV)
0
50
100
150
200
250
300
350
400
time (ms)
Figure 1.2

2. This question relates to the design of an electrical stimulation circuit for a spinal cord implant for pain relief.

   a) Given the stimulus is a current-mode, charge-balanced, asymmetric biphasic waveform with the timing of the different phases being 2:1:4:1 (cathodic:interphasic:anodic:shorting), sketch and complete the charge delivery profile shown in Figure 2.1 (this shows the profile for only the first 100μs). Annotate the different phases. [4]

   b) Sketch the corresponding current waveform to the charge delivery profile you completed in your answer to part (a). [4]

   c) Design the stimulator circuit to generate the appropriate current pulses required for bipolar electrodes given a 500μA current source, labeling the different control signals required. [4]

   d) Design a state machine to generate the appropriate control signals for the circuit you provided in your answer to (c). [4]

   e) Compare monopolar and bipolar electrode configurations describing one benefit of each configuration. [2]

   f) Explain how the electrode material may influence the design. [2]

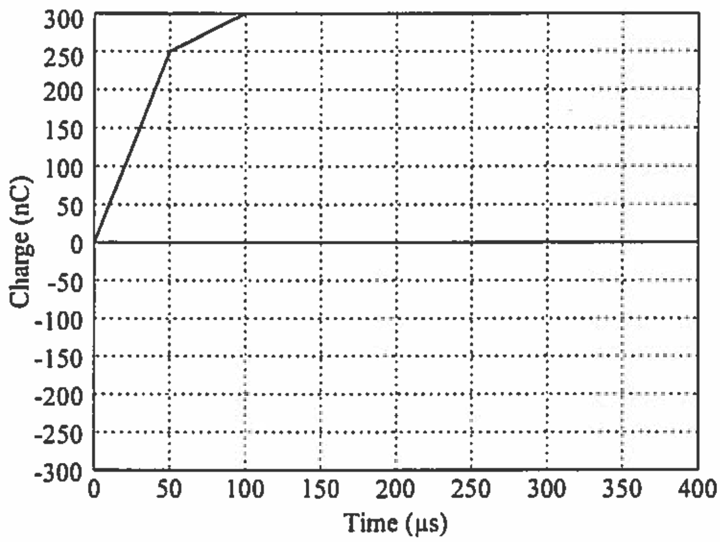


Figure 2.1

3. This question relates to the design of chemical sensor instrumentation.

a) Explain the principle of cyclic voltammetry using illustrations where necessary. [4]

b) Figure 3.1 shows an Ion-Sensitive Field Effect Transistor. The threshold voltage of the device is modulated be a pH dependent potential described by:

$$V_{chem} = \gamma + 2.3\alpha U_t pH$$

whereby Υ is a grouping of constant potentials, U_t is the device thermal voltage (26mV) and α is a sensitivity factor ranging from 0-1.

i. State two reasons why this sensor well suited for applications such as DNA sequencing? [2]
ii. Derive and calculate the maximum sensitivity achievable using this sensor. [2]
iii. Sketch the schematic of a circuit used to instrument to this sensor and describe its operation. [4]

c) Figure 3.2 shows an amperometric sensor used for the detection of DNA hybridization. The sensor works on the principle of a redox reaction confirming hybridization on WE1 at a cell potential of V_{cell}=100mV. An additional electrode, WE2 is added for sensor drift compensation. It is desirable that the output of any instrumentation system uses the difference between the hybridization reaction and drift to confirm a reaction.

i. Design instrumentation to interface to this sensor, which provides the cell bias, V_{cell} and a suitable readout that can utilize the second electrode, WE2 to increase the signal-to-noise ratio at the output. You are required to show all your schematics and label voltages where necessary. [6]
ii. Explain why the counter electrode, CE, is larger than the working electrode, WE1. [2]

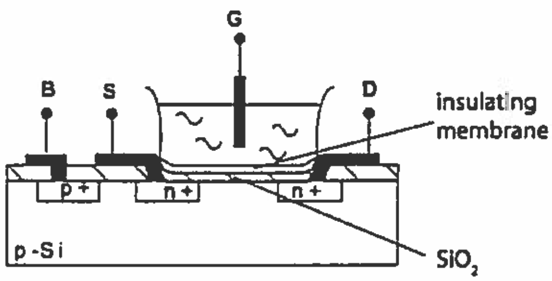


Figure 3.1

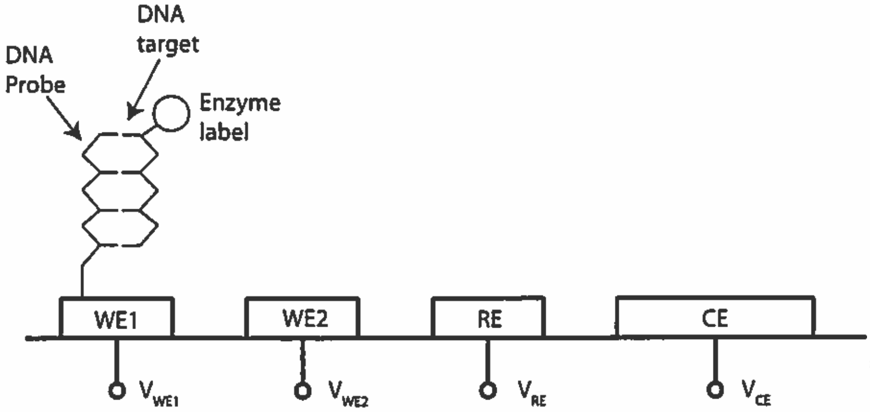


Figure 3.2

4. This question relates to the design of a system for neonatal electroencephalography (EEG) monitoring. The monitor has 3 electrodes, one on either side of the head recorded independently with a reference connected to the ear of the baby. The signal is primarily contaminated with heart rate (ECG, 120 beats per minute) and breathing signals (respiration, 30-50 breaths per minute).

a) Given the EEG bandwidth of interest is stated as 2-40Hz, without any pre-processing ranges from +/- 100μV and requires a minimum resolution of 1μV.
   i. What would be the required ADC resolution and sampling rate (assuming Nyquist sampling)? [2]
   ii. What data rate would be required to transmit the raw data (eg. wirelessly) [2]

b) If the raw data is to be transmitted, encoded using Hamming (7,4) determine the following:
   i. The required data-rate. [1]
   ii. Encode the 8-bit word "183" (decimal value) using Hamming (7,4). [3]
   iii. Describe how Hamming (7,4) provides error checking and/or error detection. [2]

c) To maximize data transmission bandwidth and extract useful features from the data, the ECG and respiration need to be removed.
   i. Suggest two methods for removal of the ECG and respiration signals. [2]
   ii. State one challenge of each method. [2]

d) The typical signals during normal sleep/wake cycling are show in Figure 4.1. The duration of the sleep-wake cycle gives some indication of the development of the brain and can detect abnormalities. A system is required that will detect the types of activity depicted in Figure 1(sleep-wake discharges). These burst-quiet periods range from 3-20 seconds. *(Note: you can assume the ECG and respiratory artifacts have already been removed).*

   Draw a block diagram for a system that would detect this type of activity and classify it. The system is required to output an indicator of the burst activity and the quiet period (0 for quiet, and 1 for bursting). It also needs to follow this with the duration in seconds of this activity. Estimate what would be the maximum new data rate? [6]

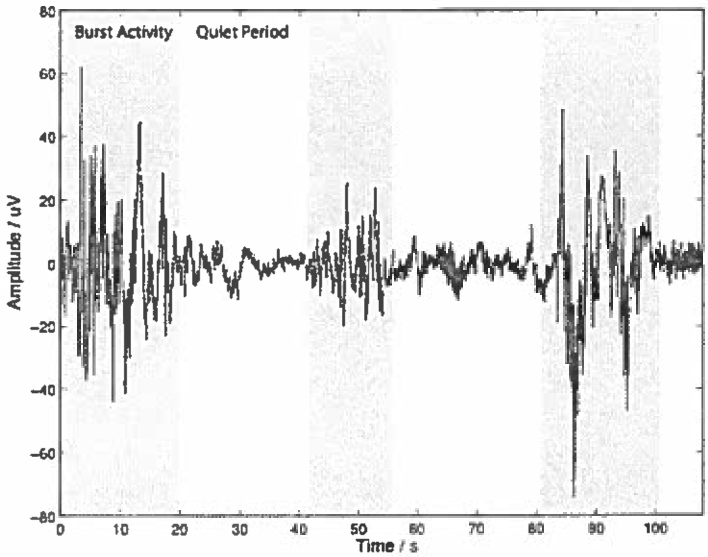


Figure 4.1 – Discontinuity data from a single channel neonatal EEG.
Data shows burst activity between quiet periods.

5. This question concerns a retinal prosthesis for the restoring vision.

a) Sketch a system block diagram of a retinal prosthesis that would help a blind person to potentially recognise large objects around him. Clearly label each block and briefly explain the role of each of them. [7]

b) If the target visual acuity and equivalent frame rate are 25 x 25 pixels at 20 frames per second and given that targeted neurons require minimum Qmin=50nC for stimulation,

i. Define the key specifications for the stimulator (the current magnitude and pulse width for each phase, and the period/repetition rate). Assume biphasic, symmetric stimulation pulses (where the minimum interphase delay is negligible) and that no more than one row of stimulation electrodes (25 in total) can be simultaneously on. [3]

ii. Sketch the stimulation waveform at a single electrode and clearly label all relevant parameters. [2]

c) If the maximum allowable charge density for a Pt electrode is qm=150μC/cm^2,

i. What is the electrode minimum area required and calculate the diameter D of the electrode? You may assume the electrodes are flat and circular. [2]

ii. What is the minimum size of the electrode array if the minimum spacing between adjacent electrodes is d=94μm? [1]

d) If the electrode-tissue impedance is R=10kΩ□calculate the average power dissipation at the load impedance for a single electrode and for the whole stimulation array. [3]

e) What is the electrode voltage needed to drive each electrode if a design requirement is that the minimum stimulation strength is at least two times Qmin (i.e. 100nC)? [2]

6. This question concerns power supplies for body worn and implanted medical electronics.

a) The link efficiency of a wireless power transfer system is given in Equation (1):

$$\eta_{link} = \frac{k^2 Q_{TX} Q_{RX}}{\left(1+\sqrt{1+k^2 Q_{TX} Q_{RX}}\right)^2} \quad (1)$$

where k is the coupling factor and Q_{TX} and Q_{RX} are the Q-factors of the transmit and receive coils respectively.

i. What do k and QRX/QTX physically represent? Give a formula for each. [4]
ii. In the design of a wireless power transfer system, what factors have a strong influence on the coupling factor, k? [2]
iii. What factors have a strong influence on the Q-factor of the coils? [2]

The skin depth in a conductor is given in equation (2):

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} \quad (2)$$

where ρ is the material resistivity, ω is the frequency of operation and μ is the magnetic permeability.

iv. By considering only equations (1) and the coil Q-factor (using equation (2)), what frequency should an inductive wireless power system be operated at to ensure maximum link efficiency? [3]
v. What important effect was not taken into account in part iv) and how would this change your choice of frequency for maximum link efficiency? [2]

b) Motion-driven energy harvesting devices have been used on body-worn electronics applications, with the Seiko kinetic watch probably being the best known.

i. Explain the principle of operation of an inertial energy harvester. [3]
ii. What, fundamentally, limits the output power of such devices? [2]
iii. Explain why a simple passive full-wave diode rectifier is a poor choice for using as an interface circuit to an electromagnetic harvester. [2]