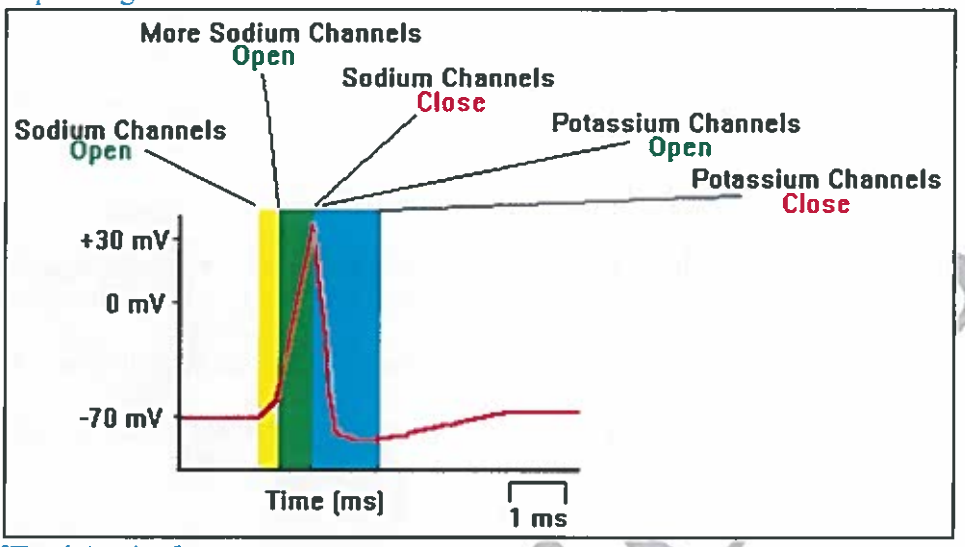
1. This question relates to the design of an instrument for measuring bio-potentials.

   a) Explain how an action potential is generated referring to the ionic flow of sodium and potassium ions. You are required to sketch the waveform of an action potential and annotate each phase, explaining the mechanism contributing to these. [4]

[bookwork]
Explain figure shown



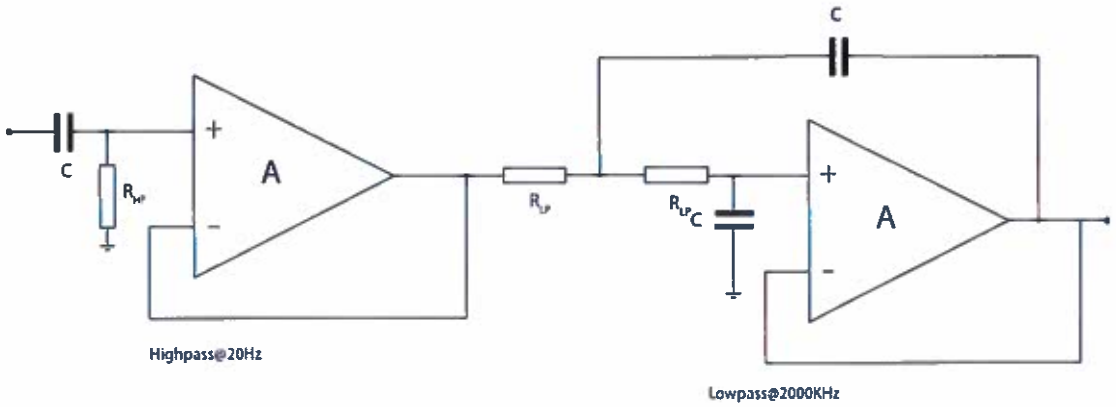
[Total 4 points]

   b) Table 1.1 lists five commonly observed bio-potentials and their amplitude and frequency characteristics. A doctor requires an instrumentation system to record activity from the quadriceps muscles to aid rehabilitation during stair climbing. A schematic of a suitable instrumentation system is shown in Figure 1.1 to measure the signal in Figure 1.2. The gains of the first and second instrumentation amplifiers are 10 and 50 respectively and the system runs off a +/-3V supply.

   c) (i) Design a suitable band pass filter (B.P.F in Figure 1.1) to extract the signals of interest. You may assume a 40dB/decade roll off for the low-pass and 20dB/decade roll off for high pass sections. State equations for cut off frequencies and select suitable resistors. You may assume you have 10nF capacitors to your disposal. Show all circuit schematics and annotate component values. [4]

Using table below for EMG:
High pass cut off: f_{HP}=20Hz
$R_{HP}=1/2\pi Cf_{HP} = 1/2\pi(10nF)(20Hz) = 7.95\ M\Omega$ [1 point]
Low pass cut off: f_{LP}=2KHz
$R_{LP}=1/2\pi Cf_{LP} = 1/2\pi(10nF)(2KHz) = 79.5K\Omega$ [1 point]

Low pass 40dB/decade: Sallen Key can be used
High pass 20dB/decade: Opamp with RC
A potential solution [2 points]:



[Total 4 points]

When the doctor conducts the stair climbing experiment he notices significant interference on the on the EMG signal, as shown in Figure 1.2, of a periodic nature.

ii) Why will this be a problem for the instrumentation system shown in Figure 1.2 ?

The signal has an amplitude of 10mV, the gain of IA2*IA2 is 500, so the out V_{sig} will be 5V which will saturate IA2.

[Total 2 points]

In order to extract the measured EMG signal shown in Figure 1.3 a potential solution is to use feedback on the instrumentation amplifier.

ii) Explain why and show that the feedback arrangement using an integrator with $\tau = RC$ and a gain stage of $-\frac{1}{B}$ around IA2 is a suitable solution to filter out this unwanted periodic signal.

Deriving the transfer function Vsig/V1 you will see the solution is a High pass filter if B=100 which can filter out the unwanted signal [2 points for explantation]

Derivation [3 points]:

$$V_{sig} = -A(V_1 - V_2),$$

$$V_2 = -V_{sig}\frac{1}{sRC * B}$$

$$V_{sig} = -A\left(V_1 + V_{sig}\frac{1}{sRC * B}\right),$$

$$V_{sig}\left(1 + \frac{A}{sRC * B}\right) = -AV_1,$$

$$with\ A = B,$$

$$V_{sig}\left(\frac{1 + sRC}{sRC}\right) = -AV_1,$$

$$\frac{V_{sig}}{V_1} = -A\left(\frac{sRC}{1 + sRC}\right)$$

[Total 5 points]

[5]

iii) Choose suitable values for B, R to filter out the unwanted signal shown in Figure 1.2, assuming C=10nF.

B=100 so closed loop gain is 1. [1]

Period so signal is 0.5 seconds, so F_{sig}=2Hz,, so chose F_{HP}=2.2Hz

$R_{HP}=1/2\pi Cf_{HP} = 1/2\pi(10nF)(2.2Hz) = 72.3\ K\Omega$ [1 point]

[Total 2 points]

iv) Calculate values for resistors R1 and R2 to maximize the dynamic range for the detected signal shown in Figure 1.2.

EMG amplitude signal +5mV to – 4mV, assume 10mVptp.
Maximum gain = 6V/10mV =600.
Gain of IA1*IA2=500
Gain of A3=600/500=1.2 [2 points]
1.2=(1+R2/R1)
R2/R1=0.2 therefore R2=2KΩ and R1=10KΩ [1 point]
[Total 3 points]

Table 1.1

Signal	Frequency range (Hz)	Amplitude range (mV)
ECG	0.1 – 300	0.05 – 3
EEG	0.5 – 40	0.001 – 1
EMG	20 – 2000	0.001 – 100
Neural Spikes	300-5000	0.001 – 0.5
Local Field Potentials	10-200	0.001 – 5

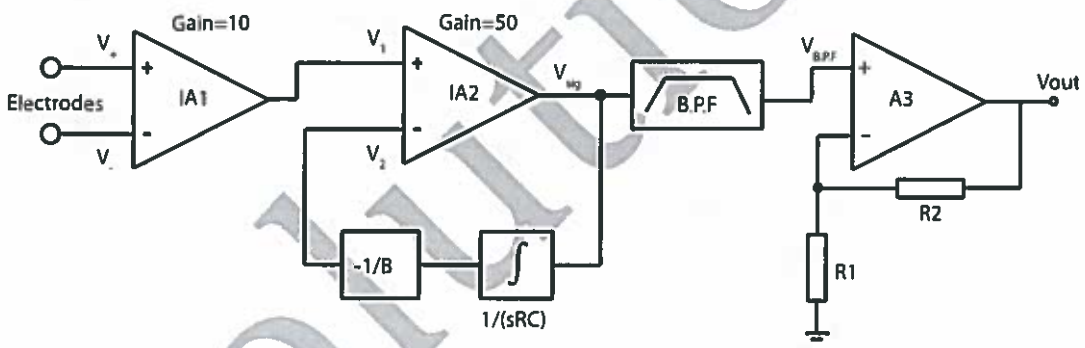


Figure 1.1

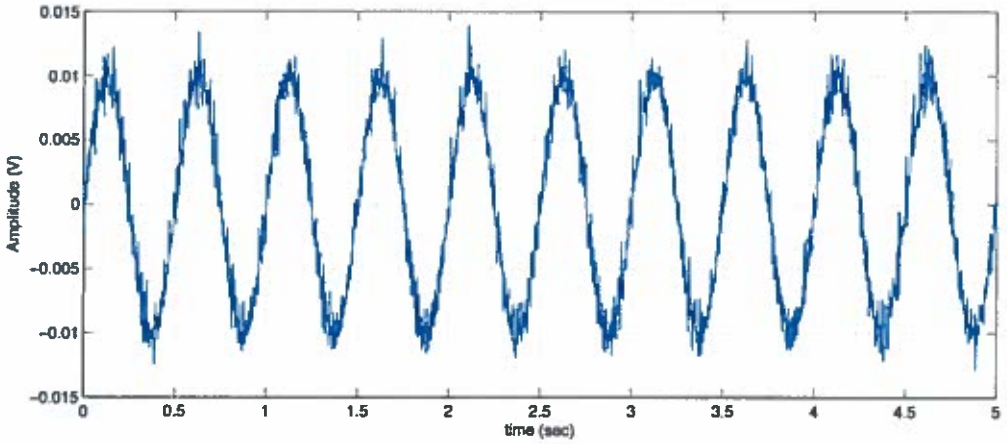


Figure 1.2, EMG signal with motion artifact

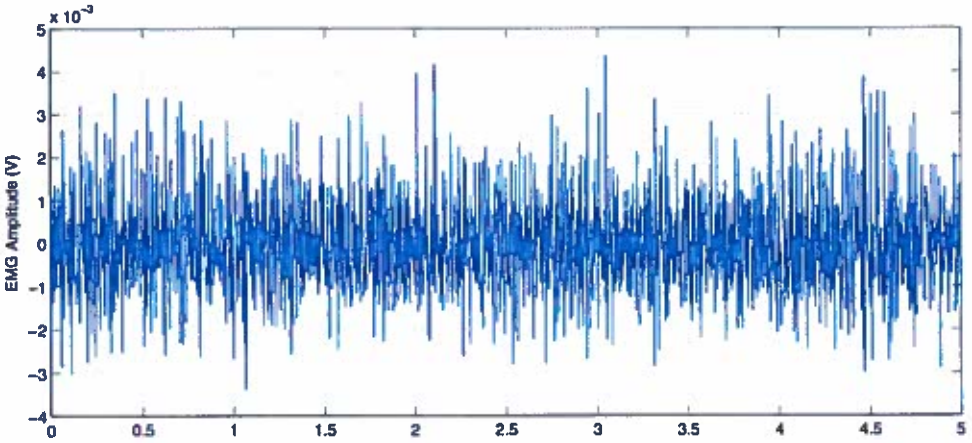


Figure 1.3, Extracted EMG signal

2. This question relates to electrical stimulation.

a) Briefly describe *current-*, *voltage-*, and *charge-mode* stimulus generation for electrical stimulation. [4]

Electrical stimulation involves "injecting" charge into biological tissue using electrodes ("exchanging" the electrons in the metal with "ions" in the electrolyte) to modulate some action (e.g. activate a muscle, neural tissue, or some other electrically excitable cell). After stimulation, it is essential to ensure any injected charge is removed to avoid tissue damage through charge build up (e.g. electrolysis occurring at the electrode). [1]

Current-mode stimulation uses a fixed current source that is precisely controlled using digital timing. The charge delivered is thus very well known – provided the current source is precise, and there is no jitter in the underlying clock. [1]

Voltage-mode stimulation applies a fixed voltage, and therefore since the electrode impedance is unknown (and variable), an external circuit is required to monitor the current flowing into the tissue so that it can then be charge balanced. [1]

Charge-mode stimulation charges a known capacitance to a fixed voltage and then dumps (i.e. discharges) this into the tissue. As the electrode impedance again is unknown (and variable), the capacitor will not full discharge but rather share charge with the tissue. Thus external circuits are required to fully discharge and/or achieve precise charge balancing. [1]

b) Compare the relative merits and drawbacks between these methods with respect to power efficiency, voltage compliance, safety and circuit complexity. [4]

Delivery Method	**CMS**	**VMS**	**QMS**	
Voltage Compliance	High	**Low**	Medium	[1]
Power Efficiency	Low	**High**	Medium	[1]
Charge Safety	**High**	Low	Medium	[1]
Circuit Complexity	**Low**	High	Medium	[1]

c) Select and justify which of the 3 methods would be most suitable for the following applications: [6]

(i) A wearable functional electrical stimulation (FES) system

Voltage-mode stimulation [1] Since body-worn, charge balancing safety is not an issue- so VM stimulus generation would be easiest (and most power efficient). [1]

(ii) An implantable cardiac defibrillator

Charge-mode stimulation [1] Provides an upper limit to the amount of charge being delivered (which is often significant) – for safety. Also, it is challenging to generate such a large stimulus directly driven by active devices – for implementation. [1]

(iii) An implantable cochlear prosthesis

Current-mode stimulation [1] Typically requires multiple channels so need to be able to control the current, and timing (thus have good control over charge) – to avoid damage to electrodes and/or tissue. Cannot rely on capacitive coupled electrodes (due to large channel count – bulky). [1]

d) A 32-channel current-mode cortical stimulator achieves a 2% charge imbalance during continuous operation. Describe the suitability of the following charge balancing solutions: [6]

(i) Capacitive coupled electrodes

Although this provides the safest charge balancing scheme. Due to the stimulus magnitude required the capacitance size is significant and thus cannot be implemented on chip. Any capacitors thus have to be discrete and are thus bulky. 32 discrete capacitors cannot thus be implemented in a tiny implantable device. [2]

(ii) Implementing a shorting phase

A multichannel cortical stimulator implies the electrodes would be small, and thus of high impedance. Also to avoid destructive interference (or crosstalk) it is essential that any stimulation strategy ensures that only one channel is being stimulated at any one moment in time (time multiplexed). Implementing a shorting phase in a 32-channel system (with high impedance electrodes) would thus probably not remove all the charge (due to large time constant and stringent timing requirements). [2]

(iii) Active charge balancing (metering with compensation)

This would be the most appropriate method of charge balancing such a stimulator although this would require extra circuits. This would involve operating a full stimulation cycle (or multiple cycles) and then monitoring the electrode voltages. If these are non-zero then compensating current (pulses) could be applied until the "residue" is removed. [2]

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

a) State one desirable and one undesirable characteristic for chemical sensors.

Desirable:
Linearity
Sensitivity
Selectivity

Undesirable:
Drift
Hysteresis
Any of the two [Total 2 points]

b) The potentiostat system shown in Figure 3.1 is used to drive a three-electrode amperometric glucose sensor.

i) Explain and what is the role of the potentiostat and the function of the reference and counter electrodes

Bookwork
Potentiostat is used to provide a constant cell potential Vcell between the Working Electrode and the Reference electrode. Typically an op-amp in feedback is used to apply a bias to the Reference electrode. The counter electrode is used to supply the current to working electrode so as not to change the potential of the reference electrode.
[Total 3 points]

The sensor shall be used to measure a physiological glucose range of 0-20mM. The output current of the sensor maps to the range of IF = 0-400nA. The peak redox current is given by the following equation for a scan rate of 1V/s:

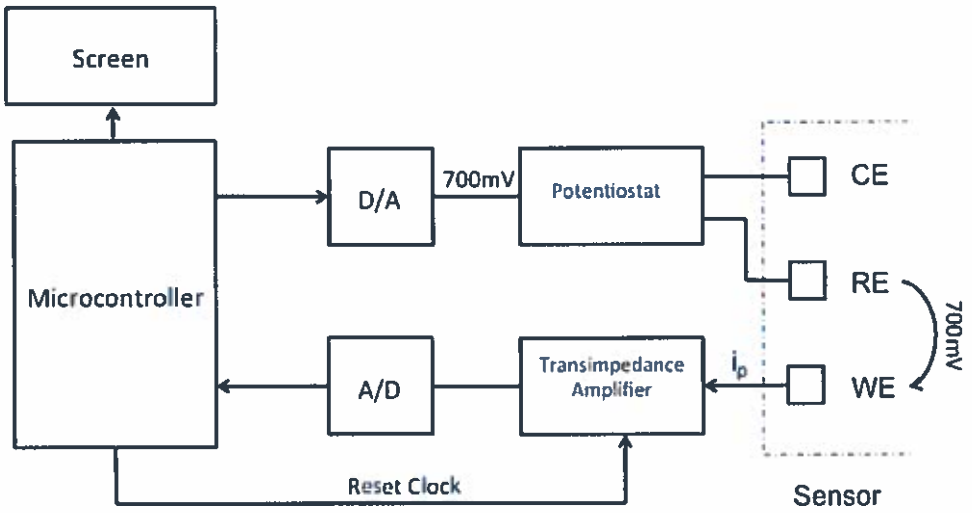
$$i_p = 2.69 \times 10^5 n^{3/2} A D^{\frac{1}{2}} C$$

where n=2 are the number of electrons given by the redox reaction and the diffusion coefficient D=4.38X10^{-8} m^2/s.

ii) Calculate a suitable area A, for the Working Electrode that will map the required concentration to the required current range.
We require a maximum ip=400nA for a concentration C=20mM
ip/C =2x10^{-5}=2.69x10^5*2$^{1.5}$*A*(4.38x10^{-8})$^{0.5}$
A=
[Total 2 points]
iii) The system shown in Figure 3.1 operates of a dual supply with VDD=5V and VSS=-5V. The transimpedance amplifier is clocked at a frequency f=10KHz. Calculate a value for the capacitor C_M which ensures the maximum utilization of dynamic range at 20mM of glucose.

Vout max = 5V since common mode is at 0
IF=CΔV/ΔT =$C_m V_{outMax}$ *2f= C_m5V *10KHz =400nA
Cm=4pF
[Total 3 points]
iv) Sketch a system level diagram of a glucometer using this system which could be used to measure blood glucose in diabetes.

A possible solution from the lecture notes. Need to specify that Vcell=700mV for glucose sensors and reset signal for trans-impedance amplifier.

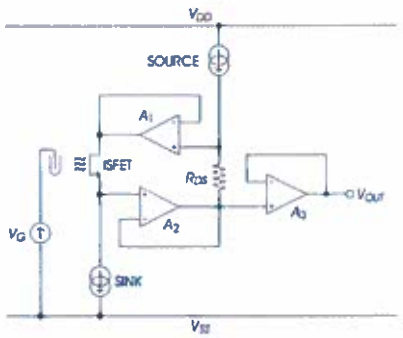


[Total 5 points]

c) The sensor shown in Figure 3.2 is an Ion-sensitive Field effect transistor.

i) Sketch the schematic of a circuit used to instrument to this sensor and describe it's operation.

Bookwork.
Identification and explanation that a constant charge method is required and explanation of the operation [2]
Schematic [2]
Equation for vchem [1]



Circuit diagram of an ISFET source-and-drain follower circuit
[Total 5points]

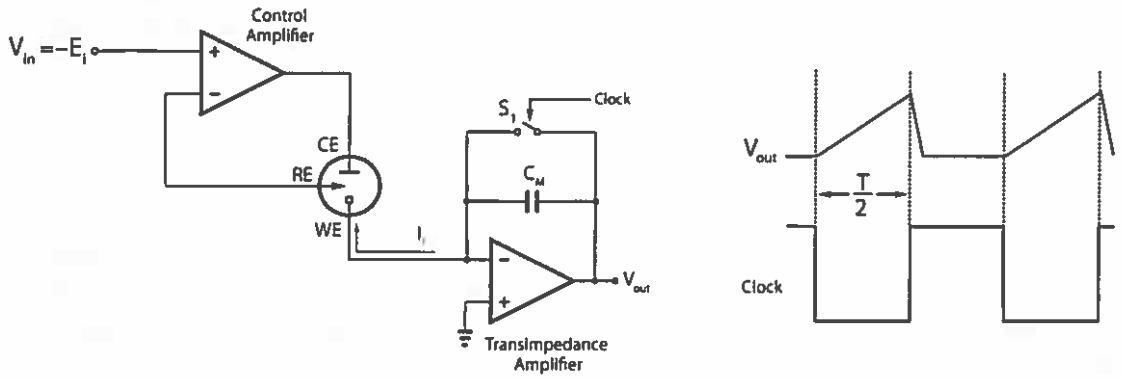


Figure 3.1

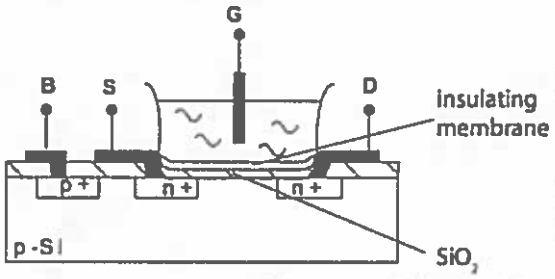


Figure 3.2

4. This question concerns inductive power transfer (IPT) systems for body worn and implanted medical electronics.

a) Safety of IPT systems in medical applications is paramount:

i) Name two adverse effects that can be observed on the human body if subjected to excessive electric or magnetic fields.

[2]

ii) Discuss which organisations are responsible for setting electric and magnetic field strength safety limits and how the limits would be used to determine if an IPT transmitter is safe for use in human proximity.

[5]

iii) An IPT transmitter system is certified safe for human exposure. Why would the system need to be recertified if powering a medical implant? Is the system more of less likely to meet the human exposure limits for a person with the receiver implanted, or for a person without the implant?

[3]

[bookwork]

i) Two negative effects that can be seen in the human body under E and B fields are:

- *Tissue heating*
- *Nerve and muscle stimulation*

[2]

[bookwork]

ii) The application of regulations is different in different countries with several bodies engaging in standards. The ICNIRP and IEEE produce a set of recommended limits which are referred to by the WHO and it is then up to countries to determine how these are applied locally. In Europe, the new EMF directive (going active in 2016) is based on the ICNIRP limits)

[2]

Determining the safety of an exposure can be done in 3 parts:

1. *Check to see if the fields produced by the system fall within the ICNIRP or IEEE reference levels at the closest point of access for a person*
2. *If yes, then the system is immediately considered safe*
3. *If no, simulations should be undertaken to calculate internal B and E fields as well as specific absorption rate for tissue heating*

[3]

[extension of taught material]

iii) The magnetic and electric fields inside the human body will change significantly between the situation where a person without an implant stands in the proximity of an IPT system compared to when the person with an implant stands close to an IPT system – currents in the receiver cause high local electric and magnetic fields. Thus the situation is likely to be far worse i.e. the system is much less likely to meet the standard when the receiver is implanted.

b) This question relates to power management of an implantable cochlear prosthesis.

a) The device consumes an average power of 200µW (excluding stimulation power). Given the following parameters determine what capacity of implantable battery would be required in order to operate the device for a week. State any assumptions that are made. [10]

Number of electrodes:	25
Electrode impedance:	15kΩ
Stimulation type:	Current-mode (symmetric biphasic pulses)
Average stimulus magnitude:	100nC
Stimulation rate (per channel):	500 cycles/s

- To calculate the duration of each stimulation cycle = 500 cycles/s * 25 channels = 12500 stimulation cycles / sec. => 1/stim cycles per sec = 80µs (per cycle). [1]
- If cycles are biphasic and symmetrical -> 40µs cathodic phase followed by 40µs anodic phase. [1]
- Given average stimulation magnitude of 100nC -> Q=I x t => Average stimulation current is thus, I = Q/t = 100nC/0.4ms = 250µA. [1]
- Assuming the average stimulation current is 25% the maximum magnitude, then the maximum stimulation current would be 1mA. [1]

- Thus to support a 1mA current (through a 15kΩ electrode) -> Vcompliance = I x R = 1mA x 15k = 15V. This assumes that any voltage drops across other components in negligible in comparison. [1]

- Average power consumption for stimulation is therefore P = Iaverage + Vcompliance = 250μA x 15V = 3.75mW. [1]

- Total average power consumption for the cochlear implant during operation is thus 200uW + 3.75mW = 4.25mW. For a 15V supply this corresponds to an average current of 283μA. [1]

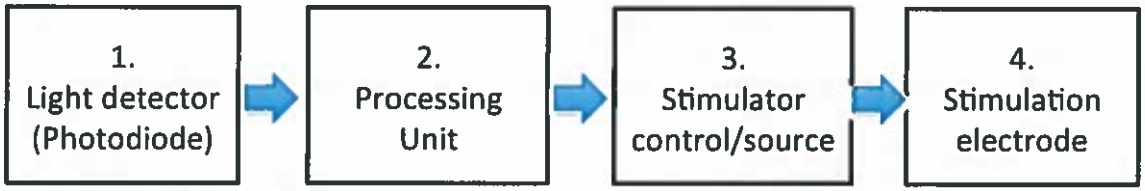
- If the device is operated for an average of 18hrs a day, then the energy capacity required for a week would be 283μA x 18hrs x 7 days = 35.7mAh (assuming a 15V battery). [1]

- If this is to be boosted up from a 3V battery (assuming some losses in DC-DC conversion), a 250mAh, 3V battery should be sufficient. [2 – for identifying 15V cells done exist, and doing calculation].

5. A blind cockroach needs to avoid light areas and find dark places to survive.

(a) Make a block diagram of an "eye prosthesis" which would solve the task of informing the cockroach about the ambient light level by stimulating its optic nerve. Clearly label each block and very briefly explain the role of each of them.

Answer
A system block diagram:



1. Light detector: converts light into electrical signal (phototransduction). Could be a photodiode.
2. Processing unit/electronics: takes the output of (1) and processes it according to some algorithm to calculate the stimulation patterns.
3. Stimulator control/current source: circuitry for controlling the stimulation and the current source
4. Stimulator: the wire and electrode

[2 marks for the system block diagram + 1 mark for each description 1-4 = 6 marks in total]

(b) Only one platinum electrode is used for the optic nerve stimulation. The stimulation is created using a current source producing I_{mx}=10□A. Design and draw the current stimulus waveform if the stimulation frequency is f=10Hz and minimum interphase delay is t_i=2ms. Assume biphasic, symmetric stimulation pulses. The threshold for stimulus is Q_{th}=50nC for the stimulus pulse durations between 3ms and 200ms. Clearly mark on the diagram all elements of your stimulation waveform and explain their role.

Answer
Stimulation waveform diagram:

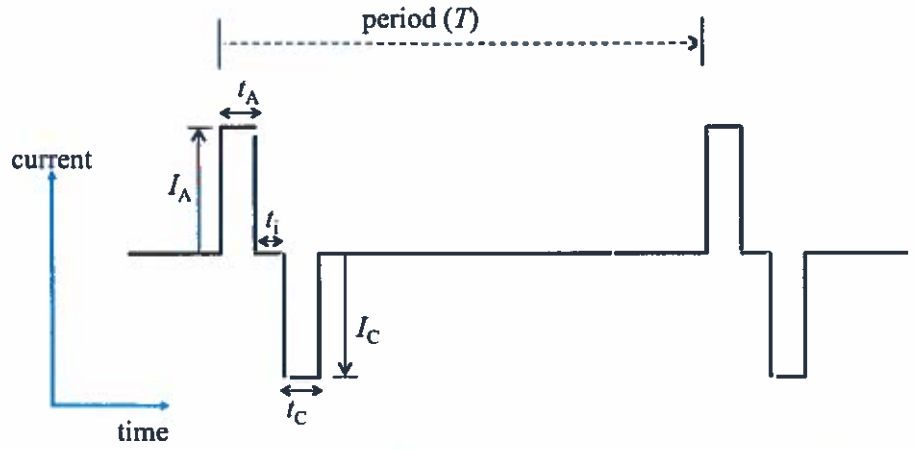


Figure 1. [2 marks for the stimulation waveform diagram]

- Stimulus waveform period: T=1/f = 100ms. [1 mark]
- $I_{anodic} = I_A = I_{mx} = 10$ A, $t_{anodic} = t_A = Q_{th} / I_{anodic} = 50nC/10$ A = 5ms. 3ms< t_A <200ms, so assumption for using the threshold charge is correct. [1 mark]
- biphasic, symmetric stimulus therefore: $I_{cathodic} = I_C = I_A = 10$ A, $t_{cathodic} = t_C =$ 5ms. [1 mark]
- Interphase delay t_i=2ms.
- Total time for delivering the threshold stim = 5+2+5 = 12ms < 100ms – fits within one stimulation cycle.

[total = 5 marks]

(c) It is needed to encode three different stimulation levels: the threshold stimulus, 2x and 4x the threshold stimulus. Show the stimulus waveform for the last two.

Answer:
Pulse width modulation controls the stimulation intensity. Same as Fig.1, with different values for
- 2x: $t_A = t_A = 10$ms [0.5 marks]
- 4x: $t_A = t_A = 20$ms. Total time for delivering the stim = 20+2+20 = 42ms < 100ms – fits within one stimulation cycle. [0.5 marks]

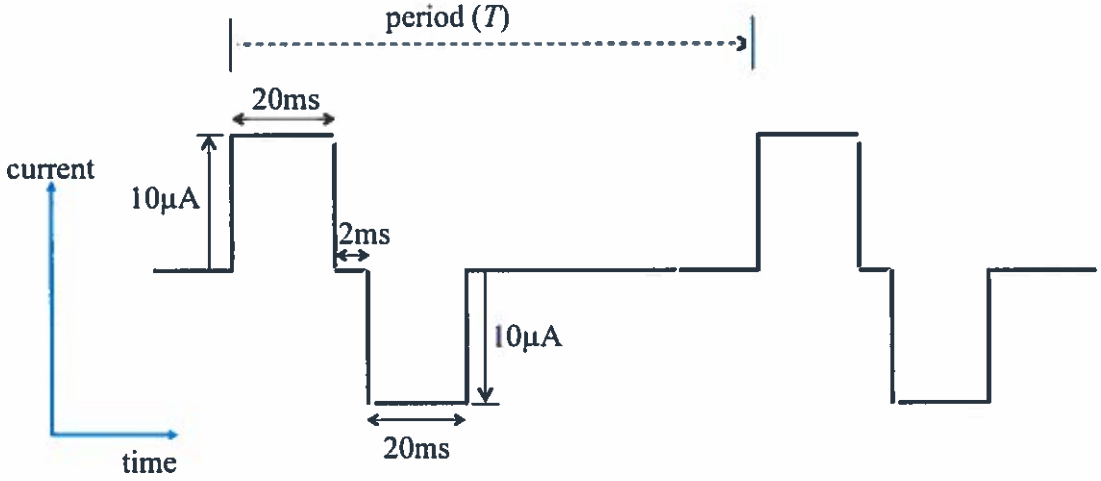


Figure 2: Stimulation diagram for 4x case, very similar for 2x case. [1 mark for each stimulation waveform diagram]

[total = 3 marks]

(d) The maximum allowable charge density for a Pt electrode is q_m=150□C/cm^2. Calculate the minimum diameter of the electrode (D) if only the surface of the tip of the electrode is exposed and the maximum stimulus produces 4xQ_{th}

Answer:

Area = $4*Q_{th} / q_m$ = 200nC / 1.5□C/mm^2 = 0.133mm^2 [1 mark]

Area = □*D^2/4 => D = 412□m [1 mark]

[total = 2 marks]

(e) If the electrode-tissue impedance is R=10k□□calculate the average power dissipation at the load impedance for all three stimulation levels.

Answer:

Average power dissipation for the threshold level of stimulation is:

Active time for the electrode: $t_{active} = t_A + t_C$ = 10 ms,

[1 mark]

$P_1 = R * I^2 * t_{active} * f$ = 10 k□□ * (10 □A)^2 * 0.010 s * 10 Hz = 0.1□□W

[2 marks]

P_2 = 0.2□□W [0.5 marks]

P_4 = 0.4□□W [0.5 marks]

[total = 4 marks]