IMPERIAL COLLEGE LONDON

BSc and MSci DEGREES – MAY 2013, for Internal Students of the Imperial College of Science, Technology and Medicine

This paper is also taken for the relevant examination for the Associateship

ADVANCED CHEMISTRY THEORY IIIB

Paper 1

Thursday 09th May 2013, 09:30-11:45

PLEASE NOTE THAT IT IS DEPARTMENTAL POLICY THAT THESE EXAM QUESTIONS MAY REQUIRE UNDERSTANDING OF ANY PRIOR CORE COURSE.

USE A SEPARATE ANSWER BOOK FOR EACH QUESTION. WRITE YOUR CANDIDATE NUMBER ON EACH ANSWER BOOK.

Year 3/0513 **Turn Over**

3.I5 – Bioinorganic Chemistry

Answer parts a) **AND** b) and **EITHER** part c) **OR** d) of this question.

a) Answer **ALL** parts of this question.

i) Draw the chemical structures of any **THREE** of the following four amino acids:

- Aspartic Acid (Asp);
- Cysteine (Cys);
- Histidine (His);
- Tyrosine (Tyr).

(3 marks)

ii) For the three amino acids you have chosen, put them in order of increasing pKa.

(1 mark)

iii) For **EACH** of your three chosen amino acids suggest the identity of one metalloprotein or enzyme in which the amino acid plays a key role in coordinating a metal atom or ion in the active site. In each case state the metal involved and its oxidation state(s).

(3 marks)

b) Answer **ALL** parts of this question.

i) Draw the molecular orbital diagram for $^3O_2$.

(4 marks)

ii) With reference to your molecular orbital diagram, discuss how dioxygen binds to the two copper centres in oxy-haemocyanin.

(3 marks)

iii) Spectroscopic studies of oxy-haemocyanin using Infrared spectroscopy show absorption at 755 cm^{-1}. Explain the origin of this absorption band.

(2 marks)

c) Answer **ALL** parts of this question.

i) Despite its abundance in the Earth's crust, the bioavailability of iron is poor. Why is this?

(2 marks)

ii) Explain why iron is potentially toxic to organisms in its 'free' (aqueous complex) form.

(2 marks)

QUESTION CONTINUED OVERLEAF

iii) With the aid of a schematic diagram of the metal binding site, explain how transferrin is able to reversibly complex Fe(III).

(5 marks)

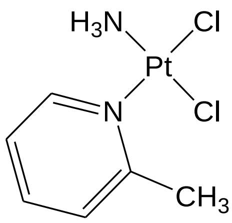
d) Answer **ALL** parts of this question.

i) Briefly describe the main mechanisms of resistance to *cis*-platin in tumour cells.

(3 marks)

ii) Picoplatin (**A**) is currently undergoing clinical trials where it has shown a promising ability to overcome platinum drug resistance in *cis*-platin resistant cell lines. Discuss the key structural feature(s) in **A** which may lead to its activity.

(3 marks)



A

iii) Suggest a synthesis for Picoplatin (**A**) starting from *cis*-[$PtCl_2(NH_3)_2$]

(3 marks)

3.I6 – Symmetry and Spectroscopy

Answer **BOTH** parts of this question.

a) Determine Γ_{vib} and assign the spectrum by completing the table below for the D_{3h} symmetry nitrate anion NO_3^-. Show your working.

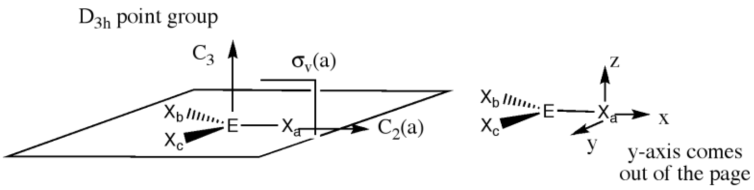
vibration (cm^{-1})	activity	symmetry	normal mode
1405	(IR and Raman depol)		
1068			
831		A_2''	out-of-plane umbrella
692			

(13 marks)

b) Answer any **TWO** parts of this question.

i) Determine if the operations $C_2(a)$ and $\sigma_v(a)$ commute using either diagrams or matrices. Use as your basis the cartesian coordinates identified on the diagram below. Show your working.

(6 marks)



ii) Identify the components **A-D** for the C_4 point group multiplication table shown below. What two features of the multiplication table identify this group as abelian?

C_4	E	C_4^1	C_2	C_4^3
E	E	C_4^1	C_2	C_4^3
C_4^1	C_4^1	C_2	**D**	**C**
C_2	C_2	**D**	E	**B**
C_4^3	C_4^3	**C**	**B**	**A**

(6 marks)

iii) Use the equation given below to identify and show which irreducible representations of the C_{4v} point group relate to modes that are IR active or inactive.

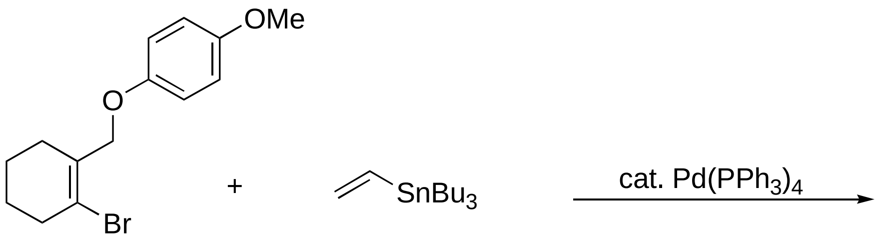
$$A_1 \in \left\{ \Gamma^{\langle f_i |} \otimes \Gamma^{| f_j \rangle} \otimes \Gamma^{m} \right\}$$

(6 marks)

3.O1 – Organometallic Complexes in Organic Synthesis

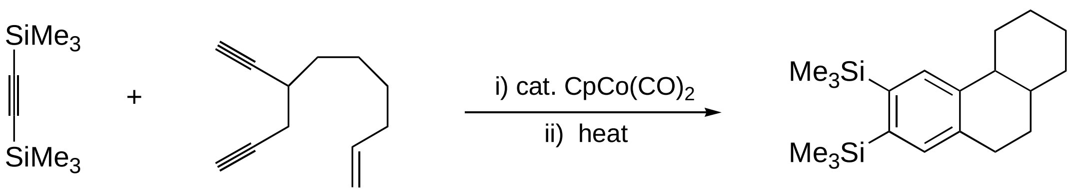
Answer any **FIVE** of the six parts a)-f) of this question.

a) Write down the product of the reaction shown below.



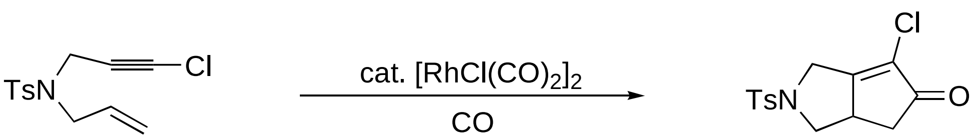
(5 marks)

b) Explain what is happening in the following transformation.



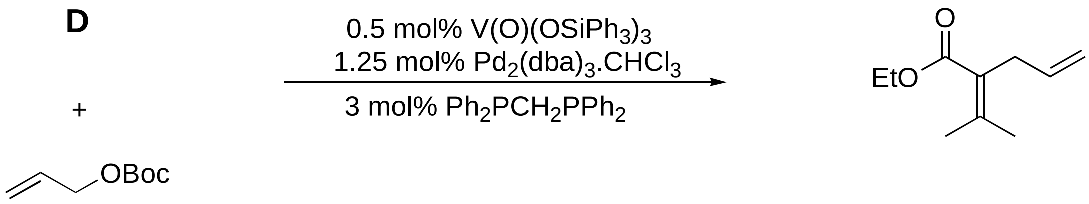
(5 marks)

c) Draw a catalytic cycle to explain the following reaction.



(5 marks)

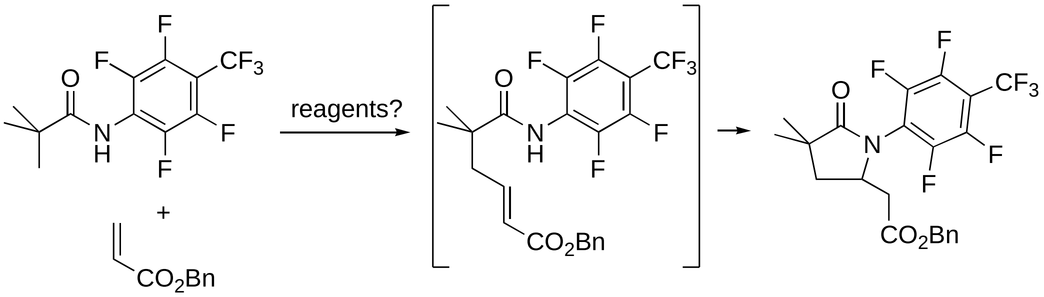
d) Write down the structure of the missing substrate **D**. The ratio of [Pd]:[V] is high (5:1). Suggest a by-product that might be generated if this ratio is lowered. [Boc = C(O)OBu^t; dba = dibenzylideneacetone]



(5 marks)

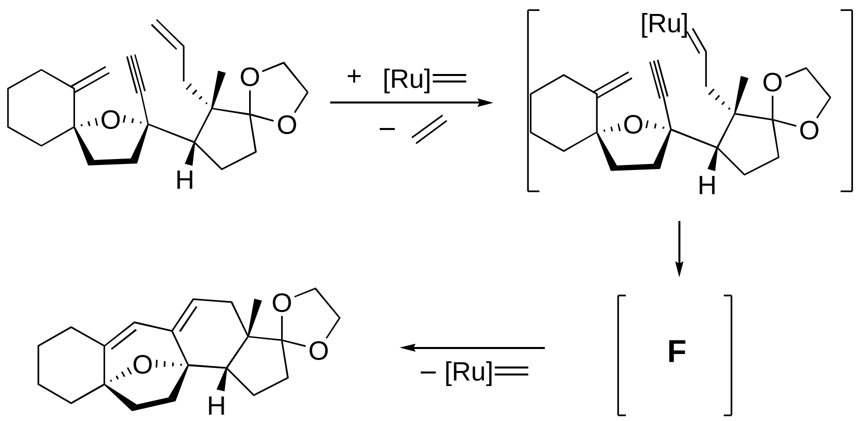
QUESTION CONTINUED OVERLEAF

e) Suggest reagents for the following reaction.



(5 marks)

f) The sequence below depicts an ene-yne-ene metathesis sequence catalysed by a ruthenium carbene represented by [Ru]=. Write down the structure of intermediate **F**.



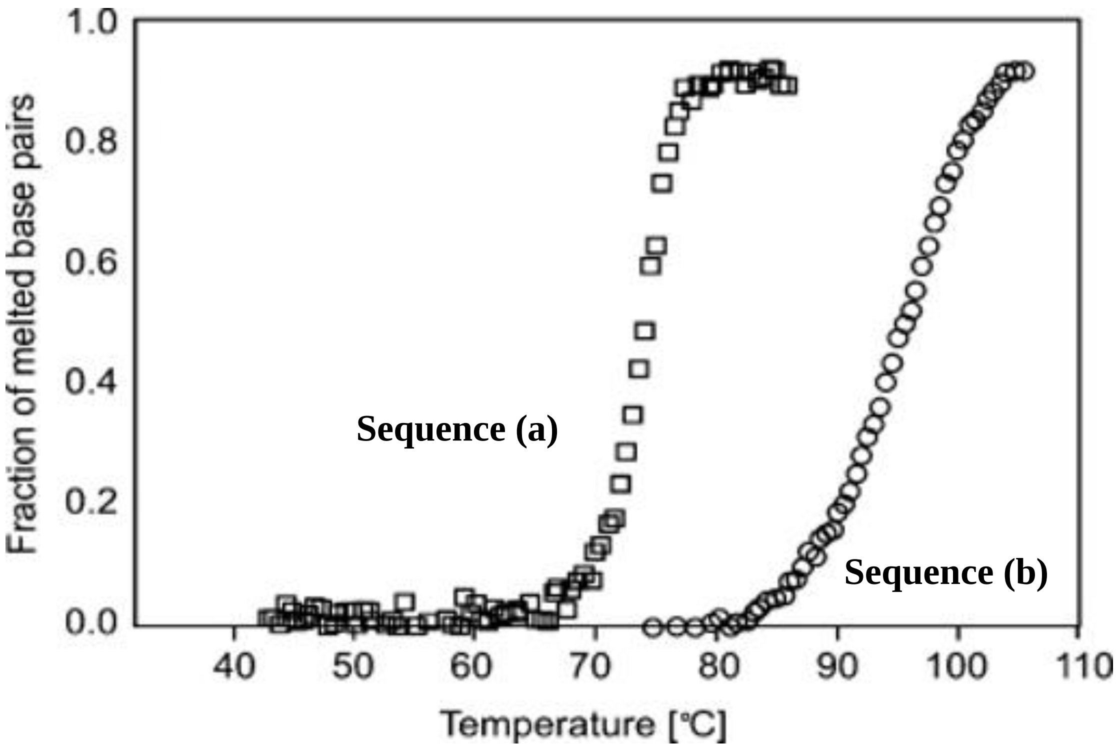
(5 marks)

3.O2 – Biological Chemistry

Answer **EITHER** part a) **OR** part b) of this question.

a) Answer **ALL** parts of this question.

The diagram below shows a thermal denaturation ('melting') curves for two different sequences of double stranded B-DNA:



On the basis of the data shown answer the following questions in each case giving an explanation for your answer:

i) Which sequence has the higher GC content?

(5 marks)

ii) What would happen to the melting curve of (a) if a molecule that bound into the major groove was added?

(5 marks)

iii) What would happen to the melting curve of (b) if a mismatched base was introduced into the middle of the sequence?

(5 marks)

QUESTION CONTINUED OVERLEAF

iv) What would happen to the melting curves if the experiment were repeated at higher ionic strength?

(5 marks)

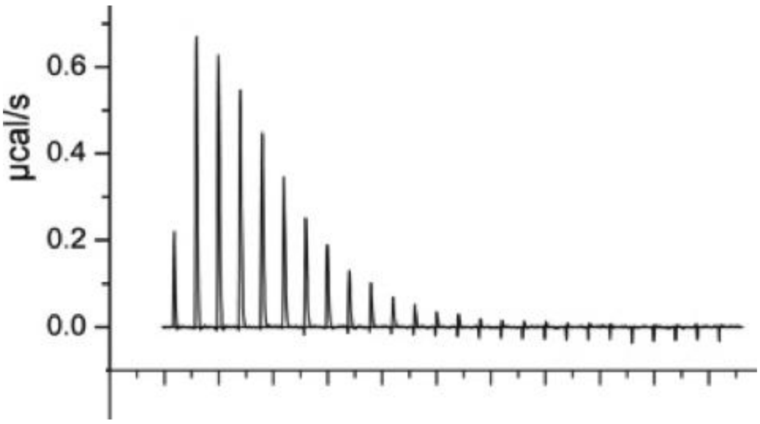
v) Describe **ONE** method by which you could measure the fraction of melted base pairs.

(5 marks)

b) Answer **ALL** parts of this question.

You are investigating functional properties of a small, glycan binding protein for which you have the amino acid sequence but no three dimensional structure. As part of your investigations you obtain the following data:

Addition of the glycan results in an increase in the intensity of the protein's fluorescence (excitation wavelength 280nm, emission wavelength 345nm) by 15%. There is also a shift of 0.12ppm and a broadening of peaks in the aromatic region of the ^{1}H NMR spectrum. Isothermal titration calorimetry gives the following thermogram when the glycan is injected into a solution of the protein:



Injection Number

Analysis of the thermogram gives the following results: Stoichiometry 1 glycan/protein, Dissociation Constant 3×10^{-6} M, Standard Enthalpy Change +34 kJ mol^{-1}.

The protein loses its ability to bind the glycan and also shows a decrease in fluorescence intensity (excitation wavelength 280nm, emission wavelength 345nm) by 80% when cooled below 10^0C.

Based on these data answer the following questions:

i) Interpret the spectroscopic changes upon glycan binding in terms of the possible nature of the binding site.

(5 marks)

QUESTION CONTINUED OVERLEAF

ii) Account for the shape of the thermogram.

(5 marks)

iii) Calculate the free energy and entropy changes upon glycan binding (Assume the experiment is carried out at 25 ^{o}C). Comment on your results in the light of your answer to part i).

(5 marks)

iv) Interpret the observations on the effect of temperature on the protein in terms of the intramolecular forces that maintain the protein's native structure.

(5 marks)

v) Describe **ONE** other experimental technique that you could use to characterise the effects of low temperature on the protein.

(5 marks)

3.O5 – Reactive Intermediates

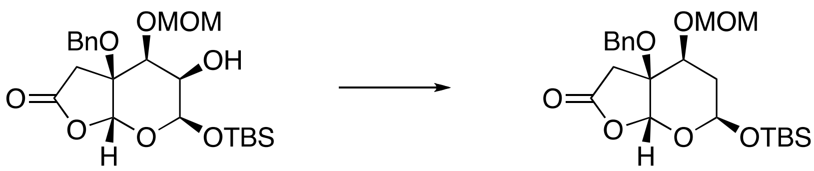
Answer **ALL** parts of this question

a) Describe the requirements for a successful intermolecular carbon-carbon bond forming radical chain reaction between an alkyl halide and an alkene as mediated by tributyltin hydride. By consideration of the nature of the alkene and any propagating radical species show how these conditions can be satisfied.

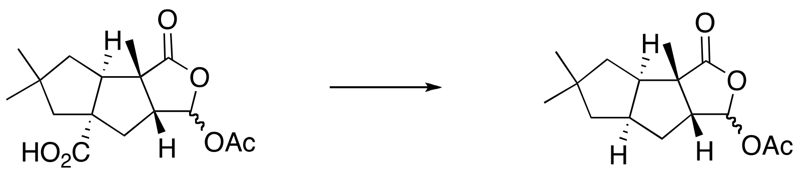
(5 marks)

b) Suggest a radical-based method for carrying out **ONE** of the following transformations, giving reagents and mechanisms. More than one step may be required.

(i)

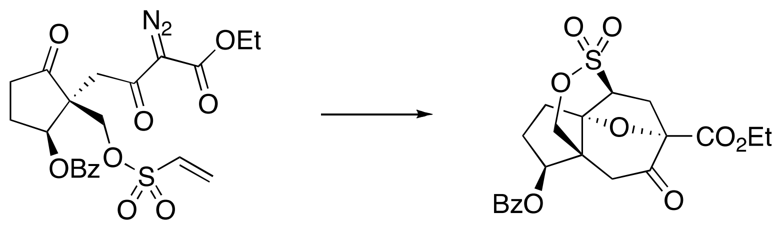


(ii)



(8 marks)

c) Provide possible reagents/conditions for the following transformation and provide a detailed, annotated mechanism commenting on all aspects of selectivity.



(12 marks)

3.P1 – Modern Analytical Instrumental Techniques

Useful equations that might be needed to answer questions a), b) and c)

nλ = d(sinα + sinβ)	$\tau_f = \frac{1}{k_r + k_{nr}}$	$\tau_q = \frac{1}{k_F + k_q[Q] + k_{NR}}$	$\phi_f = \frac{k_r}{k_r + k_{nr}}$
$A = -\log T = \log \frac{P_0}{P} =$	$E = \frac{k_{FRET}}{k_r + k_{nr} + k_{FRET}}$	$\left(\frac{S}{N}\right)_n = \sqrt{n}\left(\frac{S_i}{N_i}\right)$	$A = \frac{d\beta}{d\lambda} = \frac{n}{d\cos(\beta)}$
$F = k\phi_f P_0 2.303\varepsilon bc$	$\frac{n_{upper}}{n_{lower}} = \exp\left(-\Delta E / kT\right)$	$S = kP + k_d$	$r = \frac{\lambda f}{n\pi R}$
$E = \frac{1}{1 + (\frac{r}{R_0})^6}$	$NA = n\sin\theta \cong \frac{L}{2f}$	$\sigma = \sqrt{\lim_{N\to\infty} \frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}$	

Answer part a) and **EITHER** part b) **OR** part c) of this question.

a) Answer **ALL** parts of this question.

i) Write down equations for:

1. Fluorescence lifetime,
2. Natural lifetime,
3. Quantum yield

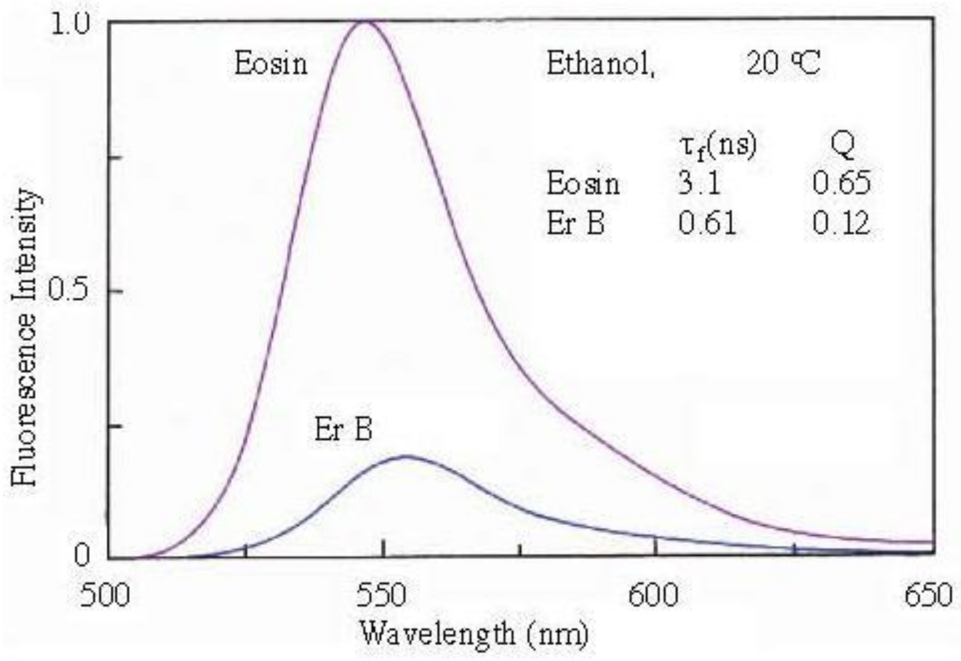
All equations should be expressed as a function of radiative and non-radiative rates.

(2 marks)

ii) Using the figure shown overleaf, calculate the natural lifetime, radiative and non-radiative decay rates for Eosin and Er B. What rate accounts for the lower quantum yield of Er B?

(5 marks)

QUESTION CONTINUED OVERLEAF



iii) Using the equation for fluorescence quantum yield as background information, define a similar expression for phosphorescence quantum yield. Explain all terms present.

(1 mark)

iv) Phosphorescent lifetimes are typically near 1-10 ms. Assume that the natural lifetime for phosphorescence emission of Eosin and Er B is 10 ms, and that the non-radiative decay rates are the same for the triplet state as for the singlet state. Estimate the phosphorescence quantum yield of Eosin and Er B.

(2 marks)

v) For a FRET based system consisting of a single donor and acceptor, plot the dependence of the energy transfer efficiency on the distance (r) between the donor and acceptor.

(3 marks)

vi) Give 3 examples of what makes a good FRET pair. Use diagrams to explain your answers.

(5 marks)

QUESTION CONTINUED OVERLEAF

b) Answer **BOTH** parts of this question.

i) An absorption spectrometer contains a malfunctioning wavelength selector. The output was found to be producing two wavelengths with power P_0' and P_0''. The following equation can be used to correct for this artefact:

$$A_{total} = \log\left(\frac{P_0' + P_0''}{P_0' 10^{-\varepsilon' bc} + P_0'' 10^{-\varepsilon'' bc}}\right)$$

Using a diagram qualitatively plot the absorbance as a function of concentration for:

1) ε' = 1000 and ε'' = 1000
2) ε' = 1500 and ε'' = 500

(Hint: assume $P_0' = P_0''$, b = 0.1, and use a concentration range between 0 and 0.01).

(5 marks)

ii) Assume a fluorescence spectrometer is used in i) rather than an absorption spectrometer. The total fluorescence intensity can be defined by the following:

$$F_{total} = 2.303k\phi_f bc(P_0'\varepsilon' + P_0''\varepsilon'')$$

Describe the differences that you would expect to find when plotting F as a function of concentration as opposed to absorbance as a function of concentration?

(2 marks)

c) Answer **ALL** parts of this question.

i) Using a diagram describe the useful range of an analytical method including the limit of detection, dynamic range, and limit of linearity. Make sure to label all parts of the diagram.

(3 marks)

ii) How does the sensitivity affect the instrument response in i)?

(1 mark)

QUESTION CONTINUED OVERLEAF

iii) The following data were obtained for repetitive weighings of 1.004 g standard weight on a top loading balance.

1. 1.003	2. 1.000	3. 1.001
4. 1.004	5. 1.005	6. 1.006
7. 1.001	8. 0.999	9. 1.007

mean: 1.003 g   Std Dev: 0.0028

1) Calculate the signal to noise ratio.
2) How many measurements would have to be averaged to obtain a signal to noise ratio of 500?

(3 marks)

3.P6 – Molecular Electronic Materials

Answer part a) and **EITHER** part b) **OR** part c) of this question.

a) Answer **ALL** parts of this question.

Figure 1 shows a schematic diagram of a bilayer solar cell that has been fabricated using a combination of two organic semiconductors (A) and (B). The LUMO and HOMO energies of organic semiconductor (A) are 2.8 eV and 5.1 eV respectively. The LUMO and HOMO energies of organic semiconductor (B) are 3.8 eV and 6.8 eV respectively. The work functions of the aluminium (Al) and indium tin oxide (ITO) electrodes are 4.0 eV and 4.7 eV respectively.

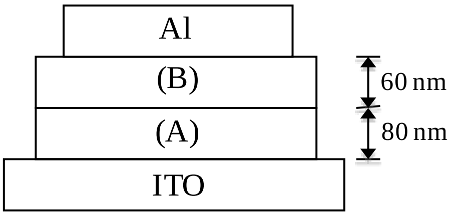


Figure 1

i) Draw an energy band diagram for the device at short circuit in the dark.

(2 marks)

ii) Draw an energy band diagram for the device at the open circuit point under intense illumination.

(2 marks)

iii) When the device is assembled in the dark and the organic semiconductor layers are sandwiched between the aluminium and ITO electrodes (as in Figure 1), electrons flow from the low work-function electrode to the high work-function electrode. Calculate the number of electrons transferred in this process. Assume a device area of $1 cm^2$ and a dielectric constant of the polymer of 2.8. Comment on your answer and state any assumption(s) in your calculation.

(5 marks)

iv) What are the limitations of the solar cell device in Figure 1? How might these limitations be addressed? Explain your reasoning.

(6 marks)

QUESTION CONTINUED OVERLEAF

b) Answer **BOTH** parts of this question.

i) Explain why, in principle, the quantum yield (QE) of a solar cell may be equal to 100% but the energy efficiency (P_{out}/P_{in}) operating under full solar illumination will always be less than 100%.

(5 marks)

ii) An organic solar device is illuminated by monochromatic light of 580 nm wavelength with an intensity of 1.8 mW/cm^2. Estimate the maximum photocurrent the solar cell can deliver under these conditions. If the device achieved an open circuit voltage of 0.8 V and a fill factor of 0.6 under these illumination conditions, calculate the power conversion efficiency.

(5 marks)

c) Answer **BOTH** parts of this question.

i) Describe how the time-of-flight (ToF) technique can be used to determine the charge carrier mobility in organic semiconductor films.

(5 marks)

ii) State the relationship between the exciton diffusion length (L), the exciton lifetime (τ) and the diffusion coefficient (D). Hence obtain an estimate of D if the exciton lifetime is 500 ps and the exciton diffusion length is 7 nm.

(5 marks)