ENGINEERING TRIPOS PART IB

Friday 6 June 2003 2 to 4.30
2 to 3.30 Foreign Language Option

Paper 8

SELECTED TOPICS

Answer **one** *question from Section A. In addition:*

If you are not taking the Foreign Language option, answer **four** *questions, taken from only* **two** *of Sections B–G. Not more than two questions from each section may be answered.*
If you are taking the Foreign Language option, answer **two** *questions from* **one** *of Sections B–G.*

All questions carry the same number of marks.

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

Answers to questions in each section should be tied together and handed in separately.

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

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SECTION A *Business Economics*

Answer not more than ***one*** *question from this section*

1 (a) Explain why a firm will continue production in the short run even if it is making a loss providing it can cover its variable costs. For how long will it be willing to continue to make a loss? [6]

(b) (i) For what reasons would you expect a monopoly to charge a higher price than a company operating under perfect competition? [5]

(ii) Under what conditions would you expect a monopoly to charge a lower price than a company operating under perfect competition? [3]

(c) Explain why competition between oligopolists may reduce total industry profits. [6]

2 (a) What factors may influence the level of investment in the macroeconomy? [10]

(b) What factors may influence the level of consumption in the macroeconomy? [10]

SECTION B *Civil and Structural Engineering*

*Answer not more than **two** questions from this section*

3 A metro scheme is being considered for a major city, in which there are many fragile masonry buildings. Three types of ground condition exist at the level of the proposed tunnels: in one area of the city the ground is a stiff clay with an average undrained shear strength of $150\ \text{kN/m}^2$, in the second the ground is soft clay with an average undrained shear strength of $30\ \text{kN/m}^2$, and in the third area the ground is sands and gravels below the water table. You are asked to provide advice to the client on the following questions:

(a) Describe what is meant by the New Austrian Tunnelling Method (NATM), and in which of the ground conditions it is most appropriate. What are the potential risks with this method? [3]

(b) Define the stability ratio used to assess the stability of a tunnel. Assuming the unit weights of the stiff clay and soft clay to be $20\ \text{kN/m}^3$ and $17\ \text{kN/m}^3$ respectively, estimate the stability ratio for tunnels at depths of 15 m in both types of clay, assuming zero support is provided to the tunnel face during excavation. What is the significance of your answers? [4]

(c) Give two examples of techniques for controlling groundwater when tunnelling in the sands and gravels, describing the principles of how they are effective. [3]

(d) Why does settlement potentially cause damage to masonry buildings? Give two examples of protective measures that might be implemented, and comment on their applicability for the three different ground conditions. [4]

(e) Give three reasons why instrumentation and monitoring are important for this metro scheme. Give three examples of instrumentation that might be installed. [6]

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4 A 10 m deep excavation is to be temporarily supported by a smooth retaining wall, as shown in Figure 1. The wall is anchored at a depth of 2 m below the ground surface. The wall retains a loose, silty sand and penetrates a distance of 4 m into a stiff clay. The water table is at the top of the clay. A surcharge of 30 kN/m^2 is applied at the ground surface.

The unit weight of the sand is 18 kN/m^3 and its critical state angle of friction is 30°. The unit weight of the clay is 20 kN/m^3, its critical state angle of friction is 25°, and its undrained shear strength is 75 kN/m^2.

(a) Assume that the excavation is undertaken very quickly, and that the wall moves sufficiently for active pressures to be mobilized behind it and passive pressures in front of it.

(i) Calculate the pressures acting on the wall, and sketch the pressure distribution. [8]

(ii) Calculate the anchor force required to maintain equilibrium, ignoring the pressure acting on the wall above the anchor. [4]

(b) The excavation, together with the applied surcharge, is accidentally left for a long time, so that the water pressures in the clay return to their original value before the excavation was undertaken.

(i) Calculate the new pressures acting on the wall, and show the change in pressure distribution on your sketch for part (a) (i). [4]

(ii) Calculate the new anchor force required to maintain equilibrium, again ignoring the pressure on the wall above the anchor. [4]

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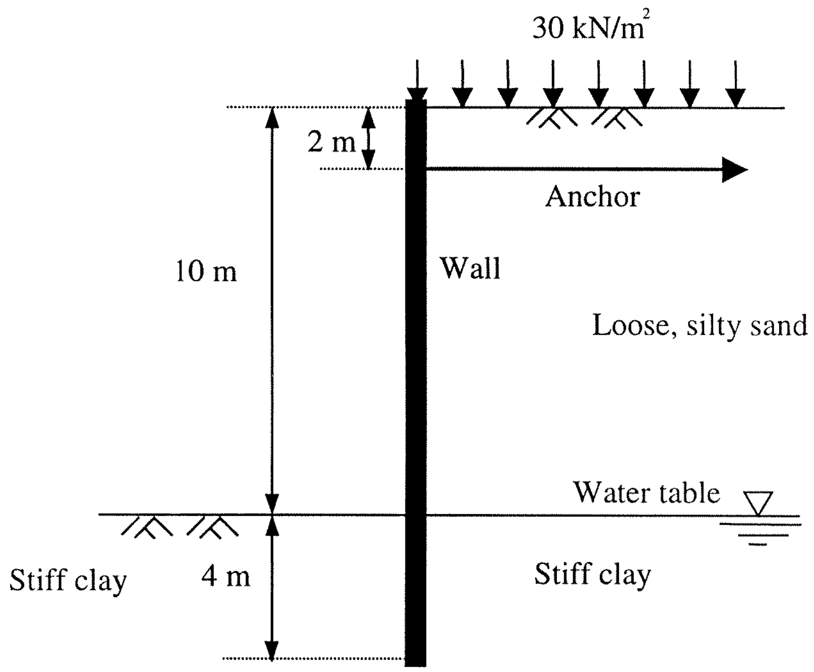

Fig. 1

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5 You have been asked to design a reinforced concrete retaining wall to resist the loads from a 2.4 m high earth embankment. Two design options are being considered, as shown in Fig. 2(a) and 2(b). In the first option the wall has uniform thickness, t , and in the second it is uniformly tapered with thickness $2t$ at the bottom and $t/2$ at the top. The reinforcing steel has a yield strength of $f_y = 460\,\mathrm{N/mm^2}$ and the concrete strength is $f_{cu} = 40\,\mathrm{N/mm^2}$. The lateral loading on the wall has the profile shown in Fig. 2(c). Partial factors on loading are already included in the derivation of this profile.

(a) Determine the maximum bending moment and shear force for use in designing the wall. [4]

(b) For Design Option 1 determine a suitable wall thickness, t , and the required primary flexural reinforcement at the critical section. Suggest an appropriate layout for this reinforcement. [5]

(c) Use the value of t , calculated in part (b) above, to define the wall thicknesses of Design Option 2. Determine the required amount of primary flexural steel reinforcement at the critical section for this alternative wall design, and suggest an appropriate layout for this reinforcement. [5]

(d) Assume the design choice will be based on cost alone and that the only difference between the two design options is the quantity of primary flexural reinforcement and concrete used in the wall. The cost of concrete is £200 per cubic metre and of steel £1200 per tonne. Which of the two designs would be most economical? [4]

(e) Check the shear capacity at the critical section of your preferred design option and, if required, suggest (without calculation) what options you might consider to remedy any inadequacy. [2]

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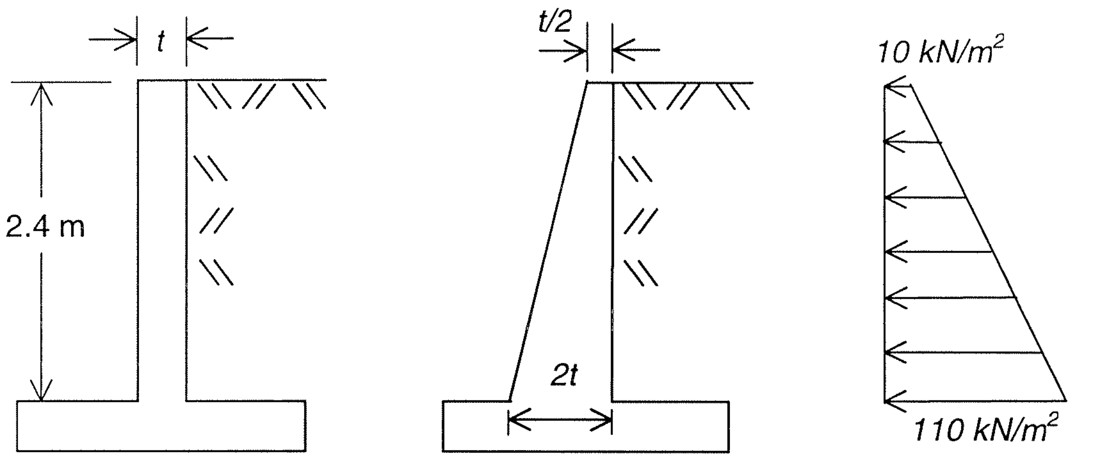

(a) Option 1 (b) Option 2 (c) Loading Profile

Fig. 2

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SECTION C *Mechanical Engineering, Manufacture and Management*

Answer not more than **two** *questions from this section*

6 A new type of 2D lattice material has the microstructure sketched in Fig. 3. Each strut has a length l and thickness t, and the lattice material has unit thickness into the page. The lattice material is made from an elastic-ideally plastic solid of Young's modulus E_S and yield strength σ_{YS} .

(a) Sketch a unit cell for the periodic structure. [4]

(b) Show that the relative density $\bar{\rho}$ of the lattice material is given by

$$\bar{\rho} = \frac{2t}{l}$$ [4]

(c) Obtain an expression for the Young's modulus E_1 and the yield strength σ_{Y1} of the lattice material for uniaxial loading along the x_1-direction, in terms of $\bar{\rho}$ and the solid material properties. [6]

(d) Calculate the yield strength σ_{Y2} of the lattice material for uniaxial loading along the x_2-direction, in terms of $\bar{\rho}$ and the solid material properties. [6]

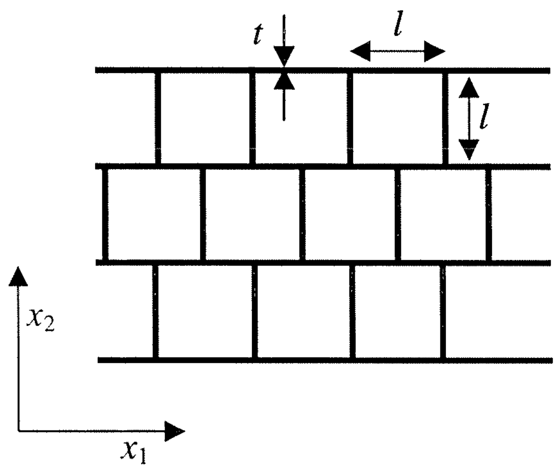

Fig. 3

7 It has been suggested that monolithic steel hull construction for a 10 m long patrol boat be replaced by sandwich construction, with aluminium alloy face sheets, and a foam core made from the same aluminium alloy.

(a) Describe the potential modes of failure at the joints between internal bulkheads and the sandwich hull. [6]

(b) How are the failure modes in (a) affected by delamination between the sandwich face sheets and core? [4]

(c) Suggest three design constraints for minimum weight design, and outline the procedure to arrive at the optimal design. [5]

(d) Explain the advantages of sandwich construction in resisting low velocity collisions with a submerged rock. [5]

8 Explain the following phenomena, with examples where appropriate.

(a) Cast aluminium alloy foams have a lower strength but higher ductility than forged lattice materials of the same density. [4]

(b) The cheapest production route for lattice materials is dependent upon batch size. [4]

(c) The pressure for plastic indentation of foams is comparable to the uniaxial yield strength of the foam, while for a fully dense metal the hardness is three times the yield strength. [4]

(d) The blast resistance of metallic foam is enhanced by adding a heavy buffer plate. [4]

(e) The hydrostatic strength of a metallic foam is dictated by the presence of imperfections, while the uniaxial strength is relatively insensitive to the presence of imperfections. [4]

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SECTION D *Aerothermal Engineering*

Answer not more than **two** *questions from this section*

9 (a) An aircraft cruises at Mach 0.8, at an altitude where the pressure and temperature are 29 kPa and 226 K, respectively. Each of the turbofan engines has a core mass flow rate of 60 $\mathrm{kgs^{-1}}$, and a bypass ratio of 5. The jet velocity, V_j, is 350 $\mathrm{ms^{-1}}$ for both the core and bypass streams. Determine the flight velocity and calculate the stagnation pressure, P_{02}, and stagnation temperature, T_{02}, at the engine inlet, assuming no loss in the inlet ducting. Calculate also the gross thrust and the net thrust from each engine. You may assume that at this flight condition the convergent propelling nozzles are just choked. [5]

(b) When the propelling nozzles are choked, the *total* mass flow rate of air through each engine, $\dot{m}_a$, may be expressed as:

$$\dot{m}_a = \mathrm{f}\left(\dot{m}_f, P_{02}, T_{02}, c_p, LCV, A\right),$$

where $\dot{m}_f$ is the mass flow rate of fuel, c_p is the isobaric specific heat capacity of air, LCV is the lower calorific value of the fuel, and A is a characteristic cross-sectional area of the engine. Form two non-dimensional groups from these variables, one involving $\dot{m}_a$ and the other involving $\dot{m}_f$. Explain why the groups have a different form. [5]

(c) At the end of cruise, the aircraft moves to a higher altitude where the pressure and temperature are 18 kPa and 216 K respectively. The flight Mach number increases to 0.9. Assume that the non-dimensional operating point of the engine is unchanged. Explain why, at this new flight condition, the pressure at the nozzle exit plane is not atmospheric. Calculate the new *total* mass flow rate of air through each engine. If the sum of the bypass and core nozzle exit areas is 3.0 $\mathrm{m^2}$ for each engine, determine the net thrust at the new cruise conditions. [10]

Take $\gamma = 1.4$ and $R = 287\ \mathrm{Jkg^{-1}K^{-1}}$ for air. Neglect the mass flow of fuel.

10 (a) Why do aircraft jet engines have more compressor stages than turbine stages? Explain briefly the consequences of having:

(i) too few turbine stages;

(ii) too few compressor stages. [4]

(b) A compressor is to be designed with a constant axial velocity, V_x , and constant blade mean radius. The Euler Work Equation states that $h_0 - UV_\theta = \text{const.}$, where h_0 is the stagnation enthalpy, U is the mean blade velocity and V_θ is the tangential velocity. Show that the stage work coefficient is given by

$$\psi = \frac{\Delta h_0}{U^2} = \phi(\tan\alpha_2 - \tan\alpha_1)$$

where Δh_0 is the stage stagnation enthalpy rise, $\phi = V_x/U$ is the flow coefficient, and α_1 and α_2 are the rotor inlet and exit flow angles respectively in an absolute frame of reference. [4]

(c) The compressor has a stagnation pressure ratio of 25 and an isentropic efficiency of 88%. The mean radius of the blades is 0.5 m, and the rotor speed is 5730 rpm. Assuming the work per stage is constant throughout the compressor, determine the minimum number of stages if ψ is not to exceed 0.4 when the inlet stagnation temperature is 288 K. What is the value of ψ for this number of stages? [5]

(d) The stages are to have zero swirl at inlet, and $\phi = 0.5$ throughout. Determine the absolute flow angle at inlet to the stators and the relative flow angles at inlet and exit from the rotors. Sketch the velocity triangles and blades for a typical stage. [7]

Take $\gamma = 1.4$ and $c_p = 1010 \text{ Jkg}^{-1}\text{K}^{-1}$ for air.

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11 (a) Explain briefly the terms *propulsive efficiency, thermal efficiency* and *overall efficiency*. How are they related? Show that the overall efficiency is given by

$$\eta_0 = \frac{1}{SFC}\frac{V}{LCV}$$

where SFC is the (thrust) specific fuel consumption, V is the flight velocity, and LCV is the lower calorific value of the fuel. [5]

(b) Why do civil aircraft often fly at higher altitudes at the end of cruise than at the beginning? An aircraft weighing 600 tonnes at the beginning of cruise is to fly at Mach 0.86 at an altitude of 31,000 feet. Using the information in Table 1 and Fig. 4 below, estimate the wing area required for these cruise conditions. [5]

(c) 200 tonnes of fuel are used during the cruise period. Determine the ideal altitude at the end of cruise, assuming the Mach number remains constant at 0.86 . [5]

(d) Estimate the distance travelled during cruise if the overall efficiency remains constant at 35%, and the fuel has a calorific value of 43 MJ/kg. You may use without proof the Breguet Equation for the range

$$s = \frac{V(L/D)}{g\,SFC}\times\ln\left(\frac{W_1}{W_2}\right)$$

where L/D is the lift to drag ratio, and W_1 and W_2 are the weights at the beginning and end of cruise respectively. [5]

Take $\gamma = 1.4$.

Altitude (feet)	Temperature (K)	Pressure (kPa)	Density (kg/m^3)
31,000	226.73	28.7	0.442
33,000	222.82	26.0	0.336
35,000	218.81	23.8	0.380
37,000	216.65	21.4	0.285
39,000	216.65	19.7	0.316
41,000	216.65	17.9	0.287

Table 1 ICAO Standard Atmosphere

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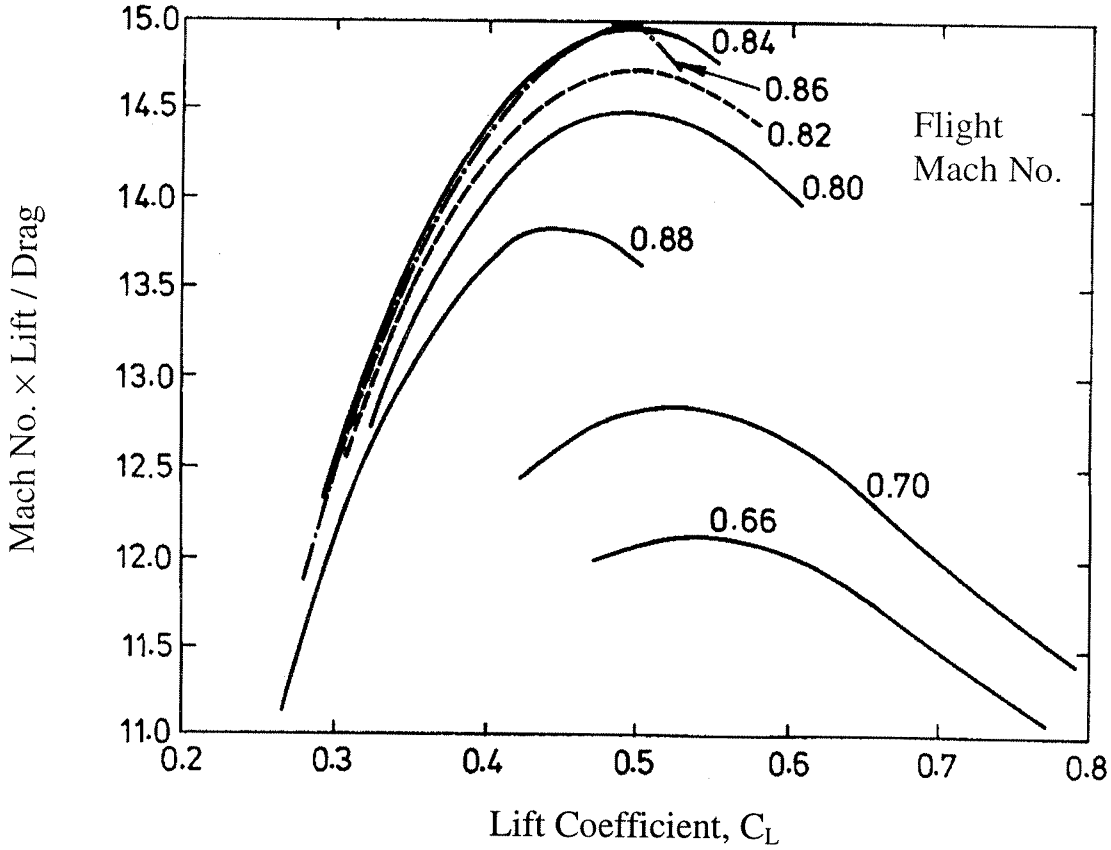

Fig. 4

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SECTION E *Electrical Engineering*

*Answer not more than **two** questions from this section*

12 A silicon MOSFET has a channel length L in the direction of current flow and a width W. The channel region below the gate insulator has been uniformly n-doped to a depth D with a doping density N_D so that the device is ON when the gate-source voltage $V_{GS} = 0$ V . Silicon has a relative permittivity of 11.8 and the electron drift velocity at high fields is shown in Fig. 5.

(a) Write down the equation relating the carrier transit time, τ , of the FET to the carrier mobility, μ , channel length, L , and the drain field, E_d . Under what conditions is this equation valid? [2]

(b) Starting from Gauss's Law of Electrostatics, show that the gate threshold voltage, V_T, required to turn the device OFF is given by

$$V_T = \frac{eN_D D^2}{2\varepsilon_0 \varepsilon_r}$$

where e is the electronic charge, and ε_r is the relative permittivity of silicon. What is the maximum electric field due to application of this threshold voltage in the channel? [6]

(c) In 1970, a MOSFET of this type had a channel length of $10\,\mu\text{m}$, a gate threshold voltage of 1 V , a drain source voltage of 0.5 V and a doping density in the channel of $10^{20}\,\text{m}^{-3}$. Calculate the thickness of the doped channel layer and the carrier transit time. [5]

(d) Faster transistors are designed by reducing all dimensions by a scaling factor, R . Devices fabricated in 2000 have a scaling factor of $R = 100$ compared with devices fabricated in 1970. What is the new channel dopant concentration if the electric fields are the same as for the 1970 device? [2]

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(e) What is the minimum carrier transit time of the 2000 device and the minimum drain source voltage required to achieve this? [2]

(f) What are the limits to further improvements in device performance? [3]

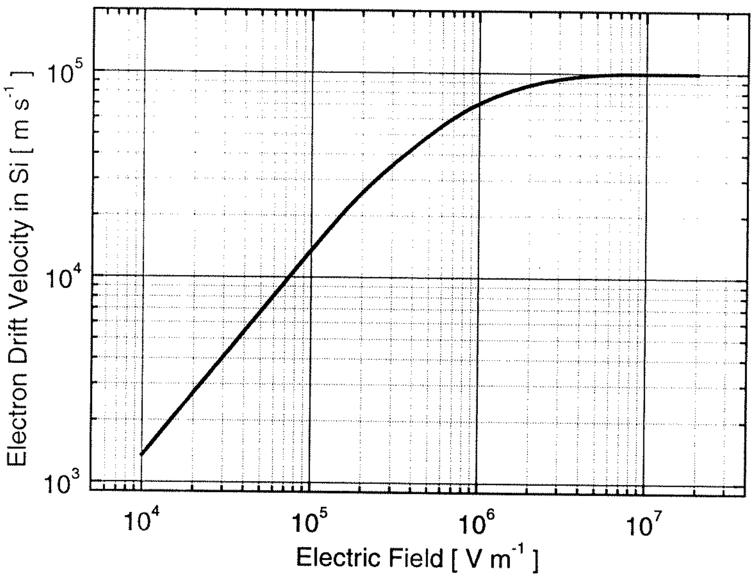

Fig. 5

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13 (a) Differentiate between positive and negative photoresist, and with the aid of sketches show how the "lift-off" technique can be used to deposit a thin metal dot on a silicon substrate. [7]

(b) Describe two methods of growing silicon dioxide and discuss the potential problems of using this material as the gate insulator in MOSTs, as device dimensions continue to shrink. [6]

(c) The manufacture of a high frequency MOST requires the diffusion of an n-type dopant (phosphorus) into the source and drain to form a contact layer, with the intervening channel region protected by a SiO_2 masking layer.

(i) With the aid of Figs. 6, 7 and 8, estimate the thickness of the source and drain contact layer formed if the diffusion process is performed at 1100 °C for 30 minutes. The dopant density in the p-type silicon substrate is 4×10^{22} atoms m^{-3}. [4]

(ii) Given that the diffusion coefficient for phosphorus in SiO_2 at 1100 °C is 1×10^{-19} m^2 s^{-1}, estimate the phosphorus concentration immediately beneath the SiO_2 if this layer is 100 nm thick. Is the phosphorus concentration sufficiently low for the device to operate? [3]

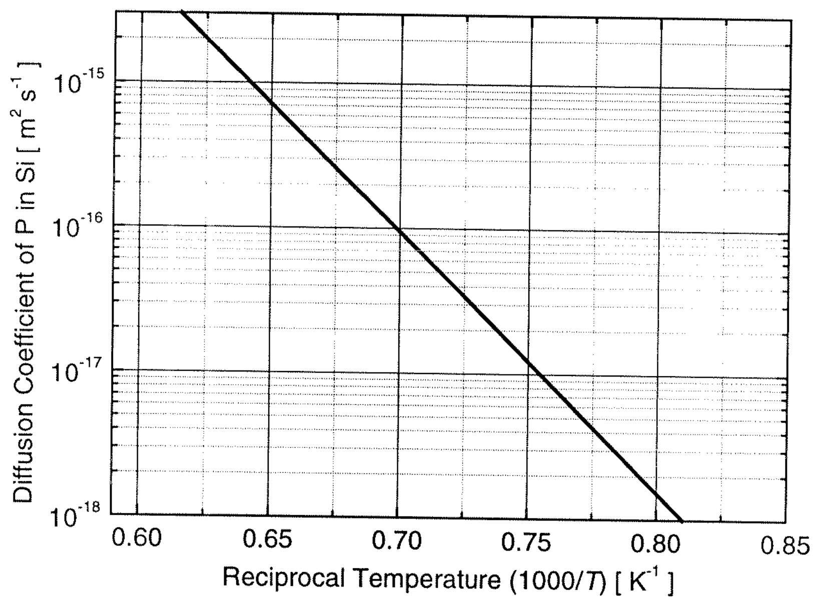

Fig. 6

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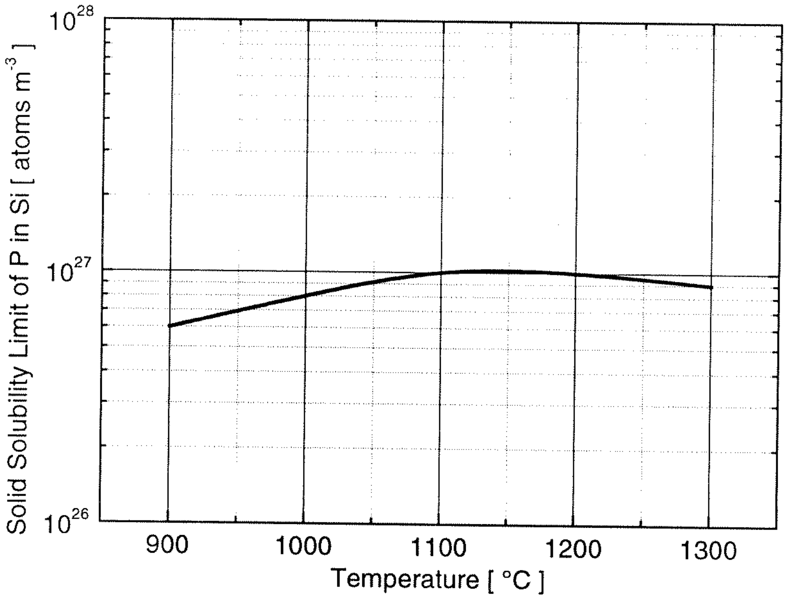

Fig. 7

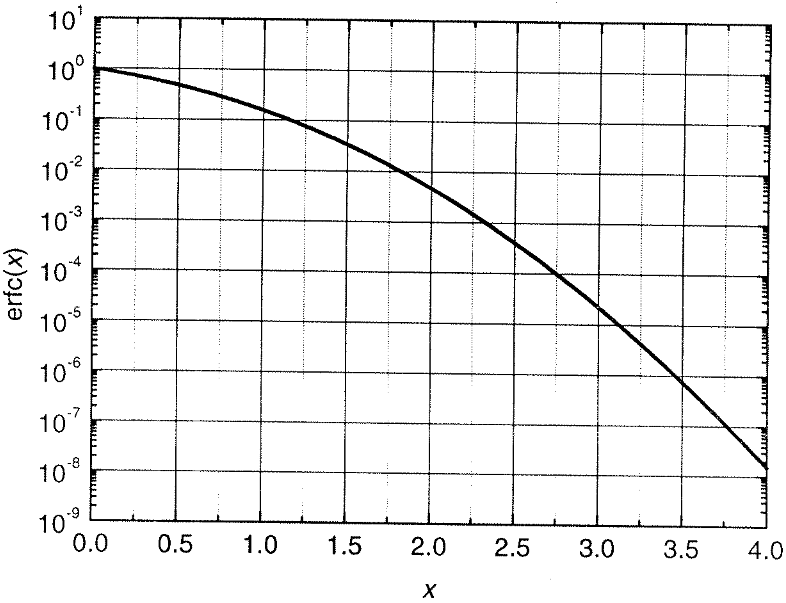

Fig. 8

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14 (a) What is the experimental evidence that electrons can behave as waves? [4]

(b) Derive an expression for the wavelength, λ, of an electron in terms of its kinetic energy, E, and its effective mass, m^*. [3]

(c) The limiting expression for the tunnelling current density, J, through an insulating barrier of thickness d and height V is of the form,

$$J = J_0 \exp(-2kd)$$

where J_0 is a constant and k is the modulus of the wavenumber. Express this equation in terms of E and m^* of the electron and V and d of the barrier. [4]

(d) It is desired to replace the SiO_2 gate insulator in a MOSFET with a new oxide of larger relative permittivity than SiO_2. The SiO_2 insulator layer has a thickness d_1 and a relative permittivity ε_{r1}. What is the thickness d_2 of the new oxide if its relative permittivity is ε_{r2} and the capacitance per unit area of the device is unchanged? [4]

(e) The new oxide will have a different value of V and m^* compared with SiO_2. Qualitatively compare the magnitude of the tunnelling current through the gate oxide layer in the devices incorporating SiO_2 and the new oxide from part (d). What is the figure of merit for comparing different oxides in terms of the leakage current through the gate insulator? [5]

SECTION F *Information Technology*

Answer not more than **two** *questions from this section*

15 You are required to design a low power network suitable for mobile computers and other devices. The system will be used to provide location information as well as communication facilities.

(a) Outline the main characteristics of the Active Badge Infra-red network in terms of the following:

(i) physical layer protocol;
(ii) data link layer protocol;
(iii) capability of generating location information. [8]

(b) Outline the main characteristics of the Bluetooth radio network in terms of the following:

(i) physical layer protocol;
(ii) data link layer protocol;
(iii) capability of generating location information. [8]

(c) Comment on a hybrid system, which has sufficient performance for transmission of audio data, yet can accurately locate objects which are physically close together but are situated in different rooms. [4]

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16 (a) For a virtual memory system:

(i) briefly describe the structure and function of a virtual memory system; [2]

(ii) explain the terms *page*, *page table*, *page fault* and indicate the criteria for choosing a page size; [2]

(iii) what is the purpose and function of the Translation Lookaside Buffer? [2]

(iv) draw a diagram of a virtual memory system, naming all the fields of all the data structures involved. [2]

(b) After briefly pointing out the structural similarities between virtual memory systems and cache systems, explain the differences in greater detail. [6]

(c) Describe and compare three page replacement strategies, including the *optimal page replacement algorithm*. Describe Belady's anomaly and say which of the strategies you cite exhibit it. [6]

17 The Auto-ID tagging system can be loosely described as a radio-based bar code.

(a) Describe the general architecture of the system and the main technical challenges involved. [6]

(b) Discuss its technical advantages and disadvantages compared to the optical bar code. [4]

(c) Discuss the security risks of this technology. [4]

(d) Describe the implementation of an access control scheme under which tags can be identified by their owner but not by unauthorized readers. What resources are needed in the tag to support this mode of operation? [6]

SECTION G *Biological and Medical Engineering*

Answer not more than **two** *questions from this section*

18 (a) Draw a diagram representing the principal mechanical elements of the mammalian eye. [4]

(b) Explain why the effect of the eyeball inertia is negligible under normal conditions. Write down a first-order approximation to the transfer function linking the neural oculomotor command to ocular angular deviation. What is the approximate value (in Hz) of the characteristic frequency? [3]

(c) Sketch the time-course of a typical human saccade, and the corresponding command pattern of action potentials in a single motor fibre. [4]

(d) How are neural circuits in the brainstem believed to generate the command pattern of part (c)? Draw a block diagram that shows how the desired pattern is created from an input pulse whose width corresponds to the desired saccadic amplitude. [3]

(e) What condition has to be met to optimise the time-course of the resulting saccade, by eliminating glissades? How is the appropriate parametric adjustment achieved? [4]

(f) Why is it believed that the termination of the input pulse is determined ballistically, rather than via immediate feedback from the eye? [2]

19 Write brief notes on each of the following.

(a) The advantages of a scheme of construction in which the complete prescription for making all the parts of an organism is contained within each of its cells. [4]

(b) The way in which the family of proteins can include materials having a very wide range of mechanical properties. [4]

(c) The consequences of reversing the direction of rotation of the flagellar motors in the swimming of bacteria such as *E. coli.* [4]

(d) The different circumstances in which a flagellar filament can change from one discrete helical waveform to another. [4]

(e) How single-letter mutation in a DNA sequence can significantly alter the conformation of an assembly of identical protein molecules. [4]

20 (a) The weight, mg, of a hovering animal is supported by the downwash from wings of length R flapping through an angle Φ in the **horizontal** plane. Far below the animal, the pressure in the downwash jet returns to atmospheric, the downwash velocity w is steady, and the cross-sectional area, A, of the jet is half that at the level of the beating wings, A_0.

(i) Show that the downwash velocity, w_0, at the level of the wings is given by

$$w_0 = \left[\frac{mg}{2\rho\Phi R^2}\right]^{\frac{1}{2}}$$

where ρ is the density of air ($1.2\ \mathrm{kg\,m^{-3}}$). [4]

(ii) Show that the power P required to generate the downwash per unit weight supported is given by $P/mg = w_0$. For a 75 kg animal flapping wings with $R = 2$ m through an angle of 2 radians, what is the power? [5]

(iii) Although hovering animals range in mass by over six orders of magnitude, the proportion of body mass that is flight muscle is almost constant. The power output per unit mass of muscle is also relatively constant. Given these facts, how should wing length vary with body mass, and how does this compare with isometric scaling? [3]

(b) (i) Describe the differences in swimming modes for eels and for fish such as the trout. What are the primary characteristics of these swimming modes that affect the way these creatures propel themselves? [4]

(ii) Determine the non-dimensional parameters important to the study of swimming fish, based on the fish's swimming speed, length, tail amplitude, body wavelength, and fluid parameters. How are these important in understanding how different species of fish swim? [4]

END OF PAPER