Version HJJ/5

EGT2
ENGINEERING TRIPOS PART IIA

Monday 23 April 2018 9.30 to 11.10

Module 3B5

SEMICONDUCTOR ENGINEERING

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.*

Write your candidate number ***not*** *your name on the cover sheet.*

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed
Engineering Data Book

10 minutes reading time is allowed for this paper at the start of the exam.

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

1 A one-dimensional potential well has width L and barriers of potential V_0, as shown in Fig. 1. An electron of energy $E < V_0$ is confined by this well.

(a) Assume that the well is infinitely deep such that $V_0 \to \infty$. The time independent part of the electron wavefunction is of the form

$$\psi = A\sin(kx)$$

where A and k are constants.

(i) Determine the values of the constants A and k of the wavefunction. [20%]

(ii) Derive an expression for the energy E of the electron. [10%]

(iii) Assume the uncertainty in the electron's position is $\Delta x = L$. What is the minimum uncertainty in the electron's energy? How does this value compare with the ground state energy? [20%]

(b) Assume the depth of the potential well is *finite* and $E < V_0$.

(i) Find the solution to the time independent Schrödinger equation in the regions $x < 0$ and $x > L$ that lie outside the boundaries of this *finite* potential well. Do not determine the values of the integration constants unless they are equal to zero. Describe how this quantum mechanical behaviour in the regions $x < 0$ and $x > L$ differs from the behaviour of a particle obeying classical mechanics. [20%]

(ii) Sketch the time independent part of the electron wavefunctions for the lowest three energy levels in the *finite* potential well. [10%]

(iii) Consider a periodic array of finite potential wells, each occupied by one electron, with a distance d between adjacent wells, where $d \gg L$. Explain what happens to the electron energy levels as d is reduced towards L. [20%]

Note: The time-independent Schrödinger equation in one dimension is

$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2} + V\psi = E\psi.$$

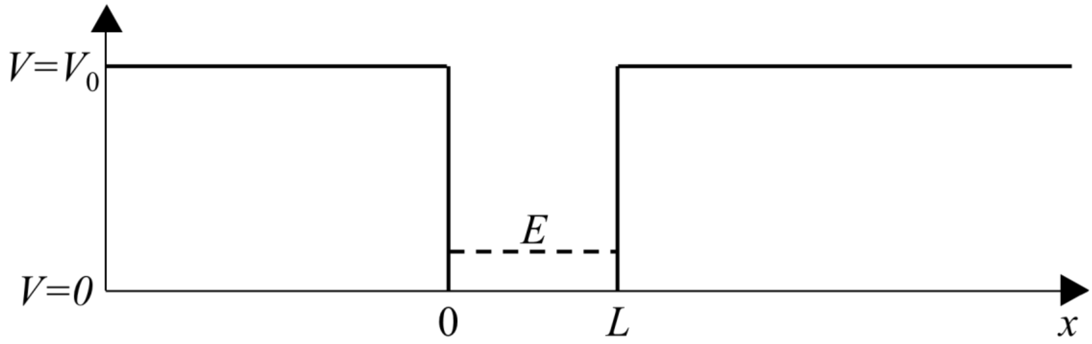

Fig. 1

2 (a) Outline the assumptions and boundary conditions used to derive Sommerfeld's *free electron model*. [10%]

(b) Explain the formation of energy gaps at the Brillouin zone boundaries in the *nearly free electron model*. [30%]

(c) Starting with the group velocity v of an electron wavepacket, given by

$$v = \frac{d\omega}{dk},$$

show that an electron in a semiconductor responds to an applied force as if it has an effective mass m^* given by

$$m^* = \hbar^2 \left(\frac{d^2E}{dk^2} \right)^{-1}.$$

[30%]

(d) A Si sample is substitutionally doped with boron atoms giving a Fermi level 150 meV above the valence band edge at room temperature. The effective density of states in the valence band is 1.8×10^{19} cm^{-3} and the intrinsic carrier density is 1.0×10^{16} cm^{-3}.

(i) Calculate the conductivity of the sample. [15%]

(ii) Plot the density of free holes as a function of inverse temperature. Label the three distinct regions in the graph. Comment on the relative size of the slope in each of the three regions. [15%]

3 (a) Define and explain what are referred to as base transport factor and emitter injection efficiency in the context of a p^+np Bipolar Junction Transistor (BJT). [10%]

(b) The n-type semiconductor used for the base region has a doping density of 10^{22} m^{-3}, an intrinsic carrier concentration of 1.8×10^{12} m^{-3}, a hole mobility μ_h of 400 cm^2 V^{-1} s^{-1} and a life time for excess holes τ_h of 10^{-6} s.

(i) Calculate the hole diffusion length L_h in the base region. State all assumptions made. [10%]

(ii) A 0.6 V forward bias is applied to the emitter–base junction. Calculate the excess hole concentration $\Delta p_n(0)$ injected into the base at the edge of the emitter depletion region. State all assumptions made. [15%]

(c) Starting from the continuity equation, show that the excess hole concentration in the base as function of distance x from the base edge of the emitter depletion region is given by

$$\Delta p_n(x) = \Delta p_n(0)\frac{\exp[(W_b - x)/L_h] - \exp[(x - W_b)/L_h]}{\exp(W_b/L_h) - \exp(-W_b/L_h)}$$

where W_b is the undepleted width of the base. Assume that the excess hole concentration at the base edge of the collector depletion region is zero, i.e. $\Delta p_n(W_b) = 0$. State any further assumptions made. [35%]

(d) Sketch $\Delta p_n(x)$ for $W_b = 2$ µm and the calculated value of L_h in (b)(i). [10%]

(e) Explain how the BJT emitter, base and collector currents can be derived from $\Delta p_n(x)$. [10%]

(f) The emitter injection efficiency of a BJT can be improved by using a heterojunction that introduces a barrier for minority carrier injection from the base into the emitter. Draw a band diagram of such a heterojunction bipolar transistor in the active mode of operation. [10%]

Note: The continuity equation for holes is

$$\frac{\partial(\Delta p)}{\partial t} = -\frac{\Delta p}{\tau_h} - \mu_h \varepsilon \frac{\partial(\Delta p)}{\partial x} + D_h \frac{\partial^2(\Delta p)}{\partial x^2}.$$

4 (a) Figure 2 shows the variation of the electric field across a Schottky barrier diode at room temperature. The doping concentration of the semiconductor is 10^{22} m^{-3}. The semiconductor has an electron affinity of 4.0 eV and its effective densities of states in the conduction and valence band both are equal to 3×10^{25} m^{-3}.

(i) Use the Poisson equation to determine if the semiconductor is n-type or p-type. [10%]

(ii) Calculate the built-in potential of the Schottky barrier diode and the work function of the metal. State all assumptions made. [25%]

(iii) Draw an equilibrium band diagram of the diode. Indicate the built-in potential in the diagram. [10%]

(b) The current flow I through the Schottky barrier diode as a function of applied bias V can be derived based on the thermionic emission theory as

$$I = I_s\left[\exp\left(\frac{eV}{\eta kT}\right) - 1\right]$$

where I_s is the reverse saturation current and η the ideality factor. Explain how and why η will change:

(i) when the doping density of the semiconductor is increased to 10^{24} m^{-3}; [10%]

(ii) when the diode is cooled with liquid nitrogen. [5%]

(c) Current flow in a biased p$^+$n diode can be derived considering minority carrier injection and extraction, resulting in a similar expression as in (b).

(i) Sketch the distribution of minority carriers either side of the depletion region for a reversed biased p$^+$n junction. [10%]

(ii) Explain and compare what transport processes dominate I_s for the p$^+$n diode and the Schottky barrier diode. [15%]

 (cont.

(iii) Explain the avalanche breakdown process for a p^+n diode which leads to a sharp increase in current once a critical reverse bias V_{br} is exceeded. Explain whether V_{br} is larger for GaAs or Ge at room temperature and for the same doping density. [15%]

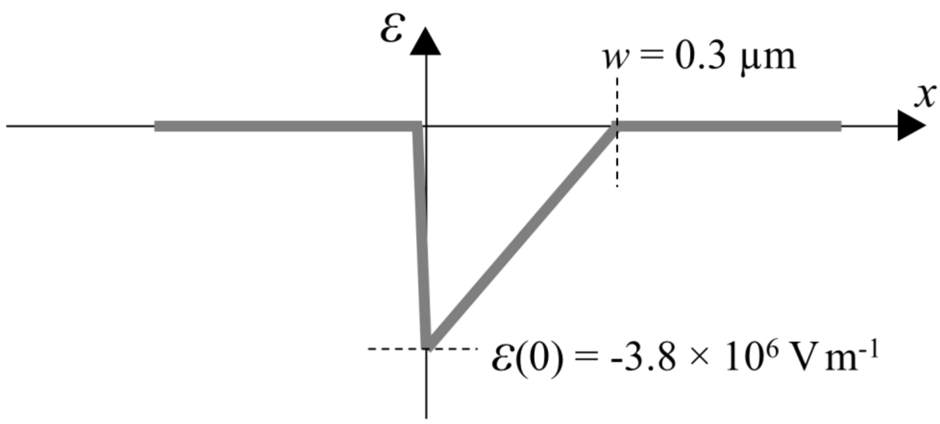

Fig. 2

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