University of KwaZulu-Natal
School of Electrical, Electronic and Computer Engineering

Main Examination: 14 Nov 2013
Nuclear and Semiconductor Physics (ENEL2NP H2)

Duration: 2 hours

Examiners: Internal: Mr J.C. Archer
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External: Dr. J. Poole

General Instructions:

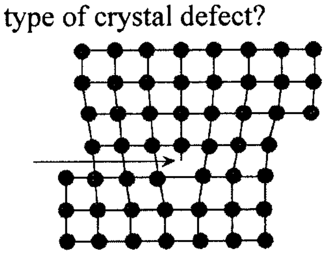
1. Full marks are equal to 120 marks
2. Follow the instructions carefully
3. Answer ALL questions
4. Please keep answers neat and concise. Take note of the mark assignment.
5. The use of any calculator is permitted
6. Note that some equations and formulae are given
7. **Sections A&B, C&D must be answered in DIFFERENT BOOKS**
8. Multiple choice questions to be answered IN THE RESPECTIVE BOOKLETS (No MCQ sheet)

Section A & B (60 marks)
Answer questions in a DIFFERENT BOOK to Section C&D

Section A: Multiple choice questions

Instructions: Please only write your answers (A, B, C, D or E) in the MCQs ***in your answer book****. Each MCQ is worth 3 marks and there is no negative marking. Use the back pages of the question paper for your rough work.*

A1. The figure below refers to what type of crystal defect?



(A) Substitutional defect
(B) Interstitial defect
(C) Vacancy
(D) Line dislocation
(E) None of the above

A2. In the formula below, what indicates energy discretisation?

$$E_n = \frac{-m_0 e^4}{(4\pi\varepsilon_0)^2 \bar{h}^2 n^2}$$

(A) m_0
(B) ε_0
(C) $\bar{h}$
(D) n
(E) None of the above

A3. A semiconductor is said to be extrinsic if:
(A) It is undoped
(B) It has equal donor and acceptor impurity concentrations
(C) It is operating at very high temperatures, specifically $T > 500$ K
(D) All of the three above
(E) None of the above

A4. What are the two types of carrier transport mechanisms (currents) in a semiconductor and what causes each?
(A) Drift and diffusion, due to electric field and majority carrier effective mass respectively.
(B) Diffusion and drift current, due to ionised impurity scattering and phonon scattering respectively.
(C) Diffusion and drift, due to carrier density gradients and localised electric field respectively.
(D) Drift and tunnelling current, due to electric field and quantum mechanics phenomena respectively.
(E) None of the above

A5. Which of the following can be used to increase the space charge width?
(A) Increase of dopants
(B) Decrease in temperature
(C) Increase in applied forward voltage
(D) All of the above
(E) None of the above

A6. Which of the following statements about the pn junction is false?
(A) V_{bi} is establish due to uncovered charge in the space charge region
(B) The diffusion process stops due to the applied electric field
(C) The width of the space charge region is affected by dopants
(D) The space charge region is called the depletion region
(E) None of the above

A7. In an npn BJT, current in the collector is determined by:
(A) The electron concentration gradient in the base
(B) The hole concentration gradient in the base
(C) The majority carrier concentration in the base
(D) The electric field in the E-B space charge region
(E) None of the above

A8. A MOSFET has a p-type drain and a threshold voltage of $V_T = -0.3$ V. The device is a:
(A) N-channel enhancement mode device
(B) N-channel depletion mode device
(C) P-channel enhancement mode device
(D) P-channel depletion mode device
(E) None of the above

A9. Why do IGBTs have a vertical structure?
(A) For higher blocking voltages
(B) To attain higher leakage currents
(C) Lower forward voltage drop
(D) To minimise parasitic capacitance
(E) None of the above

A10. Which one of the following is one of the requirements to initiate latching in an SCR?
(A) $V_{GK} > V_T$
(B) $I_A > I_H$
(C) $I_A < I_G$
(D) $I_A > I_L$
(E) None of the above

Section B: Written answer questions

Question B1 (6 marks)

Draw an appropriately labelled graph of a semiconductor's *conductivity* as a function of temperature, and explain the depicted behaviour. (6)

Question B2 (5 marks)

Consider a pn junction fabricated from silicon with the following parameters:

$N_a = 10^{15}$ cm^{-3} $T = 300$ K $V_{bi} = 0.8$ V Assume full ionisation.

a) Calculate N_d. (3)

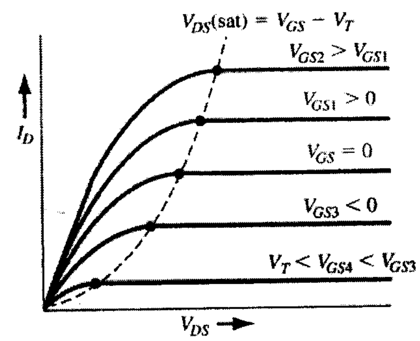
b) Calculate the concentration of holes in the n-type bulk, far from the junction. (2)

Question B3 (5 marks)

Explain with the use of a figure, how an npn BJT can be used for voltage amplification. Be sure to mention specific parameters that are relevant. (5)

Question B4 (6 marks)

Consider the figure below relating to MOSFETs:



a) Identify the device type and mode. (2)

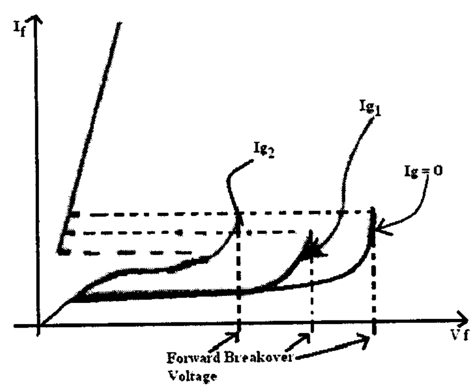
b) Explain the behaviour of the trace identified as $V_{DS}(sat)$. (4)

Question B5 (4 marks)

When and why are IGBTs useful? (4)

Question B6 (4 marks)

Explain the behaviour shown in the following graph relating to SCRs: (4)



– END OF SECTION B –

Constants and Conversions for Section C & D

mass of ^{1}H: M(^{1}H) = 1.007825 u
mass of proton: M(p) = 1.007276 u
mass of neutron: M(n) = 1.008665 u
mass of electron: M(e) = 5.486×10^{-4}
mass of alpha particle: M(^{4}He) = 4.002603 u

$e = 1.602 \times 10^{-19}$ C
$N_A = 6.02 \times 10^{23}$ atoms/mol
$E_n = -13.6(Z/n)^2$ eV
$R_H = 1.09678 \times 10^7$ m^{-1}
$\varepsilon_0 = 8.85 \times 10^{-12}$ C^2/N.m^2

$hc = 1240$ eV.nm
$h = 6.626 \times 10^{-34}$ J.s = 4.1357×10^{-15} eV.s
$a_0 = 0.0529$ nm
$\frac{e^2}{4\pi\varepsilon_0} = 1.440$ eV.nm
$c = 2.998 \times 10^8$ m/s

1 u = 931.5 MeV/c^2 = $1.6605402 \times 10^{-27}$ kg
1 eV = 1.602×10^{-19} J
1 rad = 0.01 Gy = 10^{-2} J/kg

1 Ci = 3.70×10^{10} decay/s
1 Bq = 1 decay/s
1 rem = 0.01 Sv

Section C & D (60 marks)

Answer these questions in a DIFFERENT BOOK to Section A & B

Section C: Multiple choice questions

Instructions: Please only write your answers (A, B, C, D or E) to the MCQs in your answer book. Each MCQ is worth 3 marks and there is no negative marking. Use the back pages of the question paper for your rough work.

C1. Bohr's quantum condition on electron orbits required

(A) that the angular momentum of the electron about the hydrogen nucleus equal $n\hbar$
(B) that no more than one electron occupy a given stationary state.
(C) the electrons to spiral into the nucleus while radiating electromagnetic waves.
(D) that the energies of an electron in a hydrogen atom be equal to nE_0, where E_0 is a constant energy and n is an integer.
(E) None of these is correct.

C2. For the principle quantum number $n = 4$, how many different combinations of l and m_l can occur?

(A) 4 (B) 3 (C) 7 (D) 16 (E) 25

C3. In the decay scheme

$$ {}^{A}_{Z}X \longrightarrow {}^{\ A}_{Z+1}Y + \_\_ + \_\_ $$

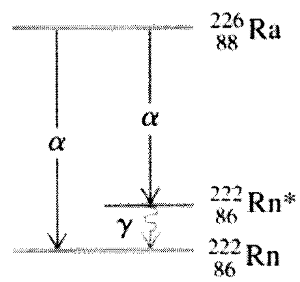
the blanks should contain

A) β^{+} and $\bar{\nu}$ B) β^{-} and ν C) β^{-} and $\bar{\nu}$ D) β^{+} and ν E) β^{+} and n

C4. A radioactive nucleus with Z = 92 and A = 235 decays through a series of alpha, beta, and gamma emissions to a stable nucleus with Z = 82 and A = 207. The number of alpha particles and the number of beta particles emitted during the entire process are

(A) 8 alpha particles and 6 beta particles.
(B) 7 alpha particles and 4 beta particles.
(C) 7 alpha particles and 10 beta particles.
(D) 14 alpha particles and 7 beta particles.
(E) None of these is correct.

C5. The diagram below shows two ways by which ${}^{226}_{88}$Ra decays to ${}^{222}_{86}$Rn. If the energy of the



photon emitted when the excited nucleus ${}^{222}_{86}$Rn* decays to ${}^{222}_{86}$Rn is 0.186 MeV, what is the energy released when ${}^{226}_{88}$Ra decays to ${}^{222}_{86}$Rn*?
(M(${}^{226}_{88}$Ra) = 226.025403 u, M(${}^{222}_{86}$Rn) = 222.017571 u)

(A) 4.645 MeV
(B) 4.871 MeV
(C) 173.259 MeV
(D) 0.744 MeV
(E) 0.186 MeV

C6. A radioactive sample of the iodine isotope ^{131}I, which has a half-life of 8.04 days, has a measured activity of 5 mCi at the time of shipment. Upon receipt in a medical laboratory, the activity is measured to be 4.2 mCi. How much time, in days, has elapsed between the two measurements?

(A) 6.75 (B) 1.40 (C) 2.02 (D) 0.93 (E) 0.53

C7. Neutrons are effective particles for penetrating the nucleus because of their

(A) small size.
(B) small mass.
(C) lack of charge.
(D) cheap production.
(E) easy control.

C8. A typical fission reaction is given by the following reaction equation:

$$^{235}_{92}\mathrm{U} + \mathrm{n} \rightarrow {}^{92}_{36}\mathrm{Kr} + {}^{141}_{56}\mathrm{Ba} + 3\mathrm{n}$$

The Q value (energy released) in this reaction is closest to.
(M(^{235}U) = 235.043922 u, M(^{92}Kr) = 91.926156 u, M(^{141}Ba) = 140.914411 u)

(A) 173.286 MeV
(B) 191.675 MeV
(C) 111.783 MeV
(D) 189.234 MeV
(E) 201.023 MeV

C9. The control rods in a nuclear reactor are used to

(A) produce neutrons.
(B) add fuel to the reactor.
(C) fragment elements by fission.
(D) absorb γ rays.
(E) absorb neutrons.

C10. In an experimental inertial-confinement fusion reactor, inertial confinement has a confinement duration of $\tau = 2.0 \times 10^{-10}$ s. What must the density of the fusible material be in order to meet Lawson's criterion?

(A) 2.0×10^{24} particles/cm^3
(B) 5.0×10^{23} particles/cm^3
(C) 6.0×10^{23} particles/cm^3
D) 2.5×10^{23} particles/cm^3
E) 7.0×10^{23} particles/cm^3

Section D: Written answer questions

Question D1 (5 marks)

Given that the radius of a Bohr orbital is $r_n = a_0 n^2$, where a_0 is the Bohr radius and n labels the energy level, find the velocity (in m/s) of an electron that is in the $n = 4$ state of hydrogen.

Question D2 (5 marks)

The mass and energy balance equation for β^+ - decay of a nuclide ^A_ZX is,

$$M^*(N, Z) \times c^2 = [M^*(N+1, Z-1) + m_e] \times c^2 + Q,$$

where M^* are the nuclear masses and m_e is the mass of the electron. Derive an expression for the Q value in terms of the atomic masses $M(N, Z)$ and $M(N+1, Z-1)$ and state what the condition is for β^+ decay to occur. (*Hint*: the nuclear mass is the difference between the atomic mass and the mass of Z electrons, where Z is the proton number of the nuclide.)

Question D3 (5 marks)

Carry out a detailed calculation to show whether $^{239}_{94}$Pu requires low energy or high energy neutrons for fission. (M(^{239}Pu) = 239.052156 u and M(^{240}Pu) = 240.053807 u)

Question D4 (7 marks)

The PBMR typically produces 120 MW of electrical power and has an efficiency of 40% for converting nuclear energy to electrical energy. If each fission releases 180 MeV of energy, estimate the minimum amount (in kg) of ^{235}U that needs to undergo fission in order to run the PBMR per year of continuous use. (M (^{235}U) = 235.043922 u)

Question D5 (8 marks)

D5.1 Explain what is meant by the *relative biological effectiveness* (RBE) of a particular type of radiation. (3)

D5.2 During a diagnostic X-ray examination, a 1.2 kg portion of a broken bone receives a dose of 40×10^{-3} rem. If the RBE of X-rays is 1, how many joules of energy did the bone recieve? (5)

Table 4.1 | Effective density of states function and effective mass values

	N_c (cm^{-3})	N_v (cm^{-3})	m_n^*/m_0	m_p^*/m_0
Silicon	2.8×10^{19}	1.04×10^{19}	1.08	0.56
Gallium arsenide	4.7×10^{17}	7.0×10^{18}	0.067	0.48
Germanium	1.04×10^{19}	6.0×10^{18}	0.55	0.37

Table 4.2 | Commonly accepted values of n_i at $T = 300$ K

Silicon	$n_i = 1.5 \times 10^{10}$ cm^{-3}
Gallium arsenide	$n_i = 1.8 \times 10^{6}$ cm^{-3}
Germanium	$n_i = 2.4 \times 10^{13}$ cm^{-3}

$$R'_n = R'_p = \frac{\delta n(t)}{\tau_{n0}}$$

$$x_{dT} = \left(\frac{4\epsilon_s \phi_{fp}}{eN_a}\right)^{1/2}$$

$$J = qNv_d \qquad \text{A/cm}^2$$

$$i_C = I_S \exp\left(\frac{v_{BE}}{V_t}\right)$$

$$V_{bi} = \frac{kT}{e}\ln\left(\frac{N_a N_d}{n_i^2}\right) = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

$$n_0 = \frac{(N_d - N_a)}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2}$$

$$E_n = \frac{-m_0 e^4}{(4\pi\epsilon_0)^2 2\hbar^2 n^2}$$

$$W = \left\{\frac{2\epsilon_s (V_{bi} + V_R)}{e}\left[\frac{N_a + N_d}{N_a N_d}\right]\right\}^{1/2}$$

$$\frac{i_C}{i_E} = \alpha$$

$$n_0 p_0 = n_i^2.$$

$$i_E = i_{E1} + i_{E2} = i_C + i_{E2} = I_{SE}\exp\left(\frac{v_{BE}}{V_t}\right)$$

$$J_{p|drf} = (ep)v_{dp} = e\mu_p p\text{E}$$

$$p_0 = \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a - N_d}{2}\right)^2 + n_i^2}$$

Table B.3 | Physical constants

Avogadro's number	$N_A = 6.02 \times 10^{+23}$ atoms per gram molecular weight
Boltzmann's constant	$k = 1.38 \times 10^{-23}$ J/K $= 8.62 \times 10^{-5}$ eV/K
Electronic charge (magnitude)	$e = 1.60 \times 10^{-19}$ C
Free electron rest mass	$m_0 = 9.11 \times 10^{-31}$ kg
Permeability of free space	$\mu_0 = 4\pi \times 10^{-7}$ H/m
Permittivity of free space	$\epsilon_0 = 8.85 \times 10^{-14}$ F/cm $= 8.85 \times 10^{-12}$ F/m
Planck's constant	$h = 6.625 \times 10^{-34}$ J-s $= 4.135 \times 10^{-15}$ eV-s $\frac{h}{2\pi} = \hbar = 1.054 \times 10^{-34}$ J-s
Proton rest mass	$M = 1.67 \times 10^{-27}$ kg
Speed of light in vacuum	$c = 2.998 \times 10^{10}$ cm/s
Thermal voltage ($T = 300$ K)	$V_t = \frac{kT}{e} = 0.0259$ volt $kT = 0.0259$ eV

Property	Si
Atoms (cm^{-3})	5.0×10^{22}
Atomic weight	28.09
Crystal structure	Diamond
Density (g/cm^{-3})	2.33
Lattice constant (Å)	5.43
Melting point (°C)	1415
Dielectric constant	11.7
Bandgap energy (eV)	1.12
Electron affinity, χ (volts)	4.01
Effective density of states in conduction band, N_c (cm^{-3})	2.8×10^{19}
Effective density of states in valence band, N_v (cm^{-3})	1.04×10^{19}
Intrinsic carrier concentration (cm^{-3})	1.5×10^{10}
Mobility (cm^2/V-s)	
Electron, μ_n	1350
Hole, μ_p	480