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Formula sheet at end of paper

The University Of Sheffield.

DEPARTMENT OF ELECTRONIC AND ELECTRICAL ENGINEERING

Spring Semester 2014-15 (3.0 hours)

EEE6206 Power Semiconductor Devices

Answer **FOUR** questions. **No marks will be awarded for solutions to a fifth question.** Solutions will be considered in the order that they are presented in the answer book. Trial answers will be ignored if they are clearly crossed out. **The numbers given after each section of a question indicate the relative weighting of that section.**

The following questions are related to the properties of semiconductors.

1. **a.** List the main differences in electrical properties between metals, insulators and semiconductors. **(2)**

b. Briefly discuss the main difference between direct and indirect bandgap semiconductors, providing an example of each type. **(3)**

c. Define the terms Fermi-level and thermal runaway in a semiconductor. **(4)**

d. Briefly describe what is meant by an intrinsic semiconductor. **(2)**

e. Taking care to comment on any key issues, determine whether a Silicon ingot with an n type doping of $1\times10^{15}/cm^3$ operating at 250°C (523K) has reached its maximum operational temperature.

Hint: You may assume the maximum temperature of operation of a semiconductor occurs when the intrinsic carrier concentration is the same as the background doping. **(5)**

f. Calculate the Fermi-level position from the intrinsic energy level of a Silicon ingot of p type doping of $5\times10^{15}/cm^3$ at 27°C (300K), assuming complete ionisation of impurities. **(4)**

The following questions are mostly related to fabrication and PiN power diodes.

2. a. Describe two techniques to form junctions in high voltage devices during the device fabrication process, taking care to explain how these techniques are used to form structures at the cathode and anode region of the device. **(3)**

b. Explain why shallow and short n+ source/cathode regions are formed with impurities of a low diffusion coefficient in n-channel MOSFETs or n-channel IGBTs. Comment on why is it important to keep such regions shallow. **(3)**

c. Calculate the built-in potential of the following:

i) Silicon PN junction with an acceptor doping concentration of $1\times10^{18}/cm^3$, donor concentration of $1\times10^{13}/cm^3$, and an intrinsic carrier concentration of $1\times10^{10}/cm^3$ at 27°C (300K). **(5)**

ii) Discuss any difference between current voltage characteristics if the semiconductor material was changed from Silicon to Silicon Carbide. **(3)**

d. Calculate the drift region width and concentration for a Silicon Carbide PiN structure for a voltage rating of 3300V. Assume a 20% pass band. **(6)**

The following questions are mostly related to metal-semiconductor Schottky diodes.

3. **a.** Draw and label the metal semiconductor energy band diagram for a metal contact to an n-type semiconductor for the following conditions

i) Thermal equilibrium, **(2)**

ii) Forward biased, **(2)**

iii) Reverse biased. **(2)**

Provide labels for the Fermi Level, Work Functions, Conduction Band, Valence Band, Vacuum level and ground state.

By reference to these band diagrams describe the on-state and off-state behaviour. **(2)**

b. Describe the on-state conduction mechanism of a Schottky diode. **(1)**

How does it differ from a PiN diode? **(1)**

What differences would you find if you compare on-state and switching characteristics of high voltage PiN and Schottky diodes? **(2)**

c. Calculate the on-state forward voltage drop of a Silicon Carbide Schottky diode operating at a current level of 100A. The drift region thickness is 10μm and a doping concentration of $1\times10^{15}/\text{cm}^3$. The cross-section area of the die is 5mm x 5mm and it has a built in potential of 0.9V. **(8)**

The following questions are mostly related to bipolar transistors (BJTs) and thyristors.

4. **a.** i) Draw the forward current voltage characteristics of a high voltage bipolar transistor including open base and open emitter breakdown performance. **(4)**

ii) Explain the breakdown mechanism for open base operation and comment on how this compares to the maximum breakdown voltage. **(3)**

b. Consider a silicon BJT transistor with an N- collector thickness of 100μm. Calculate the breakdown voltage of a punch through BJT operated in a shorted emitter configuration. Consider an N-doping concentration of $1\times10^{14}/cm^3$ and critical electric field strength of 2×10^5V/cm. **(4)**

c. To the nearest 100V, what is the breakdown voltage of the structure in part (b) if the drift region doping concentration is increased to 5×10^{14} /cm^3 and the critical electric field remains at 2×10^5V/cm. You may assume that the electric field profile is triangular and the critical electric field strength (E_c) can be determined by $E_c = \frac{2BV}{W}$; where BV is the breakdown voltage.

Hint: calculate depletion layer thickness and electrical field strength at an applied voltage of 500V. Vary this voltage until maximum breakdown voltage is obtained. **(5)**

d. Draw and label the current voltage characteristic of a thyristor. Label any key features and define the switching current and holding current. **(4)**

The following questions are related to Metal-Oxide-Semiconductor devices (MOSFETs).

5. **a.** Draw and label a Metal-Oxide-Semiconductor energy band diagram for a p-type semiconductor for the following conditions:

(i) Flat-band condition, **(3)**

(ii) Accumulation, **(3)**

(iii) Inversion. **(3)**

Define Threshold voltage of a MOSFET using these energy band diagrams. **(2)**

b. Calculate the threshold voltage of an n-channel MOSFET with an oxide thickness of 100nm and a p-body doping of $1\times10^{17}/cm^3$ at both room temperature and at 125°C (398 K). **(4)**

c. Draw a cross-section through a power MOSFET taking care to label any significant features including practical elements. List the parasitic capacitances in this device and how do they influence its switching behaviour? **(5)**

The following questions are related to the Insulated Gate Bipolar Transistor (IGBT).

6. **a.** Briefly describe two main differences between a Power MOSFET and an IGBT **(2)**

b. Describe the main differences between PT, NPT and FS technologies in an IGBT **(3)**

c. Briefly describe the phenomena of latch-up in an IGBT and discuss means of minimising this effect. **(2)**

d. Describe the operating behaviour of a reverse-Conducting IGBT, the means by which it can be realised in practice and its principal benefits. **(5)**

e. Draw cross-sections through typical planar and trench IGBT structures and discuss the differences in their operation. **(5)**

f. List the factors and the effects of gate resistance of an IGBT device performance. **(3)**

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EEE6206 Power Semiconductor Devices: Material Constants and Formula Sheet

Physical Constants:

Electron Charge (q)	1.63e-19 (C)
Boltzmann's Constant (k)	1.38e-23 (J/K)
Permittivity of free space (ε_0)	8.85e-14 (F/cm)

Materials Constants:

Silicon	
Energy Bandgap (E_G)	1.12 (eV)
Dielectric Constant/Relative Permittivity (ε_r)	11.7 (pu)
Intrinsic Carrier Concentration (n_i)	1e10 (/cm^{-3})
Electron Mobility (μ_n)	1400 (cm^2/v-s)
Holes Mobility (μ_p)	450 (cm^2/v-s)
Critical Electric Field Strength (E_c)	4010$N_D^{0.125}$ (V/cm)
Silicon Carbide (4H-SiC)	
Energy Bandgap (E_G)	3.26 (eV)
Dielectric Constant/Relative Permittivity (ε_r)	9.8 (pu)
Intrinsic Carrier Concentration (n_i)	1e-10 (/cm^{-3})
Electron Mobility (μ_n)	900 (cm^2/v-s)
Holes Mobility (μ_p)	120 (cm^2/v-s)
Critical Electric Field Strength (E_c)	3e6 (V/cm)
Oxide	
Dielectric Constant (ε_r) / Relative Permittivity	3.9 (pu)

Useful Formulas:

$$\rho = \frac{1}{q\ N_D \mu_n}\ (\Omega - cm) \tag{1}$$

$$R = \rho\ \frac{L}{A}\quad (\Omega) \tag{2}$$

$$BV_{Diode} = \frac{E_{crit}^2 \epsilon_s \epsilon_o}{2qN_D} \qquad (V) \tag{3}$$

$$BV_{PT-BJT} = E_c W_p - \frac{qN_D {W_p}^2}{2\varepsilon_r \varepsilon_o} \qquad (V) \tag{4}$$

$$W_{max} = \sqrt{\frac{2\epsilon_s BV}{qN_D}} \quad (cm) \tag{5}$$

$$E_c = \frac{2BV}{W} \qquad (V/m) \tag{6}$$

$$N_D = \frac{{E_c}^2 \varepsilon_s}{2qV} \qquad (cm^{-3}) \tag{7}$$

$$N_C = 4.83 \times 10^{15} T^{\frac{3}{2}} \, (cm^{-3}) \tag{8}$$

$$N_V = 1.71 \times 10^{15} T^{\frac{3}{2}} \, (cm^{-3}) \tag{9}$$

$$ni^2 = N_v N_c exp \frac{-qE_G}{kT} \, (cm^{-3}) \tag{10}$$

$$\psi_B = E_i - E_F = \frac{kT}{q} ln\left(\frac{N_A}{n_i}\right) \, (eV) \tag{11}$$

$$V_{bi} = \frac{kT}{q} ln\left(\frac{N_A N_D}{{n_i}^2}\right) \, (V) \tag{12}$$

$$\epsilon_s = \epsilon_r \epsilon_o \qquad (F/m) \tag{13}$$

$$V_{TH} = V_{FB} + 2\psi_B + \frac{t_{OX}}{\varepsilon_{OX}}\sqrt{2qN_A\epsilon_{si}(2\psi_B)} \quad (V) \tag{14}$$

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