## UNIVERSITY OF SWAZILAND

### FACULTY OF SCIENCE AND ENGINEERING

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING

MAIN EXAMINATION TITLE OF PAPER: COURSE NUMBER: TIME ALLOWED: 2013/14 SOLID STATE ELECTRONICS EE429 3 HOURS

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**INSTRUCTIONS:** 

ANSWER ANY FOUR OUT OF FIVE QUESTIONS.

EACH QUESTION CARRIES 25 MARKS.

MARKS FOR DIFFERENT SECTIONS ARE SHOWN ENCLOSED IN SQUARE BRAKETS.

THIS PAPER HAS 6 PAGES INCLUDING THIS PAGE.

DO NOT OPEN THE PAPER UNTIL PERMISSION HAS BEEN GIVEN BY THE INVIGILATOR. Q1. (a) Copper crystallizes in the fcc structure and has an atomic weight, M = 63.54 g/mole. Assume that the copper atoms are identical spheres which are tightly packed. Given that the density of copper is 8.94 g/cm<sup>3</sup> and Avogadro's number is  $N_A = 6.022 \times 10^{23}$  atoms/mole, find:

(i) the number of atoms per unit cell;	[2]
(ii) packing fraction of atoms;	[2]
(iii) volume of a unit cell;	[6]
(iv) lattice constant, a (the unit cell dimension);	[2]
(v) the radius of a copper atom.	[2]

(b) Consider an electron whose normalized time independent wave function is

$$\psi(x) = 2\alpha \sqrt{\alpha} x e^{-\alpha x} \qquad \text{for } x > 0$$
$$= 0 \qquad \qquad \text{for } x \le 0.$$

For what value of x do we get the maximum probability of finding the electron at the position x? [5]

(c) The normalized time dependent wave function for an electron of mass m is

$$\psi(x,t) = Ae^{-a[(mx^2/\hbar)+jt]}$$
, where  $j = \sqrt{-1}$ .

A and a are positive real constants. Given that,

$$\int_{0}^{\infty} e^{-ax^{2}} dx = \frac{1}{2} \left(\frac{\pi}{a}\right)^{\frac{1}{2}}$$

and

$$\int_{0}^{\infty} x^{2} e^{-ax^{2}} dx = \frac{1}{4a} \left(\frac{\pi}{a}\right)^{\frac{1}{2}}$$

(i) Find A;

- (ii) Calculate the expectation value,  $\langle x^2 \rangle$  [3]
- Q2. (a) Find the energy position of the Fermi level for 9 electrons in an infinite 1-D potential well with a 100 Å width. [3]
  - (b) The effective mass of electrons,  $m_c$  in the conduction band and that of holes,  $m_v$  in the valence band of germanium at 300 K are,  $m_c = 0.56m_e$  and  $m_v =$

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[3]

0.40 $m_e$  where  $m_e$  is the mass of a free electron. The respective mobilities at 300 K are  $\mu_e = 3900 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$  and  $\mu_h = 1900 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$ . The band gap of germanium is  $E_g = 0.66 \text{ eV}$ . Calculate:

(i) the effective density of states $N_C$ and $N_V$ for germanium at 300 K;	[4]
(ii) the intrinsic concentration, $n_i$ for germanium at 300 K;	[2]

- (iii) the intrinsic conductivity of germanium at 300 K. [2]
- (c) (i) The conductivity of a semiconductor is  $\sigma = en_c\mu_{e+} en_v\mu_h$ . Will doping always increase the conductivity? Under what circumstances can doping decrease the conductivity? [2]
  - (ii) Show that the minimum conductivity for silicon is obtained when it is *p*-type doped such that the hole concentration is

$$p = n_i \sqrt{\mu_e/\mu_h}$$

and the corresponding minimum conductivity is

$$\sigma_{min} = 2en_i \sqrt{\mu_e \mu_h} . \qquad [6]$$

- (iii) For silicon  $\mu_e = 1350 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$ ,  $\mu_h = 450 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$  and  $n_i = 1.0 \times 10^{10} \text{ cm}^{-3}$ . Calculate p and  $\sigma$  at the point of minimum conductivity for silicon at 300 K and compare with the intrinsic values. [6]
- Q3. (a) A silicon wafer has been doped *n*-type with  $N_D = 10^{17}$  cm<sup>-3</sup> phosphorus atoms. The electron drift mobility for Si is 800 cm<sup>2</sup>V<sup>-1</sup>s<sup>-1</sup> and  $n_i = 1.0 \times 10^{10}$  cm<sup>-3</sup>.
  - (i) Calculate the conductivity at 300K. [3]
  - (ii) Where is the Fermi level with respect to the Fermi level  $(E_{Fi})$  in intrinsic silicon at 300K? [4]

The above silicon wafer is further doped with  $N_A = 9 \times 10^{16}$  cm<sup>-3</sup> boron atoms.

- (iii) Calculate the conductivity at 300 K. [3]
- (iv) Where is the Fermi level,  $E_F$  with respect to the Fermi level  $E_{Fi}$  in intrinsic silicon at 300 K? Is the wafer *n*-type or *p*-type? [4]
- (b) An *n*-type silicon sample is doped with  $N_D = 10^{15}$  cm<sup>-3</sup> phosphorus atoms. For this low level of doping the electron mobility is essentially the same as for

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intrinsic silicon,  $\mu_e = 1350 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$ . The donor energy level for phosphorus in silicon is 0.045 eV below the conduction band edge energy. The effective density of states  $N_C$  and  $N_V$  for silicon at 300 K are  $N_C = 2.8 \times 10^{19} \text{ cm}^{-3}$  and  $N_V = 1.2 \times 10^{19} \text{ cm}^{-3}$ . In the question below ignore the temperature dependence of  $N_C$  and  $N_V$ , use their room temperature values. The band gap of silicon is  $E_g = 1.1 \text{ eV}$ .

- (i) Calculate the room temperature (T = 300 K) conductivity of the sample; [4]
- (ii) Estimate the temperature above which the sample behaves as if it is intrinsic.
  [7]
- Q4. (a) Many semiconductors are well suited for light emission, particularly the compound semiconductors with direct band gaps. The general property of light emission is called luminescence. Name and describe the three most important types of luminescence. [6]
  - (b) A 0.46  $\mu$ m thick sample of GaAs is illuminated with monochromatic light of hv = 2 eV. The absorption coefficient  $\alpha$  is  $5 \times 10^4 \text{ cm}^{-1}$ . The light intensity incident on the sample is 10000 W. The band gap for GaAs is 1.43 eV. Find:
    - (i) the total energy absorbed by the sample per second in J/s; [4]
    - (ii) the rate of excess thermal energy given up by the photons to the lattice before recombination, in J/s; [4]
    - (iii) the number of photons per second given off from recombination events, assuming perfect quantum efficiency. [4]
  - (c) An **unilluminated** Si  $p^+$  -*n* junction with a donor concentration  $N_D = 5 \times 10^{16} \text{ cm}^{-3}$ and area  $A = 10^{-3} \text{ cm}^2$  has  $\tau_p = 1 \text{ µs}$  and  $D_p = 10 \text{ cm}^2/\text{s}$ . Find the current *I* for a forward bias  $V_f = 0.5 \text{ V}$ ,  $n_i = 1.5 \times 10^{10} \text{ cm}^{-3}$ . [7]
- Q5. (a) Assume a constant source of phosphorous diffusion at 1000°C into 1  $\Omega$ -cm ptype Si. For 1  $\Omega$ -cm p-type silicon we have  $N = 1.7 \times 10^6$  atoms/cm<sup>3</sup>. The activation energy for the diffusion is  $E_a = 3.69$  eV. The diffusion constant  $D_0 =$ 10.5. The surface phosphorous is held constant at  $10^{21}$  cm<sup>-3</sup>. Given that the complementary error function, *erfc*  $3.1 = 1.7 \times 10^{-5}$ , calculate the time required to achieve a junction depth of 1 µm. [10]
  - (b) In addition to offering the advantages of miniaturization, give three advantages of the simultaneous fabrication of many ICs on a single Si wafer. [3]
  - (c) (i) Clearly define the relative magnetic permeability using equations to support

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the definition.

(ii) The magnetic susceptibility of copper is -0.5×10<sup>-5</sup>. Calculate the magnetic flux density when subjected to a field whose magnitude inside copper is 10<sup>4</sup> amperes/metre.

#### **APPENDIX A – PHYSICAL CONSTANTS**

Mass of a free electron  $m_e = 9.109 \times 10^{-31}$  kg Planck's constant  $h = 6.626 \times 10^{-34}$  J-s Planck's constant (reduced)  $\hbar = \frac{h}{2\pi} = 1.0546 \times 10^{-34}$  J-s Boltzmann constant  $k = 1.381 \times 10^{-23}$  JK<sup>-1</sup> kT at room temperature kT = 0.0259 eV Avogadro's number (particles per mole)  $N_A = 6.022 \times 10^{23}$  per g mole Permeability of free space  $\mu_0 = 4\pi \times 10^{-7}$ Hm<sup>-1</sup> Permittivity of free space  $\epsilon_0 = 8.85 \times 10^{-12}$  Fm<sup>-1</sup> Electronic charge  $e = 1.6 \times 10^{-19}$ C Speed of light  $c = 2.998 \times 10^8$  ms<sup>-1</sup>

**APPENDIX B – UNIT CONVERSIONS** 

1 eV =  $1.6022 \times 10^{-19}$  J 1 Å (angstrom) =  $10^{-10}$  m 1 µm (micron) =  $10^{-6}$  m 1 nm = 10 Å =  $10^{-9}$  m 1 µs (microsecond) =  $10^{-6}$  s

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[4]

# **APPENDIX C – EQUATIONS**

$$\begin{split} E_{n} &= \frac{n^{2} \pi^{2} \hbar^{2}}{2mL^{2}} \\ N_{c} &= 2 \bigg( \frac{2\pi m_{c} kT}{h^{2}} \bigg)^{\frac{3}{2}} \\ n &= N_{D} = N_{c} e^{-(E_{c} - E_{p})/kT} \\ n &= N_{D} = N_{c} e^{-(E_{c} - E_{p})/kT} \\ N_{v} &= 2 \bigg( \frac{2\pi m_{v} kT}{h^{2}} \bigg)^{\frac{3}{2}} \\ p &= N_{A} = N_{v} e^{-(E_{v} - E_{p})/kT} \\ n_{i} &= p_{i} = \sqrt{N_{c} N_{v}} e^{-E_{g}/2kT} \\ \sigma &= en\mu_{e} + ep\mu_{h} \\ np &= n_{i}^{2} \\ n &= N_{D} = N_{c} e^{-(E_{c} - E_{p})/kT} \\ V_{0} &= \frac{k_{B}T}{q} ln \frac{N_{A}N_{D}}{n_{i}^{2}} \\ W &= \bigg[ \frac{2\varepsilon V_{o}}{q} \bigg( \frac{1}{N_{A}} + \frac{1}{N_{D}} \bigg) \bigg]^{\frac{1}{2}} \\ N(x, t) &= N_{o} erfc \bigg( \frac{x}{2\sqrt{Dt}} \bigg) \\ I_{t} &= I_{0} e^{-cd} \\ L_{p} &= \sqrt{D_{p} \tau_{p}} \\ L_{n} &= \sqrt{D_{n} \tau_{n}} \\ I &= qA \bigg( \frac{D_{p}}{L_{p}} P_{n} + \frac{D_{n}}{L_{n}} n_{p} \bigg) (e^{\frac{qv}{kT}} - 1) - qAg_{op}(L_{p} + L_{n} + W). \end{split}$$

## END OF EE429 EXAMINATION

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