BITS, PILANI – DUBAI
DUBAI INTERNATIONAL ACADEMIC CITY
SEMESTER I 2011-2012

CLASS: EEE III Year **Date: 9 Jan 2012**

EEE C381 ELECTRONIC DEVICES AND INTEGRATED CIRCUITS

Max marks: 80 Weightage: 40% **COMPREHENSIVE EXAMINATION** Time allowed: 3 hours

---

Note: Answer ALL questions. All symbols have their usual significance unless otherwise stated

Q1 In a certain semiconductor made of Si, the Fermi Energy E_F is as much close to the conduction band edge E_C as it is to the intrinsic Fermi level E_i. The semiconductor is in thermal equilibrium at 300 K

(a) Is the semiconductor n-type, p-type or intrinsic?

(b) Determine the electron and hole concentrations (n_o and p_o respectively) in the semiconductor. Make appropriate assumption and indicate the assumption made.

(c) What is the probability for a hole to occupy the valence band edge E_V?

(d) Determine N_C and N_V for the semiconductor

(10 marks)

Q2. A sample of Si is doped simultaneously with donors (N_D = 5x10^{13} cm^{-3}) and acceptors (N_A = 4.5x10^{13} cm^{-3}).

(a) Determine the thermal equilibrium electron and hole concentrations at 300 K
(b) The semiconductor is exposed to a light source at t = 0 such that an excess electron and hole concentration of 10^{10} cm^{-3} is produced in the semiconductor. Does this correspond to low level or high level injection? Explain.
(c) If the lifetime of minority carriers is 10^{-10} sec, determine the generation rate g_{op} of excess carriers.
(d) Determine the location of the quasi Fermi levels E_{Fnq} for electrons with respect to the thermal equilibrium Fermi level E_F in the semiconductor

(10 marks)

Q3. A Si p-n junction has its p-side doped with $N_A = 10^{18}$ cm^{-3} and the n-side doped with $N_D = 10^{17}$ cm^{-3} respectively. The p-n junction is held in thermal equilibrium at **350** K. Calculate:

(a) The Fermi energy levels E_{Fn} and E_{Fp} (relative to the intrinsic energy levels) for both the n- and p-side of the junction. Hence draw the equilibrium energy band diagram for the p-n junction.
(b) The contact potential V_o, using the data on the doping densities. Compare this result with that obtained through part (a) above.
(c) The widths of the depletion region in the n-side (x_{no}) and the p-side (x_{po}), and the total depletion width W. Comment on the values obtained in relation to the doping concentrations on each side of the junction.
(d) The peak electric field E_o and the location of the peak electric field.

(16 marks)

Q4 An abrupt Si p-n junction has the n-side doped with $N_D = 10^{18}$ cm^{-3} and the p-side doped with $N_A = 10^{16}$ cm^{-3}. In the absence of any bias, the depletion capacitance was found to be 10 pF at 300 K.

(a) How much reverse bias is required to provide a depletion capacitance of 5 pF?
(b) What is the area of the junction?

(6 marks)

Q5 Starting from a bare wafer (Figure 1) it is desired to make a pattern of silicon dioxide (Figure 2). Illustrate how a photolithography process can be used to accomplish this, with (a) **positive** photoresist and (b) **negative** photoresist.

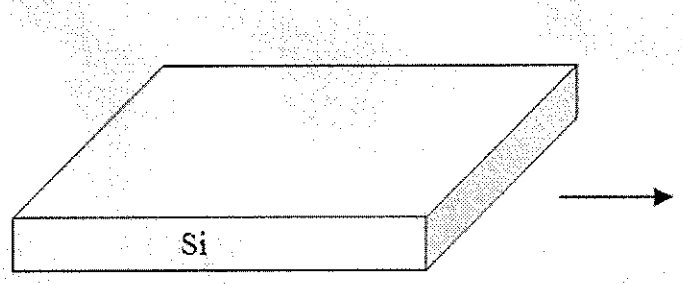


Figure 1

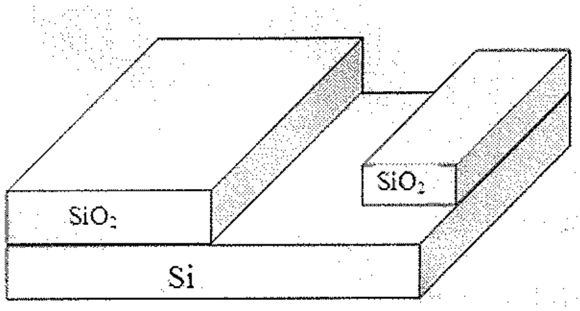


Figure 2

(5 marks)

Q6. Draw the energy band diagram of an ideal [Metal] – [Oxide] – [p type Semiconductor] structure under the condition of onset of strong inversion. In the diagram, indicate the Fermi levels of metal and semiconductor, conduction and valence band edges of semiconductor, intrinsic Fermi energy E_i of the semiconductor. Correlate the applied voltage V on the metal with the Fermi levels.

(5 marks)

Q7. Calculate the surface potential ϕ_s at the onset of strong inversion for a MOS structure at 77 °C corresponding to a substrate doping of $N_A = 5\times10^{16}$ cm^{-3}. The semiconductor is silicon. Determine W_m at the onset of strong inversion. If the oxide is 0.01 μm thick, and the flat band voltage V_{FB} is zero, determine the threshold voltage for the MOS device.

(8 marks)

Q8. Explain briefly the operating principle of a solar cell. Under what conditions a solar cell would be supplying maximum power to a load? Light is incident on a p-n junction optoelectronic device at 300 K, with an optical generation rate $g_{op} = 10^{15}$ cm^{-3}.s^{-1}. Assume a symmetrical junction, with $p_p = n_n = 10^{18}$ cm^{-3}. The minority carrier lifetime is 10^{-7} s. Determine the open circuit voltage V_{oc} for the device. Assume depletion region width W negligible compared to L_n or L_p.

(10 marks)

Q9 Draw the energy band diagram of a p^+-n-p transistor under cut off mode of operation and mark all relevant energy levels in the diagram.

(4 marks)

Q10. Using a two transistor analogy for a p-n-p-n structure, show how the structure can function as a rectifier. Draw typical $I - V$ characteristics for the device and identify the reverse blocking, forward blocking and forward conducting states. Name one application of the device.

(6 marks)

END OF PAPER

LIST OF SELECTED FORMULAE AND PHYSICAL CONSTANTS

$$p_p = N_v e^{-(E_F - E_v)/(kT)}$$

$$n_n = N_c e^{-(E_c - E_F)/(kT)}$$

$$V_o = \frac{kT}{q} \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

$$W = \sqrt{\frac{2\varepsilon_s}{q}\left[\frac{1}{N_a} + \frac{1}{N_d}\right](V_o - V)}$$

$$N_c = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$$

$$N_v = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2}$$

$$W_m(for MOS) = \sqrt{\frac{2\varepsilon_s}{q}\left[\frac{1}{N_a}\right](2\phi_B)}$$

TABLE OF SELECTED CONSTANTS

Parameter	Symbol	Value	Units
Electronic Charge	q	1.6×10^{-19}	C
Boltzmann's constant	k or k_B	1.38×10^{-23}	J/K
Permittivity of free space	ε_o	8.85×10^{-14}	F/cm
Dielectric constant of Si (ε_r)	ε_{Si}	11.7	-
Dielectric constant of SiO_2 (ε_{ox})	ε_{SiO2}	3.9	-
Intrinsic carrier concentration in Si	n_i	1×10^{10} at 300 K 2.75×10^{11} at 350 K	cm^{-3}
Bandgap of Si	E_g	1.12	eV

BITS PILANI DUBAI CAMPUS
SEM 1 2011 – 2012 III YEAR EEE
EEE C381 ELECTRONIC DEVICES AND INTEGRATED CIRCUITS TEST 1

ANSWER ALL QUESTIONS TIME: 50 MINS TOTAL MARKS 50 WEIGHTAGE: 25%
All symbols have their usual significance. Assume suitable values for constants if necessary.

Question 1

An n-type Si at room temperature (300 K) has a thermal equilibrium electron concentration of $1\text{x}10^{18}$ cm^{-3}.What is the probability for an electron to occupy the conduction band edge E_c? Bandgap of Si = 1.12 eV. Intrinsic carrier concentration for Si at 300 K = $1\text{x}10^{10}$ cm^{-3}.

(8 marks)

Question 2

A semiconductor sample is in thermal equilibrium at 300 K. The bandgap energy is 0.9 eV and the intrinsic carrier concentration n_i is $4\text{x}10^{13}$ cm^{-3}. The sample is doped with donor impurities such that E_F is 0.02 eV above the intrinsic Fermi Energy level E_i.

(i) Calculate the thermal equilibrium electron and hole concentrations, n_0 and p_0 respectively.

(ii) Determine the donor impurity concentration N_D in the semiconductor. Is it justified to assume N_D to be the same as n_0? Why?

(iii) If the donor impurity concentration is doubled, how much closer would the Fermi Level be to the bottom of the conduction band?

(12 marks)

Question 3

Assume that there is a special semiconductor material whose bandgap energy is adjustable. The semiconductor is doped with $1\text{x}10^{15}$ cm^{-3} donor atoms. Assume complete ionization of the donor atoms. The effective density of states functions for the semiconductor are given by $N_c = N_v = 1.5\text{x}10^{19}$ cm^{-3} at 400K . If the thermal equilibrium electron concentration in the semiconductor is required to be no greater than $1.01\text{x}10^{15}$ cm^{-3} at 400 K, what should be the minimum bandgap energy of the material?

(12 marks)

Question 4

A Si p-n junction has donor and acceptor doping concentrations N_D and N_A of 10^{16} cm^{-3} and 10^{18} cm^{-3} respectively. The p-n junction is held at 300 K. Assume that $n_i = 10^{10}$ cm^{-3} and ε_r for Si = 11.8. Calculate under thermal equilibrium conditions, the Fermi energy levels (relative to the intrinsic energy levels) for both the n- and p-side of the junction. Hence draw the equilibrium energy band diagram

(8 marks)

Question 5

For the semiconductor in Question 1 above, 10^{13} electron-hole pairs (EHP) / cm^3 are created every microsecond. Determine the optical generation rate g_{op}. If the carrier lifetime $\tau_n = \tau_p$ = 2μsec, determine the excess electron or hole concentration in the sample. Does this correspond to low injection? Determine the positions of the electron and hole quasi Fermi levels relative to the intrinsic Fermi level.

(10 marks)

BITS, PILANI – DUBAI
DUBAI INTERNATIONAL ACADEMIC CITY

YEAR III EEE C381 – ELECTRONIC DEVICES & INTEGRATED CIRCUITS

Test 2 Date: 11 Dec 2011 Max marks: 40 Weightage: 20% OPEN BOOK

Answer ALL questions .All symbols have their usual significance. Use suitable values of constants wherever appropriate. **Time allowed: 50 minutes**

Q1

A Si solar cell has an I-V characteristics as shown in Figure 1.

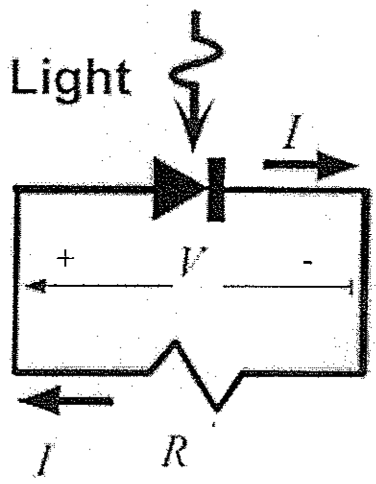


Figure 2

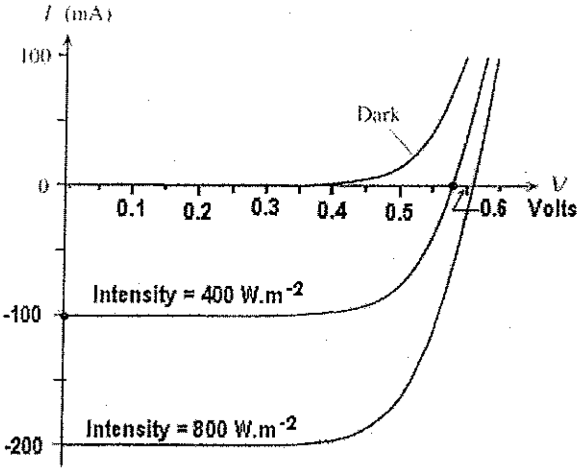


Figure 1

(a). In Figure 2, a steady light of intensity 400 $W.m^{-2}$ is incident on the solar cell which drives a load R ohms with a voltage V = 0.5 Volt. Indicate on figure 1(provided as a separate sheet) the load line for the circuit. Hence determine the operating point. Also indicate the open circuit voltage and the short circuit current and determine the Fill Factor.

(8 marks)

(b) The intensity is now increased to 800 $W.m^{-2}$. How much power does the solar cell deliver to the load now? If the efficiency of the solar cell in this circuit is 7%, what is the junction area of the solar cell?

(8 marks)

Q2.

Draw the energy band diagram for an n^{+}-p-n transistor in saturation mode of operation. Indicate in the diagram, band gap, the conduction and valence band edges, Fermi levels, depletion regions, contact potential and the applied bias voltages V_{EB} and V_{CB}.

[4 marks]

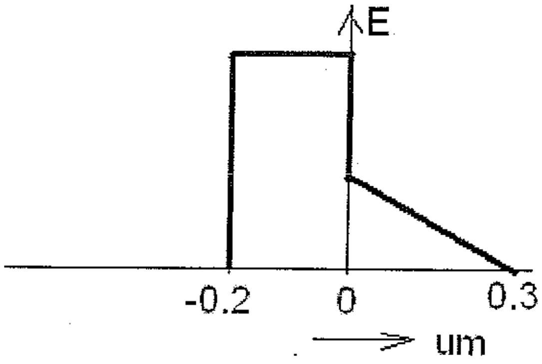
Q3.

Consider a p-n-p transistor operated at 300 K with emitter, base and collector doping levels set at $N_E = 10^{18}$ cm^{-3}, $N_B = 10^{16}$ cm^{-3} and $N_C = 10^{15}$ cm^{-3} respectively. The physical width of the base region is 1.0 μm. The emitter-base forward bias is 0.5V. To obtain a neutral base width of 0.5 μm, how much reverse bias has to be applied between the base-collector? Assume $n_i = 10^{10}$ cm^{-3}.

[10 marks]

Q4

A certain MOS structure is made with p-Si material as the semiconductor, SiO_2 as the oxide and Aluminum as the metal. The electric field distribution in the MOS structure for a certain operating condition is shown below:



Determine the MOS Capacitance. Assume unit area of cross section. Plot the potential distribution across the MOS structure

[5 marks]

Q5.

An n-channel Si JFET has p^+ regions doped with 10^{18} acceptors /cm^3 and an n-channel with 10^{16} donors/cm^3. Assume T = 300 K and $n_i = 10^{10}$ cm^{-3}. If the channel half width a is 1.5 μm, compare the pinch off voltage V_P for the JFET with the contact potential V_o for the p-n junction. The effect of the contact potential V_o is to provide an effective gate potential $V_G' = (V_G - V_o)$ instead of V_G. Determine the minimum drain voltage V_D needed to provide a saturation drain current for an applied gate voltage $V_G = -2$ V. The source terminal is grounded.

[5 marks]

END OF PAPER

Given: Bandgap of Si = 1.12 eV . Intrinsic carrier concentration n_i for Si at 300 K = 10^{10} cm^{-3}.
ε_r of Si = 11.8. ε_r of SiO_2= 3.9 Permittivity of free space = 8.85 x 10^{-14} Farad / cm.
Electronic Charge = 1.6 x 10^{-19} Coul. Boltzmann's constant = 1.38 x 10^{-23} J/K

EDIC III Year 2011-12 Sem 1 Test 1

Marking Scheme .

Q1 $n_o = n_i \exp\left[\frac{E_F - E_i}{kT}\right] = 10^{18}\,cm^{-3}$; $n_i = 10^{10}\,cm^{-3}$

kT = 0.026 eV at 300K

Solving, $E_F - E_i = 0.026 \ln\left[10^{18}/10^{10}\right] = 0.4789$ eV — ③

The probability for an electron to occupy the cond. band ~~eg~~edge E_c is $f(E) = \frac{1}{1+\exp\left[\frac{E_c - E_F}{kT}\right]}$ — ①

$E_c - E_i \approx \frac{E_g}{2} = 0.56$ eV Hence $E_c - E_F = 0.56 - 0.4789 = 0.081$ eV

$f(E) = \frac{1}{1+\exp\left[0.081/0.026\right]} = \underline{\underline{0.0423}}$ — ④

Q2.

(i)

$n_o = n_i\, exp\left[\frac{E_F - E_i}{kT}\right]$. $n_i = 4\times10^{13}\ cm^{-3}$. $(E_F - E_i) = 0.02$ eV. kT at 300 K = 0.0258 eV.

$n_0 = 8.68 \times 10^{13}\ cm^{-3}$. [2 marks]

$p_0 = n_i^2/n_0 = 1.842 \times 10^{13}\ cm^{-3}$ [2 marks]

(ii) From charge neutrality condition,

$N_D^+ + p_0 = N_A^- + n_o$

The sample is doped with donor impurities, so $N_A^- = 0$.

$N_D^+ + p_0 = n_o$ or, $N_D^+ = n_o - p_o = 6.8416 \times 10^{13}\ cm^{-3}$ [2 marks]

n_o has two contributions, one due to intrinsic property of the semiconductor, and the other due to impurities. In this case, both these contributions are of the same order. It is not justified to assume, $N_D^+ \approx n_o$ [1 marks]

(iii) If N_D is doubled, $N_D^+ = 2 \times 6.8416 \times 10^{13}\ cm^{-3} = 1.368 \times 10^{14}\ cm^{-3}$

From charge neutrality equation, $N_D^+ + n_i^2/n_0 = n_o$

Solving, $n_o = 1.476 \times 10^{14}\ cm^{-3}$. (The other solution is invalid)

Correspondingly, $p_o = n_i^2/n_o = 1.084 \times 10^{13}\ cm^{-3}$ [3 marks]

Furthermore, $n_o = n_i\, exp\left[\frac{E_F - E_i}{kT}\right]$

$(E_F - E_i) = kT.\ln((n_o/n_i)) = 0.0337$ eV

Initially, $(E_F - E_i)$ was 0.02 eV. Now, it is 0.0337 eV.

The intrinsic Fermi energy is almost at the mid band level, in both cases.

Hence, due to N_D being doubled, the Fermi energy E_F is shifted by 0.0137 eV towards the conduction band edge. [2 marks]

Q3

$N_D^+ = 10^{15}$ cm^{-3}
$n_o(\max) = 1.01 \times 10^{15}$ cm^{-3} at 400 K

From the equation $N_D^+ + n_i^2/n_0 = n_o$

$n_i^2 = n_o.(n_o - N_D^+)$
$= 1.01 \times 10^{28}$ cm^{-6} under limiting conditions

[5 marks]

Also, $n_i^2 = N_c N_v \, exp\left[-\frac{E_g}{kT}\right]$

kT at 400 K = (0.0258/300)x400 = 0.0344 eV.

Hence $E_g = kT. \ln[(N_cN_v)/n_i^2] = 0.8196$ eV [5 marks]

This is the **minimum** energy bandgap that will provide a $n_o(\max) = 1.01 \times 10^{15}$ cm^{-3}. Any value of E_g lower than this will result in more electron-hole pairs available in the semiconductor. [2 marks]

Q4

In the n-type region, $N_D^+ = 10^{16}$ cm$^{-3} \approx n_n$

$p_n = n_i^2/n_n = 10^{20}/10^{16} = 10^4$ cm^{-3}

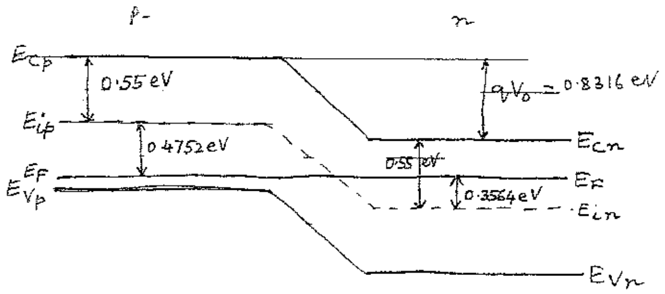
In the p-type region, $N_A^+ = 10^{18}$ cm$^{-3} \approx p_p$

$n_p = n_i^2/p_p = 10^{20}/10^{18} = 10^2$ cm^{-3}

At thermal equilibrium, $E_{Fn} = E_{Fp} = E_F$

Thus, for n-type, $E_F - E_{in} = (kT)\ln(n_n/n_i) = 0.0258.\ln(10^6) = 0.3564$ eV [3 marks]

for p-type, $E_{ip} - E_F = (kT)\ln(p_p/n_i) = 0.0258.\ln(10^8) = 0.4752$ eV [2 marks]



[3 marks]

Q5 Excess carrier generation rate $g_{op} = \frac{10^{13}}{10^{-6}}$ $cm^{-3}s^{-1}$

$g_{op} = 10^{19}$ $cm^{-3}s^{-1}$

Steady state excess carrier concentration ③

$\Delta n = \Delta p = g_{op} \times \tau_p = 2 \times 10^{13}$ cm^{-3}

~~Since the~~ To check for low injection, ~~chee~~ compare $\Delta n = \Delta p$ with majority carrier concentration.

For the problem, $\Delta n = \Delta p = 2 \times 10^{13}$ cm^{-3} ②

$n_0 = 1 \times 10^{18}$ cm^{-3}.

Since $\Delta n << n_0$ (less than 1%) it is low injection.

$n = n_0 + \Delta n = 1.00002 \times 10^{18} = 10^{10} \exp\left[\frac{E_{Fn} - E_i}{kT}\right]$

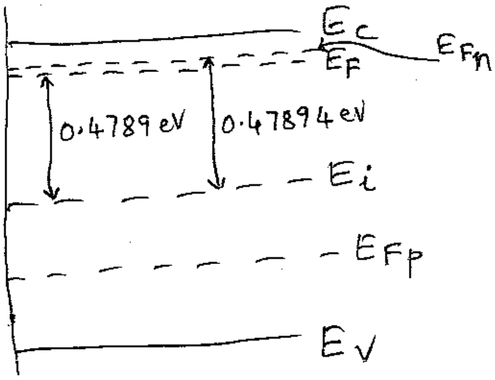
T = 300K, hence $kT = 0.026$ eV

$E_{Fn} - E_i = 0.47894$ eV

$p = p_0 + \Delta p = \frac{n_i^2}{n_0} + \Delta p = 10^2 + 2 \times 10^{13} \approx 2 \times 10^{13}$

$= 10^{10} \exp\left[\frac{E_i - E_{Fp}}{kT}\right]$ ⑤

$E_i - E_{Fp} = 0.1976$ eV



Set - A

NAME: ______________________________ ID NO. ________________________

BITS, PILANI – DUBAI
DUBAI INTERNATIONAL ACADEMIC CITY

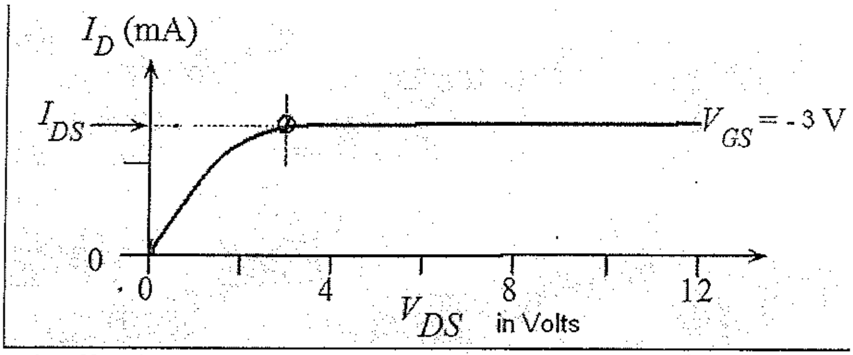
YEAR III EEE C381 – ELECTRONIC DEVICES & INTEGRATED CIRCUITS

Quiz 2 **Date: 30 Nov 2011** **Max marks: 14** **Weightage: 7%**

Answer ALL questions **Time allowed: 20 minutes**

Q1

A n-type Si with doping density $N_d = 5 \times 10^{16}\ cm^{-3}$ and thickness 2a is sandwiched between two p^+-Si layers. The p^+ ends are connected to the Gate with a potential V_G, one end of the sandwiched n region is tied to the source $V_S = 0V$, while the other end is tied to the drain potential, V_D. The JFET characteristic is as shown:



Determine the pinch off voltage, V_P. Hence determine the thickness of sandwiched n-region

[7 marks]

Q2.

Draw a model of a MOS capacitance indicating the relative contributions of the oxide and depletion capacitances as the applied voltage is varied.

[3 marks]

NAME: ______________________ ID NO. ______________________

Q3.

Under the influence of a forward bias of 0.65 volts across the E – B terminals, with emitter doped at 10^{18} cm^{-3} and the base doped at 10^{10} cm^{-3} determine the concentration of injected electrons and holes at either edge of the depletion region. Is this low level injection? Assume room temperature.

[4 marks]

List of Selected Formulae

For a JFET

$$W \approx \sqrt{\frac{2\varepsilon_s}{q}\left[\frac{1}{N_D}\right]V}$$

Table of Physical Constants

Physical Constant	Symbol	Value	Units
Electronic Charge	q	1.6×10^{-19}	C
Boltzmann's constant	k	8.625×10^{-5}	eV/K
Planck's constant	h	6.626×10^{-34}	J.s
Permittivity of free space	ε_o	8.85×10^{-14}	F/cm
Dielectric constant of Si	ε_{Si}	11.7	-
Dielectric constant of SiO_2	ε_{ox}	3.9	-
Electron mass	m	9.11×10^{-31}	kg
Speed of light	c	3×10^8	m/s
Intrinsic carrier concentration in Si at 300 K	n_i	10^{10}	cm^{-3}

NAME: ______________________ ID NO. ______________________

BITS, PILANI – DUBAI
DUBAI INTERNATIONAL ACADEMIC CITY

YEAR III EEE C381 – ELECTRONIC DEVICES & INTEGRATED CIRCUITS

Quiz 1 **Date: 2 Nov 2011** **Max marks: 16** **Weightage: 8%**

Answer ALL questions **Time allowed: 20 minutes**

Q1

A Si p-n junction is formed by doping acceptor atoms in the p-side ($N_a = 5 \times 10^{18} cm^{-3}$) and donor atoms in the n-side. The junction is at thermal equilibrium at 300 K. A contact potential of 0.85 V is observed. Fill up the following table:

Donor doping concentration N_D in the n-side	Electron concentration in the n-side far away from the depletion region	Hole concentration in the p-side far away from the depletion region	Electron concentration in the p-side far away from the depletion region	Hole concentration in the n-side far away from the depletion region
$3.15 \times 10^{15} cm^{-3}$	$3.15 \times 10^{15} cm^{-3}$	$5 \times 10^{18} cm^{-3}$	$20 cm^{-3}$	$3.168 \times 10^{4} cm^{-3}$

$$.85 = .026 \ln\left(\frac{N_a N_d}{10^{20}}\right)$$

[5 marks]

Q2.

For the problem in Q1, determine maximum electric field in the depletion region

[4 marks]

$$W = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_a}+\frac{1}{N_a}\right)V_0} = 5.913 \times 10^{-5} cm$$

$$V_0 = \frac{1}{2} \times W \times \mathcal{E}_0 \Rightarrow \mathcal{E}_0 = \frac{2V_0}{W} = 2.875 \times 10^{4} V/cm$$

Q3.

For the junction described in Q1 above, a forward bias of 0.7 V is applied. Estimate the depletion capacitance formed. Use an approximation $N_A >> N_D$. Assume unit area of cross section of the junction

[4 marks]

$$C_j = \frac{\epsilon_s}{W} \ ; \quad W = W_0 \sqrt{1 - \frac{V}{V_0}} = 2.484 \times 10^{-5} cm$$

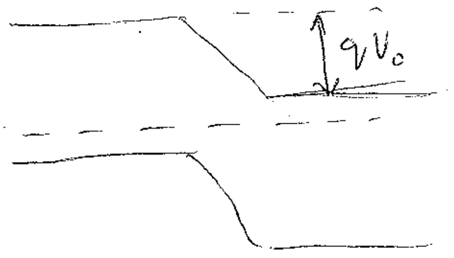
$$= 4.17 \times 10^{-8} F/cm^2$$

NAME: ______________________ ID NO. ____________________

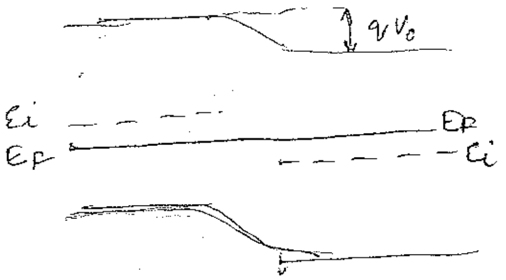
Q4

If a *p-n* junction is heated to a high temperature, how would the contact potential V_o change?
[Increase ? [✓ Decrease] ? Remain constant?] Explain using band diagram.

[3 marks]



Room temp



high temp

Both n + p semiconductors tend to move towards intrinsic nature when heated to high temp (since ni can become comparable or even greater than N_A or N_d) Hence qV_0 and V_0 is lower eventually zero.

List of Selected Formulae

For an abrupt p-n junction .

$$C_j = \frac{A\varepsilon_s}{W} \qquad V_o = \frac{kT}{q}\ln\frac{N_A N_D}{n_i^2} \qquad N_A x_p = N_D x_n \qquad W = \sqrt{\frac{2\varepsilon_s}{q}\left[\frac{1}{N_A}+\frac{1}{N_D}\right](V_o - V)}$$

Table of Physical Constants

Physical Constant	Symbol	Value	Units
Electronic Charge	q	1.6×10^{-19}	C
Boltzmann's constant	k	8.625×10^{-5}	eV/K
Planck's constant	h	6.626×10^{-34}	J.s
Permittivity of free space	ε_0	8.85×10^{-14}	F/cm
Dielectric constant of Si	ε_{Si}	11.7	-
Dielectric constant of SiO_2	ε_{ox}	3.9	-
Electron mass	m	9.11×10^{-31}	kg
Speed of light	c	3×10^8	m/s
Intrinsic carrier concentration in Si at 300 K	n_i	10^{10}	cm^{-3}

$$W = \sqrt{\frac{2\epsilon_s}{q} \cdot \left(\frac{1}{N_a} + \frac{1}{N_a}\right) \cdot V_0}$$

$$= 5.913 \times 10^{-5} \text{ cm}$$

$$= 0.5913 \ \mu\text{m}.$$

$$\frac{1}{2} \cdot W \times \mathcal{E}_0 = V_0.$$

$$\mathcal{E}_0 = \frac{2V_0}{W} = \underline{2.875 \times 10^{4}} \ \text{V/cm}.$$

$$W = \underbrace{\sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_a} + \frac{1}{N_a}\right)} \cdot \sqrt{V_0}}_{W_0} \cdot \left(\frac{\sqrt{V_0 - V}}{\sqrt{V_0}}\right)$$

$$= W_0 \cdot \sqrt{1 - (V/V_0)}$$

$$= 2.484 \times 10^{-5} \text{ cm}$$