Roll No.:.......................

National Institute of Technology, Delhi

Name of the Examination: B. Tech (Make Up)

Branch	**: ECE**	**Semester**	**: I**
Title of the Course	**: Solid State Devices**	**Course Code**	**: ECB 201**

Time: 3 Hours **Maximum Marks: 50**

Note:

- **Questions are printed on BOTH sides. Answers should be CLEAR ANDTO THE POINT.**
- **All parts of a single question must be answered together. ELSE QUESTION SHALL NOT BE EVALUATED.**

Use following data if not given in a problem: ε_o = 8.85x10^{-14}F/cm, ε_r (SiO_2) = 3.9, ε_r (Si) = 11.8, At room temperature for Si [μ_n = 1350cm^2/V·S, μ_p = 480 cm^2/V·S, n_i = 1.5x10^{10}/cm^3, E_g = 1.12 eV], k = 8.62 x10^{-5}ev/K, $\tau_n = \tau_p$= 1μs, E_g(Ge) = 0.7 eV, n_i (Ge)= 2.5x10^{13} /cm^3.

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1. Sketch qualitatively voltage vs. capacitance of an n-substrate MOS structure in absence of interface charges. Also present an equilibrium circuit combination of C_{ox}, C_{it} and C_d. [3+2]

2. Sketch and label 1/C^2 vs. increasing reverse bias of a pn junction diode having slope as 2x10^{22} $F^{-2}V^{-1}$ and intercept as 0.86 V at voltage axis. If the junction area is 1 μm^2, then find doping concentrations of both lightly and heavily doped regions of the pn junction diode. [2+3]

3. Draw and label properly the energy band diagram of a junction made by two different materials A and B whose data are given below: [5]

Material	Electron Affinity ($q\chi$)	Band Gap (E_g)	E_C - E_F	E_F - E_V
A (p-type)	4.5 eV	1.4 eV	--	0.3 eV
B (n-type)	4.5 eV	1.8 eV	0.3 eV	--

4. A metal-semiconductor (MS) junction is made between a metal of work function $q\varphi_m$ = 4.6 eV and a p-type Si doped with 1.5x10^{14} /cm^3 at room temp. Sketch and label the energy band diagrams across the MS junction before contact and after contact. [$q\chi_{Si}$ = 4.05 eV]. [2.5 + 2.5]

5. Consider a Ge crystal at room temperature doped with 5x10^{17} /cm^3 As atoms. Find equilibrium electron, hole concentrations and position of the Fermi level w.r.t intrinsic energy level (E_i) and conduction energy band (E_c). Draw the energy band diagram also. [5]

6. For a Si bar having length 4 μm. doped n-type at 10^{17} /cm^3. Calculate the current for an applied voltage of 2 V having a cross sectional area of 0.01 cm^2. If the voltage is now raised at 100 V what will be the change in current? Electron and hole mobilities are 1350 cm^2/V- [5]

sec and 400 cm^2/ V-sec for low electric field. For higher field, saturation velocity for electron is $V_s = 10^7$ cm/sec.

7. Consider a Si sample kept at room temperature having band gap $E_g = 1.12$ eV. [5]

(a) If the Fermi level E_F, is located exactly at the middle of the band gap for this sample, then what will be the probability of finding an electron at $E = E_C + 2KT$.

(b) If the Fermi level E_F, is located such that $E_F = E_V$, then what will be the probability of finding an electron at $E = E_V + KT$.

Note: Put *"Tick (√)" Marks* on the write option wherever applicable (Bold) / *Fill in the blanks.*

8. (a) In an *npn* Si/$Si_{1-x}Ge_x$ heterojunction bipolar transistor (HBT), base is **heavily/ lightly** doped and increases the **hole/ electron** injection efficiency. [2]

(b) Body or substrate bias effect **increases/ decreases** the current in MOSFETs and Boron ion implantation **increases/ decreases** the threshold voltage (V_T) in n-channel MOSFETs. [2]

(c) Usually in MOS scaling, the oxide layer thickness **increases/ decreases** and gate capacitance of the device **increases/ decreases**. [2]

(d) Substrate leakage current in n-MOS devices are due to secondary **electrons/ holes** and this current **increases/ reduces** at higher gate voltage. [2]

(e) Avalanche breakdown voltage **increases/ decreases** as band gap of the semiconductor increases and this voltage **increases/ decreases** as doping of the lighter region decreases. [2]

(f) The probability of finding an electron at an energy level 4kT above the Fermi level would be ____0.0183_______and number of electrons would be 0.0183×10^{19} /cm^3 if the density of states is 10^{19} /cm^3. [2]

(g) For a Si at a given temperature it is found that 1×10^{10} electrons/ cm^3 have moved from valance band (VB) to conduction band (CB) when density of atoms is 10^{22} /cm^3. Then number of holes in the VB would be ______10^{10}_______ and this will be a factor of value ________10^{-11}______ of the total available electrons in the VB. [3]

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Useful Equations

Fermi-Dirac e^- distribution: $f(E) = \dfrac{1}{e^{(E-E_F)/kT}+1} \equiv e^{(E_F-E)/kT}$ for $E \gg E_F$

Equilibrium: $n_0 = \displaystyle\int_{E_c}^{\infty} f(E)N(E)dE = N_c f(E_c) = N_c e^{-(E_c-E_F)/kT}$

$$N_c = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2} \quad N_v = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2} \quad \begin{aligned} n_0 &= n_i e^{(E_F-E_i)/kT} \\ p_0 &= n_i e^{(E_i-E_F)/kT} \end{aligned} \quad n_0 p_0 = n_i^2$$

$$p_0 = N_v[1-f(E_v)] = N_v e^{-(E_F-E_v)/kT}$$

$$n_i = N_c e^{-(E_c-E_i)/kT}, \quad p_i = N_v e^{-(E_i-E_v)/kT} \quad n_i = \sqrt{N_c N_v}\, e^{-E_g/2kT} = 2\left(\frac{2\pi kT}{h^2}\right)^{3/2} (m_n^* m_p^*)^{3/4} e^{-E_g/2kT}$$

$$\begin{aligned} n &= N_c e^{-(E_c-F_n)/kT} = n_i e^{(F_n-E_i)/kT} \\ p &= N_v e^{-(F_p-E_v)/kT} = n_i e^{(E_i-F_p)/kT} \end{aligned} \qquad np = n_i^2 e^{(F_n-F_p)/kT}$$

$$\frac{d\mathscr{E}(x)}{dx} = -\frac{d^2\mathscr{V}(x)}{dx^2} = \frac{\rho(x)}{\epsilon} = \frac{q}{\epsilon}(p - n + N_d^+ - N_a^-) \quad \mathscr{E}(x) = -\frac{d\mathscr{V}(x)}{dx} = \frac{1}{q}\frac{dE_i}{dx}$$

$$\frac{I_x}{A} = J_x = q(n\mu_n + p\mu_p)\mathscr{E}_x = \sigma\mathscr{E}_x$$

Diffusion length: $L \equiv \sqrt{D\tau}$ Einstein relation: $\dfrac{D}{\mu} = \dfrac{kT}{q}$

Continuity: $\dfrac{\partial p(x,t)}{\partial t} = \dfrac{\partial \delta p}{\partial t} = -\dfrac{1}{q}\dfrac{\partial J_p}{\partial x} - \dfrac{\delta p}{\tau_p}$ $\quad \dfrac{\partial \delta n}{\partial t} = \dfrac{1}{q}\dfrac{\partial J_n}{\partial x} - \dfrac{\delta n}{\tau_n}$

For steady state diffusion: $\dfrac{d^2\delta n}{dx^2} = \dfrac{\delta n}{D_n\tau_n} \equiv \dfrac{\delta n}{L_n^2}$ $\quad \dfrac{d^2\delta p}{dx^2} = \dfrac{\delta p}{L_p^2}$

Equilibrium: $V_0 = \dfrac{kT}{q}\ln\dfrac{p_p}{p_n} = \dfrac{\mathrm{kT}}{\mathrm{q}}\ln\dfrac{N_a}{n_i^2/N_d} = \dfrac{\mathrm{kT}}{\mathrm{q}}\ln\dfrac{N_a N_d}{n_i^2}$ $\quad \dfrac{p_p}{p_n} = \dfrac{n_n}{n_p} = e^{qV_0/kT}$ $\quad W = \left[\dfrac{2\epsilon(V_0-V)}{q}\left(\dfrac{N_a+N_d}{N_a N_d}\right)\right]^{1/2}$

Junction Depletion: $C_j = \epsilon A\left[\dfrac{q}{2\epsilon(V_0-V)}\dfrac{N_d N_a}{N_d+N_a}\right]^{1/2} = \dfrac{\epsilon A}{W}$

One-sided abrupt p^+-n: $x_{n0} = \frac{WN_a}{N_a + N_d} \simeq W$ $\quad V_0 = \frac{qN_d W^2}{2\epsilon}$

$$\Delta p_n = p(x_{n0}) - p_n = p_n(e^{qV/kT} - 1)$$

$$\delta p(x_n) = \Delta p_n e^{-x_n/L_p} = p_n(e^{qV/kT} - 1)e^{-x_n/L_p}$$

Ideal diode: $I = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)(e^{qV/kT} - 1) = I_0(e^{qV/kT} - 1)$

Stored charge exp. hole dist.: $Q_p = qA\int_0^\infty \delta p(x_n)dx_n = qA\Delta p_n \int_0^\infty e^{-x_n/L_p}dx_n = qAL_p\Delta p_n$

$$I_p(x_n = 0) = \frac{Q_p}{\tau_p} = qA\frac{L_p}{\tau_p}\Delta p_n = qA\frac{D_p}{L_p}p_n(e^{qV/kT} - 1)$$

$$I_{Ep} = qA\frac{D_p}{L_p}\left(\Delta p_E \operatorname{ctnh}\frac{W_b}{L_p} - \Delta p_C \operatorname{csch}\frac{W_b}{L_p}\right)$$

$$I_C = qA\frac{D_p}{L_p}\left(\Delta p_E \operatorname{csch}\frac{W_b}{L_p} - \Delta p_C \operatorname{ctnh}\frac{W_b}{L_p}\right)$$

Substrate bias: $\Delta V_T \simeq \frac{\sqrt{2\epsilon_s qN_a}}{C_i}(-V_B)^{1/2}$

Oxide: $C_i = \frac{\epsilon_i}{d}$ $\quad$ Depletion: $C_d = \frac{\epsilon_s}{W}$ $\quad$ MOS: $C = \frac{C_i C_d}{C_i + C_d}$

Inversion: $\phi_s\,(\text{inv.}) = 2\phi_F = 2\frac{kT}{q}\ln\frac{N_a}{n_i}$ (6-15) $\quad W = \left[\frac{2\epsilon_s\phi_s}{qN_a}\right]^{1/2}$

$Q_d = -qN_aW_m = -2(\epsilon_s qN_a\phi_F)^{1/2}$ (6-32) $\quad$ At V_{FB}: $C_{FB} = \frac{C_i\,C_{\text{debye}}}{C_i + C_{\text{debye}}}$

$$\Delta p_E = p_n(e^{qV_{EB}/kT} - 1)$$
$$\Delta p_C = p_n(e^{qV_{CB}/kT} - 1)$$

$$I_B = qA\frac{D_p}{L_p}\left[(\Delta p_E + \Delta p_C)\tanh\frac{W_b}{2L_p}\right]$$

$$B = \frac{I_C}{I_{Ep}} = \frac{\operatorname{csch} W_b/L_p}{\operatorname{ctnh} W_b/L_p} = \operatorname{sech}\frac{W_b}{L_p} \simeq 1 - \left(\frac{W_b^2}{2L_p^2}\right)$$

(Base transport factor)

$$\gamma = \frac{I_{Ep}}{I_{En} + I_{Ep}} = \left[1 + \frac{L_p^n n_n \mu_n^p}{L_n^p p_p \mu_p^n}\tanh\frac{W_b}{L_p^n}\right]^{-1} = \left[1 + \frac{W_b n_n \mu_n^p}{L_n^p p_p \mu_p^n}\right]^{-1}$$

(Emitter injection efficiency)

$\frac{i_C}{i_E} = B\gamma \equiv \alpha$ (7-3) $\quad \frac{i_C}{i_B} = \frac{B\gamma}{1 - B\gamma} = \frac{\alpha}{1-\alpha} \equiv \beta$ $\quad \frac{i_C}{i_B} = \beta = \frac{\tau_p}{\tau_t}$

(Common base gain) $\quad$ (Common emitter gain) $\quad$ (For $\gamma = 1$)