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Electrical and computer Engineering, Fall 2023 Breadth Exam

Problems 2/3/4 **TTG Area: Energy and Sustainability** **ECGR3133**

Solid State Electronics

Formula sheet

$<Q> = \frac{\int_{-\infty}^{\infty} \psi^* Q \psi\, dx}{\int_{-\infty}^{\infty} \psi^* \psi\, dx}$, $(\Delta x)(\Delta p) \geq \hbar$, $(\Delta E)(\Delta t) \geq \hbar$, $f(E) = \frac{1}{1+\exp(\frac{E-E_F}{kT})}$ E_n for an infinite quantum well = $(n\pi\hbar)^2/2mL^2$, $np = n_i^2$, $n_o = N_c \exp[-(E_c - E_F)/kT]$, $p_o = N_v \exp[-(E_F - E_v)/kT]$, $n_o = n_i \exp[(E_F - E_i)/kT]$, $p_o = n_i \exp[(E_i - E_F)/kT]$, $\sigma = q(n\,\mu_n + p\,\mu_p)$, $E(eV) = 1.24/\lambda(\mu m)$, $R_H = 1/qp$ or $R_H = -1/qn$, $q = 1.6\times10^{-19}$C, $h = 6.63\times10^{-34}$ J-s $= 4.14\times10^{-15}$ eV-s. $m_e = 9.11\times10^{-31}$ kg, $n_i(Si, 300K) = 1.5\times10^{10}$ cm^{-3}. $kT/q = 0.0259$ eV at 300K. $k = 1.38\times10^{-23}$ J/K $= 8.62\times10^{-5}$ eV/K. $J_n(x) = q\mu_n n(x)E(x) + qD_n \frac{dn}{dx}$, $J_p(x) = q\mu_p p(x)E(x) - qD_p \frac{dp}{dx}$,

$E(x) = \frac{D_p}{\mu_p}\frac{1}{p}\frac{dp}{dx}$ (built-in field), $E(x) = -\frac{D_n}{\mu_n}\frac{1}{n}\frac{dn}{dx}$, $\frac{D}{\mu} = \frac{kT}{q}$, $n_i^2 = N_c N_v \exp(-E_g/kT)$

$\delta n = \delta p = g_{op}\tau_n$, $\tau = \frac{1}{\alpha_r(n_o + p_0)}$, $\Delta\sigma = qg_{op}(\tau_n\mu_n + \tau_p\mu_p)$, $J_n(x) = \mu_n n(x)[\frac{dF_n}{dx}]$,

$E_o = -\frac{q}{\varepsilon}N_a x_p = -\frac{q}{\varepsilon}N_d x_n$

$$\boldsymbol{V_o = \frac{kT}{q}\ln\frac{p_p}{p_n} = \frac{kT}{q}\ln\frac{n_n}{n_p} = \frac{kT}{q}\ln\frac{N_a N_d}{n_i^2}} \qquad \boldsymbol{x_{p0} = \frac{WN_d}{N_a + N_d},} \qquad \boldsymbol{x_{no} = \frac{WN_a}{N_a + N_d}}$$

$$J_n(x) = q\mu_n n(x)[\frac{dF_n/q}{dx}] = \sigma_n[\frac{dF_n/q}{dx}], \quad J_p(x) = q\mu_p p(x)[\frac{dF_p/q}{dx}] = \sigma_p[\frac{dF_p/q}{dx}]$$

Under external reverse bias V_r:

$$W = \left[\frac{2\varepsilon V_o}{q}\left\{\frac{1}{N_a} + \frac{1}{N_d}\right\}\right]^{1/2} \Rightarrow \left[\frac{2\varepsilon(V_o + V_r)}{q}\left\{\frac{1}{N_a} + \frac{1}{N_d}\right\}\right]^{1/2}$$

W depends on $\sqrt{V_o}$

and

$$x_{p0} = \frac{WN_d}{N_d + N_a} = \left[\frac{2\varepsilon(V_o + V_r)}{q}\frac{N_d}{N_a(N_a + N_d)}\right]^{1/2}$$

$$x_{n0} = \frac{WN_a}{N_d + N_a} = \left[\frac{2\varepsilon(V_o + V_r)}{q}\frac{N_a}{N_d(N_a + N_d)}\right]^{1/2}$$

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1. A. Calculate the intrinsic carrier concentration in Si at T=350K given E_g=1.12 eV, $N_c = 2.8x10^{19}$, and $N_v = 1.04x10^{19}$. 15 points

1. B. Circle the correct answers: 20 points

A. The energy band in solids forms due:

a. The ionic nature of bonds, which leads to donation of electrons from one atom to a neighboring atom.
b. Interaction of valence electrons in the solid.
c. The uncertainty principle
d. Recombination of holes and electrons

B. Semiconductors are classified into direct and indirect bandgap materials. What criteria are used in this classification?

a. The conduction band minimum is located at the center of the lattice.
b. The semiconductor can directly conduct electricity using very low voltage
c. The valence band is totally filled and the conduction band is totally empty. Only external means of excitation can take the electrons to the conduction band.
d. The position of the conduction band minimum and the valence band maximum. If they have the same k value then the material is direct, otherwise indirect.
e. The doping level is very high and the carrier concentration does not obey the mass action law.
f. The conductivity depends on the direction of electron motion

C. Diffusion of carriers in a semiconductor is driven by:

a. Applied voltage
b. Concentration gradient
c. Steady-state uniform exposure to light

D. In compensated semiconductors, the Fermi level position depends on the

a. The sum of N_d and N_a
b. The difference between N_d and N_a
c. There will be two Fermi level for each dopant type
d. Density of state

2. In semiconductors, the electron and hole concentrations depend on the density of state and the probability of finding an electron at a given energy. Assume that the density of states is constant and equal to N_v in the valence band and N_c in the conduction band and given the Fermi-Dirac distribution function f(E)

$$f(E) = \frac{1}{1 + \exp(\frac{E - E_F}{kT})}$$

Calculate the electron concentration n and the hole concentration p knowing that $|E-E_F| >> kT$.

30 points

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3. A. Given the diode equation $I = I_o\,[\exp(qV/kT) - 1]$, approximate the relation for: (a) the case of forward bias ($qV > kT$), (b) the case of reverse bias, and (c) for $V = 0$ 20 points

3. B. The carrier concentration dependence on temperature is shown in the figure below. The plateau in the curve corresponds to $n_o = 10^{18}$ cm^{-3}. A. Indicate the dominating excitation mechanism in each region: intrinsic, ionization, extrinsic, mixture of more than one. 15 points

B. What is the doping density in the sample?