ELEG 340 - Fall 08
Solid-State Electronics
Quiz 3

23 October 2008 NAME Solution

Time Limit: 30 minutes

Closed Books and Notes. You may use your own calculator, but may not loan or borrow one (ask proctor if you have questions). Put expression in a final form as best you can.

Guidelines:

I. Full credit requires the final dimensions/ units for all numerical quantities that you calculate.

II. Show all work and calculations for full credit; accuracy to 2 significant figures is sufficient.

III. Assume that the material is silicon at room temperature (300 K), unless otherwise stated.

IV. At room temperature (300K), thermal energy $k_BT = 0.026$ eV, silicon has intrinsic concentration n_i = 1 (or 1.5) x 10^{10} cm^{-3}, and recombination lifetimes: τ_n, τ_p = 1 μsec; dielectric constant $\kappa_{Si} = 11.8$;.

Permittivity of free space $\varepsilon_o = 8.85 \times 10^{-14}$ F/cm; electron charge $|q| = 1.6 \times 10^{-19}$ Coul;

V. Equations:

$p_{op} = i\hbar d/dx$ $\quad f_{FD}(E) = 1/[1 + \exp(E-E_F)/k_BT]$ $\quad E = Q\,V$

$n = n_i\exp[(E_F-E_i)/k_BT]$. $\quad p = n_i\exp[(E_i-E_F)/k_BT]$ $\quad n_op_o = n_i^2$ $\quad np = n_i^2e^{(Fn-Fp)/kBT}$

$J_n = q\mu_n n\mathcal{E} + qD_n dn/dx$ $\quad J_p = q\mu_p p\mathcal{E} - qD_p dp/dx$ $\quad \sigma_{elec} = q(n\mu_n + p\mu_p)$

$U_n = (n_p-n_{po})/\tau_n$ $\quad U_p = (p_n-p_{no})/\tau_p$ $\quad p' = p - p_o = g_{opt}\tau_p$ $\quad n' = n - n_o = g_{opt}\tau_n$

$C_{dep} = \kappa_s\varepsilon_o A/W$ $\quad C_{diff} = qI\tau/k_BT$ $\quad D/\mu = k_BT/q$ $\quad L = \sqrt{(D\tau)}$

$\partial p/\partial t = -1/q\ \partial J_p/\partial x - p'/\tau_p$ $\quad \partial n/\partial t = -1/q\ \partial J_n/\partial x - n'/\tau_n$;

$\partial p/\partial t = D_p\ \partial^2 p/\partial x^2 - p'/\tau_p$ $\quad \partial n/\partial t = D_n\ \partial^2 n/\partial x^2 - n'/\tau_n$

score 23

$\varphi_{bi} = k_BT/q\ \ln(N_AN_D/n_i^2)$ $\quad W_{dep} = [2\kappa_s\varepsilon_o/q\ (1/N_A + 1/N_D)(\varphi_{bi} - V_F)]^{1/2}$

$I = qA(D_pp_n/L_p + D_nn_p/L_n)[e^{qV/kT} - 1] = I_o[e^{qV/kT} - 1]$;

$p_n(x_{no}) = p_{no}(x_{no})e^{qVf/kT}$; $\quad n_p(-x_{po}) = n_{po}(-x_{po})e^{qVf/kT}$

1. A sample of Ge at room temperature (300K) is p-type doped with $N_A = 1\times10^{16}$ cm^{-3}, which are fully ionized. For Ge at 300 K, $n_i = 2.5\times10^{13}$ cm^{-3}, hole mobility $\mu_p = 1900$ cm^2/V-s, and electron mobility $\mu_n = 3900$ cm^2/V-s. Calculate the electrical conductivity, σ.

$$\sigma = pq\mu_p = 10^{16} \text{cm}^{-3} \times 1.6\times10^{-19}\,C \times 1900\ \text{cm}^2/\text{V-s}$$

$$= 1.6\times1.9\times10^{16-19+3}\ \text{cm}^{-3+2}\ \frac{\text{Coul}}{\text{V-s}}$$

$$= 1.6\times1.9\ \frac{1}{\Omega\text{-cm}}$$

$$= 3.1\ S/\text{cm}$$

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2. A one-sided step junction of silicon is uniformly doped with $N_A = 10^{18}$ cm^{-3} on the p-side, and $N_D = 10^{15}$ cm^{-3} on the n-side. Assume that the built-in (contact) voltage is $\varphi_{bi} = 0.7$ volts. What is the equilibrium depletion width, W_{dep}?

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$$W = \sqrt{\frac{2K_S\epsilon_0}{qN_D}\phi_{bi}}$$

$$= \left[\frac{2\times11.8\times8.85\times10^{-14}\,F/\text{cm}}{1.6\times10^{-19}\,C\times10^{15}\,\text{cm}^{-3}}\times0.7\,V\right]^{1/2}$$

$$= \left[\frac{2\times1.18\times8.85\times0.7}{1.6}\times\underbrace{10^{-14+1+19-15}}_{10^{-9}}\ \frac{F\cdot V\,\text{cm}}{C}\right.$$

$$= \left[\frac{2\times1.18\times0.885\times0.7}{1.6}\right]^{1/2}\times10^{-4}\ \text{cm}$$

$$= 0.9\ \mu m$$

3. A junction of silicon has an equilibrium depletion width W = 0.5 μm. Calculate the depletion capacitance per area C'_{dep}, in thermal equilibrium. (Hint: the text calls C_{dep} the "junction" capacitance)

$$C' = \frac{K_S \epsilon_0}{W} = \frac{11.8 \times 8.85 \times 10^{-14} F/cm}{0.5 \times 10^{-4}\ cm}$$

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$$= 2 \times 1.18 \times 0.885 \times 10^{1+1-14+4}\ F/cm^2$$

$$\approx 1 \times 10^{-8}\ F/cm^2$$

4. Consider a one-sided step junction of silicon, uniformly doped with $N_A = 10^{18}$ cm^{-3} on the p-side, and $N_D = 10^{16}$ cm^{-3} on the n-side. (a) calculate the equilibrium concentration of minority holes at the depletion edge of the n-side, $p_{no}(x_{no})$. (b) using the law of the junction, calculate the new concentration of holes at the depletion edge $p_n(x_{no})$ under a forward bias $V_F = +0.5$ volts.

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a) $$p_{no} = \frac{n_i^2}{N_D} = \frac{10^{20}\ cm^{-6}}{10^{16}\ cm^{-3}} = 10^4\ cm^{-3}$$

b) $$p_n(x_{no}) = p_{no} e^{qV/kT}$$

$$= 10^4\ cm^{-3}\, e^{\underbrace{0.5/0.026}_{\approx 0.5 \times 40 = 20}}$$

$$e^{20} \approx 10^8$$

$$\approx 10^{12}\ cm^{-3}$$

5. A junction of silicon under forward bias V_F has a concentration of minority holes at the depletion edge on the n-side, $p_n(x=x_{no})$ given by the law of the junction. The *excess* concentration of holes, $p_n' = p_n - p_{no}$, decays exponentially as $e^{-x/Lp}$. With this x-dependence, calculate an analytical expression for the diffusion current (only) of holes that flows under this concentration gradient. Hint: ignore any other currents that may be flowing.

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$$p_n'(x_n') = p_{no}\left(e^{qV/kT} - 1\right)e^{-x_n'/L_p}$$

$$J_p = -q D_p \frac{dp_n}{dx}$$

$$\boxed{J_p = +q \frac{D_p p_{no}}{L_p}\left(e^{qV/kT} - 1\right)}e^{-x_n'/L_p}$$

$x_n' = 0$ at $x = x_{no}$

6. Sketch the I-V characteristics of a *real* (non-ideal) pn junction diode and label on your drawing the following regions: (a) forward bias ; (b) reverse bias ; (c) breakdown ; (d) your choice of *one* other effect such as generation/recombination current, or Ohmic limit.

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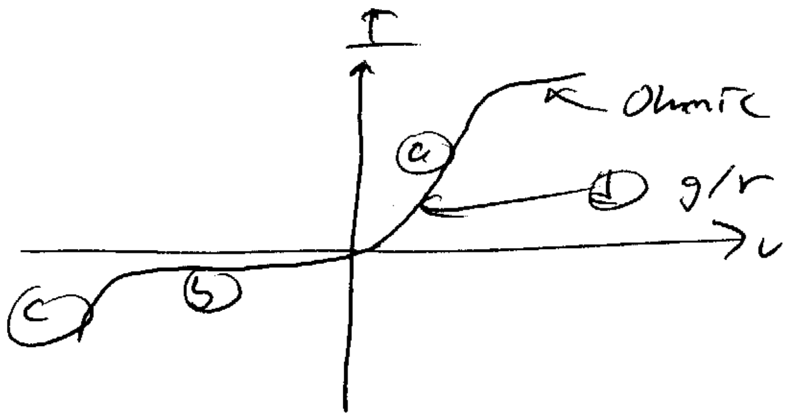

7. Sketch the band diagram of your choice of a metal-semiconductor junction, and indicate whether the semiconductor is n-type or p-type, and whether your band diagram shows a rectifying or Ohmic contact.

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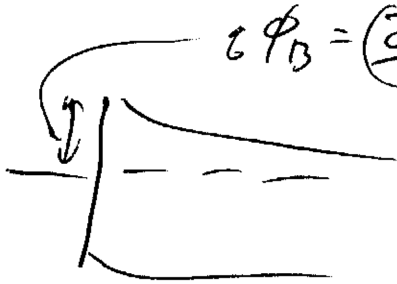
$q\phi_B = (\Phi_m - \chi) q$



rectifying

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n-type