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PUID: _____

ECE 305 – Fall 2018

Exam 3 – Thursday, March 22, 2018

This is a closed book exam. You may use a calculator and the formula sheet at the end of this exam. Following the ECE policy, the calculator **must** be a Texas Instruments TI-30X IIS scientific calculator.

To receive full credit, you must **show your work** (scratch paper is attached).

The exam is designed to be taken in 60 minutes (or less). Be sure to fill in your name and Purdue student ID at the top of the page. DO NOT open the exam until told to do so, and stop working immediately when time is called. The last 2 pages are equation sheets, which you may remove, if you want.

100 points possible,

I) 40 points (8 points per question)

II) 30 points

III) 30 points

Course policy

If I am caught cheating, I will earn an F in the course & be reported to the Dean of Students.

I repeat: _____

Signature: _____

Part I: Answer the 5 multiple choice questions below by entering them on your IDP-15 Scantron.

1 (8 points). Which of the following quantities have a linear relationship for a $n^+ - p$ junction?

- a. $1/N_A$ vs V_R
- b. N_D vs V_R
- c. $1/C_j^2$ vs $1/N_A$
- d. $1/C_j^2$ vs V_R
- e. N_D vs V_{bi}

2 (8 points). Why does photogenerated current in a pn junction flow in the opposite direction compared to current generated in the same pn junction under forward bias?

- a. The electron-hole pairs generated far from the junction are driven primarily by the electric field
- b. Photons generate holes only; forward-biased pn junctions generate electrons only
- c. Reverse bias is necessary to absorb photons which gives rise to the current
- d. Photons generate electron-hole pairs; forward-biased pn junctions recombine electron-hole pairs
- e. All of the above

3 (8 points). What dominates the current beyond the reverse bias breakdown voltage in Schottky diode?

- a. Carrier avalanche
- b. Recombination in the space-charge region
- c. Quantum-mechanical tunneling
- d. Series resistance
- e. Diffusion current

4 (8 points). For an ideal metal-semiconductor diode made from p-type GaAs, which current term dominates under reverse bias?

- a. Electron injection from the metal to semiconductor
- b. Electron injection from the semiconductor to metal
- c. Hole injection from the semiconductor to metal
- d. Hole injection from the metal to semiconductor
- e. Electron-hole recombination in the semiconductor

5 (8 points). To make an ohmic contact to an n-type semiconductor without using metal, we can replace the metal with:

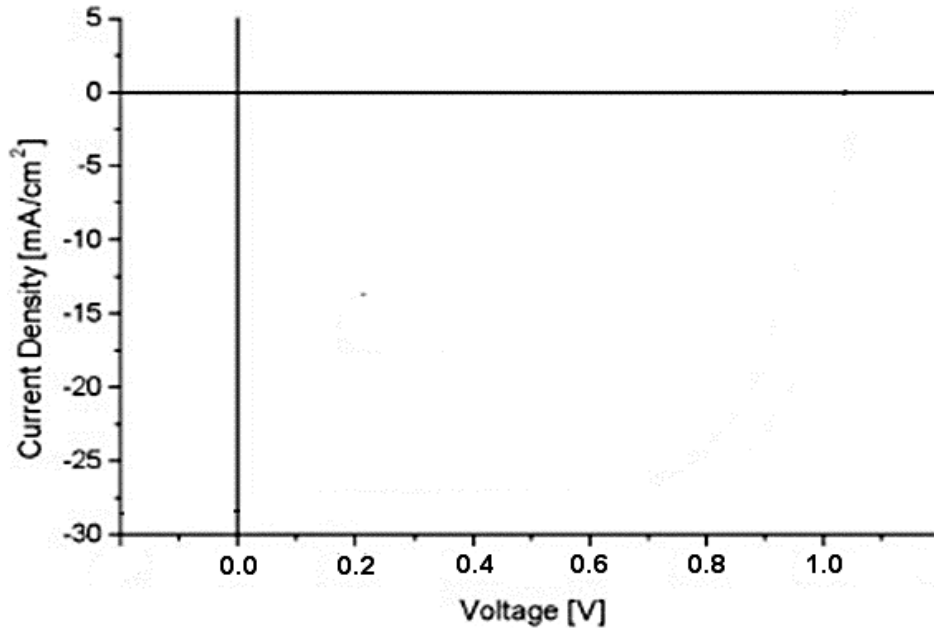
- a. An oxide, forming a heterojunction
- b. A n^+ semiconductor, forming a homojunction
- c. A p^+ semiconductor, forming a homojunction
- d. a or b
- e. a or c

Part III (Free Response, 30 points)

Assume that we have a p-n junction solar cell with dark current per unit area $J_o = 0.4 \text{ nA/cm}^2$, short circuit current per unit area $J_{sc} = 22.5 \text{ mA/cm}^2$, ideality factor $n = 1.6$, and cross sectional area $A=10^{-4} \text{ cm}^2$. Note that the solar constant $P_{in} = 100 \text{ mW/cm}^2$.

- a. Calculate the open-circuit voltage (V_{oc}) and fill factor of this cell. Hint: use $FF = \frac{z_{oc} - \ln(z_{oc} + 0.72)}{z_{oc} + 1}$, where $z_{oc} = qV_{oc}/nk_B T$ is the reduced open-circuit voltage.

- b. Draw the current density-voltage relation for this cell on the graph below, for voltages between 0 and V_{oc} . Label the x- and y-intercepts.



- c. Compare the efficiency of this solar cell quantitatively to one made of a metal-silicon (Schottky) diode with identical properties, except for its dark current, which is determined by Richardson's equation, with $\Phi_{BN} = 0.7 \text{ eV}$ and $m_n^* = 0.26m_o$.

ECE 305 Exam 3 Formula Sheet (Spring 2018)

You may remove these pages from the exam packet, and take them with you.

Physical Constants	Silicon parameters ($T = 300$ K)
$h/2\pi = \hbar = 1.055 \times 10^{-34}$ J·s	$N_C = 3.23 \times 10^{19}$ cm ⁻³
$m_0 = 9.109 \times 10^{-31}$ kg	$N_V = 1.83 \times 10^{19}$ cm ⁻³
$k_B = 1.38 \times 10^{-23}$ J/K	$n_i = 1.1 \times 10^{10}$ cm ⁻³
$q = 1.602 \times 10^{-19}$ C	$K_s = 11.8$
$\epsilon_0 = 8.854 \times 10^{-12}$ F/m	$E_g = 1.12$ eV; $\chi = 4.03$ eV

Miller Indices: (hkl) {hkl} [hkl] <hkl>

Density of states $g_C(E) = \frac{(m_n^*)^{3/2} \sqrt{2(E-E_C)}}{\pi^2 \hbar^3}$

Fermi function $f(E) = \frac{1}{1+e^{(E-E_F)/kT}}$

Intrinsic carrier concentration $n_i = \sqrt{N_C N_V} e^{-E_g/2kT}$

Equilibrium carrier densities: $N_C = \frac{1}{4} \left(\frac{2m_n^* kT}{\pi \hbar^2} \right)^{3/2}$

$N_V = \frac{1}{4} \left(\frac{2m_p^* kT}{\pi \hbar^2} \right)^{3/2}$

$n_0 = N_C e^{(E_F - E_C)/kT} = n_i e^{(E_F - E_i)/kT}$

$p_0 = N_V e^{(E_V - E_F)/kT} = n_i e^{(E_i - E_F)/kT}$

Space charge neutrality: $p - n + N_D^+ - N_A^- = 0$

Law of Mass Action: $n_0 p_0 = n_i^2$

Non-equilibrium carriers: $n = N_C e^{(F_N - E_C)/kT}$ $p = N_V e^{(E_V - F_P)/kT}$ $np = n_i^2 e^{(F_N - F_P)/kT}$

Conductivity/resistivity: $\sigma = \sigma_n + \sigma_p = q(n\mu_n + p\mu_p) = 1/\rho$

Drift-diffusion current equations: $J_n = nq\mu_n \mathcal{E}_x + qD_n \frac{dn}{dx} = n\mu_n \frac{dF_n}{dx}$ $\frac{D_n}{\mu_n} = \frac{kT}{q}$

$J_p = pq\mu_p \mathcal{E}_x - qD_p \frac{dp}{dx} = p\mu_p \frac{dF_p}{dx}$ $\frac{D_p}{\mu_p} = \frac{kT}{q}$

Carrier conservation equations: $\frac{\partial n}{\partial t} = +\nabla \cdot \left(\frac{J_n}{q} \right) + G_n - R_n$

$\frac{\partial p}{\partial t} = -\nabla \cdot \left(\frac{J_p}{q} \right) + G_p - R_p$

Poisson's equation: $\nabla \cdot (\epsilon \mathcal{E}) = \rho$

SRH carrier recombination: $R = \Delta n / \tau_n$ or $R = \Delta p / \tau_p$

Minority carrier diffusion equation: $\frac{\partial \Delta n}{\partial t} = D_n \frac{\partial^2 \Delta n}{\partial x^2} - \frac{\Delta n}{\tau_n} + G_L$ $L_{D,n} = \sqrt{D_n \tau_n}$

PN homojunction electrostatics: $V_{bi} = \frac{kT}{q} \ln \left(\frac{N_D N_A}{n_i^2} \right)$ $\frac{d\mathcal{E}}{dx} = \frac{\rho(x)}{K_s \epsilon_0}$

$W = \sqrt{\frac{2K_s \epsilon_0 V_{bi}}{q} \left(\frac{N_A + N_D}{N_A N_D} \right)}$ $x_n = \left(\frac{N_A}{N_A + N_D} \right) W$ $x_p = \left(\frac{N_D}{N_A + N_D} \right) W$ $\mathcal{E}(0) = \sqrt{\frac{2qV_{bi}}{K_s \epsilon_0} \left(\frac{N_A N_D}{N_A + N_D} \right)}$

PN diode current: $\Delta n(0) = \frac{n_i^2}{N_A} (e^{qV_A/kT} - 1)$ $\Delta p(0) = \frac{n_i^2}{N_D} (e^{qV_A/kT} - 1)$

$J_D = J_o (e^{qV_A/kT} - 1)$ $J_o = q \left(\frac{D_n}{L_n} \frac{n_i^2}{N_A} + \frac{D_p}{L_p} \frac{n_i^2}{N_D} \right)$ (long) $J_o = q \left(\frac{D_n}{W_p} \frac{n_i^2}{N_A} + \frac{D_p}{W_n} \frac{n_i^2}{N_D} \right)$ (short)

Non-ideal diodes: $I = I_o (e^{q(V_A - IR_s)/kT} - 1)$ $J_{gen} = -q \frac{n_i}{2\tau_o} W$

Photovoltaics: $V_{oc} = \frac{nkT}{q} \ln \left(\frac{J_{sc}}{J_o} \right)$ $J_{PV} = J_o (e^{qV_A/kT} - 1) - J_{sc}$

Small signal model: $G_d = \frac{I_D + I_o}{kT/q}$ $C_J = \frac{K_s \epsilon_o A}{\sqrt{\frac{2K_s \epsilon_o V_{bi}}{q N_A}}} = A \sqrt{\frac{q K_s \epsilon_o N_A}{2V_{bi}}}$ $C_D = G_d \tau_n$

MS diode properties: $qV_{bi} = |\Phi_M - \Phi_S|$ $\Phi_{BP} = \chi + E_G - \Phi_M$ $\Phi_{BN} = \Phi_M - \chi$

$J_D = J_o (e^{qV_A/kT} - 1)$ $J_o = A^* T^2 e^{-\Phi_B/kT}$ $A^* = \frac{4\pi q m^* k_B^2}{h^3} = 120 \frac{m^*}{m_o} \frac{A}{cm^2 \cdot K^2}$