NAME:_____FULL SOLUTION_________ **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 II (Free Response, 30 points)

Consider a crystalline silicon n-p step homojunction ideal diode at room temperature (T=300 K). The n-type region has doping N_D=2·10^{17} /cm^3, width $W_N = 5$ µm, minority carrier μ_p=150 cm^2/V·s and minority carrier τ_p=1 µs. The p-type region has doping N_A=3·10^{18} /cm^3, width $W_P = 10$ µm, minority carrier μ_n=300 cm^2/V·s, and minority carrier τ_n=3 µs at T=300 K. Assume the dopants are fully ionized.

a. Calculate whether the diode is long or short, and the dark current density J_0 of the diode.

   D_n=300*0.0259=7.8 cm^2/s; L_n=sqrt(D_n * τ_n)=48 µm

   D_p=150*0.0259=3.9 cm^2/s; L_p=sqrt(D_p * τ_p)=20 µm; therefore it is short on both sides.

   Jo=q* ni^2 *[Dn /(W_p*N_A) + Dp/(W_n*N_D)]   (short)

   =(1.6e-19 C)*(1e20/cm^6)[7.8 cm^2/s/(1.0e-3 cm*3e18/cm^3) + 3.9 cm^2/s/(5e-4 cm*2e17/cm^3)]

   =6.65e-13 A/cm^2=0.665 pA/cm^2

b. For crystalline silicon, assume that the critical breakdown field is $\mathcal{E}_{cr} = 2 \cdot 10^5$ V/cm. The V_{bi} of this device is 0.936 V. Use this information to calculate the reverse breakdown voltage V_{BR} of the diode.

   Ecr^2=2q(Vbi+Vbr)*ND/(Ks*eps0) (one-sided)

   Vbi+Vbr=Ecr^2*Ks*eps0/(2q*ND)

   Vbr=(2e5 V/cm)^2 * (11.8 * 8.854e-14 F/cm)/(2*1.6e-19 C*2e17 / cm^3)- 0.936

   V_{BR} =0.653-0.936 = -0.283 V

c. Assume that the critical breakdown field scales as the square of the bandgap voltage. For aluminum gallium arsenide with a bandgap of 1.94 eV, with otherwise identical parameters as silicon, what is the corresponding value of V'_{BR}at which breakdown would be expected?

   If Ecr'^2=3Ecr^2=2q(Vbi+Vbr)*NA*ND/(NA+ND)*(Ks*eps0)

   $V_{bi} + V'_{BR}$=3 * [Ecr^2*Ks*eps0/(2q*ND)]=3*1.306=3.918

   $V'_{BR} = 1.959 - 0.936$ V

   V'_{BR}=1.023 V.

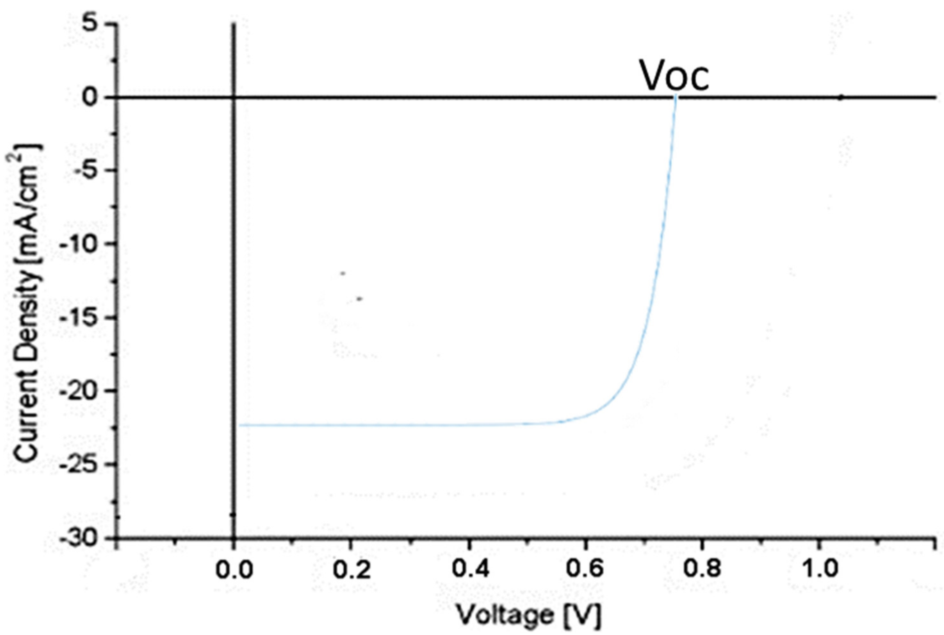
Part III (Free Response, 30 points)

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

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

$z_{oc} = 17.84$, FF=0.792, $V_{oc} = 0.74$ V.

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 $\Phi_{BN} = 0.7$ eV and $m_n^* = 0.26m_o$.

For the PN diode, $\eta_{PN} = \frac{J_{sc}V_{oc}FF}{P_{in}} = \frac{(22.5\ \mathrm{mA/cm^2})(0.74\ \mathrm{V})\cdot(0.792)}{100\ \mathrm{mW/cm^2}} = 0.132$

For a Schottky diode $J_o = A^*T^2e^{-\Phi_B/kT} = 5.14\ \mu\mathrm{A/cm^2}$, so $z_{oc} = 8.38$, $V_{oc} = 0.347$ V, FF=0.658.

$\eta_{MS} = \frac{(22.5\ \mathrm{mA/cm^2})(0.347\ \mathrm{V})\cdot(0.658)}{100\ \mathrm{mW/cm^2}} = 0.051$, which is less than half of the prior device performance.

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	$N_C = 3.23 \times 10^{19}\ \text{cm}^{-3}$
$m_0 = 9.109 \times 10^{-31}$ kg	$N_V = 1.83 \times 10^{19}\ \text{cm}^{-3}$
$k_B = 1.38 \times 10^{-23}$ J/K	$n_i = 1.1 \times 10^{10}\ \text{cm}^{-3}$
$q = 1.602 \times 10^{-19}$ 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: $N_C = \frac{1}{4}\left(\frac{2m_n^* kT}{\pi\hbar^2}\right)^{3/2}$ $\quad N_V = \frac{1}{4}\left(\frac{2m_p^* kT}{\pi\hbar^2}\right)^{3/2}$

$n_0 = N_C e^{(E_F-E_C)/kT} = n_i e^{(E_F-E_i)/kT}$ $\quad p_0 = N_V e^{(E_V-E_F)/kT} = n_i e^{(E_i-E_F)/kT}$

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

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

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

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

Drift-diffusion current equations:

$$J_n = nq\mu_n \mathcal{E}_x + qD_n\frac{dn}{dx} = n\mu_n\frac{dF_n}{dx} \qquad \frac{D_n}{\mu_n} = \frac{kT}{q}$$

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

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

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

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

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

$J_D = J_o\left(e^{qV_A/kT} - 1\right)$ $J_o = q\left(\frac{D_n}{L_n}\frac{n_i^2}{N_A} + \frac{D_p}{L_p}\frac{n_i^2}{N_D}\right)$ *(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: $I = I_o\left(e^{q(V_A - IR_s)/kT} - 1\right)$ $J_{gen} = -q\frac{n_i}{2\tau_o}W$

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

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

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

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