NAME:______________________________ **PUID:**________________________

ECE 305 – Spring 2018

Final Exam (Exam 5) – Thursday, May 3, 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). However, the full two hours will be allowed, if you need them. 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 3 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.

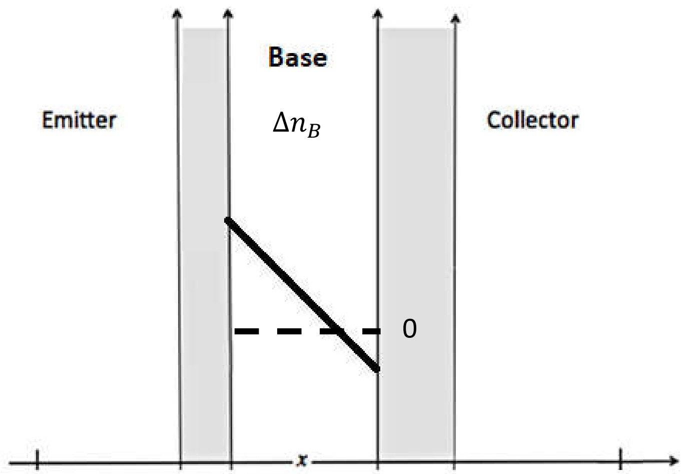
I repeat: ____

____

Signature: ____

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

1 (8 points). Which is true for the npn BJT given the information below?



a. The BJT is operating in the saturation mode
b. The BJT has negligible recombination at base
c. The BJT is operating in the forward active mode
d. Both a. and b.
e. Both b. and c.

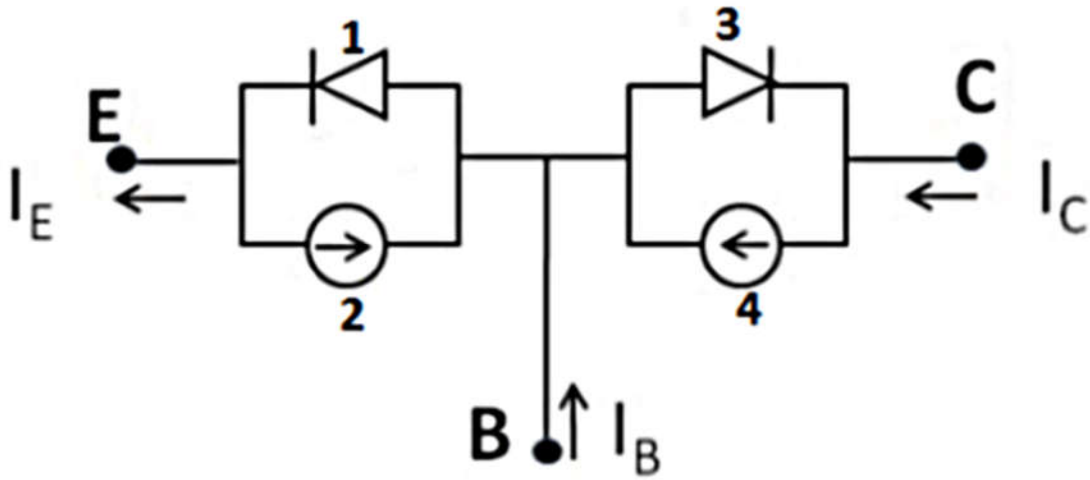
2 (8 points). Maximizing which of the following ratios increases the gain in a bipolar junction transistor?

a. Ratio of emitter to base doping
b. Ratio of emitter to collector doping
c. Ratio of base to emitter band gap
d. Ratio of base to emitter width
e. None of the above

3 (8 points). Compared to forward active mode, ____ in the inverted active mode.

a. the emitter injection efficiency is typically higher
b. the emitter injection efficiency is typically lower
c. the base transport factor is typically lower
d. the base transport factor is typically higher
e. the base transit time is typically longer

4 (8 points). Which of the following components of the Ebers-Moll model depicted below cannot be neglected in describing the reverse active mode?

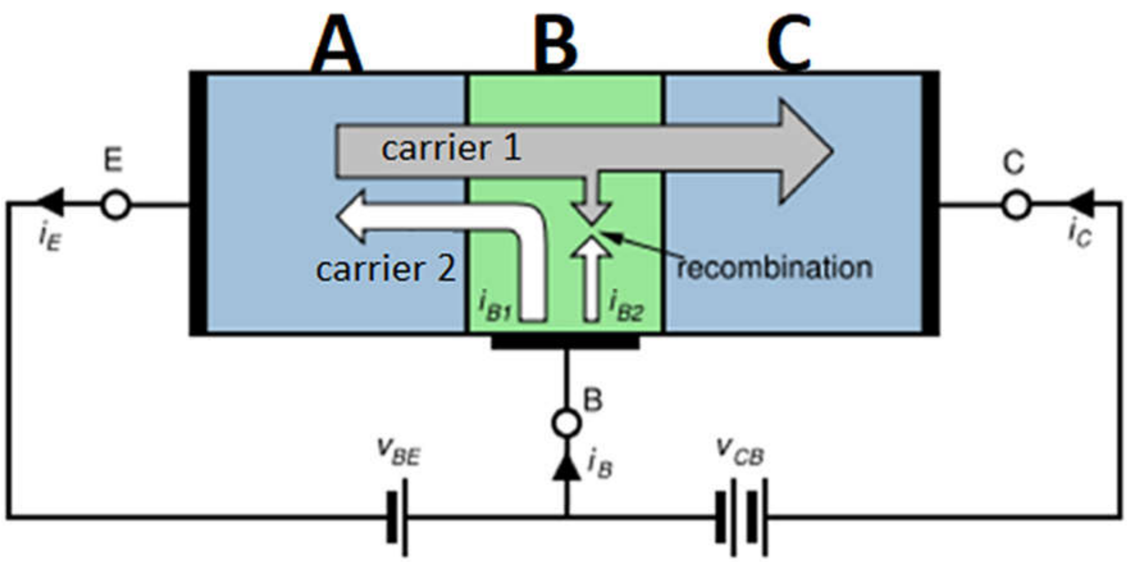


a. 1,4
b. 1,3
c. 1
d. 2,4
e. 2,3

5 (8 points). The Early effect in a BJT is caused by which phenomenon?

a. Quantum mechanical tunneling
b. Impact ionization
c. SRH recombination
d. The decreasing width of the quasi neutral (flat-band) region in the base
e. Current crowding

Part II (Free Response, 30 points)



The schematic of a silicon BJT is shown above, where i_E, i_C, and i_B are emitter current, collector current, and base current respectively, with the arrows showing the current directions. The three regions A, B, and C in the schematic have dopant concentrations of 10^{17} cm^{-3}, 10^{16} cm^{-3} , and 10^{15} cm^{-3} respectively.

a. Name the type of carrier represented by carrier 1 in the diagram. From that, state the dopant type (donor or acceptor) for region B.

b. If the silicon in region B is replaced with another semiconductor with a larger bandgap (e.g., gallium arsenide), and the emitter current is held constant, what do you expect to happen to i_B?

Continued on next page….

Part II (continued)

Assume that the BJT is operating in the forward active region, with I_C=8 µA; thicknesses W_E=0.6 µm, W_B=0.3 µm, and W_C=2.2 µm; minority carrier diffusion constants D_A=2 cm²/s, D_B=20 cm²/s, D_C=12 cm²/s for regions A, B, and C; and minority carrier diffusion length L_{nB}=1.2 µm for region B.

c. What is the emitter injection efficiency γ_F?

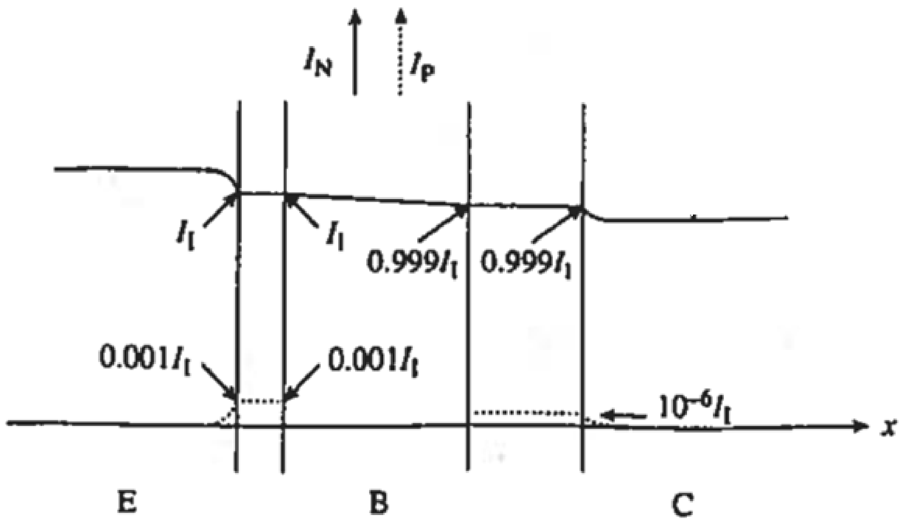
d. What is the base transport factor α_T?

e. What is the common base current gain α_{dc}?

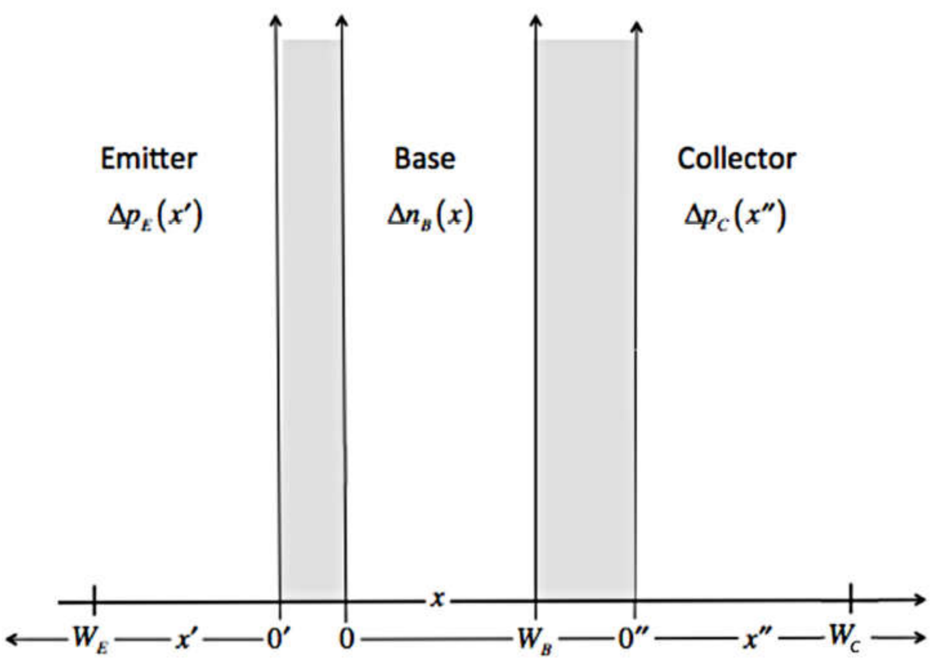
f. What is the emitter gain β_{dc}?

Part III (Free Response, 30 points)

Consider the electron and hole currents (I_N and I_P, respectively) for a npn BJT plotted below. The recombination currents can be neglected everywhere.



a. Sketch the corresponding excess carrier concentration in all the white regions below. Justify your sketch.

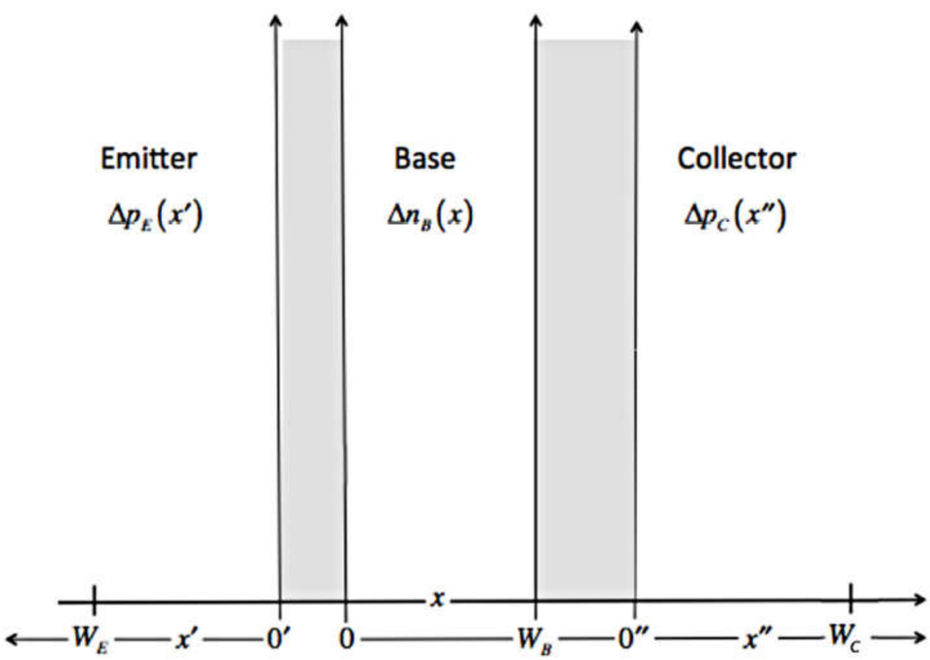


Continued on next page….

Part III (continued)

b. Write down the base current due to excess minority carriers in terms of $\Delta n_B(0)$, $\Delta n_B(W_B)$, and W_B (and other relevant constants). How is this related to I_1 from the diagram above?

c. Sketch the excess carrier concentration in all the white regions if V_{CB} flips its sign (i.e., is inverted), but everything else remains the same. What is the name of the resulting mode of operation for this BJT?



ECE 305 Exam 5 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)**
$/2\pi = \quad = 1.055 \times 10^{-34}$ 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 $g_C(E) = \frac{(m_n)^{3/2}\sqrt{2(E-E_C)}}{\pi^2 \quad ^3}$

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: $N_C = \frac{1}{4}\left(\frac{2m_n kT}{\pi \quad ^2}\right)^{3/2}$ $\qquad N_V = \frac{1}{4}\left(\frac{2m_p kT}{\pi \quad ^2}\right)^{3/2}$

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

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

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

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

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

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

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

Poisson's equation: $\nabla \quad (\epsilon \quad) = \rho$

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

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

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

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

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

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

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

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

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

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

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

MOS capacitors: $W = \sqrt{\frac{2K_s\epsilon_o\phi_s}{qN_A}}$ cm $\qquad _s = \sqrt{\frac{2qN_A\phi_s}{K_s\epsilon_o}}\ \frac{\mathrm{V}}{\mathrm{cm}}$

$$Q_B = \quad qN_A W(\phi_s) = \quad \sqrt{2qK_s\epsilon_o N_A\phi_s}\ \frac{\mathrm{C}}{\mathrm{cm^2}}$$

$$V_G = V_{FB} + \phi_s + \Delta\phi_{ox} = V_{FB} + \phi_s \quad \frac{Q_s(\phi_s)}{C_{ox}}$$

$$C_{ox} = K_o\epsilon_o/x_o \qquad V_{FB} = \Phi_{ms}/q \quad Q_F/C_{ox}$$

$C = C_{ox}/\left[1 + \frac{K_o W(\phi_s)}{K_s x_o}\right]$ $\qquad V_T = \quad Q_B(2\phi_F)/C_{ox} + 2\phi_F$ $\qquad Q_n = \quad C_{ox}(V_G \quad V_T)$

MOSFETs: $I_D = \quad WQ_n(y=0)\ v_y(y=0)$

$I_D = \frac{W}{L}\mu_n C_{ox}(V_{GS} \quad V_T)V_{DS}$ $\qquad I_D = WC_{ox}v_{sat}(V_{GS} \quad V_T)$

Square Law (for $V_{GS} \geq V_T$): $I_D = \begin{cases} \frac{W}{L}\mu_n C_{ox}[(V_{GS} \quad V_T)V_{DS} \quad V_{DS}^2/2], & 0 \leq V_{DS} \leq V_{GS} \quad V_T \\ \frac{W}{2L}\mu_n C_{ox}(V_{GS} \quad V_T)^2, & V_{DS} \geq V_{GS} \quad V_T \end{cases}$

Bipolar transistors: (assuming NPN, short emitter, base, and collector)

Ebers-Moll Equations:

$$I_C(V_{BE}, V_{BC}) = \alpha_F I_{F0}\left(e^{qV_{BE}/k_BT} - 1\right) - I_{R0}\left(e^{qV_{BC}/k_BT} - 1\right)$$

$$I_E(V_{BE}, V_{BC}) = I_{F0}\left(e^{qV_{BE}/k_BT} - 1\right) - \alpha_R I_{R0}\left(e^{qV_{BC}/k_BT} - 1\right)$$

$$I_{F0} = qA\left(\frac{D_{nB}}{W_B}\frac{n_i^2}{N_{AB}} + \frac{D_{pE}}{W_E}\frac{n_i^2}{N_{DE}}\right)$$

$$I_{R0} = qA\left(\frac{D_{nB}}{W_B}\frac{n_i^2}{N_{AB}} + \frac{D_{pC}}{W_C}\frac{n_i^2}{N_{DC}}\right)$$

$$\alpha_F = \gamma_F \alpha_T$$

$$\alpha_R = \gamma_R \alpha_T$$

$$\alpha_F I_{F0} = \alpha_R I_{R0}$$

$$\gamma_F = \frac{I_{En}}{I_{En} + I_{Ep}} = \frac{1}{1 + \frac{D_{pE}}{D_{nB}}\frac{W_B}{W_E}\frac{N_{AB}}{N_{DE}}}$$

$$\alpha_T = \frac{I_{Cn}}{I_{En}} = \frac{1}{1 + \frac{1}{2}\left(\frac{W_B}{L_{nB}}\right)^2}$$

$$\beta_F = \frac{\alpha_F}{1 - \alpha_F}$$

$$\alpha_F = \frac{\beta_F}{1 + \beta_F}$$