USAF ACADEMY
DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

ECE 321
Electronics I
Fall 2016
Graded Review #1

ACADEMIC TESTING MATERIAL

ACADEMIC SECURITY: This examination is not released from academic security until 1630 on Monday, 26 September 2016. Until this time, you may not discuss the examination contents or the course material with anyone other than your instructor.

INTEGRITY: Your honor is extremely important. This academic security policy is designed to help you succeed in meeting academic requirements while practicing the honorable behavior our country rightfully demands of its military. Do not compromise your integrity by violating academic security or by taking unfair advantage of your classmates.

AUTHORIZED RESOURCES: Attached equation sheet and one 8.5 x 11 " reference sheet you create.

- You have 90 minutes.
- Box your final answer where appropriate.
- Show all work to qualify for partial credit.
- Organize your work. Your instructor must be able to follow your solution process.
- Use engineering notation with three significant figures for final answers. Do not round intermediate results.

PROBLEM	VALUE	EARNED
1 Knowledge/Comprehension	40	
2 Comprehension/Application	40	
3 Analysis	40	
4 Analysis	40	
5 Design	40	
Total	200	

NAME Solution & Cutsheet SECTION_____

Documentation:

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Multiple Choice General Knowledge

1. (40 points - 8 points each)
1.1 An ideal non-inverting voltage amplifier features

a) zero input resistance (R_i), zero output resistance (R_o)
b) zero input resistance (R_i), infinite out resistance (R_o)
c) infinite input resistance (R_i), zero output resistance (R_o)
d) infinite input resistance (R_i), infinite output resistance (R_o)
e) none of the above

1.2 A non-ideal voltage amplifier suffers from

a) infinite bandwidth
b) finite bandwidth
c) infinite open-loop gain
d) infinite closed-loop gain
e) none of the above

1.3 Increasing the operating temperature of a semiconductor device will generally

a) increase the effective density of states, N_c and N_v.
b) increase the thermal voltage, $V_T = kT/q$.
c) increase the intrinsic carrier concentration, n_i^2.
d) decrease the mobility of carriers μ_n and μ_p.
e) all of the above

1.4 In an intrinsic silicon semiconductor, the Fermi level, E_F, is generally near

a) the conduction band edge, E_C.
b) the valence band edge, E_V.
c) the middle of the band gap.
d) 0.56 eV below the valence band edge, E_V.
e) 0.56 eV above the conduction band edge, E_C.

1.5 The dominant current in a reverse-biased diode (not in breakdown) results from

a) drift current
b) diffusion current
c) recombination current
d) high injection current
e) none of the above

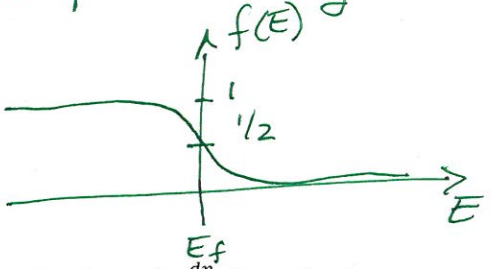
2. (40 pts - 10 points each)

2.1 Describe in your own words what is meant by the Fermi function, $f(E)$. How does $f(E)$ change with increasing energy E? What value does $f(E)$ have when $= E_F$? Sketch $f(E)$ vs. E.

def (4) decreases with E (3) $f(E_F)$ (3)

The Fermi function shows probability of an electron having energy E.

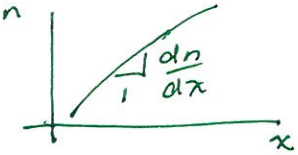
$f(E_f) = 1/2$



2.2 Diffusion current density for electrons is given by $J_n = qD_n\frac{dn}{dx}$. Describe in your own words what is meant by the gradient term $\frac{dn}{dx}$. Use a sketch to support your answer.

def (5) picture (3) current direct. (2)

dn/dx is the change in concentration of electrons, n, wrt x. In the picture dn/dx is the slope of $n(x)$. The slope is positive. Higher concentration of n on the right indicates diffusion to the left and hence current to the right



2.3 Drift current density for electrons is given by $J_n = qn\mu_n E$. Describe in your own words what is meant by the mobility term μ_n. How does it change with temperature? How does it change with doping level?

def (5) effect of T (3) Current direction (2)

Mobility is the ratio of drift velocity to electric field $v_{drift,n} = -\mu_n E$ In positive E electrons drift at velocity (speed) $\mu_n E$ in the negative direction leading to positive current. Mobility, μ_n, generally decreases with increasing temperature.

2.4 When a pn junction is created, a region called the depletion layer (or depletion region or space charge region) is formed. Explain the rationale for the name(s) and describe the electric field that results.

Creation of ions fixed (5) Electric field E direction (5)

Electrons leave (diffuse) area of high conentration, N-type, and go to P-type filling shell in acceptors. Free carriers are depleted, and fixed charged ions (positive in N and negative in P) are created. The resulting $\bar{E}$ field points from positive ions to negative ions, so from N-type to P-type.

Semiconductor Physics - Analysis

3. (40 pts) You decide to use intrinsic gallium arsenide (GaAs) to fabricate your high speed integrated circuit. Answer the questions below regarding GaAs. The band gap for GaAs $E_g = 1.42$ eV; $N_C = 4.7 \times 10^{17}/\text{cm}^3$; $N_V = 9.0 \times 10^{18}/\text{cm}^3$. Use $kT = 25$ meV ($T = 290°K$).

3.1 (10 pts) Determine the intrinsic carrier concentration for GaAs.

Equation (5)
Values (3)
Ans (2)

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

$$= \sqrt{4.7\cdot 10^{17} \cdot 9.0\cdot 10^{18}}\, e^{-1.42/(2)(0.025)}$$

$$= 9.53\cdot 10^{5}/\text{cm}^3$$

3.2 (15 pts) Determine the intrinsic Fermi level, E_i, at room temperature relative to the conduction band edge, E_C. Does E_i lie above or below middle of the gap?

Equation (6)
Values (3)
Ans (2)

$$n = N_c e^{-(E_c - E_F)/kT} \Rightarrow n_i = N_c e^{-(E_c - E_i)/kT}$$

above mid-gap

$$E_c - E_i = kT \ln\left(\frac{N_c}{n_i}\right) = 25\,\text{meV} \ln\left(\frac{4.7\cdot 10^{17}}{9.53\cdot 10^{5}}\right) = 673.\ \text{meV}$$

(4) E_i is 673 meV below E_c which is above the middle of gap.

3.3 (15 pts) You decide to use donor doping to increase the carrier concentration. Assume you found $E_i = 0.70$ eV below E_c and $n_i = 10^6/\text{cm}^3$. What is the maximum **nondegenerate** donor doping concentration?

rationale 9
equation 4
answer 2

E_F could rise to $3kT$ below E_c before semiconductor becomes degenerate

$3kT = 75$ meV so E_f rises by 625 meV

this corresponds to $e^{625\,\text{meV}/25\,\text{meV}}$ increase over n_i =>

$$n \sim N_d = 9.53\cdot 10^{5} \cdot e^{625/25}$$

$$= 7.20\cdot 10^{16}/\text{cm}^3$$

pn Junction Diode

4. (40 pts) You fabricated a silicon (Si) pn junction diode with $N_d = 10^{15}/\text{cm}^3$, $N_a = 10^{16}/\text{cm}^3$, $n_i = 1.5 \times 10^{10}/\text{cm}^3$, and $E_g = 1.12$ eV. Use $kT/q = 25.0$ mV.

4.1 (10 pts) Calculate the built-in voltage, V_{bi} (Hu referred to this value as ϕ_{bi}; Sedra and Smith call it V_0.)

Equation 5

Values 3

Ans 2

$$V_{bi} = V_T \ln\left(\frac{N_a N_d}{n_i^2}\right) = 25\text{mV} \cdot \ln\left(\frac{10^{16} \cdot 10^{15}}{(1.5 \cdot 10^{10})^2}\right) = 613.\text{mV}$$

4.2 (10 pts) Calculate the depletion width, W, when $V_A = 0$. Use $V_{bi} = 0.7$ V in place of the answer you found above.

Equation 5

Values 3

Ans 2

$$W = \sqrt{\frac{2\epsilon_{si}}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)V_{bi}} = \sqrt{\frac{2(11.7)(8.854 \cdot 10^{-14})}{1.6 \cdot 10^{-19}}\left(\frac{1}{10^{16}} + \frac{1}{10^{15}}\right)0.7}$$

$$= 99.85 \cdot 10^{-6}\ \text{cm} = 0.9985 \cdot 10^{-4}\ \text{cm} = 0.999\ \mu\text{m}$$

4.3 (10 pts) Sketch an energy band diagram when the applied voltage, $V_A = 0$ V. Label the n and p sides. Clearly indicate E_V, E_C, E_i, E_F, and qV_{bi}.

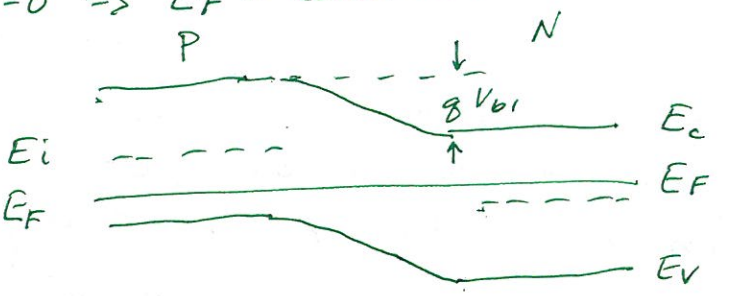
2 ea label

+2 correct relation

$E_c - E_F$

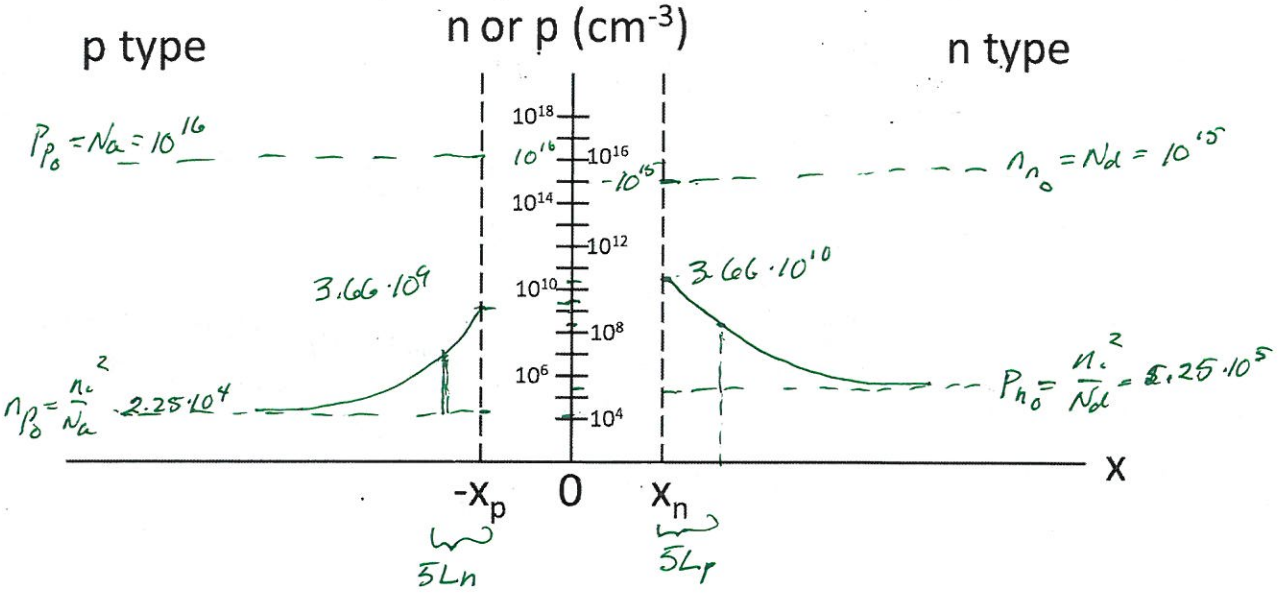
$E_F - E_V$

$V_A = 0 \Rightarrow E_F = \text{constant}$



$E_F - E_V$ p side $<$ $E_c - E_F$ n side

4.4 (10 pts) You apply a forward bias of $V_A = 0.3$ V. Using the numbers from above, sketch $p_n(x)$, p_{n_0}, p_{p_0}, $n_p(x)$, n_{p_0}, and n_{n_0} at the appropriate values. Qualitatively label L_n and L_p. Note that $-x_p$ and x_n are **not** drawn to scale.



increase in minority carriers

$e^{0.3/0.025} = 1.63 \cdot 10^{5}$

$n_p(-x_p) = 3.66 \cdot 10^{9}$

$p_n(x_n) = 3.66 \cdot 10^{10}$

L_n / L_p is decay by 63.2% or 0.368

$5\,L_n / L_p$ decay by about 99.3% or to 0.00674

1 pt each at $-x_p$ or x_n

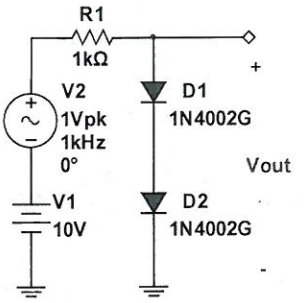
1 pt each shape of "decay"

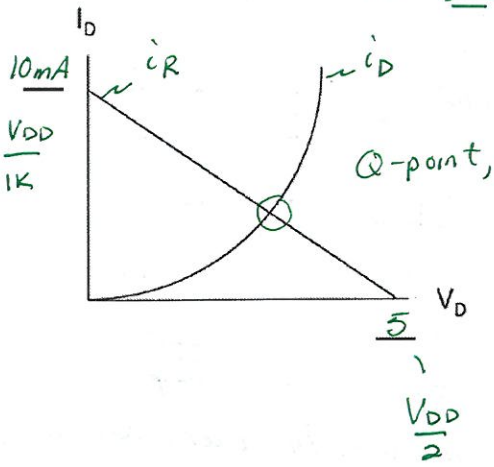
1 pt each for some reasonable attempt at L_p L_n

pn Junction Diode – Large and Small Signal Model

5 (40 pts) You want to use a pn junction diode ($I_s = 10$ nA and $n = 1.4$) in the circuit below for voltage regulation. Assume $V_{bi} = 0.9$ for this junction. Use $V_T = kT/q = 25.0$ mV.

5.1 (10 pts) Circuit the location of the operating point and fill in labels for the end points of the load line. V_D is the voltage across one of the two diodes. The voltage across the other diode is the same.





5.2 (10 pts) Determine the operating point using numerical iteration. Stop when the difference is less than 1% for V_D.

0 guess

1 KVL to get current

2 shockley to get V_D

repeat

process 8

answer 2

did not double V_D -2

$V_D = 0.7$V	$2V_D = 1.4$	$V_R = 8.6$	$I_R = 8.6$mA	$V_D = 0.478$	) actually could stop here
0.478V	0.957V	9.04V	9.04mA	0.480	) < 1%
0.480V	0.960V	9.04V	9.04mA	0.480	

$V_D = 0.480$ V $\quad I_D = 9.04$ mA

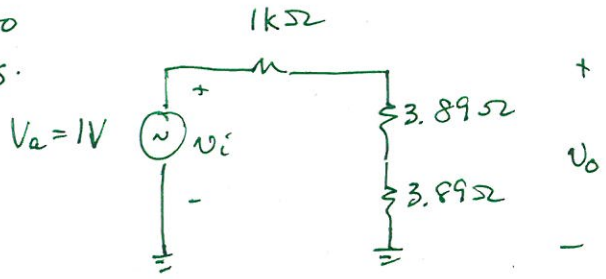
5.3 (10 pts) Assume you found $I_D = 9.0$ mA. What is the small signal resistance r_d at the operating point? Draw the small signal model. Is the small-signal model appropriate for analyzing the system? (Hint: Find the maximum change in the voltage across the diodes and determine if it is small enough for the model to be valid.)

r_d - 4 pts

ΔV_d - 3 pts

compare to nV_T - 3 pts.

$$r_d = \frac{nV_T}{I_D} = \frac{1.4 \cdot 25mV}{9\,mA} = 3.89\,\Omega$$



$$\Delta v_d = 1V \cdot \frac{3.89}{1K + 2(3.89)}$$

$$= 3.86\,mV$$

$$nV_T = 35\,mV$$

$\Delta v_d \ll nV_T$ almost a factor of 10

$\Rightarrow$ probably valid

5.4 (10 pts) What is the peak-to-peak voltage of the output, V_{out}, based on the 2-V_{pp} input signal? Based on this result, what is the line regulation of the voltage regulator.

Output due to $2V_{pp}$ input +5

$$v_{in-pp} = 2V$$

Line reg +5

$$v_{out\,pp} = 2V_{pp} \cdot \frac{2 \cdot (3.89)}{1K + 2 \cdot (3.89)} = 7.72\,\frac{mV_{pp}}{V_{pp}} \cdot 2\,V_{pp}$$

$$= 15.4\,mV_{pp}$$

The line regulation divides out the input

$\Rightarrow$ line regulation $= 7.72\,mV/V$

or $0.772\,\%$

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