Solutions to Exam 1 EE 461G Spring 2000

This exam is closed book and closed notes. You may use only this test booklet and your calculator. Any equations or constants you might need are in an equations sheet at the end of the exam. Under no circumstances can you speak to or exchange calculators, etc. with other students in the class.

Total Points: 100
Time: 80 minutes (8am – 9:20am)

- Write your name at the top of the exam and your initials at the top of each sheet.
- Sign the honor pledge at the end of the exam.
- Show all of your work. Try to use only the pages provided (write on back if necessary)
- Give units in your answer.
- Note the point value of each question and try to at least attempt each problem. Partial credit will be given for all problems involving calculations.

***True or False**: For each of the following statements, circle T if it is true and F if it is false.*

2 pts. each.

T [✓ F] 1. Circuits with nonlinear elements *do* obey the *Superposition Principle*.

[✓ T] F 2. In an *intrinsic semiconductor*, the number of free electrons is equal to the number of holes.

T [✓ F] 3. In an extrinsic semiconductor, *acceptor* and *donor* impurities both provide extra electrons which alter the conductivity of the material.

[✓ T] F 4. At room temperature, an n-type dopant provides an extra electron and a positively charged ion.

T [✓ F] 5. The depletion layer in a pn junction contains a large number of free carriers such as electrons and holes.

[✓ T] F 6. For a diode with $V_D > Vf$, the piecewise linear model is a straight line modeled by a resistor and a voltage supply.

[✓ T] F 7. In an nMOS transistor, during active operation there is an “inversion layer” of electrons underneath the gate oxide.

[✓ T] F 8. The threshold voltage, V_{TR}, of an enhancement-mode nMOS transistor is greater than that of a depletion-mode nMOS transistor.

[✓ T] F 9. The emitter-base junction of a BJT must be forward biased for current to flow through the device.

T [✓ F] 10. The collector-base junction of a BJT must be forward biased for forward-active operation.

[✓ T] F 11. Semiconductor materials have a mostly empty *conduction band* and a small *band gap*, Eg, (relative to electron thermal energy level at room temperature).

T [✓ F] 12. There are more free carriers available at low temperatures than there are at high temperatures.

***Multiple Choice**: <u>Circle</u> the answer that best fits the question. (26 points)*
3 pts. each.

13. Which of the following is NOT needed for graphical analysis of a circuit with one nonlinear element:

a) Thevenin equivalent circuit at the two ports of the nonlinear element

b) Plot of the nonlinear element i-v characteristics

[✓ c) A quadratic equation representing the entire circuit]

d) Load line representing the Thevenin equivalent circuit

14. Which of the following does NOT describe a *hole* as defined in electronics:

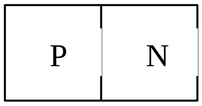
a) the absence of an electron in the valence band

[✓ b) the absence of an atom in a semiconductor crystal]

c) behaves like a positively charged carrier

d) can contribute to the conduction of current

15. In creating a depletion layer in the P-N junction shown here, which <u>*one*</u> statement IS true:



a) holes flow from right to left

b) electrons flow from left to right

c) hole diffusion current is from right to left

[✓ d) electron diffusion current is from left to right]

16. Which of the following is NOT a factor in *diode breakdown* (consider all types of diodes):

a) very high electric fields in the depletion layer

[✓ b) very strong forward bias voltages]

c) high energy electrons create avalanche breakdown

d) quantum mechanical tunneling

17. Which type of diode is commonly operated under reverse bias:

[✓ a) Zener diode]

b) Tunnel diode

c) Schottky diode

d) standard P-N junction diode

18. Which of the following electronic components has a linear i-v characteristic:

a) MOSFET

[✓ b) Resistor]

c) Bipolar Transistor

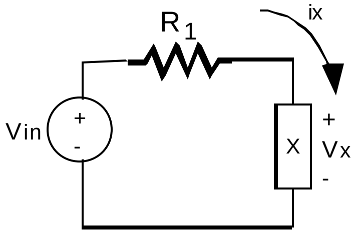
d) P-N Diode

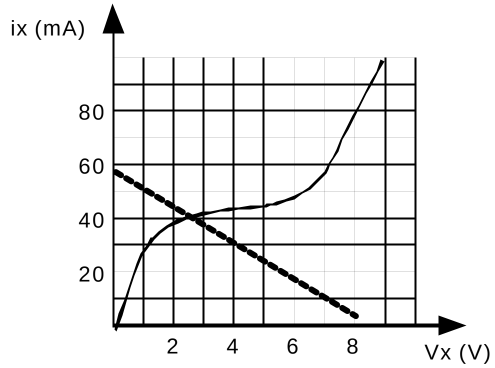
19. For each of the following, circle which type of transistor the item is associated:
1 pt. each.

[✓ MOSFET]	BJT	gate oxide
[✓ MOSFET]	BJT	channel region
MOSFET	[✓ BJT]	collector and emitter terminals
[✓ MOSFET]	BJT	channel length modulation
[✓ MOSFET]	BJT	body effect
MOSFET	[✓ BJT]	Early voltage
[✓ MOSFET]	BJT	threshold voltage
MOSFET	[✓ BJT]	base width modulation

Calculation*: Solve the following problems in the space provided and on the backs of these pages if necessary. You may work on scrap paper, but you must show the major steps on these test pages.*

20. Graphical Solutions: An unknown device X is connected to a resistive circuit. The device has an i-v curve shown below. *5 pts.*





(a) If Vin = 8V and R_1 = 133Ω, plot the load line for the resistive circuit on the ix-vx plot.

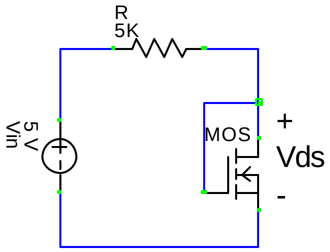
isc = Vin / R1 = 8 / 133 = 60 mA - y-axis intercept
Vin = 8 V - x-axis intercept

(b) Estimate the operating point of the circuit (i_x and Vx)

i_x = 40 mA

Vx = 2.5 V

21. Iterative Solutions: The circuit shown here consists of a "diode connected" nMOS transistor ($V_{GS} = V_{DS}$), and a Thevenin equivalent circuit. Assume that the nMOS device is in saturation with a current i_D so that it acts as a simple square law device with constants k and V_{TR}. *10 pts.*



(a) Write the two equation that describe this circuit (1 KVL eqn. and 1 MOS eqn.).

$\text{Vin} - V_{DS} = i_D \text{ R1}$

$i_D = k\,(V_{GS} - V_{TR})^2,\ V_{DS} = V_{GS}$

(b) Write the "root equation" for this circuit. $f\,(V_{DS}) = 0$.

$(\text{Vin} - V_{DS}) / \text{R1} - k\,(V_{DS} - V_{TR})^2 = 0 = f\,(V_{DS})$
or
$\text{Vin} - V_{DS} - \text{R1}\,k\,(V_{DS} - V_{TR})^2 = 0 = f\,(V_{DS})$

(c) Write the derivative of the "root equation" from part (c). $df\,(V_{DS})/\,dV_{DS} = 0$.

$-1 / \text{R1} - 2\,k\,(V_{DS} - V_{TR}) = 0 = df\,(V_{DS}) / dV_{DS}$
or
$1 + 2\,\text{R1}\,k\,(V_{DS} - V_{TR}) = 0 = df\,(V_{DS}) / dV_{DS}$

22. <u>pn Junction Diode</u>: A diode is operated at room temperature with Is = 10^{-10} A and η=2.

10 points

(a) What is the diode current i_D if the voltage across the diode is V_D = 0.65V?

i_D = Is {exp($V_D/\eta V_T$) – 1} = 10^{-10} {exp(0.65/0.05) – 1}

<u>i_D = 44.2 μA</u>

(b) What is the diode current i_D if the voltage across the diode is V_D = -1V?

If V_D is negative, the diode is in reverse bias and <u>i_D = 0 A</u>
(Actually, i_D = -Is = -10^{-10} A ≅ 0)

(c) What voltage V_D is required for a diode current of 200μA?

$V_D = \eta V_T \ln(1 + i_D/Is) = (2)(0.025) \ln(1 + 200\mu/10^{-10})$

<u>V_D = 0.725 V</u>

23. <u>Bipolar Transistor</u>: A BJT has a base current of i_B = 5μA and a gain of β_F = 150 V/V.

10 points

(a) If the BJT is operating in the forward active region, what is the value of the collector current, i_C? Assume we can ignore effect of V_A for now.

$i_C = \beta_F i_B$ = (150) (5μ)

<u>i_C = 750 μA</u>

(b) What is the value of the emitter current, i_E?

$i_E = i_C + i_B$ = 750μ + 5μ

<u>i_E = 755 μA</u>

(c) If V_A = 75, what is i_C at V_{CE} = 5V?

$i_C = \beta_F i_B (1 + V_{CE} / V_A)$ = (150) (5μ) (1+ 5 / 75)

<u>i_C = 800 μA</u>

24. MOS Current Flow: For each of the following conditions, identify the region of operation and calculate the drain current, i_D, in an MOS transistor. Assume $k = 0.5\ mA/V^2$, $V_{TR} = 1\ V$

10 points

(a) $V_{GS} = 0.5$, $V_{DS} = 5$, $V_{SB} = 0$

$V_{GS} < V_{TR}$ so the device is OFF

$i_D = 0\ A$

(b) $V_{GS} = 2.5$, $V_{DS} = 5$, $V_{SB} = 0$

$V_{GS} > V_{TR}$, $V_{DS} > (V_{GS} > V_{TR})$, so it's in the Saturation Region

$i_D = k\ (V_{GS} - V_{TR})^2 = 0.5m\ (2.5 - 1)^2$
$i_D = 1.1\ mA$

(c) $V_{GS} = 2.5$, $V_{DS} = 1$, $V_{SB} = 0$

$V_{GS} > V_{TR}$, $V_{DS} < (V_{GS} > V_{TR})$, so it's in the Triode Region

$i_D = k\ [2\ (V_{GS} - V_{TR})\ V_{DS} - V_{DS}^2] = 0.5m\ [2\ (2.5 - 1)\ 1 - 1^2]$
$i_D = 1\ mA$

25. Semiconductor Physics: A silicon sample at room temperature is doped with *acceptor* atoms so that $N_A = 10^{16}\ cm^{-3}$ and $N_D = 0$.

5 points

(a) Is the material p-type or n-type?

p-type (because it's doped with 'acceptors')

(b) If $p_0 = 10^{16}\ cm^{-3}$, what is the electron concentration, n_0, at room temperature?

$n_0 = n_i^2 / p_0 = (1.45x10^{10})^2 / 10^{16}$

$n_0 = 2.1x10^3\ cm^{-3}$

Honor Pledge

By signing below, I pledge that I have neither given nor received aid on this exam, nor have I witnessed any other student giving or receiving aid.

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Equations Sheet

Basic Equations

$V = I R$

$Q = C V$

Semiconductor Device Physics

$p_0 n_0 = n_i^2$

$p_0 + N_D = N_A + n_0$

Diodes

$i_D = Is \{\exp(V_D/\eta V_T) - 1\}$

FETs

$i_D = k [2 (V_{GS} - V_{TR}) V_{DS} - V_{DS}^2]$

$i_D = k (V_{GS} - V_{TR})^2$

$i_D = k (V_{GS} - V_{TR})^2 (1 + \lambda V_{DS})$

$k = ½ \mu C_{OX} W/L$

BJTs

$i_E = i_{E0} [\exp(V_{BE}/nV_T) - 1]$

$i_E = i_C + i_B$

$i_C = \beta_F i_B$

$i_C = \beta_F i_B (1 + V_{CE}/V_A)$

slope of “constant-current” region = $i_C(0) / V_A$

Constants

$V_T = kT/q = 25$ [mV] (at T = 300K, room temperature)

$k = 1.38 \times 10^{-23}$ [J/K]

$q = 1.6 \times 10^{-19}$ [coulombs]

$n_i = 1.5 \times 10^{10}$ [cm^{-3}], for Si at room temperature

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Homework 6 EE 461G Spring 2000

Problem 1: If a MOSFET is biased in saturation with $i_D = 10\mu A$ and $V_{DS} = 5$ V, what is the current at $V_{DS} = 6V$ if $\lambda = 0.01 V^{-1}$?

Problem 2: Calculate the channel length modulation factor, λ, for an nMOS device in saturation if $i_{D1} = 100\mu A$ for $V_{DS1} = 3V$, and $i_{D2} = 110\mu A$ for $V_{DS2} = 5V$. Assume $V_{SB} = 0$ V, k and V_{TR} are constant, and V_{GS} does not change.

Problem 3: A Bipolar transistor is operated in forward active region with $i_B = 5\mu A$. What is the collector current, i_C for $V_{CE} = 4$ V. Your solution must take into account the upward slope characteristics of the forward active (i.e. constant current) region. Assume $\beta_F = 150$ and $V_A = 120$ V.

Problem 4: Calculate V_A for a bipolar device if $i_C(0) = 100\mu A$ and $i_C = 105\mu A$ at $V_{CE} = 4$ V.

Problem 5:

(a) A sample of pure silicon ($N_A = N_D = 0$) is doped with Phosphorus so that $N_D = 10^{12}$ cm^{-3}. What are the electron and hole (n and p) concentrations in the sample at room temperature? Is the material n-type or p-type?

(b) If we add an *additional* Boron doping of $N_A = 10^{16}$ cm^{-3} to the sample above, what are n and p now? Is the material now n-type or p-type?