ECE 3040 Microelectronic Circuits

Exam 2

March 28, 2008

Dr. W. Alan Doolittle

Print your name clearly and largely: Solutions

Instructions:
Read all the problems carefully and thoroughly before you begin working. You are allowed to use 1 new sheet of notes (1 page front and back), your note sheet from the previous exam as well as a calculator. There are 100 total points in this exam **plus a bonus problem at the end of the exam.** Observe the point value of each problem and allocate your time accordingly. SHOW ALL WORK AND CIRCLE YOUR FINAL ANSWER WITH THE PROPER UNITS INDICATED. Write legibly. If I cannot read it, it will be considered to be a wrong answer. Numeric answers without supporting work will be counted as wrong. Do all work on the paper provided. Turn in all scratch paper, even if it did not lead to an answer. Report any and all ethics violations to the instructor. Good luck!

Sign your name on **<u>ONE</u>** of the two following cases:

I DID NOT observe any ethical violations during this exam:

___

I observed an ethical violation during this exam:

___

First 20% **True /False and Multiple Choice - Select the most correct answer(s)**

1.) (2-points) True / False: The capacitance of a pn junction is larger in forward bias.

2.) (2-points) True / False: Diode leakage current increases as the semiconductor doping increases.

$I_0 \propto \frac{1}{N_{A,D}}$

3.) (2-points) True / False: The primary source of leakage current in pn diode is due to minority carrier drift current.

4.) (2-points) True / False: The steeper the energy band diagram slope is the greater (in magnitude) the electric field.

5.) (2-points) True / False: A high voltage BJT must hold of a large base-collector voltage so the base quasi-neutral region width must be large in order to prevent "punch through".

6.) (2-points) True / False: The emitter current of a forward active BJT becomes minority carrier current in the base and majority carrier current in the collector.

7.) (2-points) If an engineer wanted to use a BJT to turn a motor (large current) on and off repetitively, which two combination of bias modes are best for this switching operation?

a. Forward Active and Cutoff
b. Forward Active and Saturation
c. Saturation and Cutoff
d. Inverse Active and Cutoff
e. This is silly, a BJT cannot be used as a switch

8.) (2-points) The collector current in a forward active biased BJT ...

a. ... is β times the base current Ib
b. ... is β/(β+1) times the emitter current Ie
c. ... is α times the emitter current Ie
d. ... primarily is made of majority carriers originating from the emitter.
e. None of the above

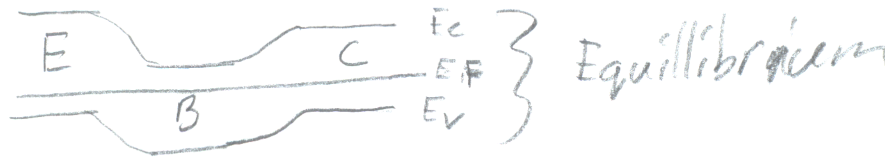
9.) (2-points) In a full wave rectifier, the current through a resistive load...

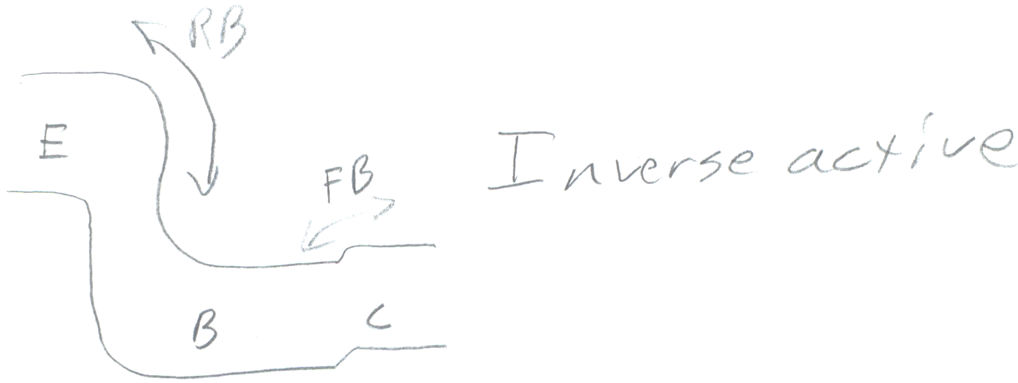
a. ...flows through only 2 diodes at any given time.
b. ...always flows in the same direction.
c. ...results in a stable DC output.
d. ...consumes no power.
e. None of the above

10.)(2-points) The law of the junction ...

a. ...describes the balance between electrons and hole in equilibrium, $np=n_i^2$.
b. ...describes the balance between electrons and holes at the depletion region edges as a function of the voltage across the junction.
c. ...predicts that excess minority carriers will be present at the depletion region edges under reverse bias.
d. ... predicts that excess minority carriers will be present at the depletion region edges under forward bias..
e. None of the above

11.) (a - 10 points) Help a Clemson student out. He has biased a BJT backwards from his desired intention. Draw the energy band diagram of a pnp transistor biased in INVERSE active.



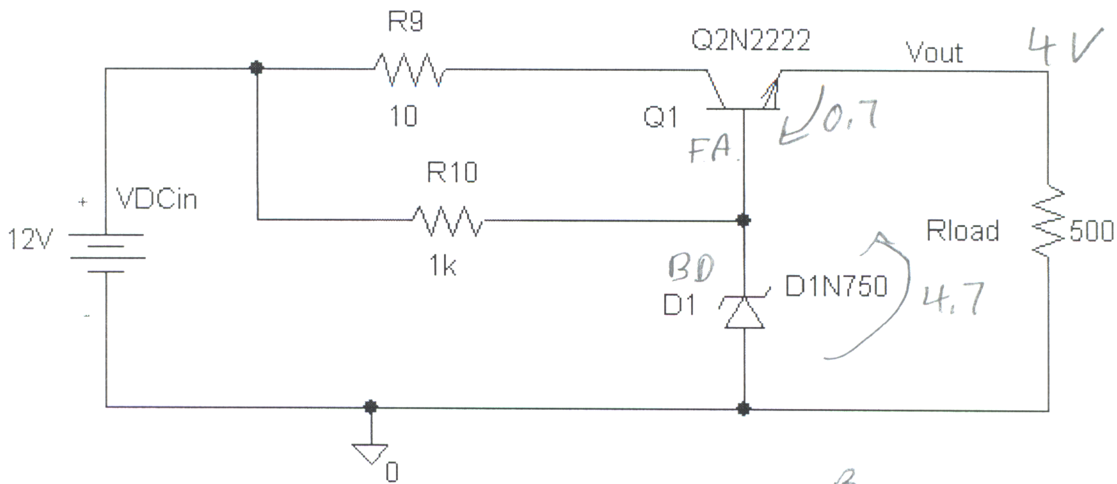


(b - 10 points) Explain in THREE sentences or less why the BJT does not function well in this mode. You can use equations if needed to support your reasoning.

1) $\beta \cong \frac{D_B L_E N_E}{D_E W N_B}$

Since in a BJT, $N_E > N_B > N_C$, inverse active bias effectively reverses the doping resulting in $N_C^* > N_B^* > N_E^*$. Thus from equation 1 above, β will be small resulting in minimal (if any) current gain. The transistor acts as a poor (or no) amplifier.

12) (20 – points)
For the following circuit, (from Homework 5) assuming the turn on voltage of all forward biased junctions are 0.7 volts and the Zener diode has a breakdown voltage of 4.7 volts and always remains operating in breakdown mode, what is the smallest load resistor, Rload, for which the circuit operates as a voltage regulator. Unlike the homework problem, you may assume β is infinite (very large) such that the base current, Ibase, is negligible.



$\beta = \infty \Rightarrow I_C = \frac{\beta}{\beta+1} I_E \Rightarrow I_C = I_E$

For small R_{Load}, I_E is large, thus we are concerned that Q_1 leaves Forward active and enters saturation. For the boundary from Forward active to saturation,

$V_{BE} = 0.7V$ + $V_{BC} = 0$

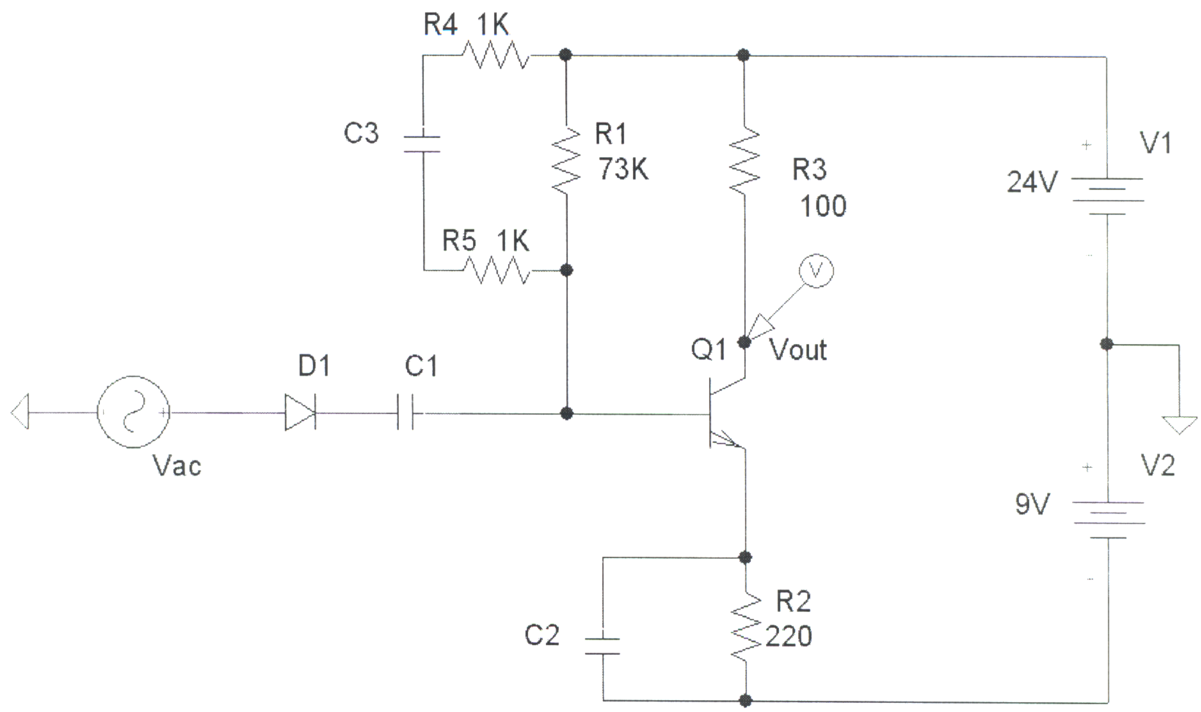
Since $V_B = 4.7\text{ V}$, the $V_{BC} = 0 \Rightarrow V_C = 4.7$

Thus, $I_C = I_E = \frac{12V - 4.7}{10\Omega} = 0.73$ Amps

Thus, R_{Load} minimum is $\frac{4V}{0.73A} = 5.48\Omega$

13). **Pulling all the concepts together for a useful purpose**:
(40-points total: DC solution = 12 points, conversion to small signal model = 12 points, AC solution = 12 points and 4 points for accuracy of the graph)

For the circuit below:
Diodes: $V_{turn\ on}$=0.7 V and I_o=I_s=25.9e-6A (a large power diode).
Q1: $V_{turn\ on}$=0.7 V, I_s=1.83e-14A, β_{DC}=100, V_A=15V .
VinAC = 1mV amplitude (i.e. 2mV peak to peak) at 1 kilohertz (period of 1 millisecond)

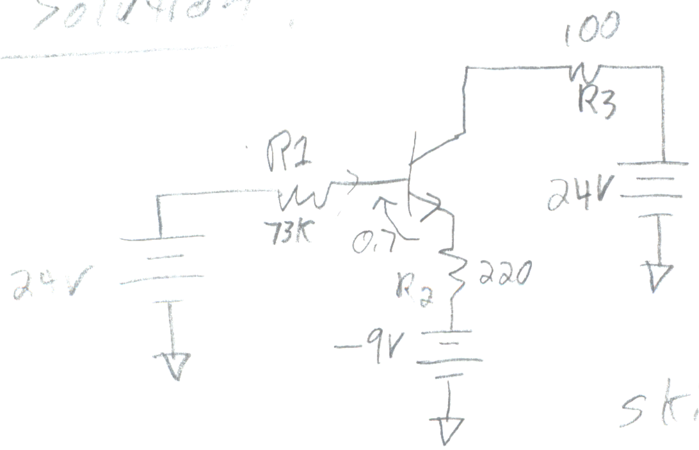


Given the above input voltage, Vac, sketch and accurately label a plot of the output waveform Vout on the graph paper provided on the next page. To do this you must solve the DC and AC solutions of the circuit. Assume the turn on voltages for all forward biased junctions are 0.7 V. You may assume all capacitors are very large values and are thus, AC shorts. Additionally consider the circuit to be operated at low frequencies where you can neglect all small signal capacitances of transistors and diodes. Also, neglect all resistances that result from quasi-neutral regions. **For full Credit, be sure to check your assumptions on the mode of operation of the transistor and to clearly label the axes and amplitude of sin functions in your plot**.

Hint: Use the CVD/Beta analysis for the DC transistor solution. Then apply your results to convert to the small signal model for both the BJT and diodes (i.e. do not ignore the small signal model of the diode).

Extra work can be done here, but clearly indicate with problem you are solving.

DC Solution:



Note: The circuit is already Thevenized! Ain't I nice!

Do not overlook this skill (Thevenin + Norton) even though it was not needed here.

$$-9V + I_E R_2 + 0.7 + I_B R_1 = 24$$

$$I_B = \frac{24 + 9 - 0.7}{(\beta+1) R_2 + R_1} = 339\mu A$$

$$I_C = \beta I_B = 100 I_B = 33.9\,mA$$

$$I_E = (\beta+1) I_B = 101 I_B = 34.3\,mA$$

Diode DC

$I_D = 0$

$V_C = 24V - R_3 I_C = 20.6\,V$ } > RB ✓

$V_B = 24V - R_1 I_B = -0.76\,V$ } 0.7 math ✓

$V_E = -9V + I_E R_2 = -1.46\,V$

F.A. Verified

$V_B > V_E$

$V_C > V_B$

Conversion to AC model:

$$g_m = \frac{I_C}{V_T} = \frac{33.9mA}{0.0259} = 1.3097\ S$$

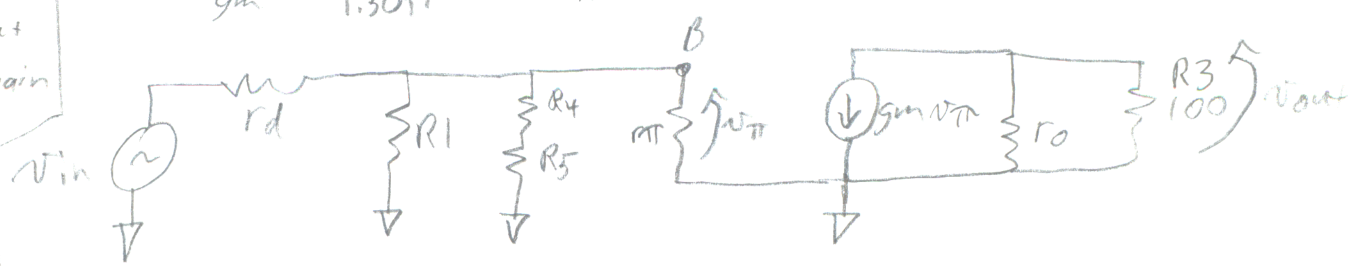
$$r_o = \frac{V_A + V_{CE}}{I_C} = \frac{15 + 22.06}{33.9mA} = 1092.5\,\Omega$$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{1.3097} = 76.35\,\Omega$$

$$r_d = \frac{I_D + I_S}{V_T} = \frac{0 + 25.9e{-6}}{0.0259}$$

$$r_d = 1000\,\Omega$$

Note: Compared to our homework problems, I_C is larger resulting in a smaller r_o + r_π but a larger gain g_m



Extra work can be done here, but clearly indicate with problem you are solving.

$$A_V = \left(\frac{v_{out}}{v_{in}}\right) = \left(\frac{v_{out}}{v_\pi}\right)\left(\frac{v_\pi}{v_{in}}\right)$$

(1) (2)

(1) $-g_m v_\pi (r_o \| R_3) = v_{out}$

(2) $v_\pi = v_{in} \dfrac{R_1 \| (R_4 + R_5) \| r_\pi}{r_\pi \| R_1 \| (R_4 + R_5) + r_d}$

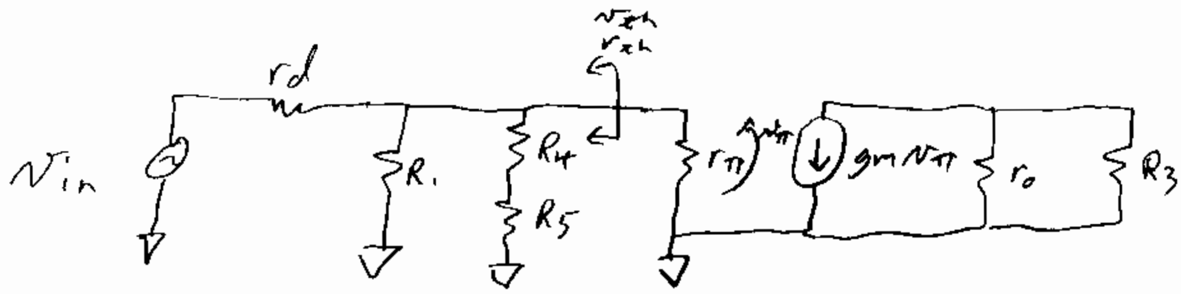
$$A_V = \left[-g_m (r_o \| R_3)\right]\left[\frac{R_1 \| (R_4 + R_5) \| r_\pi}{r_\pi \| R_1 \| (R_4 + R_5) + r_d}\right]$$

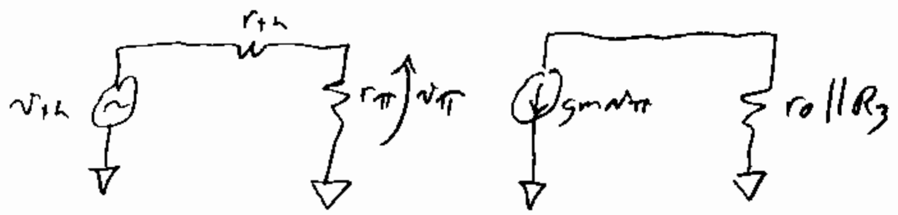
$$= \left[-119.98\right]\left[0.0684\right] \ V/V$$

$$\boxed{A_V = -8.21 \ V/V}$$

Alternative AC Solution:

Slightly longer but follows more closely what we did in previous examples.





(3) $v_{th} = \dfrac{(R_4+R_5)\|R_1}{r_d + (R_4+R_5)\|R_1} v_{in}$ $\quad r_{th} = r_d \| R_1 \| (R_4+R_5) = 660.6\,\Omega$

$$A_v \quad \frac{v_{out}}{v_{in}} = \underset{①}{\left(\frac{v_{out}}{v_\pi}\right)} \underset{②}{\left(\frac{v_\pi}{v_{th}}\right)} \underset{③}{\left(\frac{v_{th}}{v_{in}}\right)}$$

1) $v_{out} = -(g_m v_\pi)(r_o \| R_3)$

$$\frac{v_{out}}{v_\pi} = -g_m (r_o \| R_3) = -119.98 \text{ v/v}$$

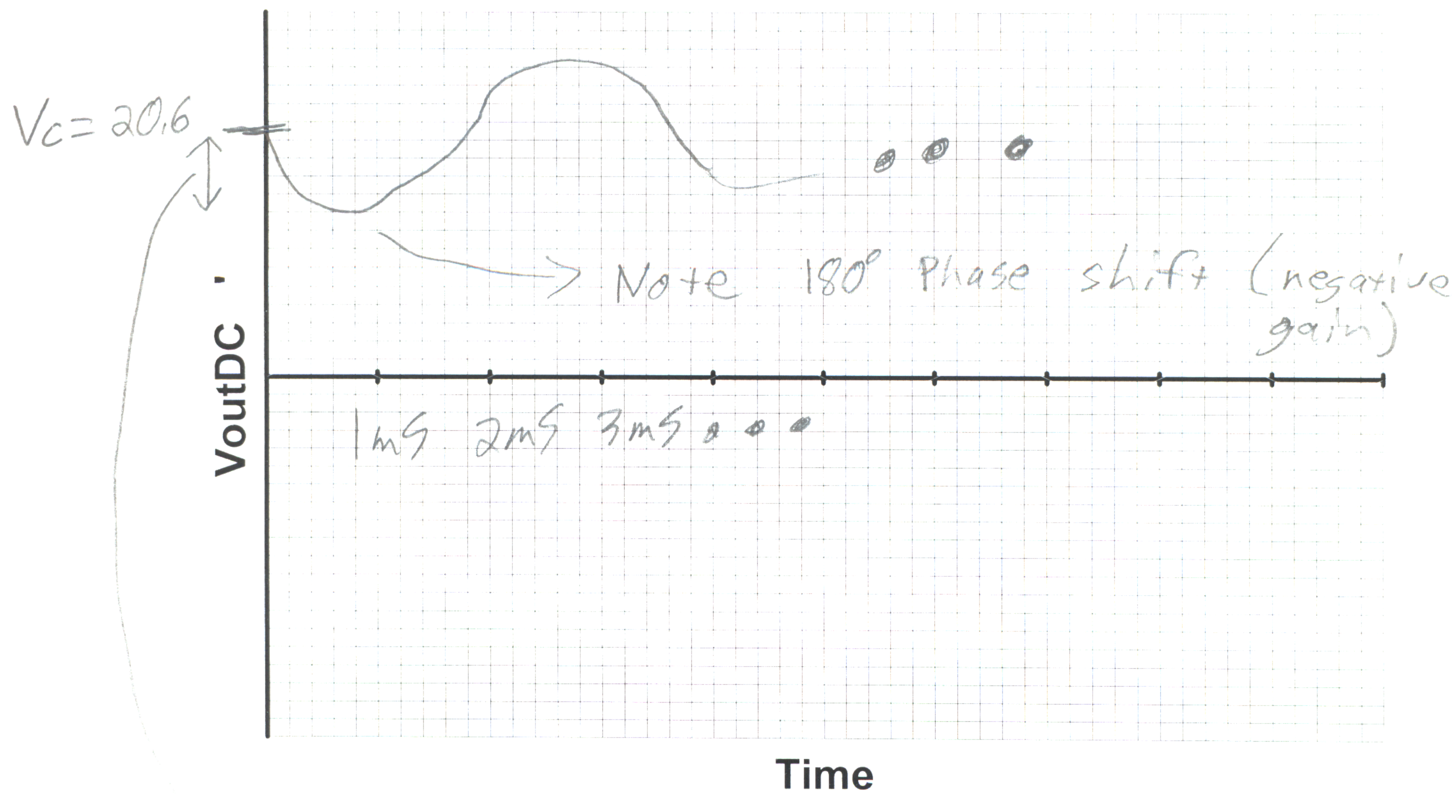
2) $$\frac{v_\pi}{v_{th}} = \frac{r_\pi}{r_{th} + r_\pi} = 0.103 \text{ v/v}$$

3) $$\frac{v_{th}}{v_{in}} = \frac{(R_4+R_5)\|R_1}{r_d + (R_4+R_5)\|R_1} = 0.66$$

$$A_v = (-119.98)(0.103)(0.66)$$

$$A_v = -8.21 \text{ v/v}$$

Answer Page



Amplitude = 8.2 mV

Bonus #1: 10 points (NO PARTIAL CREDIT - EITHER RIGHT OR WRONG)
For the last problem above, estimate using the simplified clipping limits technique used in class (i.e. NOT the Ebers Moll model) the maximum output swing possible without distortion.

Since V_c is closest to 24 V supply, Swing is limited by cutoff,

$V_{out\,max} = 24V - V_C = 24.0 - 20.6$

$V_{out\,max} = 3.4V$