Spring 1999
D.P. Neikirk, Instructor

EE 379K Microwave Devices
Take-home Final Exam
OPEN BOOKS AND NOTES

You have until Weds., May 12 at 4:00 pm to turn in this exam. Return the exam to either my ENS 635 office or my JJPRC office. You MAY NOT discuss this exam prior to 5/12/99 at 4:00 pm with anyone other than me. Do not ask anyone (other than me) questions related to this course after starting work on the exam. You really shouldn't have too much trouble with these questions, so you are on your honor not to abuse the conditions set forth for this take-home exam. **Please staple all your work to the exam, and carefully label your answers. Make sure your answers are VERY neat and legible so I can easily read (AND GRADE!) your work!**

Things you may or may not find useful:

$\varepsilon_o = 8.854 \times 10^{-14}$ F/cm $\quad \mu = 4\pi \times 10^{-9}$ H/cm $\quad c = 3 \times 10^{10}$ cm/sec

$\sqrt{j} = \frac{1}{\sqrt{2}}(1 + j)$ $\qquad (1 \pm x)^{1/2} = 1 \pm \frac{1}{2}x - \frac{1}{8}x^2 \pm \ldots$ for $|x| < 1$

$$(1+x)^{-n} = 1 - nx + \frac{n(n+1)}{2!}x^2 - \ldots \; ; \qquad (1-x)^{-n} = 1 + nx + \frac{n(n+1)}{2!}x^2 + \ldots \text{ for } x^2 < 1$$

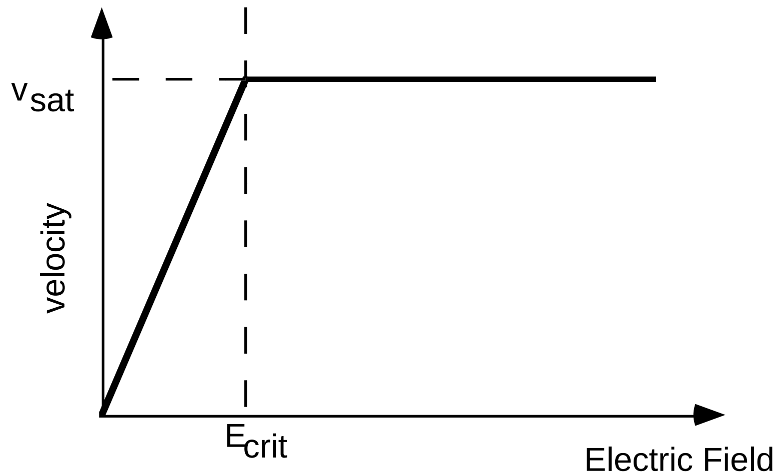
$$\sin(\phi) = \phi - \frac{\phi^3}{3!} + \frac{\phi^5}{5!} - \ldots \qquad \cos(\phi) = 1 - \frac{\phi^2}{2!} + \frac{\phi^4}{4!} - \ldots$$

$$\tan^{-1}(\phi) = \phi - \frac{\phi^3}{3} + \frac{\phi^5}{5} - \ldots \text{ for } \phi^2 < 1$$

$$\tan^{-1}(\phi) = \frac{\pi}{2} - \frac{1}{\phi} + \frac{1}{3\phi^3} - \ldots \text{ for } \phi > 1; \qquad \tan^{-1}(\phi) = -\frac{\pi}{2} - \frac{1}{\phi} + \frac{1}{3\phi^3} - \ldots \text{ for } \phi < -1$$

NAME: ______________________________

1. (25 points) Consider a semiconductor that has a velocity-field curve as shown below. (Both axes are linear.)



HINT: in the latter parts of this problem don't forget about Poisson's equation $\frac{\partial E}{\partial x} = \frac{q}{\varepsilon}\left(n - N_D^+\right)$.

(a) Can the Gunn effect occur in this material? Explain.

(b) Assume the **material remains space charge neutral** (with n-type doping concentration N_D) and that the sample is W long. If there is an electric field present in the sample, does it vary with position? The (specific) differential resistance (units are Ω-cm^2) of the material is given by the incremental change in voltage across the sample for an incremental change in current density, i.e.

$$r = \frac{\partial V}{\partial J} = \left(\frac{\partial J}{\partial V}\right)^{-1}$$

What is r in terms of W and $\frac{\partial J}{\partial E}$, where E is the electric field in the sample? Recalling ohm's law, what do we normally call $\frac{\partial J}{\partial E}$?

(c) Recall that a fundamental definition of current density is the number of coulombs crossing a unit area per unit time. Thus, the current density J is related to the carrier density n and their velocity v. Using this, what is r in terms of W, q, n, and $\frac{\partial v}{\partial E}$? What do we usually call $\partial v/\partial E$?

Again, assume the material remains space charge neutral (with n-type doping concentration N_D).

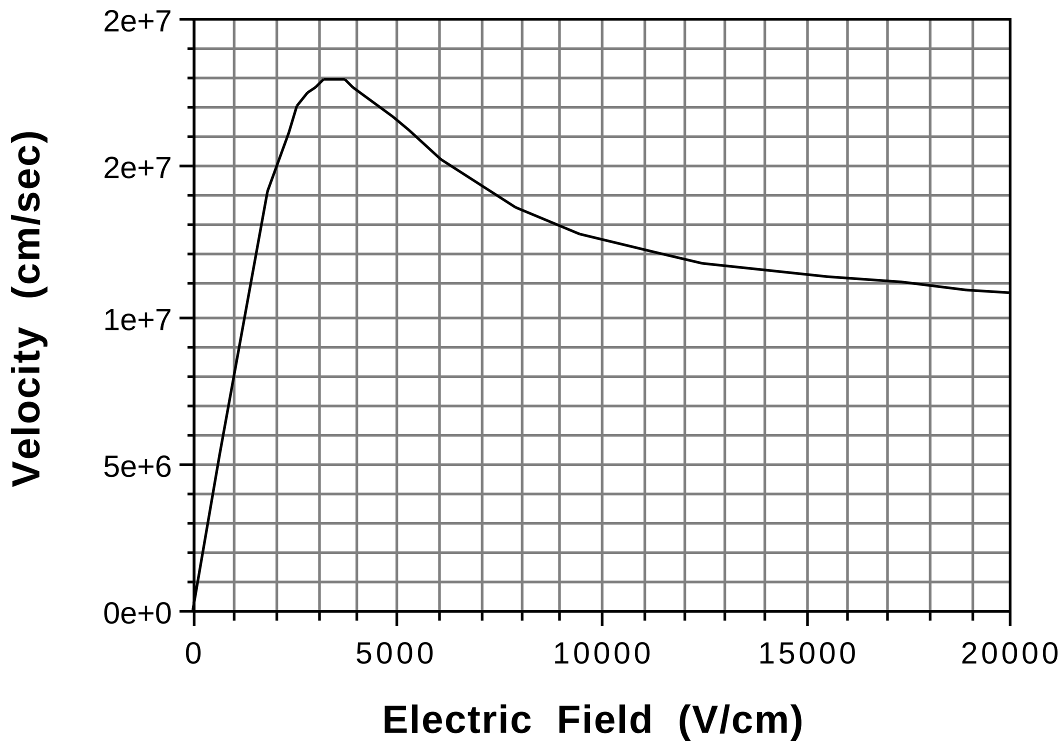
(d) For fields below E_{crit}, what is r? For fields above E_{crit}, what is r? Again, assume the material remains space charge neutral (with n-type doping concentration N_D).

(e) What is the maximum current density that can flow through this sample if it is to have a finite, constant conductivity, in terms of N_D and v_{sat}? What is the maximum electric field that can exist in this sample if it is to have a finite, constant conductivity?

(f) If I apply a current density $J = qN_Dv_{sat}$, what would the carrier density n most likely be in the sample? If I apply a current greater than qN_Dv_{sat}, can the sample remain space charge neutral?

NAME: ________________________________

2. (25 points) Consider a semiconductor that has two valleys in its conduction band, one with a low effective mass, and another with a much higher effective mass. Due to inter-valley transfer, the velocity field curve for the material is as shown below.



HINT: This problem is SIMPLE!

(a) Over what range of fields would this material have a roughly constant, field-independent conductivity, and behave essentially as a simple resistor?

(b) What causes the Gunn effect? For this material, over what range of fields might a Gunn domain form?

(c) If a Gunn domain does form, outside the domain, the field is E_o. Over what range of values can E_o be in? (Hint: recall the "equal areas rule")

(d) For a Gunn diode operating in the "transit time" mode, how are the frequency, length L of the device, and $v(E_o)$ related?

(e) Assuming the dc voltage V_{dc} across a Gunn diode is mostly due to the (approximately) constant electric field E_o outside the domain, how would V_{dc} change as the device design is changed to provide higher oscillation frequency (i.e., what is $V_{dc}(f)$, assuming that at each frequency a device length is used to satisfy part (d) above).

(f) For a 10 GHz oscillation frequency, approximately how long should a Gunn diode be if it is made out of this material? About what is E_o? About what is V_{dc}? Now for a 100 GHz oscillation frequency, approximately how long should the Gunn diode be? About what is E_o? About what is V_{dc}? Do you expect much change in output power as you go from 10 to 100 GHz? Why?

NAME: ______________________________

3. (25 points) Recall that we found that the small-signal impedance produced by a depletion region through which carriers travel at a constant (saturation) velocity is given by

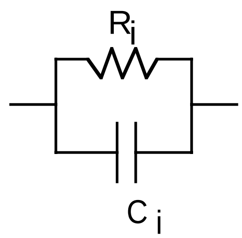
$$Z_D = \frac{1}{j\omega C_D}\left[1 - \frac{J_{RF}^{c}(0)}{J_{RF}^{tot}} \cdot \frac{1 - e^{-j\theta_D}}{j\theta_D}\right];$$

$$\mathbf{Re}(Z_D) = \frac{\gamma}{\omega C_D \theta_D}\left[\mathbf{cos}(\theta_i) - \mathbf{cos}(\theta_D + \theta_i)\right]$$

where

$$C_D = \frac{\varepsilon}{W} \;;\; \theta_D = \frac{\omega W}{v_{sat}} \;;\; \text{and} \quad \frac{J_{RF}^{c}(0)}{J_{RF}^{tot}} = \gamma\ e^{-j\theta_i}$$

is the ratio of the injected (ac) conduction current $J_{RF}^{c}(0)$ to the total (ac) current J_{RF}^{tot} which characterizes the injection region. Assume that we have a device in which the injector is characterized by a simple parallel RC circuit **(R_i > 0)**, as shown below:



(a) For this injector, what are $\frac{J_{RF}^{c}(0)}{J_{RF}^{tot}}$, and hence γ, and θ_i, as a function of R, C and ω? (give θ_i in terms of a $\tan^{-1}$ function). Find the real part of Z_D , $\mathbf{Re}(Z_D)$, as a function of R, C, θ_i, θ_D, v_{sat} and ω.

(b) At $\omega = 1/R_iC_i$, what is θ_i? To obtain maximum negative resistance from the drift region, what should θ_D be at this frequency? What is $\mathbf{Re}(Z_D)$ at this frequency?

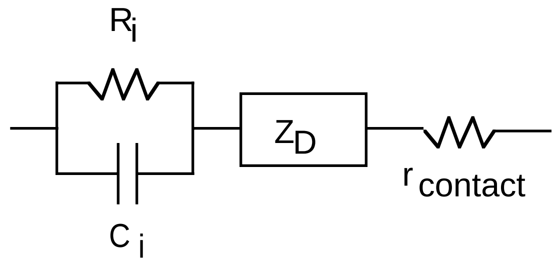
(c) For high (high compared to what?) frequencies, what is θ_i? To obtain maximum negative resistance from the drift region, what should θ_D be at high frequency? What is the magnitude of $\mathbf{Re}(Z_D)$ (as a function of ω) at high frequency?

(d) For low (low compared to what?) frequencies, what is θ_i? Is there a drift angle θ_D which can still produce a negative resistance? If so, to obtain maximum negative resistance from the drift region, what should θ_D be at low frequency? BE CAREFUL!! It might be useful to use the trig identity $\mathbf{cos}(\theta_D + \theta_i) = \mathbf{cos}\,\theta_D\ \mathbf{cos}\,\theta_i - \mathbf{sin}\,\theta_D\ \mathbf{sin}\,\theta_i$. Regardless, be very careful about the order of any Taylor series expansions you might use.

(e) What is the magnitude of $\mathbf{Re}(Z_D)$ (as ω goes to zero) for the choice of θ_D in part (d) above? Using this and the results of parts (c) and (d), sketch $\mathbf{Re}(Z_D)$ as a function of ω. At what frequency is $\mathbf{Re}(Z_D)$ a negative maximum? Practically speaking, would there be any obvious problem in building a device which operates under this condition?

NAME: ______________________________

4. (25 points) Let's re-do the last problem, but phrase it differently. The whole device is



(a) Let's assume that you can decrease R_i as ω goes up such that $\omega = 1/R_iC_i$ is true at each frequency, i.e., $R_i = 1/\omega C_i$. Now find the real part of the **total** impedance of the "intrinsic" device **Re**$(Z_D + Z_i)$ in terms of C_i, v_{sat}, ω, and ε. Find the frequency ω_{ci} at which **Re**$(Z_D + Z_i)$ is zero, in terms of C_i, v_{sat}, and ε.

(b) Since C_i is a "cold" capacitance, let's write it as a geometrical parallel plate capacitance with plate separation W_i. Now give ω_{ci} in terms of v_{sat} and W_i. Pick some numbers you think would give a reasonable upper bound on how big ω_{ci} could be, and evaluate ω_{ci}.

(c) Now let's add the impact of finite specific contact resistance r_c. Find the resistive cut-off frequency ω_{cr} at which the real part of the total device impedance **Re**$(Z_D + Z_i + r_c)$ goes to zero, in terms of v_{sat}, W_i, ε, and r_c. For $v_{sat} = 10^7$ cm/sec, $W_i = 100$ Å, $\varepsilon_r = 10$, and $r_c = 10^{-7}\ \Omega\ cm^2$, find ω_{cr}.

(d) Now let W_i go to zero (which would give ω_{ci} = infinity!), but keep r_c. From this, what is the upper bound on ω_{cr}? For $v_{sat} = 10^7$ cm/sec, $\varepsilon_r = 10$, and $r_c = 10^{-7}\ \Omega\ cm^2$, find ω_{cr}. What do you think the chances are of building a solid state oscillator operating at a fundamental frequency of 1 THz?

NAME: ______________________________