June 9, 2011
Final Exam – Four Pages Total.

You need to show enough steps leading to the answer, unless instructed otherwise. For all numerical answers, two significant figures are acceptable.

Use provided blank sheets of paper as your answer sheets. Write your name on the first page and page number on each page. Tidy answer sheets are highly recommended.

Good luck!

Multiple Choice

These multiple choice questions do not need any explanation. Write your answers in your answer sheet, not on the questions.

1. (7 points) Which of the following is *not* true within the ideal diode theory of a *pn* junction? Assume a forward bias (only) for definiteness.

(a) All currents can be calculated by considering the minority carriers only.

(b) The majority carriers also contribute to the current in an important way.

(c) The law of the junction, which can be proven within this theory, would remain correct to all orders in the perturbation theory, i.e. even when the low level injection assumption breaks down.

(d) The minority carrier injected will also "back-drift," but this contribution need not be considered as it is a higher order quantity in the perturbation theory.

2. (6 points) Which of the following assumptions is *not* invoked in deriving the ideal diode equation?

(a) No recombination-generation in the depletion region.

(b) Low-level injection.

(c) Narrow-base diode; i.e., the widths of the n and p quasi-neutral regions are much less than the respective minority carrier diffusion lengths.

(d) No "other" processes; i.e., no photo-generation, avalanching, tunneling, etc.

3. (7 points) Under reverse biasing and small forward biasing, the dominant current component in most Si *pn* junction diodes maintained at room temperature is ____________.

(a) the diffusion current
(b) the R-G current
(c) the ideal-diode current
(d) the drift current

"Off-the-top-of-head" questions

The questions below are mainly for testing your acquired memory. However, there is rarely such a thing as "just remembering something" in physics. Anything remembered must be "context-rich." The spirit of these questions may be best characterized as follows: suppose you are attending a scientific conference, and you are talking with other scientists in the hall way – then these issues came up, and you say "I know, I know ... I learned them in a course!", and so you are trying to recall them and explain them. So, your "explanation" may not be complete, but it should be effective, for the purpose of demonstrating and corroborating your knowledge.

10 points each. Three questions required. Extra credit if you do more.

4. What is the typical value of the dielectric relaxation time in a doped semiconductor? Describe, in a sentence or two, the physical significance of this time scale.

5. What is the unit of the diffusion constant D_n or D_p and what is its typical value? Provide a short justification of your answer for the unit, using a formula, for example the Fick's law involving the diffusion constant or any other formula that you handily remember.

6. What is the unit of the mobility and what is its typical value? Provide a short justification of the answer for the unit, using a formula, for example the definition of the mobility, the Einstein relation, or any other formula that you handily remember in connection with the mobility.

7. What is the depletion approximation? Give the mathematical formula summarizing the approximation, and the range of x (position) where the formula applies. Explain the physical meaning/origin of this approximation.

True or False?

Write your answer as "T(rue)" or "F(alse)," and then briefly explain why your answer is correct, in two or three short sentences.

10 points each. Five questions required. Extra credit if you do more.

8. A current is flowing through a *pn* junction. The widths of the quasi-neutral regions are much (like 10 times) greater than the respective minority carrier diffusion lengths. At either end of the device, far away from the depletion region, nearly 100 % of the current is carried by the majority carriers.

9. The ideal diode equation ("Shockley equation") is useless as far as the magnitude of the current is concerned, while the equation may describe the generic bias dependence of the diode current.

10. A Schottky diode is better suited than a *pn* junction diode, when the device needs to switch fast as the direction of the bias is reversed.

11. The "junction capacitance" of a *pn* junction diode – i.e. the total charge stored in the depletion region divided by the total voltage applied across the depletion region – increases as the device gets more reverse biased.

12. Si owes its success as key material for complex devices such as Intel processors more to the MOSFET (metal-oxide semi-conductor field effect transistor) than to the BJT (bi-polar junction transistor).

13. In a Si *pn* junction diode, the R-G processes in the depletion region due to deep trap states improve the conductivity both in forward bias and in reverse bias, relative to the conductivity calculated in the ideal diode theory.

14. In a Si solar cell, the R-G processes within the depletion region due to deep trap states improve the efficiency, relative to the efficiency calculated in the ideal diode theory.

The following two problems are required. Show all steps leading to your answer.

15. (50 points) Consider a step *pn* junction device made of Si, operating at the room temperature. $N_A = 2.0 \times 10^{14}$ cm^{-3} (p side) and $N_D = 1.0 \times 10^{14}$ cm^{-3} (n side). Within the depletion approximation, answer the following questions.

(a) What is the value of the builtin-potential, V_{bi}?

(b) Sketch the energy band diagram. Your diagram should contain the following information: (i) the position of the metallurgical junction, (ii) how the values of E_c, E_v E_i, E_F vary (or not) as functions of x (position), and (iii) the value of eV_{bi}.

(c) Sketch E (the electric field), V (the electrostatic potential function) as functions of x.

(d) Express $\log n$ and $\log p$ as functions of n_i, E_F and E_i (and the temperature). Based on those expressions, make sketches of $\log n$ and $\log p$ as functions of x.

(e) A hole is located at top of the valence band at the far end of the p side. It is traveling across the junction, with the total energy being conserved. Sketch its potential energy and kinetic energy, as functions of x.

(f) Sketch the current densities $J_{p,drift}$ and $J_{p,diffusion}$ as functions of x.

(g) A forward bias of $V_A = 0.20$ V is turned on. Find the quasi-Fermi levels F_P and F_N as functions of x, within the ideal diode theory. Sketch the energy band diagram, including the quasi-Fermi levels.

16. (50 points) Consider a Si *pn* junction device used as a solar cell, operating at the room temperature. Do *not* assume that $p \gg n$ or $n \gg p$. The width of the depletion region is W, the minority carrier diffusion lengths are L_p and L_n, and the minority carrier lifetimes are τ_p and τ_n. N_A and N_D are the acceptor and donor density levels in the p and n regions, respectively. The crossection of the device is A. The e-h pair production rate arising due to light absorption is given by G_L, everywhere except in the depletion region, due to the ideal diode theory, which we apply in this problem. Let V be the junction voltage generated by the solar-cell. The law of the junction can be used without proving it.

(a) What is the excess minority carrier concentration on the n-side a large distance away from the metallurgical junction?

(b) What is the excess minority carrier concentration at the n side edge of the depletion region?

(c) What is the excess minority carrier concentration on the p-side a large distance away from the metallurgical junction?

(d) What is the excess minority carrier concentration at the p side edge of the depletion region?

(e) What is the total current, I, flowing through the device?

(f) Sketch the I-V curve, assuming that G_L is a large enough number to give a noticeable photo-voltaic effect on the I-V curve.

(g) The solar cell is connected to a load that can be modeled as a resistor with resistance R. Eliminate V from your formula of the current to find the implicit equation for I (which can be solved numerically).

(h) In your sketch of the I-V curve, mark the following three points of operation: (1) connection to a load (mark the position qualitatively, paying attention to the signs of V and I), (2) open circuit, (3) short circuit.

(i) Suppose that there is a finite internal serial resistance R_S in this solar cell (at electrode-semiconductor contacts, for example). Sketch how the I-V curve changes due to R_S.

17. (Extra Credit, 20 points) Explain why a *pnp* BJT (bipolar junction transistor), with the usual doping configuration, $p_E \gg n_B > p_C$ (E = emitter, B = base, C = collector) would show poor amplification in the inverted mode, in comparison to the active mode, i.e. if the emitter and the collector are swapped "by mistake."