ECE 494

Part B - Semiconductor Devices

Introduction

The objective of this laboratory is to enhance your knowledge of the basic semiconductor devices with hands-on experience, by measuring their basic characteristics. The four series of experiments include: measurements on diodes, a silicon solar cell, and two types of transistors (BJI and MOSFET). The background for these experiments is provided in the course on semiconductor devices (ECE 374), which is a prerequisite for this laboratory. Some simulation assignments in this course are directly related to the physical measurements that are conducted in the laboratory. Therefore, notes and problem solutions from the course may be a valuable material for review before the laboratory sessions. In addition, textbook references are given for each series of experiments.

THE LABORATORY REPORT

The report you turn in after completion of each series of experiments is the main product of the team's work which will be used for grading. Therefore you should devote enough attention to this final but critical step in the laboratory experience. Writing good technical reports is a valuable skill, which in the future will help advance your professional career.

The purpose of the laboratory report is to provide information on the measurement procedures, the experimental results and their analysis, as well as interpretation and discussion. The discussion and conclusions are very important parts in a report as they show what knowledge you gained by doing the experiments.

There is no one best format for all technical reports but there are a few simple rules concerning technical presentations which should be followed. Adapted to this laboratory they may be summarized in the following recommended report format:

1. Cover page
2. Introduction
3. Experimental Procedure
4. Experimental Data
5. Discussion
6. Conclusions

Detailed descriptions of these items are given below.

1. Cover page should have the names of the team members, and a designation such as Group 3, if the groups are numbered. It should also contain the number and the title of the experiments. Cover page should also have the date of the report delivery, not the due date.

2. Introduction should contain a **brief** statement in which you state the objectives, or goals of the experiments. It should also help guide the reader through the report by stating, for example, that experiments were done with three different circuits or consisted of two parts etc. or that additional calculations or data sheets can be found in the appendix.

3. Procedure describes the experimental setup and how the measurements were made. Include here circuit schematics with the values of components. Mention the instruments used, their settings and describe any special measurement procedure that was used.

4. Experimental Data section should be presented clearly with references to the procedure and schematic used in measurements. Include data tables with titles identifying the measurements and column headings with symbol of measured quantities and the units. Extensive tables can be put in an appendix while the main form of data presentation in this laboratory are graphs, with proper captions and labels. This section may also include some calculations or data analysis, for example trend lines fitted to the data points.

5. Discussion is a critical part of the report which testifies to the student's understanding of the experiments and its purpose. In this part of the report you should include analysis of the data, deriving of parameters (for example the saturation current and ideality factor of a diode) and comparison of the experimental results with a theory or simulations.

6. Conclusions should contain short statements closing the report. State if the results of the experiment are reasonable and in agreement with the theory. If there were differences between measured and expected results, can they be attributed to the precision of the instruments used or the experimental procedure? You may also say what could have been done differently, how experiments may be improved, or make other comments on the laboratory. Constructive and original statements are highly valued.

THE REPORT FORMAT

In this third electrical engineering laboratory the students are expected to provide professional quality report in the form that will be soon expected from them in the "real world". Below is a short list of important rules that should be checked before submitting a report.

1. Cover page should be complete with the experiment title, students' names and the dates of the experiments.
2. Number all pages except the title page.

3. Number all tables. The number and the table title should be **above the table**. Each column should have name or a symbol and the units of the listed values. For example: "*Table 1 Drain current vs. gate voltage for* $V_{DS} = 3$ *V*"
4. Number all figures and tables in the order as they appear in the report text. All figures should have captions **below the figure**, with the figure number and the text describing its contents. For example: *"Fig. 1 Circuit for measuring forward bias diode characteristic"* or *"Fig. 4 Reverse bias characteristic of 1N4001 diode with a linear trendline"*. Note that schematics, charts, or pictures of waveforms are all figures. Use reference to figure numbers in the text discussing the data.
5. Pay special attention to graphs. Each axis must have a label (can be a symbol) showing what quantity it represents as well as units, for example: " I_D [*mA*]". If this plot represents a MOSFET drain current as a function of drain voltage, the value of the gate voltage must be given on the graph or in the caption. If the graph shows three curves for different gate voltages, labels next to the curves or a legend with these voltages must be included.

Experiment Series 1 - Diodes

Diode Prelab Assignment:

(1) Write the diode equation, $I_D\ (V_D)$, identifying the key parameters: saturation current and ideality factor. You will be extracting the values of these parameters from the data obtained in the experiments.

(2) Draw an equivalent circuit of a real diode that includes the symbol of a diode, series resistance and a shunt resistance.

Using PSPICE or MULTISIM simulate $I_D(V_D)$ curves for a real diode in the forward and reverse bias. Use the circuit from (2) with an ideal diode, and two resistors, one in 5Ω - 15Ω range, and one in 10 GΩ – 20 GΩ range. Plot $I_D(V_D)$ forward bias curves on a linear and a semi-log graphs in 0 – 1 V voltage range and the reverse bias curve on a linear graph in 1 – 20 V range.

(3) Design circuits for measuring $I_D(V_D)$ characteristics of a diode with (a) forward bias and (b) reverse bias. Draw schematics of the circuits for these measurements showing a dc voltage source, a resistor in series with the diode (for preventing excessive diode current), a voltmeter and an ammeter. Assume $I_D \leq \sim 300$ mA. Determine the resistance and the power rating of the resistor you will need.

Hint: Schematics in cases (a) and (b) may not be the same. Consider internal impedances of the voltmeter and the ammeter and the expected currents through the diode and the instruments in the two cases.

Reference: Jasprit Singh *Semiconductor Devices*, John Wiley & Sons 2001. pp. 174 – 207.

Experiments with Semiconductor Diodes

(1) Use circuits from prelab (3) to measure forward and reverse bias characteristics of a silicon diode (1N4148). **Measuring forward current (up to ~ 300 mA) do not exceed the rated power of the series resistor or the diode power rating (500 mW).** To measure reverse bias current you will need a very sensitive ammeter. While recording values of the diode voltage V_D and the corresponding current I_D, plot these values on I_D (V_D) graph using Excel or other graphing program. This will help you to decide how many data points (and where) are needed to obtain a smooth curve of the diode characteristic.

Your goal is to determine the saturation current, the ideality factor and possibly series resistance from the forward bias I-V curve (on a semi-log graph) and the shunt resistance from the reverse bias curve (on a linear graph).

Hint: The diode equation on the semi-log graph is a straight line (except near the origin). Its slope and the intercept are defined by the diode parameters. You can select (paste and copy in Excel) the data range with points on the straight part of semi-log plot and fit to them an exponential trend line, displaying its equation on the graph. At high current and *voltage values the characteristic diverts firm the exponential. This part of the characteristic can be plotted on a linear graph and if it is close to a straight line, the diode resistance can be obtained from a linear trend-line equation.*

(2) Zener Diode. Measure currents at a few values of forward bias voltage to convince yourself that the diode performs as expected. Concentrate on the reverse bias characteristics, where at a certain voltage (~ 5V for 1N4733A) the current rapidly increases at the breakdown. **Make sure you have series resistor in place protecting the diode and the current meter. Do not use the sensitive meter used for the reverse bias measurement in (1).** Do not be concerned with very low current that you can not measure until you reach voltage near the breakdown. Plot data on a linear I-V graph and fit the linear trend line only to the points on the straight part of the curve. Its slope will give you Zener resistance R_z and its intercept with the voltage axis Zener voltage V_z for this particular diode.

(3) LED. Repeat (1) for an LED. Concentrate on the forward bias to determine the saturation current, the ideality factor and series resistance from the I-V curve. Note the current and voltage at which the diode starts emitting light and the light color.

(4) Temperature dependence of the diode reverse current. Using a temperature controlled hot plate, measure the reverse bias current at V_D = -15 V as a function of temperature. The diode must be in contact with the hot plate, pressed against it with thermally insulating material, such as Styrofoam. Perform measurements in temperature range 30 ^{o}C to 100 ^{o}C, approximately every 10 ^{o}C. Increase the temperature dial very slowly; once you overshoot the desired value the plate takes time to cool down. Do not attempt to get exact specific temperature value but let it settle at a stable reading. As the temperature stabilizes so does the diode current. Plot *ln(I$_D$)* vs. *1/T(K)* and find if this data follows the equation $I = I_0 \cdot \exp\left(-\frac{E_G}{2k_B T}\right)$. From the graph find the value of E_G. What is the meaning of this parameter?

(5) Diode switching. Supply a square wave signal (± 1V) to a 1N4001 diode through a 100 ohm series resistor. Connect the scope probe across the diode and record the waveform at the frequencies of 1 kHz and 5 MHz.

Report and Analysis

Present clearly all schematics of the experimental circuits, showing the diode, resistors and the instruments used for measuring voltage and current. Show all relevant clearly labeled graphs and include data tables. The data tables must have titles indicating to which measurements they refer (they can be put in an appendix).

Extract parameters of the diodes: saturation current, ideality factor, equivalent series and shunt resistances from measurements (1) and (3), parameters R_z and V_z from measurements (2), and

E_G from measurements (4). The values of the parameters must be clearly related to the graphs of the data and trend lines form which they were derived.

Points to discuss:

a) Are the values of the derived parameters reasonable, in agreement with your understanding of the measured devices?
b) What is a major difference between forward bias characteristics of the silicon diode measured in (1) and LED measured in (3). For comparison, plot the two characteristics on the same linear graph. What explains the difference between the two characteristics?
c) What is the meaning of E_G derived form measurements (4) and what its value is expected to be?
d) Explain the difference between the waveforms at the two frequencies in (5).

You may add any other comments and interesting observations from the experiments.

Experiment Series 2 – Solar Cell

Solar Cell - Pre-laboratory assignment

(1) Draw the equivalent circuit representing a solar cell. Use a current source representing the photoelectric current and resistors representing the shunt and series resistances.

(2) Simulate I-V characteristic of the device. Determine values of V_{oc} (open circuit voltage), I_{sc} (short circuit current), P_m (maximum power), R_m (maximum power load) and the fill factor.

References: Jasprit Singh *Semiconductor Devices*, John Wiley & Sons 2001. pp. 463 – 467.
http://en.wikipedia.org/wiki/Theory_of_solar_cell

Solar Cell Experiments

(1) Measure the solar cell I-V characteristic (in dark). In these measurements you treat the solar cell as a diode. Use the same methods for obtaining forward and reverse bias characteristics as in the diode experiment series (1). Do not exceed the current of 200 mA through the cell. Plot your results. The purpose is to derive the diode parameters: saturation current, ideality factor and the two resistances.

(2) Position the incandescent light source approximately 8 cm (3 inches) directly above the cell. **Make sure that the lamp and the cell positions are stable and do not change during these measurements.** Measure the voltage across the cell and current through a load resistor. Change the load resistor value from less than 1 ohm to hundreds of ohms, or more. The purpose is to obtain the I-V curve of the solar cell operating as a power source.

To obtain the open circuit voltage (V_{OC}), connect a voltmeter across the cell terminals without the load resistor. The high impedance of the voltmeter will give you a true value of the open circuit voltage.

To measure a current close to the short circuit current (I_{SC}), connect the ammeter across the diode terminals. Use a high range of the ammeter (ampere terminal on the bench-top multimeter). Connect also a voltmeter across the diode terminals. The voltage shown by the voltmeter will indicate that it is not a true short circuit but close to it. Alternatively, you may use a low value resistor of known value (< 1 ohm), measure the voltage across it and calculate the current from Ohm's law.

Hint: If you have resistors of known values (resistor substitution box) you may perform the whole experiment by measuring only voltages and calculating currents.

Whichever method you use plot the data as you go along to see where you need more points to obtain a smooth characteristic.

(3) From the curve obtained in 2, determine the maximum power and the corresponding load resistance. Place your solar cell under the calibrated solar illuminator and measure the voltage across the cell terminals with the load resistor corresponding to the maximum power. Note the reading of the sun illuminator output in units of Sun. The purpose is to calculate the efficiency of the solar cell.

Report and Analysis

Present clearly all schematics of the experimental circuits, showing the diode, resistors and the instruments used for measuring voltage and current. Extract parameters of the diodes: saturation current, ideality factor, equivalent series and shunt resistances from measurements (1).

Derive V_{oc} I_{sc}, P_{max}, and FF (fill factor) from the measurements (2).

Estimate the solar cell efficiency from the measurements (3). The solar cell used in this lab has the area of 4 cm^2 (20mm x 20 mm). The solar irradiation unit of 1 Sun = 1.0 kW/m^2.

Points to discuss:

- How the values of the solar cell parameters compare with the parameters of the diodes tested in experiments series 1? What may explain these differences?
- Is the measured value of the solar cell efficiency reasonable?

Experiment Series 3 - BJT

BJT Prelab Assignment:

Read carefully the description of the experiments described below. Design the circuits you will use for the measurements. Include resistors between each of two power supplies that will be used in the measurements. Choose appropriate resistor values assuming maximum current through the transistor ≤ 50 mA and its power rating of 500 mW. The resistors usually used in the lab are rated at 250 mW.

Experiments with BJT

(1) Using an N-P-N transistor in the common base circuit, measure and plot I_c as a function of V_{BC} at three different values of V_{EB}. *Note: Measure the values of the resistor in the emitter circuit (~ 100 Ω) prior to the measurements. Set the value of the emitter power supply for each V_{BC}. From the difference between the power supply voltage and V_{BC} you can also determine I_E.*

(2) Using the same transistor in the common emitter circuit, measure and plot I_C as a function of V_{CE} at three different values of I_B.

(3) Measure and plot I_C as a function of V_{BE} for the N-P_N transistor operating in the active mode.

Report and Analysis

Present clearly all schematics of the experimental circuits, showing the transistor, any resistors used and the instruments for measuring of voltage and current.

Present all graphs and include data tables. Comment on the curves and the mode of transistor operation (active, saturations, …?).

From (1) calculate and plot $\alpha = I_C/I_E$ as a function of I_C.

From (2) calculate β and plot it as a function of I_C. Can you see the effect of base width modulation in $I_C(I_{CE})$ plots. If so, try to derive the Early voltage V_A.

The collector current is controlled by V_{BE} as given by the Ebers-Moll equation:

$$I_C = I_S\ [e^{(V_{BE}/V_T)} - 1]$$

Using the data of (3) derive the electron charge q_e and compare it with the known published value.

Experiment Series 4 – MOSFET

MOSFET - Pre-Laboratory Assignment

1. Design a circuit for the measurements of n-type enhancement mode MOSFET I-V characteristics (see the experimental part below)

2. For an n-channel MOSFET sketch I_D (V_{DS}) curves for three different gate voltages. Identify different regions of the transistor operation.
What is the relation between V_{DS} and V_{GS} for the transistor to operate in the saturation region?

3. For an n-channel MOSFET plot I_D versus V_{GS} for a fixed value of $V_{DS.}$
Does the plot have a different shape (is described by different functions) in the linear and saturation regions?

Note: For 2 and 3 you may show simulations (those from ECE 374 are OK) or draw the plots by hand.

Reference: Jasprit Singh *Semiconductor Devices*, John Wiley & Sons 2001. pp. 393 – 415.

MOSFET – Experiments

1. Measure $I_{DS}=f(V_{GS})$ in the linear (ohmic) region for two low values of $V_{DS.}$ Estimate the threshold voltage from the plot.

2. Measure $I_{DS}=f(V_{GS})$ in the saturation region for $V_{DS} \geq V_G$. From the plot $(I_{DS})^{1/2}$ vs. V_{GS} determine of the threshold voltage V_T and the factor $k = \frac{W}{L_{eff}} k' = \frac{W}{L_{eff}} \mu_{eff} C_{ox}$

Hint: you could make these measurements with the transistor in the "diode connection" ($V_D = V_G$). Do you know why?

3. Measure the MOSFET output characteristics: $I_{DS}=f(V_{DS})$ for three different values of $V_{GS} > V_{Th}$. Identify the linear (ohmic) and saturation regions on the graph.

Report and Analysis

Present clearly all schematics of the experimental circuits, showing the transistor, any resistors used and the instruments for measuring of voltage and current.
Present all graphs and include data tables. Compare the values of V_{Th} derived from measurements 1 and 2. Plot the transistor transconductance in the saturation region, g_m, as a function of V_{GS}, based on the factor derived form measurements 2.
Do you see the effect of the channel length modulation in the data of part 3?

ECE 494 – B Laboratory Report

Experiment Series: **……………………………..**

STUDENT TEAM N**o** ____

<u>On my honor, I pledge that I have not violated the provisions of the NJIT Student Honor Code</u>

Name	Signature
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Experiment performed on date _________

Report submitted on date _________

Returned for corrections on date _________   Grade ______

Returned after corrections on date _________   Grade ______

FINAL