

# Advanced Undergraduate Laboratory in Semiconductor Device Physics Using Virtual Instrumentation

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## I. Introduction.

One of the many subjects that is covered in teaching VLSI is semiconductor device physics. It is well known that the physics of the semiconductor devices is subtle and it draws from many different areas of science and engineering. Typical electrical engineering students usually have difficulty in seeing the relevance of a mandatory course in semiconductor electronic devices. During the past few years of teaching a course in this area, I have noticed that there are many notions and ideas in device physics that can be very easily demonstrated in a laboratory environment while being relatively difficult to be shown theoretically. Hence, I have developed a series of simple, thirty minute experiments to demonstrate some of these "difficult to grasp" but "easy to see" notions in device physics.

It is also well known that some hands-on experiments almost always improve the learning process. Experiments help students to get a feel for "abstract" ideas. They also provide students with an opportunity to actively participate in the process of learning. On the negative side, experiments often take too much time to complete. Some of them do not work even with the help of teaching assistant or the instructor himself. Some of the experiments are just a waste of time. Moreover, the connection between the laboratory and the lecture is often not clear. The faculty member who is in charge of the course usually delegates the time consuming laboratory part of the course to a teaching assistant or another faculty member who disjointedly runs the experiments. These are the conclusions that I have reached personally when I was a student and by talking to many students from all over the United States and the World.

From the pedagogical point of view, therefore, experiments should run smoothly without waste of time and they should be designed to unambiguously demonstrate the "principle" they are supposed to show. They should add to the quality of

a course and should be an integral part of the lectures. Once students are drawn to a field by going through these well-designed experiments, there is ample time in the future for them to become familiar with the real world; to realize that one needs to know the "guts" of the equipment to be a good experimentalist and engineer. Hence the philosophy that I have adopted in developing the laboratory component is to have convenient but meaningful computer controlled experiments that can be performed in 20-30 minutes. Most of the results of these experiments are in graphical form and they clearly illustrate an idea that is covered during the lecture.

## II. Incorporation Into The Course .

The Semiconductor Electronic Devices course in Electrical Engineering and Applied Physics Department at Case Western Reserve University is a mandatory 3-credit hour course taken by Juniors in the Spring Semester and it uses Ben G. Streetman's "Solid State Electronic Devices" book [1]. We have supplemented this course with a laboratory component to: i) motivate and sustain the interest of our undergraduates in the basic operation of electronic devices, ii) teach them the principles of device operation and integrated circuits so that they will appreciate the application of these devices in systems and circuits, and iii) provide them with an opportunity to gain knowledge through a hands on experience.

To develop a historical perspective, we have also incorporated Encyclopedia Britannica's video tapes, which cover the recent history of electronic devices, during the first week of the class to show the students how everything fits together. Essay-type questions are also asked throughout the course to enhance the communication skills of students.

There are 15 weeks in the Spring semester of which one week is the Spring break and one week is usually spent on midterm examination. Each week is essentially divided to two parts of two hours of lectures and a one hour laboratory.

Homework is based on the laboratory experiments and there is approximately five laboratory sessions and twelve sets of homework. Each laboratory session is repeated four times and there is two set-ups. Students (enrollment is usually around 60-64 each year) are divided to groups of four. Each group has 20 minutes to perform the experiments. The experimental set-ups remains intact for 3-4 more days in case any of the groups wishes to repeat the experiments. There are 2-3 days available to set-up new experiments and fine tune the experimental procedure.

Finally students are asked to incorporate some of the devices that they have characterized in a final project dealing with amplification and optical transmission and detection of a high frequency (less than 100MHz) signal through a multimode optical fiber. This final project provides the students with a further motivation and also places the semiconductor devices in a more meaningful frame work of their use at the system level. Thus, the students are motivated to learn the physics of these devices by using them in a communication system. This laboratory course integrates device physics with the use of simulation of circuits (such as P-Spice) and design and construction of a communication system.

### III. Experiments.

Starting with experiments to illustrate the concepts of energy band-gap and positively charged quasi-particles in semiconductors, students progress to examine optical processes and electrical conduction in a variety of important electronic materials and devices. Each of these experiments is performed in twenty minutes and they incorporate state-of-the-art virtual instrumentation techniques to reduce the time needed for data acquisition. Hence, the students have enough time to carefully perform the experiment and understand the fundamentals behind the phenomena that they are examining. A balance is maintained, however, between the ease of use and pedagogical considerations.

The most puzzling concepts for students in the beginning of the course are the notions of the energy band-gap in semiconductors and positive quasi-particles (holes). To address these conceptual difficulties, energy band-gap is detected using optical transmission spectroscopy (through a direct band-gap material such as GaAs) and resistivity as a function of temperature measurements. Hall measurements, and thermoelectric measurements are used to demonstrate the existence of positively charged quasi-particles in semiconductors.

Optical processes in semiconductors is demonstrated using three sets of measurements: photoconductivity, electroluminescence (using light emitting diodes and semiconductor lasers), and electrical power generation in illuminated p-n junctions (solar cell). Excess carrier generation/recombination lifetime is examined by observing the photoconductivity decay in a silicon photoresistor illuminated by a GaAs pulsed laser diode (microsecond pulses are readily available commercially).

The principles of operation of minority carrier devices (p-n junctions, bipolar junction transistors, and p-n-p-n switching devices) and majority carrier devices (Schottky diodes, metal-oxide-semiconductor capacitors, and field effect transistors) are examined experimentally starting with a thorough examination of the current versus voltage (I-V) and capacitance versus voltage (C-V) characteristics of p-n junction and Schottky diodes and metal-oxide-semiconductor structures. Dynamic charge storage effects is demonstrated using transient recovery measurements.

The terminal characteristics of bipolar junction and field effect transistors are examined and understood based on the operation of their fundamental building blocks; i.e., p-n junctions, Schottky diodes and MOS structures. More specifically, there is two laboratory sessions devoted to BJT's and MOSFET's. Parameters such as base to collector current amplification ratio, junction capacitances, and switching characteristics are determined for BJT's. The gate capacitance, transconductance, flatband voltage, interface trap density between gate oxide and the channel, and threshold voltage are determined for MOSFET's.

Figure 1 shows a typical set-up and the virtual instrumentation window that students observe on their computers. Before running the program, students make sure that all the equipment is turned on. They choose parameters of the experiment on the Macintosh screen. In this particular example that, the set-up is for performing transmission spectroscopy of semiconductors, and students choose the range of the scan of the light wavelength and the sensitivity of the detector. Then they run the program by clicking on the start button. There is a chart recorder on the screen that shows the result of the measurement while the experiment is being performed. This is added so that students do not get board and gives them the indication that the experiment is

successfully running. After the experiment is completed the result is shown in a graph at the lower portion of the screen. Students can use the data in a graphic form and either print or plot it or they can copy the data file to their own floppy and use number of different numerical analysis and graphic programs on board to do numerical integration/ differentiation, scaling, and any other operation that may be required.

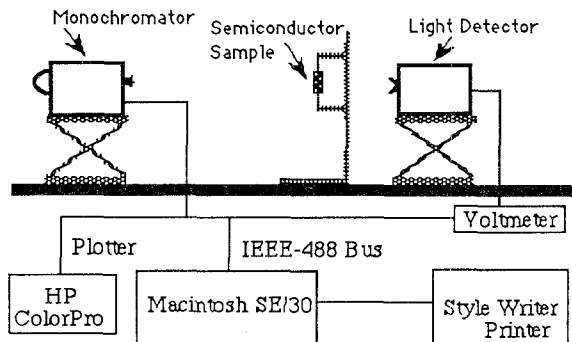


Figure 1.a The set-up used in the band-gap measurement (spectroscopy).

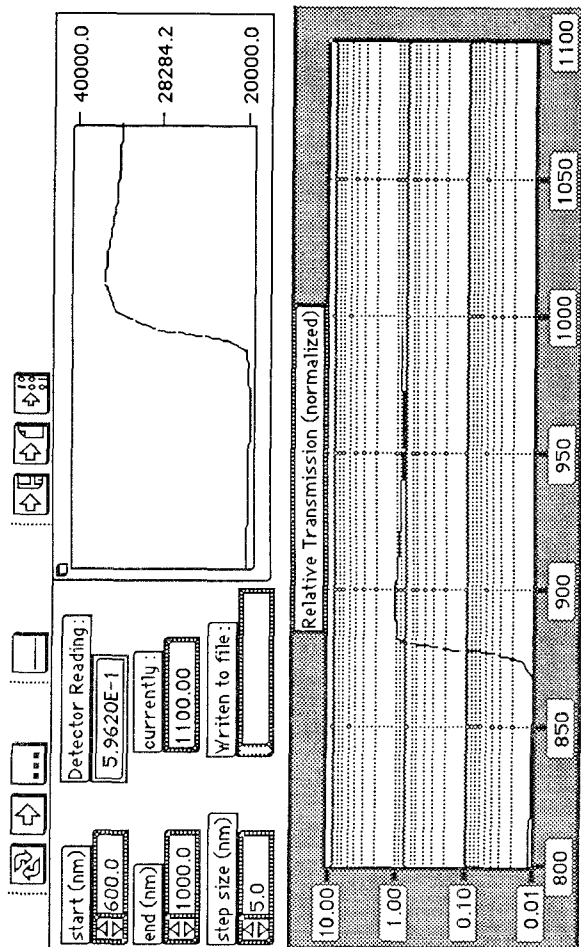


Figure 1.b The Macintosh screen for the spectroscopy experiment.

In all of the experiments, students use a personal computer (Macintosh SE/30) to acquire data through IEEE-488 (GPIB) interface board. Students at CWRU are exposed to Macintosh personal computers starting their freshman year and, hence, they already know how to use these computers. We have installed a virtual instrumentation software (LabView) [2] in SE/30's to eliminate any difficulty associated with the data acquisition. Passage, Stat-View and other data analysis and graphic softwares are used to reduce the data and present it in a meaningful and illustrative format. The philosophy behind the above steps is to reduce the amount of time that is needed to perform the experiments and to acquire the data so that students can concentrate on understanding the experimental results. To enable students to know about the experiments before coming to the class, a "read me" file was posted on the freenet which is accessible to all of the students in the campus through a fiber-optic network. Off-campus students could access these files using a modem. An example of a "read me" file is shown in figure 2.

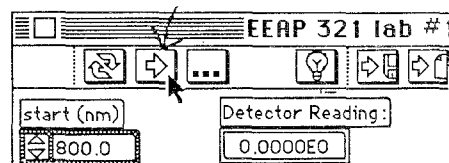
### EEAP 321 - Lab #1 Energy Band Gap Measurements

**Purpose:** In this experiment, we determine the energy band gap and the resistivity of a semiconductor material.

#### A. Transmission vs. Wavelength :

Here, we want to determine the energy band gap of a material. The experiment set-up includes a monochromator which transmits light of a desired wavelength, a chopper to pulse the light, a semiconductor material (InP) in the path of the light, and a detector which outputs a voltage proportional to the intensity of light transmitted through the material..... **Directions:** From the "EEAP 321 Lab Folder" window, double-click on "EEAP 321 Lab #1" to start LabView and load the program which drives the experiment. To start the experiment, click on the arrow at the top border of the panel as shown below.

Click this button to start



After you run the experiment, determine the critical wavelength  $\lambda_{gap}$  and determine the energy band gap  $E_{gap}$ .

Figure 2 A typical "read me" file.

#### IV. Final Project.

Students are asked to incorporate some of the devices in a final project dealing with amplification and optical transmission and detection of a high frequency signal through a multimode optical fiber. The final project provides the students with a further motivation; it also places the semiconductor devices in a more meaningful frame work of their use at the system level. Thus, students learn the device physics motivated by using them in a communication system.

#### V. Feedback From Students.

Here we present some of the student's comments about the laboratories. Students were asked to write their views on the overall course quality on the usefulness of the laboratory, and other matters related to the course. We quote here only that part of the students comment that deals with laboratories.

".....the labs are fun and really help to reinforce the material and give "real world" applications of the stuff we do in class..... Labs are bringing together the lectures and the readings from the book. The concrete examples create a better understanding..... They (labs) are well organized and presented (and are) interesting. It would help if we could look at the "read me" files for the lab before going in - not all of us have easy access to Macs. Lab assistants seem interested, knowledgeable and helpful..... When my lab group meets on Thursdays, sometimes the lab is not quite ready to go. In other words, it seems like the earlier lab groups are at a disadvantage. This is, in my opinion, a minor problem because the slightly unpolished labs that the early lab groups are exposed to are nonetheless very illustrative of the material..... Labs (are) good observations, (and they are) fun. Sometimes printouts of labs do not exactly depict actual lab..... Labs help me understand material much better..... The labs are fairly well organized..... The LabView set-ups and the actual equipment used could be better explained. The way the equipment works on a block diagram level would help us understand the device properties being measured..... Overall it is a very well organized course. Most students were pleasantly surprised to find there is an EE Prof. who cares about undergrads."

The following is an observation by one of the students who had chosen to keep a journal of lectures and laboratories. This particular passage is from her observations of the spectroscopy laboratory that was designed to show the existence of a band-gap energy in semiconductors.

"Since this was the first part of the first lab for this class, I really did not know what to expect. I had paid very close attention in class to any mention of the experiment; I must admit that I was quite nervous about the whole experience. Professor Tabib-Azar had assured the class that the lab was created to help us better understand the material covered in class, but usually extra labs or projects go one step beyond fundamental principles that I don't fully understand and leave me even more confused than before. ( I was especially wary of this lab because we had just discussed Schrodinger's equation, a topic which had confused me for years, in class.) I entered the first lab expecting to leave baffled."

"When the experiment started, the computer showed a very clear graph of current from the photo detector vs. wavelength of light sent to the semiconductor. For a second, I was confused because the wavelengths scanned from higher to lower, and the graph showed the higher wavelengths to be on the right, I thought that the experiment was showing results exactly opposite to those I had expected. I asked the TA (teaching assistant) about this and he pointed out my error in reference. With this cleared up in my mind, I could now explain how and, more importantly, why the experiment worked. For the first time ever, a lab had cleared up a hazy understanding in my mind. This lab proved to me that photons of high enough energy are absorbed into semiconductors."

The above observations and comments overwhelmingly point to the fact that a well designed and prepared laboratories can indeed be very useful in increasing student's interest in subjects that are not necessarily very popular to begin with.

VI. Conclusion. We supplemented the semiconductor electronic devices course with a laboratory component to: i) motivate and sustain the interest of our undergraduates in the basic operation of electronic devices, ii) teach them the principles of device operation and integrated circuits so that they will appreciate the application of these devices in systems and circuits, and iii) provide them with an opportunity to gain knowledge through a hand on experience.

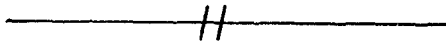
Our experiments were run by Macintosh SE/30 personal computers equipped with Lab View that was used as virtual instrumentation software that controlled the equipment through IEEE-488 interface board. The experiments were designed to clearly show the ideas that was discussed in the

lectures and they could be run in 20-30 minutes. Judging from the student's performance in the course and their comments throughout the course I concluded that these laboratories were very helpful and successful in clarifying the course material as well as increasing the level of curiosity of students. More importantly, laboratories increase the active involvement of students in the process of learning.

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### VII. References.

1. B. G. Streetman, Solid State Electronic Devices. Third edition (1990). Prentice Hall, Englewood Cliffs, NJ.
2. LabView by National Instruments, Bridge Point Parkway Austin, TX.



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Massood Tabib-Azar was born in Tabriz, Iran, in May '58. He received the M.S. and Ph.D. degrees in electrical engineering from the Rensselaer Polytechnic Institute in '84 and '86 respectively. In 1987, he joined Case Western Reserve University as an Assistant Professor. His current research interests include optical sensors and actuators, electrical and optical properties of novel materials such as multiple quantum wells, superlattices, and HTS devices. His teaching interests include development of courses in the area of electronic device physics with an emphasis on the problem solving approaches and the use of computer aided instruction tools. He is author and co-author of more than 30 journal publications.

Dr. Tabib-Azar is a recipient of the '91 Lilly Foundation Fellowship and he is a member of New York Academy of Sciences, IEEE (Electron Devices), APS, AAPT, and Sigma Xi research societies. He is an Associate Professor at Case and an Adjunct Professor of Electrical Eng. at Tehran University.

