Automated Parametric Tests for Novel Semiconductor Materials and Devices

Sabino Torres¹, ² (Senior), Jonathan Miller²
Ramesh C. Dwivedi², Padmini Periaswamy³, Mohan Ketkar¹, R. Wilkins², and R.K. Pandey³

¹Department of Engineering Technology
Prairie View A&M University, Prairie View, TX 77446
²NASA Center for Applied Radiation Research
Prairie View A&M University, Prairie View, TX 77446
³Department of Electrical and Computer Engineering
The University of Alabama, Tuscaloosa, AL 35487

Abstract

A summer internship of 2005 provided valuable hands-on experience by (1) studying novel semiconductor devices and materials using capacitance versus voltage (C-V) and current versus voltage (I-V) measurements, (2) analyzing C-V and I-V data for these materials and devices, (3) modeling new semiconductor materials and devices based on metal oxide semiconductor field-effect transistors (MOSFET), and (4) performing resistivity measurements on materials using four-point probes for pre-radiation testing. This paper describes experiences gained and skills developed during an undergraduate summer internship.

The C-V and I-V measurements help understand the electrical characteristics of the electrical devices by plotting and analyzing the overall shape and values of the C-V and I-V curves. The engineering technology curriculum includes courses in basic electronic devices and computer applications which introduce the student to the characteristics of basic electrical devices. This prepares engineering technology students to design the test set-up and perform experiments using up-to-date software and test equipment and apply this to novel devices.

The experimental set-up for C-V measurements included the Model-82 DOS Simultaneous C-V Software, Keithley Instruments: KI 230 voltage source, KI 590 C-V analyzer, and KI 595 quasi-static C-V meter. The device-under-test (DUT) samples are placed in a probing station that includes a stereo microscope, a light shielded enclosure with hot and cold chuck.

The experimental set-up for I-V measurements included the Interactive Characterization Software (ICS), a KI 2361 trigger controller, and KI 236 source measure unit (SMU). The test equipments were interconnected using IEEE 488 bus for data acquisition.

The materials tested were ferroelectric ceramic, integrated ferroelectric (PNZT) and silicon (Si) structures, components-off-the-shelf (cots), novel Ilmenite-hematite ceramic (IHC) samples, and pseudobrookite (PsB) single crystals. Ferroelectric, wide band gap pseudobrookite, Fe₂TiO₅, single crystals and IHC ceramic magnetic-semiconductor samples were provided by the Laboratory for Electronic Materials and Devices at the University of Alabama - Tuscaloos. This research was funded by a grant from NASA as part of the Center for Applied Radiation Research (CARR) at Prairie View A&M University.
Introduction

For decades engineers and scientists have used C-V and I-V measurement methods to study the characteristics of semiconductor devices and materials. The engineering technology majors are also capable of performing and understanding these measurements based on current curriculum content. The user friendly software allows engineering technology majors to perform data acquisition, data plotting, and analysis. The engineering technology curriculum includes computer application courses and allows engineering technology students to prepare the laboratory test set-up and perform experiments using software and test equipment available in the open markets.

A recent (2005) summer internship provided hands-on experience in the test and measurements methods used in the semiconductor industry. Because of shrinking geometry (scaling) of devices in accordance with Moore’s Law to ever achieve higher circuit density, there is need to perform automated parametric testing on devices similar to those measurement represent in this paper.

The semiconductor properties of materials are related with the energy band gap [1] between valence band and conduction band. This paper includes work done with silicon with band gap of 1.1 eV, as well as Ilmenite-hematite (IH) materials with a band gap of approximately 3.1 eV and PsB crystals. The Ilmenite-hematite [2] samples are listed as IHC1 and IHC2 in Table 1. All the samples tested are summarized in Table 1, all measurements were performed at the NASA Center for Applied Radiation Research (CARR) at Prairie View A&M University for data analysis.

Table 1 lists sample names, type of electrical contacts on the sample, and the device model used for testing. For instance, a two terminal structure can be tested as I-V or C-V. A three or four terminal structure is tested as a MOSFET as shown in the measurement column of Table 1.

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Type of Contact</th>
<th>Model</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>IHC1</td>
<td>Ag</td>
<td>MOSFET</td>
<td>I-V</td>
</tr>
<tr>
<td>IHC2</td>
<td>Ni</td>
<td>MOSFET</td>
<td>I-V</td>
</tr>
<tr>
<td>PsBXtal</td>
<td>Ag</td>
<td>MOSFET</td>
<td>I-V</td>
</tr>
<tr>
<td>Ferroelectric</td>
<td>Pt</td>
<td>MOS</td>
<td>C-V</td>
</tr>
<tr>
<td>PNZT structure</td>
<td>Pt</td>
<td>MOS</td>
<td>C-V</td>
</tr>
<tr>
<td>Diode (1N4001)</td>
<td>Standard Leads</td>
<td>p-n diode</td>
<td>I-V</td>
</tr>
<tr>
<td>MOSFET NT E465</td>
<td>Standard Leads</td>
<td>MOSFET</td>
<td>I-V</td>
</tr>
</tbody>
</table>

Table 1: Samples tested and their characteristics

Experimental Details

Hardware

The hardware setup requires several instruments to link with the IEEE 488 bus. On this bus an instrument is configured as a ‘talker’ or a ‘listener’, each instrument has an IEEE 488 bus address. The instrument data acquisition is performed by a PC using an application software.

The instruments for the C-V measurement include a KI 230 voltage source, KI 590 C-V analyzer, and KI 595 quasi-static C-V meter. The device under test (DUT) is placed on a chuck. In this case the device is shown with six capacitor structures labeled one through six as shown in figure 1(a) and electrically connected to probes as shown in figure 1(b). The device is held in place by a vacuum system and the probes are observed and manipulated by viewing through a
stereo microscope, figure 1(c). The I-V measurements are done in a similar manner except that the instruments used are KI 2361 trigger controller and KI 236 source measure unit (SMU).

Figure 1: (a) Schematic drawing of the Ferroelectric Ceramic sample, (b) Placement of probes on device contacts, 6 contacts are shown (c) viewing the device under test through a stereo microscope

Figure 2 shows a text fixture box. The box facilitates electrical connections for some samples, provides electrical isolation for the samples and is light tight. The devices IHC1, IHC2, PsBXTal were mounted in the box and the box was connected to test instruments by means of tri-axial cables. Tri-axial cables have an extra electro-magnetic shielding guard, compared to regular BNC cables, allowing for higher accuracy in the measurement of low voltage/current signals.

Figure 2: HP Test Fixture. Ilmenite-hematite (IHC1) sample mounted for I-V measurements examintation.

Software

The commercial Model 82-DOS Simultaneous C-V [3] software was used for quasistatic and high frequency C-V measurement. This software contains drivers for the KI 590, KI 595, and KI 230 instruments. The Interactive Characterization Software (ICS) was used for I-V measurements. The ICS software provides the drivers for SMUs KI 236 and the trigger controller KI 2361. The operation of the Model 82-DOS Simultaneous software requires programming of several user friendly screens. A typical screen for data acquisition is shown in Figure 3. In this figure, note that the range, frequency, model for circuit test, start voltage, stop voltage, bias voltage, time delay between samples, step size of the voltage sample and filter if any are programmed in this screen. All of these parameters are chosen and entered by the user.
The ICS software [4] allows for I-V programming and data acquisition by programming several interactive screens. First of all, a device type is selected in the software. For example, a four terminal MOSFET device is shown to be selected in Figure 4. The terminals of the selected device when double-clicked allow the opening of the programming screen for the SMUs.

A typical SMU programming screen is shown in Figure 5. Note that the screen allows programming and plotting of the curves for two variables. A third variable, used as a step or sweep permits the measurement and plotting of a family of curves. The data can be saved and exported to a desired destination.
Results

The Ilmenite-hematite sample IHC1 and IHC2 were tested as three terminal. The measurements taken for these devices are shown in Figures 6 - 11. The SMUs were programmed accordingly using the software screens describe earlier. Figures 6, 7, 8, 9, and 10 are single I-V curves (characteristics) and Figures 10 and 11 show a family of I-V curves. The bend in the curves indicates varistor-like properties of the Ilmenite-hematite devices. The data show that the curves shift when the electric field is applied at the gate voltage.

Figure 6: Ilmenite-hematite sample IHC1, with Ag contacts. I-V characteristics: $I_D$ versus $V_D$, $V_G = 0$. Sweeping $V_D$ from -5V to 5V, $V_G$ constant at 0.

Figure 7: Ilmenite-hematite sample IHC1, with Ag contacts. I-V characteristics. $I_D$ versus $V_D$, $V_G = -5V$. Sweeping $V_D$ from -5V to 5V, $V_G$ constant at -5V.
For comparison, we show below representative results for a three terminal and two terminal commercial silicon devices. Figure 12 represents a standard textbook family of curves for $I_D$ versus $V_{DS}$ for commercially available MOSFET NTE 465. The curves indicate that this device has good MOSFET device characteristics. NTE 465 comes with four terminals namely substrate, source, drain, and gate. However, in this measurement the substrate and source were connected to a common ground and the device was effectively tested as a three terminal device. The SMUs were programmed accordingly.
The SMU connections for commercially available semiconductor diode, 1N4001 are shown in figure 13(a). Figure 13(b) represents I-V characteristics of a good p-n diode 1N4001 that was tested as a two terminal device. Note that the I-V measurements for a two terminal device require only one SMU.

Comparison of the data for the devices made from the novel ilmenite-hematite material with standard commercial silicon devices show the devices behave very differently. While the ilmenite-hematite devices have a non-linear curve, they are not like the silicon diodes which show strong rectifying behavior. In addition, the third terminal measurements on the ilmenite-hematite devices did not show transistor-like behavior.

Figure 14 shows the quasistatic and the high frequency (100 KHz.) C-V measurements of MOS capacitor with a structure of Al/SiO2/Si. Several properties of this structure can be determined using Model 82-DOS Simultaneous C-V software. The properties of interest are device interface traps (DITs), doping depth profile and band bending [5]. However, this analysis is kept out of the scope of this paper.
Summary and Conclusion

This paper is intended to demonstrate that students in an engineering technology curriculum can perform many tasks that are typically associated only with engineering majors. The background provided by the curriculum provides the basis for performing and understanding the basic electrical measurements. The technology background also provides student a firm basis in established technology allowing comparisons between new technologies and the established technologies. The professors who participated with the technology student during the summer internship were generally satisfied with the performance of the technology student who took and analyzed the data. Furthermore, this student worked well in partnership with an electrical engineering student also working on the project. This provides evidence that engineering technology students are fully capable of contributing to cutting-edge research and should be given a greater opportunity and responsibility in performing and managing research and engineering tasks.

Acknowledgement

This work was funded by NASA through the Center for Applied Radiation Research (CARR) at Prairie View A&M University under Grant # NCC-9-114. The authors acknowledge Mr. Jonathan Miller, senior electrical engineering student, who also participated in the measurements described in this paper. We also thank DoE and ONR for supporting oxide magnetic semiconductor research at the University of Alabama, Tuscaloosa, AL from where we received samples of IH, PsB and Ferroelectrics.
References


Sabino Torres, Jr. is a senior in Computer Engineering Technology department at Prairie View A&M University in Texas. He is member of Tau Alpha Phi and IEEE local chapter. His interest include in digital design, computer programming, and robotics.

Jonathan Miller is a senior in Electrical Engineering department at Prairie View A&M University in Texas. His interests include control systems and robotics.

Ramesh C. Dwivedi, P. E. is a Research Specialist at NASA Center for Applied Radiation Research (CARR) at Prairie View A&M University in Texas. His interest includes space radiation effects on electronics, digital design, radiation detectors, and teaching course in College of Engineering.

Dr. Padmini Periaswamy is an Associate Research Engineer in the Electrical and Computer Engineering Department of the University of Alabama, Tuscaloosa, AL. She is a graduate (Ph.D) of the Indian Institute of Science, Bangalore, India; and a junior Fellow of Germany’s prestigious Alexander von Humbolt Foundation. Her research expertise includes growth and characterization of epitaxial films for microelectronics, ceramic processing and characterization, and fabrication and evaluation of varistor devices for radhard electronics. She has published extensively in referred journals and has some patents to her credit.

Dr. Mohan A. Ketkar is an Assistant Professor and ELET Coordinator in the Department of Engineering Technology at Prairie View A&M University in Texas. He received his masters and doctorate in Electrical Engineering from University of Wisconsin-Madison. His research area includes communications in electronics, instrumentation, RF circuits, and numerical methods.

Dr. R. Wilkins is an Associate Professor in the Department of Electrical Engineering at Prairie View A&M University in Texas. He is the Director of NASA Center for Applied Radiation Research (CARR) at Prairie View A&M University. He has published many papers in space radiation effects and space radiation shielding.

Dr. R.K. Pandey is Cudworth Endowed Professor of Electrical and Computer Engineering, Adjunct Professor of Physics; and the Director of Laboratory of Electronic Materials and Device Technology at the University of Alabama, Tuscaloosa, Alabama. He has held many administrative positions including department Headship and NSF Center Directorship. He has published extensively in highly respected journals and holds six US patents for his inventions. He is a Fellow of the American Ceramic Society.