Automating Energy Bandgap Measurements in Semiconductors Using LabVIEW

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Abstract: *In this paper, we report the development of an automated system for energy bandgap and resistivity measurement of a semiconductor sample using Four-Probe method for use in the undergraduate laboratory of Physics and Electronics students. The automated data acquisition and analysis system has been developed using National Instruments USB-6008 DAQ Card and Student version of LabVIEW 8.5 Development System Software. One of the objectives of the development has been to motivate students to the use of computers in science experimentation/education besides other advantages. The developed system performs energy bandgap measurements by analyzing resistivity variations for the semiconductor sample over a wide range of temperature. The acquired data is also available for both online and offline analysis. The final results are generated in the form of a report for onward use and verification.*

Keywords: Computer interfacing, automatic Four Probe, data acquisition, PC based experiments, band- gap measurements

Introduction

In semiconductor solids, atoms are arranged in an ordered densely packed diamond structure. The wave-functions of the packed atoms overlap and interact and spread into energy levels. Since there are large number of atoms in the crystal ($\approx 10^{23}$ cm^{-3}) this result in bands of energy levels. The band gap E_g separates the valence band and the conduction band and determines the intrinsic conductivity/resistivity. Resistivity is the most fundamental property of a semiconductor and is a critical parameter in both materials research and wafer fabrication. A semiconductor's resistivity depends primarily on the bulk doping and can be enhanced by doping it with n-type or p-type impurity elements. The dopants reduce the band gap of a semiconductor material leading to increased conduction even at room temperature.

The resistivity can affect a device's series resistance, threshold voltage, capacitance, and other parameters. Semiconductor material research and device testing require electrical characterization that often involves determining the resistivity and Hall mobility of a sample. Since at the undergraduate level, students do a detailed study of semiconductors and solid state devices, it is important that they experimentally measure the resistivity and thus find out the band gap of semiconductors. A four-point probe and the appropriate test equipment can be used to determine the resistivity. The present application automates these measurements.

Also, in our earlier development for measuring the mobility through Hall Effect [1, 2], the resistivity of the sample under study was given as input parameter from the manufacturer's datasheet. Since resistivity can be directly computed from the present automated system, it can be integrated as a module with the Hall Effect Setup. Therefore, the two setups make up for a complete electrical characterization of any semiconductor sample.

More so, automated data acquisition and analysis allows students to generate experimental data, draw graphs, re-examine the variables and identify possible errors as well as running the experiment again, if necessary, during class. Therefore, through the present automation, they can now focus entirely on the experiment and on its underlying physics rather than spending most of the time collecting and plotting data for later analysis.

Theory

Band gap calculations require measurement of resistivity with respect to its variation with temperature. Many conventional methods for measuring resistivity such as soldering contacts to the sample are unsatisfactory for semiconductors. Soldering, a process of making metal interconnect by melting a low temperature filler metal, directly on to the sample can disrupt the properties of the sample through heating and carrier injection. A metal-semiconductor contact can be formed by depositing a metal over a highly polished and cleaned semiconductor wafer by various deposition techniques. If the semiconductor has low dopant concentration i.e. if it is lightly doped, the resultant junction is a metal- lightly doped semiconductor contact. Metal-lightly doped semiconductor contacts are usually Schottky or rectifying in nature and there tends to be minority carrier injection by one of the current carrying contacts [3]. An excess concentration of minority carriers will affect the potential of other contacts and modulate the resistance of the material, hence giving an unsatisfactory result. The four probe technique overcomes these faults by using pressure contacts and

allows measurements to be made on a smaller area; hence there will be lesser variation in the properties of the crystal over the smaller area.

Hence, Four Probe method has been employed to measure band gap of a semiconductor sample. This involves four collinear small sharp probes placed on a flat surface of the sample to be measured as shown in Figure 1. A constant current is passed between the outer contacts and the resulting floating potential between the inner contacts is measured.
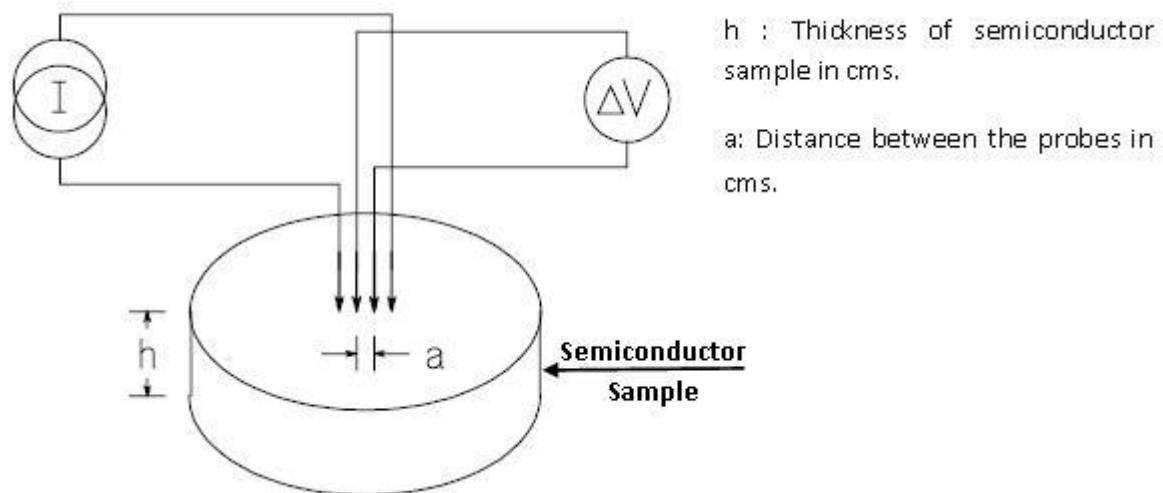
Fig. 1: Four-Probe Setup for Band gap measurement

The resistivity is calculated from Ohm's law and the geometry of the sample. If the temperature is increased, more electrons will be excited into the conduction band so the conduction will increase, therefore the resistivity will decrease. Since the resistivity is highly dependent on the temperature, we vary the temperature while taking measurements, and hence are able to find the resistivity as a function of temperature. If a plot is then made of ln ρ vs. 1/T then the slope will be proportional to the bandgap of the sample.

The electrical conductivity (σ) for a semiconductor sample having both electrons and holes is given by [4, 5]:

$$\sigma = (n_i q \mu_e + p_i q \mu_h) \qquad (1)$$

Where n_i and p_i are electron and hole concentration while μ_e and μ_h are electron and hole mobilities.

In an intrinsic semiconductor n$_i$ = p$_i$ and $n_i = KT^{\frac{3}{2}}e^{-\frac{Eg}{2kT}}$ (2)

Since T$^{3/2}$ (μ_e + μ_h) variation is small in comparison to exponential term, from equation (1) and (2), we get

$$ln\rho = \frac{Eg}{2kT} - lnK \qquad (3)$$

Where ρ is resistivity equal to 1/σ. Equation (3) is used to calculate the bandgap E$_g$. The slope must be found from the part of the plot where the temperature is high and the intrinsic component of conduction dominates; the slope is linear in this region. At the undergraduate level, students perform this experiment to estimate the bandgap of a given semiconductor. The experiment requires simultaneous measurement of voltage, current and temperature for estimation of the bandgap and resistivity calculations.

Experimental Setup

System Configuration:

Figure 2 shows the block diagram for carrying out the measurements using the data acquisition system based on NI USB-6008 DAQ Card [6]. The three analog input channels of the data acquisition card are connected in differential mode to measure the semiconductor sample voltage, input current to the sample and the temperature using an LM135 temperature sensor. The developed software is integrated to the hardware and acquires these measurements for the estimating bandgap of the semiconductor under study.
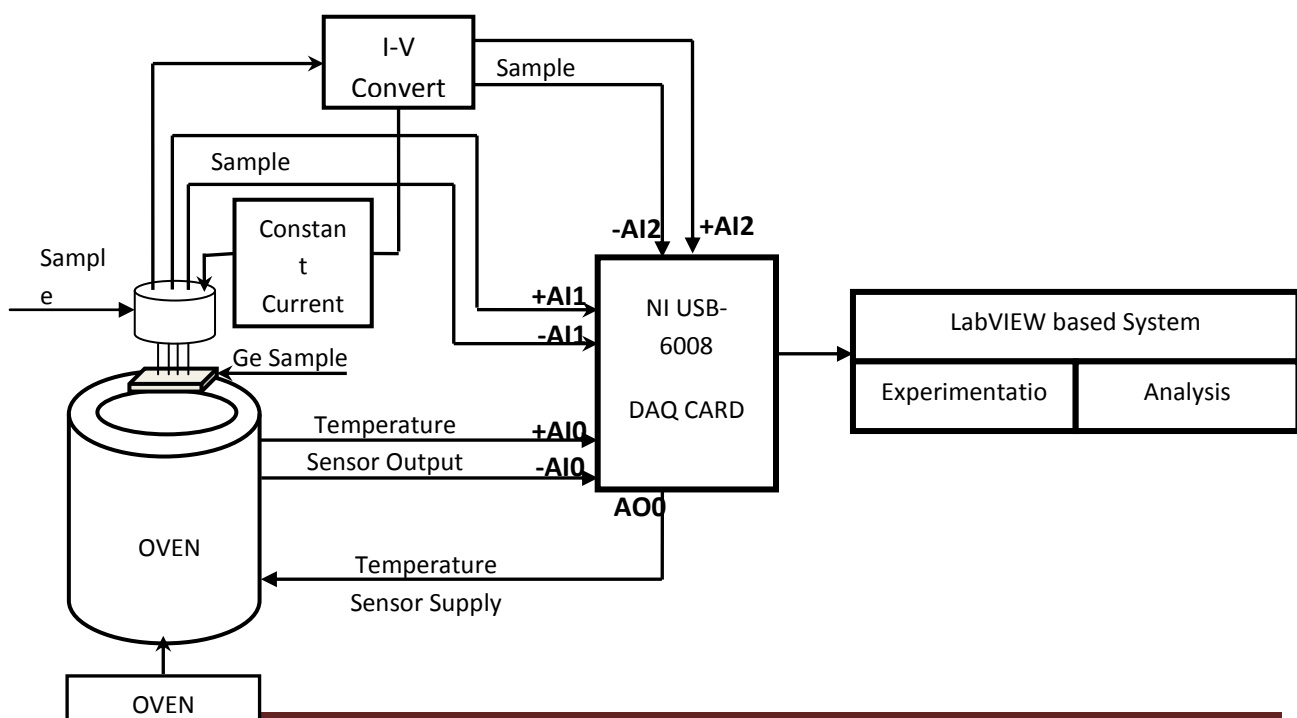
Fig. 2: Block Diagram for NI USB-6008 based Data Acquisition System

System Implementation:

The developed software is a Lab VIEW based graphical user interface. Lab VIEW is a graphical programming environment used by millions of engineers and scientists to develop sophisticated measurement, test, and control systems using intuitive graphical icons and wires that resemble a flowchart. Lab VIEW offers unrivalled integration with thousands of hardware devices and provides hundreds of built-in libraries for advanced analysis and data visualization.

The developed application can be broadly classified into two sections: Experimental and Analysis. In the developed application, on start-up, the user is directed either to proceed with experimentation or the analysis tab which is used to analyze previously acquired experimental data. The two sections are described as below.

Experimental Section:

The experimental section of the developed interface consists of the acquisition of the sample voltage, current and temperature to determine the bandgap as shown in Fig. 3(a) and 3(b). Fig. 3(a) is the front panel graphical interface for online acquiring and display of the data. This section can be divided into following modes:
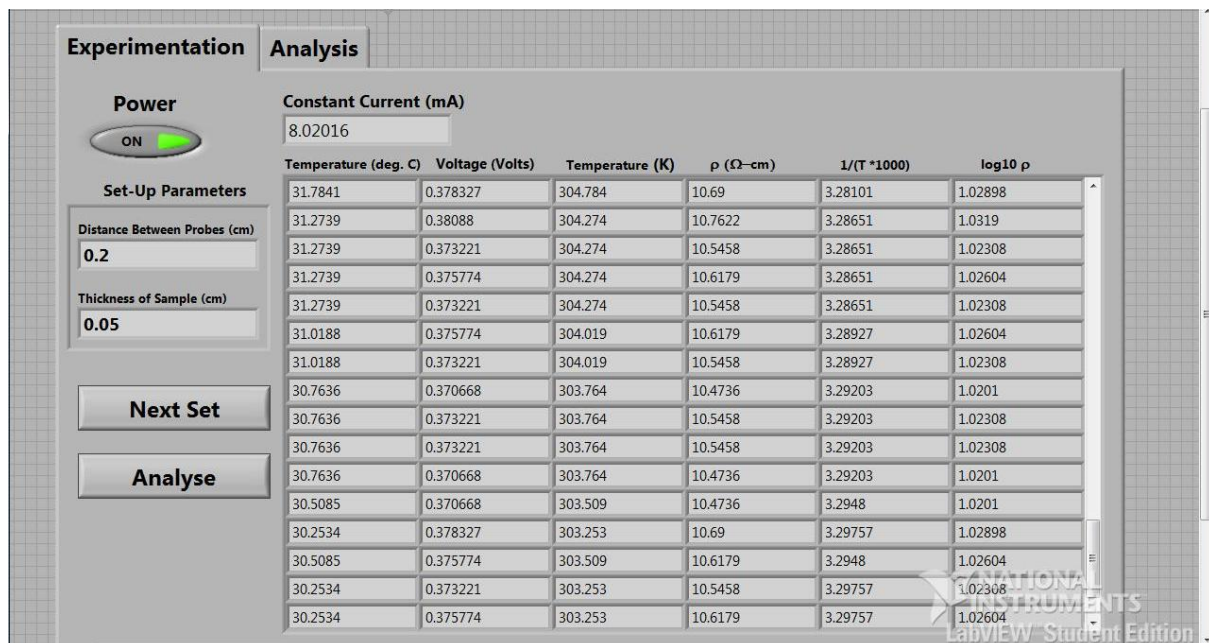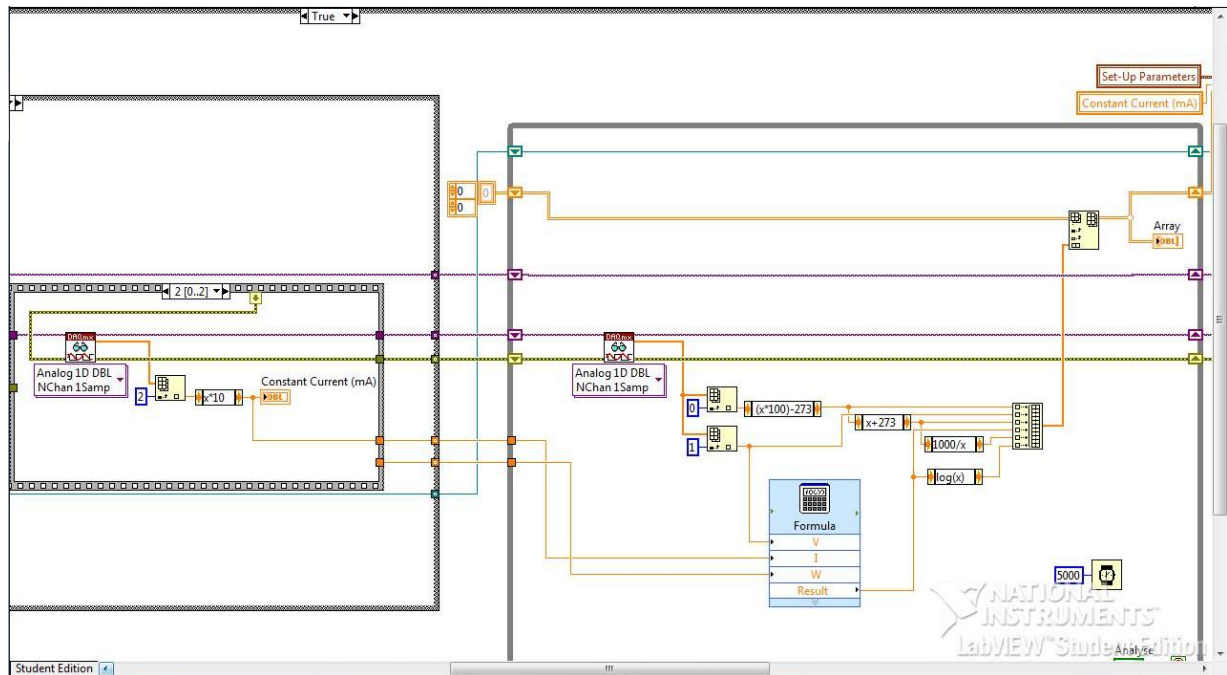

Temperature (deg. C)	Voltage (Volts)	Temperature (K)	ρ (Ω−cm)	1/(T *1000)	log10 ρ
31.7841	0.378327	304.784	10.69	3.28101	1.02898
31.2739	0.38088	304.274	10.7622	3.28651	1.0319
31.2739	0.373221	304.274	10.5458	3.28651	1.02308
31.2739	0.375774	304.274	10.6179	3.28651	1.02604
31.2739	0.373221	304.274	10.5458	3.28651	1.02308
31.0188	0.375774	304.019	10.6179	3.28927	1.02604
31.0188	0.373221	304.019	10.5458	3.28927	1.02308
30.7636	0.370668	303.764	10.4736	3.29203	1.0201
30.7636	0.373221	303.764	10.5458	3.29203	1.02308
30.7636	0.373221	303.764	10.5458	3.29203	1.02308
30.7636	0.370668	303.764	10.4736	3.29203	1.0201
30.5085	0.370668	303.509	10.4736	3.2948	1.0201
30.2534	0.378327	303.253	10.69	3.29757	1.02898
30.5085	0.375774	303.509	10.6179	3.2948	1.02604
30.2534	0.373221	303.253	10.5458	3.29757	1.02308
30.2534	0.375774	303.253	10.6179	3.29757	1.02604

Fig. 3(a): Front Panel Diagram for the Experimental Section of the developed Four Probe System

Fig. 3(b): Part of Block Diagram for the Experimental Section of the developed Four Probe System

1. **Power ON/OFF:** When the user enters the experimental section and powers on the VI with the switch provided on the front panel, the user is prompted to create the datalog file to save online data. After creation of file, the VI prompts the user to input the sample thickness and the distance between the probes used in the four probe set-up. These parameters are thereby stored in the datalog file and act as the input to the bandgap and resistivity calculations. The VI then prompts the user to provide a constant current to the sample. The user may quit from the VI anytime by switching the Power button to OFF state.

2. **Data Acquisition:** As soon as the user sets the constant current value and presses the OK button on the prompt, the constant current value is read by the NI USB-6008 DAQ Card from Analog Input, AI3 and a supply of 5 Volts is provided at the Analog Output AO0 for the LM135 temperature sensor used. The VI then automatically moves into self acquisition mode thus acquiring sample voltage and temperature sensor voltage from Analog Inputs AI1 and AI0 respectively at a sampling rate of 5 seconds for each successive observation.

3. **Calculations:** The acquired parameters are simultaneously used to calculate the values of temperature, T and resistivity, ρ thus evaluating 1/T and ln ρ values to be plotted in Analysis section. This simultaneous estimation of resistivity helps the user to interpret the values so as to take necessary action in case of any discrepancies unlike the basic set up where the calculations are only done after

the completion of the experiment. The calculated values are automatically saved into the datalog file on completion of data set.

4. **Next Set:** When the user has acquired the desired number of data points for the graph plotting, he/she may take another set of readings for a different constant sample current value by clicking on the NEXT button. As soon as the user presses this button, the VI utilises the power of the event handler to again initiate the acquisition of current and supply of sensor voltage for next set of observations followed by the simultaneous acquisition of temperature and sample voltage.

Fig. 3(b) is the block diagram of the developed VI which provides the functionality to the front panel graphical interface. The various features are discussed as under:

1. A datalog file is created in the write only mode by the user at the beginning of the application for storing all the experimental data. This utilizes the power of Lab VIEW where one can easily store large amount of data in a small size datalog file. A datalog file cannot be read directly by the user. However, storing the data in a reduced size low level format which is easier to understand by the computer, it makes processing of data much faster.

2. The dialog interfaces in Lab VIEW makes it easier for the student to enter the required parameters for calculation. The user is prompted after file creation for entering the various parameters of semiconductor sample under study.

3. Now, the user is ready to start the experiment and as can be seen from the figure a continuous while loop is used to acquire the current values from the external hardware. This acquisition is stopped as soon as the student reaches the desired current level.

4. Another while loop has then been incorporated for acquisition of temperature and voltage values from NI-USB 6008. This is a continuous acquisition loop running at an interval of 5 seconds. This loop is externally controlled by the user and is stopped only when he/she presses the Next Set or Analyse Button on the front panel.

5. Every time the Next Button is pressed, the user activates an event case handler where the previous acquired values are stored in the earlier created datalog file. The steps 3 and 4 are then repeated for the next set of observations for the sample under study.

6. When all the data sets have been acquired, the student presses the Analyse Button on the front panel to analyse the observations for the sample. On pressing this button, the control of the program again enters into an event handler which closes the datalog file for any further writing and sends all the acquired data to the Analysis section discussed below.

Analysis

The analysis section for the developed interface works in two modes: Online Mode and Offline Mode. This section also provides the user to generate an HTML report or printed report for the experiment results as shown in Fig. 4(a) and 4(b). The different modes of working are discussed as under:
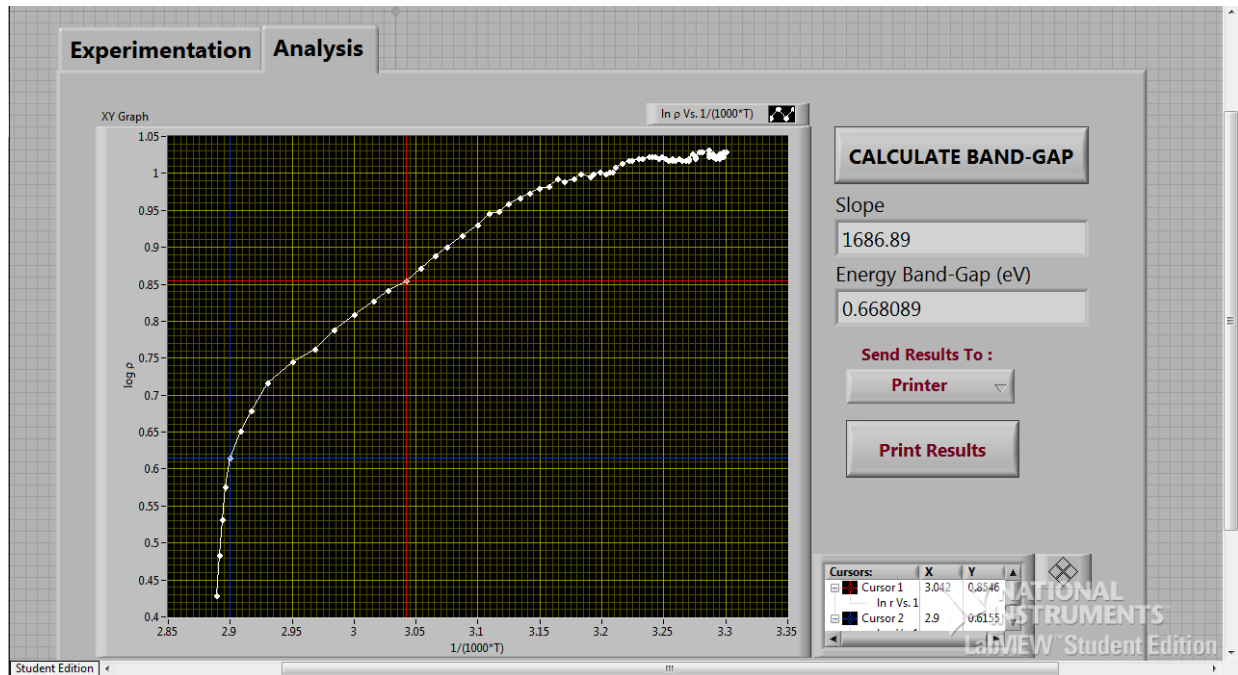

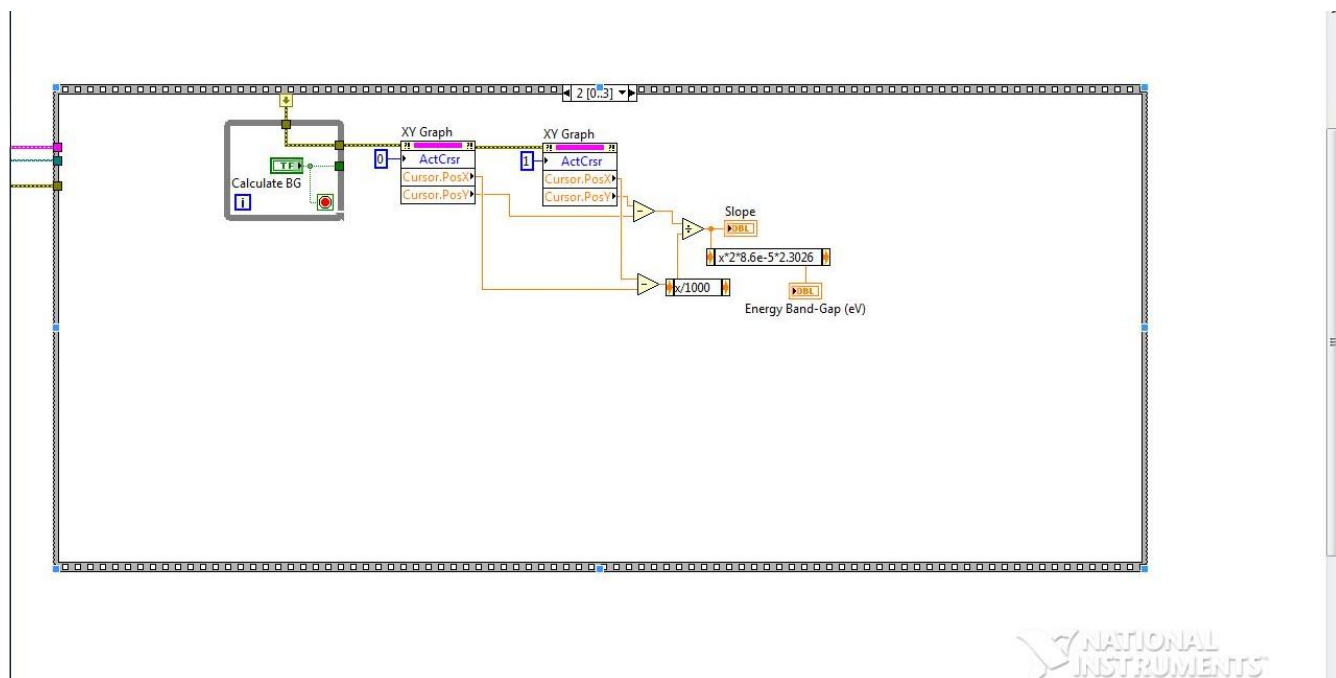**Fig. 4(a): Front Panel Diagram for the Analysis Section of the developed Four Probe System**

Fig. 4(b): Front Panel Diagram for the Analysis Section of the developed Four Probe System

1. **Online Mode:** When the user wants to analyse the acquired set of observations, he/she may click on the ANALYSE button to move to Analysis Tab. The Analysis tab plots the first set of observations acquired by the user on an X-Y graph and prompts the user to set the two cursor points for slope calculations. Two cursors for X-Y graph are then activated automatically to enable user to select the desired points. The CALCULATE BANDGAP button may then be pressed for estimation of the bandgap for the sample under study. The slope calculation between two points selected on the curve is done using equation (3) which determines the bandgap. The next set of observations can then be analysed by pressing NEXT button on Analysis Tab till all the acquired data sets are analysed by the user. For ease of use, the number of sets acquired during experimentation is displayed on top of the graph in Analysis Routine.

2. **Offline Mode:** The analysis section has been provided with an option for offline working which helps the user to analyse any previously stored datalog file for bandgap and resistivity calculations. The user can enter into this mode by selecting Analyse Data option at the start up of program.

3. **Results:** The results of the Experiment/ Analysis are used to generate the report for the sample under study. The user may generate an HTML Report/ Printer Version of Report as per the requirement.

Fig. 4(b) is the block diagram of the developed VI. The various features are discussed as under:

1. The VI starts off with a case structure to decide whether the data to be analysed has been acquired online or any previously acquired data is to be analysed by the user. In case of online data, the VI reopens the datalog file created in the read only mode and reads in the first set of data acquired for the sample under study. This data is then displayed on a waveform graph.

2. Two cursors have been created for the slope calculation on the waveform graph and the property node of cursors is utilised for getting the position of the two cursors on the graph.

3. The numeric functions of the Lab VIEW have been utilised for calculation of slope and Energy Bandgap.

4. The next set of data is then analysed in a similar manner by reading the datalog file until the last data set has been reached.

5. For an offline data analysis, any datalog file which has been earlier created using this developed application can be opened in read only mode and the data again displayed on the waveform graph for analysis. The above steps are then repeated for the analysis of all the data sets stored in the datalog file.

6. The program also utilizes the report generation toolkit of Lab VIEW for generating records. The report can be generated either in HTML or a printer friendly version where in all the data acquired and analysed is printed in a web-based HTML format or can be directly printed using a printer.

Results

The semiconducting sample evaluated in the experiment is of Germanium. It can be easily seen that the resistivity is decreasing with increase in temperature. Therefore, students can easily make out and verify the relationship between resistivity and temperature for semiconductors. The value of resistivity can be calculated for a given temperature. Also, the application displays the value of the bandgap which is computed from the slope of the curve. The average calculated value of energy bandgap for germanium from the experiment is 0.668 eV after recording many sets which matches very well with the manufacturers' datasheet value of 0.664 eV.

Conclusion

The developed automated system has many distinct advantages in comparison to the present conventional system:

Software Section:

1. **Constant Acquisition Rate:** The developed system is an improvement over the conventional system since the acquisition rate of the data is uniform and is not dependent on the user. This increases the reliability of results by ensuring that an optimum number of observations are taken. The temperature inside the oven used in the experiment varies at a slower rate at lower temperatures and at a faster rate as the temperature reaches 150°C. The students thus fail to take observations at equal intervals of temperature increase during rapid heating or cooling of the system. This limitation is taken care of by maintaining a constant acquisition rate for the entire range of temperature increase. The observations can be taken for both increasing as well as decreasing temperature.

2. **Online Plotting and Calculations:** The calculations for resistivity and ln ρ values are estimated online for every data point acquired in the VI. This acts as an obvious advantage over the conventional system which involved a lot of student time in experimentation and its analysis. The online estimation of these values helps the student to analyse the readings taken during experimentation. In case of any discrepancies in results, an appropriate remedial action can be taken.

Hardware

This set up reduces the error in the temperature measurements in comparison to using a thermometer. Also, during rapid increase of temperature, the delay in the reading of temperature and voltage by the user in the manual mode may result in errors in the observations thus giving erroneous results. These problems in the present set up have been removed by the use of a temperature sensor and the USB 6008 DAQ card which can read the analog input data up to a maximum speed of 10kS/s which is much higher in comparison to the rate of temperature increase.

Others

1. These automated measurements through the use of data acquisition systems have a great motivational impact on the students to the use of computers in science experimentation/education.

2. The developed automated system can be readily integrated to an already developed system for semiconductor characterisation based on Hall Effect Study. In the earlier development, the resistivity of the sample under study was given as input parameter to the system from the manufacturer's datasheet. Now, it can be directly calculated by the developed system and integrated as a module with the Hall Effect Setup. Therefore, the two setups make up for a complete electrical characterisation of any semiconductor sample.

3. The power of Lab VIEW as a scientific language is fully utilised for estimation of the above mentioned values and slope estimation along with graph plotting feature of the system. The bandgap calculations for multiple data sets are easily calculated and report generated by the user online. This has greatly reduced the experimentation and analysis time for the students.

4. The developed system greatly reduces the time of experimentation from 2 hours to half an hour thus saving appreciable experimentation time. The system analyses and generates report of experimentation in real time and saves all the time on analysis of the experimental observations.

5. The set up is cost effective due to the multipurpose usage of the DAQ card and it eliminates the use of costly equipments like the main unit of the Four Probe Set up.

Acknowledgments

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