EEE 489: Final Report
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Table of Contents

List of Illustrations:

Abstract:
Hall effect measurement systems are powerful characterization tools used in solid-state electronics and materials applications. These systems measure critical parameters of a material such as resistivity, carrier concentration, and mobility. These values are particularly important in determining the performance of Transparent Conductive Oxide (TCO) films used in solar cells, a topic that Professor Zachary Holman is presently researching at Arizona State University. Currently, commercial Hall systems cost upwards of $20,000. In an effort to reduce the cost of research, a room temperature Hall system with commercial grade capabilities was developed using a Keithley 2460, two permanent Neodymium magnets and LabVIEW. The system can autonomously perform measurements over multiple input currents to obtain accurate data to within 5% of commercial systems at a cost of only $1,278.

Project Scope and Requirements:

The Hall system developed by the senior design team will serve as a tool used in the Holman Lab located on ASU's Tempe campus. The primary use of the tool will be to measure the resistivity, mobility and carrier concentration of TCOs. The Holman Lab studies the growth and processing of TCOs to apply them to high performance silicon heterojunction solar cells, an illustration of which is shown in Figures 1 and 2. These thin layers of what most often is Indium Zinc Oxide or Indium Tin Oxide gather electron-hole pairs generated in the silicon heterojunctions and transports them to the silver busses which deliver the solar generated current to a load. The use of TCOs minimizes the solar cell's parasitic resistances which hinder photovoltaic efficiencies and energy conversion [1].

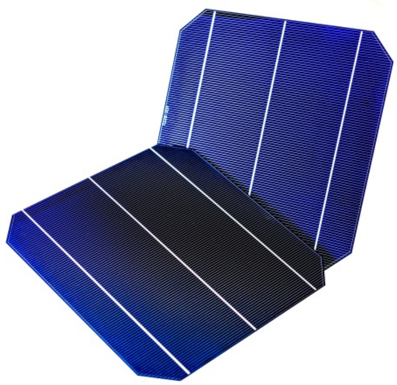


Figure 1: Image of a typical Silicon Heterojunction Solar Cell [2].

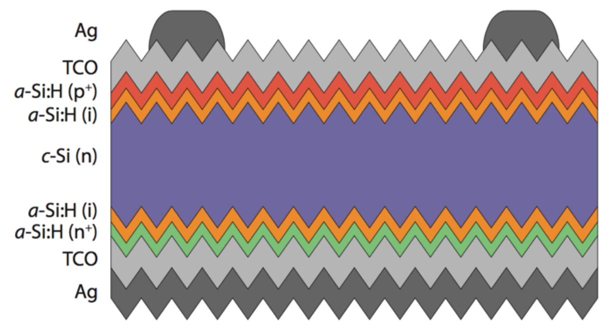


Figure 2: Cross-section of a Silicon Heterojunction Solar Cell [1].

The ideal TCO is optically transparent over a wide range of wavelengths, while having metallic-like current carrying properties. To achieve these properties, the goal during the growth of TCO layers is to minimize sheet resistance R_S while maximizing carrier mobility μ and finding a careful balance of carrier concentration n to maximize conductivity and minimize free carrier absorption. The Holman Lab studies the effects of introducing hydrogen and oxygen impurities in TCOs during sputtering to tune the carrier density of these layers [1]. These studies require the use of a Hall effect measurement system to accurately determine these material characteristics which are crucial to overall solar cell performance. The Holman lab is in need of such a system at a price less than that offered by current commercial vendors.

The system requirements as specified by Professor Zachary Holman, principle investigator of the Holman Lab, are as follows:

- Accurate resistivity measurements in the range of 10^{-5} – 10^{2} Ω-cm
- Accurate mobility measurements in the range of 1 – 10^{7} cm^2/Vs
- Accurate carrier concentration measurements in the range of 10^{7} – 10^{21} cm^{-3}
- Demonstrate measurement accuracies comparable to Ecopia HMS-3000 to within 5%
- Budget constrained to < $2,000

This report outlines the technical and budgetary details of the Hall system that meets the requirements specified above at a cost of $1,278. The scope of the instrument is not restricted to TCOs, but can be used for any low to mid resistivity thin film material. The low cost and versatility of the system signifies its potential to expand to multiple labs. The cost of the cheapest known commercial Hall system is $18,400, making the prototype developed by the senior design group a potential market competitor. This project hopes to play a part in enabling researchers to develop new materials for future technologies at an affordable cost.

Technical Background

Testing Procedure/Theory

A van der Pauw probe configuration can be used to measure the resistivity and mobility of thin film semiconductor materials [3]. Four probes are positioned at the periphery of a square sample as shown in Figure 3. Resistivity of the sample can be measured by sourcing a current through combinations of two adjacent pins on the sample and measuring the voltage drop between the remaining two pins. This process is outlined below:

$$R_{14,23} = V_{23}/I_{14} \quad R_{23,41} = V_{14}/I_{23} \quad R_{43,12} = V_{12}/I_{43} \quad R_{12,43} = V_{43}/I_{12} \qquad (1\text{-}8)$$
$$R_{41,32} = V_{32}/I_{41} \quad R_{32,41} = V_{41}/I_{32} \quad R_{32,21} = V_{21}/I_{34} \quad R_{21,34} = V_{23}/I_{14}$$

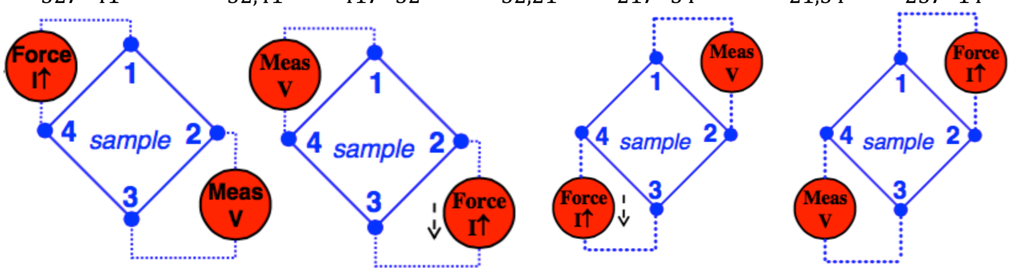


Figure 3: Configuration of resistivity measurements.

$$R_A = (R_{14,23} + R_{41,32} + R_{23,41} + R_{32,41})/4 \qquad (9)$$
$$R_B = (R_{43,12} + R_{32,21} + R_{12,43} + R_{21,34})/4 \qquad (10)$$
$$exp(-\pi R_A/R_S) + exp(-\pi R_B/R_S) = 1 \qquad (11)$$
$$\boxed{\rho = R_s t} \qquad (12)$$

where R_s is sheet resistance and t is the thickness of the sample [4]. A description of how this routine has been implemented into LabVIEW can be found in the *LabVIEW Interface* section of this report.

The mobility of the sample is then measured using a similar method in the presence of a magnetic field B. The mobility is given by:

$$\boxed{\mu_H = \frac{t\Delta R_{24,13}}{B\rho}} \qquad (13)$$

where $\Delta R_{24,13}$ is the change $R_{24,13}$ due to the magnetic field [4]. Four different SMU configurations are tested as shown in Figure 4 using both polarities of magnetic field so that 8 mobilities are measured. The final reported mobility is the average of these 8 measurements.

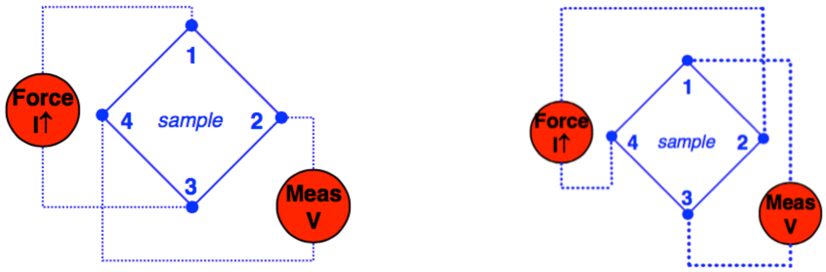


Figure 4: Configuration of Hall measurements.

The carrier concentration can then be determined:

$$\boxed{n \approx \frac{1}{q\mu_H \rho}} \tag{14}$$

Magnetic Field Source Structure

Hall measurement systems require a strong magnetic field with a high degree of uniformity. The setup uses two permanent 1.3 T magnets to generate a uniform magnetic field over an area of 12.5 cm^2. This region of uniformity guarantees the test samples, typically 1 cm^2 in size, will always remain within the constant field. The magnetic field strength at the surface of the sample has been measured using a Gauss meter as 0.5 T. A field strength on this order of magnitude is required to ensure measurement values are distinguishable above noise within the system. However, this field requires a support structure for the magnets due to the attractive forces between them.

The two neodymium magnets are separated by a total of 15 mm. At this distance, the magnets have several hundred pounds of attractive force. To counteract this attraction, a support frame constructed from Aluminum 6061 has been developed. The particular grade of aluminum was chosen for its nonferrous nature and its ability to resist compression. With the magnets in place, the frame shows no sign of bowing or any structural weakening.

The second portion of the system is the magnetic lid and guide rails (see Figures 5 and 6). This system ensures that the sample and springboard mount (see Figure 7) are not damaged when sliding the sample into the narrow 15 mm gap between the magnets. This will extend the lifetime of the sample mount as it will not be exposed to any additional forces resulting from users inadvertently contacting the side walls of the structure. The material used for the magnetic lid was Delrin (acetyl plastic). This material is robust also has electrostatic dissipative properties that will ensure the accuracy of testing results.

The support structure effectively contains the magnets and secures them permanently in place. The magnetic lid design allows for the sample holder to easily be inserted through an edge connector on the underside of the structure. The measurement signals run from the sample holder, into the edge connector, through wires within the magnetic lid, and then out of the support structure through a DB9 adapter that is wired to the rest of the Hall measurement system (See Figure 8).

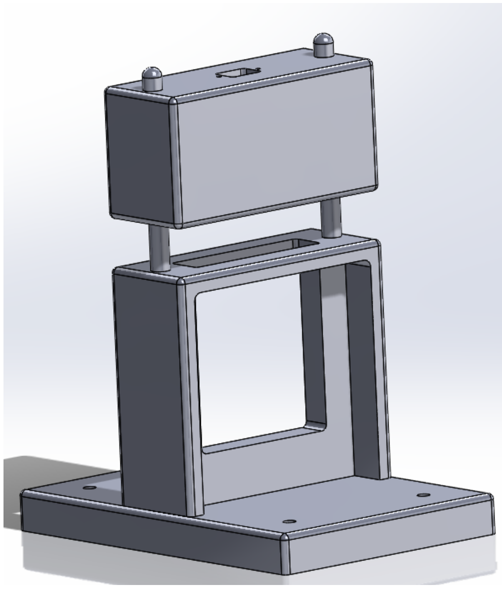


Figure 5: Magnetic support structure and Delrin lid.

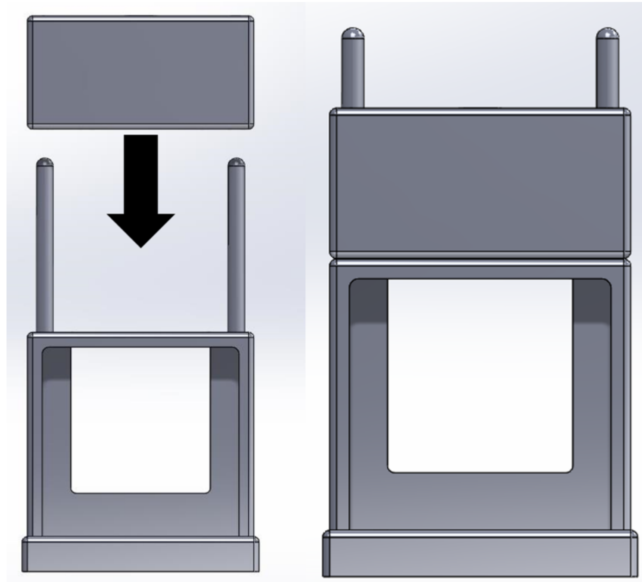


Figure 6: Delrin lid structure

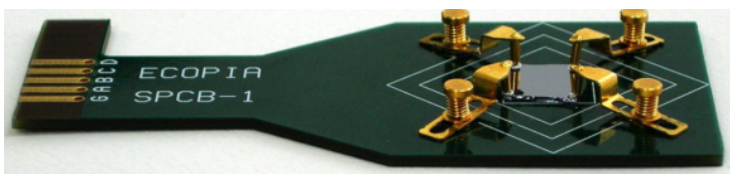


Figure 7: Ecopia SPCB-01 sample holder [5].

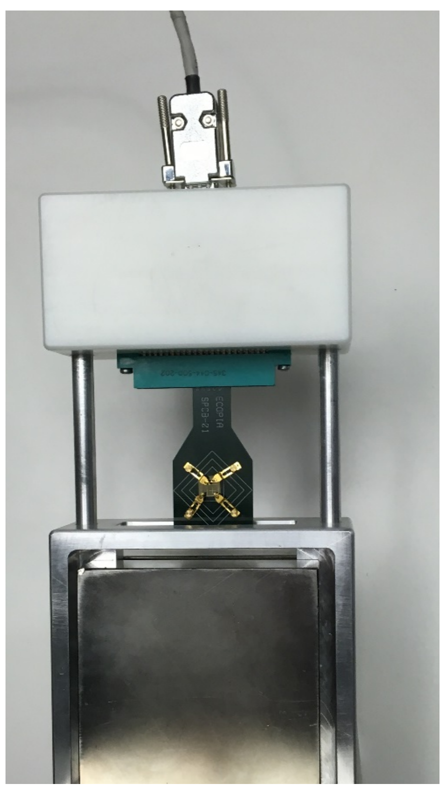


Figure 8: Final test apparatus

Switching Matrix Implementation

The Van der Pauw technique is predicated on the ability to take multiple measurements across different positions on the sample. While the Keithley 2460 SMU has all of the measuring and sourcing abilities needed to perform the required measurements, it does not have the capability to switch sourcing and measuring between its four leads. An external switching matrix was built with two 8 channel relay modules to allow for automated switching, thus compensating for the shortcomings of the Keithley measurement system. The matrix allows any output of the SMU to reach any of the four probe locations contacting the sample during testing (see Figure 9).

The switching matrix is controlled by the Arduino Mega which is driven by the LabVIEW software. This is done by sending either a 1 or a 0 to the Arduino from LabVIEW which applies 0 V or 5 V to a specific relay. Since these relays are active low, the relay changes states by applying a ground (0 V) to one of the eight pins on the relay module. The system is designed to make eight resistivity measurements followed by twelve Hall measurements. The switching matrix that was designed and constructed accomplishes the same purpose as expensive commercial systems, at a much lower price.

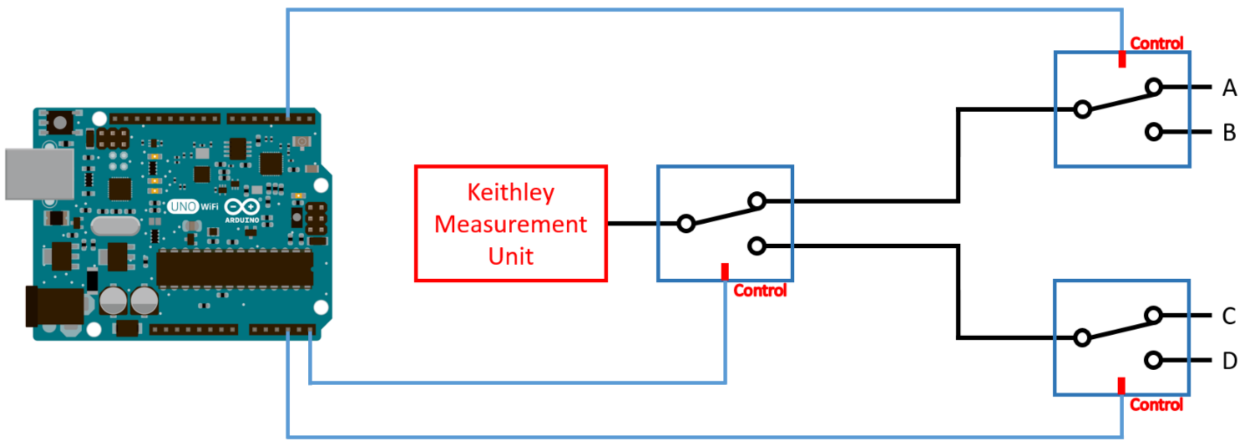


Figure 9: Schematic showing how the switching matrix allows any SMU input to reach any probe location on the sample.

LabVIEW Interface

The software needed to control the hardware was developed in LabVIEW, since it provides a clear user interface and is compatible with both the Keithley 2460 and the Arduino Mega. The program allows the user to enter the thickness of the sample and pick the three currents over which to perform the measurements. Once all testing is complete, the data appears in a table on the front panel as shown in Figure 10 which includes calculated columns of each measurement as well as a progress bar which informs the user of the system's progress. The final data is exported to a text file as shown in Figure 11. The block diagram of the entire testing routine can be seen in Figure 12. Both measurement sequences are performed by sourcing a current through two pins and measuring the induced voltage on the remaining two pins as described in the *Testing Procedure/Theory* section. The entire measurement process takes three and a half minutes to complete.

The resistivity measurements are done using eight different pin configurations. The outputs of the Arduino are assigned values that relay the SMU outputs to the desired locations on the sample. Once measurements have been done for each of the three currents, the pin values are changed in order to switch the locations of the sourced and measured signals for the next measurement sequence. The eight measured values are input into the numerical equation solver subVI which solves Equation 11 to obtain sheet resistance values. The resistivity is then found by multiplying these sheet resistance values by the sample thickness.

Once the resistivity sequence has completed, the pins are switched to the configuration needed to perform Hall measurements as described in the *Testing Procedure/Theory* section. Twelve measurement configurations are used to obtain eight mobility values, then averaged to obtain a single mobility value. The program first calculates resistance values over the different pin configurations outside the influence of the magnetic field, and then prompts the user to place the sample in the magnetic field. The same measurements are then repeated. In order to offset the effect of earth's magnetic field the program requires the user to flip the orientation of the sample and place it in the magnetic field to repeat the measurement process. The difference between the four resistance values using both polarities of magnetic field and the four resistance values outside the magnetic field are taken to compute mobility (see Equation 13) The carrier concentration is found by using the calculated mobility and resistivity values (see Equation 14).

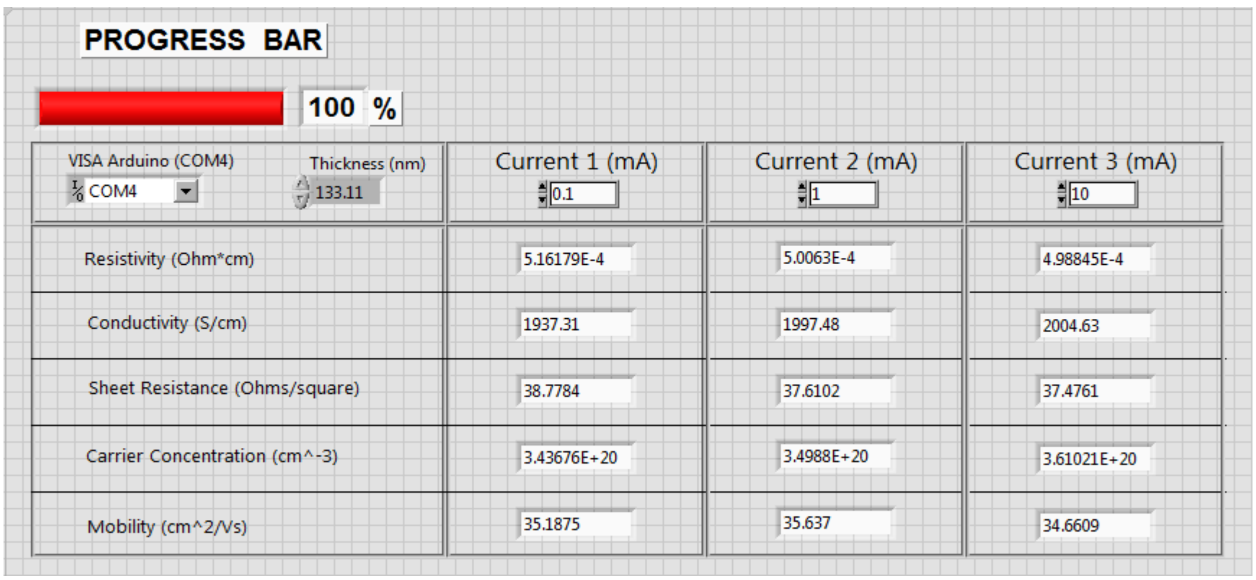
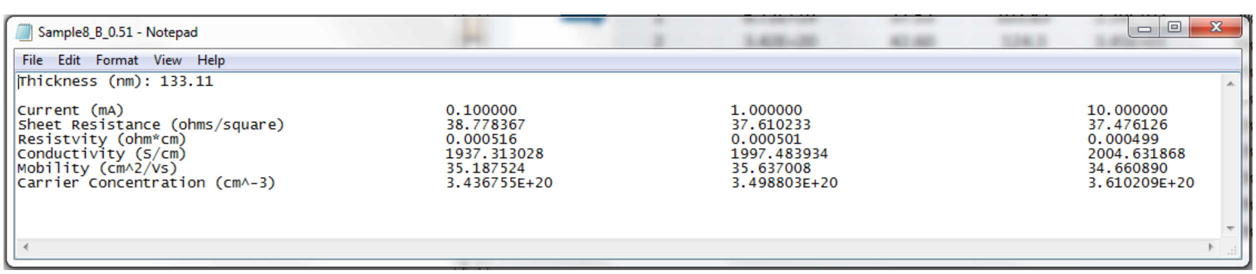


Figure 10: Front panel and user interface of Hall Effect measurement system.



Sample8_B_0.51 - Notepad

File Edit Format View Help

Thickness (nm): 133.11

Current (mA)	0.100000	1.000000	10.000000
Sheet Resistance (ohms/square)	38.778367	37.610233	37.476126
Resistvity (ohm*cm)	0.000516	0.000501	0.000499
Conductivity (S/cm)	1937.313028	1997.483934	2004.631868
Mobility (cm^2/Vs)	35.187524	35.637008	34.660890
Carrier Concentration (cm^-3)	3.436755E+20	3.498803E+20	3.610209E+20

Figure 11: Text file of exported data.

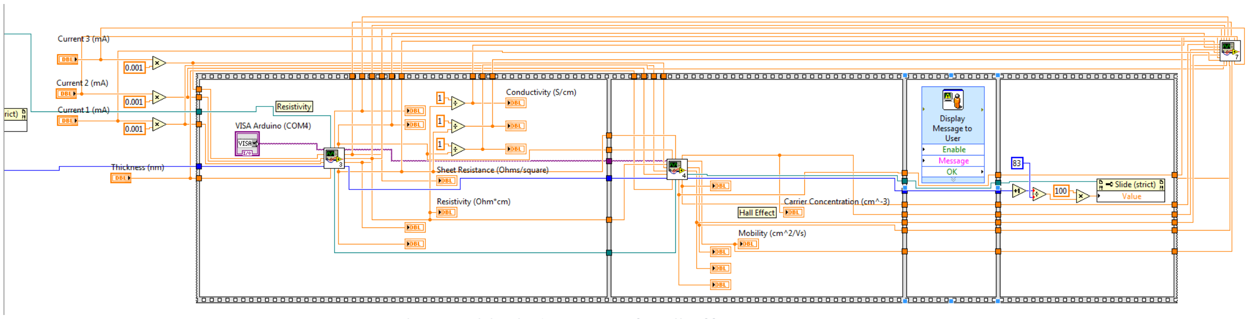


Figure 12: LabVIEW block diagram of Hall effect measurement system.

Project Results and Testing:

The prototype for the room temperature Hall effect measurement system has been completed. However, for the design and testing sequence to be considered a success, the system must demonstrate the ability to provide accurate experimental data. In order to verify accuracy, a set of eight IZO TCO samples of varying oxygen doping concentrations was tested on the developed system and a commercial system that is known to be calibrated and accurate. The commercial unit used for comparison was the Ecopia HMS-3000.

Carrier concentration, mobility, and resistivity were selected for testing, as they are the parameters the Holman Research Group is most interested in when studying TCOs. The data, seen in Table 1 below, suggests the developed Hall system is comparable to the Ecopia measurement unit. Nearly all measurement values are within 5 percent of the commercial unit, suggesting the constructed Hall system is a viable option when collecting reliable data on thin film materials.

A discrepancy of five percent between the two systems may seem large, but it is in fact a reasonable margin of uncertainty considering the system is intended for use on thin film materials. Research on these materials often checks for general trends and is interested in measurements that provide data related to the order of magnitude of parameters such as carrier concentration and mobility. This is a direct result of thin films being difficult to characterize as assumptions such as homogenous thickness and doping cannot always be applied. Therefore, due to the nature of these materials, the small discrepancy between the commercial unit and the system constructed for the Holman Research Group is negligible. While the margin of discrepancy is minuscule, ideally there would be no difference between the developed and commercial measurement systems. It is possible the variation in experimental data between the two measurement setups is the result of any number of reasons including a difference in materials used, the precision of the measurement units, or some unaccounted for non-ideality that causes a slight skewing of measured values.

The experimental data displayed in Figures 13-16 suggest that the developed Hall system is consistent with measurements taken on a commercialized unit. A total of eight IZO thin film samples were tested and demonstrate both the accuracy and consistency of the system.

Table 1: Samples measured compared to Ecopia system.

	Carrier Concentration (cm^{-3})			Mobility (cm^2/Vs)			Resistivity (Ω·cm)		
Sample	Ecopia	System	% difference	Ecopia	System	% difference	Ecopia	System	% difference
1	4.94E+19	4.81E+19	2.56	38.5	39.1	1.38	3.28E-3	3.32E-3	1.22
2	3.28E+20	3.18E+20	3.02	44.2	45.0	1.69	4.30E-4	4.36E-4	1.32
3	2.24E+20	2.19E+20	2.51	50.9	51.7	1.63	5.47E-4	5.52E-4	0.86
4	2.18E+20	2.30E+20	5.49	51.2	48.4	5.47	5.59E-4	5.61E-4	0.36
5	3.57E+20	3.50E+20	2.08	35.1	35.6	1.44	4.97E-4	5.01E-4	0.72
6	2.00E+20	1.99E+20	0.57	51.7	51.1	1.10	6.03E-4	6.14E-4	1.76
7	1.49E+20	1.47E+20	0.84	54.5	54.8	0.49	7.71E-4	7.73E-4	0.31
8	3.28E+20	3.29E+20	0.21	38.1	37.6	1.31	4.99E-4	5.04E-4	1.10

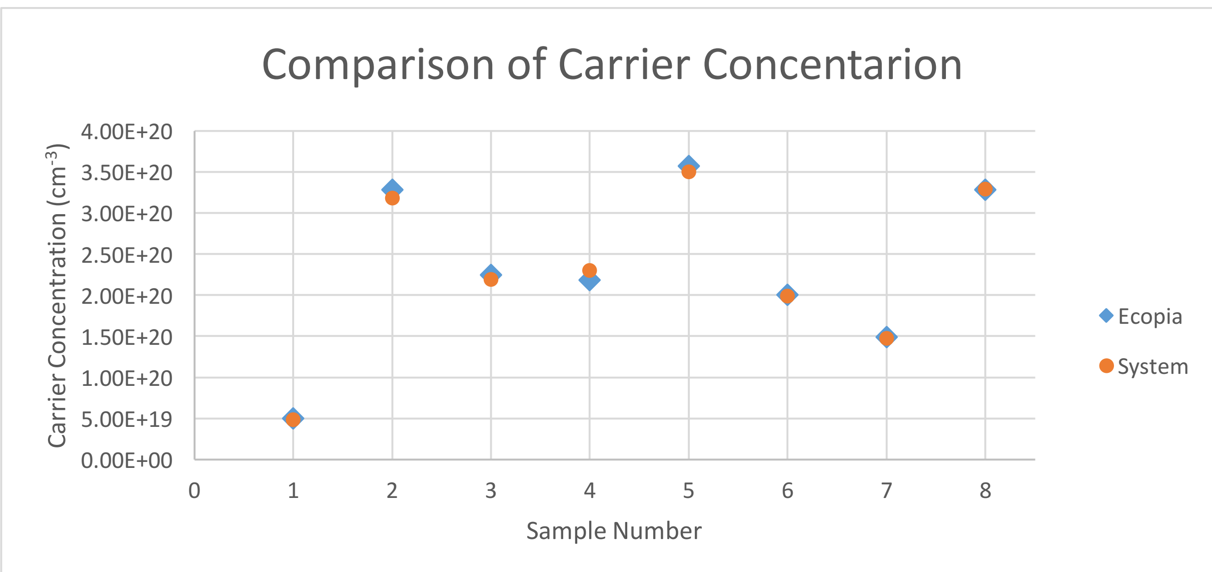


Figure 13: Comparison of carrier concentration of six different samples for Ecopia HMS 3000 and the Hall system developed for the Holman research group.

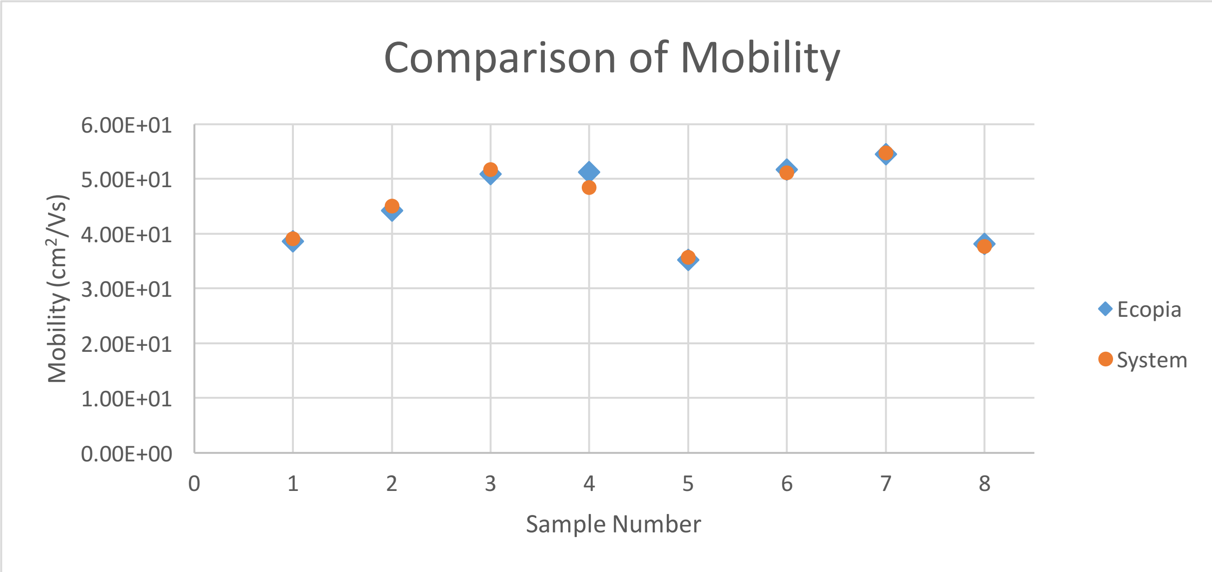


Figure 14: Comparison of carrier mobility of six different samples for Ecopia HMS 3000 and the Hall system developed for the Holman research group.

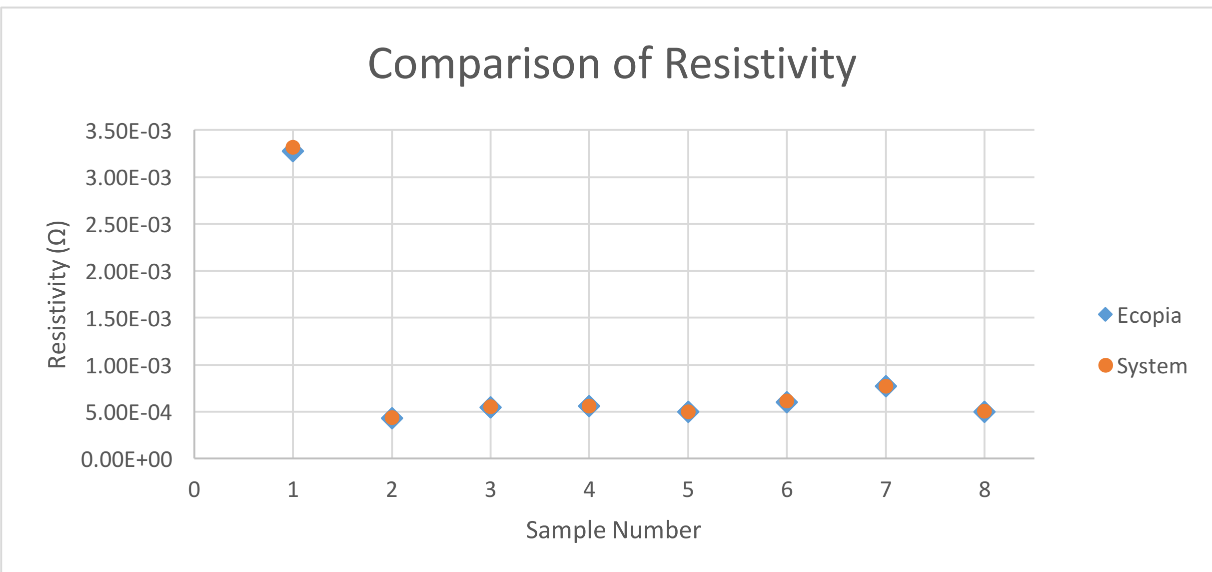


Figure 15: Comparison of resistivity measurements of six different samples for Ecopia HMS 3000 and the Hall system developed for the Holman research group.

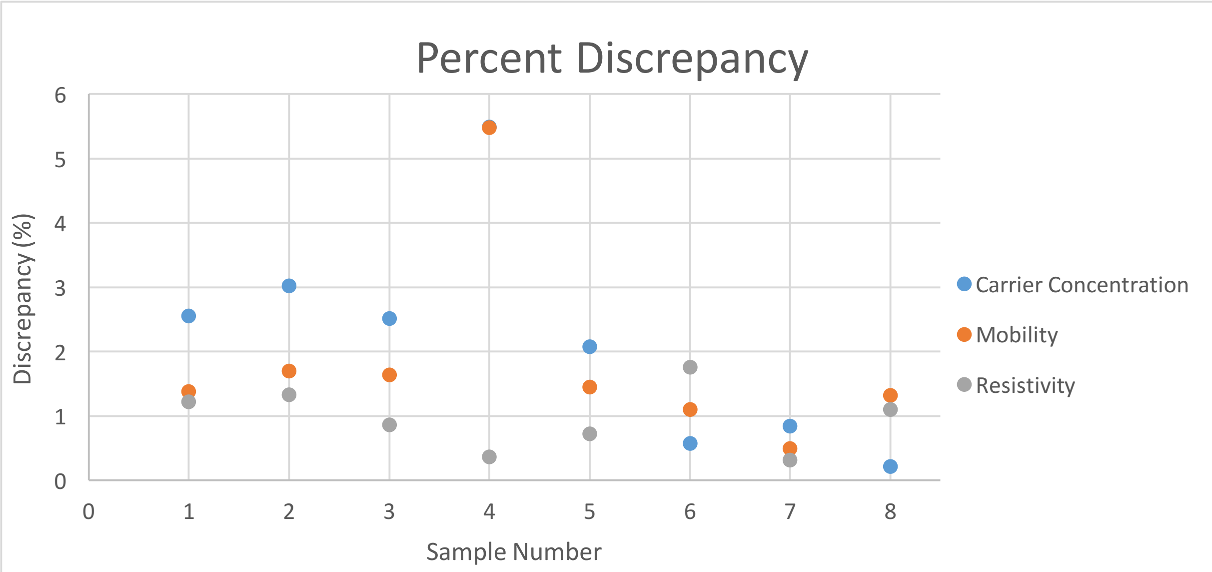


Figure 16: Demonstrates the percent discrepancy between the Ecopia HMS 3000 and developed Hall system for each.

Budget Summary:
The budget consists mostly of small components for the overall system to function properly. The most costly equipment was the magnets, GPIB cable, magnetic structure, and Keithley 2460 SMU. The Keithley 2460 is not included in the budget as it was previously purchased for other uses in Dr. Holman's lab. This SMU is very crucial to the experimental setup, so it is worth noting that if the Hall system were to be replicated, a Keithley 2460 would have to be purchased. The Neodymium magnets and their support structure are big expenses but also the cheapest option available for their function. The last important piece of equipment was the GPIB cable. While the system was tested at the beginning of the semester using a USB cable, it was discovered that a GPIB cable was necessary to reliably establish communication to the Keithley 2460 for running measurements.

The components that will be described next are all necessary while being much cheaper. The Arduino Mega is needed to switch the relays to the correct state. The PCB edge connector is the connector used to insert the sample spring clip board to the Delrin lid. The DB9 connector is used to connect the top of the Delrin lid to the outputs of the relays. This is necessary for the freedom to move the measurement setup freely around the lab. The breadboard jumper wires are required to send the Arduino signals to the relays. The switching box was purchased to package all of the electronics in a neat and orderly fashion, which protects it from system users. Velcro was also purchased to hold all of the electronics down to the box to support them in place. The panel mount USB connector, USB to USB, and USB cable were purchased to neatly route cables from the box to all other pieces of equipment. These additions were necessary to create a system that is versatile, user friendly and robust.

Man hours Justification

During the first semester, the senior design group spent approximately 7.5 hours per week planning out the project and documenting work. This occurred for 15 weeks, totaling to approximately 450 man-hours between the four group members. This time was spent researching the fundamentals of the Hall effect measurement, choosing appropriate hardware, designing system outline, and researching potential software options. During the second semester, the group spent 15 to 20 hours a week building the system, totaling to approximately 900 to 1,200 man-hours. More time was spent on the project this semester due to delays in designing the magnetic structure, troubleshooting, and testing the system's accuracy. The majority of the time was spent designing the system's software in LabVIEW to interface with the Switch Matrix and Keithley 2460.

Table 2: Budget

Item	Company	Product Number	Quantity	Price per Unit ($)	Total cost ($)
Neodymium Magnets	CMS Magnetics	NB060-42NM	2	116.12	232.24
NI GPIB-USB-Adapter	National Instruments	778927-01	1	219.00	219.00
Magnetic Field Apparatus	ASU Machine Shop	N/A	1	704.97	704.97
PCB edge connector	Electronic Surplus	50-20A-30	1	3.00	3.00
8 Channel Relay Module	JBtek	N/A	2	8.98	17.96
Arduino Mega	Arduino	A000067	1	32.95	32.95
DB9 9 Pin connector	Amazon	N/A	1	5.73	5.73
Breadboard jumper wires	Boundto	N/A	1	9.98	9.98
Switching Box	Amazon	N/A	1	27.95	25.00
Panel mount USB	Amazon	N/A	1	3.70	3.70
USB to USB adapter	Amazon	N/A	1	3.93	3.93
USB cable	Amazon	N/A	1	5.69	5.69
Velcro	Amazon	N/A	1	10.74	10.74
Total					1277.84

Schedule Overview:
The schedule did not change significantly from the original Gantt chart that was written at the end of the first semester. Measuring the magnetic field was not completed by the specified deadline because there was a delay in mounting the magnets into the support structure. There were many complications in the process of developing the hardware and making sure the specs of the design could meet the required system standards. Because of these delay, measuring the magnetic flux density of the magnets was thrown off schedule. This was a simple fix since it only took a couple of minutes once the magnets were inside the magnetic field apparatus.

There was one task that was not on the initial Gantt chart which was the development of the switching matrix. This was not included because the group was expecting to use a switching matrix in Dr. Mariana Bertoni's lab. When it became unavailable, it became necessary to build a switch matrix from scratch. This tool was described in the *Switching Matrix Implementation* section of this report. This task costed the group extra time to build, but most of the research was done in the previous semester while preparing for this scenario. It then only took two to three weeks to complete this task. In the end, everything projected to be accomplished at the beginning of the semester has been completed.

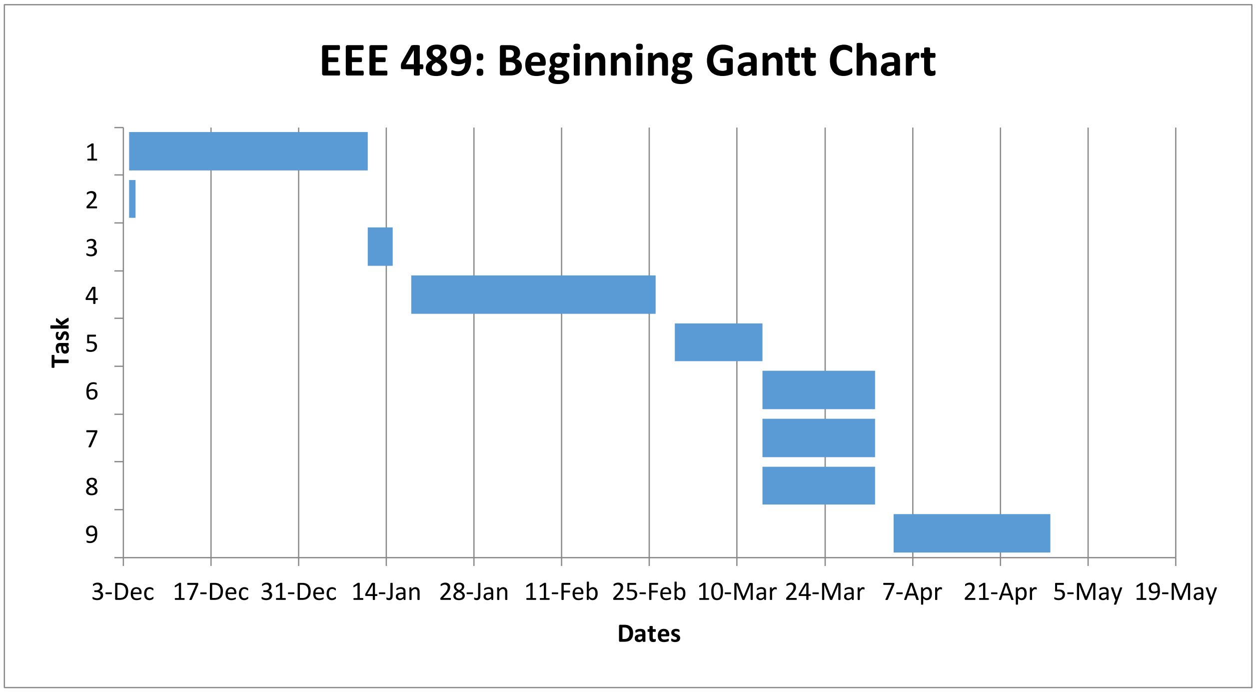


Figure 17: Timeline from the beginning of the spring semester.

Task not initialized   Completed Task

Table 3: Timeline from beginning of semester

Task	Task Category	Start Date	End Date	Duration	
1	Send CAD file to machine shop	12/4	1/11	49	
2	Order permanent magnets	12/4	12/5	1	
3	Measure flux density	1/11	1/15	4	
4	Develop card holder	1/18	2/26	45	
5	Interface equipment	2/29	3/14	37	
6	Write code to perform calculations	3/14	4/1	14	
7	Write code to export data	3/14	4/1	25	
8	Develop GUI	3/14	4/1	25	
9	Test system	4/4	4/29	31	

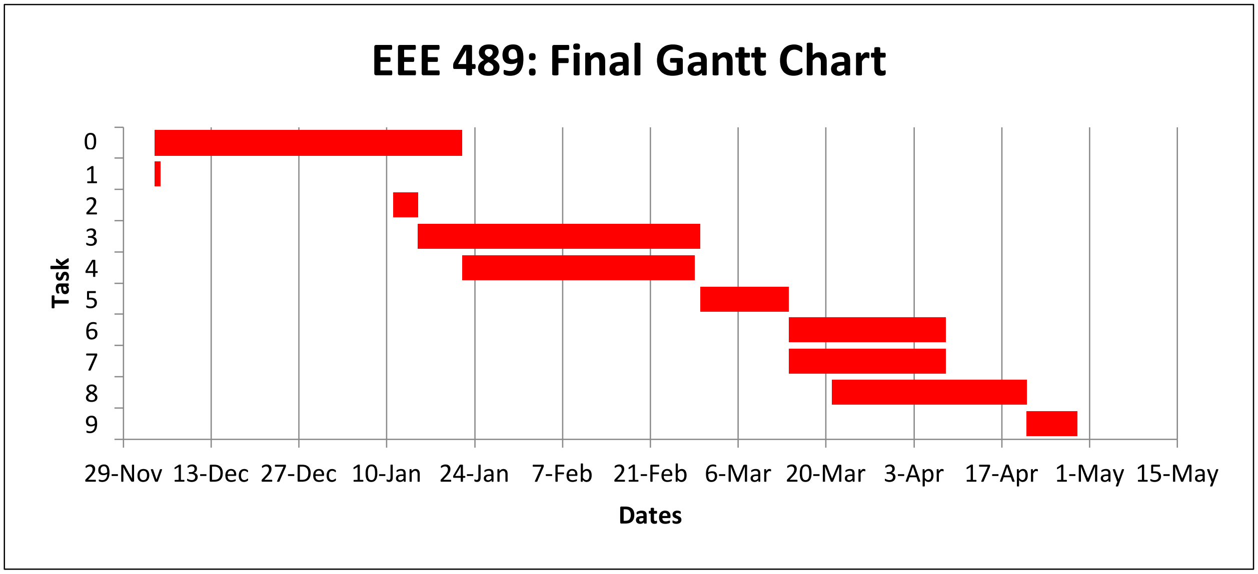


Figure 18: Current Timeline

Task not initialized   Completed Task

Table 4: Current Timeline

Task	Task Category	Start Date	End Date	Duration	
0	Submit CAD file of magnetic apparatus to machine shop	4-Dec	22-Jan	49	
1	Order neodymium magnets	4-Dec	5-Dec	1	
2	Measure magnetic flux density	11-Jan	15-Jan	4	
3	Development of switching circuit	15-Jan	29-Feb	45	
4	Develop and design magnet lid with PCB edge connector	22-Jan	28-Feb	37	
5	Determine hardware to interface between Hall system and measurement equipment	29-Feb	14-Mar	14	
6	Develop and program Van der Pauw testing sequence	14-Mar	8-Apr	25	
7	Develop method to export experimental data to meet established requirements	14-Mar	8-Apr	25	
8	Develop GUI	21-Mar	21-Apr	31	
9	Test system	21-Apr	29-Apr	8	

ABET Criterion:

Economics

Research facilities are always looking for ways to minimize expenses. The developed measurement system saves Dr. Holman's lab approximately $15,000 dollars, allowing the research group to allocate these funds to other uses. Overall, decreasing the price of test equipment in a research lab allows the lab to conduct more research per dollar spent.

Environmental

The room temperature Hall effect measurement system was designed to meet the specific needs of Dr. Zachary Holman's lab. The Holman research group, funded by Quantum Energy and Sustainable Solar Technologies (QESST), focuses on improving photovoltaic system efficiencies. QESST is a conglomerate of research labs scattered throughout the country whose goal is to develop new technologies that can generate large amounts of energy with minimal environmental consequences.

Manufacturability

Due to the simplistic design of the Hall system, production of the system has the potential to be scaled up to a manufacturable level. Manufacturing this product will further bring down the cost of the system per unit, which can decrease the price at which each unit can be sold. This system can also be applied in a semiconductor manufacturing process where it can easily be used to verify and tune process parameters.

Sustainability

The Hall effect measurement system is used to characterize and improve modern photovoltaic technologies. These technologies are able to capture sustainable solar energy and can provide efficient energy collection for more than 25 years with minimal maintenance. Photovoltaic technologies based on semiconductor materials could not be developed without characterization tools such as Hall effect measurement systems.

Conclusion:

This report presents a technical outline of the construction of a low cost Hall effect measurement system with commercial grade capabilities at a total cost of $1,278. The system's accuracy has been successfully demonstrated by comparing the measurements of 8 TCO samples to that of a commercial Hall measurement unit. The results of the system comparisons indicate that the constructed Hall system can successfully measure a thin film's resistivity, mobility, and carrier concentration to an accuracy of 5%. The system will be used as a semiconductor characterization tool in the Holman Research Lab, where its primary function will be to characterize TCOs to be applied to high performance solar cells. The system meets all technical and budgetary requirements as specified by Professor Zachary Holman, project advisor and principle investigator of the Holman Research Lab. This low cost instrument will enable the Holman Research Group to further develop new materials for sustainable technologies and has the potential to be used in various electronic material applications.

References

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