LOW-COST AUTONOMOUS TLM MEASUREMENTS

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Neil Wang

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Executive Summary

The purpose of our project is to create a probe system capable of accurately measuring and reporting the contact resistance of solar cell surfaces for use by solar researchers at Case Western Reserve University. This probe system uses a technique known as the Transmission Line Method (TLM), which effectively measures the total resistance of the solar cell with various contact lengths, from which we can extract the surface resistivity as well as monitor variations in contact resistivity. The team designed, manufactured, and tested a probe system that utilizes a Keithley 2400 multimeter, a custom circuitry system, and a user's computer. This design efficiently performs TLM measurements and outputs the data to the user's computer at a significantly lower cost than the commercial alternative. Experimental results of this device indicate further calibrations are necessary and the team has identified several solution approaches to improve accuracy and precision.

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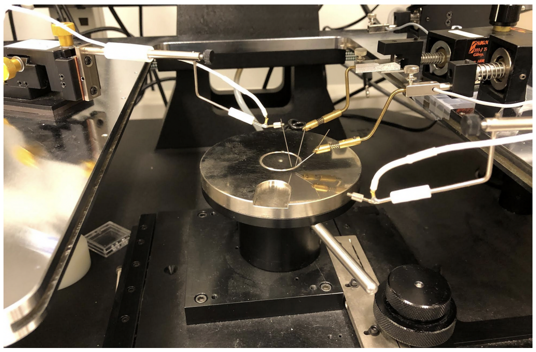
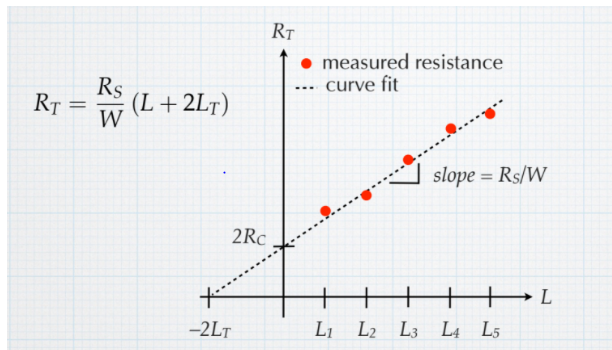
Problem Statement

Introduction of the General Problem

The degradation of solar cells is as complex as it is significant for renewable energy research. Scientists must measure numerous structural and chemical properties of the solar cell to gauge its rate of decline and these methods often require slow or costly procedures. This report will focus on one particular solar cell property: sheet and contact resistivity. To measure them, researchers will often use the Transmission Line Method (TLM) to measure resistance values at various distances on the solar cell (Figure 1a) and generate a linear plot of resistance vs distance. (Figure 1b)





(a) (b)

(Fig 1. TLM manual system (a) with the resulting plot, in which the desired values like sheet resistance and contact resistivity can be extracted using linear regression (b).[1])

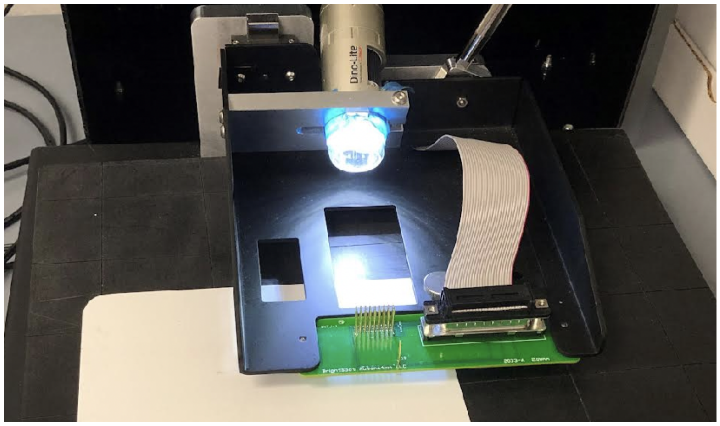
This plot of resistance vs. distance can then be used to calculate the contact resistivity of the solar cell.

Problem of Manual Approach - Time

Unfortunately the TLM technique is slow and inefficient when done manually, as the researcher must carefully align probes on each individual grid line multiple times for a single cell, record the data in a computer, and perform analysis to get the resistivity values. The manual method also introduces an aspect of human error, as different researchers may align and make probe contact slightly differently from each other.

Problem of Automated Approach - Cost

An alternative approach to manually recording resistance values with a probe station is to use a commercially available device such as BrightSpot Automation's ContactSpot device (Figure 2)



(Fig 2. BrightSpot Automation ContactSpot device courtesy of Nafis Iqbal of University of Central Florida.)

This device performs TLM measurements with fixed pins on a PCB that make contact with the solar cell at its gridlines, and sends the processed data to a user's computer. While this design is highly efficient, it also comes with a high cost that is not within the budget of the lab we are working with, the MORE Center. A recent quote put the device cost at approximately $18,000.

Approach

To solve the first problem of tedious measurements, our approach utilizes some of the design choices of the ContactSpot device. The first example is the use of spring-loaded pins that are equally spaced in a row on a pcb and are placed onto the solar cell's gridlines. This eliminates the need for slow probe repositioning and the spring mechanism ensures strong contact is made without exerting excess pressure, which could cause the fragile solar cell to break.

The use of a device with multiple rows of pins eliminates the need to manually reposition the pins between all the measurements, but it does introduce a new problem: the measurement device must be capable of taking a measurement in between each individual pair of pin rows one at a time. (i.e., the device must perform a resistance measurement by delivering and measuring voltage/current between the pins in rows 1 and 2, then repeat the process between the pins in rows 1 and 3, then rows 1 and 4, etc.) Our approach to control measurement between multiple pairs of pin rows was to combine mechanical relays and an Arduino to switch connections, so that only one pair of pins are connected at a time and a resistance measurement can then be taken.

This brings us to the actual resistance measurement device, which in our case needs to be both accurate and affordable. Our approach was to incorporate the MORE Center's multimeter, a Keithley 2400, which significantly reduces cost and maintains the high accuracy and precision necessary to monitor small changes in resistance.

The last component of our approach is the software, which is required to control both the Arduino we used for pin switching as well as the Keithley 2400 which actually performs the voltage measurement. Additionally, our software is required to process the resistance data output by the Keithley. By plotting the total resistance versus the increasing distance along the grid line, we can use linear regression to extrapolate the y and x axes intercept, as well as the slope of the linear fitting, which represent the contact resistance, effective transfer length, and sheet resistance respectively. In order to accomplish all of this, we used a Python program to interface with the Keithley and perform the data analysis; we also used the pyFirmata package to allow the Python program to control the pins on our Arduino as well.

Background & Context

Measuring sheet and contact resistivity of solar cells is just one of the many ways in which labs like the Solar Durability and Lifetime Extension Center (SDLE) and Materials for Opto/Electronics Research and Education Center (MORE) at CWRU examine the degradation of cells over time. Other measurement techniques such as crystal structure imaging and light microscopy are all part of a general goal of forecasting the degradation of solar cell materials. A greater understanding of solar cell degradation provides better forecasts for cell efficiency in the span of decades, enables consumers to accurately calculate expected return for solar cell investments, and supplies insights into creating more efficient and longer lasting solar cells.

As it relates to our device and measuring resistivity, there is also an interesting discipline gap being made between electronics and materials research. Chemistry of materials researchers may tend to stick to their particular profession as it is what they are most comfortable with. Our device lends itself to both electronics and materials and is a rather uncommon instrument, as evidenced by the fact that we were only able to find one commercial alternative at a high premium.

Success Criteria

Automation

The first success criterion we set for ourselves pertains to the usability and speed of our device. The device must perform measurements in <5 minutes and must take <20 minutes to set up. This criterion was met, since it takes only ~10 minutes to download our code and run it in the terminal. Furthermore, it takes only a few seconds to position a solar cell on our device, and our device performs measurements and calculations in <1 minute. Thus, an average measurement can be performed by a first-time user of our device in under 12 minutes. For a user who has already used our device and has the code downloaded to their computer already, measurements take an average of only ~1 minute to perform.

This criterion had a significant impact on our design, as we wanted to provide a compelling argument for using our device over the more time-consuming manual probe method. This was accomplished by incorporating a mechanical relay switching mechanism between pins so that dozens of measurements could be performed quickly.

Accessibility

The second success criterion was to return the data to the user in a CSV format, as a CSVfile is accessible and useful for the eventual data analysis. Without meeting this criterion, users would have to spend significant time recording the measured resistance values and converting them to the preferred format of CSV. This criterion was met since our device not only outputs the data as a CSV file, but also performs all summary statistics and visualizes the data in a helpful line graph.

Accuracy and Precision

The third and fourth success criteria pertain to measurement accuracy and precision. The criteria for precision was set rather high, with <1% error for contact resistivity. For accuracy, we used a benchmark of 10% within the accepted values as determined by University of Central Florida's ContactSpot device. These criteria were not met and will be explained in more detail in the Verification & Results section of the report. With regard to design choices, the tradeoff between quality and budget was the most significant as components such as the spring loaded pins (that make contact with the solar cell) are quite costly. The group felt that despite taking up 27% of the total cost of the design, these spring-loaded pins were worth the premium for their ability to make good contact with the solar cell and measure resistance. (It should be noted that the accuracy and precision error found are unlikely to be a result of poor quality components.)

Constraints

After discussing the success criteria of our project in terms of level of automation, data accessibility, and measurement accuracy, it is time to discuss the constraints.

Automation

To automate the process of the Keithley 2400 connecting to the pairs of pins separately and one at a time, it was necessary to develop a switching mechanism that was simple enough to build and wire without introducing any additional electrical variance into the circuit. While components such as transistors were considered, they did not stay within the constraint of no additional electrical interference.

Technical

While automation increases the scope of the project and adds extra levels of complexity, it also introduces variability in internal resistance of the circuit. As various relays must be connected to a pcb with varying distances between them, our design introduces an aspect of internal resistance that changes with each measurement. If all wires and connectors were the same, the effects of internal resistance would be minimized by the 4-wire measurement technique that the Keithley uses. However as various testing of our circuit showed, resistance varies by each pair of pins depending on the lengths of wire.

Accessibility

Controlling an Arduino is usually accomplished within the Arduino IDE which performs several setup tasks. However, since one of our success criteria is to output easily accessible data, all connectivity setup and data handling needed to be done in a single Python program so that the transition from Keithley and Arduino was seamless and the user was not required to coordinate the operation of multiple programs simultaneously. This added more complexity to the software design but in return reduced complexity for the user and supported the scope of having an intuitive user interface.

Technical

Software development is limited to languages that could access the Keithley, perform linear regression, and output data in a CSV and graph format. Python seems to be the optimal choice for performing all 3 in one script. The Pandas library for handling data and analysis, Matplotlib for graphing, and PyFirmata for interfacing with the Arduino. Pyfirmata was chosen over other similar libraries for its Arduino Due support as well as it's documentation for connecting to a user's computer and switching pins in a desired format.

Accuracy and Precision

Arguably the most difficult and vital constraint, our design needs to record measurements both accurately (as compared to the commercial device, ContactSpot) and precisely for the same solar cell. As mentioned earlier this constraint added a significant cost factor for items such as the spring loaded pins, which need to make good contact with the solar cell, have low internal resistance, and be delicate so as not to damage the sample. Precision is arguably the more important factor as solar cell research focuses on the rate of degradation and changes in efficiency over time exposed to harsh conditions.

Technical

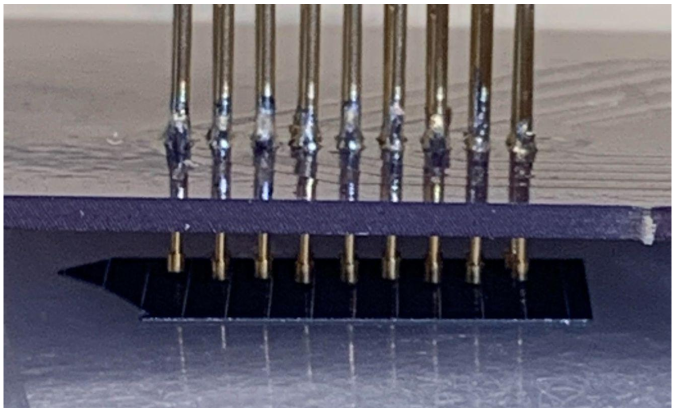
Precision constraints were set by the group as <1% error for measurements of the same sample. More specifically, this is the standard error of the mean of sheet resistance for a collection of measurements. Sheet resistance is measured as Ω/□, or Ohms per square, and can be calculated using the contact resistivity (mΩ*cm2) and the transfer length (cm) of the solar cell. Sheet resistance is derived from the slope of the resistance vs distance graph and width of the solar cell, while transfer length can be calculated with the x intercept of the same graph. As contact resistivity is the product of the contact resistance and the effective transfer area, more uncertainty is included in the calculation of contact resistivity thus introducing a greater challenge for quality measurements.

Result

Our project did not meet this precision criteria as our measurements standard error was ~40% of the mean contact resistivity for 13 samples of the same cell. The standard error for sheet resistance however was much lower at 1.8%. A partial explanation for the likely cause is explained next and a more data oriented and complete explanation is provided in the validation and results section.

Technical Precision Constraints In Depth

Precision is largely dictated by the quality of contact between the probes and the metal fingers on the solar cell. Physically, each of the PCB's 25 pins should be perpendicular to the measurement surface in order to make perfect level contact with the gridlines on the solar cell's surface. However, due to the small size of the working area, soldering each probe caused difficulty in maintaining a completely perpendicular position for each probe. As a result, the distances between the probes differ, resulting in erroneous contact between the probes and the gridlines, as illustrated in figure 3 below.

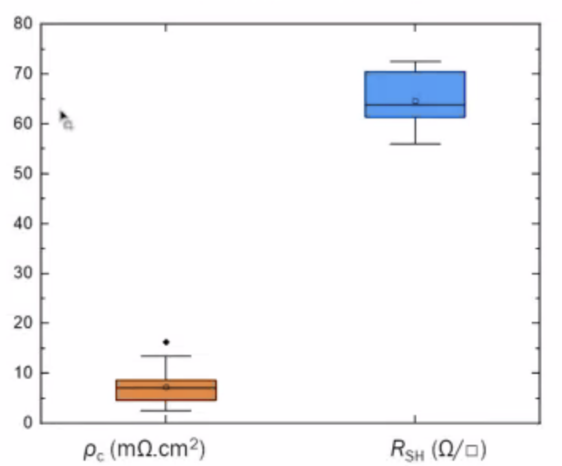


(Figure 3. The misalignment of each sensing probe with the gridline. Due to the varying distances and tilted angles, probes cannot establish perfect contact on each gridline.)

A further constraint pertaining to the probes is the relative rigid nature of the spring loaded probes. The probe tips are not uniformly distributed on the same level. Due to the disparity in length, the shorter probes hover, leaving an empty area between the gridline and the probe. Though this issue can be resolved by applying general pressure to the PCB and compressing the springs on each probe to the same level, there is a strong potential that the pressure will damage or even fracture the surface of the measuring solar cell. See the Appendix Part A for a more detailed description of solid state factors affecting measurement quality.

Technical Accuracy Constraint in Depth

The second measurement criteria, accuracy, is also an important constraint for our design. As a benchmark for accurate measurements, the team collaborated with PhD student Nafis Iqbal at the University of Central Florida to obtain accurate measurements using their ContactSpot device. Nafis' measurements are not on the same solar cell as our test cell though, so an assumption was made that our cells and his cells are similar enough to be compared. With that in mind, our criteria for accuracy was less strict at having a <10% difference between the mean of each group of measurements. Shown below is the statistical summary of the ContactSpot devices' measurements. (Figure 4)



(Figure 4. Sample solar cell's average Contact resistivity (left) and sheet resistance (right) measured by ContactSpot using TLM method from Nafis Iqbal of University of Central Florida).

We unfortunately did not meet this criteria either, as our mean sheet resistance was 15% higher than the mean of the ContactSpot device. The contact resistivity was much worse being double the mean of the ContactSpot contact resistivity.

Standards

Comma Separated Values (CSV)

RFC 4180 Common Format and MIME Type for Comma-Separated Values (CSV) Files , Internet Engineering Task Force (IETF) 2005. [Online]. Available: https://datatracker.ietf.org/doc/html/rfc4180. [Accessed: 03-Dec-2021]

Outlines and specifies the format for saving data as a Comma Separated Values (CSV) file. Data must be separated by special characters (in this case commas) and appropriate measures must be taken to denote line breaks (CRLF pairs) and "escape" other special characters. These guidelines are necessary for our design because they ensure data is stored and sent in a common format that is useful for research purposes. Since our data is numerical and column names don't contain special characters, these guidelines are handled by Pandas to_csv() function.

User Interface

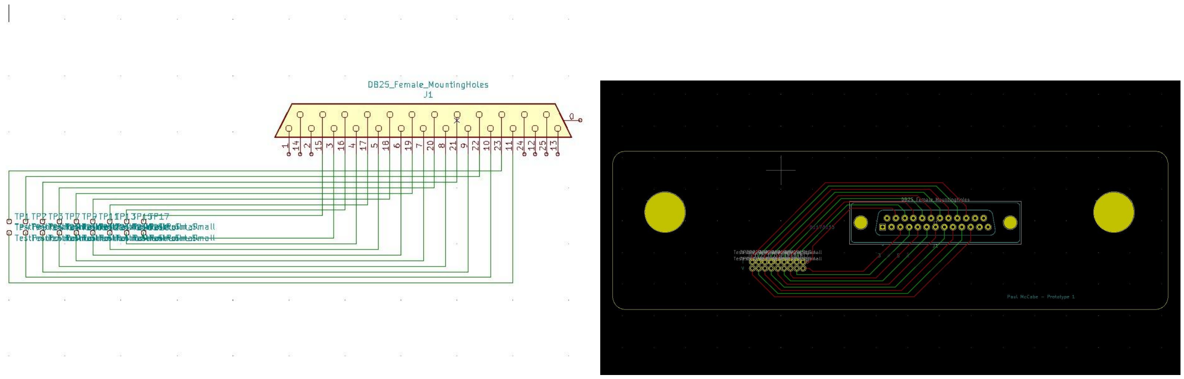
McMaster University - User Interface Standards - R. Jesuratnam, A. Khan, A. Mata, and J. Sandhu, Computing and Software Wiki RSS, 23-Nov-2017. [Online]. Available: http://wiki.cas.mcmaster.ca/index.php/User_Interface_Standards. [Accessed: 03-Dec-2021].

Describes a standard set of user-interface guidelines to ensure a simple and intuitive process. Although our script is simple enough that it doesn't need a window with menu bars and buttons, we did follow the guidelines for error and success messages as that is what is displayed in the terminal. Examples of such guidelines for error messages include making them straightforward, easy to derive the problem area, and do not use complicated words. For success messages, our design confirms when successful measurements are made, displays the information with clarity and simplicity, and indicates if measurements are in the ballpark of acceptable ranges in real time.

Printed Circuit Board Files

KiCad - Schematic and PCB Layout File Formats - KiCad Web Services, 2021. [Online]. Available: https://dev-docs.kicad.org/en/file-formats/. [Accessed: 03-Dec-2021].

This is a combination of two standards, kicad_pcb and kicad_sch files. kicad_sch files describe the schematic of a pcb layout and compiles circuit components and connections information into a standardized file format. This file format is then translated into the actual placements of circuit board components in the kicad_pcb file, which is a standard for manufacturers to print circuit boards. Our design used the KiCad application and parts libraries to assemble the schematics and pcb layout as shown below in Figure 5. Our design followed these standards because of its common use, relatively easy assembly in KiCad software, and its compatibility with manufacturer's accepted file formats.

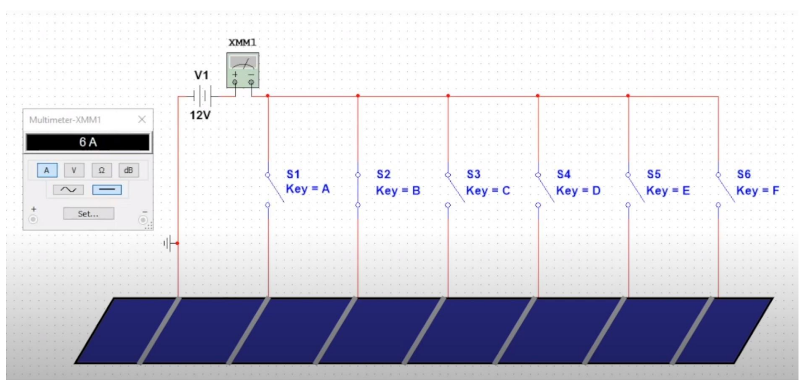


(Figure 5. Schematic layout (kicad_sch) on the left and PCB layout (kicad_pcb) on the right)

Approach

Introduction - Overall Circuit Design

The first steps of the design process centered around what main components were going to be necessary to complete autonomous TLM measurements. While our team knew that a Keithley 2400 would be necessary for resistance measurements and a PCB with fixed pins were necessary for making contact with the solar cell, there still was a gap in how the Keithley would connect to each pair of pins separately and sequentially. The initial idea was to use multiple voltage controlled switches all arranged in parallel so that individual switches could be turned on and off one at a time, therefore only one pin pair would be connected at a time. See Figure 6 below.

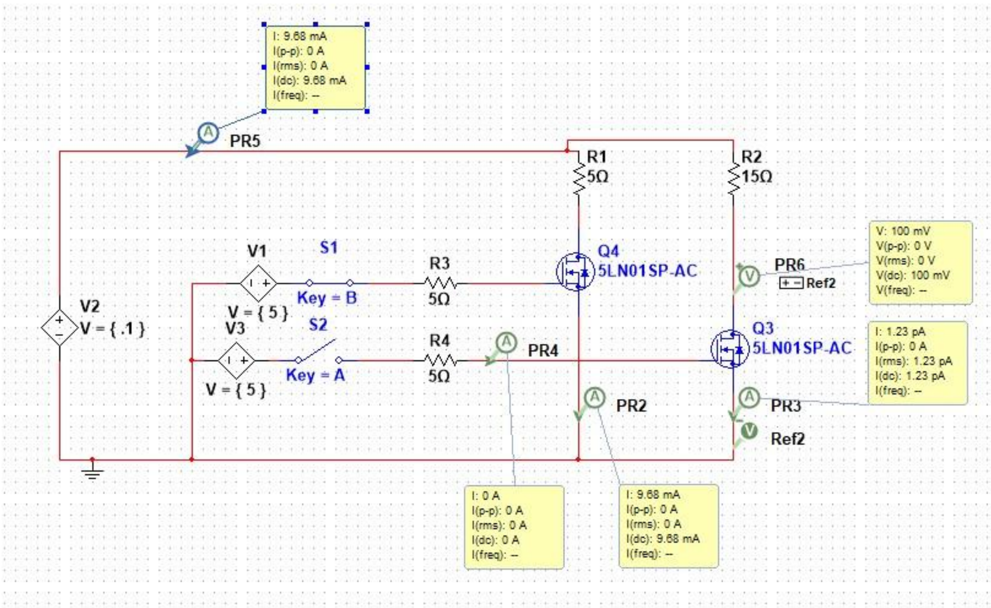


(Figure 6. Switches connected in parallel to a voltage source and multimeter with switch 2 being the only one closed. Red lines touching the solar cell represent spring loaded pins making contact.)

With this design, the multimeter can measure each solar cell length individually through the same wire. Figure 6 for example shows the first pin from the left and the 2nd pin from the left are connected in series with the solar cell between them. All other pins are disconnected at this snapshot, since the switches in front of each of them are open.

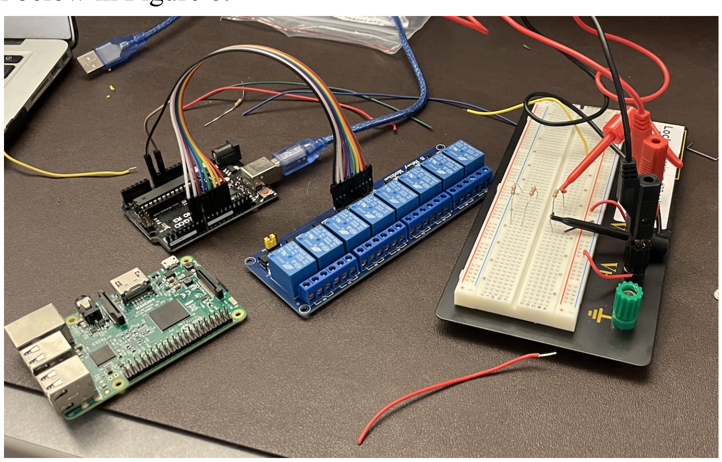
Introduction - Switching Mechanism

While the concept idea uses switches controlled by the press of a key in the simulation, our design needed switches controlled by a computer in real life. PNP transistors as voltage controlled switches were the first idea. However, through testing in simulations as seen below in Figure 7, we found this approach introduced varying voltage drops as the source voltage affected the input and output voltages of the transistor. This would not be appropriate for our design, as measurements at such a low voltage sweep (.1V to -.1V) would be significantly affected by these variations.



(Figure 7. Simulation of a .1 V source applied across multiple voltage controlled switches (transistors) on the right. Current through a switched-off transistor would slowly bleed until it eventually approached zero.)

The next option for a switching mechanism was between solid state or mechanical relays. Mechanical relays appeared to be the better alternative, as they did not introduce electrical interference to the circuit as compared to the solid state relays. A set of 8 mechanical relays were then ordered and tested with an Arduino Uno as shown below in Figure 8.



(Figure 8. An Arduino Uno (left) connected to a set of 8 mechanical relays (middle) and multiple resistors (right).)

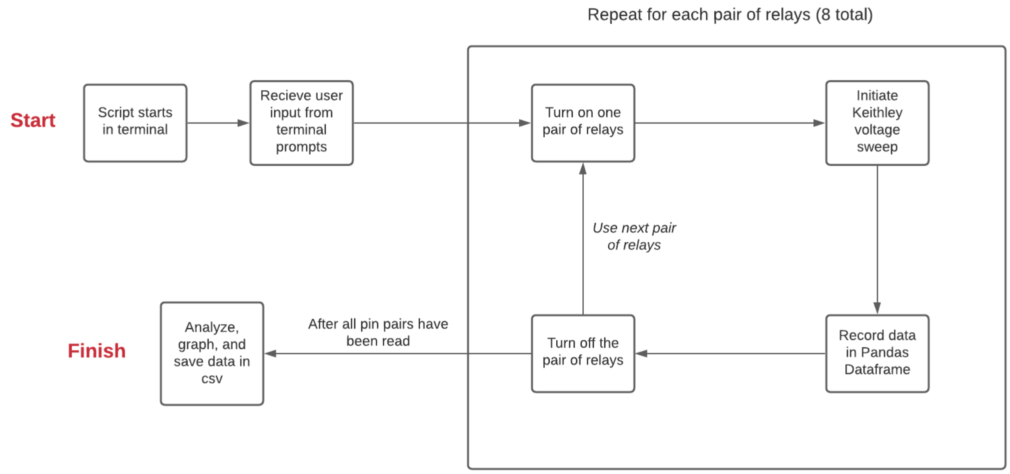
A Keithley multimeter confirmed accurate measurements of the resistors when individual relays were switched on and no resistance values when the relays were switched off. After confirming that the mechanical relays could be operated and did not introduce excess electrical interference to the circuit, the team moved on to microcontroller pin switching mechanism.

Introduction - Microcontroller Pin Switching for Relays

Our design needed a programmable mechanism to control the relays as well as perform data analysis of the measurements. The two choices were between Arduino and Raspberry Pi, with Raspberry Pi as the first explored option.

Initially, the Raspberry Pi seemed the more attractive alternative for its ability to perform both the pin switching and the data analysis necessary to create CSV files and graphs. There was also the added benefit of coding in whatever language was preferable. However, through the advice of our teacher, Professor Greg Lee, the group ultimately decided to forgo the Pi in favor of the Arduino for two main reasons. First, the Raspberry Pi configuration and coding was much more complex and time consuming than we initially thought. Setting up network connections, connections to the user's computer for data transfer, and coding in the Pi would be far more difficult than doing the same in an Arduino. While not essential, the Pi also represented a bit of an overkill scenario in terms of necessary computing power for our purposes and budget. The second reason we switched to Arduino was its ability to interface with Python, which we did not know was possible until Professor Lee informed us of it.

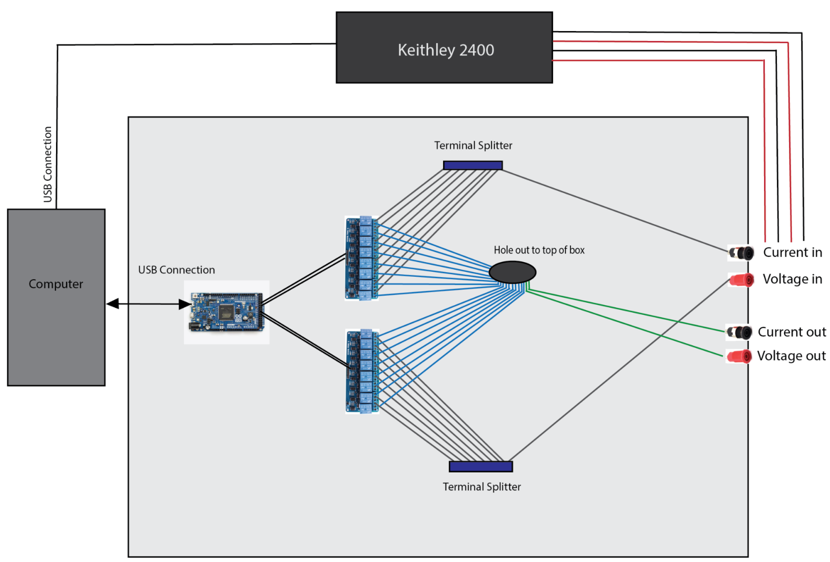
The idea of combining Arduino and Python was quite significant, as it opened up the possibility to include every necessary software function of our design in a single script. The proposed script would initiate Keithley voltage sweeps, control the mechanical relays for pin switching, and compile all the data into a single CSV and graph file. The Arduino Due was then finalized as our design's microcontroller since it had enough analog pins to control our 16 relays at once. Below is a simple block diagram of the script. (Figure 9)



(Figure 9. Simple process diagram from start to finish of the Python script that handles inputs, data collection, and data analysis.)

Chosen Design - Apparatus Overview

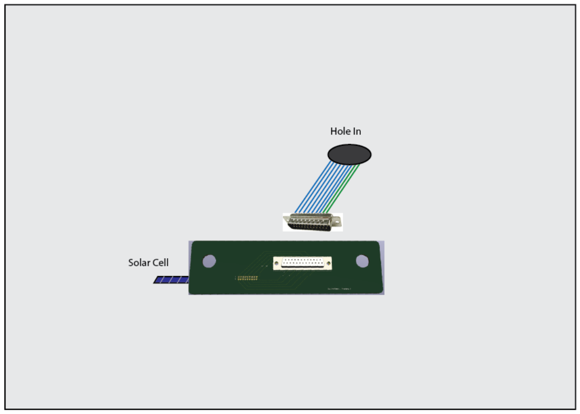
Once the key components such as the switching mechanism and microcontroller were tested and finalized, we arrived at a final design for our apparatus. Below is the circuitry as it sits in an acrylic box. (Figure 9)



(Figure 9. Inside-view of the main circuit connections of the finalized design. The hole out in the middle is a physical hole that the blue and green wires travel through to get to the PCB stand mentioned later.)

Notice that the Keithley connects to our apparatus via banana plugs on the far right, which hold the banana cables in place as the Keithley performs measurements. Those first 2 connections then travel to terminal splitters which connect a set of relays in parallel with one another. The terminal splitter on the top is for current pins and the bottom for voltage pins. (Remember that we decided on a 4-wire Ohms measurement technique to reduce the effects of the internal resistance of our circuit, which is why there are 2 pairs of current and voltage probes.)

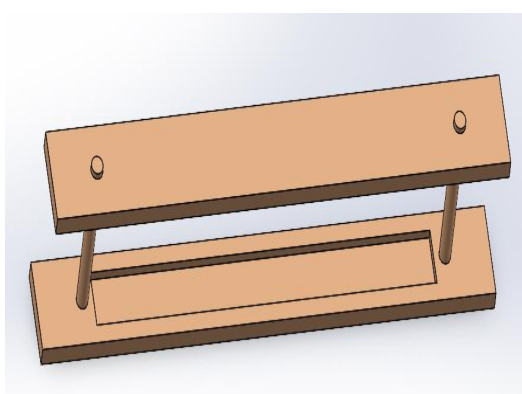
Next is the physical structure that supports the solar cell as measurements take place. This is located on top of the box that holds our circuitry and keeps the overall design tight and compact. (Figure 10)



(Figure 10. Bird-view of the measuring platform. Wires from the relays pass through a hole in the top of the box and arrive at the PCB on top of the box)

Notice that the wires are placed in a 25-pin d-sub connector, which connects the wires to the PCB and also allows for a PCB to be switched with another one very easily. The reason a different PCB may be used is because not all solar cells have the same distance between gridlines. In the event of a different solar cell being measured, the user would only have to slightly modify our KiCad files and assemble the new PCB rather than do all that and rewire/solder a new PCB into the circuit.

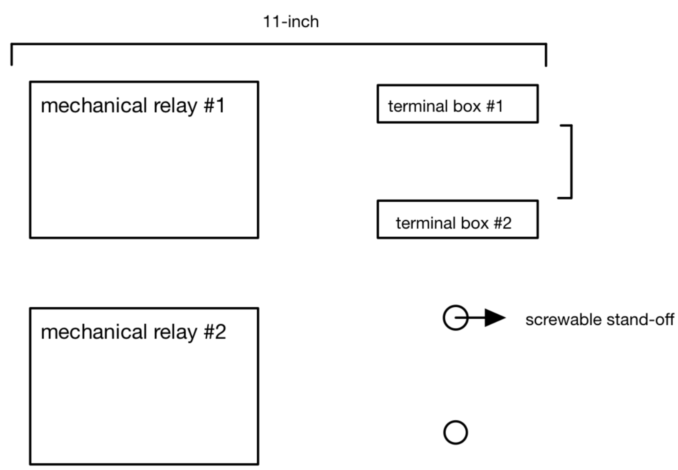
The last major component of our design is the physical structure which holds the PCB in place over the solar cell. While we considered replicating the ContactSpot's hinge mechanism (Figure 2) that rests on the solar cell, it was determined to be too difficult to replicate for our time span of 1 semester. Our simpler alternative was to guide the PCB with 2 metal rods straight down onto the solar cell as seen in Figure 11 below. The tradeoff of this solution vs the more complex one is that the user must apply pressure to keep the pins engaged as measurements are taking place.



(Figure 11. Measuring stage for the solar cell. The PCB on top slides down and onto the solar cell below that sits between the two rods.)

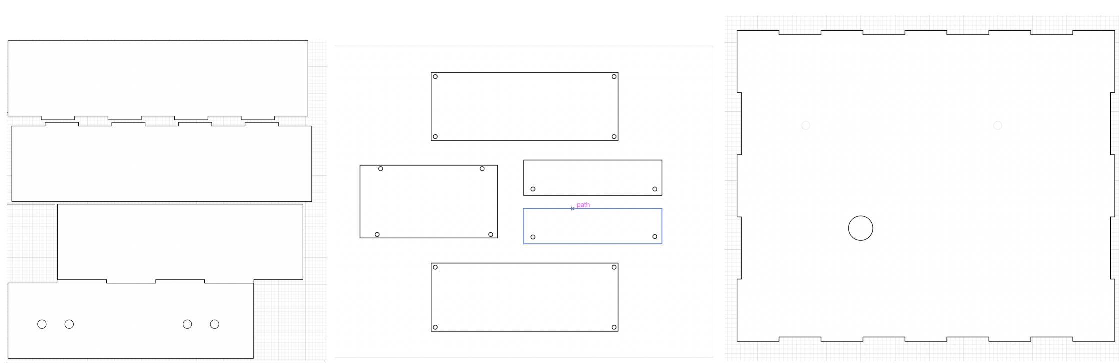
Chosen Design - Apparatus Assembly

Our team chose to design a box to contain all of our electronic components fixed into place, so that the whole setup would be easy to move if necessary and would be self-contained on a lab bench. Thus, we drew up various to-scale layouts for our components to figure out how they should be arranged to allow for the smallest possible container.



(Figure 12. Initial drafts of component layout.)

Ultimately, our team decided an 11x9 inch box would accommodate our components. We then used Adobe Illustrator to outline the sides of our box as well as the holes to accommodate standoffs to mount the components in the box base, as well as holes on the sides and tops to accommodate port connections from our circuit to the Keithley 2400, the Arduino to the user's computer, and the mechanical relays to the PCB. We designed the sides and lid of the box with a ridged pattern so that the lid could be placed on the box and not move around, but also be removable rather than glued into place. We did this to allow easier access to the box interior in case later users have a need to modify our circuit or replace components.

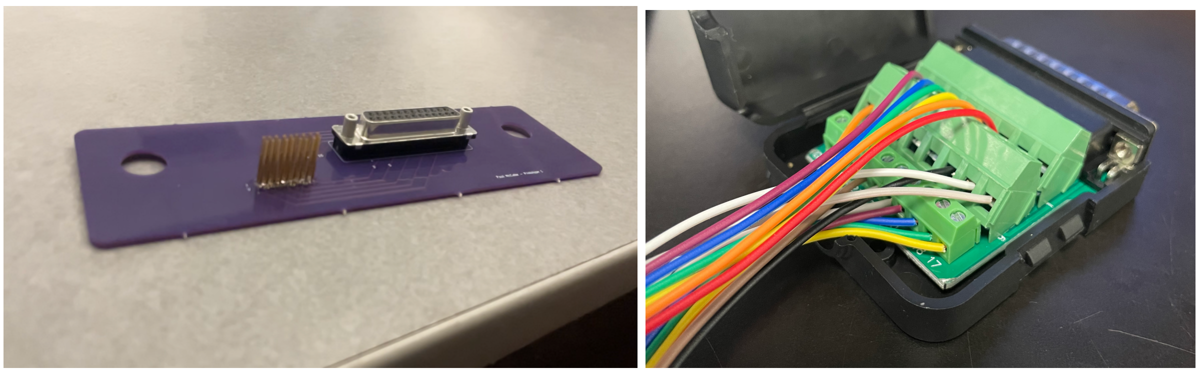


(Figure 13. Acrylic board designed in CAD for laser cutting. Holes' positions are specified for the screwable stand-off and wiring pass-through.)

After we had laser cut our box sides from acrylic plastic, we glued them together and mounted our components into place with standoffs, then ran the wiring between components to form our final circuit.

Chosen Design - Circuitry Assembly

After ordering the necessary materials, the team carefully assembled and tested the various circuitry components. The spring-loaded pins and 25 pin d-sub connector were soldered onto the PCB and then tested to ensure there were no shorts between the pins and there was conductivity from pin hole to connector.



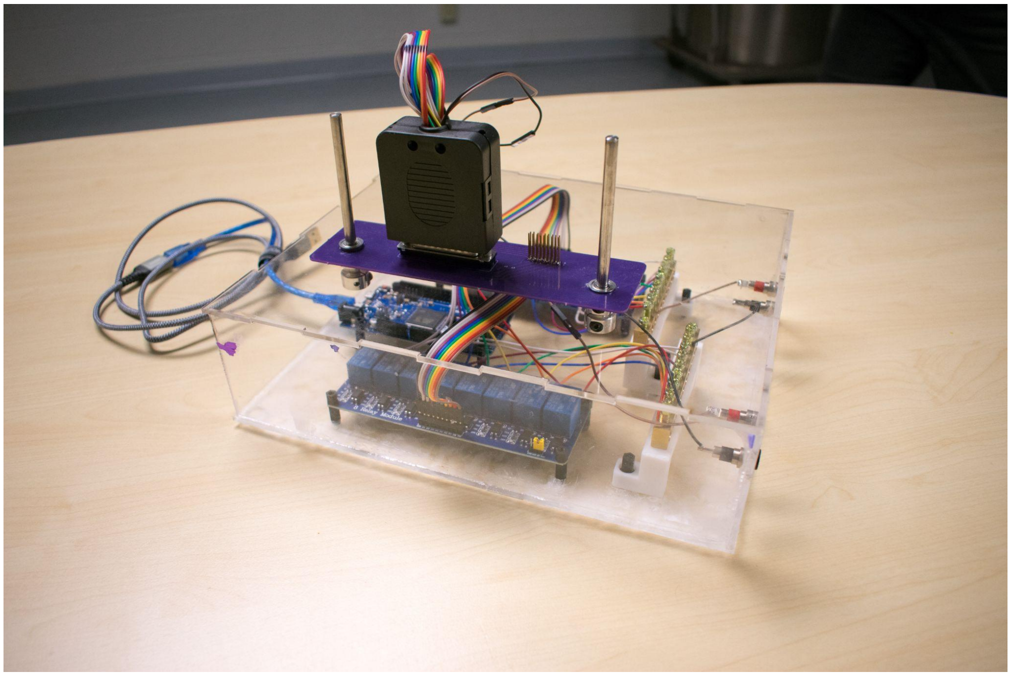
(a) (b)

(Figure 14. PCB with soldered pin receptacles and 25 pin d-sub connector (a), and the adjustable 25 pin d-sub male connector with color coded wires(b).)

Next the 25 pin male connector was wired. Screw-in wire holders were used for easier future repairs and each colored wire was placed specifically so that the 8 colors would correspond to sequential pins. (Figure 14b)

Color coded wires are especially helpful for debugging, as it allows users to quickly locate potential wire faults when looking at faulty measurements. An example of this occurred already, as the group was validating test results of the instrument and a pin wasn't being read correctly. Since colors were documented and easily recognizable, it took very little time to find the particular problem wire and discover it had become disconnected.

Lastly the rest of the components were wired together and placed on screw-in stabs in the acrylic box. The stabs suspend the Arduino Due, mechanical relays, and terminal splitters off the ground and can be easily adjusted if a component needs replacement. The same 8 colors that were used in the d-sub connector are repeated for connecting to the relays and terminal splitter. Below is the entire circuit assembled. (Figure 15)



(Figure 15. Completed TLM measurement system, with PCB, mechanical relays, Arduino Due integrated in one unity.)

Notice the black marking on the wires coming out of the top of the d-sub connector. This is to differentiate the group of wires going to current pins from the voltage pins, as the two color groups are identical.

Design Changes - Future Work

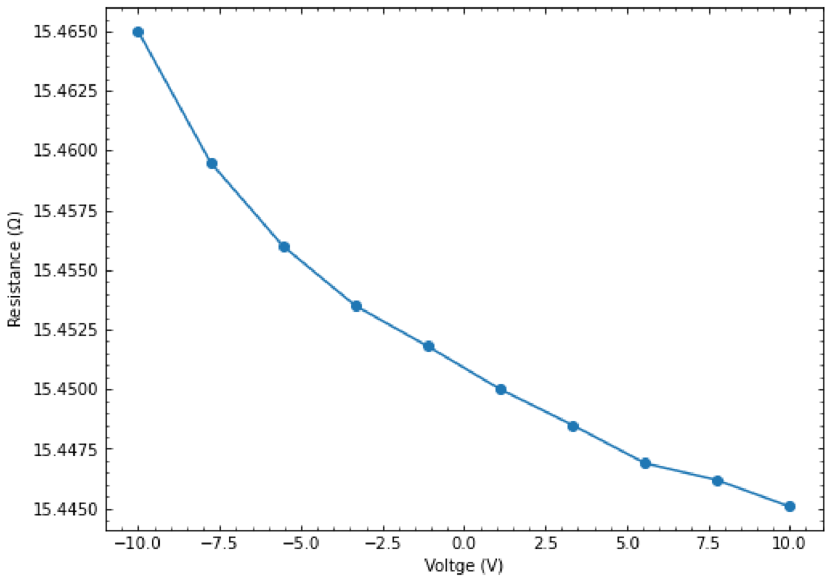
Even before device verification begins, two interesting design aspects can be observed. The first is that the shaft color holding the metal rods upright are too tall for the pins to touch down onto the surface. Therefore a raised platform will need to be attached to bring the floor height higher. (The group used a small plastic box as a temporary stand for measurements.) This platform will actually involve an extra PCB that came with the order and be used to help align the solar cell with the pins. Aligning the solar cell so that the probes land directly on the gridlines is actually quite difficult when the PCB is over it. Therefore placing an exact copy of the pcb along the same rails underneath the cell will allow the user to line the solar cell gridlines with the probe holes much more easily.

The second observation is that light travels through the clear case and hits the solar cell from underneath. This may or may not be problematic since background light may be strong enough to induce a slight voltage difference in the solar cell. Future designs may include a shroud of some sort with black acrylic or some other material/coating depending on if further testing indicates a significant difference in measurement quality.

Verification & Results

Voltage Sweep Results

The functionality of the measuring system is tested to be stable and clear. Each measurement can be operated under 30 seconds, depending on the number of data points that the user wants in their voltage sweep of each pair of pins. When a large number of points are sampled at each grid line, a larger range of data will be analyzed, leading to smaller deviation. The tradeoff of more points however is the increased time of operation. When looking at individual voltage sweeps, each sweep being averaged out to a single resistance measurement, the Keithley records precise resistance measurements with the 4-wire method. (Figure 16)

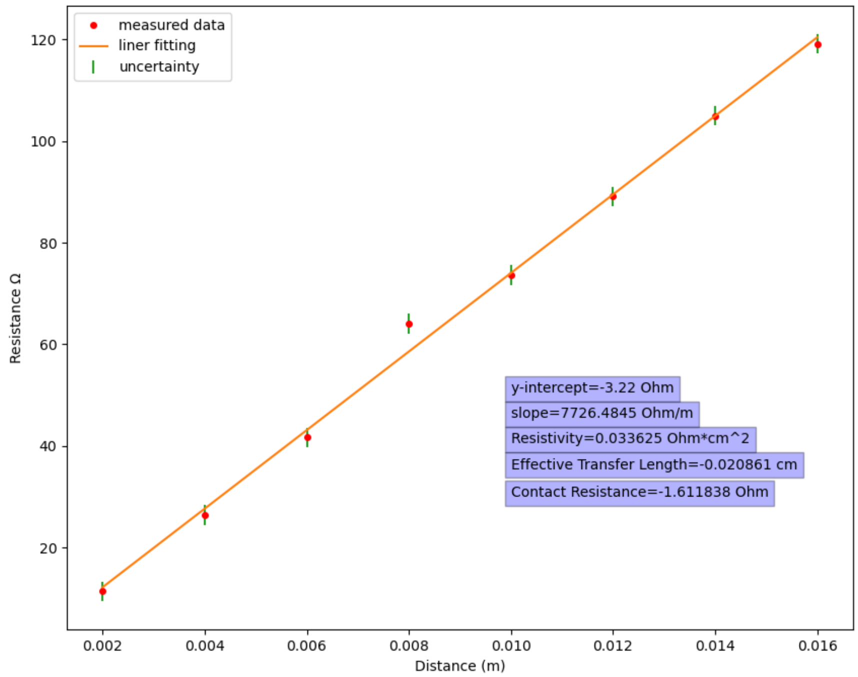


(Figure 16. Resistance vs. Voltage. Resistance measurement on an nominally 16 Ω resistor using the system for a voltage range -10V~10V.)

Notice that the range of calculated resistances is from 15.465 Ohms to 15.445 Ohms for a 16 Ohm resistor. This small range is promising for precision results but seems to hint at external factors playing a role in the accuracy of the Keithley.

Sheet and Contact Resistance Results

Below is a single sample of our test solar cell using our device. (Figure 17)



(Figure 17. Resistance vs. Distance. With the distance increasing, the total resistance in between grid lines is correspondingly increasing. Using the TLM approach, desired values like resistivity and contact resistance are shown in the plot.)

This graph indicates that the TLM method appears to be working well overall as the points line up linearly and fairly close to each error bar. However we find that when resistivity is calculated from the slope and y intercept of the graph, we get very different results. Below is the table of 13 measurements of the same sample for resistivity and sheet resistance. (Table 1)

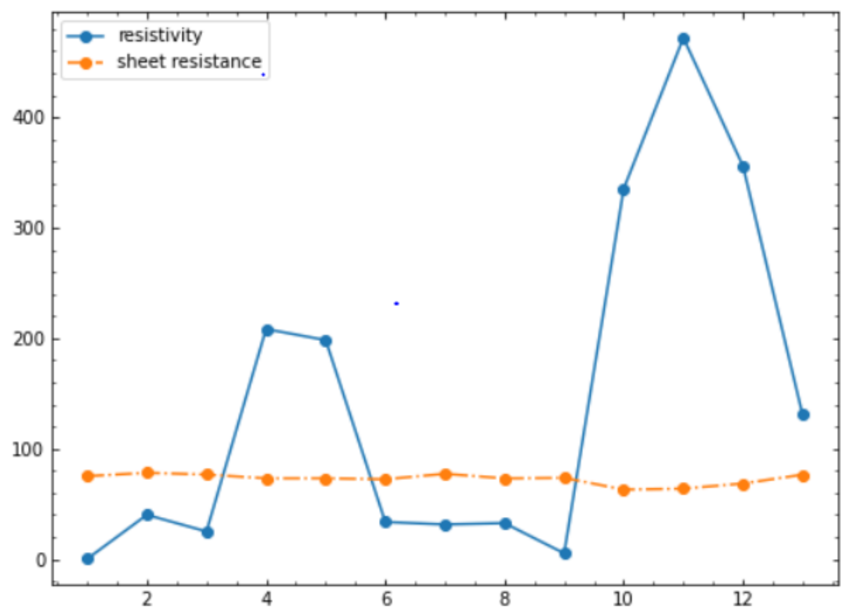
Number of Measurement	Resistivity ($m\Omega/cm^2$)	Sheet Resistance ($\Omega/\square$)
1	0.14	75.066
2	40.073	78.173
3	25.006	76.544
4	208.281	73.116
5	198.290	73.158
6	33.625	72.265
7	31.369	77.231

8	32.587	73.047
9	5.211	73.522
10	335.517	62.889
11	471.917	63.799
12	355.972	68.432
13	130.633	76.431

(Table 1. The resistivity and sheet resistance values for the same solar cell from 13 measurements)

And below is the visualization of Table 1, which shows a rather stable behavior of the sheet resistance, but fluctuating resistivity values.

```
Average resistivity=143.7401 mOhm*cm^2
Average sheet resistance=72.5904 Ohm
```



(Figure 17. Resistivity and sheet resistance values for 13 tests, with an average resistivity 143.74 $m\Omega/cm^2$ and sheet resistance 72.59 $\Omega/\square$)

It is apparent that large discrepancies exist in the calculated resistivity measurements shown in blue while sheet resistance varies much less. This is not entirely surprising, as resistivity is calculated by both the slope and the y intercept of our fitted line. Since we can see the slope, or sheet resistivity, is rather constant, it must be that the y intercept, or transfer length is the cause of the variations.

Likely Cause of Variations in Transfer Length

Further investigation of the solar cell revealed that the pins were not all making good contact with the solar cell gridlines. The pins on the far left, in other words the pins that are always engaged, were slightly misaligned so that the probes were sometimes not on the gridlines. This would explain why the transfer length seemed to vary. Due to the first pins not making good contact with the metal gridlines, every resistance value calculated between pairs of pins would add this extra resistance, therefore shifting the resistance vs distance graph up while keeping the slope the same. Future work will fix these misaligned pins as well as any others, however this is something that is still being developed.

One argument against this hypothesis is that the ContactSpot device seemed to mimic this behavior of price sheet resistance measurements and imprecise contact resistivity measurements. We can assume that the ContactSpot pins are well aligned and making good contact, so why is this effect still there? This leads us to the conclusion that there may be other factors not yet taken into account.

Other Factors Affecting Measurement Quality

Although outside the scope of this technical report, it is worth mentioning that a study has already been done on improving TLM measurement quality. A paper from University of Central Florida Siyu Guo lists several factors that affect TLM measurements such as resistance in pins, light hitting the sample, and more. [3] Future research is needed to explore these factors and improve the quality of our device's measurements.

Project Management

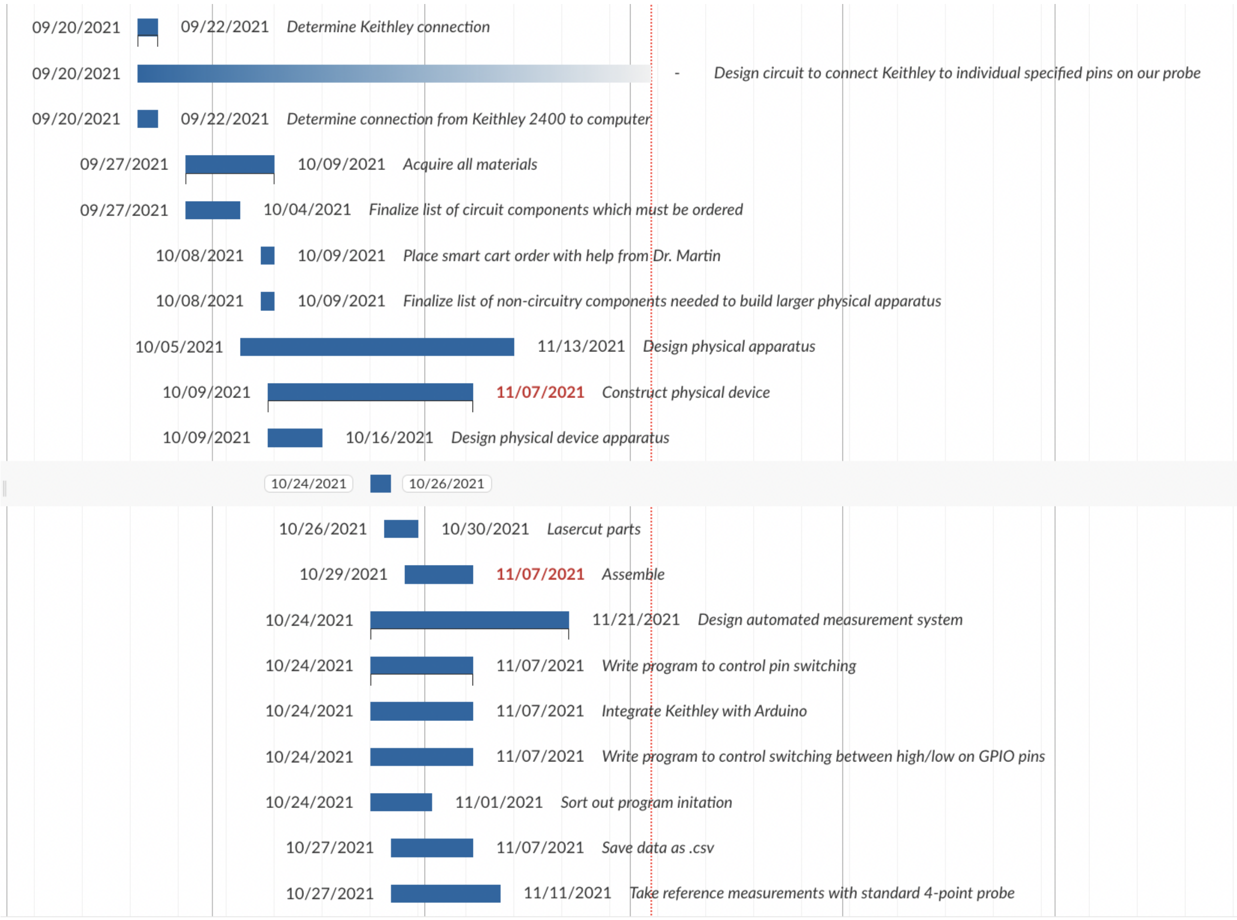
Work Breakdown

Our work breakdown structure involved essentially dividing the project work into three sections: designing the initial circuit, constructing the physical apparatus, and creating the software program which handled the autonomous measurement-taking. Although all three team members worked on all three sections, each had one area for which they took primary responsibility: member Paul McCabe worked most on designing the circuit, Kehley Coleman did much of the physical assembly, and Neil Wang took charge of software development to automate the measuring process. Here is a more detailed outline of the breakdown of work that we ultimately did on this project:

- Designing the circuit
    - Determining necessary components (i.e. mechanical relays for switches, Arduino to control relays, etc.)
    - Designing the PCB in KiCAD
    - Drawing up the wiring
- Physical assembly
    - Designing the layout of components inside a case and the
    - Using CAD software to outline and laser cut acrylic plastic to form the case
    - Mounting components using standoffs and wiring the circuit
    - Soldering pins into PCB
- Software/autonomous measurement development
    - Finding a package to allow control of the Arduino via a Python program
    - Coding a voltage/current sweep to allow the Keithley to measure resistance
    - Integrating Keithley and Arduino control in one Python program
    - Data output including calculations and plotting; saving results as .csv file
    - Testing the apparatus on solar cells to ensure it ran correctly

Gantt Chart

Below is the Gantt chart our team created in OpenProject:



Budget

Although no formal budget was mentioned to us by our advisor, we wanted and were successfully able to keep the cost of materials under 500$.

Item	Total Cost ($)
Spring loaded pins	74
Custom PCB	70
Arduino Due	32
Pin receptacles	32
Acrylic sheets	27

25 pin d-sub connector female	25.5
Mechanical relays	18
Shaft collars	18
25 pin d-sub connector male	13
Silicone rubber adhesive	12.50
10 pin terminal splitter	12
Color coded wires	12
Banana jack plugs	9
Flanges	4
6mm steel shafts	4
Total	**363**

Relevant Courses

Course	Description	Role in Project
ECSE 245	Practical electronics lab work and the design of circuits containing non-linear semiconductor devices	Knowledge from this course, particularly the lab component, was applied: ● When doing the physical wiring of the circuit ● When operating the Keithley 2400. ● When simulating performance of the original circuit design in Multisim
ECSE 321	Analysis of fundamentals of semiconductor physics, including metal-semiconductor junctions.	Knowledge from this course was applied: ● To the calculation of resistivity from the resistance measurement ● To the analysis of the solar cell behavior as it pertained to the type of metal-semiconductor contact (Ohmic vs. Schottkey, etc.)

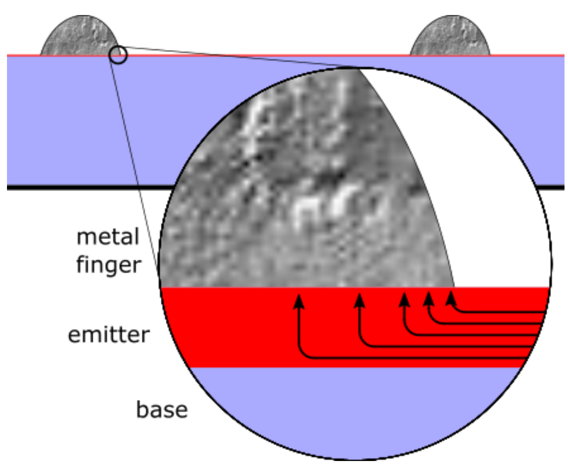
ECSE 344	The design and analysis of physical circuits, including selection of operating points for BJT & FET amplifiers and computer modeling of circuit operation.	Knowledge from this course was applied: ● In our initial drafts of our Arduino switching design, which involved using MOSFET transistors as switches

Appendix

Part A

Here we present two hypothetical factors contributing to the fluctuation in the acquired data.

Regarding the critical significance of contacts in the measurement process, two distinct types of contacts would be established at the metal-probe interface. Ohmic or Schottky contacts are the most prevalent, depending on the contact quality. While Ohmic contacts have linear current-voltage characteristics, Schottky contacts behave as non-linear. Schottky occurs when the metal's fermi level creates an excessive potential barrier for the electron to cross from the metal to the semiconductor. While ideal solar cell contacts are Ohmic, a poor contact will typically bring non-linear features into the device, interfering with the calculation procedure used to determine the final resistivity value [1]. Generally for semiconductor devices, metal contact can be improved by annealing the device in a single-tube furnace at a high temperature (200°C–300°C) for 1-3 hours, depending on the semiconductor material. However, high temperatures degrade the solar cell's surface, defeating the goal of monitoring the natural surface degradation of solar cells.



(Figure 18. Current congregates near the metal finger's edge due to the metal contact's increased conductivity [2])

Another constraint for precise measurements of the surface of solar cells is the current crowding. Typically, the metal gridlines have a greater conductivity than the doped semiconductor underneath [2]. While electrons in the semiconductor travel uniformly in the lateral direction, they pass through the metal finger in a nonuniform manner vertically, with the maximum concentration at the metal finger's edge, as illustrated in figure 1. Thus, the crowding effect significantly reduced the sensing precision at each gridline. Along with the probes' irregular distances, the electrons exchanging at the probe-metal interface fluctuate according to the probes' contact spot with the gridlines.

References

[1] "TLM measurement," *PVEducation*. [Online]. Available: https://www.pveducation.org/pvcdrom/tlm-measurement. [Accessed: 03-Dec-2021].

[2] "Contact resistance," *PVEducation*. [Online]. Available: https://www.pveducation.org/pvcdrom/design-of-silicon-cells/contact-resistance. [Accessed: 03-Dec-2021].

[3] "Detailed investigation of TLM contact resistance measurements on crystalline silicon solar cells," *University of Central Florida*. Siyu Guo 2017 [Science Direct]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0038092X1730395X. [Accessed: 03-Dec-2021].