

ECE4806: Major Design Project
Team #30: Micron Dynamics of Electron Tunneling

Project Summary

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Purpose

This is an internal document detailing – with maximum clarity and a focus on *concise and intuitive first-principles* explanations – the background, scope, and progress of our project. It will be treated as our knowledge/reference ‘baseline’, and can be appended to or edited by any team-member whenever necessary. The purpose of this is to provide a mechanism for all of us to efficiently be on the same page at all times and correct ourselves if we are not, as well as act as a ‘bank of details’ which we can refer to to create whatever other senior-design submissions are expected of us.

The high-level gist of our project is that ultimately, at some point in our 1-year senior-design period, we will be manipulating cells in a ReRAM array in such a way as to investigate the effects of the manipulation of a target cell on its neighboring cells. Said target cell will be manipulated by controlling voltage and current to it, and the behavior of neighboring cells will be observed by reading the electrical characteristics they exhibit.

The github repository linked below contains all our measured data; the code for our data processing script which we used to automate our data compilation and interpretation process; and the historical report files generated from said script.

<https://github.com/mihirsavadi/MicronDynamicsOfElectronTunneling>

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1 Project Background

1.1 What is a ReRAM Array and how it is manipulated

1.1.1 Fundamentals

A ReRAM array is illustrated from a side and top perspective in Figures 1 and Figures 2 respectively. When a potential is placed between the top copper layer (at the higher potential) and bottom platinum layer, a filament between the layers made up of copper ions forms. When the potential is removed, this filament stays in place.

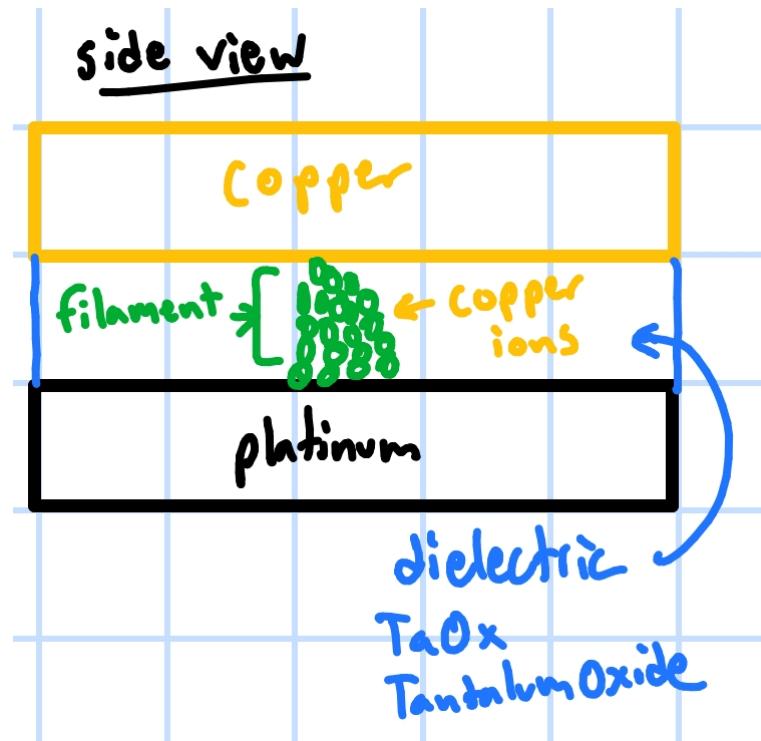


Figure 1: Simplified side view of a single memory cell

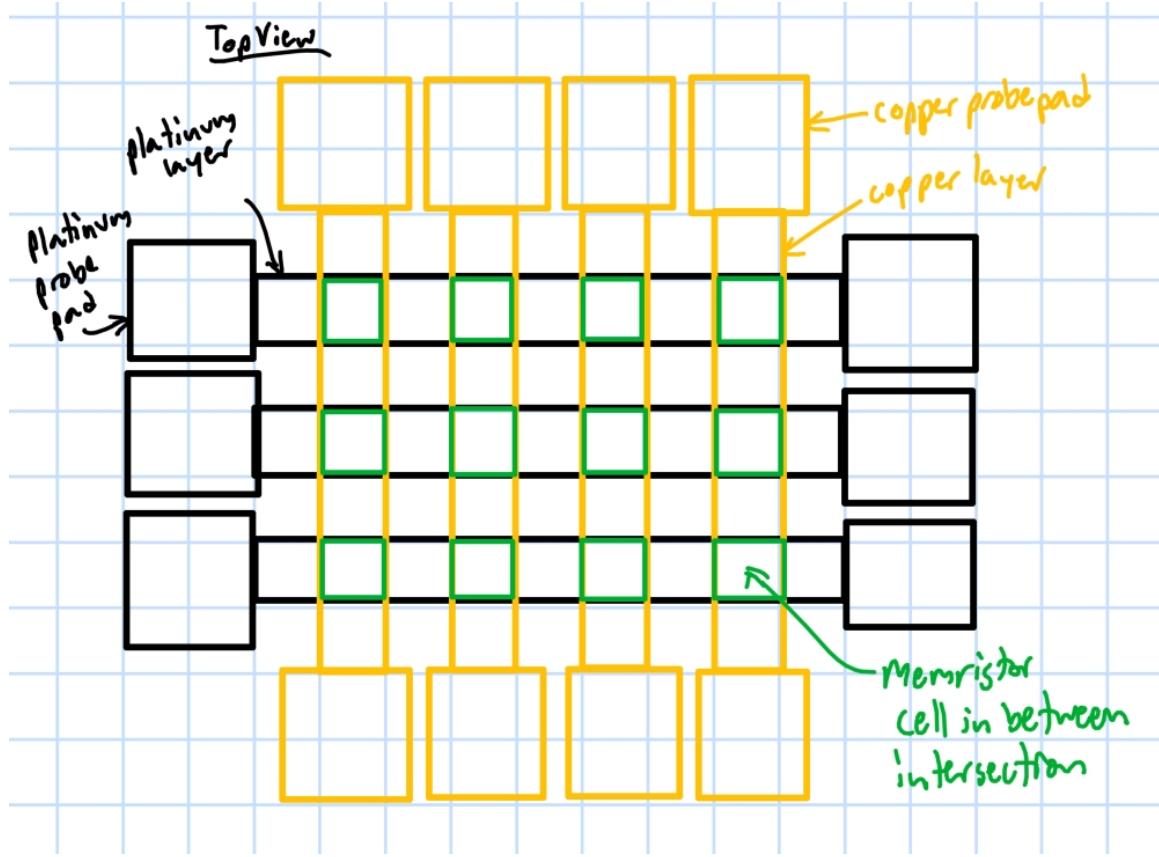


Figure 2: Simplified top view of a single device array

Note that a Logic 0 or 1 is represented in the cell by virtue of the resistance measured across it.

Note that a current limit (referred to as the **compliance current** – I_{CC}) needs to be enforced to the supply of any voltages applied to the cell in order to avoid thermal runaway which would destroy the device entirely. I_{CC} controls the thickness/strength of the filament. If I_{CC} is too high, the filament will be too strong and we won't be able to reset the memory cell later (i.e. remove the filament). $5\mu A < I_{CC} < 70\mu A$ as given by Dr.Orlowski. In some cases we may use $I_{CC} > 70\mu A$ (e.g. $260\mu A$) to demonstrate that a $cell_n$ that was set with a strong filament can be resilient towards the heat transfer from the switching of $cell_t$ (see Section 2 for nomenclature and context references).

In order to create the filament on a fresh device, a voltage V_{form} is required to be applied between the layers. This will be done via a linear ramp from $0V$ to V_{form} , and will remain at V_{form} until the compliance current is hit. Alternatively, a potential $> V_{form}$ can be applied in order for the compliance to be hit faster, below a certain limit (4.5-5V). This can be seen in the line labelled '(1)' in Figure 3 below. Once this is done the memory cell is considered set.

Then in order to set or reset the memory cell, the filament will have to be 'built-up' or 'weakened' respectively. This can be done by applying a potential V_{set} or V_{reset} accordingly. The length of time for which a potential has to be applied can be determined by the current flowing through the

device (which we will measure), as this is a direct indication of the state of the filament, and by extension the resistance of the filament. As can be seen in Figure 3, once V_{reset} is hit, because the filament will have been weakened significantly, no current flows and the curve drops back to an I of effectively 0A. The same logic as described in the previous paragraph with regards to potentials $> V_{form}$ applies to V_{set} and V_{reset} .

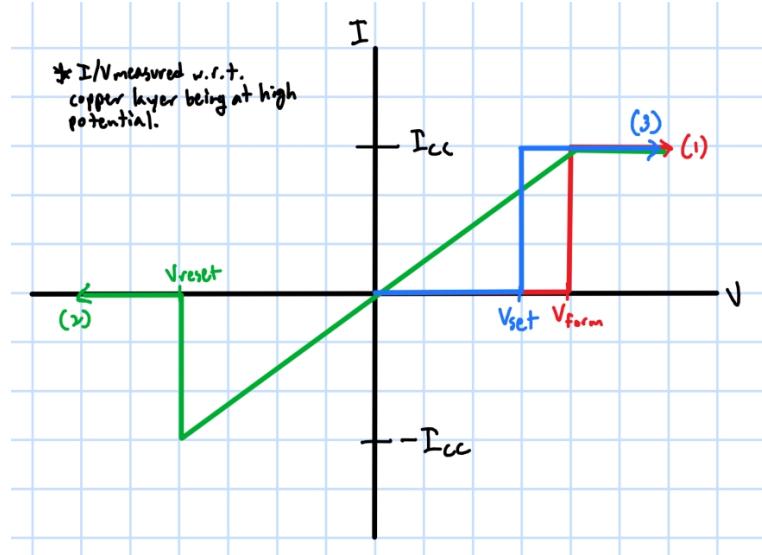


Figure 3: $I - V$ Curve showing V_{form} , V_{set} , and V_{reset}

The realistic construction of the ReRAM array devices we will be working on can be seen in the Figure 4 below.

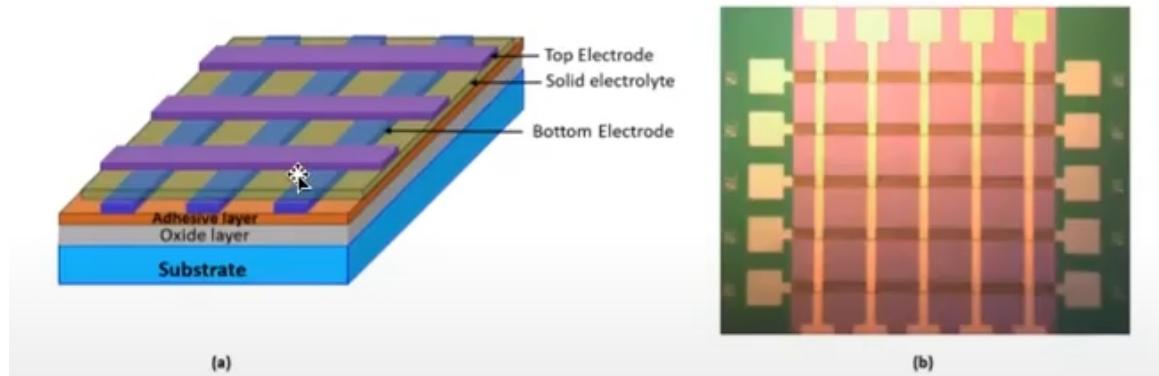


Figure 4: Perspective of our device construction in reality

1.1.2 Terminology

Filament: The conductive path between the copper and platinum layers made up of copper ions.

Electrode: Each ‘line’ in the top or bottom layer of copper or platinum.

Cell: The volume of the intersection between a copper and platinum electrode where the filament is formed. This is the memory cell that we check the resistance of in order to determine whether a logic 0 or 1 has been stored in it. The cell can also be referred to as a **Memristor**. Amrita will often refer to this as **device** as well. No matter the array type, the edge-to-edge distance between any neighboring cell will always be $150\mu\text{m}$ – this is a result of the design of the grid design we are using.

Dielectric: The material in between each electrode within which the cells form. In our lab is Tantalum Oxide (TaOx), and is only slightly opaque.

Contact Pad: The which our probes contact in order to get continuity with the electrodes.

Array: An arrangement of electrodes with platinum in columns and copper in rows, the intersections between which are where our filaments are formed. For the wafers we are handling, these are only 1 layer deep - i.e. the stackup is just copperElectrode–TaOx(FilamentLayer)–PlatinumElectrode, as opposed to copperElectrode–TaOx(FilamentLayer)–PlatinumElectrode–TaOx(FilamentLayer)–copperElectrode–…

Grid: A matrix-ish arrangement of arrays on each wafer half. See coordinate system description and Figure 7 below for how arrays are mapped in each grid. The layout of the grid is determined by the mask we use, which is expensive and complicated to acquire, so we only use the one that Amrita and the lab have been using – meaning that we will only ever deal with only type of Grid type.

Device: The arrangement of material stackup for a grid – Amrita and the lab personnel have multiple varieties. For our scope, these variances only occur in material thicknesses within our general Copper-TaOX-Platinum and substrate stackup. Each stackup, differed in terms of the thicknesses of each layer in said stack up, are referred to by ‘Device x ’ where x is typically some 2 digit number. The final wafer that we will be using for data collection (see Section 2) will be 150nm copper, 25nm TaOx, and 50nm Platinum – referred to as Device junassigned_j . Amrita has a pdf of a set of drawings labelling all the device variances. We will only be using device 43 and 44 – 43 is characterized by having 100nm copper layer, whilst 44 has a 130nm copper layer. This x number is typically written in sharpie on the underside of the wafer.

Wafer: The silicon wafer upon which each half has a grid of the same device type. The wafers are then cut in half. These are grown by Amrita in the photolithography lab. We run our experiments on these. Amrita only has a single photolithography mask for growing our ReRAM grids on the wafers, so this is a major constraint. It usually takes her 14 straight hours to grow a set of grids from scratch on a single wafer, although she plans to make atleast 1 new one within the Spring 2021 semester so that we can observe cell formation using V_{form} . The other wafers are old in the order of years old, so and most of their cells have been formed already.

1.1.3 Photolithography Process & Wafer Coordinate System

The Mask governs the pattern etched on the wafer. A fresh wafer is a circle with a small portion of its perimeter straightened, which is called the ‘primary flat’. Figure 5 below is an image of the mask. Notice it has shapes grouped on 4 sides of the mask - we’ll call these the North South East West Quadrants. During photolithography, only the northern quadrant is what is focused on, and is where the final arrays will end up when the process is done. Between each step in the photolithography process, the Mask is rotated 90°, then 180°, then 90°. If you look at Figure 5 you can see each quadrant is slightly different, but their ‘macro’ grid layout is the same. This is because each quadrant is responsible for etching different features of the arrays. Because our final arrays only coincide with the positioning of the northern quadrant, our wafer will only have a finished grid of arrays on one half of it. For convenience we cut the wafer in half, resulting in what can be seen in Figure 6 – this is the final wafer that we use in our experiments.

In order to locate any cell in any array in any wafer of any device configuration reliably and consistently, we need to come up with a coordinate system and naming convention. Figure 7 is a screenshot of a portion of the mask with each of the arrays in our standard grid numbered. The pattern of this numbering should be self evident. Cells within arrays are then referenced in a 2dimensional coordinate system with the origin in the bottom left corner of the array. A clean standardized format for referencing a cell is as follows

$$\text{location}(\text{cell}_i) = (d_0, r_0, c_0, r_1, c_1, r_2, c_2) \quad (1)$$

where d_0 is device type.

where r_0 is the primary row number (the red number in Figure 7)

where c_0 is the primary column number (the green number in Figure 7)

where r_1 is the secondary row number (the blue number in Figure 7)

where c_1 is the secondary column number (the yellow number in Figure 7)

where r_2 is the row of the cell in the array defined by $(d_0, r_0, c_0, r_1, c_1)$

where c_2 is the column of the cell in the array defined by $(d_0, r_0, c_0, r_1, c_1)$

If any detail from eqn 1 does not to be articulated or is not applicable for whatever reason, then place a ‘-1’ in where necessary. For example, Figure 8 is photo of the probes measuring a certain cell in a certain array. Correlating this photo to our grid layout shown in Figure 7, we can surmise that the wafer is upside down and we are looking at the cell identified by $(-1, 4, 7, -1, -1, 0, 4)$. d_0 is -1 because I forgot to record what the the device type was in this image. r_1, c_1 are -1 because these parameters are irrelevant for this particular array (observe Figure 7 to see which ones they are relevant for). If for whatever reason we were not able to use contextual clues to zero in on the position of the array in the grid, r_0, c_0 would have both been -1 too.

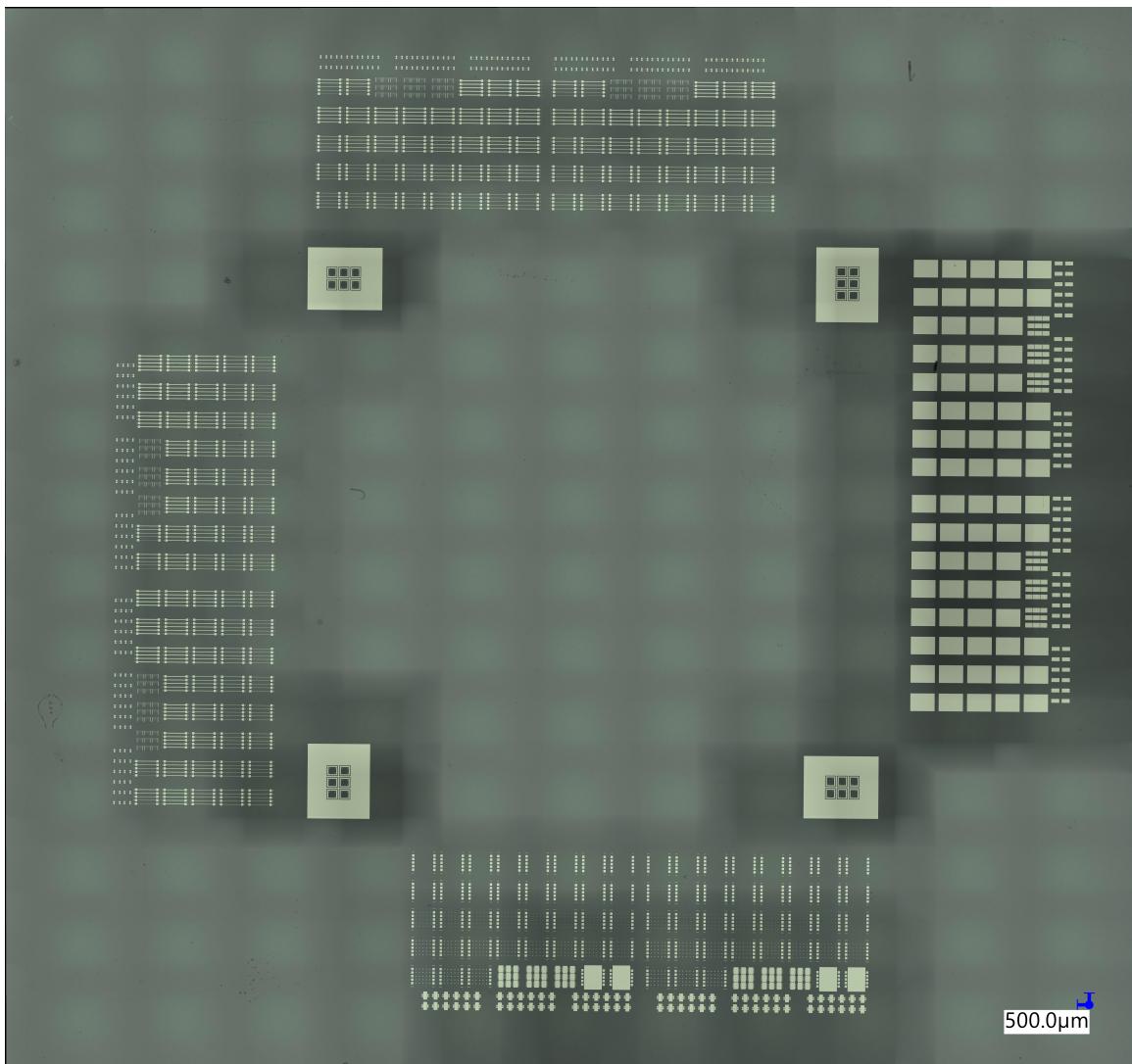


Figure 5: The mask we use with all 4 quadrants in view.

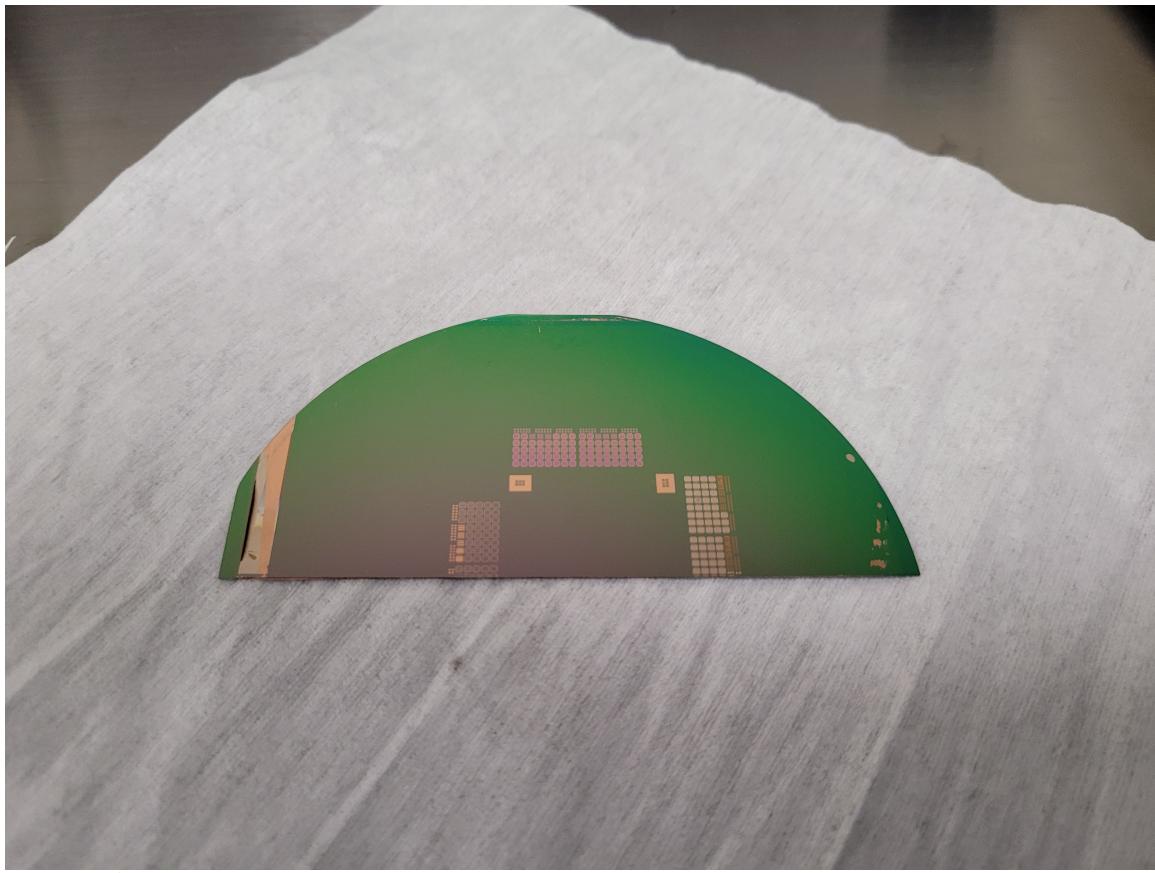


Figure 6: A finished and cut wafer that we use all the time. Notice the flats on the top and side of the wafer. These are irrelevant. Also notice the grids that appear on the sides that seem cutoff. These are artifacts of the mask and its 4 quadrants during the etch-rotate photolithography process we described earlier – they are incomplete. The complete arrays that we use are located in the grid at the top.

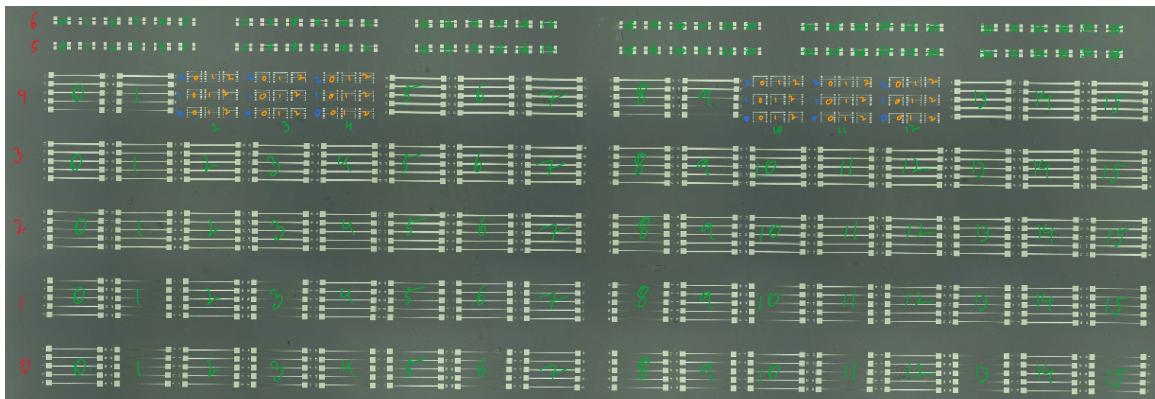


Figure 7: An illustration of the grid coordinate system.

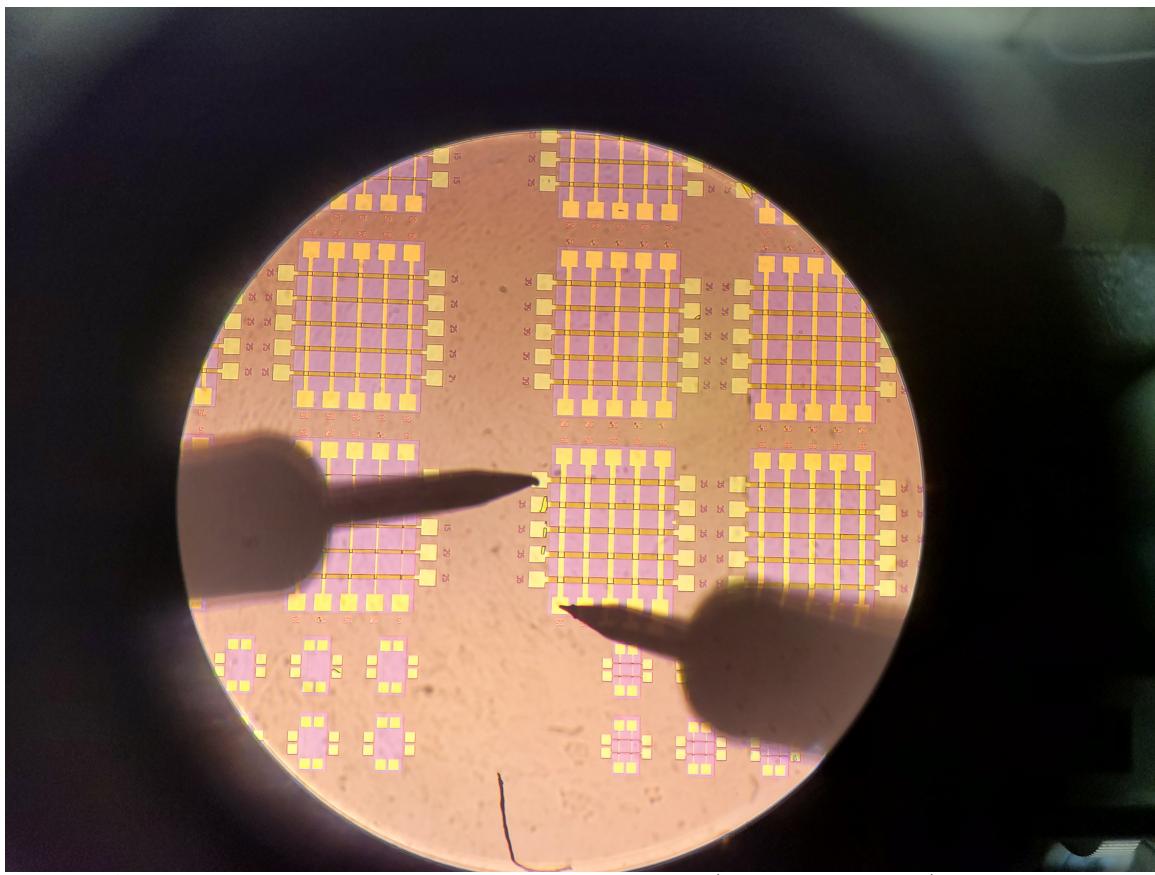


Figure 8: A photo of the microscope view of us targeting the cell at $(-1, 4, 7, -1, -1, 0, 4)$. The pinkish square encapsulating the cells in the arrays is the TaO_x dielectric – the middle layer. Below it is the platinum layer, the electrode contact pads for which are located just outside the pinkish square. At the top is the copper layer, the electrode contact pads for which look as if they are contained within the pinkish square.

1.1.4 (TODO) Thermal effects on electron tunneling in neighbors

Explain how two levels of thermal energy in a filament (from switching within a period of time) result in copper ion displacements, as well as filament conduction degradation, as explained in video in our shared google drive – <https://drive.google.com/file/d/1HNudbTjQwhGMvVA0n-Gc4JBXrSSjBQt3/view?usp=sharing>.

1.2 Who are we working with

Dr. Orlowski is the lab director and in charge of the Micron Lab at Virginia Tech, overseeing the Micron research work as a whole. Dr. Orlowski is as our SME, and potentially will have to play the role of customer as well.

Amrita Chakraborty is one of our Senior Design GTA's, as well as the main point of contact for all clean-room/semiconductor related senior design projects. We work with her very closely, and she is the one that guides lab familiarization and day to day hands-on project work. Amrita assumes the role of SME as well.

Zuzanna is our contact with Micron, however communication has been lackluster – no reply on the first outreach, followed by a reply after an email reminder, followed by no reply once again. She would potentially be our customer, or would have put us in touch with other Micron employees who would be better suited, or even just for more exposure. But with the non-determinism of communication, to assign her as customer seems risky.

As of the 2022 Spring semester our customer is no longer a representative at Micron – this was established after an entire semester's worth of effort in keeping up correspondence with Micron proving indirectly that they were not interested in the role-playing aspect of this senior design project. Amrita Chakraborty will act as our SME and Dr. Orlowski as our customer – this assignment is far more appropriate and closer to the reality of how our project has been panning out: Amrita helps us facilitate lab equipment and procedures as well as being a direct source of expertise in the knowledge-area of our project; Dr. Orlowski is the director of the Micron research efforts at Virginia Tech among which Amrita's PhD research efforts is a part, our project is guided in the 'big picture' by biweekly meetings with Dr. Orlowski, and we are in consistent communication with Amrita throughout the week.

1.3 What are we being asked to do

The ultimate aim of this project is for us to investigate the effects a target cell's neighbor's states as a result of setting and resetting said target cell. From empirical experience in the past, Dr. Orlowski and his lab have observed strange quantum behavior on the states of neighboring cells whereby their states were changed from their resting states, and non-deterministically returned to their original resting states an unknown amount of time later. These effects are said to be occurring due to the thermal changes in the device around the target cell as a result of the setting/resetting of the target cell.

Our job would be to figure out a reliable and repeatable way in which to manipulate the device and collect data that illustrates the behavior mentioned above. However doing this is challenging as there are many lab and equipment dependent constraints in play, described in Section 1.4. Section 2 details our final solution.

1.4 The resources we have and their constraints

1.4.1 Lab

We will be working in Whittemore 617, which contains all the lab equipment. Figure 9 is a wide shot of our entire setup, with the probe-microscope bench, and the Keithley machine in view.

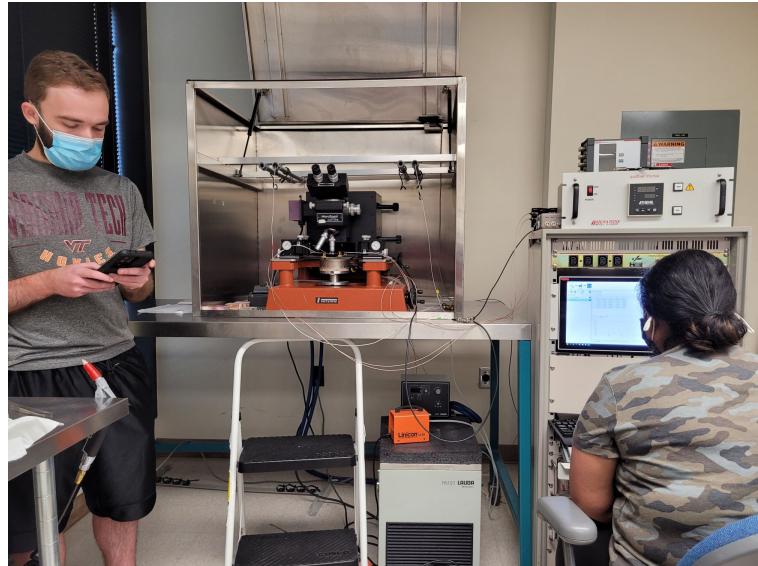


Figure 9: Nick, Amrita, the Probe-Microscope bench, and the Keithley Machine, all in one lovely picture.

List of Constraints

- Access during weekdays during working hours.
- Amrita needs to be present.

1.4.2 Keithley Machine - Keithley 4200A-SCS

Figure 10 shows what the Keithley Machine looks like. The interface is pretty much like a computer. It even runs windows 10. The purpose of the machine is to act as a precision power supply, measurement device, and data logger for our micro electronics experiments. Currently, the software we use within the Keithley machine to do all of this is called Clarius, the GUI of which can be seen in Figure 11.



Figure 10: The Keithley machine. Idk why LATEX insists on making this image sideways.

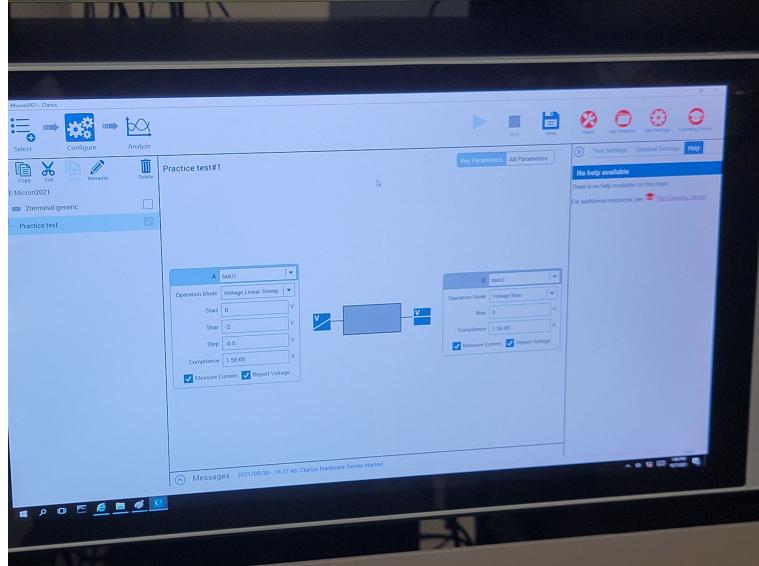


Figure 11: What the clarius software on the keithley machine looks like.

List of Constraints

- list constraints here (*note from Dr. Orlowski: the team may brainstorm the constraints perceived during the project so far. It would be a great legacy for the future teams working on this technology and be aware of some possible showstoppers.*)

1.4.3 Probe-Microscope Setup

Figure 12 shows our probe microscope setup. The black things with the knobs are what the probes are attached to. They allow for precise movement of the probes in space.

TODO!: talk about probes, the 4 wire setup and reasoning, its limitations etc.

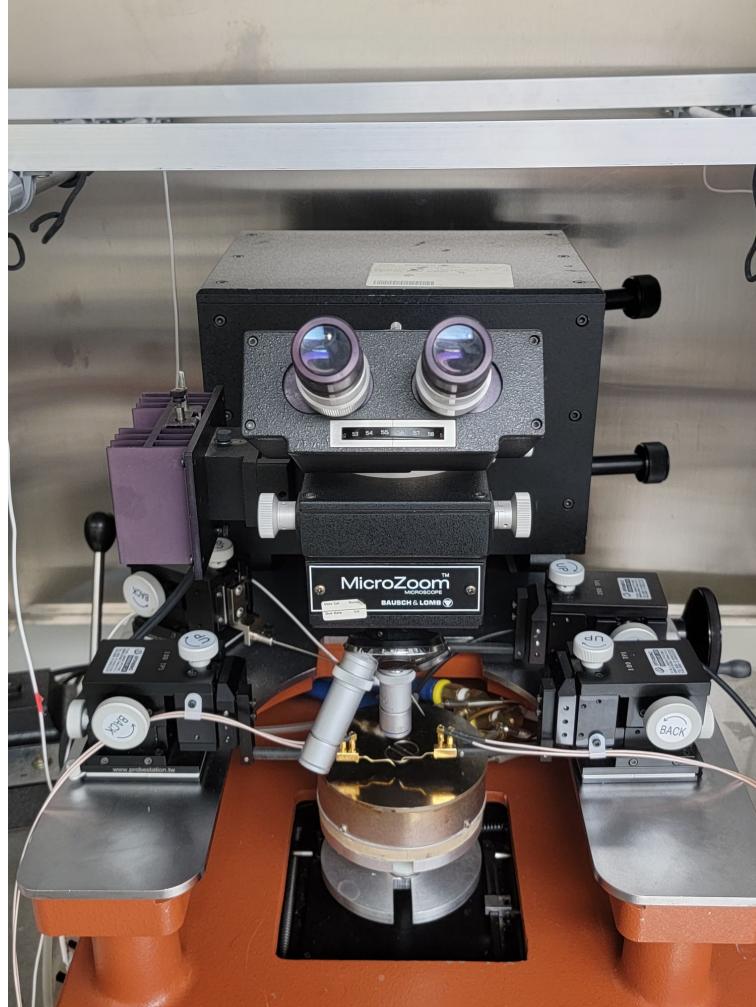


Figure 12: A front-on view of the probe-microscope setup.

List of Constraints

- 4 probes in setup. No choice about this that's how it's setup. Currently (and for the foreseeable future) only 3 probes exist. Meaning we can only contact 3 contact pads. The implications of this is that the neighbors we can observe must be perpendicular to our target cell as they would share a common ground. To observe a diagonal neighbor would require a separate reference

ground and therefore 2 extra probes beyond the 2 used for manipulation of the target cell.

1.4.4 PMU's

enter description here – general description, its interfaces, software, etc

List of Constraints

- list constraints here.

1.4.5 Grid on Wafer Setup

enter description here – general description, its interfaces, software, etc

List of Constraints

- New wafers with new sets of grids on them takes Amrita 14 straight hours to make. Most of the ones on hand are already pretty old. She estimates to make at least one new one in the Spring 2021 semester for us to be able to observe cell setting using V_{form} . We will mostly be using old wafers on the order of years old, the cells of which have been set a long time ago.
- Mask is fixed and pre fabricated. A new one cannot be made. So the arrangements and sizing of grids on the wafer is fixed to what we have. When doing bulk data collection we will need to cleverly work around the inefficiencies that arise from the way the grids are arranged in order to not be inhibitively slow.

1.4.6 Consumables

Figure 13 is a picture of the tweezer we use, which is very expensive (in the hundreds of dollars) due to its material properties that make it safe for handling raw wafers.

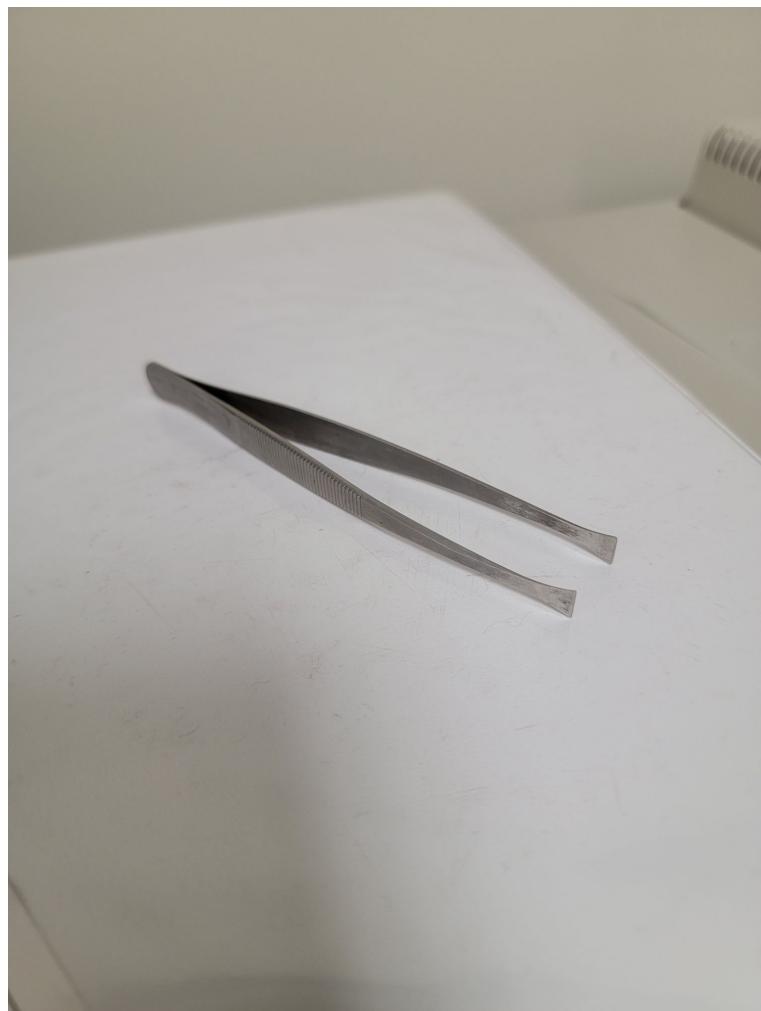


Figure 13: Our glorious and supreme tweezer. May it have mercy on us.

List of Constraints

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2 Overall Solution Breakdown

2.1 Data Collection Related Nomenclature

Refer to section 1.1.2 for a reminder of what any certain ancillary term may mean.

$cell_t$: the target cell who's current and voltage we are manipulating.

$cell_n$: the cell neighboring $cell_t$ who's voltage we fix and current we observe.

Cell Pair : a single pair of ($cell_t, cell_n$) that we manipulate and observe at any given point during our data collection.

Cell Pair Set : the set of all cell pairs that we would like to manipulate and collect data for throughout the duration of our senior design project. Cell pairs can be varied in terms of what array type they lie in in the overall grid, as well as where in a particular array they could be situated. These positional factors can influence how thermal energy is transferred from $cell_t$ to $cell_n$, and by extension can also influence potentially differing behaviors we might notice in the set/reset status of $cell_n$ over time.

P_t : the probe connected to $cell_t$.

P_n : the probe connected to $cell_n$.

P_{gnd} : the probe connected to the common ground between $cell_t$ and $cell_n$.

V_{P_t} : The voltage that is applied to $cell_t$ through P_t . This will vary as a function of time during data collection. It is an independent variable/controlled input in our data collection.

I_{ccP_t} : The compliance current (i.e. current limit) that is applied to $cell_t$ through P_t . This will also vary as a function of time during data collection. It is an independent variable/controlled input in our data collection.

I_{P_t} : The actual current that flows through $cell_t$ at any given point in time. This is a dependent variable/observed output in our data collection.

V_{P_n} : The voltage that is applied to $cell_n$ through P_n . This will stay constant throughout the data collection process as the purpose of $cell_n$ is just to observe whether or not it is set (by observing the current passing through it), which will be affected by the thermal energy produced from switching $cell_t$. It is an independent variable/controlled input in our data collection.

I_{ccP_n} : The compliance current that is applied to $cell_n$ through P_n . This will stay constant throughout the data collection process for the same reason as above. It will be far less than I_{ccP_t} because we only need to observe the set/reset condition of the filament in $cell_n$. It is an independent variable/controlled input in our data collection.

I_{P_n} : The actual current that flows through $cell_n$ at any given point in time, which will tell us if a filament is formed or not in $cell_n$. This is a dependent variable/observed output in our data collection.

V_{P_t} shape : The arrangement of V_{P_t} values against time that we would like the Keithley machine, programmed through clarius, to achieve when manipulating $cell_t$ according to our desired waveform.

Icc_{P_t} shape : The arrangement of Icc_{P_t} values against time that we would like the Keithley machine, programmed through clarius, to achieve when manipulating $cell_t$ according to our desired waveform.

Run File : In any clarius project we can create ‘run files’, which when clicked on shows an arrangement of interconnected blocks that allow the user to select certain parameters with which to manipulate our P_t , P_n , and P_{gnd} probes. Then, when the play button at the top right of the GUI is hit, the probes are then influenced to output the parameters we described in the software. The Voltages of these probes can be arbitrarily manipulated against time in each Run File. However for each Run File, each probe can only have a single Icc compliance current which cannot be manipulated. If a different Icc is required, another subsequent Run File will be needed. Each run file will be named in the order in which it is executed, so the first run file will be ‘1’, next will be ‘2’ and so on.

Run Folder : Each clarius project can contain multiple Run Files ordered under a single drop down. This drop down will be referred to as a Run Folder. If we click on a run folder and then hit ‘play’ at the top right of the clarius GUI, then all the Run Files contained within it will be run in order. By cleverly arranging a series of Run Files we can achieve complete arbitrary control of Icc and V for any of our probes against time, as we desire. This will be essential in achieving our desired ‘test cycle’, which will be described below.

Test Cycle : A single test cycle is achieved by a specific ordered set of appropriately designed Run Files under a single Run Folder. When said Run Folder is ‘played’, a test cycle will be executed. An ideal test cycle can be defined by plotting certain V and Icc values against time for each probe. This ideal test cycle would describe how, in an ideal world, we would want to manipulate the parameters of our probes in order to achieve adequate stimulus of $cell_t$ in order to observe thermal-cycling effects in $cell_n$.

We can vary the set and reset V shapes and Icc shapes in our test cycle, as well as vary how often and with what frequency these various set and reset shapes will appear over time in our test cycle.

Once this ideal test cycle is well defined, we would then work on replicating it as closely as possible by creating a series of Run Files within a single Run Folder.

2.2 Wafers Currently on Hand

Details about wafers we have produced for the express purpose of data collection are referred below:

Wafer 1 **Date Created :** ???

Comments : Copper electrodes faulty. 23nm of Tantalum Oxide (manufacturing limit is 25nm). Platinum is 50nm and Copper is 150nm. Strange form and set behavior. Super short cell lifespan of less than 5 to 10 cycles.

Wafer 2 **Date Created :** 11th March 2022

Comments : No faulty copper electrodes. 25nm of Tantalum Oxide. Platinum is 50nm and Copper is 150nm.

2.3 The Human Algorithm for Data Collection

The following series of steps is run for each cell-pair in a pre-determined cell-pair set. This cell-pair set, and the positional and size variances within it, needs to be established before commencing data collection.

1. Form and set $cell_n$ for every cell pair. With a fresh untouched wafer each $cell_n$ would have never been formed before.
2. Create a master directory called “data”. Then, starting from the first cell-pair in the cell-pair set, do the following:
 - (a) Set P_t , P_n , and P_{gnd} appropriately on the wafer according to the identified coordinates of the target cell-pair.
 - (b) Click run the Run Folder representing the intended test cycle.
 - (c) Collect the csv’s produced by clarius into a thumb-drive, and name them with the following naming convention: “[coordinate of $cell_t$]_[coordinate of $cell_n$]_[name of test cycle]_measurement.csv”. The coordinate entries will follow Eq 1.
 - (d) Take the best picture of the view through the microscope of the probes placed on $cell_n$ and $cell_t$, and save it somewhere according to the following naming convention: “[coordinate of $cell_t$]_[coordinate of $cell_n$]_scopeimage.jpg”
 - (e) In a text file called “[coordinate of $cell_t$]_[coordinate of $cell_n$]_notes.txt” include the date and time that cell-pair was tested, the date and time $cell_n$ was initially formed and set, as well as any other notes or observations that were made.
 - (f) Save the .jpg, .csv, and .txt described above into a subdirectory under the master “data” directory called “[coordinate of $cell_t$]_[coordinate of $cell_n$]”.

At the end, we should have a database of all our measurements under the aforementioned “data” directory which can then be easily and comprehensively parsed by any elementary data processing script to extract information from.

2.4 How to Connect the Probes, and Cell-Pair Spatial Arrangements

TODO: describe how the probes need to be connected with GND at a higher potential, what probes get connected to copper vs platinum and why. Also describe how we approach organizing where cell-pairs are located relative to each other. Note from Dr. Orlowski – At first you’ll pick two neighboring cells sharing the same electrode (first along the Pt electrode). The most suitable choice would be to pick a cell in the corner of the array as the $cell_t$. This way the $cell_t$ will have four neighboring cells along the Pt electrode. The cell $cell_n$ will be the next neighboring cell. Time permitting we may later on look into what happens to the second, third, and fourth neighbor along the same Pt electrode.

2.5 Data Entry Protocol [***IMPORTANT***]

For ANY manipulation done to any cell, the CSV log from the Keithley machine MUST be saved. The following naming conventions and protocols **must be adhered to at all times**.

This standardization allows for a script to me made that could, at any point in time, parse over all CSV's in a directory and instantly generate a comprehensive tabulated human-readable database in the form of a GUI, spreadsheet, report file-set or whatever.

See existing examples in the data base to get a good idea. Right now they are in "root/Data/CSV's" in the google drive.

NOTE the two different naming conventions for 3 probe and 2 probe measurement cases. The difference should be delineated by observing the difference in naming convention.

2.5.1 Naming CSV's for 3 Probe Measurements

This is for 3 probe measurements where a target and neighbor cell are being read simultaneously.

NOTE!!: The specific probes connected to copper, platinum, and ground must be specified in the comments. See section 2.5.3 for details on how to enter comments.

{cell_t coordinate}-{cell_n coordinate}-{date in YYMMDDHHMM[SS] in 24hr}-{name of runfolder}.csv

{name of runfolder}

The name of the runfolder should reflect whatever the run folder is called in Clarius. This runfolder name should be descriptive enough to identify which Test Cycle we are running. If the user wants to find our what parameters were used throughout this run (like switch rate, compliance currents etc) they should just refer to the Test Cycle wherever it is saved.

2.5.2 Naming CSV's for 2 Probe Measurements

This is for 2 probe measurements of a single cell at a time.

NOTE!!: The probe connected to the platinum and the probe connected to the copper must be specified in the comments. See section 2.5.3 for details on how to enter comments.

{cell coordinate}-{date in YYMMDDHHMM[SS] in 24 hour system}-{activity}-{activity parameters}.csv

{device coordinate}

See the summary document for the format of this.

{date in YYMMDDHH[SS]}

If the date today is the 21st of Feb 2022 at 1:56pm, you put 2202211356 here. You can typically get minutes by seeing when the timestamp on the CSV file. In the case that two runs are made within the same minute, a two digits seconds counter may be appended to the end. So 21st of Feb 2022 at

1:56:37pm would be 220221135637.

{activity} and {activity parameter}

There are four possible activities you can do to a cell - Form, Set, Reset, Observe. Each of these have their own activity parameters as listed below.

FORM {start voltage}-{end voltage}-{ramp rate in volts per second}-{compliance current. need to include units}

RESET {start voltage}-{end voltage}-{ramp rate in volts per second}-{compliance current. need to include units}

SET {start voltage}-{end voltage}-{ramp rate in volts per second}-{compliance current. need to include units}

OBSERVE {platinum voltage}-{copper voltage}-{compliance current}

e.g. (device, 0,0,-1,-1,0,0)_2202211333_form_0_5_0.5_50uA.csv

Cell (0,0,-1,-1,0,0) was Formed on the 22nd of Feb 2021 at 1.33pm with a ramp rate of 1V/s between 0 and 5V at with a compliance current of 50uA. The device is called 'device' because we haven't given it a numerical reference yet.

2.5.3 Entering Comments and Observations in a CSV

Any and all comments and observations should be included at the top of the csv between two lines that only contain three consecutive dashes, e.g.

```
---  
Insert comments and observations here  
---  
<rest of csv here>
```

NOTE!!! : Make sure to specify the probe connected to copper and platinum (and ground for 3-probe) in the comments. The labels should follow what is outputted in the clarius CSV's - probe 'A', 'B', 'C'.

2.6 Timeline For The Rest of the Project

In order to determine our final cell-pair set and test cycle, we need to achieve certain milestones according to the following timeline:

1. [done] Wafer needs to get done. **deadline before 20th Feb 2022**

2. [done] While the wafer is being done, and for some time after it is done, random cell-pairs needs to be played with in order to build an intuition into what V and I_{cc} shapes will be the most conducive for our test cycle. Note, in order to maintain consistency, the cell-pairs used here should not be included in our final cell-pair set for data collection. **deadline before 27th Feb**
3. [interruption] From the previous step it was discerned that, from the various strange cell performance characteristics that were observed, there were significant manufacturing defects in the wafer. Cell cycle lifetimes were very short (2-5 cycles for 10um and 0 to 2 for 15um); set's only worked with higher I_{cc} than for form's, which was strange; and our third ground probe was faulty – found by the clarius consistently showing cells to be set even though they had never been stimulated before. We were not able to accomplish the next step as a result – creating an idealized test cycle during our 3rd of march meeting – since we had no steady information to work off of. As a result, over spring break, Nick and Amrita were going to be in Blacksburg and would be working on creating a new wafer and collecting the information that we needed to get us out of the mud and hopefully regain our footing.
4. Build an idealized test cycle – characterized in a csv for excel sheet which can then be plotted. Heavy input from Dr. Orlowski and Amrita will be required here (if not the majority of input). The intended cell-pair set for final data collection will also need to be determined here. **deadline before 6th March 2022 t.b.d**
5. Based on the idealized test cycle established in the previous milestone, create a Run File that replicates it as closely as possible. Needs to be tested to ensure a good match. This will likely be quite a tedious job, so a full week+ needs to be dedicated to it. **deadline before 13th March 2022 t.b.d**
6. Finally go ahead and run through the entire cell-pair set and complete data collection, as per Section 2.3. This will likely be the most time consuming milestone to achieve. In parallel start working on the posters and final presentations for expo on the **20th of April 2022 t.b.d**. **deadline before 31st march 2022, 8th april worst case.**