EITP25 – Memory Technology for machine Learning

Lab 1: ReRAM Characterization

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Updated: 25.03.2020

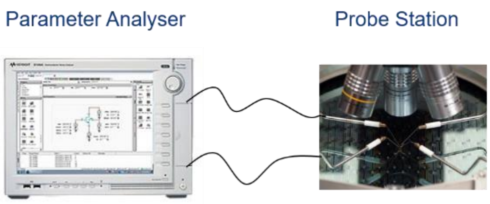
Lab instructions

To do before the lab:

- Go through the lab manual to know what to expect
- Get familiar with ReRAM metrics
    - Forming
    - Switching (SET/RESET)
    - Endurance
    - Retention
- Briefly read through the following short paper to gain understanding of the stack you will measure:
  P. Chen et al., "**Bulk Oxygen–Ion Storage in Indium–Tin–Oxide Electrode for Improved Performance of HfO2-Based Resistive Random Access Memory**", *IEEE Electron Device Letters*, vol. 37, no. 3, pp. 280-283, 2016. Available: 10.1109/led.2016.2522085.

Material/Equipment used

- Probe-station (A system with small needles/probe tips which we can use to controllably land on the devices (ReRAMs in this case) fabricated on a chip)
- Parameter analyser (Used to force/measure a voltage or current in to the needles of the probe station connected)
- Fabricated chip with ReRAM stack



[Image ref: https://www.wsiwebanalys.se/probe-station-manufacturer-chooses-wsi-as-seo-agency/amp/ , https://www.keysight.com/en/pd-582565-pn-B1500A/semiconductor-device-analyzer?&cc=SE&lc=eng]

Aim of the lab

At the end of the lab, you should have a first-hand feel of how a resistive random access memory (ReRAM) device used in neuromorphic computing behaves. You will characterize a ReRAM by performing both direct current (DC) measurements and pulsed measurements. Through these measurements you will be able to extract important performance metrics that today's memory community is interested in.

ReRAM electrical characterization (DC and pulsed)

Introduction

A ReRAM is device with a thin oxide layer sandwiched between two electrodes which is used for resistive switching. The switching event from high-resistive-state (HRS) to low-resistive-state (LRS) is called the "set" process. Conversely, the switching event from LRS to HRS is called the "reset" process. Usually for new samples, the initial resistance is very high and a large voltage is needed for the first cycle to trigger the switching behaviors for the subsequent cycles. This is called the "forming" process in which a filament is formed in the oxide which makes it possible to have an electrical connection between the two metal electrodes. The switching modes of ReRAM can be broadly classified into two switching modes: unipolar and bipolar.

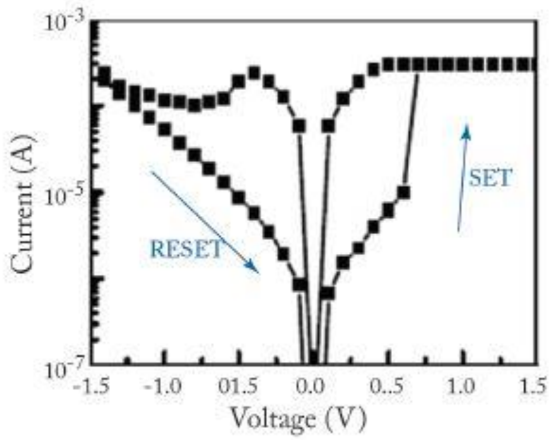


Fig.1 Standard IV switching curve of a bipolar ReRAM showing SET and RESET [S. Yu, *Resistive random access memory (RRAM)*]

Unipolar switching means the switching depends not on the polarity of the applied voltage but the amplitude.. Thus set/reset can occur at the same polarity. Bipolar switching, conversely, depends on the polarity of the applied voltage. Thus set can only occur at one polarity and reset can only occur at the opposite polarity. You will measure the bipolar characteristics of the fabricated ReRAM.

You are expected to write a report which would include ReRAM data plotting and analysis. There are some questions after each measurement section which you are expected to answer in your lab report. How the lab report should be structured exactly is explained at the end of the lab manual. Please submit your reports before the **10th of May**.

Device Fabrication Background

The ReRAMs were fabricated at the Lund Nanolab on a Si-substrate. The bottom electrode (BE), 60 nm TiN, was first deposited using atomic layer deposition (ALD). The switching oxide (HfO2) was deposited using ALD, and is 3 nm thick as well. To limit the active device area, a spacer material was deposited in which small via-holes were opened up using photolithography to define the ReRAM area. A schematic of the fabricated device post-lithography and etching down to the electrical BE is shown in Fig. 2.

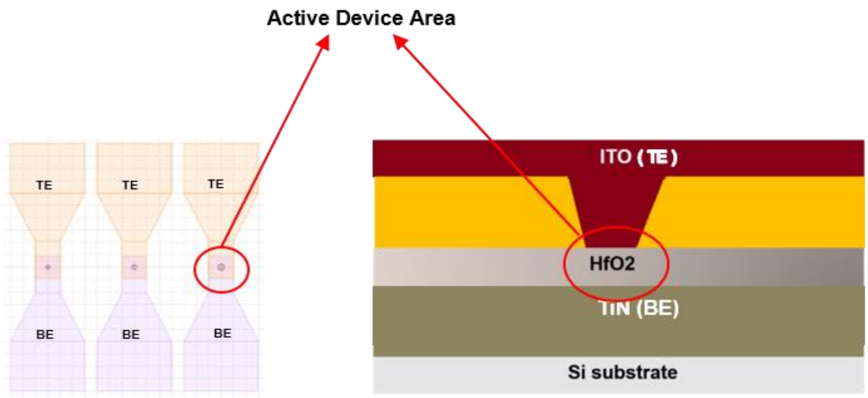


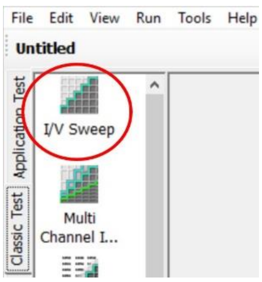
Fig.2 Top view and the cross-sectional view of the ReRAM you will measure

DC measurements (setup):

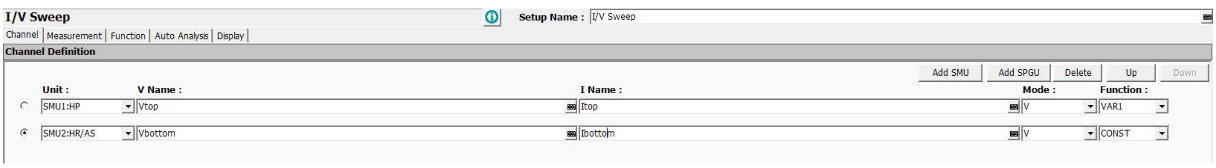
The goal of these first measurements are to measure basic ReRAM switching characteristics (FORM, SET and RESET). The data measured should then be plotted and the variation in the switching voltages to be analyzed using cumulative distribution plots. Please use the parameter analyzer to make these measurements by following the steps given below:

1. Start Easy expert

2. Go to classic test and I/V Sweep

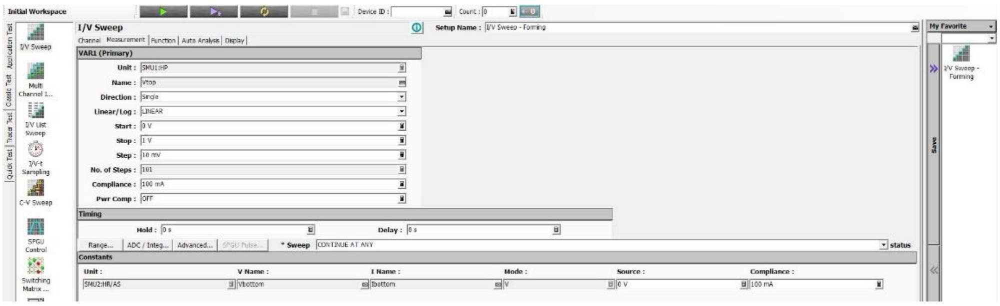


3. **Set up probes:** Under the CHANNEL section, check the SMU numbers that are actually probing the device and select them in UNIT. SMU stands for source measurement unit. An SMU has the ability to force a current or a voltage and measure/sense it at the same time. Assign the top and bottom electrode and set the bottom electrode to a constant in FUNCTION so that it could be grounded. The top electrode is set to VAR1 to enable voltage sweeping at the top electrode.



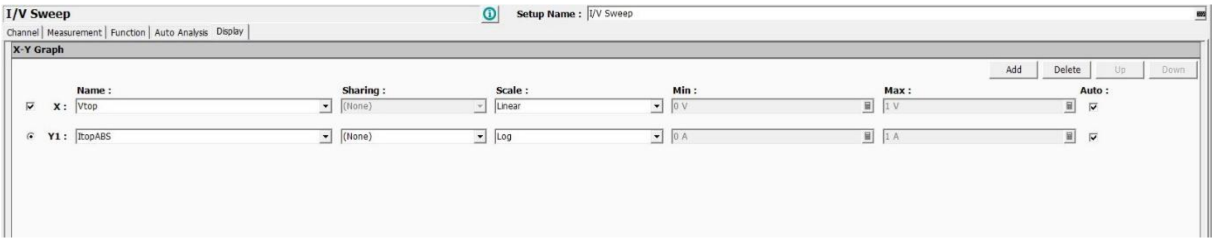
4. **Setting up measurement parameters:**

Give a suitable voltage range to perform the ReRAM FORM operation. For the oxide thickness of 3 nm used here, it is typically between 3 V and 4.5 V depending on the ReRAM area. Set the compliance current level to 100 uA to prevent device breakdown. Set a positive voltage sweep range Change the direction to 'double' instead of 'single' so that you could see the ReRAM holding its new low resistive state (LRS).



5. Use the abs() function to display only the absolute values of current that you measure on the top electrode (As during the RESET operation, you would have a negative voltage sweep and therefore negative values of current measured).

6. Under the DISPLAY section, select what you want to plot on the X and Y axis. Select the range to be auto and set the Y axis to log scale. As it is an IV measurement, you would have the voltage applied to the top electrode on the x-axis and the measured top electrode current on the y-axis.



Use the above setup to perform FORM, SET (+ve bias) and RESET (-ve bias) operations by changing the voltage ranges and note down the switching voltages in the table below.

SET [V]	RESET [V]	LRS [ohm]	HRS [ohm]

After 10 cycles of successive switching, lower the compliance current to 50 uA. Try to switch the ReRAM for 10 more cycles. Note the switching voltages in the table below.

SET [V]	RESET [V]	LRS [ohm]	HRS [ohm]

Plots for the lab report:

1. Plot IV for the measured switching cycles and also include the tables above in your report.
2. Plot cumulative distribution (CD) plots for SET and RESET to get a glimpse of the stochastic behavior which is used in mimicking the synapse of a neuron. An example of how the plot looks is given below. An example is shown in Fig.3. which shows the CD of forming voltages for 10 different measured ReRAMs.
3. You will also be given switching data of a sample where 0.5 nm-thick Al_2O_3 is introduced between TiN and HfO_2. Literature says multi-level switching can be achieved with an Al_2O_3 /HfO_2 stack, so we fabricated it. The same device was measured with V_{stop} = -1.5 V and -2 V. Plot CD plot of the LRS and HRS for both V_{stop} measurements and verify if there is more than one level? Give reasons for your observation. (Hint: Look carefully at both HRS)
   (V_{stop} is the maximum voltage applied on the reset side)

Questions for the lab report:

1. How do the LRS and HRS compare to the measurement done with higher compliance level?
2. Which compliance level is suited for RRAM stability and why? Give a reason based on the measured ReRAM data.
3. Is the parameter analyzer compliance current limit working? (HINT: Check the current level after forming and compare it to the current level during the FIRST RESET)

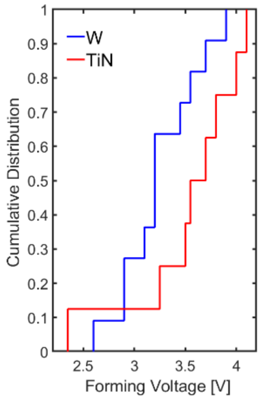
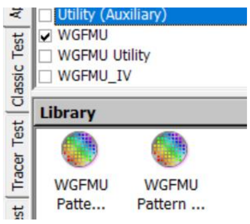


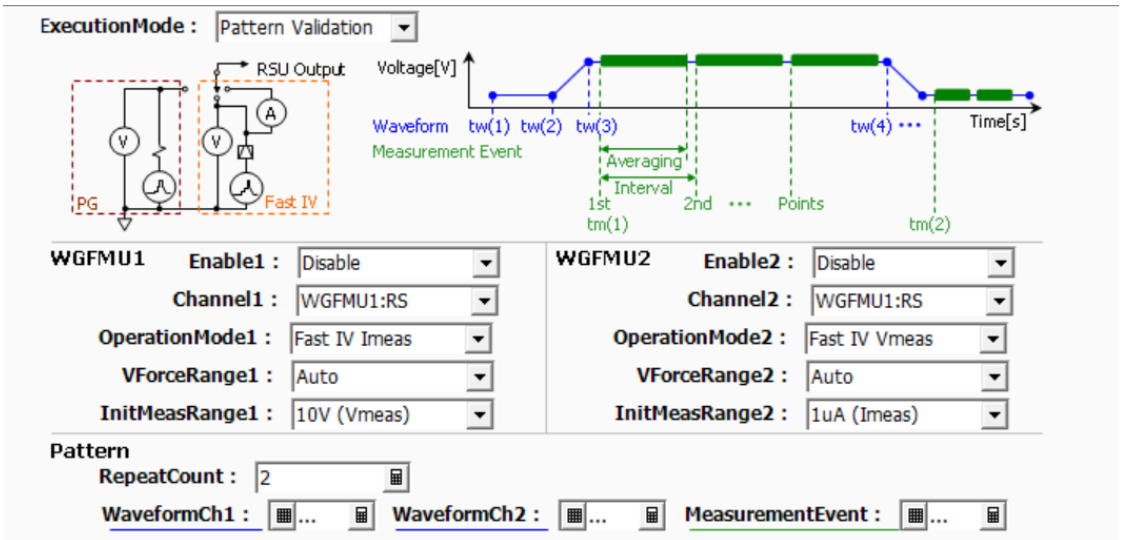
Fig.3 Example Cumulative distribution plot

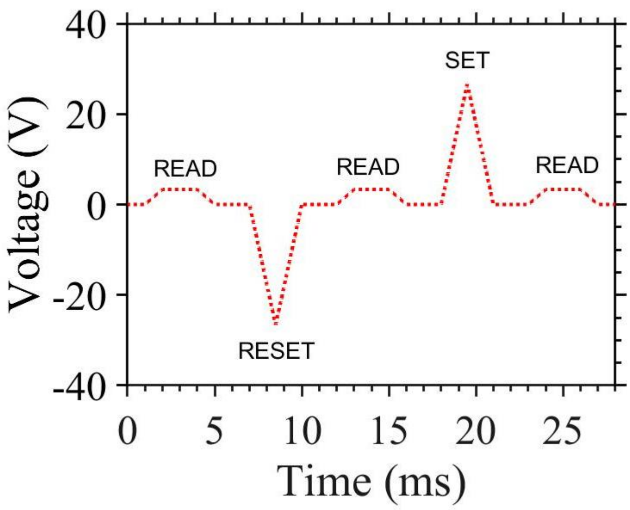
Pulsed measurements for ReRAM endurance:

1. Select the WGFMU (Waveform generator fast measurement unit) under category and recall WGFMU pattern editor. A WGFMU basically allows us to generate waveforms for pulsed measurements and do fast pulsing up to a programmable resolution of 10 ns.



2. Set up the probes so that input pulses are applied to the top electrode of the ReRAM. An example of the setup is given below which you can follow. Create the pulse train as shown in figure to perform the following operations in order: read,RESET,read,SET,read. While setting up the pulse train, the 1st column would correspond to time and the 2nd column to the voltage applied. The pulse train can be setup by clicking the button next to 'WaveformCh1,Ch2'.





3. Save the data after every 10 cycles and try to get an endurance of 100 cycles or until device failure.

Plots for the lab report:

1. Plot the measured current for the applied voltages.
2. Also plot the endurance upto 100 cycles or until device failure where you would plot the high resistance (HRS) and low resistance state (LRS) of the ReRAM.

Questions for the lab report:

1. Comment on why the READ pulses are significantly smaller than the WRITE pulses
2. What is the resistance window for the measured data? (Hint: Check READ current after set and reset)

3. Now equipped with the knowledge of how to characterize a ReRAM. Describe a way you would set up a measurement to show how a ReRAM could be used in neuromorphic computing assuming you have the same equipment as used in this lab. (It's more of an open question and there is no one correct answer to this. Be creative!)

Lab report

Summarizing what's needed for the report: The lab report should be written in a regular lab report format, i.e. contain the sections; **Introduction, Theory, Methods, Results and Discussion, Summary**. Put the most weight on the Theory and Discussion part and make sure to thoroughly and critically discuss all the results that you present. All figures should have figure captions and be correctly referenced in the text. Please write the report in English. Plagiarism is obviously prohibited and all reports will be checked via URKUND. Submit the report via Canvas before **10th May.**