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Energetic Behavior of Resistive Random-Access Memory Cells

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In order to investigate the switching characteristics of Resistive Random Access Memory cells (ReRAM) in terms of their thermodynamic free energy properties, we need to build a number of models that replicate the system. This report contains the models used to investigate filament growth patterns based on different boundary conditions applied to the electrode-filament system. Using Comsol Multiphysics software, we determined that when a fixed voltage is applied to each electrode in the electrode-filament system, we should expect filament dissolution that resets our cells into the High Resistance State (HRS). If we instead fix a set amount of charge on each electrode, we expect that filament growth will occur spontaneously, setting our cells into a Low Resistance State (LRS). This report also explores the balance between establishing a fixed voltage between the electrodes too quickly - where filament growth may not occur - while still optimizing the switching time of these cells with an applied voltage pulse.

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Energetic Behavior of Resistive Random-Access Memory Cells

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Abstract

In order to investigate the switching characteristics of Resistive Random Access Memory cells (ReRAM) in terms of their thermodynamic free energy properties, we need to build a number of models that replicate the system. This report contains the models used to investigate filament growth patterns based on different boundary conditions applied to the electrode-filament system. Using Comsol Multiphysics software, we determined that when a fixed voltage is applied to each electrode in the electrode-filament system, we expect filament dissolution that resets our cells into their High Resistance State (HRS). If we instead fix a set amount of charge on each electrode, we expect that filament growth will occur spontaneously, setting our cells into a Low Resistance State (LRS). This report also explores the balance between optimizing the switching time of these cells while ensuring that a fixed voltage is not established between electrodes too quickly, as this could inhibit filament growth.

I.   Introduction

The current generation of memory cells are approaching their physical limits. In order to keep increasing the density of memory cells, a number of groups are working to develop alternatives to traditional information storage. One of the front-runners in this search is Resistive Random-Access Memory (ReRAM). This particular type of memory cell is promising because it has a fast switching time, small size, simple scalability, CMOS compatibility, and it is nonvolatile - meaning that information is not lost when the cell is disconnected from its power source. Some have suggested that ReRAM could become a type of universal memory (Mellor 2013). A universal memory can function as flash, RAM, and a hard drive, simplifying how information is stored and accessed within a computer (Fink 2014). One of the challenges that lies ahead in moving this technology forward is investigating the switching mechanism between states of these cells. This paper will detail computational simulations that begin to probe the optimal switching conditions for these cells.

A ReRAM cell consists of metal oxides such as SiO_2 and TiO_2. When we apply a potential difference between two metals separated by a small gap, we create an electric field between the two electrodes. In certain metal oxide and solid electrolyte materials, the electric field produced in the metal oxide region causes either metal cations or oxygen vacancies to drift toward the opposite electrode, forming a conductive filament (see figures 1A, 1B). These cells are altered via a quick voltage pulse that creates or destroys the filament and can later be read by finding the resistance of the cell to a smaller amount of current that does not alter the conduction channel between the electrodes (Miao 2011). Cells that produce metal cations to form the

conducting filament are called Electrochemical Metallization (ECM) cells or

Conductive-Bridging Random-Access Memory (CBRAM) while cells that create filaments with

oxygen vacancies are called Valence Change Memory (VCM) cells. The conduction channel

created by the filament can be created or destroyed by applying a voltage pulse to set or reset the

cell into a Low Resistance State (LRS) or High Resistance State (HRS). With these two

programmable states, the cells are able to store bits of digital information. Because these cells are

altered by the amount and direction of current flowing through them, they are often referred to as

memristors, a predicted circuit element that changes resistance based on the history of current

that has traversed it (Lentz 2013).

The specific goal of my research was to investigate the expected switching behavior of

these cells based on global parameters such as charge and voltage, for the time ignoring local

phenomena like nucleation that also contribute to filament growth. To examine the energetic

properties of these cells, I created computer simulations to examine the effect that different

global parameters have on the total electric energy of the electrode system. The electric energy of

our capacitor-like system allows us to predict the behavior of the cell as the system will deform

into the most energetically favorable configuration possible. Using these simulations, we can get

a better understanding of the predicted filament growth or dissolution patterns inside the

conduction channel region.

II.   Methodology

In order to simulate the effect of global parameter changes on the total electric energy of

the memory cells, I used the simulation software COMSOL Multiphysics. COMSOL is a finite

element analysis software that allows the user to build geometric configurations and define the

material properties of the device they want to simulate. The user can then define the size of the individual elements that the model will be broken into in order to examine the physical effects that the simulation imposes on each of these elements. This analysis enables the user to examine how their device or tool should behave under the specified physical conditions. Of the many different physics packages available for COMSOL, I used the electrostatics package exclusively because, although the software is smart, it does not simulate the material deformities that take place in the conduction region of ReRAM cells. In order to manually simulate conduction channel growth, I incrementally changed the height of the filament in the model in order to simulate filament growth and then found the total electric energy of the cell at each of the different filament heights.

To test the expected filament growth pattern of the ReRAM cells, I first built a fixed charge and a fixed voltage model to get accustomed to the software and make sure that the basic energetic predictions were correct. After building these simpler models, I created a 2-dimensional embedded circuit model to test the predicted filament growth patterns of ReRAM cells in a setting more closely resembling how they would function inside of a computer. To do this, I placed the cells into the virtual circuit shown in figure 4A. I then attached the cell, represented by capacitor C2 in the circuit, to an RC circuit with a known characteristic RC time. In order to simulate the effect of different voltage pulse speeds that can be applied to the cell, I tracked the total electric energy of the cell as a function of filament height for each moment in time as more charge flowed through the circuit and began to saturate the cell. We can then search for a tipping point where the total energy changes from decreasing with increased filament height to increasing with increased filament height.

III.   Results and Discussion

In order to get a feel for the software and make sure that everything was working, I started my research by attempting to build a fixed charge model of a ReRAM cell. Using the electrostatic COMSOL package, I incrementally increased the height of a cylindrical filament between two capacitor plates, partially bridging the gap between electrodes (figure 2A). In a capacitor with a fixed amount of charge, we would expect the energy stored to behave according to equation 1 where Q is the amount of charge stored on the capacitor and C is the capacitance:

$$E = Q^2/2C \tag{1}$$

An increase in the height of the filament increases the capacitance so in the case where there is a fixed amount of charge on each plate of the capacitor, we expect that an increase in capacitance will decrease the amount of total electric energy of the system. Our predictions for this model were correct as increased filament height decreases the total energy of the cell (figure 2B). Due to the decreasing trend in the cell's energy, we would expect that a filament will grow spontaneously between electrodes in an electrochemically active ReRAM cell when there is a fixed amount of charge on each of the electrodes of the cell. The presence of the filament would set the cell into a LRS that can then be read with a smaller amount of current.

After building the fixed charge model, I created a fixed voltage model of the same dimensions with the same incrementally increasing filament heights (figure 3A). Fixing the voltage between plates of a capacitor results in the capacitor behaving according to equation 2 where C is once again the capacitance and V is the voltage:

$$E = CV^2/2 \tag{2}$$

As can be seen in figures 3B, computational simulations matched our theoretical prediction that increased filament height increases the capacitance and therefore increases the energy stored in a capacitor. Due to the increase in total electric energy as a result of increased filament height, we do not expect to see spontaneous filament growth under fixed voltage conditions. Furthermore, if the cell is in the LRS when we establish a fixed voltage between electrodes, we would expect the filament to dissolve to reduce the total energy of the system, resetting the cell back to the HRS.

Having seen the results of the fixed charge and fixed voltage models, we next wanted to get insight into how these cells would behave as a part of an array of cells accessible by a computer. Placing our cell into the simulated circuit shown in figure 4A, we were able to find a tipping point where the cell transitions from fixed charge behavior into fixed voltage behavior. Although the specific energy and time step magnitudes are not representative of what we would see in a real cell (and I do not have data on the specific time steps), we can see that there is a balance between a short characteristic RC time where fixed voltage conditions occur more quickly and a longer RC time where we see more fixed charge-type behavior. Figure 4B is a graph representing electric energy as a function of filament height for different moments in time where varying amounts of charge have saturated our cell. We can determine from this graph that for our simulated system, the 7th of 20 time increments is the last moment in time where we would expect to see further spontaneous filament growth. A voltage pulse that saturates our cell past this saturation level will halt conduction channel growth and possibly begin to dissolve the forming filament. With more experimental observations and more exact modeling, we could find the fastest possible voltage pulse that could be applied to a ReRAM cell in order to ensure sufficient filament growth for switching between states.

IV.   Conclusions

These computational models show that global parameters play a key role in predicting filament growth patterns based on thermodynamic energetic trends. A fixed amount of charge on either side of the conduction channel of ReRAM cells should result in spontaneous filament growth while a fixed voltage difference should cause the dissolution of an existing filament. Integrating these cells into a circuit, we see that a voltage pulse that establishes a fixed voltage between electrodes too quickly will not cause sufficient filament growth to switch to the LRS so there is a compromise between switching speed and switching accuracy.

V.   Current Developments and Future Research

My mentor professor, Dr. Karpov of the University of Toledo, is working with Israeli and European colleagues to further connect the theory behind the switching mechanism of these cells with experimental observations and techniques. Dr. Karpov recently received a three year grant by Semiconductor Research Corporation to investigate these cells so it will be interesting to see what his team will be able to discover.

Some recent advances in memristor technology have brought these cells closer to the market. In 2010, nonprofit Chinese research and development organization Industrial Technology Research Institute (ITRI) demonstrated switching times of less than 0.3 ns, over ten times faster than Static RAM (SRAM), the fastest random-access memory widely used (Lee 2010). ITRI has also demonstrated that ReRAM is scalable below 30 nm and that the oxygen vacancies that allow filament growth can form in regions as small as 2 nm (Cen 2008).

A number of companies are pursuing commercial production of these cells (Rambus, Panasonic, and HP to name a few). HP CTO Martin Fink recently suggested that memristor

drives could be commercially available with a 100 TB capacity by 2018. Others were quick to temper expectations as to the ambitious timetable of these developments but in any case, it is a sign that this technology could play an important role in computers in the near future (Mellor 2013).

VI.   References

Cen, C.; Thiel, S.; Hammerl, G.; Schneider, C. W.; Andersen, K. E.; Hellberg, C. S.; Mannhart, J.; Levy, J. (2008). "Nanoscale control of an interfacial metal–insulator transition at room temperature". *Nature Materials* **7** (4): 298. doi:10.1038/nmat2136. PMID 18311143.

Fink, Martin. "HP Discover 2014 Barcelona Keynote see 12:11". *Youtube*. Hewlett Packard. Retrieved 4 December 2014.

H-Y. Lee et al., IEDM 2010.

Lentz, Florian, Bernd Roesgen, Vikas Rana, Dirk J. Wouters, and Rainer Waser. "Current Compliance-Dependent Nonlinearity in TiO_2 ReRAM." *IEEE Electron Device Letters* 34.8 (2013): 996-98. Web.

Mellor, Chris. "HP 100TB Memristor Drives by 2018 – If You're Lucky, Admits Tech Titan." *The Register*. Biting the Hand That Feeds IT, 1 Nov. 2013. Web. 13 Feb. 2016.

Miao, Feng, John Paul Strachan, J. Joshua Yang, Min-Xian Zhang, Ilan Goldfarb, Antonio C. Torrezan, Peter Eschbach, Ronald D. Kelley, Gilberto Medeiros-Ribeiro, and R. Stanley Williams. "Anatomy of a Nanoscale Conduction Channel Reveals the Mechanism of a High-Performance Memristor." *Advanced Materials* 23.47 (2011): 5633-640. Web. 3 Mar. 2016.
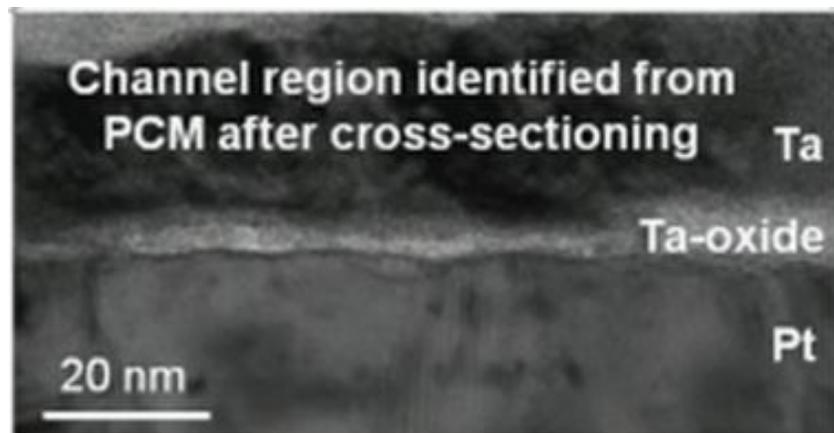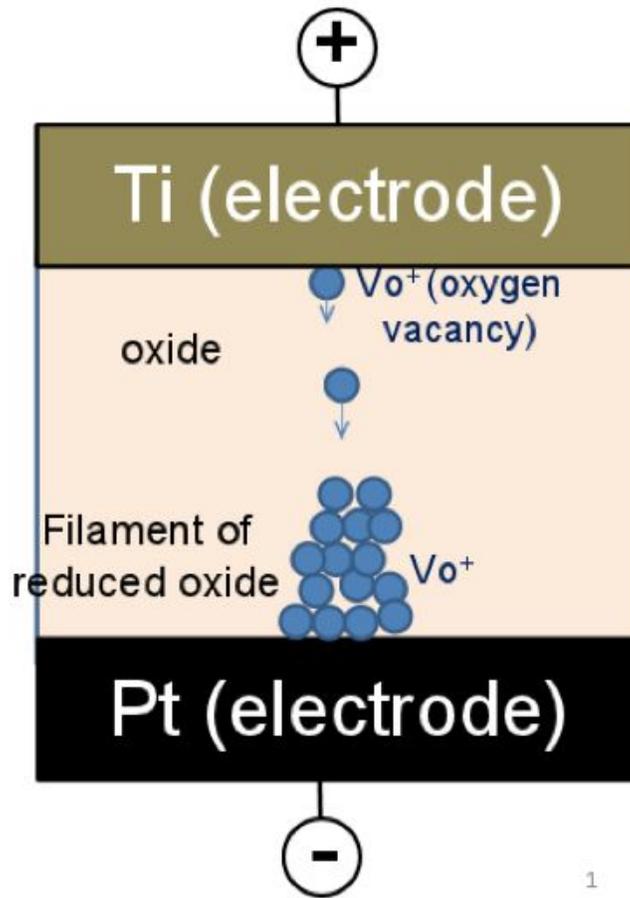
VII.   Figures

Figure 1A: Diagram of oxygen vacancies developing in the conduction channel of Titanium Oxide-based switch with approximate size estimates.

Figure 1B: TEM (Tunneling Electron Microscope) image of the conduction channel region (image from Miao 2011)
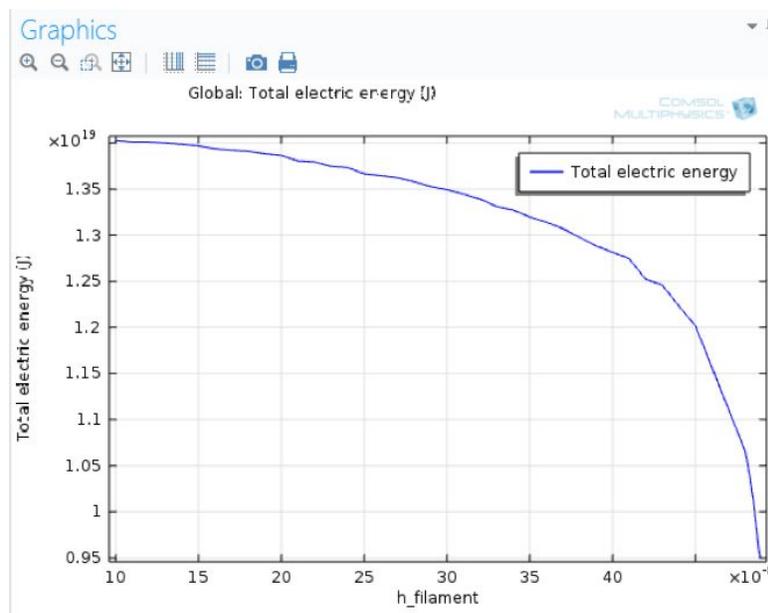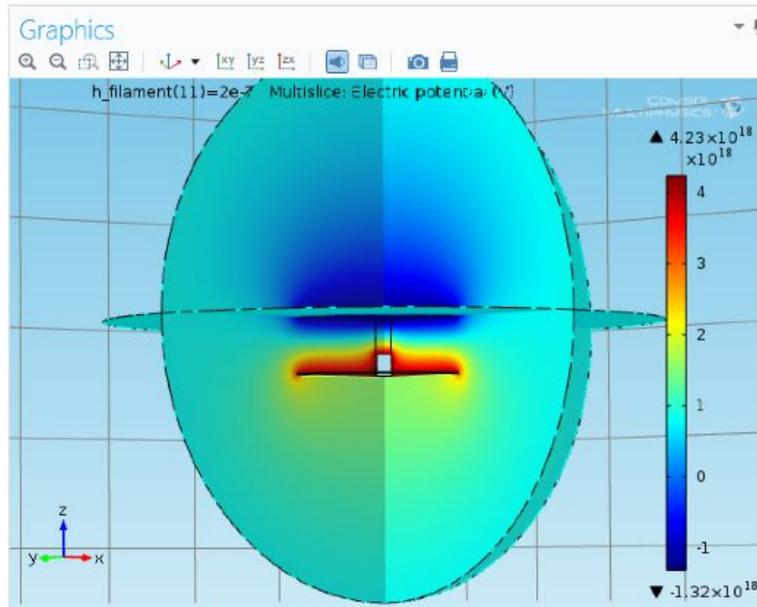
Figure 2A: 3-Dimensional graphical representation of the energy stored in the fixed charge model. The red region shows higher amounts of fixed charge while the blue represents lower amounts of fixed charge as determined by the scale at the right (you'll notice that I loaded these plates up with far too much charge but we're only looking at the trends for now).. The capacitor plates are covered by the charge distribution.

Figure 2B: Plot showing total electric energy as a function of filament height for the fixed charge model. Filament height is given in nanometers and energy is given in Joules.
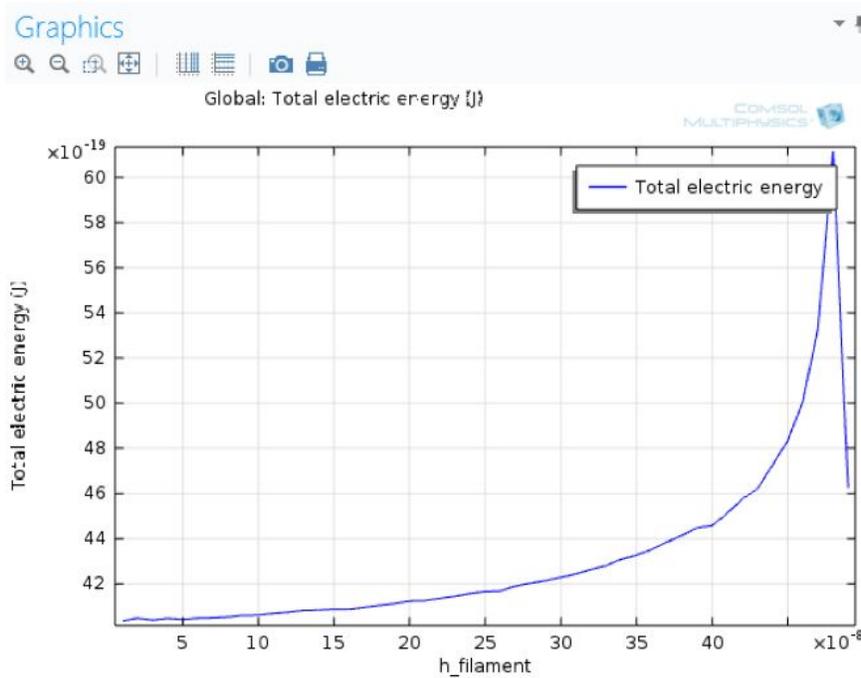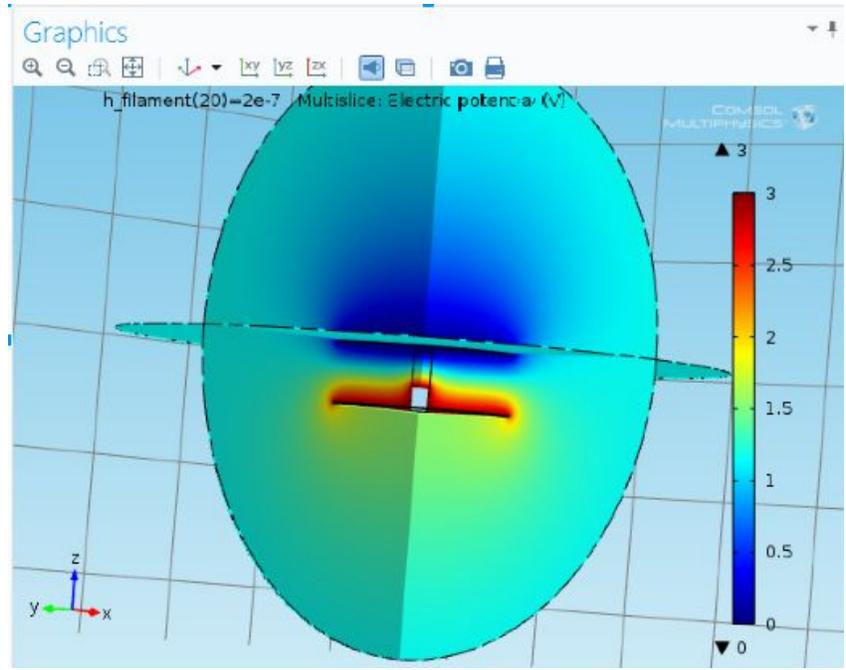
Figure 3A: 3-Dimensional graphical representation of the energy stored in the fixed voltage model. The red region shows higher positive voltage while the blue represents lower voltage as given by the scale to the right. The capacitor plates are mostly hidden by the voltage distribution.

Figure 3B: Plot showing total electric energy as a function of filament height for the fixed voltage model. The final dip in energy results from the filament completely connecting the conduction channel and is not representative of what would happen in a real filament.
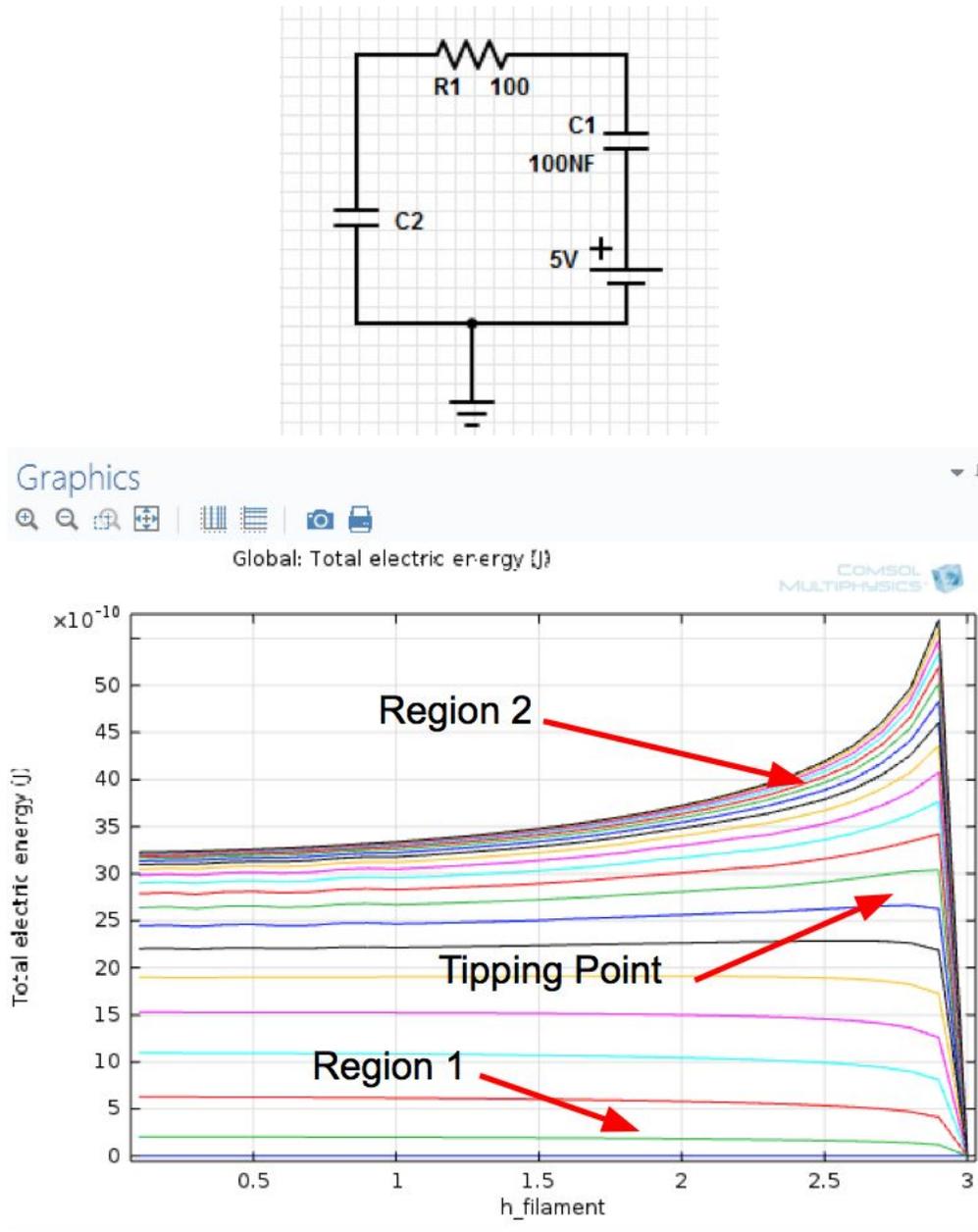
Figure 4A: ReRAM cell integrated into a circuit. The ReRAM cell is represented by capacitor C2.

Figure 4B: Plot of total electric energy as a function of filament height with each line representing a different moment of time where more charge has saturated the electrodes of the ReRAM cell. We would expect to see filament growth in the conduction channel in region 1 while we would expect filament dissolution in region 2. There is a tipping point somewhere in between. Time steps increase from bottom to top as the capacitor becomes more saturated.