Memristors, a nonvolatile memory device and alternative to transistors, were theorized by Leon Chua in 1971. They serve as a solution to the increasing demand in power efficiency and performance in neuromorphic computing. As of now, there is a bottleneck in performance for transistors as they do not model the synaptic activity inside the brain as ideally as they could. Memristors are currently in early stages of development and cannot be integrated into products on a commercial scale. The technology behind them, however, is promising in that it is a low-power non-volatile memory device.

Memristors work using a thin metal - metal oxide film that can vary its resistance based on the total oxygen vacancies. One can vary the resistance by applying a current in the forward or reverse direction, and the oxygen vacancies serve as charge carriers. With such functionality, the oxygen depleted layer will have a lower resistance than the oxygen rich layer. The device can provide simple ON and OFF states with the prior method as well as a gradient of values (to display multiple bits). An equation to better describe the binary representation of memristor voltage values can be seen below.

\[
\frac{V}{R} = \frac{R_{\text{on}}}{W} + \frac{R_{\text{off}}}{D}
\]

The two variables coupled with the "on" and "off" resistance values are the width of the oxygen rich region and the diameter of the entire device. Following this equation, the "on resistance" is reached at w>D and the "off resistance" would be reached at w=0.

The memristor device built in this project is the same structure found in the paper by Kumar et al [1]. A Hafnium-hafnium oxide base with a 50 and 150 Å layer, respectively. With these structure layers, the active range for the memristor is with -2 and 2 volts. The behavior seen in the paper can be seen below, and the goal is to observe whether the same results can be obtained.

### Methodology

**During training**, we learned in detail how to operate the evaporator, Filmetrics Spectrometer, and Mercury Probe. For example, in the case of the evaporator we learned about key terms associated with its operation such as the scale factor, z-ratio, density, STM/2 software, cooling chamber, pressure control, current inflow and most importantly how to operate the machine.

Afterwards, our first practice wafer was fabricated within the evaporator. Within this practice sample we used copper as a test run material to deposit onto the silicon wafer surface through the process of evaporation. The goal was to deposit approximately 200Å of copper onto the silicon surface which was somewhat achieved as the Filmetrics software yielded results that were constantly changing but were still in reasonable range within each other. The average reading on the Filmetrics software was approximately 204.5Å. Afterwards, this process of depositing test run materials onto a silicon wafer was repeated several more times so that we could ensure that the machinery was operating sufficiently before we proceeded to the main objective.

We then proceeded to deposit a single layer of hafnium oxide onto a silicon wafer to ensure that the hafnium oxide would correctly exhibit its electrical properties upon measurements with the mercury probe. After successfully melting the hafnium oxide sample within the evaporator we confirmed its electrical properties by running a voltage-current sweep on the mercury probe which is characterized by the figure below.

The same procedure for hafnium oxide was then executed but this time using pure hafnium as the deposited layer. The main objective of this was to again ensure that the evaporating hafnium yielded the appropriate results so that we could use our official memristor samples we had a high degree of confidence that each layer would be deposited correctly.

While Filmetrics would have helped to determine film thickness, it assumes a single uniform layer. Since the layer being deposited was non-uniform (and since there were 2 layers instead of 1), we concluded that the data produced was inaccurate. When layers can be deposited more uniformly, however, using the spectrometer and determining film thickness will help in future projects and analysis.

### Analysis and Results

The next step in the procedure was to deposit 60 Å of hafnium oxide via the evaporator. Afterwards a waiting period was needed in order to allow the roughing pump pressure to step down. Once the pressure was normalized the second layer of 150Å of pure hafnium was able to be deposited through the evaporator once again. The first memristor wafer was then transferred over to the mercury probe where we conducted a variety of tests to confirm that the wafer sample displayed the appropriate electrical characteristics of a memristor such as hysteresis. To ensure that the data was correct, a second wafer was processed in the same manner.

The initial procedure was verifying that the machinery could properly evaporate hafnium and hafnium oxide layers, as well as accurately graphing the I-V characteristics via the mercury probe. After the verification process was a success, two memristor structure wafers were made with a 50Å hafnium oxide and 150Å hafnium film. Measurements were taken with incremental voltage ranges (-2 to 2V, -3 to 3V, -4 to 4V, and -5 to 5V), and a hysteresis curve was most visible in the -2 to 2V. This is in accordance with the paper by Kumar et al. [2] regarding voltage range, and a hysteresis behavior can be seen in the memristor structure wafers fabricated in the MPEL. This victory is promising since the memristor was built using machinery that is specialized for transistors; if CMOS machinery and companies can easily add memristor manufacturing into their plot line, then the future for memristor technology is very promising. Verifying such behavior “hands the baton” to SJSU faculty and future students who wish to experiment further with the novelty of memristor structures and technologies (beyond simply fabricating the device).

### Key References


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