Design of Mixed-Signal Circuit Board for RRAM (Resistive Random-Access Memory) Crossbar Testing

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Motivation

With increased use of artificial intelligence and machine learning, interest has grown in custom on-chip hardware implementations to accelerate these algorithms. An integral computation within these algorithms is dot-product multiplication, which, through the use of new memristor technology, can be executed faster and with higher power efficiency than traditional CMOS circuits.

Problem Statement

This project seeks to test the hypothesis that resistive random-access memory (RRAM) devices in a crossbar configuration can be used to implement operations such as vector-matrix-multiplication to accelerate the hardware implementation of machine learning algorithms.

Background

What is a memristor?

- A newly-utilized device that holds variable resistances based on input voltages.
- Unique I-V curve: Pinched Hysteresis Loop

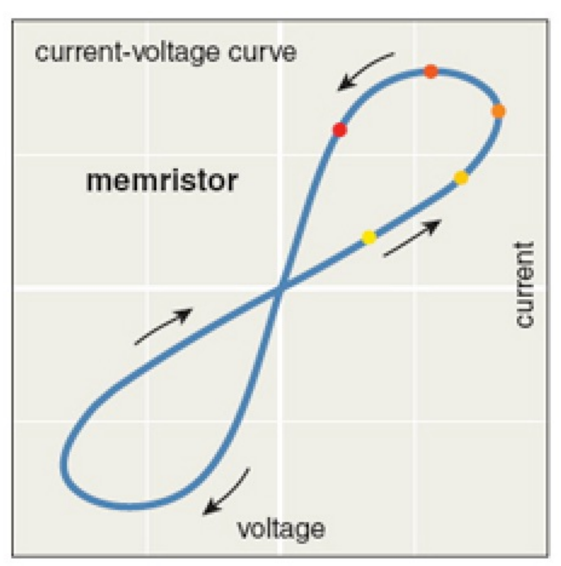

Figure 1. Memristor I-V Curve

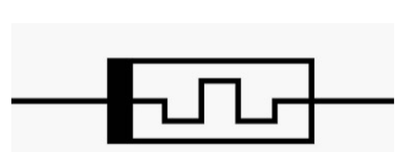

Figure 2. Memristor Circuit Symbol

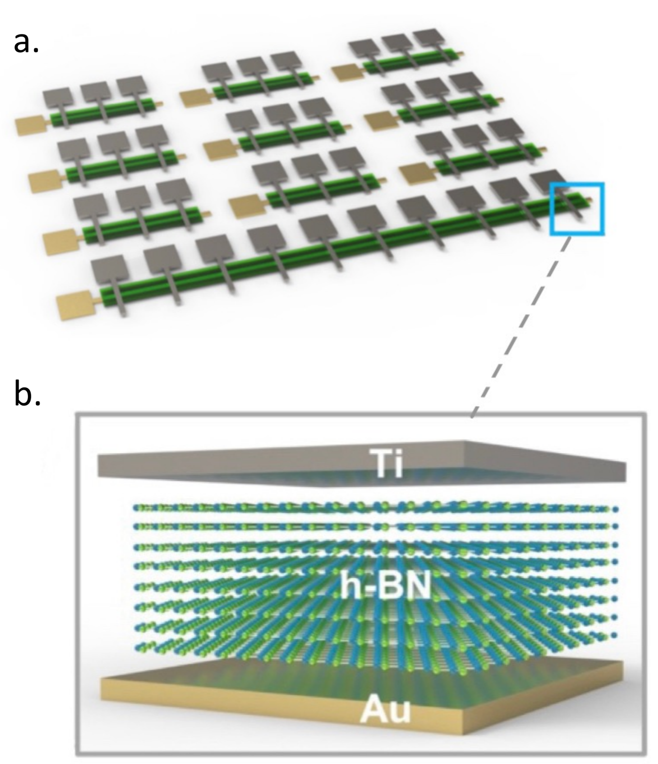

Figure 3. a. Memristor Crossbar Array
b. Cross-Sectional Schematic of Boron-Nitrite Devices Used

Methods

Compound Memristive Synapse:

Due to volatility in the fabricated devices, the dot-product computation was not feasible to compute, and thus a simpler demonstration was produced –the compound memristive synapse – which employs multiple bistable memristors in parallel to form one synapse. This can be computed by:

- **Pulsing positive voltages** on a device in high resistance state (HRS) to set to low resistance state (LRS)
- **Applying a small, non-conductance changing voltage** (ranging from -.2 V to .2 V) on the top electrodes
- Grounding the bottom electrode
- **Measuring total output current**
- **Repeat**, changing each memristor state from HRS to LRS iteratively

Hardware methodology:
The electrical characterization was conducted on a Cascade semi-automatic probe station using a Keithley 4200 semiconductor characterization system, and on a National Instruments (NI) PXI system. The DC I-V measurements were performed using source measure units (SMUs) with the Keithley system, and an Analog Output Device (AO) with the NI. The pulse programming experiments use a combination of pulse measure units (PMUs) for programming pulses and SMUs for reading currents, switching automatically using a Keithley remote amplifier/switch (4225-RPM).

Figure 4. Probe Station

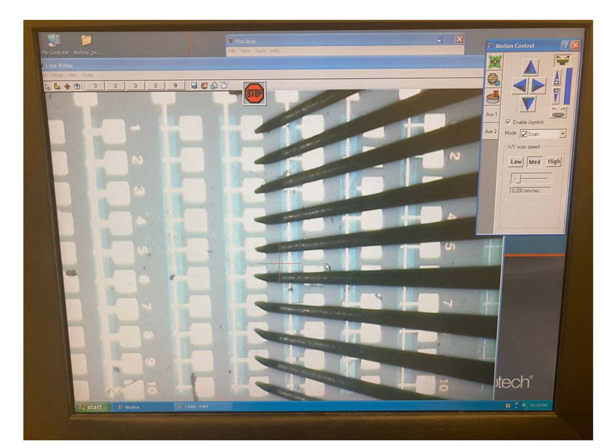

Figure 5. Probe Card on Wafer

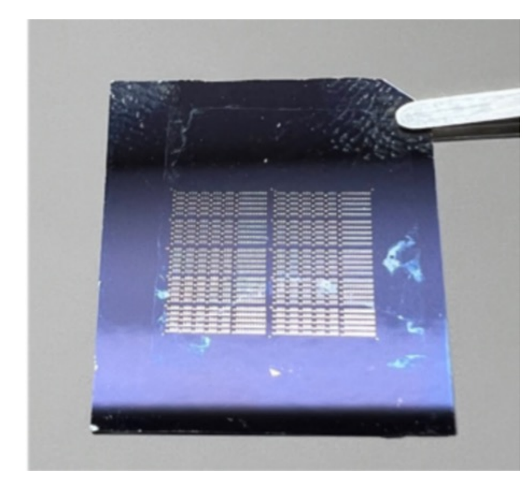

Figure 6. h-BN Memristor Array on Silicon Wafer

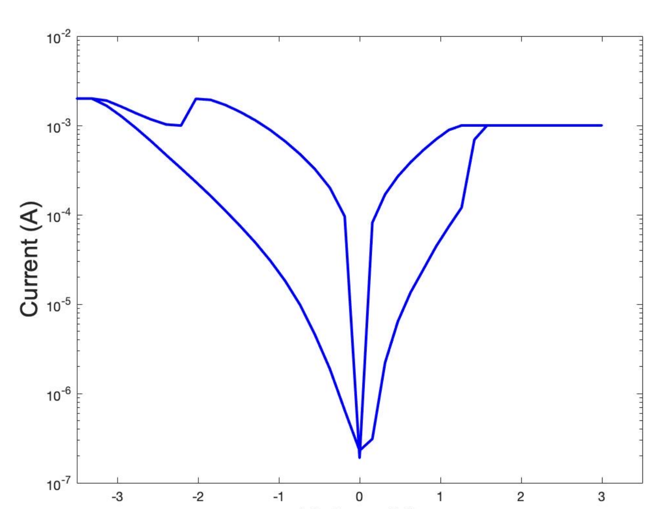

Figure 7. Measured DC Sweep of RRAM Device from -3.5 V to +3.5 V.

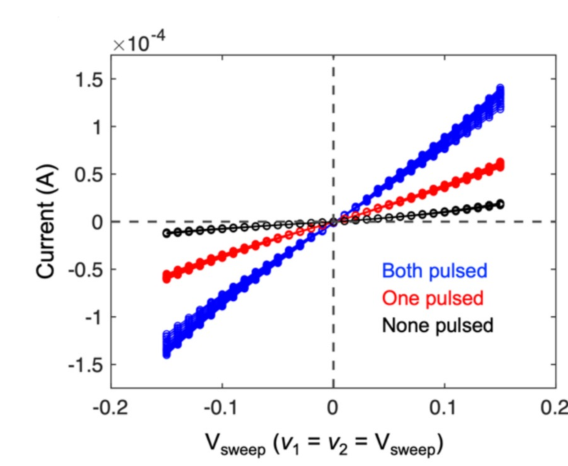

Figure 8. DC Sweep of two RRAM Devices from -1.5 V to +1.5 V. Linearity indicates non-changing conductance.

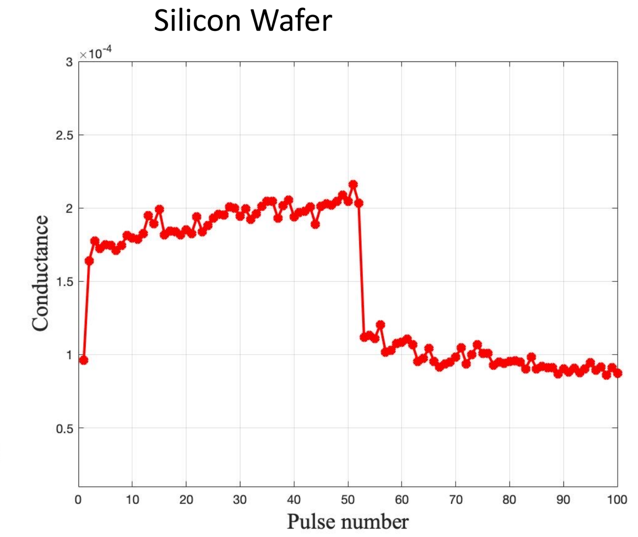

Figure 9. Average Conductance of RRAM Device After 5 Cycles. First 50 pulses: +.6 V. Second 50 pulses: -.72 V.

Results

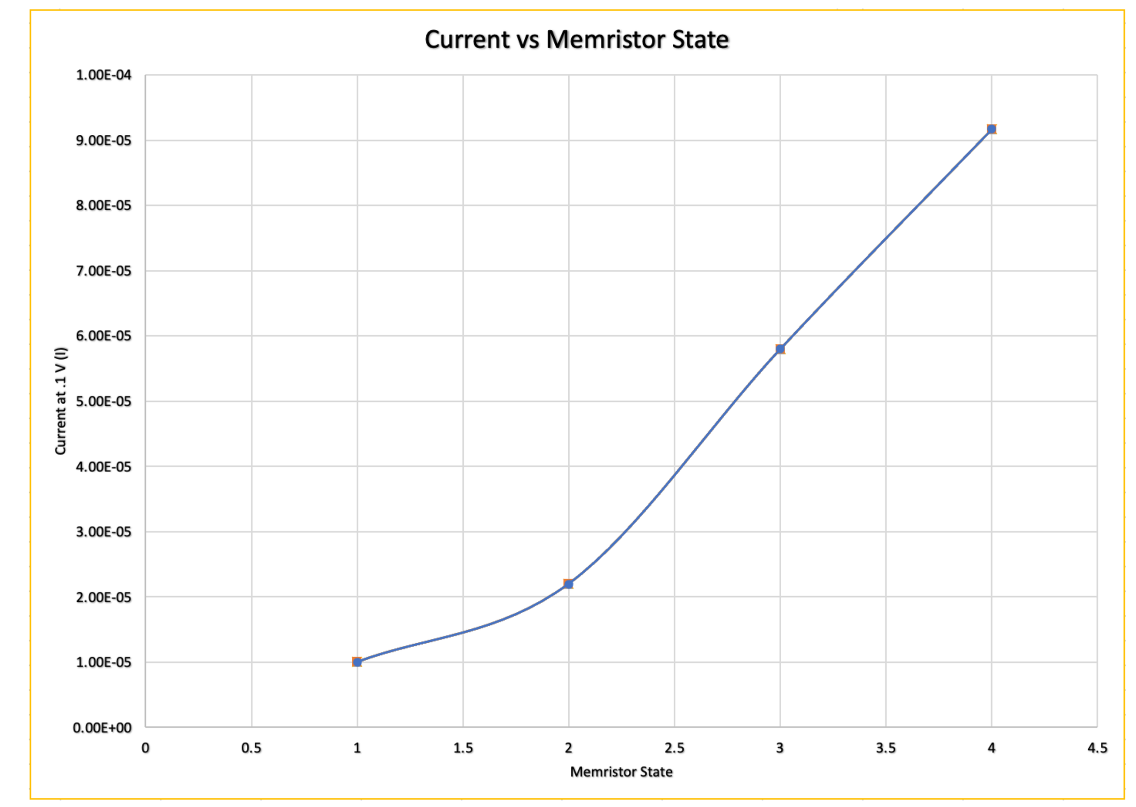

Figure 10. Current vs Memristor state of 3 RRAM devices in a row.

First state: All devices in HRS.
Second state: First device in LRS, rest in HRS.
Third state: Two devices in LRS, third in HRS.
Fourth state: All devices in LRS.

The linearity of this graph highlights the ability to utilize multiple RRAM devices as one reliable synapse for use in AI implementation.

Future Research

Future research can explore the hardware implementation of a linear regression model as seen by figure 11.a below if fabrication improves and devices are able to hold continuous conductances reliably. If not, a compound synapse can be used in place of a single device to train the same model.

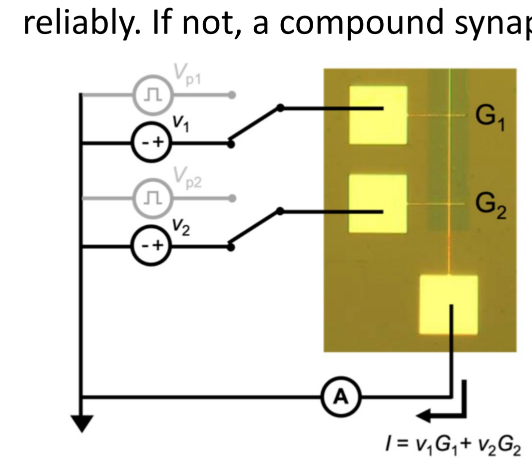

Figure 11. a. Schematic of memristor setup for dot-product operation.

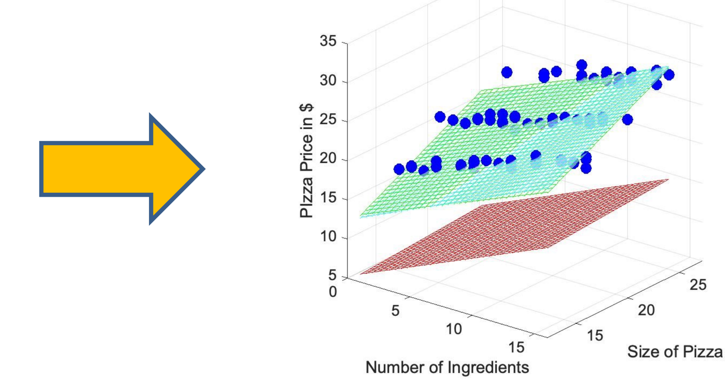

Figure 11. b. Model prediction fit to training data before training (red) and after (green).

Conclusion

Memristors are viable devices to use in dot-product multiplication, and thus pose as unique solutions to AI/ML acceleration. However, due to the volatility of the boron-nitrite (h-BN) devices, a simpler demonstration, the compound memristive synapse, was conducted to highlight the unique characteristics and possible implementations of RRAM devices.

Acknowledgements

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