Characterization of Synaptic Electronic Devices for Brain-Inspired Computing Systems

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Research Motivation

With increasing data, energy consumption, and the end of Moore's law nearing, neuromorphic circuits are now being researched as an alternative computing paradigm. As these circuits mimic the brain not only in computation schemes but also in architecture, energy-efficient and scalable neuromorphic devices, such as the hexagonal Boron Nitride (h-BN) memristor, are required to act as synapses to support cognitive computations. H-BN memristors offer the ability to be analog-based accelerators to make neuromorphic computing systems a reality.

This project seeks to address the research question: Are h-BN memristors promising candidates to implement brain-inspired computing devices and circuits? To answer this question, comprehensive electrical measurements of h-BN memristors will be taken to characterize the electrical properties of these devices.

Research Methods

Electrical characterization was conducted on a Cascade semi-automatic probe station using a Keithley 4200 semiconductor characterization system. The dc I-V measurements were performed using source measure units (SMUs), while the pulse programming experiments used a combination of pulse measure units (PMUs) for programming pulses and SMUs for reading currents. In the pulse programming experiments, we switch between PMUs and SMUs automatically using a Keithley remote amplifier/switch.

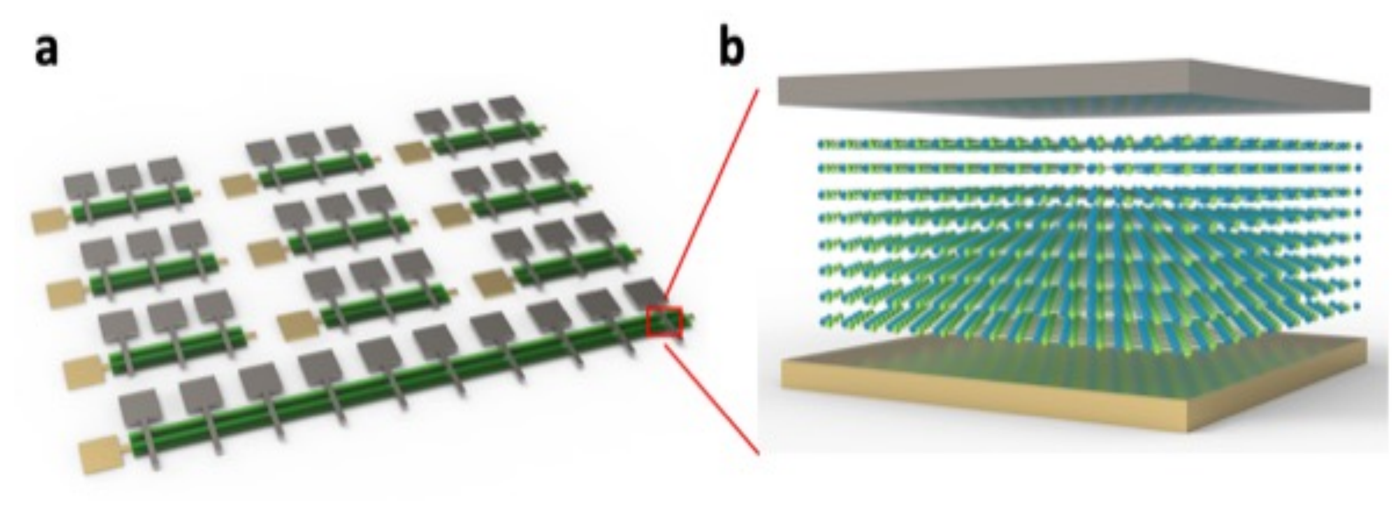

Figure 1: Image (a) shows h-BN memristors arranged in the 2D synaptic crossbar array design. Image (b) provides a cross-sectional schematic of a single h-BN

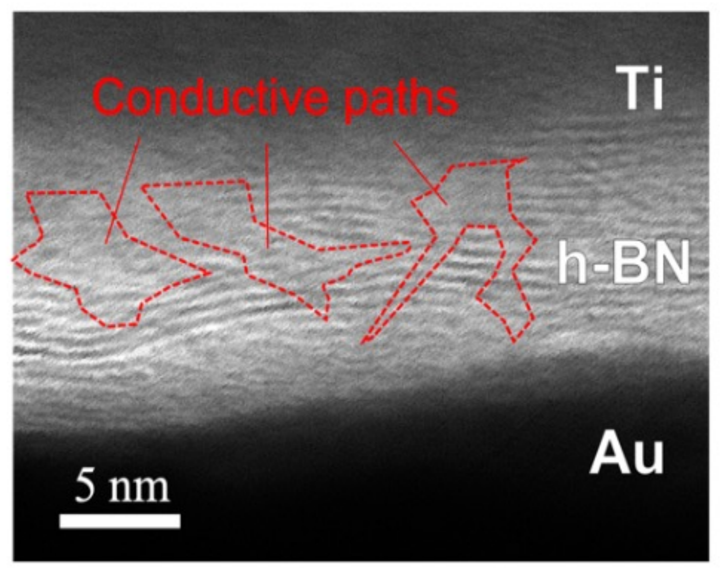

Figure 2: Cross-sectional TEM image of an Au/h-BN/Ti memristor indicating local defects responsible for the formation of conductive paths.

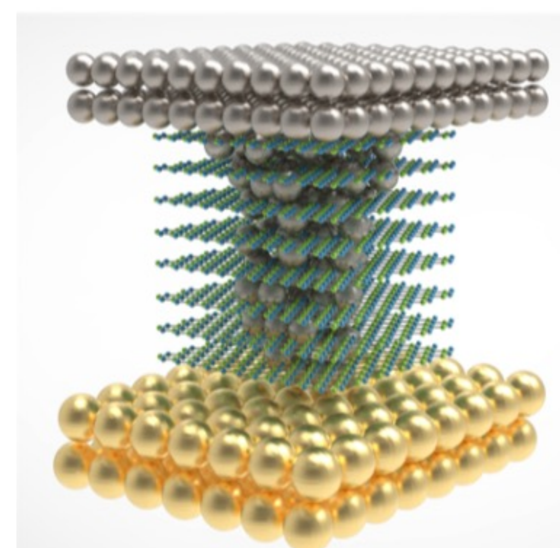

Figure 3: A representation of conductive nanofilaments in a h-BN memristor.

Memristors as Artificial Synapses

The human brain utilizes the synaptic plasticity in its neural network for learning and information processing. The term "plasticity" describes the change in conductivity, or the weight, of synapses caused by stimulation through external pulses, allowing for the exchange of information between neurons.

In parallel, h-BN memristors act as synapses of an artificial neural network, communicating information by changing their conductance, or synaptic weights, in response to electrical stimulation via voltage pulses. Like the synapses of a brain, the non-volatile nature of memristors allows them to retain memory of synaptic weight (resistance) changes.

As a result, by adjusting the stimulation pulse width and pulse amplitude applied, h-BN memristors can be used to successfully mimic various synaptic functions.

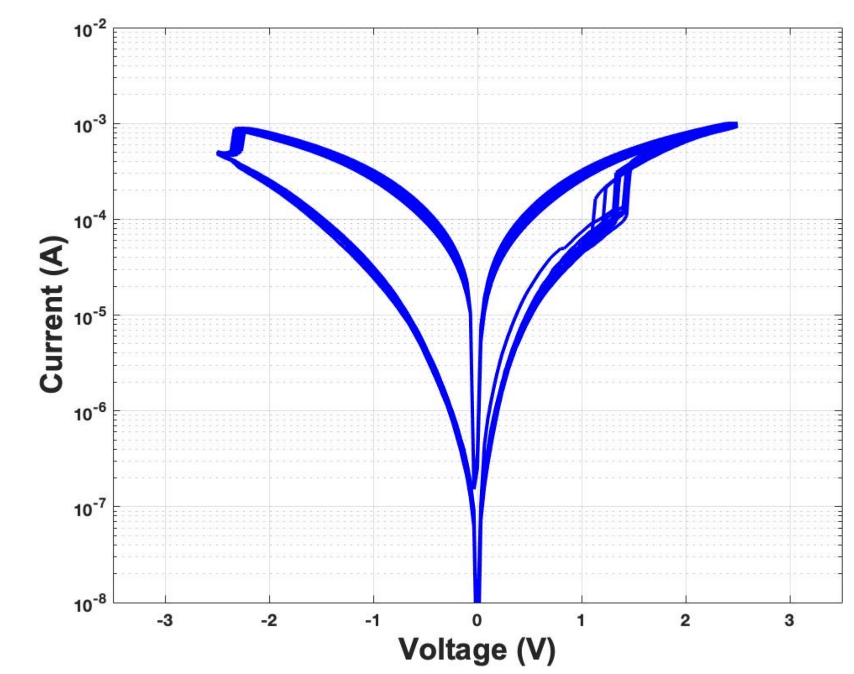

Figure 4: Dual sweep I-V curve measured during 10 cycles with 0.1 mA and 1 mA compliance, respectively.

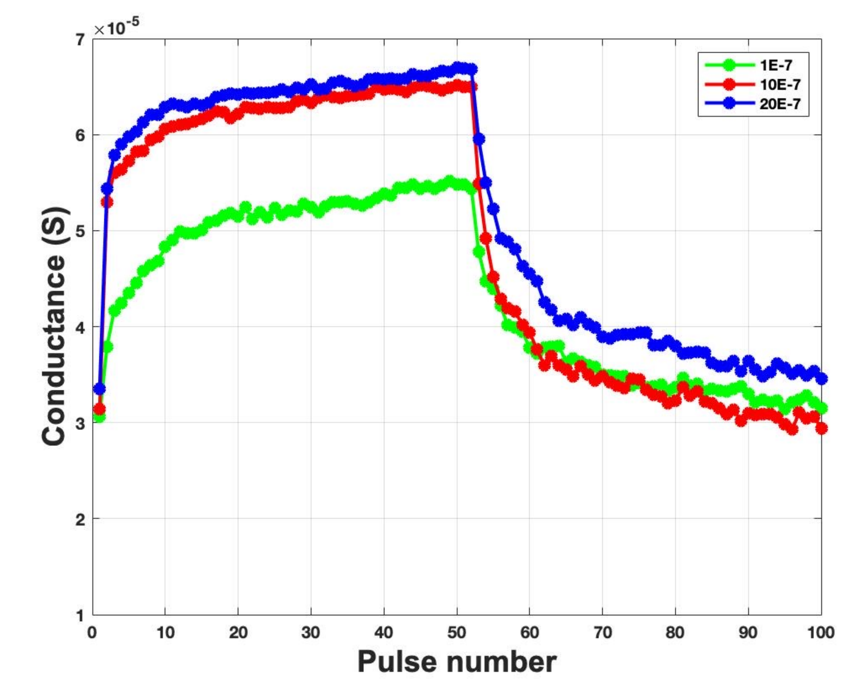

Figure 5: Each line represents the average of 5 cycles of pulsing programming (50 positive pulses followed by 50 negative pulses. Here, pulse width is varied.

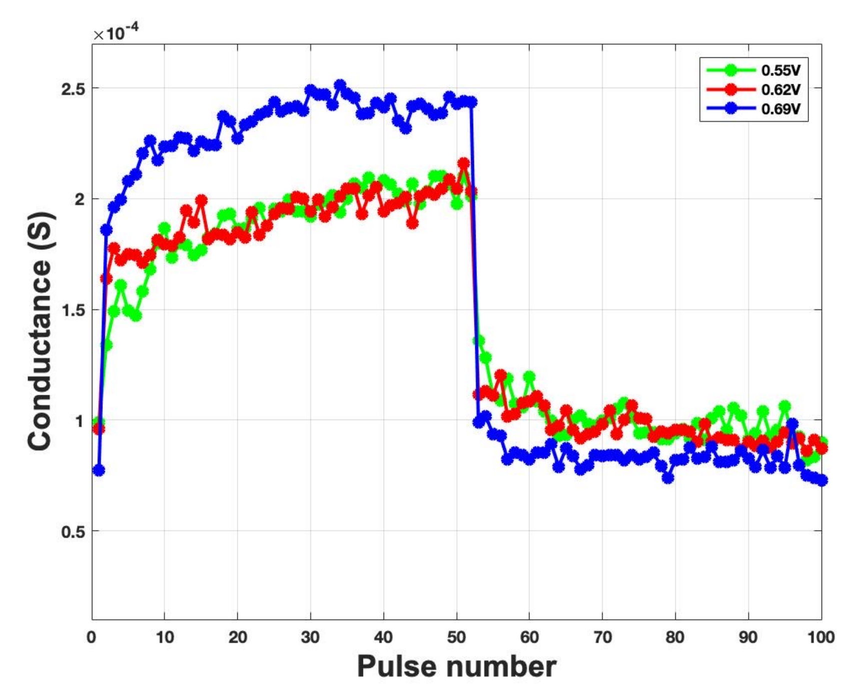

Figure 6: Each line represents the average of 5 cycles of pulsing programming (50 positive pulses followed by 50 negative pulses. Here, pulse amplitude is varied.

Memristor Characterization and Results

The h-BN memristors are two-terminal structures with a h-BN resistive switching layer nestled between the top and bottom metal electrodes. Generally, for testing, a high, positive voltage is applied to a h-BN memristor to drive the penetration of metallic titanium (Ti) ions from the top electrode into the switching layer to create a conductive nanofilament. Then, a negative voltage of the same or greater amplitude is applied to facilitate the dissolution of this filament by reversing the movement of the Ti atoms, leaving the device with low conductance.

In a dual sweep measurement, the current-voltage (I-V) characteristics of the device are obtained by sweeping the voltage across the top electrode and measuring the current passing through the device while grounding the bottom electrode. The dual sweep allows for a clear visualization of the memristor's switching behavior between high resistance state (HRS) and low resistance state (LRS). The width of the transitions between states indicates a wider range of potential states that can be programmed into a memristor. In a narrow hysteresis curve (I-V curve), the range of voltages to set states is more limited than if the curve was broad. Regardless, an observable transition between currents of at least three orders of magnitude in a dual sweep indicates a reliable binary resistive switching operation.

A pulsing measurement can be used to show the gradual change in a memristor's conductance. A sequence of positive followed by negative voltage pulses with varying amplitudes and widths are applied while current is measured using a small read voltage of 0.1 V. The smoothness and slope of the potentiation (gradual rise) and depression (gradual fall) of conductance indicates the analog programmability of the memristor. The conductance of a memristor can be increased by two methods: 1) increasing the pulse width, and 2) increasing the pulse amplitude. By changing one parameter and holding the other constant, the effects of pulse amplitude and width can be studied.

Pulsing measurements composed of five cycles of 50 positive pulses and 50 negative pulses for varying pulse widths show that an increase in pulse width of one order of magnitude, from 1E-7 s to 10E-7 s, affects conductance more significantly than an increase from 10E-7 s to 20E-7 s.

Similarly, increasing pulsing amplitude by a consistent increment can also increase conductance. After the lowest pulse amplitude for an acceptable pulsing I-V curve was identified, the positive pulse was increased in steps of 0.07 V, with the negative pulse adjusted accordingly. By changing the pulse amplitude by 0.07 V, the conductance also changed; however, less dramatically.

This project uniquely offers a comprehensive description of the multi-state programming of h-BN memristors using voltage pulses. The characterization and testing via pulse programming highlights the built-in neuromorphic properties of h-BN memristors.

FURI

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