Analyzing memcapacitive and memristive capabilities of lipid and polymer bilayers for use in smart materials

Megan Pitz, Colin Basham, Ryan Weiss, Joseph Najem, PhD, Andy Sarles, PhD

Tickle College of Engineering; Department of Mechanical, Aerospace, and Biomedical Engineering

Background

Neuromorphic engineering is the practice of creating software and hardware computing systems that mimic the connectivity and adaptivity of neurons and synapses in the brain. The goal of this approach is to enable computing technologies that are both reconfigurable and capable of co-located processing and memory, features that make the brain very efficient at computation. [2]

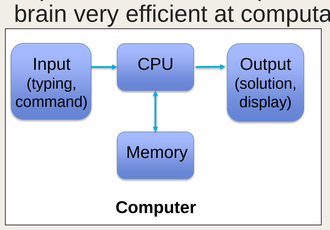
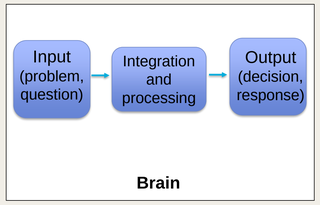
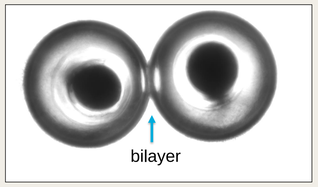


Figure 1: Memory and processing in a computer vs. in the brain. [1]



Artificial lipid and polymer bilayers are used as models to study cell membranes and neuron synapses.

Figure 2: Aqueous droplets hanging on electrodes in oil solution. Monolayers form around each droplet and are then connected to form a bilayer.



Bilayers can be modeled mathematically as a resistor and capacitor in parallel. Memory circuit elements combined with artificial bilayers are one way to solve the problem of collocated processing and memory. Memristors and memcapacitors are circuit elements with memory capabilities. These circuit elements are dependent on voltage, state variables, and time. [3]

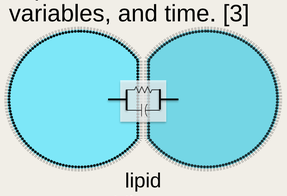


Figure 3: Schematic showing a bilayer modeled as a resistor and capacitor in parallel.

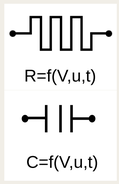


Figure 4: Memristor and memcapacitor symbols and defining functions.

Artificial bilayers with memory capabilities can also be used to mimic synapses during neuron firing. With voltage-dependent channel proteins included in the aqueous droplets, applied voltage allows ions to traverse droplets, as neurotransmitters cross synapses.

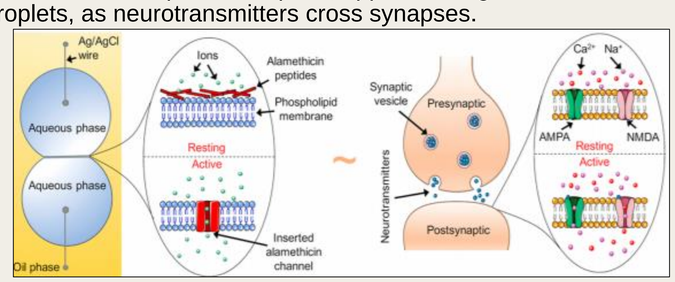


Figure 5: Voltage-dependent channel proteins in an artificial bilayer mimic synaptic behavior in a neuron. [4]

Research Gap

Our artificial bilayer model has been used to test static characteristics of lipid and polymer bilayers such as tension, resistance, and capacitance vs. area. However, artificial bilayers had not been used for dynamic measurements looking for memcapacitance. Solid manufactured memristors have been used in artificial neural networks before, but a biomolecular memristor is reconfigurable and flexible, and could have more applications.

Research Objectives:

1. Quantify memcapacitance for polymer bilayers in different oil mediums with input signals of varying amplitudes and frequencies.
2. Demonstrate the reconfigurability and adaptability of a neuron using a biomolecular memristor.

Testing Memcapacitance in Polymer Bilayers

Memcapacitance was measured using a non-adhesive bilayer formed from the tri-block copolymer PEO-PDMS-PEO. A sine wave voltage with triangle wave overlaid were run through the bilayer and the output current was recorded.

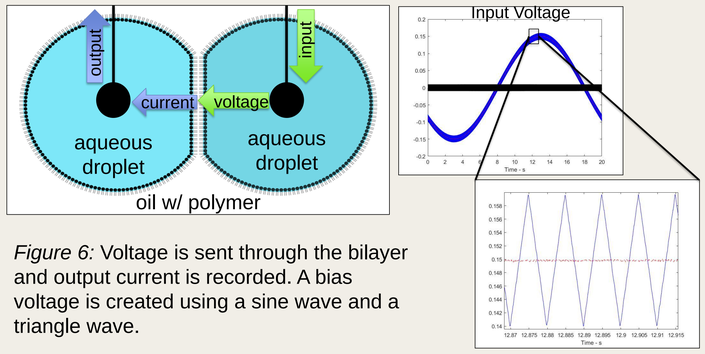


Figure 6: Voltage is sent through the bilayer and output current is recorded. A bias voltage is created using a sine wave and a triangle wave.

Bias voltage and charge were calculated using the input voltage and output current. Charge was calculated using bias voltage and measured capacitance.

$$V_{bias} = V_{total} - V_{triangle}$$

Sine wave voltage — Sine wave voltage + triangle wave voltage

$$Q = V_{bias} * C$$

Charge — Measured capacitance

Using a Biomolecular Memristor as a Neuron Synapse

Adhesive bilayers with the protein alamethicin were used to create a voltage-dependent gated membrane. Voltage pulses were sent through the membrane and the resulting current was amplified and converted to a voltage using a gain stage circuit before being sent through a solid-state neuron circuit.

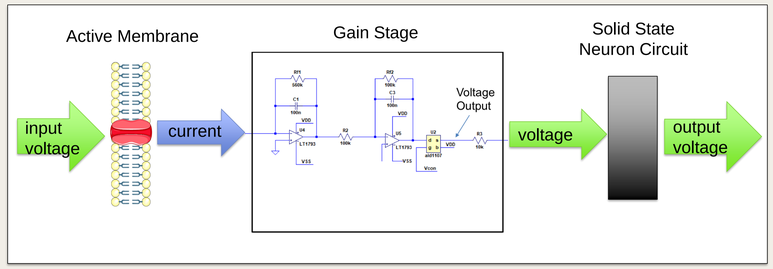


Figure 7: Schematic showing how voltage through a gated membrane is used to power a solid state neuron.

The solid-state neuron circuit accumulates voltage until it reaches a set threshold voltage. When the threshold is reached, another voltage spike is created, indicating neuron firing.

Discussion and Conclusion

Output current was recorded and processed in MATLAB.

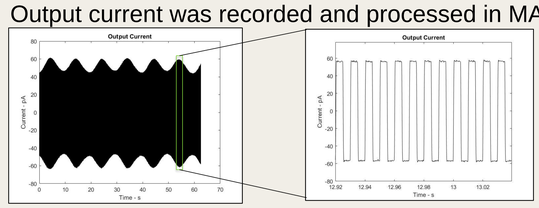


Figure 8: Raw output current for a sine wave input of amplitude 150mV and frequency 0.05Hz.

Decane and hexadecane oils were used to test for memcapacitance in a PEO-PDMS-PEO bilayer. The charge vs. voltage plots for both oils showed clear hysteretic curves, indicating memcapacitance. For identical input conditions, an increased area in the QV curve is apparent on the decane curve.

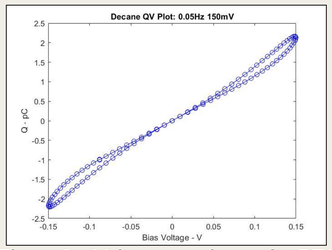


Figure 9a: Voltage vs. charge for PEO-PDMS-PEO in decane at an amplitude of 150 mV and an input frequency of 0.05 Hz.

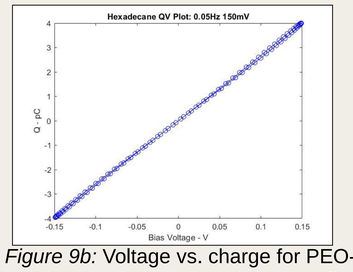


Figure 9b: Voltage vs. charge for PEO-PDMS-PEO in hexadecane at an amplitude of 150mV and an input frequency of 0.05 Hz.

Analysis of QV curves at varying frequencies showed a “sweet spot” at a frequency of 0.05Hz. Comparing amplitudes indicates a correlation between increased amplitude and increased area in the QV curve.

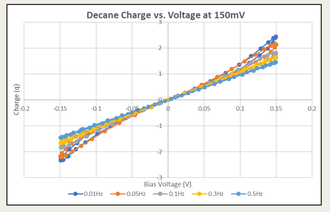


Figure 10a: Voltage vs. charge for a PEO-PDMS-PEO bilayer in decane with an input amplitude of 150mV.

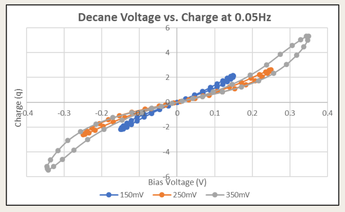


Figure 10b: Voltage vs. charge for a PEO-PDMS-PEO bilayer in decane with an input frequency of 0.05Hz.

The alamethicin voltage-gated bilayer was tested in hexadecane with varying gap lengths between pulses.

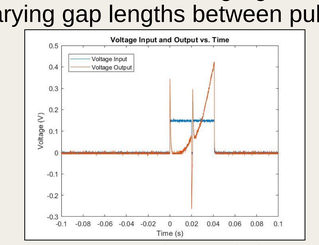


Figure 11a: Input pulses and alamethicin insertion for 20ms pulse and 1ms gap.

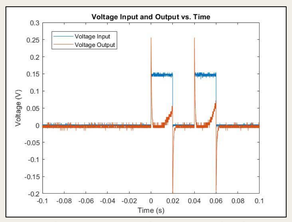


Figure 11b: Input pulses and alamethicin insertion for 20ms pulse and 20ms gap.

When there are larger gaps between pulses, the output voltage is less likely to reach the threshold potential that will cause the neuron to fire.

Future Directions

The next step for characterizing memcapacitance is to define the state variables of the bilayer that cause changes in area of the QV curve. The next step in creating a biomolecular memristor-based neuron is to determine pulse and gap widths for ideal firing rate.

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Sources: [1] How Computers Work: The CPU and Memory. (n.d.). Retrieved April 09, 2018, from http://homepage.cs.uri.edu/faculty/wolfe/book/Readings/Reading04.htm [2] I., G., H., & K, T. (2011, September 14). Frontiers in Neuromorphic Engineering. Retrieved April 09, 2018, from https://www.frontiersin.org/articles/10.3389/fnins.2011.00118/full [3] L. Chua, "Memristor-The missing circuit element," in IEEE Transactions on Circuit Theory, vol. 18, no. 5, pp. 507-519, September 1971, doi: 10.1109/TCT.1971.1083337, http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1083337&isnumber=23413 [4] Memristive Ion Channel-Doped Biomembranes as Synaptic Mimics

Joseph S. Najem, Graham J. Taylor, Ryan J. Weiss, Md Sakib Hasan, Garrett Rose, Catherine D. Schuman, Alex Belianinov, C. Patrick Collier, and Stephen A. Sarles, ACS Nano Article ASAP, DOI: 10.1021/acsnano.8b01282