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SYNCHRONIZATION OF MEMRISTIVE NEURONAL OSCILLATORS

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Abstract. The article discusses a memristive neuromorphic system, which is comprised of two analog memristive neurons - Fitzhugh-Nagumo - connected via a memristive device with the composition Au/Zr/SiO_2/TiN/Ti/SiO_2/Si. This system mimics the biologically plausible dynamics of ion channels in neurons, as well as the interneuronal synaptic connections. It has been demonstrated that the memristive device exhibits synaptic plasticity when influenced by a signal from the presynaptic electrical neuron. Experimental results have shown forced synchronization modes with frequency ratios of 1:1, 2:1, N:1. The system described above effectively replicates the dynamics of synaptic connections in neural networks of the brain. From an applied perspective the adaptive properties of the memristor make it suitable for developing neurosensory devices.

Key words: memristor, neuron, synapse, synchronization, neuromorphic system.

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Introduction

Recent years have seen a variety of electronic models of neurons and neural networks proposed, which are successfully utilized for implementing neuromorphic interfaces and mimicking the structure and functions of biological neural networks in the brain [1,2]. To construct biologically plausible models, it is essential to consider the interaction between neurons, simulated using electronic elements. Such elements should be able to replicate key characteristics of biological synapses, including signal transmission and adaptive restructuring (plasticity) of connections, which underpin cognitive functions [3]. In this context, the memristor emerges as a favorable element for integration into electronic signal transmission and processing circuits in artificial neural networks [4,5].

One notable application of memristors is the creation of nonlinear oscillators [6-8]. Such models gather significant attention due to their potential in developing devices that emulate brain functions [9-11]. Unlike classical formal neurons and neural networks utilized in machine learning, pulse neural oscillators (spiking neurons) exhibit intrinsic nonlinear dynamics and can demonstrate nontrivial nonlinear effects in signal generation and transmission. Consequently, investigating the dynamic properties of such systems [12], particularly synchronization, is crucial. Synchronization of neural pulses, a specific form of dynamic interaction typified by the simultaneous activation of a group of neurons, is pivotal in various cognitive functions, including memory formation and information recognition.

Recent studies have showcased the high effectiveness of memristive systems in studying synaptic plasticity [13].

This work presents an experimental study on the adaptive behavior of a memristive device, along with connected memristive neuro-like generators [14], utilizing the memristive device as an artificial synapse to explore various synchronization modes.

Materials and method

The developed neuromorphic system includes an electronic memristive circuit of the FitzHugh-Nagumo (FHN) generator, a non-inverting voltage amplifier, a load resistor with a resistance value of 4.3 kΩ, and an energy-independent memristive device formed by a thin-film metal-oxide-metal structure – Au/Zr/SiO_2/TiN/Ti/SiO_2/Si.

Components: The analog memristive FitzHugh-Nagumo (FHN) neuron consists of four principal components:

- an oscillatory RL circuit,
- a voltage divider block,
- an amplifier block, and
- a nonlinearity block based on a laboratory energy-independent memristive device.

Detailed descriptions of the analog memristive FHN neuron [14] and energy-independent memristive devices can be found in reference literature [15,16]. The memristive FHN generator was designed and simulated using Micro-Cap software, with the layout implemented in "SPRINT LAYOUT" software. The generator exhibits key neuronal characteristics, such as excitability threshold and the ability to toggle between excitation and self-oscillation modes.

Operation overview: the memristive FHN neuron generates a neuron-like signal that affects the memristive device, initiating the process of oxidation-reduction properties within the filament of its dielectric layer. Adjustments to the resistance of the variable resistor allowed control over the amplitude of one of the devices to achieve forced synchronization between the two generators (Fig. 1).

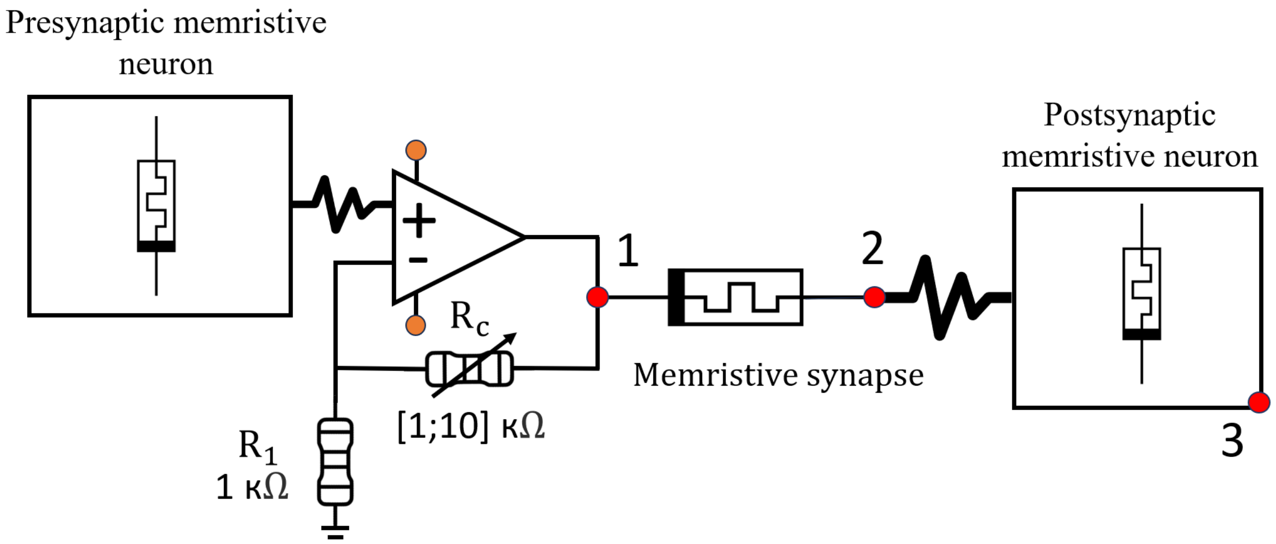

Fig. 1. Experimental flowchart depicting the interaction between a presynaptic memristive neuron and a postsynaptic memristive neuron through a memristive device. $Au/Zr/SiO_2/TiN/Ti/SiO_2/Si/grass$. R_c is the potentiometer indicating the coupling strength. In the presynaptic neuron, the nonlinear element was recreated using a structure $Au/Ta/ZrO_2(Y_2O_3)/Pt/Ti/glass$. The postsynaptic neuron used the structure $Au/Ru/ZrO_2(Y_2O_3)/Pt/Ti/glass$.

All experiments were performed using the C7-334 "AlphaTrek" oscilloscope. The switching characteristics of the memristive structure were measured at room temperature and normal atmospheric pressure using the Agilent B1500A semiconductor analyzer by Keysight at a scanning speed of 8 V/s. The signal amplitude produced by the presynaptic neuron varied in the range of 0.5 to 6.5 volts.

Results

During the experiment, we investigated how neuron-like signals with varying voltage amplitudes affect the switching parameters of a memristive device. This research is crucial for determining synchronization intervals for further analysis. To facilitate this, we connected the device to a signal generator as outlined in the circuit shown in Figure 1, at points 1 and 2. The signal from the generator was applied to the upper electrode (Au) of the memristive structure, while the signal from the lower electrode (Ti) was routed through a load resistor to the second channel of the oscilloscope. Simultaneously, the signal from the generator was displayed on the first channel of the oscilloscope.

We discovered that the amplitude of the output signal from the generator influences the ability of the memristive structure to switch from a high resistance state (HRS) to a low resistance state (LRS) and vice versa. The adaptive behavior of the device is a function of the changes in resistance, which depend on the parameters of the electrical stimulus (Fig. 2).

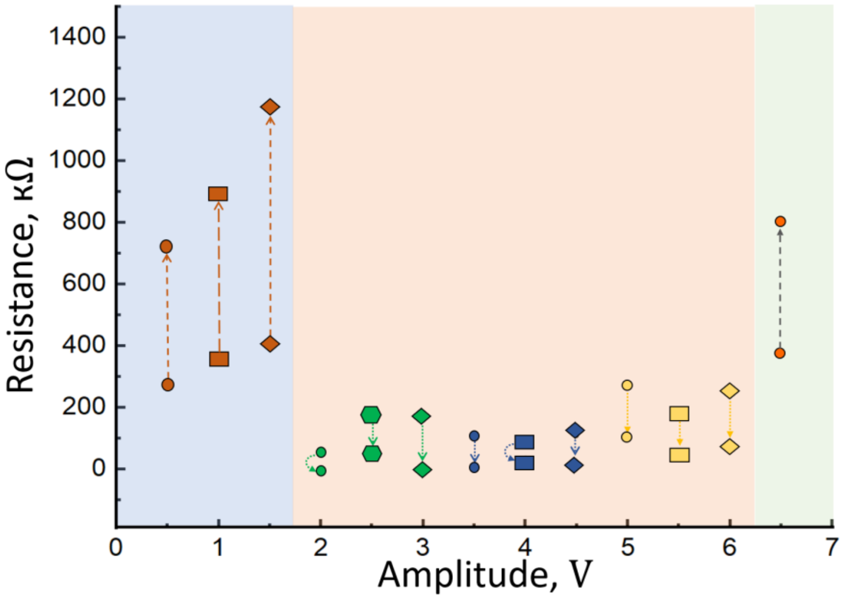

Fig. 2. The dependence of the resistance of the memristive device Au/Zr/SiO_2/TiN/Ti/SiO_2/Si on the output signal from the presynaptic neuron FHN. Each point represents a specific voltage level, while the arrows indicate changes in the device's resistance.

From Figure 2, we infer that varying the output signal amplitude within the range 0.5 to 1.8 V leads to the memristive device switching to a higher resistance state. This is attributed to the insufficient voltage to facilitate switching within the device. A similar effect is observed when the output voltage amplitude exceeds 6 V, causing the structure to transition to an extreme resistance state and become unresponsive to each spike. In scenarios where the voltage is too low (below 1.8 V) or too high (above 6 V), the conducting channels in the oxide layer remain intact, thereby preventing the device from switching.

Increasing the signal amplitude from 2 to 5.5 V causes the device to transition from a high-resistance state (220 kΩ) to a low-resistance state (25 kΩ). It is important to note possible significant differences in the resistance values between the device's initial and final states due to the inherent stochastic nature of the switching process.

The transition to a less conductive state of the memristive device with a SiO_2 oxide film is characterized by the disruption of Si-O-Si bonds under the influence of an electric field, accompanied by the formation of neutral oxygen vacancies. The migration of charged interstitial oxygen ions facilitates the oxidation and reduction of conducting filaments [15].

The experimental results confirm the adaptive behavior of the memristive device with the structure Au/Zr/SiO_2/TiN/Ti/SiO_2/Si, while the connection of memristive generators aims to emulate the property of plasticity.

After performing the electroforming process on the memristive structures and calibrating the generators, we conducted a study on their behavior within an electronic synapse, employing memristive devices Au/Zr/SiO_2/TiN/Ti/SiO_2/Si (Fig.3). The experiment followed the scheme shown in Figure 1, with oscilloscope readings taken from points 1 and 3. Initially, the first FHN neuron was set to autonomous oscillation mode, while the second one was set to excitatory mode.

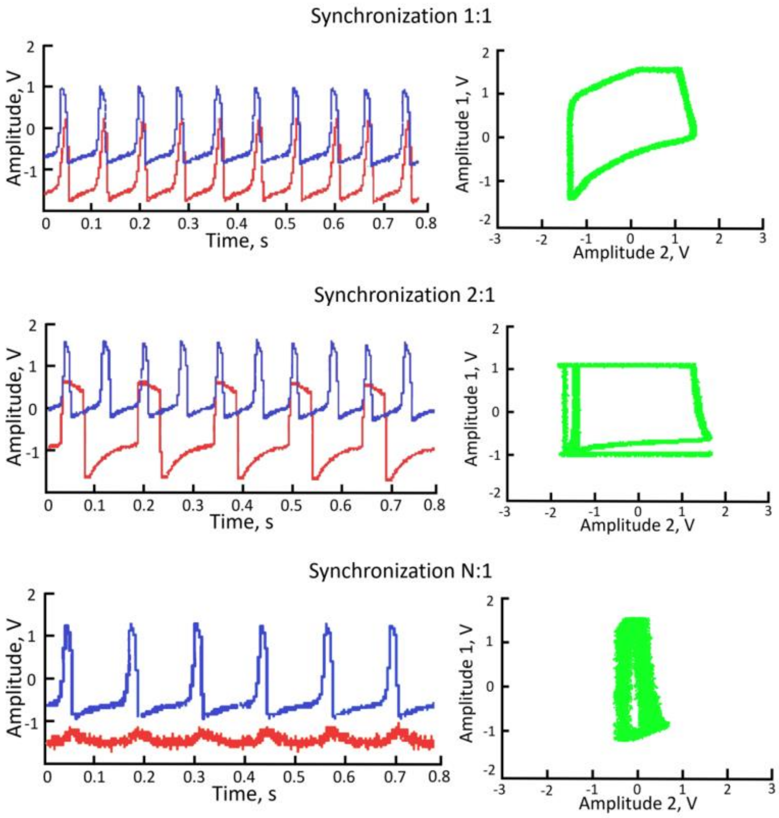

Fig. 3. Amplitude characteristics and their corresponding phase portraits for interacting generators through a memristive device Au/Zr/SiO_2/TiN/Ti/SiO_2/Si, with synchronization ratios 1:1, 2:1 and N:1. The amplitude of the postsynaptic neuron is shown in red, while the amplitude of the presynaptic neuron is shown in blue.

Conclusion

This study demonstrates the experimental application of a metal-oxide-metal thin film structure for investigating the phenomenon of synchronization. By integrating two FitzHugh-Nagumo memristive neurons using a memristive device Au/Zr/SiO_2/TiN/Ti/SiO_2/Si, we have developed a novel neuromorphic system and thoroughly analyzed its dynamic behavior. The system achieved various synchronization modes, including 1:1, 2:1, N:1, along with the phase trajectories of the system.

The relative compactness and high sensitivity of this system render it a highly promising tool for neurosensory devices that require high bandwidth [17].

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