Imitation of synaptic coupling of electronic neurons by memristive device

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Summary. The dynamics of two electronic neuron oscillators coupled via memristive device has been investigated. Such model mimics the interaction between synaptically coupled brain neurons with the memristive device imitating neuron axon. The synaptic connection is provided by the adaptive behaviour of memristive device that changes its resistance under the action of spike-like activity. It is shown experimentally that such connection gives rise to forced synchronization with 1:1 and 1:2 locking ratios.

Design of perspective neuromorphic compact devices (including micro- and nanochips) reproducing the functions of the brain is one of the perspective areas of modern science and technology. Such systems would permit to develop artificial neurochips-implants allowing for the impact on electroexcitability cells (nerve cells – neurons, heart muscle cells – cardiomyocytes) to manage their activity, as well as to replace the damaged nervous tissue.

The electronic circuits should reproduce all dynamical regimes of nerve pulse generation in single neurons. Synaptic coupling between the neurons is a crucial point for the network design providing reliable signal transmission. Moreover, the coupling strength can be variable depending on the ongoing neuron activity, what is called synaptic plasticity. One of the recent attempts to implement artificial synaptic coupling was the development of optically coupled electronic neurons based on photodiodes, light emitting diode and passive optical fiber [1]. The neurons coupled by such a synapse demonstrate complex response dynamics.

In this work, this approach is extended to the system of two electronic neurons coupled by memristive device (Fig. 1). Each neuron is implemented as a pulse signal generator based on the FitzHugh-Nagumo equations [2]. The change in resistance under the action of electric field (current) is a fundamental property of memristive device as an analog of memristor [3] and is equivalent to the change in coupling strength of pulse generators.

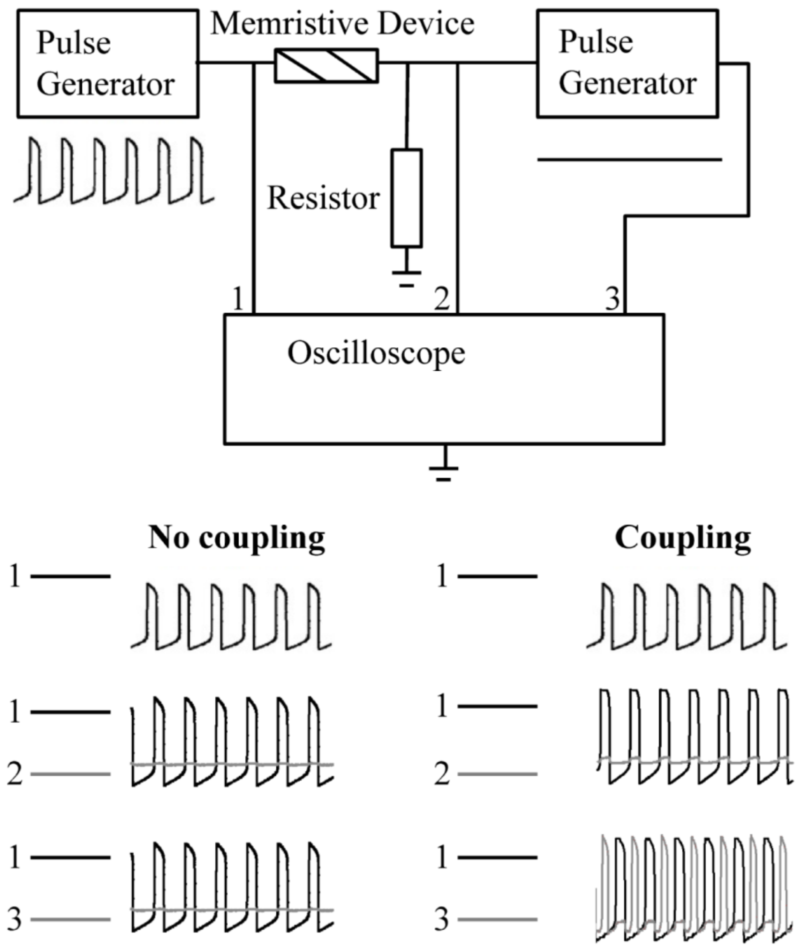

Fig. 1 The scheme of electronic neurons coupling via memristive device

This model provides a qualitative description of the main neurons' characteristics including excitable and self-oscillatory dynamics. The pulse generators' coupling is implemented by a CMOS-compatible memristive devices based on a 'metal-oxide-metal' nanostructure deposited by the methods of magnetron sputtering. A thin film of oxide (40 nm) is sandwiched between the bottom TiN/Ti (25/25 nm) and top Au (40 nm) electrodes. Two different kinds of oxides with dominating ionic or covalent bonding are used. Zirconium oxide is a typical ion conductor and possess a high mobility of oxygen vacancies, the concentration of which can be tuned by doping with stabilizing yttrium oxide. Silicon oxide is also intrinsic resistive switching material that seems to be the most compatible with the current technology. Memristive devices demonstrate the bipolar resistive switching behavior, and the resistive state is determined by the interplay between the reduction-oxidation processes in a system of conducting pathways (filaments) grown in oxide film. Due to the stochastic nature of filament rupture / recovery and the intrinsic asymmetry of the given phenomena, the considered memristive device can be considered as a multi-stable nonlinear system [4]. By applying complex periodic signal from the electronic neuron to the Au/ZrO_2(Y)/TiN/Ti or Au/SiO_2/TiN/Ti memristive devices, the adaptive behavior has been shown for both kinds of memristive nanostructures. The response to the pulse neuron-like activity is shown to depend on the kind of oxide used in the memristive nanostructure.

The coupling of electronic neurons is implemented by using the Au/ZrO_2(Y)/TiN/Ti memristive nanostructure characterized by the wider range of sensitivity to the amplitude of neuron-like signal. The output signal from the first pulse generator is applied to the input (upper electrode) of memristive device. The output signal from memristive device (from bottom electrode) is sent to the input of the second pulse generator. Such unidirectional signal transmission implements the functionality of the excitatory synaptic coupling. By increasing the amplitude of signal from the first electronic neuron, it is found that such memristive coupling can provide forced synchronization of the second electronic neuron. Synchronization regimes with frequency locking ratios 1:1, 1:2 are observed by varying the amplitude of the first neuron signal.

In conclusion, the model composed of two electronic neurons coupled by memristive device is realized. It is demonstrated that such memristive connection is functionally similar to the excitatory coupling between living neurons and can provide inter-neuron synchronization. The adaptive behaviour of memristive device can provide synaptic plasticity of this coupling, because the coupling strength can be variable depending on the ongoing activity of neuron-like generator (amplitude). Such neuromorphic models based on memristive interface can be applied in the design of neurohybrid systems consisting of living neurons and electronic control devices.

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References

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