SCIENCE CHINA
Information Sciences

• LETTER •

June 2018, Vol. 61 060427:1–060427:2
https://doi.org/10.1007/s11432-017-9348-3

Special Focus on Memristive Devices and Neuromorphic Computing

Excitatory and inhibitory actions of a memristor bridge synapse

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Received 27 September 2017/Revised 15 December 2017/Accepted 18 January 2018/Published online 10 April 2018

Citation Yang C J, Adhikari S P, Kim H S. Excitatory and inhibitory actions of a memristor bridge synapse. Sci China Inf Sci, 2018, 61(6): 060427, https://doi.org/10.1007/s11432-017-9348-3

Dear editor,

One of the bottlenecks of the analog circuit implementation of neural networks comes from the fact that the number of synapses to be implemented is huge. The important functions needed to be specified in a synapse are analog weighting (multiplication) and memory [1]. Large amount of silicon area is needed to build analog multipliers and analog memories using conventional CMOS technologies.

Memristor [2] is known as an ideal element in which both analog multiplication and analog memory functions are embedded. However, negative memristance (resistance of memristor) which is equivalent to negative weighting is not available. To resolve this problem, Kim et al. presented a memristor bridge synapse [1]. There are several desirable features in memristor bridge synapse. One of them is signed weighting. The feature comes from the co-operation of two different configurations of back-to-back memristor pairs. Also, linearity in programming is excellent due to the complimentary action of back-to-back connected memristors. Another desirable feature of the memristor bridge synapse-based neural networks is that processing speed of the memristor bridge synapse-based neural networks [3] is faster than that of OP amp-based counterpart since the bandwidths of OP amps are considerably limited.

Among the features discussed above, we investigated the source of the signing (+, −) operation of the memristor bridge synapse which was not known yet. Specifically, we uncovered that each set of back-to-back memristor pair of the memristor bridge synapse acts as an independent synapse and that the signing operation comes from the fact that one of sub-synapses of the memristor bridge synapse acts like an excitatory action and the other one does like an inhibitory action of a biological synapse.

Biological neural synapses. In biological neural networks, synaptic weightings and summations are performed in synaspes and cell bodies, respectively. In a cell body, there are two different types of gates for producing positive or negative pulses, namely excitatory or inhibitory gates. The negative weighting is built not by the use of negative weighting elements but by a negative pulse generated from an inhibitory gate at the cell body.

Suppose a cell makes two connections to the next cell after weighting by $W_{\rm ex}$ and $W_{\rm in}$ as in Figure 1(a). If they are summed via excitatory and inhibitory synapses, respectively, the excitatory gate produces a positive pulse while the inhibitory gate produces a negative one. Therefore, the output of neuron N2 is proportional to the sum of those two pulses with opposite polarities. Let outputs of N1 and N2 be $O_{\rm N1}$ and $O_{\rm N2}$, respectively. Then,

$$O_{\rm N2} = \lambda \left(W_{\rm ex} O_{\rm N1} + (-W_{\rm in} O_{\rm N1}) \right),$$

or

$$O_{\rm N2} = \lambda \left(W_{\rm ex} - W_{\rm in} \right) O_{\rm N1} = \lambda W_{\rm N1} O_{\rm N1}, \qquad (1)$$

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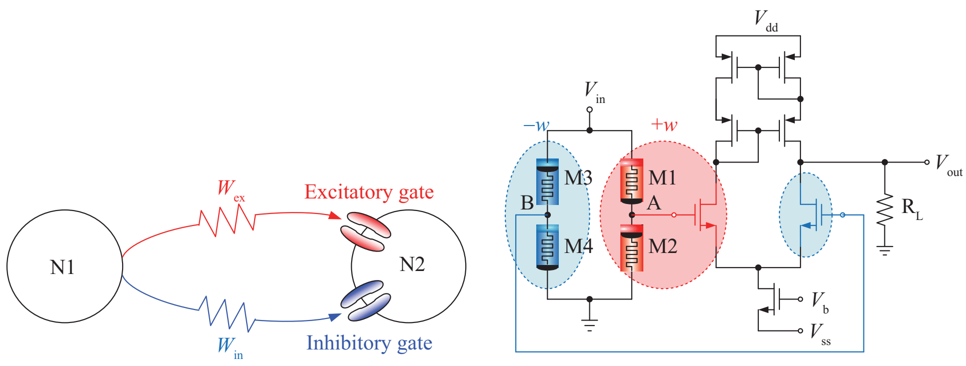

Figure 1 (Color online) An architectural comparison between biological neuron and memristor bridge synapse-based artificial neuron. (a) Biological neuron; (b) memristor bridge synapse-based artificial neuron.

where λ is coefficient. In (1), the sign of W_{N1} is

$$\begin{aligned}&\text{positive when } W_{\mathrm{ex}} > W_{\mathrm{in}},\\&\text{negative when } W_{\mathrm{ex}} < W_{\mathrm{in}},\\&\text{zero when } W_{\mathrm{ex}} = W_{\mathrm{in}}.\end{aligned} \tag{2}$$

The combined behavior of excitatory and inhibitory synapses becomes a signed synapse with +, − and zero sign. A biological cell achieves a signed weighting arbitrarily by adopting such an excitatory and inhibitory paradigm.

Excitatory and inhibitory actions with Memristor bridge Synapse. Figure 1(b) is an artificial neuron where a synapse and a cell body are built with a memristor bridge synapse circuit and an active load combined with a differential amplifier. The voltages at the two output terminals A and B of the memristor bridge synapse are

$$\begin{cases} v_{\mathrm{A}} = \dfrac{M_2}{M_1+M_2} v_{\mathrm{in}} = W_{\mathrm{A}} v_{\mathrm{in}},\\ v_{\mathrm{B}} = \dfrac{M_4}{M_3+M_4} v_{\mathrm{in}} = W_{\mathrm{B}} v_{\mathrm{in}},\end{cases} \tag{3}$$

where W_{A} and W_{B} are synaptic weights built with M1, M2 and M3, M4, respectively.

Voltages, v_{A} and v_{B} are obtained via multiplications between two weights and v_{in}, respectively. These two weights are concocted with two different types of back-to-back configurations. The weight values can be altered by programming the memristors. Both outputs of the memristor bridge synapses are applied to the input terminals of differential amplifiers. The voltage output of the differential amplifier in saturation mode is linearly proportional to the difference between two voltages, namely,

$$\begin{aligned} v_{\mathrm{out}} &= \mu\,(v_{\mathrm{A}} - v_{\mathrm{B}})\\ &= \mu\left(\frac{M_2}{M_1+M_2} - \frac{M_4}{M_3+M_4}\right) v_{\mathrm{in}}, \end{aligned} \tag{4}$$

or

$$v_{\mathrm{out}} = \mu\,(W_{\mathrm{A}} - W_{\mathrm{B}})\,v_{\mathrm{in}} = \mu W_T v_{\mathrm{in}}, \tag{5}$$

where $W_{\mathrm{ex}} = \frac{M_2}{M_1+M_2}$, $W_{\mathrm{in}} = \frac{M_4}{M_3+M_4}$ and W_T is a composite weight of this circuit. In (5), the back-to-back memristor pair of (M1, M2) performs a positive synaptic weighting while that of (M3, M4) performs a negative synaptic weighting. Thus, a memristor bridge synapse is composed of two opposite weighting circuits. Comparing between (1) and (5), it is clear that actions of memristor bridge synapse is equivalent to those of excitatory and an inhibitory synapses of a biological neuron, respectively.

Conclusion. In this article, we uncover that each set of back-to-back memristor pair of the memristor bridge synapse acts as an independent synapse and that the signing operation comes from the fact that one of sub-synapses of the memristor bridge synapse acts like an excitatory action and the other one does like an inhibitory action of a biological synapse.

Acknowledgements This work was supported in part by U.S. Air Force (Grant No. FA9550-13-1-0136), Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (Grant Nos. NRF-2016R1A2B4015514, NRF-2015H1D3A1062316) and Brain Korea 21 PLUS Project, National Research Foundation of Korea.

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