ASSOCIATIVE LEARNING BASED ON SYMMETRIC SPIKE TIME DEPENDENT PLASTICITY

Binbin Guo[1,2], Yimao Cai[1], Yue Pan [1], Zhenxing Zhang[1,2], Yichen Fang[1],Ru Huang[1]**

[1] Peking University Shenzhen Graduate School, Shenzhen 518055, CHINA

[2] Institute of Microelectronics, Peking University, Beijing 100871, CHINA

*Email: caiyimao@pku.edu.cn;ruhuang@pku.edu.cn

ABSTRACT

Spike-timing-dependent-plasticity (STDP) is an important leaning rule in organisms. In the application of neural computation, it is meaningful to apply symmetric STDP to associative learning. In this paper, an electronic synapse with symmetric STDP features was demonstrated. Meanwhile, taking Pavlov's experiment as an example, a model of neural network was built with this electronic synapse and successfully simulated the Pavlov's experiment, indicating the proposed symmetric STDP synaptic circuit can mimic the working principle of associative learning.

Keywords: STDP, memristor, electronic synapse, associative learning

INTRODUCTION

Spike-timing-dependent-plasticity (STDP) is the learning rule of synapse. Synaptic plasticity ranges with the time interval between pre- and post-spikes. Generally, the shorter the time interval is, the more evident of the plasticity change [1]. On the macro level, as associative learning is the common phenomenon in humans, many researchers have tried to build some neural networks to simulate it. In the neural network, synapse is the key component because of its plasticity [2]. So how to design electronic synapse to implement associative learning has become the focus in neuromorphic research. For instance, Yuriy V. Pershin used a memristor emulator to build an electronic synapse [3]; Martin Ziegler made an electronic synapse by using a single memristive device and analogue electronic circuitry [4]. On the other hand, it is found that synapses with features of symmetric STDP such as GABAergic synapse play critical roles in associative learning phenomenon [5], therefore building the neural network based on proper electronic synapse to well address the relationship between STDP and associative learning is essential in memristor oriented neuromorphic investigation.

In this paper, a synaptic circuit with symmetric STDP features based on oxide memristor and CMOS circuit was designed. This simple circuit can successfully apply the biological characteristics of symmetric STDP of synapse to associative learning. Moreover, by using this circuit, we built a neural network to mimic the Pavlov's experiment, which is the classic associative learning phenomenon in the nature. Through this experiment, the symmetric STDP behavior of this artificial synapse correlated very well to the function of an actual synapse and this neural network demonstrated clearly the relationship between STDP and associative learning.

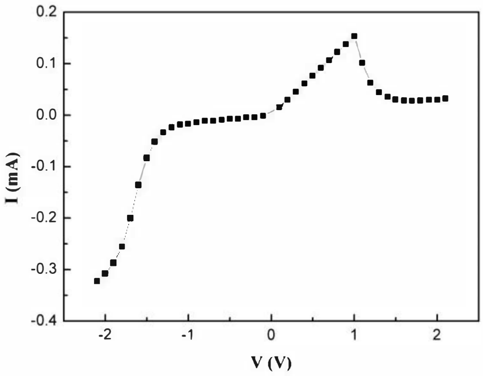

Figure 1: The typical I-V characteristics of the device measured by voltage pulse scan of different amplitude. The pulse width is fixed at 50ns.

IMPLEMENT OF SYMMETRICAL STDP CIRCUIT

As mentioned, our electronic synapse is composed of oxide memristor and CMOS circuit and the memristor device is the fundamental of synapse plasticity. In our circuit, the change of the resistance is used to simulate the change of synapse weight. As a result, a RRAM model was applied for this oxide memristor in our synapse circuit. This model is built with Verilog-A, similar to ideal model of memristor, in which the adjustment of electric resistance is achieved by changing the pulse width and pulse amplitude. In this model, the oxide memristor shows bipolar behavior, which means a positive pulse leads to increasing of the resistance while a negative pulse causes a decrease. In this experiment, the threshold voltage of memristor is set to 1V and the pulse width is fixed at 50ns but with varying amplitudes, which means the electric resistance would only be changed with the pulse amplitude. The resistance of memristor ranges from 6.5kOh to 65kOhm during synapse plasticity modulation in our simulation. Figure 1 shows the simulated typical I-V characteristics of our device by voltage pulse scan of different amplitude. It shows that different pulse amplitude will bring different resistant change of the memristor in the electronic synapse. The following work, we will use this character to accomplish our synapse circuit.

The electronic synapse hybrid circuit with this modeled memristor and CMOS devices was designed as shown in Fig. 2, in which few-cent normal transistors was used. Compared with traditional mimic synapse by a single memristor which often requires special processed signals, this hybrid synapse circuit can work with a simple square-wave pulse, which can dramatically simplify the design of other components of neuromorphic system. In this circuit, with a consistent pulse signal when the time of pre and post spikes differs, the pulse amplitude on the memristor will be different and the resistance of the memristor will be modified by the applied bias, leading to STDP adjustment in the circuit. In details, as shown in Fig. 2, Md1 and Md2 which are connected as a diode can produce the exponentially decay signal. D is a delay unit that separates the signal from different paths. IN1~4 enhances the signal. Buf1~2 enhances the driving force of the exponentially decay signal.

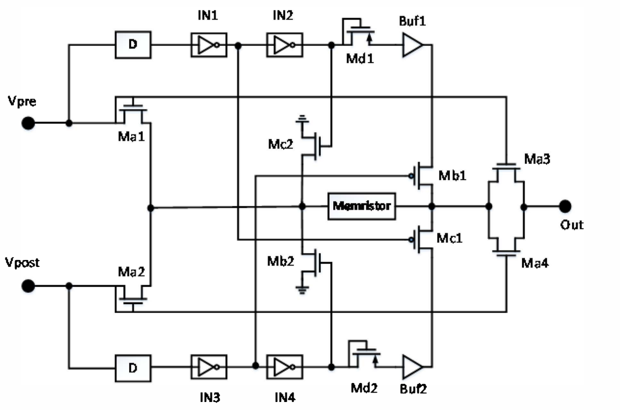

Figure 2: Schematic illustration of the designed electronic synapse hybrid circuit with symmetrical STDP characteristics

When there is a pulse signal in the Vpre, there will be an exponentially decayed signal in Md1 and the aptitude of this signal is decreasing constantly. In the effective time range of the exponentially decayed signal, Mb1 will be on when the signal of Vpost arrivals. At the same time, the signal from Md1 will go through Mb1, memristor and Mb2. As a result there will be a pulse through the memristor and the resistance of the memristor will decrease and hence the plasticity of this synapse will be increased. When the interval time between Vpre and Vpost is longer, the change of plasticity of this synapse is greater. Similarly, when the postsynaptic signal appears first, the resistance of the memristor will increase and hence the plasticity of this synapse will be decreased.

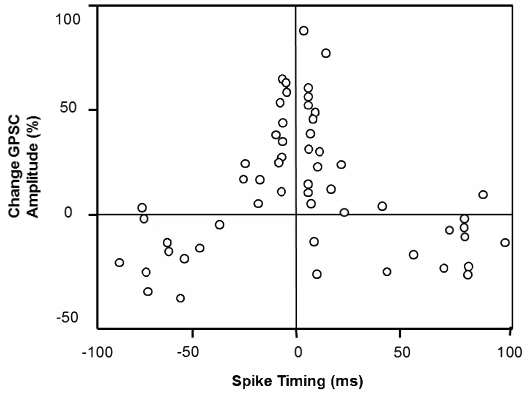

Figure 3 : Symmetric STDP curve of GABAergic Synapses detected in organisms

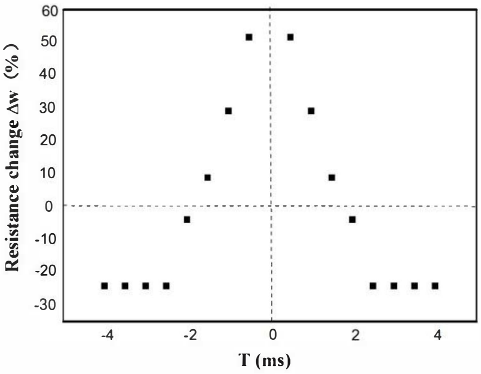

Figure 4: Result of simulated experiment, the stimulus is regarded as a single stimulus when its time exceeds 2ms

RESULTS AND DISCUSSION

Figure 4 shows the result of the simulated symmetric STDP circuit, which is similar to a symmetric curve in biological synapse as shown in the Fig. 3. As shown in the Fig. 4, within the effective time range, triggering of the pre-synaptic and post-synaptic neurons will generate change in stroke weight. The shorter time interval would bring greater change. However if the time interval between pre- and post-synaptic signals exceeds a certain range, the stroke weight will decrease consequently. It is worth noting that when the time interval exceeds a certain limit, the activities of pre- and post-synaptic neurons should be taken as independent event of each neuron which will make the memristor stay in reverse state and the resistance will return to the maximum value. In our simulation, the limit time interval is set to 2ms, so the negative resistance change turns out when the time interval exceeded 2ms. Moreover, the negative resistance change will reach the saturation soon to the maximum value. This reverse feature matches the GABAergic synapse character very well [5].

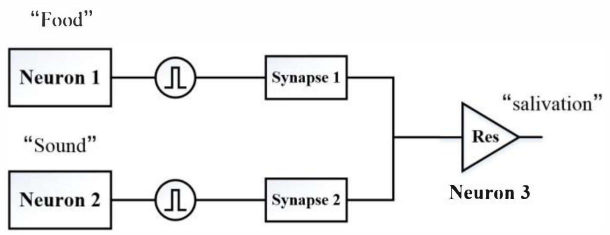

Figure 5: Model of associative learning in artificial Pavlov's neural network

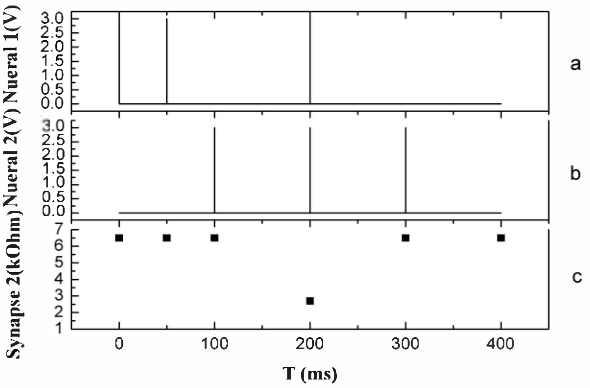

Figure 6: Results of simulated model of associative learning, the measurement unit of pulse is ns, the measurement unit of observation time is ms. a, signal of neuron 1; b. signal of neuron 2; c. change of stroke weight. At the time of 200ms, the time interval between presynaptic neuron and postsynaptic neuron is 1ms and the synaptic weight increases (the resistance of RRAM decreases)

As shown in Fig. 5, our artificial Pavlov's neural network model based on this hybrid electronic synapse is composed of three neurons and two synapses. Neuron 1 and Neuron 2 stand for the unconditioned food stimulation and conditioned sound stimulation respectively. Neuron 3 stands for response correlating to the dog's salivation in Pavlov's experiment. At the initial stage, the resistance of Synapse 1 is low which means its weight is high enough to act as a pathway. When there is a signal in Neuron 1, Neuron 3 will react. We focus on Synapse 2, which is in high impedance state at the initial state and consequently the signal of Neuron 2 cannot be sent to Neuron 3. When there is a signal in Neuron 2, Neuron 3 will not react. If the signal in Neuron 1 and Neuron 2 exist in the same time, Neuron 3 will react. However, after the several operations simultaneously with signals of Neuron 1 and 2, only single signal from Neural 2 could also induce the react of Neural 3 due to the increased weight of Synapse 2. Fig. 6 shows the simulated data of this artificial Pavlov's neural network model corresponding to the Pavlov's experiment. At the time of 50ms, when only Neuron 1 is stimulated, Synapse 2 is still in the high impedance state, and the weight value is low. At 100ms, when only Neuron 2 is stimulated, Synapse 2 is still in the high impedance state, the weight value is low. At 200ms, we set the time interval as 1ms which is still within the effective range of time interval and stimulate both the Neuron 1 and Neuron 2. At this time, the resistance of Synapse 2 decreases, so the signal of Neuron 2 can arrive at Neuron 3 very well. After a period of time, when Neuron 2 is stimulated again, the resistance of Synapse 2 returns to the initial state, and as a result the weight of Synapse 2 decreases again, which correlates very well to the phenomenon that the dog's salivating reaction will disappear after a period of single stimulus of ring bell in the Pavlov's experiment.

SUMMARY

In this paper, a symmetric STDP synaptic circuit hybrid with oxide memristor and CMOS devices was demonstrated, which can act similarly to the function of biological synapse in associative learning. Moreover, an artificial neural network model based on this proposed electronic synapse was built to mimic Pavlov's experiment. The simulation result shows that the artificial neural network model can successfully demonstrate the biology phenomena in Pavlov's experiment and verify the relationship between STDP and associative learning.

ACKNOWLEDGEMENTS

This work was supported in part by National Basic Research Program of China (No.2011CBA00601), National High Technology Research and Development Program of China (No.2011AA010401 and No.2011AA010402), and National Natural Science Foundation of China (No.61376087, No.61006062, and No.60625403).

REFERENCES

[1] Snider, G.S. *Nanoscale Architectures*, Anaheim, June 12-13, 2008, pp. 85-92.

[2] Ting Chang, Sung-Hyun Jo, Kuk-Hwan Kim, Patrick Sheridan, Siddharth Gaba and Wei Lu. *Applied Physics A,* vol. 102, 2011, pp 857-863.

[3] Yuriy V. Pershin, Massimiliano Di Ventra. *Neural Networks,* vol. 23, 2010, pp. 881-886.

[4] Martin Ziegler, Rohit Soni, Timo Patelczyk, Marina Ignatov, Thorsten Bartsch, Paul Meuffels and Hermann Kohlstedt, *Advanced Functional Materials,* vol. 22, 2012, pp. 2744-2749.

[5] Melanie A. Woodin, Karunesh Ganguly, Mu-ming Poo. *Neuron*, vol. 39, 2003, pp. 807–820.