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Implementation of adaptive neuron based on memristor and memcapacitor emulators

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ABSTRACT

Adaptive response to timely constant stimuli is a common feature of biological neurons. Implementation of neurons with such features is important for achieving biologically plausible networks using electronic systems. Emerging memristor devices open new horizons in electronically implementation of neural networks with high integration density and low power consumption. Promising potential applications can be considered for mem-elements (memristor, memcapacitor, and meminductor) with their built-in memory-properties. Since the dynamics of mem-elements makes them suitable for direct emulation of biological features of real neurons, it is expected that implementation of real neurons with complicated behavior to be straightforward using mem-element without complicating the implementation of the whole neuron circuit. Mem-elements are still unavailable commercially, so we utilize the mem-elements emulators to evaluate the feasibility of using these elements in the implementation of adaptive neurons. To ensure that there is the possibility of practical implementation of our neuron circuit, we used mem-elements emulators in SPICE simulations instead of mem-elements behavioral models. This work is among the first papers in the implementation of adaptive neurons using mem-elements. Here, using memristor and memcapacitor emulators the neuristor with adaptive behavior is implemented in SPICE environment. We use two different methods for induction of adaptive behavior to the neuristor response. In the first method, the capacitor in the primary circuit of neuristor is replaced with memcapacitor. Alternatively, the coupling resistor in the primary circuit of neuristor is replaced with the memristor in the second method. Results show that, the feature of memristor/memcapacitor in changing its resistance/capacitance during time upon excitation with current or voltage, makes the neuristor behavior to be adaptive in both methods, i.e. the neuristor shows the spike-frequency adaptation behavior in response to the continuous external stimulus, where the frequency of generated spikes depends on the duration of the external input stimulus.

1. Introduction

The human brain contains around 100 billion neurons and one quadrillion synapses [1]. Each neuron acts as a processing unit in the brain, which consists of soma, dendrites, and axon. Information from one neuron flows to another neuron across a synapse. Neurons communicate with each other by releasing action potentials in the form of spikes. Action potentials are generated by special types of voltage-gated ion channels embedded in a neuron's membrane [2], causing the momentary change in electrical potential on the surface of the neuron. Hodgkin and Huxley described a conductance-based model to explain the ionic mechanisms underlying the initiation and propagation of action potentials in the squid giant axon [3]. The spatial and temporal pattern of these spikes represents information in neural networks [4,5]. The firing rate of neurons is related to the strength of the inputs stimuli in which stronger stimulation causes higher firing rate of the neuron. The recent history of neurons electrical activity affects the generated spike train, known as spike-frequency adaptation [6]. This mechanism affects neuron activation in the brain, so that the firing rate of neuron spikes is reduced during a sustained stimulus. It is believed that the existence of several different ion channels in the neuron with different time constants and thresholds are the main reason for spike-frequency adaptation. Several processes can produce the spike-frequency adaptation. In a number of silicon-based neurons, a mechanism is used to produce slow ionic currents with each spike that are subtracted from the input current to the neuron [7]. This mechanism serves as a negative feedback, which is modeled differently in several silicon-based neurons [7]. In some silicon-based neurons, the effect of calcium-dependence, after-hyperpolarization potassium currents in real neurons, is

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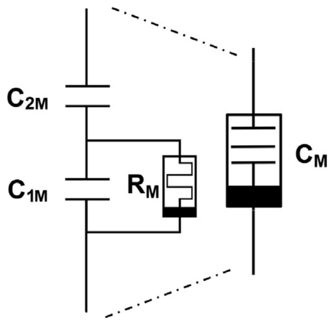

Fig. 1. The circuit implementation of memcapacitor including memristive device [26].

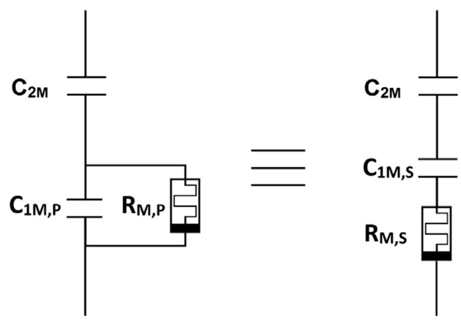

Fig. 2. Impedance transformation in memcapacitor sub-circuit. Parallel $R_{M,P}$–$C_{1M,P}$ to its equivalent series $R_{M,S}$–$C_{1M,S}$.

modeled by integrating the spikes produced by the neuron and subtracting the resulting current from the membrane capacitance. In these neurons, in addition to the membrane potential variable, the second slow variable is also introduced in the model to produce different spiking behaviors [7]. Using adaptive threshold in the neuron is another way to model the spike frequency adaptation [7].

The memristor (memory + resistor) is considered as the fourth basic element of electrical circuits that directly relates the flux linkage with the charge flow, originally postulated by Chua [8]. For the first time, a successful fabrication of a very compact and non-volatile nano-scale memristor was introduced by Strukov [9]. The resistance of memristor can be altered by supplying a voltage or current to it, so remembering information is the main feature of this device. Several potential applications of the memristor as introduced in literature are neuromorphic, in memory computation, programmable logic, chaotic signal generators, memristor-based security applications, etc [10–14].

Implementation of neurons and synapses using memristor is reported in several studies [10,16–26]. Memristor functionally behaves like synapse, therefore, using memristor in the neuromorphic circuit instead of transistors could lead to analog circuits with both high connectivity and high density likes the human brain. Chua showed that in the Hodgkin–Huxley equations, sodium and potassium ion-channel memristors are the key to generating the action potential, and they are the key to solve several unresolved anomalies associated with these equations [15]. Sah et al. showed that the potassium and sodium ion-channels in the axons of the neurons exhibit all the fingerprints of memristors, and in fact, they are locally-active memristors [16]. Jo et al. described a hybrid system composed of complementary metal-oxide semiconductor neurons and memristor synapses that can support spike timing dependent plasticity [17]. Kim et al. proposed a compact and power efficient memristor bridge synapse consisting of four identical TiO_2 memristors which is able to perform zero, negative, and positive synaptic weightings [10]. Wang et al. showed that

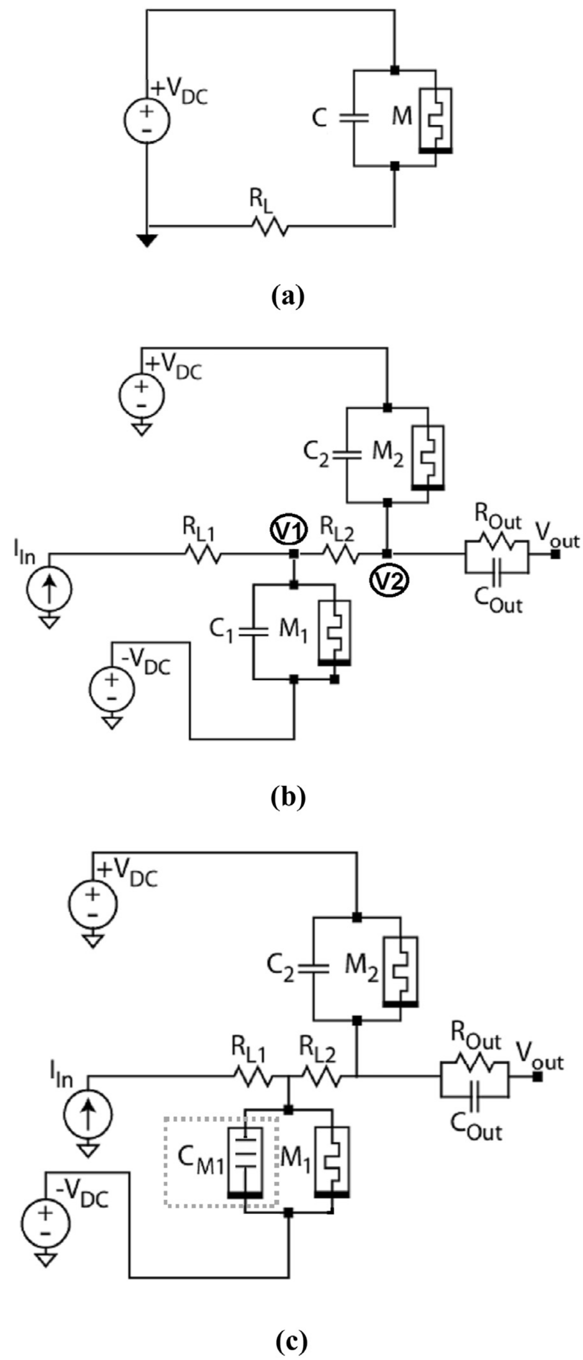

Fig. 3. The circuit implementation of neuristor, **(a)** relaxation oscillator, **(b)** the original circuit of neuristor presented in [22], **(c)** the circuit in which the capacitor C_1 is replaced by memcapacitor C_{M1} .

their diffusive Ag-in-oxide memristor and its dynamics enable a direct emulation of both long- and short-term plasticity of biological synapses, representing an advance in electronic hardware implementation of neuromorphic functionalities [18]. Kim et al. indicated that the dynamic evolutions of internal state variables of oxide-based memristor enables it to exhibit Ca^{2+}-like dynamics, making it suitable for hardware implementation of critical synaptic functions, realistically [19]. Kim et al. showed that analog resistive switching behaviors in a SiN_x-based memristor exhibits gradual set and reset switching characteristics, making it suitable for synapse devices implementation in neuromorphic applications [20]. A useful guideline for manipulating and designing of memristor as the

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