FCS Based Memristor Emulator with Associative Learning Circuit Application

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Abstract: *In this paper, new fully floating memristor emulator circuit that consumes ultra-low energy is presented. This proposed circuit is simple because of the fact that it doesn't contain any multiplication or various block circuits to obtain nonlinear characteristics of memristor. Transistors are operated in subthreshold region to obtain the non-linear behavior. Floating Current Source (FCS) is used in memristor emulator design to decrease the energy consumption of emulator. Associative learning is a type of the learning mechanisms and designed memristor are used in classical associative learning circuit successfully. All results are compatible with both memristor characteristics and learning mechanisms of circuit.*
Keywords: Memristor, Emulator, Non-linear Resistor, FCS, Associative Learning.

1. Introduction

In 2008, Stanley Williams from the Hewlett-Packard Company announced the fabrication of the TiO_2 memristor [1], which was introduced in [2-3]. Memristor provide to us the missing linkage between charge and flux from the symmetry and completeness. This new passive element is a two terminal element that exhibit a pinched hysteresis characteristic between voltage and current, and no current is flowing through the memristor when applying zero voltage. Memristance, memristor resistance, depends on direction of the flowing current. For example, memristance increases when current flows in one direction and decreases when another current direction. When no current is flowing through the memristor, the memristor resistance retains the last resistance state. Memristors have some unique properties such as non-linearity, non-volatility and high density storage technology. Many researchers developed the memristor emulators and models [4-12] after 2008 because of its fabrications difficulties. The announced TiO_2 memristor is a two terminal, nano-scale, passive element and has ultra-low power dissipation. But these developed memristor emulators are not fulfill all unique properties. Dynamic Threshold voltage (DTMOS) MOSFET which was proposed by Assaderaghi and co-workers is suitable for ultra-low voltage circuit applications. [13]. The gate terminal of the transistor is connected to the body terminal of the same transistor to generate the DTMOS transistor. Here, the threshold voltage of the transistor is a function of its gate voltage. This function provides to us very low leakage current because of the fact that threshold voltage becomes high when V_{GS}=0. Learning and memory is the most important activity in creatures, especially in humans. Learning is a capability to gain new information and memory is the storage capability of information during very long time and it can be recallable in anytime. These two capabilities become in neurons and synapses and human brain consists of approximately 10^{11} neurons and 11^{15} synapses. That is why; researchers need use the high-density circuit elements to provide high-efficient brain-like systems. Synapses which are part of learning activities act resistor, polarized and frequency dependent circuit elements. Memristors have all these properties [14].

In this paper, DTMOS based simple floating memristor emulator is presented with ultra-low power dissipation. This emulator which has fully floating characteristic can be operated with very low frequencies. A memristor based circuit which is capable of associative memory is operated as an application of proposed memristor emulator. All simulations are obtained successfully with TSMC CMOS 0.18 um process parameters.

2. DTMOS based Floating Current Source

The first DTMOS was proposed by Assaderaghi and co-workers [13,15-16]. The body terminal of the transistor is connected to the gate terminal of the same transistor to obtain DTMOS. The threshold of the transistor becomes the function of the gate voltage and we can obtain high threshold voltage at zero bias, low threshold voltage at V_{GS}=V_{DD}. The circuit symbol of DTMOS transistor is shown in Figure 1. High energy efficient is very important in VLSI systems that is why we used DTMOS transitors in our emulator to obtain ultra-low energy consumption.

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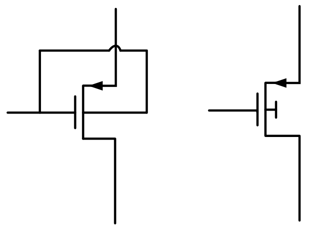

Figure 1. DTMOS transistor connection and its circuit symbol [15].

We used DTMOS based floating current source to implement memristor emulator circuit. The circuit symbol of the FCS is shown in Fig.2.

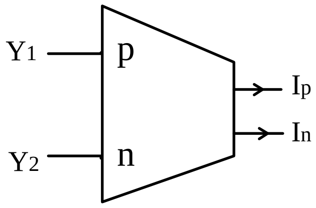

Figure 2. Circuit symbol of FCS.

Voltage difference of Y_1 and Y_2 is transferred to the output as a current. The terminal relations of the FCS are as below:

$$I_{B1}-I_{B2}-(I_n+I_p)=0 \quad (1)$$

$$I_{B1}=I_{B2} \quad (2)$$

$$I_p=-I_n \quad (3)$$

where I_{B1} and I_{B2} represent bias currents. The structure of FCS is shown in Fig.3.

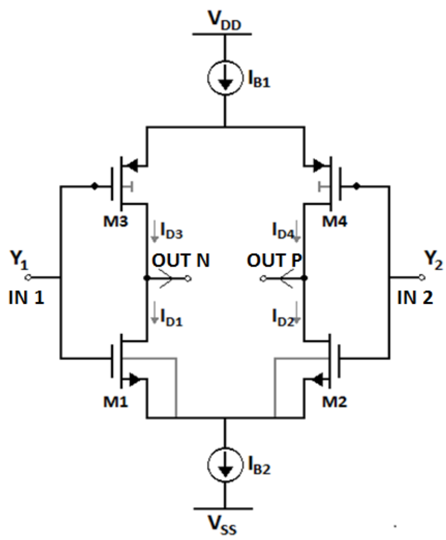

Figure 3. The circuit of DTMOS based FCS.

3. FCS Based Memristor Emulator Circuit

A fully floating memristor emulator circuit is designed by using only one FCS, one capacitor and two pMOS transistors as shown in Fig 4. Both transistors gates are driven by capacitor which is connected to the Ip terminal of FCS. The Y_1 and Y_2 terminals of FCS are connected to the drains of pMOS transistors that are operated as a nonlinear resistor. If Y_1 terminal voltage becomes higher than Y_2 terminal voltage, memristor behaves as an incremental non-linear resistor. Memristor exhibits decremental characteristics if Y_1 terminal voltage becomes higher than Y_2 terminal voltage. Capacitor is used for both as a memory and as a transistor driver. The bulk terminals of both T_1 and T_2 transistors are connected to the drain terminal and these transistors are operated in subthreshold region to obtain non-linear characteristic of memristor.

In this circuit, transistors have exponantial relationship between voltage and current when operated in subthreshold region. The output current of the FCS charged the capacitor and if the voltage on the capacitor has lower value, transistors can be operated under the threshold regime.

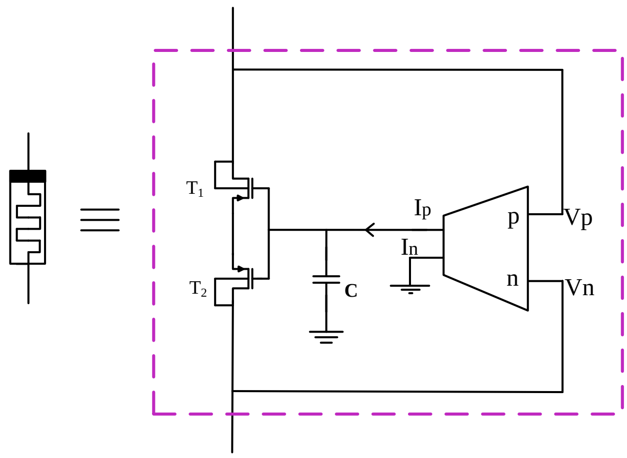

Figure 4. Proposed Memristor Emulator Circuit. Here, capacitor value is 10 nF, the aspect ratios for both transistors are 50 µm/1µm.

In the proposed circuit, DTMOS based FCS structure has three important behaviors to implement memristor emulator circuit: 1. High input resistor, 2. Efficient voltage controlled current source, 3. Ultra-low energy consumption. Memristors exhibit pinched hysteresis characteristic under periodic sinusoidal signal and depends on the frequency values.
The voltage on the capacitor is:

$$V_C=\frac{1}{C}\int I_P dt \quad (4)$$

Capacitor element provides to us memory effect of the proposed meristor emulator as shown in equation 4. Nonlinear behavior of the emulator circuit can obtained when transistors are operated in subthreshold region. If the voltage on the capacitor which is connected to the output terminal of the FCS can be controlled the transistors are operated under the threshold region.

We designed our emulator for low voltage and frequencies applications that is why we operated our emulator at lower frequencies regions. Firstly, we applied 50 mV periodic sinusoidal signals with various frequencies to the presented emulator. As shown in Fig. 5, designed memristor behaves as a linear resistor at higher frequencies, and exhibit non-linear behavior under very low frequency regions.

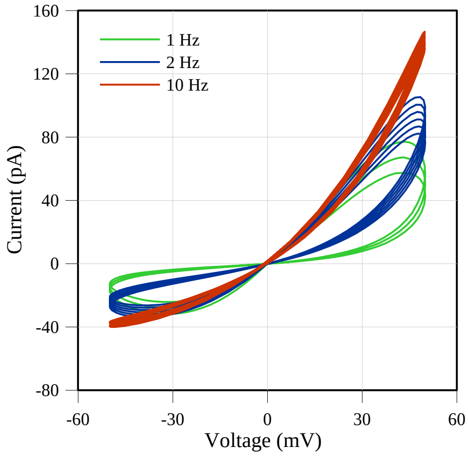

Figure 5. Voltage - Current characteristics of memristor with different 1 Hz, 2 Hz and 10 Hz respectively.

We applied eight pulses to the incremental and decremental terminals of memristor emulator respectively. Proposed memristor current depends on the direction of the applied signal as shown from Fig. 6. The current decreases when signal is applied from the incremental terminal and the current increases when voltage applied from opposite direction.

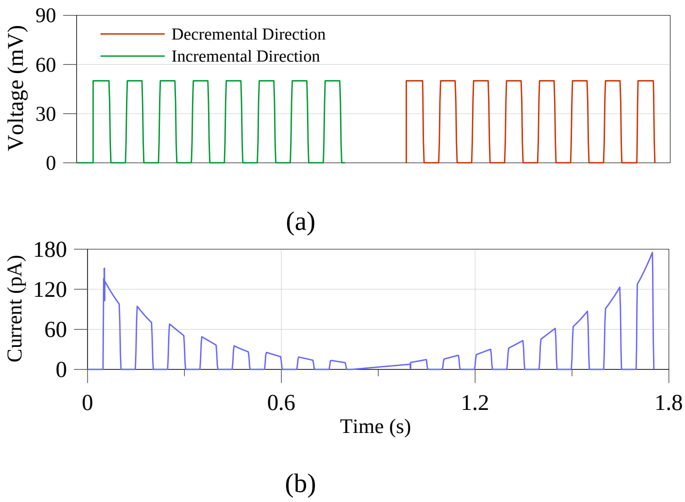

Figure 6. Variations of the memristor current for eight pulses along the time. The pulse with and voltage value of applied signal is 50 ms and 50 mV, respectively.

4. Associative Learning with Memristor

Associative learning which is a kind of important learning activity is a classical conditioning and Pavlov's dog experiment can be thought to understand it. Pavlov showed food to his dog and the dog began salivate. Pavlov then rang a bell when showed the food to the hungry dog. After a few times, the dog began salivate when Pavlov only rang the bell. We have built the circuit as shown in Fig.7 [17].

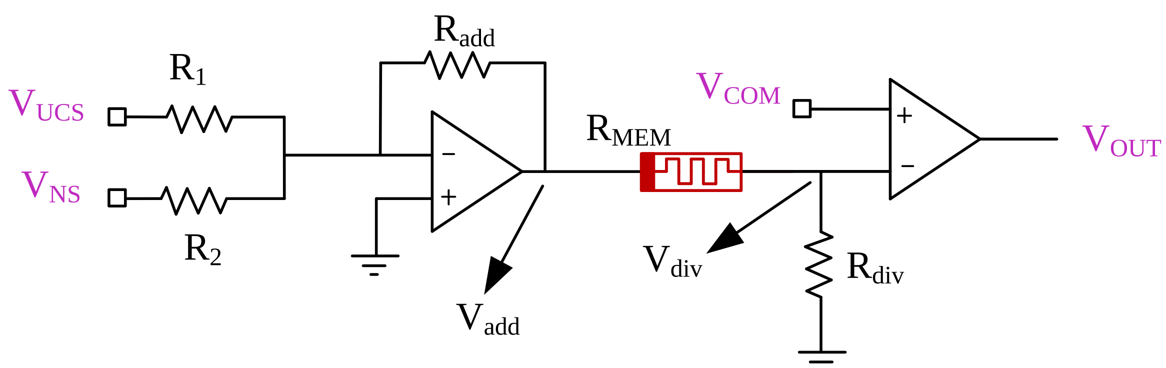

Figure 7. Memristor based circuit for classical conditioning [17]. R1=50 kΩ, R2=250 kΩ, Radd=50 kΩ, Rdiv=2 GΩ, VCOM= -5 mV.

In the circuit wihich can be seen from Fig.7, unconditional stimulus is represented by V_{UCS}, neutral stimulus such as sound is represented by V_{NS}. Each stimulus is inversely summed and Rdiv behaves voltage divider of Vadd. Here, the memristance change of memristor depends on the applied voltage to obtain the learning mechanism. If the memristance changes, the voltage of the voltage divider circuit changes. Therefore we can control the learning mechanism of the circuit. V_{COM} is compared with Vdiv and the Operational Amplifier (Op-Amp) produces the output voltage according to V_{COM} value. The variation of the memristor resistance is key point in this circuit. Learning activity is depends on the Vdiv voltage namely depends on the memristance.

Here we applied five 50 mV input voltage pulses to the both inputs (V_{UCS} and V_{NS}) of the circuit which is shown in Fig.7.

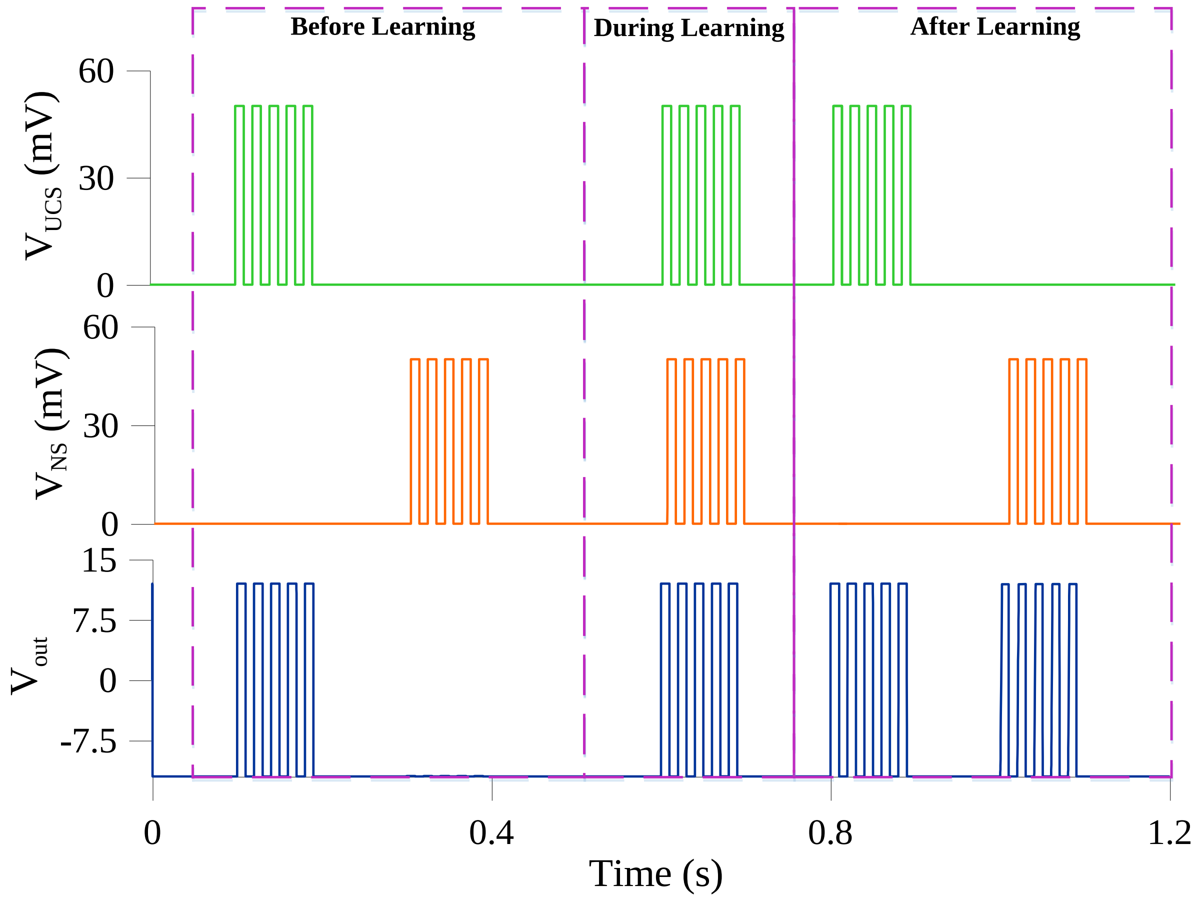

Figure 8. Simulation results of the classical conditioning circuit for before learning, during learning and after learning.

When input signal is applied to the V_{UCS} input Vout voltage can be obtained before learning. Input signal is applied only to the neutral stimulus input (V_{NS}), we cannot see any voltage at the output terminal of the circuit. Before learning stage, we can obtain output voltage only when applied signal to the V_{UCS} terminal. During learning stage, when we applied signal to the both terminals at the same time we can see voltage at the output terminal. After learning stage, when we applied voltage signal to the both V_{UCS} and V_{NS} input terminals at the different time scales, we can obtain voltage at the output terminal of the circuit.

6. Conclusions

We designed FCS based fully floating simple memristor emulator which consumes ultra-low power. Memristor is the last invented passive circuit element and researchers need to learn its potential applications because of the its some unique behaviors. Memristors consume ultra-low power and suitable for neuromorphic circuit applications. That is why; new fully floating memristor emulator which is suitable for low voltage and power applications was presented. We used the proposed emulator in associative learning circuit and analyzed its learning activities. Each simulation results are compatible with both theory and previous studies.

7. References

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