Hardware Implementation of a Low Power Memristor-Based Voltage Controlled Oscillator

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***Abstract*- Designing and implementation of a low frequency voltage controlled oscillator to achieve a wide tuning range with a practical small area and low power constraints is a challenge. In this paper, the challenge is overcome by replacing the large values of resistances that occupy large Silicon area in the conventional design by memristors and hence smaller values of capacitances are used. Therefore, this paper proposes and characterizes a hardware implementation of a memristors-based voltage controlled oscillator that used in Electrical Neural Stimulation. The basic proposed circuit generates low frequency signals that range from 1.2 KHz to 3.4 KHz with small area and low power consumption about 0.49 mW. In addition, four-stages D-flip-flops are used as a frequency divider circuit to reduce the frequency range from KHz range to Hz range which is very useful in biomedical and embedded systems applications.**

Keywords- Electrical Neural Stimulation, Memristor, Voltage Controlled Oscillator, D-flip-flops.

I. INTRODUCTION

Neural stimulation is very important in biomedical applications and it is used in treating chronic pain. Parkinson's disease (PD) patients exhibit symptoms that worsen with time if not treated early. Deep brain stimulation in subthalamic kernel is found as a therapy for Parkinson's disease [1], [2]. The frequency that used by Parkinson's disease therapy varies from 130 Hz to 185 Hz among human [1].

With the fast development of the electronic industry new devices have become increasingly important such as memristor. This passive element was theorized and characterized by [3], [4]. It has many valuable characteristics such as: non-volatility properties, high performance, high-density, nano-scale size, and low power device [5], [6], [7]. It is useful for many modern small size applications such as: nonvolatile memory, low power and remote sensing systems, neuromorphic applications, and analog computation [8]. Memristors have recently been fabricated by Knowm Inc Company for hardware applications [10].

The main challenge that faces the designing and implementation of a low frequency voltage controlled oscillator (VCO) is how to achieve a wide tuning range with a practical small area and low power constraints to be useful in many different applications, such as biomedical applications.

This main challenge has been overcome in our previous work [2], where the large values of resistances that occupy large Silicon area in the conventional design are replaced by nano-size memristors. Hence, smaller values of capacitances are used. However, in [2] the designed memristors-based VCO was verified using Cadence software simulation, where Verilog-A memristor model is used.

This paper is an extension to the previous work reported in [2]. It presents the hardware implementation details of the proposed VCO circuits in [2]. Also, it addresses the measurements results with a comparison between the resistors-based and memristors-based circuits as a verification process.

The rest of the paper is organized as follows. Section II briefly reviews the previous work reported in [2]. Section III introduces Knowm's memristor: structure, work principles, generalized metastable switch (MSS) model, and programming. Section IV presents the prototype circuits implementation details and concerns. The measurement results of the prototype are demonstrated in Section V. Finally, conclusion is in Section VI.

II. REVIEW OF THE PREVIOUS WORK REPORTED IN [2]

To provide a theoretical foundation for this work, this section briefly reviews the previous work reported in [2]. Figure 1 shows the building block of the proposed VCO system, which has two added features; generate low frequency signal, and memristors-based instead of resistors. The system contains three building blocks; the VCO circuit, level shifter circuit, and frequency divider. The VCO includes three sub components; a Schmitt trigger, two stages of operational amplifier, and an integrator. The level shifter circuit is an inverter to change the VCO output voltage rails to (0, V_{DD}) instead of (+ V_{DD}, - V_{DD}).

Fig. 1 The building block of the proposed VCO system in [2].

Finally, a frequency divider which includes of number of D-flip-flops stages reduces the VCO frequency (i.e., kHz range) to very low frequency (i.e., Hz range) which is very useful for the deep brain stimulation. The number of D-flip-flops stages depends on the required frequency reduction ratio. In [2] the verification process was only limited to simulation in Cadence software and no actual hardware prototyping is implemented.

III. Knowm Memristor

Knowm Inc is an American company that was founded in 2015 and works toward neuro-memristive applications. In January 2018 the Knowm memristors have been become available on the open-source memristor discovery platform [8].

The Knowm memristors, also known as the Knowm Self Directed Channel (SDC) memristors, come in three variants: Tungsten (W), Tin (Sn), and Chromium (Cr), which refers to the metal introduced in the active layer during fabrication. Each memristor type has the same basic material structure, but they differ in the active metal added to the active layer [8]. Tungsten (W) type has been used throughout this work and it is available in packaged devices as shown in Fig. 2.

The Knowm Multi-Stable Switch (MSS) model provides the description of an idealized two-state element that switches probabilistically between its two states as a function of applied voltage bias and temperature. A single memristor is modeled by a collection of MSSs states changing over time, which captures the memory-enabling hysteresis behavior [8].

The I-V relationship for Knowm memristor MSS model is show in (1):

$$I = \emptyset I_m(\mathrm{V},\mathrm{T}) + (1-\emptyset) I_s(\mathrm{V}) \qquad (1)$$

where I is the total current, I_m is the memory-dependent current, I_s is a Schottky diode current. $\emptyset \in [0,1]$, a value of $\emptyset = 1$ represents a device does not contain a Schottky diode effect [8]. More details on how to model I_m and I_s are addressed in [8].

The memristor programming to write a certain value of its state (resistance) is done by Knowm Kit along with analog discovery board and its software as shown in Fig. 3. The attained memristor resistance cycles between high and low resistance values by switching the polarity of the applied potential across the device. Also, the attained memristor resistance depends on the value of the applied potential and its time duration. Therefore, the resistance value is related at any time to the amount of metal located within the active layer, where the application of an external voltage causes the channels to transition between conducting and non-conducting states [9].

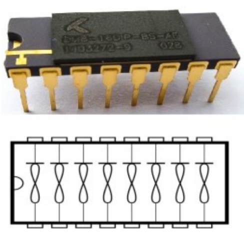


Fig. 2 Knowm Memristor Package [9].

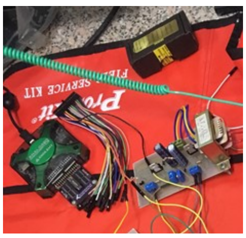
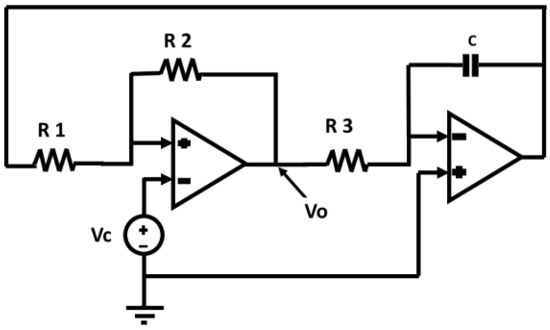


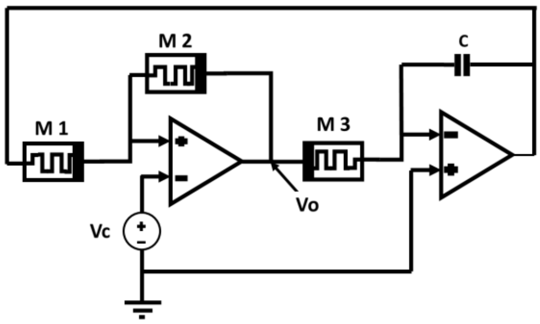
Fig. 3 memristor programming using Knowm Kit along with analog discovery board.

IV. Implementation of VCO Prototype Circuits

This section presents the hardware implementation details of the proposed VCO circuits reported in [2]. The basic hardware circuit schematic diagrams for both resistors-based and memristor-based VCO are shown in Fig. 4 [2]. Figure 5 shows the complete printed circuit boards (PCBs) arrangement for implementing the memristor-based VCO prototype circuit. This arrangement shows the implemented basic VCO circuit which consists of PCB power supply circuit, PCB Schmitt trigger and integrator circuit, and PCB memristor kit. The low power dual operational amplifier (LM 358) is used in both Schmitt trigger and integrator implementations with ± 2V supply voltage. The memristor used in the circuit is Tungsten Knowm memristor.



(a) Resistors-based VCO circuit



(a) Memristors-based VCO circuit

Fig. 4 basic hardware circuit schematic diagrams for both resistors-based and memristors-based VCO [2].

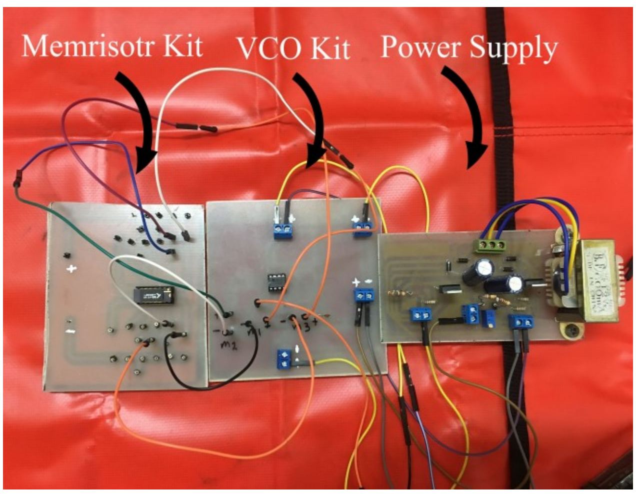


Fig. 5 The complete printed circuit boards (PCBs) arrangement for implementing the memristor-based VCO prototype circuit.

The hardware implementation of the VCO system has been done by using the commercially available Known memristor kit and integrated circuits in combination with necessary discrete components.

The output of the implemented VCO is connected to the Digilent Analog Discovery2 through its pinouts that shown in Fig. 6 [10], to used it as an oscilloscope. Digilent Analog Discovery2 is a multi-function instrument that allows users to measure visualize, generate, record, and control mixed signal circuits of all kinds [10].

V. MEASUREMENT RESULTS AND DISCUSSION

In this section, the VCO outputs for the practical implementation of VCO circuit are illustrated for both resistors-based and memristor-based VCO for different values of V_c.

A. Resistors-Based VCO

The resistors-VCO circuit which is shown in Fig.4 (a) is implemented, where the values of the three resistors are (R_1 = 30 KΩ, R_2 = 400 KΩ, and R_3 = 500 KΩ), and the capacitance value (C = 1nF). The control voltage (V_c) value is swiped from 0.1 V to 0.45 V with step 0,05 V. The VCO output was displayed by using Analog Discovery 2 as an oscilloscope.

Figures 7, 8, and 9 show three snapshots for VCO output signal versus time for three different values of (V_c), which are: 0.1, 0.35, and 0.45 V.

As shown in the above three figures, the oscillation frequency of VCO output signal varies form 2.9 KHz for V_c = 0.1 V to 1.5 KHz for Vc = 0.45 V which follows the same trend reported in [2].

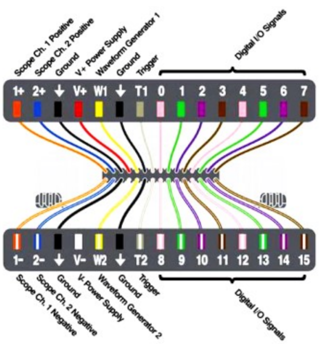


Fig. 6 Analog Discovery 2 pinout diagram [10].

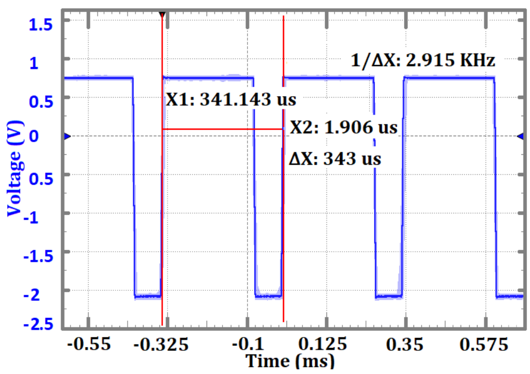


Fig.7 Output signal with frequency =2.9 KHz for Vc = 0.1 V.

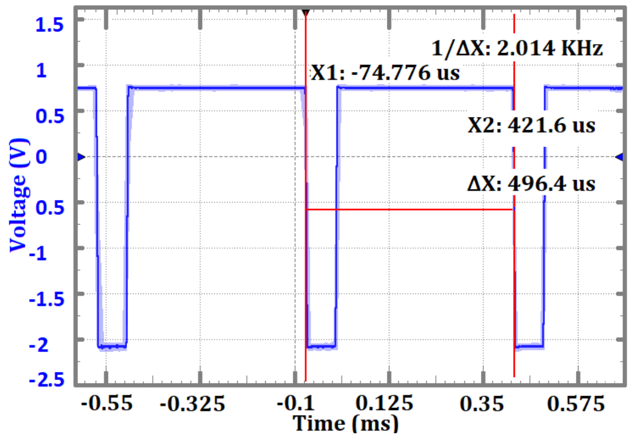


Fig. 8 Output signal with frequency =2.0 KHz for Vc = 0.35 V.

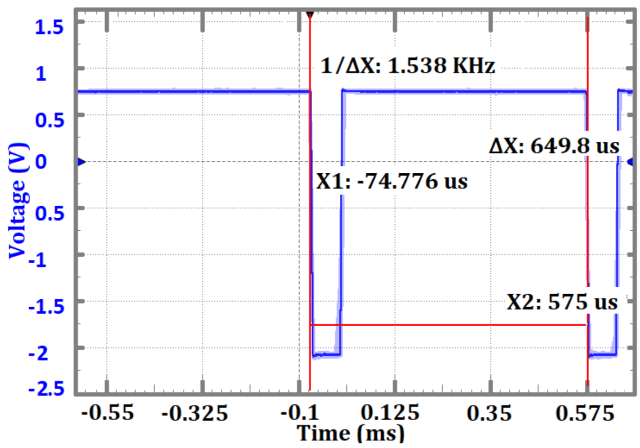


Fig. 9 Output signal with frequency =1.5 KHz for Vc = 0.45 V.

B. Memristor-Based VCO

The memristors-VCO circuit which is shown in Fig.4 (b) is implemented, where the values of the three memristor are programmed as (M_1 = 30 KΩ, M_2 = 400 KΩ, and M_3 = 500 KΩ), and the capacitance value (C = 1nF). Also, the control voltage (V_c) value is swiped from 0.1 V to 0.45 V with step 0.05 V.

Figures 10, 11, and 12 show three snapshots for VCO output signal versus time for three different values of (V_c), which are: 0.1, 0.35, and 0.45 V.

As shown in these figures, the oscillation frequency of VCO output signal varies form 3.4 KHz for Vc = 0.1 V to 1.19 KHz for Vc = 0.45 V which follows the same trend reported in [2] as in (2).

$$f = 1/T \tag{2}$$

where, the time period T is given by:

$$T = 4MC\beta L_+^2 \left(1/(L_+^2 - V_c^2)\right) \tag{3}$$

where M refers to the integrator input memristor value that is designed such that M equals R_{off}, C refers to the capacitance value. β refers to the value of ($M2/M1$) where M_1 and M_2 are Schmitt trigger circuit input memristor and feedback memristor values, respectively. L_+ is the value of $+V_{DD}$ of circuit and V_c is the control voltage value.

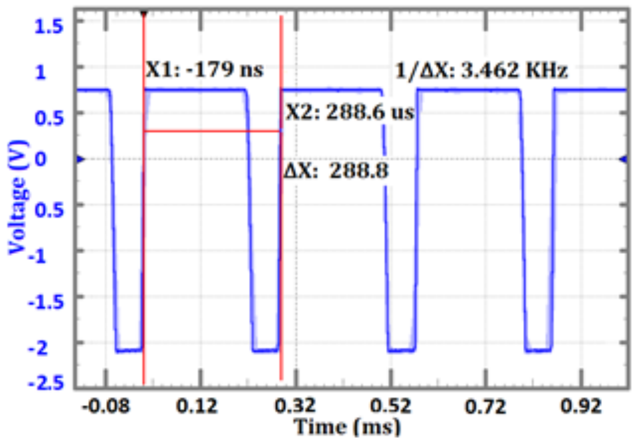


Fig. 10 Output signal with frequency = 3.4 KHz for Vc = 0.1 V.

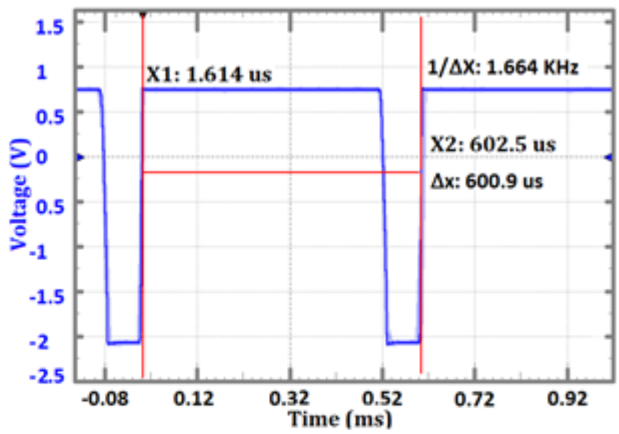


Fig. 11 Output signal with frequency = 1.6 KHz for Vc = 0.35 V.

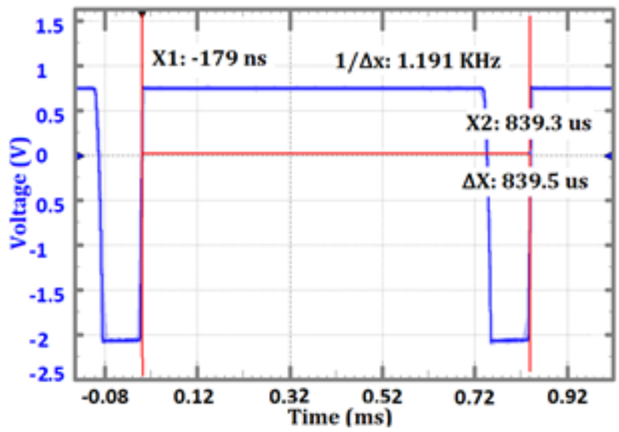


Fig. 12 Output signal with frequency = 1.19 KHz for Vc = 0.45 V.

Figure 13 shows a comparison for the possible full range of VCO frequencies for both memristor-based and resistor-based VCO. The VCO is restricted in this range due to the selected resistor values. As shown, there is a fair agreement between the two designs and the worst deviation in the full frequency range is about 0.5 KHz.

Finally, a frequency divider which consists of number of D-flip-flops stages can be used to reduce the VCO frequency (i.e., kHz range) to very low frequency (i.e., Hz range) which is very useful for the deep brain stimulation. The number of D-flip-flops stages depends on the required frequency reduction ratio.

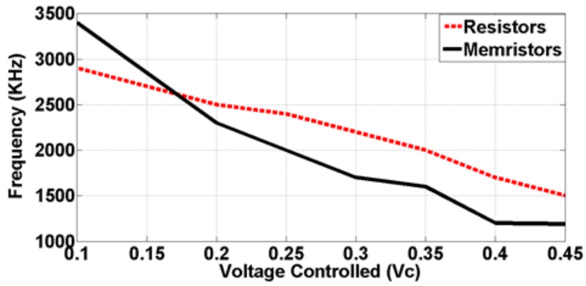


Fig. 13 Output oscillation frequency versus the controlled voltage for resistors-based and memristors-based VCO.

VI. Conclusion

A Hardware prototype of memristors-based low frequency voltage-controlled oscillator circuit is implemented and compared with resistors-based one with the same circuit structure. There is a fair agreement between the two designs and the worst deviation in the full frequency range is about 0.5 KHz. The implemented prototype achieves a frequency range from 1.2 KHz to 3.4 KHz with low power consumption equals 0.49 mW and achieves a low silicon area compared to passive elements. As a future work, a refresh circuit for the memristors used in the VCO could be added to maintain the resistance value after several periods of operation.

Achnowledgment

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References

[1] Limousin, Patricia, et al., "Electrical stimulation of the subthalamic nucleus in advanced Parkinson's disease," *New England Journal of Medicine*, vol. 339, no. 16, pp. 1105-1111, October 1998.

[2] M. I. Selmy, H. Mostafa and A. A. S. Dessouki, "Low power memristor based voltage controlled oscillator for electrical neural stimulation," *2017 Intl Conf on Advanced Control Circuits Systems (ACCS) Systems & 2017 Intl Conf on New Paradigms in Electronics & Information Technology (PEIT)*, Alexandria, 2017, pp. 344-347.

[3] L. Chua, "Memristor-the missing circuit element," *IEEE Transactions on Circuit Theory,* vol. CT-18, no. 5, pp. 507-519, September 1971.

[4] D. B. Strukov, G. S. Snider, D. R. Stewart, and R. S. Williams, "The missing memristor found," *Nature*, *Nature,* vol.453 (7191), pp. 80-83, June 2008.

[5] Nafea, Sherif F., et al. "Read disturbance and temperature variation aware spintronic memristor model," *2016 IEEE Canadian Conference on Electrical and Computer Engineering (CCECE*2016), Vancouver, BC, Canada, May 2016, pp. 1-4.

[6] Elshamy, Mohamed, Hassan Mostafa, and M. Sameh Said, "Comparative review of the TiO2 and the spintronic memristor devices," *IEEE 27th Canadian Conference on Electrical and Computer Engineering (CCECE2014)*, Toronto, ON, Canada, May 2014, pp. 1-6.

[7] Elshamy, Mohamed, Hassan Mostafa, and M. Sameh Said. "Comparative review of the TiO2 and the spintronic memristor devices." *2014 IEEE 27th Canadian Conference on Electrical and Computer Engineering (CCECE). IEEE, 2014.*

[8] Kirar, Vishnu Pratap Singh, "Memristor: the missing circuit element and its application," *World Academy of Science, Engineering and Technology, International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering,* vol. 6, no. 12, pp. 1395-1397, 2012.

[9] Alex Nugent, "Self Directed Channel Memristors," *Knowm Inc*, April 2019.

[10] Digilent Inc., "Analog Discovery 2™ Reference Manual," Revised September 14, 2015.