NanoScale TiO2 based Memory Storage Circuit Element:-Memristor

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Abstract— four fundamental circuit variable in which relation between charge and flux linkage first introduce by Prof. Leon Chua in his Research Proposal at IEEE Transaction on circuit theory based on the symmetric background. However, using this relation he predicted fourth fundamental element which is known as Memristor. The first NanoScale TiO2 based physical model of Memristor is proposed by Hewlett-Packard Laboratories. Therefore new research field emerged out "Analog and Digital circuit designing using Memristor". Still many faults in physical model of Memristor which has proposed by HP Laboratories. So many challenging researches going on for making perfect physical model of Memristor. In this paper we review properties of Memristor, the physics behind fourth fundamental circuit element as well as we discussed first physical model of Memristor introduced by HP. Some potential application also discussed here and last we proposed major challenges for Memristor development and which future work can be carried out using Memristor.

Keywords— Fourth Circuit Element, Memristor, Nanoscale, Circuit Designing, Neuromorphic.

I INTRODUCTION

In the 20^{th} Century we just had three fundamental circuit elements which are well known as a resistor, an inductor, and a capacitor. But now in 21^{st} Century Electronics world growing very fast. So we required a device which will have High speed operation capability, Low power Consumption and required less space. So we have to find out new fundamental circuit element which can satisfy this all properties and open new opportunity for changing electronics world. As we all know three fundamental circuit elements the resistor, the inductor and the capacitor. We are also known about these circuit elements, which are related to four basic electronics variable voltage, current, charge, and flux linkage. Voltage-current relation defined by the resistor, charge-voltage relation defined by the capacitor and flux linkage-current relation defined by the inductor. But amongst this variable no one observes missing link between charge-flux linkage relations before 1971. From symmetry arguments, Chua proposed there should be an element which gives a relation between charge and flux linkage without internal Power Supply [1], [2]. A functional relation between charge and magnetic flux linkage, $M = d\phi / dq$. So, In 1971 Leon Chua [1], Predicted the existence of a fourth fundamental circuit element, which he called a Memristor. He proved that Memristor behaviour could not be represented by any circuit built using only the other three elements, based on this he said the Memristor is truly a fundamental circuit element. Memristor is a contraction of memory resistor, because its remember history.

After many years in 2008, one of the Scientist at the Hewlett–Packard (HP) laboratories proposed NanoScale TiO2 based physical model of memristor an published this research work in Nature publication. Which filled up missing relation between charge and flux linkage, which was predicted by Chua [1], [2], [3]. NanoScale TiO2 based Memristor Having Properties like it can store Value in itself. So we can consider it is a single bit storage device if we define threshold for it. This unique property valuable for electronics world and opens door for many Applications such as Analog and Digital logic design, soft Computing, Synapses Design using Memristor. The Memristor is the first element which can remember his resistance itself depends upon how much, charge flowed through it. The Memristor behaves like a *linear resistor with memory* but also exhibits many interesting nonlinear characteristics. Until now There are many electronic models presented to show the electrical behaviour of Memristor devices such as, Simmons tunnel barrier model, the linear ion drift model, the nonlinear ion drift model, and the Threshold Adaptive Memristor (TEAM) model [1], [3], [4]-[6]. The memristor devices are not available in market until now, good physical model-to-hardware quality have not been yet been reported in the published literature [7].

This Paper organized as following, In Section I Introduction of Memristor, section II Physics behind Memristor and review its properties which are proposed by Chua [1]. Section III gives Idea about NanoScale TiO2 based Physical model of memristor constructed by HP Laboratory in 2008 and its Defects. In Section IV, We Discussed Some Potential Application of Memristor. Section V we discuss Major Challenges for developing a physical model of Memristor using Nan Scale Material and many future work can be carried out using Memristor for changing electronics world section VI summary of memristor.

II PHYSICS BEHIND MEMRISTOR

Four fundamental electromagnetic variables co-relate with each other and give six different relations. These four variable details given in table 1. The definition of voltage and current as well as a fundamental elements resistor, inductor and capacitor mathematical relation we can observe in table 2.

Table 1: Electromagnetic Quantities

Symbol	Name
V	Voltage
I	Current
Φ	Magnetic Flux
Q	Charge

Table 2: Fundamental Definition in terms of mathematical equation

Sr.No	Definition	Equation
1	Voltage	$d\varphi = vdt$
2	Current	$dq = idt$
3	Resistance	$dv = Rdi$
4	Inductance	$d\varphi = Ldi$
5	Capacitance	$dq = Cdv$

From fig 1 Prof. Chua[1] observe there is no relation defined between two electromagnetic variable charge and flux linkage until now, so he filled up missing relation between charge and flux linkage and introduce fourth fundamental circuit element which is known as Memristor.

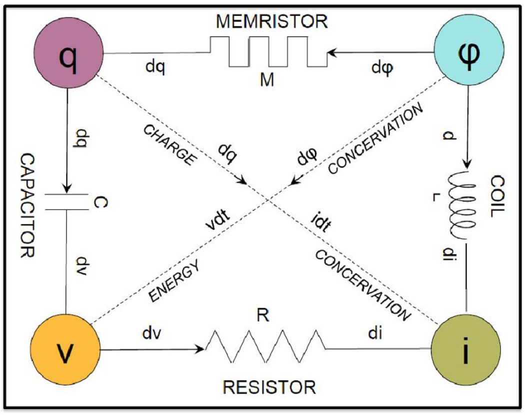

Fig. 1 Symmetry diagram showing the 6 distinct possible Realizations based on the four circuit variables. Courtesy of C.Lütken [8].

Definition of Fourth Fundamental Circuit Element in terms of mathematical Equation as follow,

$d\varphi = Mdq$ ………………(1)

Where M is memristance of Memristor and the fact that the magnetic flux of the device (φ) is a function of electric charge that has passed through the memristor [1], [2].

$\varphi = f_m(q)$ ……..…………(2)

If we deffrentiated equation (2) with respect to time, we got equ. (3)

$\frac{d\varphi}{dt} = \frac{df_m(q)}{dq}\frac{dq}{dt}$ ….……………..(3)

From the definition of voltage and current we can rewrite equation (3) in terms of voltage and current.

$v(t) = \frac{df_m(q)}{dq} i(t)$ ....…………(4)

If we further rewrite equation (4) in terms of memristance then its look like ordinary resistance equation.

$v(t) = M(q)\, i(t)$ ....…………..(5)

Where, $M(q) = \frac{df_m(q)}{dq}$ also, from equation (5), we can say that the device have memory of charge which has passed through it. So instead of charge if we use state variable w then equation gives more clarity about current memory state of the device.

$v(t) = M(w)\, i(t)$ ....………..(6)

Thus, qualitatively, Chua's fourth fundamental circuit element would have an electrical resistance that is a function electric charge quantity that has passed through its terminals. Furthermore, the device would exhibit memory; its resistance value would be retained even while not in use. Chua introduces his new device the Memristor, a combination of the words memory and resistor. Chua then present Memristor circuit symbol as shown in fig. 2

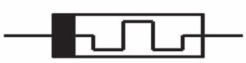

Fig. 2 Electrical Symbol of memristor

III THE PHYSICAL MODEL OF MEMRISTOR

After 4 decade, research team leader R.S. Williams, Who is working at HP labs, announced that they had fabricated NanoScale TiO2 based device which is exactly satisfying the condition of Chua's Memristor [9].

The HP Memristor is a device made up of Nanoscale TiO2 thin films sandwich between two platinum electrodes with total length D. In fig 3 we can see that Thin Film divided into two parts doped (TiO2-x) and undoped (TiO2) region. Doped region is represent low resistance which is define as Ron and undoped region is represent high resistance which is define as Roff. The width of Doped region is w and total length of Thin film is D. Memristor resistance State is dependent on the value of w. if w=0 then we can get high resistance state and if w=D then we can get low resistance state [9]. Similarly fig 4 represents convention naming of High and Low resistance.

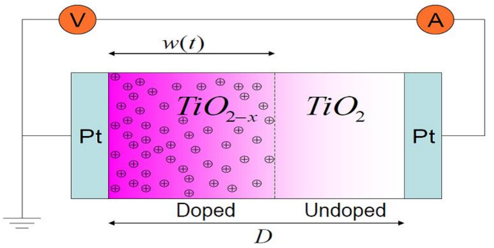

Fig. 3 Cross-section of the first HP TiO2-memristor consisting of a high conductive (doped) and a low conductive (undoped) part Placed in between two platinum electrodes. [8] Courtesy of C. Lütken.

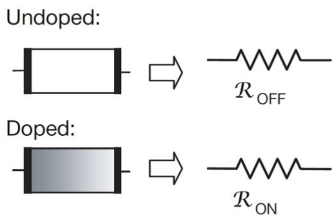

Fig. 4 Resistance Naming Convention [3]

the entire resistance of the thin film can be consider as series combinations of two resistances Ron and Roff, so Memristor resistance depends upon value of width w. which shown in Figure 5.

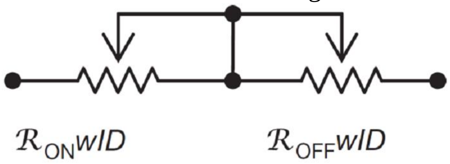

Fig. 5 Electrical Structure of the HP Memristor [3]

From Fig5, we can write mathematical equation of Memristor. Which represent V-I behaviour of Memristor [9], [10].

$$V(t) = \left(R_{ON}\frac{w(t)}{D} + R_{OFF}\left(1 - \frac{w(t)}{D}\right)\right) i(t) \qquad \text{......…………..(7)}$$

Memristor made of thin film having two regions TiO2-x and TiO2. According to drift theory doped region width increment with respect to time which mathematically express as follow [10].

$$\frac{dw(t)}{dt} = \mu_v \frac{V_{ON}}{D} \qquad \text{...……………(8)}$$

Above equation can be writing in terms of current and resistance from [10],

$$\frac{dw(t)}{dt} = \mu_v \frac{R_{ON}}{D}\, i(t) \qquad \text{.....…………..(9)}$$

Integrating both side above equation with respect to time [10],

$$w(t) = \mu_v \frac{R_{ON}}{D}\, q(t) \qquad \text{……………..(10)}$$

Substituting equation (10) into equation (7) and assuming that Ron << Roff, equation (11) can be realized [10]. Equation (11) shows that the incremental resistance of the device is a function of the charge that has passed through it [9]. The device should therefore behave as a Memristor.

$$v(t) = M(q)\, i(t) \qquad \text{…………… (11)}$$

Where, $M(q) = R_{OFF}\left(1 - \frac{\mu_v R_{ON}}{D^2} q(t)\right)$

It can be seen that the magnitude of the memristance effect is inversely proportional to the square of the thin film size D. Thus, the effect is 1,000,000 times more at the nanometre scale than at the micrometer scale [9].

The voltage-current relationship of the memristor gives a pinched hysteresis show in Figure 6(a). TiO2 easily self-doped with oxygen vacancies which provide some sort of mobility. So for First Physical Model, TiO2 has been selected as the Fabricating material of the memristor by HP Labs [3]. If we are applied 1~2 V to the NanoScale TiO2 thin film, a observable electric field is generate in the thin film and the drift velocity of the charge species is exponentially increased. A Typical I-V characteristic of TiO2 based memristor shown in fig. 6(b) [3].

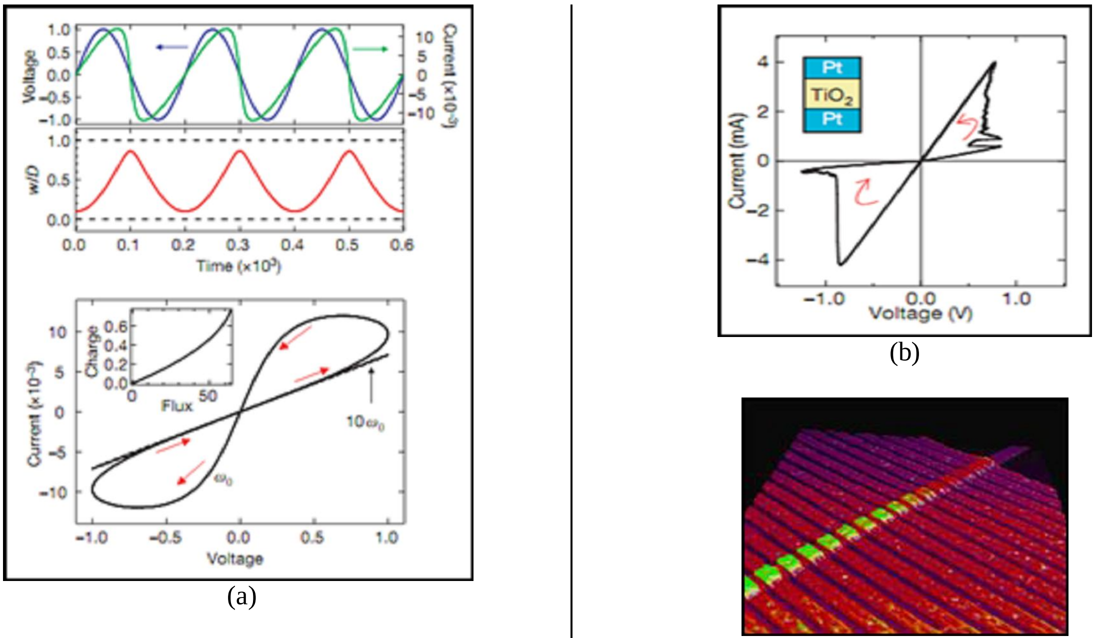

Fig. 6(a) characteristic voltage-current curve, (b) actual calculated I-V curve in TiO2, (c) AFM diagram with 17 Memristor [3] [11]

However, the formulas presented in the HP paper are based on voltage as the dependent variable making them unwieldy for convenient use. The models do not properly distinguish the internal and external electric field.

IV POTENTIAL APPLICATIONS

The interesting NanoScale properties of memristor will be becomes a main attraction for circuit designing, soft computing, memory technology and neuromorphic hardware solution in the coming future [12].

A. *Memristor for Memories:* The fast switching performances at very low biasing with low power consumption promises the memristor will be next option in the memory technology in general and DRAM in specific[12], [13]. The Moore's expected law does not fulfil with the conventional technologies, hence the integration of technologies such as spintronics, carbon nano tube field effect transistors and Memristor will be a better solution for System on Chip domains (SoC) [12],[14].
B. *Memristor for Neuromorphic Computation:* The field of neuromorphic computing tries to overcome the problem of sequential execution and memory latency of conventional computer architecture using Memristor. The resistive memristor structure mimics the synaptic behaviour of the human brain. The non-volatile property of memristor makes a better solution and addressed some of the challenges in front of Neuromorphic Computation [12], [15], [16].
C. *Memristor for Logic Design:* An IMPLY logic gate is a simple way to perform logic operations with Memristor. This logic gate can be integrated within a memristor-based memory and, together with FALSE, provide a complete logic family [12], [17].

V MAJOR CHALLENGES AND FUTURE WORK

The Memristor major challenges are its relatively low speeds, Heat dissipation problem in TiO2 based physical model and the need for designers to learn how to build circuits with the new element. Though hundreds of thousands of memristor semiconductors have already manufactured, there is still much more to be improved. No design standards until now fix. Needs more defect engineering. Analog and Digital Circuit Design:-Using Memristor Different Combinational, Arithmetic, and filter Circuit Can be design which will use low power, gives more functionality and Need Less Space as Compare to transistor based Circuit.

V SUMMARY OF MEMRISTOR

Memristor is fourth fundamental circuit element which were predicted by prof. Leon Chua in 1971.after four decade first physical model of Memristor proposed by HP laboratory, which was made up of NanoScale material. The

HP Labs Simple device fabricated using TiO2 thin film. This device manufacturing process is easy but still effective fabrication method required for NanoScale process. Because there is heat dissipation and low speed problem in that model. The Memristor having several potential application based on his electrical properties which will change the electronics world. So many further researches carried out on Memristor for the changing of electronics and neuromorphic engineering.

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