VerilogA modeling of the memristor for circuit applications

Da Xia and Lili He
xiada080@gmail.com
San Jose State University, San Jose, CA, USA

ABSTRACT

The memristor has attracted great attention in recent years due to the high demand of nano-sized high performance nonvolatile memories. Furthermore, recent breakthrough in nanotechnology makes the fabrication of the memristor a reality. In this work, the switching mechanism and the resistive switching behavior that take place in the memristor are introduced. The ionic transportation mechanism is used to explain the resistive switching process. In addition, a working model for the memristor that based on the existing oxygen vacancy migration mechanism is conducted. A VerilogA model of the memristor that based on this working model is proposed. Simulation results using this VerilogA model compliment existing proposals well. In conclusion, the future of the memristor is promising.

Keywords: memristor, VerilogA, simulation

1 INTRODUCTION

Semiconductor memories are vital in modern system on chip (SOC) designs. Most popular memories include volatile memories, such as dynamic random access memory (DRAM), static random access memory (SRAM), and nonvolatile memories, for example, flash memory. However, as the channel length of transistors has been scaled down to 28 nm, all conventional memories mentioned above are reaching the limitation of Moor's Law. Clearly, traditional memories will lose their scalabilities in the near future, and we will not able to improve their performances any more. Consequentially, numbers of alternative approaches have been proposed as a replacement of normal memories. Among all opportunities, the memristor is viewed as one of the most promising long-term solution.

The concept of the memristor was first introduced by Leon Chua in 1971 [1]. The memristor was proposed as the forth basic circuit element. Figure 1 shows the relationships between current, voltage, electrical charge, and flux linkage. A resistor defines the relationship between current and voltage while a capacitor is defined by the relationship between electrical charge and voltage. Similarly, an inductor characterizes the relationship between current and flux linkage. These three electrical elements provide three basic relationships between the four basic electrical constituents. In addition, the definition of current gives the relationship between current and charge while the Lenz's law provides the relationship between voltage and magnetic flux [2]. However, the element that can directly relate electrical charge and flux was not defined at that time. Thus, from the symmetry point of view, Dr. Chua predicted the existence of the memristor that connects charge and flux together. Dr. Chua also proved that the memristor is truly a fundamental electrical element because its properties can not be realized only by passive elements [1].

In 2008, Strukov et al. successfully manufactured the first real memristor [3]. It has two metal electrodes and an insulating layer which is made from TiO_2. This realization of the memristor has triggered a new period of the study of such device. The study of the memristor is now widespread. In this paper, we first introduce the switching mechanism of the TiO_2 based memristor. Later we will cover the conduction of an existing memristor model. Computer simulation results of the memristor based on a VerilogA model will be presented and discussed. Finally, several future applications of the memristor will be introduced.

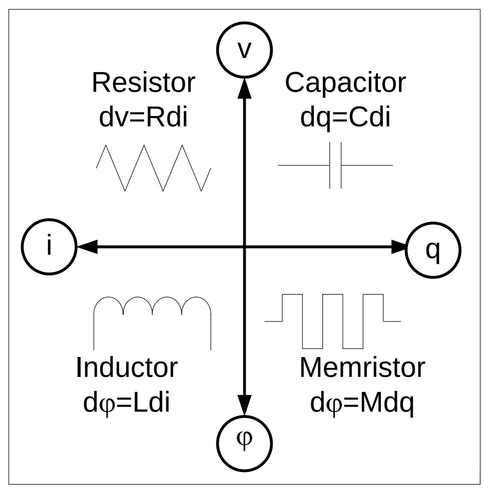

Figure 1. Four fundamental electrical elements and the definitions of resistor, capacitor, inductor, and inductor

2 SWITCHING BEHAVIORS AND MECHANISMS

There are two basic switching behaviors, namely, bipolar and unipolar. The memristor typically exhibits bipolar switching behavior. That is, the set and reset processes happen at opposite voltage polarities. The intrinsic resistive switching mechanism in the memristor for bipolar resistive switching is mainly attributed to oxygen vacancy migration effect. Oxygen vacancies in the

NSTI-Nanotech 2011, www.nsti.org, ISBN 978-1-4398-7139-3 Vol. 2, 2011

memristor are mobile. They tend to build conductive filaments that grow from one electrode to another when a programming voltage is applied. The conductivity of the memristor can be controlled by the programming voltage.

More specially, a memristor consists of an insulating layer of TiO_2 and oxygen-poor TiO_{2-x}. The resistance of the doped TiO_2 region is significantly lower than that of the TiO_{2-x} region. The memristor is totally turned on when the entire resistive layer is doped and is totally turned off when the whole insulating layer is undoped. In order to change the resistance of the memristor, one can move the oxygen vacancies in the memristor by changing the applied voltage. When the applied voltage is removed, oxygen vacancies will freeze in the memristor. Thus, the memristor shows a nonvolatile attribute.

3 MEMRISTOR MODELING

In Dr. Chua's paper [1], the memristor was modeled as a two-terminal element and was defined by the electrical charge and flux-linkage:

$$q(t) = \int_{-\infty}^{t} i(\tau) d\tau \tag{1}$$

and

$$\varphi(t) = \int_{-\infty}^{t} v(\tau) d\tau \tag{2}$$

It behaves as a nonlinear resistor with memory. For a charge-controlled memristor, it can be characterized as:

$$v(t) = M(q(t)) \cdot i(t) \tag{3}$$

and

$$M(q) = d\varphi(q) / dq \tag{4}$$

Note that the value of M(q) depends on the charge that has passed through the memristor before and the M(q) contains the unit of resistance. Thus, M(q) is called incremental memristance. If the voltage of a memristor is determined, then the memristor becomes linear time variant. Furthermore, if the charge and the flux of a memristor have a linear relationship, the memristor reduces to a normal resistor. The memristor has several interesting properties. For example, the power consumption of a memristor is always positive when M(q) is greater than zero, which means the memristor is a passive element. In addition, the resistive switching behavior is more dominant in low frequency region [4].

A memristor can be modeled as two resistors in series [3]. This simple model is shown in Figure 2.

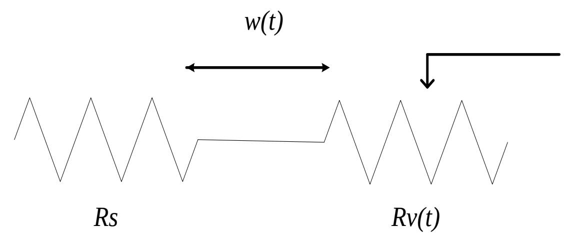

Figure 2. A simple model for the memristor

Rs is constant and is very small. Rv(t) is time-variant and is a function which depends on the thickness of the doped region. The I-V characteristic of the memristor can be expressed in Equation 5:

$$V(t) = I(t) \cdot [Rs + Rv(t)] \tag{5}$$

Furthermore, Rv(t) can be expressed as:

$$Rv(t) = \frac{\rho}{A}[D - w(t)] \tag{6}$$

and

$$\frac{dw(t)}{dt} = \frac{\mu Rs}{D} I(t) \tag{7}$$

where A is the area of the device, w(t) is the thickness of the doped region (the low resistance region), D is the thickness of the insulating layer, and μ is the carrier mobility of oxygen vacancies in the insulating layer. Equation 5 to 7 give the definition of a simple memristor.

In real cases, the carrier mobility of oxygen vacancies in the insulating layer is a function of the thickness of the doped region w(t). It is called non-linear drift effect, which means the carrier mobility reduces at both boundaries of the resistive layer. This effect can be well characterized by a window function [2]. The nonlinear drift effect can be described in Equation 8 and 9:

$$\frac{dx}{dt} = k \cdot I(t) \cdot f(x) \tag{8}$$

and

$$f(x) = 1 - (2x - 1)^{2p} \tag{9}$$

where x = w(t)/D, k = μRs/D and p is an integer. Figure 3 shows the window function with different values of p. The nonlinear drift effect is more significant when p is large. Moreover, note that the function is zero at both boundaries, which means the memristor does not show any memory attribute at both boundaries.

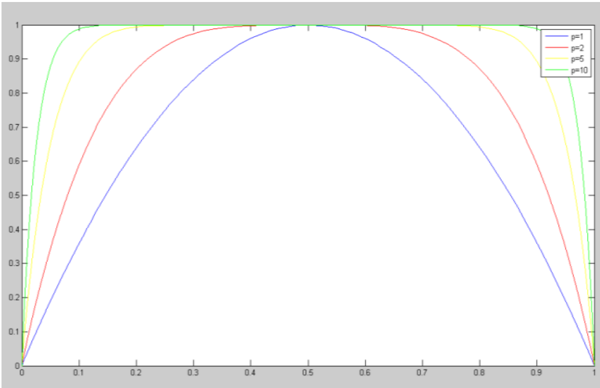

Figure3. Window function with different values of p

4 COMPUTER SIMULATION RESULTS AND DISCUSSION

Since the physical model of the memristor was given, modeling the memristor within VerilogA seems to be easy. The memristor was modeled as a two-terminal device using Equation 5 to 9. In addition, the nonlinear drift effect was characterized by the window function proposed by Joglekar and Wolf [2]. Table 1 shows the parameters of the memristor model that was used in the computer simulation. Since the initial thickness of the doped region is 10 nm and the insulating layer has a total thickness of 20 nm, the initial equivalent resistance of the memristor is 5,000 Ω.

Table 1.
Parameters for the memristor model

R_{off}	R_s	D	μ	w_0
10,000 Ω	10 Ω	20 nm	1 μ	10 nm

The effect of the window function was first investigated. The window function coefficient p was 1 and 10, respectively. The simulation result is shown in Figure 4. Clearly, the nonlinear drift effect is more significant when p is small. When p is large, the memristor can change its resistance more easily.

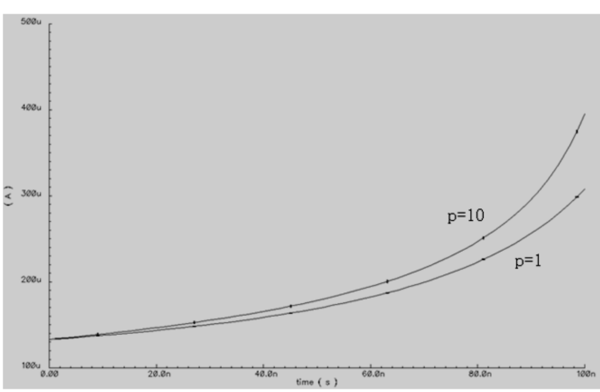

Figure 4. The effect of the window function

It was predicted that the memristor is purely dissipative [1]. That is, the input current/voltage and the output voltage/current do not have any phase shift. This property was observed in our work. Figure 5 shows the AC input voltage and its corresponding AC output current. Apparently, the phase difference between the input voltage and output current is zero.

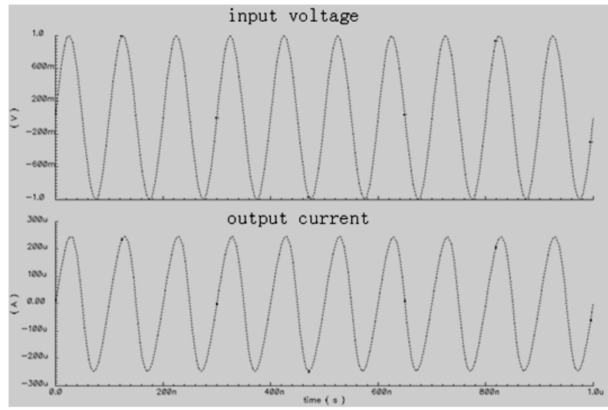

Figure 5. Zero phase shift of the memristor

Another interesting property of the memristor is that the resistive switching behavior of the memristor is more significant in the low frequency region. As the operating frequency of the memristor goes to infinity, the memristor reduces to a simpler resistor [4]. This frequency dependent property is shown in Figure 7 and 8, the test bench is shown in Figure 6. The initial equivalent resistance of the memristor was 5000 Ω. As we can see, when the frequency of the input voltage is 10 MHz, the output current of the memristor differs from the output current of a 5000 Ω resistor. However, when the operating frequency increases to 1 GHz, the memristor reduces to a normal resistor and the output of the memristor is the same as that of the 5000 Ω resistor. It is because when the input frequency is high, the time for oxygen vacancies to travel in the insulating layer is very short, which means the memristor has little time to change its resistance.

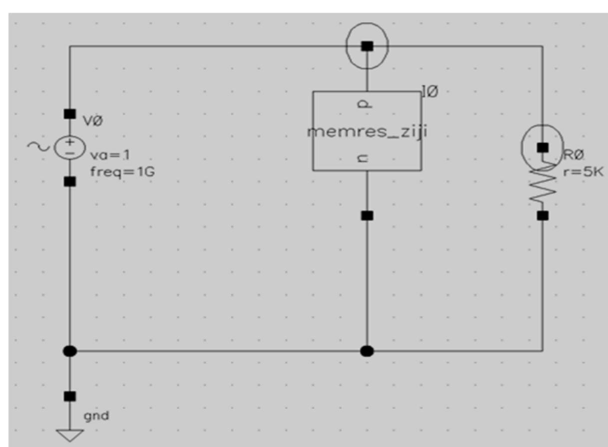

Figure 6. The test bench

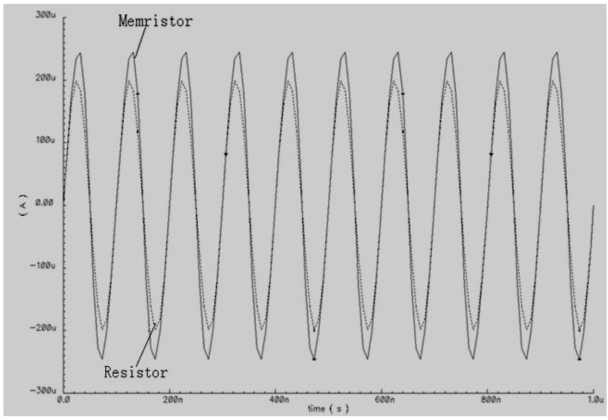

Figure 7. The AC output @ 10 MHz

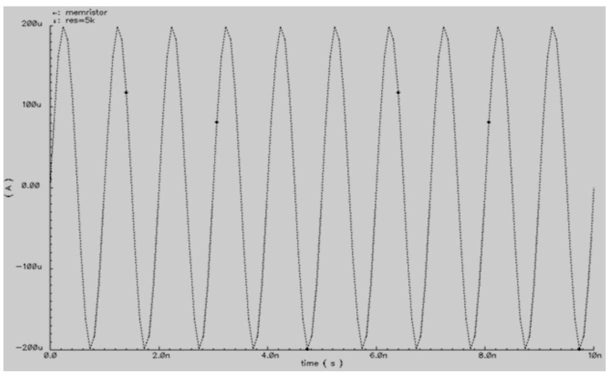

Figure 8. The AC output @ 1 GHz

Finally, the zero-input response of a source free memristor-capacitor (MC) system was studied. It was predicted that the time constant of a MC system, depends on the polarity of the programming voltage, may be smaller or larger than that of a RC system (the initial equivalent resistance of the memristor and the resistance of the normal resistor are same) [2]. The simulation result is shown in Figure 9. Clearly, the MC system charges faster this time than the RC system because the equivalent resistance of the memristor decreases when the programming voltage is positive.

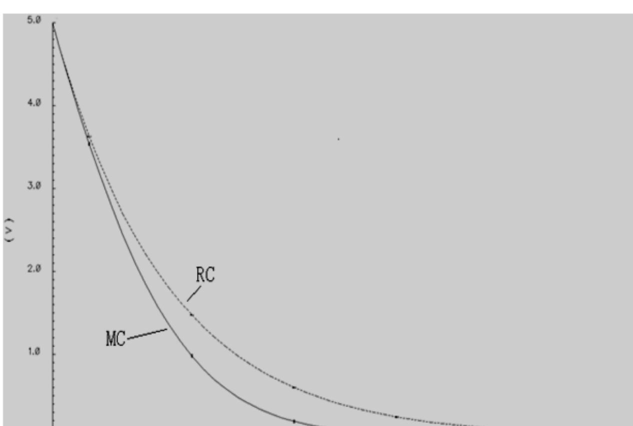

Figure 9. The zero input response of the MC system

5 FUTURE APPLICATIONS OF THE MEMRISTOR

Potential applications of the memristor are plenty. The most important application of the memristor should be used in nonvolatile memories. A memristor based SRAM was already proposed [5]. In addition, the memristor can be implemented into logic cells [6]. The memristor can be also used in analog circuits. The memristor has already be used into a variable gain amplifier [7]. Lots of other applications of the memristor are still under investigation.

6 SUMMARY

In this work, the unipolar and bipolar switching behaviors was first studied. The memristor typically exhibits bipolar resistive switching attribute. Then, the switching mechanism of the memristor was discussed, in which the movement of oxygen vacancies play an important role. A simple physical model of the memristor manufactured by Strukov er al. was then conducted and analyzed. Computer simulation results of the memristor that based on a VerilogA model were presented and discussed. This VerilogA model works well in predicting the behavior of the memristor. It should help researchers and engineers on the study of the memristor and memristor based circuits. Finally, potential applications of the memristor were introduced. It is our strong belief and expectation that the memoristor will play important role in microelectronics in near future.

REFERENCES

[1] Chua, L. O., “Memristor – The missing circuit element,” Circuit Theory, 18(5), 507-519, 1971
[2] Joglekar, Y. N., & Wolf, S. J., “The elusive memristor: Properties of basic electrical circuits,” European Journal of Physics, 30, 611, 2009
[3] Strukov, D. B. et al., “The missing memristor found,” Nature, 453, 80-83, 2008
[4] Chua, L. O., & Kang, S. M., “Memristive devices and systems,” Proceedings of the IEEE, 64(2), 209-223, 1976
[5] Wang, W. et al., “Nonvolatile SRAM cell,” Electron Devices Meeting, 2006
[6] Kaeriyama, S. et al., “A nonvolatile programmable solid-electrolyte nanometer switch,” Solid-State Circuits, IEEE Journal of, 40(1), 168-176, 2005
[7] Wey, T. A., & Jemison, W. D., “An automatic gain control circuit with TiO_2 memristor variable gain amplifier,” NEWCAS Conference, 2010