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Delayed Switching Applied to Memristor Content Addressable Memory Cell

Wanlong Chen, Xiao Yang and Frank Z. Wang

***Abstract*— Memristor is short for memory resistor, which provides a functional relation between flux and charge. Professor Leon Chua named and formulated it in his paper "Memristor—The Missing Circuit Element" in 1971. The memristor has a special effect, 'the delayed switching effect', which is the memristor switching takes place with a time delay. Content addressable memory (CAM) is a type of associative memories that is adopted in high speed searching applications. The new Memristor-CAM cell has been proposed, which included two memristors; one is used as an important part of the comparator that is instead of the traditional logic gate; and another one is for storing the data as a storage element. In this paper, we report that applying the memristor delayed switching effect to the novel design of the Memristor Content Addressable Memory (M-CAM) cell. The delayed switching effect is used to control the changing time of the memristor's state, which can enhance the performance, decrease the searching time and save energy.**

***Index Terms*—Memristor, memory, CAM, content addressable memory, delayed switching**

I. INTRODUCTION

Currently, there is a hardware search engine application available which works generally faster as compared to an algorithmic approach type of search-intensive applications. These are known as "Content-addressable memories (CAMs) [1]. Basically, a CAM works in such a way that it compares data which are input by the users against the stored data in the application and returns matching data as requested. With the usage of CAMs, search operation could be conducted in just a single clock cycle. This is possible as the CAMs are made up of conventional semiconductor memories (usually SRAMs are used) and enhanced with added comparison circuitry and because of the single clock cycle, this has made their search and fetch data relatively more efficiently as compared to many other hardware or software based search applications [2]. As the CAM's ability to read data in a shorter time frame, it is recommended that high search speed hardware is required but again this requirement does not limit the usage of CAMs in other variety of applications. Because of the CAM's parallel comparison characteristic that the most transistors are working at the same time on each operation, therefore, the power cost of CAMs is often significant [3].

The first physical memristor (memory resistor) device based on a nanoscale thin-film of titanium dioxide was announced by Dmitri B. Strukov and his colleagues at HP (Hewlett-Packard) in 2008 [4], [16]. The memristor makes a new era to the computer science. The memristor's non-volatile property that a memristor can keep information without power supporting makes memristors more suitable as computer memory elements [5]. As shown in Fig.1, the memristor can retain the low resistance (R_{on}) after the power supply is removed (the period after T3). The storage structure based on memristors is highly scalable and reveals the likelihood of the ultra-high density of memories [6]. Among the emerging nanotechnologies options, the memristors have become a very promising candidate for building the storage structures because of its shorter switching time, higher capacity, and lower power consumption [7]. In this paper, we use the memristors to replace the traditional transistors as storage elements and comparing elements for saving energy and improving the performance of the CAM.

In 2010, Wang had discovered a memristor's peculiar magneto-electronic effect and named it as 'delayed switching effect' [8], which is shown in Fig. 1, the switching from high resistance (R_{off}) to the low resistance (R_{on}) which takes place only with a time delay $T_d \approx T_1 \approx T_2$ after an input voltage is applied.

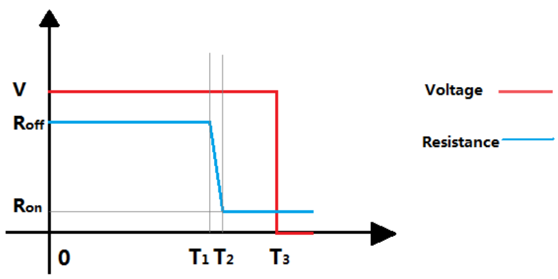

Fig. 1. The memristor's delayed switching effect: the switching from the high resistance (R_{off}) to the low resistance (R_{on}) due to a voltage pulse takes place with a time delay $T_d \approx T_1 \approx T_2$. The memristor's non-volatile feature: the memristor can keep the memory state (R_{on}) in power off condition (the time after T_3).

This paper is organized as follows: Section II is an introductory section that reviews the memristor; the memristor delayed switching effect and content addressable memory (CAM). Section III describes the new design of the memristor CAM cell. In Section IV, the circuit experiment and the result are reported in detail. Section V discusses the most important issue that is the M-CAM characterization.

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Eventually, Section VI offers brief conclusions.

II. Background

A. Memristor

Chua in 1971 proposed the memristor (a contraction for memory resistor) in his paper "Memristor-The Missing Circuit Element" [9], it was introduced as the fourth basic element with the resistor, the capacitor and the inductor of the electrical circuits. It is named as the missing element since the missing link between flux and charge is represented by the memristor. The memristor has a similarity with resistors, inductors and capacitors; they are all passive elements. In fact, a memristor has the ability as a non-linear resistor with memory; since the resistance of the memristor can be retained without power supply. Hence, compared with DRAMs, CAMs based on memristors are not overwritten multiple times a second because it does not fade with time.

B. Delayed switching

It was found that, considering a piecewise linear memristor model giving two states (on and off), the switching in a memristor takes place with a time delay (this peculiar scenario is named 'delayed switching'). Based on the research on this feature, it has revealed that time delay depends on the voltage which means a higher voltage takes place a shorter delay [8]. By this means, the state of memristor could be controlled that only the applied pulse which is wider than the delayed-switching time can change the memristance. As introduced, memristance responds to the integration of current, so a small pulse for a long period can also change the memristor's state after the time delay is reached [10]. Thus, the memristor won't work properly if the delayed switching effect has not been considered before memristors are applied in real circuitry.

C. Content addressable memory (CAM)

The content addressable memory (CAM) is an efficient hardware in digital systems and applications. Every CAM storage element has the capability of saving data (such as hard disk) and comparing its stored information with the data broadcasted by the central controller. Currently, there are two types of CAMs, one is binary CAM, which can store and search binary words ('1' and '0') and the other one is ternary CAM, which can store and lookup ternary states ('1','0',and 'X'), 'X' can be '1' or '0' which is not cared in some applications [11].

A CAM stores data in a similar way with a traditional random access memory (RAM). For a RAM, data are fetched by giving an address. However, in CAM, the wanted address is returned by comparing the stored data and the supplied search data. CAM is ideally suited for several functions; including Ethernet data compression, image coding, cache tags, high-bandwidth address filtering, and fast lookup of routing, user privilege, security encryption information on a packet-by-packet basis for high-performance data switches, pattern-recognition, firewalls, bridges and address lookup [1], [12]. The main CAM's application today is network routers which are used to forward and classify the IP packets [13].

III. Memristor-CAM Cell

A. Memristor content addressable memory (M-CAM)

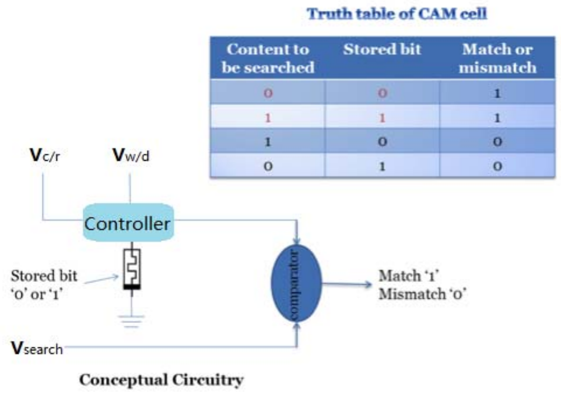

Fig. 2. The Memristor-CAM cell conceptual circuitry and its truth table. A table shown at top right corner is the truth table of the comparison process of the memristor-CAM cell. $V_{c/r}$ indicates the voltage for controlling the controller and reading the memristor. $V_{w/d}$ indicates the voltage for writing the deleting (or resetting) the memristor. Apparently, the different signals will give 'mismatch', otherwise 'match' will be given.

The conceptual circuitry shows a new memristor CAM cell that stores data using single memristor which can be stored bit '0' or '1' [15]. Apparently, from Fig. 2, data can be read from the cell through the line (V c/r); data can be written or deleted into the cell through the second line (V w/d); the line of V search is responsible for the transmission of the data that user would like to search. The comparator can analyse and return the result of "match" or "mismatch" once the search data and stored data have been compared.

IV. Circuit Experiment

This peculiar scenario, delayed switching, would affect both read and write operations in memory. Normally, there are three cases and the circuit experiments demonstrate the influences of delayed switching in all these three cases. A switching delay of approximate 7ms was set to the memristor emulator which was used in previous experiments [10], [14]. In this microcontroller-based memristor emulator, a non-volatile potentiometer was chosen to mimic the important non-volatile feature of memristor. Based on the applied pulse width, distinct behaviours happen and no voltage drop on a memristor when applied pulse is removed since memristor is a passive element.

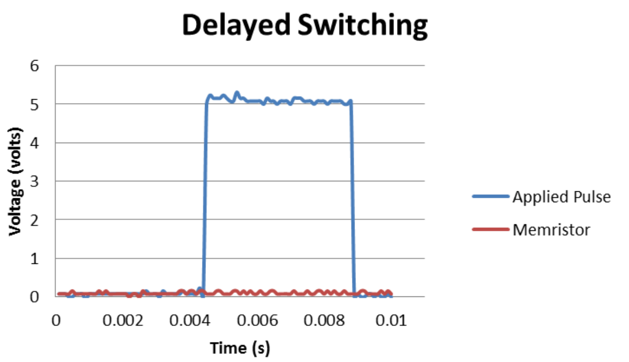

Fig. 3. The applied pulse is shorter than the switching delay in time. In this case, memristor's state keeps unchanged. Memristor keeps its ON state throughout the pulse. The applied pulse is 5V in amplitude and approximate 4ms in width which is shorter than switching delay (7ms).

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As mentioned in previous sections, if the applied pulse is shorter than the switching delay in time, the memristor's state keeps unchanged as shown in Fig. 3. In memory's write operation, this case should be avoided since it leads a misoperation when a state change is expected. However, the read operation can benefit from this situation because a state change is unwanted when reading the data stored in memory. Moreover, a lower voltage pulse can be used in a read operation to achieve the same effects and this will be elaborated in latter section in detail.

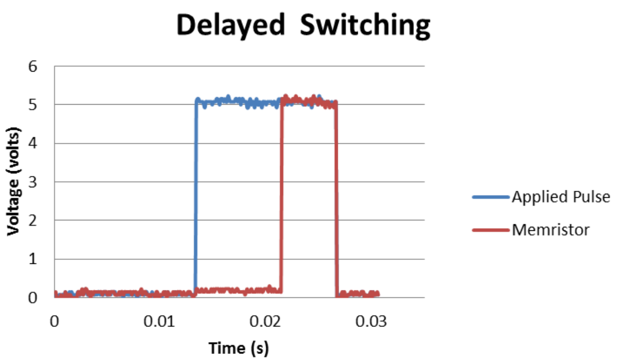

Fig. 4. The applied pulse is slightly longer than the switching delay. Memristor's state is changed from ON state to OFF state after the time delay. The applied pulse is 5V in amplitude and 13ms in width which is slightly longer than switching delay (7ms).

The second case, shown in Fig. 4, demonstrates that the applied pulse is slightly longer than the switching delay which leads the state change of the memristor. After that, memristor will consume extra power since the applied pulse has not been removed after the state change. Fig4 is self-explanatory that the extra power consumption depends on how long the pulse is still applied after the memristor's state is changed. Therefore, the similar case demonstrated in Fig. 5 consumes more power than the second one since its applied pulse is much longer.

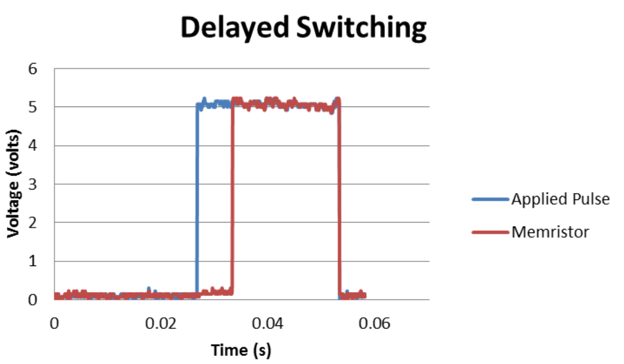

Fig. 5 The applied pulse is much longer than the switching delay. Memristor's state changes from ON to OFF since the applied pulse is much longer than the time delay. The applied pulse is 5V in amplitude and 26ms in width which is much longer than switching delay (7ms).

Accordingly, concerns on delay switching are critical when memristors are applied in real application. It affects not only the read and write operation but also the power consumption of memory. To achieve a read operation without affecting the stored data, the applied pulse should be shorter than the time delay. Conversely, a write operation should have an applied pulse which is longer than the time delay to override memristor's state. Otherwise, a misoperation would happen. For reducing the power consumption of the memristor-based memory, the applied pulse should be as short as possible but longer than the time of the switching delay.

V. M-CAM Characterization

A. *The power of the M-CAM cell*

The resistance of the memristor depends on the complete past history of the current, i.e., the time integral of the current from $t = -\infty$ to $t = t'$, so the state equation (1) of the memristor can be given by

$$q(t) = \int i(t)dt = \int \frac{V \cdot dt}{R} = \frac{V}{R} \times t \tag{1}$$

The state of the memristor can be changed from off state to on state, or from on state to off state, therefore

$$q_{off-on} = \frac{V}{R_{off}} \times T_{off-on} \tag{2}$$

$$q_{on-off} = \frac{V}{R_{on}} \times T_{on-off} \tag{3}$$

Since the resistance of the memristor depends on the complete past history of the current, we obtain

$$q = q_{off-on} = q_{on-off} \tag{4}$$

The heat dissipation during one cycle, which included a single switching from R_{off} to R_{on} and another single switching from R_{on} to R_{off}, can be obtained by

$$W = W_{off-on} + W_{on-off} = \frac{V^2}{R_{off}} T_{off-on} + \frac{V^2}{R_{on}} T_{on-off} \tag{5}$$

Based on (2), (3), (4), we get

$$W = \frac{2V^2}{R_{off}} T_{off-on} = \frac{2V^2}{R_{on}} T_{on-off} = 2 \times V \times q \tag{6}$$

The time (T) of one cycle includes a single switching from R_{off} to R_{on} and another single switching from R_{on} to R_{off} (clear operation).

$$T = T_{off-on} + T_{on-off} \tag{7}$$

Based on (2), (3), (4), (7), we get

$$T = \frac{R_{off} + R_{on}}{R_{off}} \times T_{off-on} \tag{8}$$

As we can get the total heat dissipation (6) of one cycle (8), the power can be obtained by

$$P = \frac{W}{T} = \frac{2V^2}{R_{off} + R_{on}} \tag{9}$$

It is assumed that the memristor's resistance of the off-state is *k* (the off-to-on resistance ratio) times that of the memristor's resistance of the on-state, which is given by

$$R_{off} = k \times R_{on} \tag{10}$$

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Substituting (10) into (9), we have the power

$$P = \frac{2V^2}{(1+k)\times R_{on}} \tag{11}$$

The relationship between the voltage V, the resistance R_{on} of the memristor's on state, the off-to-on resistance ratio k and the power P is described in (11), which concludes that the power is depended on the applied voltage and the material of the memristor fabrication. From (11) and Fig. 6, it is obvious that (i) the increase in the voltage brings about an increase in the power; (ii) the greater the off-to-on resistance ratio is, the lower the power is; (iii) the decrement of the memristor's resistance causes an increase in the power.

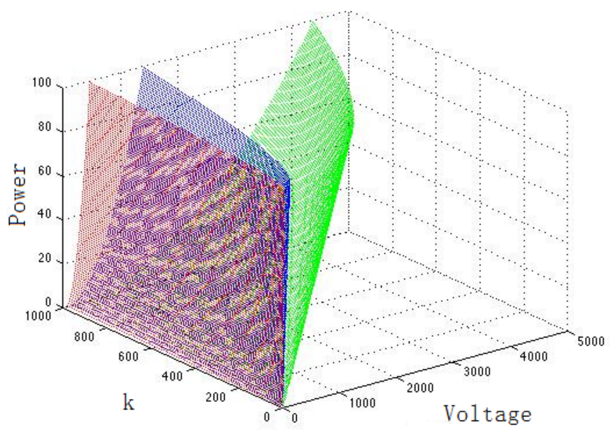

Fig. 6. The relationship between the voltage *V*, the resistance of the memristor on state R_{on}, the off-to-on resistance ratio *k* and the power *P*. [R_{on}=3.8(red), 38(blue), 380(green)]

B. *Working frequency of the M-CAM cell*

The maximum working frequency f_{max} of the M-CAM cell is given by

$$f_{max} = 1/T_d \tag{12}$$

If the power is removed before the switching takes place, the memristor keeps unchanged. Therefore, for switching the memristor, the time (T) of the voltage should be chosen in such a way that $T > T_d$. However, in order to save energy, T should be greater than T_d, but close to T_d. As a consequence, the ideal working frequency of the M-CAM cell is $1/T_d$. Physically, the working frequency increases with the voltage, but is limited by the heat dissipation.

VI. Conclusion

The memristor has some peculiar effects and useful features, such as delayed switching effect and non-volatile. With these effects and features, this new CAM cell design reduces the power consumption, storage element size and design complexity compared with traditional storage elements. The proposed CAM cell design is the initial step to develop a general and large scale CAMs based on memristors.

References

[1] Pagiamtzis K and Sheikholeslami A (2006), "Content-addressable memory (CAM) circuits and architectures: A tutorial and survey", Solid-State Circuits, IEEE Journal of. Vol. 41(3), pp. 712-727. IEEE.

[2] Tyshchenko O and Sheikholeslami A (2008), "Match sensing using match-line stability in content-addressable memories (CAM)", Solid-State Circuits, IEEE Journal of. Vol. 43(9), pp. 1972-1981. IEEE.

[3] Chang Y-J and Liao Y-H (2008), "Hybrid-type CAM design for both power and performance efficiency", Very Large Scale Integration (VLSI) Systems, IEEE Transactions on. Vol. 16(8), pp. 965-974. IEEE.

[4] Strukov DB, Snider GS, Stewart DR and Williams RS (2008), "The missing memristor found", Nature. Vol. 453(7191), pp. 80-83. Nature Publishing Group.

[5] Ho Y, Huang GM and Li P (2009), "Nonvolatile memristor memory: device characteristics and design implications", In Computer-Aided Design-Digest of Technical Papers, 2009. ICCAD 2009. IEEE/ACM International Conference on. , pp. 485-490.

[6] Vontobel PO, Robinett W, Kuekes PJ, Stewart DR, Straznicky J and Williams RS (2009), "Writing to and reading from a nano-scale crossbar memory based on memristors", Nanotechnology. Vol. 20(42), pp. 425204. IOP Publishing.

[7] Liu Y (2011), "Architecture for Memristor-based Storage Structures". Duke University.

[8] Wang FZ, Helian N, Wu S, Lim M-G, Guo Y and Parker MA (2010), "Delayed switching in memristors and memristive systems", Electron Device Letters, IEEE. Vol. 31(7), pp. 755-757. IEEE.

[9] Chua L (1971), "Memristor-the missing circuit element", Circuit Theory, IEEE Transactions on. Vol. 18(5), pp. 507-519. IEEE.

[10] Wang FZ, Helian N, Wu S, Yang X, Guo Y, Lim G and Rashid MM (2012), "Delayed switching applied to memristor neural networks", Journal of Applied Physics. Vol. 111(7), pp. 07E317-07E317. AIP.

[11] Agrawal B and Sherwood T (2008), "Ternary CAM power and delay model: Extensions and uses", Very Large Scale Integration (VLSI) Systems, IEEE Transactions on. Vol. 16(5), pp. 554-564. IEEE.

[12] Peng M and Azgomi S (2001), "Content-addressable memory (cam) and its network applications", In International IC--Taipei Conference proceedings. , pp. 1-3.

[13] McAuley AJ and Francis P (1993), "Fast routing table lookup using CAMs", In INFOCOM'93. Proceedings. Twelfth Annual Joint Conference of the IEEE Computer and Communications Societies. Networking: Foundation for the Future, IEEE. , pp. 1382-1391.

[14] Yang X, Chen W and Wang FZ (2013), "A Memristor-CAM (Content Addressable Memory) Cell: New Design and Evaluation.", In International Conference on Computer Science and Information Technology. , pp. 1045-1048.

[15] Eshraghian K, Cho K-R, Kavehei O, Kang S-K, Abbott D and Kang S-MS (2011), "Memristor MOS content addressable memory (MCAM): Hybrid architecture for future high performance search engines", Very Large Scale Integration (VLSI) Systems, IEEE Transactions on. Vol. 19(8), pp. 1407-1417. IEEE.

[16] Williams R (2008), "How we found the missing memristor", Spectrum, IEEE. Vol. 45(12), pp. 28-35. IEEE.

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