Memristor In Non-Volatile Memory Technology and Computer Architecture

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Abstract. The memristor is the fourth passive basic electronic component after resistance, inductance, and capacitor. Traditional storage technology is progressively encountering more and more difficulties as information technology advances at the rate predicted by Moore's Law, including issues with power consumption, read and write speeds, storage capacity, and other issues. Memristor is a novel non-volatile memory technology that offers a wide range of potential applications and significant research value. It is now a strong rival to next-generation memory technology. This article provides an overview of the memristor's operating principle, presents its current state of application based on available research, and goes into great depth on the state of nonvolatile memory research. Lastly, a summary and outlook for the memristor's future development are provided. Memristors are predicted to surpass Moore's Law's constraints in the future, advance the advancement of storage technology, and provide ground-breaking assistance in the creation of computer architecture and new technologies.

Keywords: Memristor, Non-volatile Memory, The Working Principle, Crossbar Array.

1. Introduction

Since the first computer was created in 1946, the von Neumann architecture has played a significant role in separating memory and computation and enabling the call and processing of data via instructions. The reading and writing speeds of conventional memory and CPUs might not be able to keep up with the speed at which software technology is developed in the future due to the Internet's big data and artificial intelligence development. The concept of memristor was initially put forth by Professor Leon O. Chua of the University of California, Berkeley in 1971. Leon Chua used symmetry reasons (in Figure 1) to support his theory, that is, in addition to resistance, capacitance, and inductance, there should be a fourth basic element – memristor [1]. Memristors, sometimes known as "memory-resistors," are simple two-terminal circuits that can recall their internal resistance state based on the input stimulus's past. According to Leon O. Chua, there should still be a relationship between charge and magnetic flux in nature, but at that time, no material could be found that could adequately describe this relationship given the state of technology. Chua came up with the idea that the relationship between flux and charge time integrals of voltage and current, respectively the characteristics of memristors [2]. Despite his demonstration of the element's several intriguing and important circuit features, no practical physical model or memristor example was provided at the time [1].

The HP team did not find a material with memristor properties until 2008. The partially doped TiO2 was found to have unique electrical characteristics when the team applied voltage at both ends of the device for a resistance test. Specifically, the resistance of the device increased when current flowed from the undoped side to the doped side and decreased when current flowed from the doped side to the undoped side. The ability to remember the historical current is one of resistance's qualities. This information served as a starting point for later studies on the circuitry and construction of memristors.

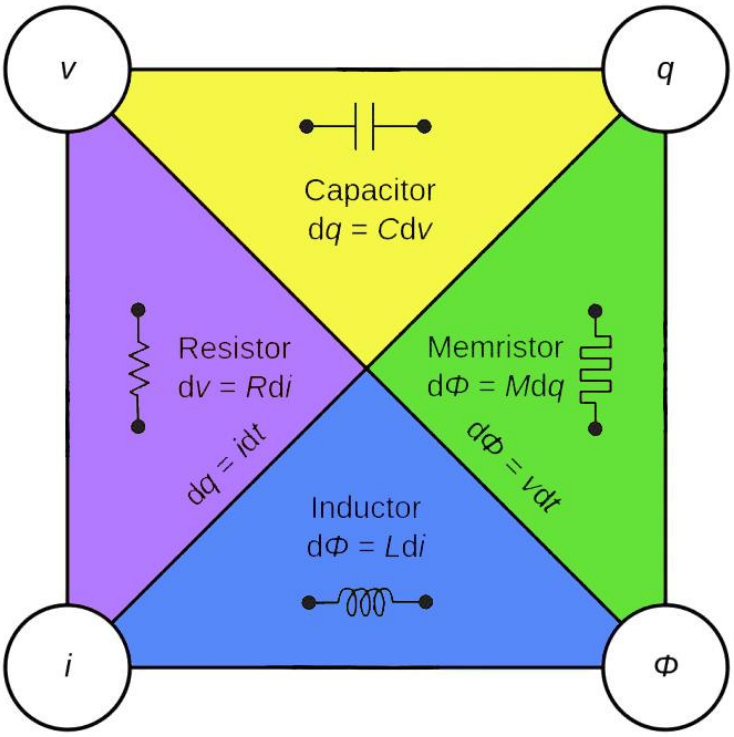


Figure 1: The four fundamental two-terminal circuit elements: resistor, capacitor, inductor, and memristor

The discovery and research of memristor has a profound impact on the development of many fields. In recent years, based on the nonlinear and non-volatile characteristics of memristors, the research in the field of memory has made rapid progress, and the RRAM designed by the HP team using memristors has shown outstanding advantages in terms of storage density, access speed, power consumption, and cost. And its technology, which also makes it in the field of neural networks has excellent prospects for development, the application of the Crossbar array in the field of storage and computing gives the memristor in the deep learning neural network great potential. In the big data age, traditional computing systems encounter challenges such as memory barriers [3]. The "memory wall," or the crucial performance bottleneck in systems, is the speed difference between memory and logic [4]. With Moore's law coming to an end and the anticipated small gains in processing power that follow through on scaling, it is unclear if hardware constraints will cause advancements to slow down or stop entirely [5]. Memristor-based computer architectures have demonstrated significant potential as supplementary or replacements for conventional von Neumann-based computing systems.

2. Method

2.1. How the memristor works

The memristor's resistance mechanism is a physical process wherein an applied voltage or current causes ions or holes to migrate, changing the memristor's internal resistance. According to research by Leon O. Chua, the link between magnetic flux and electric charge is the foundation for the memristor's operation. A memristor's resistance is determined by the amount of charge that passes through it, unlike traditional resistors. This indicates that a memristor's resistance state is correlated with the amount of charge it has previously experienced; therefore, the term "memory" resistor. When a periodic voltage or current signal with a zero-average value drives a memristor, its most distinctive characteristic is the zero-crossing hysteresis curve (in Figure 2) in the voltage-current plane. When the memristor was first physically built in 2008, HP LABS initially declared the existence of the zero-crossing hysteresis curve as a feature. The memristor's current-voltage curve is represented by a zero-

crossing hysteresis curve. Boundary variations between doped and undoped areas cause memory to not be continuous. After the voltage hits its maximum, the current starts to accelerate and keeps rising even if it is increasing more slowly at first. Because the current always equals zero when the voltage equals zero, the loop closes once more at the origin. All memristors have hysteresis curves that intersect at zero. The zero-crossing hysteresis curve is used as a fingerprint to identify a memristor since each one has its own set of characteristics and fingerprints [6]. Because memristors vary in some ways from capacitors, resistors, and inductors, they may be used in a wide range of innovative applications that are not possible with RLC networks alone [7]. Also， Memristors offer a wide range of possible uses because of their special electrical characteristics, including nonvolatile memory, artificial neural networks, logic and computational circuits, nonlinear circuit designs, and more.

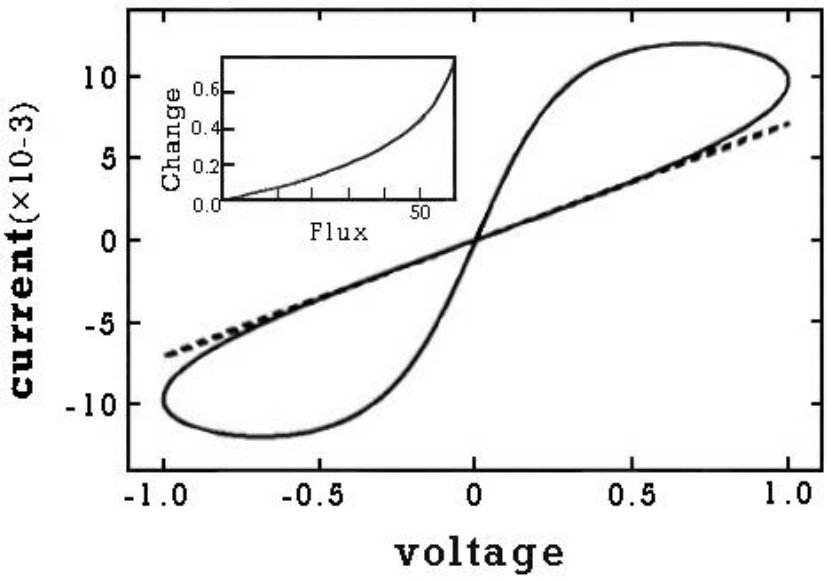


Figure 2: A zero-crossing hysteresis curve in the current-voltage characteristic of Memristors

2.2. Principle

The fundamental mathematical model may be generated by a theoretical examination of the memristor structure's electrical characteristics. The voltage value multiplied by the memristor's memristor value yields the current value. In the time domain, the remembrance value is a function of the flux, which is an integral function of the voltage. The voltage integral in the time domain represents the remembrance value [8]. It is possible to determine a relationship between the memristor's conductance value and the applied historical voltage [8]. The memristor has a memory function because even in the event of a voltage disconnect, the memristor's memristor value remains constant due to the constant magnetic flux [8].

The boundary transfer model is the most often used memristor structure model at the physical model level (in Figure 3). A doped semiconductor sheet is positioned between the two metal electrodes at the ends of the boundary transfer model. According to the model, the semiconductor layer between the electrodes is made up of an undoped area or a low-doping concentration region with high resistance and a high-doping concentration region with low resistance. The boundary W migration in the area of high doping concentration is driven by the bias voltage of the load at both ends of the structure. As a result, the resistance of the structure to the outside changes with applied voltage and time. This model is unique in that if the voltage is cut off, the border W remains stationary, indicating that it is frozen. The memristor "remembers" how much voltage was ultimately supplied in this way.

Hewlett-Packard invented a version of the memristor in 2008 that consists of two platinum electrodes sandwiched between a layer of insulating titanium dioxide, or TiO2. A portion of the TiO2 layer is "doped"; this means that it contains oxygen vacancies, which function as positive ions and

release electrons, which are capable of conducting electricity. The location of the boundary between the doped and undoped areas determines the device's overall resistance. Additionally, an applied electric field can shift this boundary. A forward bias voltage increases the doped region and decreases the resistance as it moves higher from the middle of the sequence; a reverse bias voltage moves downward from the middle and leaves the majority of the layer undoped, increasing the resistance.

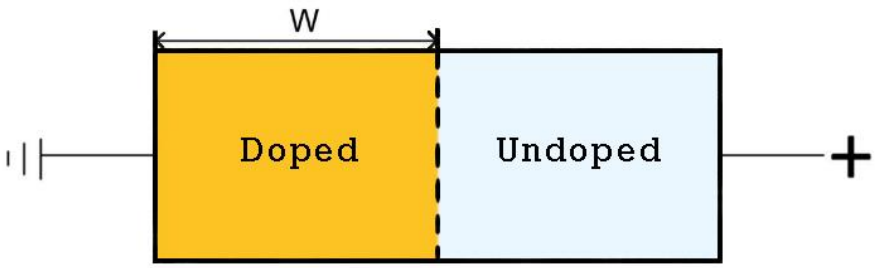


Figure 3: Schematic of TiO_2 Memristor

The electrical behavior and switching dynamics of memristive devices are similar to those of synapses and neurons, owing to their ion migration-based operating principles. As such, these devices hold great promise for brain-inspired computing [9].

3. Result

3.1. Application of memristor in the field of Information storage

In recent years, nonvolatile memory technology has drawn interest as a possible general-purpose memory substitute. A memory that can store data without losing it over an extended length of time even in the absence of a power source is known as non-volatile memory. NVMS typically have advantages such as high density, fast read speed, and low leakage power [10]. Any properly functioning information processing system must have permanent and temporary data storage, which is now provided by COMs-based memory such as SRAM, DRAM, and flash memory [11]. Nonetheless, some experts have hypothesized that the shrinking of devices will cause development difficulties for COMs-based memory. Nonvolatile memory is a hot topic right now, and memristors might play a big role in NVM research. Memristors are distinctive in several ways when it comes to information storage. It uses a relatively small amount of both energy and space. Resistive Random Access Memory, Phase Change Random Access Memory, Fe Random Access Memory, Magnetoresistive Random Access Memory, MolybDenum Disulfide Random Access Memory, and more novel forms of non-volatile memory are still in the development stage. A new kind of memory called RRAM was created using memristor technology. RRAM stores information according to the variation in impedance between the oxide and the electrode. In particular, it applies a pulsed voltage to a metal oxide sheet, which causes a significant resistance differential, representing data "0" and "1". In addition to making production easier, the memory's very basic structure of metal oxide sandwiched between electrodes on both sides helps accomplish features like high-speed rewriting and low power consumption. RRAM has several benefits, including compact size, high access speed, and extremely low power consumption. These attributes provide a lot of potential applications in the field of future storage technology.

Memristors are a formidable rival for the upcoming generation of non-volatile memory because of their low power consumption, great scalability, simple structure, quick operating speed, and low energy requirements. Memristors' non-volatility, high compatibility, quick reaction time, and low power consumption in CMOS systems have all been experimentally shown by HP LABS. For the time being, nevertheless, RRAM still faces a lot of issues. For instance, ways to enhance the device's storage, lessen the discreteness of the transition parameters, lower the device's erase current, and so on.

3.2. Application of memristor in the field of Logical operation

Memristors can mimic the land, or, and not fundamental logic gates. This is because the memristor's resistance value may change based on the direction and amount of current flowing through it, carrying out logical operations. Logical operation function can be accomplished, for instance, by varying the resistance value of the memristor to represent distinct logic states. Since memristors have variable resistance rather than just two states, like transistors, their resistance may represent a variety of states, including "on" and "off." This means that memristors can be utilized to develop novel computational models and analog computers. The two operands must be represented in some form for each arithmetic operation, including addition, subtraction, multiplication, and division. In practically all circuits that are in use today, the signal value is represented by voltage or current. Addition, subtraction, multiplication, and division are the fundamental arithmetic operations. A summation operation (M1+M2) is the total memristor of two memristors connected in sequence [12]. A reader may write any subtraction operation as M1+(-M2) [12]. For example, M1-M2[12]. This indicates that the memristor must be in series with another memristor that has a memristor of -M2 to perform subtraction [12] (in Figure 4). An op-amp-based inverting amplifier with a memristor may be used to create the corresponding operation circuit for division and multiplication operations. The use of a memristor in logic operation not only makes calculations much more efficient but also opens up new avenues for the creation of more effective logic operation devices.

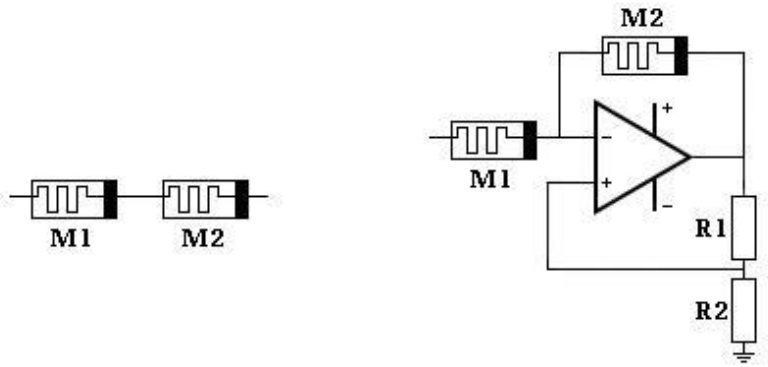


Figure 4: Addition and subtraction circuits for memristors

3.3. Application of memristor in the field of neural network

The extensive connections across neurons in biological systems provide a high degree of parallel processing capacity, which is essential for their high efficiency [13]. Ion flow can accurately control the synaptic weight between two neurons, and it is generally accepted that biological systems can learn and operate through the adaptation of synaptic weight [13]. Moreover, memristors perform biological synapses' functions. Neural networks rely on synapses, and as memristor resistors' characteristics are influenced by their previous states and mimic the functioning of neural synapses in the brain, they may be used to model synaptic connections in the human brain and for related research on neuromorphic circuits. Simulating the synaptic plasticity of brain networks, memristors may simultaneously carry out intricate computing tasks. Because of this, memristors are crucial parts of neural networks. Traditional DNN neural networks mainly rely on software to run on CPU and GPU platforms, and due to the necessity of transferring data between the processor and memory units, DNN data flows are transformed into enormous physical instructions that are executed by digital computers. This process requires a significant amount of computational power and places a limit on performance [14]. The advent of the memristor has given individuals a new way of thinking.

Incorporated into vast crossbar arrays to create neural networks, they use physical laws directly to do effective in-memory computation with massive parallelism [9]. The bar array is this. Crossbar arrays (in Figure 5), which are made up of word and bit lines that are perpendicular to one another, are an efficient computer system architecture. Memristors can be arranged so that they create a storage

unit at their intersection. Every memristor in the bar array can be a synapse in an artificial neural network, and the resistance value of the memristor can represent the synapse's weight. In addition, the memristor can modify its resistance value in response to variations in the external voltage or current to update the weight of the neural network. Furthermore, the horizontal bar array is capable of large-scale parallel computation, which is comparable to neural networks' capacity for parallel data processing.

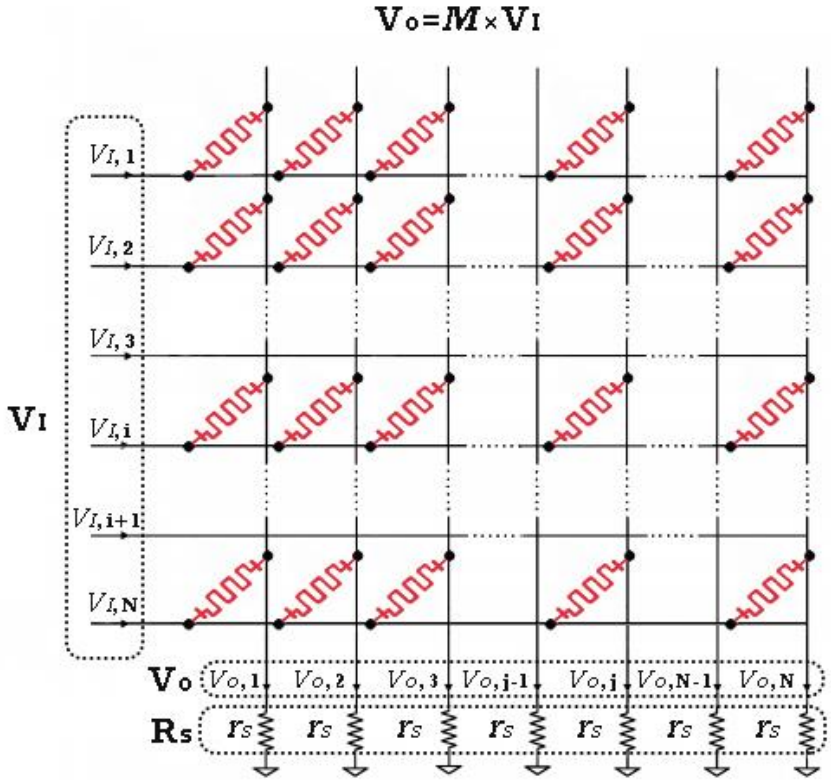


Figure 5: A memristor corssbar array

The emergence of crossbar arrays opens up a new avenue for hardware-level neural network realization. This technology has the potential to significantly increase computing efficiency and decrease energy consumption, and it is also crucial for advancing the fields of machine learning and artificial intelligence.

4. Conclusion

Memristor is a ground-breaking innovation in computer science and electronic engineering that will boost computer systems' dependability, processing capacity, and power efficiency. It offers the potential for new storage systems because of its distinct storage effect properties, miniaturization, quick read and write speed, and low power consumption. Memristors also provide the technical basis for the realization of memory and computing integration architecture, which helps to break the limitations of traditional von Neumann computing architecture and improve the efficiency of data processing. The integration of storage and computing is an important development direction of computing technology in the post-Moore era. Simultaneously, the memristor possesses the fundamental properties of parallel matrix multiplication and addition operations, rendering it an efficient tool for computing tasks in neural networks. This makes it a significant technology that will aid in the advancement of artificial intelligence hardware in the future. However, research on the large-scale array integration technology of the memristor structure is still ongoing, as are the intricate physical phenomena within it. Practical applications depend heavily on the memristor's dependability and longevity; when it is used more frequently, material fatigue may cause the memristor's

performance to decline. However, the resistance in the most promising crossbar memristor systems is frequently uneven in the structure distribution or resistance drifts, so one of the challenges for future research will continue to be producing high-performance crossbar memristor arrays with micro and nano dimensions. Memristor cannot currently be produced or used on a big scale because of the aforementioned issues. Therefore, in the future, researchers should continue to explore the mechanism, materials, and structure of memristors, so that memristors can play a more important role in the field of information technology.

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