

Preparation of Memristor and Research of Resistance-Change Mechanisms

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Abstract: The memristor, a recently developed electronic component, has the potential to address the limitations of data processing and storage in traditional von Neumann architecture computers. It is a promising substitute for traditional CMOS components in artificial neural networks due to its distinctive low power consumption, rapid response time, and non-volatile memory characteristics. The precise nature of the resistive change mechanism of the memristor remains unclear. The majority of research to date has focused on three main mechanisms: ionic, electronic and thermal. In regard to the selection of materials, the electrode components of memristors may be composed of metals, carbon-based materials, or conductive oxides, which possess the capacity to carry the current and engage in the resistive reaction. Memristors display a multitude of prospective applications in the field of memory devices and brain-like computing systems, given their superior characteristics. For instance, organic memristors may be employed in the biomedical sector for the production of wearable devices, given their affordability, simplicity of fabrication and biocompatibility. Furthermore, inorganic and organic materials can be combined, which is anticipated to facilitate the development of memristors with enhanced performance. These developments underscore the significance of memristors in next-generation computing and storage technologies.

Keywords: Memristor, Material, Resistance Change Mechanisms, Material Preparation, Dielectric Layer, Electrodes.

1. Introduction

Memristors represent a distinct fourth category of electronic component, distinct from the traditional resistive, capacitive and inductive types. Memristors have the potential to function in a manner analogous to transistors, in that they can retain the charge that has passed through them after a power failure. It is therefore possible that memristors may prove to be a superior alternative to transistors in digital integrated circuits due to the latter's inherent limitations. The research and development of memristors is expected to further improve the computing power of processors, overcome the memory barrier and address the growing discrepancy between the computing throughput of processors and the bandwidth of memories. Secondly, the potential applications of memristors cover a wide range of fields, including computing, biology and medicine, and offer a huge scope for further development.

From another perspective, the memristor exhibits similarities to the synaptic function of the human brain, which is both calculable and storeable. The technology can be employed to develop neuromorphic computations that emulate the architectural configuration of the human brain,

facilitating the integration of computational and storage functions. This has the potential to enhance the chip's capacity for computation and data storage while reducing its power consumption and eliminating the significant energy overhead associated with the frequent movement of data between memory and the central processor. Furthermore, the intelligent chip constructed with a memristor is capable of online learning, which is anticipated to address issues that remain unresolved by current machine systems.

This paper will commence with an introduction to the background and characteristics of memristors. Given that the resistance mechanism of memristors is still under investigation, this paper will present a list of the most commonly observed resistive mechanisms (ionic effect, electronic effect, thermal effect) and provide illustrative examples. Subsequently, this paper will focus on the currently most commonly used memristor materials and the methods used to prepare them. This will include a discussion of the materials used for the dielectric layer and the materials used for the electrodes. With regard to both dielectric layer materials and electrode materials, the current scope of research encompasses a diverse range of materials, including perovskites, metals, graphene, carbon nanotubes, binary metal oxides, sulphides, organic materials, and a multitude of other potential candidates. In light of the spatial limitations, this study does not provide a comprehensive overview of memristor applications in machine learning.

2. The introduction of memristor

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2.1. The Background of memristors

The exponential growth in the volume of data that is both processed and stored has created a significant challenge for computers based on the von Neumann architecture. The width of the data transfer channel between the CPU and the memory is a limiting factor that restricts the further arithmetic improvement of humans. In light of these considerations, the artificial neural network (ANN) is regarded as the most probable solution to this problem. It is capable of storing and processing data in a manner analogous to the biological responses observed in the human brain. At present, memristors are being employed in artificial neural networks as a means of supplanting the conventional CMOS components [1].

2.2. The Characteristics of memristors

The memristor is a nanoscale, non-volatile memory device with inherent low-power, high-response, and state-switching characteristics. These properties make it a promising candidate for replacing transistors in logic circuits and brain-like computing circuits that integrate data storage and parallel computation [2]. Furthermore, the memristor has the potential to overcome the limitations of the Von Neumann architecture. Table 1 shows a comparison of memory and storage technologies for various electronic components.

Note that circuit-level overheads for the listed performance metrics are in general different among different device technologies and could often dominate individual device performance.

Table 1: Comparison of memory and storage technologies

	Memristor	PCM	STTRAM	SRAM	DRAM	Flash (NAND)	HDD
		<u>Prototypes</u>		<u>Commercialized technologies</u>			
Reciprocal density(F^2)	< 4	4-16	20 – 60	140	6 – 12	1 – 4	2/3
Energy per bit(pl)	0.1 – 3	2 – 25	0.1 – 2.5	0.0005	0.005	0.000002	$1 - 10 \times 10^9$
Read time(ns)	< 10	10 – 50	10 – 35	0.1 – 0.3	10	100,000	$5 - 8 \times 10^6$
Write time(ns)	–10	50 – 500	10 – 90	0.1 – 0.3	10	100,000	$5 - 8 \times 10^6$
Retention	years	years	years	As long as Voltage applied	<<second	years	years
Endurance(cycles)	10^{12}	10^{15}	10^{15}	$> 10^{16}$	$> 10^{16}$	10^4	10^4

*The energy to operate NAND Flash is typically hundreds of picojoules per bit primarily because accessing the memory cells requires charging word and bit lines to high voltages. 'Smaller number represents an effective area for multi-level cells. PCM, phase-change memory: STTRAM, spin torque transfer random access memory: SRAM, static RAM: DRAM, dynamic RAM: HDO, hard disk drive [3].

3. The Mechanism of resistance change

The precise nature of the resistive mechanism of the memristor remains unclear, with some controversy surrounding this topic. The three fundamental categories of resistive processes are ionic, electrical, and thermal effects.

3.1. Ionic Effect

The ionic effect represents the primary mechanism of the memristor, whereby the resistance is altered as a consequence of ion transport and a chemical reaction occurring under the influence of an electric field. The ion effect can be further subdivided into two categories: the cation effect and the anion effect [4].

3.1.1. The mechanism of cation migration

The Cation Migration Mechanism ECM reaction (ElectroChemical Metallization) entails that the dielectric layer of the memristor is a solid electrolyte, and the two electrode materials exhibit disparate electrochemical activities (typically comprising active and inert metals). During operation, the active metal functions as the anode, while the inert metal serves as the cathode. The memristor's principal mechanism, the ionic effect, alters the resistance of a circuit due to the movement of ions and a chemical process that occurs when an electric field is present.

3.1.2. The mechanism of anion migration

The materials employed in the dielectric layer of a memristor based on the anion migration mechanism are predominantly insulating oxides, while their electrode materials are typically inert metals. This configuration presents a challenge in achieving the transition between the high and low resistance states of the memristor through participation in the redox reaction, which is a key aspect of the device's functionality. Consequently, a memristor based on the anion migration mechanism is capable of achieving the transition between the high and low resistance states of the memristor through the introduction of an applied voltage between the two electrodes, which is achieved through the electrically stimulated change of the resistance in the sandwich structure of metal-insulator-metal (MIM) [5].

3.2. Electron Effect

The redox processes and physical thermal effects caused by ion migration are not included in the pure electron method, which is essentially distinct from the ion migration mechanism. The transition between the memristor's high and low resistance states is enabled by a purely electronic mechanism, which is based solely on the capture and release of electrons. To illustrate, the incorporation of amorphous silicon components doped with nitrogen or oxygen between metal electrodes results in the establishment of consistent electrical conductivity on the nanoscale. The formation of electronic pathways in amorphous insulators is contingent upon the overlapping of gap states, which are in turn regulated by bound charges. Furthermore, the stabilisation of electronic gap states is dependent upon electron-lattice interactions. It follows that the memristor can be made to transition between insulator and metal for high and low resistance states by applying pressure [6].

3.3. Thermal Effect

The Joule thermal effect, which gives rise to discernible ion motions in response to variations in temperature, serves as the foundation for the operational principle of the memristor. This results in a modification of the memristor's high and low resistance states. At this juncture, the conductive channel material of the memristor may comprise metal atoms or oxides with metallic properties. The characteristics of thermal memristors are manifested in the form of Lissajous-type i-V curves (current vs. voltage difference). Consequently, a comparable behaviour in q-T curves (heat flux vs. temperature difference) can be identified as a distinctive feature of thermal memristors [7].

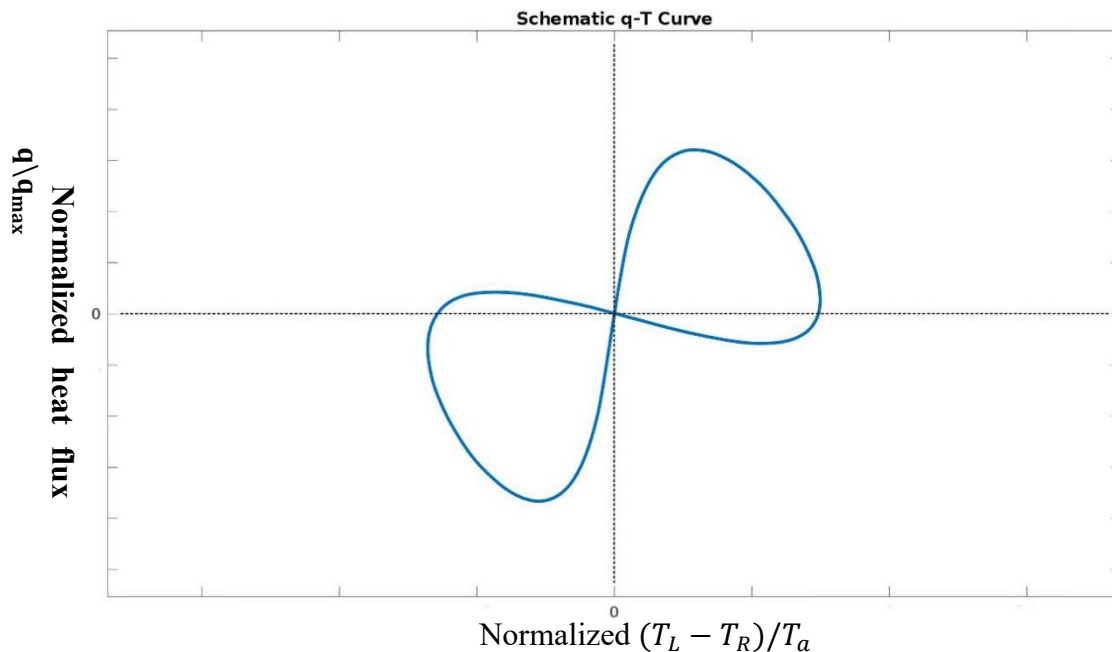


Figure 1: Lissajous Curve of Thermal Memristors [7]

4. The Preparation of Memristor

The selection of materials for the memristor encompasses both the material utilized in the dielectric layer and that employed in the electrode layer. The distinction between the materials employed determines the resistance mechanism and the performance of the memristor.

4.1. Electrode Material

The electrode material of the memristor must have the function of conducting current and participating in the resistive reaction. These can be transparent conductive flexible oxides such as metals, carbon based materials such as graphene and carbon nanotubes, nitrides, indium tin oxide (ITO), doped ITO and F-doped tin oxide (FTO). Novel electrode materials such as TiO_x, SiO_x and AlO_x are simple, highly stable, low cost and compatible with conventional CMOS processes. HfO_x and TaO_x are promising due to their high on/off ratios, sub-nanosecond operating speeds and durability beyond 10¹⁰ cycles [8].

Perovskites are materials with an ABX₃ structure. Common perovskites include MAPbI₃, (C₄H₉NH₃)₂PbBr₄, LaFeO₃ and MAPbBr₃. Perovskites have novel optoelectronic properties as memristor electrode materials: mixed conductivity of ions and electrons, switchable majority carrier concentration, and slow photocurrent decay. Consequently, perovskite materials are considered to be innovative materials with considerable potential for the advancement of next-generation neuromorphic memristors [9].

In terms of implementing artificial synapses, organic memristors have the advantages of low cost, easy fabrication, high flexibility, good biocompatibility and many adaptive scenarios compared to inorganic memristors, such as those in the redox system of ethyl viologen dichloride [EV(C₁₀H₈)₂]²⁺/containing triphenylamine polymer (BTPA-F). This allows them to be used in applications such as wearable devices or even skin implant systems [10].

4.2. Dielectric layer materials

The material of the dielectric layer has an important influence on the realisation of the storage function of the memristor. Inorganic materials are stable in nature, clear in mechanism and compatible with CMOS; organic materials are less difficult to prepare and have a wide range of application prospects. At the present time, the most commonly utilised dielectric layer materials for memristors are metal oxides, sulfides, organic materials and two-dimensional materials [11].

Binary metal oxides are simple in structure, diverse in type, easy to control in composition ratio and their preparation process is highly compatible with existing CMOS processes. Various binary metal oxides such as TaO_x, TiO_x, NiO, AlO_x and HfO_x are considered as possible materials for memristor fabrication due to their resistive switching characteristics. Multimetall oxides, as they were the first materials to be investigated for the realisation of memristors, are currently available as ternary oxides LiCoO₂, SrZrO₃, SrRuO₃, quaternary oxides (LaSr)_{1-x}MnO₃, La_{0.33}Sr_{0.67}FeO₃, Pr_{0.7}Ca_{0.3}MnO₃, and quintuple metal oxides Pr_{0.625}La_{0.375}MnO₃, etc. are used in the application of memristors.

Sulphides, as candidates for the fabrication of both high-speed and multivalent electronic devices, are favourable for ion transport due to their rich functional defect properties, their high-speed properties can meet the demand for read/write speeds, and their multivalued properties can be applied to high-density storage of memristors as well as to analogue neural network computation. For example, carbon nitride supported resistive switching of ultrafine lead sulphide based devices [12], and high and low resistance state switching of memristors with CuS [13].

Due to their low cost, high flexibility, simple film formation mechanism and high biocompatibility, organic materials have attracted much interest as potential memristor synthesis materials for biomedical applications. At present, organic materials that are commonly used in memristors include egg proteins, filipin proteins, bovine serum proteins, etc., organic small molecule materials such as TPP (TetraPhenylPorphyrin) and arachidonic acid, etc., and organic polymer materials such as PVP (PolyVinyl Pyrrolidone).

In recent years, some researchers have proposed that memristors with better performance can be made by combining inorganic materials with organic materials. DNA is the biological macromolecule with the best data storage capacity at present, and the sequential arrangement of its A-T and C-G base pairs is very similar to that of a binary digital computer code. By reversibly doping DNA, its intrinsic trap state can be induced, resulting in room-temperature resistive switches that can be stably repeated at room temperature [14].

5. Conclusion

The memristor is a new computing and storage device that is emerging as a key technological advance to overcome the drawbacks of conventional von Neumann architectures. The limitations of conventional computing designs in terms of speed and energy efficiency are becoming increasingly apparent as the need for data processing and storage grows exponentially. Memristors, with their unique physical properties, offer a solution to this problem. As well as offering the advantages of non-volatility, low power consumption and high responsiveness, memristors enable more compact and efficient digital integrated circuits than CMOS tubes, laying the foundations for the development of brain-like computing and artificial neural networks.

The materials development of memristors, in terms of the choice of materials that make up the memristor, is based on innovations in the materials of the electrodes and the dielectric layer. They all have a significant impact on the performance of the memristor, whether they are metal oxides, organic compounds or new two-dimensional materials. In particular, organic materials have great potential for achieving biocompatibility and high flexibility. In addition, combining the composite structure of inorganic and organic materials can further enhance the performance of memristors and expand their application scenarios in computing, electronic devices and biomedicine.

At present, the resistance mechanism of memristors is still under continuous research. The main resistance mechanisms include ionic effect, electronic effect and thermal effect. The development of memory-computing integrated electrical devices and computing architectures can be aided by understanding and exploiting the different mechanisms, which can also increase the efficiency of the transition of memristors between high and low resistance states.

As a key component of next-generation storage and computing technologies, memristors have a wide range of prospects for research, development and application. With careful study and continued development, memristors will play a role in information technology in the future. In addition to improving computing performance, the development of memristors opens up new avenues for the development of artificial intelligence and brain-like computing. Memristors are expected to be widely used in a variety of industries in the near future to support the advancement of science and technology for the benefit of human society.

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