The Operating Mechanism and Resistance Variation Characteristics of Zno-Based Memristors

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Abstract. As the fourth basic circuit element predicted by theory, the memristor has become the cornerstone of a new computing paradigm technology. Among the numerous candidate materials for memristors, zinc oxide (ZnO) has attracted significant attention due to its excellent properties of low power consumption and high efficiency, as well as its mature preparation process featuring low cost and easy scalability. This paper will elaborate on the working principle, structure, and material characteristics of ZnO-based memristors; compare them with other mainstream memristors from four aspects: preparation cost, core performance, scenario applicability, and environmental stability; and analyze the advantages and disadvantages of ZnO-based memristors; further propose solutions to their defects and discuss their development potential.

Keywords: Memristors; ZnO material; resistance variation; valence change memory mechanism.

1. Introduction

The new round of technological revolution is in the ascendant. The rapid development of the Internet of Things (IoT), big data, and artificial intelligence (AI) technologies has put forward higher requirements for efficient data storage and processing. Memristors have become core supporting devices in the field of information technology due to their characteristics of non-volatility, high storage density, and low power consumption.

Among mainstream memristors, ZnO-based memristors, benefiting from the inherent properties of ZnO, not only possess excellent resistive switching performance and high integration potential but also feature mature preparation compatibility and application potential for multiple scenarios. These advantages endow ZnO-based memristors with unique competitiveness, especially in the fields of neuromorphic computing and high-density storage [1]. However, due to the inherent defects of ZnO, ZnO-based memristors exhibit poor performance stability in high-temperature and high-humidity environments, which limits their scenario adaptability in practical applications.

In the following, the author will elaborate on the working principle, structure, and various core performance indicators of ZnO-based memristors; compare them with other mainstream memristors to specifically analyze the advantages, disadvantages, and development potential of ZnO-based memristors; and propose solutions to their defects based on existing research results.

2. The Operating Mechanism of ZnO-Based Memristors

The core operating mechanism of ZnO-based memristors is to dynamically regulate the migration and aggregation of oxygen vacancies in the ZnO thin film through an external electric field, thereby realizing the reversible switching of the device between the "High Resistance State (HRS)" and the "Low Resistance State (LRS)”. These two states (HRS and LRS) can correspond to "0" and "1" in computers, enabling functions such as information storage and logic operations [2]. As shown in Part (a) of Fig. 1, the entire process can be divided into two key stages: Set and Reset, and these two stages are closed and recyclable [3]. Next, I will start with these two stages (Set and Reset) and explain the working principle of ZnO-based memristors in detail.

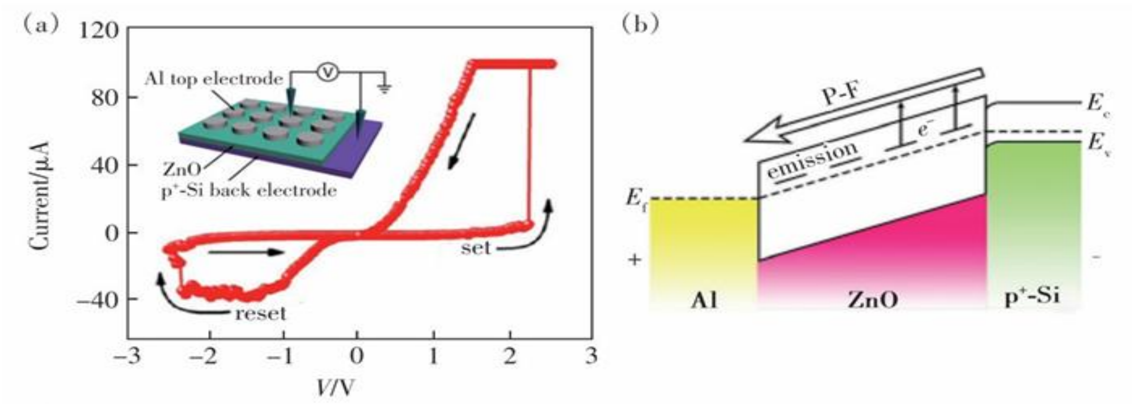

Fig. 1 (a) Mechanistic Insights and Modeling of Memristive Behavior in Zinc Oxide Devices; (b) a digital memristive switching behavior in its current-voltage (I-V) response [3].

2.1. Origin of the Initial State (HRS)

Oxygen molecules in the air are easily adsorbed on the surface of zinc oxide (ZnO), and the adsorbed oxygen molecules capture free electrons in the conduction band of ZnO ($O_2 + e^- \rightarrow O_2^-$), forming a surface depletion region—a region with extremely poor conductivity. This is the origin of the initial state [3]. In logic operations or neuromorphic computing applications, the High Resistance State (HRS) is equivalent to an "off-switch". Its high-resistance characteristic significantly inhibits current transmission, realizing the blocking and isolation of circuit signals [4].

2.2. Set and Reset Processes

By applying an electric field force, O^{2-} ions are driven to migrate out of the region. After their migration, a large number of oxygen vacancies are left in the bulk phase of ZnO. As the electric field force is continuously applied, the concentration of oxygen vacancies gradually increases. When it reaches a critical value, the dispersed oxygen vacancies spontaneously aggregate in a serially connected manner, forming an oxygen vacancy-conductive path. Free electrons can be transmitted unimpeded through this path, thereby significantly reducing the resistance. From the perspective of actual data, when the oxygen vacancy conductive path is fully formed, the device current jumps from the nA level (10^{-9}~10^{-8} A) in the high resistance state (HRS) to the μA level (10^{-6}~10^{-5} A) in the low resistance state (LRS), and the resistance decreases from the MΩ level (10^6 Ω) to the kΩ level (10^3 Ω), realizing the switching from HRS to LRS.In logic operations or neuromorphic computing applications, the Low Resistance State (LRS) is equivalent to an "on-switch". To summarize, the Set process is the switching from the High Resistance State (HRS) to the Low Resistance State (LRS), during which an oxygen vacancy conductive path is formed, corresponding to the "data writing" process. The Reset process is the switching from the LRS back to the HRS, where the reflux of O^{2-} ions is driven to fill the oxygen vacancies, thereby breaking the formed oxygen vacancy conductive path, which is the "data erasing" process [3].

3. The Mainstream Structure of ZnO-Based Memristors

The structural design of Zinc Oxide (ZnO)-based memristors centers on the basic framework of "Electrode-Functional Layer-Electrode" (Metal-Insulator-Metal, MIM). The substrate serves as the "fundamental platform" that supports the entire device structure, while metals (primarily used as electrodes) are usually attached to the surface of the substrate in the form of thin films or specific configurations. Zinc oxide, acting as the functional layer, is sandwiched between the substrate and the electrodes, and it is very thin, typically with a thickness ranging from 10 to 100 nanometers.

3.1. The Roles of Different Components in Zinc Oxide (ZnO)-Based Memristors

3.1.1 Substrate

In this structure, the fundamental role of the substrate is to protect the fragile functional layer, preventing the device from failing due to damage or fracture of the functional layer. Another important role of the substrate is to regulate the growth quality of the zinc oxide (ZnO) functional layer. The lattice matching degree and surface flatness of the substrate determine the crystallinity and microtopography of the ZnO thin film, which in turn affects the resistive switching stability [4]. In conclusion, the substrate is an essential structure for the practical application of ZnO-based memristors. For instance, in flexible applications, flexible substrates (such as polyimide, PI; polyethylene terephthalate, PET) need to be selected to ensure the device is bendable and foldable. In transparent applications, transparent substrates (such as glass, transparent flexible PI) should be adopted to achieve the optical transparency of the device [3].

3.1.2 Metal Electrodes

In this structure, the metal electrodes serve as a charge bridge between the external circuit and the zinc oxide (ZnO) functional layer, and are also the direct reason for regulating the switching of the memristor [3]. Meanwhile, when they cover the surface of the ZnO functional layer, they also effectively isolate oxygen and moisture in the air, preventing the ZnO from being affected by the environment and thereby slowing down the rate of its performance degradation [3].

3.1.3 ZnO Functional Layer

The zinc oxide (ZnO) functional layer is the core component of ZnO-based memristors—it serves as the key carrier for realizing the memristive effect and is also the primary reason why ZnO-based memristors stand out among various types of memristors [2]. Next, focusing mainly on zinc oxide, I will introduce the advantages and disadvantages of ZnO-based memristors and compare them with other mainstream memristors.

4. Advantages and Disadvantages of ZnO-Based Memristors Compared with Mainstream Memristors

As mentioned earlier, the zinc oxide (ZnO) functional layer plays an extremely important role in ZnO-based memristors. The advantages of ZnO-based memristors are basically the embodiment of the advantages of ZnO itself, while the disadvantages of ZnO-based memristors are mostly caused by the inherent defects of ZnO. On the whole, the advantages of ZnO-based memristors mainly lie in material properties and preparation costs [3], while their disadvantages are mainly reflected in environmental stability and performance consistency [5]. Next, by comparing ZnO-based memristors with mainstream memristors, I will elaborate on the development potential of ZnO-based memristors from these four aspects.

4.1. Advantage

Low material cost, simple preparation process, and easy large-scale production are the most significant advantages of zinc oxide (ZnO)-based memristors, especially when compared with memristors based on relatively rare metals [6,7]. As mentioned earlier, this advantage is mainly attributed to ZnO itself. From the perspective of raw material cost, the price of ZnO raw materials (such as zinc oxide powder and zinc salts) is only 1/20 that of HfO_2 (hafnium is a rare metal), and ZnO has abundant reserves (the zinc content in the Earth's crust is approximately 70 ppm, far higher than hafnium's 0.0004 ppm). From the perspective of process compatibility, ZnO-based memristors do not require harsh conditions such as high-temperature annealing or vacuum, nor do they need to be prepared in the dark like organic memristors; they can be completely fabricated via smelting or low-temperature magnetron sputtering. This advantage can meet the growing demand for memristors from the rapidly developing information technology.

Low cost does not equal low performance. In fact, ZnO-based memristors possess excellent electrical properties. For example, in core indicators such as on/off ratio, switching speed, and endurance, ZnO-based memristors are significantly superior to organic memristors, and even have partial comparability with HfO_2-based memristors (which are known for their "high stability"), especially after being doped with lithium (Li) metal [5]. This stands in sharp contrast to their relatively low cost and relatively simple preparation process. From specific data, the on/off ratio of pure zinc oxide (ZnO)-based memristors is typically 10^3–10^5, and it can be increased to 10^4–10^6 after lithium (Li) doping (forming ZnO: Li), which is much higher than that of organic memristors (10^1–10^2) [7]. This means that ZnO-based memristors can clearly distinguish between the "0" and "1" states and reduce the information storage bit error rate to below 10^{-9}, meeting the high-density storage requirements in the Information Age. In terms of power consumption, although ZnO-based memristors consume slightly more power than organic memristors, their power consumption is far lower than that of TiO_2-based memristors. Moreover, organic memristors usually have large leakage currents, leading to higher long-term power consumption instead. From the perspective of switching speed, ZnO-based memristors have a more obvious advantage. The switching speed of pure ZnO-based memristors can reach 10–100 ns; after Li doping, benefiting from the faster diffusion speed of Li ions, the switching speed can be further increased to 1–10 ns. This is close to that of HfO_2-based memristors (0.1–5 ns) and much faster than that of organic memristors (1–10 μs) [8]. It can be seen that, from the perspective of electrical performance alone, although ZnO-based memristors are not as good as HfO_2-based memristors, they have approached HfO_2-based memristors in many aspects. However, the advantage of the low cost of ZnO-based memristors is something that HfO_2-based memristors cannot match.

Finally, the strong scenario adaptability and versatile expansion potential are the most unique advantages of ZnO-based memristors. Relying on their photosensitive and transparent semiconductor properties as well as good flexible compatibility, ZnO-based memristors can be adapted to many special scenarios that are difficult to cover by other types of memristors. In terms of photosensitivity, when exposed to 365 nm ultraviolet light, ZnO-based memristors can excite additional free electrons, reducing the Set voltage by 50% (e.g., from 2V to 1V). Based on this property, "photo-electrical dual-control memristors" can be fabricated, which are used in optical encryption and memory units of ultraviolet sensors [8]. In contrast, TiO_2-based and HfO_2-based memristors require doping with elements like Fe and Ni to achieve weak photosensitivity, while organic memristors have almost no photosensitive capability. For transparency, ZnO thin films have a visible light transmittance of over 85%. When combined with transparent electrodes such as ITO and AZO, fully transparent memristors with a transmittance of more than 80% can be made [9,10]. These are suitable for embedded storage in transparent display panels and integrated sensing-memory systems for smart windows. TiO_2-based memristors are opaque, and although organic memristors are transparent, their stability is poor (transmittance drops by 20% after 30 days); neither can fulfill this function. Regarding flexible compatibility, ZnO thin films can be grown on flexible substrates like PI and PET, with a minimum bending radius of 5mm and performance fluctuation of less than 10% after 1,000 bending cycles. HfO_2-based memristors have inferior flexibility due to brittle thin films (prone to cracking when the bending radius exceeds 20 mm), and TiO_2-based memristors require high-temperature fabrication (flexible substrates can only withstand temperatures below 200 °C). Organic memristors, while having good flexibility (bending radius of 1 mm), are sensitive to moisture and heat (failing when the temperature exceeds 80 °C), limiting their applicable scenarios.

4.2. Disadvantage

However, the main drawback of ZnO-based memristors is their poor environmental stability, as they are easily affected by oxygen and water vapor. This is also the core shortcoming of ZnO-based memristors, limiting their application in open environments. When O_2 and H_2O in the air are adsorbed by ZnO, a surface oxide layer (ZnO_2) and hydroxyl groups (-OH) form on the ZnO surface. These substances greatly consume oxygen vacancies, leading to a decrease in high-resistance state (HRS) resistance and a nearly 50% drop in the on/off ratio. In environments with humidity above 60%, ZnO thin films are prone to hydrolysis. Once microcracks appear on their surface, the leakage current increases from 10^{-9} A to 10^{-7} A, and the cycle life drops from 10^4 cycles to less than 10^3 cycles. Compared with other memristors, some are less likely to have such problems. For example, HfO_2-based memristors form a stable HfO_2 passivation layer on their surface (which does not react with O_2 or H_2O) and can remain stable in air for more than one year. Other memristors can address this issue at a lower cost; organic memristors, for instance, can isolate water vapor in the air through encapsulation.

In addition to the aforementioned functional failure under high-humidity environments, ZnO-based memristors also suffer from performance degradation at high temperatures. Specifically, the critical temperature at which the performance of ZnO memristors begins to decline significantly is usually 80°C. Due to the intensified thermal vibration of the ZnO lattice, the distinction between resistance states becomes blurred—the on/Off ratio drops from 10^3-10^4 to 10^1-10^2. When the temperature exceeds 120°C, it becomes difficult to maintain normal resistive switching functionality, resulting in the loss of switching and data storage capabilities.

In contrast, HfO_2-based and TiO_2-based memristors, which also belong to the metal oxide-based category, exhibit significantly better high-temperature resistance than ZnO-based memristors. Therefore, ZnO-based memristors are mainly suitable for general industrial environments (-10°C ~ 80 °C) and cannot be directly used in medium-high temperature or extremely high-temperature industrial scenarios.

5. Improvement Methods for the Defects of ZnO-Based Memristors

The defects of ZnO-based memristors limit their scenario adaptability in practical applications. However, there are multiple solutions to enhance the performance stability of ZnO-based memristors in high-humidity and high-temperature environments. Firstly, Doping Modification: It refers to improving the properties of ZnO by doping other elements. For example, relevant studies have confirmed that Sn-Al co-doping can effectively enhance the stability of oxygen vacancy conductive filaments, reduce their sensitivity to water vapor, and improve their high-temperature resistance. Secondly, Packaging Technology: It refers to isolating the device from the external environment using materials with excellent airtightness (such as ceramics and metals). For instance, ceramics can withstand high temperatures above 800°C and completely block the contact between moisture and the ZnO layer. Thirdly, Structural Design Improvement: It refers to enhancing its performance in high-humidity and high-temperature environments by adopting multi-layer heterostructures or optimizing electrode designs. A typical example is adding a dielectric layer on the ZnO layer. The ZnO-based memristors optimized through the above solutions can increase their performance-stable temperature to over 150 °C and also exhibit excellent long-term stability in high-humidity environments [11, 12].

6. Summary

To sum up, ZnO-based memristors can achieve a good balance among performance, cost, and integrability, and are easy to realize large-scale production. Moreover, they have multi-scenario adaptability in terms of application expansion, and their defects in environmental stability can be remedied by a variety of solutions. This enables ZnO-based memristors to have broad development potential in current and future applications, especially with significant advantages in fields such as big data storage, artificial intelligence, the Internet of Things (IoT), and environmental monitoring. Future research can focus on the following two directions: Firstly, continue to explore solutions for improving defects, such as optimizing their electrical conductivity, stability, and resistive switching characteristics by adjusting the type and concentration of doping elements; Secondly, further expand their applications in fields like artificial intelligence, the Internet of Things, and biomedicine, and develop more advanced and intelligent electronic devices and systems.

References

[1] Wang Hong, Yan Xiaobin. Overview of resistive random access memory (RRAM): Materials, filament mechanisms, performance optimization, and prospects. Phys. Status Solidi-Rapid Res. Lett., 2019, 19 (10): 1900073.

[2] Shi Jiajuan, Shan Xuanyu, Wang Zongqiang, et al. Research progress of ZnO-based memristive devices. Chinese Journal of Luminescence, 2025, 46(5): 753-769.

[3] Hu C, Wang Q, Bai S, et al. The effect of oxygen vacancy on switching mechanism of ZnO resistive switching memory. Appl. Phys. Lett, 2017, 110(7): 073501.

[4] Tomino R V, Vakulov Z E, Polupanov N V, et al. Nanoscale - resistive switching in forming-free zinc oxide memristive structures. Nanomaterials, 2022, 12(3): 455.

[5] Chen Jianbiao, Gao Liye, Xu Jiangwen, et al. Photoresistive switching charateristics of ZnO nanorods array. Journal of Northwest Normal University (Natural Science), 2022,58(2), 34-39.

[6] Shanghai Huzhen Industrial Co., Ltd. (n.d.). Human Aldehyde Dehydrogenase (ALDH) ELISA Kit. Shanghai Rapidbio. Retrieved June 10, 2024, from https://www.shruji.com/product/aldh119447

[7] Li Shouliang, Yue Wenijng, Li Yang. Preparation of Tungsten Oxide-Zinc Oxide Memristor and Its Neural Synaptic Property. Journal of University of Jinan (Science and Technology), 2024,38 (3).

[8] Wang Yucheng, Zheng Jiawei, Shang Yueyang, et al. LTP–LTD transformation of unipolar pulse voltage-driven zinc oxide memristors via TiO2 thin layer incorporation. Journal of Materials Chemistry C, 2024, 4.

[9] Han Jiaqi, Mao Hongchen, Lin Ya. Near-Infrared Optoelectronic Memristor with All-Optical Modulation for Microscopic Biological Motion Recognition. Advanced Materials, 2025: e10185.

[10] Simanjunta F M, Ohno T, Chandrasekaran S, et al. Neutral oxygen irradiation enhanced forming-less ZnO-based transparent analog memristor devices for neuromorphic computing applications. Nanotechnology, 2020, 31(26).

[11] Feng Yixuan, Wang Lida, Yang Zhengqi, et al. Effect of ZnO as corrosion product on corrosion behavior of zinc-iron corrosion protection systems. 2024, 227:111802.

[12] Sokolov PS, Baranov AN, Solozhenko VL. Phase stability and thermal expansion of ZnO solid solutions with 3d transition metal oxides synthesized at high pressure. ChemRxiv. 2023.