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Prospective

Impact of electrical testing strategies on the performance metrics of bio-organic-based resistive switching memory

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Abstract
Resistive Random-Access Memory (ReRAM) is considered as one of the most promising non-volatile memory technologies because of its high scalability, fast switching speed, and low power consumption. While many review papers are focused on investigating material types, material properties, device fabrication methods, and device structures, the influence of electrical testing strategies on ReRAM performance has yet been reviewed, particularly for bio-organic-based ReRAM. This review compiled, analyzed, and discussed how compliance current, voltage sweep rate, voltage sweep range, and voltage sweeping direction affect the ON/OFF ratio, read memory window, and both SET and RESET voltages of ReRAM.

Introduction
In the rapidly evolving landscape of data storage technologies, one of the most promising technologies for non-volatile memory applications is resistive random-access memory (ReRAM). Compared with other emerging memories, ReRAM devices have high scalability, fast operation speed, low power consumption, a high degree of integration, and a simpler manufacturing process.[1,2] These attributes make ReRAM a promising candidate to replace conventional memory technologies to meet the ever-increasing demand for high-density and low-power memory.[3,4] The importance of ReRAM extends beyond typical memory applications, attracting the attention of the wider scientific community for diverse potential applications, such as neuromorphic computing where emulation of synaptic behavior is important, and flexible electronics where flexibility of the materials is advantageous.

The concept of resistive switching (RS) in memristive layers has been discovered and studied for over 60 years. Resistive switching memory is an innovative gadget that integrates memory storage and data processing capabilities in a single cell.[5,6] It can be used not only for non-volatile memory but also as a basic element in neuromorphic computation and information security.[5,7] The memory has a basic Metal–Insulator-Metal (MIM) structure [Figure 1(a)] with a memristive layer sandwiched by top electrode (TE) and bottom electrode (BE). The switching behaviors can be categorized accordingly by measuring the forward and revised current–voltage (I–V) using different electrical measurement strategies. Depending on the polarity of the external electric field, the switching behaviors can be divided into two common RS behaviors, unipolar RS behavior using the same voltage polarity, and bipolar RS behavior requiring opposite polarities for SET and RESET processes, as depicted in Figure 1(b) and (c), respectively. Also, the switching in ReRAM is more likely to be digital [Figure 1(b), (c)] where the transition from high to low resistance or vice versa is appropriate for storing data. On the other hand, analog switching [Figure 1(d)] allows for constant resistance changes, making it possible for multilevel data storage and neuromorphic computing. Hysteresis in ReRAM devices can be zero crossing [Figure 1(e)], without any charge trapping or storage effect, or non-zero crossing [Figure 1(f)], showing a lag in responding to an applied voltage.

Different classes of engineering materials are used as the memristive layer for resistive switching memory, such as inorganic, organic, and bio-organic. Some materials often used are inorganic, such as transition metal oxides, these are preferred because of their robust electrical characteristics and scalability. Fossil fuel-derived organic materials such as polymers and small molecular materials have features like low-cost fabrication and flexibility but more difficulties in stability and endurance. Bio-organic materials using natural polymer and bio-compatible substances extracted from plants, viruses, and living or once-living things have been studied for their eco-compatibility and opportunities in creating green electronic devices.[2,8] The advancement of bio-organic-based ReRAM devices demonstrated significant progress from 2006 to 2024[2,8–16] with improvement in functionality and performance over time. These materials contribute to

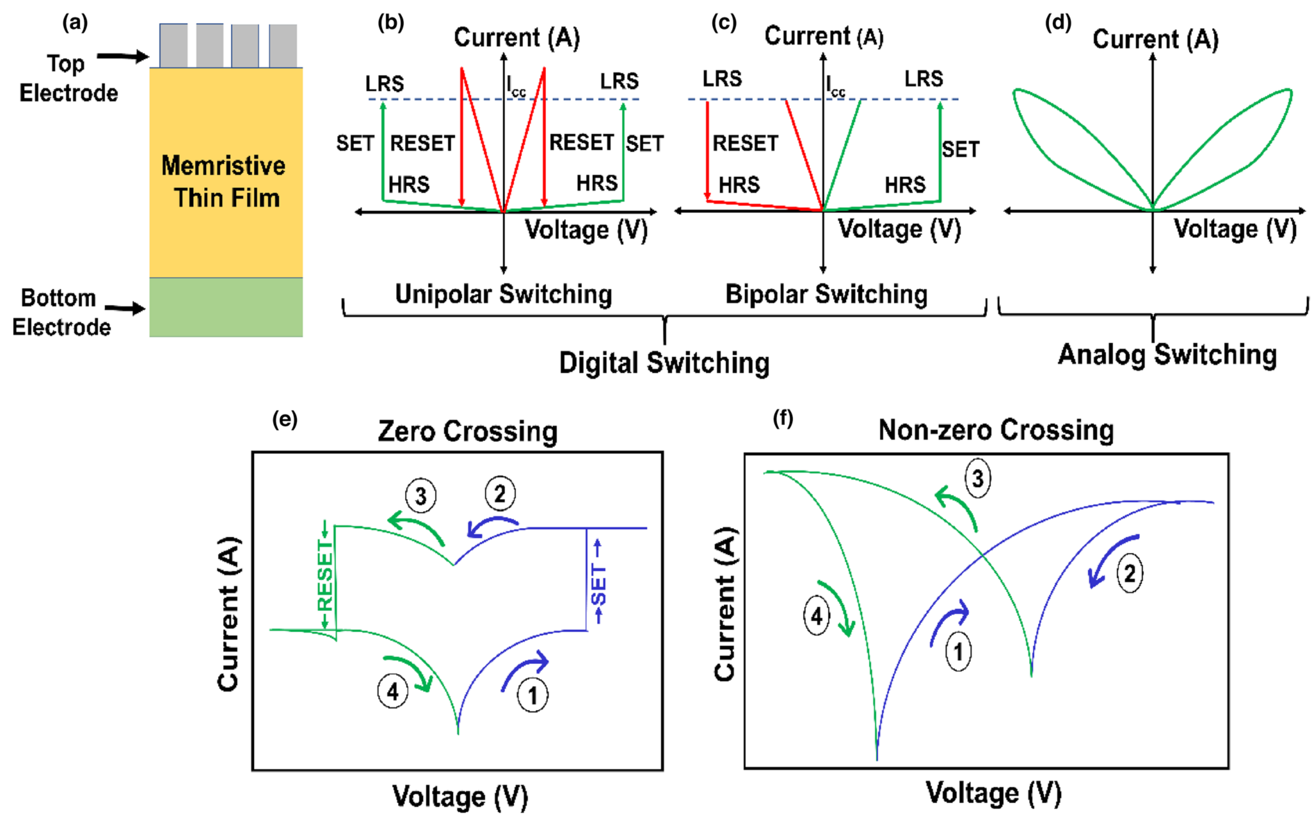

Figure 1. (a) Schematic cross-sectional view of a ReRAM. Different types of RS characteristics in a ReRAM device: (b) Unipolar, (c) Bipolar, (d) Analog switching (e) Zero, and (f) Non-zero Crossing. The figure is modified from the Ref. 2.

reducing electronic e-waste and, therefore, support the sustainable development goals set by the UN. The design of a bio-organic-based ReRAM [Figure 2(a)] is affected by TE and BE materials [① in Figure 2(a)], bulk memristive thin film [② in Figure 2(a)], intermediate layer (IL) between electrodes and memristive layer (③ in Figure 2a), substrate [④ in Figure 2(a)], and electrical measurement strategy [⑤ in Figure 2(a)]. The selection of appropriate and suitable materials with optimum process parameters is crucial to ensure a high performance and reliability non-volatile memory can be produced. The performance metrics of ReRAM, namely ON/OFF ratio, endurance, retention, and read memory window

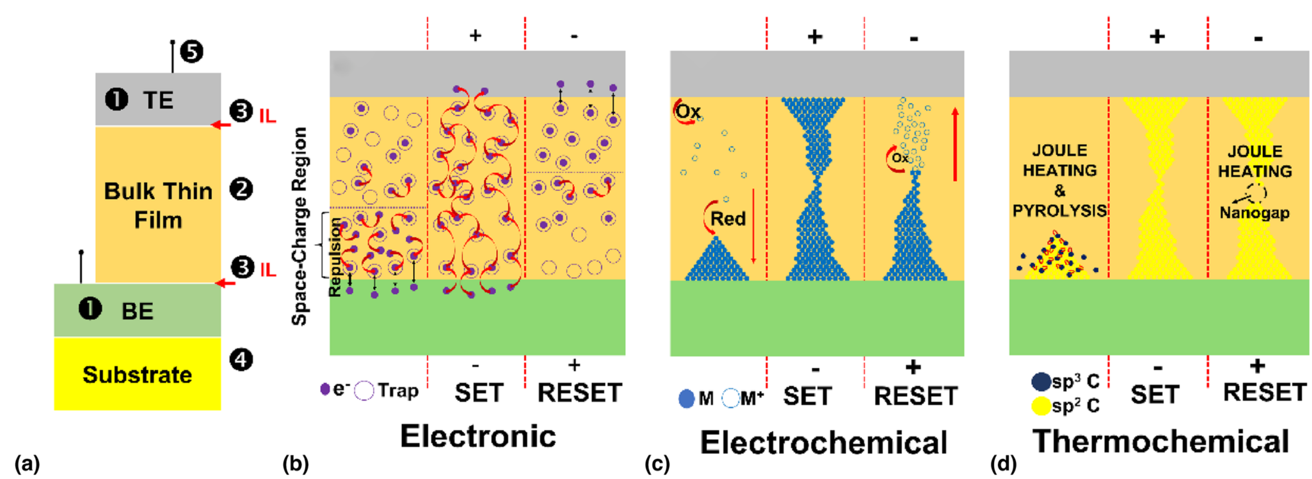

Figure 2. (a) Essential components in a bio-organic based ReRAM with the numbers elaborated in main text. Three types of resistive switching mechanisms in bio-organic-based ReRAM devices: (b) Electronic, (c) Electrochemical, and (d) Thermochemical controlled ReRAM. The figures are modified from the refs.[2,18]

are deeply intertwined with the material properties that define the resistive switching mechanism and governing the overall performance of the memory.

Although several review papers in the literature have discussed the role of electrode materials, bulk memristive thin film,[8,17,18] intermediate layer, and substrate, there is a noticeable gap in the literature regarding electrical testing strategies, which this review aims to address. The performance metrics of ReRAM are profoundly influenced by the electrical testing strategies employed during device characterization. Variations in compliance current settings,[19–21] voltage sweep rates,[19] sweep range,[22] and sweep direction can lead to significant difference in device behaviors. Therefore, understanding and standardizing these measurement techniques are crucial for accurately evaluating and enhancing ReRAM performance and facilitating the development of more efficient and reliable ReRAM devices. This review paper aims to underscore, for the first time, the impact of various electrical testing strategies on the performance of bio-organic-based ReRAM devices.

Resistive switching mechanisms in bio-organic based reram

The basic working principle of ReRAM is the RS mechanism, which means that by applying an electric field across the active memristive layer, the resistance changes reversibly from high resistance to low resistance states and reverted to the original state depending on the applied voltage and polarity due to the formation and rupturing of conductive paths within the memristive layer that connecting the two electrodes. It has been reported that three typical mechanisms [Figure 2(b–d)] govern the formation of conductive paths within the memristive layer in bio-organic based ReRAM. Electronic mechanism includes trapping and detrapping of charge carriers in defect sites within the active memristive layer [Figure 2(b)], in which the change of RS depends on the ability of electrons and holes to move under an electric field.[2] Electrochemical mechanism involves the migration of ions, such as oxygen vacancies or metal cations, within the active memristive layer [Figure 2(c)]. The formation and dissolution of conductive filaments composed of these ions can switch the resistance states.[2] Thermochemical mechanism engages local heating from different sources that induces thermally driven transition of phase changes [Figure 2(d)].

Designing concept of bio-organic based reram

Bio-organic based ReRAM devices are designed with several important materials and layers, each of which is crucial to the overall device performance and functionality. The key components of the ReRAM design [Figure 2(a)], such as the electrodes①, bulk thin film②, intermediate layer (IL) ③, substrate ④, and electrical testing strategies ⑤, are briefly reviewed in this section. In ReRAM devices, electrodes play a significant role in deciding the performance and reliability of the devices based on the symmetry, type of electrode material, size, thickness, and deposition process. Both symmetric and asymmetric may be used where symmetric design provides a uniform electric field that attributes to a more stable switching, while asymmetric design provides the optimized electric field and current flow for best performance. The thickness of the electrodes is another critical dimension that affects the contact resistance and scalability of the devices. Different electrodes, including metallic (Pt, Au, Ag), transparent conductive oxides (ITO, AZO), and 2D materials (graphene, TMDCs) are chosen depending on the application and compatibility with the used active RS material.[23] Electrode deposition processes such as sputtering, thermal evaporation, and chemical vapor deposition used in the fabrication process must be fine-tuned to produce uniform and defect-free electrodes. The bulk memristive thin film has a notable contribution in defining the resistance states and switching properties in ReRAM devices that can be controlled by physical thickness, type of material, and purity of raw material. The molecular weight and concentration of the active compound and deposition technique together with the formulation, all may influence the quality of the resultant film. Spin coating and sputtering are common methods of deposition. The drying temperature, time, and environment also have a very significant role in achieving the right thickness of the film. Additionally, intentionally incorporated entities like metallic elements, ionic compounds, and nanostructures can enhance the RS performance of the film.[18]

The intermediate layer (IL) in ReRAM devices plays an essential role in modulating the interaction between the electrodes and active RS layer, thereby directly affecting device performance and reliability. This layer can increase the roughness of the interface, decrease the interfacial contact resistance, and eliminate the diffusion of atoms between layers so that the performance and stability of the device can be improved. The control parameters for the IL include material type, thickness, and deposition process. Examples of the materials include metal oxides and nitrides that are deposited using either atomic layer deposition or chemical vapor deposition. The substrate in ReRAM devices is an essential component that is responsible for the overall structural support and impacts the mechanical and electrical characteristics of the device. Substrates can be mechanically rigid like glass and semiconductors or mechanically flexible like polymers and metallic foils.[23] Each type offers distinct advantages: rigid substrates ensure mechanical stability, and compatibility with standard manufacturing processes, while flexible substrates open the opportunities for engineering bendable and wearable devices. Substrate surface preparation is important for removing undesirable surface contaminants and improving bonding. This includes both wet- and dry-cleaning techniques, chemical treatment, and functionalization to enhance the adhesion between the layers. In addition, accurate and reliable electrical testing strategies are essential for evaluating the performance of the ReRAM. These electrical testing strategies are explained thoroughly in the next section.

Electrical testing strategy

Key parameters in the electrical testing strategy include compliance current, voltage sweep rate, direction of sweeping voltage, and voltage sweep range. In addition, external stimuli such as temperature and magnetic fields can also influence the RS properties, providing information about the device's stability but this is not included in this review.

Compliance current (ICC)

Compliance current (I_{CC}) significantly impacts the performance of RS devices. In general, the higher the I_{CC}, the lower value of resistance can be obtained in low resistance state (LRS) and, therefore, the higher ON/OFF ratio due to the formation of thicker, denser, and more robust conductive filaments. But this higher current also increases power consumption and might complicate the RESET process because a higher electric field is required to break these thicker filaments. It can be seen from the literature that in Ag/Keratin/FTO devices, the increase in I_{CC} from 1 to 5 mA helps enhanced the ON/OFF ratio but at the same time impacts the LRS resistance.[20] Additionally, in Ag/Sericin/Au devices, the increase in I_{CC} increases the conduction paths and improves the ON/OFF ratio and stability. Likewise, in the case of Ag/Polymanose/ITO devices, it has been observed that increasing the I_{CC} the LRS resistance reduces while on the other hand, it results in a more stable device at the cost of higher power consumption.[19] One of the other reported outcomes attributed to the adjustment of the I_{CC} is the achievement of multilevel or multistate memory.[21,24,25] It has the advantage that a single memory cell stores more than one bit of information thereby significantly increasing the storage density. By carefully adjusting the I_{CC}, various resistance states may be consistently set and read, allowing the implementation of multilevel memory. For example, the study based on Ag/pectin/ITO demonstrated that by modulating I_{CC}, one can define the size and shape of the conductive filaments in a ReRAM cell to achieve multi-resistance level distinction. The I_{CC} does not only set the current flowing through the device but also regulates the physical processes responsible for RS includes filament

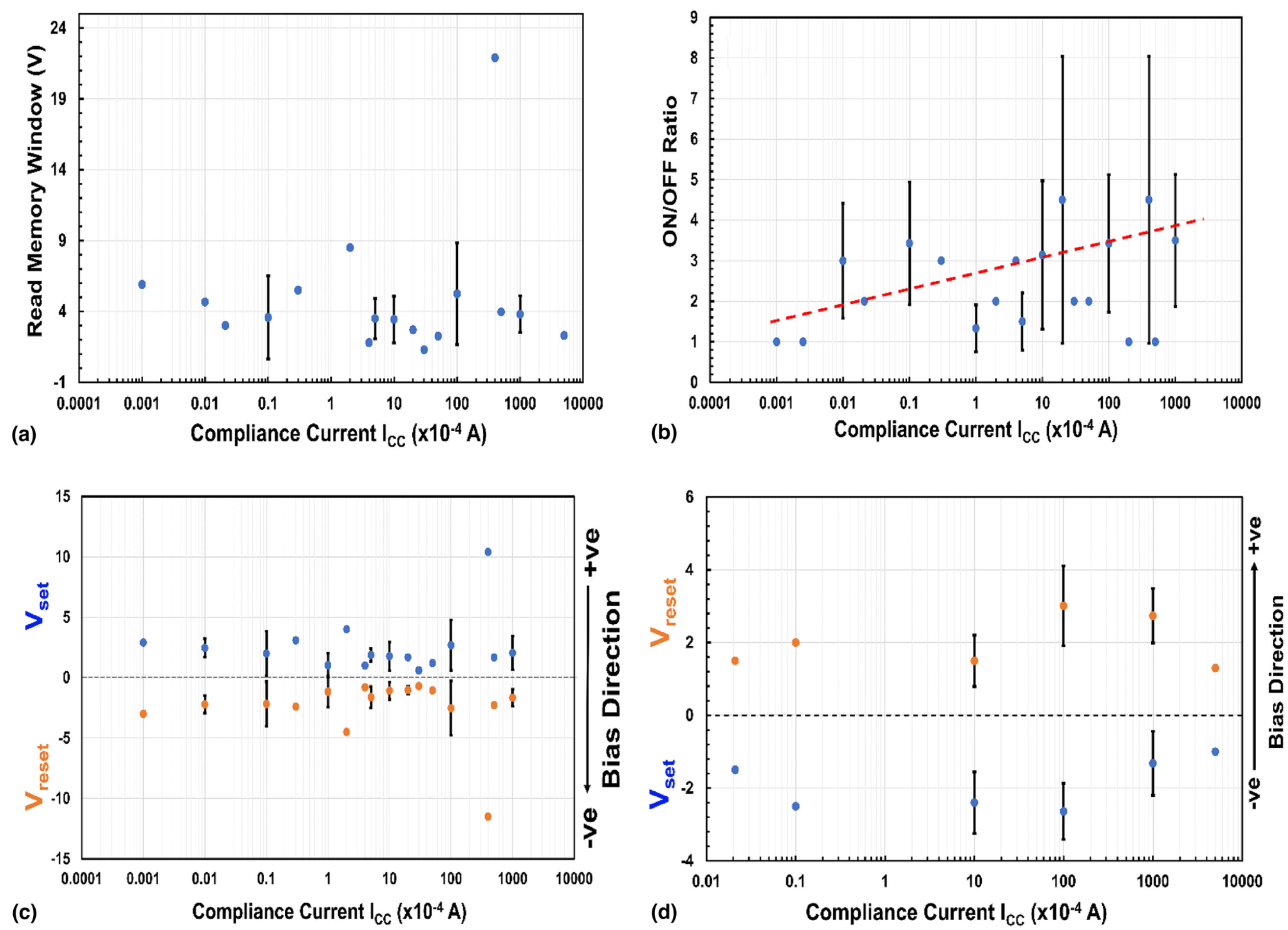

Figure 3. Effect of compliance current, I_{cc}, on (a) read memory window, (b) ON/OFF ratio, and V_{set} and V_{reset} of (c) positively, and (d) negatively swept bio-organic-based ReRAM. The dotted red line in (b) serves as a visual guide to illustrate the general trend of the data.

growth and russbeen compiled from various review[2,8,17,18,23] and research articles,[9,10,14–16,19,26–30] and plotted against the I_{CC} using standard deviation, as shown in Figure3, for clarity and ease of interpretation.

The read memory window which represents the voltage range for reliable memory state reading, fluctuates approximately within the range of 1 V to 6 V [Figure 3(a)]. Generally, no significant difference in the memory window was observed with variations in the I_{CC}. The ON/OFF ratio, measuring the current contrast between high and low resistance states, varies with I_{CC} [Figure 3(b)]. The dotted line in Figure 3b serves as a visual guide and does not represent a goodness-of-fit curve. The ON/OFF ratio was typically reported approximately within the range of 1 to 5. Generally, an overall increment in the ON/OFF ratio is observed with increasing I_{CC} as visualized by the dotted red line. The I_{CC} does not significantly affect both V_{set} and V_{reset} when the bias direction is from positive to negative [Figure 3(c)]. However, a noticeable variation in both voltages is evident with changes in I_{CC} when the voltage biasing direction is from negative to positive [Figure 3(d)]. Based on the analysis, a substantial majority of literature focused on biasing in the positive to negative direction. Such trends indicate that enhanced device performance is accompanied by a higher power consumption, which shows that I_{CC} should be optimized in applications of RS devices to balance the two factors.

Voltage sweep rate

Voltage sweep rate is also an important factor affecting ReRAM device performance, as a lower sweep rate enables more time for cation formation and growth of thick filament while a higher sweep rate results in a higher LRS resistance arising from a larger tunneling gap. It was reported in the literature that the ON/OFF ratio generally increases with an increasing sweep rate. For instance, in the Ag/polysaccharides/ITO device, the ON/OFF ratio increased from 5 at 0.01 to 7 at 10 V/s, indicating approximately a 10% improvement[21]. This trend is attributed to the faster formation and rupture of conductive filaments at a higher sweep rate, leading to more distinct resistive states. The sweep rate plays a significant role in determining the switching kinetics, as it influences the mobility of ions and charge carriers within the bulk bio-organic material. For materials with relatively low ion migration rates, such as transition metal oxides, a slower sweep rate enables a more stable resistive switching. On the other hand, bio-organic, organic, and polymer-based materials show a faster sweep rate response in terms of their resistive switching performance.

Based on the literature, data from various review[2,17] and research articles[11,14,19,21] for V_{set}, V_{reset}, ON/OFF ratio, and read memory window in relation to voltage sweep rate are plotted using standard deviation, as shown in Figure 4. The read memory window [Figure 4(a)] fluctuates approximately between 1 and 7 V, although variations in I_{CC} resulted in no substantial change in the memory window. The ON/OFF ratio [Figure 4(b)] generally falls within the range of 1 to 6 and it is observed that the ON/OFF ratio tends to increase with the increment in the sweep rate. The dotted line in Figure 4(b) serves as a visual guide and does not represent a goodness-of-fit curve. Additionally, both SET (V_{set}) and RESET (V_{reset}) voltages [Figure 4(c, d)] exhibit an increasing trend as the sweep rate increases, irrespective of the voltage sweeping direction. Analysis indicates that most literature focuses on biasing in the positive to negative direction. It is important to consider such trends for ReRAM devices to gain ideal energy efficiency and performance since a higher ON/OFF ratio provides a higher reliability and stability of in data retention.

Voltage sweep range

Voltage sweep range significantly affects the filament radius and rupture gap, enabling multilevel RS to be formed. For Ag/DNA-CTMA/ITO device, extending the sweep range from − 1.5 V to − 4 V resulted in a substantial increase in the memory window, from 2.7 to 4.75, which is a 79.93% improvement. This suggests that a wider sweep range improves switching efficiency by allowing for larger changes in alternating voltage in the resistance states. On the other hand, in Au/lignin/ITO device, when the sweep rate increased from +2 to +3 V, the ON/OFF ratio increased by approximately 48.74%[22]. This suggests that the voltage sweep range over the system is dependent on the properties of the material that is being used and therefore proper optimization is critical for each system. The choice of the sweep range is critical, as it is possible to stress the memristive layer beyond its capability, leading to degradation or failure. By setting up the proper sweep range, one can secure the measurement of the entire hysteresis loop and evaluate the stability and endurance.

Conclusion

The bio-organic as a novel group of engineering material employed as the memristive layer for non-volatile memory ReRAM offers substantial challenges to the scientific community, as the objective to produce a reliable and high-performance device for some customized applications is still long way to go. Due to their bio-organic nature, these materials are biodegradable and environmentally friendly, coupled with their adjustable electrical characteristics, making them perfect for sustainable memory applications. This review focuses on the impact of electrical testing strategies on the performance of bio-organic-based ReRAM devices reported from 2006 to 2024. It has been demonstrated that compliance current, voltage sweep rate, and voltage sweep range and direction can cause significant variations in device behaviors, namely V_{set}, V_{reset}, ON/OFF ratio, and read memory window. These results highlight the importance of electrical testing methodologies for ensuring reliable and comparable RS performance. Moreover, by understanding the electrical testing strategies presented within the scope of this review,

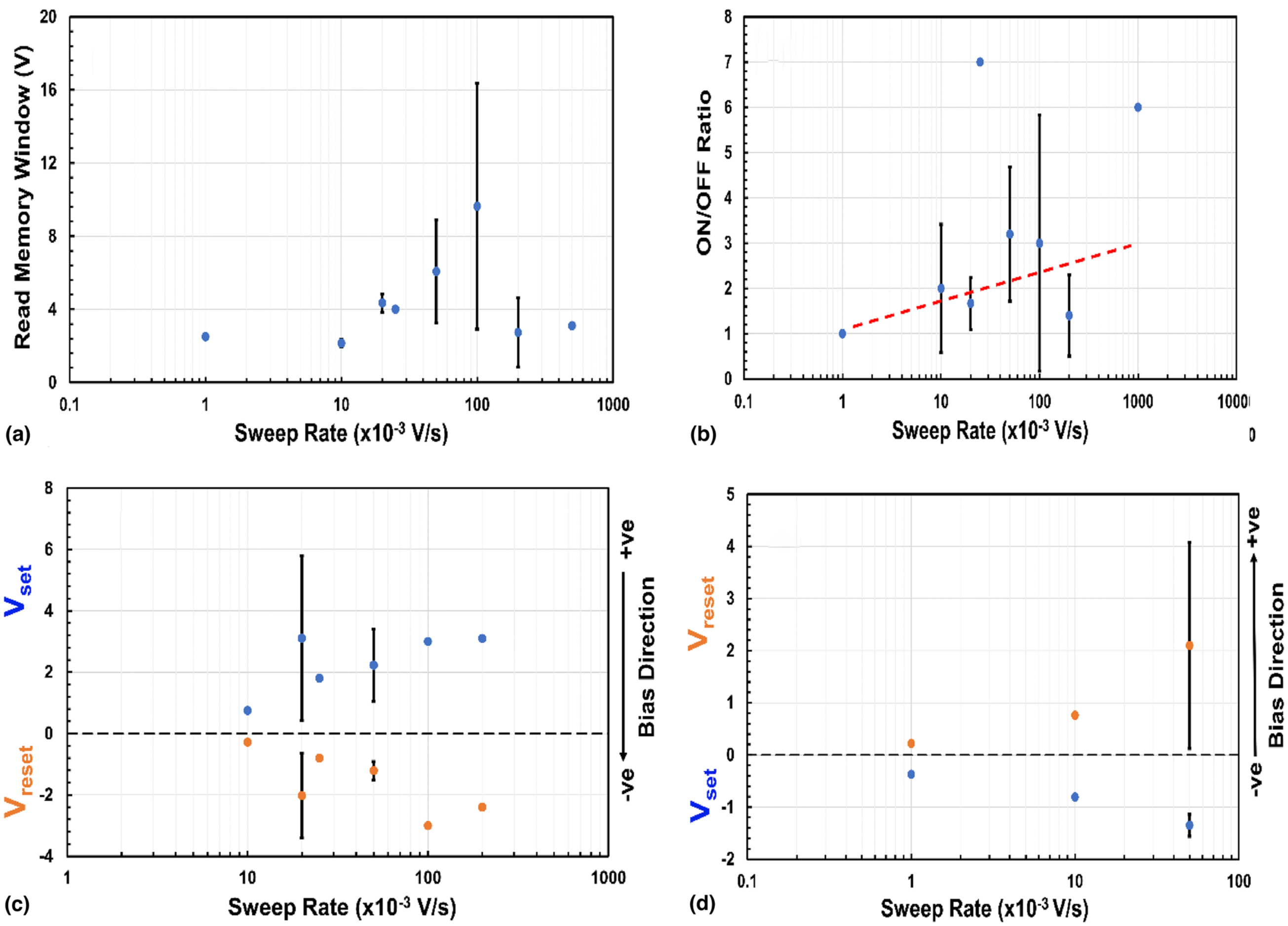

Figure 4. Effect of voltage sweep rate on (a) read memory window, (b) ON/OFF ratio and V_{set} and V_{reset} of (c) positively, and (d) negatively swept bio-organic-based ReRAM devices. The red line in (b) serves as a visual guide to illustrate the general trend of the data.

it provides some fundamental information in assisting the designing and testing of the device for the potential of utilizing it in data storage for consumer electronic applications.

Author contributions

All authors contributed equally to this work.

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Data availability

Reference to the datasets analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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