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Research Article

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Nanosphere Structured V_2O_5 Memristors for Artificial Neurons

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Abstract: Resistive random access memory (ReRAM) has emerged as a promising candidate for next-generation non-volatile memory and neuromorphic computing owing to its simple metal–oxide–metal architecture, low power consumption, and scalability. In this work, we report the hydrothermal synthesis of crystalline V_2O_5 nanospheres and investigate their suitability for memristive switching applications. Phase-pure orthorhombic V_2O_5 nanospheres were synthesized using an ethylene-glycol-assisted hydrothermal method and comprehensively characterized by X-ray diffraction, electron microscopy, and elemental analysis. The nanospheres exhibit high crystallinity, uniform morphology, and homogeneous elemental distribution. Memristive devices fabricated on SiO_2/Si substrates with Au top electrodes demonstrate stable bipolar resistive switching behaviour with well-defined SET and RESET voltages, reliable endurance, and long-term retention. The resistive switching mechanism is attributed to oxygen-vacancy-mediated electrochemical metallization involving reversible formation and rupture of conductive filaments within the V_2O_5 nanospheres. Furthermore, the devices exhibit analog conductance modulation suitable for synaptic functionalities, highlighting their potential for neuromorphic computing applications. These results establish V_2O_5 nanospheres as a viable active material for multifunctional memory and neuromorphic devices.

Keywords: V_2O_5 Nanostructures, Memristor; Reram, Resistive Switching, Transition Metal Oxides, Hydrothermal Synthesis, Non-Volatile Memory: Neuromorphic.

1. Introduction

The rapid growth of data-centric technologies and artificial intelligence has intensified the demand for advanced memory devices that can overcome the limitations of conventional charge-based memories [1]. Traditional non-volatile memories such as flash memory face fundamental challenges related to scaling, power consumption, and endurance, motivating the exploration of alternative memory technologies [2]. Among emerging candidates, resistive random access memory (ReRAM) has attracted significant attention due to its simple device structure, fast switching speed, low operating voltage, and compatibility with complementary metal–oxide–semiconductor (CMOS) technology [3]. ReRAM operates based on reversible resistance switching between high-resistance and low-resistance states under an applied electric field. This phenomenon is commonly observed in transition metal oxides, where the migration of ions or vacancies leads to the formation and rupture of conductive filaments [4]. In addition to digital memory operation, the analog modulation of resistance in ReRAM devices enables the emulation of biological synapses, making them highly attractive for neuromorphic computing systems [5].

Among various transition metal oxides investigated for ReRAM applications, vanadium oxides have gained interest due to their multiple stable oxidation states, strong redox activity, and rich defect chemistry. In particular, vanadium pentoxide (V_2O_5) offers a layered crystal structure and high oxygen mobility, which are favourable for resistive switching processes [6]. The presence of oxygen vacancies and reversible V^{5+}/V^{4+} redox transitions plays a critical role in controlling the electrical conductivity of V_2O_5, thereby governing its memristive behaviour [7]. Recent studies have demonstrated that the resistive switching performance of V_2O_5-based devices is highly sensitive to material morphology, crystallinity, and defect distribution [8]. Nanostructured architectures such as nanowires, nanosheets, and nanoparticles can significantly enhance device performance by increasing the effective surface area, modulating the local electric field, and providing controlled pathways for filament formation [9]. However, achieving uniform, phase-pure, and structurally stable V_2O_5 nanostructures through scalable and low-temperature synthesis routes remains a challenge. In this context, hydrothermal synthesis offers a versatile and cost-effective approach for producing well-defined metal oxide nanostructures with controlled morphology and high crystallinity. The use of ethylene glycol as a reaction medium can further regulate nucleation and growth kinetics, enabling the formation of uniform nanospheres while stabilizing the desired oxidation state [10]. Despite these advantages, systematic studies correlating the structural and microstructural characteristics of hydrothermally synthesized V_2O_5 nanospheres with their memristive and neuromorphic functionalities are still limited. In this work, we report the hydrothermal synthesis of V_2O_5 nanospheres and investigate their structural, morphological, and microstructural properties in detail. Memristive devices fabricated using these nanospheres exhibit stable bipolar resistive switching, good endurance, long-term retention, and analog conductance modulation suitable for synaptic behaviour. The resistive switching mechanism is analyzed in terms of oxygen vacancy migration and electrochemical metallization, providing insight into the structure–property–performance relationship of V_2O_5 nanosphere-based ReRAM devices.

2. Experimental Section

2.1 Materials and Reagents

All chemical reagents were of analytical grade and used as received without further purification. The vanadium precursor and solvents employed in the synthesis were procured from commercial suppliers with stated purities ≥99%. Ethylene glycol (EG) was used as the primary solvent and reaction medium due to its high boiling point and structure-directing capability. Deionized water was used for all washing steps. Silicon substrates with a thermally grown SiO_2 layer (SiO_2/Si) were used for thin-film deposition and device fabrication.

2.2 Hydrothermal Synthesis of V_2O_5 Nanostructures

V_2O_5 nanostructures were synthesized via a hydrothermal route using ethylene glycol as the reaction medium. In a typical synthesis, the vanadium precursor was dissolved in ethylene glycol under continuous stirring to obtain a homogeneous solution. The resulting precursor solution was transferred into a autoclave, sealed, and maintained at 180 °C for 8 h. During the hydrothermal process, ethylene glycol played a dual role as a high-boiling solvent and a structure-directing agent, facilitating controlled nucleation and growth of V_2O_5 nanostructures while stabilizing the oxidation state of vanadium. After completion of the reaction, the autoclave was naturally cooled to room temperature. The obtained precipitate was collected by centrifugation and thoroughly washed several times with deionized water and ethanol to remove unreacted species and residual organics. The product was then dried at moderate temperature in air to obtain the final V_2O_5 nanostructured powder.

2.3 Characterization Techniques

The phase purity and crystalline structure of the synthesized V_2O_5 nanostructures were examined using X-ray diffraction (XRD) with Cu Kα radiation (λ = 1.5406 Å). The diffraction patterns were analyzed to identify the crystal phase and assess crystallinity. The chemical composition and oxidation states of the constituent elements were investigated by X-ray photoelectron spectroscopy (XPS). High-resolution spectra of V 2p and O 1s regions were recorded to confirm the valence state of vanadium and the presence of lattice oxygen and defect-related oxygen species. The surface morphology and microstructural features of the V_2O_5 nanostructures were studied using scanning electron microscopy (SEM). Further insight into the internal structure, particle dimensions, and crystallinity was obtained through transmission electron microscopy (TEM) and high-resolution TEM (HRTEM) analyses. Lattice fringe measurements from HRTEM images were used to verify the crystalline nature of the synthesized material.

2.4 Device Fabrication for Memristor/ReRAM

For memristor device fabrication, the synthesized V_2O_5 material was dispersed in an appropriate solvent to form a uniform coating solution. Thin films were deposited onto SiO_2/Si substrates using a spin-coating technique, ensuring uniform film coverage. The coated films were dried and subjected to mild thermal treatment to remove residual solvent and improve film adhesion. Top metal electrodes were deposited by thermal evaporation of Au through a shadow mask, defining the active device area. The resulting device architecture consisted of a metal/V_2O_5/SiO_2/Si structure, suitable for resistive switching measurements.

2.5 Electrical Measurements

The current–voltage (I–V) characteristics of the fabricated devices were measured under ambient conditions using a Keysight B2912A precision source/measure unit. Voltage was applied to the top electrode while the bottom substrate was grounded. The voltage sweep rate was maintained at 0.04 V s^{-1} for all measurements to ensure consistent switching behaviour. Endurance, retention, and switching performance analyses were conducted to evaluate the stability and reliability of the memristive devices. All electrical measurements were repeated across multiple devices to ensure reproducibility and consistency.

3. Result and Discussion

3.1 Structural Analysis (XRD)

The crystalline structure and phase purity of the hydrothermally synthesized V_2O_5 nanospheres were investigated using X-ray diffraction (XRD), as shown in Figure 1.

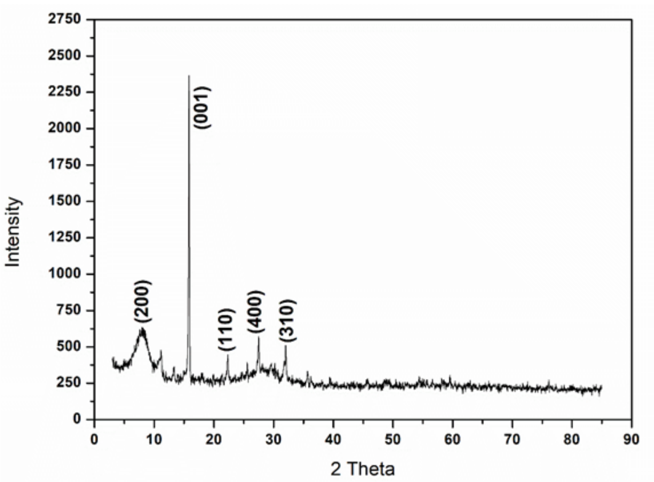


Figure 1. XRD Spectrum of V_2O_5 Nanospere

The diffraction pattern exhibits a series of well-defined and sharp peaks, indicating a high degree of crystallinity. All observed diffraction peaks can be indexed to the orthorhombic α-V_2O_5 phase, which is consistent with standard reference data and previously reported studies on crystalline V_2O_5 nanostructures [11]. No additional peaks corresponding to lower vanadium oxides such as VO_2 or V_2O_3 were detected, confirming the phase purity of the synthesized material. This indicates that the hydrothermal conditions employed in this study effectively stabilized vanadium in its highest oxidation state (V^{5+}). The narrow full width at half maximum (FWHM) of the diffraction peaks further suggests good crystallite quality, which is beneficial for achieving stable and reproducible resistive switching behaviour. A well-ordered crystal lattice facilitates controlled migration of oxygen vacancies, which plays a decisive role in the resistive switching characteristics of transition-metal-oxide-based memristive devices [3].

3.2 Morphological Analysis (SEM)

The surface morphology of the synthesized V_2O_5 nanostructures was examined by scanning electron microscopy (SEM), and the corresponding images are presented in Figure 2. The SEM micrographs reveal the formation of uniformly distributed nanospheres with relatively narrow size distribution. The nanospheres appear densely packed yet individually distinguishable, indicating uniform nucleation and growth during the hydrothermal process. The formation of a spherical morphology can be attributed to the role of ethylene glycol, which acts as a structure-directing agent by regulating surface energy during crystal growth. Such nanosphere architectures provide a comparatively large surface area and abundant grain boundaries, which are advantageous for memristive applications. In resistive switching devices, these features can enhance localized electric field concentration and provide multiple active sites for conductive filament formation, thereby contributing to reduced operating voltages and improved device uniformity [12].

3.3 EDX and Elemental Mapping

The elemental composition of the V_2O_5 nanospheres was analyzed using energy-dispersive X-ray (EDX) spectroscopy. The EDX spectrum (Figure 3a) confirms the presence of vanadium (V) and oxygen (O) as the only detectable elements, indicating the absence of extraneous impurities. The elemental ratios are consistent with the stoichiometry of V_2O_5. Elemental mapping images (Figure 3b–d) further demonstrate a homogeneous spatial distribution of vanadium and oxygen throughout the nanospheres. This uniform elemental distribution confirms compositional consistency across the nanostructures and excludes the possibility of phase segregation or localized elemental clustering. Such chemical homogeneity is essential for achieving reproducible resistive switching behavior, as non-uniform stoichiometry can lead to unstable filament formation and cycle-to-cycle variability in memristive devices [13].

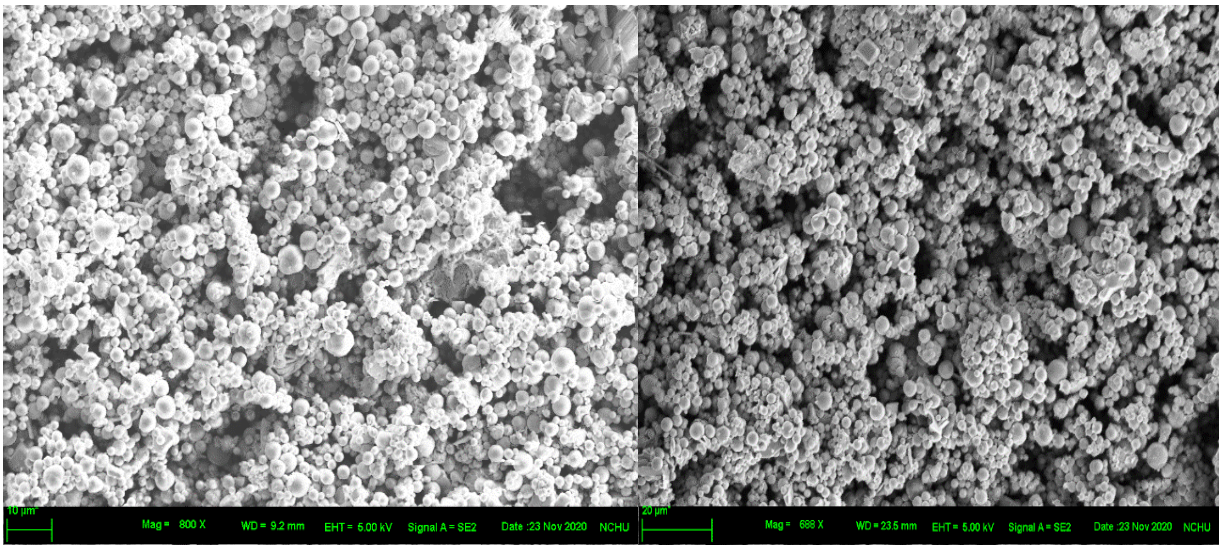
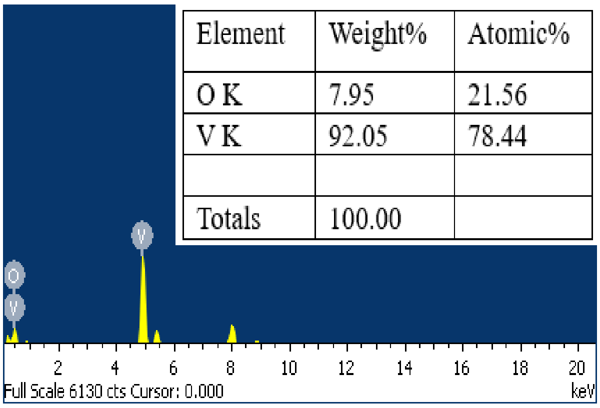
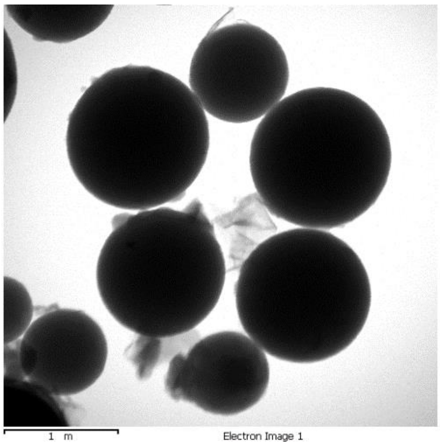


Figure 2. SEM Images of the V_2O_5 Nano spheres

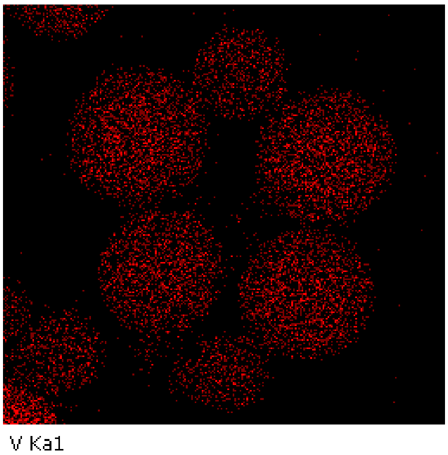


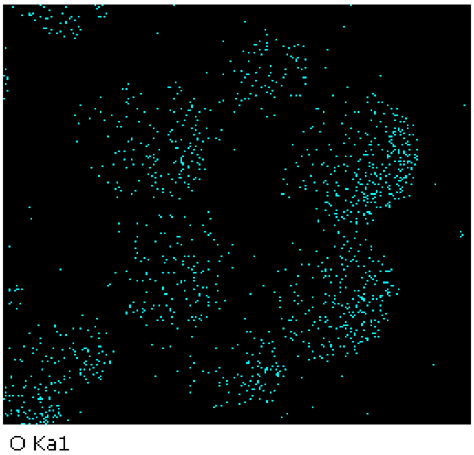
Element	Weight%	Atomic%
O K	7.95	21.56
V K	92.05	78.44
Totals	100.00	

(a)



(b)





(c) (d)

Figure 3. (a) EDX spectrum, **(b)** SEM image of nanosphere morphology, and elemental mapping of **(c)** Vanadium and **(d)** Oxygen.

2.4 Microstructural Analysis (TEM/HRTEM)

Transmission electron microscopy (TEM) was employed to further investigate the internal structure of the synthesized V_2O_5 nanospheres. The TEM images (Figure 4a and b) confirm the spherical morphology observed in SEM analysis and show well-defined nanospheres with clear boundaries. The relatively uniform contrast across individual nanospheres suggests dense packing and structural uniformity. SAED and High-resolution TEM (HRTEM) images (Figure 4c and d) reveal distinct lattice fringes, confirming the crystalline nature of the nanospheres. The measured interplanar spacing of approximately **0.202 nm** corresponds well with the characteristic lattice planes of orthorhombic V_2O_5, further corroborating the XRD results. The presence of continuous and well-resolved lattice fringes without noticeable amorphous regions indicates high structural quality. Such well-ordered crystalline frameworks are particularly favourable for memristive devices, as they provide stable pathways for oxygen vacancy migration and controlled formation and rupture of conductive filaments. This structural integrity is expected to contribute to enhanced switching reliability, endurance, and data retention performance [6].

3.5 ReRAM Device Characteristics and Resistive Switching Behaviour

Figure 5 (a-c) illustrates the schematic representation of the fabricated memristive device based on V_2O_5 nanospheres deposited on a SiO_2/Si substrate with Au top electrodes. The current–voltage (I–V) characteristics of the device were measured at room temperature under ambient conditions, and a stable bipolar resistive switching behaviour was observed. Initially, the device resides in a high-resistance state (HRS), attributed to the insulating nature of V_2O_5 and the presence of surface-adsorbed oxygen species that trap free carriers. Upon sweeping the voltage from 0 V to positive bias, the current increases gradually until a sudden increase is observed at approximately 1.4 V, corresponding to the SET process. During this transition, the device switches to a low-resistance state (LRS), indicating the formation of a conductive path. The LRS is retained when the voltage is swept back to 0 V, confirming the non-volatile nature of the switching behaviour. When a negative voltage is applied, the device resets back to the HRS at approximately −1.5 V, corresponding to the RESET process.

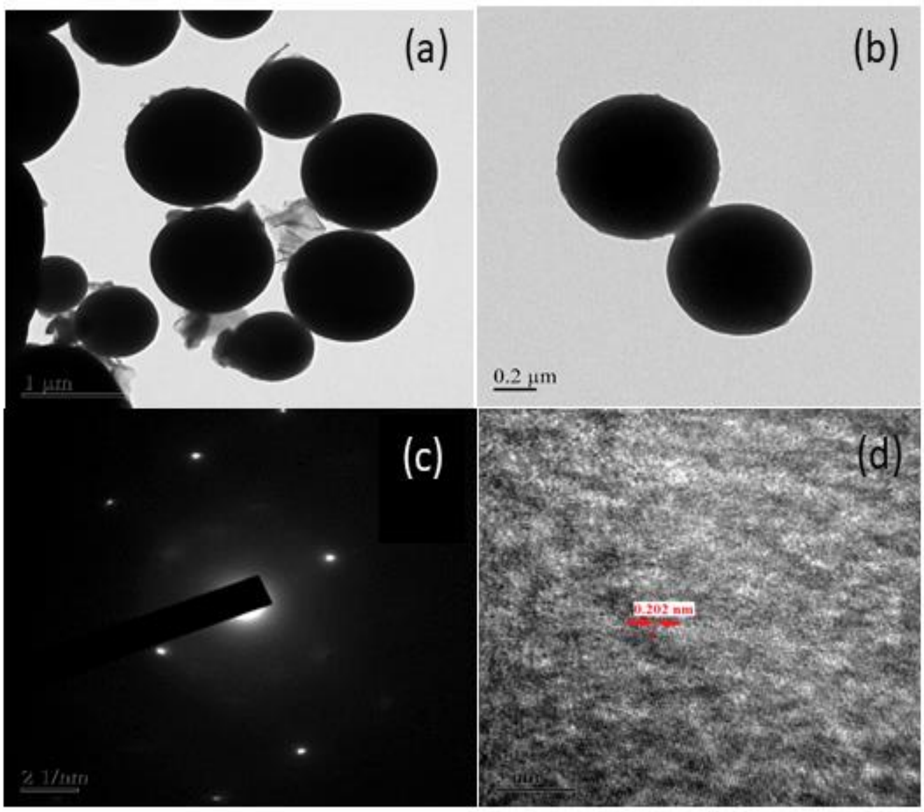


Figure 4. (a) And **(b)** TEM images, **(c)** SAED pattern and **(d)** HRTEM image of V_2O_5 nanospheres

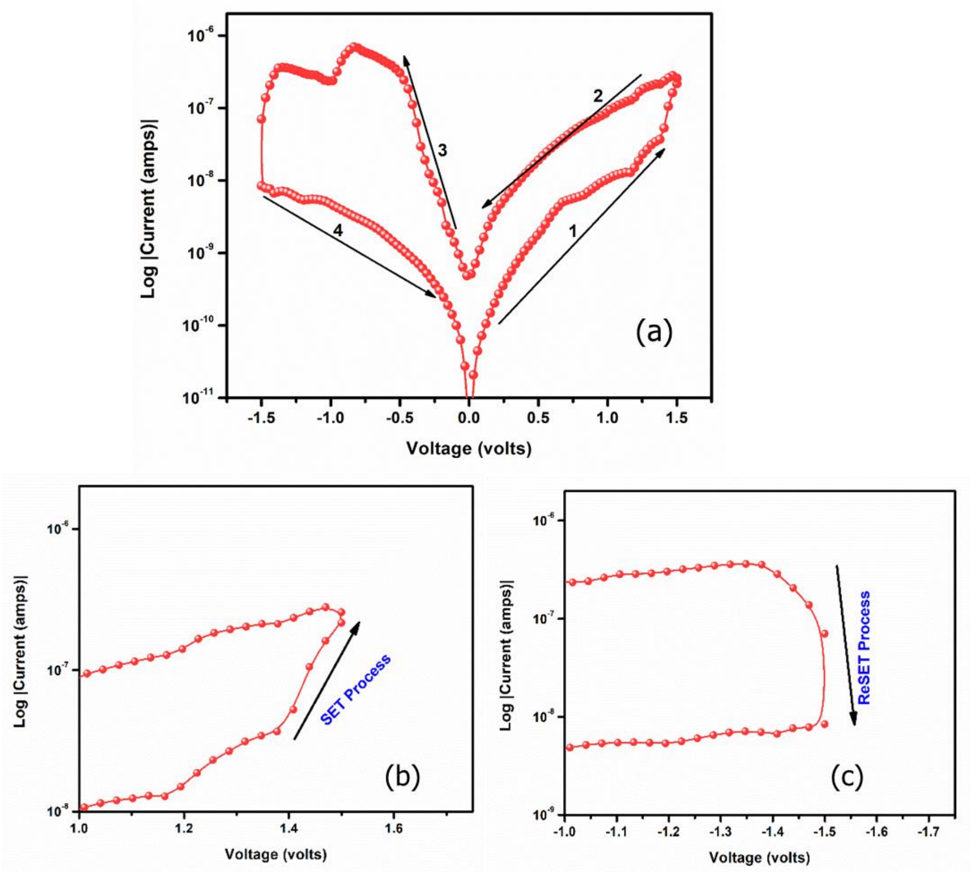


Figure 5. **(a)** Memristive performance **(b)** SET process and **(c)** RESET Process of V_2O_5 nanospheres

The device remains in the HRS during the subsequent voltage sweep to 0 V. The symmetric nature of the SET and RESET processes confirms stable bipolar resistive switching, which is essential for non-volatile memory applications [12].

3.6 Resistive Switching Mechanism

The resistive switching behaviour observed in the V_2O_5 nanosphere-based devices can be explained by an oxygen vacancy-mediated electrochemical metallization (ECM) mechanism. When a positive voltage is applied to the Au top electrode, an electric field is established across the V_2O_5 layer, driving the migration of oxygen ions (O^{2-}) toward the bottom electrode. This migration leaves behind oxygen vacancies (V_O), which act as donor-like defects and enhance local conductivity [4, 14 and 6]. As the concentration of oxygen vacancies increases, localized reduction of V^{5+} to lower oxidation states (V^{4+}/V^{3+}) occurs, leading to the formation of a conductive filament composed of reduced vanadium oxide phases. Once this filament bridges the top and bottom electrodes, the device transitions to the LRS (SET process). The nanosphere morphology, with its high surface area and distributed electric field, facilitates uniform filament formation and reduces localized thermal stress. Upon application of a negative bias, the electric field reverses, causing oxygen ions to migrate back toward the filament region. This results in the partial re-oxidation and rupture of the conductive filament, restoring the device to the HRS (RESET process). The reversible formation and rupture of oxygen-vacancy-rich filaments account for the observed bipolar switching behaviour [13].

3.7 Endurance, Retention, and Reliability

The endurance performance of the V_2O_5 nanosphere-based ReRAM devices was evaluated by repeatedly switching between the HRS and LRS for 200 consecutive cycles (Figure 6a). Although a slight reduction in resistance contrast was observed with increasing cycles, the ON and OFF states remained clearly distinguishable throughout the test, demonstrating good endurance stability. Retention characteristics were assessed by monitoring the resistance states over a time span of up to 10^4 s at a read voltage of +1 V. As shown in Figure 6b, both HRS and LRS states remained stable without significant degradation, confirming reliable non-volatile memory behaviour. These results indicate that the V_2O_5

nanosphere-based devices possess sufficient reliability for practical ReRAM and neuromorphic computing applications [15].

3.8 Implications for Neuromorphic Computing

Symmetric synaptic weight update characteristics between long-term potentiation (LTP) and long-term depression (LTD) is a crucial factor in designing synaptic devices that directly affects learning accuracy of neuromorphic computing. As shown in Figure 7(a), we measured the long-term plasticity of the device by applying a pulse train consisting of potentiation (VPOT), depression (VDEP) and read pulses.

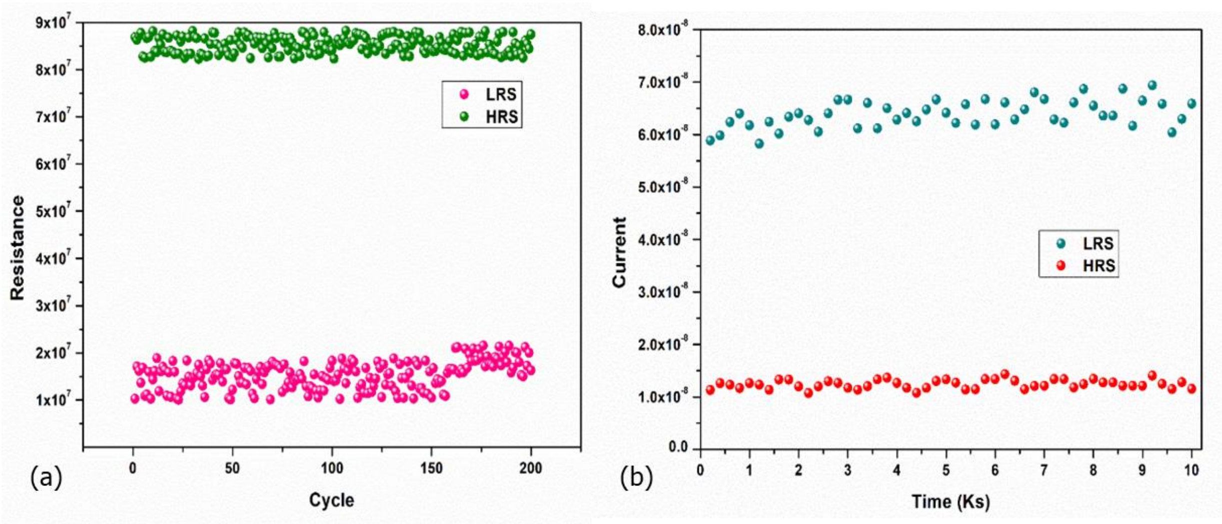


Figure 6. **(a)** Endurance and **(b)** Retention Test of V_2O_5 nanosphere

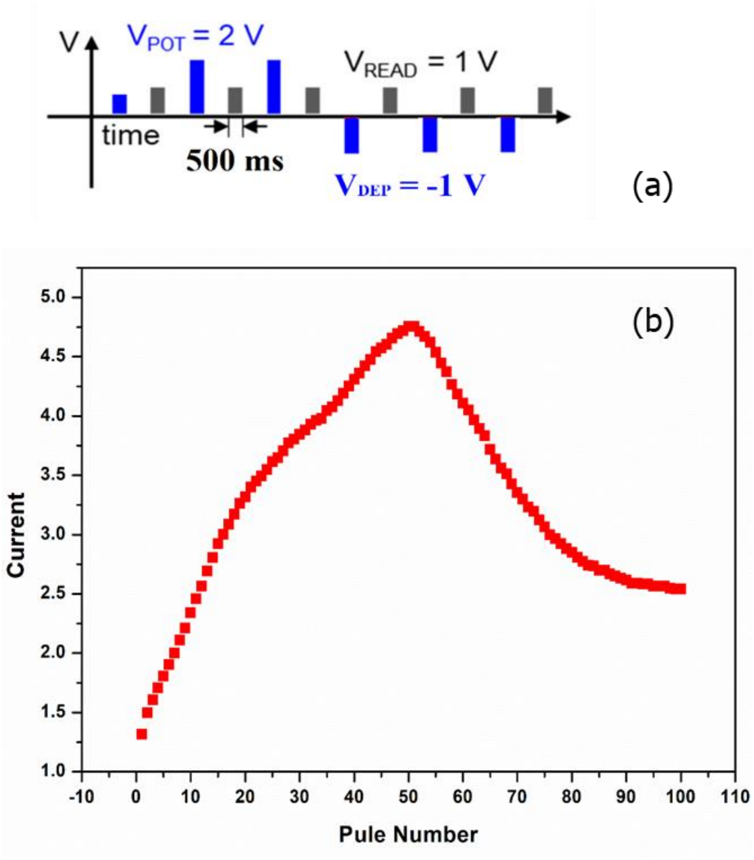


Figure 7. **(a)** Pulse Train and **(b)** Conductance of potentiation and depression

The VPOT was fixed at +2 V during the potentiation process while the VDEP was varied as -1 V as shown in Figure (Pulse train). Each potentiation and depression were performed for 50 cycles each. The duration time of each pulse was 500 ms and the pulse interval was ~2 s. As shown in Figure 7(b), the acquired channel conductance represents a non-volatile behaviour. Thus, increasing and decreasing the channel conductance can be regarded as synaptic LTP and LTD, respectively. Beyond binary memory operation, the gradual and repeatable modulation of conductance observed in the V_2O_5 nanosphere devices suggests their potential for synaptic applications. The ability to emulate long-term potentiation (LTP) and long-term depression (LTD) through controlled voltage pulsing highlights the suitability of these devices for neuromorphic computing systems. The symmetric and stable conductance updates are critical parameters for achieving high learning accuracy in hardware neural networks [5].

4. Conclusion

In summary, phase-pure and highly crystalline V_2O_5 nanospheres were successfully synthesized via an ethylene-glycol-assisted hydrothermal method. Comprehensive structural and microstructural analyses confirmed the orthorhombic crystal structure, uniform spherical morphology, and homogeneous elemental distribution of the synthesized nanospheres. Memristive devices fabricated on SiO_2/Si substrates using these nanostructures demonstrated stable bipolar resistive switching behaviour with well-defined SET and RESET voltages, reliable endurance over repeated cycles, and excellent data retention. The resistive switching mechanism was attributed to oxygen-vacancy-mediated electrochemical metallization involving the reversible formation and rupture of conductive filaments within the V_2O_5 nanospheres. The nanosphere morphology plays a crucial role in facilitating uniform electric field distribution and stable filament dynamics. Furthermore, the observed analog conductance modulation and symmetric potentiation–depression behaviour highlight the potential of these devices for neuromorphic computing applications. Overall, this study demonstrates that hydrothermally synthesized V_2O_5 nanospheres are promising candidates for multifunctional ReRAM and synaptic devices. The insights gained from this work provide a valuable foundation for the rational design of vanadium-oxide-based memristive systems for next-generation non-volatile memory and neuromorphic computing technologies.

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Author Contribution Statement

Mohanbabu Bharathi: Conceptualization, Methodology, Investigation, Writing Original Draft. Shanshan He: Formal analysis, validation, Writing original draft, Lingjun He: Formal analysis, validation, Writing original draft. Donghui Guo: Conceptualization, Formal analysis, validation, Writing review and Editing. All the authors read and approved the final version of the manuscript.

Does this article screened for similarity?

Yes

Conflict of interest

The Author's declares that there is no conflict of interest anywhere.

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