Research Progress of Bismuth-Based Ceramic Materials in Anodes of Sodium-Ion Batteries

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Abstract. With the growing demand for sustainable energy storage, sodium-ion batteries (SIBs) have emerged as a promising alternative to lithium-ion batteries due to sodium's abundant resources and low cost. This review focuses on bismuth (Bi)-based ceramic materials—bismuth vanadate ($BiVO_4$), bismuth molybdate (Bi_2MoO_6), and bismuth oxide (Bi_2O_3)—as anode materials for SIBs. These materials offer high theoretical capacities (352-386 mAh/g) via reversible alloying reactions, with Bi_2MoO_6 additionally leveraging Mo^{6+}/Mo^{4+} redox reactions for enhanced capacity (>420 mAh/g). Key challenges, including poor conductivity (<10^{-4} S/cm) and severe volume expansion (180%-220%), are addressed through composite strategies, such as carbon coating and three-dimensional conductive networks (e.g., $BiVO_4$/carbon composites achieving >80% capacity retention after 200 cycles). Structural design, such as layered frameworks in Bi_2MoO_6 (0.38 nm interlayer spacing) and cubic fluorite structures in Bi_2O_3, optimizes ion diffusion and mechanical stability. Despite progress, issues like interlayer peeling in Bi_2MoO_6 and high-cost carbon nanotubes in Bi_2O_3 remain. Future research should prioritize multi-scale structural engineering (e.g., yolk-shell architectures), electrolyte optimization, and low-cost synthesis (e.g., biomass-derived carbon) to unlock the commercial potential of Bi-based ceramics for large-scale energy storage and low-end power applications.

Keywords: bismuth vanadate; bismuth molybdate; bismuth oxide; sodium-ion batteries; anode materials.

1. Introduction

With the booming development of the global new energy vehicle industry and the continuous increase in the demand for renewable energy grid connection, high-performance battery technology is under unprecedented pressure for iteration [1]. Lithium-ion batteries (LIBs), with their excellent energy density (150-250 Wh/kg) and long cycle life (>1000 cycles), dominate the fields of power batteries and energy storage systems. However, the highly concentrated geographical distribution of lithium (Li) resources, along with the ecological environmental problems and supply chain security risks during the mining process, severely restricts their large-scale application. In addition, the inherent thermal runaway safety hazards of lithium batteries and the high cost of materials (accounting for more than 40% of the total battery cost) further limit their in-depth penetration in the energy storage field.

Against this backdrop, sodium - ion batteries (SIBs), with their remarkable advantages. Due to the abundance of sodium (Na) in the earth's crust is 400 times that of lithium, the SiB enjoyed the advance in producibility, cost - effectiveness, and environmental friendliness to LIBs, and have become ideal candidates to replace LIBs. Although the working principle of SIBs is similar to that of LIBs, their core challenge for SIBs is the relatively large radius of Na^+ ions (1.02 Å vs. 0.76 Å for Li+ ions), resulting in extremely low sodium - storage efficiency of traditional graphite anodes with a capacity of only 30 mAh/g [2]. Therefore, the development of SIB anode materials with high capacity and long life has become the research focus in the current field of electrochemical energy storage.

The key technical bottleneck of sodium - ion battery anode materials is to balance high - capacity storage and structural stability. Currently, mainstream hard - carbon anodes face issues such as a capacity ceiling (<300 mAh/g) and insufficient rate performance. Alloy - type materials such as Tin (Sn)- and Antimony (Sb)-based materials, although having theoretical capacity advantages (>600

mAh/g), have a volume expansion rate of over 300% during charge-discharge processes, which is extremely likely to cause electrode pulverization and failure. Bismuth (Bi), as a Group VA metal, can achieve a theoretical capacity of 385 mAh/g through a reversible alloying reaction ($Bi + 3Na^+ + 3e^- \leftrightarrow Na_3Bi$), and has a stable reaction voltage platform (~0.6 V vs. Na^+/Na) and excellent safety. However, the volume expansion rate of pure bismuth during the cycling process reaches 244%, leading to the collapse of the electrode structure and rapid capacity decay, which limits its practical application.

Bismuth-based ceramic materials, such as bismuth vanadate ($BiVO_4$) and bismuth molybdate (Bi_2MoO_6), provide a new path for optimizing the performance of sodium - ion battery anodes due to their unique crystal structures and electrochemical activities. By introducing transition metals (such as V and Mo) to form composite oxides, these materials can not only regulate the electronic structure and relieve volume expansion but also enhance the kinetic performance through the ion/electron co - conduction mechanism. For example, the monoclinic phase of $BiVO_4$ has a high electron mobility, and the layered structure of Bi_2MoO_6 could effectively buffer volume changes. Combining nanoscale design (such as bismuth@carbon core - shell structures) with electrolyte formulation optimization can further improve the cycle stability and rate response of bismuth - based materials.

In recent years, research on bismuth - based ceramic materials has achieved phased breakthroughs. For example, Wang et.al prepared bismuth - graphene composites through laser irradiation technology, achieving a capacity retention rate of >80% after 1000 cycles. A team from Tianjin University synthesized bismuth@carbon nano - anodes by one - step pyrolysis, with a capacity retention rate of 79% after 1000 cycles [3]. Nevertheless, key problems such as insufficient conductivity and interfacial side reactions (such as unstable SEI films) of these materials still need to be solved.

This article takes the anode materials of sodium - ion batteries as the research core, focuses on the frontier applications of bismuth - based compounds, and constructs a multi - dimensional analysis framework. Firstly, starting from the crystal structure and sodium-storage mechanism, it deeply analyzes the structure - property relationships of typical materials such as $BiVO_4$ and Bi_2MoO_6. Combining innovative synthesis processes and composite modification strategies, it reveals their practical application paths in the battery system. Secondly, based on key indicators such as energy density, cycle life, and rate performance, it systematically compares the technical characteristics of different bismuth - based ceramic materials in terms of conductivity and volume expansion control, and clarifies their adaptation boundaries in different application scenarios. Finally, aiming at the bottlenecks of conductivity and structural stability that restrict material performance, it proposes systematic solutions such as nanostructure optimization, carbon-based composite enhancement, and electrolyte cooperative regulation, providing theoretical support for promoting the industrial application of bismuth-based ceramic materials.

2. Case Descriptions

2.1. Bismuth Vanadate ($BiVO_4$)

Bismuth vanadate is an inorganic functional material with a perovskite-type structure. Its crystal structure can be divided into a monoclinic phase (scheelite-type) and a tetragonal phase (zircon-type). As an anode material for sodium - ion batteries, its sodium-storage mechanisms mainly include:

Alloying - based Sodium Storage: The Bi^{3+} sites generate Na_3Bi through a reversible alloying reaction, contributing the main capacity (theoretical value of 367 mAh/g).

Ion Intercalation - assisted Sodium Storage: The VO_4^{3-} tetrahedral structure provides partial intercalation channels for Na^+, effectively improving the charge transfer kinetics.

The $BiVO_4$/carbon composite system prepared by ball-milling can significantly alleviate the volume expansion effect (with a capacity retention rate of >80% after 200 cycles). At the same time, the introduction of a carbon - based conductive network greatly enhances the electronic conductivity of the material and optimizes its rate performance.

2.2. Bismuth Molybdate (Bi_2MoO_6)

Bismuth molybdate exhibits a layered crystal structure, which is composed of alternating $Bi_2O_2^{2+}$ cation layers and MoO_4^{2-} anion layers. The interlayer spacing reaches 0.38 nm, providing an efficient channel for Na^+ diffusion. Its sodium - storage behavior has a dual- mechanism:

Alloying at Bismuth Sites: Bi^{3+} reacts with Na^+ to form Na_3Bi, contributing a theoretical capacity of 352 mAh/g.

Redox Reaction at Molybdenum Sites: The reversible valence change of Mo^{6+}/Mo^{4+} provides additional capacity.

The Bi_2MoO_6@carbon nanocomposite prepared by the carbonization of metal-organic frameworks (MOFs) can effectively inhibit volume expansion through carbon - layer coating. It can achieve a capacity retention rate of >79% after 1000 cycles and still maintain a stable capacity output of >200 mAh/g at a high rate of 10 C.

2.3. Bismuth Oxide (Bi2O3)

Bismuth oxide exists in a cubic fluorite-type structure (space group Fm3m). In the crystal lattice, $Bi^{3+}$and $O^{2-}$are closely packed to form a high-density ionic conductor framework. Its sodium storage mechanism is mainly based on the alloying reaction: Bi^{3+} is reversibly converted to generate Na_3Bi, with a theoretical capacity of up to 386 mAh/g, and the voltage plateau is stable at 0.55 V (vs. Na^+/Na). However, pure bismuth oxide has extremely poor intrinsic conductivity (conductivity < 10^{-5} S/cm), and the volume expansion rate during the alloying process is as high as 220%, leading to the rapid pulverization and failure of the electrode.

Through the composite strategy of nanosizing and carbon nanotubes (CNT), its electrochemical performance can be effectively improved: First, Bi_2O_3 nanoparticles with a size of 50~100 nm are prepared by the sol-gel method to reduce the ion diffusion path; then, they are combined with CNT through ultrasonic dispersion to construct a three-dimensional conductive network. As an electron transfer bridge, CNT increases the conductivity of the composite material to 10^{-2} S/cm. At the same time, its flexible tubular structure buffers the volume expansion stress and avoids the structural damage caused by the direct contact of particles. After modification, the capacity retention rate of the Bi_2O_3@CNT composite material is > 70% after 200 cycles, and the reversible capacity reaches 270 mAh/g at a current density of 100 mA/g, which is significantly improved compared with pure bismuth oxide (the capacity retention rate in the same period < 40%), demonstrating the key role of the conductive network and the nanostructure in improving the sodium storage performance of bismuth-based oxides.

3. Analysis & challenge

3.1. Bismuth Vanadate ($BiVO_4$)

The synthesis of $BiVO_4$ often employs the hydrothermal method or the sol-gel method [4]. Using $Bi(NO_3)_3·5H_2O$ and NH_4VO_3 as precursors, they are dissolved in an ethylene glycol solution at a molar ratio of 1:1. The pH is adjusted to 5~7, and a sol is formed after magnetic stirring (800 rpm, 2 h). Subsequently, a hydrothermal reaction at 180°C for 12 h yields monoclinic $BiVO_4$ nanoparticles with a particle size of approximately 50 nm. By adjusting the pH value of the reaction system (tetragonal phase is formed under acidic conditions, and monoclinic phase is formed under weakly alkaline conditions), the control of the crystal phase can be achieved. To enhance the conductivity, $BiVO_4$ and graphene are mixed by ball milling (rotation speed 40 Hz, time 2 h) to form a carbon-coated structure, and the carbon content is usually 10~30 wt%.

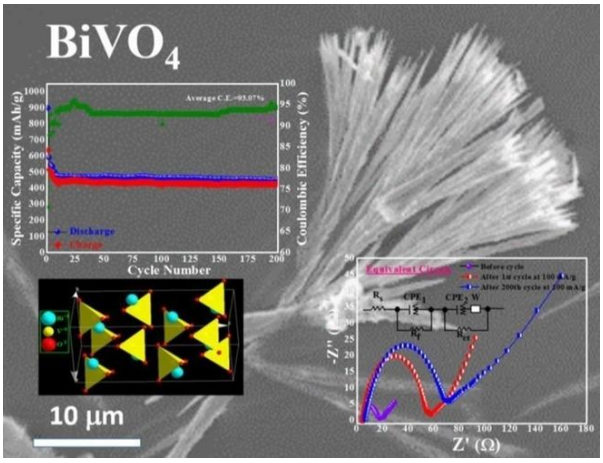

Fig. 1: SEM morphology of $BiVO_4$[4]

The material characterization uses scanning electron microscopy (SEM) to observe the morphology, Fig. 1 displays scanning electron microscopy (SEM) images of $BiVO_4$ under different pH values and ball-milling times. Monoclinic spindle-like particles with a particle size of approximately 50 nm form under pH=5 and 2 hours of ball-milling, while tetragonal spherical particles are generated at pH=7 with 3 hours of ball-milling [4].

The sodium storage mechanism of $BiVO_4$ is mainly based on the alloying reaction, in which Bi^{3+} reacts with Na^+ to form Na_3Bi, with a theoretical capacity of 367 mAh/g, and the voltage plateau is stable at 0.6 V (vs. Na^+/Na). After carbon composite, the material has a capacity retention rate of over 80% after 200 cycles, and the reversible capacity reaches 280 mAh/g at a rate of 1 C, which is nearly double that of the pure phase material. This is attributed to the construction of the conductive network by the carbon layer and its buffering effect on volume expansion: the carbon layer increases the conductivity of the material by two orders of magnitude, and at the same time, it suppresses about 180% of the volume expansion through physical confinement[5].

Studies have shown that the sodium storage performance of the monoclinic $BiVO_4$ is better than that of the tetragonal phase because its open crystal structure is more conducive to the diffusion of Na^+. In addition, phosphorus doping (P-$BiVO_4$) can further improve the performance: phosphorus element is introduced through a one-step wet chemical method to form an amorphous/nanocrystalline biphasic structure, and the capacity retention rate still reaches 85% after 1500 cycles, which is attributed to the high ionic conductivity of the amorphous layer and the structural stability of the crystal phase.

Although the carbon composite significantly improves the sodium storage performance of $BiVO_4$, it still faces the challenges of intrinsic kinetic limitations and the complexity of polycrystalline phase control. The coexistence of the monoclinic and tetragonal phases is likely to cause interfacial stress and accelerate structural degradation. In the future, the charge separation efficiency needs to be further optimized through atomic layer deposition (ALD) or heterostructure construction (such as $BiVO_4/MoS_2$). In addition, exploring bimetallic doping (such as Mo, W) may adjust the energy band structure and increase the sodium ion diffusion coefficient. From the application perspective, the actual capacity of $BiVO_4$ is still lower than the theoretical value. It is necessary to reduce side reactions through electrolyte optimization (such as using ether solvents) or interface engineering (such as introducing an artificial SEI membrane). At the same time, in large-scale preparation, the uniformity problem of carbon composite needs to be solved to avoid performance degradation caused by local agglomeration.

3.2. Bismuth Molybdate (Bi_2MoO_6)

The modification of Bi_2MoO_6 often uses the metal-organic framework (MOF) carbonization method.[6,7] Using $Bi(NO_3)_3$, $(NH_4)_6Mo_7O_{24}$ and terephthalic acid as raw materials, a Bi-Mo bimetallic MOF precursor is prepared by the solvothermal method (150 °C, 12 h), and then carbonized

in an argon atmosphere (500°C, 6 h) to form a Bi_2MoO_6@carbon nanocomposite, with a carbon layer thickness of approximately 5~10 nm. Fig. 2 compares the SEM morphology of pure Bi_2MoO_6 (BMO) and composites with different carbon contents (BMO/NO-C-5, BMO/NO-C-7, BMO/NO-C-9). Pure BMO exhibits a blocky structure, while the composites show uniform carbon layer coating on nanoparticles. Increasing the carbon content (5%→9%) reduces particle size to 50-80 nm and improves dispersibility.

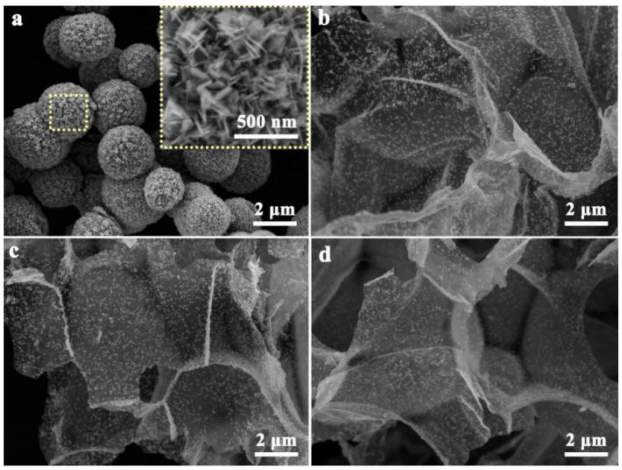

Fig. 2 SEM images of BMO (a), BMO/NO-C-5 (b), BMO/NO-C-7 (c) and BMO/NO-C-9 (d).[7]

The sodium storage mechanism of Bi_2MoO_6 involves both the alloying of bismuth sites and the redox of molybdenum sites, with a total theoretical capacity of over 420 mAh/g. After being coated with MOF-derived carbon, the material has a capacity retention rate of 79% after 1000 cycles, and can still maintain a capacity of over 200 mAh/g at a high rate of 10 C. This benefits from the fast ion diffusion path of the layered structure (interlayer spacing of 0.38 nm) and the synergistic protective effect of the carbon layer: the carbon layer not only constructs a conductive network but also suppresses about 150% of the volume expansion through the confinement effect.

Studies have shown that phosphorus doping (P-Bi_2MoO_6) can further improve the performance. Phosphorus element is introduced through a one-step wet chemical method to form an amorphous/nanocrystalline biphasic structure, and the capacity retention rate still reaches 85% after 1500 cycles, which is attributed to the high ionic conductivity of the amorphous layer and the structural stability of the crystal phase.

The layered structure of Bi_2MoO_6 is prone to interlayer peeling during cycling, leading to the loss of active sites. In the future, it is necessary to enhance the structural stability through interlayer cross-linking (such as introducing metal bonds) or the design of a three-dimensional porous structure. In addition, the high-temperature energy consumption and complex process of the MOF carbonization method limit its large-scale application, and it is necessary to explore low-temperature synthesis strategies (such as hydrothermal carbonization) or low-cost precursors.

From the mechanism perspective, the redox reaction kinetics of molybdenum sites is slow, which may become a bottleneck for high-rate performance. Activating the Mo^{6+}/Mo^{4+} reaction through surface modification (such as noble metal deposition) or defect engineering (such as introducing oxygen vacancies) can improve the charge transfer efficiency.

3.3. Bismuth Oxide (Bi_2O_3)

The modification strategy of Bi_2O_3 mainly involves nanosizing and carbon nanotube (CNT) composite. First, Bi_2O_3 nanoparticles with a size of 50~100 nm are prepared by the sol-gel method, and then combined with CNTs through ultrasonic dispersion (power 300 W, time 1 h) to form a three-dimensional conductive network, and the CNT content is usually 40~70 wt%. The characterization methods include SEM to observe the CNT network structure, TEM to analyze the interfacial bonding between Bi_2O_3 and CNT, and electrochemical impedance spectroscopy (EIS) to test the charge

transfer resistance. The results show that the charge transfer resistance of Bi_2O_3@CNT is approximately 50 Ω, which is significantly lower than 500 Ω of the pure phase.

The sodium storage mechanism of Bi_2O_3 is mainly based on the alloying reaction, as shown in Fig. 3, with a theoretical capacity of 386 mAh/g, and the voltage plateau is stable at 0.55 V (vs. Na^+/Na). After CNT composite, the material has a capacity retention rate of over 70% after 200 cycles, and the reversible capacity reaches 270 mAh/g at a current density of 100 mA/g, which is nearly double that of the pure phase. The three-dimensional network of CNTs not only serves as an electron transfer bridge but also buffers about 220% of the volume expansion through mechanical support, avoiding pulverization caused by direct contact of particles [8].

Studies have shown that bismuth nanoparticles anchored on graphene induced by laser irradiation can further improve the performance. Through ultraviolet laser irradiation, bismuth nanoparticles form chemical bonds with graphene, and the capacity retention rate reaches 94.4% after 2000 cycles, which is attributed to the strong interfacial bonding of the "inlaid" structure and the confinement effect of the carbon layer.

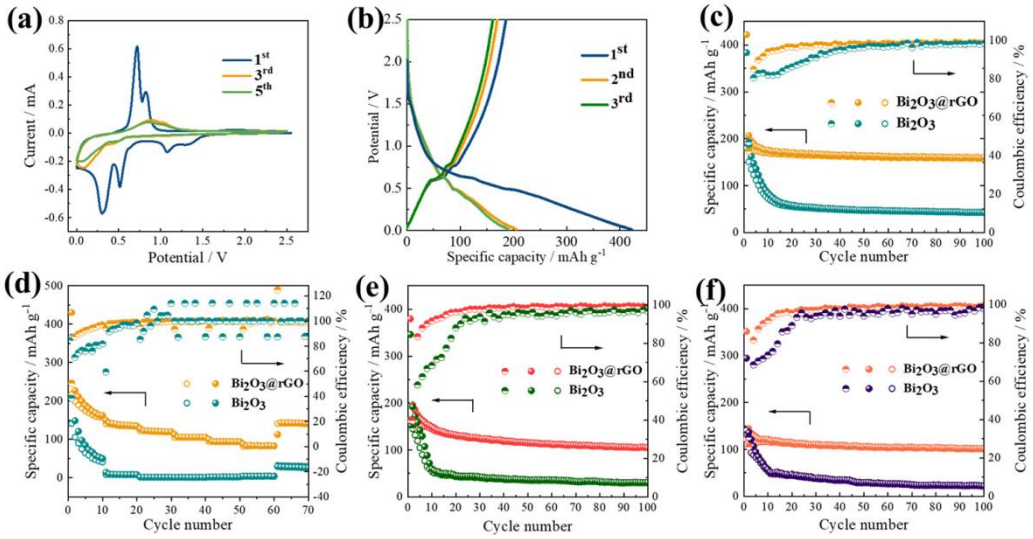

Fig. 3. (a) CV curves and (b) discharge-charge curves of Bi_2O_3@rGO. (c) Cycling performance of Bi_2O_3@rGO and Bi_2O_3 at 50 mA g^{-1}. (d) Rate performance of Bi_2O_3@rGO and Bi_2O_3 at 50 mA g^{-1}. (e) Cycling performance at 200 mA g^{-1} and (f) at 1 A g^{-1}. [8]

The volume expansion problem of Bi_2O_3 has not been completely solved, and the CNT network may break due to stress accumulation during long-term cycling. In the future, it is necessary to explore flexible carbon matrices (such as graphene aerogels) or core-shell structures (such as Bi_2O_3@TiO_2@CNT) to enhance mechanical stability. In addition, the high cost of CNTs limits its large-scale application, and it is necessary to develop low-cost carbon sources (such as biomass-derived carbon) or self-assembly strategies (such as freeze-drying) to reduce the preparation difficulty. From the perspective of the electrolyte, ether-based electrolytes (such as dimethoxyethane) can improve the cycling stability by forming a stable SEI membrane. For example, the capacity retention rate of Bi_2O_3in the ether-based electrolyte reaches 94.4% after 2000 cycles, which is significantly better than that of the ester-based electrolyte. Therefore, the optimization of the electrolyte-electrode interface is an important direction for future research.

4. Summary and Suggestion

$BiVO_4$ features a dual sodium storage mechanism, delivering a high theoretical capacity of 367 mAh/g through the alloying reaction at Bi^{3+} sites, while the VO_4^{3-} tetrahedral structure allows partial intercalation of sodium ions, optimizing charge transport kinetics. Carbon composite significantly enhances cyclic stability, with capacity retention exceeding 80% after 200 cycles, and the high electron mobility of the monoclinic phase contributes to excellent rate performance. However, the

preparation process requires strict control of pH and crystal phase regulation. Hydrothermal or sol-gel methods demand precise reaction conditions, leading to low efficiency in large-scale production. Additionally, the coexistence of monoclinic and tetragonal phases easily induces interfacial stress, and local agglomeration during carbon composite may affect performance uniformity. Develop template-free simple synthesis processes (such as spray drying) to reduce preparation complexity, and suppress polycrystalline interfacial stress by surface coating with inert oxides (e.g., Al_2O_3). For the uniformity issue of carbon composite, introduce self-assembly technology to achieve in-situ growth of carbon layers and avoid particle agglomeration during ball milling.

The layered structure of Bi_2MoO_6 provides a wide interlayer spacing of 0.38 nm, significantly promoting sodium ion diffusion. The sodium storage mechanism combines bismuth site alloying (352 mAh/g) with molybdenum site redox reactions, with a total theoretical capacity exceeding 420 mAh/g. After MOF-derived carbon coating, the material maintains 79% capacity after 1000 cycles and can stably deliver over 200 mAh/g at high rates (10 C). However, the layered structure is prone to peeling during cycling, leading to loss of active sites; MOF carbonization requires high temperature (500°C) and complex precursor preparation, resulting in high energy consumption and cost, which limits industrial applications. Thus, enhance interlayer forces by introducing metal cations (such as K^+, Mg^{2+}) to inhibit peeling; explore biomass-derived carbon as an alternative to MOF precursors, such as lignin or cellulose as carbon sources, to reduce synthesis costs and achieve green production. Meanwhile, design three-dimensional porous structures (such as foam carbon loading) to improve structural stability.

The cubic fluorite structure endows Bi_2O_3 with a high-density ion-conducting framework, and the alloying reaction has a theoretical capacity of 386 mAh/g with a stable voltage plateau (0.55 V). Carbon nanotube (CNT) composites construct a three-dimensional conductive network, increasing the conductivity to 10^{-2} S/cm, with capacity retention exceeding 70% after 200 cycles, and the mechanical support effectively alleviates 220% volume expansion. The pure phase has extremely poor conductivity ($<10^{-5}$ S/cm), CNTs are costly and have complex ultrasonic dispersion processes, and the CNT network is prone to fracture due to stress during long-term cycling. In addition, sodium ion diffusion paths are still limited in the close-packed lattice. Thus, replace CNTs with low-cost carbon sources (such as graphene oxide or carbon black) and construct a porous carbon skeleton by freeze-drying to reduce costs. Meanwhile, design core-shell structures (such as Bi_2O_3@C@TiO_2), using the rigid support of the TiO_2 layer and the flexible buffering of the carbon layer to synergistically inhibit volume expansion and further improve cycle life.

Those advantages and disadvantages were concluded and showed in Table. 1. Based on the characteristics of these three materials, the optimization of bismuth-based ceramic materials needs to follow a collaborative strategy of "structural design - interface regulation - process innovation":

Structural Design: Develop hierarchical porous structures (such as yolk-shell types) or heterojunctions (such as $BiVO_4$/Bi_2MoO_6) to balance ion diffusion efficiency and structural toughness;

Interface Regulation: Induce the formation of a stable SEI film through electrolyte additives (such as $LiPF_6$ or fluorinated solvents) to reduce interfacial side reactions;

Process Innovation: Develop continuous production processes (such as roll-to-roll coating) to reduce energy consumption in nanosization and carbon composite, and promote the transition from laboratory to industrialization.

Through breakthroughs in the above directions, bismuth-based materials are expected to achieve large-scale applications in low-cost energy storage fields

Table 1. Comparison of Various Bi-based Anodes

Type	advantages	disadvantages
$BiVO_4$	-High theoretical capacity -Good rate performance after carbon composite	-Complex phase control in synthesis- -Risk of local agglomeration in carbon composite -Moderate volume expansion (180%)
Bi_2MoO_6	-Layered structure for fast Na^+ diffusion -High total capacity -Excellent cycle stability	-Interlayer peeling during cycling -High-temperature MOF carbonization process -Slow redox kinetics of Mo sites
Bi_2O_3	-High theoretical capacity -Stable voltage plateau -Effective volume buffering via CNT network	-Poor intrinsic conductivity -Need CNTs composite -Severe volume expansion

5. Conclusion

This study systematically investigates the sodium storage mechanisms, performance characteristics, and optimization pathways of bismuth-based ceramic materials such as bismuth vanadate ($BiVO_4$), bismuth molybdate (Bi_2MoO_6), and bismuth oxide (Bi_2O_3) as anodes for sodium-ion batteries. The main conclusions are as follows:

Bismuth-based materials offer high capacity and environmental adaptability but require balancing sodium storage mechanisms and structural stability. All three materials achieve high theoretical capacities through alloying reactions ($BiVO_4$: 367 mAh/g; Bi_2MoO_6: 352 mAh/g; Bi_2O_3: 386 mAh/g), with Bi_2MoO_6 additionally enhancing total capacity (>420 mAh/g) through molybdenum-site redox reactions. However, pure-phase materials commonly face issues of volume expansion (180%-220%) and insufficient conductivity ($<10^{-4}$ S/cm), necessitating composite strategies for optimization. For example, carbon coating increases the cycle stability of $BiVO_4$ from <50% for the pure phase to over 80%, while CNT networks enhance the conductivity of Bi_2O_3 by five orders of magnitude.

2) Composite modification and structural design are critical for performance enhancement $BiVO_4$ relies on carbon composites to build conductive networks, with the monoclinic phase being more advantageous due to its high electron mobility, but multi-phase interfacial stress must be addressed; Bi_2MoO_6's layered structure (0.38 nm interlayer spacing) significantly promotes ion diffusion, and MOF-derived carbon coating achieves 79% capacity retention after 1000 cycles, though interlayer delamination risks still require mitigation via metal cation cross-linking; Bismuth oxide buffers 220% volume expansion through a 3D CNT network, and laser-irradiated graphene anchoring extends cycle life to over 2000 cycles, but the cost and dispersion challenges of CNTs limit industrial application.

3) Future research must focus on multi-dimensional collaborative optimization Despite the potential of bismuth-based materials, three major bottlenecks must be overcome for commercialization:

Structural toughness: Develop hierarchical porous (e.g., yolk-shell) or heterojunction structures (e.g., $BiVO_4/MoS_2$) to simultaneously enhance ion diffusion and anti-expansion capabilities;

Interface stability: Suppress side reactions and optimize interfacial impedance through electrolyte regulation (e.g., ether-based solvents) or artificial SEI film design;

Process innovation: Explore low-cost synthesis routes (e.g., biomass carbon as an alternative to MOF precursors, spray drying) to reduce energy consumption and costs in nanosization and composite processes.

In summary, bismuth-based ceramic materials, with their high capacity and resource advantages, have the potential to become differentiated alternatives to lithium-ion batteries in large-scale energy

storage and low-end power applications. Performance breakthroughs will require collaborative innovation in material design, interface engineering, and preparation technology.

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