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Editorial

Inorganic Electrode Materials in High-Performance Energy Storage Devices

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1. Introduction

This special issue focuses on the design, synthesis, optimization, and application of inorganic electrode materials in high-performance energy storage devices, covering lithium–sulfur batteries [1], lithium-ion batteries [2,3], aqueous zinc-ion batteries [4], sodium-ion batteries [5], hybrid supercapacitors [6,7], and methanol-mediated water-splitting systems [8]. It systematically presents the latest research progress in addressing key challenges such as the low conductivity, poor cycling stability, volume expansion, and sluggish reaction kinetics of inorganic electrode materials, providing comprehensive insights for the development of advanced energy storage technologies [9,10].

2. Core Research on Battery Electrode Materials

2.1. Lithium–Sulfur (Li-S) Batteries

A critical challenge regarding Li-S batteries lies in the shuttle effect of lithium polysulfides (LiPSs) and slow redox kinetics [11–14]. Against this background, Tan et al. designed a two-step thermal annealing strategy to derive wormlike N-doped porous carbon-nanotube-supported low-crystalline Co nanoparticles (a-Co-NC@C) from binary Zn-Co ZIF [1]. Ammonia-induced thermal annealing not only reduces the crystallinity of Co nanoparticles but also promotes the growth of highly graphitized N-doped carbon nanotubes. The composite structure provides sufficient sulfur accommodation space and enhanced LiPSs adsorption/catalytic activity, enabling a specific capacity of 559 mAh g^{-1} after 500 cycles at 1 C and 572 mAh g^{-1} at 3 C, with excellent stability even at high sulfur loadings (e.g., 579 mAh g^{-1} after 400 cycles at 1 C with a 2.55 mg cm^{-2} sulfur loading).

2.2. Lithium-Ion Batteries (LIBs)

For LIB anode materials, addressing volume expansion and improving conductivity are key [15–22]. Jin et al. synthesized a novel spinel high-entropy oxide ($Cr_{0.2}Mn_{0.2}Co_{0.2}Ni_{0.2}Zn_{0.2})_3O_4$ via a simple solution combustion method [3]. Benefiting from the entropy stabilization effect, the material exhibits outstanding cycling stability (132 mAh g^{-1} after 100 cycles at 100 mA g^{-1} and 107 mAh g^{-1} after 1000 cycles at 1 A g^{-1}) and rate performance (96 mAh g^{-1} at 2 A g^{-1}).

Xie et al. encapsulated ultrafine In_2O_3 particles in a carbon-nanofiber framework through electrospinning and thermal annealing [2]. The 1D carbon network inhibited In_2O_3 agglomeration, buffered volume changes, and accelerated ion/electron transport, achieving 571 mAh g^{-1} after 200 cycles at 0.3 A g^{-1} and 264 mAh g^{-1} at 3.2 A g^{-1}, significantly outperforming pure In_2O_3 electrodes.

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2.3. Aqueous Zinc-Ion Batteries (AZIBs)

AZIBs are gaining attention for their safety and inexpensiveness, but their cathode stability and ion storage capacity need improvement [23–27]. Li et al. developed a $Co(OH)_2$/CoOOH mixed-phase cathode via two-step electrochemical preparation [4]. The mixed phase reduces local structural disorder and enhances thermal stability and mechanical strength, delivering a maximum capacity of 164 mAh g^{-1} at 0.05 A g^{-1}, a high energy density of 275 Wh kg^{-1}, and 78% capacity retention after 200 cycles.

2.4. Sodium-Ion Batteries (SIBs)

Sodium-ion batteries are considered a potential alternative to lithium-ion batteries because of the abundance and inexpensiveness of sodium resources [28–33]. However, the larger ionic radius of Na^+ leads to significant volume changes in electrode materials and slow ion diffusion kinetics. Wang et al. designed and prepared carbon-shell-wrapped hollow-structured cobalt–nickel bimetallic transition metal selenides (HS-$Co_xNi_\gamma Se_2$@C) via a three-step approach of PAN coating-ZIF-67 ion exchange selenization [5]. The hollow structure provides sufficient space for buffering volume expansion during charge–discharge processes, and the synergism between Co and Ni enhances material conductivity and electron mobility. The performance is closely related to the Co-Ni ratio: an excessive amount of Ni^{2+} leads to hollow structure collapse and a reduced electrochemical surface area. The optimized material (Co:Ni ≈ 1.05:0.95) exhibits excellent electrochemical performance—a reversible capacity of 334 mAh g^{-1} after 1000 cycles at a high current density of 5.0 A g^{-1}, and a discharge capacity of 428 mAh g^{-1} at the same rate—providing new ideas for the structural design and compositional optimization of SIB electrode materials.

3. Advances in Supercapacitor and Electrocatalyst Materials

3.1. Hybrid Supercapacitors (HSCs)

Gao et al. provide a comprehensive review on HSCs based on transition metal oxides (TMOs) and carbon materials, summarizing optimization strategies, including heteroatom doping, heterostructure construction, nanocomposite formation, and MOF derivation [7]. The representative approaches include Nd-doped α-Mn_2O_3 microspheres with 862.14 F g^{-1} at 0.5 A g^{-1}, NiCoP-$NiCoO_2$/NiCo-PO_x crystalline/amorphous heterostructures with 78.7% capacity retention after 10,000 cycles, and Ti_3C_2-ZrO_2 nanocomposites achieving 75.6 Wh kg^{-1} energy density. These approaches address the trade-off between energy density and power density in HSCs, expanding their application in flexible electronics and large-scale energy storage.

Xie et al. report on a $LiClO_4$-doped polypyrrole/titanium ($LiClO_4$-PPy/Ti) electrode for use in supercapacitors [2]. The strong electrostatic interaction between pyrrole N and Ti (2.450 Å) enhances electronic conductivity (DOS: 57.321 electrons/eV) and interfacial interaction, resulting in a specific capacitance of 0.123–0.0122 mF cm^{-2} at 0.01–0.10 mA cm^{-2}, outperforming pure $LiClO_4$/Ti electrodes in this respect.

3.2. Methanol-Mediated Water Splitting

Teli et al. synthesized a Pd-MoS_2 catalyst via solvothermal methods for methanol-mediated overall water splitting [8]. The catalyst exhibits low overpotentials (133 mV for MM-OER at 10 mA cm^{-2} and 224.6 mV for MM-HER at −10 mA cm^{-2}) and excellent stability (18 h for MM-OER and 15.5 h for MM-HER). The Pd-MoS_2 | | Pd-MoS_2 cell achieves a small potential of 1.581 V and durable operation over 18 h, providing a cost-effective alternative to noble metal catalysts for hydrogen production.

4. Conclusions and Outlook

This issue showcases the diversity of and innovations in inorganic electrode materials in high-performance energy storage devices, addressing critical challenges in different systems through material design and process optimization. Future research directions include determining how to precisely control material microstructure, developing low-cost scalable synthesis methods, increasing low/high-temperature performance, and integrating multi-functional properties. The studies collected in this Special Issue provide valuable references for academic research on and industrial application of advanced energy storage materials, promoting the transition towards sustainable and high-efficiency energy storage technologies.

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