

Nanoparticles in Battery System

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Abstract

Batteries have traditionally been utilized in energy storage and power-driven systems. Thermal stability for lithium-ion batteries has been a persistent source of concern worldwide in recent decades due to thermal runaway hazards. Because of the complicated electrochemical reactions occurring at different temperatures, lithium-ion batteries have a high-temperature sensitivity and a comparatively restricted operational temperature range. As a result, several types of batteries are discussed further.

Keywords: Nanoparticles, battery, Zinc-air, Zinc-ion, Lithium-sulfur, Lithium-ion, Potassium-ion

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I. INTRODUCTION

The ever-growing demand for safe, durable, and cost-effective battery systems have motivated intensive research for exploring next-generation energy storage devices [1].

Metal-air batteries are promising clean and renewable energy storage systems, among which rechargeable zinc-air batteries (ZABs) are of great interest owing to their high energy density, intrinsic safety, low cost, and environmental friendliness [2].

Owing to them the Zn-air batteries (ZABs) have recently received extensive attention [3]. However, the sluggish kinetics of the cathodic electrochemical oxygen reduction reaction (ORR), which is a vital process of ZABs, severely impede their industrial implementation. [4]–[7]. Despite platinum-group-metal-based materials have served as efficient electrocatalysts with low overpotentials for ORR, their high cost, natural scarcity, and moderate durability hinder their large-scale commercialization [8]. Therefore, searching for cost-effective and earth-abundant electrocatalysts with excellent ORR activity and stability for ZABs is critically important but remains a great challenge.

The rapid development of portable electronics and electric vehicles has led to the development of advanced battery systems [9], [10]. Lithium-sulfur (Li-S) batteries, having high theoretical capacity, are attractive candidates for use in the field of portable energy storage as they can be used to develop electric vehicles and aircrafts [11]. The low sulfur conductivity [12], shuttle effects, and dissolution of polysulfides (LiPSs) [13] under conditions of high sulfur mass loading and high working rate, which restrict the actual energy density, limit the practical industrial and commercial applications of Li-S batteries [14], [15].

Nonetheless, there is a great deal of obstacles existing in the field of Li-S batteries research, including low utilization rate of active substances, poor coulombic efficiency and low capacity retention rate [16]. Almost all of the above problems in Li-S batteries are related to their electrochemistry of complex phase transformation and sluggish sulfur redox kinetics which caused by the nonconductive characteristic of sulfur, and polysulfide shuttle effect [17], [18].

Due to the drastic increase in the demand of electronic vehicles and portable devices, several studies have been carried out to improve the performance of lithium-ion batteries (LIBs). Particularly, several studies have focused on improving the composition and structure of the cathode and anode as they directly affect the battery performance such as its capacity and life cycle characteristics [19]. Currently, graphite, which is soft carbon, is the most commercially available anode used in LIBs. Graphite is an intercalation-type anode with a layered structure. However, its shorter life cycle compared to that of natural graphite and the limited theoretical capacity of 372 mAh g⁻¹ restrict its effective application in LIBs [20]. Therefore, it is necessary to overcome these limitations to achieve a promising long-life and high-energy-density LIB. However, organic-based liquid electrolytes that are used in most commercial LIBs are flammable and can react with Li metal when an Li metal anode is used, leading to dendritic growth of Li on the metal surface [21], [22]. Addressing this safety concern is imperative for the commercial success of LIBs. This shortcoming of LIBs can be mitigated by replacing the flammable organic liquid electrolyte with solid electrolytes (SEs) [23].

The wide applications of current lithium-ion batteries (LIBs) is impeded by the limited lithium salts and high production cost. It is urgent and significant to develop alternative secondary battery systems for LIBs [24], [25]. Because of the luxuriant reserves of potassium salts, low cost, and similar electrochemical properties with

LIBs, potassium-ion batteries (KIBs) are becoming the most promising alternatives to conventional LIBs [26], [27]. Potassium, with wide availability of mineral reserves and low standard electrode potential (-2.93 V vs. SHE), close to lithium (-3.04 V vs. SHE), enables potassium ion batteries (PIBs) an attractive alternative to lithium-ion batteries (LIBs) in stationary energy storage systems [28]–[30]. Besides, it has been reported that K ion-based electrolytes can display superior ionic conductivity than those of Li^+ and Na^+ caused by the weaker interactions between potassium ions and organic electrolyte solvents, which is favorable for achieving the ideal rate performance of the cell device [31], [32].

II. THEORY

Dendrite formation and side reactions at the Zn anode must be controlled to produce high-performance zinc metal batteries, primarily when the batteries are operated at high current densities and high temperatures. Inkjet printing silver nanoparticles report a flexible and dendrite-free Zn metal anode ($\text{AgNPs}@CC/\text{Zn}$) on a 3D carbon matrix. Experiments and DFT calculations show that Ag nanoparticles can act as heterometallic seeds for zinc deposition, which improves the carbon matrix's zincophilicity and thermal conductivity at the same time. It also encourages reversible zinc plating and peeling via Ag/Zn alloying and de-alloying reactions. This work describes a simple and inexpensive inkjet printing approach for fabricating a 3D flexible and dendrite-free Zn metal anode for foldable and heat-resistant Zn-based batteries [33].

Jin-Cheng Li et al. (2021) developed a dual-phasic carbon Nano architecture with a single-atom phase for the Oxygen reduction reaction and a nanoscale phase for the Oxygen Evolution Reaction. Carbon nanotube bridges were used to connect single Cobalt atoms supported by carbon nanotubes (single-atom phase) and nanosized Cobalt encased in zeolitic-imidazole-framework-derived carbon polyhedrons. Between the OER potential at $10 \text{ mA}\cdot\text{cm}^{-2}$ and the ORR half-wave potential, the derived dual-phasic carbon catalyst has a modest over potential difference of 0.74 V. It also has a low charge-discharge potential gap with 0.51 V at $5 \text{ mA}\cdot\text{cm}^{-2}$ and excellent discharge-charge cycling longevity. This research advances the development of rechargeable ZABs (Zinc-Air Batteries) by presenting a realistic design concept for multifunctional catalysts. It had a high energy efficiency of 71.8% and outstanding galvanostatic discharge-charge cycling endurance, with a tiny potential gap decay of 0.09 V after 100 cycles for 33.6 hours, which was substantially better than $\text{Pt}/\text{C}+\text{Ir}/\text{C}$. This study proposes a novel method for fabricating high-performance and durable bifunctional oxygen electrocatalysts [34].

By optimizing the Cobalt species in the precursor, Zhe Wang et al. (2021) developed a simple methodology for the large-scale synthesis of an N-doped porous carbon nanocage with the coexistence of atomically scattered Co-N_4 sites (Co-SAs) and tiny Co-NPs (Co-SNPs). Without losing the highly porous structure of the carbon supports, Co-SNPs can contribute to creating graphitic layers, which also act as supports for Co-N_4 sites. Additionally, compared to the $\text{Co-SAs}@NC$ -based counterpart, the $\text{Co-SAs}/\text{SNPs}@NC$ -based ZAB has a greater power density, larger specific capacity, and superior cycling stability. This research could pave the way for more rational electrocatalyst design for efficient and consistent Oxygen reduction reaction catalysis in both half-cell and commercial energy storage and conversion devices. The feasible zinc-air battery with the $\text{Co-SAs}/\text{SNPs}@NC$ catalyst has a maximum power density of $223.5 \text{ mW}\cdot\text{cm}^{-2}$, a large specific capacity of $742 \text{ W}\cdot\text{h}\cdot\text{kg}^{-1}$ at $50 \text{ mA}\cdot\text{cm}^{-2}$, and excellent cyclability [35].

Pyrolysis of the $\text{NiFe-PBA}/\text{PPy}$ fibres network rooted on carbon cloth resulted in the practical construction of a flexible 3D free-standing air-electrode. Slender N-doped carbon nanofibers' cross-linking forms the 3D network structure, which provides a high surface area and allows rapid electron/charge transport. NiFe nanoparticles are attached to a 3D network of N-doped carbon nanofibers, which provide enough stable and efficient reactive sites for OER and ORR while preventing the binder's detrimental effects. As a result, the ORR/OER catalytic activity of the $\text{NiFe}/\text{NCNF}/\text{CC}$ electrode is highly efficient and stable. Furthermore, the $\text{NiFe}/\text{NCNF}/\text{CC}$ liquid Zn-air battery has a high-power density of $140.1 \text{ mW}\cdot\text{cm}^{-2}$ and remarkable rechargeable endurance of 700 cycles. Moreover, two liquid Zn-air batteries provide sufficient power to drive a water-splitting system steadily [36].

Pulverizing Fe_2O_3 embedded in polyacrylonitrile (PAN) fibres to develop multifunctional sulfur hosts with various polysulfide anchoring and catalytic conversion activities results in hollow and porous $\text{Fe}_3\text{C}/\text{N}$ -co-doped carbon nano boxes ($\text{Fe}_3\text{C}/\text{NC}$) connected by N-doped carbon (NC) nanofibers. According to experimental and first-principles density functional theory analyses, the evenly distributed Fe_3C and N units in the nano boxes can significantly reduce the polysulfide shuttle effect. During discharge, the conversion of polysulfides (LiPSs) to Li_2S is catalyzed. Fast electron transport through NC nanofibers and enhanced Li^+ diffusion through porous nano box shells are vital components of the process. The structural properties of the nano boxes influence the extensive sulfur loading and volume change tolerance of LiPSs, resulting in synergistic redox reaction catalysis. After 240 cycles at 1°C , a high capacity of $645 \text{ mAh}\cdot\text{g}^{-1}$ was exhibited, and a high capacity of $712 \text{ mAh}\cdot\text{g}^{-1}$ with a high sulfur loading of $5 \text{ mg}\cdot\text{cm}^{-2}$ after 100 cycles at 0.2°C and an enhanced areal

capacity of 3.6 mAh.cm^{-2} . This simple approach of electrode material synthesis and electrode structure design opens up many opportunities for Li-S battery commercialization [37].

Lithium-sulfur (Li-S) batteries have been evaluated as having considerable potential in next-generation advanced energy storage systems. However, the bulk of substrates with high electrical conductivity and complete adsorption-catalysis synergy coverage is difficult to obtain. Electrospinning combined with hydrothermal treatment, nitrogen functionalized porous carbon nanofibers joined with nickel ferrite nanoparticles (NFO/NCFs) were effectively developed and applied to current collectors comprising Li_2S_6 cathode and binder free for Li-S batteries. The NFO/NCFs play an essential role in the adsorption and catalysis of polysulfides, which speeds up redox kinetics. As a result, the Li_2S_6 catholyte saturated NFO/NCFs electrode had an initial discharge capacity of 997 mAh.g^{-1} and retained the capacity at 637 mAh.g^{-1} after 350 cycles at 0.2°C , which is greater than NCFs. The composite electrode has a high area capacity of 8.35 mAh.cm^{-2} at 0.1°C and retains 6.01 mAh.cm^{-2} after 150 cycles, even with 10.2 mg.cm^{-2} sulfur loading. The findings imply that multifunction NFO/NCFs with excellent anchoring and catalysis is advantageous in achieving the goal of large-scale Li-S battery application. Other metal oxide spinel structures are thought to be capable of chemically anchoring and catalyzing lithium polysulfides, which have a tremendous amount of potential in lithium-sulfur batteries [38].

The Langmuir Schaefer approach is used in this study to produce "Janus"-structured nanocomposites with iron oxide (Fe_3O_4) nanoparticles (Fe_3O_4 NPs) and polydopamine (PDA) on each side of graphene oxide (GO) nanosheet. The Fe_3O_4 NPsGO combination is a high-capacity active material, while PDA serves as a binder due to its exceptional wet-resistant adhesive characteristic. The multilayered Janus anode was built on a Cu foil to explore the anode's electrochemical performance. The anode had a high Li storage capability of 903 mAh.g^{-1} at a current density of 200 mA.g^{-1} and a remarkable reversible capacity of 639 mA.g^{-1} up to the 1800th cycle. As a result, compared to the binder-free device, it had a larger lithium capacitance and superior cyclic behavior than the commercially available graphite anode. Based on these findings, the multilayered Janus-structured composite appears to be a suitable anode material for LIBs and energy storage devices [39].

Because of the tremendous theoretical capabilities, phosphorus-based anodes are very desirable for potassium-ion batteries (PIBs). However, their practical uses are restricted by their poor potassium storage qualities caused by weak electronic conductivity, facile self-aggregation, and significant volumetric changes during the cycling operation. For the anode material of PIBs, we inject Sn_4P_3 nanoparticles into multilayer graphene sheets ($\text{Sn}_4\text{P}_3/\text{MGS}$), considerably enhancing its potassium storage capacity. Particularly, graphene sheets may help decrease Sn_4P_3 nanoparticle aggregation, boost electronic conductivity, and maintain structural integrity. Furthermore, a sizeable accessible area for the electrolyte is provided by a large number of Sn_4P_3 nanoparticles soaked in MGS, which reduces the diffusion distance for K^+ and electrons during K^+ insertion and extraction, resulting in improved rate capability. As a result, improved $\text{Sn}_4\text{P}_3/\text{MGS}$ has a high reversible capacity of 378.2 and 260.2 mAh.g^{-1} at 0.1 and 1 A.g^{-1} , correspondingly, yet has substantial capacity retention of 76.6 percent after 1000 cycles at 0.5 A.g^{-1} . The discovery may provide an innovative technique for developing high-performance PIB electrode materials, allowing for the widespread application of low-cost rechargeable potassium ion systems [40].

Because of the abundant stocks of potassium salts and their inexpensive cost, potassium-ion batteries (KIBs) have captivated the interest of many researchers. Nonetheless, a significant difficulty impeding the practical implementation of KIBs is the lack of suitable electrode materials with stable electrochemical characteristics. Scalable anode material for KIBs is investigated here, consisting of ultrafine ZnS nanoparticles encased in three-dimensional (3D) carbon nanosheets. A ubiquitous and straightforward sol-gel approach is integrated with a standard solid-phase sulfidation route to produce this hierarchical anode. This anode's unique shape allows for effective contact with electrolytes and provides enough voids to buffer the substantial volumetric stress changes during K^+ insertion and extraction. As a result, the 3D ZnS@C electrode has a superior rate capability and steady cycling performance with 230 mAh.g^{-1} over 2300 cycles at 1.0 A.g^{-1} . According to the kinetic study, a ZnS@C anode with a significant pseudocapacitive contribution advantages a quick potassium/depotassium process. The carbon framework increases the electrode's electronic conductivity and protects its integrity structure from being harmed by frequent K^+ insertion and extraction. This multilevel construction technique paves the way for the scalable synthesis of multilayer electrode materials in alkali-ion battery development [41].

III. CONCLUSION

After analyzing the various types of batteries, such as zinc-air, zinc ion, lithium-sulfur, and potassium batteries, it is clear that Zinc-air batteries have limitations, such as poor flexibility, which falls short of the demands of wearable electronics, and the sluggish kinetics of ORR/OER, which results in a considerable charge/discharge overpotential, that also severely limits the application of Zn-air batteries. Consequently, utilizing flexible air-electrodes with high-efficiency ORR/OER activity is essential for the use of flexible Zinc-

air batteries. To independently manage the contents of single atoms and nanoparticles in the catalysts, the possible synthesis methods can be combined with other relevant techniques such as chemical vapor deposition or atomic layer deposition, which may be researched in the future. The current research proposes a cost-effective synthetic approach for a flexible 3D free-standing air-electrode that can be used for flexible Zinc-air batteries and water splitting.

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