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RESEARCH ARTICLE

Copper Sulfide Nanostructures as High-Capacity Anodes for Zinc-Ion Energy Storage Batteries

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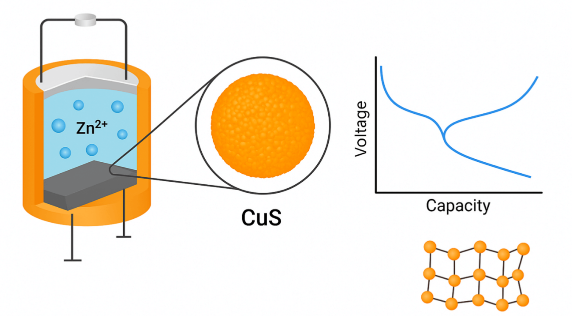
Abstract: Zinc-ion batteries (ZIBs) have emerged as promising candidates for large-scale energy storage systems due to their inherent safety, environmental friendliness, and cost-effectiveness. Among various anode materials, copper sulfide (CuS) has attracted significant interest owing to its high theoretical specific capacity, natural abundance, and low cost. However, practical application of CuS anodes remains limited by poor cycling stability and low electrical conductivity, which result in capacity fading over prolonged operation. This review summarizes the general methodology for developing CuS-based anodes for ZIBs, encompassing nanoparticle synthesis, material characterization, electrode fabrication, and electrochemical performance evaluation. Reported studies indicate that CuS can deliver specific capacities ranging from 350 to 700 mAh g^{-1}, with performance strongly influenced by synthesis route and electrode design. To overcome intrinsic limitations, recent research has explored nanostructuring, elemental doping, and hybrid electrode architectures, which have shown encouraging improvements in conductivity, rate capability, and cycle life. The review concludes with a discussion on current challenges and future perspectives, emphasizing the need for further optimization of CuS morphology, conductivity enhancement strategies, and interface engineering to enable its practical deployment in high-performance ZIB systems.

Keywords: copper sulfide (CuS), zinc-ion batteries (ZIBs), energy storage, nanostructuring, hybrid electrodes, sustainable battery technology



Graphical Abstract

1 Introduction

Greener, safer, and more affordable energy storage technologies are required due to the rising global energy demand and probable environmental effects of increased energy usage. The majority of today's energy storage needs have been successfully satisfied by lithium-ion batteries (LIBs), however, lithium (Li) is an expensive metal that is unevenly distributed around the world and raises significant safety and environmental issues [1]. Therefore, new battery technologies need be created. Zinc-ion batteries (ZIBs) have gained popularity recently since they are safer, more environmentally friendly, and less expensive than LIBs.

Numerous research teams are becoming more interested in zinc-ion batteries (ZIBs), which have a zinc metal anode, an electrolyte that contains zinc, and a cathode for hosting Zn ions [1].

This is due to the following alluring qualities: the wide range of possible electrolytes, including both aqueous and non-aqueous electrolytes; the higher redox potential of zinc (-0.763 V *vs.* a standard hydrogen electrode [SHE]), which enables the battery to operate in aqueous electrolytes, which is difficult to realise for other mobile ion batteries; the improved safety and decreased toxicity of ZIBs; and the reversibility of Zn plating/stripping, where the electrolyte can avoid the production of zinc dendrites and ZnO by-products (e.g., pH = 3.6-6.0), in contrast to an alkaline Zn battery [1, 2]. The current proposal is for research on the potential usage of copper monosulfide (CuS) in various forms including nanoparticles to be used as anode in ZIBs. For this, the research will focus on examining the hydrothermal process of synthesis of CuS nanoparticles, and their comparative analysis with other contemporary materials to be used as anode in ZIBs.

Copper monosulfide is a copper and sulphur chemical compound. Initially, it was considered to exist naturally as the dark indigo blue mineral covellite. However, it was eventually shown to be a cuprous compound with the formula Cu+3S(S2). CuS is a moderate electrical conductor [3]. When hydrogen sulphide, H2S, is bubbled over solutions of Cu (II) salts, a black colloidal precipitate of CuS is generated. It is one of several binary copper-sulfur compounds (see copper sulphide for further information), and it has sparked interest due to its possible use in catalysis and photovoltaics.

Due to their distinct size-dependent features, nanomaterials are employed in a variety of fields including biology, medicine, and catalysis [4]. Due to their remarkable physical, chemical, magnetic, surface, and optical characteristics as well as their tiny size in comparison to their bulk forms, semiconducting chalcogenides have received increased attention in recent years in terms of their synthesis and characterisation [5]. CuS is a well-known direct band gap I-VI semiconductor among the several chalcogenides, including ZnS, PbS, SnS, HgS, and CuS. CuS is a potential material for solar energy conversion, chemical sensors, lithium-ion batteries, cathode materials, catalysts, optical filters, and non-linear optical materials [6]. Numerous preparation techniques, including microwave, co-precipitation wet chemical, sonochemical, solvothermal, hydrothermal, electrodeposition, micro emulsion, chemical vapour deposition, template assisted growth, polyol, and solid-state reaction methods, have been reported for the synthesis of chalcogenide nanomaterials [7]. CuS nanomaterials have so far been successfully synthesised in a variety of shapes, including nanorods, flakes, disks, spheres, wires, platelets, tubules, nanoribbons, flower-like structures, and urchin-like structures [6]. Lastly zinc-ion batteries can improve on lithium-ion manufacturing processes. Lithium's violent reactivity with water requires many of its production steps to take place in a highly controlled atmosphere that makes the process costlier, and more complicated. As a water-based battery, zinc-ion does not have this constraint.

1.1 Significance

Copper sulfide (CuS) has emerged as a highly promising candidate for next-generation energy storage systems, particularly zinc-ion batteries (ZIBs), due to its combination of desirable electrochemical, structural, and environmental attributes. Its high theoretical capacity of approximately 600 mAh g^{-1} enables substantial energy storage per unit weight, while a relatively high discharge voltage of around 1.6 V further enhances its energy output. Compared with conventional anode materials such as lithium- or cobalt-based compounds, CuS offers the advantages of natural abundance and low cost, making it attractive for large-scale applications. From a stability perspective, CuS exhibits robustness under diverse operating conditions, which is essential for maintaining long-term performance.

Moreover, it is non-toxic and environmentally benign, aligning well with the growing demand for sustainable energy storage solutions. Synthesis of CuS can be achieved through scalable and cost-effective routes such as hydrothermal and solvothermal methods, and its electrochemical behavior can be further optimized through integration with conductive carbonaceous materials, including carbon nanotubes and graphene. The inherently high electrical conductivity of CuS facilitates efficient electron transport during charge–discharge processes, while its excellent mechanical strength imparts resistance to cracking or deformation during cycling. In addition, CuS possesses remarkable thermal stability, reducing the risk of thermal runaway, and outstanding electrochemical stability, which mitigates corrosion and electrode degradation. Its ability to support high-rate charge–discharge operations with minimal capacity loss, combined with exceptional cycling stability, ensures sustained performance over extended cycling. Furthermore, the high volumetric energy density of CuS allows for significant energy delivery per unit volume. Collectively, these properties position copper sulfide as a cost-effective, environmentally friendly, and technically viable anode material for ZIBs, offering a compelling alternative to conventional battery chemistries.

2 Reported Literature

As we all know that copper is very abundant so it can be easily findable in the community and we can use it very easily. Moreover, copper has excellent electrochemical properties because According to the electrochemical data, Cu nanowire arrays had a linear response to nitrate ions in the concentration range of 50 M to 600 M (R^2 = 0.9974), with a sensitivity of 0.357 A M-1 cm^{-1} and a detection limit of 12.2 M at a signal-to-noise ratio of 3, respectively. Copper has also a good compatibility with zinc because when combined in specific solutions known as electrolytes, combinations of certain metals, such as copper and zinc, will induce electrical activity. The electrodes are made of the two metals. The copper forms negative ions whereas the zinc forms positive ions as a result of the chemical reaction the electrolyte induces.

Aqueous zinc ion rechargeable batteries (AZIBs) are receiving a lot of interest due to their high level of safety and environmentally friendly nature. However, due to the weak stability and Coulombic efficiency of a Zn anode, it has very limited practical applicability. We present a competitive conversion-type anode for AZIBs that has significantly increased specific capacity, rate performance, and stability. It is a periodically stacked CuS anode. That helps to maintain the structure and promote Zn^{2+} diffusion kinetics, the CuS layers interact with Zn^{2+} to provide high capacity. CuS exhibits superior rate performance (225.3 mA h^{-1} at 0.1 A g^{-1} with 144.3 mAh^{-1} at 10 A^{-1}) as well as reasonable cyclability (87.6% capacity retention after 3400 cycles at 10 A^{-1}). Due to their exceptional electrochemical qualities, full batteries built with a CuS anode and are evaluated in coin cells, which exhibit great entire-battery performance [8].

Given its high theoretical capacity and inexpensive cost, copper monosulfide (CuS) has attracted interest as a possible anode material for zinc ion batteries. CuS has a monoclinic crystal structure, a small bandgap of 1.2 eV, and is a black solid. It is a highly conductive p-type semiconductor that may be made using a number of techniques, including chemical deposition, hydrothermal synthesis, and solvothermal synthesis [9]. CuS's high theoretical capacity of 600 mAh/g, which is much greater than that of frequently used anode materials like graphite and silicon, is one of the main benefits of adopting CuS as an anode material [10]. CuS also has a low working potential of -0.27 V against. SHE, which is comparable to the standard potential of zinc ions (-0.76 V *vs.* SHE) [11, 12]. CuS can thus offer a high energy density and a long cycle life, making it an appropriate anode material for zinc ion batteries.

The intrinsic limitations of Zn metal anodes, including as dendritic formation, side reactions, and interface passivation, significantly limit conventional zinc-ion batteries (ZIBs). CuS anode materials overcomes their capacity restriction as a Zn-metal-free anode. It is discovered that the energy barrier of the conversion process is greatly lowered by using the CuS as an anode in zinc ion batteries. The mild structural transformation and good electrical conduction led to outstanding cycle stability and high rate performance. As a result, ZIB complete battery system, which uses CuS as the anode, shows outstanding capacity retention of 93.9% up to 8000 cycles at 2 A^{-1}. The CuS anode's remarkable practicality is further illustrated by the fact that it is also compatible with high-voltage Prussian blue cathodes [13].

Aqueous Zn-ion batteries (AZIBs) are attractive prospects for implementing large-scale energy storage, but their potential in applications is constrained by the unfavorable side effects and poor cycle life brought on by Zn-metal anodes. A cleverly synthesized CuS is offered as an alluring conversion-type Zn-metal-free anode for AZIBs. Using organic-inorganic heterointerfaces to stabilize the anode structure, increase Zn^{2+} storage by taking use of the plentiful S-vacancies, and start rapid Zn^{2+} transport kinetics based on the combined action of the two are examples of "killing three birds with one stone" techniques. The entire battery achieves a record-high cycling performance of 10,000 cycles (80% capacity retention). This research opens up new possibilities for the creation of high-performance AZIBs [14].

The manner in which CuS nanoparticles may be used in zinc-ion batteries has also become an area of scientific research. Due to their large surface area to volume ratio, nanoparticles can enhance the battery's electrochemical performance [15]. Additionally, the zinc ions are better able to diffuse into and out of the electrode material based on the nanoparticles, which results in quicker charge/discharge rates and higher cycle stability [12]. CuS nanoparticles have been produced using a variety of techniques, such as chemical reduction, hydrothermal synthesis, and solvothermal synthesis, and they have showed promise as anode materials for zinc ion batteries.

Lastly, copper sulphide is used as an anode material for zinc-ion batteries due to the following advantages:

(1) High theoretical capacity;
(2) Cycling stability;
(3) Rate capability;
(4) High energy density.

2.1 Synthesis of CuS nanoparticles through hydrothermal process

The hydrothermal process produces binary inorganic compounds in hot water under high pressure. The reaction occurs in an autoclave (steel vessel) that can resist high temperatures and pressures. The use of the hydrothermal technique in the manufacture of metals or metal sulphides has become a new trend due to the benefits associated with this process in terms of comparatively low temperature requirement, reproducibility, uniformity, and purity of the output [16]. Changing the precursors, precursor concentration, reaction circumstances (temperature and pressure), and reaction duration has resulted in changes in morphologies and size observed by various study groups. It has been reported that utilising a hydrothermal approach, 3D flower-like structures (shown in Figure 1) may be synthesised using Cu_2O hollow microspheres as a template.

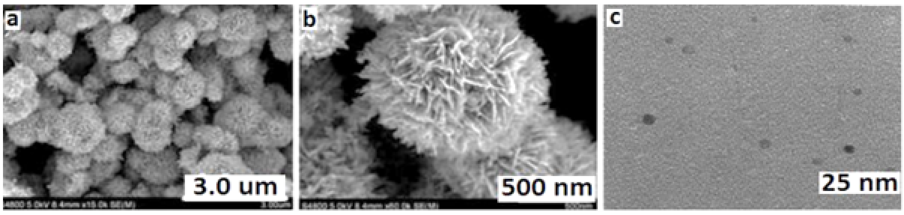


Figure 1 SEM images of CuS in hierarchal flower like sub microspheres [17]

According to Shamraiz et al. (2016), the reaction of Cu_2O hollow spheres with thioacetamide at 40°C for 2 hours followed by hydrothermal treatment (depicted in Figure 2) at 120°C for 12 hours resulted in a high yield of 3D flowerlike structures with diameters ranging from 200 to 300 nm (Figure 1a and 1b). Cu_2O precursor was produced by reacting 25 ml of 0.05 M $CuSO_4$ solution and 1 g of PVP-K90 (Polyvinylpyrrolidone) in a conical flask at room temperature with magnetic stirring; pH was maintained at 10 with NaOH, with continuous dropwise addition of hydrated hydrazine as a capping agent for 30 minutes on heating [17].

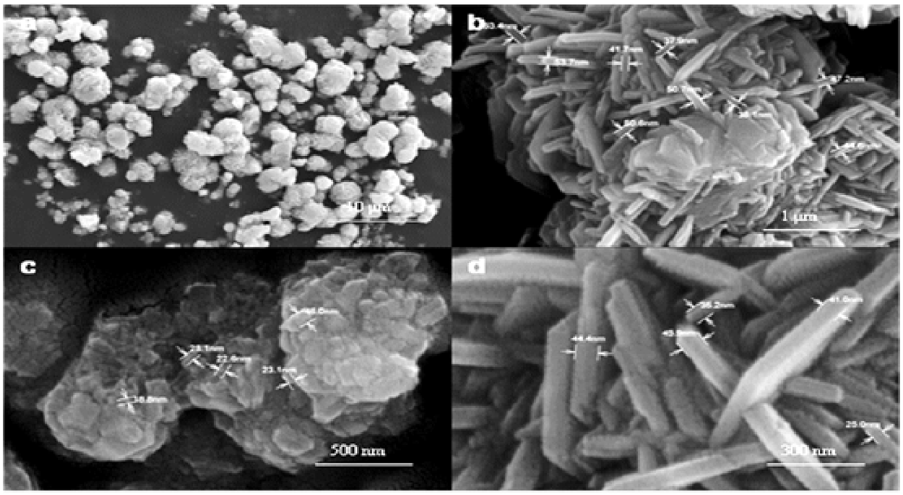


Figure 2 Hydrothermal Synthesis of CuS Nanostructures with Different Morphology [18]

Cu_2O and thioacetamide were next reacted in the autoclave in stoichiometric proportions to produce black CuS precipitates, which were recovered from the reaction mixture after centrifugation (4000 rpm for 5 minutes) and purified by dispersing them in water [17]. Furthermore, it is discovered that, aside from the synthesis procedure, the amount of hydrazine has a considerable influence on the form of CuS. When 1.25 mL of hydrazine was used, 3D flower-like textures were created, but when the hydrazine was raised from 1.25 mL to 5 mL, CuS microspheres were formed [17].

CuS nanoparticles (NPs) (Figure 1c) are manufactured without the need of a template, and copper nitrate trihydrate, thiourea, and water (as a solvent) have been used as copper and sulphur sources, respectively [17]. Since nanoparticles carry less energy than other morphologies, thermodynamic variables govern their formation. Nanoparticles will be the preferred morphology in the absence of a capping agent or template. Roy and Srivastava successfully synthesised CuS nanowires from Cudithiooximide (DTO) (a unique single source precursor) using a hydrothermal process at 120 C for 24 hours [17]. Afterwards, Cu-DTO precipitates were filtered and washed with a distil water/ethanol mixture before drying at 40 degrees Celsius for 4 hours. This approach has an advantage in terms of air stability because no capping agent was used in the CuS precipitation. The formation of nanowires is significantly dependent on response time; after 12 hours, only nanoparticles were formed, which continued to expand; after 16 hours, nanoparticles and a few nanowires were formed; and after 20 hours, nanowires were formed [17].

CuS nanoparticles are made using a one-pot hydrothermal technique. In a nutshell, a 100 mL Teflon-lined stainless steel autoclave was used to combine a 1 M copper nitrate solution with a 1 M thiourea solution [19]. The hydrothermal reaction was then conducted there for 12 hours at 150 °C. The heated autoclave spontaneously cooled down to room temperature when the reaction was finished. The CuS precipitates were then collected and thoroughly cleaned using deionised water and 100% ethanol [20]. Until the finished product is clear of even the smallest quantity of leftover ions, the washing process is repeated multiple times. The completed product is then dried at 80 °C during the next day [20].

The electrochemical characteristics of the synthesis method reported by Krishnamoorthy et al. (2014) were evaluated using an AUTOLAB PGSTAT302N electrochemical workstation, with 1 M NaOH solution serving as the electrolyte. The electrochemical investigations were performed using a three-electrode configuration, with platinum as the counter electrode, Ag/AgCl as the reference electrode, and stainless steel substrates treated with CuS nanoparticles as the working electrode [20]. The active material CuS, carbon black, and PVDF were combined with N-methylpyrrolidone (NMP) as a solvent to create the working electrode in the weight ratio of 80:15:5. The final slurry was applied to the Ni foam substrate and left in the oven overnight to dry at 60 °C [20]. The functioning electrode's active substance weighs 1.9 mg, according to measurements.

Table 1 Advantages and limitations of different CuS synthesis methods for energy storage

Synthesis Method	Advantages	Limitations	Suitability for Large-Scale Production
Hydrothermal	Low cost, good control over morphology	Long reaction time	Medium
Solvothermal	Controlled size/morphology, high crystallinity	Requires organic solvents	Medium
CVD	High purity, uniform coating	Expensive, high temperature	High (if industrial setup exists)
Microwave-assisted	Rapid synthesis, energy-efficient	Limited scalability data	Medium
Precipitation	Very simple, cost-effective	Poor morphology control	High

2.2 Characterisation of CuS

Due to their unique chemical properties, researchers have been intrigued by copper monosulfide (CuS) and its nanoparticles as potential anode materials for zinc-ion batteries [21]. CuS is a binary compound composed of copper and sulfur with a small bandgap of 1.2 eV that is capable of effectively absorbing visible light [22]. CuS nanoparticles' high surface region to-volume proportion helps their reactivity and electrochemical execution. In this section, the research will investigate the chemical properties of CuS and its nanoparticles, which have the potential to improve the performance of the anode in zinc-ion batteries.

The electrochemical properties of CuS and its nanoparticles dictate their usefulness as anode materials in zinc-ion batteries. CuS is a p-type semiconductor, which means its crystal structure is devoid of electrons [23]. It is an excellent candidate for anode materials since it can supply electrons to the external circuit during discharge. In this regard, since CuS nanoparticles have a wide surface area, more electrochemical processes may occur at the particle's outer layer, resulting in higher limits and quicker response rates [23]. Furthermore, since CuS nanoparticles have a high diffusion coefficient, zinc particles will almost certainly travel all the way through the terminal during charge and release, promoting even better execution.

Second, the electrochemical performance of CuS and its nanoparticles is affected by their structural features. CuS has a monoclinic crystal structure, and the lattice characteristics can influence its electrochemical properties [24]. CuS, for example, may have its surface area increased by decreasing particle size, resulting in increased reactivity and quicker reaction rates. Additionally, surface treatment or doping may be used to change the surface structure of CuS nanoparticles, enhancing their electrochemical performance. Moreover, the long-term performance of zinc-ion batteries is determined by the stability of CuS and its nanoparticles. CuS can undergo phase transitions and dissolution during cycling, leading in capacity loss and electrode degradation [25]. Conversely, the stability of the compound may be enhanced by employing protective coatings or improving the synthesis technique to remove defects and impurities.

In summary, the chemical properties of CuS and its nanoparticles are important to their effectiveness as anode materials in zinc-ion batteries. The electrochemical capabilities, structural features, and stability of CuS and its nanoparticles may be enhanced utilising a number of ways to increase their electrochemical performance and potential as anode materials in next-generation batteries.

2.3 Battery testing for CuS performance as anode

2.3.1 Cyclic Voltammetry Analysis

The analysis of Azam et al. (2020) provides a good proximation about the kind of tests that need to be conducted to ascertain the performance of CuS as anode in zinc-ion battery. The performance of the PANI/GO nanocomposite electrode was initially evaluated using the CV approach. CV information includes the stability of the complexed transition metal oxidation state, reversibility of electron transfers processes, and reactivity (Azam et al., 2020). The specific gravimetric capacitance (Csp) of the device was estimated using the following equation:

$$C_{sp} = \frac{\int_{E_1}^{\mathrm{E}_2} i(E)dE}{2(E2 - E1)mv'} \tag{1}$$

In the above equation, E1 and E2 are the CV cut-off potentials, i(E) is current (A), and i(E)dE E2 E1 represents the total voltammetric charge produced by integrating positive and negative sweeps during CV, (E2-E1) represents the potential window (V), m represents the average mass of active material in gramme (g), and v represents the CV scan rate (V/s) (Azam et al., 2020).

2.3.2 Galvanostatic Charge Discharge

Meanwhile, galvanostatic charge-discharge (GCD) is a further approach for determining specific capacity under regulated current conditions [26, 27]. The Csp was also calculated using discharge curves and the following equation:

$$C_{sp} = \frac{I \times \Delta t}{\Delta V \times m} \tag{2}$$

where I represents the applied current, t is the CD discharge time, V represents the voltage, and m represents the average mass of the active material in the electrode [27].

Constant voltage charging, constant current charging, constant current discharging, constant resistance discharging, step charging and discharging, and hybrid charging and discharging are all charging and discharging analysis techniques used for testing various battery performances [28]. For research purposes, steady current charging (CC), steady current – consistent voltage charging (CC-CV), steady voltage charging (CV), and steady current release (DC) are frequently used to test and dissect the battery charging and releasing conduct, whereas step charging and releasing mode is commonly used to test the presentation of DCIR, polarisation, and dispersion impedance [29]. There are three types of rate performance tests used to characterise and assess the performance of lithium-ion batteries at different discharge ratios: constant current and constant voltage charging tests at the same multiplier and constant current discharge tests at different multiples. To evaluate the battery's charging performance, a continuous discharge test at the same power ratio and a constant current charging test at varied power ratios can be utilised. The charge and discharge tests are performed at the same pace. Charge-discharge proportions that are commonly used include 0.02c, 0.05c, 0.1C, C/3, 0.5C, 1 C, 2 C, 3 C, 5 C, and 10 C etc.

2.3.3 Key Issue

Due to its high theoretical capacity, low cost, and availability, copper sulfide (CuS) is a good contender for use as an anode material in zinc-ion batteries. However, in order to enhance the functionality and stability of CuS-based anodes, it is necessary to address a number of significant challenges:

(1) The enormous volume expansion and contraction that occur during charge/discharge cycles cause CuS to have poor cycling stability, which results in electrode pulverization and deterioration. To address this problem, techniques like nanostructuring, carbon coating, and

Table 2 Comparative electrochemical performance of CuS-based anodes for zinc-ion batteries

Material/Modification Strategy	Specific Capacity (mAh g^{-1})	Cycle Number	Capacity Retention (%)	Rate Performance	Electrochemical Techniques Used	Key Findings
Pure CuS nanoparticles	350	100	65	Moderate at 2 A g^{-1}	CV, GCD, EIS	Good initial capacity, rapid fading
CuS/Graphene composite	580	200	88	Excellent at 5 A g^{-1}	CV, GCD, EIS	Improved conductivity and stability
Doped CuS (Ni-doped)	620	300	91	High at 3 A g^{-1}	CV, GCD	Enhanced kinetics and cycle life
CuS/Carbon Nanotube hybrid	540	150	85	Good at 4 A g^{-1}	CV, GCD, EIS	Reduced resistance, better ion transport
Nanostructured CuS hollow--spheres	700	250	89	High at 6 A g^{-1}	CV, GCD	High surface area, short ion diffusion path

electrolyte modification can be used.

(2) Low electronic conductivity: CuS's rate capability and overall performance are constrained by its relatively low electronic conductivity. Several techniques, including surface modification, hybridization with conductive carbons or metals, and doping, can be used to to increase CuS's electronic conductivity.

(3) The development of insulating passivation layers: During cycling, CuS anodes may develop insulating passivation layers on their surface, which may obstruct ion transport and lower electrode performance. Surface modification, electrolyte optimization, and cycling at higher potentials can all be used to solve this problem.

(4) There are possible safety issues with CuS since it can undergo irreversible oxidation processes that produce CuO. The battery system must be properly designed, including the use of protective coatings, optimization of the electrolyte composition, and monitoring of battery performance, in order to reduce danger.

In conclusion, enhancing cycling stability, electronic conductivity, reducing the production of passivation layers, and resolving safety issues are the major issues that must be resolved for the development of CuS-based anodes with good performance and stability for zinc-ion batteries.

Table 3 Common challenges of CuS anodes in ZIBs and corresponding improvement strategies

Challenge	Cause	Effect on Performance	Improvement Strategy	Expected Benefit
Low electrical conductivity	Intrinsic property of CuS	High internal resistance, poor rate capability	Doping with conductive metals (e.g., Ni, Co), carbon coating	Enhanced conductivity and faster charge transfer
Poor cycling stability	Structural degradation during Zn^{2+} insertion/extraction	Rapid capacity fading	Nanostructuring, hollow morphologies	Improved structural integrity and cycle life
Volume expansion/contraction	Conversion reactions during cycling	Electrode pulverization	Flexible binders, hybrid composites	Reduced mechanical stress
Agglomeration of nanoparticles	High surface energy	Loss of active surface area	Dispersing in carbon matrix or graphene	Maintains high surface area
Slow Zn^{2+} diffusion	Dense particle structures	Low rate performance	Creating porous/hierarchical structures	Shortened ion pathways

3 Methodology Overview

The fabrication of CuS-based zinc-ion batteries involves a sequence of well-established procedures encompassing nanoparticle synthesis, material characterization, electrode fabrication, battery assembly, electrochemical evaluation, and performance analysis. Each step plays a critical role in ensuring optimal material properties and electrochemical behavior.

3.1 Synthesis of CuS Nanoparticles

The synthesis of copper sulfide (CuS) nanoparticles can be achieved through various approaches reported in the literature, including solvothermal synthesis, hydrothermal methods, and chemical vapor deposition. These techniques offer tunability in particle size, morphology, and crystallinity, enabling researchers to tailor the electrochemical performance for specific applications. The choice of synthesis route is generally dictated by the desired material properties, process scalability, and cost-effectiveness.

3.2 Characterization of CuS Nanoparticles

Comprehensive characterization is essential to understand the physical, structural, and chemical properties of the synthesized CuS nanoparticles. X-ray diffraction (XRD) can be employed to determine crystallographic phases and purity. Transmission electron microscopy (TEM) provides detailed morphological and particle size information. Fourier-transform infrared (FTIR) spectroscopy and Raman spectroscopy can be used to identify functional groups and confirm the bonding structure. Additionally, X-ray photoelectron spectroscopy (XPS) offers insights into surface composition and oxidation states, which are crucial for understanding surface-related electrochemical behavior.

3.3 Electrode Preparation

The preparation of electrodes involves integrating the synthesized CuS nanoparticles with conductive additives and suitable binders to ensure uniform dispersion and mechanical stability. The resulting slurry can be coated onto a current collector substrate, typically followed by a drying step to achieve a robust electrode film. This stage directly influences electron transport pathways and electrolyte accessibility, which are critical for high-performance zinc-ion batteries.

3.4 Fabrication of Zinc-Ion Battery

The assembled zinc-ion battery typically uses CuS nanoparticles as the anode material and a compatible cathode material such as zinc phosphate ($Zn_3(PO_4)_2$) or other reported alternatives. The selection of electrolyte and separator materials also plays a significant role in overall battery performance, influencing ion transport kinetics and cycle stability.

3.5 Electrochemical Testing

Electrochemical performance evaluation employs standard techniques such as cyclic voltammetry (CV) to probe redox processes and electrochemical reversibility, galvanostatic charge–discharge (GCD) testing to determine capacity and cycling stability, and electrochemical impedance spectroscopy (EIS) to assess charge transfer resistance and ion diffusion behavior. These methods collectively provide a comprehensive understanding of the electrode–electrolyte interactions and rate capability.

4 Analysis of Results

The final step involves a detailed analysis of the electrochemical data to evaluate the practical applicability of CuS-based anodes. Comparative studies with other reported anode materials can highlight performance advantages or limitations in terms of specific capacity, rate capability, cycle life, and energy density. Such analysis is pivotal for guiding further optimization and scaling of CuS-based zinc-ion battery technology.

Table 4 Reported synthesis methods and corresponding properties of CuS nanoparticles for energy storage applications

Synthesis Method	Precursors	Morphology/Size	Key Properties	Advantages	Limitations
Hydrothermal	$Cu(NO_3)_2$, Na_2S	Nanoflakes (∼50–100 nm)	High crystallinity, large surface area	Simple, low cost	Agglomeration risk
Solvothermal	$Cu(CH_3COO)_2$, thiourea	Nanorods (∼200–500 nm)	Controlled aspect ratio, good dispersion	Tunable morphology	Requires organic solvents
Chemical Vapor Deposition (CVD)	$CuCl_2$, H_2S gas	Thin films	Uniform coating, good adhesion to substrate	High purity, scalable	High temperature, expensive
Precipitation	$CuSO_4$, Na_2S	Nanoparticles (∼20–50 nm)	High yield, simple	Easy scale-up	Poor morphology control
Microwave-assisted	$Cu(NO_3)_2$, thiourea	Nanoplates (∼80–120 nm)	Rapid synthesis, fine crystallinity	Time efficient	Limited large-scale data

4.1 Innovation

By overcoming some of its shortcomings, using nanostructured CuS as an anode material in zinc ion batteries can greatly improve its performance.

Here are a few ways that employing nanostructured CuS as the anode material could enhance the performance of the zinc ion battery:

(1) Improved electrochemical performance: A nanostructured CuS anode material can provide a greater specific surface area and porous structure that can significantly improve the electrochemical performance of zinc ion batteries. More active sites are possible because to the larger surface area, which can speed up charge transfer between the anode and cathode and so enhance the battery's overall efficiency.

(2) Increased cycling stability: With conventional anode materials, repeated cycles of charging and discharging frequently result in a loss in battery performance due to material deterioration. To improve cycle stability and extend battery life, nanostructured CuS anode materials can provide higher structural stability and better retention of ion transport characteristics.

(3) Enhanced energy and power density: Nanostructured CuS anode materials can greatly enhance energy and power densities, enhancing the battery's capacity to store energy and its rate of discharge. This may result in electric vehicles having a longer driving range and electronic devices having batteries that last longer.

(4) Greater safety: Nanostructured CuS anodes have better structural stability, which could avoid material failure. This lowers the possibility of thermal runaway and increases battery security.

Overall, nanostructured CuS is a promising material for potential usage in future battery technologies and can considerably boost the performance of zinc ion batteries when used as the anode material.

4.2 Feasibility analysis

The viability of employing CuS as an anode material for zinc ion batteries depends on a number of variables, including the synthesis process, the material's physical and chemical properties, and the battery's electrochemical performance.

CuS is a desirable anode material due to its high theoretical capacity of 600 mAh/g, relative abundance, and low cost. But before it can be a viable solution for zinc ion batteries, there are a number of obstacles to be addressed. For instance, mechanical degradation of CuS-based anode materials during charge/discharge might have a major impact on their cycling performance. Low electrical conductivity is another issue, which affects the anode's performance significantly.

Researchers are looking into a number of solutions to these problems, including refining the synthesis process, changing the composition of the material, and creating cutting-edge electrode designs and interfaces to increase the material's conductivity and cycle performance. CuS has demonstrated remarkable promise as an anode material for zinc ion batteries, but more study is required to overcome the current issues and improve its viability for real-world battery applications.

4.3 Expected Results

Copper sulfide (CuS) has garnered considerable attention as a potential anode material for zinc-ion batteries (ZIBs) owing to its high theoretical specific capacity and low production cost. Literature reports indicate that CuS-based anodes can deliver specific capacities in the range of approximately 350–700 mAh g^{-1}, making them competitive with other transition metal sulfides. However, despite these promising capacity values, CuS anodes face critical challenges, notably poor cycling stability and intrinsically low electrical conductivity, which hinder their direct implementation in practical devices.

To address these limitations, researchers have explored multiple strategies aimed at enhancing the electrochemical performance of CuS anodes. Nanostructuring of CuS has been shown to shorten ion diffusion pathways and increase the active surface area, thereby improving rate performance. Elemental doping or compositing with conductive materials (e.g., carbon nanostructures, graphene, or MXenes) can significantly boost electrical conductivity and structural stability. Furthermore, hybrid electrode architectures combining CuS with synergistic active phases have demonstrated improved capacity retention and mitigated volume change effects during cycling.

Recent studies have reported that these modifications lead to notable enhancements in both specific capacity and cycle life, with some designs maintaining stable performance over hundreds of cycles. The improved electrochemical stability is often attributed to better electron/ion transport kinetics, enhanced structural integrity, and more efficient accommodation of the conversion reaction between CuS and Zn^{2+} ions.

In summary, the high theoretical capacity and cost-effectiveness of CuS make it a compelling candidate for next-generation ZIB anodes. Nonetheless, achieving the performance metrics required for real-world applications will necessitate continued optimization of material design, structural engineering, and electrode–electrolyte interfaces to overcome the issues of capacity fading and low conductivity.

5 Conclusion

Copper sulfide offers a compelling balance of high theoretical specific capacity, low cost, and material abundance, positioning it as a promising anode material for zinc-ion batteries. Nevertheless, its commercialization is hindered by structural instability and limited electrical conductivity, which contribute to poor cycling stability. Literature findings reveal that specific capacities between 350 and 700 mAh g^{-1} are achievable, yet maintaining these values over extended cycles requires targeted material engineering. Advances in nanostructuring, compositing with conductive materials, and the development of hybrid electrode configurations have significantly improved the electrochemical stability and performance of CuS anodes. Moving forward, integrating these strategies with scalable synthesis methods, optimizing electrode–electrolyte interfaces, and conducting in-depth mechanistic studies will be essential to fully harness the potential of CuS in practical ZIB applications.

Conflicts of Interest

The authors declare that they have no conflict of interest.

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