

Diverse Applications of Frontier Nanotechnology in Electric Vehicles

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Abstract. As the demand for electric vehicles (EVs) and hybrid EVs (HEVs) continues to grow rapidly, improving battery performance has become essential for enhancing energy efficiency, safety, and reliability. Nanotechnology, with its ability to manipulate materials at the nanoscale, offers transformative solutions to many challenges in battery design. Since J. Goodenough discovered lithium cobalt oxide for lithium-ion batteries in 1980, significant advancements have been made, particularly through the integration of carbon-based nanomaterials. These nanomaterials have enabled higher energy densities, longer lifespans, and faster charge-discharge cycles. In addition, nanotechnology addresses critical issues such as thermal management and ion transport, offering potential breakthroughs in these key areas. By making good use of nanoparticles, scientists are developing next-generation batteries that are more efficient, durable, and environmentally friendly. This paper examines the wide-ranging applications of nanotechnology in battery development, focusing on how nanoparticles can solve current limitations and contribute to the future of EV innovation.

Keywords: Nanotechnology; nanoparticle; battery; electric vehicle.

1. Introduction

Electric vehicles (EVs) and hybrid EVs (HEVs) use internal combustion engines and electric motors as hybrid power sources, which have the advantages of good power performance, fast response and long working time of fuel engine, and the advantages of pollution due to good fuel saving effect, strong cruising power and low noise. However, the cost for the exchange of damaged batteries after the warranty period is high, which causes a significant barrier to the propagation of new vehicles among individuals. The barrier constructed by low stability, low cycle life and other problems results in the high cost of maintenance. To apply batteries to EVs and HEVs, batteries still need further improvements [1]. In order to solve those problems, the researchers are persistently searching for efficient, sustainable and environmentally friendly materials for vehicles' batteries.

As technology is improving, nanotechnology has been applied to the materials in batteries. Making electrodes and electrolytes with nanomaterials can improve the energy storage capacity and service life of batteries, and by adding nanoparticles to the coolant, the thermal conductivity and heat transfer efficiency of the conventional coolant can be significantly improved. Also, applying nanoparticles in electrodes will enhance batteries' properties, including the charge rate and internal resistance. Also, the thin films and the nanofluid made of nanoparticles and basic fluids can enhance thermal dissipation in cooling systems. These achievements in the field of battery are in the light of the characteristics of nanostructures. The enlarged surface area ensures high compatibility, and the conductivity and other properties can be aroused using specific materials such as carbon and graphene. This property opens the future world for enhancement in batteries and reduces the cost of battery exchanges.

This article will review some research demonstrating some applications of nanotechnologies used in batteries and give out a prospect for batteries using nanotechnology.

2. Nanobattery

2.1. Background

Nanobattery is a type of battery manufactured using nanotechnology, with key components such as electrodes and electrolytes measuring at the nanoscale. Nanobatteries have advantages such as high energy density, fast charging and discharging speed, and long cycle life. Through the application of nanotechnology, the performance of batteries can be improved, such as using nanomaterials to make electrodes and electrolytes, which can enhance the energy storage capacity and service life of batteries.

2.2. Application of Carbon Nanotubes in Batteries

Carbon electrodes are among the most common types of traditional electrode materials. Carbon is frequently utilized as a conductive medium in lithium-ion batteries (LIBs) to increase the positive electrode material's conductivity. However, carbon's conductivity is limited in certain ways since it is a conventional conductive media with point-to-point contact. Nonetheless, one of the most promising uses of carbon nanotubes is in the field of LIBs. First off, carbon nanotubes make great negative electrode materials for lithium-ion batteries. Second, carbon nanotubes have exceptional mechanical strength. Their conductivity can reach 105 S/m because of their special ballistic electron conduction effect and resistance to electromigration. This is especially true of the directionally grown three-dimensional carbon nanotube arrays made using chemical vapor deposition technology. It can be added to other electrode materials as a conductive addition or three-dimensional conductive structure to increase the electrode's mechanical properties as well as its capacity to transport electrons and ions.

A novel structural substance made of carbon atoms in sp^2 hybridized orbitals with only one atomic layer thickness, graphene is a member of the carbon material family. Similar to carbon nanotubes, graphene has many benefits that make it a popular material for energy storage batteries. Its high specific surface area—which can reach up to 2600 m^2/g theoretically—allows graphene-based composite electrodes to have good electrolyte compatibility, and its conductivity is far higher than that of other carbon materials. Excellent rate performance can be achieved by using graphene as the conductive structure in composite electrode materials. Numerous functional groups and defect sites are present in graphene derivatives like graphene oxide (GO) and reduced graphene oxide (RGO), which can act as growth sites for different metals and metal oxide nanoparticles. The aggregation of nanoelectrode materials during charge and discharge operations, as well as the large volume change of electrodes, may be successfully suppressed by this complex structure made of a graphene matrix, improving the cycling stability and capacity retention of electrode materials. Evanoff et al. deposited an amorphous silicon layer over directed grown carbon nanotube arrays (VACNTs) that were 70 nm thick using low-pressure chemical vapor deposition (Fig. 1). They then created a carbon nanotube nano silicon carbon layer composite electrode with a large thickness (1 mm), excellent conductivity, and high mechanical strength by depositing a thin layer of carbon outside the silicon layer. After 100 cycles at 0.2 C, the capacity holds steady at around 3000 mAh/g, and the Coulombic efficiency is nearly 100%. This suggests that arrays of directionally grown carbon nanotubes could be perfect delivery systems for low-conductivity, high-capacity LIB active materials [2].

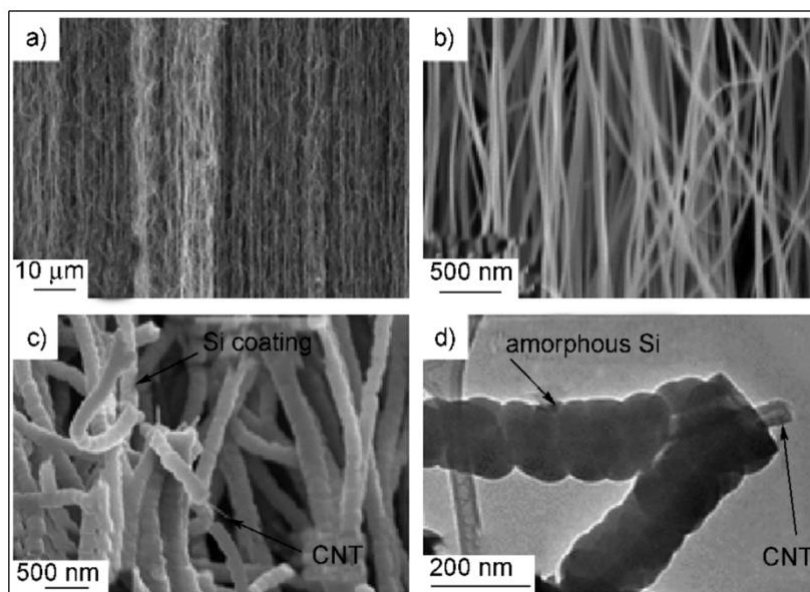


Fig. 1 Directionally grown carbon nanotube arrays [2]

Carbon nanofiber (GNF) is another type of new carbon material that has been extensively studied. This material is formed by the dissociation and adsorption of hydrocarbons on the surface of catalysts, and carbon atoms are deposited on the crystal faces of different metal catalysts. Different graphite sheet arrangements can be obtained using different catalysts and catalytic conditions. Due to its excellent conductivity and unique physicochemical properties, GNF has become an ideal carrier material for electrocatalysts. Bessel et al. prepared carbon nanofiber-supported Pt catalysts with different morphologies using the impregnation method [3]. The Pt particles of these catalysts exhibit a flattened and highly crystalline structure, indicating strong interactions between the metal supports.

Other new carbon materials, such as carbon microspheres and spherical fullerenes, have also been attempted as potential fuel cell catalysts. The carrier is a spherical carbon material, which can effectively reduce the resistance to methanol mass transfer as a catalyst carrier [4].

2.3. Application of SnSb Electrodes in Batteries

A two-electrode simulated battery was composed of nano SnSb as the working electrode, 1 mol/L LiPF_6 , EC-DEC (1:1 in V/V) as the electrolyte solution, Celgard2300 as the separator, and metallic lithium as the counter electrode (Fig. 2).

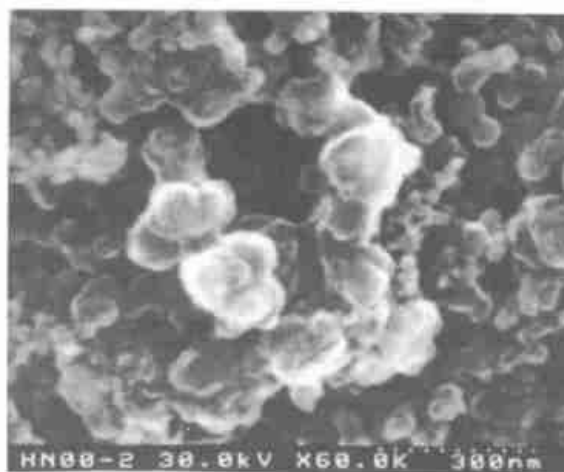


Fig. 2 A two-electrode simulated battery using SnSb as the working electrode [3]

The charge-discharge efficiency of nano SnSb reached 80% in the first week, and experimental data shows that about 15% of the capacity loss comes from the decomposition of surface oxides [3].

This is because nanoalloys are very reactive, can burn in air, and must be stored in an inert atmosphere or vacuum. However, during the electrode preparation process, its surface is inevitably oxidized. Therefore, it causes irreversible capacity loss. In the future, it is necessary to chemically modify its surface to avoid irreversible capacity loss caused by the oxide layer. Once the charging and discharging efficiency is further improved, this nano alloy is expected to replace carbon-negative electrode materials.

With the trend of reducing the operating voltage design of semiconductor devices, high-energy batteries around 2 V have become an important development direction in the future [3].

2.4. Application of Nano CuS in Electrodes

Copper sulfide is cheap and abundant in resources. It was widely studied as an electrode material for primary batteries in the 1970s, with a specific energy density of 300 Wh/kg. However, due to its crystal structure that is not conducive to ion insertion and extraction, it was long considered unsuitable for use as a reversible electrode. Later, it was found that there were certain cycling characteristics in the CuS/Cu and CuS/Li systems. Due to the low electronic conductivity of CuS, the battery capacity decays too quickly during load use. These drawbacks have prevented Li/CuS batteries from being used as secondary batteries. Inspired by the research on nano-negative electrodes, it is believed that nano-sized CuS may overcome some of the drawbacks of ordinary CuS. From Fig. 3, it can be concluded that ultrafine CuS has good cycling characteristics, but it still cannot meet the requirements of LIBs. Although the grain size of the prepared CuS is only 7 nm, the particle size after agglomeration is still very large. From a dynamic perspective, the influence of particle size is more important. Therefore, the advantages of nanomaterials may not be well demonstrated. Further work is underway [4].

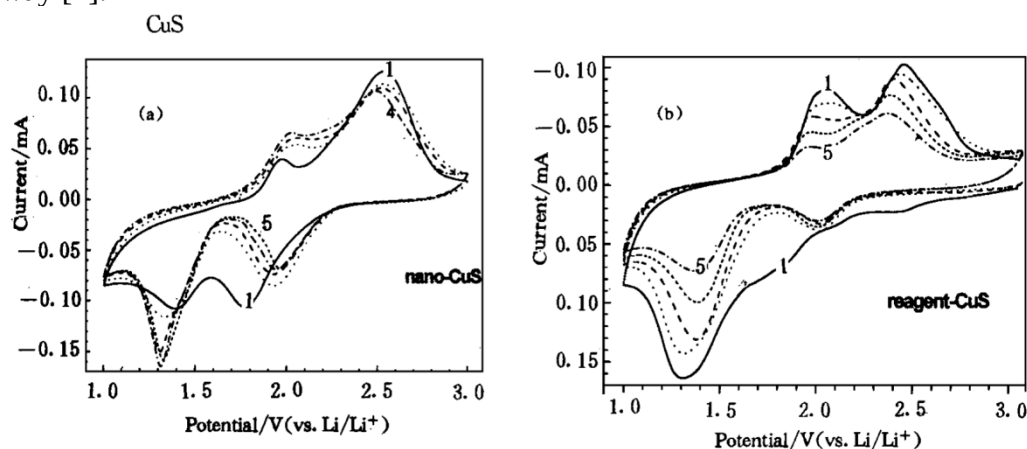


Fig. 3 I-V curve for different CuS materials [4]

3. Nanotechnology in Lightweight Materials

3.1. Background

Today, with the development of technology, lithium batteries, including LIBs (LIBs), have become the first choice for EVs and HEVs. Since the 1980s, the research of suitable electrode materials for LIBs has been constantly updated. From J. Goodenough's discovery of lithium cobalt oxide as a cathode material for LIBs in 1980 to the recent use of pure carbon and nanomaterials, the performance of electrode materials has been continuously improved. However, the materials used in current batteries have faced lots of problems. The materials used in electrodes in current batteries face huge obstacles to their development in the commercial field because of their low conductivity, low capacity and high possibility of pulverization. Since nanotechnology has been developing in recent years, great expectations on combinations of nanomaterials and active materials have been placed. To apply LIBs

to EVs and HEVs, LIBs still need further improvements in capacity, stability, structural integrity and Coulombic efficiency [5].

3.2. The Use of Nanoparticle Layer

Although materials such as Manganese oxides have long been used in the anode, their low conductivity and high possibility of induced crushing have become a huge obstacle to their development in the commercial field.

In order to improve the stability and electrochemical properties of battery materials, a plausible method of using nanoparticle layers was investigated. It suggested that the nanoparticle layer covered on the surface of the electrode not only enhances the surface area of the electrode but also allows more current to flow in the battery and improves the efficiency of the EV by reducing the weight of the battery. In addition, the nanomaterials play the role of solid-liquid separation in the battery not functioning, thus extending the shelf life of the battery. The approach could be accomplished through two steps. Firstly, the active substance in the electrode material (cathode or anode) is modified by adding nanomaterial or anode. Then, the electrode performance is improved by using nanocoating [6]. Many groups consulted this approach.

In 2021, a breakthrough occurred in the field of battery lightweight. A research team led by Kim used hydrothermal technology to create a hierarchical nanoflake-based CuO microspheres (H-CuO) composite wrapped in Graphene quantum dots (GQD) material. GQD not only reduces the resistance during charge transfer but also protects the electrode from degradation and agglomeration. The formation of microspheres filled with nanosheets on a mixture of pure H-CuO and H-CuO formed with GQD is clearly shown in positions B and C in Fig. 4. It was found that the reversible capacity reached a staggering 609 mAh/g after 200 cycles, which was far more than that of pure H-CuO composite. At a current density of 0.2 A/g, the initial Coulomb efficiency of the H-CuO/GQD composite was improved to 88.2%, compared with only 75.2% for pure H-CuO [7]. The H-CuO/GQD material is outstanding by the graphene network in its GQD coating because this structure not only provides a high surface area to volume ratio for the battery but also prevents the generation of unstable solid electrolyte interface layer (SEI) on the surface of the anode active material [7].

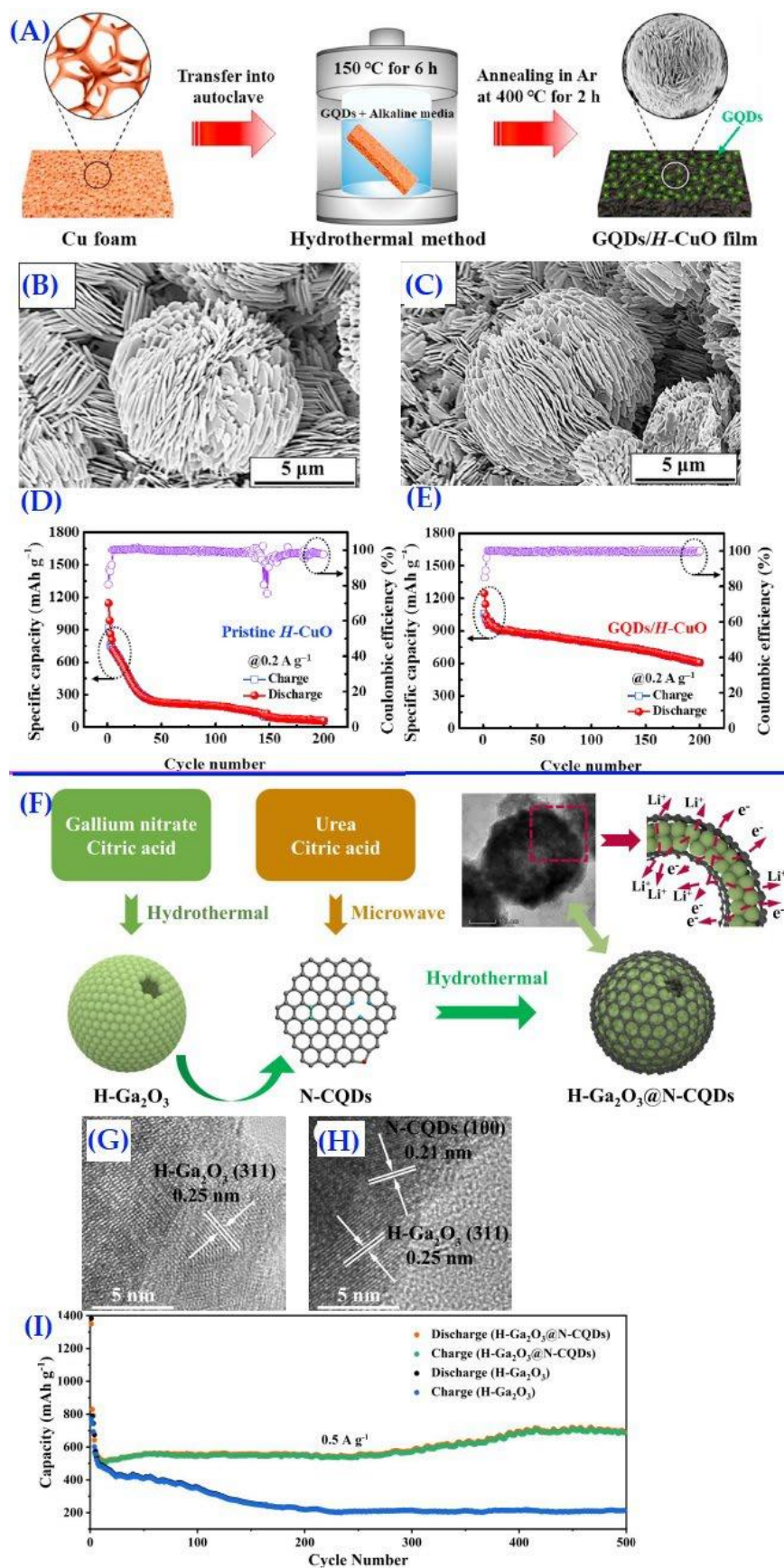


Fig. 4 Fabrication, structure and characteristics of nanoflake-based CuO microsphere and H-CuO/CQD microsphere [7]

3.3. The Use of Coral SnO₂/C Composite

Another material that can enhance batteries' properties is the coral SnO₂/C composite. Xu fabricated the coral SnO₂/C composite electrode. Using a sol-gel carbon coating method. The electrodes consist of interconnected fine single-crystal SnO₂ nanoparticles that create a coral-like structure similar to SnS₂ nanoflower. It can be seen in Fig. 5 [1].

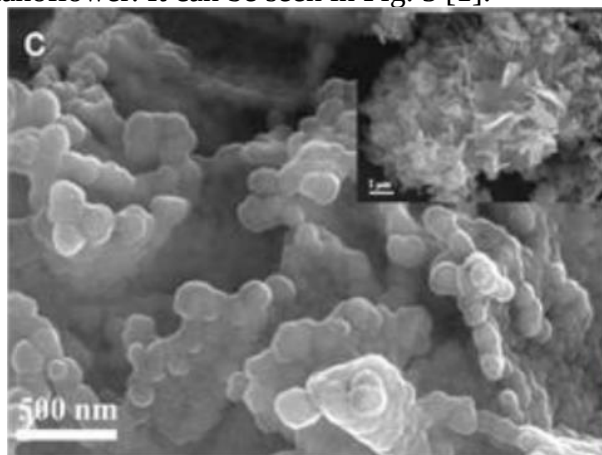


Fig. 5 Structure of coral SnO₂/C composite [1]

This structure provides more active reaction sites and shorter diffusion lengths. Additionally, The interconnected SnO₂ nanoparticles are prone to strain relaxation, producing stability, and the carbon layer lying on them provides integrated electron transport pathways (promoting continuous electron transport and prohibiting the formation of SEI membrane) to alleviate the disintegration and crushing effect of volume change. Experiments show that the optimized coral SnO₂/C composite consists of outstanding rate ability and cyclic reversibility [1].

The mechanism of this composite in Li-ion battery is illustrated in the following reaction equations [1]:



From the equations and necessary data, it can be computed that the theoretical specific capacity for coral SnO₂ is 782 mAh/g. In reality, according to Fig. 6, after 50 electrochemical cycles, the coral SnO₂/C combination maintained a capacity of 648 mAh/g, reflecting a very large discharge capacity and cycle stability.

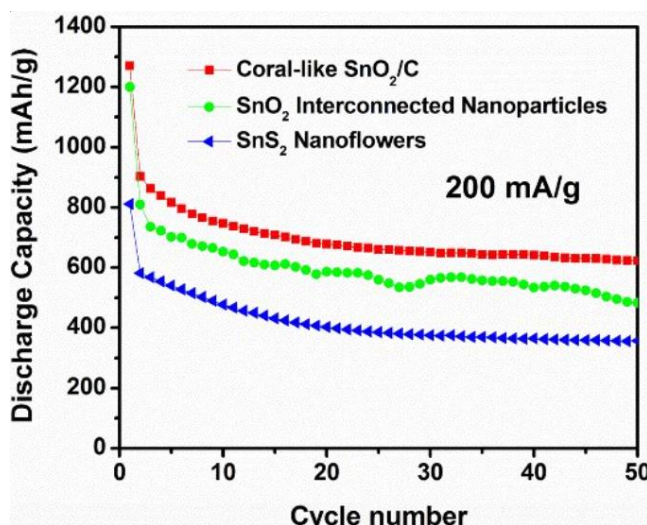


Fig. 6 Discharge capacity shown during the 50 cycles [1]

As the data shown in Fig. 7, when the current drops from 2000 mA/h/g to 100 mA/g, coral SnO₂/C shows better discharge capacity (719 mAh/g) than pure SnO₂ particles (625 mAh/g) and SnS₂ nano snowflakes (546 mAh/g), which also indicates the mechanical integrity of the layered structure.

Additionally, the coral SnO_2/C composite charge transfer resistance ($25\ \Omega$) is lower than the interconnected SnO_2 nanoparticles ($55\ \Omega$) and SnS_2 nanoparticles ($50\ \Omega$), indicating the low charge transfer resistance of the coral SnO_2/C composites [1].

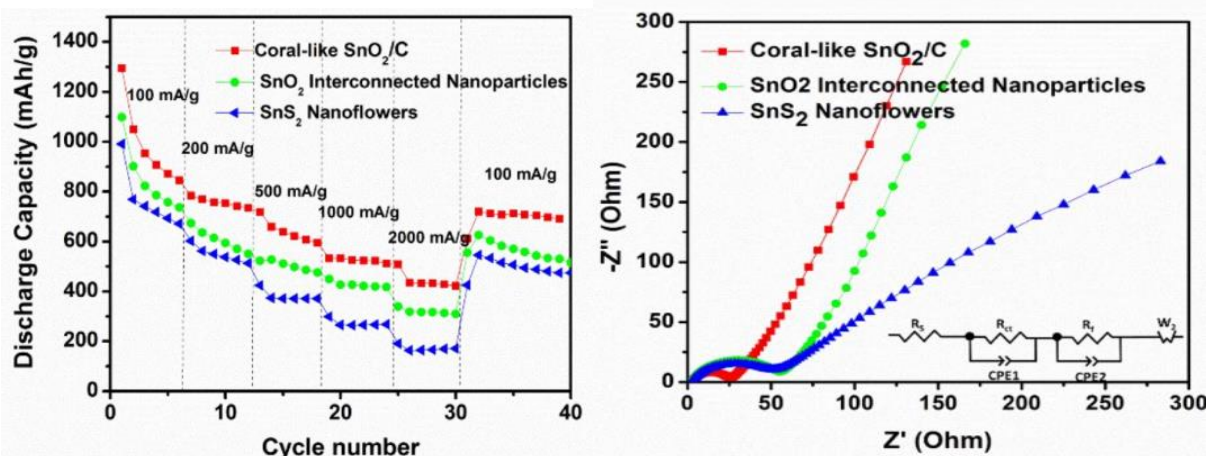


Fig. 7 Change in discharge capacity under different current and charge transfer resistances among the tested samples [1]

3.4. The Use of P-PPy Composite

The P-PPy composite was also investigated. The PPy-based compound anode could significantly improve the performance of LIBs. This particular material could be made through a two-step process: high-energy ball milling followed by PPy polymerization and sol-gel followed by PPy polymerization. The SEM image and TEM image in Fig. 8 show the structure of the selected composite [8].

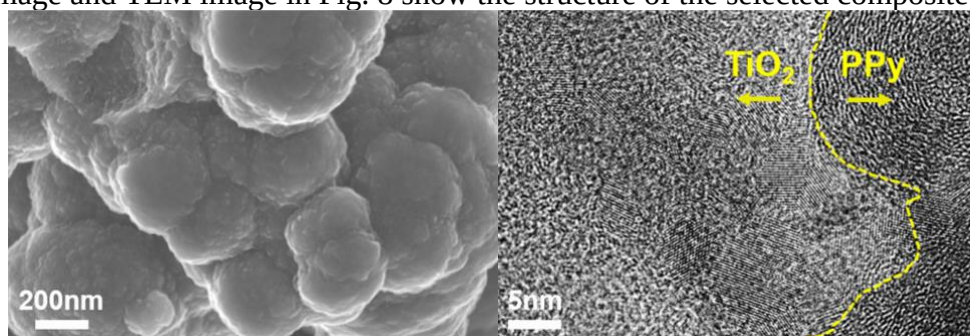


Fig. 8 The SEM image (left-hand side) and TEM image (right-hand side) [8]

The data from the result show that due to the reactivation of PPy, allowing PPy to absorb more lithium ions, the specific capacity of the P-PPy composite increased with the number of cycles to 1700 mAh/g [8].

The P-PPy anode exhibits a stable specific capacity and minimal decay. During the repeated shuttling of lithium ions, the mechanically flexible PPy can adapt to the 490% volume change of the P structure, maintaining the structural integrity reflecting the structural buffering effect of PPy. Moreover, the strong chemical bond between PPy and P blocks the direct contact between P and the electrolyte, thus alleviating the shuttling effect of Li_2P . The material of long periods and stable large specific capacity is also attributed to minimizing the formation of Li_2P [8].

This part of the review listed three structures or components which could be used for battery application. The GQD nanoparticle layer's large surface-to-volume ratio and successful prevention in the formation of SEI elongate the cell's life cycle and provide stability. The coral's active reaction sites and shorter diffusion lengths enable the cells to have a higher capacity. The P-PPy composite not only enhanced the capacity but also adapted to large volume changes in cells. In conclusion, the invention of nanolayer, the coral structure of composites and P-PPy composite can lead to a brighter future for the EV and HEV construction realm due to the basic properties they had enhanced (stability and capacity), but also other properties such as Coulombic efficiency as well.

4. Nanotechnology in Thermal Management

4.1. Application of Nanotechnology in Automotive Cooling System

The application of nanotechnology in automotive cooling systems, including the use of nanofluids and diamond nanofilms, has received increasing attention.

Firstly, nanofluids are stable suspensions formed by the dispersion of nanoscale particles in the base solution, which can enhance the heat transfer performance and thus improve the cooling efficiency. Gao et al. pointed out in "Application of Nanofluids in Engine Cooling Systems" that the thermal conductivity and heat transfer efficiency of conventional coolant can be significantly improved by adding nanoparticles to the coolant. This nanofluid can not only effectively reduce the operating temperature of the engine but also maintain stable cooling performance under high load conditions, thereby extending the life of the engine and improving fuel economy [9]. The application of nanotechnology provides a new idea and direction for the optimization and innovation of automotive cooling systems.

In addition, diamond nanofilms, as a new type of heat dissipation material, can significantly improve the service life of electronic components and the energy efficiency of the whole system by reducing the heat load of electronic components. He Hao (2022) pointed out in his master's thesis that "diamond nanoparticles have great potential in the research and development of cooling system materials due to their excellent thermal stability" [10]. This discovery provides new ideas for developing more efficient automotive cooling systems by introducing nanomaterials with high thermal stability, further improving the durability and performance of cooling systems.

4.2. Application of Nanocoating in Heat Dissipation

The potential of nanocoatings in enhancing heat dissipation efficiency has been the subject of increasing attention in recent times. Khan et al. (2020) designed hybrid micro-nano-surface coatings and demonstrated their effectiveness in enhanced heat transfer applications through synthesis and characterization. The coating markedly enhanced the heat dissipation performance by optimizing the surface structure, thereby providing a novel solution to the heat dissipation problem in electronics and industrial equipment [11]. This research result was published in the International Journal of Energy Research, which provides a robust foundation for further research and the application of nanocoatings in heat dissipation technology.

4.3. Technology Advances in Battery Thermal Management

Battery thermal management technology has become a hot area of EV research in recent years. As the demands on battery performance and lifetime increase, thermal management technologies are constantly being innovated. Researchers are currently working to develop more efficient heat dissipation materials and structures to improve the heat transfer efficiency of batteries. At the same time, intelligent thermal management systems are gradually being applied to battery thermal management to effectively extend battery life and improve the overall performance of EVs through precise temperature control and heat distribution. The development of these technologies has brought breakthroughs in battery thermal management and driven the development of the EV industry. A study points out that passive air cooling and active air cooling technologies are the focus of current research. Passive air cooling uses natural convection or forced convection to dissipate heat by optimizing the battery pack structure, while active air cooling increases airflow and improves cooling efficiency through devices such as fans (Fig. 9) [12]. The development of these technologies provides new solutions for the thermal management of pure EV batteries, helping to improve battery performance and lifetime.

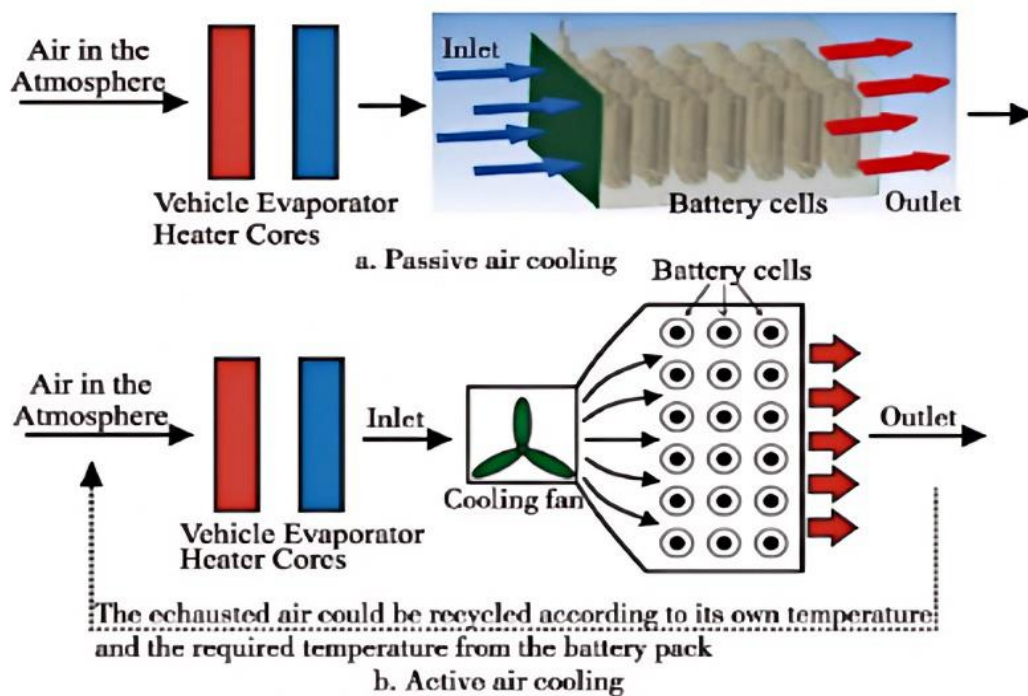


Fig. 9 a) Passive air cooling and b) active air cooling [12]

5. Safety and Environmental Issues Caused by Nanomaterials

5.1. Environmental Issues

Carbon nanomaterials (C_{60}) aqueous suspension can inhibit the growth of *Scenedesmus obliquus*, suppress the activity of large fleas, and lead to the death of large fleas. Its pollution level to aquatic organisms is roughly equivalent, harmful to algae, and toxic to large fleas. The toxicity of carbon nanomaterials may be related to the properties of the nanomaterials themselves (such as particle size, photosensitivity, high surface area, and reactivity), as well as the physiological structure, function, and sensitivity of the test organisms used [13].

5.2. Safety Issues During Use

The thermal stability of LIBs can be tested and evaluated using ARC, which is an important means of measuring the safety of LIBs. Good thermal stability means that the thermal runaway process of LIBs is long, the destructive power of thermal runaway is low, or even no thermal runaway occurs. Given that the essence of thermal runaway is the chemical reaction between various materials inside the battery, improving the thermal stability of battery materials, such as positive electrode material coating, can enhance the safety of LIBs and reduce the destructive nature of safety accidents. Negative electrode lithium deposition is also considered a possible cause of safety issues in LIBs. High-rate charging, low-temperature charging, or coating deviations in battery manufacturing can all lead to the precipitation of metallic lithium in the negative electrode. Due to the strong reactivity and heat generation of metallic lithium, the threshold for chemical reactions inside the battery is lowered, which reduces the safety of the battery. Metal foreign objects in the positive electrode material will undergo electrolysis during the charging process, becoming ions that migrate to the negative electrode and are reduced to form dendrites or highly reactive nano deposits at the negative electrode. This increases the probability of internal short circuits or lowers the threshold for exothermic reactions in the battery, ultimately leading to an increased probability of thermal runaway. Therefore, from the manufacturing of battery materials to the manufacturing of batteries, it is necessary to handle possible foreign object issues very carefully to reduce the occurrence of battery accidents. Diaphragm defects

were often overlooked in the past. The uniformity of membrane micropores is difficult to confirm through product quality, and most of them are confirmed through the battery yield of battery companies. For example, if a micropore is blocked, it is difficult to detect, but if the local diaphragm hole is blocked (or if the local impedance increases), it may cause local lithium metal precipitation, leading to safety accidents [14].

6. Future Prospects and Challenges

6.1. Future Development Prospect

Nanotechnology, as a frontier science and technology of the 21st century, has a promising future and is full of potential for further development. Researchers discussed the potential applications of nanotechnology and its future development in a range of fields [15]. This provides insight into the vast and evolving landscape of nanotechnology.

As scientific research progresses and technology continues to advance, it is anticipated that nanotechnology will facilitate groundbreaking applications across a wider range of fields. In the field of healthcare, nanotechnology will facilitate the advancement of novel drug delivery systems and biosensors, thereby effecting transformative changes in the diagnosis and treatment of diseases. In the field of energy and the environment, the application of nanomaterials will facilitate the development of more efficient and environmentally friendly energy utilization and environmental protection technologies, thereby providing substantial support for the realization of sustainable development goals. Concurrently, nanotechnology will persist in propelling innovation in the realms of electronic information and novel materials, thereby opening up new avenues for the advancement of information technology and the evolution of new materials. Nanotechnology will emerge as a pivotal driver of innovation and progress across numerous domains, exerting a profound influence on the trajectory of societal advancement.

6.2. Technical Challenges and Approaches

Nanotechnology, as a cutting-edge technology of the 21st century, has significant potential for further development. However, it also faces a number of challenges. These challenges primarily originate from the intricate nature of the technology itself, the elevated production costs, and the extensive range of potential applications.

Firstly, the research and development of nanotechnology necessitate the utilization of sophisticated instrumentation and the input of highly skilled technical professionals, which collectively serve to elevate the technical threshold associated with this field of study. To surmount this challenge, it is imperative to augment investment in scientific research, cultivate a greater number of nanotechnology professionals, and facilitate interdisciplinary collaboration and exchange.

Secondly, the production cost of nanomaterials is prohibitively high, which restricts their use in mass production. In order to reduce the production cost, it would be beneficial to explore new synthesis methods, optimize the production process and improve the production efficiency.

Ultimately, the implementation of nanotechnology across diverse sectors must align with the specific requirements and standards of each field, which can introduce complexity to its integration. In order to surmount this challenge, it is imperative that collaboration with industry be enhanced, market demand be more fully understood, and the customization of nanotechnology be promoted.

In conclusion, the challenges associated with nanotechnology cannot be overlooked. However, by implementing effective strategies to address these challenges, the long-term advancement of nanotechnology can be facilitated. The advancement of nanotechnology in the future can be facilitated by reinforcing financial commitments to scientific research, optimizing production processes and fostering industrial collaboration. This will enable the technology to make more significant contributions to the development of human society. Concurrently, it is essential to prioritize the safety and environmental impact of nanotechnology to guarantee its sustainable growth.

7. Conclusion

The advent of nanotechnology has had a profound impact on the EV industry. The optimization of battery materials through the application of nanotechnology has resulted in improvements to the range and charging efficiency of EVs, as well as a reduction in production costs. Meanwhile, the application of nanocoatings has also enhanced the durability and safety of EVs. However, the widespread application of nanotechnology still faces the challenges of cost and technical threshold. In the future, with the deepening of scientific research and continuous technological innovation, nanotechnology is expected to play a greater role in the EV industry, promoting the popularity and sustainable development of EVs and contributing to green mobility.

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