

Designing vertically lamellar architectures of carbon nanocages-polyaniline hybrid aerogels to achieve high-performance supercapacitors

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Abstract

The hybrid electrical double-layer capacitive-pseudocapacitive materials are promising electrodes for supercapacitors but suffer from uneven mixing and/or embedment of active materials. Herein, we demonstrated an effective approach to construct high-performance polyaniline/carbon nanocages (PANI/CNC) hybrid electrodes involving bidirectional freeze-casting (BFC) and low-temperature *in-sinu* polymerization of aniline in the matrix of CNC. This BFC technique introduces two-directional temperature gradients, resulting in the formation of electrodes (PANI-CNC-BFC) with a vertical lamellar structure, which provides rapid ion diffusion channels and thus boosts the electrochemical performance. Consequently, the PANI-CNC-BFC electrode exhibits excellent electrochemical performance in supercapacitors, showing a high areal capacitance of 53.2 mF/cm² and long-term stability with negligible capacitance degradation in 1000 cycles, much superior to the counterpart of PANI-CNC without the vertically lamellar architecture. This study offers a new strategy for developing supercapacitor electrodes with high capacitances and rate capabilities.

Keywords: bidirectional freeze-casting; carbon nanocages-polyaniline hybrid aerogels; supercapacitors; vertically lamellar architectures; low-temperature *in-situ* polymerization

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构筑垂直片层结构碳纳米笼-聚苯胺复合气凝胶实现 高性能超级电容器

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摘要:双电层电容-赝电容复合材料是极具前景的超级电容器电极材料,但其性能通常受到活性组分混合不均匀和/或暴露不充分等问题的影响。本研究展示了一种有效构建高性能聚苯胺/碳纳米笼(PANI/CNC)复合电极的方法,该方法结合了双向冻铸(BFC)和苯胺低温原位聚合技术,前者引入了双向温度梯度构筑了具有垂直片层结构的电极(PANI-CNC-BFC),可提供快速的离子扩散通道进而提升了电化学性能,而后者实现PANI与CNC的紧密结合提升了材料利用率。因此,PANI-CNC-BFC 电极在超级电容器中表现出优异的电化学性能,展现出高达 53.2 mF/cm²的面积比电容,在1000次循环中几乎无电容衰减,远优于不具备片层结构的 PANI-CNC 电极。本研究提供了一种开发具有高电容和高倍率性能的超级电容器电极的有效策略。

关键词: 双向冻铸; 碳纳米笼-聚苯胺复合气凝胶; 超级电容器; 垂直片层结构; 低温原位聚合

1. Introduction

The rapid development of portable electronics, electric vehicles and artificial intelligence (AI), together with dwindling fossil fuel reserves and increasing environmental pollution, has aroused enthusiasm for the imperative development of advanced energy storage devices ^[1]. Batteries and supercapacitors have garnered significant attention in electricity storage from intermittent energy sources, serving as common power sources in various circumstances ^[2]. Thereinto, supercapacitors manifest the capability of rapid electricity storage and power supply, which could manage the fluctuating energy demands of AI-powered devices and data centers. However, improving the energy density of supercapacitors remains highly challenging. There are two main kinds of electrode materials for supercapacitors: electrical doublelayer capacitive (EDLC) materials (such as nanocarbons) and pseudocapacitive materials (such as metal compounds and polymers). The hybrid electrodes composed of EDLC-pseudocapacitive materials are promising due to the combined high conductivity and high theoretical capacitances ^[3,4]. However, the hybrid electrodes usually suffer from uneven mixing and/or embedment of active materials, leading to inferior performance. To address these problems, it is necessary to select efficient active materials and design highly exposed electrode structure.

Among various carbon-based materials, hierarchical carbon nanocages (CNC) were employed as the EDLC material, which has the advantages of high specific surface area, high conductivity, coexisting macro-/meso-/micropores, and good stability ^[5-7]. The unique features endow CNC with facilitated charge/mass transport and efficient utilization of active sites, promising for electricity storage by electrostatic adsorption. Among pseudocapacitive materials, polyaniline (PANI) was chosen due to its high theoretical capacitance, easy polymerization and considerable conductivity ^[8]. The PANI/graphene/PANI sandwich-structured nanosheets exhibited good electrochemical performance, including high specific capacitance values ^[9]. However, previous reports showed that their hybridization usually led to the coating of PANI nanofibers on carbon support, hindering the expression of the electricity storage potential of PANI ^[10]. On

the other hand, the hybridization of pseudocapacitive material on nanocarbons could result in the reduction of pore structure and the suppressed electron transport, impeding the electrolyte penetration and charge transport, deteriorating the rate performance. Hence, developing an effective method to construct uniform hybrid electrodes with highly accessible active components and excellent electrical conductivity is vital.

Recently Yu et al. developed a unidirectional ice-templating technique to fabricate carbon hosts with size-tunable vertical channels [11], and further constructed the lamellar structure for biomimetic shells using the bidirectional ice-templating method ^[12]. Inspired by this, we demonstrated an effective approach to constructing highperformance PANI/CNC electrodes involving bidirectional freeze-casting (BFC) and low-temperature in-situ polymerization of aniline in the CNC matrix. This BFC technique introduces two-directional temperature gradients, resulting in the formation of electrodes (PANI-CNC-BFC) with a vertical lamellar structure. As illustrated in Scheme 1, the vertically lamellar structure of active materials provides rapid ion diffusion channels, substantially improving the electrode's electrochemical performance. In contrast, the conventional active material layer suffers from the poor electrolyte diffusion and long transport path, unfavorable to the electrochemical process. Consequently, the PANI-CNC-BFC electrode presented higher areal capacitances and faster charge transfer kinetics than PANI-CNC. This novel approach offers a new strategy for developing supercapacitor electrodes with high capacitances and rate capabilities.





2. Experiments

2.1 Materials

The hierarchical carbon nanocages (hCNC) were prepared using the *in situ* MgO template method with benzene precursor ^[13,14]. Aniline hydrochloride (Aladdin, China), potassium persulfate (K₂S₂O₈, Aladdin, China), acrylamide (AM, Aladdin, China), sodium carboxymethyl cellulose (Na-CMC; Sigma-Aldrich; Mw: ~250,000), KOH (Aladdin, China) were used as received.

2.2 Fabrication of PANI-CNC-BFC aerogel electrodes

In a typical experiment, an appropriate amount of CNC was dispersed in deionized (DI) water, and then aniline, K₂S₂O₈, and CMCNa were dissolved in the suspension. The mixture was then ground in a mortar for 15 minutes until it was uniformly blended. In the slurry, the weight ratio of hCNC, aniline, and CMCNa binder was 10.8:100:1.08 with a solid content of 14.9 wt%. Subsequently, the bidirectional freeze-casting (BFC) process was carried out, as shown in Figure 1. A 10 cm \times 3.5 cm titanium foil current collector was placed on the surface of a copper cuboid with the dimensions of 12.5 cm \times 4 cm \times 2 cm. The prepared slurry was tape-cast onto the titanium foil to form a thin film with a thickness of approximately 200 µm. After the tape-casting, one end of the copper cuboid (approximately 3 cm) was immersed in liquid nitrogen stored in a plastic foam container. Owing to the high thermal conductivity (398 W/m·K) of copper, the slurry was then frozen after 15 minutes. Induced by the upward and rightward temperature gradients, the ice crystals grew into vertically lamellar architecture, which repelled the active materials to form analogous lamellar architecture. After that, the Ti foil with frozen slurry was quickly transferred to a freeze-dryer for 12 hours to remove the ice crystals, and the aniline was *in situ* polymerized in this period, resulting in the formation of the PANI-CNC-BFC aerogel electrode. To reveal the impact of electrode structure on the energy storage performance, a PANI-CNC sample was prepared by drying the slurry tape-cast Ti foil in the oven at 60 °C, and aniline was polymerized during drying. A CNC sample was also prepared by directly drying the slurry of CNC and CMCNa tape-cast on Ti foil.

The electrolyte concentration distribution within the PANI-CNC-BFC and PANI-CNC electrodes was modelled by using COMSOL Multiphysics 6.2. The model's geometry is the same as the electrode structure of PANI-CNC-BFC, with the dimensions of 80, 20, and 15 μ m for the active material layer, channel, and wall, respectively.



Figure 1. The synthesis strategy. (A) Schematic of the BFC process of the electrode, including tape-casting, bidirectional freeze-casting, and freeze-drying; (B) Digital photo of the homemade BFC setup.

2.3 Electrode architecture and electrochemical characterization

The morphology of CNC was characterized by transmission electron microscopy (TEM) and scanning electron microscopy (SEM). The architectures of PANI-CNC-BFC and PANI-CNC electrodes were characterized by SEM. The symmetric supercapacitors were assembled by sandwiching a layer of separator with two identical electrodes. The rate capability tests were performed by cyclic voltammetry (CV) on a biologic VMP3 electrochemical station at different scanning rates (1, 2, 5, 10, 20, 50, and 100 mV/s) and by galvanostatic charge-discharge (GCD) method on a Neware battery testing system at different current densities (0.2, 0.5, 1, 2 mA/g) with the electrochemical window of 0–0.75 V. The CV at 20 mV/s were conducted to evaluate the cycling stability of symmetric supercapacitors. Electrochemical impedance spectrum (EIS) measurements were carried out within the frequency range of 1 M Hz to 0.1 Hz and amplitude of 10 mV on the VMP3 station.

2.4 Construction of flexible PANI-CNC-BFC micro-supercapacitors by screen printing strategy

The PANI-CNC-BFC micro-supercapacitors were fabricated using a screen printing strategy on a flexible substrate. The typical process was performed as follows. (1) Electrode preparation: CNC-aniline slurry was coated on the mask-screened substrate by ultrasonic spraying. To ensure sufficient electrode thickness, the spraying process was repeated three times, providing the close adhesion of CNC-aniline ink with the substrate. (2) 3D scaffold construction: Bidirectional freezing and freeze-drying techniques were employed to assemble PANI-CNC into a vertically lamellar scaffold. (3) Electrolyte addition: H₂SO₄-AM sol electrolyte containing the initiator (K₂S₂O₈ and ascorbic acid) was dropped onto the interdigitated pattern of the electrodes. After ~2 minutes, the electrolyte became a gel state, forming the micro-supercapacitors.

3. Results and discussion

3.1 Characterization of PANI-CNC-BFC aerogel electrodes

The quality of CNC is crucial to the electrochemical performance of the PANI-CNC-BFC electrode because the CNC serves as the scaffold for loading PANI and ensuring the charge/mass transport. TEM and SEM characterizations indicate that the CNC consists of hierarchical porous microspheres with an average size of 8-15 µm, which is assembled by nanosheets with submicrometer interspace. The nanosheets are interconnected hollow nanocages with an average size of 30-60 nm and a wall thickness of 2-4 nm (Figures 2A and 2B). The bulk conductivity of the CNC is about 567 S/m, which is well-suitable for application as a supercapacitor material. To further enhance the adhesion between CNC and the current collector, CMCNa was added to the slurry as a binder. The PANI-CNC-BFC aerogel electrodes were fabricated using an *in situ* oxidative freeze polymerization method. As illustrated in Figure 2C, K₂S₂O₈ pre-added in the slurry acted as the initiator to induce *in situ* polymerization of aniline into PANI on the CNC surface during the freeze-drying process. Concurrently, to engineer the vertically lamellar structure of the electrode, a bidirectional freeze-casting technique was integrated into the electrode preparation process, leading to the PANI-CNC-BFC aerogel electrode after the freeze-drying process.



Figure 2. Typical TEM (A) and SEM (B) images of CNC; (C) K₂S₂O₈ induced polymerization of aniline to PANI.

The microstructure of PANI-CNC-BFC and PANI-CNC aerogel electrodes was characterized by SEM, as shown in Figure 3. The top-view SEM images reveal a layered structure with a channel diameter of approximately 20 µm and the layer thicknesses of 10 to 20 µm (Figure 3A and 3B). The side-view SEM image (Figure 3C) further confirms the vertically aligned structure. The layer consists of porous microspheres, which are very similar with the pristine CNC. This result implies the well mixing of CNC and PANI (Figure 3D). In contrast, the PANI-CNC aerogel electrode prepared by direct tape-casting did not exhibit any lamellar structure, and the active material was randomly distributed on the Ti foil (Figure 3E). It is interesting that, besides the porous microspheres, some sheets with the size of several micrometers and the thickness of dozens of nanometers were observed (Figure 3F, marked by red circles), which are the segregated bulk PANI ^[15]. It is learned that PANI-CNC-BFC and PANI-CNC electrodes prepared by different processes show significant morphology

differences. Specifically, the PANI in the PANI-CNC-BFC forms a uniform coating on the CNC surface, while that in the PANI-CNC is phase-separated from the CNC. This disparity resulted from the different drying processes. During freeze-drying, solid water sublimates directly at low temperatures; meanwhile, the aniline was polymerized into PANI within the CNC matrix, thus maintaining the intimate contact between PANI and CNC. In contrast, during the conventional thermal drying, the liquid water was removed by evaporation, and the aniline/oligomeric PANI was concentrated during the evaporation, leading to the formation of PANI bulks after the complete removal of water. The detachment of PANI from CNC could result in the lower utilization of PANI in electricity storage due to the inferior electron conductivity.



Figure 3. SEM images of PANI-CNC-based aerogel electrodes. (A-D) PANI-CNC-BFC electrode; (E-F) PANI-CNC electrode.

3.2 Electrochemical performances

A coin-type symmetrical supercapacitor was assembled with PANI-CNC-BFC aerogel electrodes, and the electrochemical performances were evaluated using CV and GCD tests. The CV curves obtained at various scan rates exhibit the combined features of EDLC and pseudocapacitance for hybrid PANI-CNC materials (Figure 4A). The redox peaks at higher potentials show the contribution of PANI, and the CV curves at lower potentials display a near-rectangular shape, indicative of excellent EDLC

behavior. At elevated scan rates (50 and 100 mV/s), a potential shift of redox peaks was observed due to the polarization. In contrast, the CV curves for PANI-CNC showed similar shapes to those for PANI-CNC-BFC but exhibited obviously lower current (Figure 4B), indicative of the lower utilization of active materials due to the phase separation of PANI from CNC and the lack of porous structure (Figure 3E and 3F). For CNC electrode, no redox peaks were observed on the CV curves, consistent with the absence of PANI (Figure 4C). Quantitatively, the PANI-CNC-BFC electrode exhibited the highest areal capacitances at all scan rates among these three electrodes (Figure 4D). Specifically, the PANI-CNC-BFC showed the areal capacitance of 53.2, 48.8, 45.3, 44.8, 43.2, 43.1, 43 mF/cm² at the scan rate of 1, 2, 5, 10, 20, 50, and 100 mV/s. Typically, the areal capacitance reaches 43.2 mF/cm² at 20 mV/s, nearly twice that for PANI-CNC and four times that for CNC. This highlighted the critical role of the BFC process in enhancing the capacitance of 35.2 mF/cm² during 1000 cycles of CV test, exhibiting excellent cycling stability (Figure 4E).

Moreover, the influence of the PANI content in the PANI-CNC-BFC on the areal capacitance was also investigated, as shown in Figure 4F. The areal capacitance was increased with increasing the PANI amount, and the PANI-CNC-BFC with the PANI:CNC weight ratio of 100:10 has the highest areal capacitance. For the PANI:CNC ratio of 50:10 and 5:10, the areal capacitances were decreased, but were higher than that for the CNC electrode. This further indicates the contribution of PANI to the capacitance. The above results indicate that the hybridization of CNC with PANI, along with the vertically lamellar structure, significantly enhances the energy storage performance of CNC, providing an efficient means to develop advanced supercapacitor materials.



Figure 4. Electrochemical performances measured by CV. (A-C) The CV curves of PANI-CNC-BFC (A), PANI-CNC (B) and CNC (C); (D) Areal capacitances of PANI-CNC-BFC and PANI-CNC and CNC; (E) Cycling stability of PANI-CNC-BFC measured at 20 mV/s; (F) Areal capacitances of PANI-CNC-BFC with different PANI/CNC weight ratio. All the CV curves were recorded in 6 M NaOH electrolyte.

The rate and cycling performances of PANI-CNC-BFC were also tested by GCD within a potential window of 0-0.75 V, as shown in Figure 6. All the GCD curves at various current densities show quasi-linear behavior with high reversibility (Figure 6A). The areal capacitances are 10.3, 9.90, 9.54, and 9.28 mF/cm² at the current density of 0.2, 0.5, 1, and 2 mA/g, respectively. When the current density was increased by 10 times, the PANI-CNC-BFC showed a high retention of 89.7% in the areal capacitance, showing excellent rate capability (Figure 6B). Cycled at a current density of 1 mA/g, a stable areal capacity of 8.96 mF/cm² was remained after 1000 cycles, reflecting the high stability of PANI-CNC-BFC (Figure 6C). The negligible capacitance degradation of PANI-CNC-BFC could be attributed to the stable structure and smooth charge transport kinetics of the PANI-CNC-BFC.



Figure 5. Cycling stability of PANI-CNC-BFC measured by GCD tests: (A) chargedischarge profiles at different current densities; (B) Areal capacitance versus current density; (C) The cycling performance is at 1 mA/g.

EIS characterization and COMSOL simulation were carried out to investigate the charge transport kinetics of PANI-CNC-BFC and PANI-CNC, as shown in Figure 6. The EIS spectra of PANI-CNC-BFC, PANI-CNC and CNC display a well-defined high-frequency semicircle and a linear section at low frequencies. The electrode and electrolyte resistance (R_s) was determined from the high-frequency intercept of the semicircle, while the charge-transfer resistance (R_{ct}) was derived from the semicircle diameter. The PANI-CNC-BFC exhibits lower R_s and R_{ct} values (0.17 and 0.074 Ω), much smaller than those for PANI-CNC (0.66 and 0.26 Ω) and CNC electrodes (3.3and1.2 Ω), reflecting the higher conductivity and faster electrode kinetics of PANI-CNC-BFC (Figure 6B). The lower resistances were attributed to the vertically lamellar architecture of PANI-CNC-BFC, which facilitates the ionic/electrolyte transport, thereby boosting the electricity storage and release in capacitance and rate capability.

The COMSOL simulation was performed to visualize the electrolyte (6M NaOH) concentration distribution along the electrode thickness upon cell operation. The ion concentration maps of the two electrodes (PANI-CNC and PANI-CNC-BFC) were shown at the end of discharge at 3C (Figure 6C and 6D). Within the PANI-CNC-BFC electrode, the OH⁻ concentration gradient is much smaller than that of the PANI-CNC, suggesting the facilitated ions/electrolyte diffusion in the active material layer due to the lamellar channels. In contrast, the ion concentration at the bottom of the PANI-CNC is very low, which much impeded the energy storage performance due to insufficient supply of involved ions. The EIS and COMSOL results reveal the origin of the

vertically lamellar architecture to enhance the electrochemical performances of PANI-CNC-BFC, i.e., by much facilitating the charge/mass transport. This offers useful guidance to design advanced supercapacitor electrodes with high-rate capabilities.



Figure 6. Kinetic analysis. (A) Nyquist plots of the PANI-CNC-BFC, PANI-CNC, and CNC electrodes; (B) R_s and R_{ct} calculated from EIS. Inset is the corresponding equivalent circuit. (C, D) The distribution of electrolyte in PANI-CNC (C) and PANI-CNC-BFC (D) electrodes by COMSOL simulation.

3.3 Flexible PANI-CNC-BFC micro-supercapacitors

To demonstrate the application potential of PANI-CNC-BFC electrodes, flexible micro-supercapacitors were fabricated on PDMS thin film through a screen-printed ultrasonic spray technology, and vertically lamellar architectures were constructed by the BFC and freeze-drying technique (Figure 7A-7C). a series of PANI-CNC-BFC micro-supercapacitors were constructed (Figure 7C) with the dimension of 9 mm \times 9.9 mm. The CV curves of a PANI-CNC-BFC micro-supercapacitor were tested at the scan rates from 1 to 50 mV/s (Figure 7D), demonstrating the feasibility of the micro-supercapacitors. These results indicate that micro-supercapacitors were successfully fabricated, with excellent flexibility and electrochemical performance, showing the great potential of PANI-CNC-BFC electrodes in the flexible micro-supercapacitors.



Figure 7. Fabrication and characterization of the PANI-CNC-BFC microsupercapacitors. (A) Schematic preparation of flexible PANI-CNC-BFC microsupercapacitors; (B) The photo of the ultrasonic spray process; (C) The photo of PANI-CNC-BFC micro-supercapacitors on PDMS thin film; (D) CV curves of a PANI-CNC-BFC micro-supercapacitor.

4. Conclusion

In summary, carbon nanocages-polyaniline hybrid aerogels were fabricated by bidirectional freeze-casting and low-temperature *in-situ* polymerization. The vertically lamellar architectures of PANI-CNC-BFC enabled excellent electrochemical performance in supercapacitors, showing the high areal capacitance of 53.2 mF/cm² and long-term stability with negligible capacitance degradation in 1000 cycles, much superior to the counterpart of PANI-CNC without the vertically lamellar architecture. The EIS characterization and COMSOL simulation revealed that the porous lamellar structure of the PANI-CNC-BFC electrode greatly boosted charge transfer, thereby promoting capacitances and rate capabilities. In addition, the PANI-CNC obtained by conventional thermal polymerization contained segregated PANI sheets from the CNC scaffold, while the PANI-CNC-BFC by *in situ* polymerization during freeze-drying possessed uniformly coated PANI on the CNC surface, enabling the high utilization of

PANI in energy storage. Such a BFC route was extended to fabricate the microsupercapacitors on flexible substrates, showing the bright potential application. This study provided a promising approach for preparing supercapacitor electrodes with high energy density and high-rate capability, offering guidance for developing future highperformance energy storage devices.

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6. Acknowledgments

6.1 Topic Selection and background

The rapid development of portable electronic devices, electric vehicles, and artificial intelligence (AI), coupled with increased environmental awareness, has led to a growing demand for high-performance energy storage devices in today's society. Supercapacitors have attracted considerable attention due to their fast energy storage and delivery capabilities. However, significant challenges remain in improving their performance. During our literature review, we noted that the hierarchically structured carbon nanocages (CNCs) developed by Professor Zheng Hu's research group at Nanjing University exhibited excellent supercapacitor performance, showing great potential for application. However, the electric double-layer capacitance mechanism limits the energy density of CNCs. Reports have shown that "PANI/graphene/PANI" sandwich-structured nanosheets can enhance the specific capacitance of materials. Inspired by these advancements, we proposed to combine CNCs with pseudocapacitive materials to improve overall energy storage performance. In recent years, bidirectional freeze-casting techniques have been used to prepare materials with vertically oriented porous structures, providing new ideas for designing electrode structures with optimized ion transport channels. Based on these research developments and considering the limitations of existing energy storage materials in pore structure, ion diffusion, and electron transport, we proposed a research project to develop novel hierarchically structured electrode materials based on CNCs and PANI, aiming to construct vertically oriented lamellar structures using bidirectional freeze-casting technology to enhance the energy storage performance of materials. This topic aims to further improve the energy density of supercapacitors through structural optimization and material innovation.

6.2 Contributions of the team members

Wu Zhiyuan was responsible for the literature review, concept design, material preparation, performance testing, data analysis, and initial manuscript drafting.

You Yue participated in the literature review, data analysis, and manuscript revision.

6.3 Instructors

Zheng Hu, a Professor at Nanjing University served as the academic supervisor for this paper. He provided theoretical and experimental guidance and offered suggestions for manuscript revision. The above supervisory work was provided without compensation.

6.4 Other Support

This work was supported by the Ministry of Education's Key Laboratory of Mesoscopic Chemistry at Nanjing University. COMSOL simulations were completed with the assistance of Dr. Zhou Cao from the laboratory. SEM characterization was completed with the aid of master's student Qi Lina.

致谢

论文选题来源与研究背景

便携式电子设备、电动汽车和人工智能(AI)的快速发展以及环境保护意识的加强、当 今社会对高性能储能设备的需求日益增长。超级电容器因其快速储能和供电能力而备受关 注,但其性能提升仍面临重大挑战。在文献调研过程中,我们注意到南京大学胡征教授课题 组开发的分级结构碳纳米笼(CNC)材料表现出优异的超级电容性能,展现出巨大应用潜力。 然而,受限于双电层电容机制,CNC的能量密度有限。有报道显示,"PANI/石墨烯/PANI"三 明治结构纳米片可提高材料的比电容。受到这些进展的启发,我们拟将CNC与赝电容材料 相结合来提升整体的储能性能。近年来,利用双向冷冻技术,人们制备出具有垂直定向多孔 结构材料,这为设计具有优化离子传输通道的电极结构提供了新的思路。基于上述研究进展, 结合现有储能材料在孔结构、离子扩散和电子传输等方面的局限性,我们提出了开发基于 CNC 和 PANI 的新型分级结构电极材料的研究课题,拟采用双向冷冻技术构建垂直定向的 层状结构以提升材料的储能性能。这一选题旨在通过结构优化和材料创新,进一步提升超级 电容器的能量密度。

队员的工作与贡献

吴致远负责文献调研、概念设计、材料制备,性能测试,数据分析和论文初稿撰写等; 尤玥参与文献调研、数据分析和论文修改等过程。

指导老师

胡征,南京大学教授,是本论文的学术指导老师。他为本研究提供了理论和实验指导, 提供了论文修改意见。上述指导工作均无报酬。

其他支持

这项工作得到了南京大学介观化学教育部重点实验室的支持。COMSOL 模拟在该实验 室周操博士的协助下完成。SEM 表征在齐丽娜硕士生的协助下完成。