Construction of Three-Dimensional Homogeneous NiCo₂O₄ Core/Shell Nanostructure as High-Performance Electrodes for Supercapacitors

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A novel three-dimensional homogeneous NiCo₂O₄ core/shell nanowire arrays were first fabricated via a facile synthesis strategy on nickel foam as advanced binder-free electrodes. The structure and morphology of the as-synthesized samples have been characterized by X-ray diffraction (XRD), scanning electron microscopy (SEM), Energy dispersive X-ray spectrometry (EDS) and transmission electron microscopy (TEM). This novel NiCo₂O₄/NiCo₂O₄ core/shell nanowire arrays exhibited superior electrochemical performances, including high specific capacitance of 2041 F g⁻¹ at current density of 5 mA cm⁻², excellent rate performance with a capacitance retention of 88% as the current density increases from 5 to 50 mA cm⁻² and good long-term cyclic stability. These outstanding electrochemical characteristics are mainly attributed to the superstructure, which provides a large number of electroactive sites for redox reaction, shortens the ion diffusion paths and enhances the morphological stability in the electrochemical process. Moreover, NiCo₂O₄ can provide both nickel and cobalt ions for rich redox reactions, so it is expected to achieve higher capacitance and energy density than polymer materials. Hydrous RuO₂ exhibiting the remarkable pseudocapacitive behavior was recognized as the best electrode material for supercapacitors, but the high cost and toxicity hinder its widely commercial application. In order to reduce the cost of precious metal use, great efforts have been made to retrieving cheaper transition metal oxides with high rate and quasi-reversible of electrochemistry reaction, such as MnO₂, V₂O₅, Co₃O₄, ZnO, SnO₂, NiO and their composites. Recently, spinel nickel cobaltate (NiCo₂O₄) has been proposed as a very potential alternative for electrochemical materials of ES, because of its distinguished features of low cost and toxicity, high electrochemical response capacity, environmental friendliness and natural abundance. Moreover, compared to single-component oxides of cobalt oxide and nickel oxide, NiCo₂O₄ can provide both nickel and cobalt ions for redox reactions, so it is expected to achieve higher capacitance and electrochemical response capacity. There are intensive reports on the synthesis and electrochemical study of nanostructured NiCo₂O₄ with different morphologies and sizes. For example, Wang and coworkers synthesized one dimension of NiCo₂O₄ nanowires through polymer-assisted solution methods, which possess improved specific capacitance and cycle stability for ES. In addition, two dimensions of NiCo₂O₄ nanosheets successfully grown on the conductive substrates by a facile solution method also exhibit a very high specific capacitance of 1065 F g⁻¹ at the discharge current densities of 8.5 mA cm⁻². Owing to the well-defined and porous nanostructure can effectively increase surface areas and facilitate the ions transportation of pseudocapacitive materials in the electrochemical process, so a novel concept is mentioned that fabricating smart three-dimensional metal oxide core/shell nanowire arrays on conducting substrates as binder-free electrodes for ES. This novel core/shell architecture has a lot of advantages when used as the electrode materials for ES. First, the three-dimensional homogeneous core/shell architecture greatly enhances the surface areas that ensure a large number of electroactive sites for redox reaction. Second, the formation of rich and well-defined micro/nano-structures provides many ion transport pathways for quick electrolyte ion diffusion and electron transfer. Third, the porous core/shell nanowire arrays directly grow on the conductive substrate, which can avoid the appearance of “dead volume” in electrode materials caused by existence of polymer binder and conductive additives. Therefore, it is highly desirable to develop a kind of three-dimensional homogeneous NiCo₂O₄ core/shell materials on the conductive substrate. On the basis of the above considerations, we successfully developed a facile and cost-effective strategy to build three-dimensional homogeneous and porous NiCo₂O₄ core/shell nanowire arrays on the nickel foam. First, porous NiCo₂O₄ nanowire arrays strongly supported on nickel foam are obtained by a common hydrothermal way combined with a subsequent calcining process. Then a thin layer of porous and uniform NiCo₂O₄ nanoflakes coated on the synthesized NiCo₂O₄ nanowire arrays to form three-dimensional homogeneous NiCo₂O₄ core/shell nanowire arrays (NiCo₂O₄/NiCo₂O₄ core/shell nanowire arrays) on the surface of nickel foam through a quick electrochemical deposition process. Finally, the three-dimensional homogeneous NiCo₂O₄ core/shell nanowire arrays possess a well-defined and porous structure, which makes the electrode materials fully contract with electrolyte and facilitates the fast transport of electrons and ions in the electrochemical process. Consequently, the three-dimensional homogeneous NiCo₂O₄ core/shell nanowire arrays achieve a very high specific capacitance, excellent rate capability and cyclic stability, showing that the as-prepared NiCo₂O₄/NiCo₂O₄ core/shell nanowire arrays are huge potential for application of ES.

Experimental

Sample preparation. — All the chemicals were analytically grade and used without further purification. Prior to the synthesis, nickel foam (NF) was etched with 4 M HCl solution for 15 min, and cleaned.

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Electrochemical supercapacitors (ES) are considered as a kind of important next-generation devices in the energy storage field because of their many advantages of high rate performance, suitable ratio between power density and energy density, long life cycle. As we know, electrode materials play a key role in determining the performance of ES. Therefore, recent studies have been concentrated on developing appropriate materials with ideal characteristics of high surface area, good electrical conductivity and cycle stability for high-performance ES. To date, three major types of materials have been reported as the electrode materials for ES, including carbonaceous materials, conducting polymers and transition metal oxides/hydroxides.

Of these various materials, transition metal oxides have attracted significant attention, due to they can achieve much higher capacity of storage charge than carbonaceous materials and better cycling performance than polymer materials. Hydrous RuO₂ exhibiting the remarkable pseudocapacitive behavior was recognized as the best electrode materials, but the high cost and toxicity hinder its widely commercial application. In order to reduce the cost of precious metal use, great efforts have been made to investigating cheaper transition metal oxides with high rate and quasi-reversible of electrochemistry reaction and environmental friendliness to replace RuO₂, such as MnO₂, V₂O₅, Co₃O₄, ZnO, SnO₂, NiO and their composites. Recently, spinel nickel cobaltate (NiCo₂O₄) has been proposed as a very potential alternative for electrochemical materials of ES, because of its distinguished features of low cost and toxicity, high electrochemical response capacity, environmental friendliness and natural abundance. Moreover, compared to single-component oxides of cobalt oxide and nickel oxide, NiCo₂O₄ can provide both nickel and cobalt ions for redox reactions, so it is expected to achieve higher capacitance and electrochemical response capacity. There are intensive reports on the synthesis and electrochemical study of nanostructured NiCo₂O₄ with different morphologies and sizes. For example, Wang and coworkers synthesized one dimension of NiCo₂O₄ nanowires through polymer-assisted solution methods, which possess improved specific capacitance and cycle stability for ES. In addition, two dimensions of NiCo₂O₄ nanosheets successfully grown on the conductive substrates by a facile solution method also exhibit a very high specific capacitance of 1065 F g⁻¹ at the discharge current densities of 8.5 mA cm⁻². Owing to the well-defined and porous nanostructure can effectively increase surface areas and facilitate the ions transportation of pseudocapacitive materials in the electrochemical process, so a novel concept is mentioned that fabricating smart three-dimensional metal oxide core/shell nanowire arrays on conducting substrates as binder-free electrodes for ES. This novel core/shell architecture has a lot of advantages when used as the electrode materials for ES. First, the three-dimensional homogeneous core/shell architecture greatly enhances the surface areas that ensure a large number of electroactive sites for redox reaction. Second, the formation of rich and well-defined micro/nano-structures provides many ion transport pathways for quick electrolyte ion diffusion and electron transfer. Third, the porous core/shell nanowire arrays directly grow on the conductive substrate, which can avoid the appearance of “dead volume” in electrode materials caused by existence of polymer binder and conductive additives. Therefore, it is highly desirable to develop a kind of three-dimensional homogeneous NiCo₂O₄ core/shell materials on the conductive substrate.

On the basis of the above considerations, we successfully developed a facile and cost-effective strategy to build three-dimensional homogeneous and porous NiCo₂O₄ core/shell nanowire arrays on the nickel foam. First, porous NiCo₂O₄ nanowire arrays strongly supported on nickel foam are obtained by a common hydrothermal way combined with a subsequent calcining process. Then a thin layer of porous and uniform NiCo₂O₄ nanoflakes coated on the synthesized NiCo₂O₄ nanowire arrays to form three-dimensional homogeneous NiCo₂O₄ core/shell nanowire arrays (NiCo₂O₄/NiCo₂O₄ core/shell nanowire arrays) on the surface of nickel foam through a quick electrochemical deposition process. Finally, the three-dimensional homogeneous NiCo₂O₄ core/shell nanowire arrays possess a well-defined and porous structure, which makes the electrode materials fully contract with electrolyte and facilitates the fast transport of electrons and ions in the electrochemical process. Consequently, the three-dimensional homogeneous NiCo₂O₄ core/shell nanowire arrays achieve a very high specific capacitance, excellent rate capability and cyclic stability, showing that the as-prepared NiCo₂O₄/NiCo₂O₄ core/shell nanowire arrays are huge potential for application of ES.

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by ultrasonication in absolute ethanol and deionized water for 15 min each. NiCo$_2$O$_4$ nanowire arrays were synthesized on nickel foam by a simple hydrothermal method. First, 2.5 mmol of NiCl$_2$·6H$_2$O, 5 mmol of CoCl$_2$·6H$_2$O and 7 mmol of CO(NH$_2$)$_2$ were dissolved in 60 mL of deionized water at room temperature to form a clear pink solution. The mixture was transferred into an 80 mL stainless steel autoclave and the pretreated nickel foam substrate (3.0 cm × 7.0 cm) was immersed into it. Then the autoclave was heated to 120 °C and maintained at the temperature for 5 h in an electric oven. After the autoclave was naturally cooled down to room temperature, the obtained sample supported on the nickel foam was carefully rinsed several times with deionized water and ethanol, dried at 60 °C for 4 h and calcined at 350 °C for 2h in air atmosphere.

The final product was synthesized via a facile electrodeposition method with the three-electrode setup. The as-prepared NiCo$_2$O$_4$ nanowire arrays supported on nickel foam were directly used as working electrode. The saturated calomel electrode (SCE) and platinum foil were served as reference electrode and the counter, respectively. The deposition was performed in the potential range from −0.8 to −1.5 V (vs. SCE) for 20 cycles at the constant rate of 20 mV s$^{-1}$ in an aqueous electrolyte of 3 mmol Ni(NO$_3$)$_2$·6H$_2$O and 6 mmol Co(NO$_3$)$_2$·6H$_2$O. The samples were rinsed thoroughly with deionized water and alcohol. After dried in a vacuum oven at 60 °C for 4 h, the precursor were annealed at 350 °C for 2 h. The loading mass of the NiCo$_2$O$_4$ nanowires and NiCo$_2$O$_4$/NiCo$_2$O$_4$ core/shell nanowire arrays on nickel foam was about 3.1 and 4.01 mg cm$^{-2}$, respectively.

**Characterizations.**—The crystal structure of the samples were determined by X-ray diffraction (XRD, Rigaku TTR-III) equipped with a Cu Kα radiation source ($\lambda = 0.15406$ nm). The morphology and microstructure of the materials were studied by scanning electron microscopy (SEM; JEOL JSM-6480A microscope) and transmission electron microscopy (TEM; Philips CM200 FEG, 160 kV). The chemical composition was analyzed by a Thermo-NORAN energy X-ray dispersive spectrometry (EDS).

**Electrochemical measurements.**—A three-electrode system was applied to measure the electrochemical performances of all the samples using a CHI 660D electrochemical workstation. The as-prepared NiCo$_2$O$_4$ nanowires and NiCo$_2$O$_4$/NiCo$_2$O$_4$ core/shell nanowire arrays on nickel foam (1 cm × 1 cm) directly used as the working electrode, platinum foil and a saturated calomel electrode (SCE) were used as a counter electrode and reference electrode, respectively. The 2.0 M KOH aqueous solution was used as the electrolyte. Cyclic voltammetry (CV) tests were performed between −0.1 and 0.7 V (vs. SCE) at scan rates of 5, 10, 20, 50 mA s$^{-1}$. Galvanostatic charge/discharge measurements were carried out in the potential range of −0.1 to 0.55 V (vs. SCE) at the current densities of 5, 10, 20, 50 mA cm$^{-2}$. Electrochemical impedance spectrometry (EIS) tests were measured in the frequency range from 0.01 Hz to 100 kHz at the open circuit potential with the AC voltage amplitude of 5 mV. The specific capacitance is calculated from the galvanostatic discharge curves based on the following equation:

$$C = \frac{I \times \Delta t}{\Delta V \times m}$$  \[1\]

where $C$ represents the specific capacitance (F g$^{-1}$), $I$ (mA) is the discharging current, $\Delta t$ (s) is the total discharging time, $\Delta V$ (V) is the discharging potential range and $m$ (mg) is the total mass of the active materials on nickel foam.

**Results and Discussion**

**Material characterization.**—The XRD patterns of the NiCo$_2$O$_4$ nanowires and NiCo$_2$O$_4$/NiCo$_2$O$_4$ core/shell composite supported on nickel foam are shown in Fig. 1. The three strong peaks with marked 2θ values of 31.1°, 36.6°, 59.1° and 64.9° can be clearly observed and well indexed to the (220), (311), (511) and (440) planes of the spinel NiCo$_2$O$_4$ phase (JCPDS card no. 20-0781). As similar with the pattern of NiCo$_2$O$_4$ nanowires, the peaks of core/shell NiCo$_2$O$_4$/NiCo$_2$O$_4$ nanowire arrays can be indexed with spinel NiCo$_2$O$_4$ phase, indicating that the shell material is also NiCo$_2$O$_4$ and the crystal structure of NiCo$_2$O$_4$ nanowire is not influenced by electrodeposition reaction.

The morphologies of the NiCo$_2$O$_4$ nanowires and the NiCo$_2$O$_4$/NiCo$_2$O$_4$ core/shell nanowire arrays were observed by SEM. Fig. 2a shows the different magnification SEM image of the NiCo$_2$O$_4$ nanowires. As can be seen from Fig. 2a, the high-density nanowires grown uniformly on the nickel foam, forming aligned nanowire arrays with an open structure and serving as backbone for further growing NiCo$_2$O$_4$ nanoflakes. Figs. 2b and 2c illustrate that the surface of the NiCo$_2$O$_4$ nanowire arrays was fully covered by the ultrathin NiCo$_2$O$_4$ nanoflakes, forming a layer of nanoflower-like NiCo$_2$O$_4$ after the electrodeposition process. The nanoflakes were interconnected with each other forming a highly porous core/shell structure. In addition, the Energy dispersive X-ray spectrometry (EDS) mapping analysis shows that the atomic ratio of Ni to Co is close to 1 : 2 in the shell (Fig. 2d), consistent with the stoichiometric ratio of NiCo$_2$O$_4$. The EDS result further confirms that the core/shell NiCo$_2$O$_4$/.
NiCo$_2$O$_4$ structure has been successfully constructed. In such a unique structure, the space between the NiCo$_2$O$_4$ nanowires are well utilized, which would greatly increase the amount of electroactive sites for Faradaic reactions and enhance the electrochemical performance.

The microstructure and morphology of the NiCo$_2$O$_4$ nanowires and the core/shell NiCo$_2$O$_4$/NiCo$_2$O$_4$ nanowire arrays were further investigated by TEM and High-resolution TEM (HRTEM). The typical TEM image of an individual NiCo$_2$O$_4$ nanowire is shown in Figs. 3a and 3b. As Fig. 3b shows, the NiCo$_2$O$_4$ nanowire with an average diameter of 100~200 nm is constructed by numerous interconnected nanoparticles with sizes of 20~50 nm and there are a large number of mesopores inside of the NiCo$_2$O$_4$ nanowire. The HRTEM image shown in Fig. 3c obviously reveals that the spacing of the lattice fringes is ca. 0.469 nm, which can be indexed to the (111) plane of NiCo$_2$O$_4$ nanowire. From Figs. 3d and 3e, it is clearly observed that the porous NiCo$_2$O$_4$ nanowire is enclosed with ultrathin NiCo$_2$O$_4$ spinel NiCo$_2$O$_4$ phase. From Figs. 3d and 3e, it is clearly observed that the porous NiCo$_2$O$_4$ nanowire is enclosed with ultrathin NiCo$_2$O$_4$ spinel NiCo$_2$O$_4$ phase. The mesoporous structure of both the core and shell facilitates the electrolyte transport and diffusion within the electrodes.

**Electrochemical behavior.—** To investigate the electrochemical performance of the as-obtained NiCo$_2$O$_4$ nanowires and the core/shell NiCo$_2$O$_4$/NiCo$_2$O$_4$ nanowire arrays, cycle voltammetry (CV), galvanostatic charge-discharge and electrochemical impedance spectroscopy (EIS) tests were carried out in a 2 M KOH aqueous solution using a three electrode system at room temperature.

Fig. 4a shows the CV curves of the NiCo$_2$O$_4$ nanowires and NiCo$_2$O$_4$/NiCo$_2$O$_4$ core/shell nanowire arrays at a scan rate of 5 mV s$^{-1}$. Clearly, a pair of well-defined redox peaks is visible in both curves, indicating the pseudocapacitive characteristic of the sample. The redox peaks are mainly attributed to the Faradaic reactions related to M-O/M-O-OH (M refers to Ni or Co ions) associated with anions OH$^-$.

By comparison, the integrated area of CV curve for core/shell NiCo$_2$O$_4$/NiCo$_2$O$_4$ electrode measured at scan rates of 5~50 mV s$^{-1}$ in the potential range from $-0.1$ to $0.7$ V (vs. SCE). As the scan rates increase from 5 to 50 mV s$^{-1}$ the electrochemical polarization makes the anodic peaks shift to positive potential and the cathodic peaks shift to negative potential. However, the CV curves are not significantly changed by increasing the scan rate, indicating the good electrochemical reversibility of the core/shell NiCo$_2$O$_4$/NiCo$_2$O$_4$ electrode.

Galvanostatic charge/discharge tests were performed to calculate the capacitance of the NiCo$_2$O$_4$ nanowires and core/shell NiCo$_2$O$_4$/NiCo$_2$O$_4$ electrodes. Fig. 4c shows the charge/discharge profiles of the NiCo$_2$O$_4$ nanowires and core/shell NiCo$_2$O$_4$/NiCo$_2$O$_4$ electrodes at a current density of 5 mAh cm$^{-2}$ between $-0.1$ and 0.55 V (vs. SCE). It can be observed that the core/shell NiCo$_2$O$_4$/NiCo$_2$O$_4$ electrode shows higher discharging time than the NiCo$_2$O$_4$ nanowires electrode and the discharge curve exhibits typical pseudocapacitor behavior, which is consistent with the CV curves. The specific capacitance of the core/shell NiCo$_2$O$_4$/NiCo$_2$O$_4$ electrode was calculated to be 2041 F g$^{-1}$ according to the equation 1, which is much higher than the NiCo$_2$O$_4$ nanowires electrode (1274 F g$^{-1}$). Fig. 4d shows the constant current charge/discharge profiles of the core/shell NiCo$_2$O$_4$/NiCo$_2$O$_4$ electrode at various current densities ranging from 5 to 50 mAh cm$^{-2}$, respectively. At different current densities, all the charge/discharge curves are nearly symmetric without obvious internal resistance (IR) drops, indicating the high coulombic efficiency of the special core/shell NiCo$_2$O$_4$/NiCo$_2$O$_4$ electrode. To investigate the rate performance of the products, the calculated specific capacitance as a function of the discharge current density was plotted in Fig. 5a. The specific capacitance of the core/shell NiCo$_2$O$_4$/NiCo$_2$O$_4$ nanowire arrays is as high as 2041, 1976, 1869, 1834, 1788 F g$^{-1}$ at the discharge current densities of 5, 10, 20, 30 and 50 mAh cm$^{-2}$, respectively, which are much higher than the NiCo$_2$O$_4$ nanowire (1274, 1235, 1151, 1086, 942 F g$^{-1}$ at the discharge current densities of 5, 10, 20, 30 and 50 mAh cm$^{-2}$, respectively). When the current density increases from 5 to 50 mAh cm$^{-2}$, the capacitance retention of the core/shell NiCo$_2$O$_4$/NiCo$_2$O$_4$ electrode is about 88%, much higher than the NiCo$_2$O$_4$ nanowires electrode (73%), indicating that the as-synthesized NiCo$_2$O$_4$/NiCo$_2$O$_4$ core/shell nanowire arrays have better rate performance than the bare NiCo$_2$O$_4$ nanowires. It is worth noting that the results in our work are higher than various reported core/shell nanostructures, such as NiCo$_2$O$_4$@MnO$_2$ core/shell nanowire arrays (1471.4 F g$^{-1}$ at 10 mAh cm$^{-2}$), Co$_3$O$_4$@NiMoO$_4$ core/shell nanowire arrays (1230 F g$^{-1}$ at 10 mAh cm$^{-2}$), and CNT/NiCo$_2$O$_4$ core/shell structures (695 F g$^{-1}$ at 1 A g$^{-1}$). The superior rate
performance and specific capacitance might be attributed to the unique interconnected three-dimensional core/shell structure, which can greatly increase the amount of electroactive sites and shortens the diffusion paths of the electron.

The EIS tests were performed to further investigate the electrochemical behavior of the as-synthesized materials. Fig. 5b shows the Nyquist plots of the two electrodes. In the low-frequency region, the impedance plot of the core/shell NiCo$_{2}$O$_{4}$/NiCo$_{2}$O$_{4}$ electrode tends to become a vertical lines, indicating a low diffusion resistance (Warburg impedance), which can be attributed to the interconnected and porous NiCo$_{2}$O$_{4}$ nanoflakes with large surface area that have enhanced utilization of the space between the NiCo$_{2}$O$_{4}$ nanowires.

![Figure 4](image1)

![Figure 5](image2)
In the high-frequency region, the diameter of the semicircle represents the interfacial charge-transfer impedance caused by the redox reactions at the electrode/electrolyte interface and the intercept of the Nyquist plots on the Z′ axis relates to the bulk resistance. As can be seen from the Nyquist plots, the bulk resistance of the core/shell NiCo2O4/NiCo2O4 electrode is smaller than that of NiCo2O4 nanowires electrode. The results of EIS tests show that the core/shell NiCo2O4/NiCo2O4 electrode has the advantages of low diffusion resistance and fast charge transmission.

The long-term cycling stability is one of the critical factors for supercapacitor practical applications. Fig. 6 shows the long-term cyclic performances of the NiCo2O4 nanowires and core/shell NiCo2O4/NiCo2O4 electrodes evaluated by galvanostatic charge-discharge tests between -0.1 and 0.55 V at a current density of 50 mA cm\(^{-2}\) for 3000 cycles. It can be observed that the specific capacitance of the two electrodes increases gradually in the initial 500 cycles and then slowly decreases with the subsequent cycling. After 3000 cycles, the capacitance of the core/shell NiCo2O4/NiCo2O4 electrode is 1529 F g\(^{-1}\), which is still retention about 85% of its maximum capacitance (1802 F g\(^{-1}\)). This cyclic performance is superior to the NiCo2O4 nanowires electrode (74% capacitance retention after 3000 cycles) and other reported results of NiCo2O4-based nanostructures, such as Ni(OH)\(_2\)/NiCo2O4/CFP (36% capacitance retention after 1000 cycles at 5 mA cm\(^{-2}\))\(^{43}\). NiCo2O4 nanowires (81% capacitance retention after 3000 cycles at 10 A g\(^{-1}\))\(^{27}\) and NiCo2O4 nanosheets/CFP (84.4% capacitance retention after 3000 cycles at 10 A g\(^{-1}\))\(^{44}\). The stable cycling performance is attributed to the unique interconnected three-dimensional core/shell structure, which not only provides abundant surface area but also alleviates the structure damage caused by volume expansion during cycling process. In consideration of the excellent capacitive performance and the facile synthesis, the obtained three-dimensional NiCo2O4/NiCo2O4 core/shell nanowire arrays provide a great promising as electrode materials for high-performance supercapacitors.

**Conclusions**

In conclusion, a facile and extensible strategy has been developed to construct three-dimensional homogeneous NiCo2O4 core/shell nanowire arrays on Ni foam, which used as a binder-free electrode for the high-performance supercapacitors. The NiCo2O4/NiCo2O4 core/shell nanowire arrays have demonstrated a high specific capacitance of 2041 F g\(^{-1}\) at 5 mA cm\(^{-2}\) (even 1788 F g\(^{-1}\) at 50 mA cm\(^{-2}\)) and good rate performance that can retain the capacitance of 88%, when the current density increases from 5 to 50 mA cm\(^{-2}\).

Furthermore, the specific capacitance degradation is about 15% after 3000 cycles at current density of 50 mA cm\(^{-2}\), indicating a stable cycling ability. The remarkable capacitive behavior is mainly attributed to the unique interconnected three-dimensional core/shell structure, which provides a large number of electroactive sites for redox reaction, shortens the diffusion paths of the electron and alleviates the structure damage during the cycling process. These findings suggest that the three-dimensional NiCo2O4/NiCo2O4 core/shell nanowire arrays can serve as an attractive electrode material for high-performance supercapacitors.

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