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Co/Ni-MOF@MXene Electrode Material for High-performance Supercapacitor

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Abstract:
Rapid advances in the electronics industry have significantly increased the demand for high performance energy storage materials. In response, there has been a growing need in recent years to research and develop innovative materials that offer both stability and high capacity for application in sustainable energy conversion and storage systems. Large specific surface area, controllable pore pattern, tunable framework architecture, excellent electrochemical energy storage performance of MOFs. Nevertheless, in the areas of energy storage, practical applications are restricted because of their stability and structure. Herein, Co/Ni-MOF nanowires were synthesised on $Ti_3C_2T_x$ MXene by a two-step hydrothermal method. Benefitting from excellent wettability of $Ti_3C_2T_x$ MXene with the electrolyte and its high conductivity. The electrochemical exploration of Co/Ni-MOF@$Ti_3C_2T_x$ MXene composite via CV, GCD, and EIS measurements showed excellent performance. It had a specific capacitance of 1019.5 F/g at 1 A/g due to synergistic effects. The MXene's structure provided a large surface area, facilitated electron transport and ion diffusion, and enhanced activity. The composite exhibited long-term stability, retaining 75.0% capacitance after 3500 cycles at 8 A/g. The MXene structure stabilized the MOF, enhancing energy storage. Findings suggest a strategy for using MOFs as electrode materials, overcoming challenges and opening new design avenues for energy storage systems.

Keywords: MXene; Energy storage; Co/Ni metal-organic framework; Nanocomposites; Supercapacitors

INTRODUCTION

Extensive exploration of renewable and clean energy sources has been motivated by environmental pollution and global warming. Effortless energy storage devices are necessary to ensure continuous and stable energy due to the intermittent nature of renewable energy. Supercapacitors are exceptional energy storage devices that combine key attributes of traditional ion batteries and electrochemical capacitors. Traditional ion batteries are known for their relatively high energy density, which allows them to store significant amounts of electrical energy in a limited volume or mass. This characteristic is critical for devices that require sustained power over time. Supercapacitors take advantage of this property to some extent, allowing them to deliver power for longer periods of time. Electrochemical capacitors, on the other hand, have an impressive power density and are capable of rapidly charging and discharging large amounts of electrical energy. This fast response makes them ideal for applications that require quick bursts of energy, such as regenerative braking systems and certain high-power electronic circuits. Supercapacitors also benefit from this rapid charge and discharge capability, allowing them to quickly adapt to sudden changes in power demand. The fusion of these features in supercapacitors represents a distinctive solution that fills the gap between the energy storage potential of traditional ion batteries and the power delivery strengths of electrochemical capacitors, positioning them as a viable option for a wide range of energy storage needs. The performance of supercapacitors in electrochemical applications depends largely on the design and properties of the electrode materials. In essence, the structural and material properties of the electrodes are the lynchpin for optimizing the overall functionality and lifetime of the device. The investigation of supercapacitor electrodes has primarily concentrated on transition metal oxides and hydroxides, conductive polymers, materials based of carbon, and their composites. Nonetheless, these electrode materials have their own disadvantages in supercapacitor applications, such as the limited electronic conductivity and short cycle life of transition metal oxides/hydroxides, the short cycle life of conductive polymers, and materials based of carbon exhibit a low specific capacitance. Consequently, the advancement of innovative electrode materials with elevated specific capacities, extensive surface areas, and enhanced electronic conductivity has garnered significant attention from researchers.

However, the electrochemical applications of conventional MOFs are severely hampered by their poor electrical conductivity, especially in energy storage [1, 2]. In order to enhance conductivity, derivatives that are based on multifunctional MOFs have received much attention. One way to develop MOFs that are highly conductive is by adjusting their structure and composition. Porous carbon and species transition metal compounds are prepared using MOFs as excellent precursors, which can be achieved through careful selection of organic linkers and metal nodes, as well as optimization of synthesis conditions such as temperature, solvent, and reaction time. By incorporating conductive components like conjugated organic ligands or redox-active metal centers, and by controlling the framework's porosity and crystallinity, researchers can enhance the charge transport properties of MOFs, making them suitable for applications in energy storage, catalysis, and electronic devices. Additionally, MOFs serve as excellent precursors for the preparation of porous carbon materials and transition metal compounds due to their well-defined structures, high surface areas, and tunable chemical compositions. Through pyrolysis or chemical treatment, MOFs can be transformed into highly porous carbon frameworks or metal-based composites, which retain the structural advantages of the parent MOFs while gaining enhanced electrical conductivity, chemical stability, and catalytic activity. These derived materials are widely used in supercapacitors, batteries, and electrocatalysis, demonstrating the versatility and potential of MOFs as advanced functional materials. Another effective strategy to enhance the electrica conductivity of MOFs is to synthesize them on conductive substrates, which can significantly improve their performance in various applications. This approach exploits the inherent properties of highly conductive substances like CNTs, graphene, polypyrrole, polyaniline to create hybrid structures with superior electrical properties. For example, the integration of MOFs with CNTs not only provides a robust conductive network, but also enhances the structural stability of the resulting composite. Graphene, renowned for its outstanding electrical conductivity and expansive surface area, acts as a perfect foundation for the development of MOFs. This synergy not only enhances charge transfer efficiency but also significantly boosts the overall electrochemical performance. In addition, conductive polymers such as polypyrrole and polyaniline offer unique advantages due to their tunable conductivity and compatibility with MOF structures, enabling the development of materials tailored for specific applications such as energy storage, catalysis or sensing. By combining the porosity and functional versatility of MOFs with the high conductivity of these substrates, researchers can design advanced materials that overcome the limitations of traditional MOFs, opening avenues for creative solutions across various domains, including electronics and environmental science.

MXene has recently gained prominence as a highly promising material for energy storage, especially in the creation of cutting-edge supercapacitor electrodes. This growing interest is largely due to its unique combination of properties, featuring outstanding metallic conductivity, an exceptionally high specific surface area, and elevated packing density. These properties make MXene an ideal candidate for enhancing the performance of supercapacitors, which are critical components in advanced energy storage systems. MXene's metallic conductivity ensures efficient electron transport, minimizing energy losses and improving charge-discharge rates. In addition, the high packing density of MXene enables the fabrication of compact and lightweight electrodes, which are essential for applications in portable electronics and electric vehicles. As a result, MXene has attracted considerable attention from researchers worldwide, leading to numerous studies exploring its synthesis, functionalization, and integration into next-generation energy storage devices. For example, recent advances have demonstrated that MXene-based electrodes can achieve remarkable energy densities while maintaining excellent cycling stability, further solidifying.

In this study, a Co/Ni-based MOF was prepared using a single hydrothermal process protocol. This method was chosen for its ability to produce highly crystalline and structurally uniform materials under controlled conditions. To further enhance structural 、 functional characteristics of Co/Ni-MOF, multilayer MXene was strategically incorporated as a structural framework. This integration enabled the in situ preparation of the Co/Ni-MOF, resulting in the development of a unique layered microstructure characterised by three-dimensional (3D) interconnected networks. The incorporation of MXene not only provided mechanical stability, but also facilitated efficient electron and ion transport within the hybrid material. The addition of even a minimal amount of multilayer MXene significantly altered the microstructure of the Co/Ni MOF, resulting in a synergistic enhancement of its electrochemical properties. In particular, the specific capacitance and overall electrochemical performance of the complexed material were markedly enhanced, primarily attributable to the optimized interfacial interaction between MXene and Co/Ni-MOF within the composite structure. This synergistic integration facilitates efficient charge transfer and ion diffusion, which are critical for achieving superior energy storage capabilities. The resulting Co/Ni-MOF@MXene nanocomposite demonstrates exceptional electrochemical properties, as evidenced by its remarkable specific capacitance of 1019.5 F/g at a current density of 1 A/g. This value significantly surpasses that of many conventional electrode materials, underscoring the material's potential for high-performance energy storage applications. Furthermore, the nanocomposite exhibits outstanding cycling stability, retaining 75.0% of its initial capacitance after 3500 charge/discharge cycles at a high current density of 8 A/g. This robust durability, even under demanding operational conditions, highlights the material's structural resilience and electrochemical reliability. Such performance metrics position the Co/Ni-MOF@MXene nanocomposite as a highly promising candidate for advanced energy storage systems, offering an optimal balance of structural integrity, electrochemical efficiency, and long-term operational stability. These attributes make it particularly suitable for applications in supercapacitors, batteries, and other energy storage devices where high capacitance, rapid charge/discharge rates, and prolonged cycle life are essential.

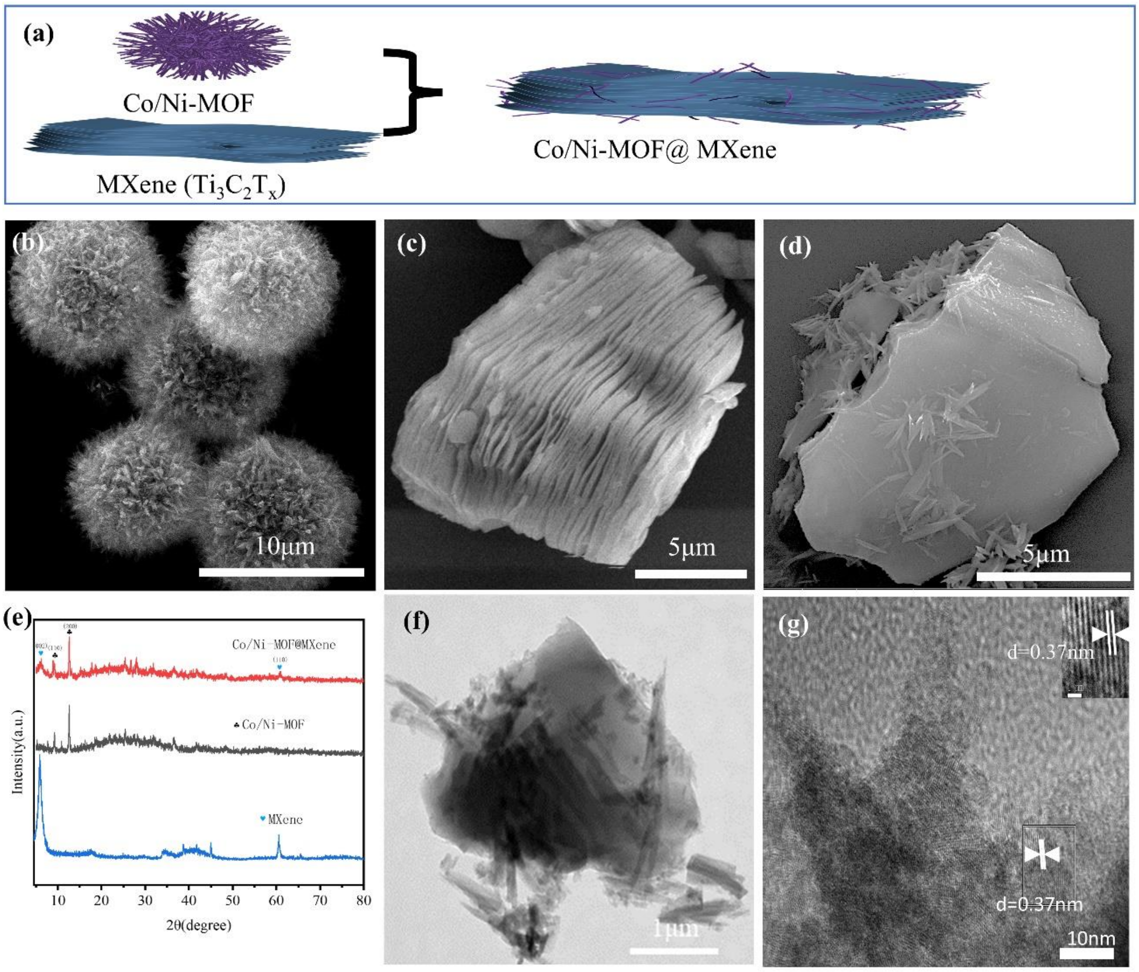

Figure 1. The material characterization of samples. (a) synthetic schematic of Co/Ni -MOF@MXene. SEM images (b) Co/Ni-MOF, (c) MXene, (d) Co/Ni-MOF@MXene. (e) XRD of Co/Ni-MOF, MXene, and Co/Ni-MOF@MXene are included, (f) TEM image of Co/Ni-MOF@MXene structure. (g) HRTEM image display the structure of Co/Ni-MOF@MXene.

EXPERIMENTAL SECTION

Reagents & Tools

$Co(NO_3)_2·6H_2O$, $Ti_3C_2T_x$ MXene, N,N-dimethylformamide (DMF), $Ni(NO_3)_2·6H_2O$, polyvinylpyrrolidone (PVP), potassium hydroxide (KOH),1,3,5-benzenetricarboxylic acid (H_3BTC), acetone, ethanol (C_2H_6O), and hydrochloric acid (HCl), All other reagents were analytically pure. A number of 1.5 cm × 2 cm nickel foams were cleaned utilizing an ultrasonic cleaning device using acetone, HCl, ethanol, Distilled water, respectively, each for 15 minutes to remove surface oils or oxide layer, The foams underwent a drying process first facilitated by a hair dryer, further drying in a vacuum oven set at 60°C. Once sufficiently dried, they were ready for use. The experimental setup consisted of several instruments, including an electronic balance 、 a magnetic stirrer, ultrasonic cleaner, polytetrafluoroethylene (PTFE) liner (50 mL), stainless steel Teflon autoclave, vacuum drying oven, (FESEM), XRD, a transmission electron microscope (TEM) setup, an x-ray photoelectron spectrometer (XPS), a CHI660e electrochemical workstation.

Prepare of Co/Ni-MOF

Figure 1（a） shows the synthetic pathway of the compound. [$Ni(NO_3)_2•6H_2O$] 、 [Co ($NO_3)_2•6H_2O$] were separated with stirring in 4 milliliters of DI water with a magnetic stirrer, with the quantities of each salt being 0.0872g. Subsequently, 0.0604 g of 1,3,5-benzenetricarboxylic acid 、0.6g of polyvinylpyrrolidone were solubilized in a mixture of 4 milliliters DMF and 4 milliliters ethanol under vigorous stirring. Aforementioned solutions were subsequently combined and stirred until a clarified mixed solution was formed. The solution was subsequently transferred into a polytetrafluoroethylene liner (50 mL) and and mixture solution experienced an increase in temperature 150°C for a while of 10 hours. The reacting medium was gradually permitted to cool to ambient temperature, ensuring a controlled and stable transition from the elevated thermal conditions under which the reaction had initially proceeded subjected to a centrifugal cleaning process, and dried, The sequential implementation of these methodological steps culminated in the successful synthesis of the Co/Ni-MOF nanosphere, a structurally intricate and functionally versatile material. Initially, the process involved the precise coordination of cobalt (Co) and nickel (Ni) metal ions with organic ligands under controlled conditions, ensuring the formation of a stable metal-organic framework (MOF). This was achieved through a solvothermal approach, wherein the reactants were dissolved in a suitable solvent and subjected to elevated temperatures, facilitating the self-assembly of the nanospheres. The spherical morphology of the resulting material was attributed to the balanced interplay of metal-ligand coordination, solvent polarity, and reaction kinetics, which collectively promoted the growth of uniform, nanoscale structures.

Prepare of Co/Ni-MOF@MXene Nanocomposites

Co/Ni-MOF@MXene composite material was prepared anew based on the MXene accordion structure, which was procured from xin xi ke ji. The Co/Ni-MOF precursor solution was prepared in the same way as before, and the purchased 450 mg multilayer MXene was dispersed and dissolved in above solution. The reaction was transferred into a polytetrafluoroethylene (PTFE) liner (50 mL) and procedure was subjected to a reaction at 150 °C during 10 hours in a closed high-pressure reactor. Subsequently, naturally cooled to room temperature in order to collect the Co/Ni-MOF@MXene by means of centrifugation. The item underwent a washing process: DMF and ethanol each had three washes, after which it was placed for 12 hours in a vacuum drying oven at 60°C. Upon weighing, average mass of Co/Ni-MOF@MXene product was found to be 0.09 g.

The prepared Co/Ni-MOF, Co/Ni-MOF@MXene were then blended with conductive carbon black、 PVDF with a precise mass ratio 8:1:1, The mixture was subsequently ground with a mortar to ensure thorough integration, followed by the addition of N-methyl-2-pyrrolidone (NMP). The slurry was then stirred for a duration of three hours to yield a coating solution. The slurry was applied individually to the nickel foam, the nickel foam was then dried in a vacuum oven at 60°C for an overnight period.The dried nickel foam was compressed for 30 seconds at a pressure of 10 MPa to form a thin sheet. Two distinct types of nickel foam sheets, each impregnated with one of the two pre-synthesized compounds, were employed as working electrodes in the experimental setup.

RESULTS AND DISCUSSION

In this article, SEM images taken at various magnifications provide a detailed visualization of the morphological features of Co/Ni-MOF, MXene, hybrid structure, Co/Ni-MOF@MXene. As shown in Figure 1(b), the morphology of the Co/Ni-MOF is displayed, revealing its distinct features. which exhibits a spherical structure with a single unit. Charge transport and ion diffusion can be facilitated by this spherical morphology. These SEM micrographs are instrumental in elucidating the structural properties of the materials under investigation, thereby contributing to a comprehensive understanding of their potential applications in the field of materials science, The SEM image of a multilayer MXene in Figure 1(c) clearly shows the character layer-like structure of MXene. Figure 1(d) presents SEM micrographs of Co/Ni-MOF@MXene composite, where introduction of multilayer MXene resulted in the dispersion of Co/Ni-MOF in the form of nanowires, rather than the conventional spherical morphology. This modification markedly enhanced both the surface area and the number of active sites available in the material. In other words, it gave the material a boost in its surface exposure and functional sites, making it more effective. The composite comprises open $Ti_3C_2T_X$ flakes and Co/Ni-MOF in a wire-like configuration, exhibiting a uniform distribution. A test range from 5 to 90° is shown in the XRD maps in Figure 1(e).XRD spectrum of Co/Ni MOF is indistinguishable from Ni-MOF[3], the data reveals two significant peaks at 9.2° and 12.62°, the peak at 9.2° is associated with the (1 1 0) plane; while the peak at 12.62° corresponds to the (2 0 0) plane. Sharp diffraction peaks on the Co/Ni-MOF are clearly visible, suggesting that it has an excellent crystal structure, the successful incorporation of MXene into Co/Ni-MOF@MXene was evidenced by the appearance of diffraction peaks characteristic of MXene. The photograph taken by TEM showing the composite can be found in the snapshot labeled Figure 1(f). It reveals that Co/Ni-MOF is distributed as scattered tiny rods on $Ti_3C_2T_x$. The polycrystalline structure of Co/Ni-MOF@MXene is visible in the HR-TEM picture (Figure1(g)). Fast Fourier transform (FFT) diffraction patterns indicate that $Ti_3C_2T_x$ (002) has planes with a lattice spacing of approximately 0.37nm.

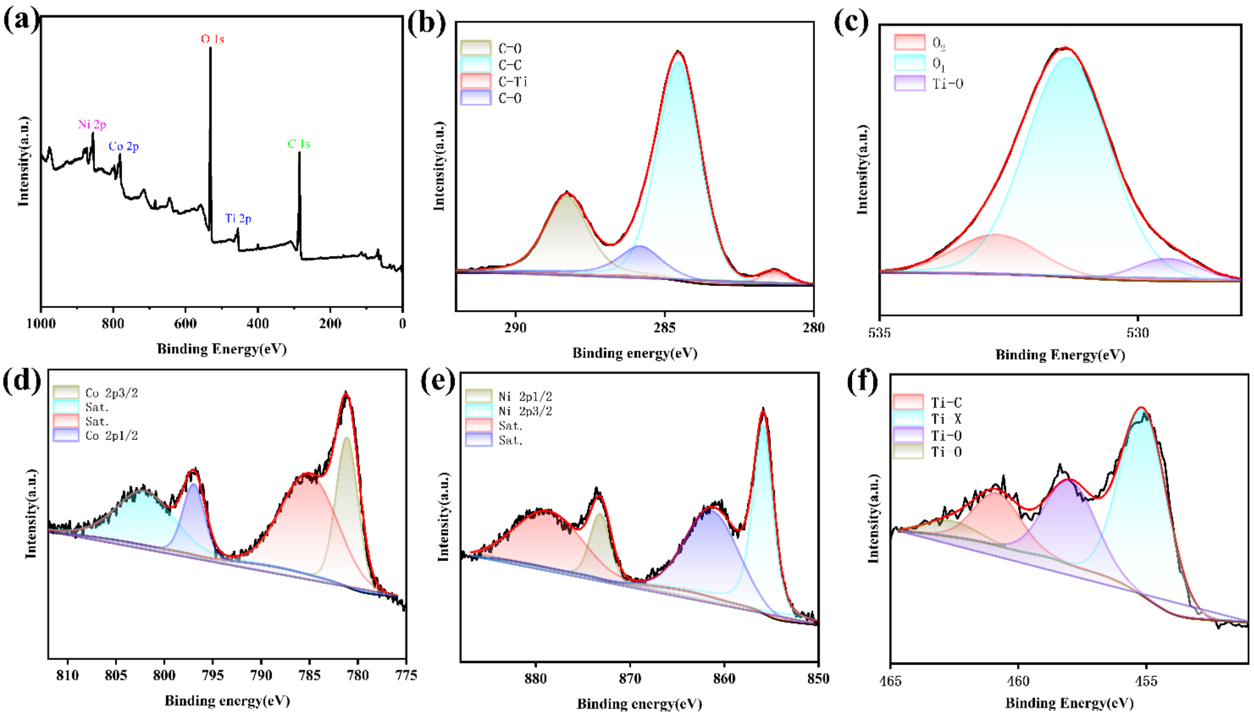

Figure 2. XPS element determination spectrum of Co/Ni-MOF@ MXene; (a) Total spectrum; (b) spectrum of C1s; (c) spectrum of O1s (d) Co2p; (e) Ni2p; (d) Ti2p.

The in - depth analysis, carried out with meticulous precision and following rigorous scientific protocols, revealed that the elements nickel (Ni), cobalt (Co), and oxygen (O) are fundamental and indispensable components of the Co/Ni-metal-organic framework (Co/Ni-MOF). These elements play crucial roles in defining the structure and properties of the Co/Ni-MOF, contributing to its unique chemical and physical characteristics. For instance, nickel and cobalt often participate in the coordination bonds that form the framework structure of the MOF, while oxygen is involved in various chemical interactions within the material. Shifting the focus to the C1s spectrum, as depicted in Figure 2(b), Each of these chemical bonds can be uniquely identified by their characteristic binding energies. Specifically, at 281.3 eV, the C-Ti bond is detected. This bond is a result of the interaction between carbon atoms from the MXene layer and titanium atoms, which is crucial for the interface formation between the MXene and other components of the composite. The binding energy of 284.5 eV corresponds to the C-C bond, which is a common feature in carbon-based materials and reflects the carbon - carbon backbone structure within the MXene or other carbon-containing moieties. The C-O bond, with a binding energy of 285.8 eV, indicates the presence of oxygen functional groups attached to carbon atoms. This could be due to surface oxidation or the incorporation of oxygen - containing species during the synthesis process. Finally, the C=O bond at 288.3 eV suggests the presence of carbonyl groups, which can significantly influence the material's surface chemistry and reactivity. Figure 2(c), the appearance of peaks at specific binding energies provides valuable information about the chemical states of the elements. The peak at 529.5 eV indicates the presence of Ti-O bonds. These bonds are integral to the structure of the MXene - based composite, as they contribute to the stability and functionality of the material. The hydroxyl oxygen, represented by the peak at 531.4 eV, is often associated with surface - bound water molecules or the presence of hydroxide groups on the material's surface. These hydroxyl groups can participate in various chemical reactions, such as proton transfer or adsorption of other species. The peak at 532.9 eV corresponds to adsorbed oxygen species, which can be important for processes such as catalysis or sensing applications. The Co 2p XPS spectrum in Figure 2(d), two primary peaks are clearly observed at 781.1 eV and 796.9 eV, which are attributed to Co 2p$_{3/2}$ and Co 2p$_{1/2}$, respectively. These peaks are characteristic of the electronic states of cobalt in the Co/Ni - MOF. The additional satellite peaks, appearing at 785.2 eV and 802.3 eV, provide further insights into the electronic structure of cobalt. Similarly, in Figure 2(e), the Ni 2p spectrum shows prominent peaks at 855.9 eV and 873.2 eV, corresponding to Ni 2p$_{3/2}$ and Ni 2p$_{1/2}$, respectively. Alongside these primary peaks, broader satellite features at 861.5 eV and 879.1 eV are also present. These satellite features are characteristic of the nickel species in the Co/Ni - MOF and can help in determining the oxidation state and chemical environment of nickel. Figure 2(f) highlights the Ti 2p spectrum. Peaks at 455.2 eV, 458.1 eV, and 460.9 eV represent Ti-X (where X could be carbon or other elements in the MXene structure) and Ti-O bonds. These bonds are essential for maintaining the integrity of the MXene layer and its interaction with other components of the composite. The peak at 462.9 eV is consistent with the Ti 2p1/2 state, further confirming the presence of Ti-C and Ti-O bonds. The X - ray photoelectron spectroscopy (XPS) analysis performed in this study offers a comprehensive and in - depth insight into the elemental composition and chemical states of Co/Ni-MOF@MXene. In energy storage applications, understanding the elemental composition and bonding can lead to the development of better-performing electrodes. Overall, this XPS analysis serves as a cornerstone for further research and development of Co/Ni-MOF@MXene - based materials.

Electrochemical Studies

The reference electrode was Hg/HgO, the counter electroade was a Pt mesh (area, 2.0 × 2.0 cm^2), and the working electrode was sample-coated nickel foam. The electrochemical characteristics of Co/Ni-MOF, Co/Ni-MOF@MXene were determined of cyclic voltammetry (CV) technique, which was employed using scanning rates that varied between 5 and 40 mV/s. GCD tests were carried out at certain current densities, 3500 consecutive GCD cycles were also performed using the same working solution, as well as electrochemical impedance tests.

The prepared Co/Ni-MOF and Co/Ni-MOF@MXene materials were subjected to evaluation within a 3.0 M KOH solution. This particular solution was chosen due to its widespread use in electrochemical studies and its compatibility with the materials under investigation. In the context of cyclic voltammetry (CV) analysis, as depicted in Figure 3(a), the integration area of the CV plots serves as a crucial parameter for assessing the electrochemical behavior of the materials. The CV plots were obtained by scanning the potential of the working electrode within a specific range at a constant scan rate. In this case, a scan rate of 10 millivolts per second was maintained for both Co/Ni-MOF and Co/Ni-MOF@MXene to ensure a fair comparison. When examining the integration area of the closed curves in the CV plots, it becomes evident that Co/Ni-MOF@MXene occupies a significantly larger area compared to Co/Ni-MOF. This difference in the integration area is indicative of the enhanced electrochemical activity of Co/Ni-MOF@MXene. The introduction of MXene into the Co/Ni-MOF structure plays a pivotal role in enhancing its performance. Specifically, the appropriate amount of multilayer MXene incorporated into Co/Ni-MOF@MXene contributes to an increase in the specific surface area of the composite material. The specific surface area is a key factor in determining the number of active centers available for electrochemical reactions. With a larger specific surface area, more active sites are exposed, facilitating a greater number of charge transfer processes. This, in turn, directly impacts the electrochemical performance of the material, as demonstrated by the larger integration area in the CV plots of Co/Ni-MOF@MXene. Figure 3(b) presents the graphical representation of these processes for both Co/Ni-MOF and Co/Ni-MOF@MXene, conducted at a current density of 1 A/g. The charge–discharge curves provide valuable insights into the capacitive behavior of the materials. In this experiment, Co/Ni-MOF@MXene exhibits a notably longer discharge time compared to Co/Ni-MOF. This extended discharge time is a clear indication of the excellent capacitive performance of Co/Ni-MOF@MXene. By calculating the specific capacitance using a well-established formula, which takes into account various parameters such as the discharge time, current density, and mass of the electrode material, the specific capacitance of Co/Ni-MOF@MXene was determined to be 1019.5 F/g. This value is a testament to the high capacitance capabilities of the composite material. Figure 3(c) further explores the charge-discharge performance of the Co/Ni-MOF@MXene composite at varying current densities, ranging from 1 A/g to 5 A/g. This investigation is essential for understanding the behavior of the material under different operating conditions. As the current density increases, the specific capacitance of the Co/Ni-MOF@MXene composite shows a decreasing trend. The specific capacitance values were determined to be 1019.5 F/g at 1.0 A/g, 989 F/g at 2.0 A/g, 775.5 F/g at 3.0 A/g, 611 F/g at 4.0 A/g, and 466.3 F/g at 5.0 A/g. This decline in specific capacitance with increasing current density can be primarily attributed to the poor utilization of active materials under high current density conditions. At higher current densities, the charge transfer processes occur at a faster rate, leading to a situation where not all of the active materials can participate fully in the electrochemical reactions.

The cyclic voltammetry characteristics of the material at various scan rates are depicted in Figure 3(d). The scan rates employed in this study include 5mV/s, 10mV/s, 20mV/s, 30mV/s, 40mV/s, with the scan voltages spanning from -0.2 to 0.8 V. As the scan rate increases, several notable trends can be observed. Firstly, the redox current experiences a steady increase. This increase in redox current is associated with the enhanced rate of charge transfer processes at higher scan rates. Secondly, the redox peaks exhibit a progressive shift in timing. This shift in the redox peaks indicates that the electrochemical reactions are occurring at different rates as the scan rate changes. Overall, these observations suggest that a good reversible redox reaction occurs at this electrode, which is a desirable characteristic for materials used in electrochemical applications. The long-term stability of the electrode material is another crucial aspect of its performance. As shown in Figure 3(e), after 3500 cycles, the electrode composed of Co/Ni-MOF@MXene maintained a capacitance retention exceeding 75.0% when subjected to a current density of 8.0 A/g.

This high capacitance retention after a large number of cycles demonstrates the excellent durability and stability of the Co/Ni-MOF@MXene electrode. Such stability is essential for practical applications, as it ensures that the material can maintain its performance over an extended period of use. The Nyquist diagram, presented in Fig. 3(f), provides valuable information about the electrical properties of the materials. The Nyquist diagram consists of semicircles and straight lines, each of which corresponds to different electrical processes occurring within the electrode. After adding MXene to the Co/Ni-MOF structure, several significant changes can be observed in the Nyquist diagram. Specifically, the intersection point on the real axis decreases significantly, and the radius of the semicircle in the high frequency region decreases gradually. These changes are indicative of a decrease in the solution resistance (R_s) and the charge transfer resistance (R_{ct}). The values of the intersection points on the real axis for the Co/Ni-MOF and Co/Ni-MOF@MXene electrodes are 1.49 Ω and 0.79 Ω, respectively, reflecting the higher internal resistance of the MOFs. Moreover, the charge transfer resistance for the Co/Ni-MOF@MXene electrodes is 1.43 Ω, which is lower than that for the pure Co/Ni-MOF electrodes (3.77 Ω). This reduction in charge transfer resistance indicates the improved conductivity of Co/Ni-MOF@MXene. The enhanced conductivity of the composites can be attributed to the successful integration of MXene, which provides an additional pathway for charge transfer within the material.

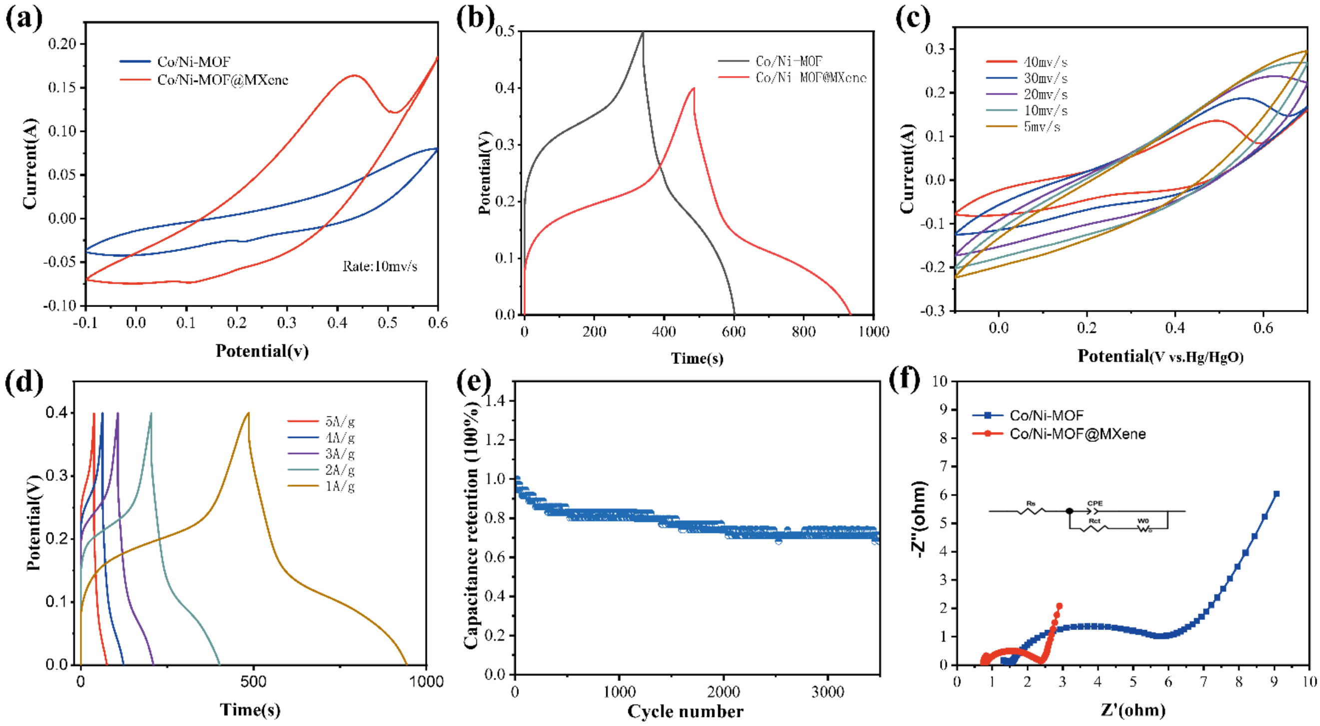

Figure 3. Electrochemical studies of samples, (a) CV profiles for Co/Ni-MOF, Co/Ni-MOF@MXene with 10 mV s^{-1}. (b) GCD profiles of two samples with 1 A g^{-1}. (c) CV plots of Co/Ni-MOF@MXene. (d) GCD profiles for Co/Ni-MOF@MXene. (e) stability of Co/Ni-MOF@MXene at 8A/g. (f) Nyquist diagrams comparing Co/Ni-MOF with Co/Ni-MOF@MXene.

A comparison of the capacitance of our product with that of nickel-cobalt and MXene-based materials can be found in Table 1. The following elements contribute to this effect: the Co/Ni-MOF and MXene create a synergistic structural combination, improving the composite structure's electrical conductivity is accomplished. The superior electrochemical properties are primarily due to the synergistic interaction between the multilayer MXene and Co/Ni-MOF nanowires. First, the growth of Co/Ni-MOF nanowires on MXene as a substrate forms a spatial three-dimensional structure thereby enhancing the availability of electroactive sites and reducing the ionic diffusion path, and maximizing the active surface area of the material, which results in a rise in specific capacitance [3]. Secondly, The layered material is distributed without overlap to ensure complete interaction with the electrolyte, increasing ion transfer efficiency[4, 5].

Table 1. Comparative analysis of capacitance values for our product against various Co/Ni and Ti3C2Tx (MXene) derived materials found in existing references.

Electrode materials	Current density	Specific capacitance	Reference
Co/Ni-MOF@MXene	1 A g^{-1}	1019.5 F g^{-1}	This work
N-$Ti_3C_2T_x$-0.5	0.5 A g^{-1}	332 F g^{-1}	[6]
$Ni/Co(OH)_2$	1 A g^{-1}	990.91 F g^{-1}	[7]
coral-like Ni/Mn-MOFs	1 A g^{-1}	531.5 F g^{-1}	[8]
$CoP@Ni_2P$	1 A g^{-1}	776.8 F g^{-1}	[9]
Ni-CoP@C@CNTs	1 A g^{-1}	708.1 F g^{-1}	[10]

CONCLUSION

In this study, the Co/Ni-MOF@MXene composites were successfully prepared via a secondary hydrothermal method. The structure displayed superior specific capacitance of 1019.5 F/g at 1 A/g along with a notable cycling stability of 75.0% over 3500 cycles at a high current density of 8.0 A/g. These excellent electrochemical properties all benefit from the synergistic effect of multilayer $Ti_3C_2T_x$ MXene and bimetallic Co/Ni-MOF. Thus, by utilizing the abundant and inexpensive reserves of cobalt and nickel, coupled with the advantages of simple synthesis, easy handling, and remarkable specific capacitance, Co/Ni-MOF@MXene composites emerge as promising candidates for supercapacitor electrodes with commendable practical utility and considerable growth potential. The impressive electrochemical performance of Co/Ni-MOF@MXene electrode material shows great potential for high-performance supercapacitor applications.

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