Innovative TiNiTex/Mn_3O_4/MXene Electrode Fabrication for Enhanced Supercapacitor Performance

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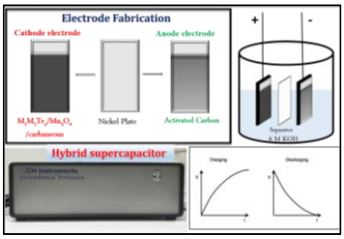

This study was focused on developing a novel electrode material for high-performance supercapacitors, comprising $TiNiTe_x$, Mn_3O_4, and MXene. These materials were integrated to enhance electrochemical performance, in order to meet the increasing demand for efficient energy storage solutions. The synthesis process involved a careful optimization to achieve a well-defined microstructure and desirable electrochemical properties. The fabricated $TiNiTe_x/Mn_3O_4$/MXene electrode demonstrated promising results, exhibiting a specific capacitance of 964 F g^{-1} at a current density of 1 A g^{-1} and remarkable cycling stability. In the new synthesized composite, $TiNiTe_x$ provides excellent conductivity and mechanical strength as the structural foundation. Mn_3O_4 enhances capacitance with its high specific surface area and pseudocapacitive properties; whereas MXene aids ion diffusion and charge storage through its exceptional conductivity and expanded interlayer spacing. The synergistic effects among the components within the well-designed $TiNiTe_x/Mn_3O_4$/MXene architecture further enhanced its energy storage capabilities. This research contributes to the development of advanced supercapacitors with improved performance and reliability, addressing the growing demand for sustainable energy technologies.

Introduction

One of the current challenges to meet the growing demand for efficient energy storage solutions, particularly in supercapacitor applications, is the pursuit for higher energy while maintaining or improving power densities. This balance is crucial for achieving optimal performance in various applications, from consumer electronics to electric vehicles and renewable energy integration devices [1].

Nowdays there is an active search for new binary metal telluride composites, including also novel synthesis methods to enhance electrochemical performance for supercapacitor applications [2]. This involves investigating different metal combinations, doping strategies, nanostructuring techniques, and surface modifications to improve specific capacitance, cycling stability, and rate capability. Another trend involves the integration of binary metal tellurides with other functional materials, such as carbon-based materials, metal oxides, conductive polymers, and MXenes, to create hybrid and composite electrode architectures [3,4].

This work aimed to design and fabricate a $TiNiTe_x/Mn_3O_4$/MXene composite as a novel electrode material to be applied in a high-performance supercapacitor. The new hybrid material is expected to combine the high conductivity of carbon materials with the pseudocapacitive properties of metal tellurides to achieve superior electrochemical performance.

Material and Methods

(1) $TiNiTe_x$ was synthesized hydrothermally by mixing titanium (IV) isopropoxide and nickel (II) chloride hexahydrate with water, ethanol and urea. After stirring for 15 minutes, sodium tellurite and hydrazine hydrate were added, turning the solution black. Then, the solution was transferred to a Teflon-lined autoclave reactor and the reaction took place at 150 °C for 12 h. Subsequently, the obtained sample was washed with water and ethanol, and dried at 60 °C for 24 h.

(2) Mn_3O_4 nanoparticles were prepared by a chemical precipitation method. To do this, manganese chloride was dissolved in water and sodium hydroxide was added dropwise under stirring. The mixture was aged, filtered, and then washed and dried to obtain Mn_3O_4 nanoparticles.

(3) MXene was synthesized by etching Ti_3AlC_2 MAX phases with HF. It was delaminated in acid, washed, and sonicated to remove impurities, resulting in MXene flakes that were dried to a fine powder.

(4) For the fabrication of $TiNiTe_x/Mn_3O_4$/MXene Composite, the $TiNiTe_x$, Mn_3O_4, and MXene components were mixed in a ratio of 80:10:10 using ultrasonication for 12 hours to ensure homogeneous distribution. For the fabrication of electrodes, PVDF was used as a binder, carbon black as a conductive additive, and N-Methyl-2-pyrrolidone as a solvent. The prepared slurry was then used to coat a nickel foam substrate using the doctor blade method and dried at 60°C for 8 h under vacuum.

Results and Discussion

Fig.1a shows the XRD pattern of $TiNiTe_x$, along with the $TiNiTe_x/Mn_3O_4$/ MXene composite. The observed pure $TiNiTe_x$ material closely matches the hexagonal structure of $NiTe_2$ and $TiTe_2$. For the composite materials, the XRD patterns confirm the phase composition of $TiNiTe_x/Mn_3O_4$/MXene materials.

Fig.1(b&c) depict HR-TEM images of the $TiNiTe_x/Mn_3O_4$/MXene composite material, confirming agglomerated nanoparticles, nanorod morphology, and MXene-related nanosheets. Furthermore, Fig. 1d HR-TEM reveals lattice fringes, corresponding to the interplanar spacing attributed to the $NiTe_2$ plane. Fig.1e displays SAED ring patterns, exhibiting a series of separated rings that correspond to the $NiTe_2$ plane. Fig.1f shows EDS results, indicating the presence of Ti, Ni, Te, Mn, C, and O.

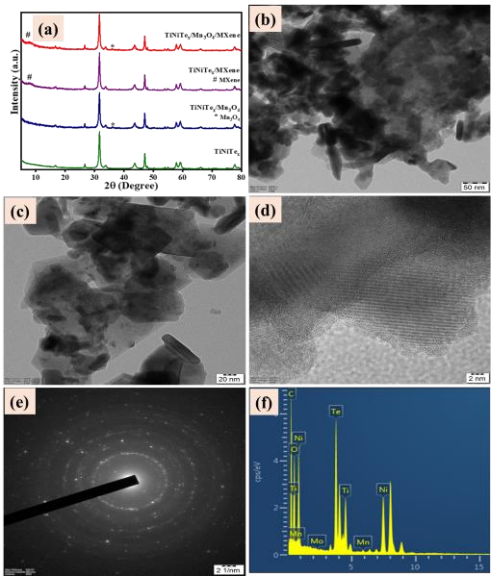

Figure 1. (a) XRD pattern of $TiNiTe_x$ and its composite materials, (b&c) HR-TEM images of $TiNiTe_x/Mn_3O_4$ /Mxene composites, (d) Lattice fringes, (e) SAED pattern, (f) EDS results.

Electrochemical analysis, including cyclic voltammetry (CV) and galvanostatic charge-discharge (GCD), was applied to evaluate the electrochemical performance of the composite. Figure 2(a&c) displays CV graphs of pure $TiNiTe_x$ and $TiNiTe_x/Mn_3O_4$/Mxene composite at scan rates ranging from 5 to 100 mV/s in 6M KOH solution. These plots indicate that the current increases with higher scan rates, demonstrating a pseudocapacitive behavior characterized by redox peaks, which suggest the occurrence of faradaic reactions together with the storage of electrostatic charge. The incorporation of MXene into the $TiNiTe_x/Mn_3O_4$ matrix notably enhanced the overall capacitance, as evidenced by the higher current densities in the CV curves of the composites compared to pure $TiNiTe_x$.

Figure 1(b&d) depicts the GCD profiles, confirming the superior electrochemical performance of the composites. The GCD curves exhibit symmetrical triangular shapes, indicating excellent electrochemical reversibility and high Coulombic efficiency. The $TiNiTex/Mn_3O_4$/MXene composites show higher specific capacitance compared to pure $TiNiTe_x$. Specifically, at a current density of 1 A g^{-1}, the composites exhibit 964 F g^{-1}, whereas $TiNiTe_x$ alone shows 531 F g^{-1}. This improvement is attributed to the synergistic effects of MXene and Mn_3O_4, which enhance the charge storage capacity and ion diffusion. Although capacitance decreases with increasing current density, the composites maintain good specific capacitance at high densities, essential for applications that demand fast charging and power delivery. These detailed electrochemical analyses highlight the great application potential of the $TiNiTe_x/Mn_3O_4$/MXene composite as a high-performance electrode material in supercapacitors.

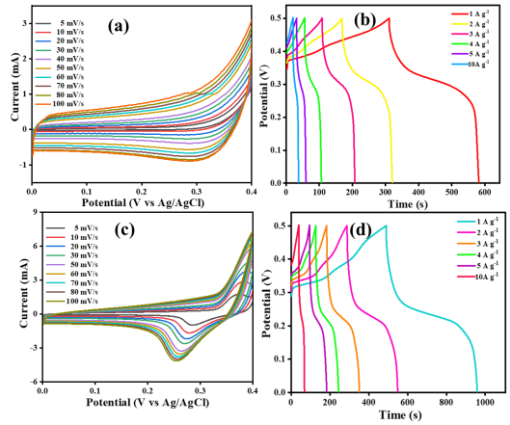

Figure 2. (a&b) CV and GCD curves of $TiNiTe_x$. (c&d) CV and GCD curves of $TiNiTe_x/Mn_3O_4$/Mxene composites.

Conclusion

The synthesis of the $TiNiTe_x/Mn_3O_4$/MXene composite electrode demonstrated its high potential for application in high-performance supercapacitors. Through a careful optimization of the synthesis procedure, the obtained electrode exhibited promising specific capacitance, cycling stability, and rate capability. This research contributes to the development of advanced energy storage systems to meet the growing demand for efficient and sustainable energy technologies. Further optimization guided by advanced characterization techniques will improve electrode performance for practical applications in supercapacitors.

Acknowledgments

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