Research of MXenes and Their Applications in Sensors and Batteries

Xiangying Meng *

Department of Physics and Technology, Beijing Jiaotong University, Beijing, China

* Corresponding Author Email: 21272016@bjtu.cn

Abstract. MXene, a novel two-dimensional material class, demonstrates significant potential across diverse applications such as electrochemical heavy metal detection, pressure sensor active material, and sodium battery composites. MXene-based sensors, in the realm of heavy metal detection, exhibit high sensitivity and selectivity, which are vital in monitoring and controlling environmental pollution. These sensors utilize MXene's distinct conductive and surface properties, facilitating efficient and precise detection of heavy metals, including lead, mercury, and cadmium. In pressure sensors, MXene contributes to enhanced performance owing to its superior electrical conductivity and mechanical strength, allowing the creation of sensitive and robust sensors apt for cutting-edge applications in robotics, wearable technology, and IoT devices. Furthermore, MXene composites in sodium batteries lead to improved battery performance in energy storage. The high conductivity and electrochemical stability of MXene, coupled with its sodium ion hosting capability, render it an optimal material for boosting sodium battery capacity and cyclability. This progress holds immense importance in developing sustainable and efficient energy storage solutions. MXene's versatility and exceptional attributes continue to propel innovation in various fields, including environmental monitoring, energy storage, and sensor technology.

Keywords: MXene, Sensors, Batteries.

1. Introduction

MXene, a novel class of two-dimensional materials composed of transition metal carbides and nitrides, has rapidly ascended to prominence in multiple scientific domains. Its applications are diverse, ranging from the electrochemical detection of trace heavy metals to its role as an integral component in the fabrication of pressure sensors and sodium-ion battery composites. The exceptional conductivity, expansive surface area, and robust adsorption characteristics of MXene materials uniquely position them for detecting heavy metals like lead, cadmium, and mercury. These metals pose significant environmental and health hazards, and MXene's ability to identify their minute concentrations is crucial for the effective monitoring of water and soil pollution levels. Furthermore, in-depth studies underscore MXene's efficacy in sensing applications, particularly in the detection of these contaminants at extremely low levels. MXene's extraordinary electrical and mechanical features are leveraged in the realm of pressure sensors. The material's inherent high electrical conductivity and flexibility pave the way for crafting pressure sensors with unparalleled sensitivity and a wide operational range. These advanced sensors are increasingly being integrated into various sectors, such as wearable technology, robotic systems, and IoT applications, where they excel in converting mechanical pressure into accurate electrical signals when it comes to energy storage, specifically in sodium-ion batteries, MXenes demonstrate their potential as superior electrode materials. The layered architecture of these materials allows for efficient intercalation of sodium ions, a key factor in achieving high-capacity energy storage. This attribute is particularly significant in advancing the performance of sodium-ion batteries, a burgeoning area of research in energy technology. MXene composites in sodium-ion batteries exhibit enhanced electrochemical performance, notably in terms of increased capacity and improved cycle stability, surpassing traditional electrode materials. This advancement holds considerable significance in developing alternative energy storage technologies to lithium-ion batteries, given sodium's greater abundance and cost-effectiveness. Additionally, the atomic-level tunability of MXenes, achievable through surface functionalization and compositional adjustments, offers avenues for property optimization tailored to specific applications. This capability is essential for engineering MXene-based materials to achieve desired functionalities in sensors and batteries. Collectively, the distinctive properties and adaptability of MXenes render them invaluable in the realm of advanced technological applications. Their contribution to boosting device performance in environmental monitoring, flexible electronics, and sustainable energy storage underscores their pivotal role in addressing critical challenges within these sectors.

2. Applications of MXenes

2.1. Electrochemical detection of heavy metals based on MXene

In the sphere of materials science, MXene represents a distinctive class of two-dimensional inorganic compounds, primarily consisting of thinly layered transition metal carbides, nitrides, or carbon nitrides. These materials, notable for their atomic-scale thickness, are characterized by the presence of hydroxyl groups or terminal oxygen on their surfaces. This unique surface chemistry endows MXenes with the metallic conductivity typically associated with transition metal carbides, setting them apart from other materials in their class. MXenes have garnered significant interest in developing electrochemical sensors, especially for environmental applications such as detecting heavy metal ions. Their exceptional conductivity, coupled with a high specific surface area and the ability for surface functionalization, positions MXenes as a superior choice in this field. The ability of these materials to be tailored at the molecular level allows for enhanced sensitivity and specificity in detecting environmental contaminants. A notable example of MXene application is found in the work of Zhu and associates, who synthesized a two-dimensional, accordion-like alk-Ti_3C_2 MXene variant [1]. This synthesis involved a meticulous process of acid etching followed by alkali intercalation, resulting in a material with unique properties. When subjected to optimized electrochemical conditions, the alk-Ti_3C_2 MXene demonstrated a heightened sensitivity and an exemplary electrical response. This variant of MXene proved to be more efficient than traditional electrode materials like carbon nanotubes and graphene, particularly in the detection of multiple heavy metal ions. In terms of performance under optimal conditions, the detection limits for Cd (II), Pb (II), Cu (II), and Hg (II) were determined to be 0.098 μM, 0.041 μM, 0.032 μM, and 0.130 μM, respectively. These findings not only reveal a high degree of sensitivity but also a strong linear correlation in the detection capabilities of MXene. Additionally, the study conducted by Zhu and colleagues delved into the interplay of interference among these four metal ions. It was observed that in a mixed ion environment, Pb (II) exhibited a propensity for preferential deposition in the presence of the other ions. Intriguingly, the sensitivity for detecting Hg (II) was found to increase in the presence of Cd (II), highlighting the complex yet beneficial interactions within the MXene matrix. Bagheri et al. prepared NH_2/SH-$Ti_3C_2T_x$ MXene by the reaction of a single layer of $Ti_3C_2T_x$ MXene with amine and sulfthyl groups. They successfully determined heavy metals in food and soil samples by ultrasonic-assisted dispersed microsolid phase extraction (d-μ-SPE) [2]. This development shows that the MXenes functionalization method is practical, and the introduction of some specific functional groups in the MXene layer can give MXene new properties, enhance the performance of materials, and expand the application field. Carbon-based nanomaterials are widely used in the construction of electrochemical sensors because of their sensitive and specific detection of heavy metals. Due to their remarkable electrical conductivity, outstanding mechanical strength, and extensive specific surface area, Multi-Walled Carbon Nanotubes (MWNTs) can be integrated into the MXene layers, specifically $Ti_3C_2T_x$, to enhance the electrode's effective surface area. Hui and colleagues have successfully implemented this integration in the creation of a novel heavy metal sensor [3]. They developed a flexible gold/polyethylene terephthalate (PET) electrode, leveraging the synergistic properties of two-dimensional nanomaterials MXene, particularly $Ti_3C_2T_x$, and MWNTs. This innovative sensor is designed for detecting copper (Cu) and zinc (Zn) ions. The sensor's design ingeniously combines the superior electrical and conductive properties of MWNTs with the high conductivity, excellent hydrophilicity, and significant surface area of MXene, along with its exceptional electrocatalytic characteristics. MWNTs serve a dual purpose in this context. Firstly, they act as an anti-stacking layer, effectively preventing the aggregation of Ti3C2Tx layers. Secondly, they function as spacers, revealing more surface area and active sites. This arrangement not only mitigates layer aggregation but also synergistically enhances the electrochemical performance when combined with Ti3C2Tx. The flexibility of this electrode allows for non-invasive on-site detection of Cu (II) and Zn (II) in biological fluids such as sweat and urine. This capability is crucial for the rapid and convenient monitoring of heavy metal levels, a vital aspect in the fields of environmental monitoring and health diagnostics. The sensor has demonstrated exceptional detection performance and holds great promise for significant contributions in these areas.

2.2. MXene pressure sensor

MXene is ideal for building active materials for pressure sensors. MXene has abundant adjustable functional groups attached to its surface, has excellent water dispersion and plasticity, and can be combined with other materials to form a variety of multi-functional materials and microstructures. Mxene-based pressure-sensitive layers have a variety of microstructures such as porous structures, hydrogels, flexible substrates, and films. The successful preparation of these microstructures has promoted the rapid development of pressure sensors. The MXene gel network is prone to collapse during compression and needs to be combined with other materials to enhance mechanical properties. Yue et al. prepared the MXene sponge pressure sensor by dipping MXene in the melamine sponge skeleton to form a three-dimensional network structure [4]. The device has good mechanical stability and high elasticity, maintaining high sensitivity and excellent cyclic stability over a wide pressure range. Adding MXene to hydrogels can improve their electrical conductivity and mechanical properties. Using poly-isopropyl acrylamide and MXene as raw materials, Zhang et al. synthesized a physically cross-linked double-network hydrogel with excellent mechanical properties and electrical conductivity (1.092 S/m) [5]. It interacts with MXene to improve its performance. The researchers have done a lot of work to make more effective use of MXene and improve its electrochemical properties. Ion selective membrane is the core component of the self-actuated nanofluid pressure sensor. The ion-selective membrane channel's surface charge induces an electrostatic repulsion, allowing only counter ions (those of opposite polarity) to inhabit the confined channel. In situations where electrolytes are propelled by pressure, this selective channel permits only the passage of counter ions, leading to a movement of net charges and the generation of an electrical signal. In their groundbreaking research, Yue and colleagues discovered that sensors based on the MXene/cellulose nanofiber composite membrane substantially advance pressure sensing technology. They effectively tackle the issue of non-linearity, a common drawback in many current pressure sensors. This innovation holds particular importance for applications within the Internet of Things (IoT) and artificial intelligence (AI) sectors [6]. The sensor's design incorporates nanoscale gaps between MXene layers, which regulate electrolyte movement and enhance selective ion transportation. This functionality is pivotal for the transformation of mechanical pressure into electrical output, allowing these sensors to be self-powered. A notable characteristic of these sensors is their linear response; the voltage and current produced are directly proportional to the applied pressure. This linearity marks a considerable improvement over conventional pressure sensors, broadening their utility in a range of practical applications.

The integration of robust cellulose nanofibers into the sensor design significantly broadens its detection capabilities. It enables fine-tuning the nano-gap existing between the MXene layers, enhancing the device's sensitivity. The paper discusses various strategies for further improving the sensor's functionality. These include tweaking the surface functional groups, varying the electrolyte concentration, and refining device assembly techniques. These advancements in two-dimensional nanofluidic pressure sensor technology are crucial for developing portable and wearable electronic devices. Their improved performance and adaptability offer extensive potential in numerous sectors. In essence, this technological advancement represents a substantial leap forward in the field of sensor technology, heralding the advent of more precise, dependable, and versatile pressure-sensing solutions suitable for contemporary technological demands.

2.3. The application of MXene composites to sodium batteries.

Metal oxide is an important component of anode materials for sodium-ion batteries, and its availability and low cost are its dual advantages. Zhao et al. used Ti3C2Tx and polymethyl methacrylate PMMA to prepare three-dimensional macroporous Ti3C2Tx as a negative material for sodium-ion batteries with a specific capacity of about 330 mAh/g at 0.25C magnification and about 120 mAh/g at 25C magnification and 2.5C The first reversible capacity is about 210 mAh/g. After 700 cycles, the reversible capacity gradually rises to a stable value. Finally, after 1,000 cycles, the reversible capacity is about 295 mAh/g [7]. Compared with the first cycle, the capacity retention rate is about 140.5% the high conductivity of Ti3C2Tx itself is also conducive to the improvement of electrochemical performance. Because the potassium ion radius is larger than sodium ion, the intercalation process is relatively more difficult, and the electrode material is usually deformed during repeated intercalation, so it is particularly important to improve the conductivity and structural stability of the material. The main strategy for improvement is to combine MXene with materials with better electrical conductivity or to build three-dimensional structures of composite materials. Guo et al. addressed the challenges these two types of post-lithium-ion batteries face due to the lack of efficient electrode materials [8]. A novel electrode material was developed by sulfur-modified MXene (specifically sulfur-modified Ti3C2Tx, abbreviated as S-T3C2Tx). The Ti-S bond was formed by introducing sulfur functional groups into the MXene matrix. This structural modification enhances the interaction between the material and sodium and potassium ions and improves the kinetic properties of the ions. The sulfur-modified Ti3C2Tx demonstrates excellent storage properties for sodium and potassium. At a current density of 0.1 mA g−1, the reversible capacity of SIBs and PIBs is as high as 151 mAh g−1 and 101 mAh g−1, respectively. At a high current density of 500 mA g−1, S-T3C2Tx exhibits excellent long-term capacity stability. Even after 2000 cycles, the storage capacity of SIBs remains at 88 mAh g−1, while that of PIBs is 41 mAh g−1. This study not only deepens the understanding of the effects of heteroatom modifications on MXene-based frameworks but also advances the prospects of MXene electrodes for energy storage applications. This research has successfully improved the electrochemical performance of sodium-ion and potassium-ion batteries by innovatively modifying MXene materials, showing great potential in the development of efficient energy storage materials. This is of great significance for the development of large-scale energy storage systems.

3. Conclusion

MXene, a versatile and innovative class of two-dimensional transition metal carbides, nitrides, and carbonitrides, has demonstrated its exceptional utility in a wide range of applications, from electrochemical sensors for heavy metal detection to active materials in pressure sensors, and as composites in sodium-ion batteries. MXene's high conductivity, large specific surface area, and adjustable surface functionalization make it an ideal candidate for detecting heavy metals like Cd, Pb, Cu, and Hg in electrochemical detection. Studies by Zhu et al. and others have shown that MXene-based sensors outperform traditional materials like carbon nanotubes and graphene in sensitivity and response and offer practical solutions for environmental monitoring and health diagnostics. The ability to introduce specific functional groups into MXene layers opens up further possibilities for enhancing its properties and expanding its applications. In pressure sensing, MXene's outstanding electrical and mechanical properties, combined with its flexible and adjustable nature, allow for the development of high-performance sensors. These sensors, capable of linearly converting mechanical pressure to electrical signals, are crucial for advancements in IoT and AI technologies. The incorporation of MXene into various microstructures like hydrogels and flexible substrates, as demonstrated by Yue et al. and Zhang et al., highlights its adaptability and effectiveness in creating sensitive and durable pressure sensors.

Furthermore, in the field of energy storage, MXene composites have proven to be valuable in enhancing the performance of sodium-ion batteries. Researchers like Zhao et al. and Guo et al. have shown that MXene when modified and combined with other materials, can significantly improve the capacity, stability, and overall performance of these batteries. These advancements are pivotal in the search for sustainable and efficient energy storage solutions. Overall, the diverse applications and potential of MXene in these critical areas underscore its significance in advancing material science and technology. Whether in environmental monitoring, wearable technology, or energy storage, MXene's role is increasingly crucial, showcasing its potential to drive innovation and address some of the major challenges in these fields.

References

[1] Zhu X, Liu B, Hou H, et al. Alkaline intercalation of Ti3C2 MXene for simultaneous electrochemical detection of Cd (II), Pb (II), Cu (II) and Hg (II) [J]. Electrochimica Acta, 2017, 248: 46-57.

[2] Bagheri S, Chilcott R, Luo S, et al. Bifunctional Amine- and Thiol-Modified Ti3C2Tx MXene for Trace Detection of Heavy Metals [J]. Langmuir, 2022, 38(42): 12924-12934.

[3] Hui X, Sharifuzzaman M, Sharma S, et al. High-Performance Flexible Electrochemical Heavy Metal Sensor Based on Layer-by-Layer Assembly of Ti3C2Tx/MWNTs Nanocomposites for Noninvasive Detection of Copper and Zinc Ions in Human Biofluids [J]. ACS Applied Materials & Interfaces, 2020, 12(43): 48928-48937.

[4] Yue Y, Liu N S, Liu W J, et al. 3D hybrid porous Mxene-sponge network and its application in piezoresistive sensor. Nano Energy, 2018, 50: 79.

[5] Zhang Y L, Chen K X, Li Y S, et al. High-strength, selfhealable, temperature-sensitive, MXene-containing composite hydrogel as a smart compression sensor. ACS Applied Materials & Interfaces, 2019, 11(50): 47350.

[6] Yue Y, Liu N S, Su T Y, et al. Self-powered nanofluidic pressure sensor with a linear transfer mechanism. Advanced Functional Materials, 2023, 33(13): 2211613.

[7] Zhao M, Xie X, Ren C E, et al. Hollow MXene Spheres and 3D Macroporous MXene Frameworks for Na-Ion Storage[J]. Advanced Materials, 017, 29(37): 1702410

[8] Guo X, Xie X, Choi S, et al. Sb2O3/MXene (Ti3C2Tx) hybrid anode materials with enhanced performance for sodium-ion batteries [J]. Journal of Materials Chemistry A, 2017, 5(24): 12445-12452