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Recent Advances in MXene-Based Materials for Solid-State Batteries: A Mini Review

Golsa Sadat Elyasi[1], Mehdi Ardjmand[2*],

[1] Department of Chemical Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran

[1*] Department of Chemical Engineering, South Tehran Branch and Nanotechnology Research Center, South Tehran Branch, Islamic Azad University, Tehran, Iran.

*Corresponding author, Email: **m_arjmand@azad.ac.ir**

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ABSTRACT

MXenes, a class of two-dimensional transition metal carbides and nitrides, have emerged as promising materials for solid-state batteries (SSBs) due to their exceptional electrical conductivity, tunable surface chemistry, and mechanical flexibility. These unique properties help address several limitations of SSBs, such as poor interfacial contact, low ionic conductivity, and structural instability. This mini-review presents a concise overview of recent developments in the application of MXenes within different components of SSBs, including their roles as electrode materials, fillers in solid electrolytes, and interfacial modifiers. Key advantages such as enhanced charge transfer, facilitated ion transport, and improved mechanical compatibility are discussed. Despite their potential, challenges such as oxidation sensitivity and difficulties in large-scale production remain significant barriers. Recent experimental studies demonstrating the benefits of MXene integration in battery systems are highlighted, providing a better understanding of their functionality. The review concludes with a perspective on future directions for incorporating MXenes into next-generation solid-state energy storage technologies, aiming for safer and more efficient devices.

Keywords: MXene, Solid-State Battries (SSBs), Solid Electrolytes, 2-Dimensional Materials, Electrochemical Performance.

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1. INTRODUCTION

A solid-state battery (SSB) is a kind of rechargeable battery that uses solid materials as both the electrode and, in certain cases, the electrodes are used along with solid electrolytes instead of the usual liquid or gel electrolytes found in traditional lithium-ion batteries (LiB) (1). These solid electrolytes (SE) can be ceramic, polymer, or glassy in nature, and they enable the transport of lithium ions between the anode and cathode (2). SSBs are considered next-generation energy storage systems because of their higher safety, greater energy density, and improved thermal and chemical stability compared to liquid-based systems (3, 4). As global energy demands increase and the need for sustainable and efficient storage systems becomes more urgent, SSBs are being widely investigated for use in transportation systems, and large-scale energy storage(5). However, the commercialization of SSBs encounters major challenges, such as low ionic conductivity of SEs, poor interface compatibility between electrodes and electrolytes, and mechanical degradation during cycling (6). To overcome these challenges, it is necessary to develop advanced materials with specific properties designed for each part of the battery.

MXenes ($M_{n+1}X_nT_x$), a novel class of two-dimensional transition metal carbides and nitrides. In the MXene formula, M represents an early transition metal, X is carbon or nitrogen, Tx represents surface terminations, and n is an integer indicating the number of 'X' layers (7). MXenes have shown exceptional promise in addressing these challenges. With their high electrical conductivity (8, 9), hydrophilic surface chemistry (10), large specific surface area (11), and mechanical flexibility (12, 13), MXenes have been explored for various roles in SSBs- from conductive electrodes to fillers in composite SEs and interfacial modifiers. This mini-review provides an overview of the recent advances in integrating MXenes into SSBs systems. The discussion covers their functions in different battery components, associated benefits and limitations, and perspectives for future research toward high performance all SSBs.

2. Structure and Properties of MXenes Relevant to SSBs

MXenes are a group of two-dimensional (2D) materials made from transition metal carbides, nitrides, or carbonitrides. They are usually described by the general formula Mn+1XnTx, where **M** stands for an early transition metal (such as Ti, V, Nb, or Mo), **X** refers to carbon and/or nitrogen, and **Tx** represents surface functional groups like –OH, –O, and –F(14, 15) and (Figure 1.). A well-known example is $Ti_3C_2T_x$, which has been widely researched for use in energy storage systems (16-20).

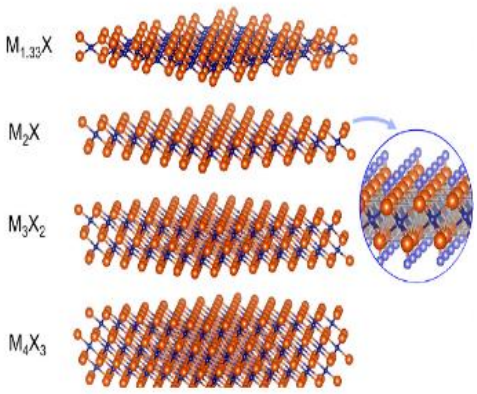
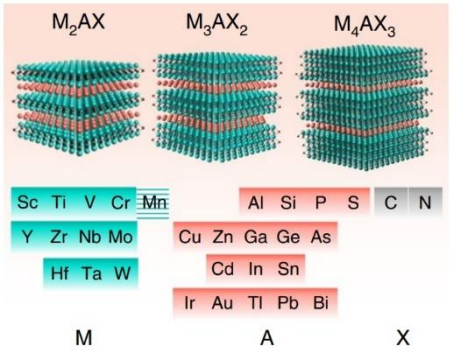


Figure 1. The two-dimensional layered structure of MXenes consists of M-X layers with (Tx: –O, –OH, –F, and/or –Cl), shown in blue. These terminations, simplified as being single-bonded to the M atoms, are located in the spaces between the M atoms, Copyright 2019 Published by Elsevier (21).

MXenes are primarily synthesized by selective etching of the A layer from their parent MAX phases (e.g., Ti_3AlC_2) using fluoride-containing acidic solutions. This etching process removes the "A" element (typically Al), resulting in stacked 2D flakes with tunable surface terminations and interlayer spacing (22-24)(Figure 2.a and b).

a



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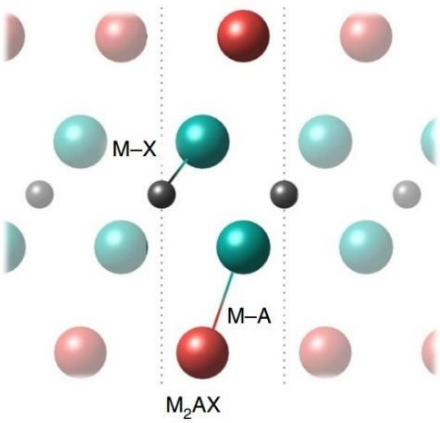

Figure 2. **a)** MAX phases are layered materials made of a transition metal (M), an A-group element (A), and carbon and/or nitrogen (X), following the formula $M_{n+1}AX_n$. **b)** Breaking the M-A bonds through selective etching of the "A" element yields Mxenes, Copyright 2022 Published by Springer Nature (25).

The unique properties of MXenes make them promising for integration into SSBs. MXenes exhibit metallic or near-metallic conductivity, enabling efficient charge transport within the electrode or across interfaces (26-30). Their 2D layered structure provides a high specific surface area, which is advantageous for increasing interfacial contact and active material loading (31-36). The presence of –OH, =O, or –F groups allows for tuning surface chemistry and enhancing ion transport (37-40). MXenes demonstrate flexibility, durability, and chemical stability, making them ideal for mitigating structural integrity during cycling (41-44).

3. MXene Application in Solid-State Batteries

The growing interest in MXenes for energy storage has led to increasing efforts to explore their potential in solid-state battery (SSB) configurations.

This section reviews the application of MXenes across different components of SSBs, including electrodes, solid electrolytes, and interfaces, which highlights their functional roles and the mechanisms by which they enhance battery performance.

3.1 MXenes as Anode/Cathode Materials

MXenes have attracted significant interest in advancing solid-state battery technology due to their metallic conductivity, two-dimensional layered structure, and surface functional groups that facilitate alkali ion transport. In particular, $Ti_3C_2T_x$ and related MXenes have shown great promise as anode materials in solid-state lithium metal batteries. For instance, Li–$Ti_3C_2T_x$ composite anodes demonstrate excellent interfacial compatibility with garnet-type solid electrolytes, achieving a remarkably low interfacial resistance of ~5 Ω·cm². Moreover, the in-situ formation of LiF at the Li–$Ti_3C_2T_x$/garnet interface effectively suppresses dendritic lithium growth, which significantly improves safety and cycling

stability (45) and (Figure 3). Building on this, recent work has shown that functionalizing the surface of $Ti_3C_2T_x$ MXene with fluorine-terminated groups leads to the formation of a stable, LiF-rich solid electrolyte interphase (SEI) layer in solid-state lithium metal batteries. This engineered SEI not only reduces interfacial resistance but also stabilizes the electrode/electrolyte interface by preventing dendrite formation and mechanical degradation during cycling. Such dual functional roles of MXene as a highly conductive host and interfacial stabilizer underscore its potential to enhance the long-term performance and safety of solid-state lithium metal batteries (46).

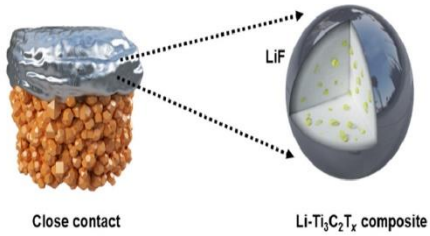

Figure 3. Li–MXene composite anode in solid-state battery: enhances interfacial contact with the solid electrolyte, lowers interfacial resistance, and prevents lithium dendrite growth by forming a protective in-situ LiF layer, Copyright 20200 Published by Elsevier.

MXenes are proving vital for enhancing cathode performance and overall battery stability in solid-state battery systems. Their high conductivity and unique structural properties enable them to effectively reduce charge-transfer resistance and ensure uniform charge distribution during electrochemical cycling, directly addressing challenges in these next-generation battery architectures. A key application is in $LiFePO_4$ (LFP) cathodes within all-solid-state configurations. For instance, research demonstrates that incorporating $Ti_3C_2T_x$ MXene significantly enhances the performance of $LiFePO_4$ cathodes in all-solid-state lithium batteries. This improvement is attributed to MXene's high electronic conductivity and superior interfacial stability, which collectively facilitate more efficient lithium ion transport and overall power delivery within the solid electrolyte environment (47).

3.2 MXenes as Solid Electrolytes Fillers or Components

While MXenes aren't primary lithium-ion conductors, their surface functional groups and compatibility with polymers make them promising as fillers in composite solid electrolytes. They significantly enhance mechanical strength, thermal stability, and ionic conductivity. A recent study highlights this by incorporating a 3D interconnected $Ti_3C_2T_x$ network into a PEO-based solid polymer electrolyte. This design improved both ionic conductivity (by weakening Li^+-PEO association via Lewis acid-base interactions) and mechanical strength. The Li||CSE||Li symmetric cell exhibited outstanding cycling stability, operating for more than 3000 hours at 0.1 mA cm^{-2} and over 2500 hours at 0.05 mA cm^{-2}. Additionally, the $LiFePO_4$||CSE||Li battery achieved a capacity of 145.3 mAh/g at 0.3 C after 300 cycles, highlighting the contribution of MXene to high-performance solid-state electrolytes (48). MXene-SiO_2 nanosheets effectively serve as functional fillers in polyacrylonitrile (PAN)-based quasi-solid polymer electrolytes (QSPEs). They enhance Li^+ transfer, boosting ionic conductivity to ≈1.7 mS cm^{-1} at 30 °C and a t_{Li^+} to 0.51. Li symmetric batteries showed remarkable stability, cycling over 1550 hours at 0.2 mA cm^{-2}. Crucially, $LiFePO_4$||CSE||Li quasi-solid-state lithium metal batteries (QSSLMBs) with this QSPE retained 81.5% capacity after 300 cycles at 1.0 C, highlighting MXene's role in robust, high-performing solid-state batteries (49). Oxygen-containing terminal groups (–OH, –O) help break down lithium salts and create continuous pathways for Li^+ transport within the polymer matrix.Moreover, MXenes enhance the

interface between the solid electrolyte and the electrodes, leading to better contact and performance, minimizing interfacial resistance (50),a key bottleneck in SSBs. Recent studies also explore heterostructures where MXenes are combined with ceramic fillers (e.g., LLZO), creating hybrid electrolytes with both high ionic and electronic control. A 3D interconnected MXene ($Ti_3C_2T_x$) network synergistically reinforced with LLZTO in a PEO-based solid polymer electrolyte. This design enhances both ionic conductivity and mechanical strength for all-solid-state lithium metal batteries. The MXene's surface groups weaken Li^+-PEO association, while its network improves mechanical robustness. The Li symmetric battery demonstrated remarkable stability, cycling for more than 3000 hours at 0.1 mA cm^{-2} and over 2500 hours at 0.05 mA cm^{-2}. In addition, the $LiFePO_4$||CSE||Li battery achieved a capacity of 145.3 mAh/g at 0.3 C after 300 cycles, highlighting the promise of MXene-ceramic hybrid electrolytes (51).

3.3 Interface Engineering with MXenes

One of the major challenges in solid-state batteries is poor interfacial contact and high interfacial resistance, particularly between rigid solid electrolytes and active materials. MXenes offer a unique solution due to their soft, conformal nature and excellent conductivity.
When used as interlayers or coatings, MXenes can buffer mechanical mismatch, enhance wettability, and reduce interfacial impedance. Their surface chemistry can also be tuned to create favorable interactions with both the solid electrolyte and electrode, enabling more stable solid–solid interfaces.

For example, $Ti_3C_2T_x$ interlayers between Li metal and sulfide-based electrolytes have been shown to suppress dendrite formation and promote uniform Li plating/stripping. This engineering approach significantly improves cycle life and safety. One study demonstrated that forming a robust solid-state electrolyte interphase using two-dimensional $Ti_3C_2T_x$ MXene on lithium metal anodes effectively prevents dendrite growth (52). Another significant work illustrated that parallelly aligned $Ti_3C_2T_x$ MXene layers help promote even nucleation and lateral growth of lithium, leading to dendrite-free metallic lithium anodes (Figure 4.). The fluorine terminations in MXene further enhance this effect by promoting the formation of a uniform and stable solid electrolyte interface (SEI) that is rich in lithium fluoride (LiF) at the anode/electrolyte boundary. This LiF-rich SEI effectively controls the movement of lithium ions, resulting in anodes with a long cycle life up to 900 hours and strong stripping–plating performance reaching 35 mAh cm^{-2}. MXene-coated anodes like these can support lithium metal batteries that maintain high cycling stability for as many as 1000 cycles (53).

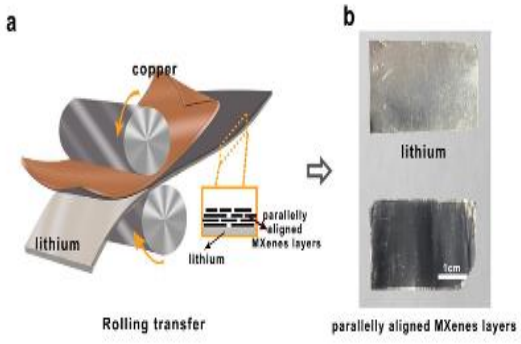

Figure 4. A schematic illustrates a rolling process used to transfer PA-MXene layers from a copper backing (PA-MXene-Cu) onto a lithium surface (PA-MXene-Li), Copyright 2019 Published by Wiley (53).

4. Challenges and Future Outlook

MXenes offer a combination of electrical conductivity, surface functionality, and mechanical compliance that make them highly attractive for use in solid-state batteries. Their ability to form strong interfacial contact with both electrodes and electrolytes, while maintaining structural integrity, makes them

valuable as active materials, conductive additives, or interface modifiers. Furthermore, the ease of surface functionalization allows for tunable interactions with various solid-state components, which can lead to improved electrochemical performance (54).

Despite these advantages, several challenges limit the widespread use of MXenes in SSBs. First, the instability of MXenes in ambient conditions, particularly their tendency to oxidize when exposed to air or moisture, can degrade their electrical properties and long-term stability (55, 56). Second, the synthesis and processing of high-quality, defect-free MXene films at scale remains complex and costly, which hinders their integration into commercial battery systems (57, 58). Moreover, the role of MXenes in ionic conductivity is still under investigation. While some surface terminations may facilitate Li^+ transport, MXenes are not inherently good ionic conductors, and their presence in excess could potentially block ion transport pathways in composite materials (37, 59). Additionally, interfacial reactions between MXenes and certain solid electrolytes (e.g., sulfide-based) could lead to the formation of resistive interphases, which negatively affect battery performance (60).

Therefore, while MXenes have demonstrated great potential in addressing critical challenges in SSBs, further work is needed to optimize their chemical stability, interface compatibility, and integration strategies for practical applications.

The unique structural and physicochemical properties of MXenes position them as highly promising materials for advancing solid-state battery (SSB) technologies. Their metallic conductivity, high surface area, and tunable surface chemistry allow them to function effectively as active materials, interfacial layers, or composite fillers. These capabilities directly address several limitations of current SSBs, such as low ionic/electronic conductivity, high interfacial resistance, and mechanical instability.

However, to translate the laboratory-scale benefits of MXenes into practical battery systems, several key challenges must be addressed. These include improving their long-term stability against oxidation, developing scalable and cost-effective synthesis methods, and ensuring compatibility with a broader range of solid electrolytes and electrode materials. Moreover, deeper understanding of their electrochemical behavior, particularly at buried interfaces and under operating conditions, is essential. Future research should also focus on exploring new MXene compositions beyond $Ti_3C_2T_x$, with optimized terminations and layered chemistries tailored for ion transport and interface engineering. Furthermore, in situ characterization techniques and multi-scale modeling will play a critical role in elucidating ion transport mechanisms and guiding material design.

Overall, the integration of MXenes into solid-state battery architectures holds great promise, but its success will depend on interdisciplinary efforts that bridge materials science, electrochemistry, and device engineering.

5. Conclusion

MXenes have emerged as a highly versatile class of two-dimensional materials with significant potential for improving the performance and reliability of solid-state batteries. Their unique combination of metallic conductivity, surface functionality, and structural adaptability enables them to contribute effectively across multiple battery components, from electrodes to solid electrolytes and interfaces.

While current research demonstrates promising results in enhancing ionic conductivity, interfacial stability, and mechanical integration, several challenges, such as oxidation sensitivity and scalability, must be overcome for real-world applications. Continued advancements in material engineering, processing methods, and fundamental understanding will be key to unlocking the full potential of MXenes in next-generation solid-state energy storage systems.

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