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Progress, Prospects and Challenges of MXene Integrated Optoelectronics Devices

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Recently, the emerging 2D materials MXene have gained a surge of attention to the production of optoelectronics devices such as solar cells, plasmonic, phototransistors, photodetectors, light-emitting diodes, photothermal therapy, and so on. Its outstanding optical and electrical characteristics, unique structure, and large specific surface area make it suitable for future use in modern optoelectronics including ultrafast lasers, light emitters, modulators, and plasmonic generators. There is a lack of critical analysis on the prospects, challenges, overview of synthesis methods, mechanisms, and future research directions of MXene despite having some reviews have been published on the applications of MXene. Therefore, this study critically analyzed the existing challenges of MXene, such as poor stability in an oxygen environment, inadequate mechanical properties, ease of stacking, temperature barrier, and so on. In addition, the fundamentals, preparation techniques, properties, and applications of MXene have been summarized. The mechanism, limitations, and benefits of different preparation methods have been mentioned. A comprehensive analysis and guidelines have been provided to improve the existing synthesis methods. The ways to overcome these challenges, prospects, and future markets of the MXene-based optoelectronic devices have been described.

1. Introduction

Over the last decade, optoelectronic devices like solar cells,[1–3] phototransistors,[4] photodetectors,[5,6] light emitting diodes,[7] photothermal therapy,[8,9] and so on have improved rapidly in terms of efficiency and quality.[10] Research on optoelectronic devices is at the top of the research ladder for modern optoelectronics and microelectronics. Researchers in this field focus on different outstanding 2D materials such as graphene, MXene, hexagonal boron nitride, black phosphorus, and others.[11] MXene's superior mechanical strength, electrical conductivity, and surface functionality have made it an essential part of the production of cutting-edge optoelectronic devices. These exceptional properties lead to MXene use in energy storage electrodes,[12] supercapacitors and batteries, enabling optoelectronic applications. The outcome published in the optoelectronics device-related literature indicates high light absorption and photodetection potential, enabling integrated systems. MXene-based photodetectors with improved sensitivity and reaction times revealed their promise for imaging, sensing, and communication systems.[13] Recent achievements have broadened applications of MXene in multifunctional areas including photothermal therapy, lasers, and light-emitting devices in in integrated optoelectronics.[1]

The synthesis of MXene is primarily divided into two types namely top-down and bottom-up methods.[14] The top-down method involves exfoliating bulk crystal volumes into the mono MXene layers, while the bottom-up strategy is considered to be a molecule and atom progress. Top-down techniques have disadvantages such as small crystals, thickness irregularities, and defects in MXene. On the other hand, bottom-up techniques have better crystallinity, fewer defects, and no -F terminations on the exterior. The type of precursor, the synthesis conditions and temperature, the morphology of MXene, and the surface properties, all differ significantly.[15,16] In the context of the advancement of modern optoelectronics, promising research is being conducted. Heo et al. reported the development of an MXene surface-coated effective solar cell

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and claimed that its efficiency is 19.69 %. However, the improvement of product design and the reduced price of the product should be taken into account.[2] Koo et al.[17] reported that the performance of polyimide-integrated graphene-based electrodes in flexible organic solar cells exceeds 15 %. Promising works have been carried out in the preparation of LED. High-performance deep-ultraviolet light-emitting diodes (LED) fabricated on glass with uniform hexagonal boron nitride have been reported.[18] In addition, Ahn et al. published an article in which they used titanium carbide MXene for the development of a highly effective LED. They also introduced a chemical neutral technique to resist the oxidation problem of MXene. Meanwhile, it would be better if they had more elaborate characterization portions.[7]

Phototransistors are one of the promising customer-demand optoelectronics which is advancing over the years.[19] Lin et al. demonstrated a highly effective phototransistor incorporated with MXene. Also, this stream has a shred of limited scholarly evidence in comparison to solar cells and others.[20] Therefore, the scope of research is available to advance this stream. Photodetectors, which are sensors that could transform photon energy from light into an electric signal, have received a lot of attention in recent years. They are critical for a variety of scientific application fields such as communications using fiber optics, process improvement, environment monitoring, security, and defense scheme applications. The MXene-based spin-incorporated photodetector was reported by Montazeri et al..[21] Xu and his team reported a review of the recent progress of the MXene-based photodetector.[22]

The application of MXene in biomedical,[23] energy storage,[24] sensors,[25] and optoelectronics[26,27] is increasing over

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the years. MXene has attracted much interest in optoelectronics applications over the years due to its remarkable and adaptable features, such as surface functionality, variable interlayer spacing, and excellent photothermal efficiency.[28] For high-efficiency LEDs, the flexible MXene electrode was used to know its phototransistors, photothermal therapy,[29] photodetectors,[30,31] and solar cells.[32,33] MXene has been widely used in these fields worldwide, and important advancements have been made in MXene-based solar cells,[32,34] phototransistors, plasmonics, LEDs, photodetectors,[30,31,35] and photothermal therapy.[29,36] Although some reviews have been published on the applications of MXene in optoelectronics, there is a lack of critical analysis on the prospects, challenges, overview of the synthesis methods, mechanisms, and future research directions of MXene. For example, Zhang et al. conducted a review that specifically focused on the application of MXene in optoelectronics.[37] Jiang et al. reported on the applications of various 2D materials including graphene, MXene, boron sulfide, and others.[38] Additionally, another review paper engrossed on MXene's application in photodetectors.[22] However, there is enough scope to write a critical review to cover the recent advancements, prospects, challenges, overview of popular synthesis methods, mechanisms and future research directions of MXene. Therefore, this review aims to provide a comprehensive overview of the recent progress, synthesis methods, applications, challenges, and future prospects of MXene in optoelectronics, serving as a credible source of information for researchers in this field.

2. Fundamentals of MXene

The MXene is made from transition metal carbides, carbonitrides, and nitrides.[39] It has the common formula $M_{n+1}X_nT_x$, which is formed by the selective etching of elements from ternary MAX phases ($M_{n+1}X_nT_x$). M indicates a preliminary transition metal (Sc, Ti, Nb, V, Zr, Mo, Hf, etc.), A represents a group of IIIA or IVA species, n means an integer between 1 and 4, and T_x denotes surface functional groups.[40] Group of MXene typically contains Ti_2C, Ti_3C_2, $(V_{0.5}, Cr_{0.5})_3C_2$, $(Ti_{0.5}, Nb_{0.5})_2C$, Ti_3CN, Ta_4C_3, V_2C, Nb_2C, and Nb_4C_3 and so on.[23,41–44]

As a result of its layered structure, MXene without delamination looks quite similar to exfoliated graphite. Higher spin-orbital coupling and various spin and oxidation states contribute to the fascinating mechanical and other features seen in the low-dimensional system, notably MXene's containing transition metals with open D-orbitals. When the aforementioned arrangements of functional groups are optimized for stability, the MXenes are the stable structure that results. For a given structure to remain somewhat stable, it must have many transition metal atoms in its ionic states so that they may donate enough electrons to X and the surface-bound functional groups.[46,47] The structure of MXene and MAX phase forming elements are illustrated in Figure 1(a–b). In this review article, the properties, synthesis, potential applications, challenges, and scopes will be discussed.

3. Properties of MXene

3.1 Optical properties of MXene

The optical features of 2D materials are of great significance in the fast-growing fields of optoelectronics. The SP^2 hybridization of graphene with the honeycomb lattice shape and the extra electron of the Pz orbital leads to linear energy-momentum and increases bonding and antibonding in π-bands in graphene [58]. As a result, they behave as massless Dirac fermions, which leads to a variety of interesting optical and transport phenomena.[48] Dirac electrons have a linearly dispersive nature, which allows them to interact with photon energies over a broad range, thus[49] making them an extremely useful material for a variety of optical[50] and optoelectronics applications.[51,52] In addition, the layer-based band gap is black phosphorus ranging from 0.3 eV in bulk to 1.5 eV[53] in monolayer structure, making it an outstanding 2D material for application in IR optics,[54,55] and optoelectronics.[54]

Similarly, MXene is a recent addition to this fascinating family of 2D materials that has generated a lot of interest because of their customizable characteristics that make them great candidates for optoelectronic applications. Theoretically, the computation of the imaginary component of the dielectric function tensor, which can be viewed as a function of photon wavelength, can be used to study several optical properties, including reflection, absorption, and transmittance. Calculations of the desired attributes are done using approximations like $HSE0_6$. This has allowed for the investigation and reporting of the energy loss function, reflectivity, and absorption spectrum of bare Ti_2C, Ti_3C_2, and $Ti3N_2$ reported in.[47] According to that research, the plasmon energies of the four structures mentioned above are, respectively, 10.00, 10.81, and 11.38, 11.62 eV. This type of band gap is making MXene a strong candidate for producing optoelectronic devices.

Nevertheless, 2D screening should have a significant excitonic effect on MXene that necessitates accounting for electron-hole interactions to quantitatively establish absorption profiles. The author theoretically examined the 2D Sc_2CCl_2 absorbance spectra, calculating the quasi-particle bandgap using GW+PRA/BSE and the band gap obtained.52 eV. They describe a methodical computational analysis of a MXene, which is 2D double-metal-layered scandium chloride carbides (Sc_2CCl_2). The two-dimensional Sc_2CCl_2exhibits weak VDW interactions, robust interlayer-decoupled optoelectronic characteristics, exceptionally high and anisotropic carrier mobilities of approximately 1 to $4.5\times10^4\ cm^2\ V^{-1}\ s^{-1}$, and thus produces quite significant drain currents. The two-dimensional Sc_2CCl_2family, in particular, has great light harvesting potential and may be used as effective contributing materials in solar cells.[56]

However, MXene has tremendous opportunities and some challenges. The applications including SERS, broadband absorber, and ultrafast laser pulse production have been made possible by MXene. The plasmonic characteristics of $Ti_3C_2T_x$MXenes, which enable the design of plasmonic devices near IR, have received attention from researchers. In contrast, some challenges were observed, such as gaining a thorough

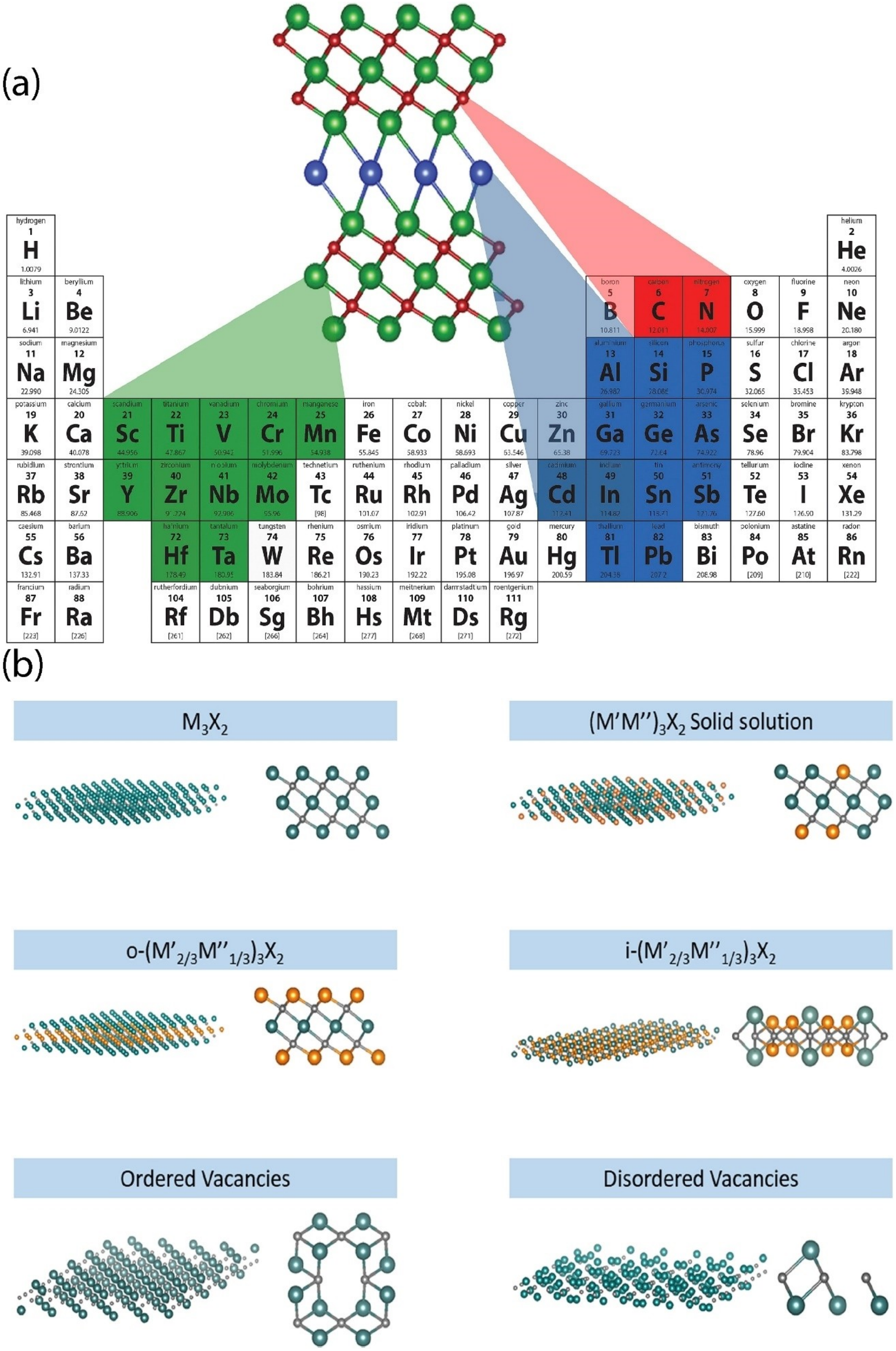

Figure 1. (**a**) Illustration of MAX phases $M_{n+1}AX_n$ forming elements from periodic table and (**b**) different structures for MXene; Reproduced with permission from Ref. [45] Copyright (2019), Elsevier.

knowledge of MXenes′ optical properties, especially their dielectric characteristics in single- to few-layer MXenes. In addition, poor structural stability and high cost are the key aspects that must be focused on to improve.

3.2 Electrical properties

MXenes are used as a contact substance for electrical and optoelectronic gadgets because of the advantages of their hydrophilicity and excellent ferrous conductivity. Most MXenes have high electrical conductivities, $Ti_3C_2T_x$ being the most common with a value of ~10^4 scm^{-1},[56] which makes them attractive for use in electronic applications.

Numerous studies have been conducted to conduct an in-depth investigation into the arrangement of bands, the density of states, and many other electrical properties. First-principal calculations and experimental findings have thus far shown that the majority of (functionalized) MXene sought to be metallic or metallic-looking, while semiconductor MXenes only take a tiny number. Because of non-terminated MXenes, the outermost layer of transition metal elements often has a high density of states at the Fermi surface. The d-electrons of transition metals dominate the DOS close to the fermi surface, whereas the p-electrons of X atoms create energy bands −3 to −5 eV below the fermi surface level.[57,58]

The electrical conductivities of $Ti_3C_2T_x$ ranged from 850 to 9870 due to differences in the following factors: surface functionality, flaw concentration, d-spacing between MXene particles, lateral dimensions, as well as delamination yield caused by the etching method.[59,60] Many notable works have been done over the years. For instance, successful electrospinning fabrication of 2D $Ti_3C_2T_x$reinforced polyvinyl alcohol nanofibers has been reported in a study. PVA nanofibers with 0.14 weight percent Ti_3C_2Tx showed a dc conductivity of 0.8 mS/cm, which is better than composites made similarly but without electrospinning. High-performance energy applications can benefit from the improved mechanical and electrical properties of the Ti_3C_2Tx / CNC / PVA composites.[61]

3.3 Mechanical properties

Mechanical properties of an emerging material have a great deal of importance due to their stability, longevity, and scalability. MXene possesses excellent physicochemical properties, superior strength, and elongation with a multilayered structure which makes it ideal for various energy devices including Li-ion batteries, and supercapacitors. It exhibits good tensile stiffness (81.71 to 561.4 N/m which is superior to common 2D materials including graphene.[62]

Aditionally, xue and his colleagues reported MXene-phenyl phosphonic diaminohexane-based biopolymer with excellent mechanical and other physiochemical properties.[63] Xie et al. studied aramid/MXene nanofiber which possesses outstanding mechanical merits.[64]

4. Preparation techniques of MXene

Having been first developed in 2011, MXenes have gained popularity due to the invention of various types of MXenes based on a variety of preparation techniques. Researchers throughout the world are investigating effective ways to overcome MXene's existing synthesis limitations and developing new synthesis methods that overcome the limitations of previous methods. In the case of HF etching, high concentrations of hydrofluoric acid were required, which are dangerous to humans and the environment. Researchers have continued to strive to find a solution to this limitation and initiate alkali etching, which is environmentally friendly. In such a way, novel types of preparation methods are being developed day by day. The classification of the synthesis of MXene is illustrated in Figure 2. This section covers the most recent research on the types of MXene preparation and a summary of each technique.

4.1 Top-down methods

Top-down methods correspond to chemical etchants such as HF acid, alkali, molten salt, etc. It begins in the MAX phase, and pressure-less synthesis conditions are involved, which require room temperature. It is possible to produce thin MXene sheets with a lateral size of several hundred nanometers. A downside of MXene is that it has small crystals, irregular thickness, and defects. The summary of the top-down and bottom-up is tabulated in Table 1.

4.1.1 Hydrofluoric acid (HF) etching

In the case of HF etching, the A is separated from the MAX by a chemical reaction, where mechanical shearing is impractical due to the metallic properties of the M–A molecules. In contrast, chemical etching (using HF, HCl, and so on) is practical because of the chemically active nature of M–A rather than strong M–X. The mechanism of the HF is drowned in Figure 3(a). The chemical reactions mentioned in equations 1–3 are taken place in the formation of MXene.[65]

$$M_{n+1}AlX_n + 3HF = M_{n+1}X_n + AlF_3 + \frac{3}{2}H_2 \tag{1}$$

$$M_{n+1}X_n + 2HF = M_{n+1}X_nF_2 + 2H_2 \tag{2}$$

$$M_{n+1}X_n + 2H_2O = M_{n+1}X_n\ (OH)_2 + H_2 \tag{3}$$

4.1.2 In-situ HF etching

In response to the environmental effects of previous HF etching methods, the in-situ HF etching method is introduced to reduce the dependency on HF by using fluoride-based salts such as

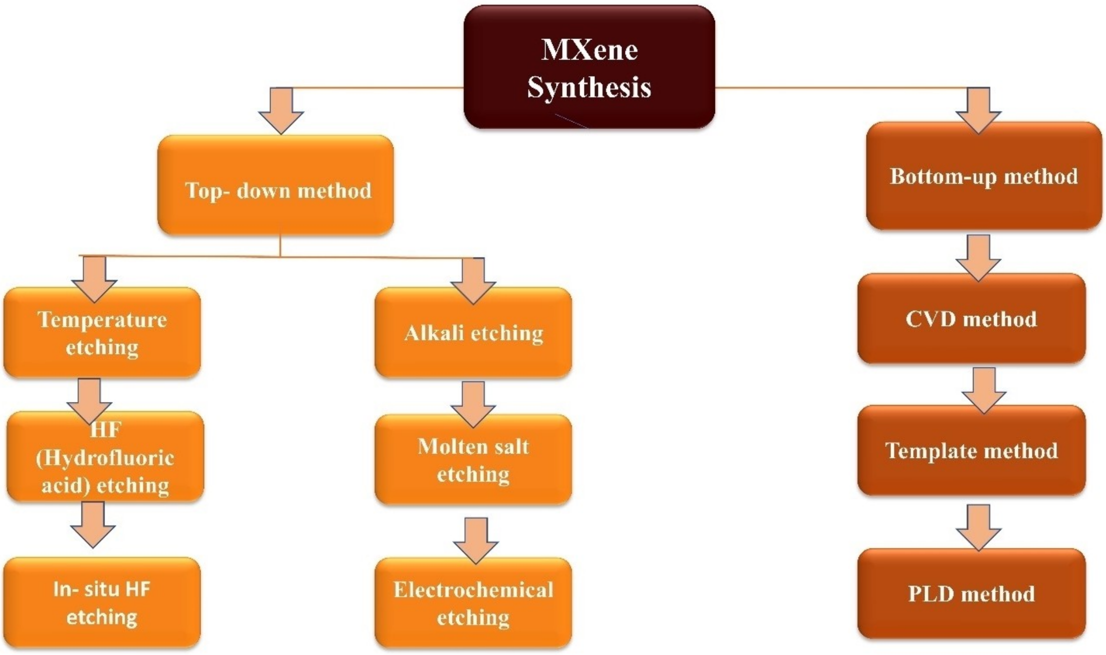

Figure 2. Major synthesis process of MXene.

LiF/NaF/KF, HCl, and other acids. The mechanism, limitations, and benefits are highlighted in Table 1, Entry 3. As a result of its short intercalation time, simultaneous etching, and intercalating properties, HCl/LiF etching is one of the oldest and most extensively studied etching methods. Cockreham et al. reported the $T_3C_2T_x$MXeneetched with CoF_2 and HCl. This $T_3C_2T_x$MXene, heterogeneity is revealed only at higher temperatures and persists up to 600 °C, stabilizing these layers at higher temperatures while maintaining access to interlayer spaces.[66] According to another study, $Ti_3C_2T_x$MXene and TiO_2–MXene composites can remove benzene by photocatalytic means under solar and NIR illumination through in situ synthesis.[67] Additionally, exploration has been carried out to develop PCN/$LaCoO_3$ Z/S heterojunctions with titanium nanoparticles embedded in situ using well-designed Ti_3C_2 MXene nano flowers.

4.1.3 Molten salt etching Method

The molten salt technique is used to delaminate the MXene layer, which has the features of high stability of $Ti_{n+1}N_n$ and effective removal of nitride-based layers of the MAX phase.[65,68] Gogotsi employed a method of molten salt etching to prepare the first MXene nitride ($Ti_4N_3T_x$) at 550 °C for 0.5 hours in the atmosphere using a mixture of salt and Ti_4AlN_3.[69] The salt mixture was KF (59 %), LiF (29 %), and NaF (12 %). Based on the important redox-controlled mechanism, Lewis acidic melts can form MXenes by etching the A-site in MAX phases, which is a good way. After this invention, many researchers put effort into advancing this molten etching technique and finding various applications.

The basic mechanism of the molten salt etching method is shown in Figure 3(b). A recent study found a substantial solar energy absorption technique of $Ti_3C_2T_x$ nanofluids through plasmon resonance, which is directly related to the increase in solar energy efficiency. It was found that $Ti_3C_2T_x$-H_2O nanofluids have the best photothermal efficiency of this, up to 91.9 %, 31.2 % greater than the base liquid, indicating their potential as a solar energy harvesting technology.[70] Other recent experiments have revealed that $Ti_3C_2T_x$ with –F surface terminations can be treated in molten salt to replace the –F with –O surface terminations in one step. When –F surface terminations are removed by –O the surface terminations, more $Ti_3C_2O_2$ is formed, increasing conductivity and electrochemical activity.[71]

4.1.4 Electrochemical etching

By employing electrolytes, the MAX phase serves as an electrode like HCl, NaCl, NH_4Cl, etc. layers are selectively removed from the MXene molecule by an electrochemical process. Titanium was eventually removed in part as well, leading to the deposition of carbon generated from carbides on the surface of the MXene. This process resulted in functional groups of Cl, –O, and –OH instead of –F terminations in the Ti_2CT_x. Additionally, it has been demonstrated that this process is a viable MXenes method for preparation.

According to a recent report, the electrochemical etching method has been used to produce fluoride-free MXene ($Ti_3C_2T_x$) which leads to the production of better quality electrochemical capacitors. With an etching efficiency of 92.2 %, the researchers employed an electrochemical etching approach to create F-free

Table 1. Summary of the preparation methods of the MXene.

Entry	Main preparation methods	Sub preparation method	Mechanism	Precursor	Limitations	Benefits	Ref.
1	Top-down method	Temperature etching method	M–A layers metallic bond is broken by the temperature	MAX phase material	The MAX phase would convert into a bulk rick salt-like structure and less effective	Setting up the synthesis is easy, and no toxic chemicals are required	[77,78]
2	Top-down method	HF (Hydrofluoric acid)etching method	The MAX phase is immense into HF solution to exfoliation of A layer		Using highly concentrated hydrofluoric acid is hazardous and has toxic impacts	Low temperature, low energy consumption, and less time required for synthesizing.	[68]
3	Top-down method	In-situ HF etching method	Mixing an acid (HCl, H_2SO_4)and a fluoride salt (LiF, KHF_2, NaF, KF and so on) to form in situ HF.		An unetched MAX phase is observed in some studies and some traces of toxic HF are produced.	Availability, low synthesis costs, less aggressive behaviour, and fewer defects	[79]
4	Top-down method	Alkali etching method	Due to the amphoteric nature of Al, alkali is used to delaminate MXene		To obtain MXene flakes, further delamination is required. High etchant concentrations hinder the process	Electrochemically applicable, non-toxic, no F groups in surface	[80,81]
5	Top-down method	Molten salt etching technique	Molten salts are used to delaminate the MXene layer which is mostly applied in nitride-based MXene.		Complexity and cost are high in this synthesis	Fluoride-free MXene, eco-friendly process, and a wide range of applications	[76,77]
6	Top-down method	Electrochemical etching	MXene is prepared from the MAX phase by an electrochemical set-up under a suitable voltage.		Formation of carbide—derived carbons (CDC) causes low yield.	Environmentally friendly process, less	[73]
7	Bottom-up method	CVD method	Chemical vapour deposition (CVD) is a process to form MXene under high temperatures with chemicals (Cu, CH_4)in a controlled atmosphere.	Starting with the atom to crystal growth	Not applicable for all types of MXene	Greater crystallinity and conductivity	[82,83]
8	Bottom-up method	Template method	TMO (Transition metal oxide is nitronate or carbonize to produce MXene in a control gas flow condition.	TMO ((e.g.–MoO3)	Nano plies are slightly thin	Higher yield than the CVD method	[3,84]
9	Bottom-up method	PLD method	Plasma enhanced pulsed laser deposition method is use plasma to obtain the Mo_2C layer	Starting with the atom to crystal growth	Have complexity	Obtain MXene crystal at a relatively low temperature	[85,86]

and Cl-containing Ti_3C_2Tx in an alkaline medium of LiOH and LiCl.[72]

For the first time, they described that creating a layer of Ti_2CT_xMXene on porous Ti_2AlC electrodes by electrochemical etching of Al from these electrodes in diluted hydrochloric acid is a less risky method. However, excessive etching issues were discovered in their research, which may be reduced by regulating the settings.[73] Another author used electrochemical etching as a method of synthesis, which leads to the production of lithium-ion batteries. According to their published study, a mild and green electrochemical exfoliation procedure is proposed to synthesize Ti_3C_2Fx and control its degree of fluorination. The electrolyte used in this experiment was a non-aqueous ionic liquid, [BMIM][PF_6]. Li-ion batteries based on MXene anodes have excellent cycling stability due to the fluorination of Ti_3C_2Fx with CF and TiF_3.[74] Moreover, HF electrochemical etching of Ti_3AlC_2 to obtain carbide-derived nanocarbon structures has been demonstrated for producing and characterization of nanocarbon structures. An electrochemical etching method based on the Ti_3AlC_2 of the MAX phase in hydrofluoric acid is proposed for producing carbide-derived nanocarbon structures. To prepare the Ti_3AlC_2 MAX phase powders, the Al, Ti, and C powders were milled, and then the powders were sintered by spark plasma sintering. In the presence of different voltages and concentrations, the solution

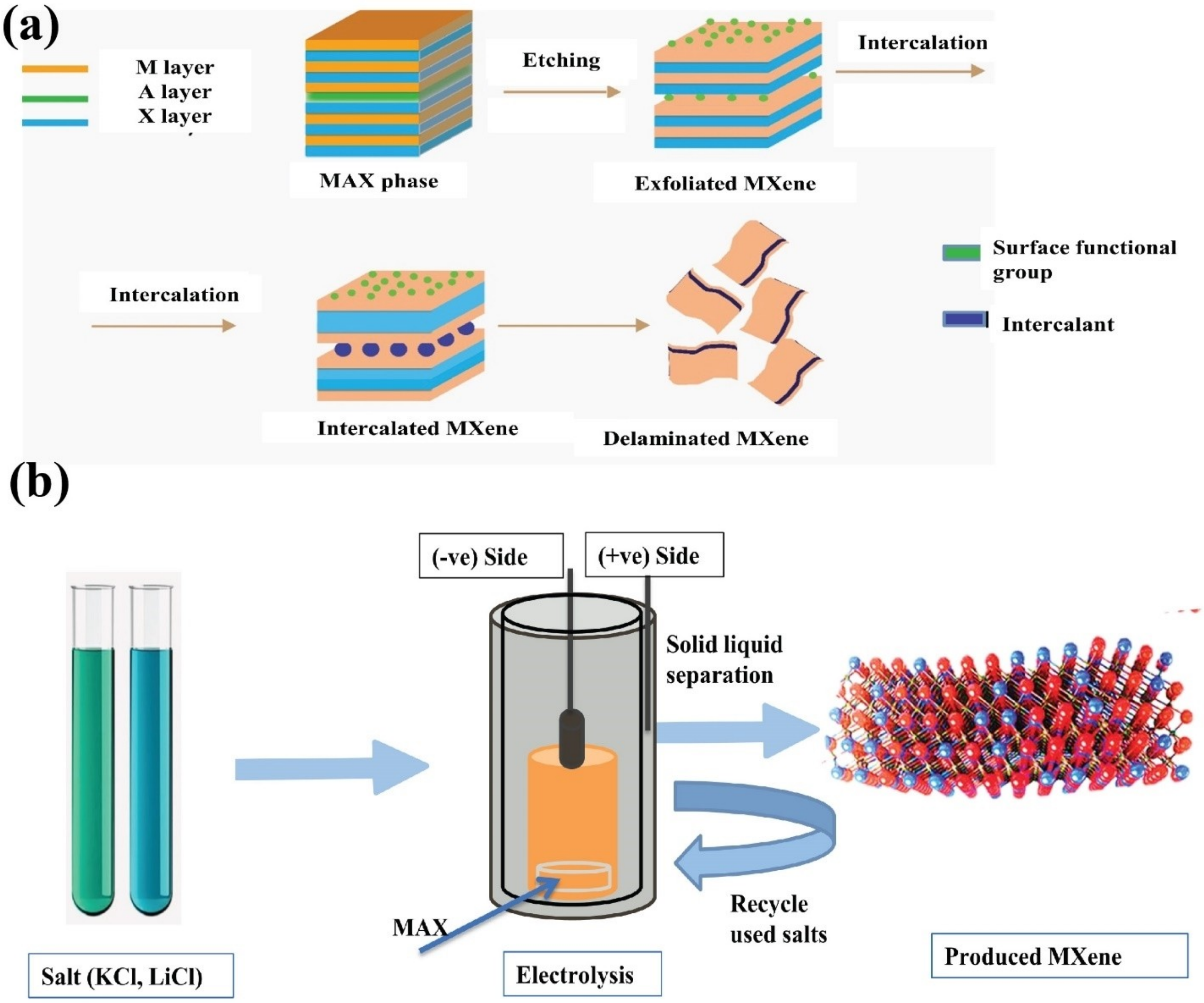

Figure 3. Schematic representation of (a) acid etching synthesis, involving various stages including etching and intercalation, to produce delaminated MXene and (b) General mechanism of the molten salt etching technique using KCl and LiCl salts through electrolysis.

of titanium and aluminium was still extruded, and carbide-derived nanocarbon structures were formed.[75]

4.2 Bottom-up methods

This method contains CVD, template, and PLD for the preparation of MXene. There are two significant types of MXene preparation: top-down technique and bottom-up technique. The top-down method entails exfoliating the bulk crystal quantities into single-layer MXene sheets, whereas the bottom-up method focusses on growth from a molecule or atom. Top-down methods pose drawbacks of small crystals, irregularity in thickness, and defects in MXene. On the contrary, bottom-up methods have better crystallinity, fewer defects in MXene, and do not contain –F terminations on the surface.[76] There are many differences in precursor type, synthesis conditions and temperatures, the morphology of MXene, and surface properties.

CVD is a method that uses high temperatures and chemicals (Cu, Mo, CH_4) in a controlled environment to create MXene, while PLD is used to create a Mo_2C layer in Figure 4(a). CVD has higher crystallinity and conductivity, but PLD produces MXene crystals at low temperatures. The synthesis is advancing day by day.

Template synthesis is a bottom-up-type synthesis technique that is used to synthesize the MXene. As shown in Figure 4(b), the precursor has to add the crystals of salts, then the coating process takes place. The mixture of the precursor and salt undergoes the ammoniating (NH_3-based process) and finally, the MoN sheets are delivered after the subsequent washing process.

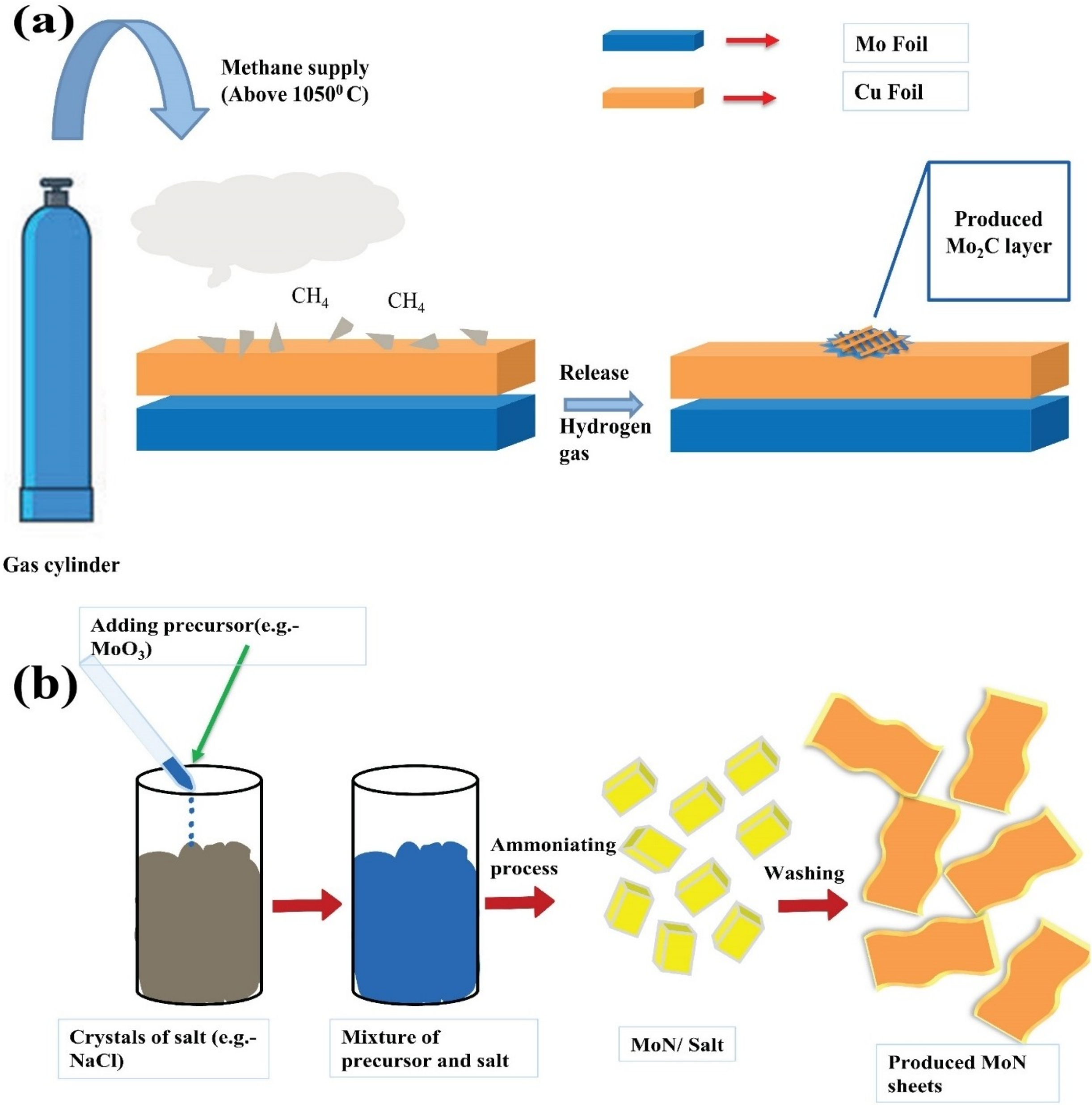

Figure 4. Common mechanism of (a) chemical vapor deposition (CVD) methods, from methane to the production of Mo2 C layer, and (b) template MXene synthesis methods, using crystals of salts for the production of MoN sheets.

5. Applications and future scope of MXene in different optoelectronics devices

5.1 Applications and future scope of MXene in solar cells

Solar energy is one of the most prevalent, cheapest, and greenest sources of energy that can be used to meet society's long-term energy needs, and it is a renewable resource.[87] Solar cells that are made of innovative materials have attracted a lot of attention. 2D materials[88] (Graphene,[20,89,90] MXene,[91] others) have gained great attention from researchers to make solar cells over the decade. This type of cell converts sunlight directly into electricity, making it one of the most practical and efficient ways to utilize solar energy.[92]

Perovskite solar cells (PSCs) have gotten a lot of received because of their rapid development regarding increasing mobility, appropriate bandgap, large carrier diffusion length, significant absorption coefficients, and so on.[93,94] The application of 2D substances in low-temperature PSCs has recently attracted consideration. According to recent works, reduced graphene-oxide-based inverted PSC with a power conversion efficiency(PCE) of 16%,[95] ultrasmall black phosphorus power conversion efficiency shows 11.26%,[96] MoS_2 based obtained 13.14%,[97] and 2D TiS_2 based found 17.37%.[98] In addition, MXene-based perovskite solar cells PCE are tabulated in Table 2.

Table 2. Progress of MXene-based solar cell's power conversion efficiency.

Entry	Basic function	Used MXene	New Approach	PCE	Ref.
1	The performance of delaminated $Ti_3C_2T_x$MXene contacted Si solar cells under AM1.5G illumination is demonstrated.	$Ti_3C_2T_x$	Contacted with Si layers	PCE obtained 11.5 %	[99]
2	Tailored lattice tape is utilized to limit the tensile interface in all-inorganic $CsPbBr_3$ perovskite solar cells for excellent efficiency.	$Ti_3C_2T_x$	The incorporation of 2D Cl-terminated Ti_3C_2 ($Ti_3C_2Cl_x$) MXene reduces superficial lattice tensile strain	11.08 %	[100]
3	The planar heterojunction perovskite solar cells by surface-modified metallic $Ti_3C_2T_x$MXene	$Ti_3C_2T_x$MXene	Surface modifications by UV-ozone treatment	17.17 %	[101]
4	Enhancement of the performance of MXene-based perovskite solar cells by oxidizing $Ti_3C_2T_x$	$Ti_3C_2T_x$	Oxidation	18.29 %	[102]
5	Perovskite solar cells with SnO_2–Ti_3C_2 electron transport layers	Ti_3C_2 MXene	Adding SnO_2 with 1.0 wt‰ Ti_3C_2	18.34 %	[103]
6	Titanium-carbide MXenes base perovskite solar cells	$Ti_3C_2T_x$	$Ti_3C_2T_x$) with various termination groups and TiO_2	20 %	[104]

In 2022, a report found that more than 24 % efficiency was obtained in a sequential vacuum-evaporated perovskite solar cell.[105]

In addition, the preparation of high-performance photovoltaic solar cells shows longer stability in performance. It possesses a great advantage in terms of being hydrophobic to prevent water to inter into the solar cell.[106] Sing and his coworkers reported advanced performance reveals by photovoltaic cells by using MXene.[107] Yu et al. reported unique charge separation solar cells by using MXene and Silicon.[108] MXene-based solar technology has bright prospects and a large market. Using MXene-enhanced PCM and optical filtration, a mathematical model of a PV/T module has been developed to advance the optoelectronics field. Compared to the traditional PV/T module, their study shows a thermal and electrical output of 5370 kWh and 5620 kWh with a thermal efficiency of 74.92 % and 14.65 %, respectively.[109] According to a recent study, tuning of nonlinear work functions of lead-halide perovskites using $Ti_3C_2/CH_3NH_3PbI_3$ ($MAPbI_3$) perovskite coupled. Varying the proportions of OH, O, and F terminations exhibits strong nonlinear behaviour, with OH groups leading to the greatest decline in work function.[110] This development has great potential to grab future markets.

5.2 Applications and future scopes of MXene in plasmonics

The term plasmonic's refers to surface plasmon resonance in condensed matter physics, one of the most technologically advanced fields.[111] A plasmonic effect arises from surface plasmons in nanomaterials and their structures.[112] These nanomaterials have a unique confinement profile that causes distinctive plasmonic effects.[113] Plasmonics is now used in different tech-based applications (Figure 5). Optical and plasmonic properties of MXene have recently been demonstrated due to their ultrathin-atomic-layer structure.[114] Although, they have only been marginally explored for use in photonic and plasmonic instruments. The use of a class of 2D materials with considerable light-matter interaction ensures an efficient quantum confinement effect.[115] Because of their extraordinary plasmonic capabilities, a wide range of materials, including semiconductors,[113,116] conductive oxides,[117–119] and dielectric materials,[120,121] have been explored as plasmonic materials. Because of their advanced characteristics, as well as bandgap manipulation and electron transmission, 2D materials have received considerable attention for plasmonic purposes, and possess a promising prospect.[115]

There are several reasons why MXenes are likely to be used in plasmonic applications, such as their tunable properties resulting from their different compositions, surface terminations, dopings, or nanocomposites with other materials.[122] Consequently, MXene can be used to create tailorable electroconductive platforms that can behave as metals or semiconductors while providing optical transparency.[123] Those properties made MXene-based devices unique and suitable for the develop high regulation cameras, superfast optical laptops, cloaking devices, lasers for modern cars, and many more.It is possible to add MXene with various polymers to make those devices.[124]

However, the bulk of MXene plasmonic applications have been studied theoretically or analytically. The reason is that the field is relatively new. The number of applications that are currently in use is small, but many are promising. The fabrication of noble metal nanoparticles such as Ag, Au, Pd, etc., and MXene nanosheets for surface-enhanced Raman spectroscopy has been reported in a recent paper.[125] Novel 2D hybrid materials can now be applied in sensors, catalysis, and optoelectronics for visible-range SERS.

Moreover, a novel technique is proposed to create novel MXenes/metal composites with distinctive chemical character-

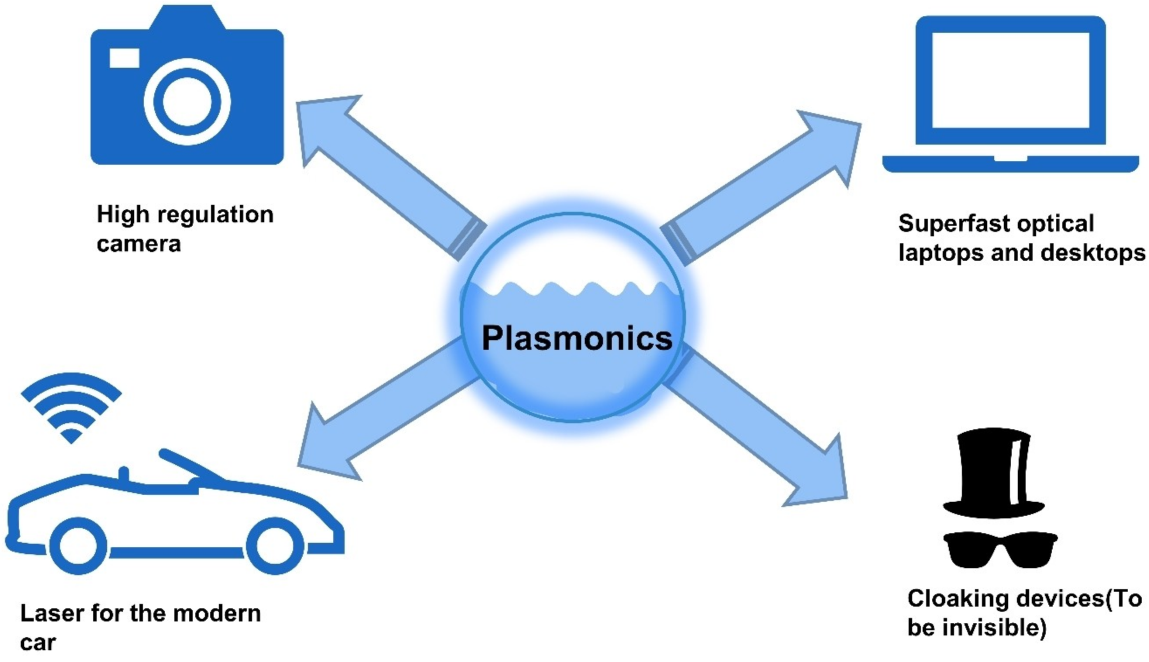

Figure 5. Different applications of plasmonics.

istics. $Ti_3C_2T_x$/Au nanocomposites are made under specific conditions, and the impact of the reduction reaction time on those environments is investigated. The contribution of the nanocomposite produced to the surface Raman reinforcement is also examined.[126]

5.3 Applications and future scopes of MXene in photodetectors

The principles of photodetectors convert incident light into electrical signals in the UV, visible, and infrared spectral regions. The main characteristic of all photodetectors is that they are all square-law detectors, meaning that they respond to an optical signal‘s intensity rather than its field amplitude, which plays a crucial function in a variety of industries, including optical communication, biological sensing, and environmental monitoring. The application of MXene in photodetection has a significant prospect. However, a 2D material-based photodetector was developed in response to the numerous drawbacks associated with traditional photodetectors today. For instance, MoS_2, $MoSe_2$, WS_2, and other transition metallic dichalcogenides are typical 2D materials. The materials feature a tunable band gap that is correlated with the number of layers. Few or many transition metallic dichalcogenides have an indirect band gap, while monolayers become semiconductors with a direct band gap. They can create phototransistors with high switching ratios, but their poor carrier mobility at room temperature limits the range of devices they may be employed in.

The discovery of the two-dimensional graphene material triggered a flurry of research on 2D materials. They exhibit remarkable chemical, physical, electrical, optical, mechanical, and thermal characteristics due to the strong covalent bond or ionic bonding forces inside the layered and the poor van der waals interactions between them, which have piqued scientists′ intense interest in their investigation. As a result, 2D material-based photodetectors have been developed. As a class of 2D substances, MXenes are members of the transition metallic carbide, nitrides, and carbon nitrides category. MXenes have a variety of functions in photodetectors, including working electrodes that are transparent, Schottky contacts, photo absorbers, and plasmonics. These roles are made possible by fascinating optical and electrical features, such as transparency, saturable absorbency, and excellent electrical conductance. Due to their excellent possibility of huge synthesis and solution-processability, MXenes are sought for use in a variety of electrical and photonic gadget solutions including photodetectors.

Self-powered photodetectors with $Ti_3C_2T_x$ /Si microstructure Schottky junctions for photoplethysmography monitoring were studied by Song et al.[127] Guo et al.[128] report the embedding of $Ti_3C_2T_x$ nanocrystals in $MAPbI_3$ microwires to improve the response and detection of the photodetector. When $Ti_3C_2T_x$ NCs are present, defects are rendered passivated, crystalline alignment, charge transport, and carrier excavation for $MAPbI_3$ microwires are improved, and the mobility of microwire-based film is booted, all of which improve photodetector performance by a factor of about ten over that of the control. MXene has gained popularity in the production of the photodetector. The $Ti_3C_2T_x$ NCs incorporated $MAPbI_3$ microwires photodetectors have maximum responsiveness and detectivity of 1.70 AW^{-1} and 7.0×10^{11} Jones in the viewable window, respectively. Their result indicates that the high conductivity $Ti_3C_2T_x$nano crystals produced by lasers are an efficient additive for the perovskite microwires to manufacture performance-enhanced optoelectronic solutions. Another author[129] worked on the problem of polydimethylsiloxane photodetector arrays fabricated on BiOCl nanosheet arrays, transferred from Cu substrates, which exhibit negligible photocurrent when exposed to UV light. The heterojunction of the Ti_3C_2Tx conduction layer on a PDMS substrate decorated with ZnO nanoparticles has been shown to provide better UV photodetector performance. These BiOCl-based photodetectors are enhanced by the heterojunction design, which encourages their widespread use in photoelectric devices.

Here Zhang et al.[130] works by simply pouring $Ti_3C_2T_x$ solution over a GaAs substrate that has been previously designed, they show how to create a high-quality $Ti_3C_2T_x$/GaAs Schottky connection. The combined photodetector has a decent response of ~1.46 A/W, a significant specific detective of $\sim 1.23\times 10^{13}$ Jones, as well as a significant ratio of 5.6×10^5, all of which demonstrate strong sensitivity over a broad waveband. Because hot electrons are produced in the $Ti_3C_2T_x$MXene layer, the photodetector can detect infrared signals up to 980 nm, which is higher than the absorption edge of GaAs. The $Ti_3C_2T_x$/GaAs schottky junction photodetector may have a lot of potential for highly efficient, self-driven photodetection projects due to the higher device performance and easy, straightforward fabrication process. Additionally, Xiong et al.[131] used a controllable strategy to construct a 3D networked $Ti_3C_2T_x$-TiO_2 heterostructure. By improving optical absorption and exciton separation, the 3D-networked heterostructure improved the performance of the photodetectors. For optical imaging, the developed photodetectors could be assembled into a large area array. On the other hand, Mo based MXene has paid a good attention. For instance, Jeon and his team reported Mo_2C based multiperiod gratings for high and broad-spectrum photodetection applications.[132]

Furthermore, many recent developments have been observed over the year. The Ti_3C_2Tx MXene flexible transparent photodetector array is intended for the 1024-pixel imaging sensor application have studied.[133] Authors[134] have constructed a high-performance ReS_2/Ti_3C_2Tx-based visible and near-infrared photodetector. Enhanced performance was achieved by using MXene ($Ti_3C_2T_x$) as the transport layer. They compared the performance of the ReS_2 /$Ti_3C_2T_x$ photodetectors with that of ReS_2 / graphene. The author[35] developed a photodetector based on the photogalvanic effect called the $Ti_3C_2T_x$ (MXene). A stacked few-layer $Ti_3C_2T_x$ with broken space inversion symmetry demonstrates an important role for the photogalvanic effect in generating polarized photocurrents at zero bias. In their study, they demonstrated that the $Ti_3C_2T_x$-MXene can be used for high-performance low-power photodetection.

A summary of materials, responsivity, detectivity, and response time of MXene-based photodetectors have presented in Table 3.

The semiconductor generation has developed since the first transistors were created in 1947, and the field of silicon-based transistors has advanced significantly. At first, amorphous silicon (a-Si) was used to construct thin-film transistors (TFTs); however, the limitation of poor mobility was identified as a persistent drawback. As indium gallium zinc oxide, which has a better motion and low off-current than a-Si, was created, this issue took a new turn. Beyond screens, memory, and sensor applications, researchers are always trying to find new uses for metal oxide semiconductors. In such a way, the development of phototransistors is going great, and MXene is bringing great progress.

Photodiodes, photoconductors, and phototransistors are the three categories that photosensors typically fall under (Figure 6). Two-terminal devices called photodiodes and photoconductors connect a photoactive substance to two electors. By accumulating photogenerated carriers in the electrodes while being exposed to light, a photodiode or photoconductor operates. Through accumulating photogeneration carriers at electrodes under light irradiation, a photodiode and a photoconductor function. In contrast to a photoconductor, which is built using the ohmic junction and has a lateral structure, a photodiode is built using p-n or Schottky junctions and has a clear vertical structure.

The source, drain, and gate electrodes of TFTs are the same three electrodes that make up the construction of phototransistors. The device works similarly to a two-terminal device by collecting photogenerated carriers that travel over the active layer. The gate bias's strength, for instance, can be used to regulate how much drain current flows through the accumulation channel. The ability of phototransistors to amplify the output signal by controlling the voltage across a gate electrode has recently been demonstrated to have advantages in the fabrication of high-performance photosensors.

Table 3. Materials, responsivity, detectivity, and response time of MXene-based Photodetectors.

Material	Responsivity	Detectivity (Jones)	Response Time	Ref.
MXene-GaAs-MXene photodetector	278 mA/W	11.6×10^{10}	500/12 ps	[135]
Perovskite-MXene-based photodetector	44.9 mA/W	6.4×10^8	48/18 ms	[136]
MXene/perovskite/MXene photodetector	84.77 A/W	3.22×10^{12}	24.6/14.7 ms	[137]
MXene/TiO_2 semitransparent UV photodetector	6 mA/W	$\sim 10^{11}$	2.27/2.54 s	[138]
Patterned-Ti_2CTx/InSe photodetector	1×105 A/W	3.5×10^{13}	0.5/26 ms	[139]
ZnO-BiOCl/TiC/PDMS photodetector	94.2 μA/W	5.86×10^{10}	2.59/0.93 s	[140]

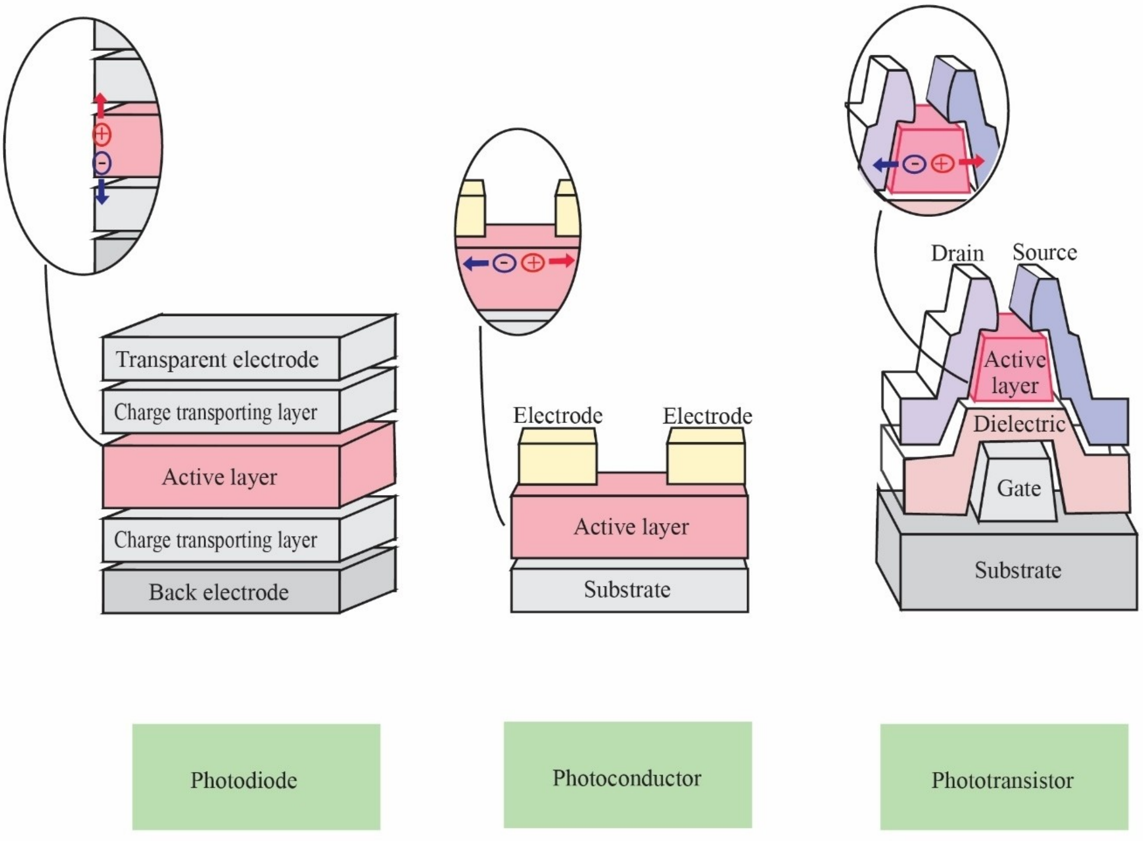

Figure 6. Schematic illustrations depicting various types of photosensors.

Lin and his colleagues[141] reported organic materials/MXene-based high-performance phototransistors over the broadband spectrum, which was challenging. This MXene-doped organic phototransistor looks promising to prepare highly effective OTP.

Enlong and his research group have introduced a next-generation vertical transistor incorporated with MXene.[142] This device reveals great potential for rapid response with simple material and design and enormous opportunities for smart photoelectronic devices [154].

5.5 Applications and future scopes of MXene in LED

The light-emitting diode known to us as LED is a commonly used standard source of illumination in electronic components, with uses ranging from your cell phone to big advertising billboards. When a forward-biased diode is used, the conduction band electrons in the semiconductor join again with holes from the valence band, releasing enough energy to yield photons that emit monochromatic light. As semiconductors, Gallium Arsenide (GaAs), Aluminum Gallium Arsenide Phosphide (AlGaAsP), Aluminum Gallium Phosphide (AlGaP), Silicon Carbide (SiC), and Zinc Selenide (ZnSe) are used for a long time.

Over the last few decades, the use of 2D materials (Graphene, MXene, BN) has attracted the attention of the manufacturer due to their excellent electrical and optical properties. Recently, MXene-based flexible LED and organic light-emitting diodes have received great attention. Figure 7 shows the MXene-based LED.

Ahn et al. reported[143] MXene sheet made of 2D titanium carbide transparent conductive electrode features such as high conductance (11670 Scm^1) and significant work function (5.1 eV). To prevent deleterious surface oxidation and subsequent electrode film deterioration, a neutralizing of chemicals technique of a conducting polymer hole that injects a layer is adopted.

Furthermore, Po Lu et al. proposed[7] a ZnO-Ti_3C_2 MXene electron transport layer for greater external quantum efficacy of perovskite nanocrystal light-emitting diodes in their article. Yi et al.[144] presented MXene-GaN van der Waals heterostructures for high-speed self-driven LED and photodetectors.

5.6 Applications and future scopes of MXene in photothermal therapy

Human health is seriously endangered by infections caused by bacteria resistant to antibiotics.[145] The development of antibiotic-independent antibacterial strategies against drug-resist-

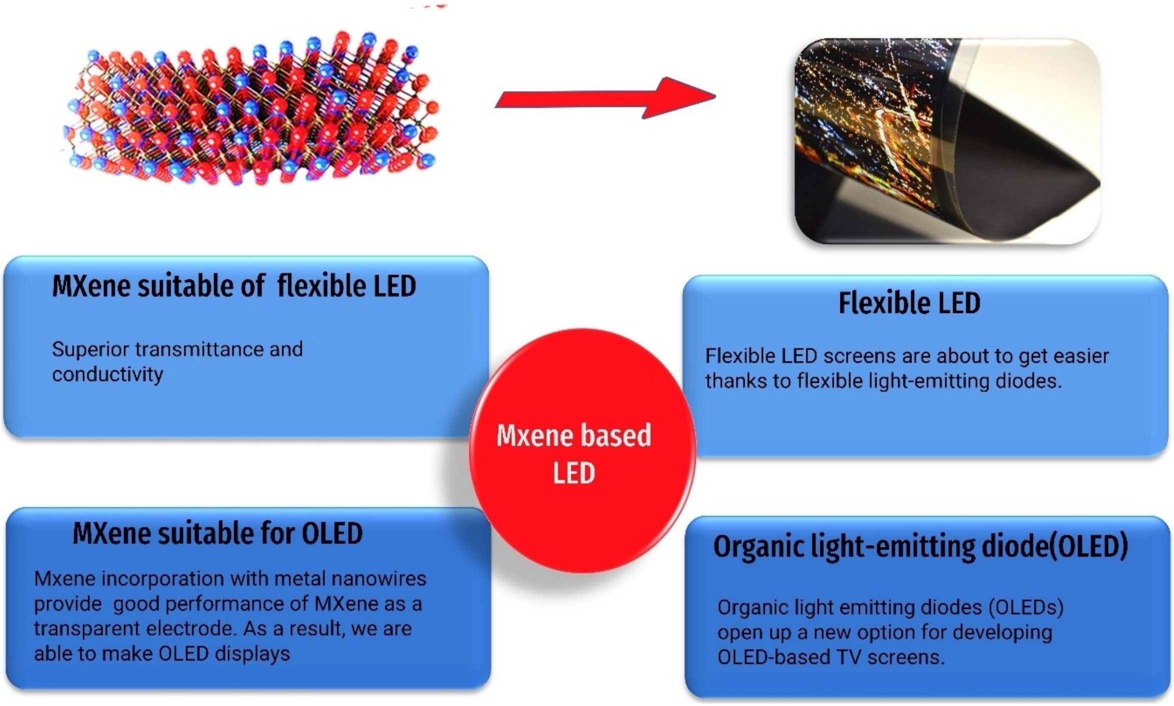

Figure 7. Schematic illustrations of the types of the MXene-based LED.

ant bacteria is of utmost significance and importance given the challenges and length of time involved in the synthesis of new antibiotics.[146,147] In this context, photothermal therapy has received a lot of attention. A mechanism is illustrated for the application of photothermal therapy on the rat in Figure 8.

MXene, a versatile usage of new materials, is also gaining a lot of attention in this respect as well. Indocyanine green-loaded $Ti_3C_2T_x$MXene for combined photothermal and photodynamic therapy for drug-resistant bacteria has been presented in a recent report.[149] Sun et al.[128] published a Valence-switchable MXene nanoplatforms for anti-infective therapy with photothermal-enhanced dual enzyme-like capabilities. Lin et al.[129] reported the production of IR780-modified Ti_3C_2 nanosheets as NIR-triggered nanoplatforms to cure laryngeal cancer in their work. The multifunctional materials discovered have a bright future in the treatment of laryngeal cancer. Xu et al.[30] revealed a conceptually innovative "dual-therapeutic prodrug nanomedicine" technique for synergistic cancer therapy. Previously, the authors[150] revealed that MXenes, a novel bioactive nanosubstance with intriguing photophysical characteristics, can improve the efficacy of focused breast cancer photothermal therapy. Also, the impact of few- and multi-layered $Ti_3C_2T_x$ mediated with PTT on 2 distinct 3D reliable breast models of cancer, such as conventional and bio-printed spheroids, was

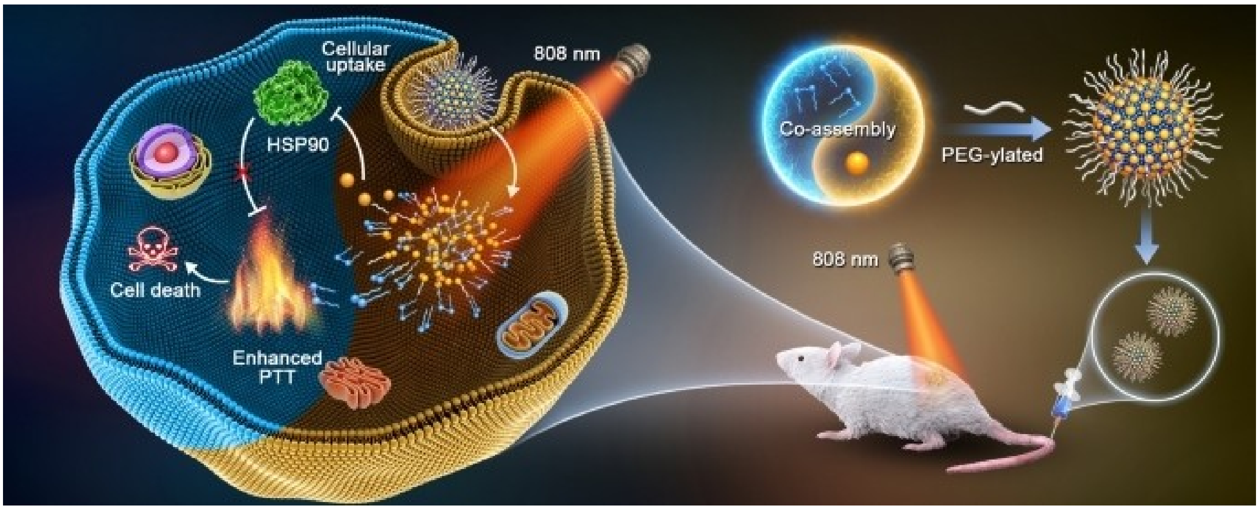

Figure 8. Photothermal therapy apply on the rat.[148] Published under CC BY License.

studied in their work. According to Liu et al.,[151] Ti_3C_2-CoNWs nanocarrier heterojunction exhibits pH-/NIR-responsive drug delivered. The photo-thermal ability of the Ti_3C_2-CoNWs nanocarrier heterojunction has been improved. Finally, a summary illustration of the applications is presented in Table 4.

6. Challenges and prospects of MXene

MXene is widely used in optoelectronics due to its tailoring structure and outstanding optical, electrical, and magnetic properties. This review found a huge opportunity for MXene-based different optoelectronics, including photothermal therapy, light-emitting diode, phototransistor, photodetector, plasmonic, and solar cells. In addition, there are great business opportunities and market demand for those devices. A graphical illustration in Figure 9 representing various prospects and challenges of MXene.

Table 4. Efficiency of MXene of applicable material in photothermal therapy.

Materials	Photothermal conversion efficiency (%)	Extinction coefficient ($l.g^{-1}$ cm^{-1})	Imaging techniques	Ref.
MnOx/Ti_3C_2-SP	22.9	5	MRI	[152,153]
$Ti3C_2$ QDs	52.2	52.8	PA, Fluorescence	[21]
Ta_4C_3-SP	44.7	4.06	PA, CT	[30]
MnOx/Ta_4C_3-SP	34.9	8.67	PA, CT, MRI	[154]
Ta_4C_3-IONP-SP	32.5	4	PA, CT, MRI	[155]
GdW_{10}/Ti_3C_2	21.9	22.5	MRI, CT	[156]
Nb_2C-PVP	36.4	37.6	PA	[156]
$Ti3C_2$-DOX-HA	58.3	28.6	Fluorescence	[37]

6.1 Overcoming the limitations of MXene

In addition to many benefits, MXene has a few drawbacks, including weak mechanical properties, easy stacking, limited lateral dimension, and poor stability in an oxygen environment.[12]

6.1.1 Improve the stability in an oxygen environment

Oxidation has been considered to be one of the major problems that ensures the quality of MXene-based optoelectronic devices. Currently, MXene's biggest problem is the instability of its materials. HF-etched MXenes are stable at room temperature, but HF is not environmentally friendly.[157] The Non-HF etchants like HCl, HNO_3, NH_4HF_2 etc. may enhance safety, and stability can vary based on the precise etchant used. Washing, delamination, and surface modifications can improve stability by changing surface chemistry.[158]

In addition, MXene materials have significantly decreased due to the oxygen environment during the preparation process. This has become a major obstacle to MXene industrialization. Meanwhile, efforts have continued to overcome this limitation for example MXene embedding with polymer (PVA, polydopamine, etc.[159,160]), preparation of minimally faulty layers, improvement of storage conditions, the substitution of organic solvents for water, and so on.[161,162] However, there is huge scope for research to make MXene perfectly resistant to oxidation. Therefore, MXenes' stability and challenges must be addressed in future research for various applications.

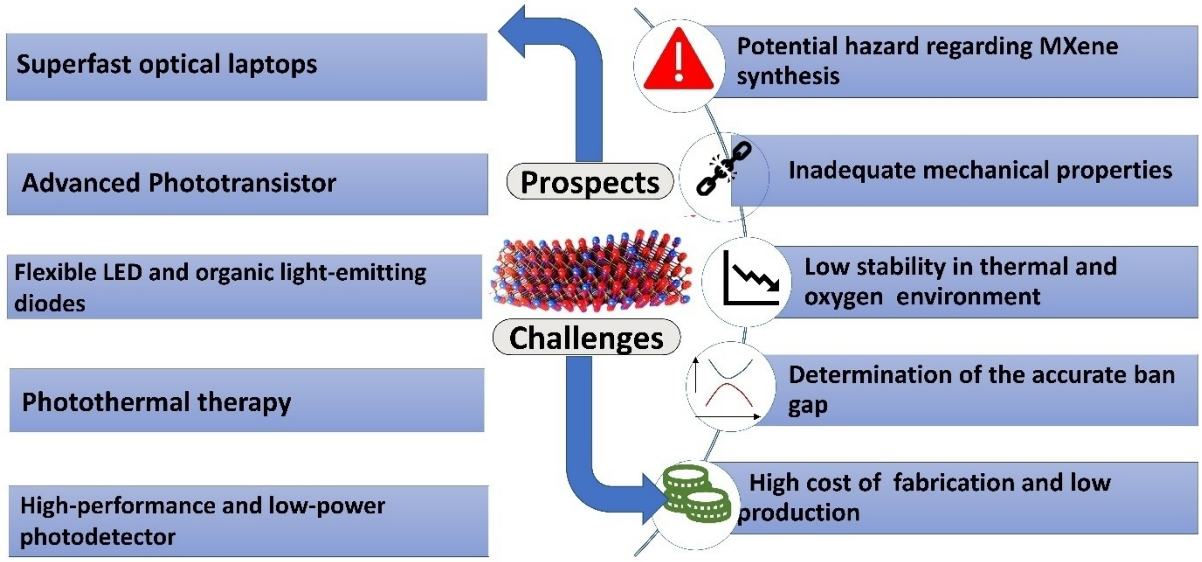

Figure 9. Graphical illustration representing various prospects and challenges of MXene.

6.1.2 Improve the mechanical properties

In addition, research is underway to improve the mechanical properties of MXene to make it more suitable for the production of LEDs, phototransistors, photodetectors, and solar cells according to the customer's demand. For instance, imparting the materials compounding like PEDOT,[163] poly diallyl dimethylammonium chloride, polyvinyl alcohol,[164] natural rubber, cellulose nanofiber,[165] cetyltrimethylammonium bromide,[166] glucose to increase the mechanical properties.

6.1.3 Improve the stacking problem

Easy stacking is one of the prime limitations of MXene which have to be overcome to face the challenge of the competitive world market demand for optoelectronic devices. However, few works have been done to overcome this challenge by adding new material.[167]

6.1.4 Boosting the conductivity

Boosting the electrical conductivity brings many benefits to modern optoelectronic instruments and research that is as a part of the continuous development of MXene. Although MXene has excellent electrical properties, this makes it a wonderful choice in the manufacturing of optoelectronic devices. When current properties are analyzed, further research could be conducted toward the modification of this material to enhance the properties mentioned above. Recently, atomic doping has been paid attention to improve conductivity. NH_3 with solvothermal treatment,[168] $(C_6H_5)_3P$[169] and $(NH_2)_2CS$[170] with minor heat treatment have been used over the years. Besides this, real terminal interchange and outer terminal imparting could be a good way to increase the conductivity of developed MXene.[171]

6.1.5 Improvement of the temperature sensitivity

Temperature sensitivity is one of the major drawbacks of MXene. Future work should be carried out to reduce the temperature sensitivity drawbacks of MXene-based optoelectronics.[172]

There is a great future opportunity to overcome those limits and modernize the sectors of optoelectronics, energy storage, and flexible electronics. The good qualities of MXene enable them to serve as electron and hole collectors, conducting additives, and buffer materials in optoelectronic applications. The good and tunable features, together with the solution processable and low-temperature technology, allow them to be considered well-matched with organic and perovskite-based optoelectronic manufacturing processes and suitable for flexible device applications.

6.1.6 Exploration of the new application of MXene

Exploration of the new application in ultra-fast lasers, light emitters, modulators, and plasmonic generators due to the appreciable properties of MXene such as high conductivity, tuneability, bandgap (0 to 2.0) eV, and tunable bandgap for this. Y.I. John and his colleagues[173] reported the development of a reliable mode-locked laser. In ref.,[174] a highly efficient $Ti_3C_2T_x$-based laser with a pulse duration of 316 fs and an output power of 0.77 W was reported. However, there is huge scope for application-based research to advance the ultrafast laser, light emitter, and other optoelectronic devices. Incorporation of MXene with various polymers to prepare nanomembrane by electrospinning has a great prospect.[175]

The defence and aviation sectors have a great application of optoelectronics due to the limitations of air RF links in underpasses, marine ships, and restricted spaces. These limitations might be overcome with modern optoelectronics, including optical repeaters and networks. For instance, the $Ti_3C_2T_x$ MXene dipole antenna at 2.4 GHz was first created and tested by the Gogotsi's team.[170] Li and his colleagues created a stretchable S-MXene dipole antenna using single-walled carbon nanotubes.[176] There are still many rooms to work on. Therefore, future research can enhance various applications in this field.

6.2 Determination of the accurate band gap

The band gap is now a significant parameter in the field of optoelectronics. MXene has received a surge of attention to tunable band gaps to meet future optoelectronics devices. However, most of the computational techniques are theoretically based. For instance, density functional theory was used to investigate double transition metal MXene's with Ti and various surface metallic and cationic layers in the ref..[177]

However, recently artificial intelligence-based band-gap computational techniques have been developed. Rajan et al.[178] reported an MXene band gap computational method based on machine learning. The authors claim that their technique will provide more accurate results than existing methods. The accurate calculation of the band gap is a key factor in the development of effective optoelectronic devices. Therefore, future research should be carried out to develop new technology-based computation methods that will offer an accurate band gap.

6.3 Improvement of existing synthesis methods

There are two major types of synthesis available, including top-down and bottom-up synthesis methods. Under two classes, there are many syntheses available. Researchers are looking for effective ways to overcome MXene's existing synthesis limitations and developing new synthesis methods that overcome the limitations of previous methods. For example, high concentrations of hydrofluoric acid are required for HF etching, which is hazardous to humans and the environment. Researchers have been working hard to find a solution to this limitation and begin to etch with environmentally friendly alkalis. As a result, new types of preparation methods are being developed daily. Future efforts should be made to achieve a sustainable, multifunctional, cost-effective, and long-term stable synthesis of MXene.

6.4 Miscellaneous future scope

Attention should be paid to the development of new products that will be commercially viable. In addition, research efforts are needed to make MXene-based optoelectronics affordable for all classes by reducing costs.[179] Also, improve photothermal and photodynamic therapy[180] should be taken into consideration. Furthermore, MXene-based nanosheets and nanomembrane tend to stack together through van der Waals contacts, resulting in a restricted number of active sites, slow ionic kinetics, and to-end average MXene material/device effectiveness. Incorporation of MXene with textiles can be a good scope in wearable electronics.[181] The global MXene Market is now estimated to reach \$26.4 million. This is expected to reach \$121.5 million in 2027, with a CAGR of 29.24 % between 2022 and 2027.[182] To work, this topic must be addressed and have a massive market demand. Therefore, the issues mentioned above must be addressed because they are significant for the advancement of optoelectronics.

7. Conclusions and future outlook

The 2D material MXene has become the most potential for solar cell, plasmonic, and other optoelectronic device materials due to its extraordinary properties. MXene has achieved popularity for different types of MXene based on diverse production processes and a wide range of applications. This study highlights the progress of this substance and its use in the field of optoelectronics. Researchers were able to identify the limitations of MXene and discuss how to overcome them so that they can benefit from it. In addition, the mentioned future research direction including the scope of band gaps and quantum dots for MXene-based modern optoelectronics and digital device production will open a new window for industrialists and scientists. Moreover, limitations have been identified in the work on MXene-based synthesis techniques to meet the global market demand. At present, the global market for MXene is estimated to be worth \$26.4 million and is forecast to reach \$121.5 million by 2027. MXene, therefore, is in dire need for improvement and must be made commercially feasible for modern optoelectronic devices by overcoming its limitations and enabling it to overcome its limitations. Considering the current and future applications of MXene, as well as addressing existing research challenges and getting a future direction with a solution, this article can be utilized as a credible source and state-of-the-art for researchers.

CRediT authorship contribution statement

Md. Tanvir Hossaın: Conceptualization, Methodology, Data collection, Writing – original draft preparation, Visualization. **Md. Reazuddin Repon**: Conceptualization, Methodology, Data collection, Writing – original draft preparation, Writing – review & editing, Supervision, Contents approval. **Md. Abdus Shahid**: Writing – review & editing, Visualization. **Ayub Ali**: Writing – review & editing. **Tarikul Islam**: Conceptualization, Resources.

Patient consent statement: Not applicable.

Permission to reproduce material from other sources: The approval and consent have been obtained where necessary. Where approval has been waived, credit has been given via appropriate citation.

Clinical trial registration: Not applicable.

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All data presented herein are constant with the published literature.

Keywords: MXene · $Ti_3C_2T_x$ · Optoelectronics · Solar cells · Light emitting diodes · Phototransistor

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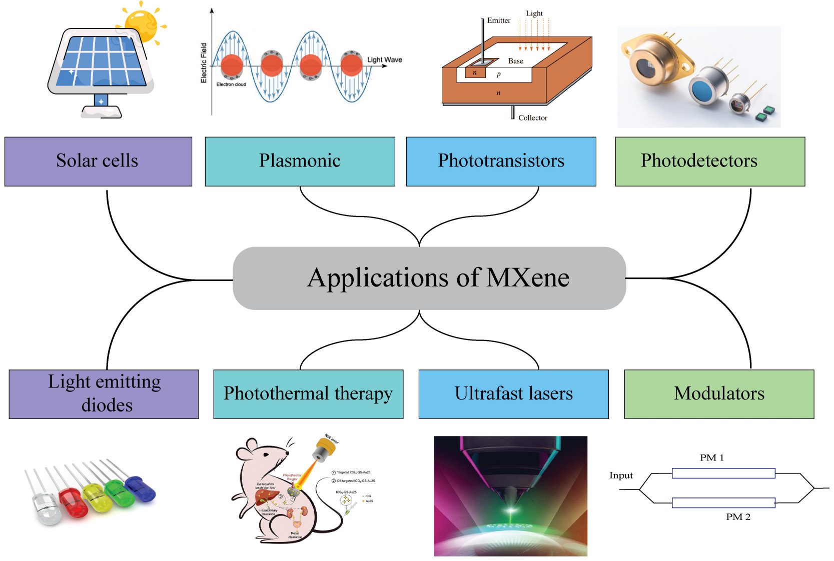
REVIEW



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Progress, Prospects and Challenges of MXene Integrated Optoelectronics Devices

This review provides an overview of the fundamentals, preparation techniques, properties, and applications of MXene, along with addressing the mechanism, limitations, and potential benefits of various methods of MXene preparation. The present paper also explores the ways that we can overcome the current challenges and provide a roadmap to the future of MXene in different fields of optoelectronics.