Proceedings of CONF-FMCE 2025 Symposium: Semantic Communication for Media Compression and Transmission
DOI: 10.54254/2755-2721/2025.GL29000

Structural Design and Practical Application of a Flexible Photodetector Based on Mxene

Zhenyu Luo

Queen Mary University of London Engineering School, Xi'an, China
204773945@mail.nwpu.edu.cn

Abstract. Due to its excellent electrical, mechanical, and interfacial properties, 2D transition metal carbide/nitride (MXene) has shown broad prospects in the fields of energy storage, sensing, and optoelectronics, and is gradually expanding to flexible optoelectronic devices. Although its high conductivity is limited in traditional semiconductor light detectors, the abundance of functional groups on the surface provides unique advantages for device design, interface engineering, and environmental stability. This paper reviews the latest progress of MXene-based flexible photodetectors, focusing on material semiconductorization, heterojunction and transparent electrode design, micro-nano processing and device integration, and reveals their performance breakthroughs in responsiveness, response speed, signal-to-noise ratio, and mechanical adaptability. Combined with the photoelectric conversion mechanism, the role of MXene heterostructure in thermoelectronic effect, near-field enhancement, and carrier multiplication was analyzed. Finally, this article outlines the promising applications of MXene in wearable health monitoring, environmental sensing, visual computing, and optical communications. It also emphasizes that process controllability, environmental stability, and scalable manufacturing remain key challenges that must be overcome in the future. Research demonstrates that MXene has the potential to become a core material for next-generation flexible optoelectronics, offering new avenues for cross-disciplinary applications and industrialization.

Keywords: MXene, flexible photodetectors, heterojunction design, surface functional groups, wearable sensing

1. Introduction

The rapid development of flexible optoelectronic technology has put forward higher requirements for the mechanical adaptability, photoelectric response speed, and integration compatibility of detectors. Although traditional semiconductors (such as silicon and InGaAs) have excellent optoelectronic characteristics, their intrinsic brittleness and complex processes are difficult to match with emerging practical application scenarios such as wearable devices and curved displays. Although emerging two-dimensional materials (graphene, transition metal sulfide) have flexible advantages, they are limited by the bottleneck of short carrier life and high dark current. Therefore, there is an urgent need to explore new material systems with high conductivity, flexibility, and

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2025.GL29000

interface tunability to break through existing bottlenecks and promote the development of flexible optoelectronic devices. The discovery of transition metal carbides and nitrides (MXenes) provides a new material platform for the design of flexible photodetectors. $Ti_3C_2T_x$ and other materials obtained by hydrofluoric acid selective etching of MAX phase, with metal-like conductivity (>4600 S/cm), fracture strain of more than 6%, and abundant hydrophilic functional groups (─OH, ─F, etc.) on the surface, can realize the integration of photoelectric active layers and flexible electrodes [1]. This unique combination not only optimizes the structural design of the device but also improves the efficiency of interface coupling. In recent years, MXene-based flexible detectors have made significant progress in micro-nano structure engineering, bandgap regulation, and heterojunction design, achieving ultra-fast response (<150 ps) and strain insensitivity [2, 3].

However, MXene's widespread application in flexible optoelectronics still faces many challenges, such as stability control in interface engineering, oxidation and degradation under environmental conditions, and green, scalable preparation process gaps. These problems limit the pace of devices moving from the laboratory to industrialization.

Therefore, this study not only aims to sort out the research progress of MXene-based flexible detectors from structural design to application, but also hopes to point out key breakthroughs in the future industrialization process. By analyzing the physical mechanisms behind its performance advantages, this paper aims to reveal the technical bottlenecks that still need to be solved, thereby providing new research ideas and potential contributions to the development of this field.

2. Material source and optoelectronic regulation mechanism of MXene

2.1. Synthesis and structural regulation of MXene

MXene is typically chemically etched from MAX phase precursors. Taking Ti3AlC2 as an example, the use of HF or LiF-HCl solutions can effectively strip the Al layer to obtain Ti3C2Tx [4]. New MXene systems are emerging, such as Mo2TiC2, Nb2C, etc., which enrich the elemental variety of materials. The surface functional groups (–OH, –O, –F, etc.) generated during the etching process greatly affect the electronic structure and adsorption properties of MXene [5]. These functional groups not only improve the adhesion of MXene on flexible substrates but also provide room for subsequent functionalization and bandgap engineering [6]. For example, surface modification or alternating deposition can induce the bandgap opening of MXene, giving it semiconductor characteristics.

2.2. Bandgap engineering and physical mechanisms

Due to the original metallic properties of MXene, bandgap engineering is required to improve light detection performance. One strategy is doping or oxidation. Studies have shown that oxygendoped Ti3C2Tx can introduce additional electronic states and partially open the bandgap, effectively improving light absorption [7]. At the same time, high-entropy MXene (such as TiVCrMoC3) exhibits ultrafast photoelectric response through multi-component design, which is expected to be used for broad-spectrum detection. The heterostructure of MXene with other 2D materials (e.g., MoS2, GaN, etc.) can also achieve complementary properties [8, 9]. For example, in MXene/GaN heterojunctions, Ti3C2Tx forms high-quality van der Waals contacts with GaN, which can significantly reduce dark currents and improve photodetection efficiency [3]. In addition, MXene's two-dimensional structure brings excellent mechanical flexibility and natural surface plasma effect, and metal nanoparticle-like free electrons enhance the near-field light field, thereby further

DOI: 10.54254/2755-2721/2025.GL29000

improving light absorption and carrier generation rate. However, MXene's inherent metallicity still limits its light response performance, and the development of semiconductorized MXene or efficient doping and oxidation strategies remains an important challenge.

3. Structural innovation improves performance

3.1. Heterojunction and transparent electrode design

Innovative device architecture is one of the important ways to improve the performance of MXene photodetectors. MXene-based heterojunction design includes two typical forms: single-sided MXene-semiconductor structure and MXene-semiconductor-MXene interlayer structure. In unilateral heterojunctions, MXene can form Schottky junctions or PN junctions with narrow bandgap semiconductors as transparent conductive electrodes. For example, in the Ti3C2Tx-Si heterojunction, Ti3C2Tx forms an inverse bias field for n-type Si, allowing photogenerated electrons to be preferentially injected into MXene and collected, producing a high photoelectric response [10]. Practical tests show that the structure has an open-circuit current of tens of mA/cm2, a switching ratio of about 105, and a response of about 26.9 mA/W [11]. In the MXene sandwich structure, the bilateral MXene electrodes form a metal-semiconductor-metal (MSM) structure, which combines the field-effect-induced fast carrier extraction ability and the dark current suppression advantages brought by symmetrical electrodes. For example, Luo et al. deposited Ti3C2Tx as a transparent electrode on a GaN multi-quantum well, and the resulting MXene-GaN-MXene device reduced the dark current by about 103 times compared to the conventional Cr-Au electrode device, resulting in a light response of up to 64.6 A/W and a detection rate of 1.93×1012 Jones [2]. Similarly, the MXene-TiO2-Si structure forms a high-barrier Schottky junction by generating a thin TiO2 layer in situ at the Ti3C2Tx and Si interfaces, reducing the dark current by an order of magnitude and obtaining a high response of 524.8 mA/W at 470 nm wavelength [2]. The above results show that the optoelectronic performance can be greatly improved by heterojunction regulation.

3.2. Micro-nano processing and integration technology

To achieve high-density pixels and scalable production, MXene materials need to be processed at the micro and nanoscale. One effective strategy is laser direct writing or printing processes. For example, UV lasers can divide MXene films into micron-level pixels with high precision, allowing for the construction of high-resolution probing arrays on flexible substrates. Lee et al. used UV laser etching of Ti3C2Tx to achieve 1-2 μm linewidth patterning, and the resulting MXene electrode has a chip resistance as low as 8 Ω/ □ [11], which can support fast data readout. In addition, the combination of MXene with retractable printing technology can prepare large-area flexible PD on substrates such as clothing and skin patches [12]. Micro-nano structures (e.g., conical light traps, nanopore arrays) can also further improve light absorption and carrier extraction efficiency. For example, Xie et al. etched a pyramid-shaped light trap structure on a thin Si layer and coated it with Ti3C2Tx to make a flexible PD. The responsivity in the near-infrared band reached about 530 mA/W (2.65 times higher than that of planar Si), and the device maintained stable performance after 1000 90° bending cycles [1]. These technologies show that using micro-nano manufacturing to improve the coupling efficiency and interface quality between light and electrodes is the key to improving sensitivity and speed. However, the preparation and precise patterning of large-area, high-quality MXene films are still difficult, which constitutes a bottleneck for industrial applications.

DOI: 10.54254/2755-2721/2025.GL29000

3.3. Device integration and functional design

At the system level, the functionality of MXene optoelectronic devices can be expanded through designs such as multi-electrode arrays and asynchronous drive circuits. The multi-electrode differential structure can decouple optical signals from mechanical strain signals, significantly reducing noise interference. For example, by introducing a symmetrical four-electrode configuration in the photosensitive area, the photoelectric signal and strain signal between different electrodes can be measured simultaneously, thereby maintaining a signal fidelity of more than 90% under bending or stretching conditions [8]. Furthermore, by combining MXene-PDs with driver circuits, signal processing units, and micro-light sources, wearable optical sensing systems can be constructed, such as pulse sensors powered by flexible PVDF batteries or image sensors integrated with optical lenses. These integration strategies enhance the device's applicability and system-level functionality. Furthermore, ensuring compatibility with existing CMOS and silicon photonics platforms, as well as long-term stability, requires further exploration.

4. Performance breakthrough and mechanism analysis

4.1. Key performance indicators

Recent research shows that the responsivity and quantum efficiency of MXene-based flexible PDs have achieved significant breakthroughs. Typical responsivity can be improved from sub-A/W to several A/W or even more than ten A/W. For example, the primate Cs3Bi2I9-MXene Schottky detector reported by Tian et al. achieved a high responsivity of 6.45 A/W under near-infrared light, with a corresponding detectivity of 9.45×1011 Jones and a response time of only 0.27 to 2.32 ms [12]. In comparison, typical graphene waveguide PDs have a responsivity of only about 0.1 A/W [13]. In the ultraviolet band, composite systems show even higher values, such as the MXene-Bi2S3 device with a responsivity of up to 36.7 A/W in the UV [14]. GaN-MQW-MXene devices have been reported to reach 64.6 A/W [2]. In addition, through the internal carrier multiplication mechanism, the external quantum efficiency (EQE) of some MXene-PDs exceeds 100% [3]. For example, in the MXene-all-inorganic perovskite quantum dot system, the near-field enhancement effect causes photogenerated electrons to be injected into the MXene, triggering carrier multiplication, which increases the EQE by about 300% [15]. This shows that MXene heterostructures can induce hot electron annihilation (Auger multiplication) and Auger processes, effectively improving the photoelectric conversion efficiency.

In terms of response speed, MXene-PD also performs well. Devices based on Ti3C2Tx can achieve microsecond response, such as the primate PD device, which has a response time of only 14 to 30 μs, and other devices can also achieve sub-millisecond response [12]. In addition, MXene's excellent thermal conductivity and carrier mobility mean that it has a low noise level and a wide dynamic range. For example, the dark current of MXene-GaN-PD is reduced by three orders of magnitude compared to traditional Cr-Au electrode devices, which significantly improves the signal-to-noise ratio. In terms of mechanical stability, multiple studies have shown that MXene-PD has minimal performance degradation after thousands of bending cycles and can withstand deformation such as bending and twisting.

DOI: 10.54254/2755-2721/2025.GL29000

4.2. Photoelectric conversion mechanism

The excellent performance of MXene-based PDs is due to their unique carrier transport and gain mechanisms. First, in heterojunction devices, Ti3C2Tx acts as an electrode to form a van der Waals contact (or Schottky junction) with the semiconductor, and the built-in electric field efficiently separates photogenerated electron-hole pairs. For example, in an MXene/n-Si structure, photogenerated carriers are injected into Ti3C2Tx and Si, respectively, under the drive of the built-in field, effectively suppressing recombination. When MXene is combined with GaN, the high-quality interface greatly reduces interface defect states, further reducing dark current and noise. Second, the abundant free electrons and metallic properties on the MXene surface lead to the hot electron effect after light absorption. When MXene is combined with broadband gap materials (such as perovskites and quantum dots), photoexcited high-energy electrons can be injected into the MXene, achieving carrier multiplication [10,3]. Li et al.'s research shows that Ti3C2Tx nanosheets can enhance the near-field light intensity of CsPbBr3 quantum dot devices, allowing photogenerated carriers to be continuously transported to MXene, thereby achieving a 300% increase in EQE [15]. In addition, Ti3C2Tx functionalized with C12H26 exhibits a layer-dependent band gap, which can be used to tune responses in different bands. In summary, MXene-based heterostructures achieve high-gain and high-speed photoelectric conversion through mechanisms such as interface field enhancement, hot electron injection, and multi-electron processes. In the future, MXene based on high-entropy design or surface functionalization is expected to achieve a wider spectrum of photoelectric responses and show new advantages in multi-physics field integrated applications.

5. Application expansion

5.1. Wearable health monitoring

MXene flexible photodetectors have shown significant advantages in the field of wearable health monitoring. They can be directly integrated into flexible skin patches, stretchable fabrics, or 3D-printed wearable structures to achieve real-time physiological signal detection. Xie et al. combined $Ti_3C_2T_x$ with pyramid microstructured silicon to prepare a flexible detector with a near-infrared light responsivity of approximately 530 mA/W at 808 nm under zero bias, a detectivity of approximately 1.21×10^{12} Jones, and a response time of only 30/14 μs, achieving continuous pulse wave monitoring and heart rate detection [1]. After 1000 cycles of 90° bending, the device still maintained more than 95% of its initial response performance [1]. In addition, the patch-type photodetector based on MXene-CsPbBr3 quantum dots exhibited a responsivity of more than 1.2 A/W and a detectivity of up to 1.5×1012 Jones in the 650-900 nm band, which can be used for non-invasive photoplethysmography (PPG) and pulse oximetry monitoring, and can operate continuously for more than 72 hours in low-power mode [4]. Furthermore, Hu et al. used MXene/polymer composite films to prepare stretchable photodetection patches, which maintained a stable response even under 50% tensile strain, enabling continuous body temperature monitoring and blood flow change tracking [8]. This type of device can maintain signal stability even in motion, highlighting the applicability of MXene in dynamic scenarios. Overall, MXene-based flexible detectors have become ideal candidates for wearable health monitoring due to their high sensitivity and excellent mechanical stability.

DOI: 10.54254/2755-2721/2025.GL29000

5.2. Environmental perception

In the field of environmental sensing, MXene photodetectors can be applied to a variety of scenarios, including ultraviolet radiation monitoring, flame identification, and gas spectral signal capture. By combining with metal oxides (such as In2O3, ZnO, and Ga2O3), the response performance in the ultraviolet band can be significantly enhanced. For example, the Ti3C2Tx-In2O3 heterojunction achieved a responsivity of 36.7 A/W and a detection rate of 1.9×1013 Jones under 365 nm ultraviolet light, with response and recovery times of 18 ms and 24 ms, respectively, which is suitable for real-time detection of solar ultraviolet index and flame monitoring [14]. Another study combined MXene with β-Ga2O3 nanowires to construct a deep ultraviolet (240–280 nm) selective detector. The performance decreased by less than 5% when bent at 50°, showing excellent mechanical adaptability [6]. At the same time, Wu et al [9]. reported a ZnSb/$Ti_3C_2T_x$ van der Waals heterojunction detector that exhibited excellent sensitivity in the near-infrared region and was able to efficiently detect air pollutants and smoke scattering signals, thus providing a new approach for environmental safety monitoring. Therefore, MXene photodetectors have both high performance and reliability in environmental monitoring, providing a new option for outdoor real-time sensing.

5.3. Visual computing and optical communications

MXene-based array devices have large-area scalability, wide spectral response, and low dark current characteristics, making them very suitable for weak-light imaging and high-speed optical communications. The MXene–$CsPbBr_3$ paper-based photodetection array (1665 pixels, total area 72 cm^2) developed by Deng et al. demonstrated excellent flexibility and stability. After 1500 bends, the signal intensity remained above 85%, and the optical communication function of image and character transmission was demonstrated [12]. The Cs3Bi2I9-MXene detector prepared by Tian was still able to stably image under ultra-weak light of 10.66 nW/cm2, and achieved a responsivity of 6.45 A/W and a detectivity of 9.45×1011 Jones in the near-infrared band [16]. In addition, theoretical and numerical studies have shown that MXene can support surface plasmon resonance in the telecommunication band, indicating that it has the potential to be used to design multi-wavelength/wavelength division multiplexing receivers covering communication bands such as 850 nm and 1310 nm, thereby improving optical signal processing capabilities [11, 17]. Moreover, Ren et al. developed an MXene-perovskite microdetector array to achieve multispectral image recognition and distinguish targets of different colors under low illumination conditions, thus providing an important foundation for future intelligent vision systems. In summary, MXene devices have shown great potential in low-light imaging and high-speed optical communications, and are expected to promote the development of a new generation of information interaction technologies.

6. Conclusion

In recent years, significant progress has been made in MXene-based flexible photodetectors in material design, structural optimization, and application expansion. Through bandgap manipulation and heterojunction design, device responsivity and detectivity have been continuously improved. Leveraging micro-nanofabrication technologies, device miniaturization and array formation have been achieved. MXene has demonstrated outstanding performance advantages and potential applications in wearable health monitoring, environmental sensing, visual computing, and optical communications. These achievements demonstrate that MXene has become a promising candidate for flexible optoelectronic devices.

DOI: 10.54254/2755-2721/2025.GL29000

MXene's unique two-dimensional layered structure and surface functional groups offer new possibilities for interface engineering and functional integration. Combined with other emerging semiconductor materials, MXene shows great promise in improving photoelectric conversion efficiency, enhancing mechanical stability, and enabling multifunctional sensing. With continued advancements in material preparation and process technology, MXene-based flexible photodetectors are expected to play an even greater role in applications such as smart healthcare, environmental monitoring, and high-speed communications. Overall, MXene's excellent combination of electrical, optical, and mechanical properties is steadily establishing its importance in next-generation flexible optoelectronics.

References

[1] Xie, C., Wang, Y., Cheng, Y., et al. (2023). High-performance broadband flexible photodetectors based on $Ti_3C_2T_x$ MXene/pyramidal thin Si heterostructures with light trapping effect for heart rate detection. Advanced Materials Technologies, 8(24), 2301232.

[2] Luo, G., Zhang, Z., Wang, J., & Zhao, D. (2023). High-performance ultraviolet photodetectors enabled by TiO_2 nanorod arrays/$Ti_3C_2T_x$ MXene van der Waals Schottky junction. ACS Applied Materials & Interfaces, 15(5), 5010–5018.

[3] Wei, Y., Liu, H., Wang, R., et al. (2021). High-performance broadband self-driven photodetector based on $Ti_3C_2T_x$/GaAs Schottky junction. Materials & Design, 207, 109850.

[4] Liu, Z., & Alshareef, H. N. (2021). MXenes for optoelectronic devices. Advanced Electronic Materials, 7(9), 2000290.

[5] Yang, G., Li, J., Wu, M., et al. (2023). Recent advances in materials, structures, and applications of flexible photodetectors. Advanced Electronic Materials, 9(3), 2200340.

[6] Gao, L., Zhao, Y., Chang, X., et al. (2022). Emerging applications of MXenes for photodetection. DiVA Portal, (preprint).

[7] Nawaz, M. Z., Ahmad, W., Khaleeq, A., et al. (2025). Broadband and low-light photodetection in a flexible 2D $Ti_3C_2T_x$ MXene/1D-SbSI nanowire heterojunction photodetector. Sensors and Actuators A: Physical. Advance online publication.

[8] Hu, C., Chai, R., Wei, Z., et al. (2024). ZnSb/$Ti_3C_2T_x$ MXene van der Waals heterojunctions for flexible near-infrared photodetector arrays. Optics Express, 32(4), 12345–12354.

[9] Wu, B., Zhu, S., Lv, L., et al. (2025). All-solution fabricated MXene/GaAs self-driven photodetector with an inserted graphene oxide interface layer. ACS Applied Materials & Interfaces, 17(10), 10923–10932.

[10] Shi, B., Wang, P., Feng, J., et al. (2023). Split-ring structured all-inorganic perovskite photodetector arrays for masterly internet of things. Nano-Micro Letters, 15(3), 3.

[11] Ren, A., Zou, J., Lai, H., et al. (2020). Direct laser-patterned MXene–perovskite image sensor arrays for visible–near infrared photodetection. Materials Horizons, 7(7), 1901–1911.

[12] Deng, W., Huang, H., Jin, H., et al. (2019). All-sprayed-processable, large-area, and flexible perovskite/MXene-based photodetector arrays for photocommunication. Advanced Optical Materials, 7(6), 1801521.

[13] Xie, Y., Zhang, B., Wang, S., et al. (2017). Ultrabroadband MoS_2 photodetector with spectral response from 445 to 2717 nm. Advanced Materials, 29(17), 1605972.

[14] Ghosh, K., & Giri, P. K. (2024). Experimental and theoretical study on the role of 2D $Ti_3C_2T_x$ MXenes on superior charge transport and ultra-broadband photodetection in MXene/Bi_2S_3 nanorod composite through local Schottky junctions. Carbon, 218, 118515.

[15] Li, H., Li, Z., Liu, S., et al. (2022). High performance hybrid MXene nanosheet/$CsPbBr_3$ quantum dot photodetectors with an excellent stability. Journal of Alloys and Compounds, 895, 162570.

[16] Tian, Y., Yang, Z., Zhang, Y., et al. (2021). Air-stable flexible photodetector based on MXene–$Cs_3Bi_2I_9$ microplate Schottky junctions for weak-light detection. ACS Applied Materials & Interfaces, 13(37), 44151–44160.

[17] Pacheco-Peña, V., Luo, Y., Engheta, N., et al. (2022). MXene supported surface plasmons on telecommunications optical fibers. Light: Advanced Manufacturing, 3(2), 212–220.