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Challenges and Fabrication Strategies for MXene-Based Flexible Micro-Supercapacitors

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Abstract: Flexible micro-supercapacitors (MSCs) based on 2D MXenes offer strong potential for next-generation energy storage in wearable and integrated electronics, yet still face critical challenges such as limited energy density, mechanical reliability, and scalable large-area manufacturing. This review surveys recent strategies to address these limitations, with a particular focus on fabrication techniques and wafer-level integration approaches. Wafer-scale processing on both rigid and flexible substrates has emerged as a key milestone toward scalable, high-yield industrial production of flexible MSCs. By examining the strengths and drawbacks of current fabrication strategies, this review highlights essential directions for advancing MXene-based flexible MSCs toward practical and widespread application.

Keywords: MXenes, Micro-supercapacitors, Flexible, 8-inch, Fabrication

1. INTRODUCTION

The rapid rise of flexible electronics, such as wearable devices, smart sensors, and integrated Internet-of-Things (IoT) systems, has triggered an urgent demand for compact, reliable, and high-performance energy storage units. While lithium-ion batteries have dominated portable electronics for decades, their limitations in mechanical flexibility, safety, and miniaturization have fueled the search for alternative energy storage solutions.

In this context, supercapacitors and their miniaturized form, micro-supercapacitors (MSCs), have emerged as compelling options due to their ultrafast charge–discharge capability, long cycling life, and excellent compatibility with flexible substrates [1].

MSCs differ from conventional supercapacitors in their design: they typically adopt planar, interdigital electrode configurations that eliminate the need for bulky separators and reduce ion diffusion paths. This architecture not only enables miniaturization but also allows direct integration onto chips or deformable surfaces. As a result, MSCs are increasingly viewed as key components in next-generation energy-autonomous systems, where size, speed, and mechanical resilience are all critical [2].

Among various electrode materials investigated, MXenes, which are two-dimensional transition metal carbides, nitrides, or carbonitrides, have attracted significant attention due to their unique combination of metallic conductivity, hydrophilic surface chemistry, high volumetric capacitance, and mechanical flexibility. The tunable surface terminations (T_x) in MXenes not only provide electrochemical functionality but also enable strong adhesion and compatibility with solution processing and microfabrication techniques [3].

Despite the growing number of publications exploring MXene-based MSCs, most previous reviews have predominantly focused on either the synthesis and fundamental properties of MXenes or their application in general electrochemical energy storage systems. Only a few studies have

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systematically examined the role of MXenes in miniaturized and patterned energy storage systems, particularly from the perspective of microfabrication strategies and wafer-level integration [4].

This review aims to fill this gap by offering a comprehensive overview of recent progress in MXene-based flexible MSCs, emphasizing three major aspects: (i) the material-level advantages and electrochemical characteristics of MXenes as MSC electrodes, (ii) the classification and comparison of diverse microfabrication techniques, including laser writing, photolithography, and printing methods, for patterning MSCs, and (iii) the scalability and manufacturability of wafer-level, large-area MXene MSC arrays toward industrial implementation.

Through this review, we aim to highlight not only the current state of MXene MSC technology but also the key strategies required to advance it toward scalable, real-world applications.

2. MXene AS AN ELECTRODE MATERIAL FOR MSCs

MXenes are a family of 2D materials typically produced by etching “A” layers from MAX phase precursors (e.g. removing Al from Ti_3AlC_2 to get $Ti_3C_2T_x$). The resulting titanium carbide MXene consists of atomically thin layers of $Ti_{n+1}C_n$ with surface terminations (T_x) like O, OH, or F. Each MXene sheet is highly conductive (metal-like) and has a large surface area accessible to ions in an electrolyte [5]. Uniquely, MXenes store charge via a combination of electric double-layer capacitance and intercalation pseudocapacitance, as ions intercalate between layers and undergo surface redox reactions without significant structural diffusion limitations [6]. This mechanism enables rapid charge/discharge (high power density) alongside high areal and volumetric capacitance.

Several inherent properties make MXenes well suited for use as electrodes in micro-supercapacitors. First, their electrical conductivity is exceptionally high; for example, $Ti_3C_2T_x$ can exceed 10,000 S/cm, which helps reduce internal resistance and enables high power output in compact MSC devices. Second, MXene films can be fabricated as ultrathin and continuous layers, often only a few nanometers thick, which aligns well with the planar interdigital layout typical of MSCs. Third, their hydrophilic nature and negative surface charge allow them to be dispersed in water or organic solvents without the need for polymeric binders. In contrast to many carbon-based materials that require insulating binders, MXene flakes can stack and adhere to substrates on their own, making it possible to create dense, binder-free electrodes with high active material content [6,7].

The hydrophilic nature of MXenes aids in their dispersion in aqueous or polar solvents, making them highly compatible with solution-based fabrication techniques such as inkjet printing, spray coating, and spin-casting. Additionally, MXene chemistry is tunable, where properties can be adjusted by surface modifications, interlayer intercalants, or forming MXene composites. Mechanical flexibility is a further advantage, allowing MXene-based MSCs to be bent, stretched, and integrated into deformable substrates without significant loss of performance [8,9].

Taken together, the unique combination of high conductivity, pseudocapacitance, processability, and flexibility makes MXenes a leading candidate for the next generation of flexible and integrated MSCs.

A representative schematic and characterization images of $Ti_3C_2T_x$ MXene are shown in Fig. 1, highlighting its distinctive layered structure and morphology as revealed through SEM and XRD analyses. The following section will delve into how these materials are architecturally configured within MSCs to achieve optimal device performance.

3. FABRICATION TECHNIQUES FOR MICRO-SUPERCAPACITORS

The development of MSCs that combine high performance with mechanical flexibility depends on the ability to pattern electrode materials with high resolution, scalability, and substrate compatibility. Numerous microfabrication strategies have been applied to MXene-based MSCs, each offering distinct advantages in terms of design freedom, integration, and manufacturing potential. In this section, we classify the main fabrication techniques and highlight representative works that demonstrate the diversity and evolution of these approaches.

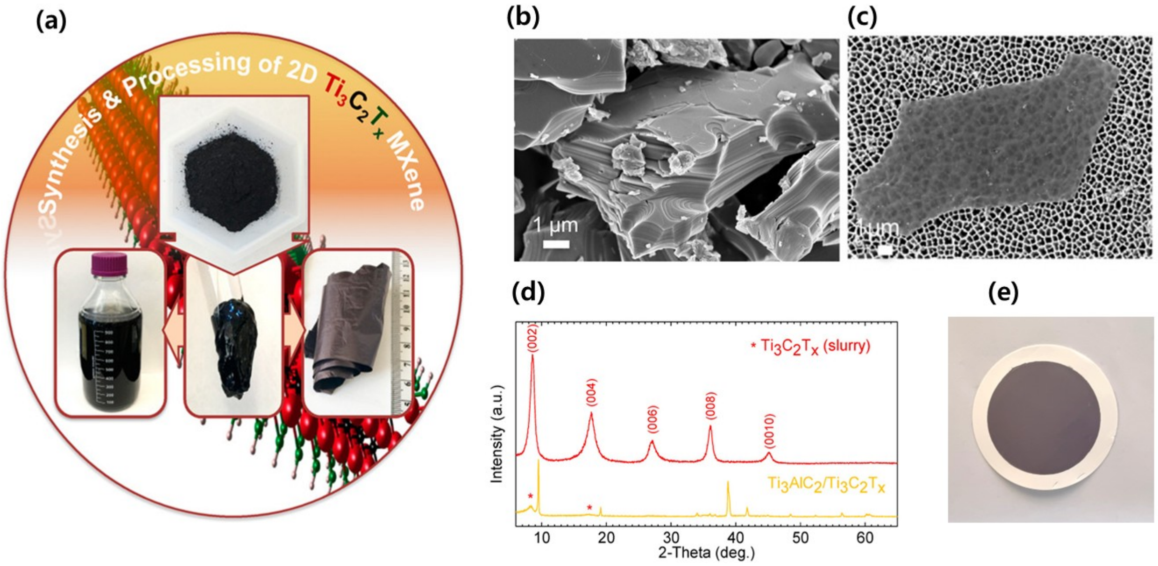


Fig. 1. (a) Schematic illustration of the synthesis and processing steps of $Ti_3C_2T_x$ MXene and (b) SEM image of Ti_3AlC_2 MAX phase, (c) SEM image of delaminated $Ti_3C_2T_x$ MXene, (d) XRD patterns of Ti_3AlC_2 and $Ti_3C_2T_x$ (slurry) confirming successful etching and structural transition, and (e) photograph of a $Ti_3C_2T_x$ MXene film prepared via vacuum filtration. (a)–(d) are reprinted with permission [3]. Copyright 2017, American Chemical Society.

3.1 Laser Patterning

Laser-based micropatterning provides a maskless and programmable method for structuring MSC electrodes, making it highly appealing for flexible device fabrication. This technique uses focused laser beams to directly ablate or cut material, enabling the creation of interdigital electrode patterns without the need for photomasks or cleanroom facilities.

A major advantage of laser patterning is its simplicity and versatility across different substrates and material systems. It allows direct writing on MXene films coated onto metallic or polymeric foils, and it supports the patterning of both symmetric and asymmetric device architectures. Additionally, laser methods can enable simultaneous fabrication of multiple units in series or parallel by a single cutting process.

Several recent studies have leveraged laser-based techniques to fabricate MXene-based MSCs. For example, N. Wang et al. utilized UV laser cutting to produce double-sided $Ti_3C_2T_x$ MSCs on nickel foil, achieving an areal capacitance of 52 mF/cm² with stable performance over 5,000 cycles [10]. The laser directly patterned both electrode layers simultaneously, demonstrating the method's efficiency and integration potential.

In a different approach, Y. Zhu et al. applied laser scribing to create composite electrodes composed of MXene and laser-scribed graphene (LSG) on flexible PET substrates. The resulting MSCs exhibited excellent mechanical flexibility and retained over 97.7% capacitance after 10,000 cycles, with a maximum energy density of 170.67 μWh/cm² at a power density of 6.2 μW/cm² [11]. This work highlights the compatibility of laser scribing with two-dimensional hybrid materials and its applicability to wearable, deformable devices.

In another study, Li et al. developed a Zn-ion hybrid MSC using $Ti_3C_2T_x$ cathodes patterned by laser direct writing on polyimide substrates as shown in Fig. 2. The devices exhibited an areal capacitance of 72.02 mF/cm² and retained 80% capacitance after 50,000 cycles following in-situ annealing. The MSCs demonstrated excellent flexibility, powering devices under bending and twisting conditions, and showed strong potential for wearable applications [12].

However, laser-based micropatterning, while attractive for maskless and rapid processing, inherently suffers from limited resolution on flexible substrates. This limitation exists because even focused laser spot sizes are fundamentally limited by diffraction to several tens of micrometers. In addition, when exposed to high-energy laser beams, flexible substrates are

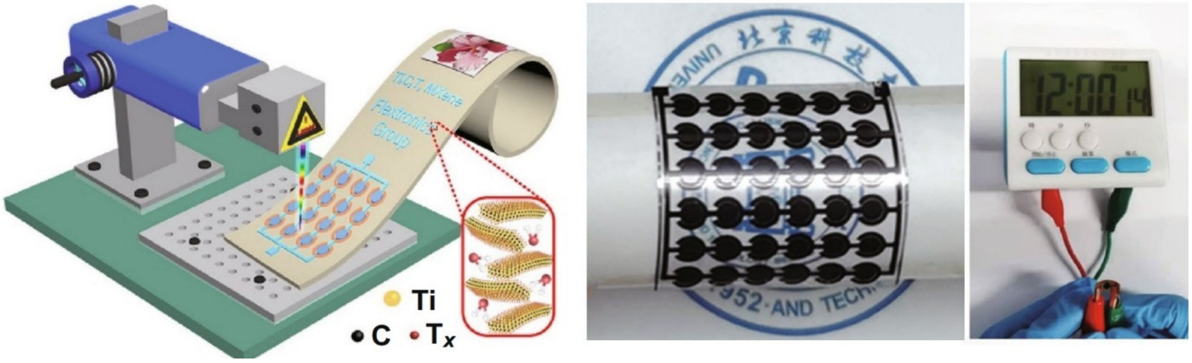


Fig. 2. Schematic illustration of the laser writing fabrication process for patterned $Ti_3C_2T_x$-based Zn-ion micro-supercapacitor (MSC) arrays, along with optical images of the resulting MSCs on a flexible substrate and a demonstration of a digital timer powered by a single MSC under a bending state. Reprinted with permission [12]. © The Author(s) 2021. Licensed under CC BY 4.0.

more likely to bend or thermally expand, leading to edge distortion and reduced pattern quality.

3.2 Screen Printing

Screen printing is a widely used technique for fabricating electrodes of MSCs due to its simplicity, scalability, and compatibility with a broad range of substrates. It enables the transfer of functional inks through a patterned mesh onto flexible or rigid surfaces, making it suitable for roll-to-roll processing and large-area device fabrication. The process is particularly appealing for planar MSC architectures with moderate feature resolution requirements.

One of the main advantages of screen printing lies in its low cost, high throughput, and ease of pattern customization. It can accommodate a variety of ink formulations, including those containing 2D materials like MXene, and allows for direct printing on flexible substrates such as PET and polyimide films. However, the method also has notable limitations in resolution, with typical minimum line widths above ~50 μm, which constrains its use in high-density circuit integration. In addition, achieving consistent ink rheology and precise mass loading control can be challenging, especially for materials with poor dispersion or high viscosity.

Recent studies have demonstrated the effectiveness of screen printing for MXene-based MSCs. Dey et al. developed a planar asymmetric MSC using $Ti_3C_2T_x$ MXene as the negative electrode and nickel selenide (NiSe) as the positive electrode. Both inks were screen-printed on silver current collectors atop flexible PET substrates. The resulting device exhibited a high energy density of 117.6 mWh/cm^3 and a power density of 1285.7 mW/cm^3, with good mechanical flexibility and capacitance retention of 72% after 1000 cycles. The electrodes maintained performance even under repeated bending, validating the method's applicability for flexible systems [13].

In a separate work, Yu et al. reported the screen printing of nitrogen-doped crumpled MXene inks to fabricate all-MXene-based symmetric MSCs. The printed devices achieved an areal capacitance of 70.1 mF/cm^2 and retained 92% of their initial capacitance after 7000 cycles. The ink formulation was tuned for shear-thinning behavior, ensuring good printability and mechanical robustness [14].

These studies highlight the potential of screen printing as a practical and scalable route for integrating MXene-based MSCs into wearable and flexible electronics. While resolution limits and ink optimization remain ongoing challenges, continued advances in material engineering and printing techniques are expanding the method's applicability for next-generation energy storage devices.

3.3 Inkjet Printing

Inkjet printing is a promising technique for fabricating micro-supercapacitor (MSC) electrodes, offering digital, maskless patterning with fine spatial control. It enables direct deposition of functional inks onto a variety of substrates in a programmable and additive manner, reducing material waste and manufacturing costs. Inkjet printing is especially attractive for flexible and miniaturized electronics, where high design freedom and scalability are required.

A major advantage of inkjet printing lies in its high patterning precision and customizability, supporting minimum feature sizes in the range of tens of micrometers or better, depending on the ink formulation and printing system. It allows rapid prototyping and easy integration with complex device architectures. However, there are significant challenges: achieving stable jetting requires careful tuning of ink viscosity and surface tension, and printed features are highly sensitive to substrate wetting behavior and drying dynamics. Additionally, maintaining consistent ink stability, preventing clogging, and managing issues like the "coffee ring effect" are critical for high-quality printing. Compared to screen printing, throughput is lower, and achieving thick or multilayered structures requires multiple passes.

Recent research has demonstrated the potential of inkjet printing for MXene-based MSCs. Zhang et al. formulated additive-free MXene inks for direct inkjet printing without surfactants or polymeric binders, avoiding post-processing steps that could degrade MXene performance. Using NMP-based MXene inks, they printed all-MXene MSCs on PET substrates, achieving fine feature widths of 50–80 μm and delivering a high areal capacitance of 1,500 mF/cm^3, attributed to the formation of dense, conductive networks. The devices maintained mechanical integrity under repeated bending and exhibited long-term electrical stability, highlighting the feasibility of high-resolution MXene patterning [5].

In a complementary study, Wang et al. developed an aqueous MXene/sodium alginate-Fe^{2+} (MXene/SA-Fe) hybrid ink to tackle issues of oxidation and restacking. Inkjet-printed MSCs fabricated with this ink showed a remarkable areal capacitance of 123.8 mF/cm^2 and energy density of 8.44 μWh/cm^2, with 91.4% capacitance retention after 10,000 cycles. The addition of SA and Fe^{2+} enabled the formation of a stable 3D network structure, suppressing MXene aggregation and enhancing ion transport, while maintaining environmental friendliness by avoiding organic solvents [15].

3.4 Spray Coating

Spray coating is a simple and scalable technique for depositing electrode materials over large areas using an aerosolized ink or suspension. This method uses a pressurized nozzle to atomize functional materials into fine droplets, which are directed onto a substrate through a shadow mask for patterned deposition. Spray coating is particularly attractive for flexible electronics, owing to its compatibility with diverse substrates, low equipment cost, and ease of upscaling to roll-to-roll processing.

One of the main advantages of spray coating lies in its manufacturing simplicity and large-area coverage. It supports deposition of solution-processed MXenes and their composites without requiring cleanroom infrastructure or high-resolution patterning equipment. Additionally, the use of masks allows for custom pattern definition in an inexpensive manner. However, spray coating faces significant limitations in spatial resolution due to the spread of droplets and mist diffusion beyond the mask edges, typically resulting in line widths >100–1,000 μm. Feature edge sharpness is difficult to maintain, especially at small scales, and the technique requires careful control of spraying parameters and ink properties to ensure uniform film thickness and adhesion.

Recent studies have validated the feasibility of spray coating for flexible MXene-based MSCs. Couly et al. demonstrated an asymmetric MXene–rGO microsupercapacitor fabricated via mask-assisted spray coating on a flexible PET substrate. The device exhibited a high energy density of 8.6 mWh/cm^3 and retained 97% of its capacitance after 10,000 charge/discharge cycles. The layered structure combined the high conductivity of MXene with the mechanical stability of reduced graphene oxide, enabling excellent performance under bending stress [16].

In another study, Guo et al. developed an all-solid-state electrochromic microsupercapacitor based on spray-coated Ti_3C_2 MXene films and a PVA/H_2SO_4 gel electrolyte. The device reached an areal capacitance of 12.5 mF/cm^2 at an operating voltage of 1 V and showed high flexibility, with electrochromic response coupled to energy storage. The process allowed direct integration of energy and display functions on flexible substrates, showing the versatility of spray coating for multifunctional MSC applications [17].

These results highlight the utility of spray coating as a viable fabrication route for large-area, flexible MSCs using MXene-based inks. While its low resolution limits its application in high-density or miniaturized architectures, spray coating remains a valuable method for prototyping and scalable manufacturing of wearable energy storage devices.

3.5 Photolithography-Based Patterning

Photolithography is a widely established microfabrication technique that enables precise patterning of electrode materials with high fidelity. It uses light to transfer geometric patterns from a photomask to a light-sensitive photoresist layer on a substrate. In the context of MXene-based MSCs, photolithography allows for the creation of finely resolved interdigital electrodes, critical for achieving compact, high-performance devices.

A key advantage of this technique is its ability to produce patterns with sub-micron resolution, which is essential for integrating MSCs into CMOS-compatible platforms or achieving high device densities. Moreover, it offers excellent repeatability and design precision, supporting wafer-level batch processing.

However, photolithography also comes with notable limitations. It requires costly equipment, cleanroom facilities, and involves multiple complex steps such as photoresist coating, exposure, development, and etching or lift-off. This makes the process less accessible and more time-consuming compared to printing or laser methods. Furthermore, applying photolithography directly onto flexible substrates poses significant challenges due to the mechanical compliance of polymers like polyimide or PET. Even minimal bending or wrinkling during photoresist coating, exposure, or development steps can cause misalignment or distortion of nanoscale patterns. Moreover, flexible substrates typically have lower thermal stability, limiting post-exposure annealing processes that are crucial for improving pattern resolution and adhesion in conventional photolithography.

Despite these hurdles, several studies have adapted photolithography for MXene MSC fabrication. Kim et al. demonstrated a scalable process to produce MSCs on an Si/SiO_2 wafer using a photolithography-lift-off approach to define 50 μm-wide $Ti_3C_2T_x$ MXene electrodes. A subset of these devices was subsequently transferred onto flexible PI substrates via a selective etching process, as shown in Fig. 3. To address poor mechanical durability and pattern delamination, they introduced a PVA buffer layer, which significantly enhanced bending stability, retaining over 90% of its capacitance after 10,000 bending cycles and increasing volumetric capacitance to 1,487.7 F/cm^3 [18].

In another work, the same group employed a photolithography-and-transfer method to fabricate MXene electrodes on a rigid Si/SiO_2 wafer, which were then transferred onto polyimide (PI) film. This approach enabled pattern uniformity and high-performance metrics, with the best-performing devices showing a volumetric capacitance of 1,727 F/cm^3 and 41.9 mWh/cm^3 energy density [19]. However, the yield remained low due to the process complexity and compatibility issues between MXene and the rigid wafer.

In summary, photolithography offers unmatched resolution and structural precision for MXene-based MSCs but remains limited by its high complexity, cost, and difficulties in flexible platform adaptation. Future advances in materials and process integration will be needed to unlock its full potential for scalable, flexible energy storage.

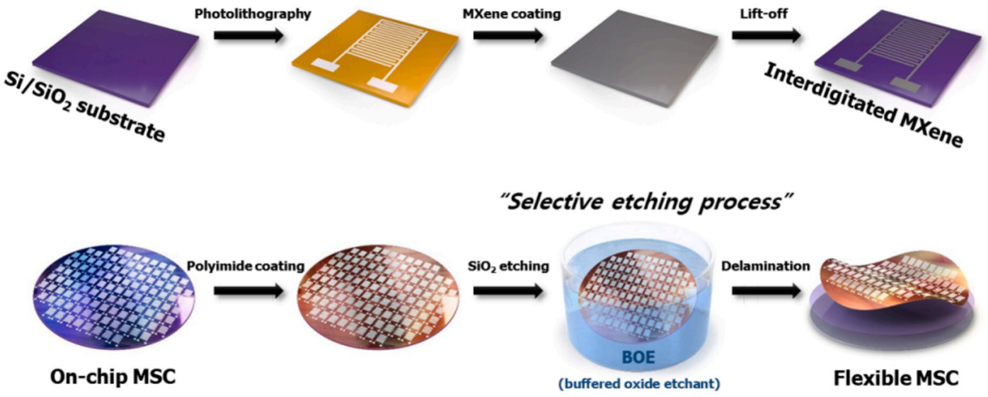
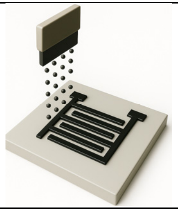
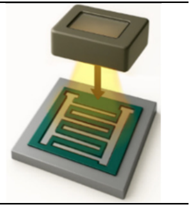


Fig. 3. Schematic of the fabrication process of flexible MXene-based micro-supercapacitors. Interdigitated patterns were defined via photolithography on a Si/SiO_2 wafer and subsequently transferred to a polyimide substrate using a selective etching technique. Reprinted with permission [18]. Copyright 2022, Elsevier B.V.

Table 1. Comparison of fabrication techniques for MXene-based micro-supercapacitors.

Technique	Resolution (typical)	Typical throughput	Advantages	Representative performances	Limitations	Substrate compatibility	Schematic illustration
Laser patterning	>20 μm; limited by spot size and thermal effects	Low to Moderate (10–100 cm^2/min)	Maskless, programmable, applicable to various substrates	52 mF/cm^2 [10] 170.67 $\mu Wh/cm^2$ [11] 72.02 mF/cm^2 [12]	Limited resolution, thermal damage, less suitable for dense arrays	Rigid; possible on flexible with challenges	
Screen printing	>50 μm; determined by mesh size and ink spreading	High (100–1000 cm^2/min)	Low-cost, scalable, compatible with roll-to-roll processes	117.6 mWh/cm^3 [13] 70.1 mF/cm^2 [14]	Low resolution, difficult fine control of ink deposition	Primarily flexible	
Inkjet printing	20–50 μm; depends on drop size, ink rheology, and wetting	Low (1–10 cm^2/min)	Digital, additive, higher resolution than screen printing	1,500 mF/cm^3 [5] 123.8 mF/cm^2 [15]	Ink formulation sensitive, lower throughput, nozzle clogging	Rigid & flexible	
Spray coating	>100–1,000 μm; limited by nozzle spread and mist diffusion	Moderate to high (50–500 cm^2/min)	Simple setup, scalable for large areas, mask-compatible	8.6 mWh/cm^3 [16] 12.5 mF/cm^2 [17]	Low resolution, edge diffusion, unsuitable for fine-feature integration	Rigid & flexible	
Photolithography-based patterning	10–100 μm typical on rigid, sub-micron achievable	Moderate (10–100 wafers/hour)	High resolution, CMOS-compatible, precise patterning	1,487.7 F/cm^3 [18] 1,727 F/cm^3 [19]	Expensive, complex process, challenging on flexible substrates	Rigid; possible on flexible with challenges	

A comparative summary of the key characteristics, strengths, and limitations of major fabrication techniques is provided in Table 1.

4. WAFER-LEVEL & SCALABLE MANUFACTURING

Although significant progress has been made in the development of MXene-based MSCs, most research still focuses on small-area devices fabricated on substrates smaller than a few square centimeters. Achieving large-area, wafer-scale integration is essential for practical deployment, yet examples of MSCs fabricated on 4-inch wafers or larger remain rare, and 8-inch flexible wafer-level integration is even more scarce.

A study by Qiu Jiang et al. demonstrated the scalable fabrication of MXene MSC arrays on a 4-inch rigid Si/SiO_2 wafer [1]. Using photolithography and spray-coating techniques, they achieved high-frequency response suitable for AC-line filtering applications. The devices showed volumetric capacitances of 30 F/cm^3 at 120 Hz and a relaxation time constant of 0.45 ms, surpassing conventional electrolytic capacitors. This work demonstrates the feasibility of wafer-scale MXene MSC fabrication through semiconductor-compatible processes, highlighting its potential as a scalable approach.

Building on this, Kim et al. extended wafer-level fabrication to an 8-inch rigid Si/SiO_2 wafer. Through a combination of photolithography and a selective etching–transfer method, they patterned interdigitated MXene electrodes, which were subsequently transferred onto flexible polyimide (PI) substrates as shown in Fig. 4. These flexible MSCs exhibited outstanding volumetric capacitance of and energy density, while maintaining excellent mechanical durability after 10,000 bending cycles. However, it is critical to note that the initial fabrication was conducted on a rigid wafer, with flexibility introduced only after the transfer step [18].

More recently, Kim et al. achieved direct fabrication of MSC arrays on an 8-inch flexible PI wafer without the need for post-transfer processes. By introducing a polymer buffer layer (PVA) between the MXene electrode and the flexible substrate, they addressed adhesion and mechanical stability issues that typically limit flexible device fabrication. The PVA buffer layer enhances mechanical durability by forming a conformal adhesive interface between the MXene film and flexible PI substrate. It relieves interfacial stress during bending, prevents delamination, and stabilizes the electrode structure during handling and cycling, supporting long-term performance under strain. The resulting flexible MSCs demonstrated high volumetric capacitance and greatly improved mechanical resilience, retaining 90.3% capacitance after 10,000 bending cycles [19].

In addition, Wang et al. reported a scalable screen-printing approach to fabricate MXene-based MSC arrays over a large-area (350 mm × 450 mm) flexible substrate, demonstrating the method's viability for high-throughput production. By engineering a shear-thinning MXene ink formulation, they achieved uniform electrode printing and enhanced ion diffusion kinetics without the need for post-processing steps. The printed MSCs exhibited high areal capacitance and strong mechanical durability, highlighting screen printing as a cost-effective and industrially scalable method for large-area MSC integration [20].

However, despite its scalability and simplicity, screen printing is inherently limited in resolution, typically producing features ≥100 μm. This constraint hampers the miniaturization of interdigital electrodes and restricts the achievable energy

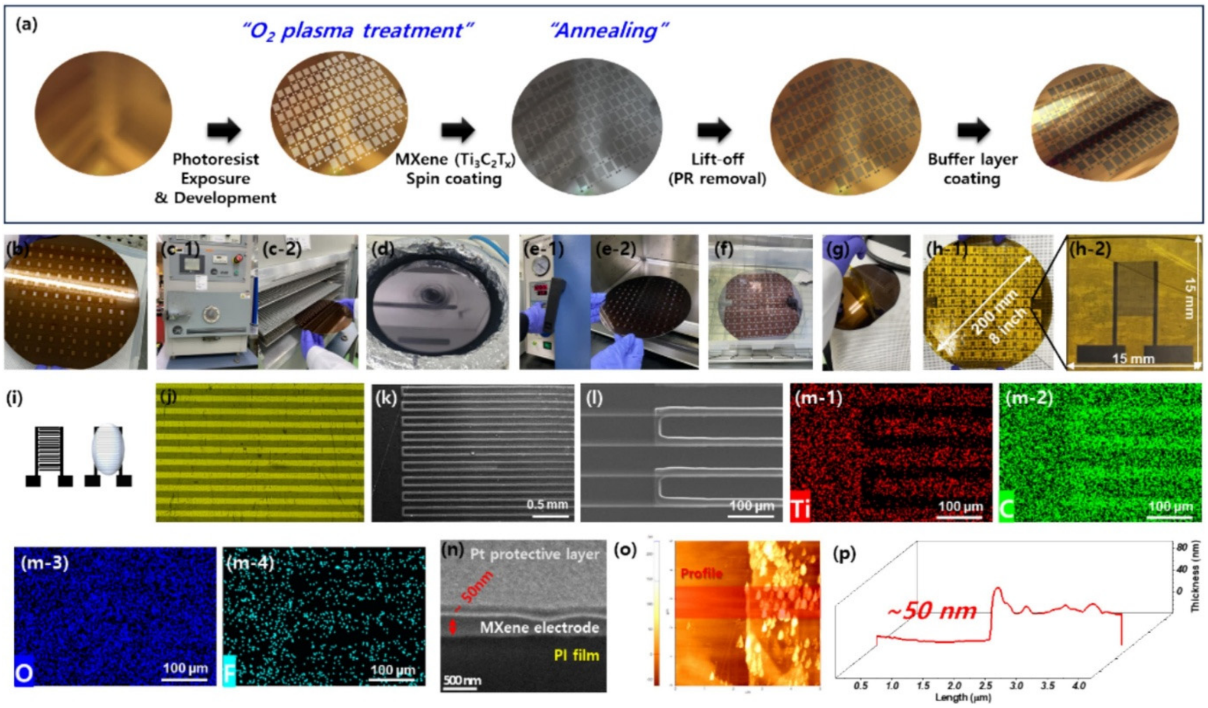


Fig. 4. Schematic and process flow for the scalable fabrication of MXene-based flexible micro-supercapacitors directly on 8-inch PI wafers, illustrating photolithographic patterning, MXene deposition, and buffer layer integration. Reprinted with permission [19]. Copyright 2025, Elsevier B.V.

and power density compared to photolithographic approaches. Moreover, uniform layer thickness and precise pattern edge definition can be difficult to control, particularly for nanoscale architectures or multilayered devices.

In parallel, the Chen group reported the monolithic integration of 10,000 MXene MSCs on a 6.5 × 7.5 cm^2 flexible substrate using self-assembled electrolyte patterning. While not strictly at the wafer scale, this approach achieved an areal device density of 210 MSCs per square centimeter, highlighting the potential of intermediate-resolution, high-density integration strategies for flexible energy storage platforms [21].

These studies collectively demonstrate that scalable fabrication techniques, including semiconductor fab-compatible photolithographic processes and emerging large-area printing methods, are essential for realizing wafer-level MXene MSCs. However, screen printing inherently suffers from limited resolution, typically above 100 μm, due to the mesh size and ink spreading during the printing process. This restricts its application in high-density integration or miniaturized device designs, where precise electrode patterning is critical. In contrast, photolithography remains the most reliable method for achieving fine-resolution, high-performance MSC architectures, especially at the wafer scale. To transition from laboratory-scale prototypes to industrial production, it is imperative to integrate MXene MSC fabrication into standardized manufacturing workflows, leveraging both mature lithography-based processes and optimized printing systems where appropriate.

Nevertheless, several challenges remain:

- Achieving sub-10 μm patterning resolution directly on flexible substrates remains difficult due to mechanical deformation and thermal constraints during processing.
- Material stability, particularly MXene oxidation during fabrication, must be carefully controlled [22].
- Cost reduction and yield improvement across wafer-scale processing will be critical for commercialization.

In conclusion, while initial demonstrations at the 4-inch and 8-inch wafer scales are promising, continuous innovation in materials science, device design, and scalable semiconductor-compatible processing will be key to bringing MXene-based flexible MSCs into widespread practical use.

5. CHALLENGES AND FUTURE DIRECTIONS

Although MXene-based flexible MSCs have shown great promise for next-generation energy storage, the field remains in an early stage compared to other thin-film battery technologies. Most current research is focused on small-scale demonstrations, and practical deployment faces several critical challenges.

One major limitation is the relatively low energy density of MSCs compared to thin-film batteries. While MXene MSCs can deliver high power densities and rapid charge–discharge capabilities, their energy storage capacity remains modest. This gap could limit their competitiveness in applications requiring long-duration operation or high volumetric energy storage. Without significant improvements in areal and volumetric capacitance, MXene MSCs may struggle to displace thin-film batteries in mainstream markets.

Another challenge lies in the scaling and integration of MSCs. Although recent studies have demonstrated fabrication on 8-inch wafers using semiconductor fab-compatible processes like photolithography, true wafer-level mass production of flexible MXene MSCs is still in its infancy. In particular, flexible substrates impose severe constraints on fabrication, as even minor mechanical deformation can disrupt nanoscale patterning required for high-resolution device architectures. Thermal processing windows are also narrow due to the low thermal tolerance of polymeric substrates, complicating post-processing steps like annealing.

In particular, electrode gaps below 1 μm present a promising yet underexplored regime for further performance enhancement. Recent studies suggest that shrinking the gap can substantially improve areal capacitance and energy density by reducing ion diffusion paths and increasing the effective interfacial area. However, this nanometer-scale region remains poorly understood, especially on mechanically deformable substrates. It is likely that unique charge storage behaviors or transport dynamics emerge at these scales, which conventional models do not fully capture. As such, in-depth investigation into the electrochemical mechanisms specific to sub-micron or nanogap structures is essential for unlocking the full potential of MXene-based flexible MSCs.

Despite these challenges, the compatibility of MXene MSC fabrication with standard semiconductor manufacturing offers a compelling strategic advantage. If wafer-scale, high-yield production of flexible MSCs can be industrialized, this would lay the foundation for early leadership in the flexible energy storage sector. Extending fabrication beyond current 8-inch platforms while preserving electrochemical performance could position MXene MSCs as a key enabling technology for next-generation energy-autonomous systems.

In this context, future research should prioritize:

- Enhancing the energy density of MXene MSCs through material innovation, architectural refinement, and control over ion-accessible surface area;
- Developing reliable nanoscale patterning strategies that are mechanically and thermally compatible with flexible substrates;
- Investigating the electrochemical behavior of nanogap structures, where unique charge storage phenomena may emerge;
- Improving oxidation resistance and mechanical stability of MXene films during wafer-level processing;
- Integrating MXene MSCs seamlessly with micro-electronic platforms to realize fully autonomous and deformable energy systems.

Ultimately, addressing these challenges will require collaborative advances in materials science, microfabrication, and flexible system integration. As understanding of nanometer-scale behavior deepens and large-scale manufacturing matures, MXene-based flexible MSCs are well positioned to lead a new era of scalable, high-performance, and structurally adaptive energy storage technologies.

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